Spinning Light: Searching for Axion Dark Matter with Magnetic Haloscopes

Asher Berlin, Alex Millar, Tanner Trickle and Kevin Zhou
arXiv:2312.11601

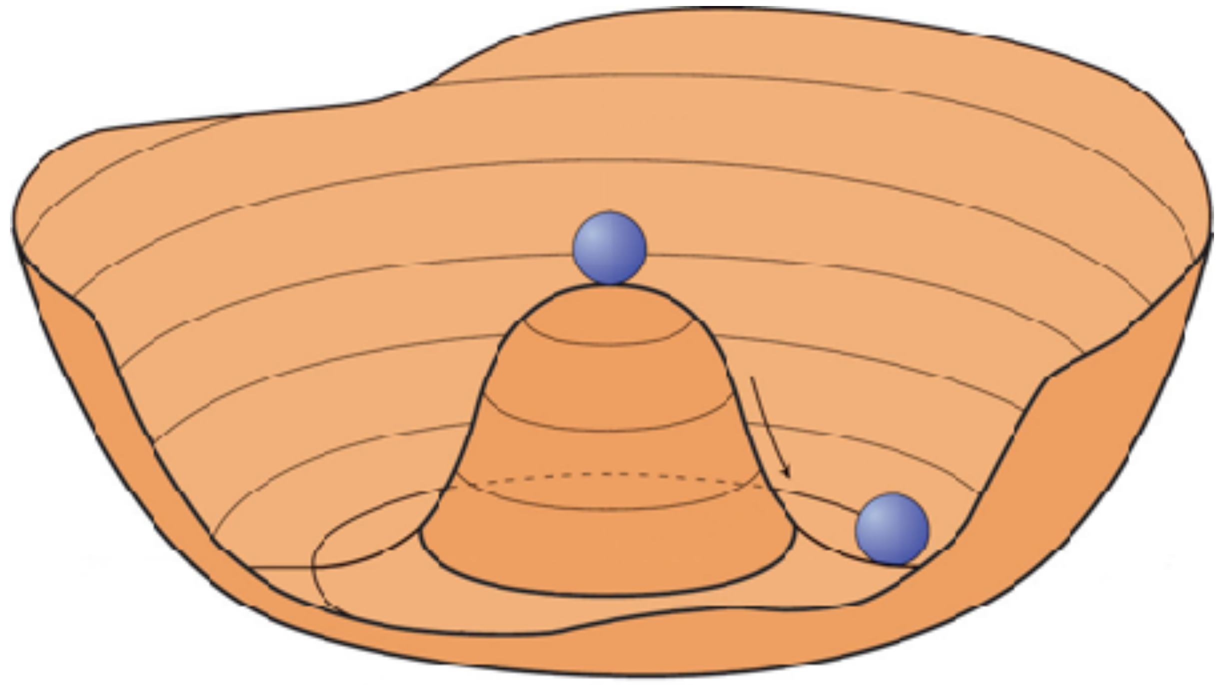
Outline

- Axion-electron interactions
- Mechanical Forces
- Absorption
- Electric Dipole Moments
- Magnetic Haloscopes

Axions

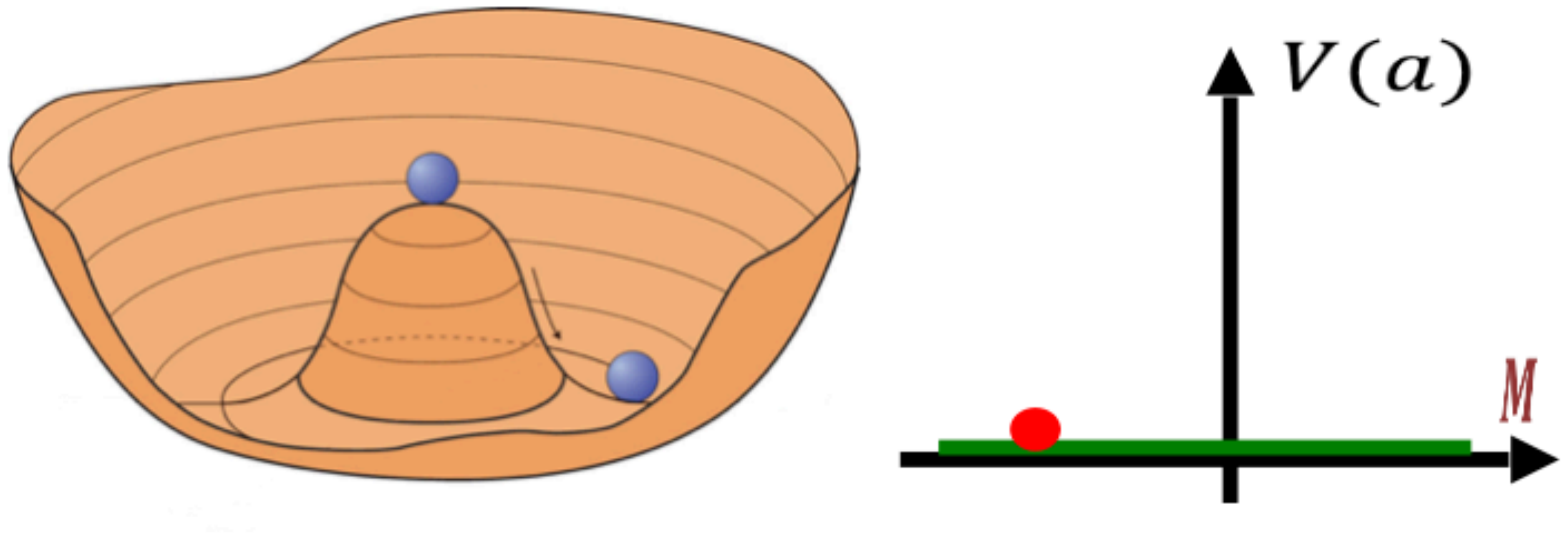
- Solution to the Strong CP problem: make θ a dynamical field so it can minimise the energy and send θ to zero
- Need a new anomalous U(1) chiral symmetry (Peccei-Quinn), which is broken at high temperature ~f_a (around 10^{12} GeV)

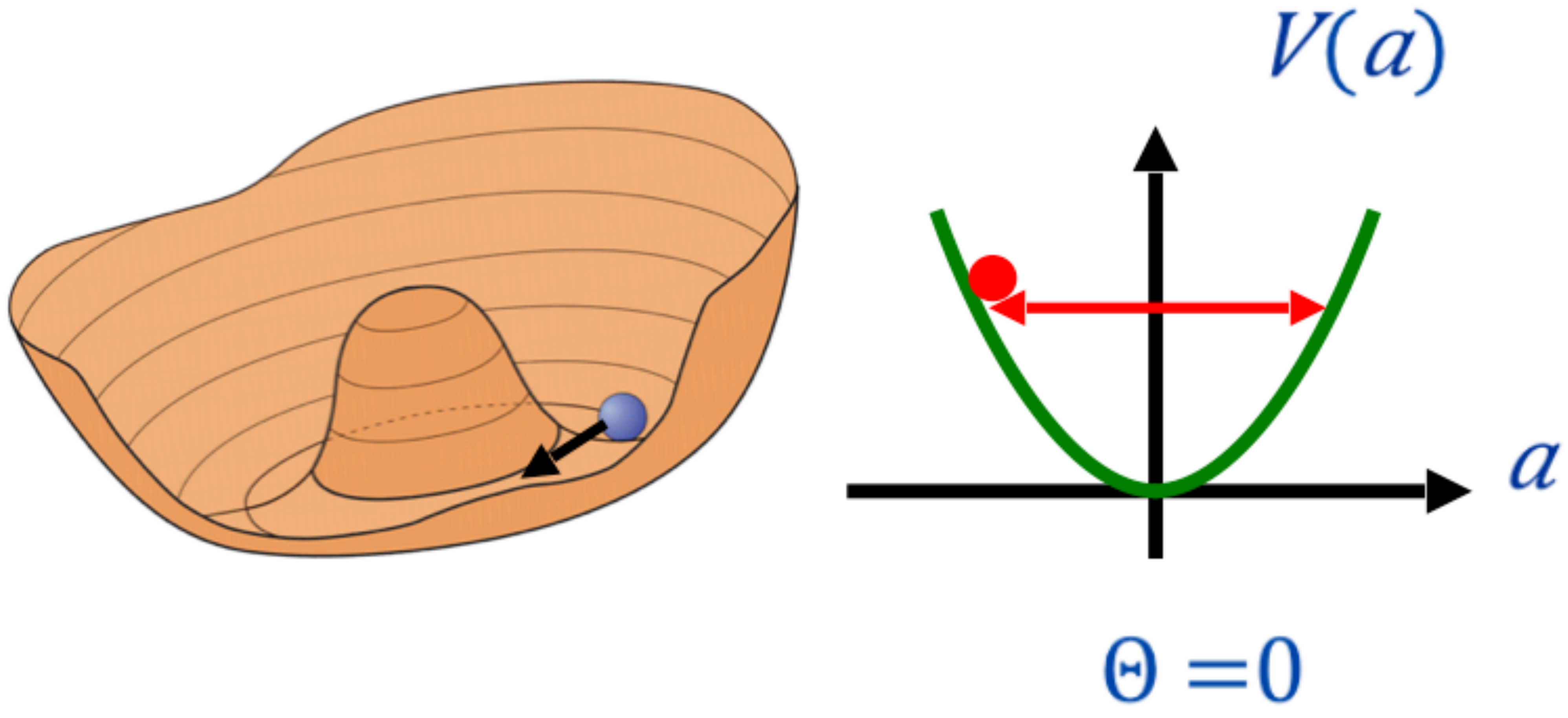
$$\mathscr{L}_{\text{stand mod + axion}} = \ldots + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



Axions

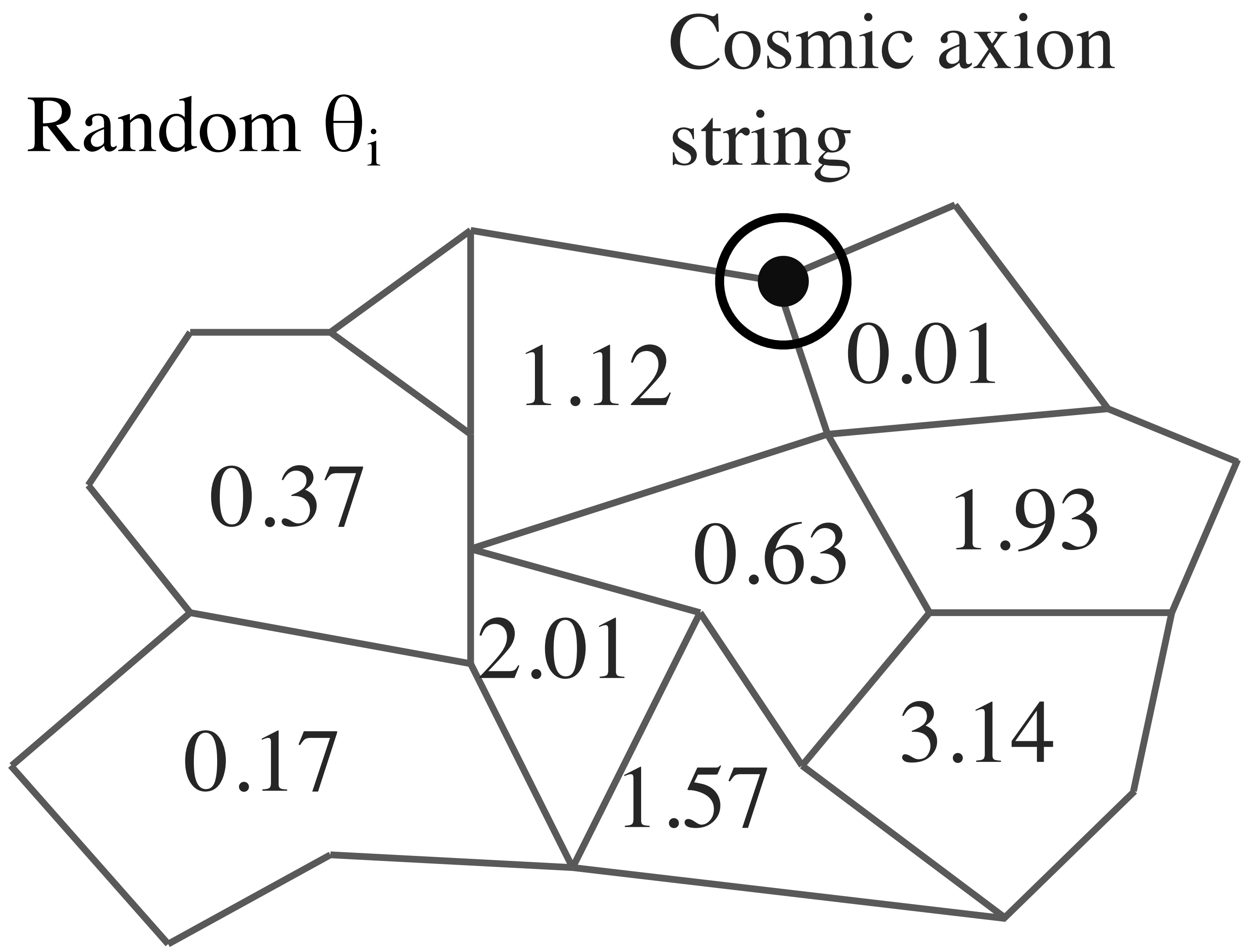
- The "axion" is the angular degree of freedom: goldstone mode!
- At the QCD scale the potential tilts as the axion acquires a mass – axion rolls down to a CP conserving minimum
- Can be produced by misalignment or topological defects





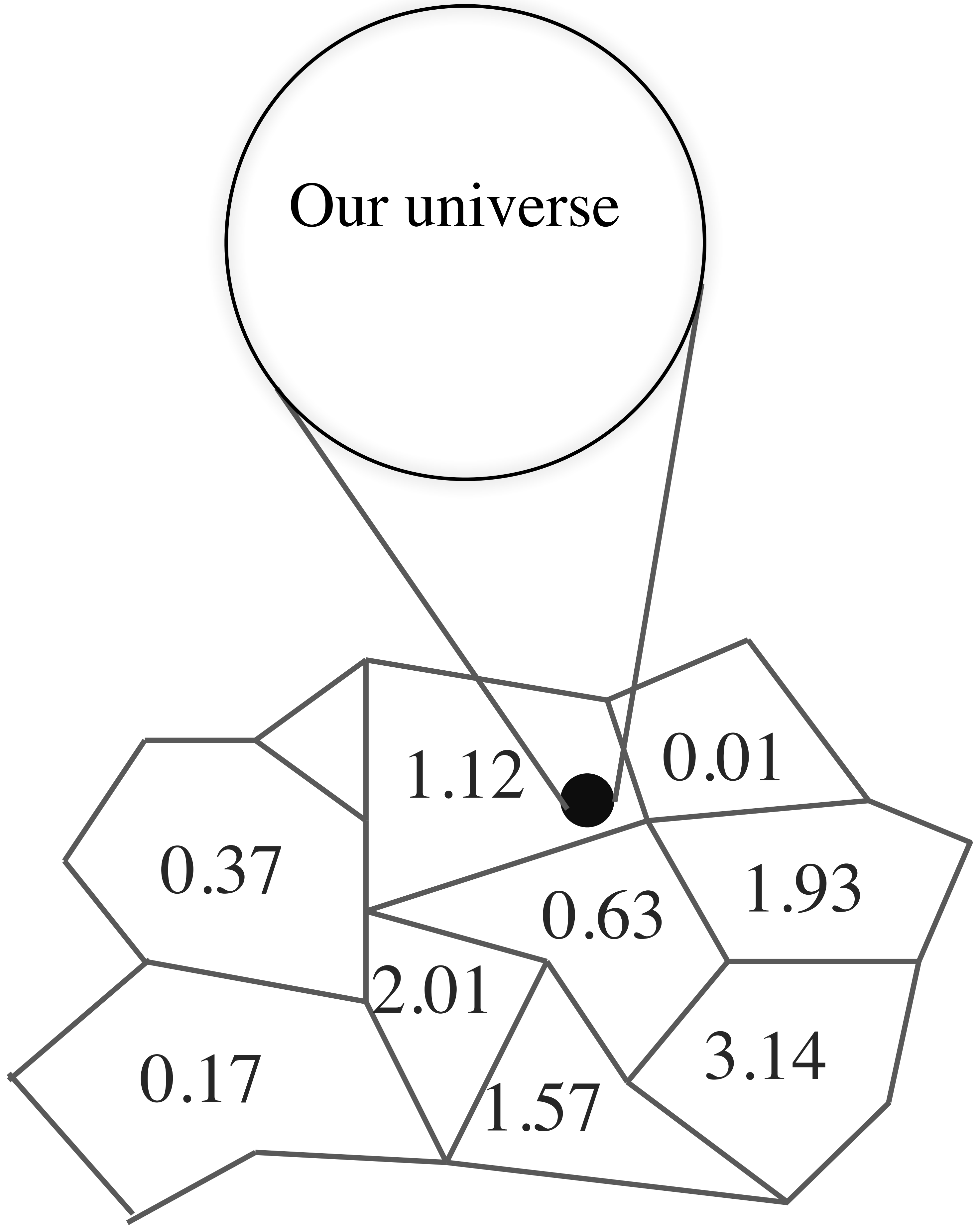
Axion DM: Scenario 1

- Scenario 1: PQ broken after inflation
- θ_i has random values in every casual region, with the dark matter density determined by the average
- Topological defects such as strings and domain walls exist in the early universe



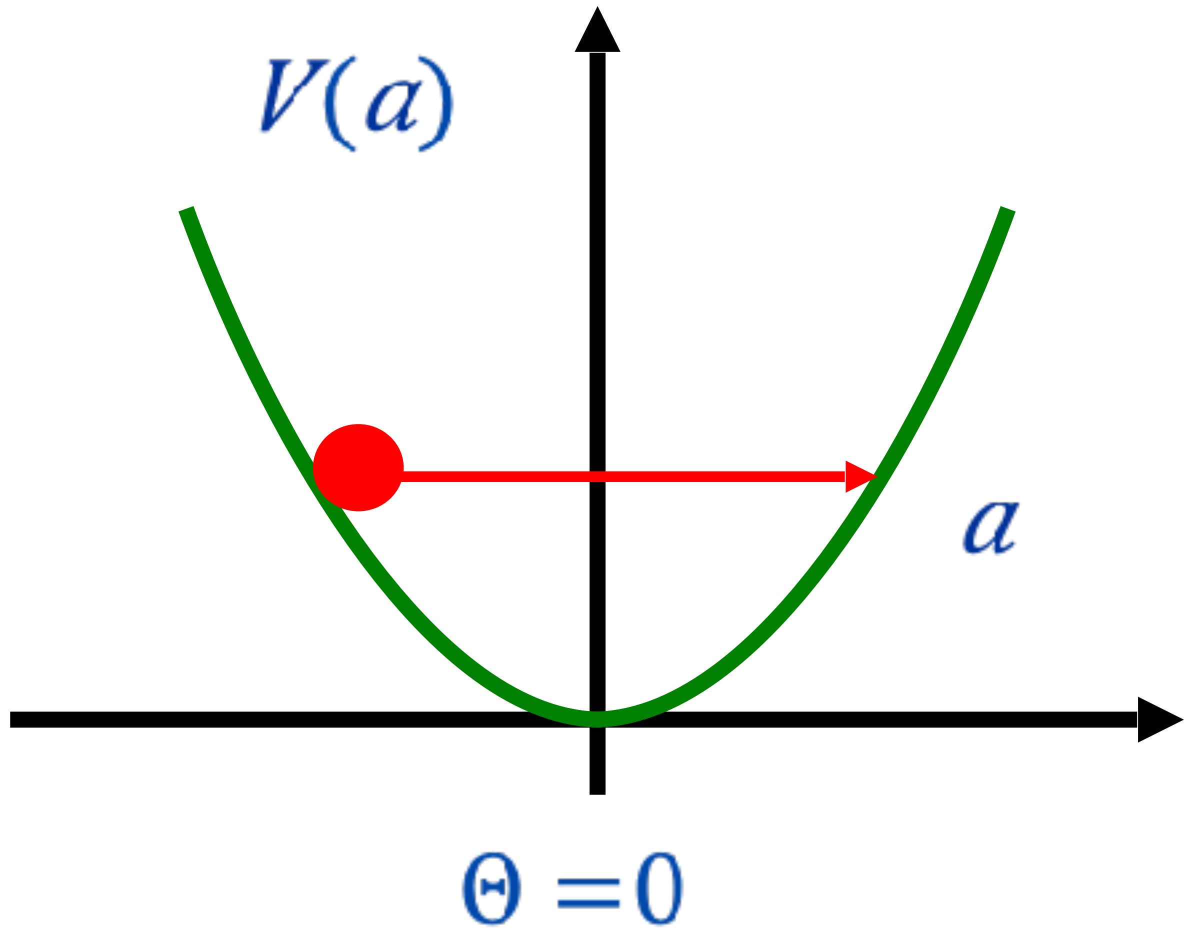
Axion DM: Scenario 2

- Scenario 2: PQ broken before inflation
- θ_i has a single random value which determines the dark matter density
- No topological defects

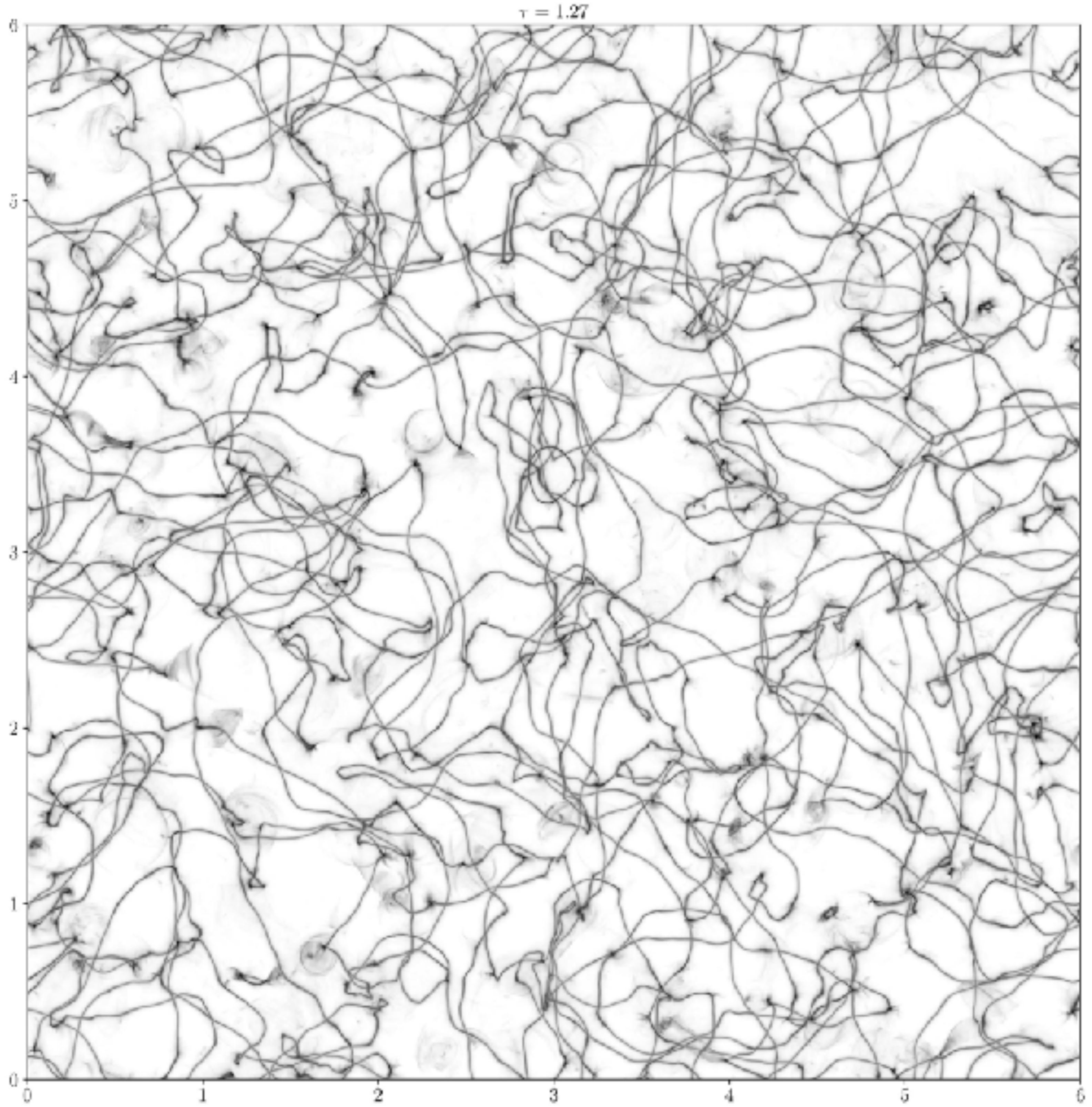


Axion Production Mechanisms

Vacuum Misalignment



Decay of topological defects



arXiv:1809.09241

Axion Production Mechanisms

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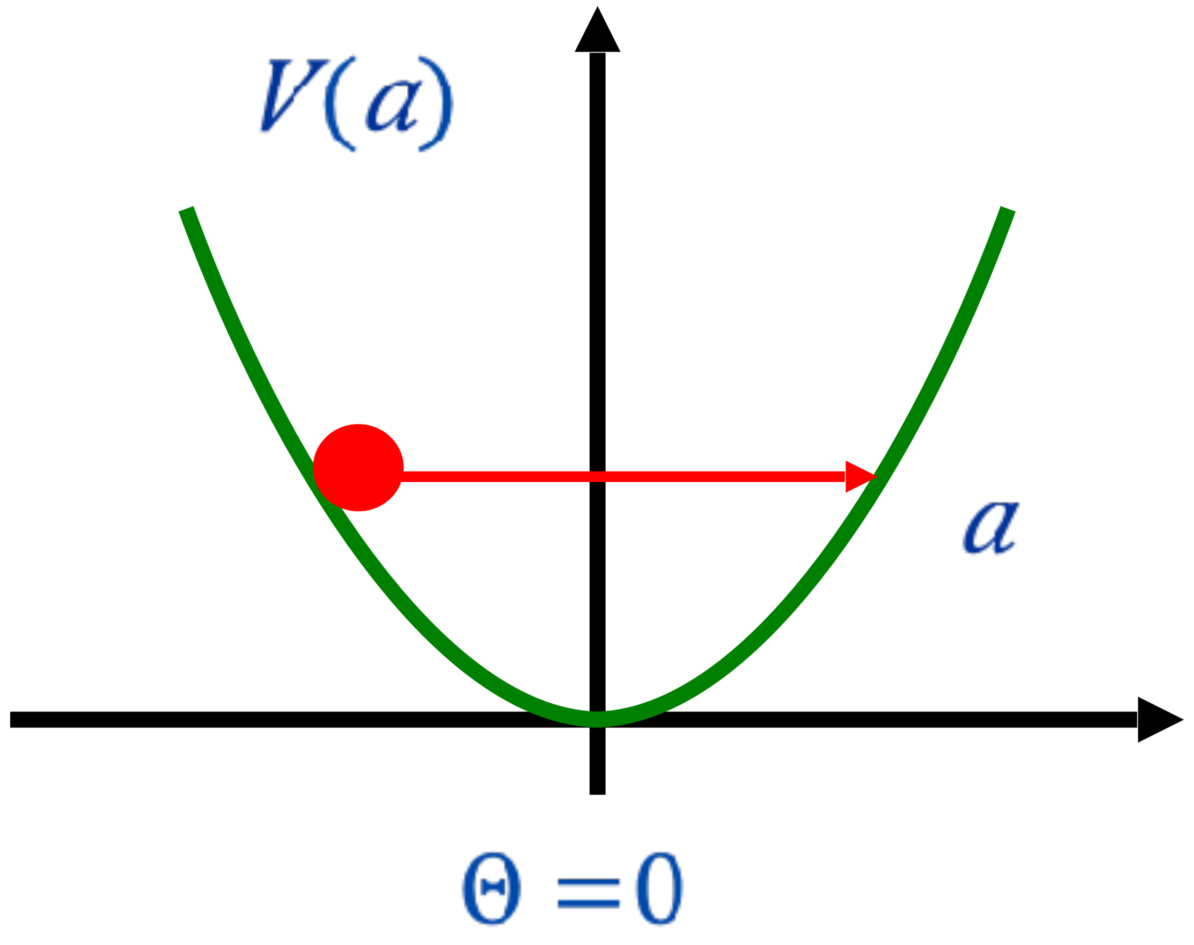
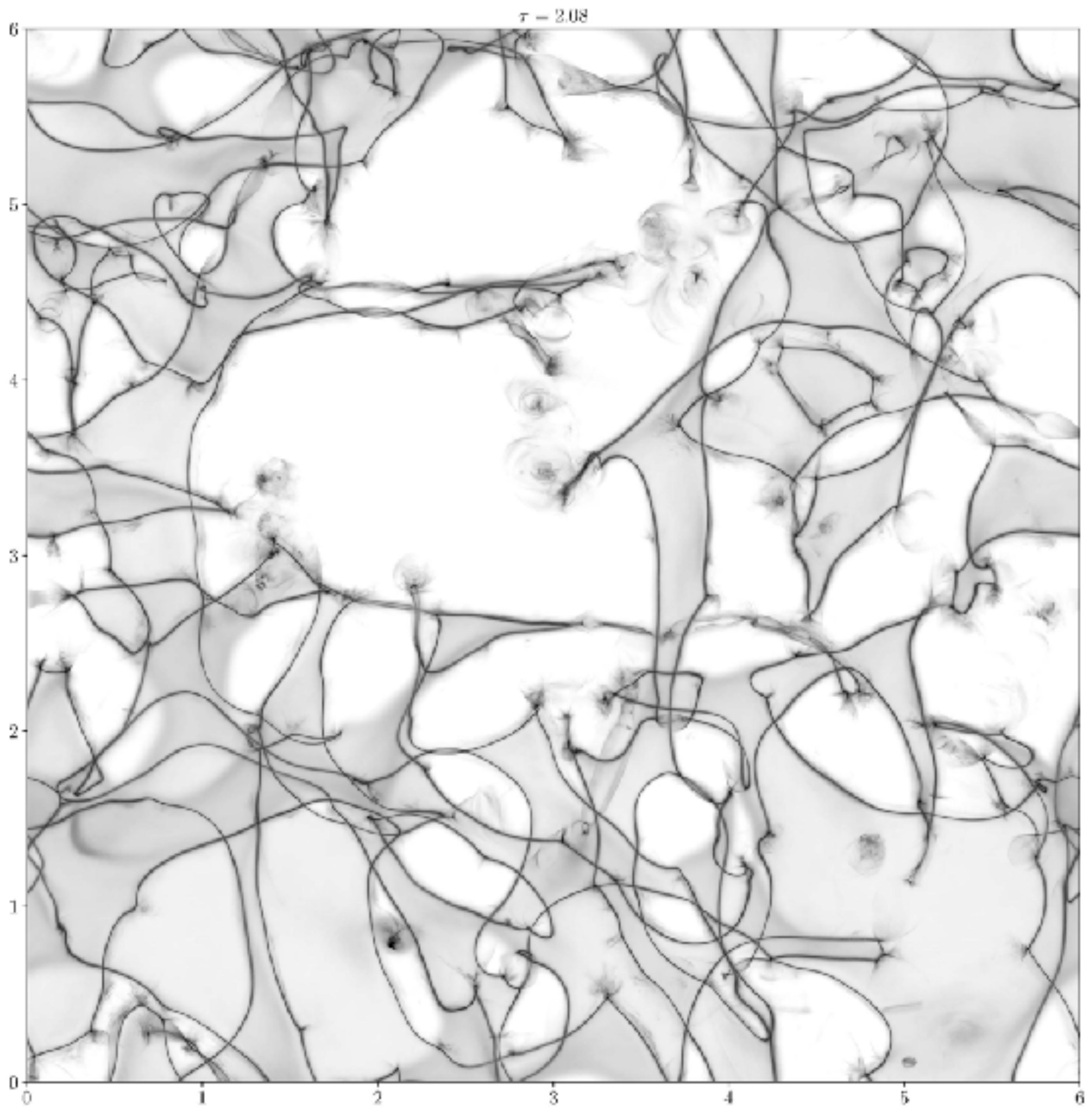


Decay of topological defects



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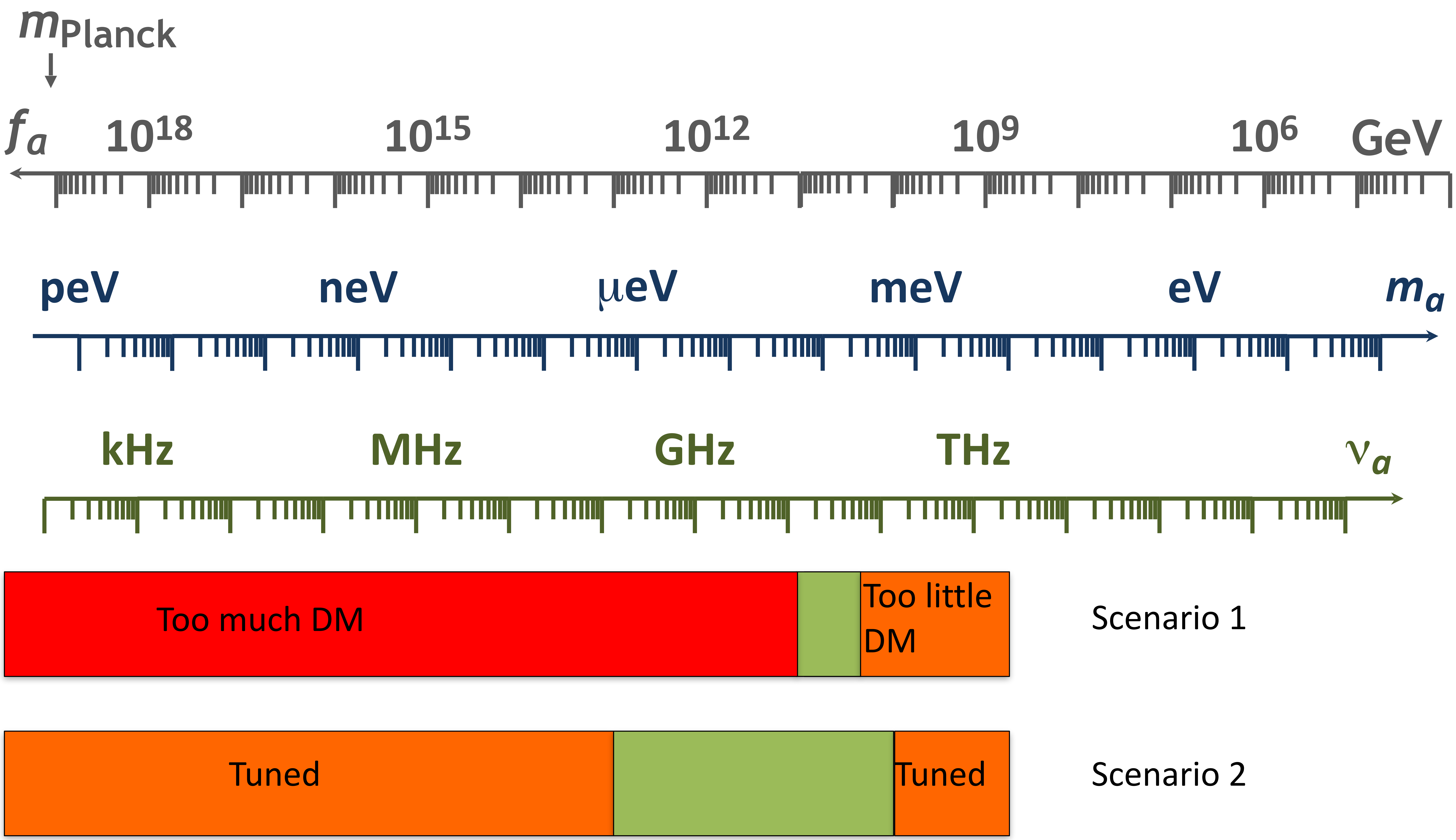
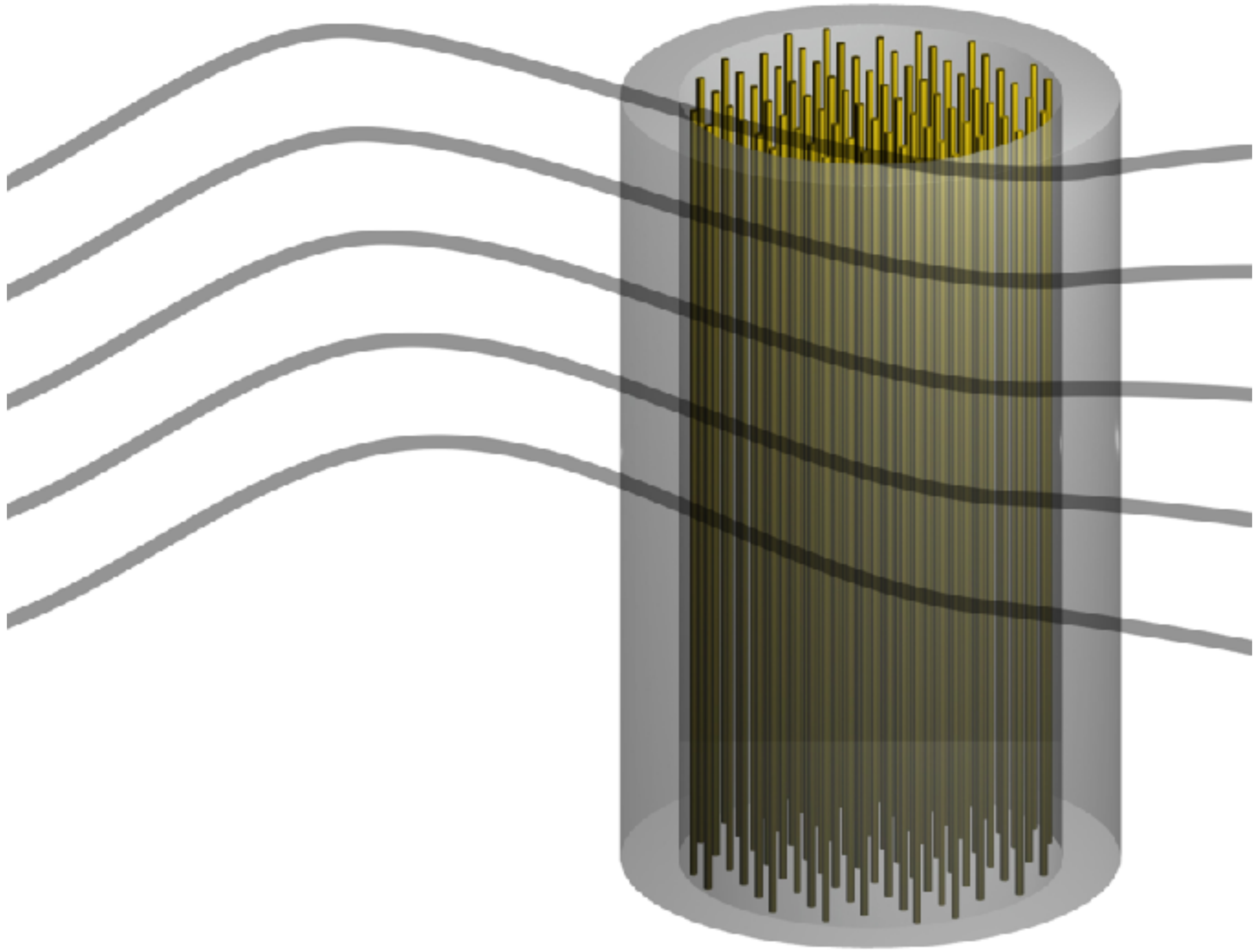

m_{Planck}
f_a
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
GeV
peV
neV
μeV
meV
eV
m_a
kHz
MHz
GHz
THz
ν_a
Too much DM
Too little DM
Scenario 1
Tuned
Tuned
Scenario 2

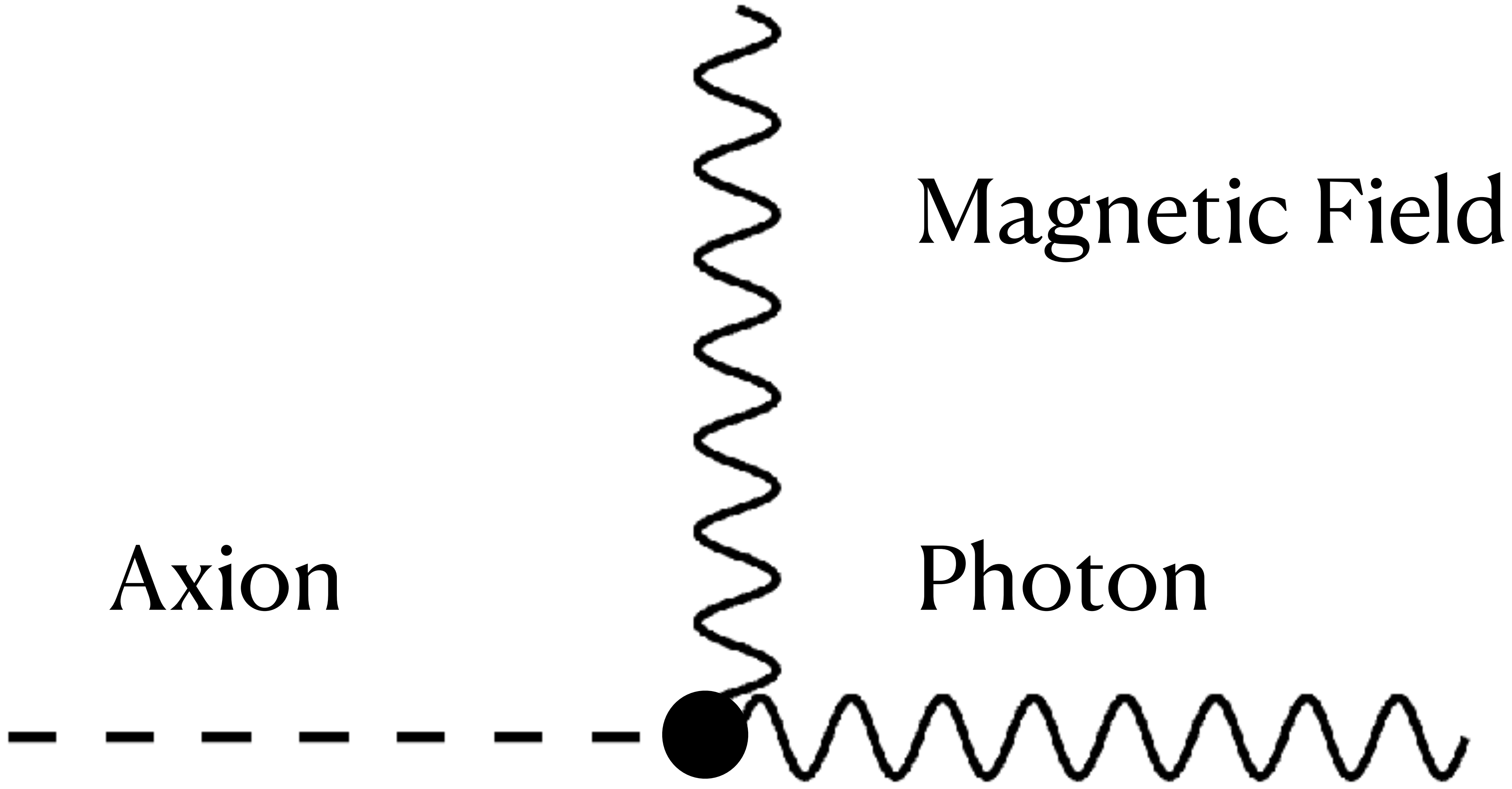
How Do You Find a Wave?

- 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

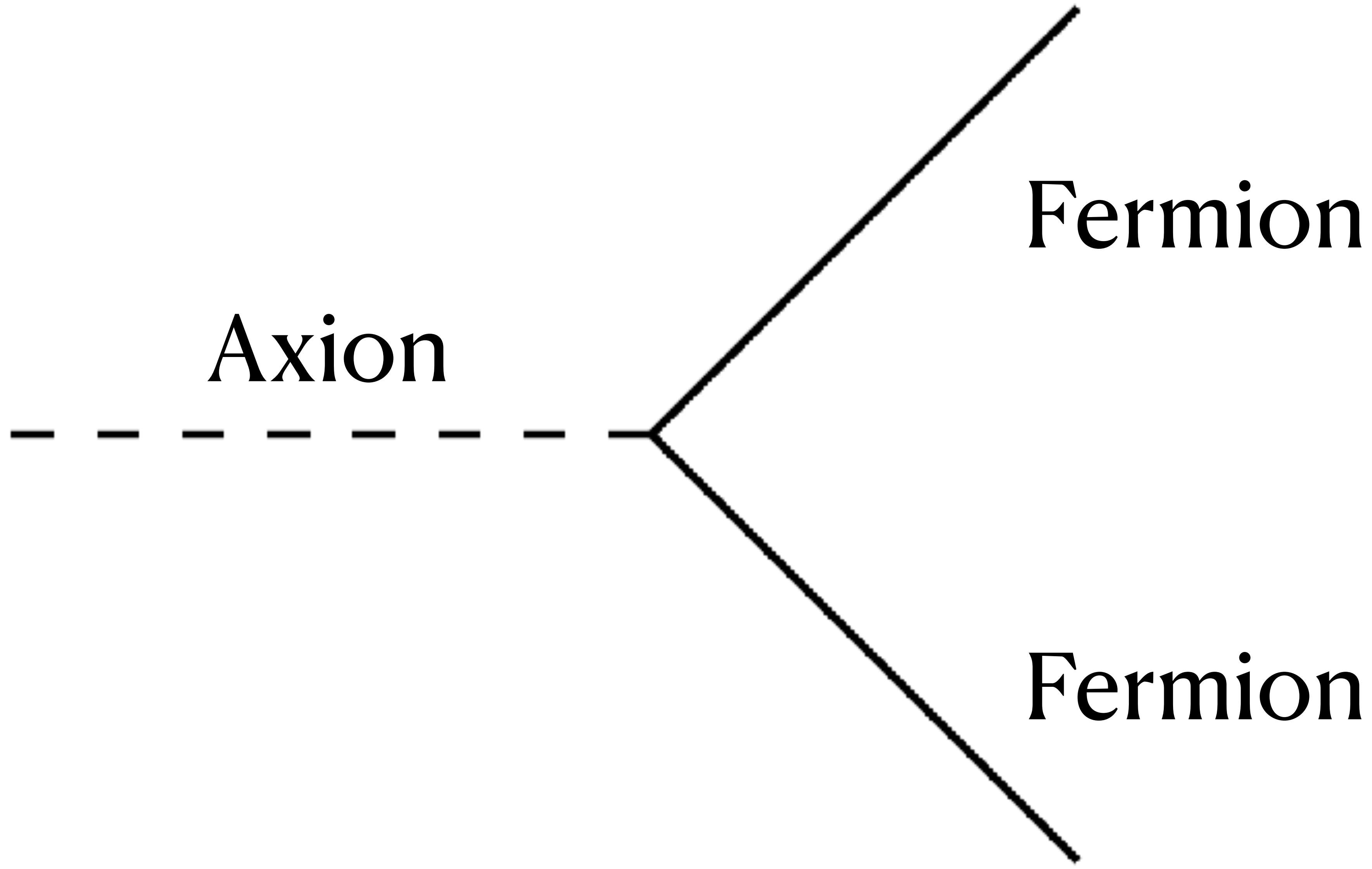


Axion Interactions

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



Coupling to electromagnetism



Coupling to matter (mostly spin)

Axion Interactions

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

Coupling to matter (mostly spin)

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

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

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

Wind

Axio-electric

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

Axion-Induced Torques

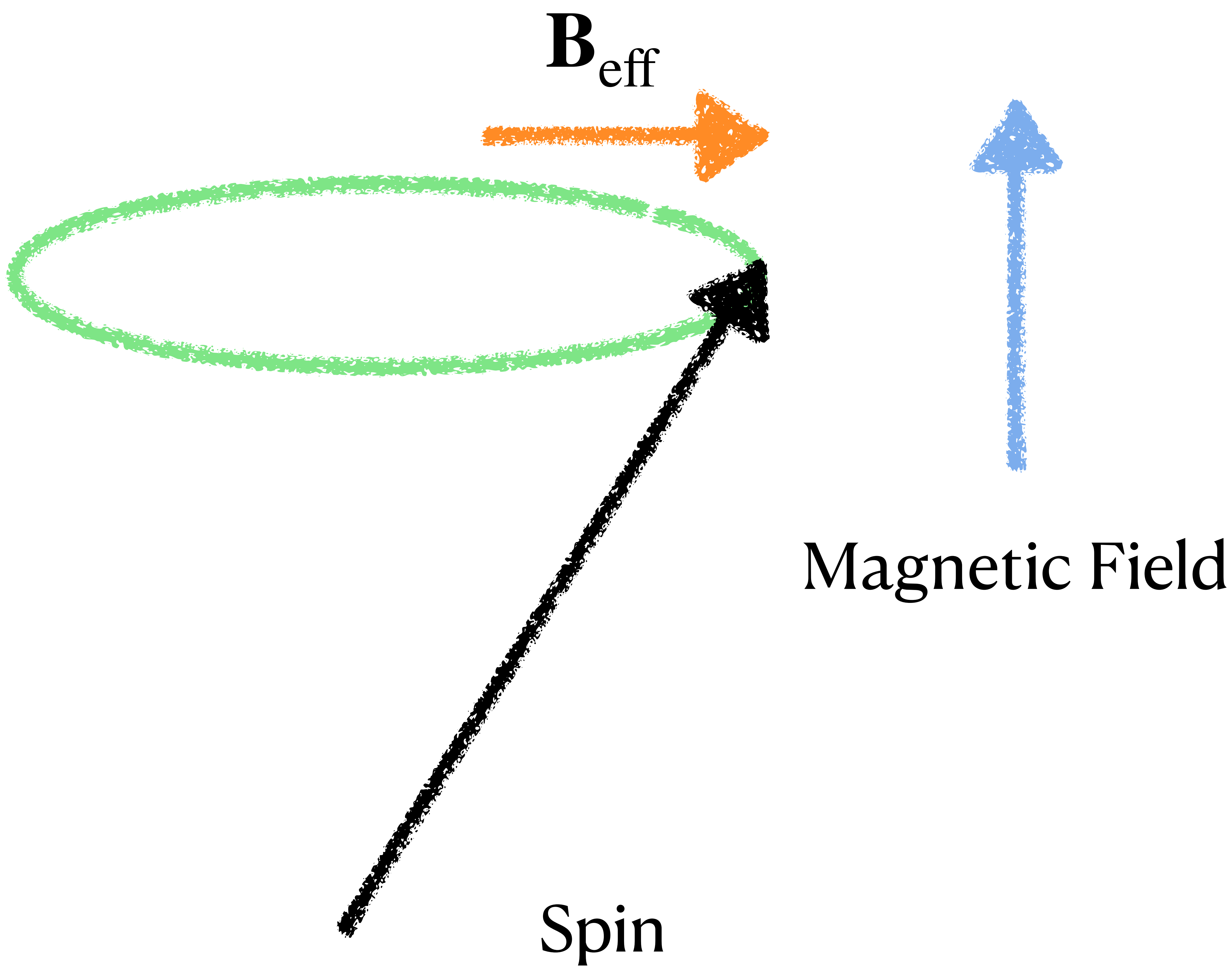
- Most well known effect of axion-fermion couplings
- Acts on spins similarly to a B-field

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

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

Axion-Induced Torques

- Most exploited fermion coupling
- Can use nuclear magnetic resonance techniques
- Includes CASPER WIND and ferromagnet haloscopes like QUAX
- Tends to be most important for low axion masses



Axion-Induced Forces

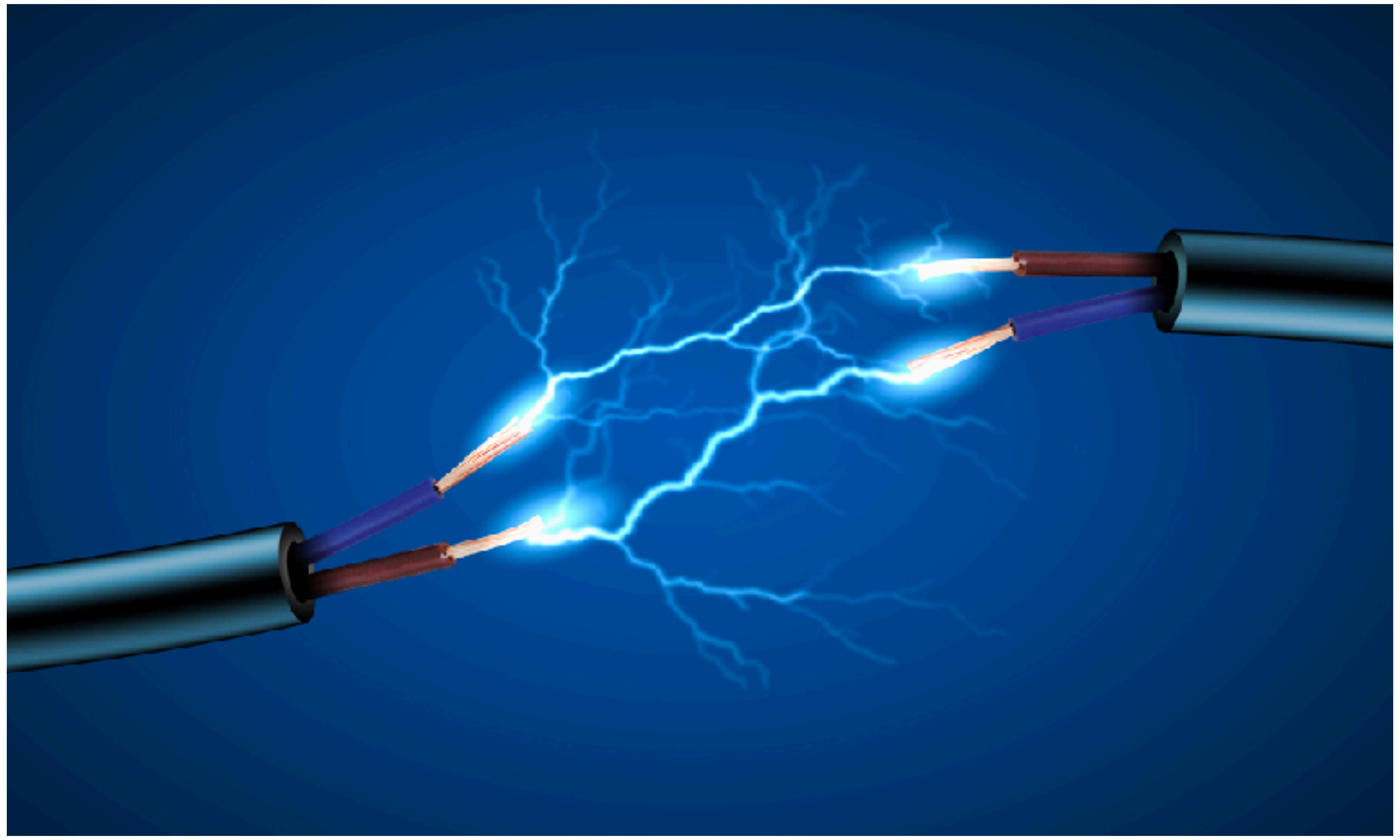
- How does the axio-electric term act on the electron?
- Need to generalize the Lorentz force law

$$\mathbf{F} \equiv m_f \frac{d\mathbf{v}}{dt} \simeq q\,\mathbf{E} + q\,(\mathbf{v} \times \mathbf{B}) + \mu_f\,(\boldsymbol{\sigma} \cdot \mathbf{B}) - \boxed{g_{af}\,\frac{d}{dt}\,(\dot{a}\,\boldsymbol{\sigma})}$$

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

Axion-Induced Forces

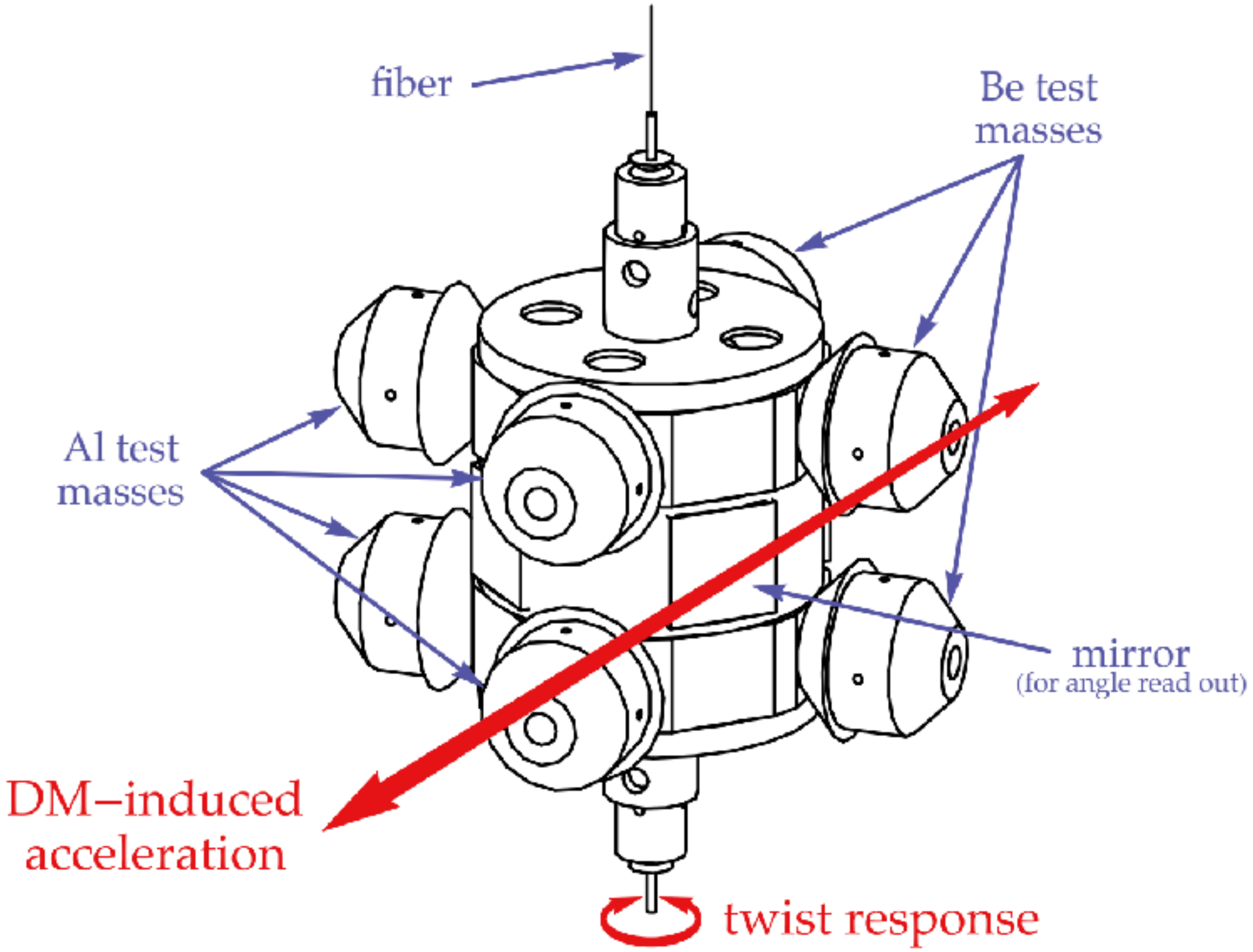
- This looks like an E-field, but it couples to spin rather than to charge
- Spin polarized case not well studied in the literature!



Mechanical Forces

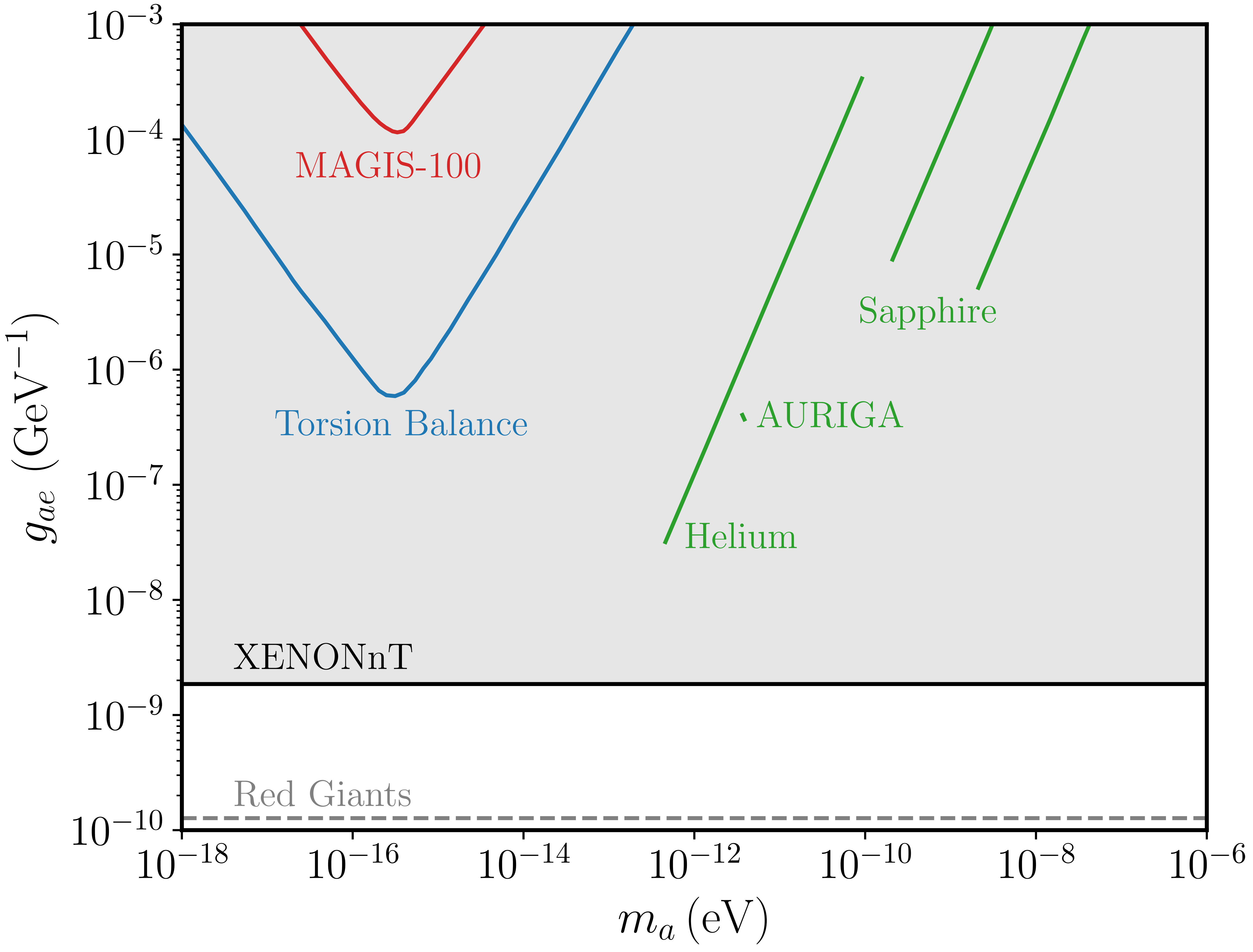
- Axio-electric term accelerates electrons
- What about bulk motion?
- Can use mechanical detectors like torsion balances to search for accelerations of spin-polarised materials
- Doesn't seem to be competitive

$$\Delta a_{af} \simeq \frac{g_{af}\,\omega_{\rm sig}\sqrt{\rho_{\rm DM}}}{m_n}\frac{2f_s}{A}$$



arXiv:1512.06165

Mechanical Forces



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

$$(\partial^2 + m_a^2)\, a = -g_{ae}\left(\underset{\substack{\uparrow\\ \text{Axio-electric}}}{\partial_t j_\sigma} + \underset{\substack{\uparrow\\ \text{Wind}}}{\nabla\cdot\mathbf{n}_\sigma}\right)$$

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

Absorption: Axio-Electric

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

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

Absorption: Wind

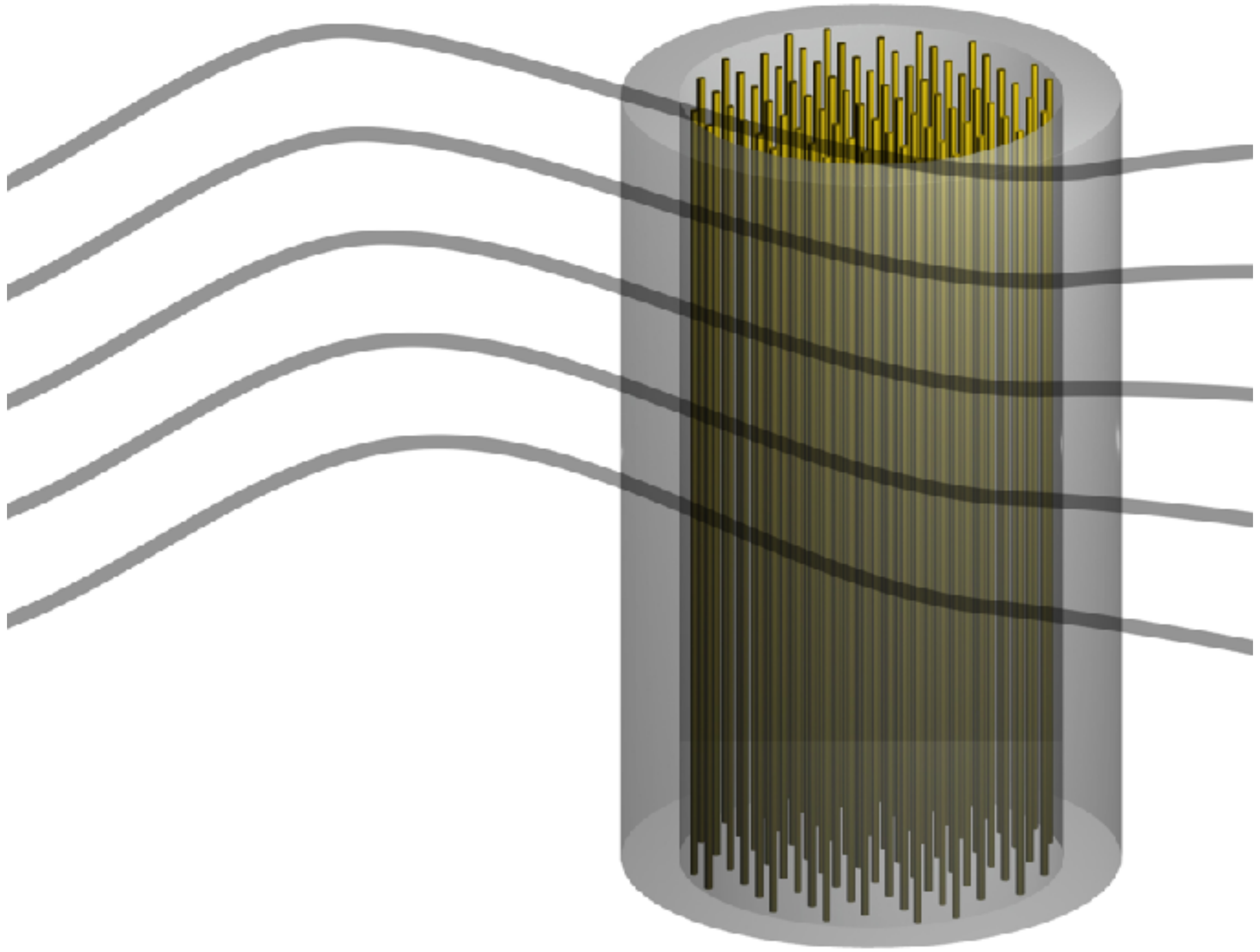
- Axion absorption onto magnons is not new (arXiv:2005.10256)
- Only been done from first principles calculations
- More generally one can just consider an arbitrary magnetized medium
- Magnetic equivalent of the “energy loss function”

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

- 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…
- Im[-1/ε] and Im[-1/μ] dependence should allow for similar devices
- I.e., spin polarized plasma haloscopes or QUAX



Spurious EDMs

- Often the axion induced electronic EDM is overestimated (or assumed constant).
- You can do a field redefinition to get

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

- With non-relativistic Hamiltonian

Looks like EDM

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

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

Electromagnetic Effects

- Effective E-field causes charges to move: generates a polarization!
- Effective B-field causes spins to torque: generates magnetization!

$$\mathbf{P} = \mathbf{P}_0 + \mathbf{P}_a = (\varepsilon - 1)\,\mathbf{E} + (\varepsilon_{\sigma e} - 1)\,\mathbf{E}_{\text{eff}}$$

$$\mathbf{M} = \mathbf{M}_0 + \mathbf{M}_a = (1 - \mu^{-1})\,\mathbf{B} + (1 - \mu^{-1})\,\mathbf{B}_{\text{eff}}\ .$$

- Effective E-field requires a spin polarised sample (where both epsilons are almost equal)
- Effective magnetization requires magnetic materials

Axion Induced Currents

- New currents to source Maxwell equations

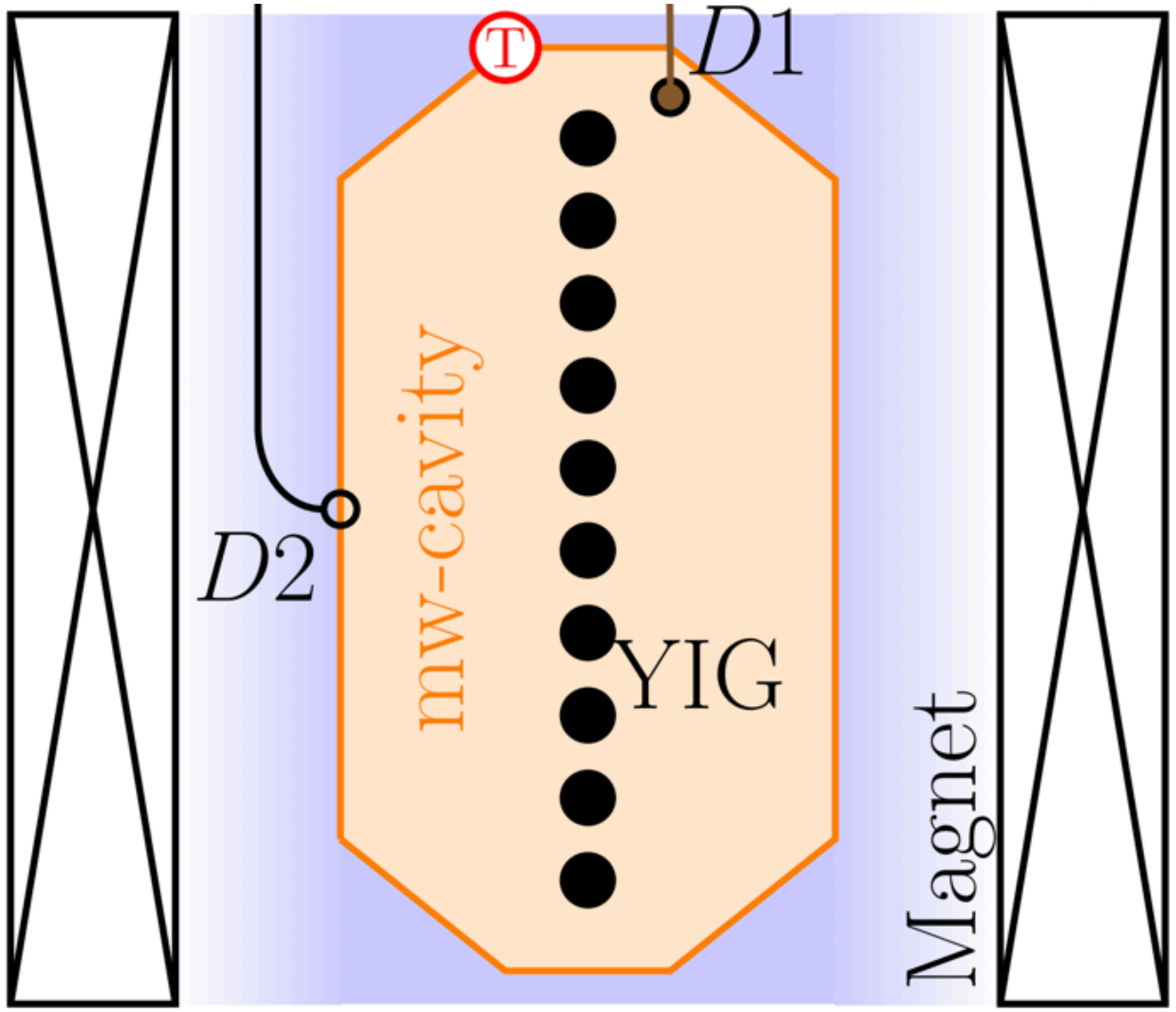
$$\mathbf{J}_a = \mathbf{J}_a^P + \mathbf{J}_a^M = (\varepsilon_{\sigma e} - 1)\,\partial_t \mathbf{E}_{\text{eff}} + \nabla \times \left((1 - \mu^{-1})\,\mathbf{B}_{\text{eff}}\right)$$

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

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

Example: QUAX

- Small balls of YIG generate currents which ring up a cavity
- Hasn't been analyzed in the language of currents
- YIG has high Q but very hard to get large samples
- Most of the cavity is empty
- Requires near perfect samples
- What about other geometries or materials?



arXiv:2001.08940

Axion-Electrodynamics

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

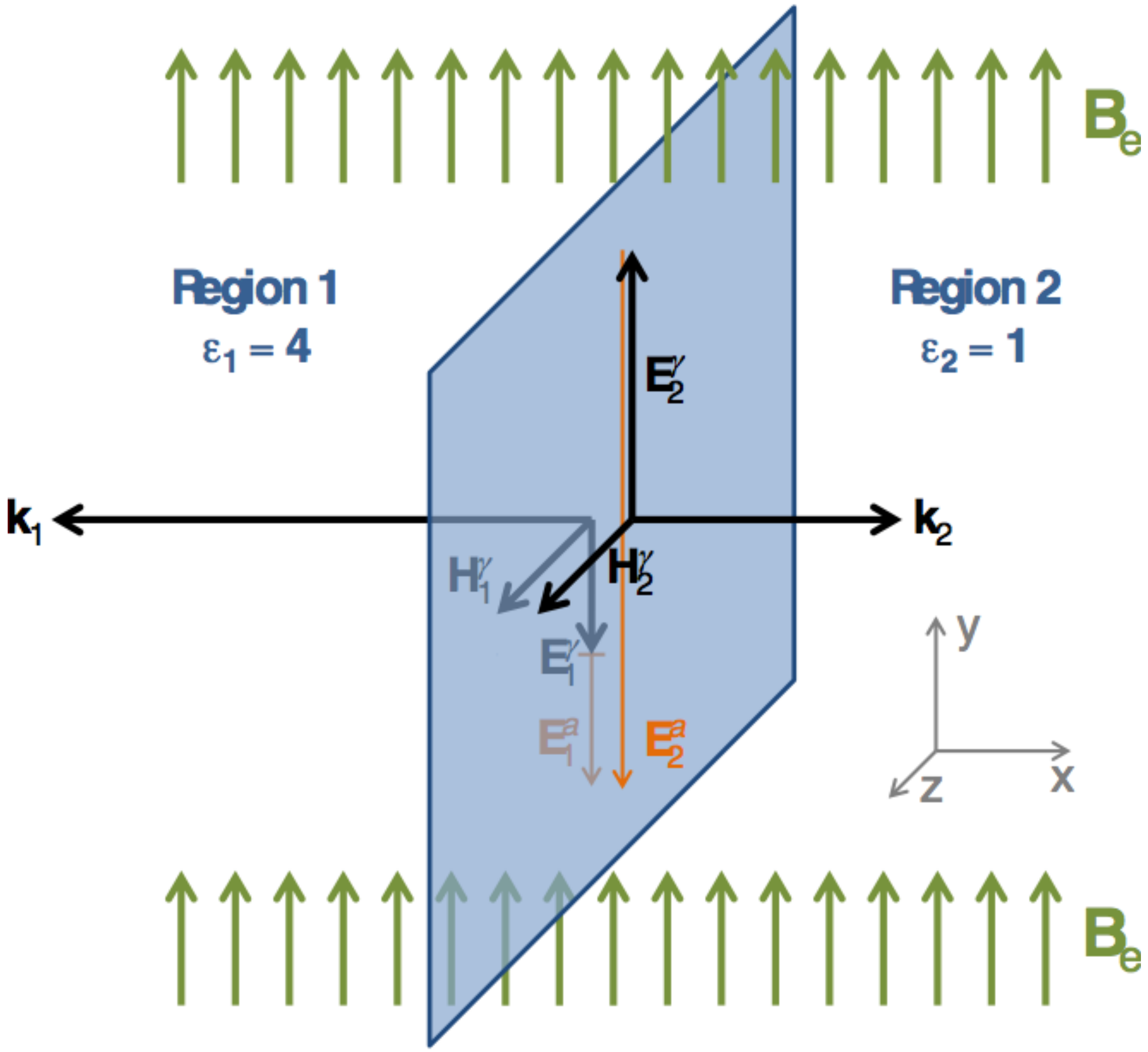
$$
\begin{aligned}
\nabla \cdot (\epsilon \mathbf{E}) &\simeq \rho_f \,, \\
\nabla \times (\mathbf{B}/\mu) - \epsilon \dot{\mathbf{E}} &\simeq \mathbf{J}_f + \boxed{g_{a\gamma} \mathbf{B}_\mathrm{e} \, \dot{a} \,,} \\
\nabla \cdot \mathbf{B} &= 0 \,, \\
\nabla \times \mathbf{E} + \dot{\mathbf{B}} &=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

Looks like a current!

Dish Antenna

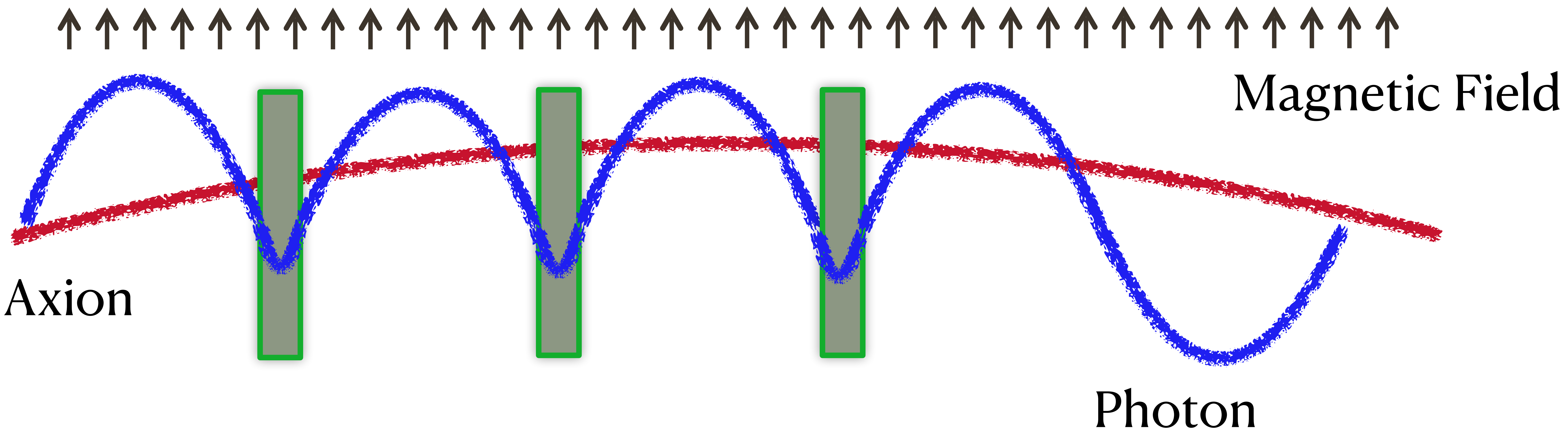
- E_a depends on the medium, so changing media causes a discontinuity (arXiv:1212.2970).
- EM won't tolerate discontinuities in the parallel E and H fields
- Regular EM waves are emitted to compensate
- No resonance!
- Completely broadband response

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



Dielectric Haloscopes

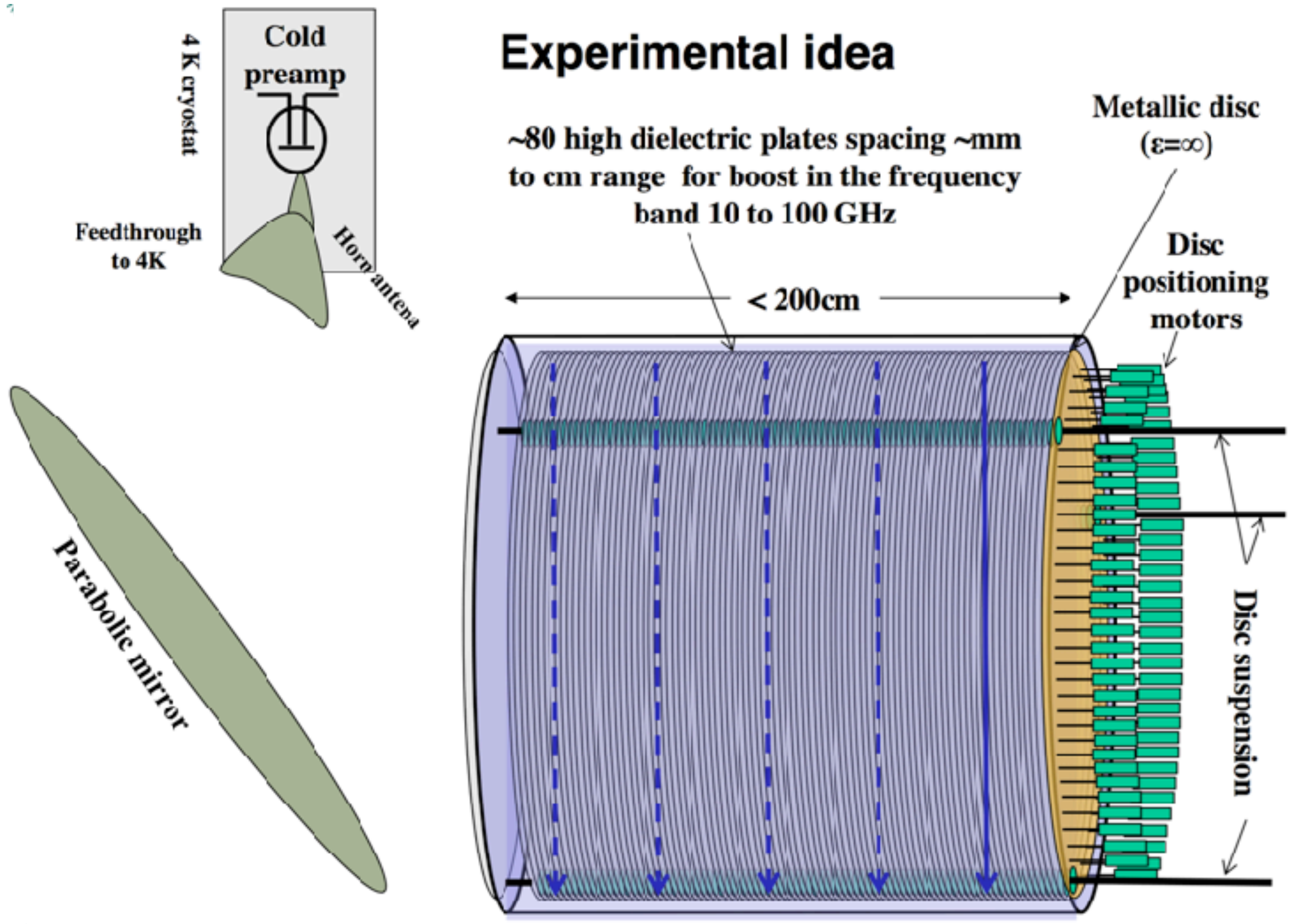
- Introduce a series of dielectric layers



- Boundary radiation emitted from each slab

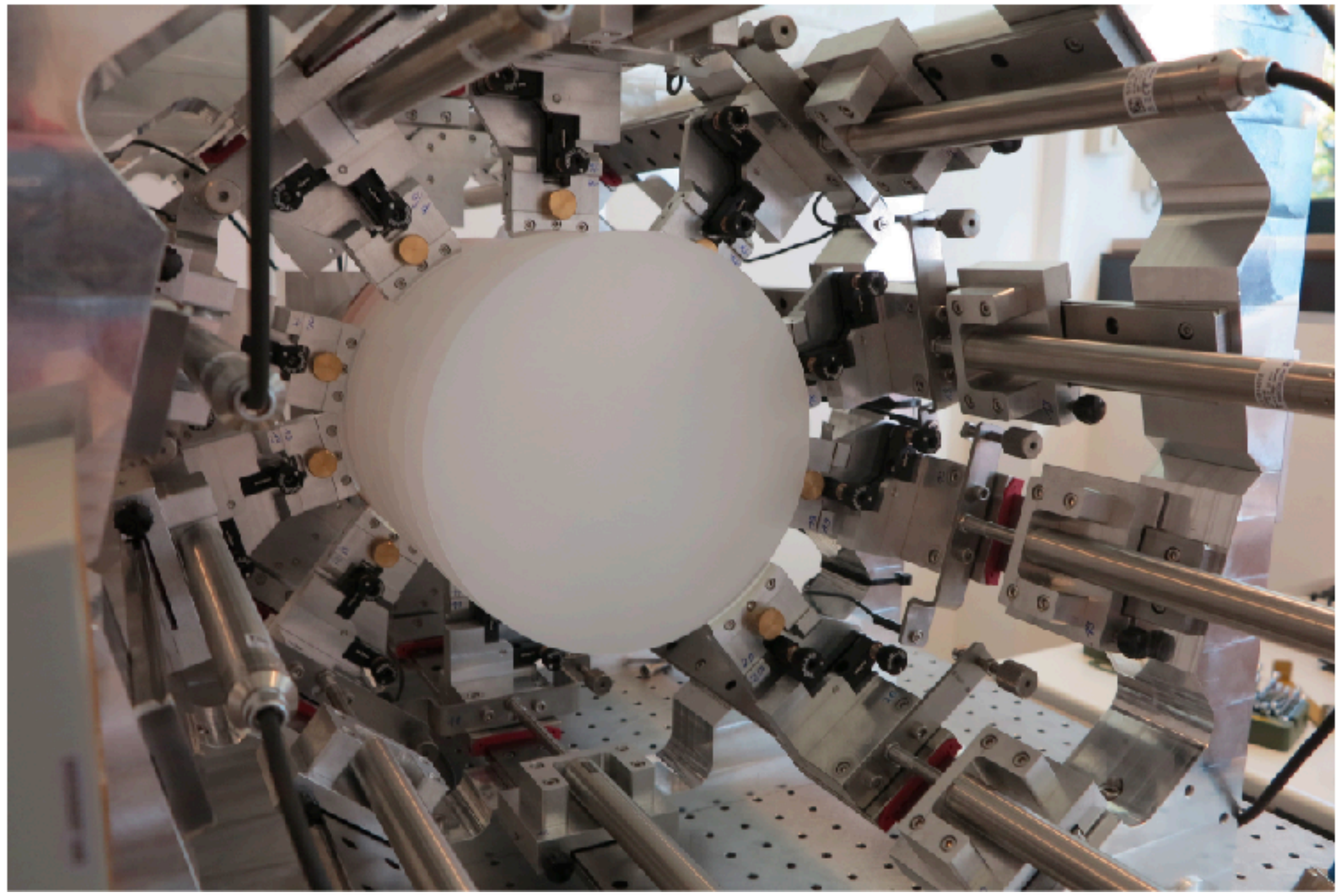
Dielectric Haloscopes

- Idea from the photon coupling (Caldwell, Dvali, Majorovits, AM, Raffelt, Redondo, Reimann, Simon, Steffen, *Phys. Rev. Lett.* 118 (2017))
- Arrange layers for constructive interference
- Tune frequencies by controlling disk spacings
- Many disks = strong signals

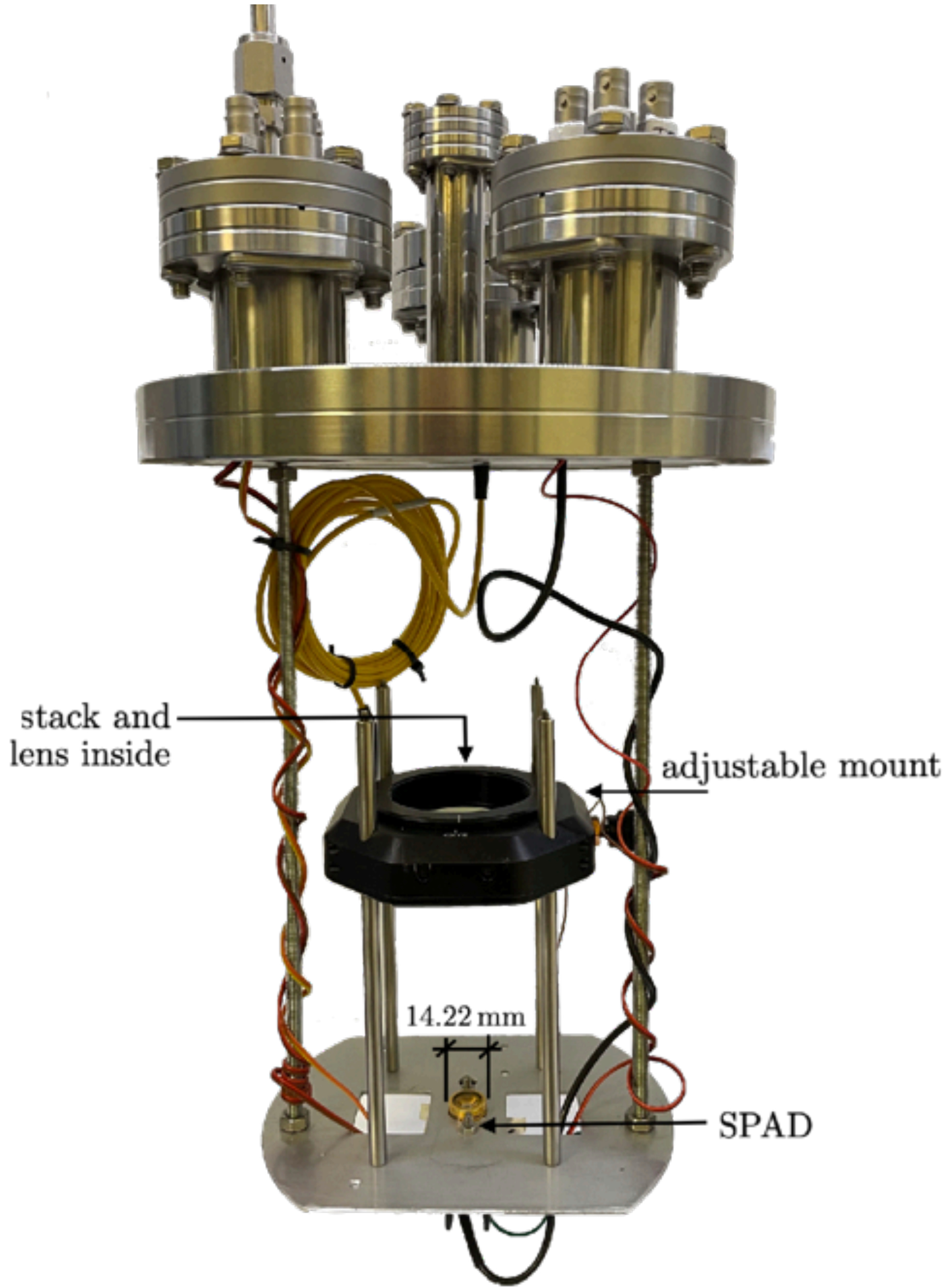


Dielectric Haloscopes

- 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

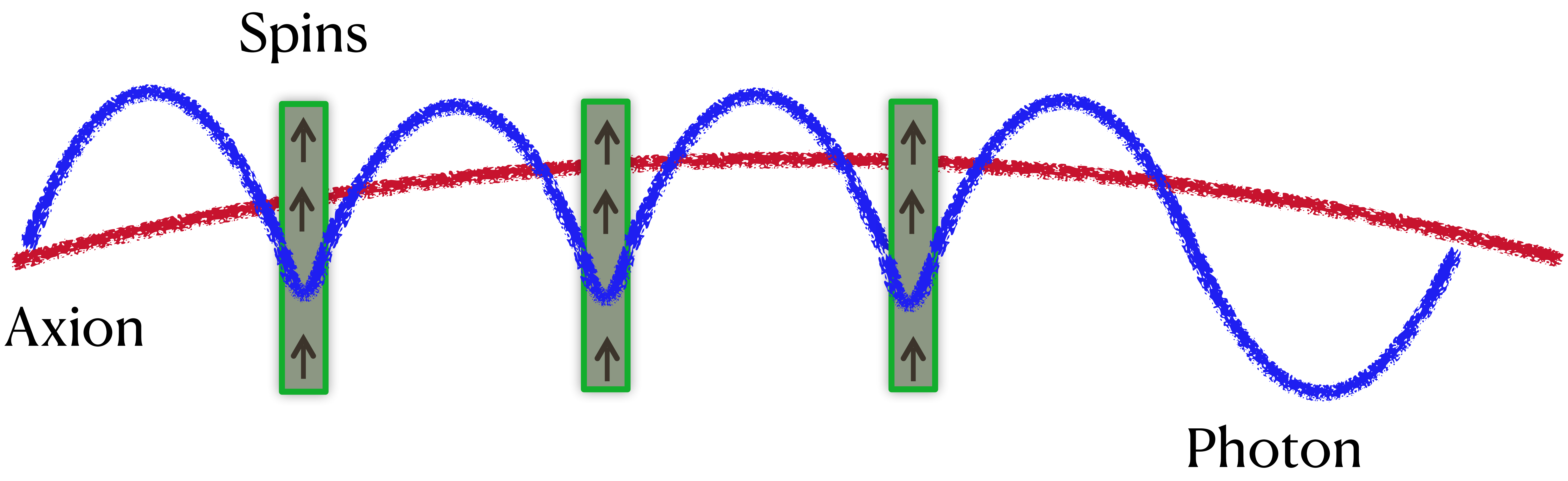
- The effective E-field moves charges which generate a “real” E-field

$$\mathbf{E} = \frac{1-\varepsilon_{\sigma e}}{\varepsilon}\,\mathbf{E}_{\rm eff}$$

- Can be discontinuous at boundaries!
- Details depend on how spin polarized the materials are

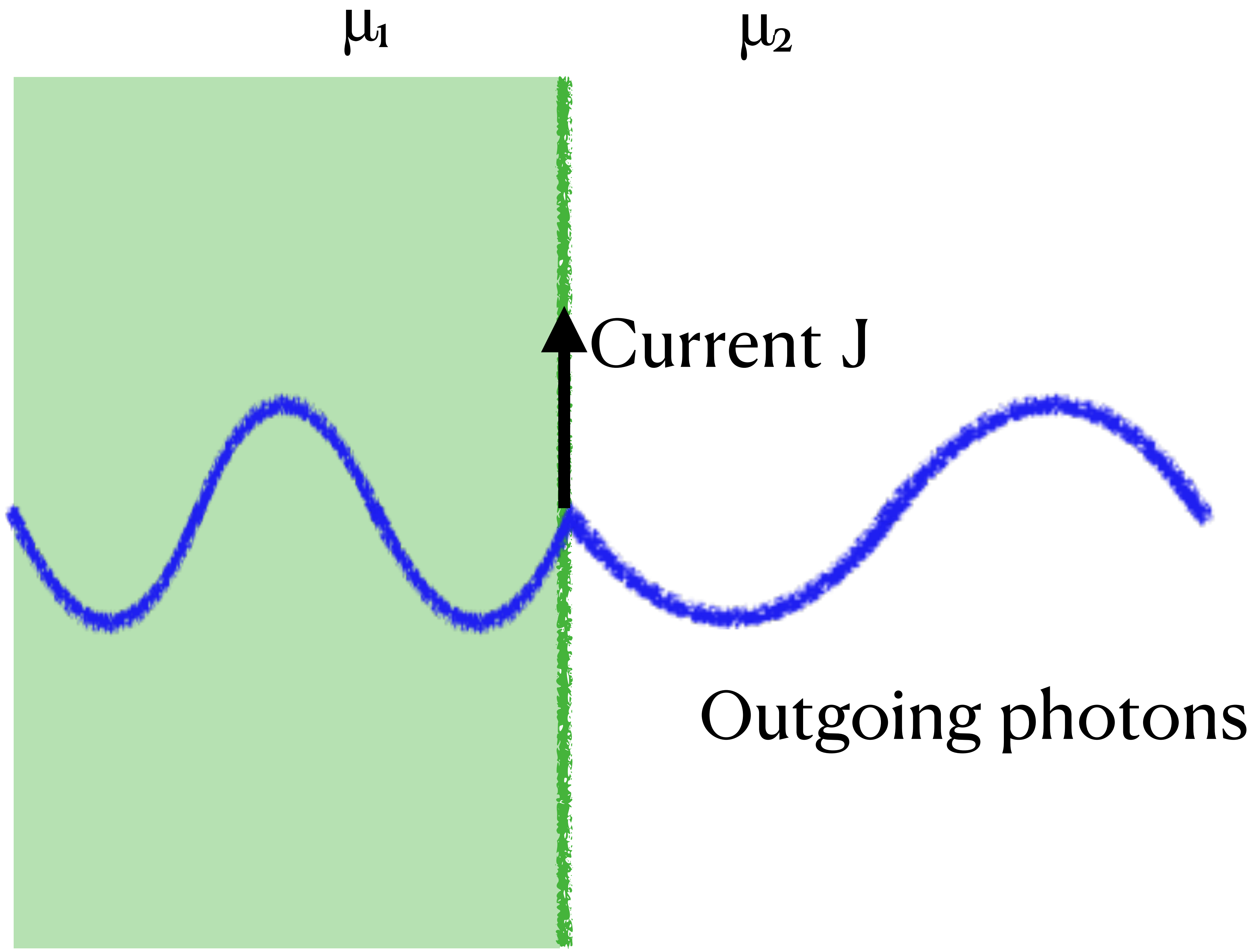
Case One: Axio-Electric

- 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!
  $\nabla \times \mathbf{B}_{\text{eff}} \propto \nabla \times (\nabla a/\mu)$
- Discontinuity in μ leads to boundary currents
- Doesn't directly map onto the photon coupling
- Better at lower frequencies



Case Two: Wind

- Full behavior needs a dedicated analysis
- Simple estimate extrapolated from N transparent slabs
- High frequency μ needs an applied B-field (Landau-Liftshitz-Gilbert equation)

$$1-\mu^{-1}=-\frac{2\mu_B\,M_0\,\omega_0}{\omega^2-\omega_M^2+i\,\omega\,\omega_M/Q_M}$$

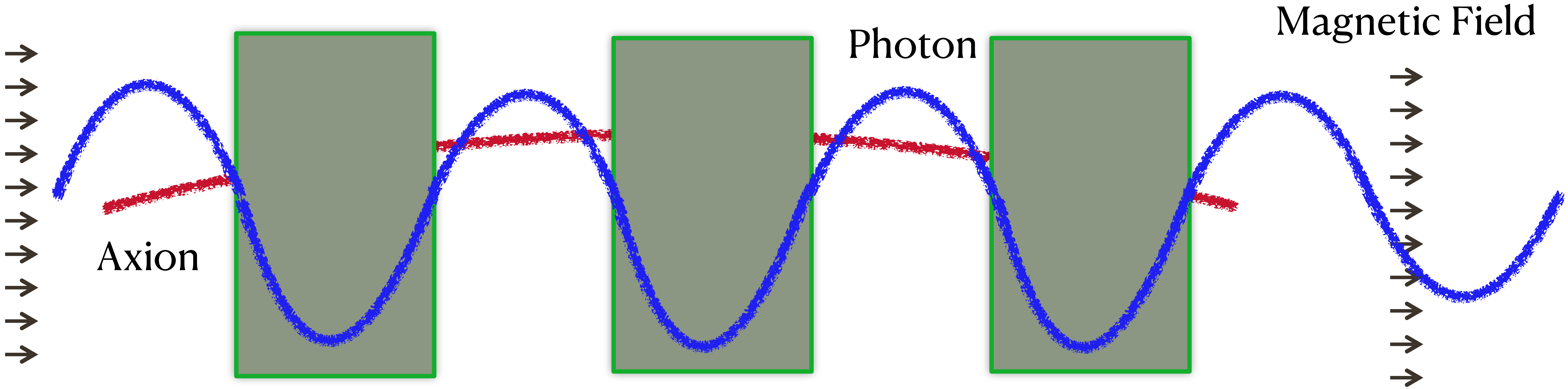
$$\omega_0\equiv 2\mu_B\left(H_0+\beta M_0\right)\quad,\quad \omega_M\equiv\sqrt{\omega_0\left(2\mu_B\,M_0+\omega_0\right)}$$

Case Two: Wind

- 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

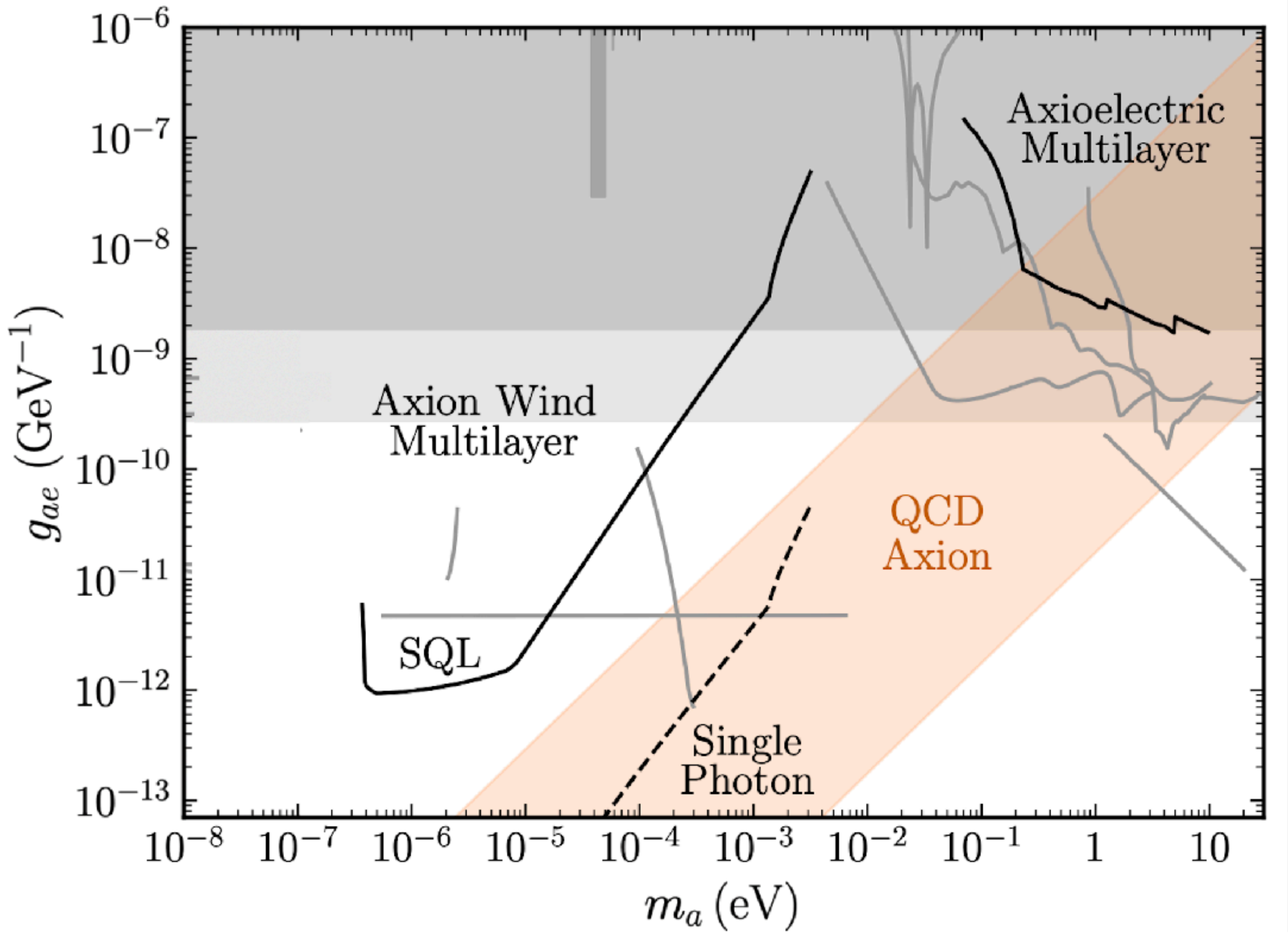
Projections

- Axio-electric is easy: recast a high frequency haloscope like MuDHI or LAMPOST
- Axion wind is better at lower frequencies
- For the wind term we assume a MADMAX-like setup ignoring O(1) factors and daily modulation

$$\mathrm{SNR} \sim \sqrt{\frac{Q_a}{Q_M}\,\frac{t_e}{m_a}\,\frac{\rho_{\mathrm{DM}}\,A}{T_n}}\,N^{3/2}\left(\frac{g_{ae}\,v_{\mathrm{DM}}\,\eta}{\mu_B}\right)^2$$

$$\eta = \left|\frac{1-\mu^{-1}}{1+i\,\sqrt{\varepsilon/\mu}\,\cot\left(n\,m_a\,d/2\right)}\right|$$

Sensitivity

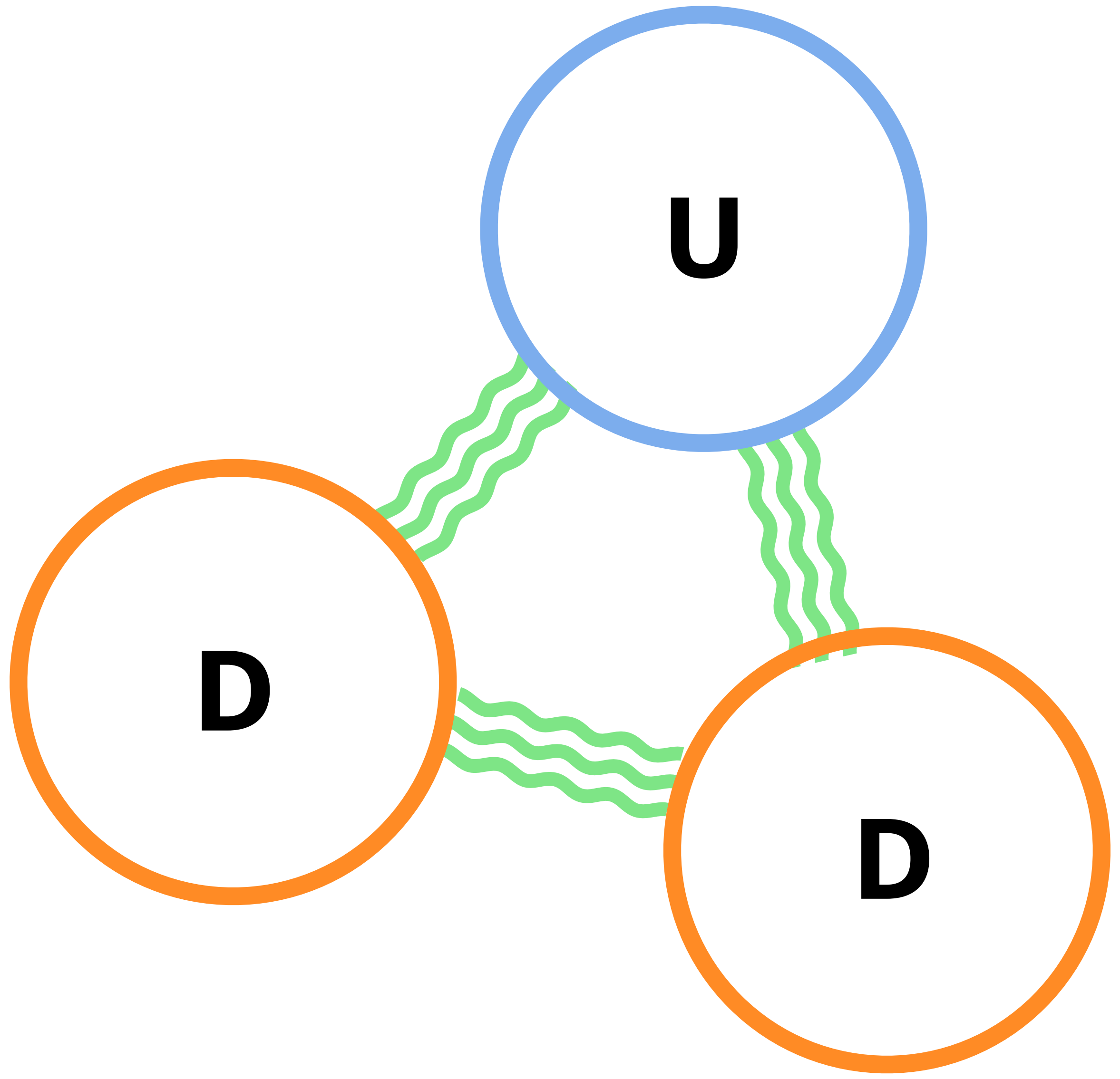


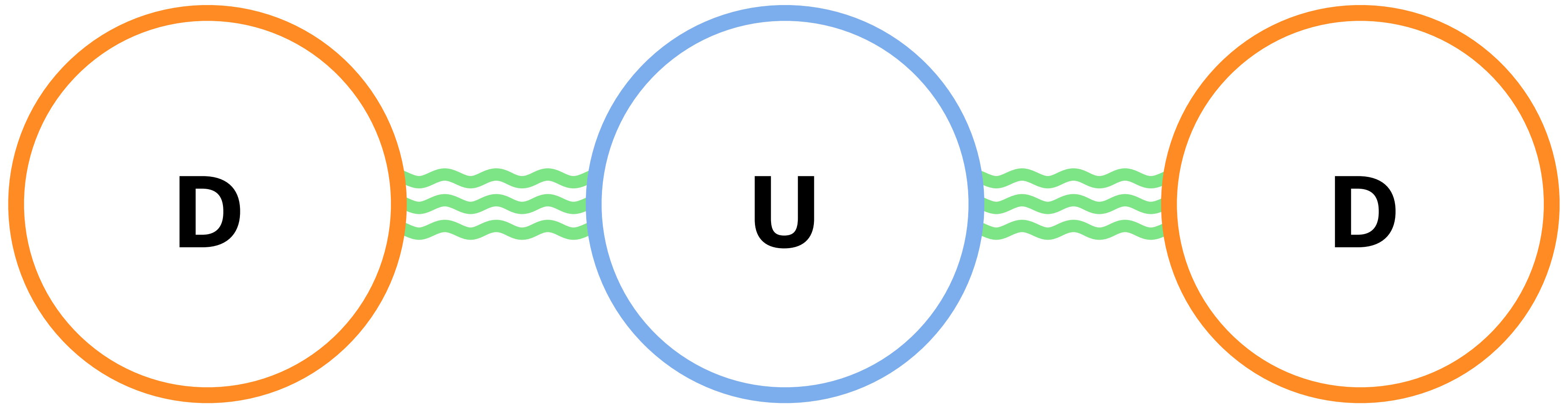
Conclusions

- Axion-fermion couplings still have lots to explore
- Absorption can just be related to ϵ and μ
- The language of currents allows for much more general experimental designs
- Need to be careful! Lots of spurious effects
- Magnetized dielectric haloscopes have interesting new phenomenology to explore

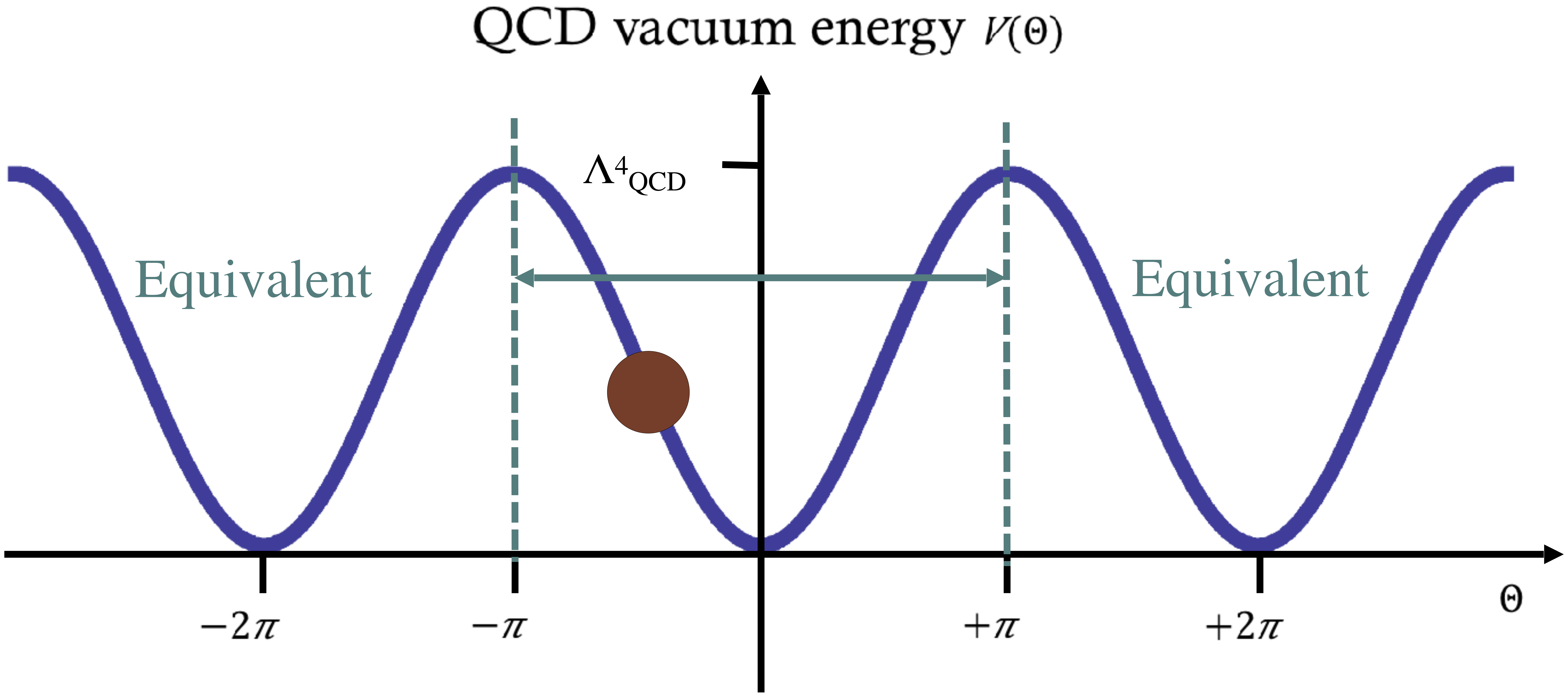
The Strong CP Problem

- The Strong force should violate time reversal symmetry!
- Governed by an angle θ
- In principle can be $\theta \in [0,2\pi]$
- Should give a large electric dipole moment!
- Limit from neutron EDM is $\theta \lesssim 10^{-10}$





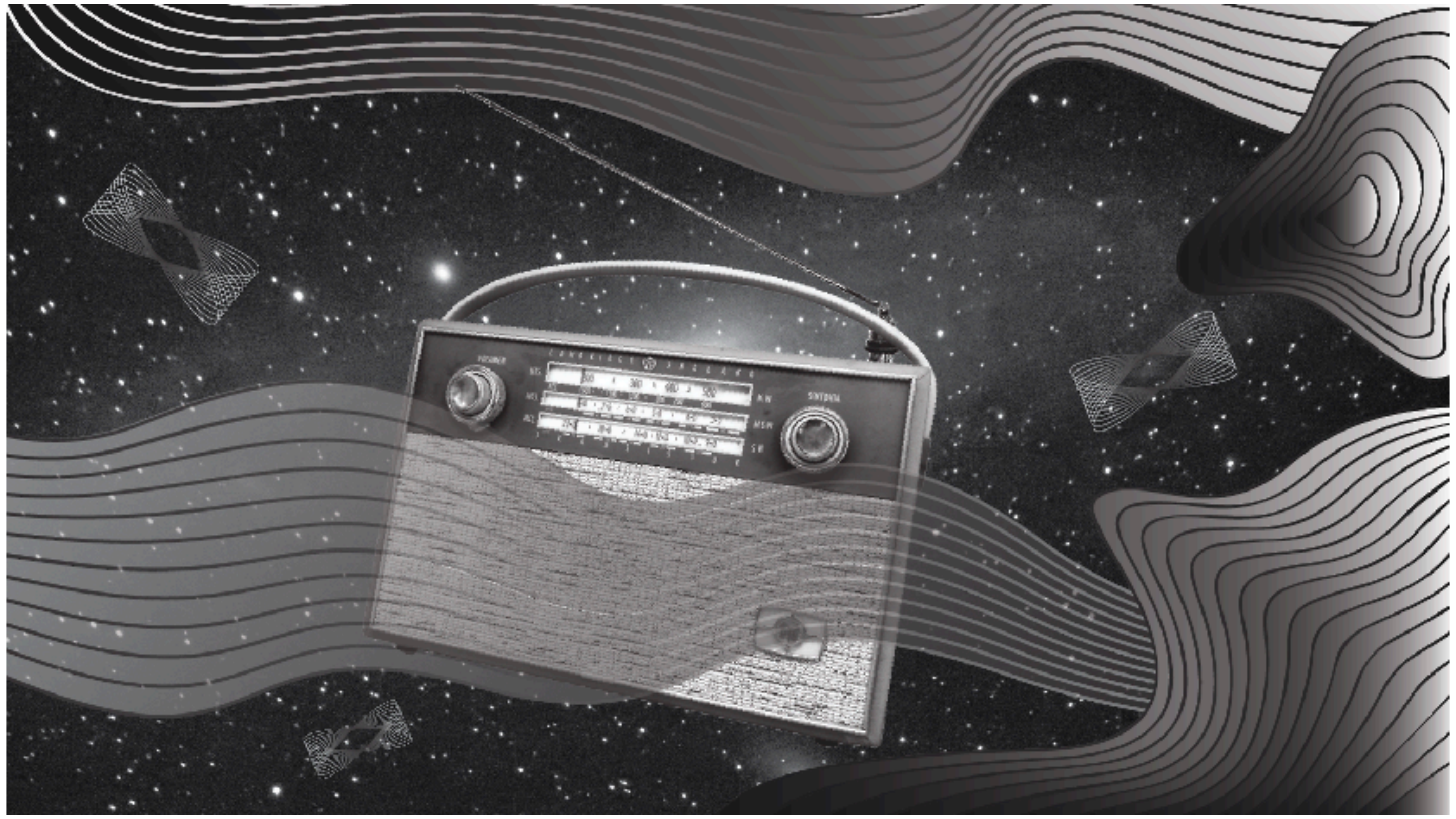
Strong CP problem



- $\theta=0$ minimizes the vacuum energy, but θ is not a dynamical term

Axion Dark Matter

- Coherent oscillations persist as dark matter
- Much lighter than wimps: ~μeV
- Acts like a classical wave!
- Looking for dark matter is like tuning a radio to find the right station (axion mass)
- Lots of new experiment ideas!



Artwork by Sandbox Studio in Symmetry Magazine