Physical Signatures of Fermion-Coupled Axion Dark Matter

Kevin Zhou

Stanford University

SLAC

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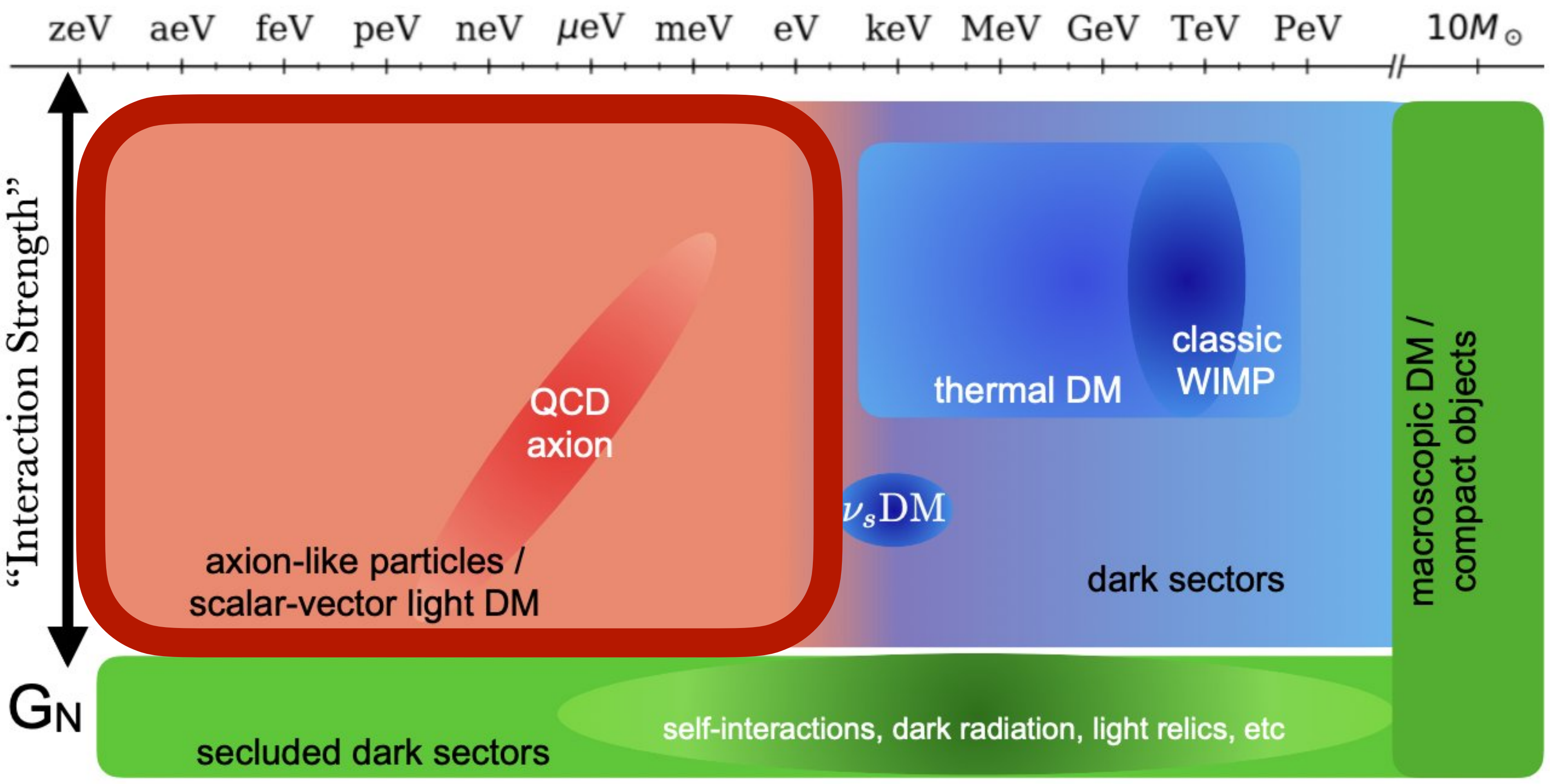
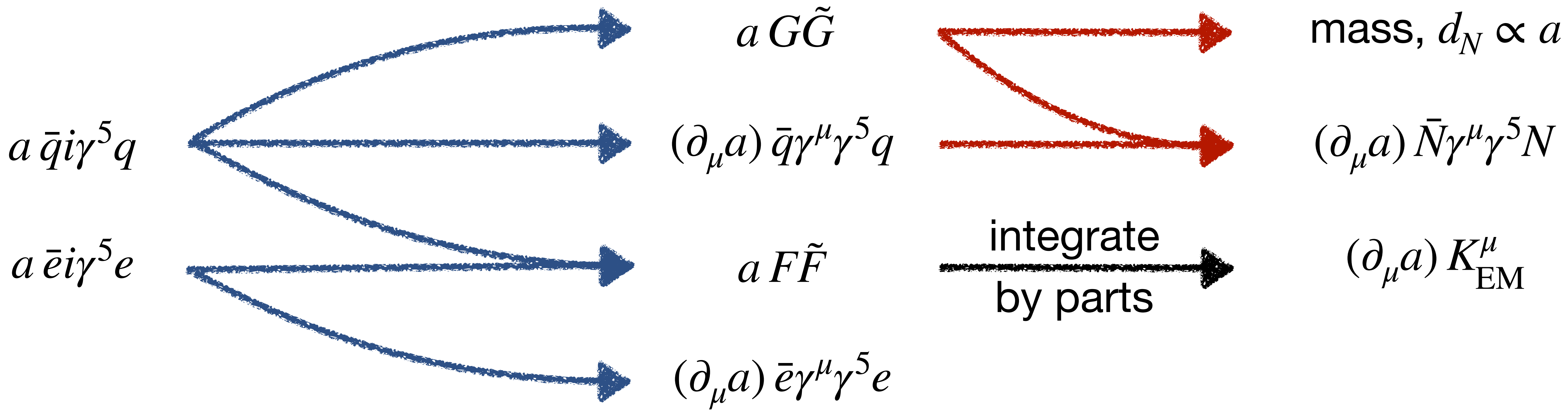
arXiv:2312.11601, with Asher Berlin, Alex Millar, Tanner Trickle



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

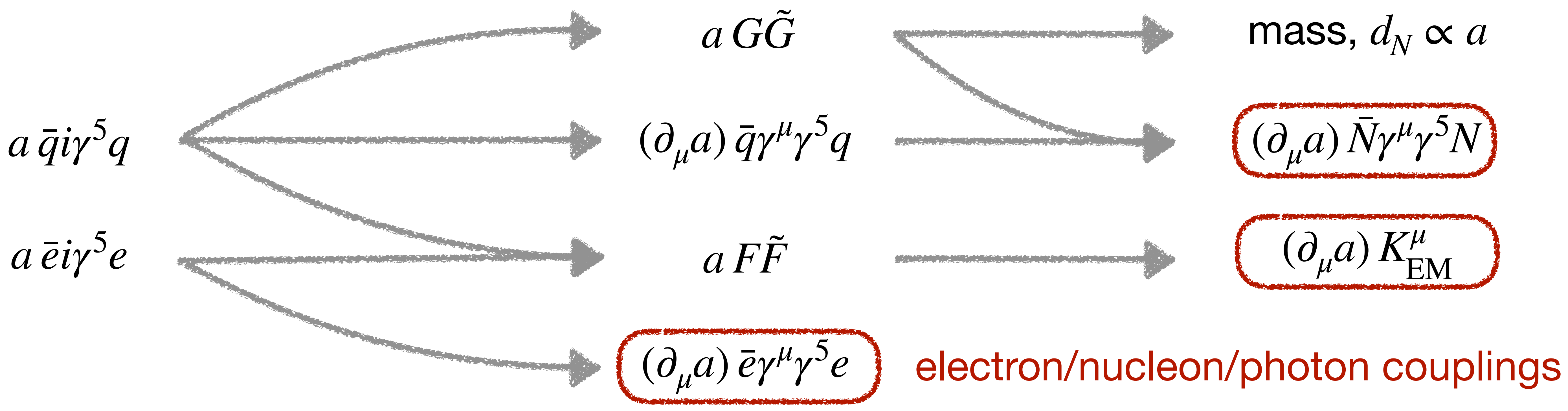


arises from spontaneous breaking of chiral symmetry at high energies

axion is Goldstone boson, so recast most interactions in derivative form by chiral field redefinitions, inducing couplings to gauge bosons by anomaly

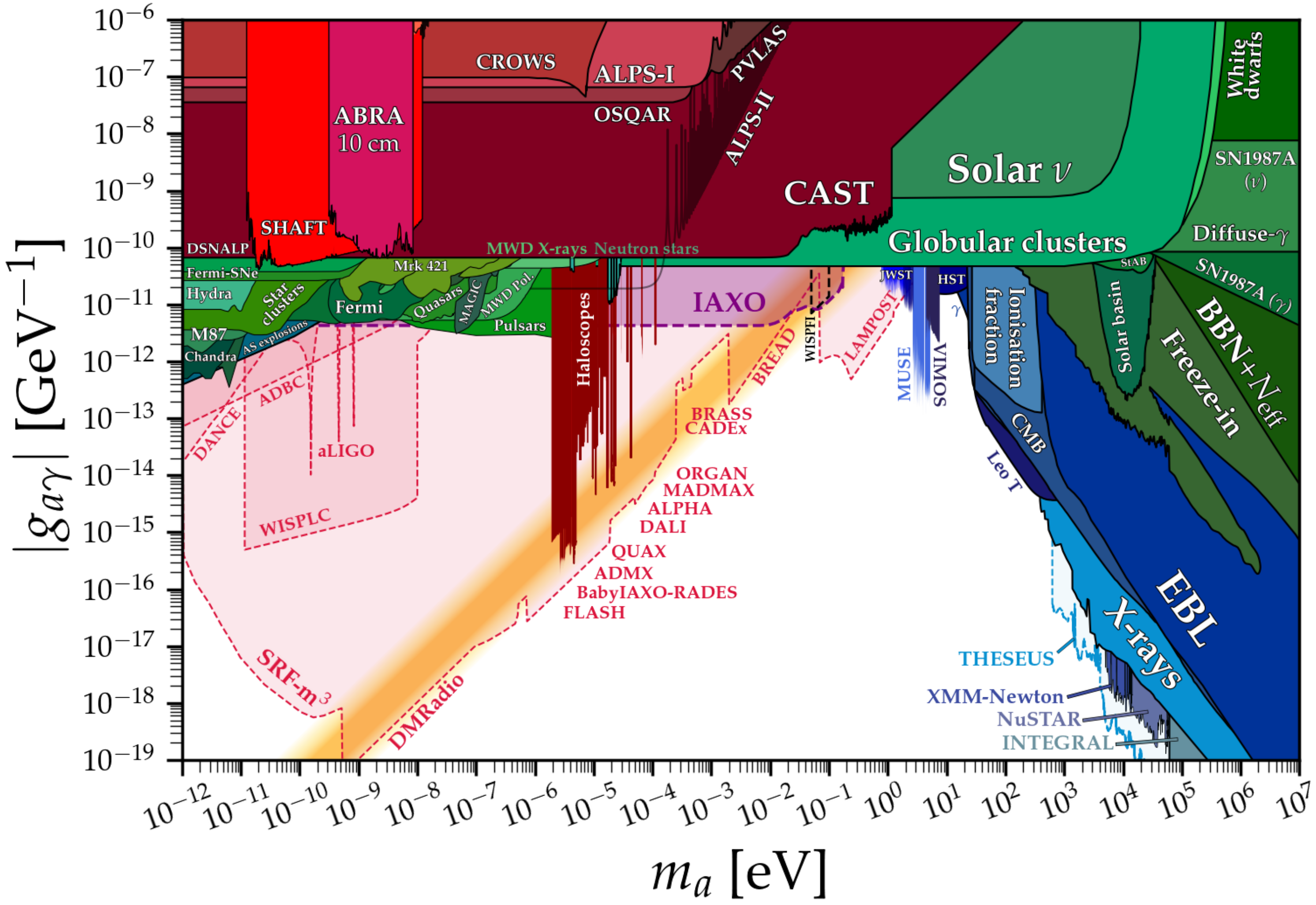
take low-energy limit to find nucleon couplings

Case study: couplings of the axion



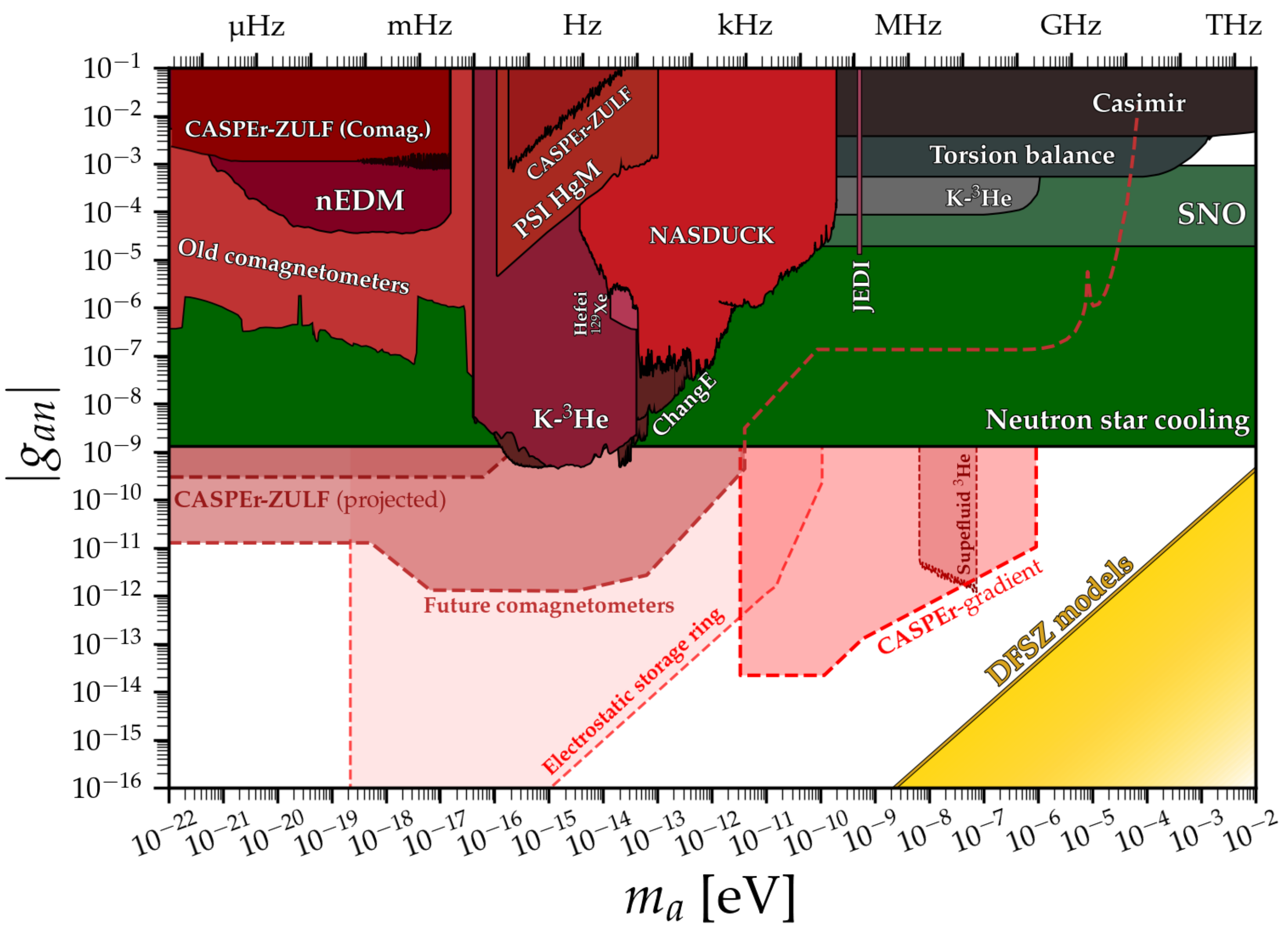
- At low energies, there are only few terms allowed by EFT, and generically all arise
- Most couplings can be written in terms of either a or $\partial_\mu a$, requiring care!
- Photon coupling generated by anomalies, α_{EM} suppressed
- Nucleon coupling requires care to avoid $aG\tilde{G}$, which would force a QCD axion
- Electron coupling arises directly from coupling at high energies, large or small

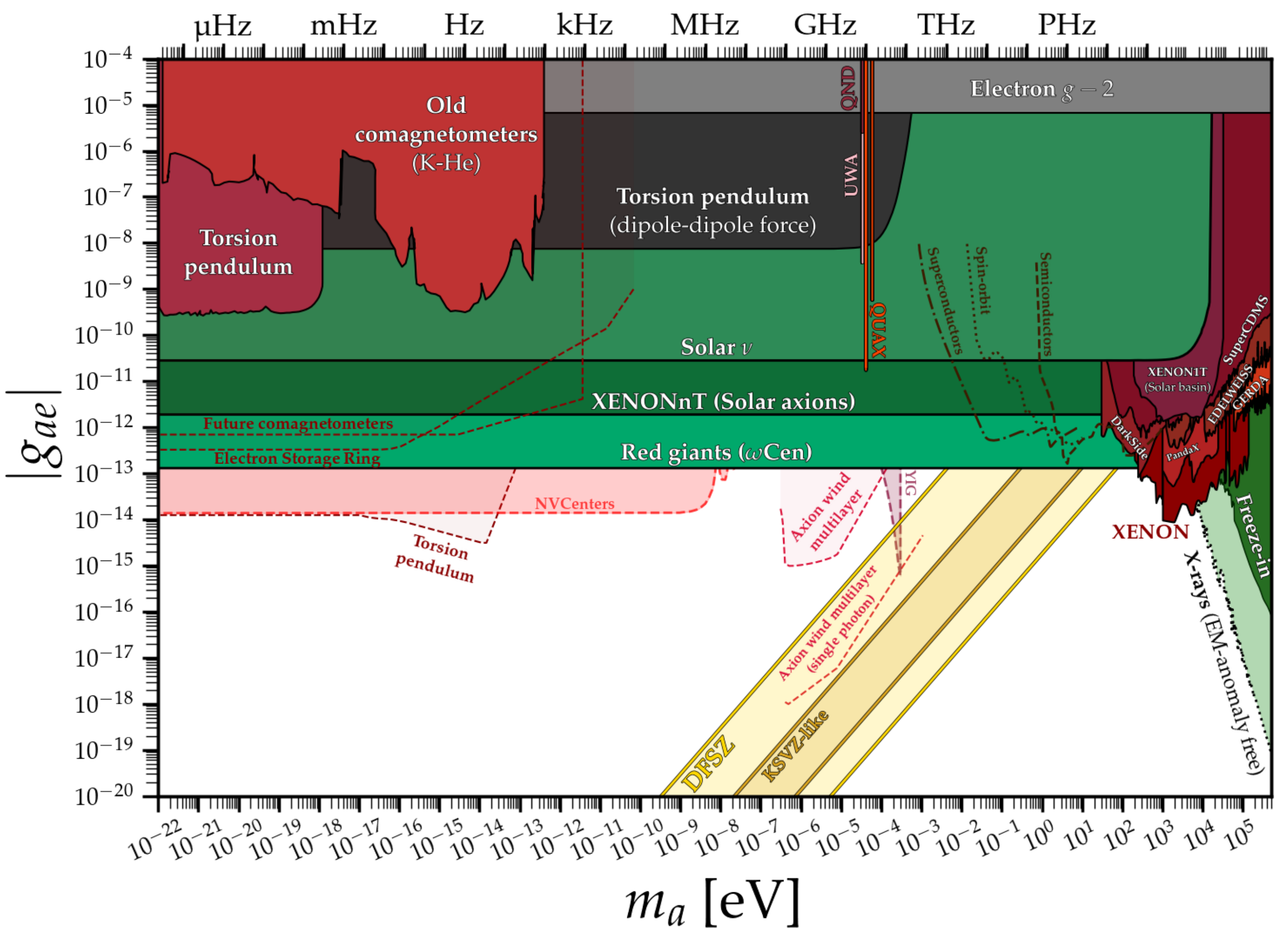
The experimental landscape



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

The experimental landscape

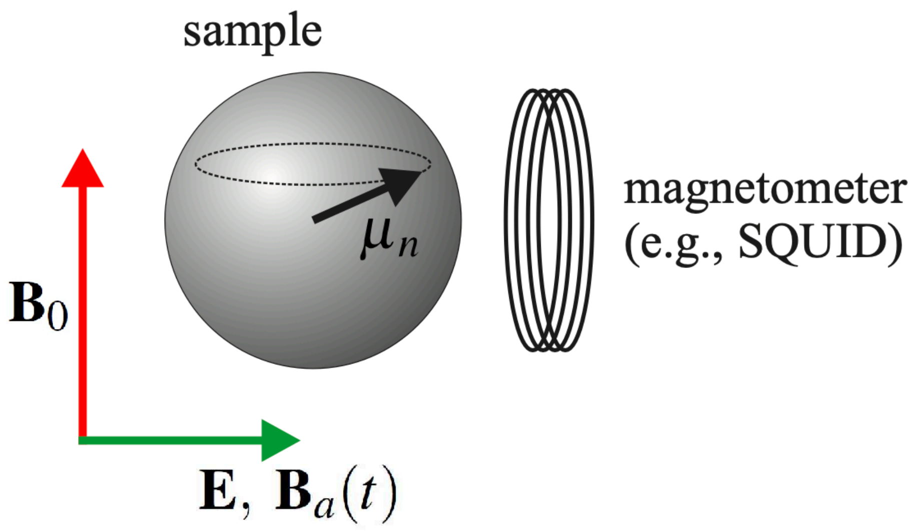




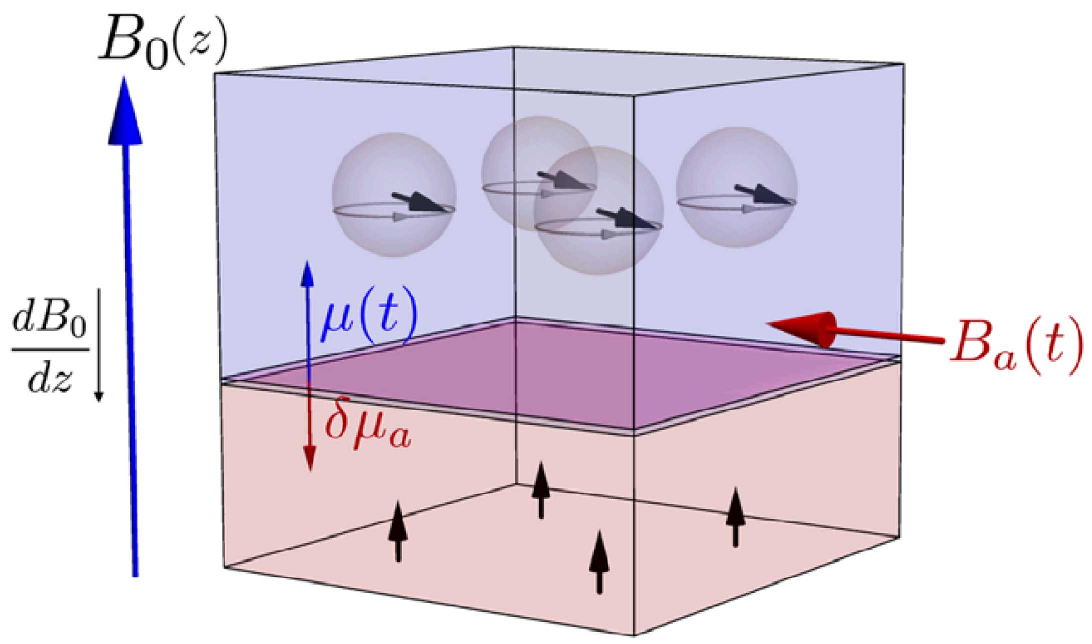
Experimental program for axion-nucleon couplings less developed, but many ideas for strong sensitivity

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

Electrons vs. Nucleons



Most proposals to search for the axion-nucleon coupling rely on the exceptional stability ($Q_{\text{eff}} \gtrsim 10^{10}$) of nuclear spin precession



Electron spins correspond to $\sim 10^3$ times bigger magnetic moment: much easier to align with each other, and generically expect larger electromagnetic signals, at higher frequencies

But electrons also tend to interact strongly with each other in material; can't have very high Q

1711.08999, 2208.14454

Understanding the Axion-Fermion Coupling

Generically has the form $\mathscr{L} \supset g\,(\partial_\mu a)\,\bar{\Psi}\gamma^\mu\gamma^5\Psi$ for fermion field Ψ

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

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

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

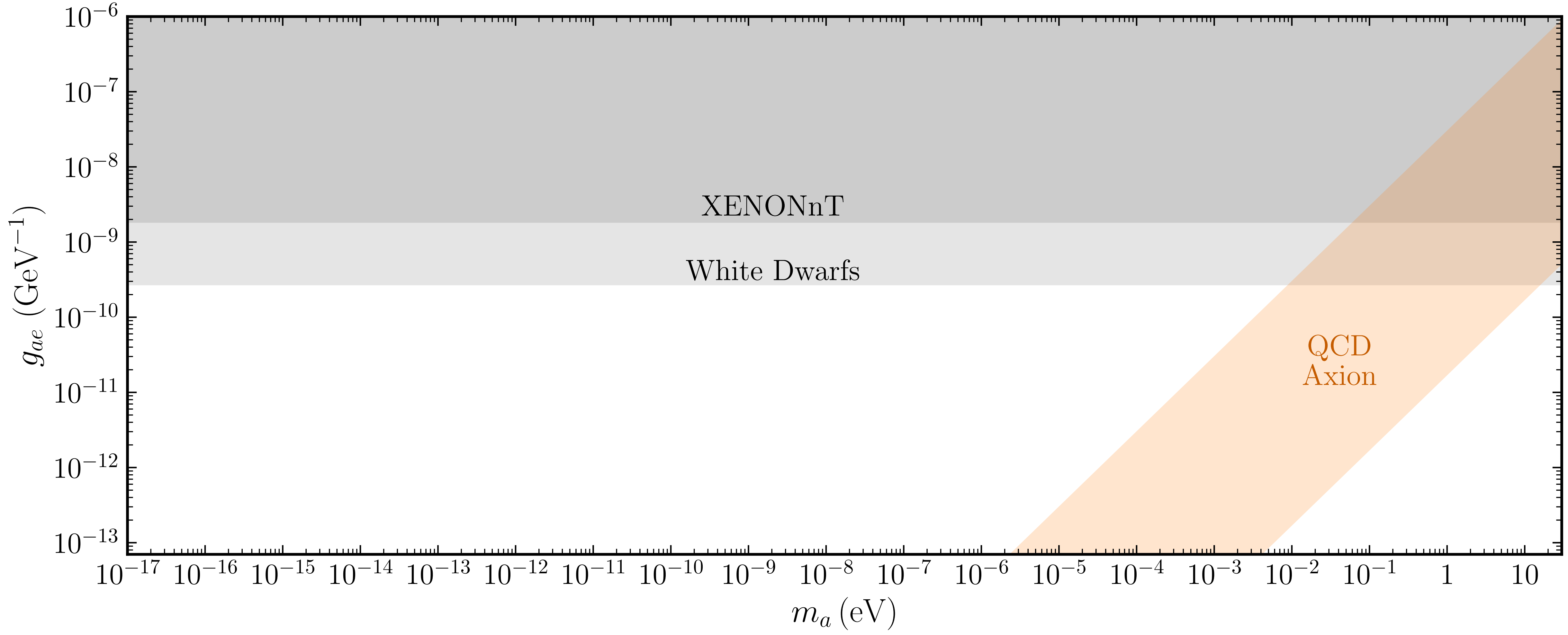
suppressed by $v_{\rm DM} \sim 10^{-3}$

“axioelectric” spin-dependent force

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

suppressed by extra factor of m_a

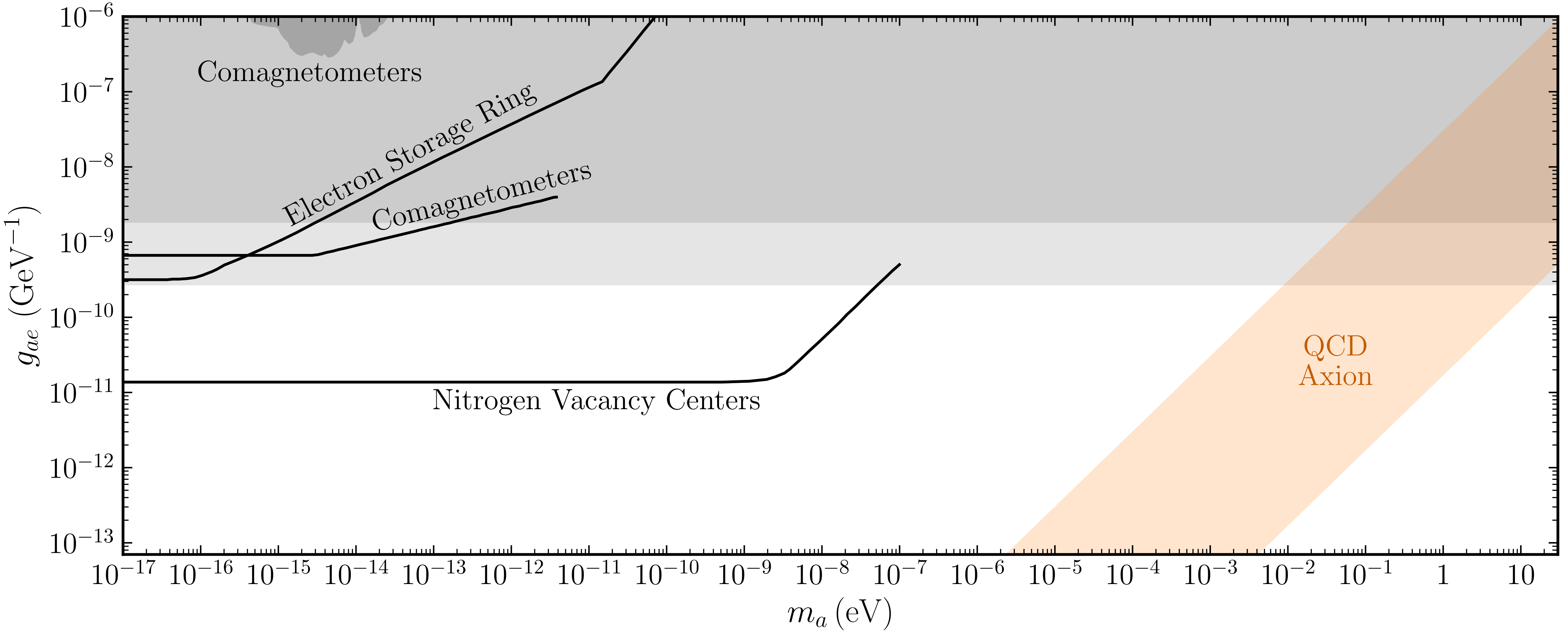
All signatures depend on derivatives of axion field



Existing bounds from solar axions detected in XENONnT,
and cooling of white dwarfs

QCD axion couplings: highest for DFSZ, suppressed for KSVZ (loop induced)

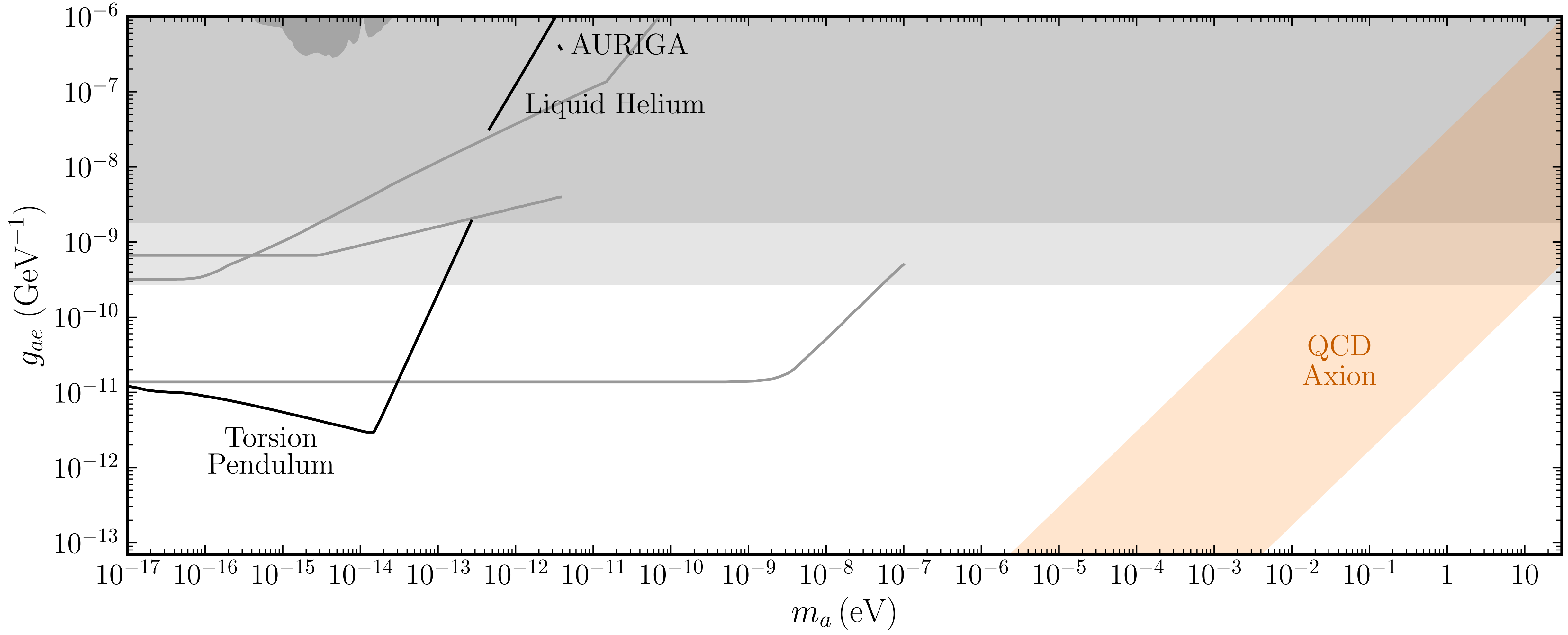
Caution: projections to be discussed vary widely in their difficulty to realize!



Can precisely measure the transverse magnetic fields induced by axion wind spin torque

To keep electron spins coherent long enough, need to spatially separate them (comagnetometer vapor, storage ring bunch, isolated NV centers)

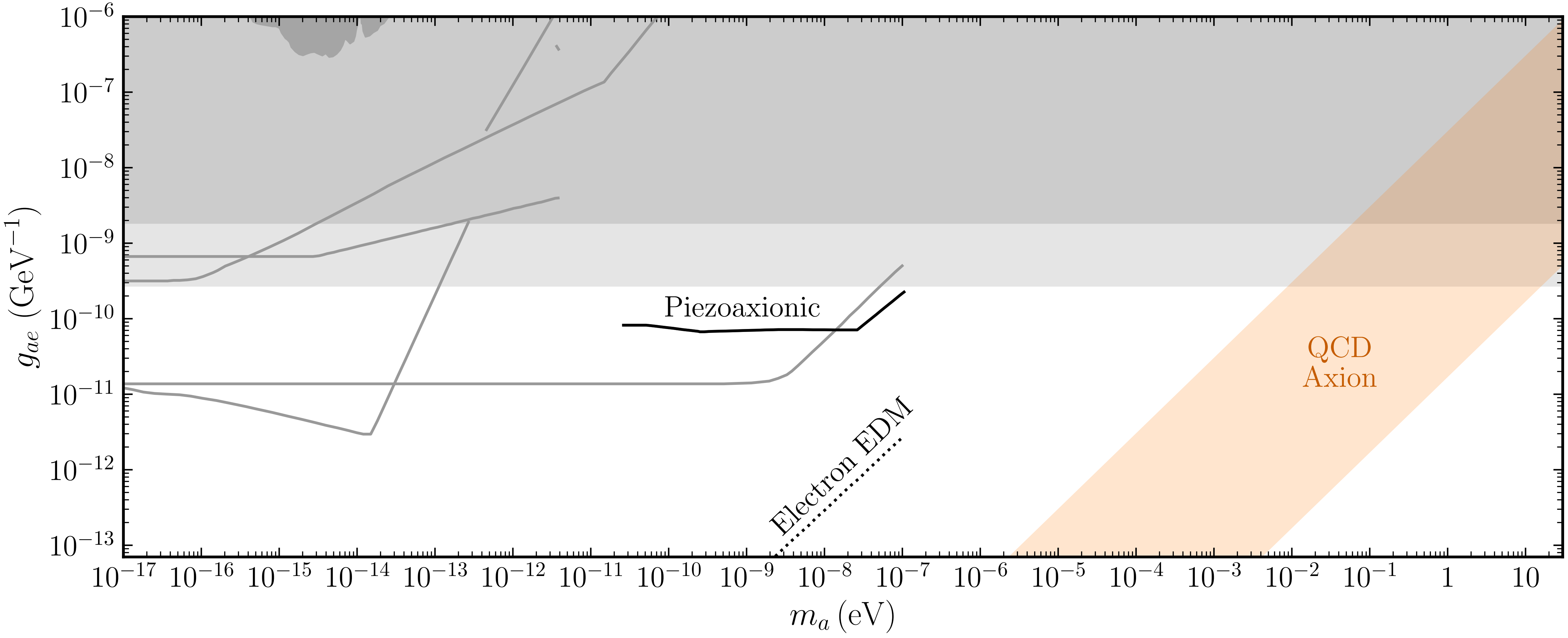
Lower number density makes it hard to probe beyond astrophysical bounds

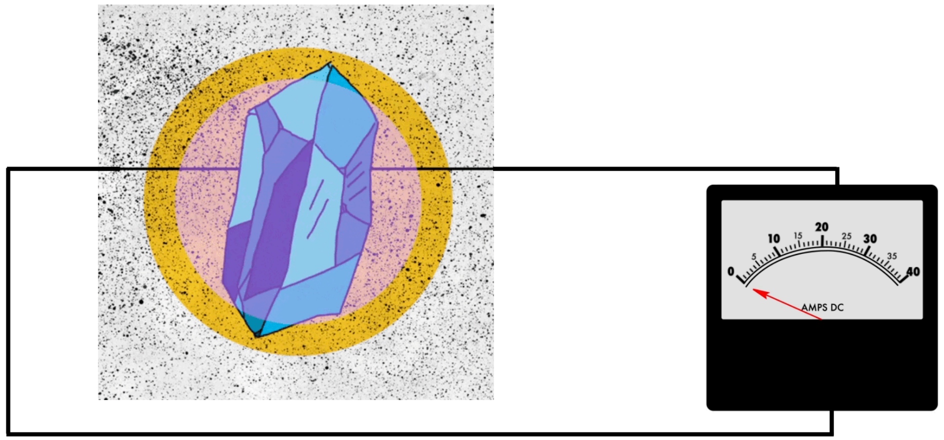


Spin polarized objects can feel mechanical torques or forces

Torsion pendulums can measure axion wind spin torque

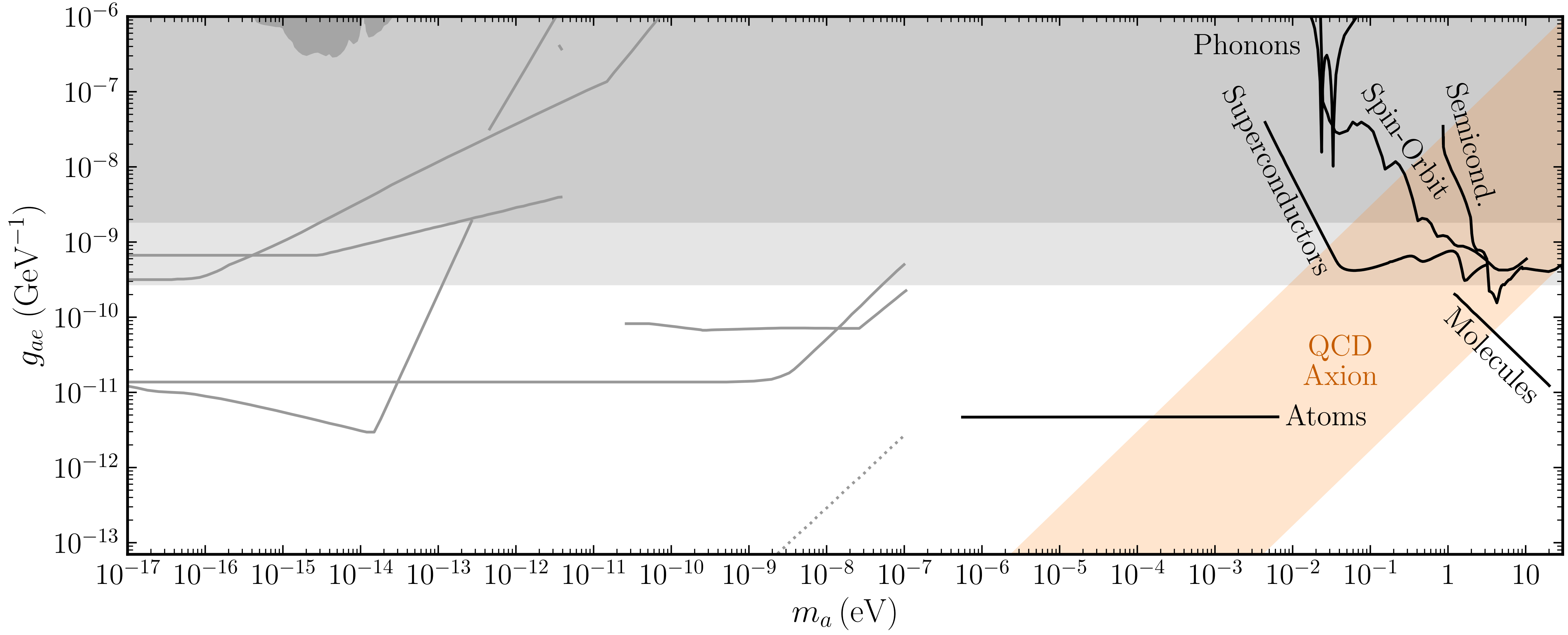
Spin-polarized mechanical resonators can be excited by axioelectric force (but suppressed by m_a)





Axioelectric term shifts atomic energy levels by $\Delta E \propto g_{ae}\,\dot{a}$, inducing oscillations in piezoelectric crystals

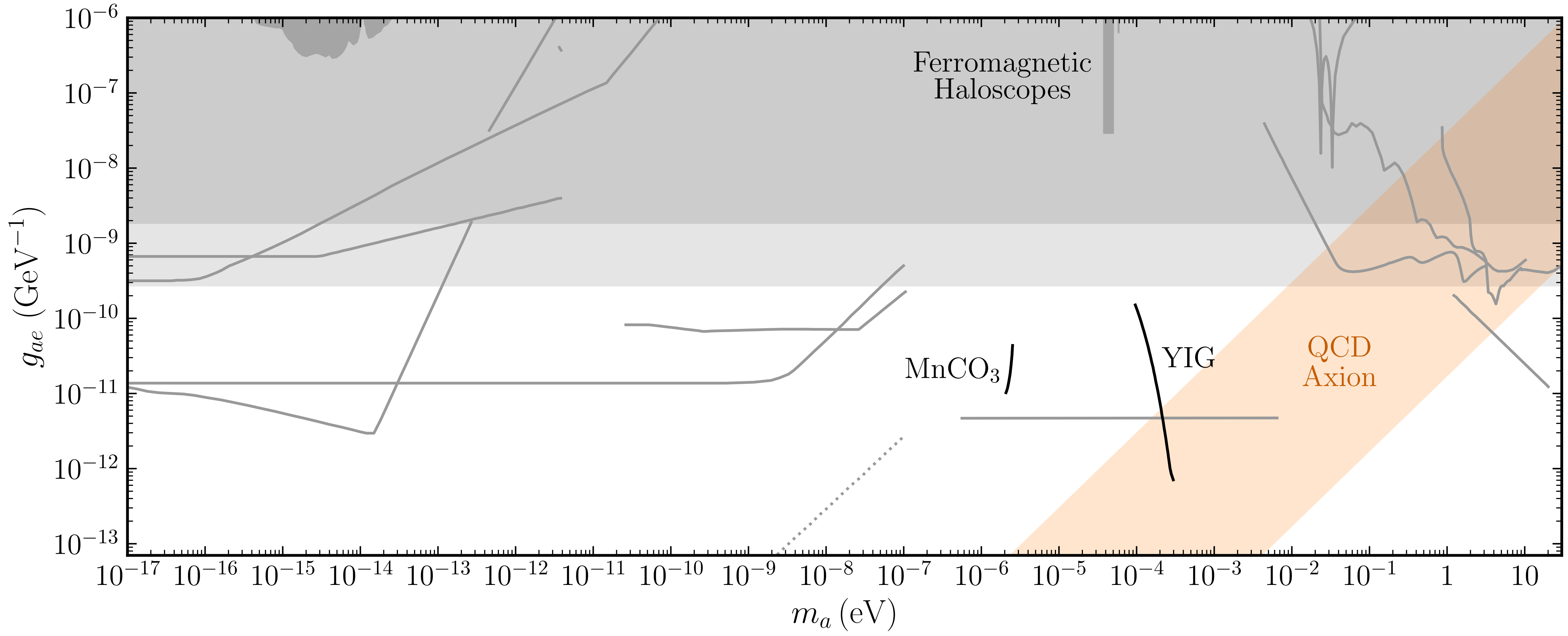
Others have (incorrectly) argued axion induces electron EDM, yielding very strong sensitivity via $\Delta E \propto g_{ae}\,a$

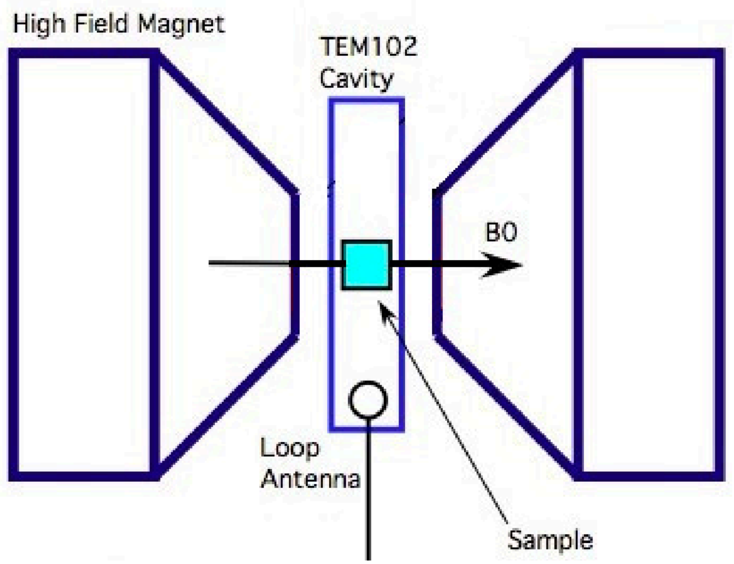


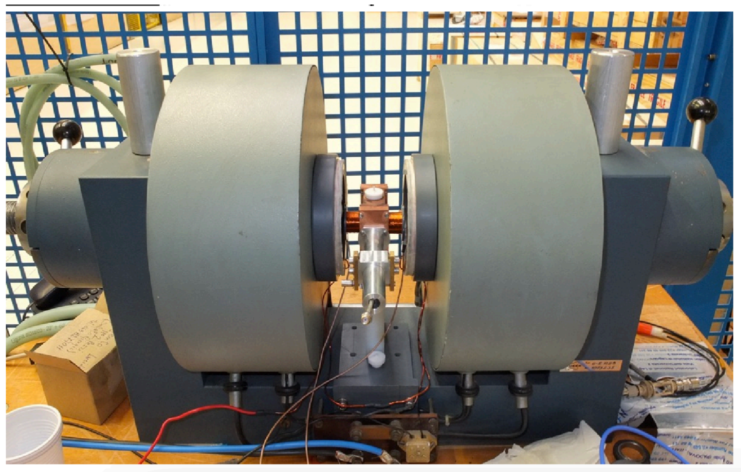
At high energies, can detect absorption of individual axions

Axioelectric force: electronic excitations, phonons

Axion wind torque: spin flip transitions, magnons

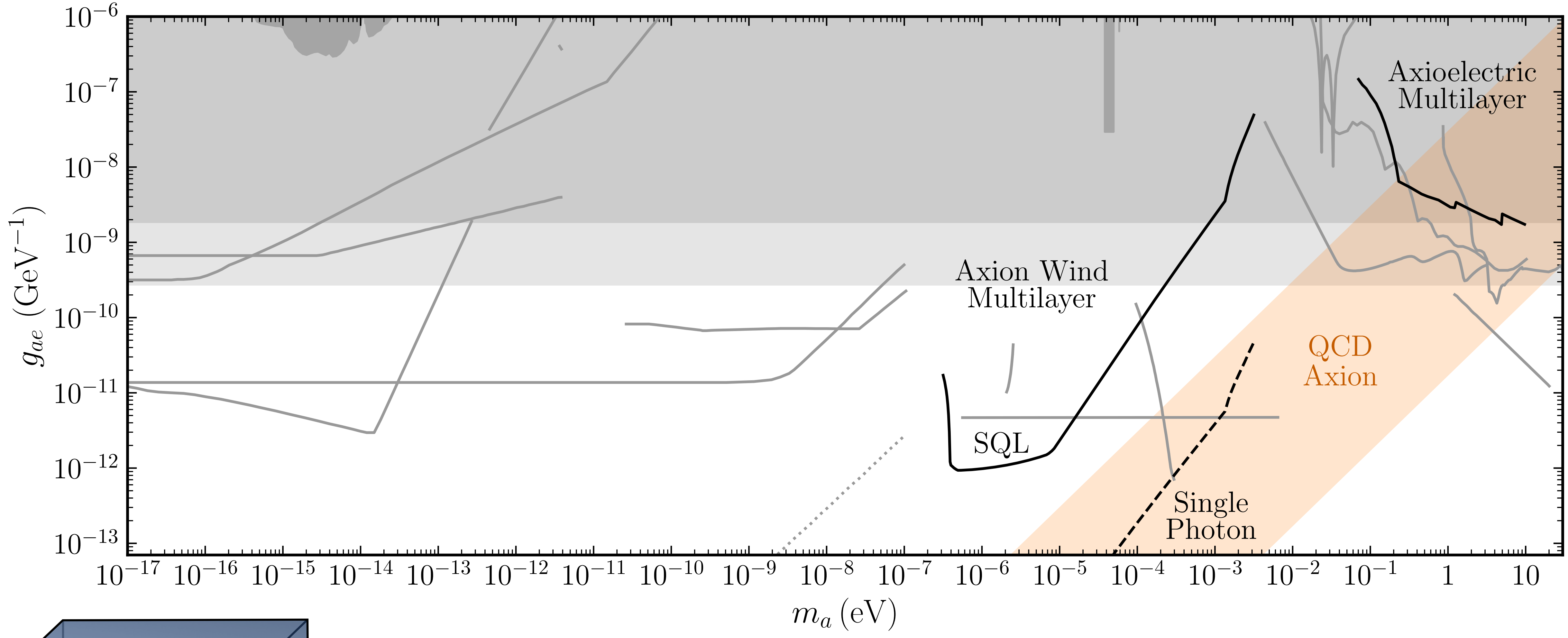


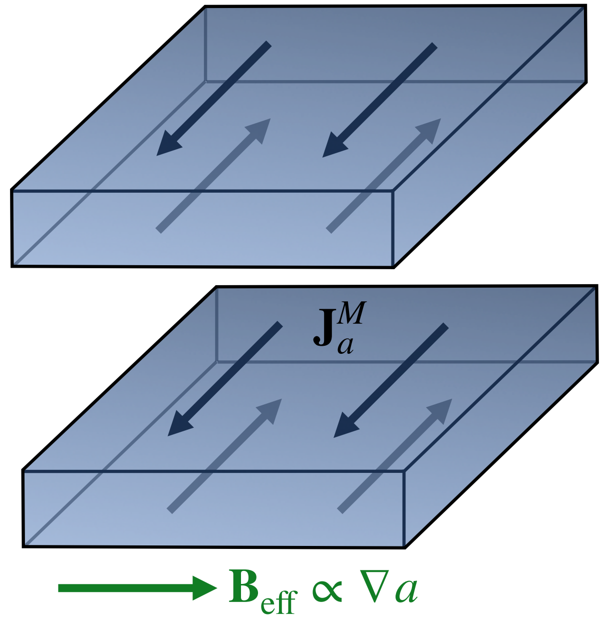




Axion wind spin torque makes ferromagnet's magnetic field rotate, resonantly driving microwave cavity

Extends FMR experiments, but hard to scale (high Q material expensive)





Our proposal: forgo cavity resonant enhancement!

Axion drives currents in slabs of magnetic materials, which produce outgoing radiation

Easier to scale up, using only common materials

The EDM Controversy

The axion-fermion coupling has two equivalent forms

$$\mathscr{L}_{\rm d} \supset g\,(\partial_\mu a)\,\bar{\Psi}\gamma^\mu\gamma^5\Psi \quad \xleftrightarrow{\text{chiral field redefinition}} \quad \mathscr{L}_{\rm nd} = -\,2mga\,\bar{\Psi}i\gamma^5\Psi$$

which have different nonrelativistic limits

$$H_{\rm d} \supset -\frac{g}{m}\,\dot{a}\,\sigma\cdot(\mathbf{p}-q\mathbf{A}) \quad \xleftrightarrow[\text{state redefinition}]{\text{unitary}} \quad H_{\rm nd} \supset -\frac{g}{2m}\,\dot{a}\,\sigma\cdot(\mathbf{p}-q\mathbf{A}) + \frac{qg}{2m}\,a\,\sigma\cdot\mathbf{E}$$

which are related by redefining states, $|\psi'\rangle = U|\psi\rangle$, so that all observables same

But this isn't manifest, as nonderivative form has different axioelectric coefficient, and a term without derivatives on a!

Coefficient of the Axioelectric Term

For simplicity take $q = 0$, where only difference is axioelectric coefficient:

$$H_{\rm d} \supset -\frac{g}{m}\,\dot{a}\,\sigma\cdot(\mathbf{p}-q\mathbf{A}) \qquad\qquad H_{\rm nd} \supset -\frac{g}{2m}\,\dot{a}\,\sigma\cdot(\mathbf{p}-q\mathbf{A})$$

It has been argued that this means axioelectric force is unphysical!
Smith (2023)

However, **any** force can be removed from a single particle Hamiltonian by working in the reference frame of the particle

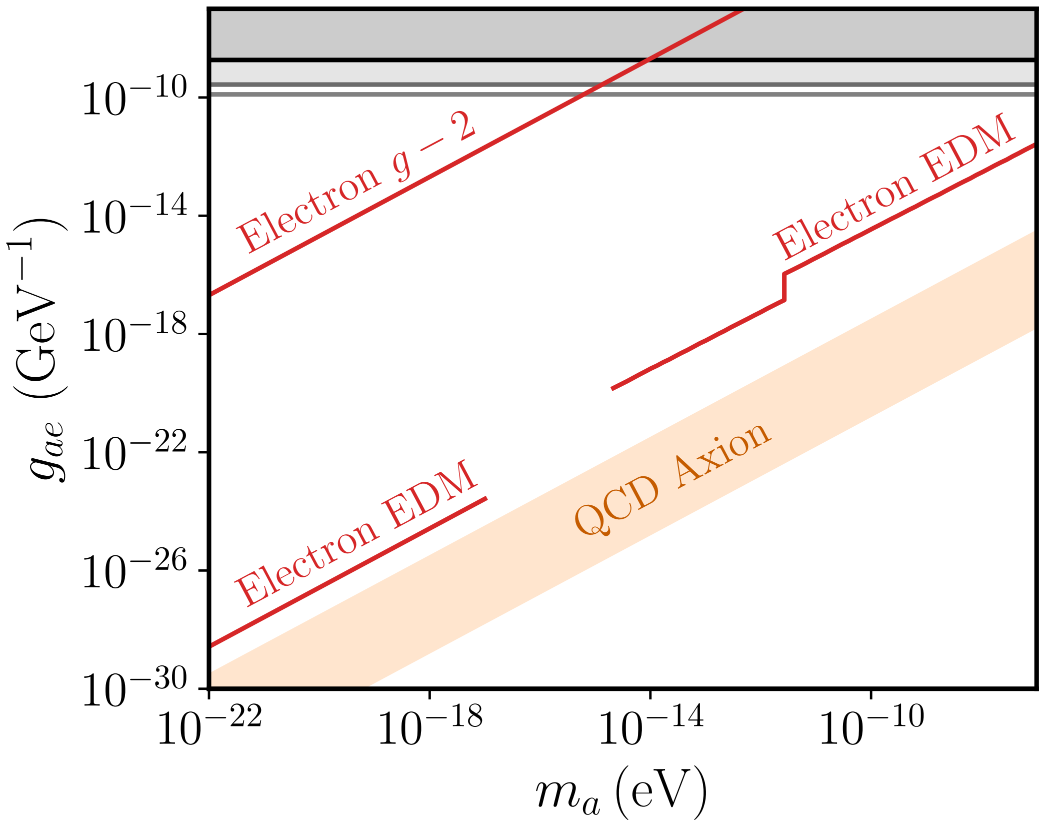
The axioelectric force is physical because it produces relative accelerations between pairs of particles; attempting to remove it in the two particle Hamiltonian will introduce complicated compensating terms in $H_{\rm nd}$

A Nonderivative Term?

For simplicity take $\dot{a} = 0$, where only difference is EDM-like term:

$$H_{\mathrm{d}} = 0 \qquad\qquad H_{\mathrm{nd}} \supset \frac{qg}{2m}\, a\, \boldsymbol{\sigma} \cdot \mathbf{E}$$

Many recent authors have claimed physical effects proportional to a, which if true, would yield **vastly** stronger constraints:



Alexander and Sims (2018)
Chu, Kim, and Savukov (2019)
Wang and Shao (2021)
Smith (2023)
Arza and Evans (2023)
di Luzio, Gilbert, and Sorensen (2023)

True and Spurious EDMs

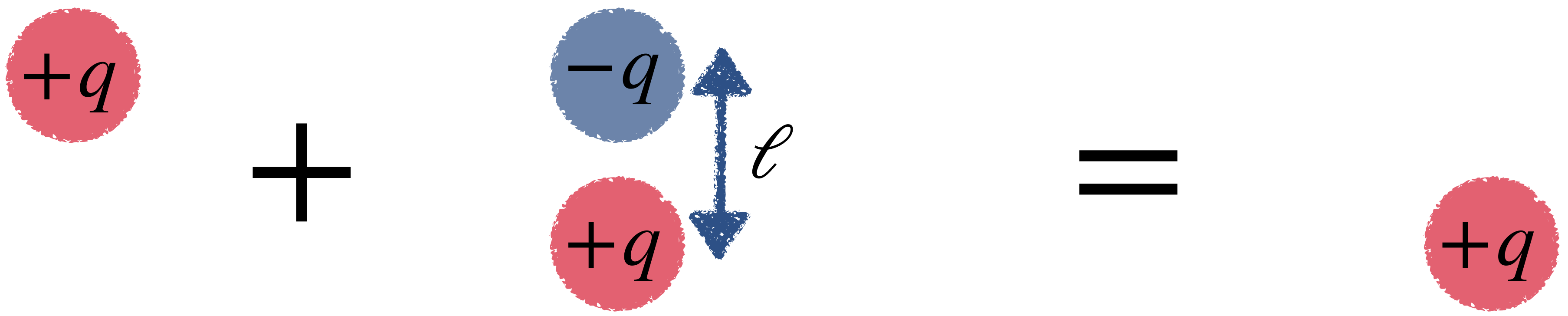
The new term is the nonrelativistic limit of a genuine EDM:

$$H_{\mathrm{nd}} \supset \frac{qga}{2m}\,\sigma \cdot \mathbf{E} \qquad\qquad H_{\mathrm{EDM}} = \frac{d}{2}\,\Psi \gamma^5 \sigma^{\mu\nu} \Psi\, F_{\mu\nu} = -\,d\,\sigma \cdot \mathbf{E} + (\text{relativistic corrections})$$

But for charged nonrelativistic particles, a constant EDM has no physical effects!

Schiff (1963)

Simple explanation of this textbook wisdom:



charge q dipole moment $d = q\ell$ charge shifted by ℓ

A nonrelativistic EDM is equivalent to unobservable shift in definition of position

True and Spurious EDMs

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$$H_{\text{nd}} \supset \frac{qga}{2m}\sigma \cdot \mathbf{E} \qquad H_{\text{EDM}} = \frac{d}{2}\Psi\gamma^5\sigma^{\mu\nu}\Psi F_{\mu\nu} = -d\,\sigma\cdot\mathbf{E} + (\text{relativistic corrections})$$

But for charged nonrelativistic particles, a constant EDM has no physical effects!

Schiff (1963)

The effects of a true EDM probed in experiments are from relativistic corrections:

$O(v/c)$ induced magnetic dipole effects

$O(v^2/c^2)$ length contraction effects

Commins, Jackson, DeMille (2007)

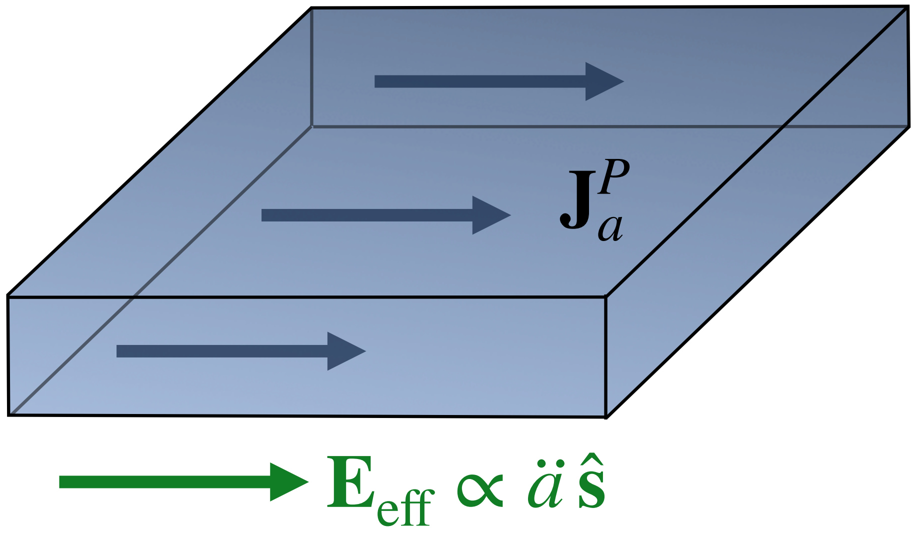
so H_{nd} contains **only** the part of H_{EDM} with no physical effect!

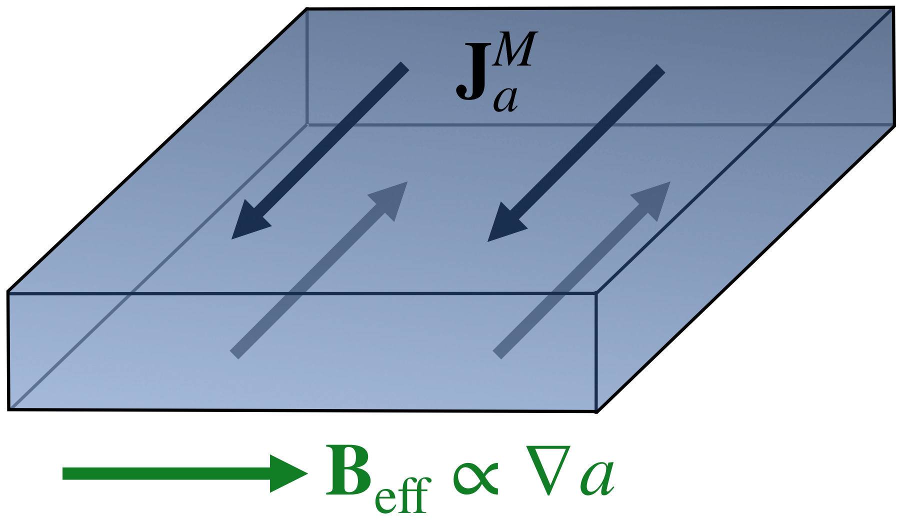
(time-varying $a(t)$ does have effect, but highly suppressed by $\sim (m_a/\text{eV})^2$)

Stadnik and Flambaum (2014)

Axion-Induced Currents

Axioelectric force and axion wind torque act like spin-coupled electromagnetic fields





$$\mathbf{P}_a = (\epsilon_\sigma - 1)\mathbf{E}_{\text{eff}} \qquad \mathbf{J}_a = \partial_t \mathbf{P}_a$$

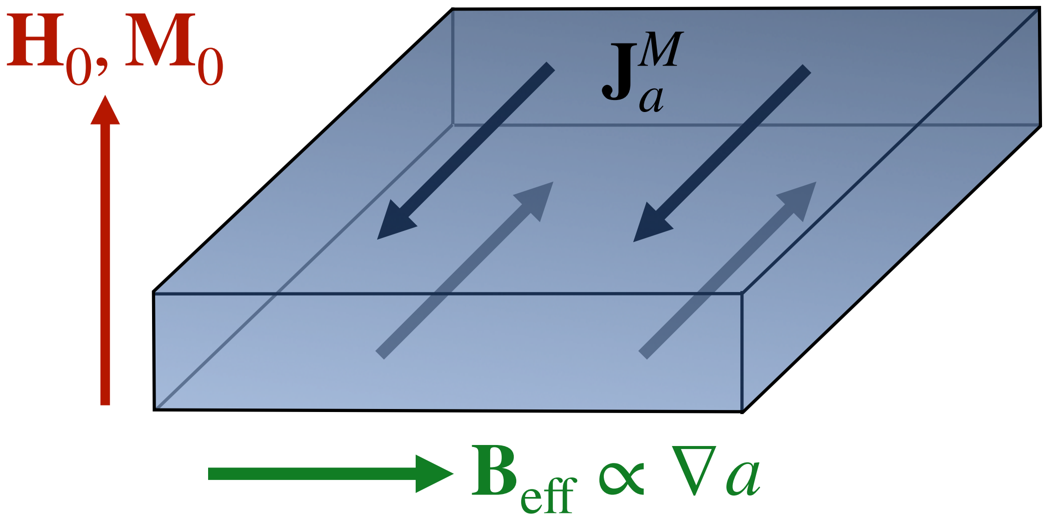
$$\mathbf{M}_a = \frac{\chi}{1+\chi}\mathbf{B}_{\text{eff}} \qquad \mathbf{J}_a = \nabla \times \mathbf{M}_a$$

"spin-weighted" permittivity
$\epsilon_\sigma \sim \epsilon$ if fully spin-polarized

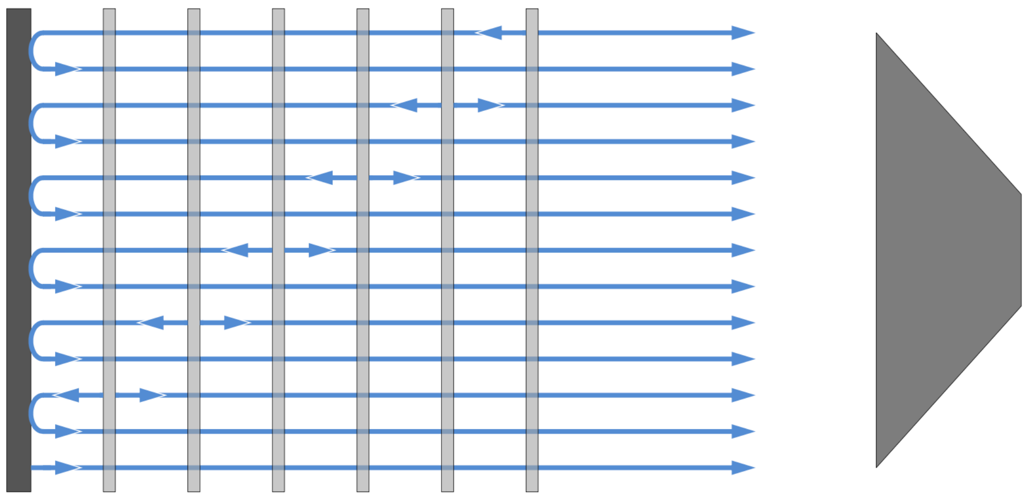
$\chi \ll 1$ unless medium is
magnetized with $\mathbf{M}_0 \perp \mathbf{B}_{\text{eff}}$

Due to these currents, radiation of frequency m_a emitted from a slab

Modeling the Magnetic Response



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



Standard model for a magnetized medium:

$$\chi_- = -\frac{(1 - i/2Q)\, M_0}{\omega/\gamma - H_0 + iH_0/2Q}$$

(magnetic quality factor Q)

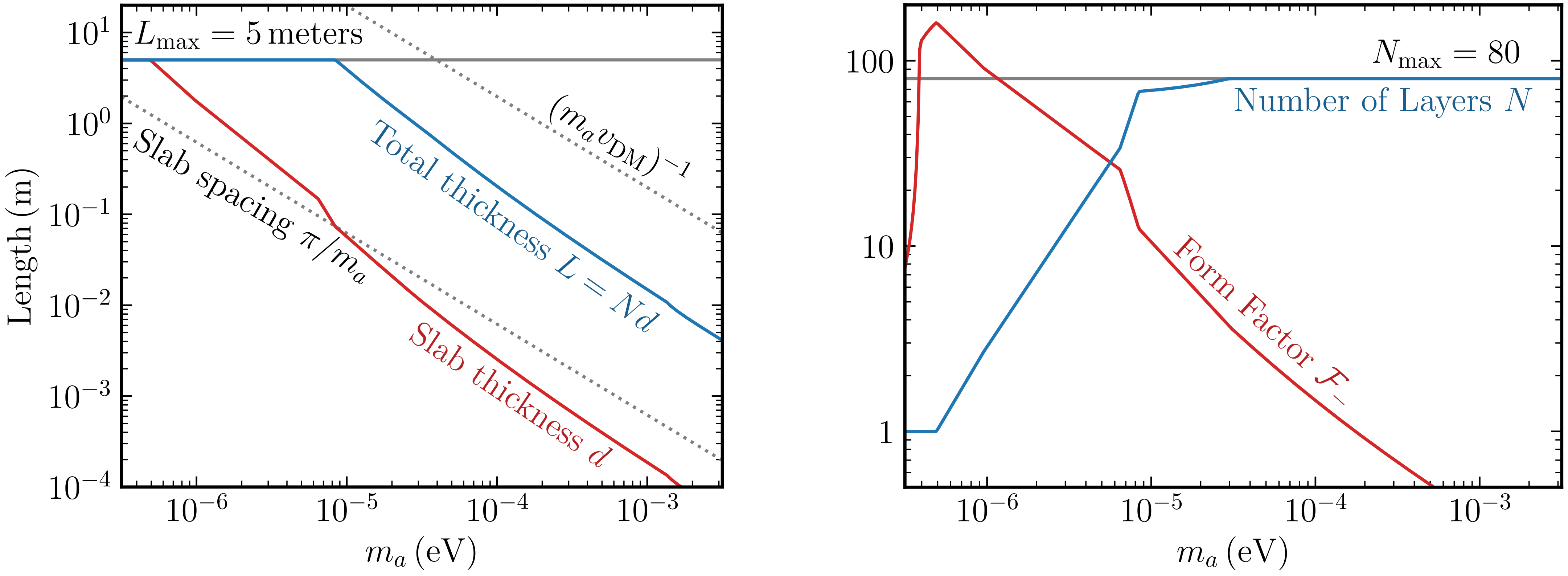
Resonance occurs at a tunable frequency ($B_{\text{ext}} \leq 10\,\text{T}$ implies $\omega \leq 10^{-3}\,\text{eV}$)

Can amplify signal by constructive interference using N layers, with tunable separation

(same principle used for dielectric haloscopes, currently being prototyped)

Optimizing the Signal Power

A magnetized multilayer experiment is effective at $m_a = 10^{-6}\,\mathrm{eV}$ to $10^{-3}\,\mathrm{eV}$



Low mass: low external field, small number of very thick slabs

High mass: high external field, large number of thin slabs

Optimized scaling of signal power: $P_{\rm sig} \sim \left(\frac{Q\,M_0}{m_e\,m_a}\right)^2 B_{\rm eff}^2\,A$

Optimizing the Material

$$P_{\text{sig}} \sim \left(\frac{Q\, M_0}{m_e\, m_a} \right)^2 B_{\text{eff}}^2\, A$$

Need a material with high Q and M_0, which must be insulating to avoid shielding

polycrystalline spinel ferrites

$Q \sim 10^2$

single crystal yttrium iron garnet

$Q \sim 10^4$

(highest known, used in all past ferromagnetic haloscope experiments)

Optimizing the Material

$$P_{\text{sig}} \sim \left(\frac{Q\, M_0}{m_e\, m_a}\right)^2 B_{\text{eff}}^2\, A$$

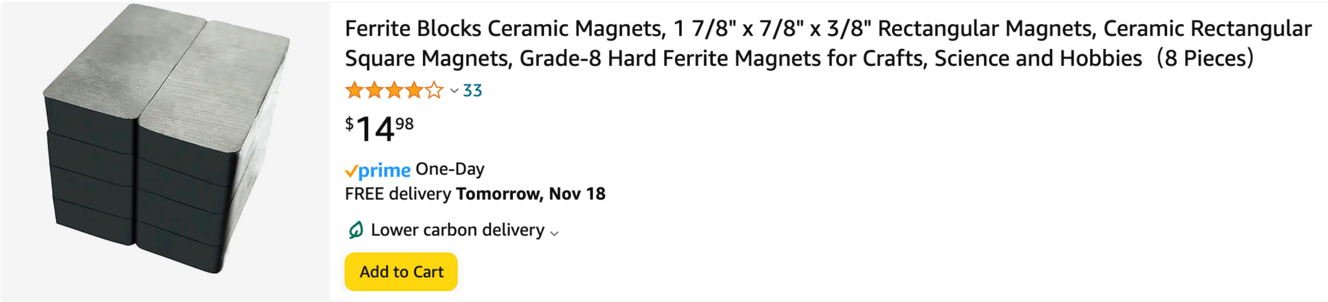
Need a material with high Q and M_0, which must be insulating to avoid shielding

polycrystalline spinel ferrites

$Q \sim 10^2$

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

common, mass produced



single crystal yttrium iron garnet

$Q \sim 10^4$

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

$\sim (\text{mm})^3$ spheres grown by artisans

Optimizing the Material

$$P_{\text{sig}} \sim \left(\frac{Q\, M_0}{m_e\, m_a} \right)^2 B_{\text{eff}}^2\, A$$

Need a material with high Q and M_0, which must be insulating to avoid shielding

polycrystalline spinel ferrites

$Q \sim 10^2$

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

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

single crystal yttrium iron garnet

$Q \sim 10^4$

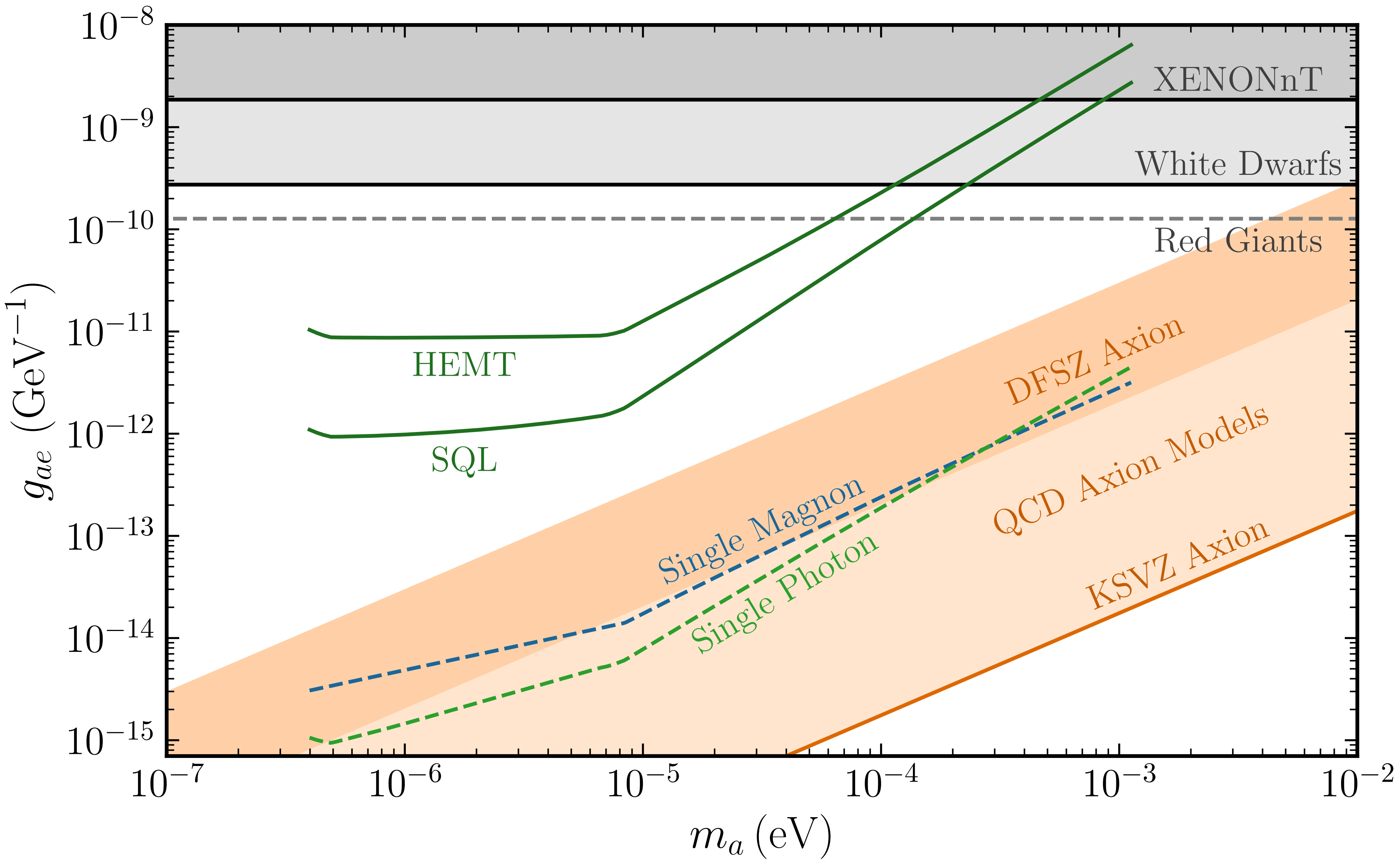
costs $\sim \$10{,}000{,}000/\text{kg}$

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

Polycrystalline ferrites make multilayer of $\sim \text{m}^3$ size practical

Quality factor not very high, but enough to benefit from multilayer structure

Projected Reach



Multilayer setup can reach new parameter space with standard readout noise

Huge potential improvement from single photon counting

Conclusion

The axion-electron coupling is simple, minimal, and generic

Experimental signatures remain underexplored

New ideas are worth investigating and building!