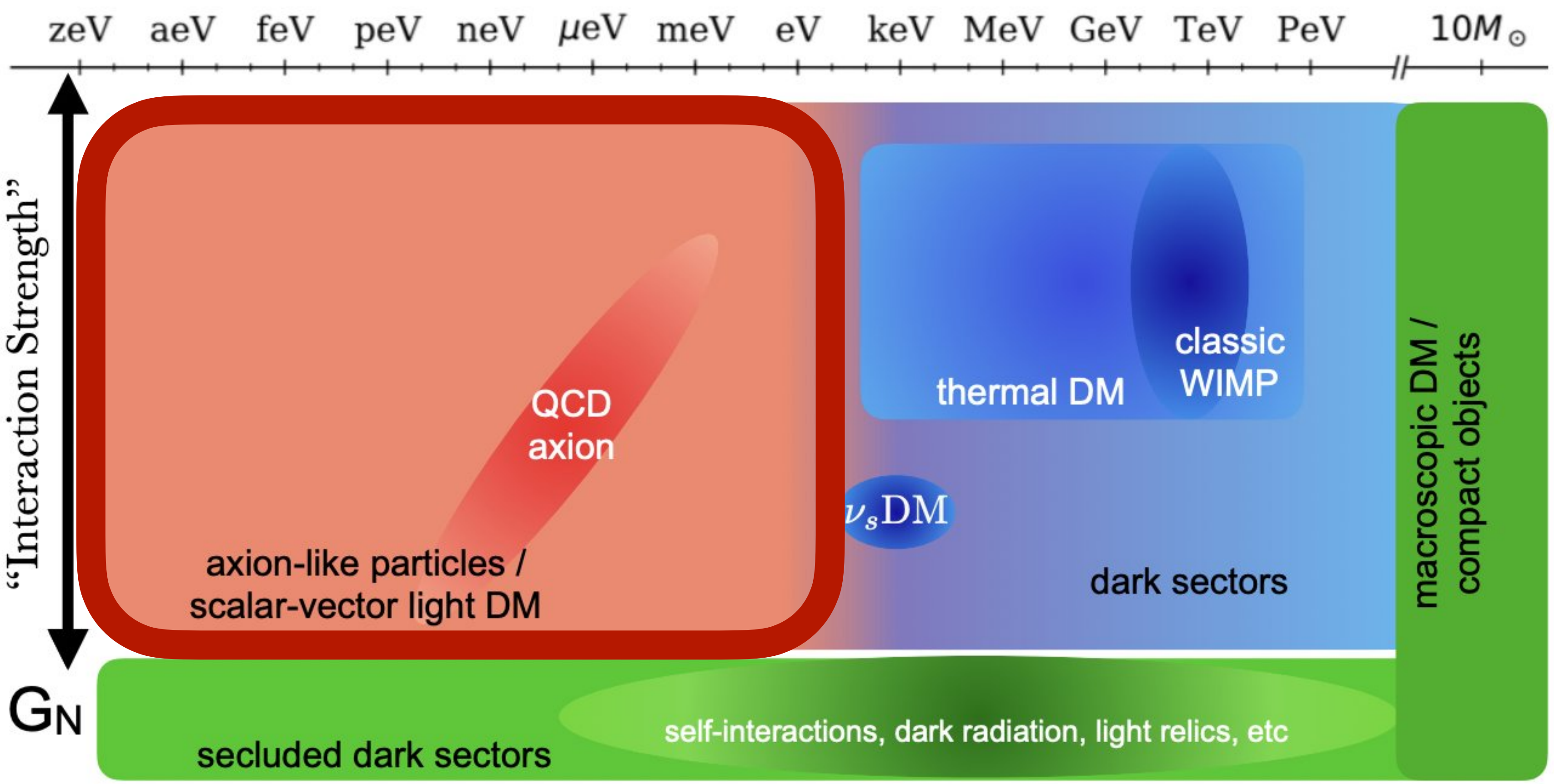
How (Not) to Probe The Axion-Electron Coupling

Kevin Zhou

UChicago Particle Theory Seminar — April 16, 2025

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



Ultralight dark matter is a subject of growing experimental interest:

- Explains apparent abundance of dark matter with simple production mechanisms
- Generic: weakly coupled ultralight fields appear in many models
- Low-hanging fruit: new small-scale experiments are needed, and very effective
- Minimal: requires introduction of only a single new field at low energies
- Bounded: only a few interactions are natural and leading in effective field theory

Couplings of a Field Theory Axion

$$
\begin{tikzcd}
 & a\,G\tilde{G} \arrow[r] \arrow[dr] & \text{mass, } d_N \propto a \\
a\,\bar{q} i\gamma^5 q \arrow[ur] \arrow[r] \arrow[dr] & (\partial_\mu a)\,\bar{q}\gamma^\mu\gamma^5 q \arrow[r] & (\partial_\mu a)\,\bar{N}\gamma^\mu\gamma^5 N \\
a\,\bar{e} i\gamma^5 e \arrow[r] \arrow[dr] & a\,F\tilde{F} \arrow[r, "\text{integrate}", "\text{by parts}"'] & (\partial_\mu a)\,K^\mu_{\mathrm{EM}} \\
 & (\partial_\mu a)\,\bar{e}\gamma^\mu\gamma^5 e &
\end{tikzcd}
$$

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 effects on nucleons

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a\,\bar{q}i\gamma^5 q \arrow[ur, bend left] \arrow[r] \arrow[dr, bend right] & (\partial_\mu a)\,\bar{q}\gamma^\mu\gamma^5 q \arrow[r] & \boxed{(\partial_\mu a)\,\bar{N}\gamma^\mu\gamma^5 N} \\
a\,\bar{e}i\gamma^5 e \arrow[r] \arrow[dr, bend right] & a\,F\tilde{F} \arrow[r] & \boxed{(\partial_\mu a)\,K^\mu_{\mathrm{EM}}} \\
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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 effects on nucleons

only a few dimension 5 operators, and all derivative couplings generically arise

$$\boxed{(\partial_\mu a)\, K^\mu_{\rm EM}}$$

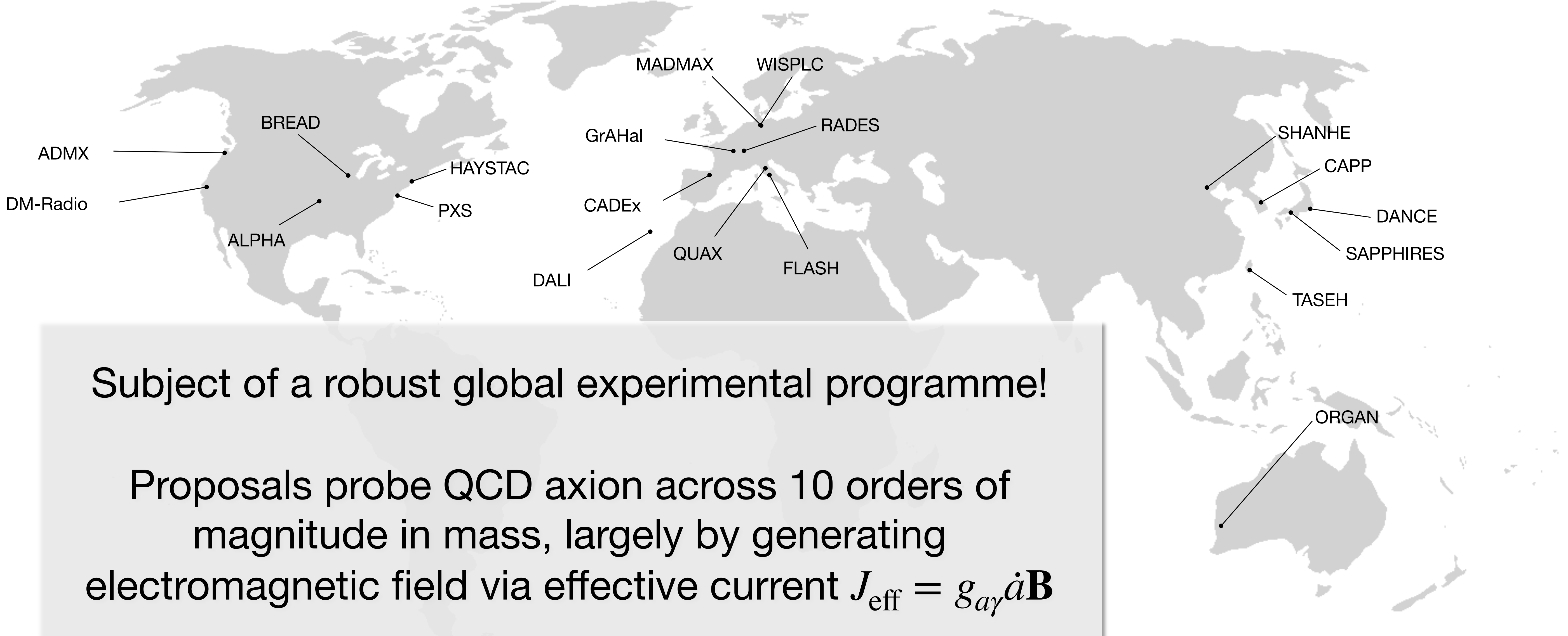
axion-photon

$$(\partial_\mu a)\, \bar{N}\gamma^\mu\gamma^5 N$$

axion-nucleon

$$(\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e$$

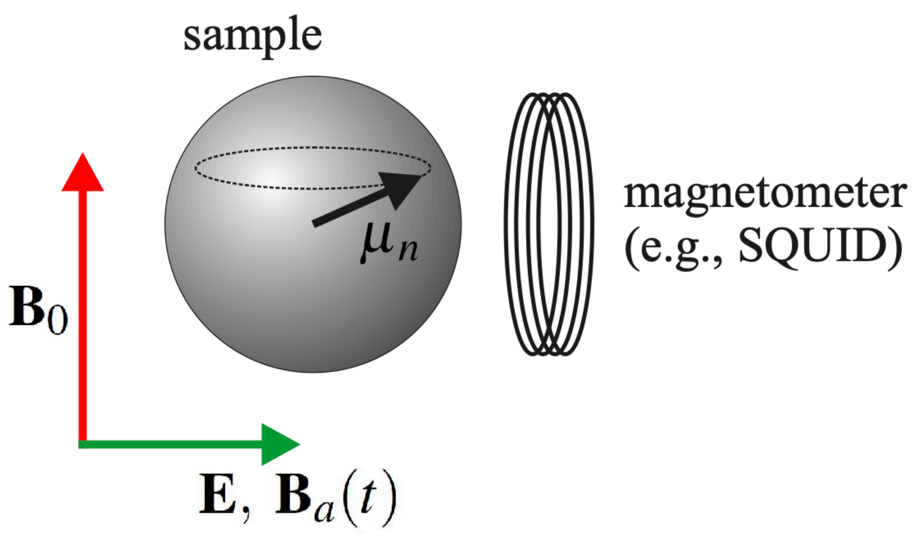
axion-electron

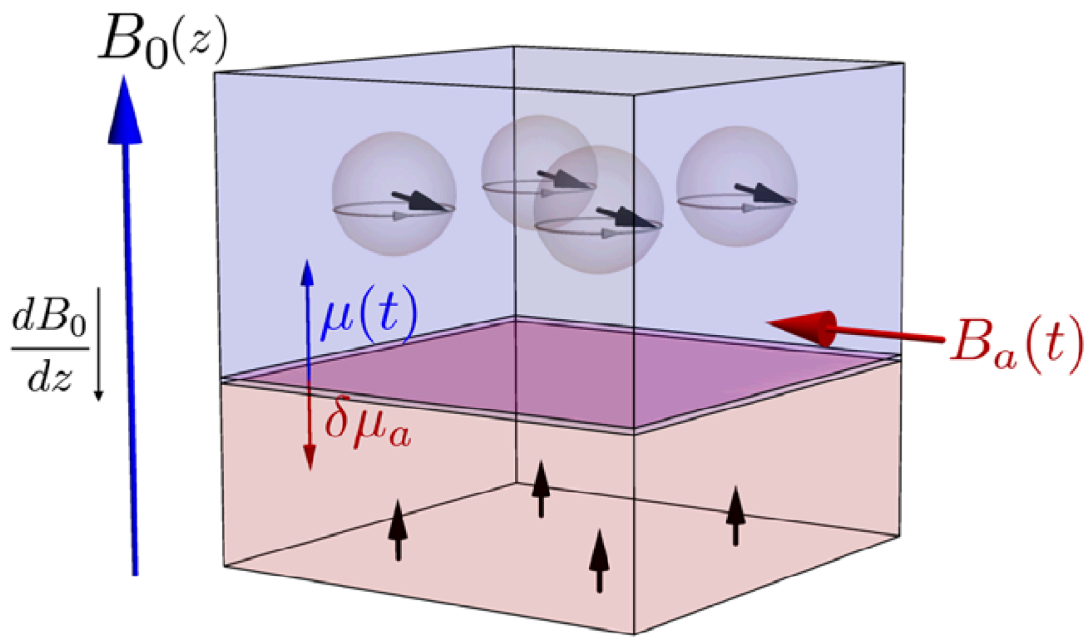


Subject of a robust global experimental programme!

Proposals probe QCD axion across 10 orders of magnitude in mass, largely by generating electromagnetic field via effective current $J_{\rm eff} = g_{a\gamma}\dot{a}\mathbf{B}$

$(\partial_\mu a)\, K^\mu_{\mathrm{EM}}$	$\boxed{(\partial_\mu a)\, \bar{N}\gamma^\mu\gamma^5 N}$	$(\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e$
axion-photon	axion-nucleon	axion-electron





Less explored, but several concepts could probe well beyond astrophysical bounds

Generally achieved by resonantly amplifying a nuclear spin torque $\tau = g_{aN}\,\hat{\mathbf{s}} \times \nabla a$

Enhanced by the exceptional stability ($Q_{\text{eff}} \gtrsim 10^{10}$) of nuclear spin precession

1711.08999, 2208.14454

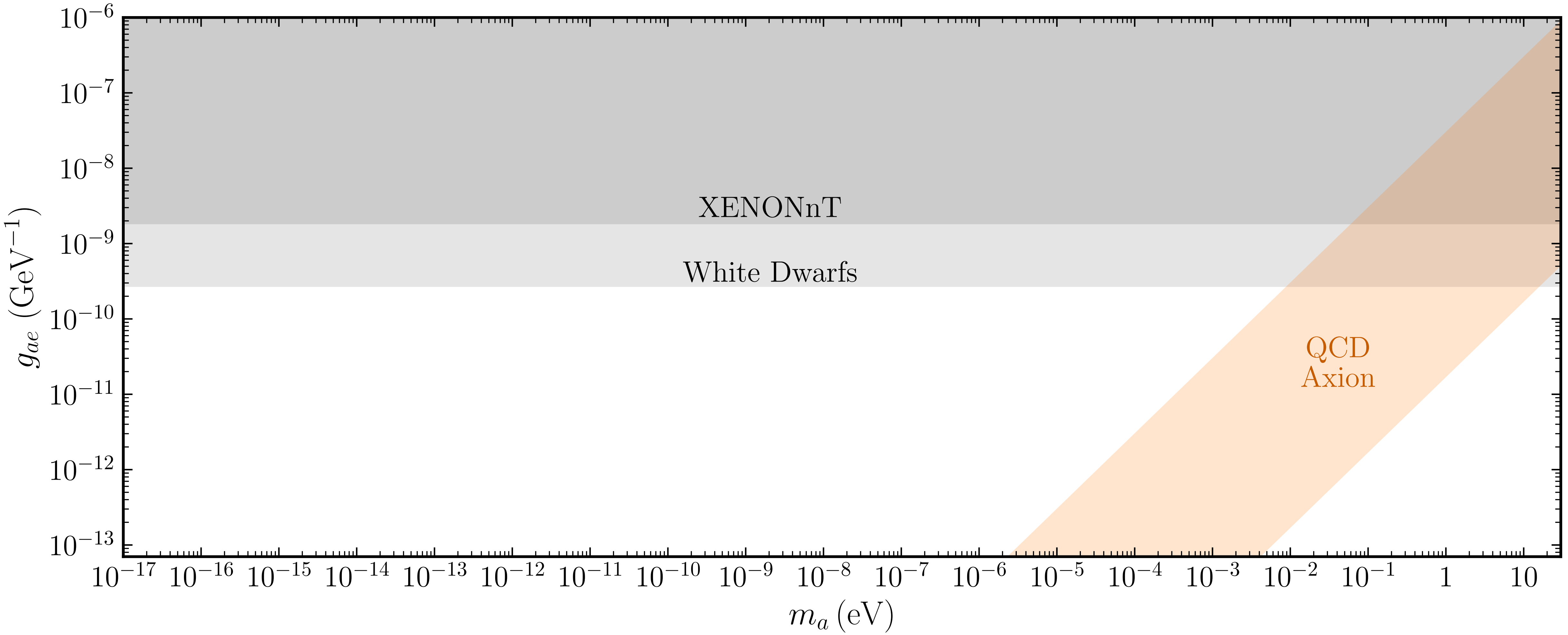
$(\partial_\mu a)\, K^\mu_{\text{EM}}$

axion-photon

$(\partial_\mu a)\, \bar{N}\gamma^\mu\gamma^5 N$

axion-nucleon

$\boxed{(\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e \quad \text{axion-electron}}$



No active experiments search for this coupling,
and even ambitious proposals have difficulty beating astrophysical bounds!

$(\partial_\mu a)\, K^\mu_{\mathrm{EM}}$	$(\partial_\mu a)\, \bar{N}\gamma^\mu\gamma^5 N$	$\boxed{(\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e}$
axion-photon	axion-nucleon	axion-electron

This talk explains:

- What this coupling does
- Why it's difficult to probe
- Why 8 previous claims of strong sensitivity were all wrong
- How it's still possible to use it to probe an meV QCD axion

The Axion-Electron Coupling

Lagrangian has axial vector current: $\mathscr{L} \supset g\,(\partial_\mu a)\,\bar{e}\gamma^\mu\gamma^5 e$

Which is a classical particle's spin 4-vector: $\int d^3\mathbf{x}\,\bar{e}\gamma^\mu\gamma^5 e \to s^\mu \simeq (\mathbf{v}\cdot\hat{\mathbf{s}}, \hat{\mathbf{s}})^\mu$

So for a nonrelativistic quantum particle: $H \supset -g\,(\nabla a)\cdot\sigma - \frac{g}{m_e}\,\dot{a}\,\sigma\cdot(\mathbf{p}-q\mathbf{A})$

"axion wind" spin torque
$\tau = g\,\hat{\mathbf{s}}\times\nabla a$

"axioelectric" term

both terms oscillate with the axion field, at $f \sim (m_a/\mu\mathrm{eV})\ \mathrm{GHz}$

$|\nabla a| \sim v_{\mathrm{DM}}\,\dot{a}$ where $v_{\mathrm{DM}} \sim 10^{-3}$

axioelectric term seems larger, but subject to traps!

Axioelectric Pitfalls

For simplicity, set $\nabla a = \mathbf{B} = 0$ and work in gauge $\mathbf{E} = -\dot{\mathbf{A}}$

$$H \simeq \frac{(\mathbf{p} - q\mathbf{A})^2}{2m_e} - \frac{g}{m_e}\,\dot{a}\,\sigma \cdot (\mathbf{p} - q\mathbf{A})$$

Idea #1: this implies $\mathscr{H} \supset -\mathbf{J}_{\text{eff}} \cdot \mathbf{A}$ where $\mathbf{J}_{\text{eff}} = (g\dot{a}q/m_e)\,\langle n_e \sigma \rangle$, a large current!

However, it would be more transparent to write: $H \simeq \dfrac{(\mathbf{p} - q\mathbf{A} - g\dot{a}\sigma)^2}{2m_e}$

No extra contribution to the current, but a new force: $\mathbf{A}_{\text{eff}} = (g/q)\,\dot{a}\sigma \quad \mathbf{F} = -g\,\dfrac{d}{dt}\,\langle \dot{a}\sigma \rangle$

Generally very small, because it is suppressed by two time derivatives

Idea #2: integrating the force over time yields $\mathbf{J} = (g\dot{a}q/m_e)\langle n_e \sigma \rangle$, a large current!

(For DFSZ axion, would be $\sim 10^3$ larger than $\mathbf{J}_{\text{eff}}$ from axion-photon coupling)

Estimating the Axioelectric Current

How large of a current can we really get from $\mathbf{E}_{\mathrm{eff}} = (g/q)\,\ddot{a}\,\sigma$?

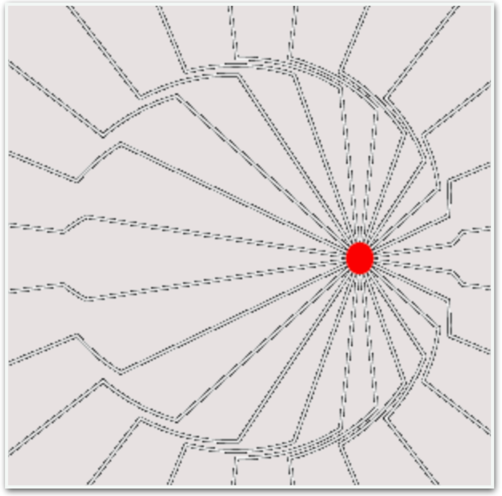
In a spin-polarized dielectric, we have: $\mathbf{J}_a = (\epsilon - 1)\,\dot{\mathbf{E}}_{\mathrm{eff}}$

But material also creates electric field: $\cancel{\nabla \times \nabla \times \mathbf{E}} + \epsilon\ddot{\mathbf{E}} = -\,\dot{\mathbf{J}}_a$

Total polarization current: $\mathbf{J}_{\mathrm{tot}} = (\epsilon - 1)(\dot{\mathbf{E}} + \dot{\mathbf{E}}_{\mathrm{eff}}) = \dfrac{\epsilon - 1}{\epsilon}\,\dot{\mathbf{E}}_{\mathrm{eff}}$

Result suppressed by **three** time derivatives! But what if charges can move?

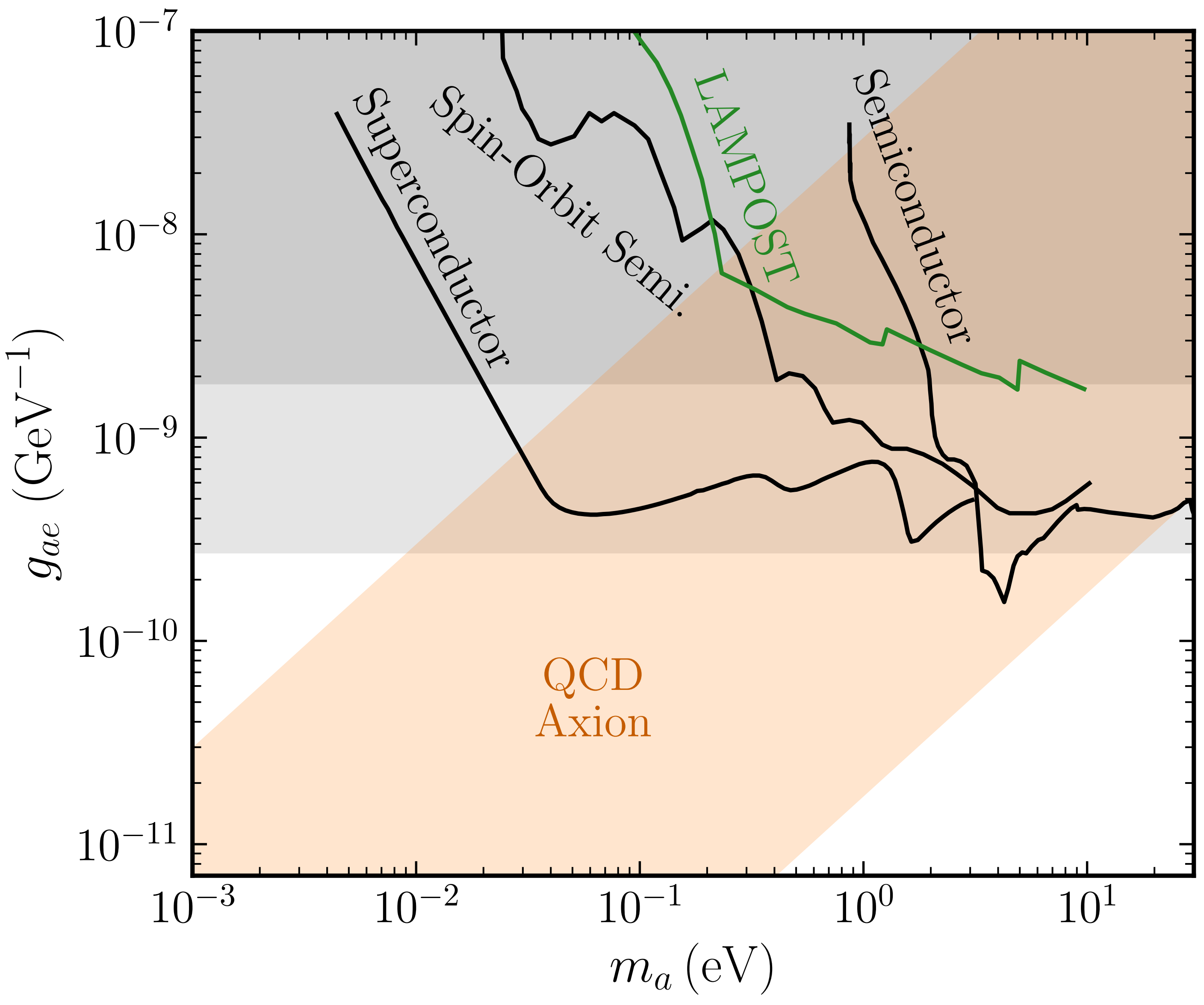
$$\epsilon(\omega) \sim \begin{cases} 1 + i\sigma/\omega & \text{ideal conductor} \\ 1 - \omega_p^2/\omega^2 & \text{ideal superconductor} \end{cases}$$



Above result holds, and implies $\mathbf{J}_{\mathrm{tot}} \sim \dot{\mathbf{E}}_{\mathrm{eff}}$ even when $|\epsilon| \gg 1$!

Physically, better conductors shield $\mathbf{E}_{\mathrm{eff}}$ more

Axioelectric Reach vs. Other Projections



Since $\mathbf{J} \propto d^3a/dt^3$, best probes are at high m_a, and still not very strong…

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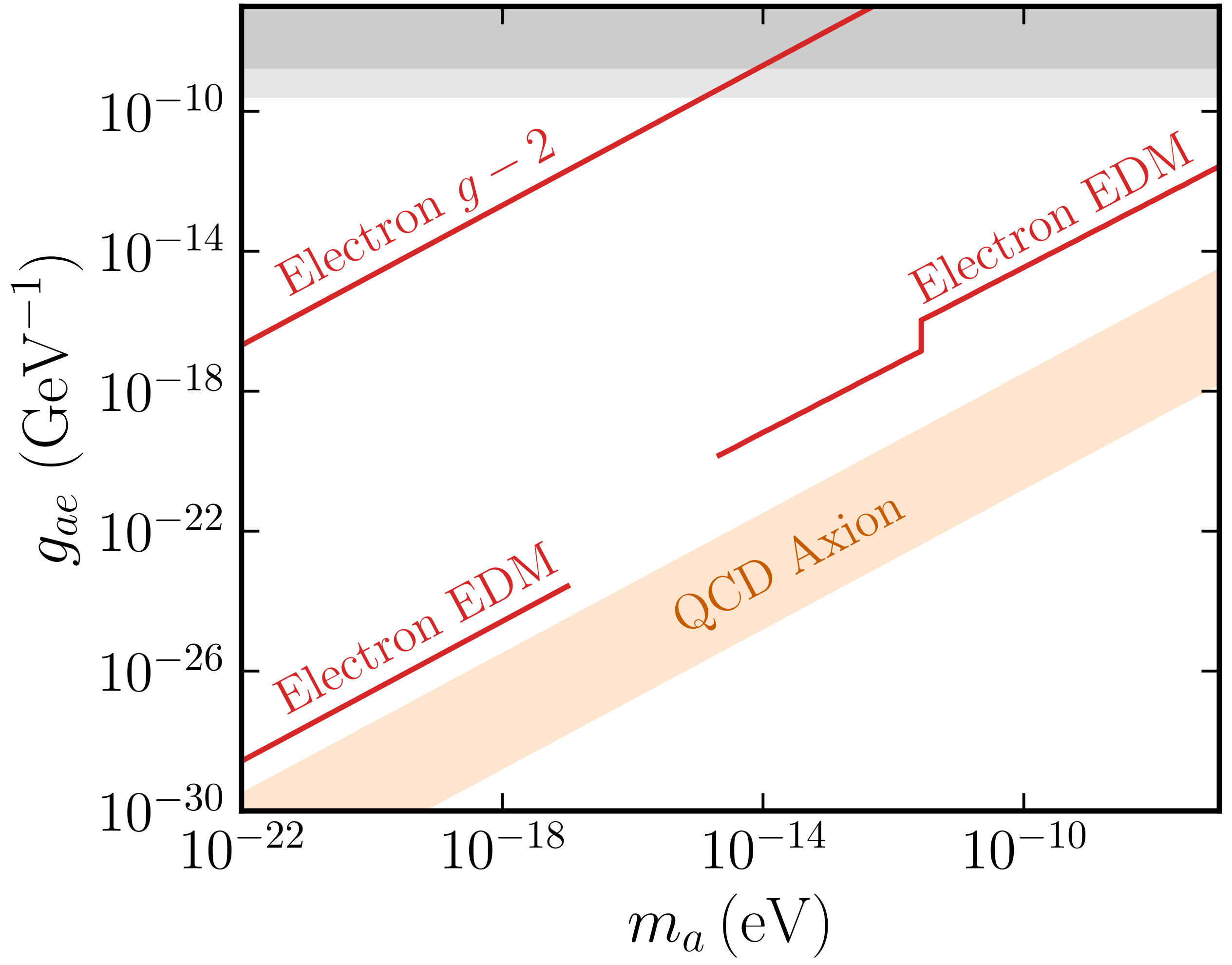


…but many recent papers claimed **vastly** stronger effects proportional to a!

The EDM Controversy

The axion-electron coupling has two equivalent forms

chiral field redefinition

$$\mathscr{L}_{\mathrm{d}} \supset g\,(\partial_\mu a)\,\bar{e}\gamma^\mu\gamma^5 e \qquad \longleftrightarrow \qquad \mathscr{L}_{\mathrm{nd}} = -\,2mga\,\bar{e}i\gamma^5 e$$

which have different nonrelativistic limits

unitary

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

state redefinition

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

$$U \simeq \exp\left(-\frac{iga}{2m}(\mathbf{p}-q\mathbf{A})\cdot\sigma\right)$$

Already noted for pion-nucleon interactions in 1950s — but not obvious how!

Coefficient of the Axioelectric Term

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

$$H_{\mathrm{d}} \supset -\frac{g\dot{a}}{m}\sigma \cdot \mathbf{p} \qquad\qquad H_{\mathrm{nd}} \supset -\frac{g\dot{a}}{2m}\sigma \cdot \mathbf{p}$$

Puzzle: why can the coefficient of a force be freely adjusted?

Resolution: **any** force can be removed from a single particle Hamiltonian by working in the particle's reference frame; only relative accelerations physical

$$H_{\mathrm{d}} \supset V(\mathbf{x}_1 - \mathbf{x}_2) - \frac{g\dot{a}}{m}(\sigma_1 \cdot \mathbf{p}_1 + \sigma_2 \cdot \mathbf{p}_2)$$

$$H_{\mathrm{nd}} \supset V(\mathbf{x}_1 - \mathbf{x}_2) - \frac{g\dot{a}}{2m}(\sigma_1 \cdot \mathbf{p}_1 + \sigma_2 \cdot \mathbf{p}_2) - \frac{ga}{2m}(\sigma_1 - \sigma_2) \cdot \nabla_1 V(\mathbf{x}_1 - \mathbf{x}_2)$$

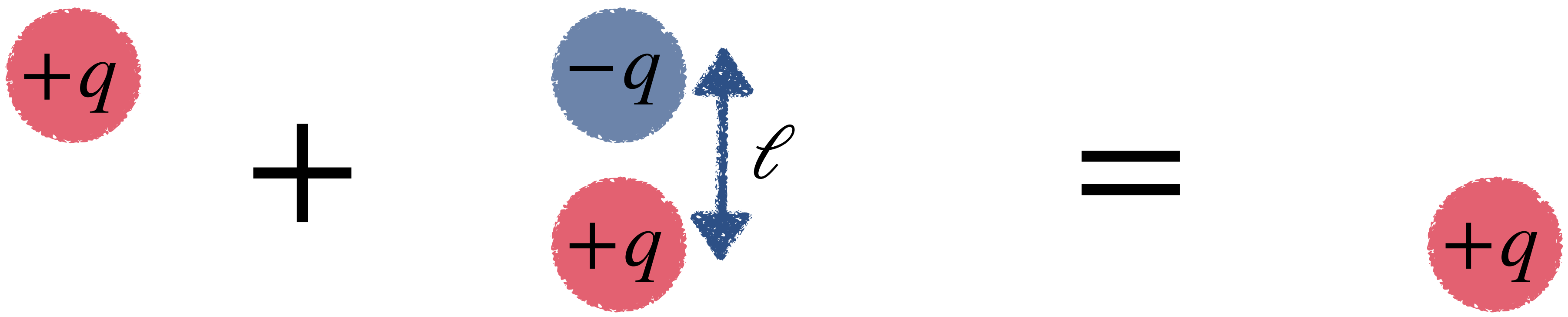
Shifting the axioelectric coefficient adds other terms with same physical effect

True and Spurious EDMs

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

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

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



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

In this limit, just equivalent to unobservable shift in definition of position!

(key intuition behind “Schiff screening”)

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The effects of a true EDM probed in experiments are from relativistic corrections:
$O(v/c)$ magnetic dipole, $O(v^2/c^2)$ length contraction

Commins, Jackson, DeMille (2007)

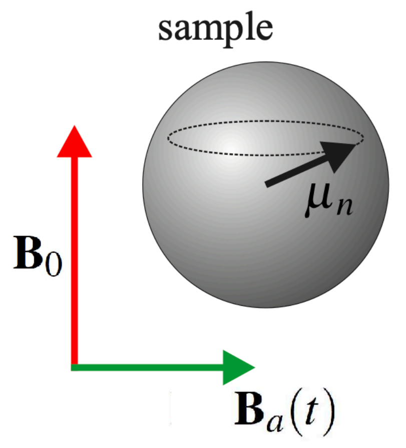
so H_{nd} contains **only** the part of H_{EDM} with no physical effect!

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

Stadnik and Flambaum (2014)

Probing the Axion Wind Torque

The axion wind spin torque tilts spins, yielding oscillating transverse magnetic field



Naively seems easier for electrons, as $\mu_e/\mu_n \sim m_p/m_e \sim 10^3$

But typical quality factors much lower!

Solid magnetic material

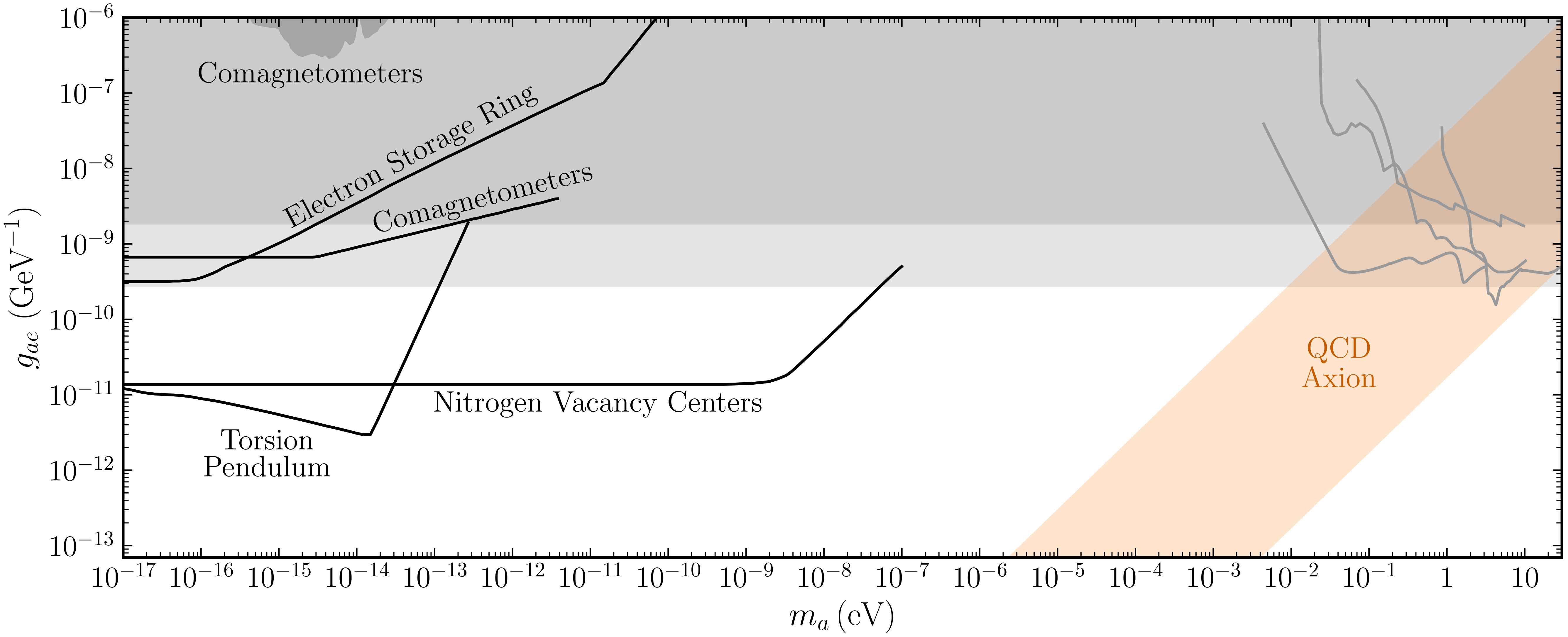
Naturally probes $m_a \sim \mathrm{meV}$ but interactions prevent very high Q

Signal is emitted meV radiation

"Separated" or "locked" electrons

Much higher Q and lower resonant frequencies possible

Signal is quasistatic magnetic field, detected by magnetometer



Separated electrons: comagnetometer vapor, storage ring bunch, NV centers (but much lower number density results in limited sensitivity)

Locked electrons: align spins to crystal, so spin torque becomes mechanical (but suppressed by inertia of nuclei, doesn't benefit from electron being light)

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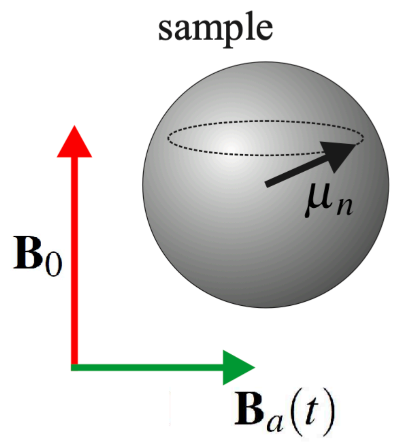

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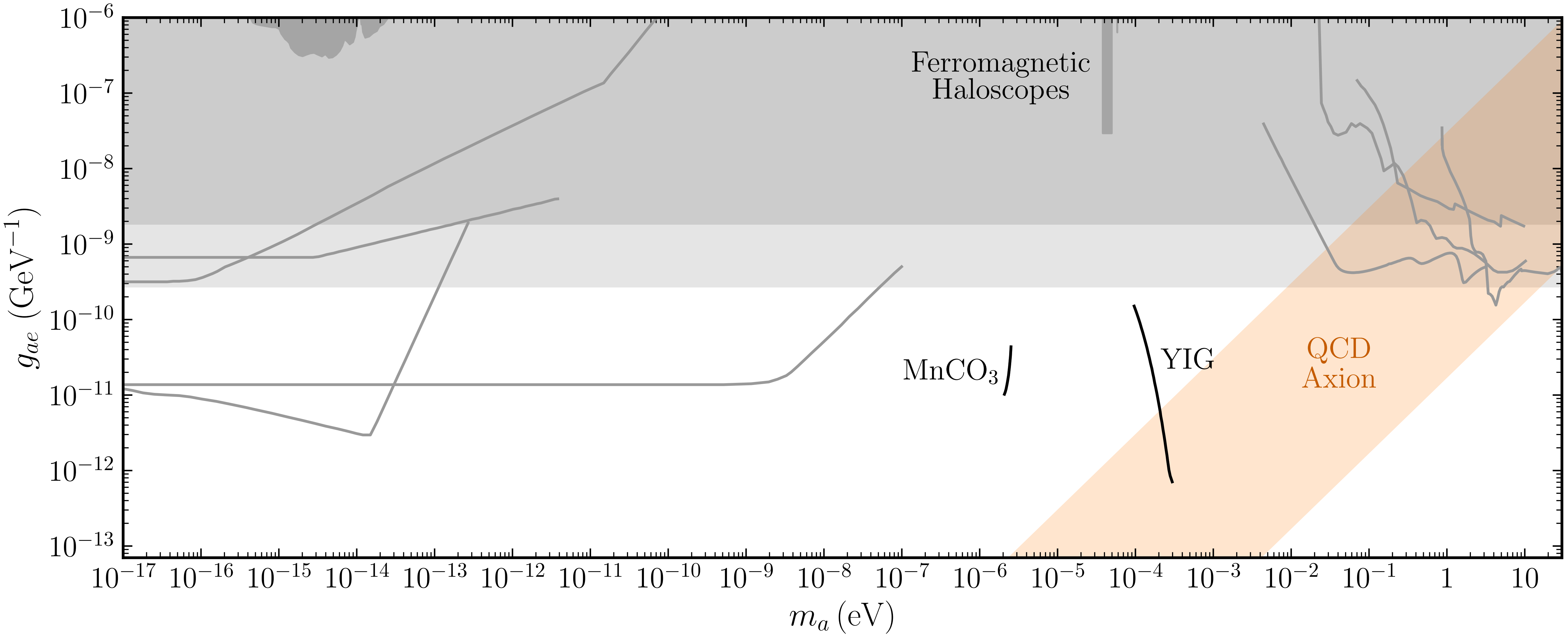
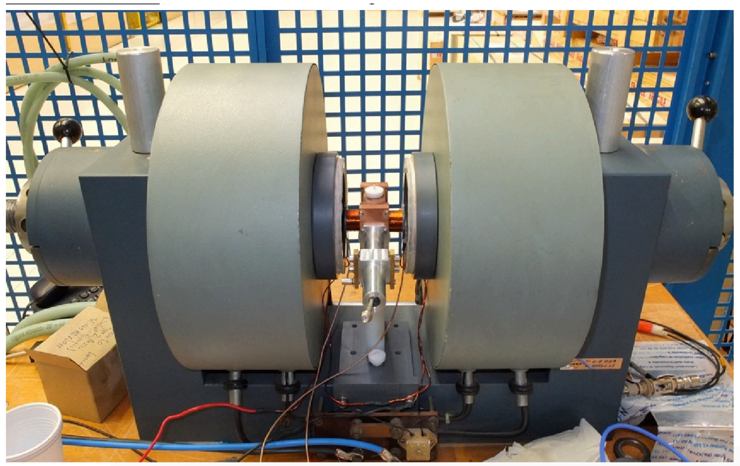
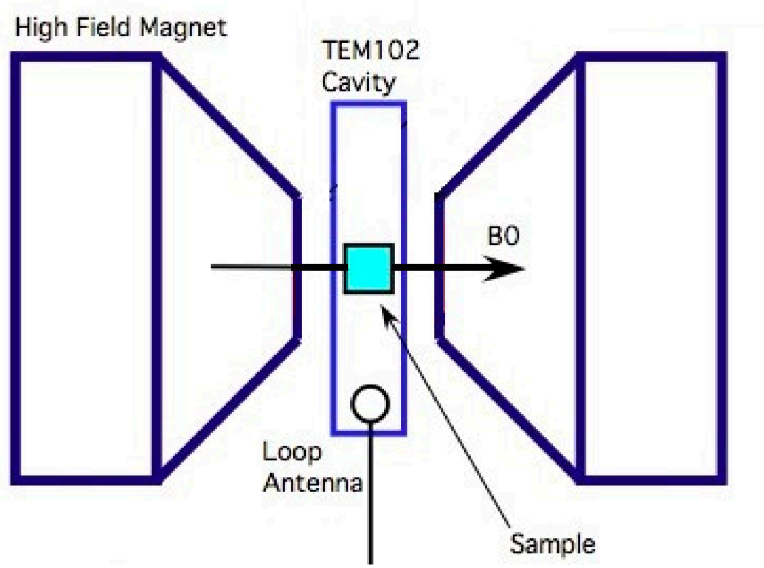




Before our work, all existing and proposed experiments used the “ferromagnetic haloscope” concept

Crescini 2017

The Ferromagnetic Haloscope



Ferromagnet spin precesses on resonance with axion, driving a cavity mode

$$P \sim B_{\text{eff}}^2 V Q_m \omega_m$$

Use yttrium iron garnet for higher Q_m

effective magnetic field

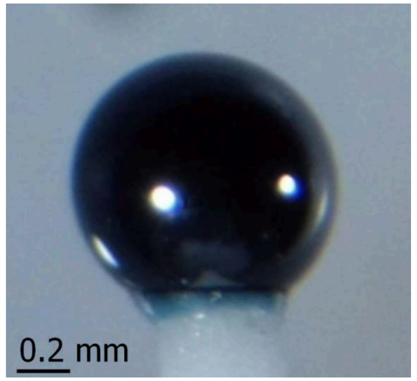
$$\mathbf{B}_{\text{eff}} = \frac{g_{ae}}{\mu_B} \nabla a$$

magnetic quality factor

$$Q_m \sim 10^4$$

sample magnetization

$$\omega_m = 2\mu_B M_0 \sim 0.03\,\text{meV}$$



$$V \sim \begin{cases} 0.005\,\text{cm}^3 & \text{QUAX (2018)} \\ 0.01\,\text{cm}^3 & \text{Flower et al. (2019)} \\ 0.1\,\text{cm}^3 & \text{QUAX (2020)} \\ 100\,\text{cm}^3 & \text{QUAX target} \end{cases}$$

Main issue: scaling sample volume

Single crystal YIG made very slowly, in mm spheres, at cost of over $\$10^7/\text{kg}$

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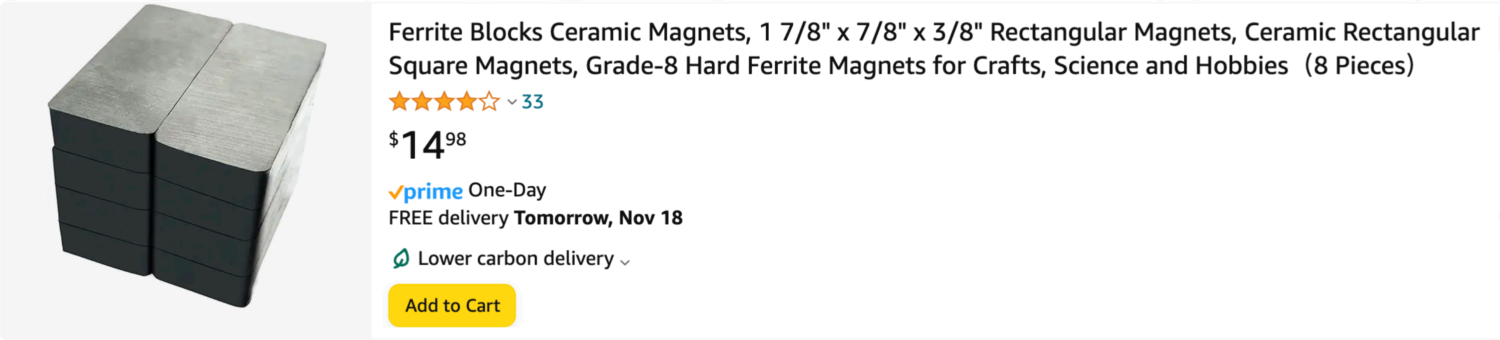
The Ferromagnetic Haloscope

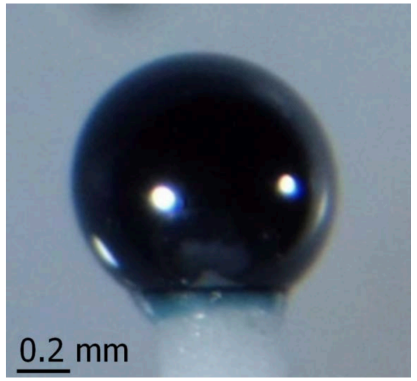
Alternative idea: replace strong resonant enhancement with overall scale

Polycrystalline spinel ferrites are cheap and mass produced



M_0 double that of YIG

$$Q_m \sim 10^2$$



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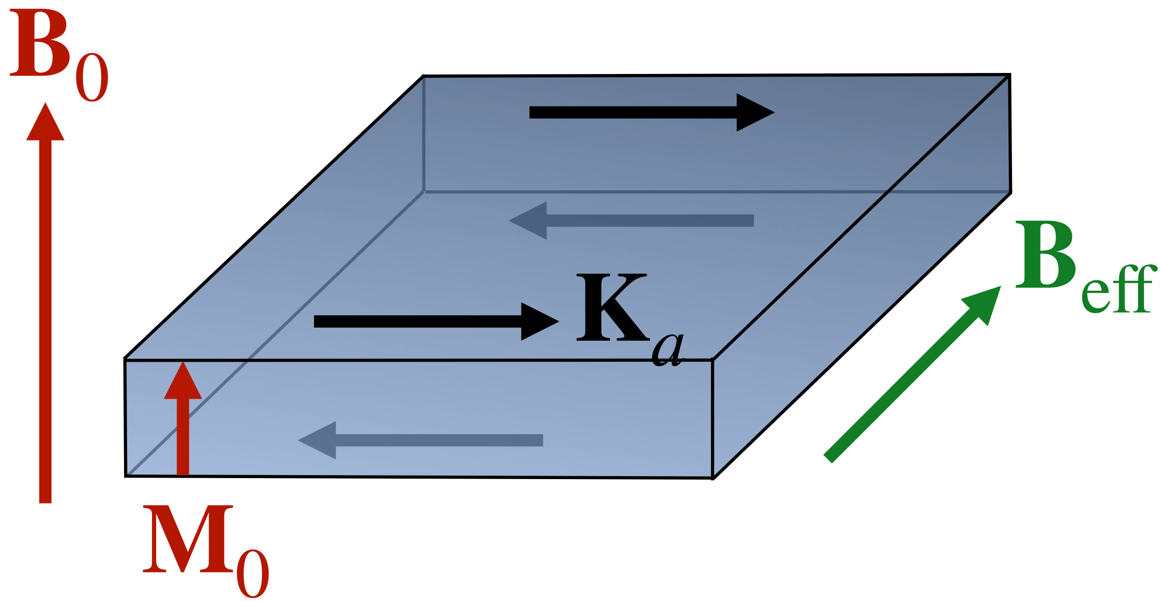
Radiation From a Slab



$$\mathbf{J}_a = \nabla \times ((1 - \mu^{-1})\,\mathbf{B}_{\rm eff})$$

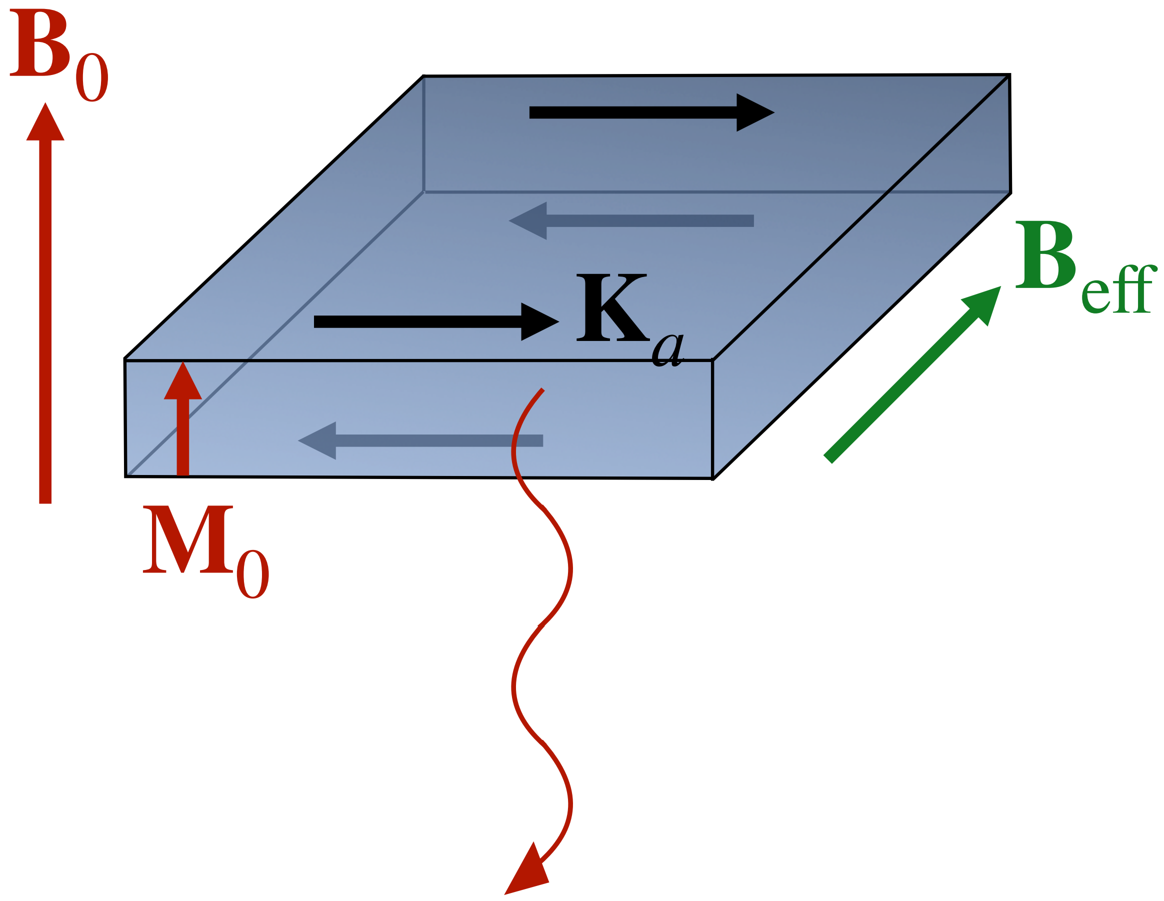
Magnetized slab carries surface currents

Solving spin equation of motion:

$$1 - \mu_-^{-1} \simeq \frac{M_0}{B_0 - (m_a/2\mu_B) - iB_0/2Q_m}$$

(for clockwise polarization)

Radiation From a Slab



much of this power is converted to outgoing radiation

$$\mathbf{J}_a = \nabla \times ((1 - \mu^{-1})\, \mathbf{B}_{\text{eff}})$$

Magnetized slab carries surface currents

$$1 - \mu_-^{-1} \simeq \frac{M_0}{B_0 - (m_a/2\mu_B) - iB_0/2Q_m}$$

Power deposited in slab maximized on resonance, at tunable frequency

($B_0 \leq 10\,\mathrm{T}$ implies $m_a \leq 10^{-3}\,\mathrm{eV}$)

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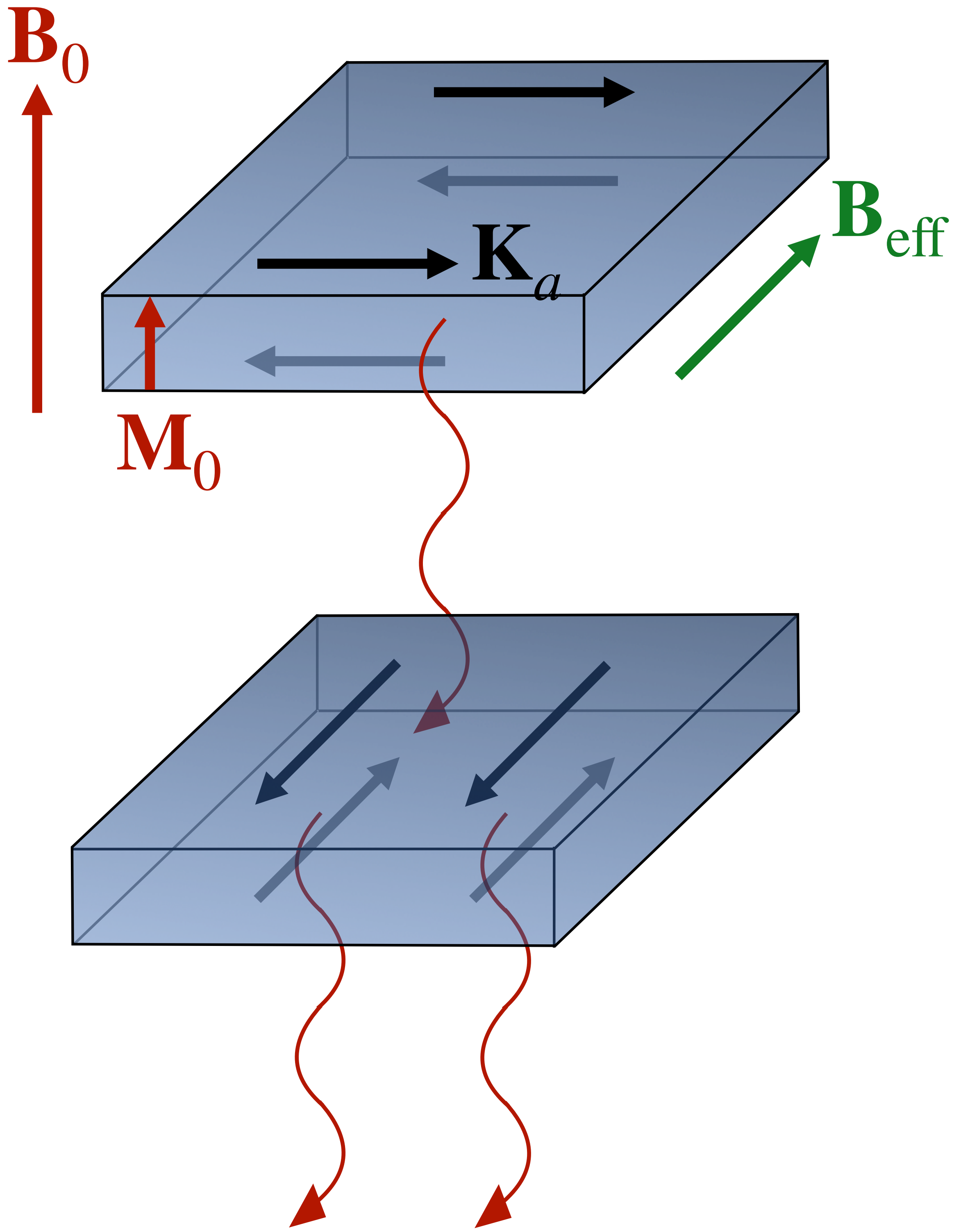

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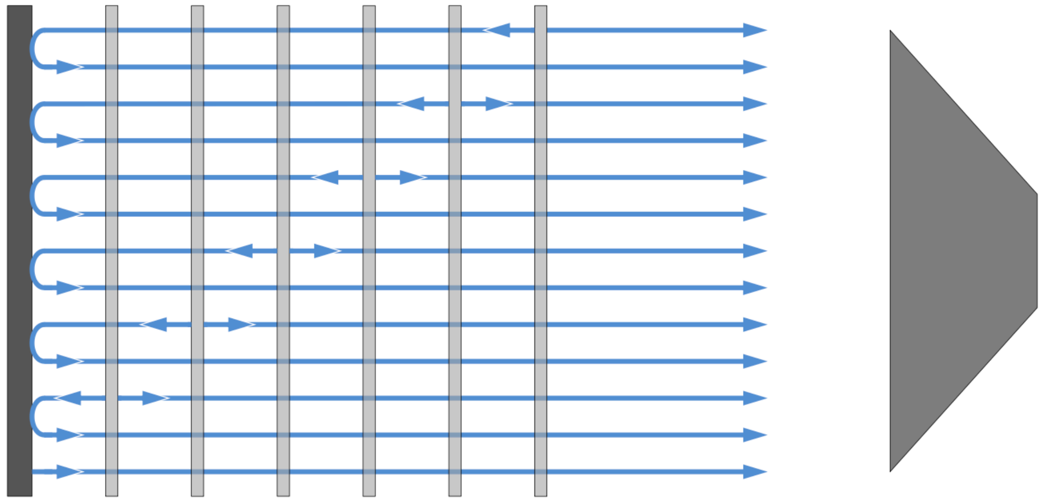
Power deposited in slab maximized on resonance, at tunable frequency

($B_0 \leq 10\,\text{T}$ implies $m_a \leq 10^{-3}\,\text{eV}$)

Place layers, with tunable separation, so emitted radiation interferes constructively

Magnetized Multilayers



Like the MADMAX experiment, radiation emitted from layers is focused on a detector

For simplicity, we consider the "transparent mode" setup:

slab spacing π/m_a, slab thickness $\pi/(\mathrm{Re}(n)\, m_a)$

$$P_{\mathrm{sig}} \sim \mathscr{F}^2 N^2 \, |B_{\mathrm{eff}}|^2 A$$

slab form factor

$\mathscr{F} \sim 1 - \mu^{-1}$

(+ material loss effects)

slab area

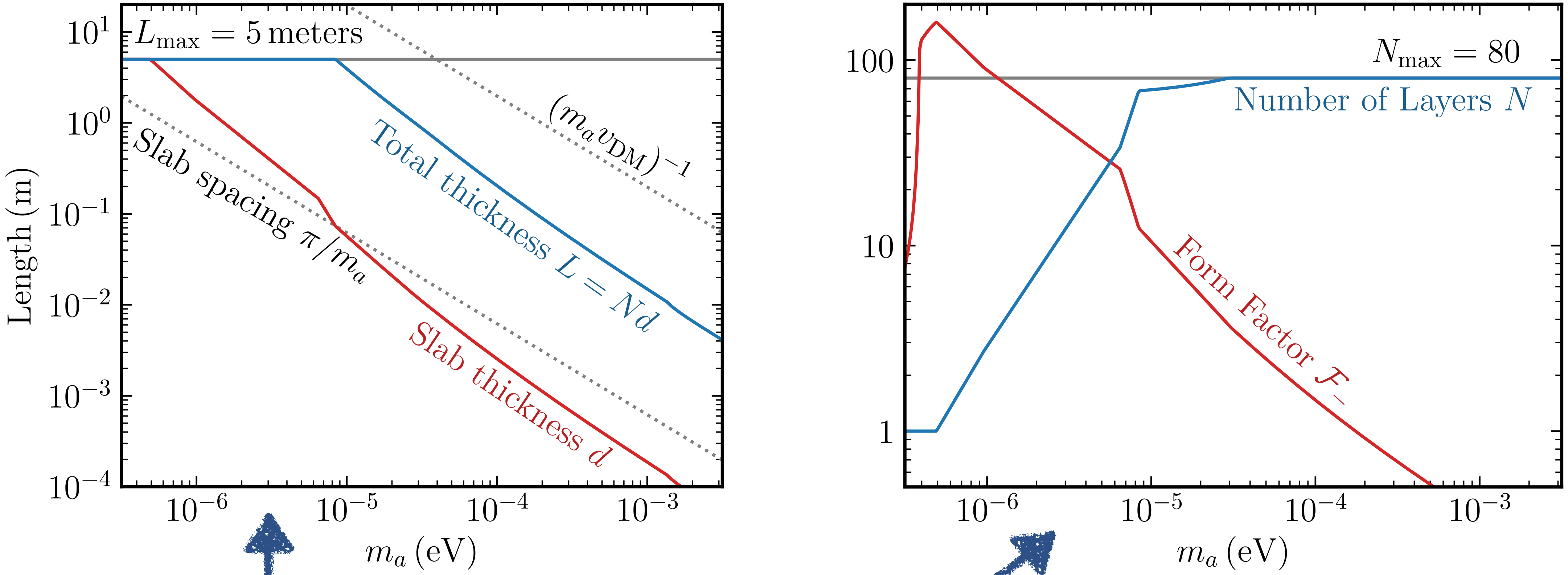
$A = 1\,\mathrm{m}^2$

number of layers

$N \leq 80$

$N \leq \mathrm{Re}(n)/(\pi\, \mathrm{Im}(n))$

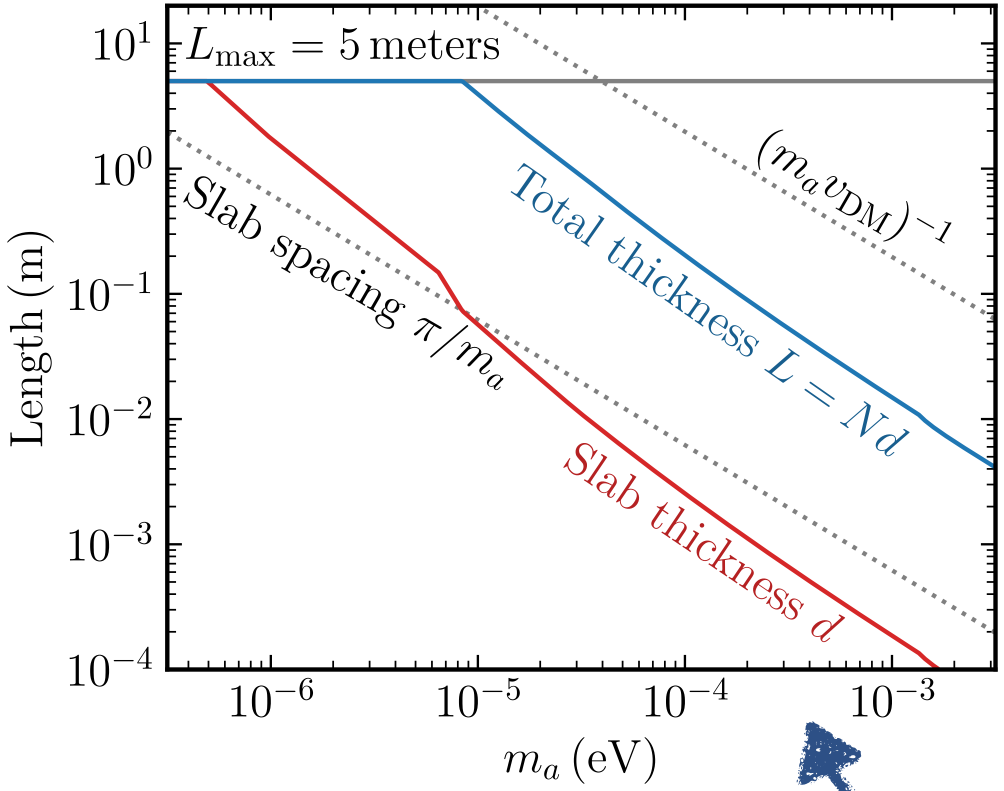
Optimizing a Magnetized Multilayer

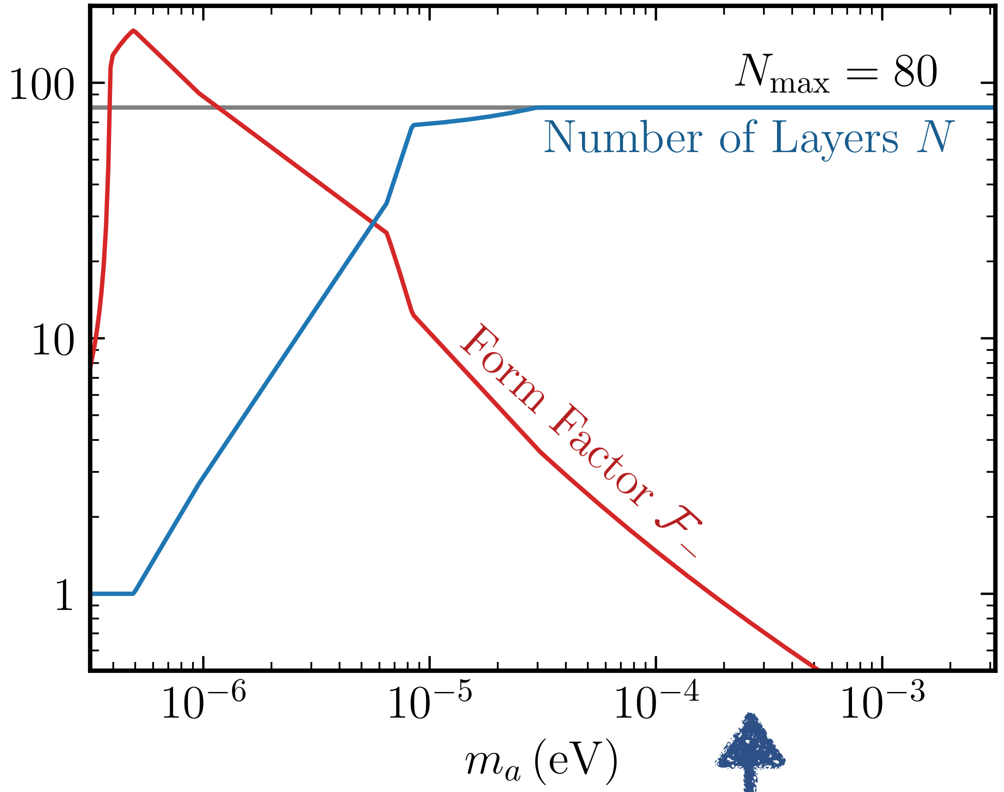


Low mass

A few thick slabs tuned close to resonance; large volume needed, but only low magnetic field

Optimizing a Magnetized Multilayer





Low mass

High mass

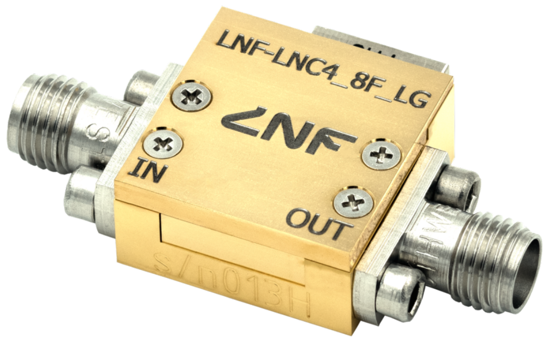
A few thick slabs tuned close to resonance; large volume needed, but only low magnetic field

Many thin slabs, which must be well off resonance to avoid absorption; high field but only in small volume

Benchmark Reach

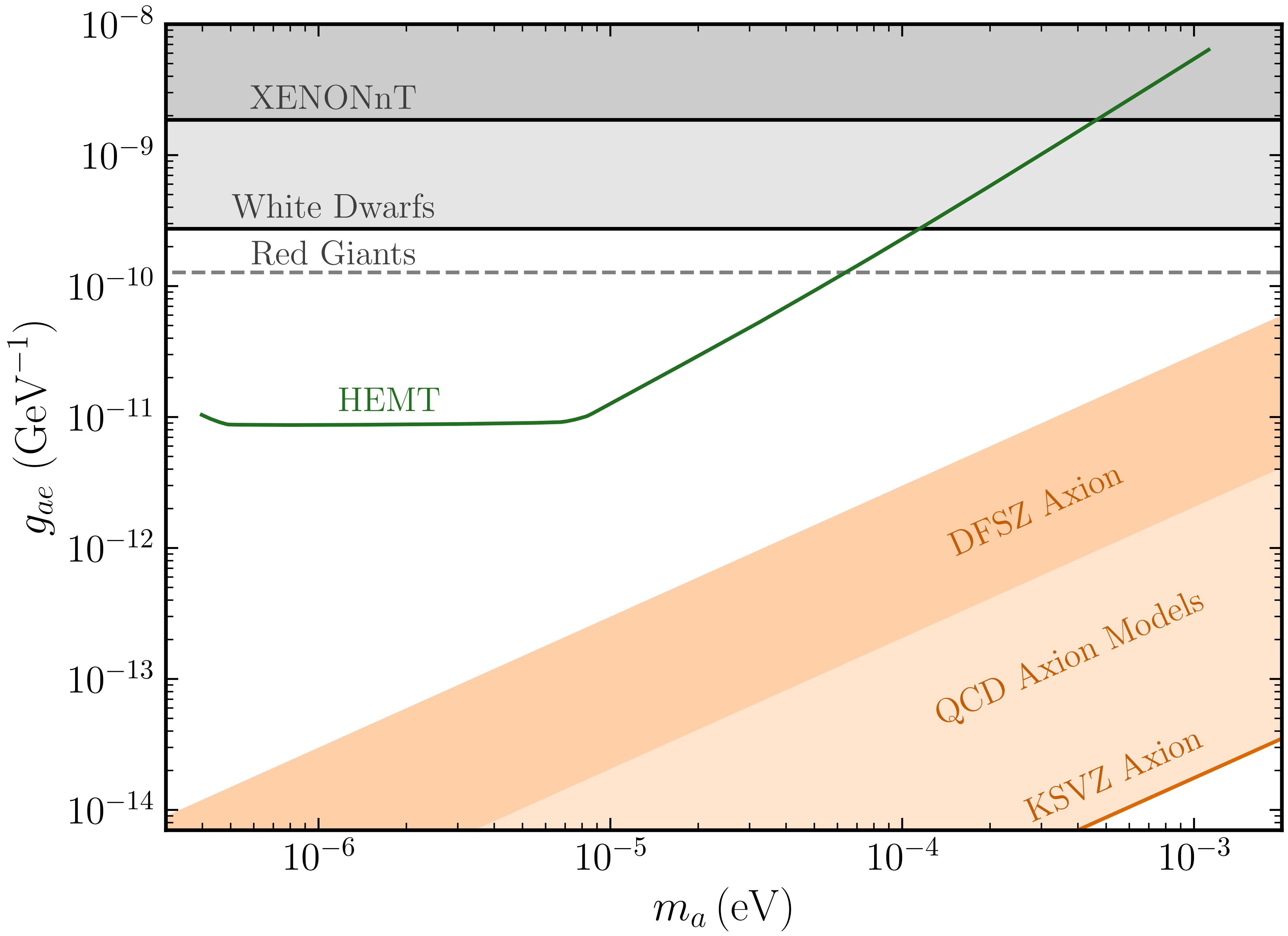
$$\text{SNR} \simeq \frac{P_{\text{sig}}}{T_n}\sqrt{\frac{t_{\text{int}}}{\Delta\nu_a}}$$

Standard HEMT amplifier



Helium cryostat cooling

$$T_n = 4\,\text{K} + T_{\text{amp}}$$



Benchmark Reach

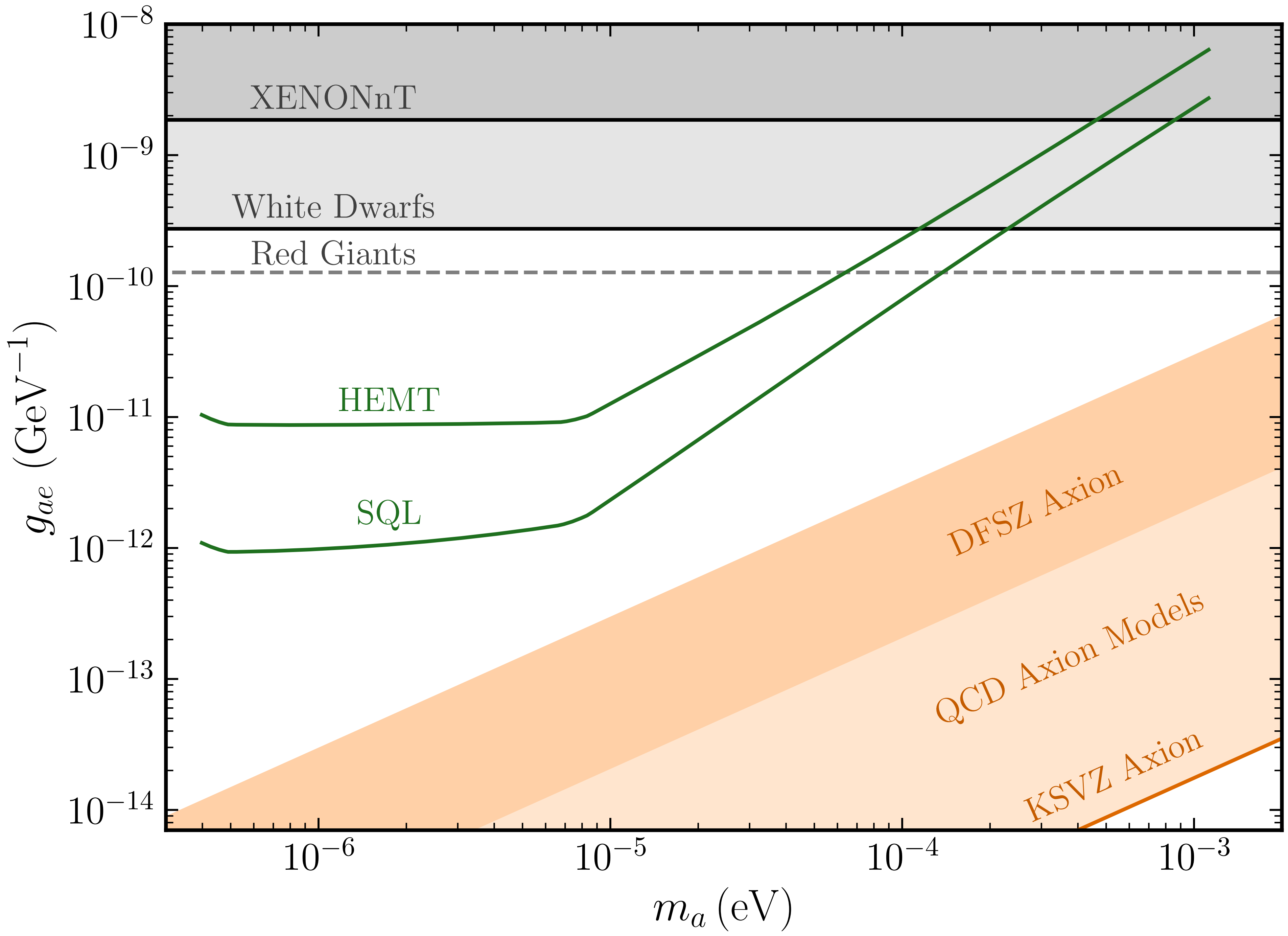
$$\mathrm{SNR} \simeq \frac{P_{\mathrm{sig}}}{T_n}\sqrt{\frac{t_{\mathrm{int}}}{\Delta\nu_a}}$$

Standard quantum limited amplification

Dilution fridge cooling

$$T_n = 40\,\mathrm{mK} + T_{\mathrm{amp}}$$

More challenging, but realized in several expts



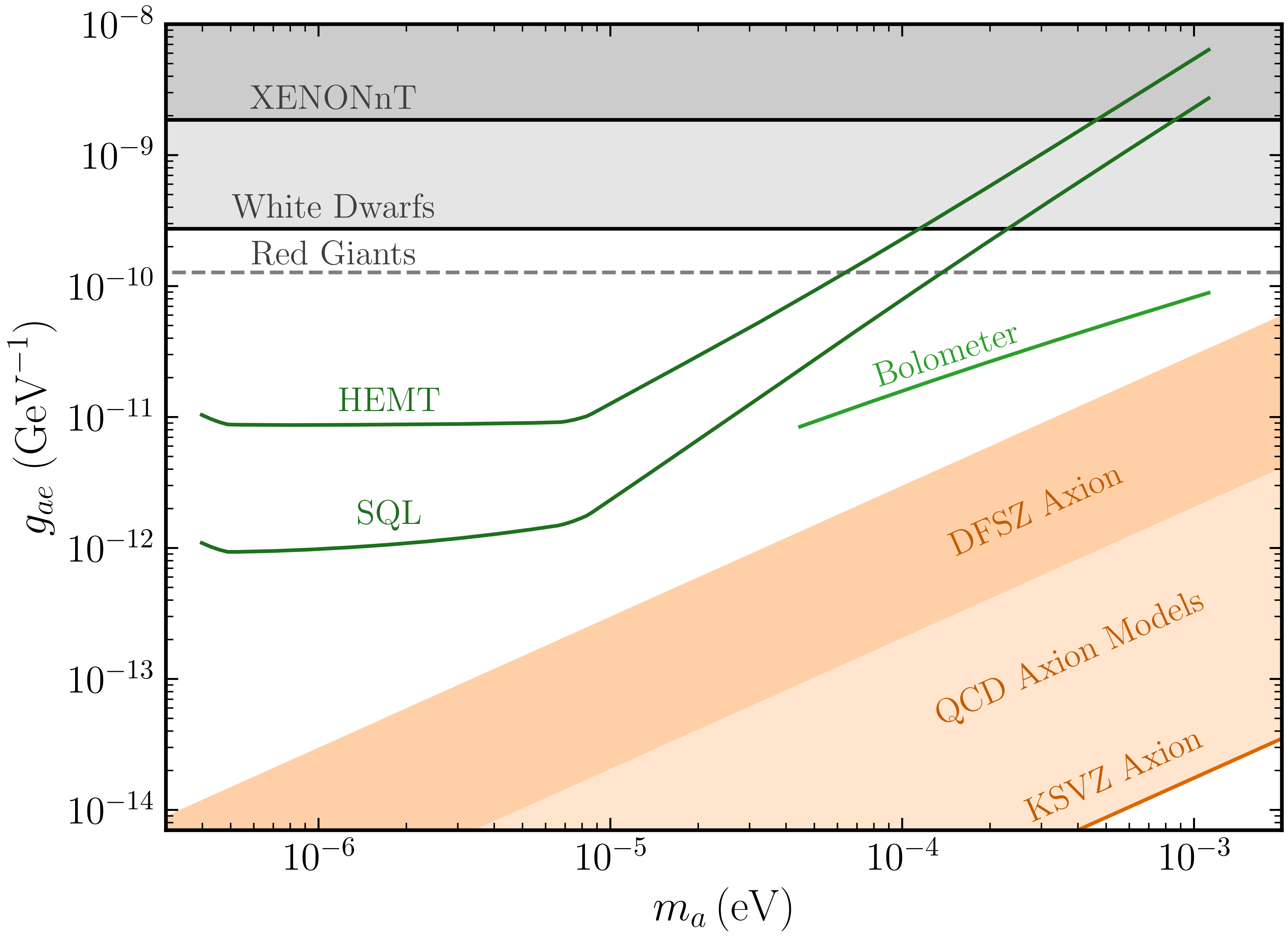
Benchmark Reach

$$\mathrm{SNR} \simeq \frac{P_{\mathrm{sig}}\sqrt{t_{\mathrm{int}}}}{\mathrm{NEP}}$$

Frequency insensitive bolometer

$$\mathrm{NEP} = 10^{-22}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$$

About 10x improvement over state of the art; target for BREAD



Benchmark Reach

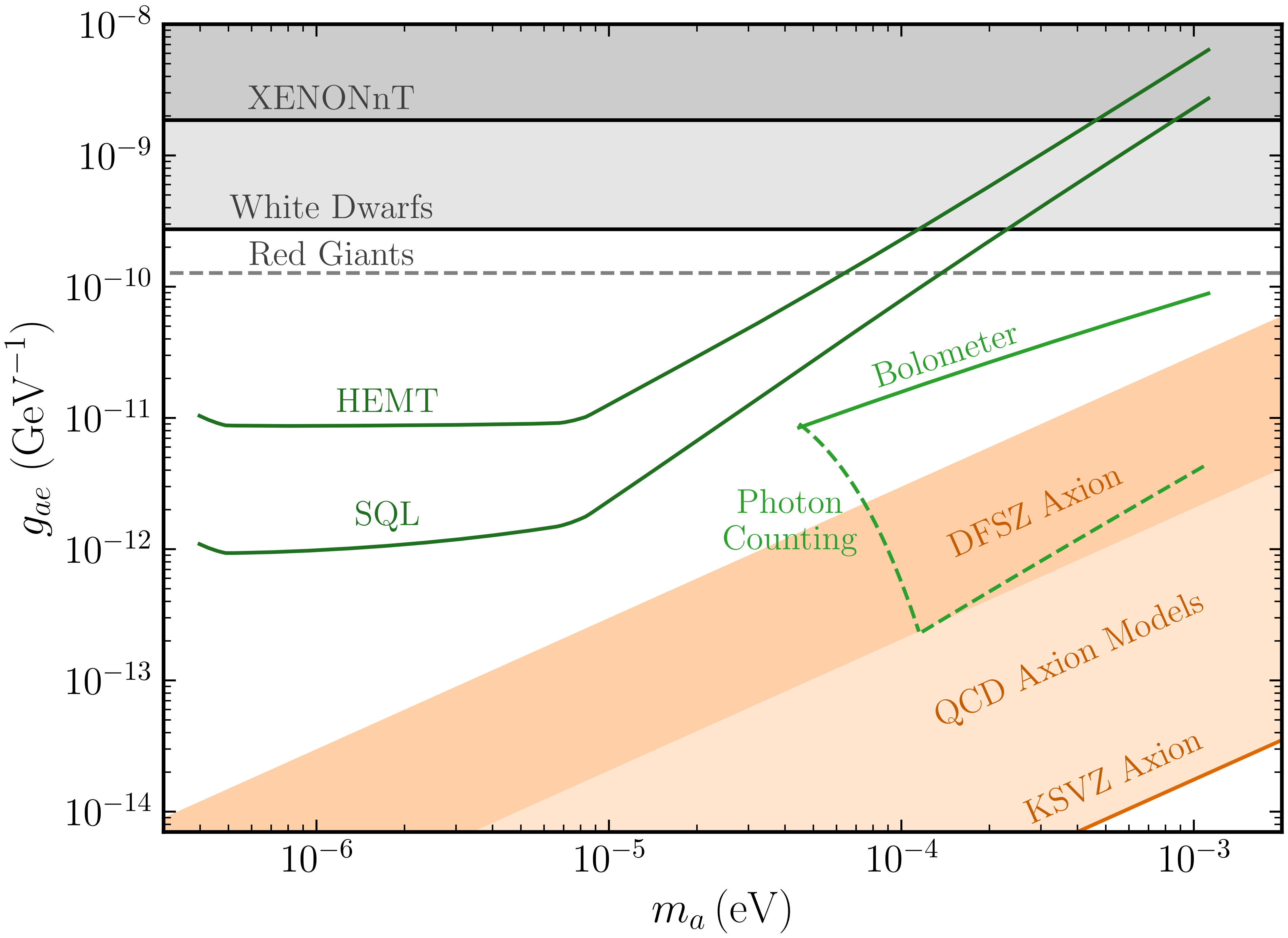
$$\mathrm{SNR} \simeq \frac{P_{\mathrm{sig}}}{m_a}\sqrt{\frac{t_{\mathrm{int}}}{\mathrm{DCR}}}$$

Thermal limited photon counting

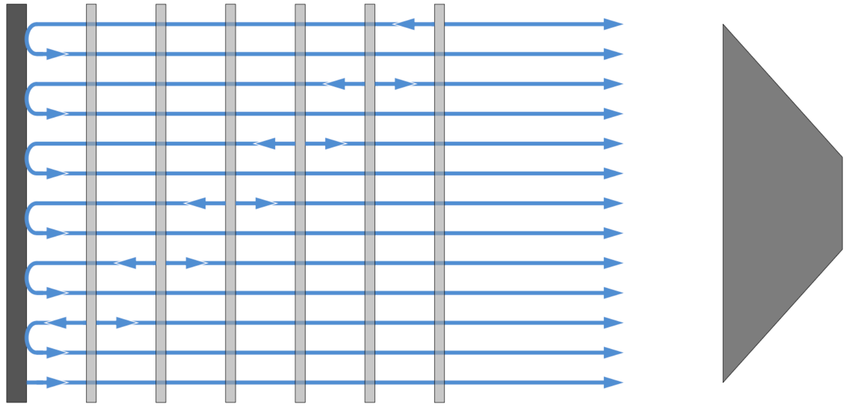
$$\mathrm{DCR} \sim \frac{\Delta\nu_s}{e^{m_a/T}-1}$$

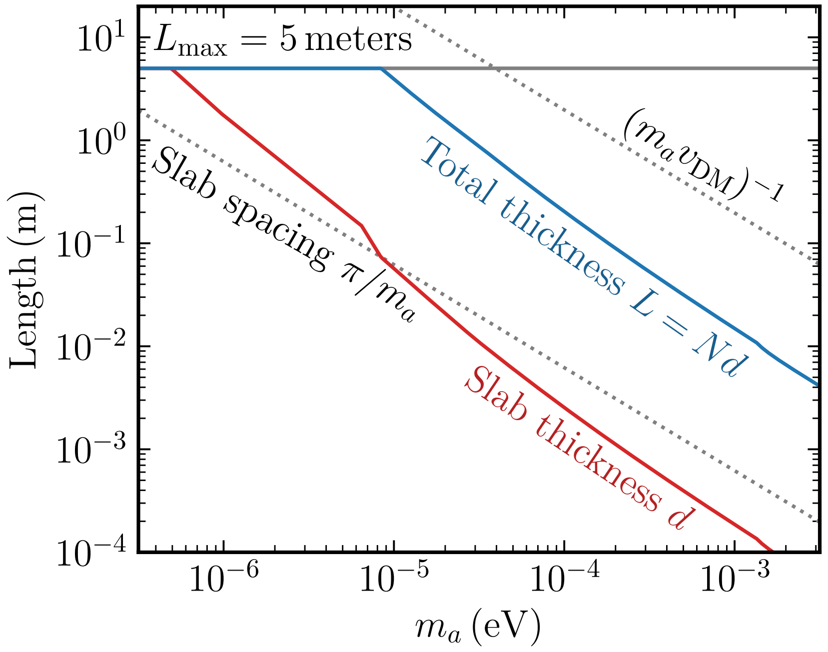
Challenging, but some prototypes at meV

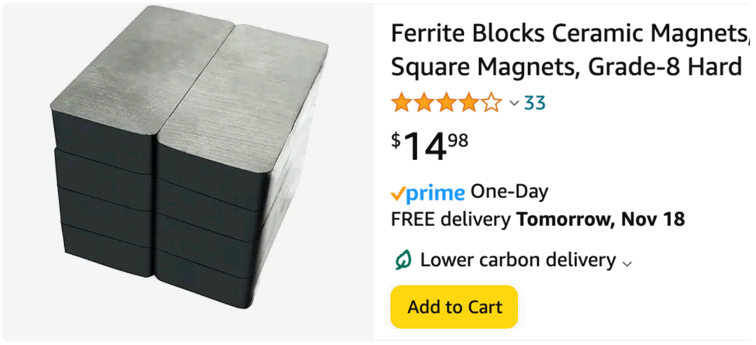
Ferromagnetic haloscopes already assume noise-free photon counting!



Open Questions







- We assumed “transparent mode” setup — how much better can one do?
- For high m_a, experiment is short but wide — is there a more convenient geometry?
- We assumed benchmarks $M_0 = 0.5\,\text{T}$, $Q_m = 100$, $\epsilon = 15$, typical for polycrystalline spinel ferrites — is there a better but still scalable option?
- What other kinds of beyond Standard Model physics can such a setup test?

Conclusion

- The axion-electron coupling is minimal and generic
- Its physical effects are simple, but can be subtle to compute
- Recent attempts to probe it all used a single concept…
- …but new ideas may allow scaling to stronger sensitivity

$$\mathscr{L} \supset g\,(\partial_\mu a)\,\bar{e}\gamma^\mu\gamma^5 e$$

$$H \supset -\,g\,(\nabla a)\cdot\sigma - \frac{g}{m_e}\,\dot{a}\,\sigma\cdot(\mathbf{p}-q\mathbf{A})$$