Probing the Axion-Electron Coupling with Magnetized Multilayers

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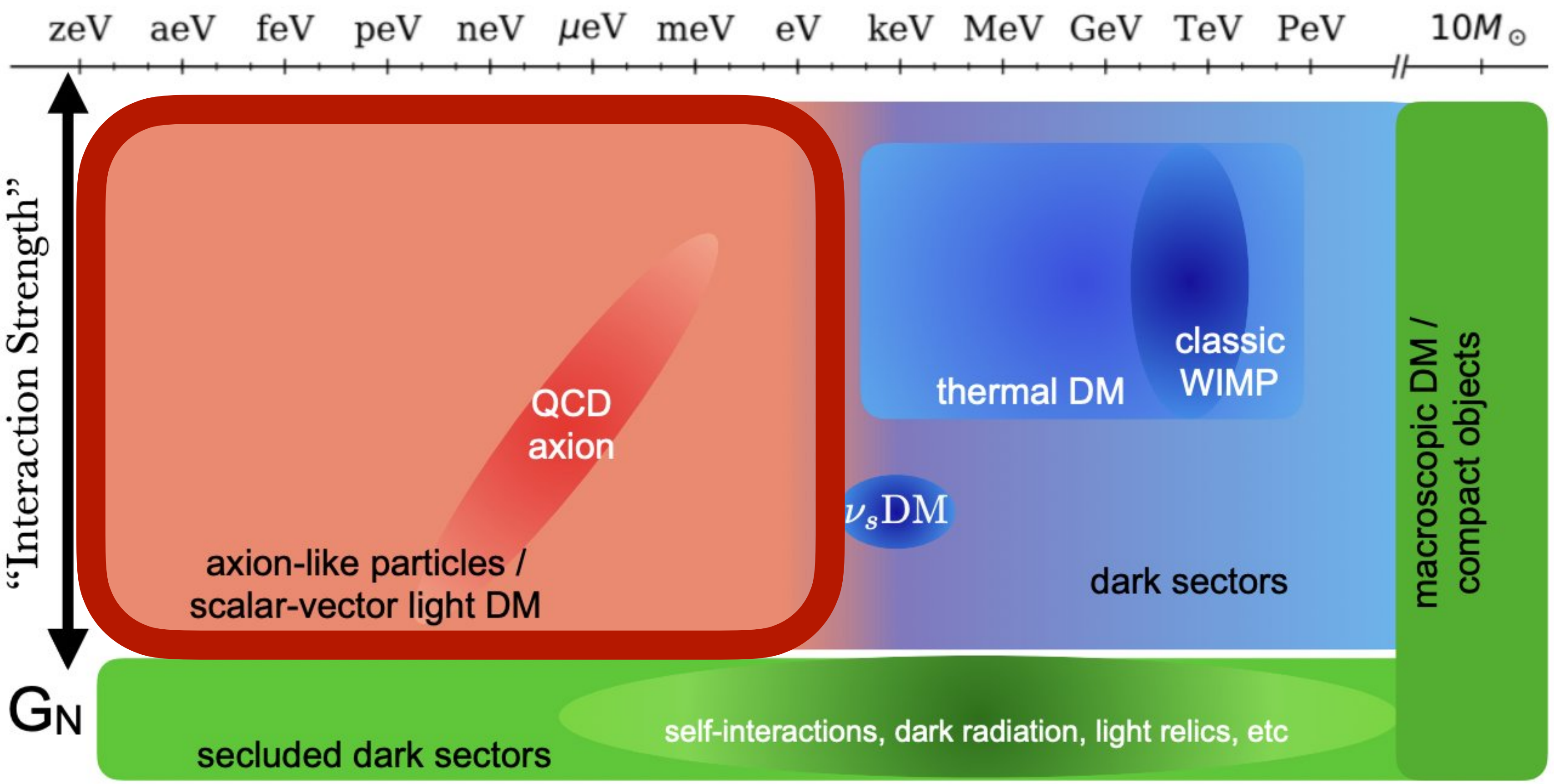
arXiv:2312.11601, with Asher Berlin, Alex Millar, Tanner Trickle



Ultralight dark matter is a subject of growing experimental interest:

- Weakly coupled ultralight fields common in extensions of the Standard Model
- Simple mechanisms to produce required amount of dark matter
- Low-hanging fruit: requires new kinds of small-scale experiments, pioneered now
- Bounded: only a few interactions are natural and leading in effective field theory

Case study: couplings of the axion

$$a\,\bar{q}i\gamma^5 q$$

$$a\,\bar{e}i\gamma^5 e$$

After spontaneously broken $U(1)_{\mathrm{PQ}}$...

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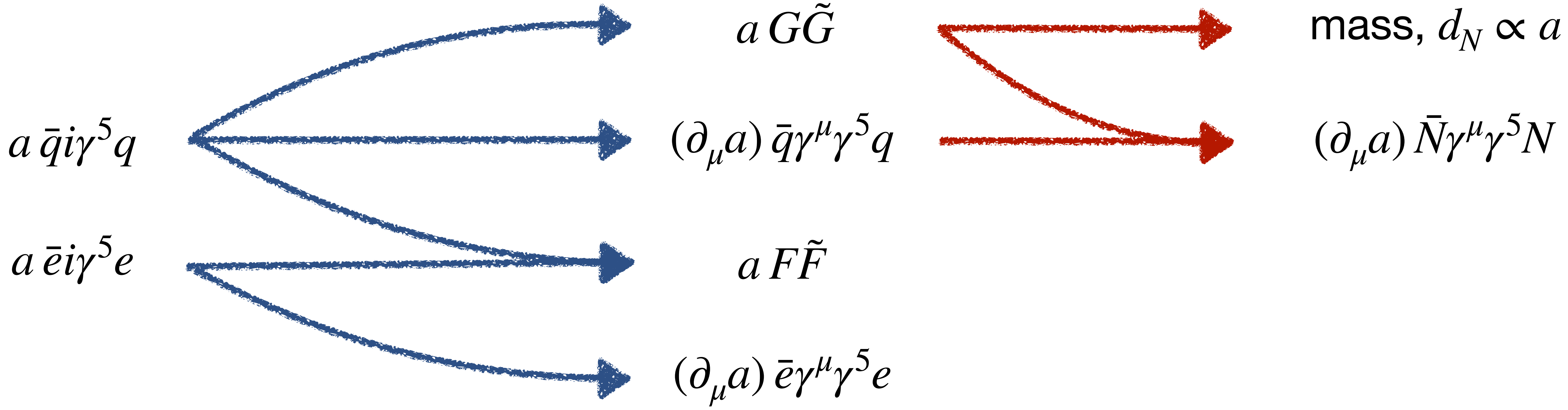

After spontaneously broken $U(1)_{\mathrm{PQ}}$, do chiral field redefinitions, take low-energy limit

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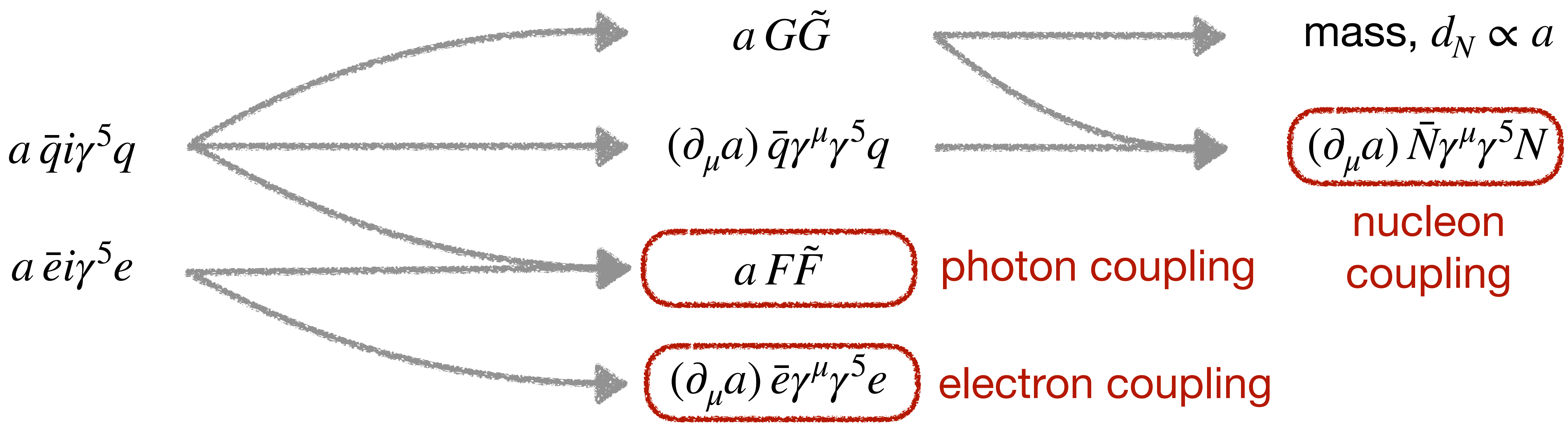
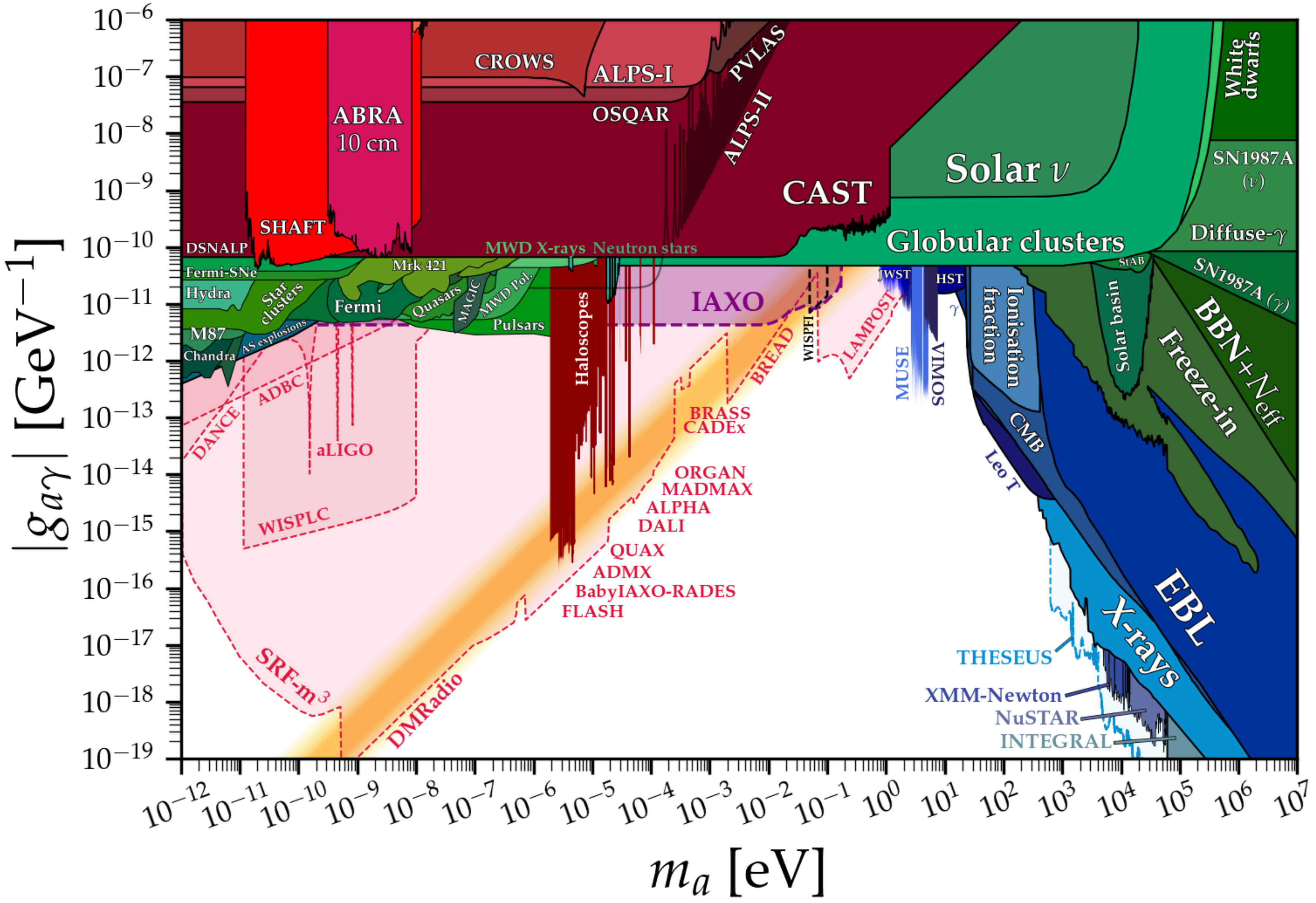


After spontaneously broken $U(1)_{\mathrm{PQ}}$, do chiral field redefinitions, take low-energy limit

Generic result is all leading terms allowed by effective field theory

Only 3 possibilities, each with distinct experimental signatures

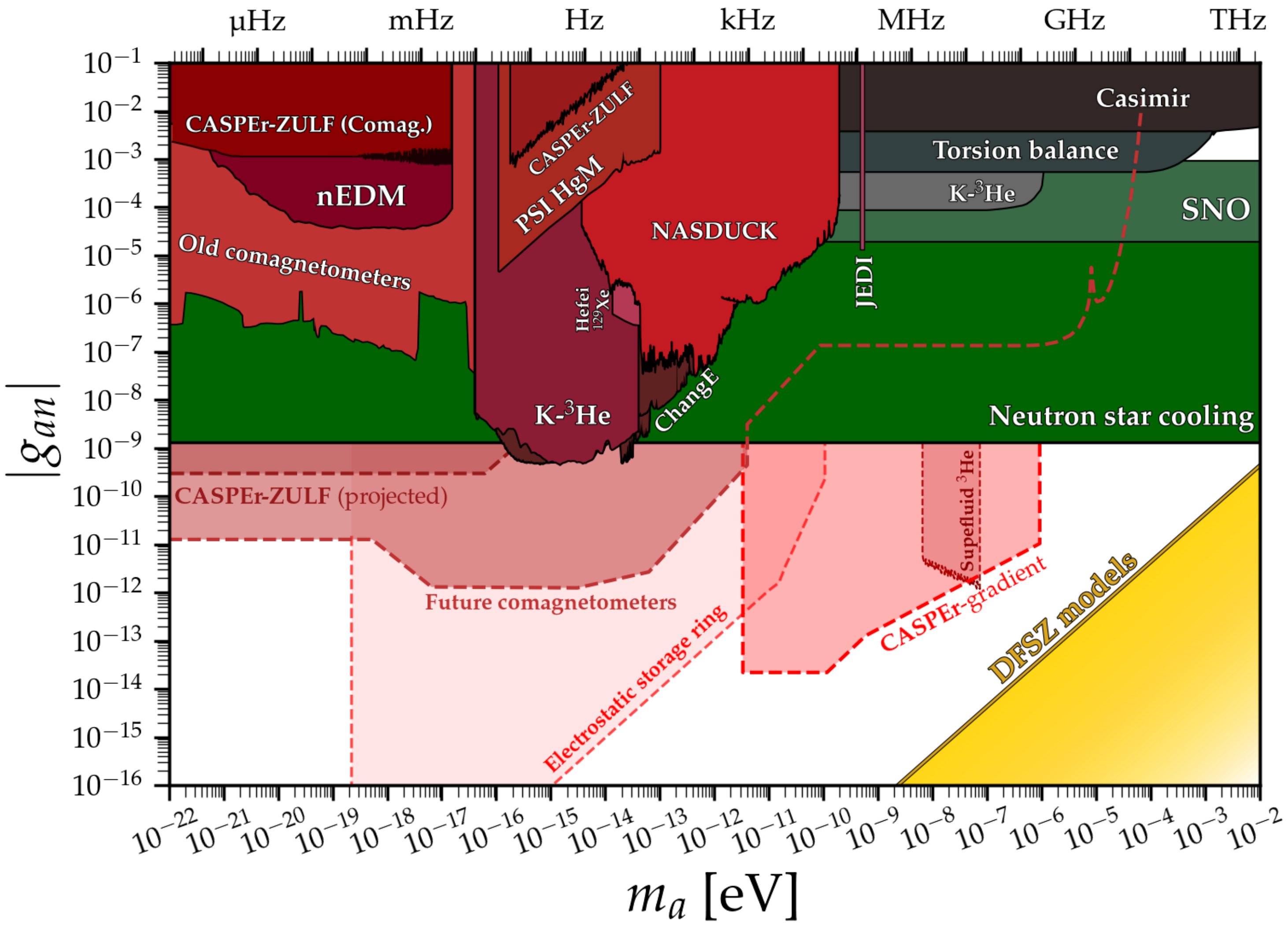
The experimental landscape

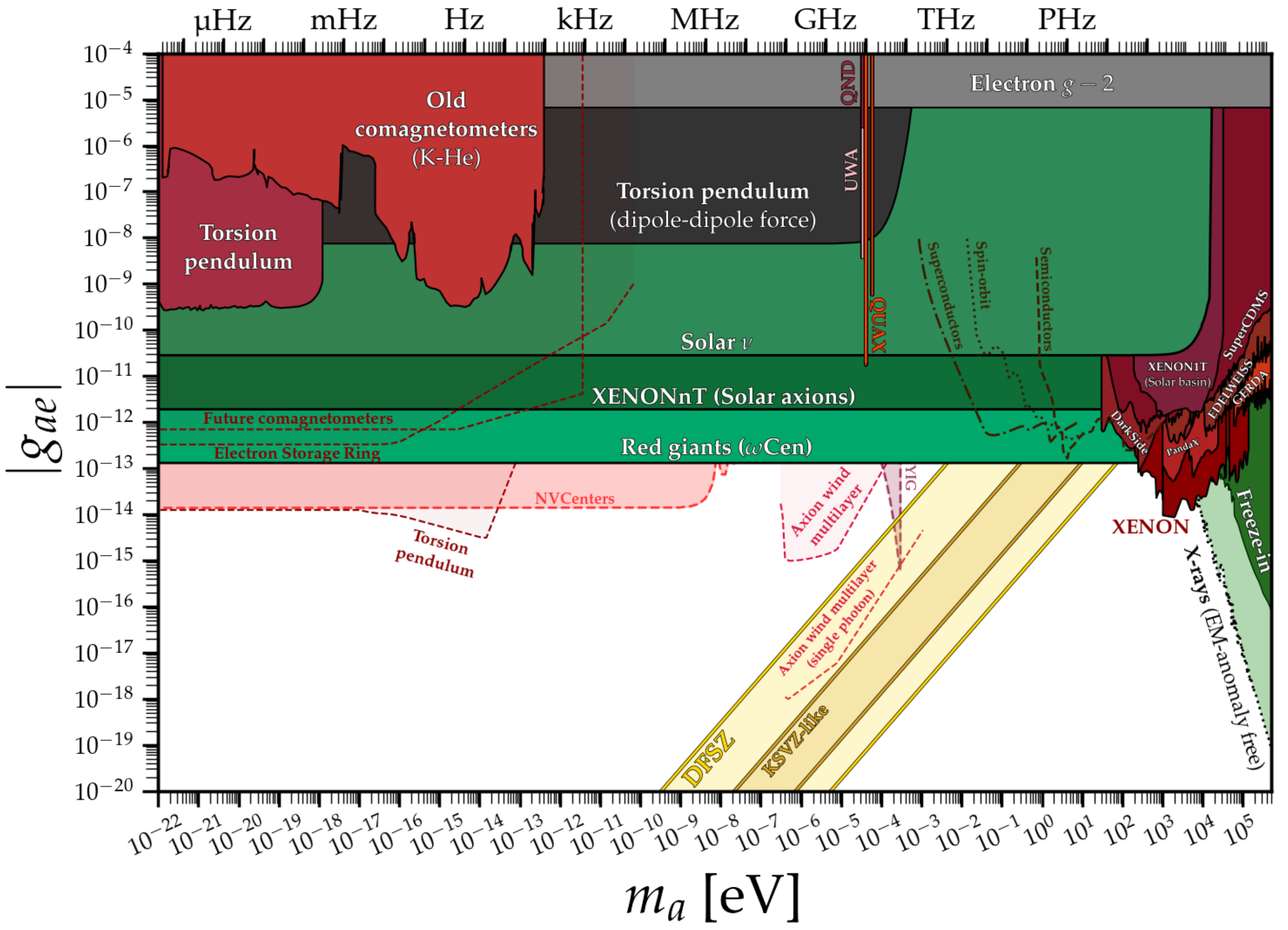


Many ongoing experiments, prototypes, and ideas to probe the axion-photon coupling

O’Hare, AxionLimits

The experimental landscape





Experimental program for axion-nucleon couplings less developed, but many ideas for strong sensitivity

Almost no ideas formulated to date for the axion-electron coupling!

O'Hare, AxionLimits

Understanding Axion-Fermion Couplings

Couplings to electrons and nucleons both have form $\mathscr{L} \supset g\,(\partial_\mu a)\,\bar{\Psi}\gamma^\mu\gamma^5\Psi$

In nonrelativistic single particle limit: $$\int d^3\mathbf{x}\,\bar{\Psi}\gamma^\mu\gamma^5\Psi \to s^\mu \simeq (\mathbf{v}\cdot\hat{\mathbf{s}}, \hat{\mathbf{s}})^\mu$$

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Resulting single particle Hamiltonian: $H \supset -\,g\,(\nabla a)\cdot\sigma - \frac{g}{m}\,\dot{a}\,\sigma\cdot(\mathbf{p} - q\mathbf{A})$

"axion wind" spin torque

$$\tau = g\,\hat{\mathbf{s}} \times \nabla a$$

suppressed by $v_{\mathrm{DM}} \sim 10^{-3}$

"axioelectric" spin-dependent force

$$\mathbf{F} = -\,g\,\ddot{a}\,\hat{\mathbf{s}}$$

suppressed by extra factor of m_a

Electrons vs. Nucleons

Electron is $\sim 10^3$ times lighter: easier to accelerate

Electron spins have $\sim 10^3$ larger magnetic moment: easier to align, make larger electromagnetic signal when rotated

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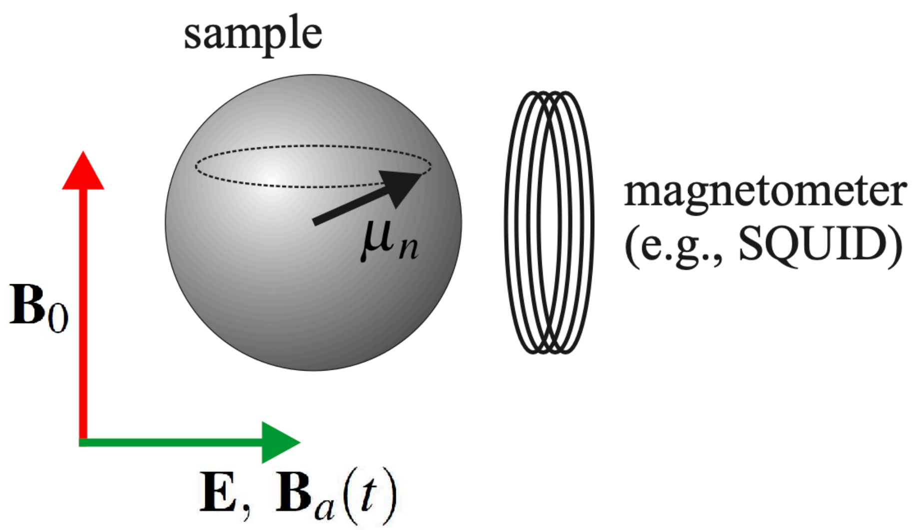
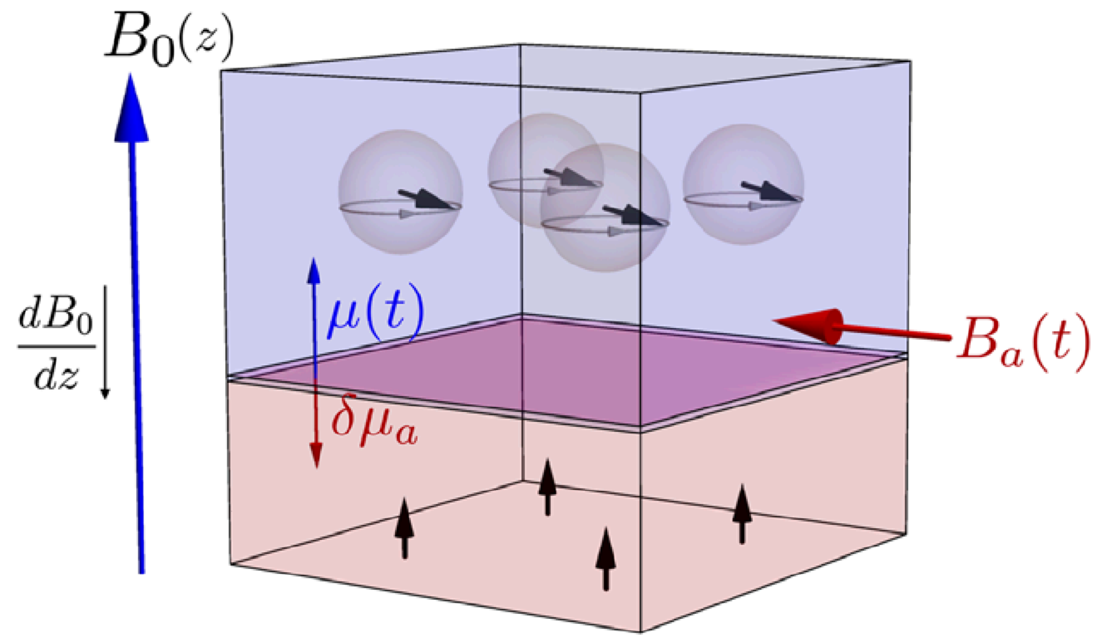
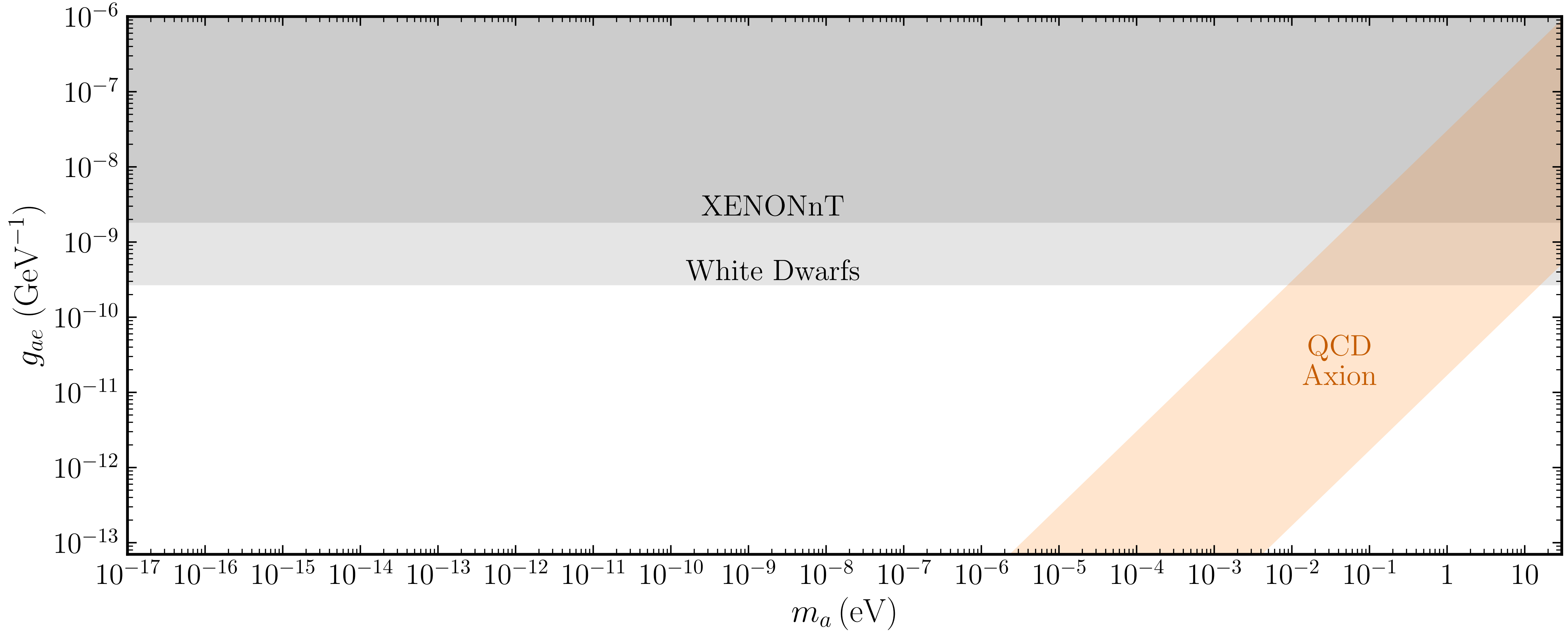
But most proposals for axion-nucleon coupling require the exceptional stability ($Q_{\text{eff}} \gtrsim 10^{10}$) of nuclear spin precession

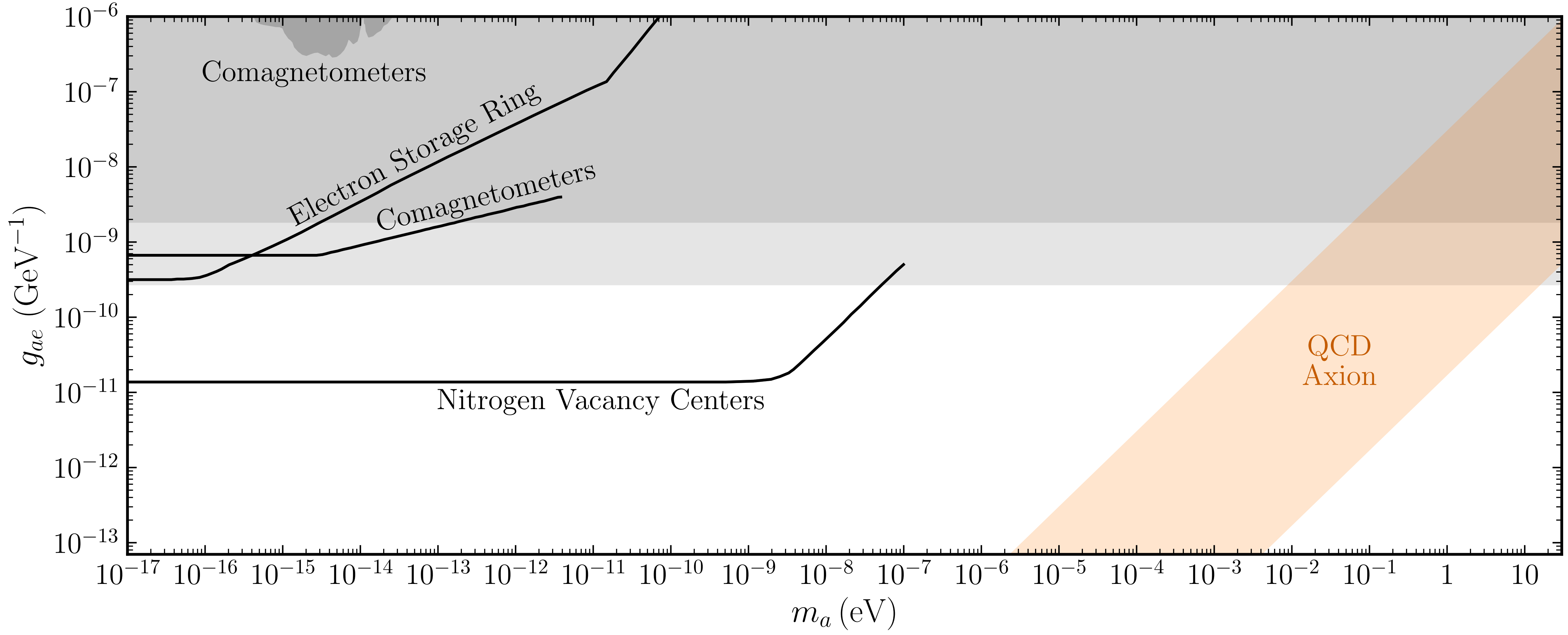
Electrons in material interact strongly with each other, can't have very high Q





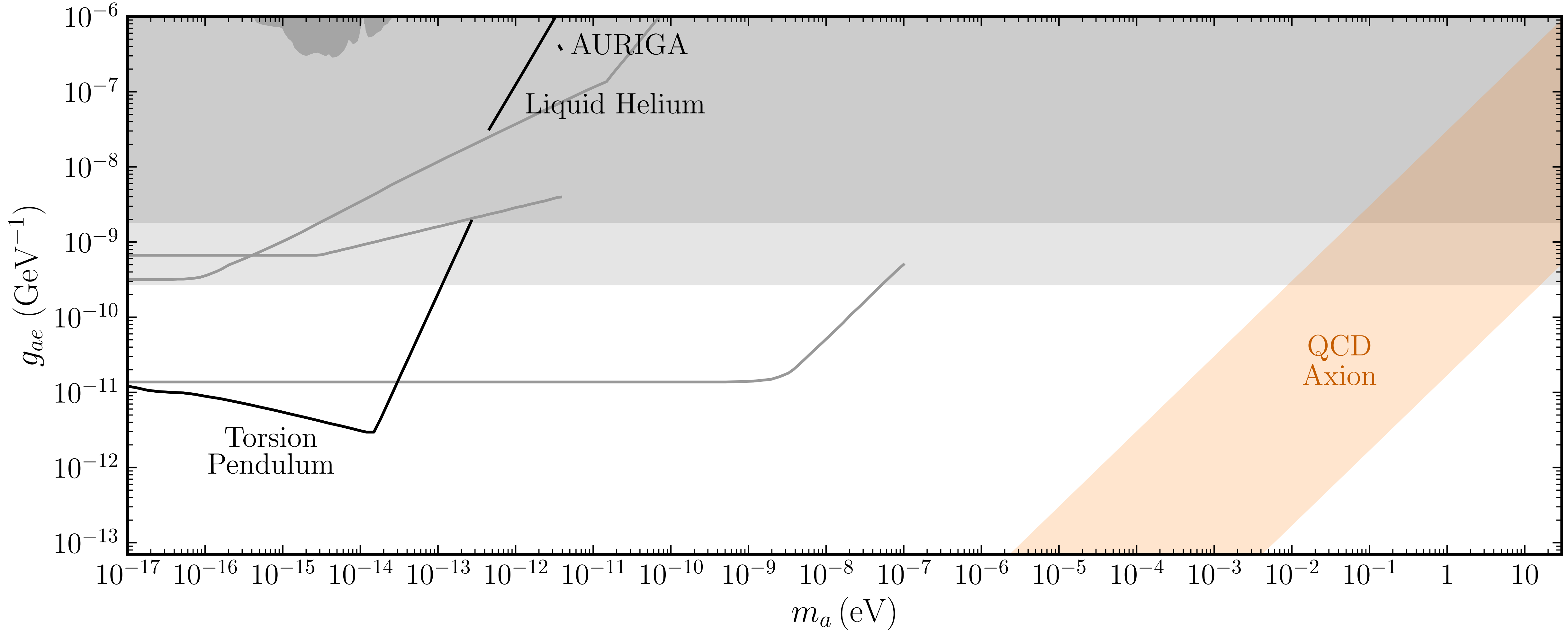


A quick overview of the experimental landscape



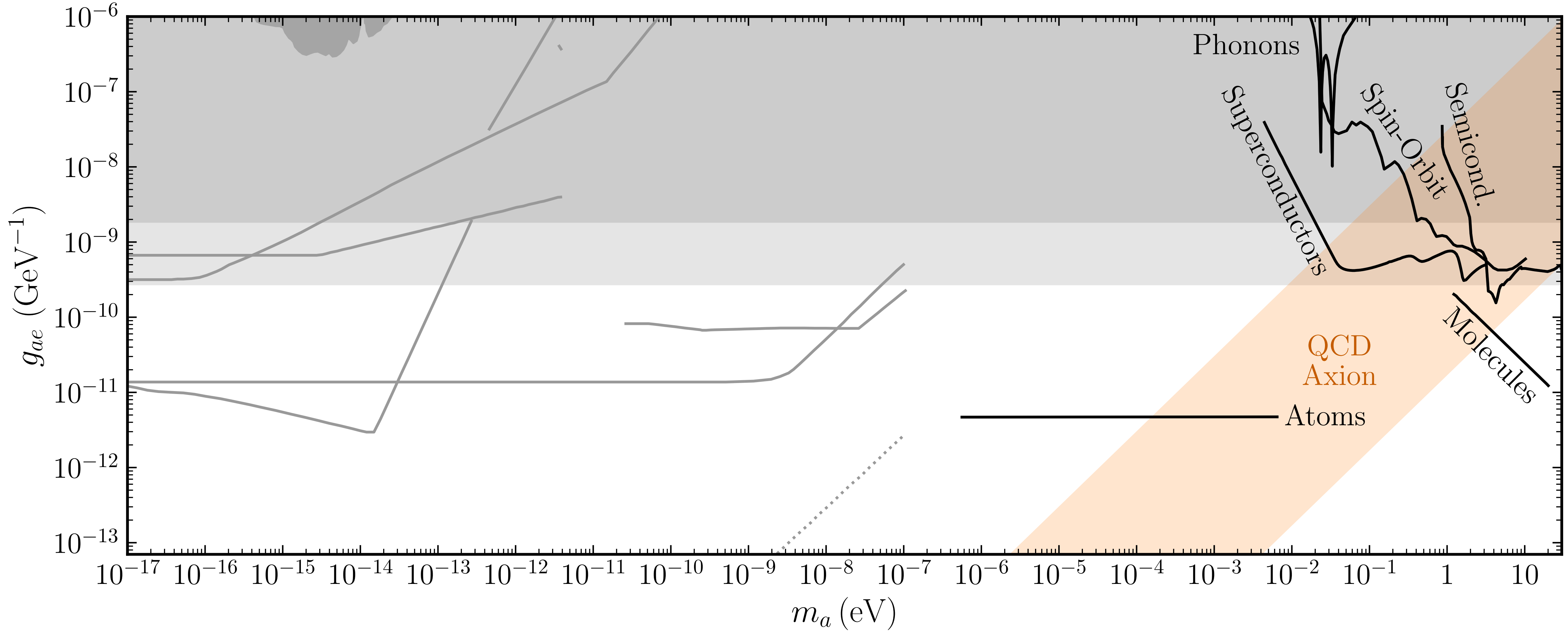
Axion wind tilts electron spins, producing transverse magnetic fields

Electron spins only coherent for long enough if spatially separated, which reduces maximum total signal strength



Spin polarized objects can feel mechanical torques or forces

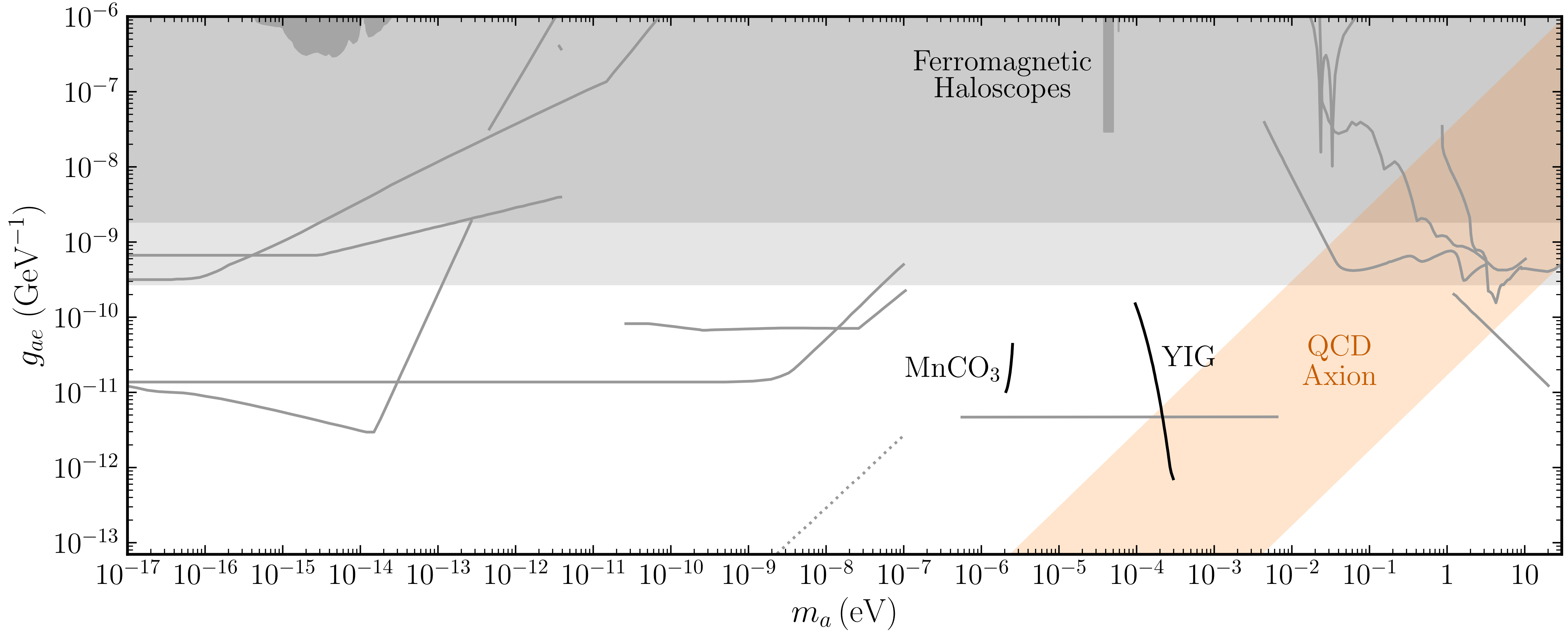
Strongest at low axion masses/frequencies, because $\Delta x \sim a/m_a^2$



At high masses, can detect absorption of individual axions

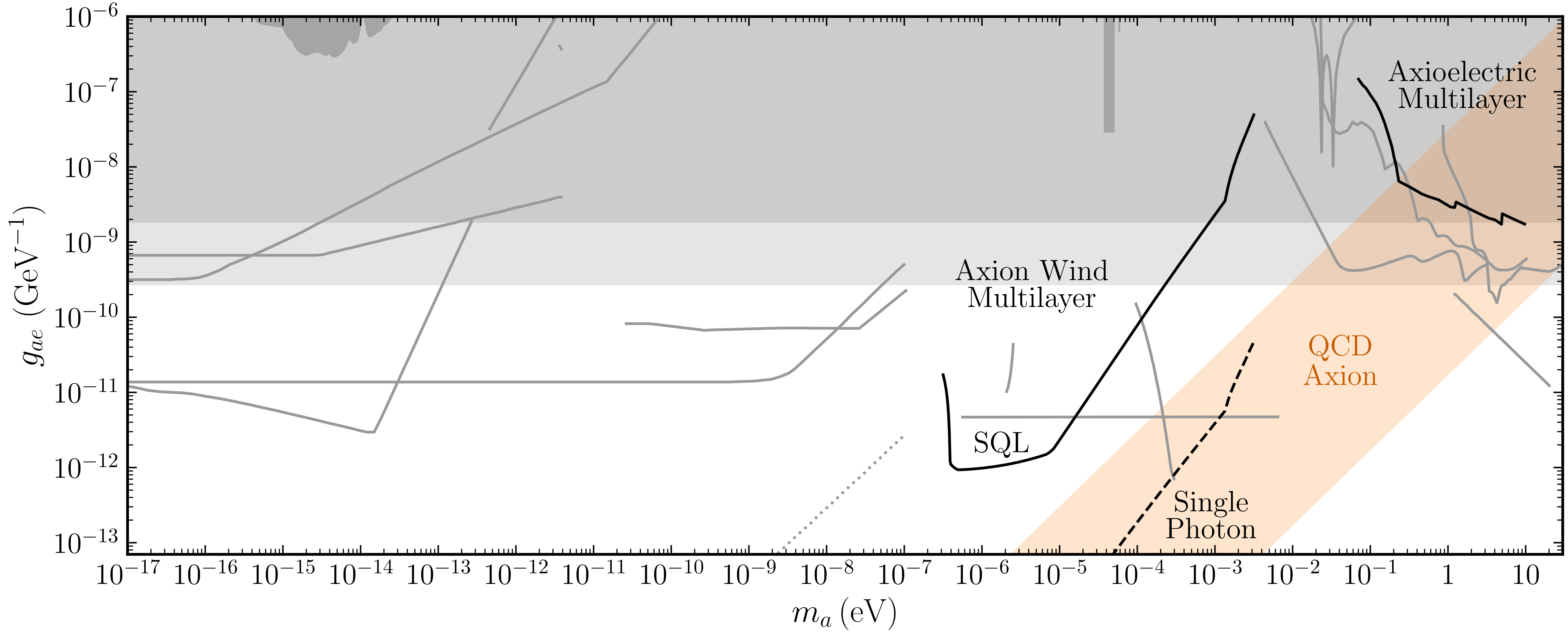
Axioelectric force: electronic excitations, phonons

Axion wind torque: spin flips, magnons



Intermediate masses are particularly motivated by simple production mechanisms

All existing searches and proposals are “ferromagnetic haloscopes”



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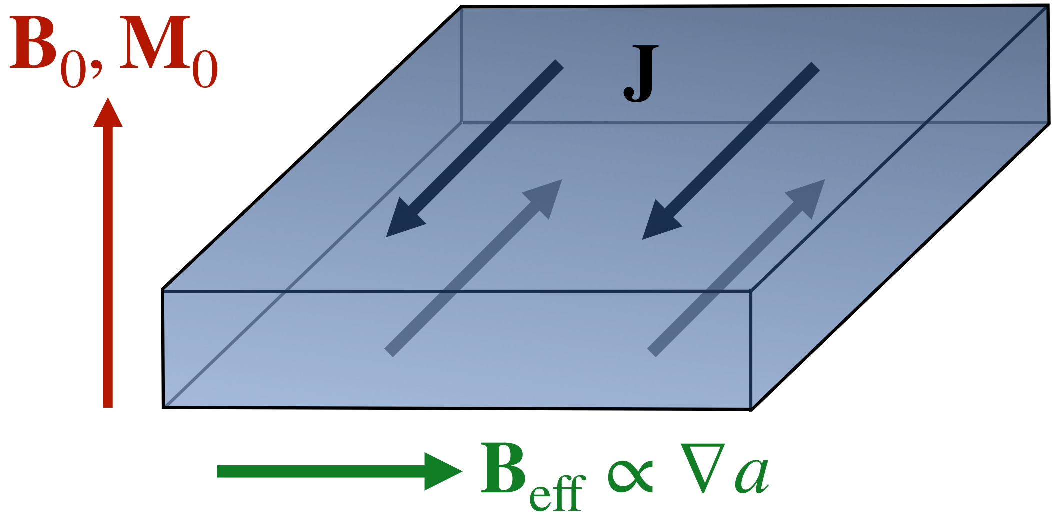
We propose to do better with magnetized multilayers

The Electromagnetic Signal



The axion wind acts like an effective magnetic field, tilting a magnetized medium's $\mathbf{M}_0$

$$\mathbf{M}_a = \frac{\chi}{1+\chi}\mathbf{B}_{\text{eff}}$$

(tunable resonance at $\omega \propto B_0$ with quality factor Q)

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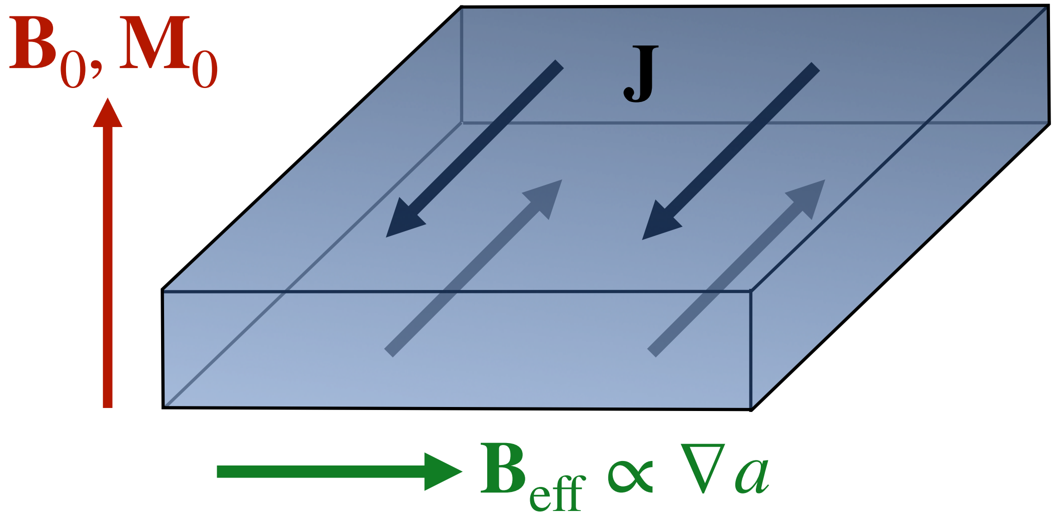

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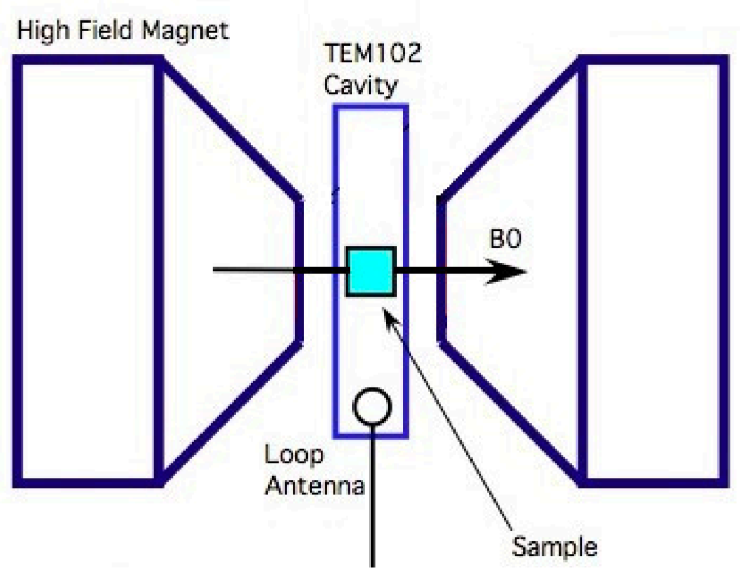
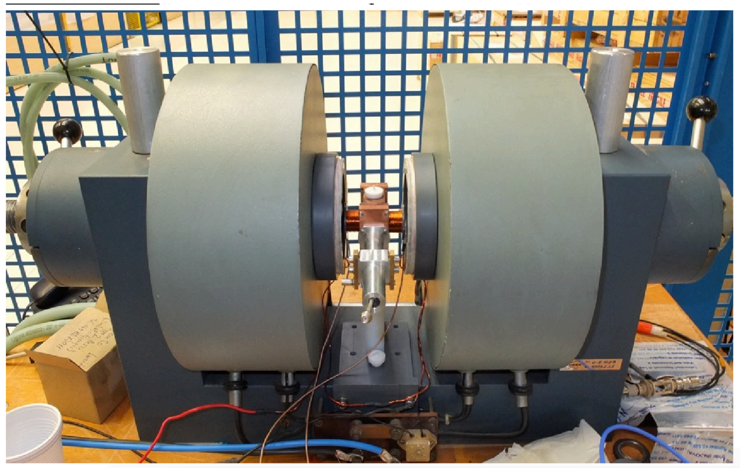
$$\mathbf{J} = \nabla \times \mathbf{M}_a$$

Transverse $\mathbf{M}_a$ corresponds to oscillating surface current, which produces radiation of frequency m_a

Ferromagnetic Haloscopes



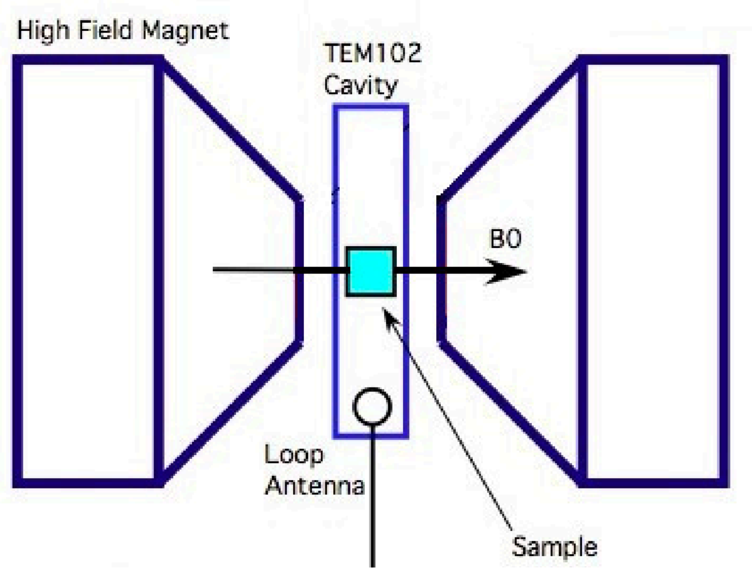


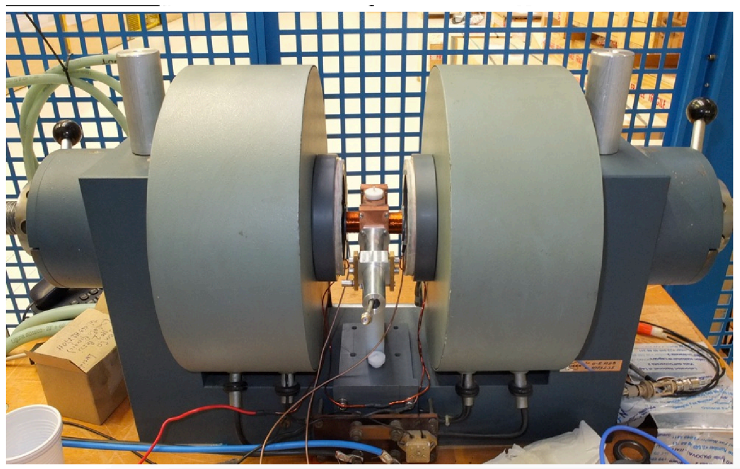
Magnet is a tiny sample of yttrium iron garnet, enclosed in microwave cavity

$$P_{\text{sig}} \propto Q\, M_0\, V$$

Crescini 2017

Ferromagnetic Haloscopes





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$$P_{\rm sig} \propto Q\, M_0\, V$$

yttrium iron garnet

$Q \sim 10^4$

$M_0 \sim 0.25\,\mathrm{T}$

costs $\sim \$10{,}000{,}000/\mathrm{kg}$

poly. spinel ferrites

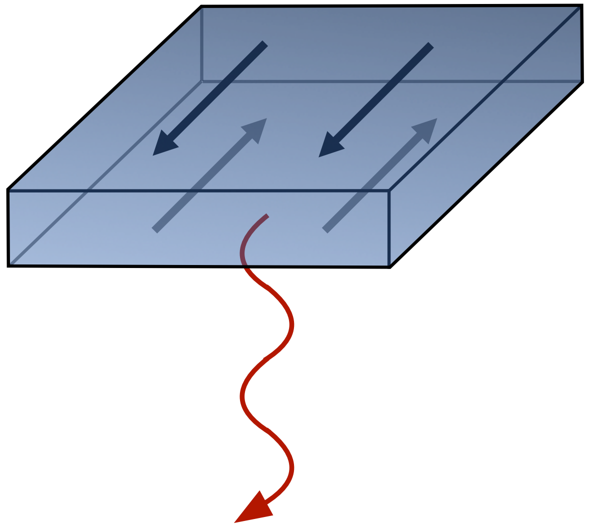
$Q \sim 10^2$

$M_0 \sim 0.5\,\mathrm{T}$

costs $\sim \$100/\mathrm{kg}$

Material with highest Q very expensive! But materials with lower Q plentiful, cheap

Magnetized Multilayer



Our proposal: instead of focusing on high Q,
increase signal power by scaling up the experiment

Magnetic slab of area $A \sim \mathrm{m}^2$ emits radiation

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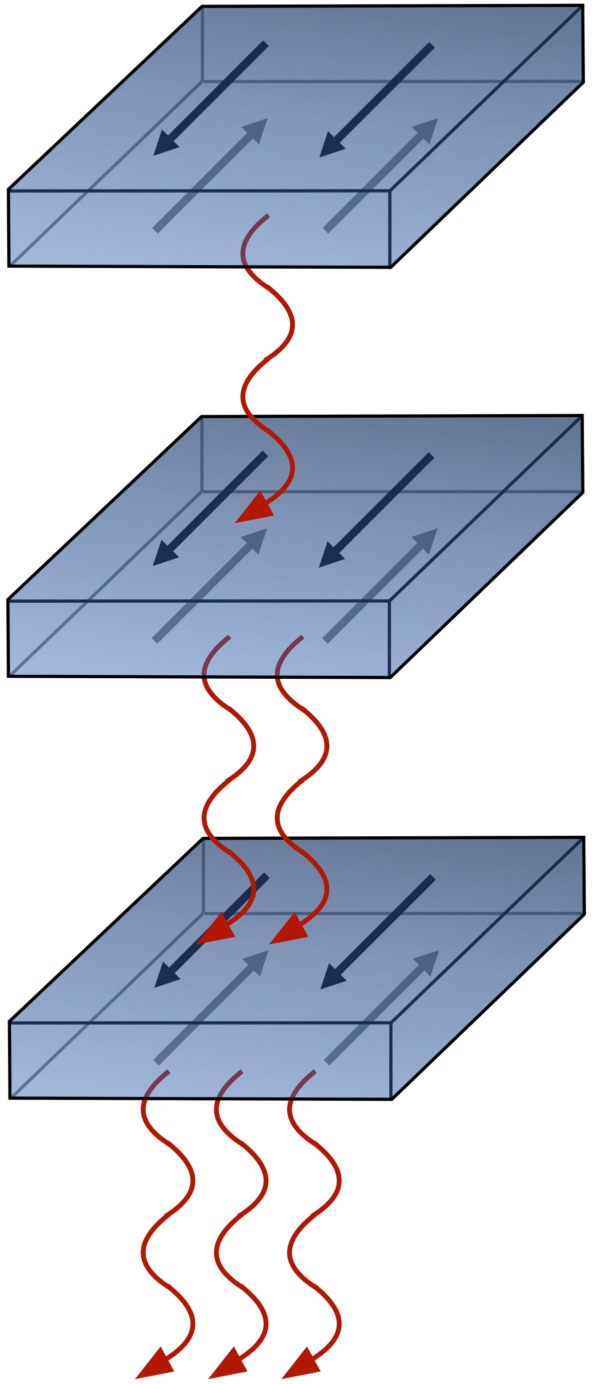


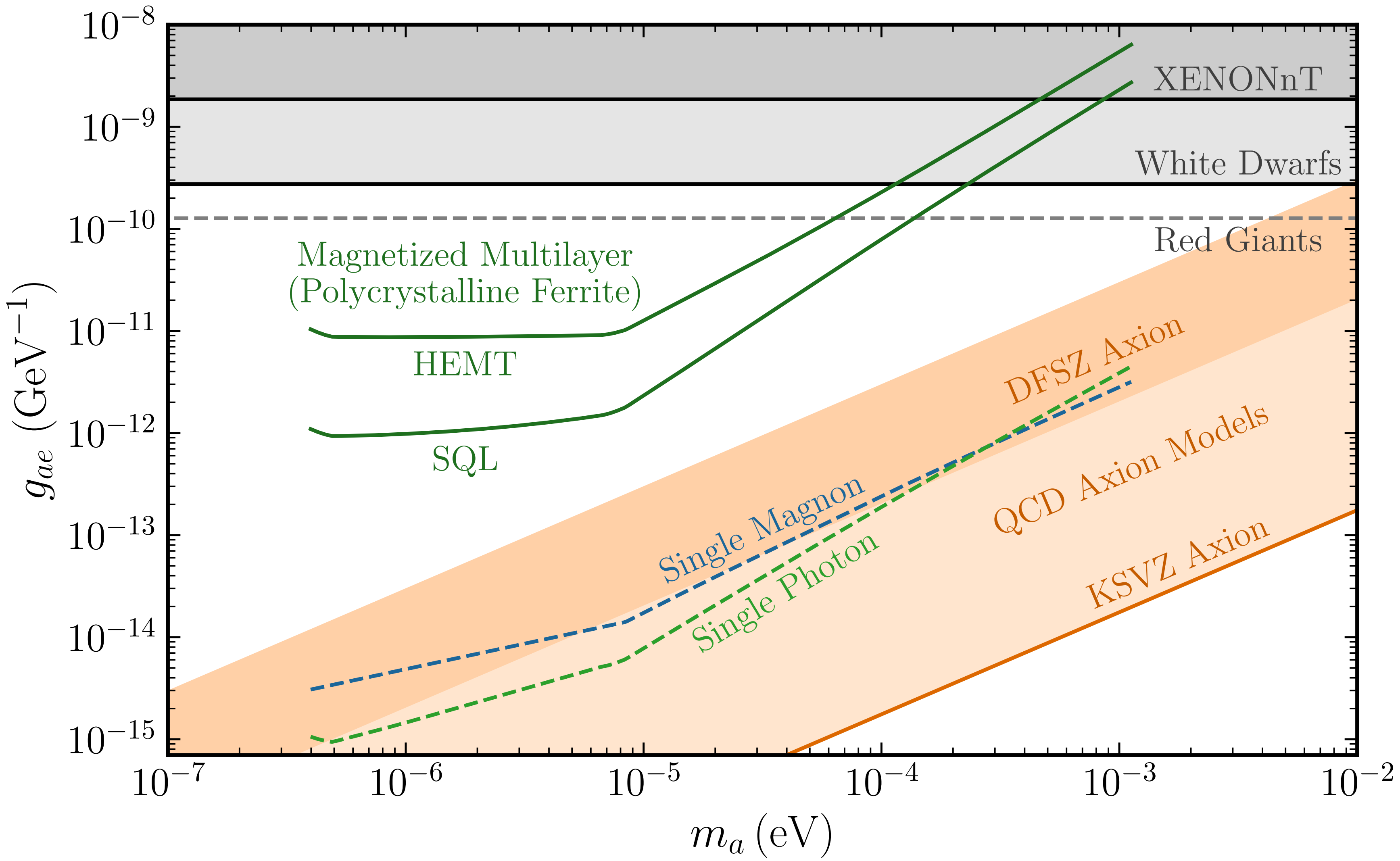
Our proposal: instead of focusing on high Q, increase signal power by scaling up the experiment

Magnetic slab of area $A \sim \mathrm{m}^2$ emits radiation

Including $N \leq 80$ slabs with appropriate spacing increases signal by constructive interference

Optimized signal power is $P_{\mathrm{sig}} \propto Q^2 M_0^2 A$

(unusual scaling arises from optimizing B_0 and N)



Setup with cheap materials can reach new parameter space with standard readout noise, probe QCD axion given single photon counting

The axion-electron coupling is generic, minimal, and underexplored — new ideas worth investigating and trying!