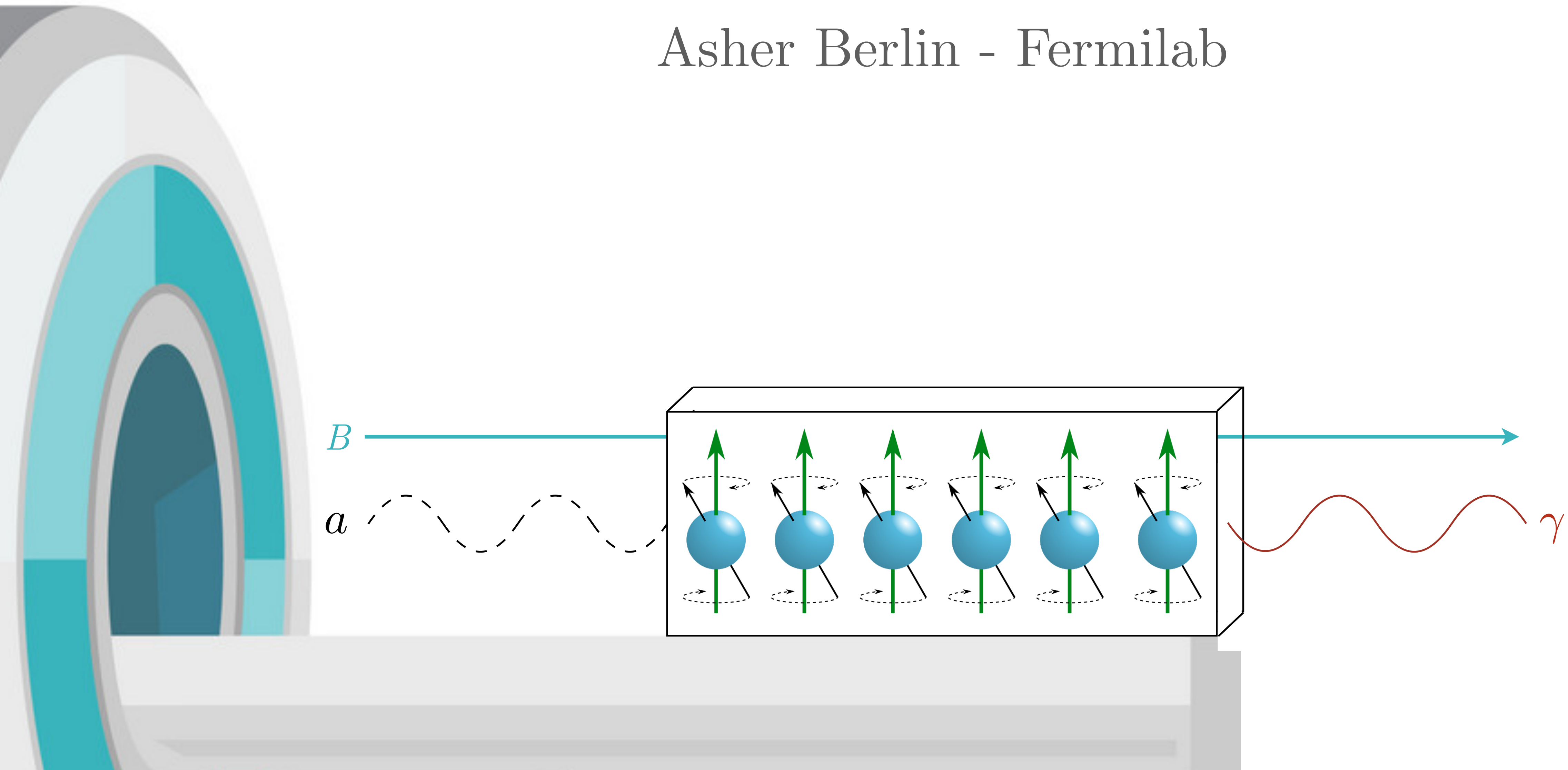
# Magnetized Stacks for Electron-Coupled Axions

Asher Berlin - Fermilab




Dark Wave Lab Workshop, Fermilab

April 16, 2024

with Alex Millar, Tanner Trickle, & Kevin Zhou

arXiv:2312.11601

# Axion Couplings

$$\mathscr{L} = \frac{\partial_\mu a}{f_a} \left( J^\mu_{\text{EM}} + J^\mu_{\text{QCD}} + J^\mu_{\text{spin}} + \cdots \right)$$

# Photon-Coupling

$$\mathscr{L} = \frac{\partial_\mu a}{f_a} \left( J^\mu_{\mathrm{EM}} + J^\mu_{\mathrm{QCD}} + J^\mu_{\mathrm{spin}} + \cdots \right)$$

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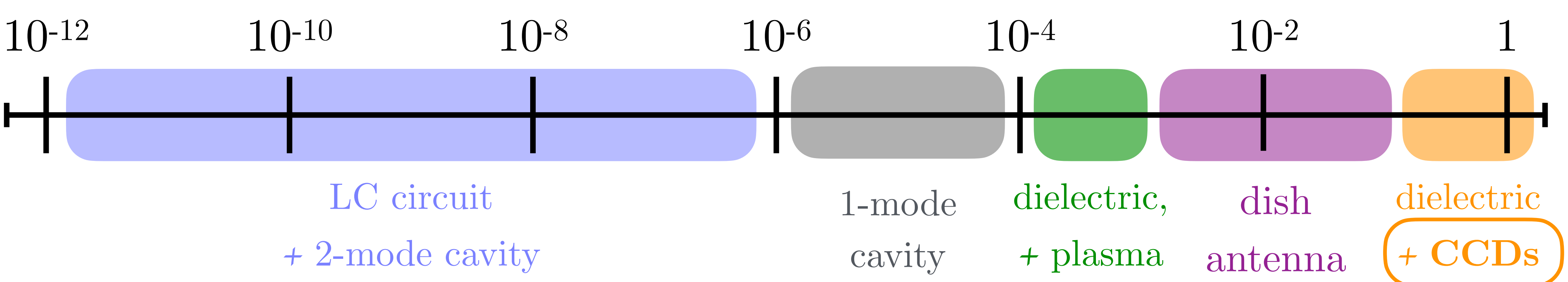
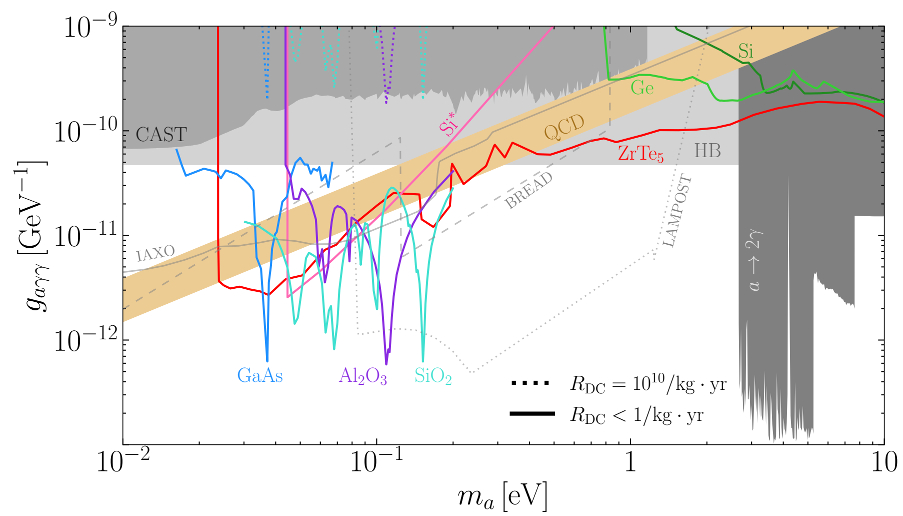
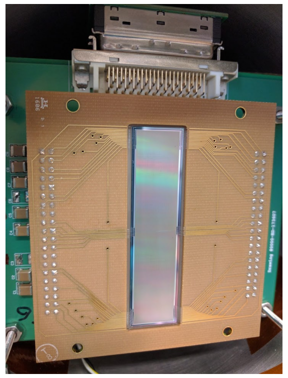
Experiments that are potentially sensitive to canonical QCD axion

$m_a$ [eV]



with Tanner Trickle
arXiv:2305.05681,
Phys. Rev. Lett.

# Electron-Coupling

$$\mathscr{L} = \frac{\partial_\mu a}{f_a} \left( J^\mu_{\mathrm{EM}} + J^\mu_{\mathrm{QCD}} + J^\mu_{e\text{-spin}} + \cdots \right)$$

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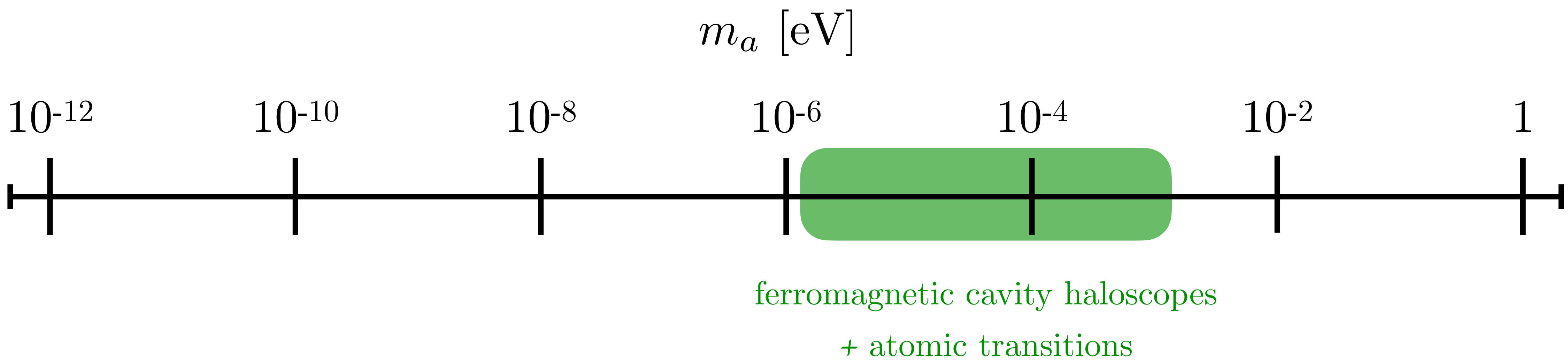

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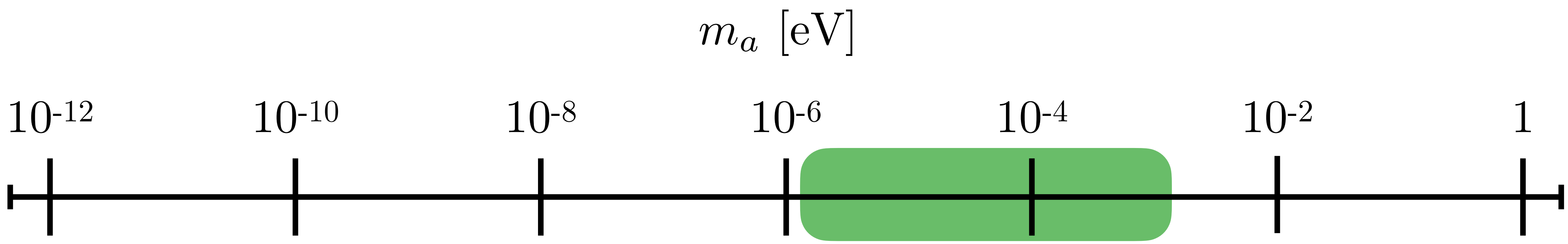
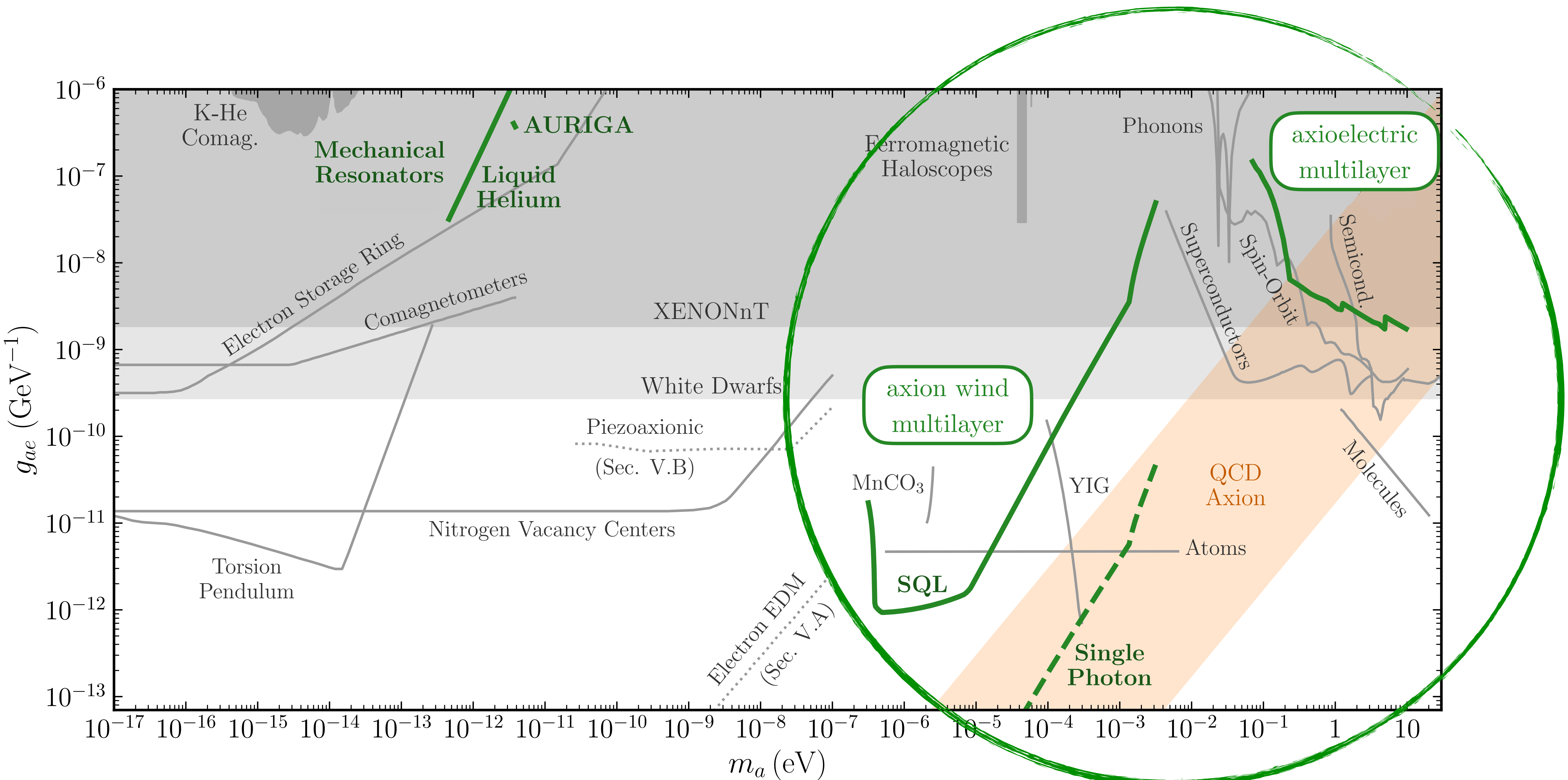



ferromagnetic cavity haloscopes
+ atomic transitions

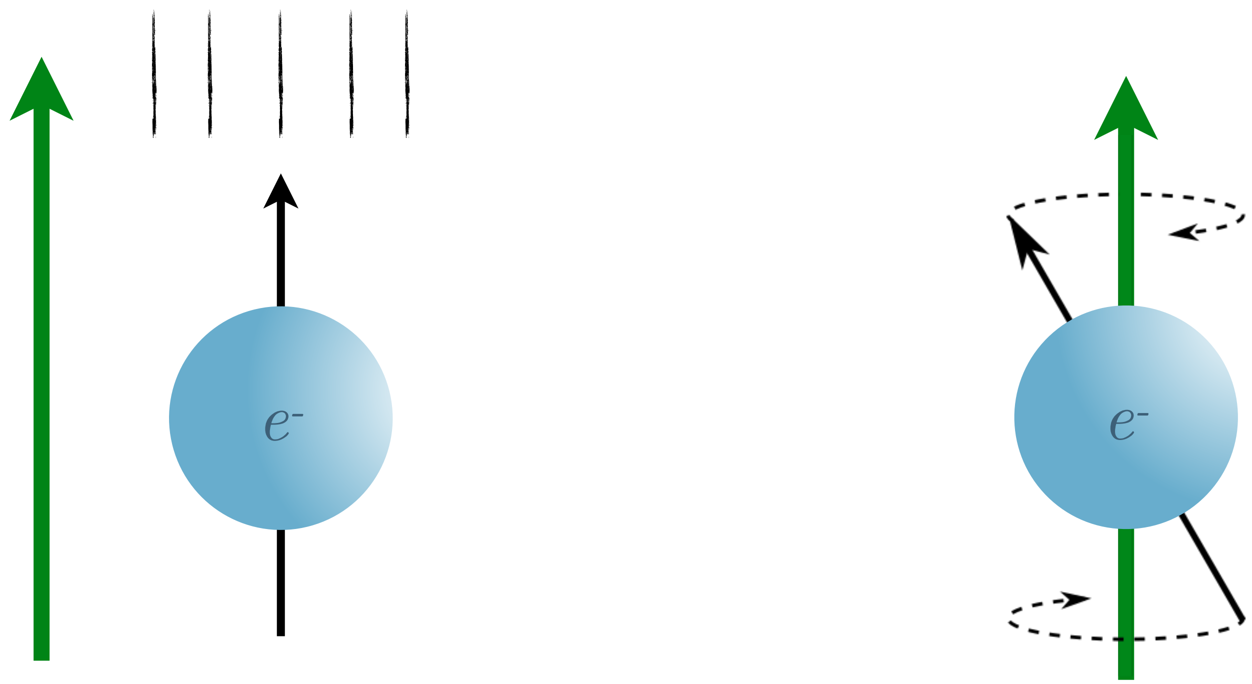
+ "**magnetized multilayers**"

(magnetized analogs of dielectric stack haloscopes)

# Electron-Coupling




“magnetized multilayers”




# I. Spin-Coupled Axions

# Electron-Coupling

*axion-electron interaction*

$$L = \int d^3\mathbf{x}\; g_{ae}\,(\partial_\mu a)\,\langle \bar{e}\gamma^\mu\gamma^5 e\rangle$$

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$$= g_{ae}\,(\nabla a)\cdot\hat{\mathbf{s}}_e + g_{ae}\,(\partial_t a)\;\hat{\mathbf{s}}_e\cdot\mathbf{v}_e$$

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---

*analogous to normal electromagnetism*

$$L_{\text{EM}} = -\mu_B\,\mathbf{B}\cdot\hat{\mathbf{s}}_e - e\,\mathbf{A}\cdot\mathbf{v}_e$$

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$$L_{\text{EM}} = -\mu_B\,\mathbf{B}\cdot\hat{\mathbf{s}}_e - e\,\mathbf{A}\cdot\mathbf{v}_e$$

$$\Longrightarrow \boxed{\mathbf{B}_{\text{eff}} = -\frac{g_{ae}}{\mu_B}\,\nabla a \quad , \quad \mathbf{A}_{\text{eff}} = -\frac{g_{ae}}{e}\,\partial_t a\;\hat{\mathbf{s}}_e}$$

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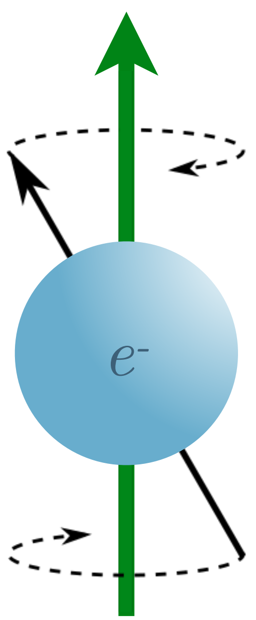
*"Axion Wind"*

Effective ***magnetic*** field that
torques spins along the dark matter wind

$$\boldsymbol{\tau} = g_{ae}\,\boldsymbol{\sigma}_e \times \nabla a \sim g_{ae}\,m_a\,a\,\boldsymbol{\sigma}_e \times \mathbf{v}_a$$

(spin torque)



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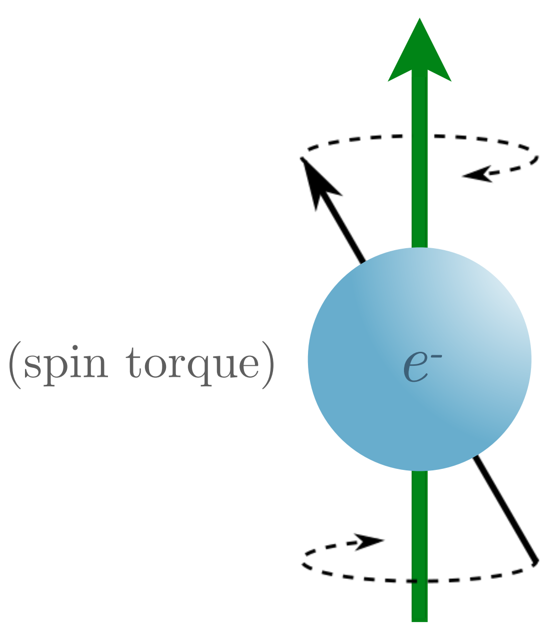
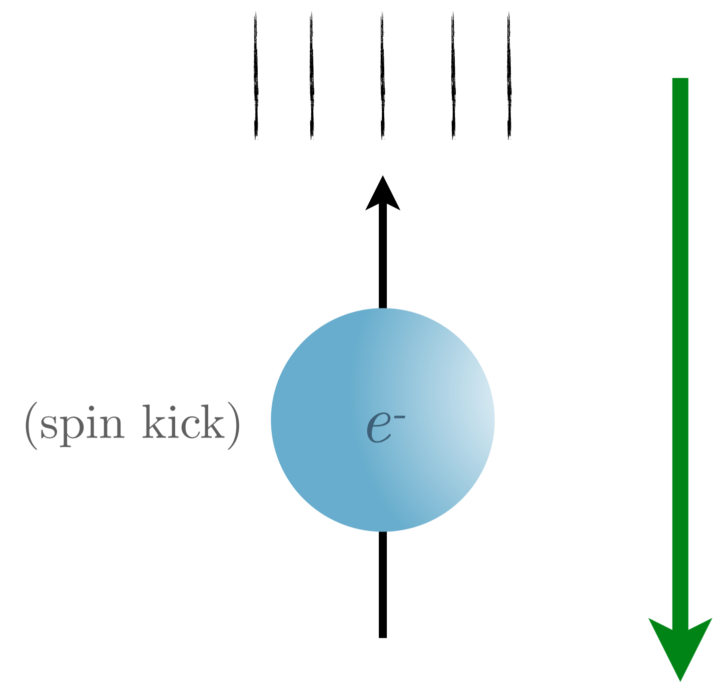
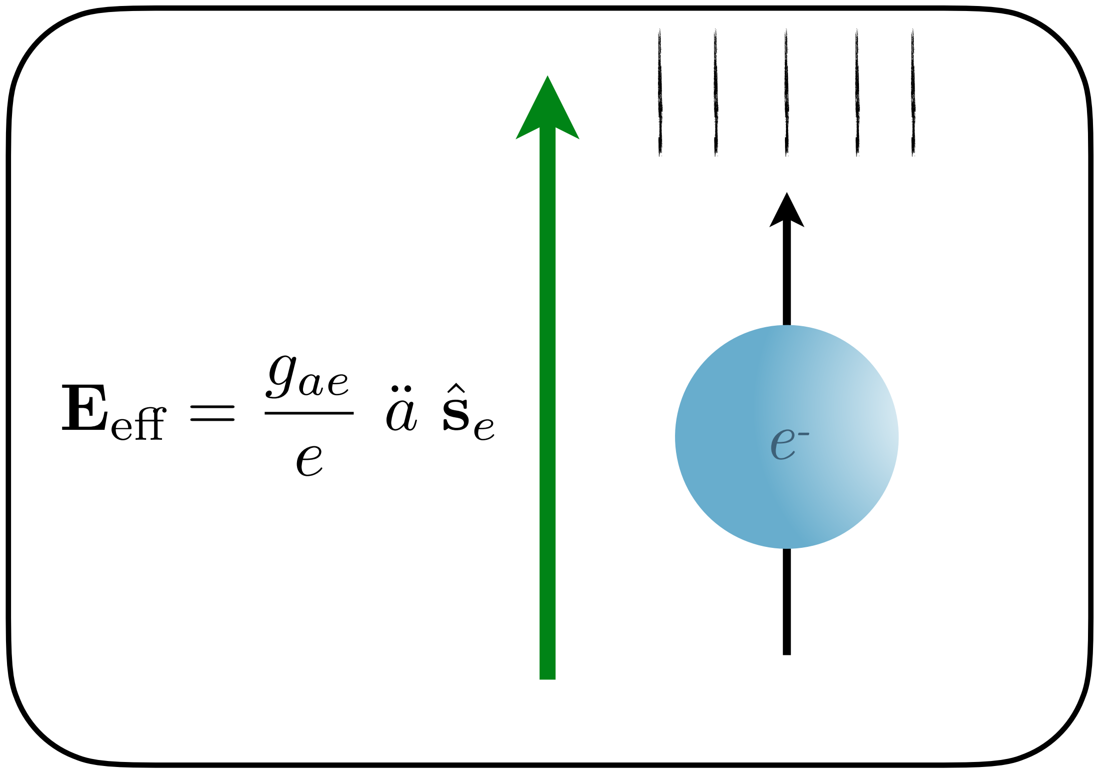


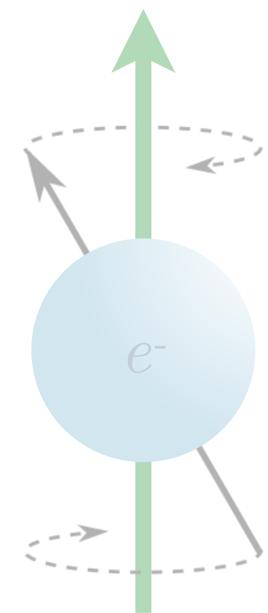

## *"Axioelectric"*

Effective ***electric*** field that pushes spins along the spin

$$\mathbf{F} = -g_{ae}\,\ddot{a}\,\hat{\mathbf{s}}_e \sim g_{ae}\,m_a^2\,a\,\hat{\mathbf{s}}_e$$





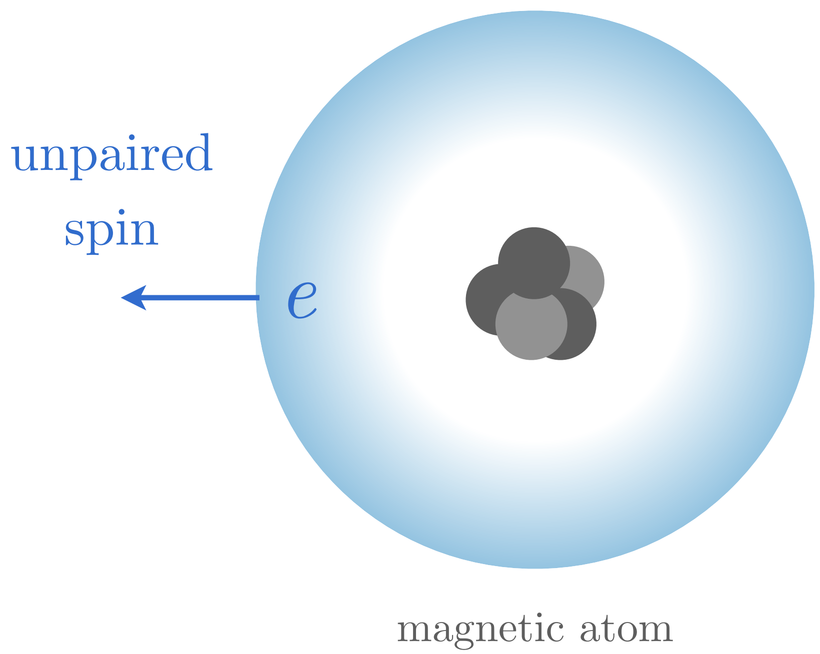

$$\mathbf{B}_{\text{eff}} = -\frac{g_{ae}}{\mu_B}\ \nabla a$$

# II. Axioelectric Multilayer

# Axioelectric

## Axioelectric Effective Electric Field

$$\mathbf{E}_{\text{eff}} \sim (g_{ae}/e)\, m_a \sqrt{\rho_{\text{DM}}}\; \hat{\mathbf{s}}_e$$



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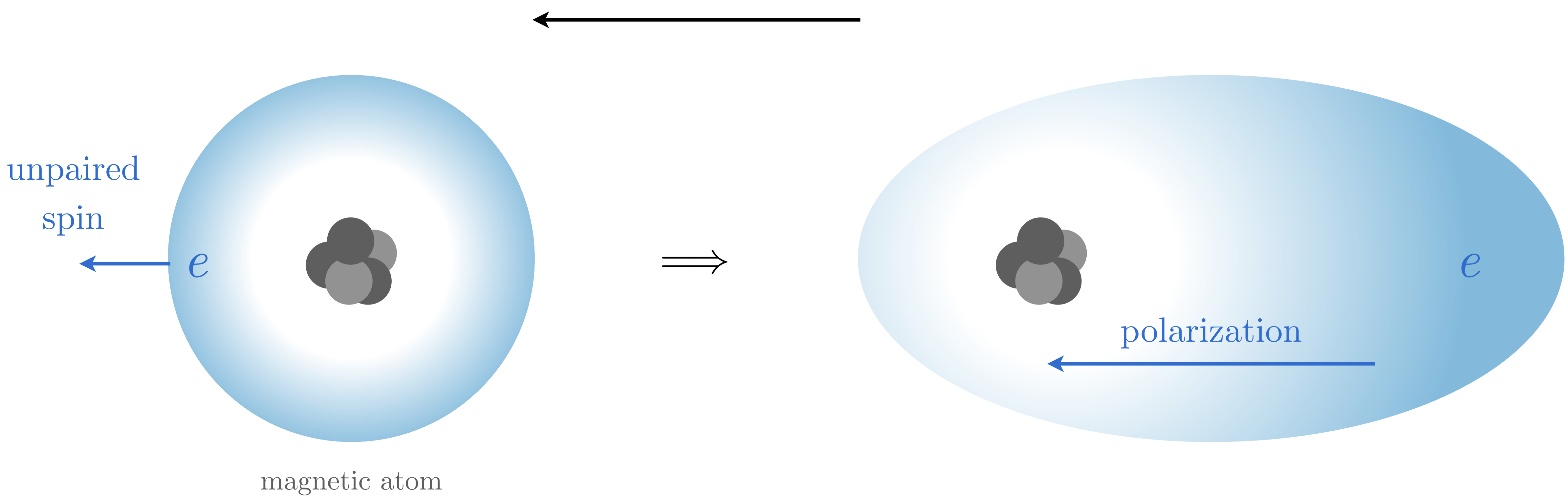



$$\mathbf{P} = \frac{\epsilon_\sigma - 1}{\epsilon}\, \mathbf{E}_{\text{eff}}$$

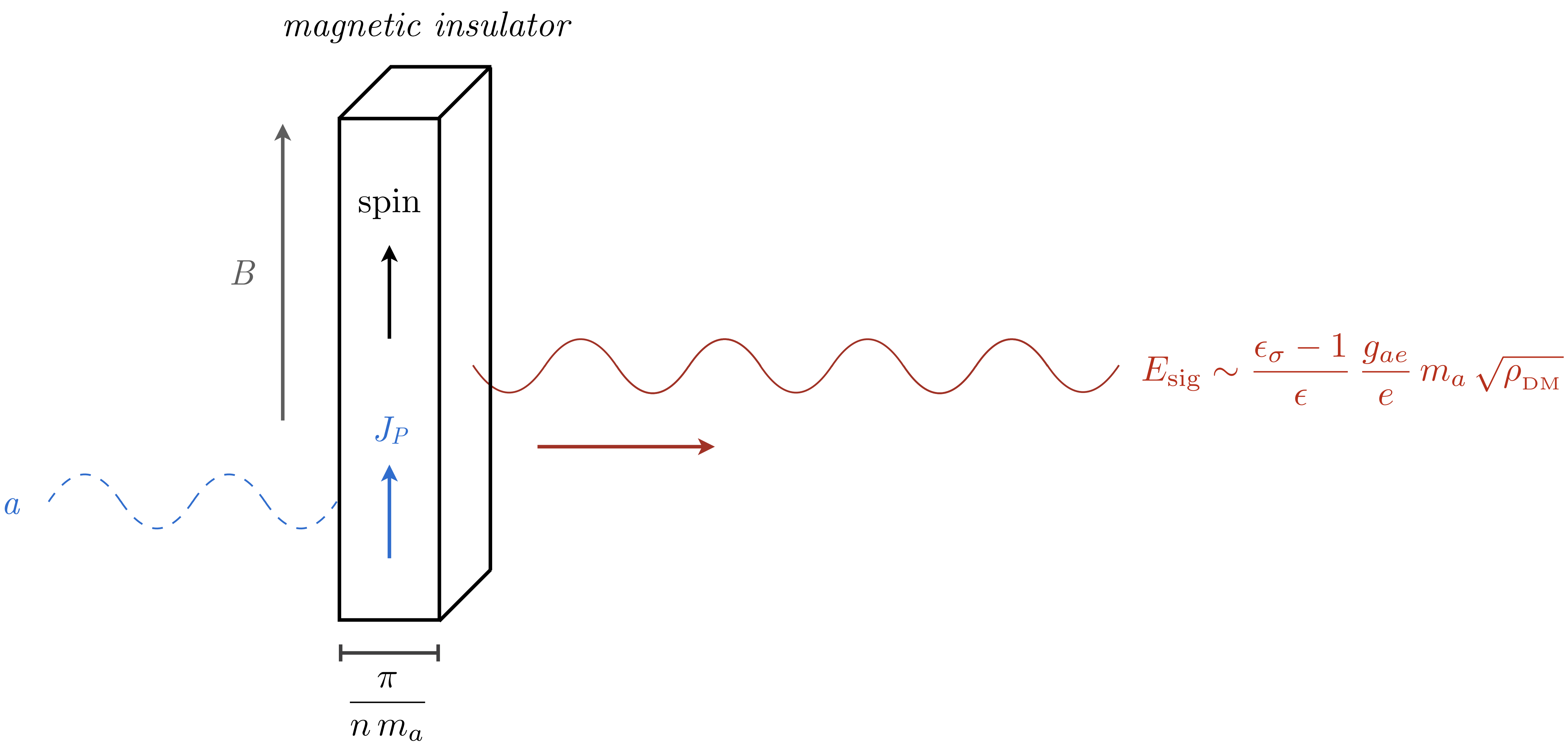
$\epsilon_\sigma \sim \epsilon$
contribution to dielectric
from unpaired $e$

physical current "$J_P$" from the oscillating polarization $\Longrightarrow$ electromagnetic signal

$$\mathbf{J}_P = -\partial_t \mathbf{P}$$

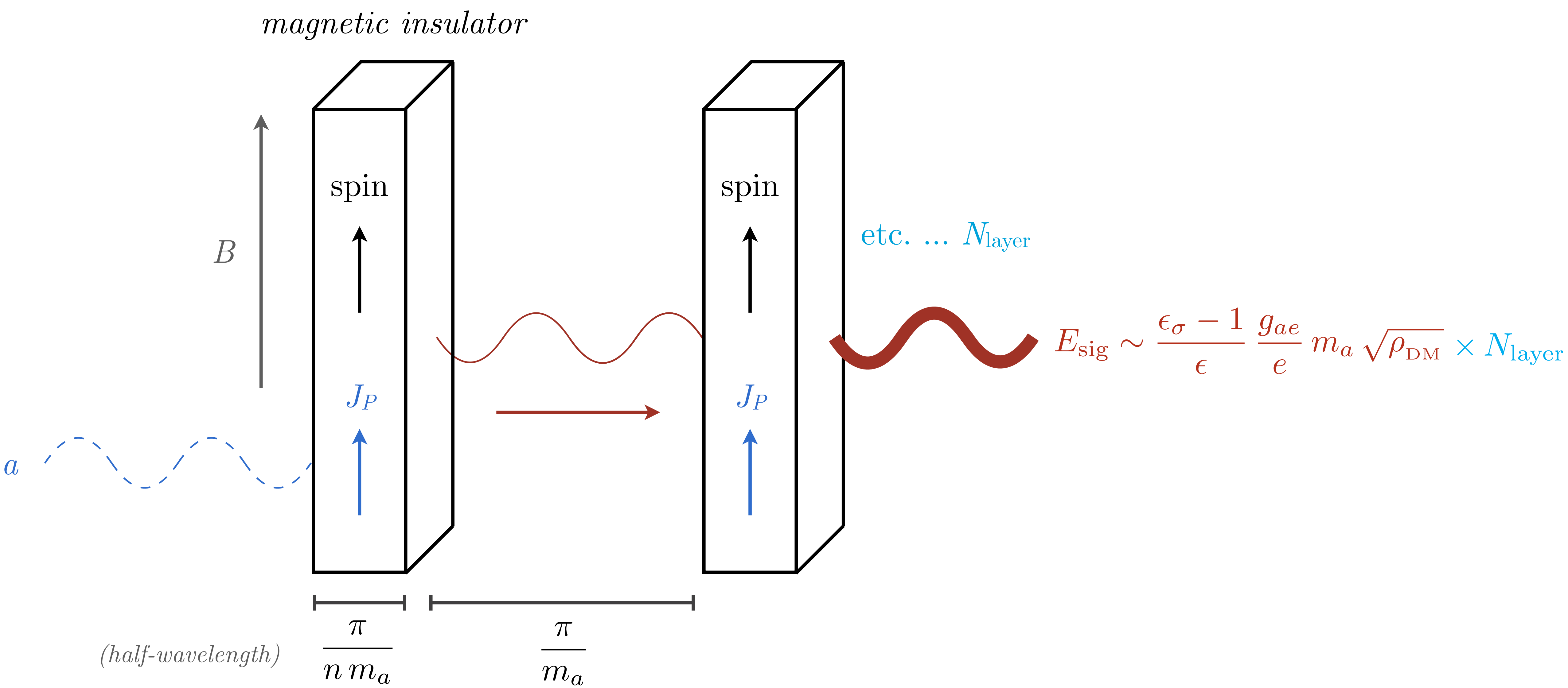
# Axioelectric

## Axioelectric Multilayer



# Axioelectric

## Axioelectric Multilayer

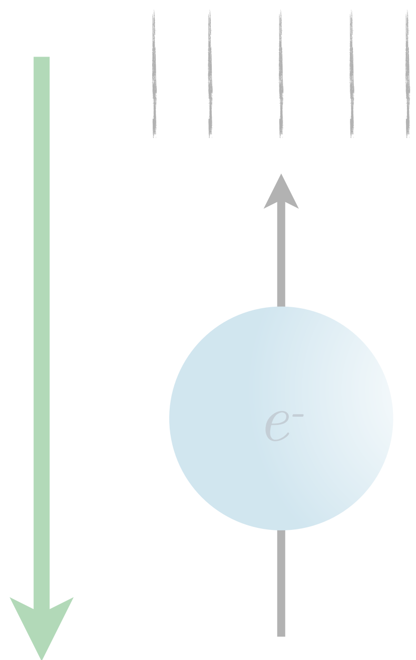


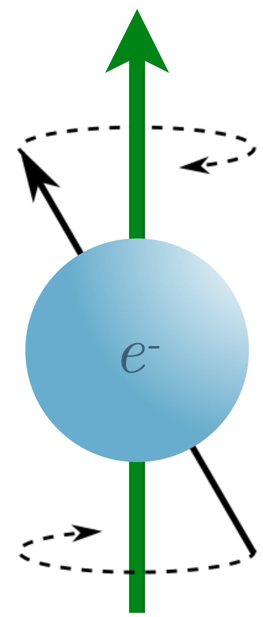

analogous to dielectric stacks MADMAX, MuDHI, and **LAMPOST**

$$\boxed{g_{ae} \leftrightarrow g_{a\gamma\gamma}\,(e\,B/m_a^2)}$$

*(QCD axion sensitivity at optical frequencies)*

$$\mathbf{E}_{\text{eff}} = \frac{g_{ae}}{e}\, \ddot{a}\, \hat{\mathbf{s}}_e$$



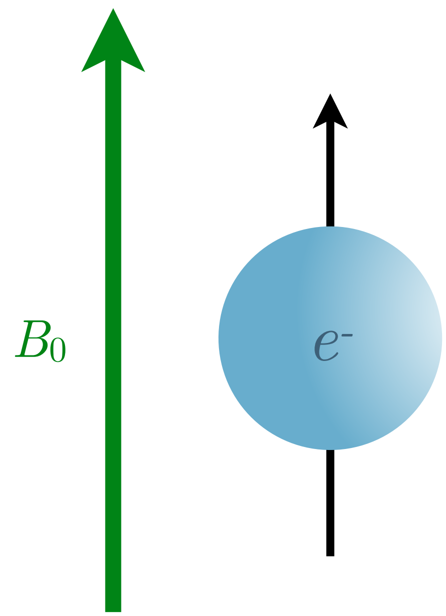

$$\mathbf{B}_{\text{eff}} = -\frac{g_{ae}}{\mu_B}\, \nabla a$$

# III. Axion Wind Multilayer

# Axion Wind

## Axion Wind Effective Magnetic Field

$$\mathbf{B}_{\text{eff}} \sim \frac{g_{ae}}{\mu_B} \sqrt{\rho_{\text{DM}}}\, \mathbf{v}_a$$



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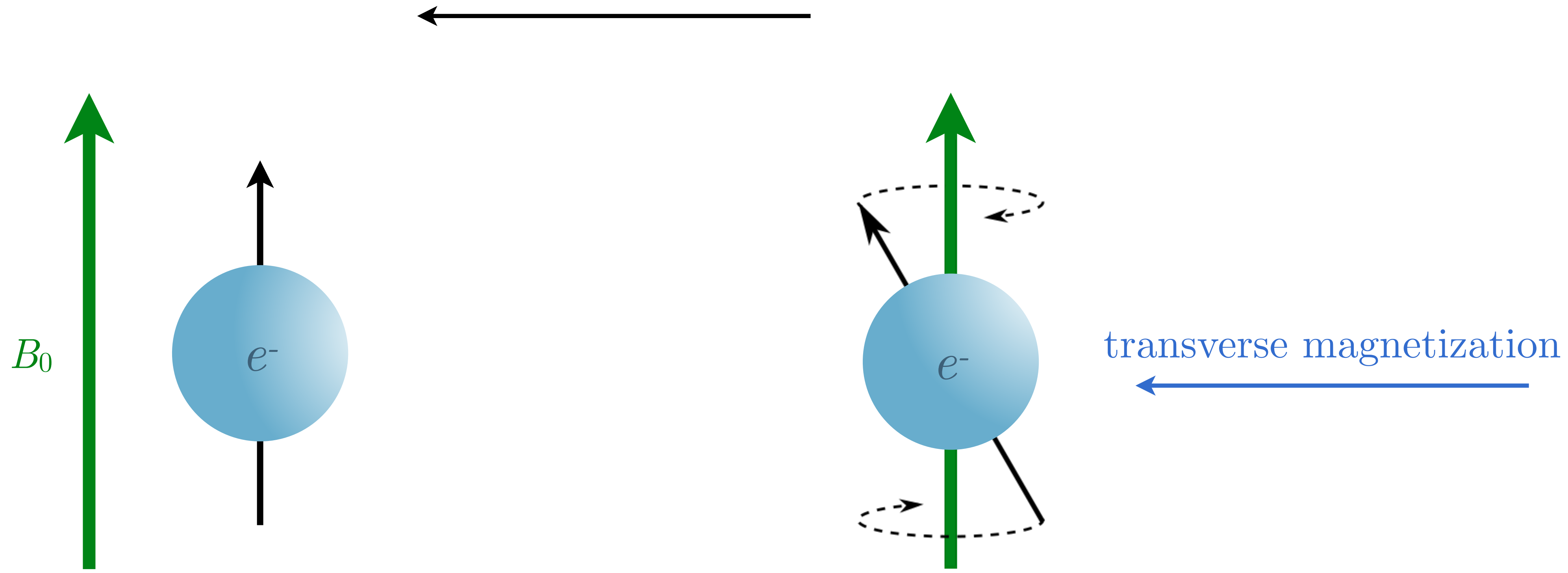


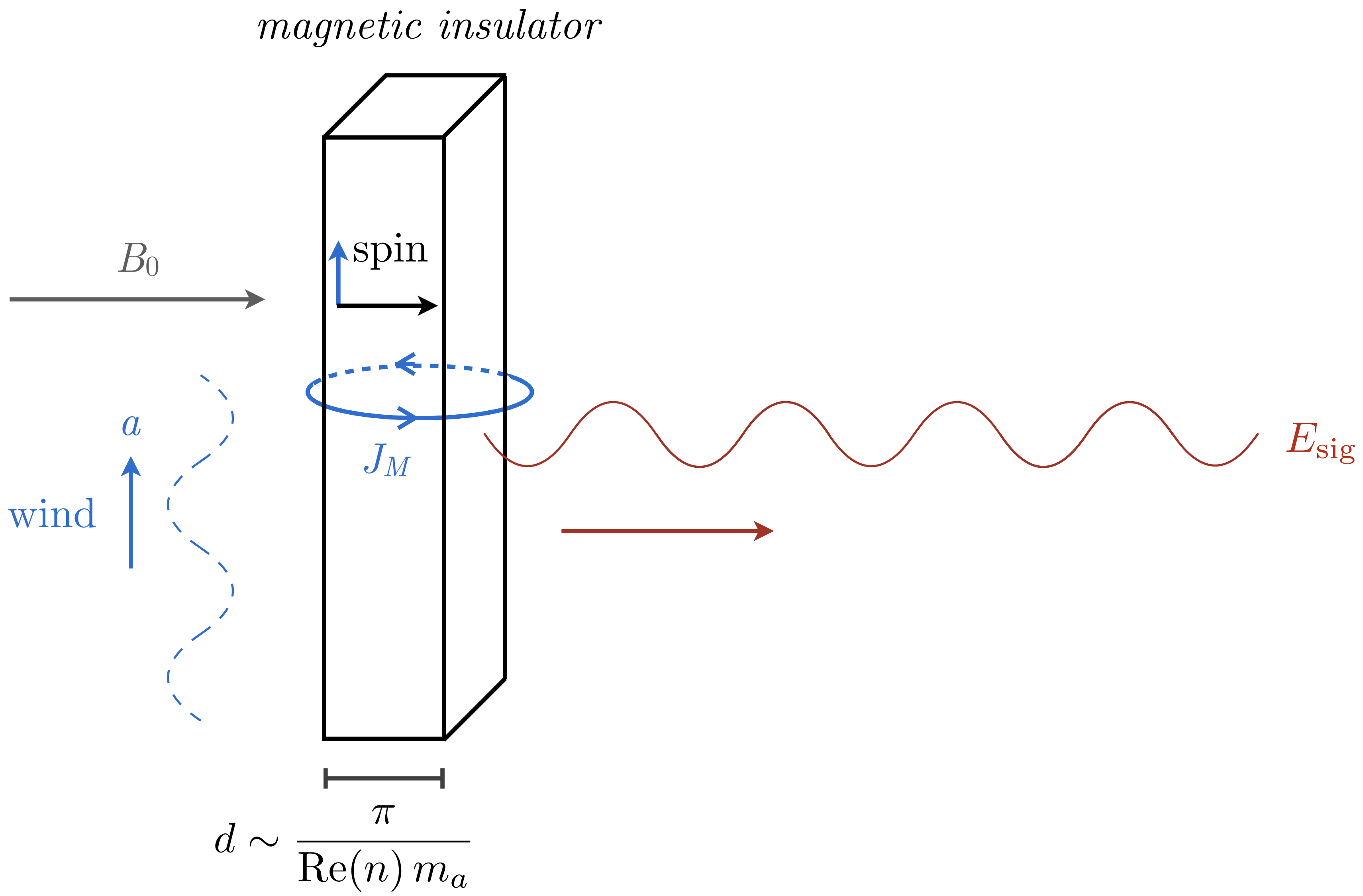

$$\mathbf{M}_\perp = (1 - \mu^{-1})\, \mathbf{B}_{\text{eff}}$$

physical current "$J_M$" from the oscillating magnetization $\Longrightarrow$ electromagnetic signal

$$\mathbf{J}_M = \nabla \times \mathbf{M}$$

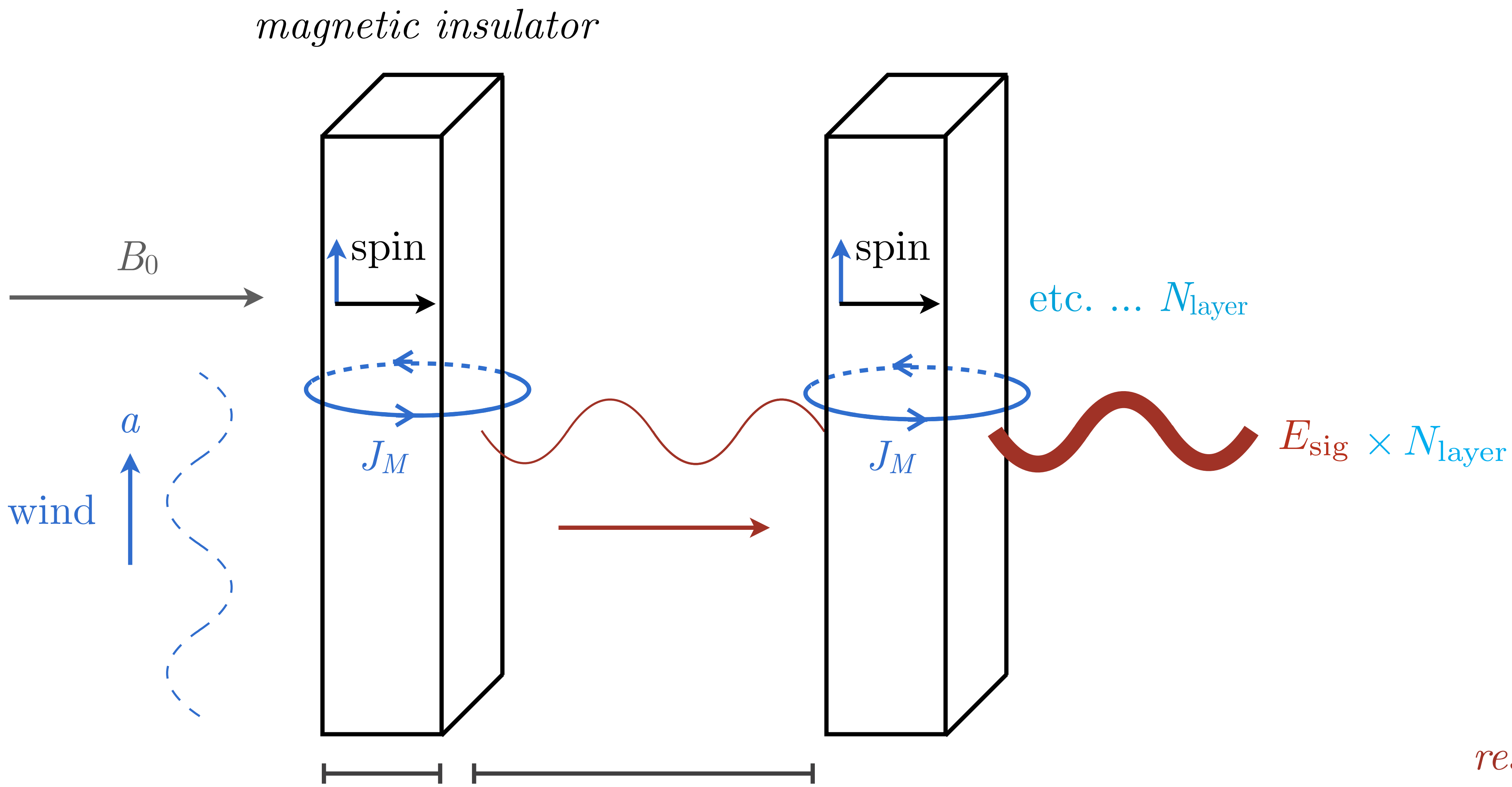
# Axion Wind

## Axion Wind Multilayer



# Axion Wind

## Axion Wind Multilayer




$$d \sim \frac{\pi}{\mathrm{Re}(n)\, m_a} \qquad \frac{\pi}{m_a}$$

*response is strong function of frequency and B-field (e.g., FMR)*

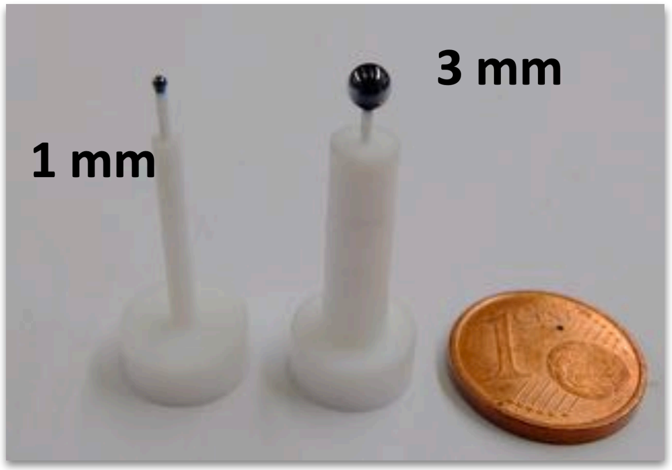
$$\boxed{E_{\mathrm{sig}} \sim \frac{\mu - 1}{\mu - in\, \cot\left(n\, m_a\, d/2\right)} \frac{g_{ae}}{e}\, m_e\, v_a \sqrt{\rho_{\mathrm{DM}}}}$$

$$\mu = \mu(m_a, B_0)$$
$$n = n(m_a, B_0)$$

# Axion Wind

*Magnetic Insulators*

## YIG




Recent efforts have focused on small samples of high-purity YIG

$$Q_{\text{spin}} \sim 10^4$$

limited by small volume

(e.g., QUAX and others)

## Ferrite ✓

Cheaply mass produced

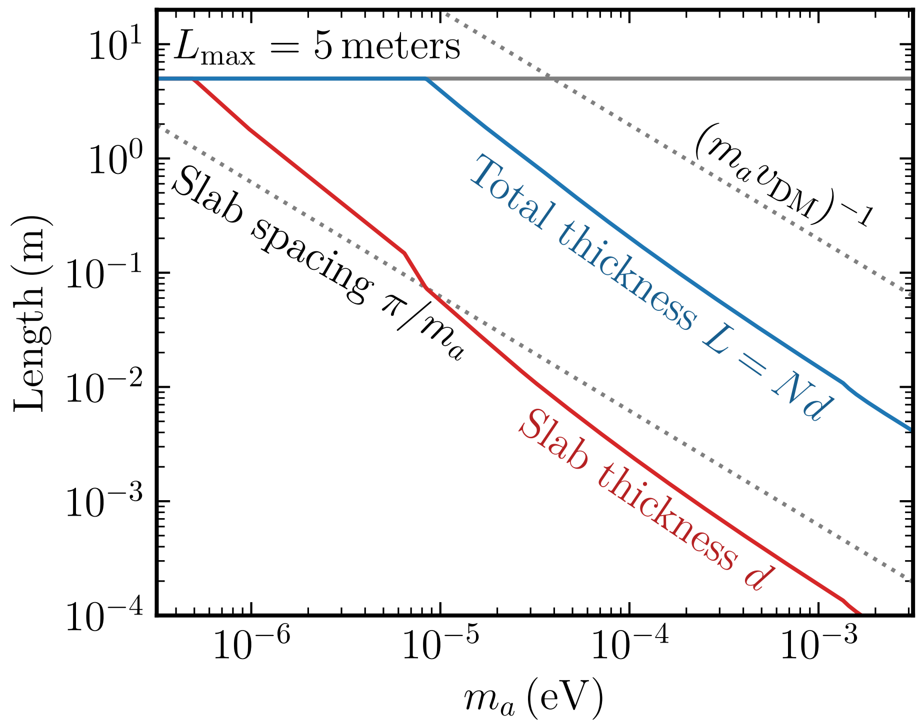
$$Q_{\text{spin}} \sim 10^2$$

enhanced by large volume

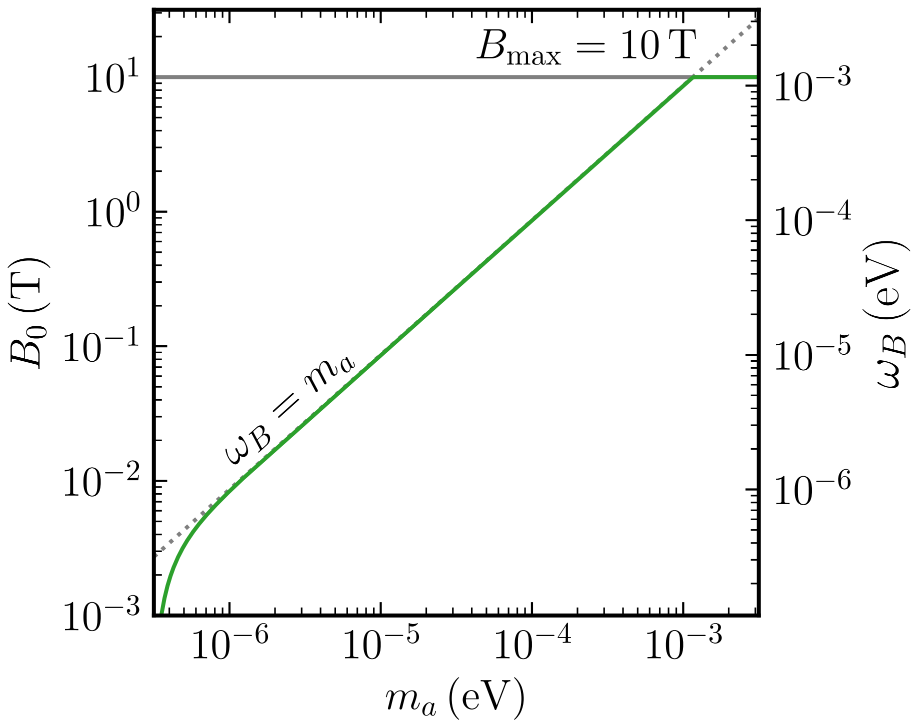
# Axion Wind

## Axion Wind Multilayer

*length of stack*




*B-field tuning*




$$\ell_{\rm screen} \sim \frac{1}{m_a\,\mathrm{Im}(n)}$$

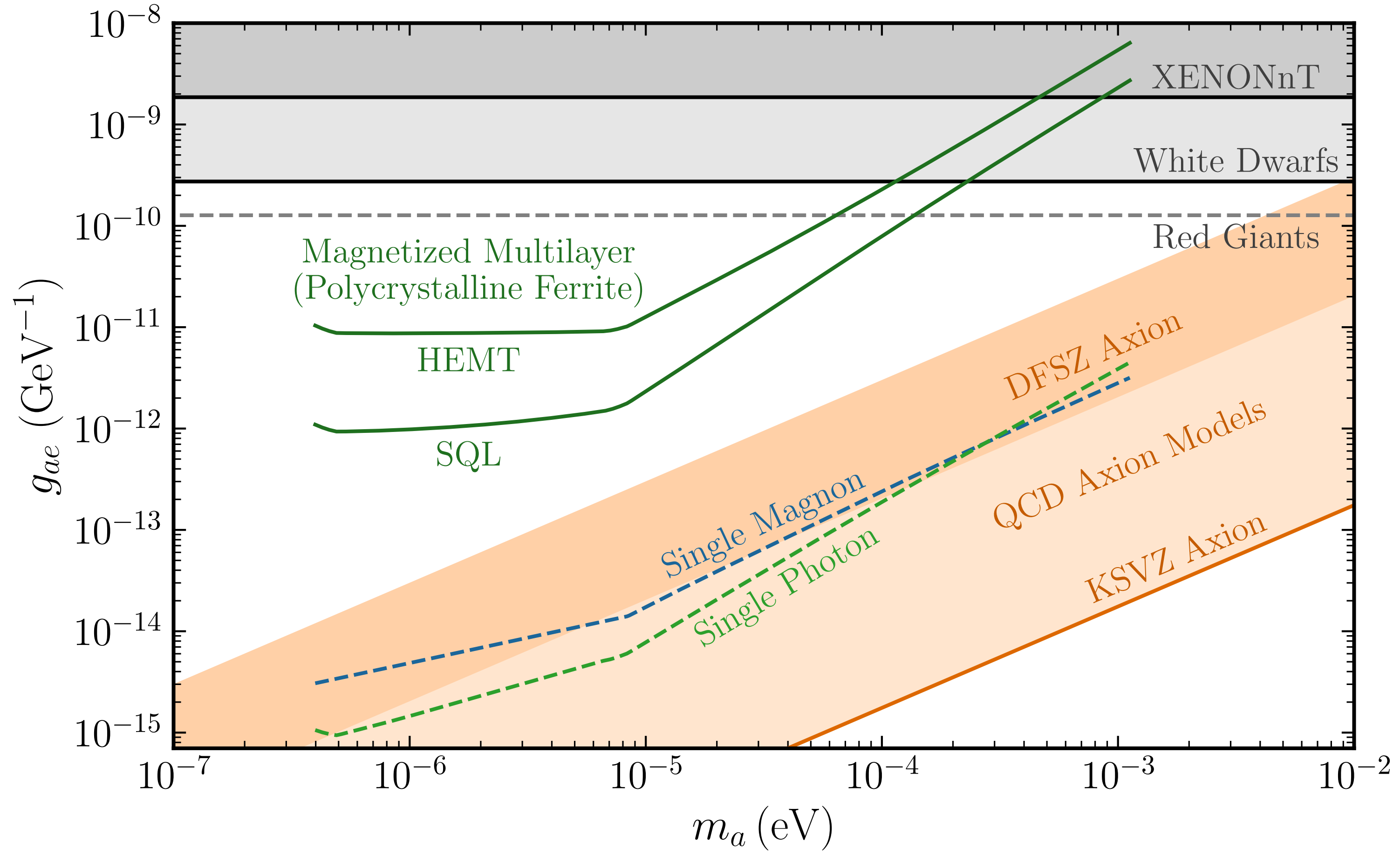
$$B_0 \sim \frac{m_a}{\mu_B} - \text{“small offset”} \qquad \textit{(FMR)}$$

$m_a \gtrsim 10^{-6}$ eV ⟷ “MADMAX-like” ⟷ $m_a \lesssim 10^{-3}$ eV

*never requires B-field that is strong AND large*

# Axion Wind

## Axion Wind Multilayer




large volume of low-$Q$ ferrite

*axion absorption into magnon-polariton hybrid more likely than into magnon*

# Summary

*Magnetic Stacks*

$$L \sim g_{aff}\ \dot{a}\ \boldsymbol{\sigma} \cdot \boldsymbol{v}_f + g_{aff}\ \nabla a \cdot \boldsymbol{\sigma}$$

*axioelectric* *axion wind*

optical magnetic stack
(~ LAMPOST/MuDHI)

RF magnetic stack
(~ MADMAX)

*Everything at leading order stems from these effects, expressed in different frames.*

# Summary

*Magnetic Stacks*

$$L \sim g_{aff}\ \dot{a}\ \boldsymbol{\sigma}\cdot\boldsymbol{v}_f + g_{aff}\ \nabla a\cdot\boldsymbol{\sigma}$$

*axioelectric* → optical magnetic stack (~ LAMPOST/MuDHI)

*axion wind* → RF magnetic stack (~ MADMAX)

*Everything at leading order stems from these effects, expressed in different frames.*

---

*Other Nuggets*

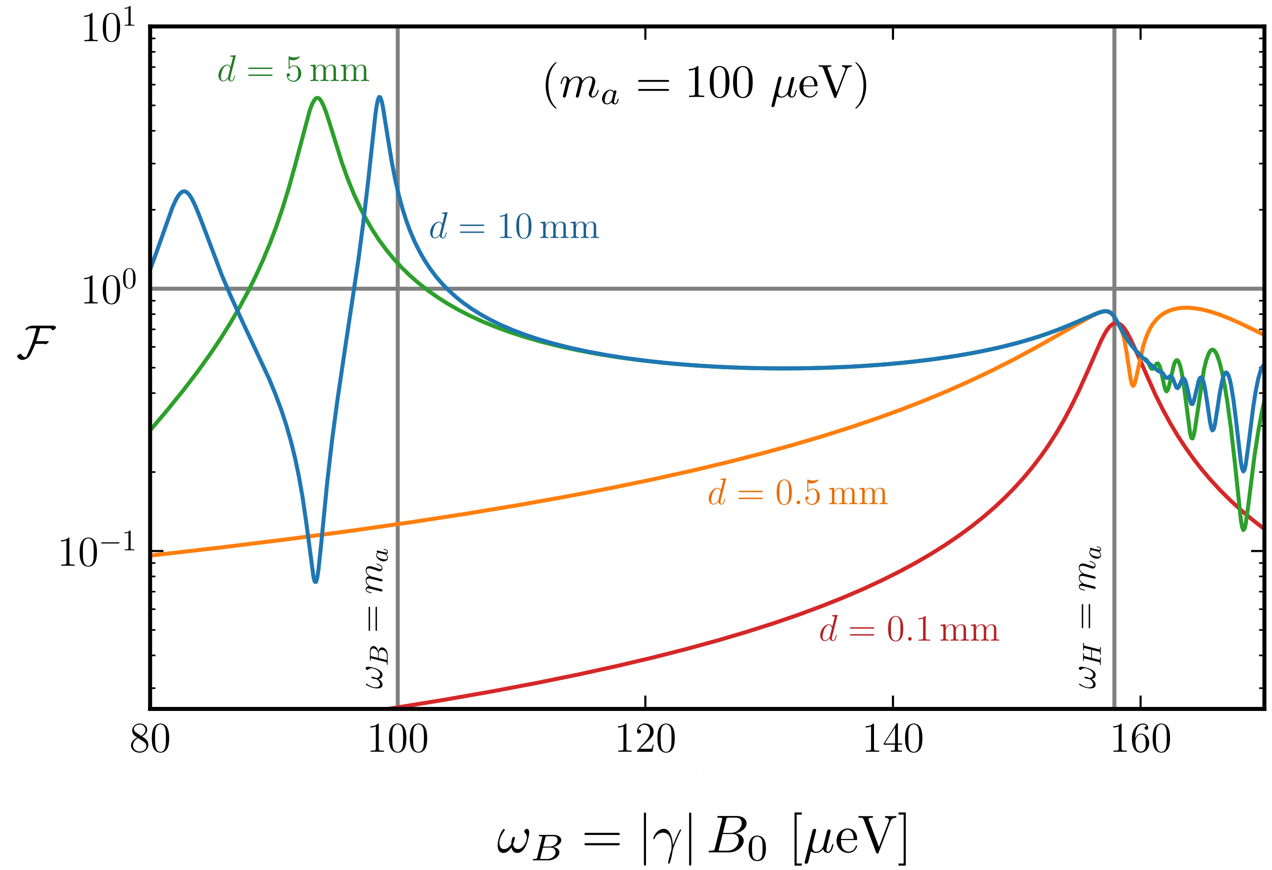
- Inclusive absorption rate ~ Im[-1/$\mu$] ("magnetic energy loss function")
- Bulk mechanical forces on spin-polarized sensors
- **No** leptonic EDMs proportional to the field value
- **No** axioelectronic energy shifts to leading order

arXiv:2312.11601

# Back Up Slides

# Axion Wind

*single layer optimization*




$$\mathcal{F} = \left| \frac{\mu - 1}{\mu + in\,\cot\left(n m_a d/2\right)} \right|$$

$$\mu = \frac{m_a - \omega_B + i\omega_B/2Q}{m_a - \omega_H + i\omega_H/2Q}$$

- **Thin slab**: $\mu(\omega_H) \sim 2i\,Q\,(\omega_M/\omega_H)$ , $\mathcal{F}_{\text{thin}}(\omega_H) \simeq Q_{\text{eff}}\,\omega_M\,d$ , $Q_{\text{eff}}^{-1} \equiv Q^{-1} + Q_{\text{rad}}^{-1}$ , $Q_{\text{rad}} = \dfrac{1}{\omega_M\,d}$

(spin response enhanced, but $\lambda \sim L_{\text{skin}}$ small $\Longrightarrow$ incoherent emission across slab $\Longrightarrow$ form factor $< 1$)

- **Thick slab**: $\mu(\omega_B) \sim (i/2Q)\,(\omega_B/\omega_M)$ , $\mathcal{F}_{\text{thick}}(\omega_B) \simeq \dfrac{\sqrt{2Q\,\omega_M/(\omega_B\,\epsilon)}}{|\cot\left(n\omega_B d/2\right)|}$

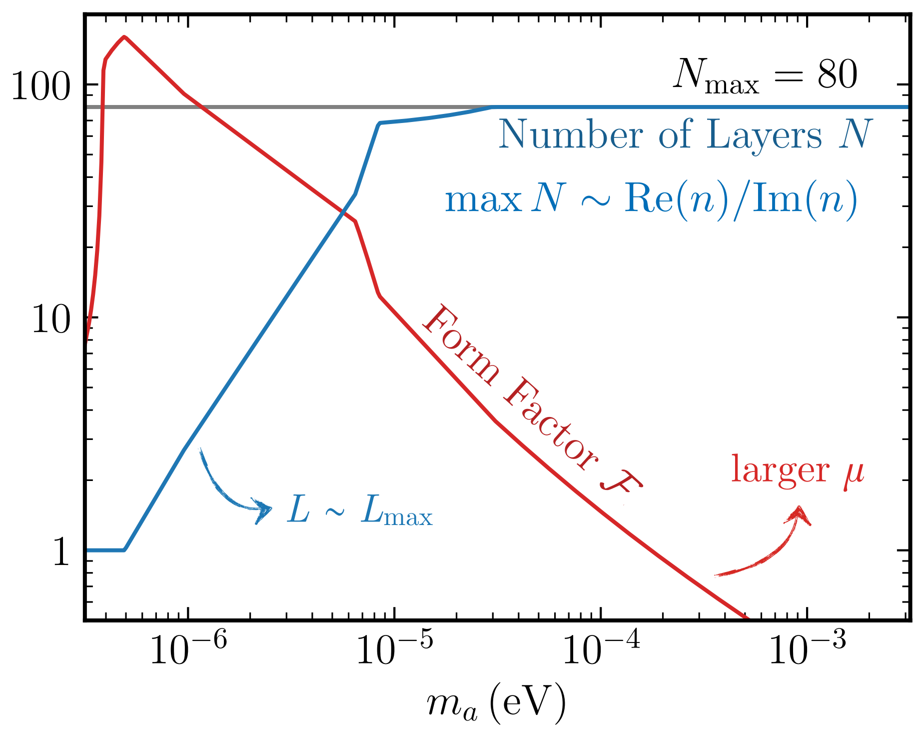
($\lambda \sim L_{\text{skin}}$ large $\Longrightarrow$ coherent emission across slab $\Longrightarrow$ form factor $> 1$)
$\omega_B < m_a \Longrightarrow \mu$ small but real $\Longrightarrow$ slab $\sim$ cavity with form factor peaking when $n\ m_a\ d \sim \pi$

# Axion Wind

*multi-layer optimization*

$$\omega_B = m_a - \Delta\omega_B \quad (\Delta\omega_B \gg \omega_B/Q)$$

$\max N_{\text{layer}} \sim \mathrm{Re}(n)/\mathrm{Im}(n)$




| **Parameters** | Description | Variable | Value | |
|---|---|---|---|---|
| **Material** | Saturation magnetization | $M_S$ | 0.5 T | |
| | Magnetic quality factor | $Q$ | $10^2$ | |
| | Permittivity | $\varepsilon$ | 15 | |
| **Experimental** | Slab area | $A$ | 1 $\mathrm{m}^2$ | |
| | $e$-fold scanning time | $t_e$ | 1 year | |
| | Maximum number of layers | $N_{\text{max}}$ | 80 | |
| | Maximum total material thickness | $L_{\text{max}}$ | 5 m | |
| | Maximum applied $B$ field | $B_{\text{max}}$ | 10 T | |
| **Noise** | | | HEMT | SQL |
| | Physical temperature | $T$ | 4 K | 40 mK |
| | Amplifier noise temperature | $T_{\text{amp}}$ | $1\ \mathrm{K}\left(\frac{m_a}{2\pi \times 4\ \mathrm{GHz}}\right)$ | $m_a$ |

**sensitivity bandwidth:** $N\dfrac{\Delta m_a}{m_a}\,,\; N\dfrac{\Delta \mathrm{Re}(n)}{\mathrm{Re}(n)} \lesssim 1 \implies \Delta m_a \sim \dfrac{\min(m_a\,,\,\Delta\omega_B)}{N} \sim \dfrac{\Delta\omega_B}{N}$

$$\Delta\omega_B \uparrow \implies \mathrm{Re}(\mu)\uparrow \;+\; \mathrm{Im}(\mu)\downarrow \implies \lambda\downarrow \;+\; L_{\text{skin}}\uparrow \implies N_{\text{layer}}\uparrow \quad (\text{compensated by smaller } \mathcal{F})$$