How (Not) to Probe
The Axion-Electron Coupling

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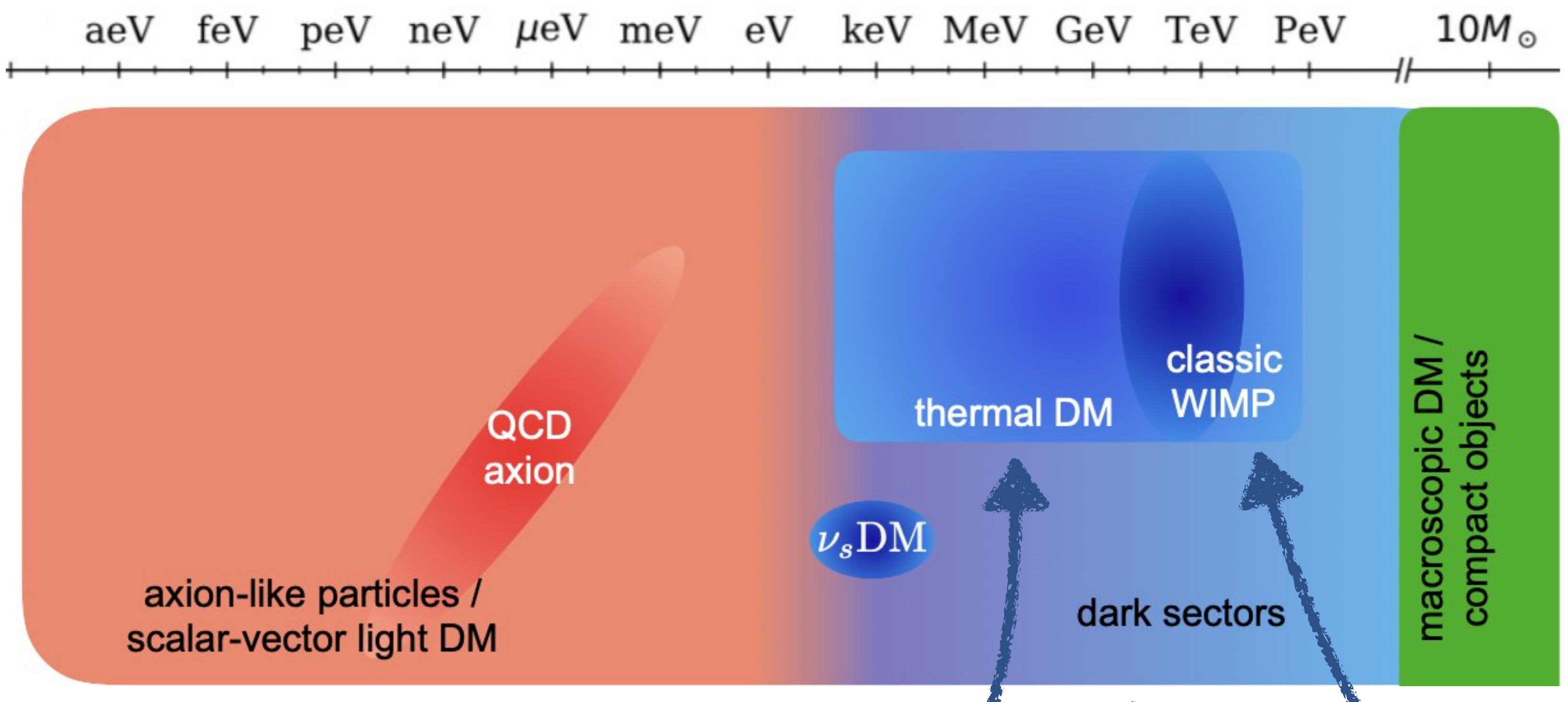
Peking University Seminar — July 17, 2025

Dark Matter Candidates



ultralight field

acts like oscillating classical field

$$\frac{f}{\mathrm{GHz}} \sim \frac{m_{\mathrm{DM}}}{\mu\mathrm{eV}}$$

field's weak forces, torques, currents can be probed by new precision experiments

"lighter particle"

probed by extending WIMP searches to lower threshold, or by direct production

theory motivation less clear, but amenable to search

macroscopic object

well-tested by astrophysical observation

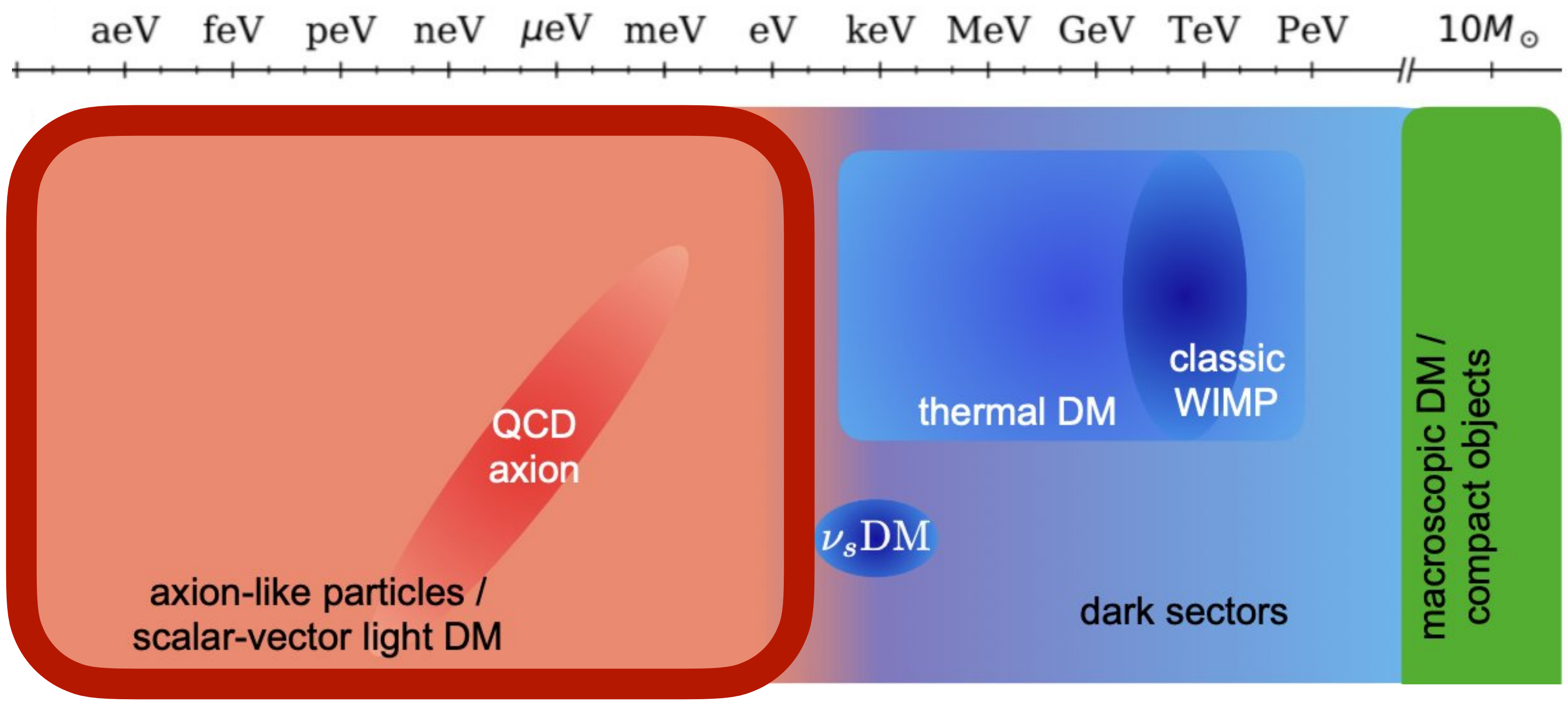
"classic WIMP"

very well-tested by direct detection and astrophysics

~95% of funding, effort

"something more complex" possible, but search strategy unclear

Why Search for Ultralight Dark Matter?



- Simply produced: gives right amount of dark matter with minimal cosmology
- Generic: required ultralight fields automatically appear in many models
- Minimal: requires introduction of only a single new field at low energies
- Low-hanging fruit: new experiments are needed, inexpensive, and very effective
- Bounded: only a few interactions are natural and leading in effective field theory

Ultralight Dark Matter Candidates

In field theory, only a few candidates are possible!

	pseudoscalar a	scalar ϕ	vector A'_μ	tensor $h'_{\mu\nu}$
naturally light with leading coupling	✓		✓	?
arises in high energy theories	✓	✓	✓	
solves tuning problems	✓	?		
simply produced	✓	✓	?	?

Couplings of a Field Theory Axion

$$a\,G\tilde{G} \qquad\qquad a\,\bar{N}\sigma_{\mu\nu}\gamma^5 N\,F^{\mu\nu}$$

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

$$a\,\bar{e}i\gamma^5 e \qquad a\,F\tilde{F} \xrightarrow[\text{by parts}]{\text{integrate}} (\partial_\mu a)\,K^\mu_{\mathrm{EM}}$$

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

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

Couplings of a Field Theory Axion

$$
\begin{tikzcd}
 & \boxed{a\, G\tilde{G}} \arrow[r] \arrow[dr, bend left] & a\, \bar{N}\sigma_{\mu\nu}\gamma^5 N\, F^{\mu\nu} \\
a\, \bar{q} i \gamma^5 q \arrow[ur, bend left] \arrow[r] \arrow[dr, bend right] & (\partial_\mu a)\, \bar{q}\gamma^\mu\gamma^5 q \arrow[r] & \boxed{(\partial_\mu a)\, \bar{N}\gamma^\mu\gamma^5 N} \\
a\, \bar{e} i \gamma^5 e \arrow[r] \arrow[dr, bend right] & a\, F\tilde{F} \arrow[r] & \boxed{(\partial_\mu a)\, K^\mu_{\mathrm{EM}}} \\
 & \boxed{(\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e} &
\end{tikzcd}
$$

Only a few dimension 5 operators possible, and generically all exist

These operators depend only on the axion derivative $\partial_\mu a$

(many proposals claim sensitivity even as $\partial_\mu a \to 0$, but are all incorrect)

However, a QCD axion can have signatures proportional to a

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

axion-photon

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

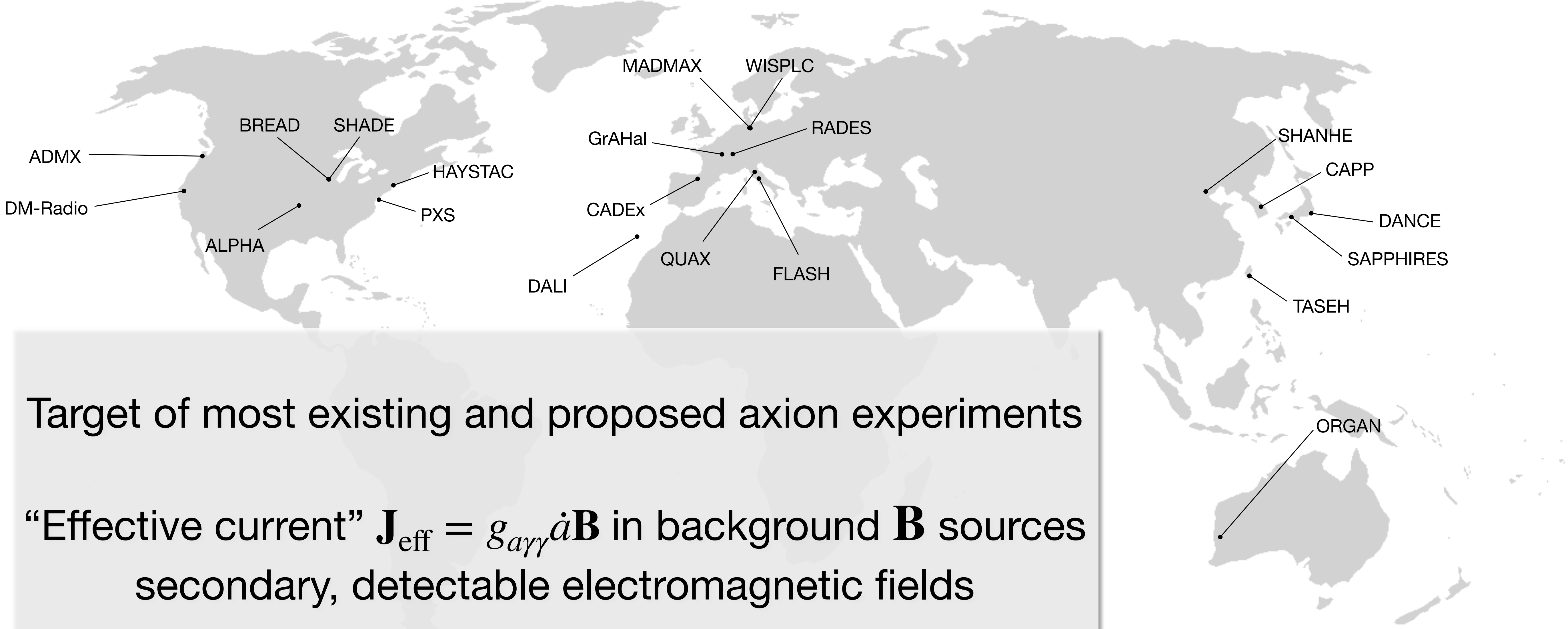
axion-nucleon

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

axion-electron

$$a\, \bar{N}\sigma_{\mu\nu}\gamma^5 N\, F^{\mu\nu}$$

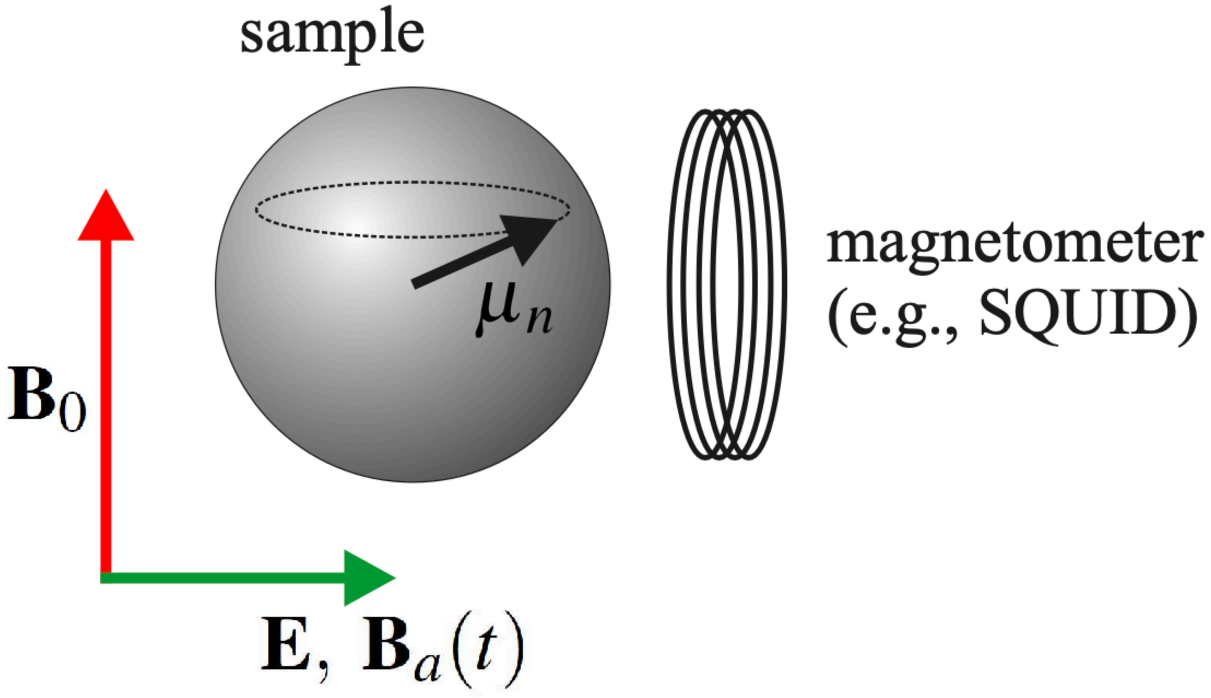
axion-EDM



Target of most existing and proposed axion experiments

"Effective current" $\mathbf{J}_{\mathrm{eff}} = g_{a\gamma\gamma}\dot{a}\mathbf{B}$ in background $\mathbf{B}$ sources secondary, detectable electromagnetic fields

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



Exerts nuclear spin torque $\tau = \hat{\mathbf{s}} \times \mathbf{B}$ through effective magnetic field $\mathbf{B}_{\rm eff} = g_{aN}\,\nabla a$

Field is very weak; need to amplify signal with nuclear magnetic resonance

Detection remains very challenging, due to weakness of nuclear spin polarization, smallness of nuclear magnetic moment

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

axion-photon

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

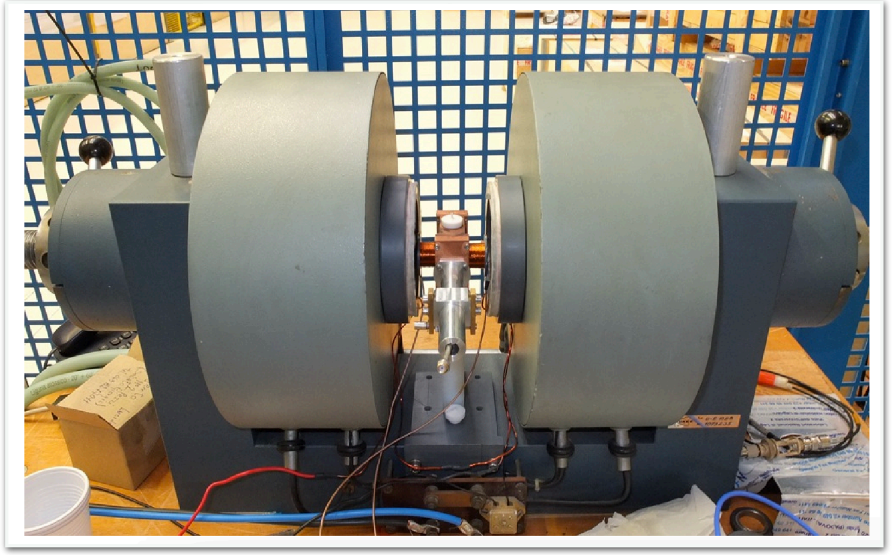
axion-nucleon

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

axion-electron

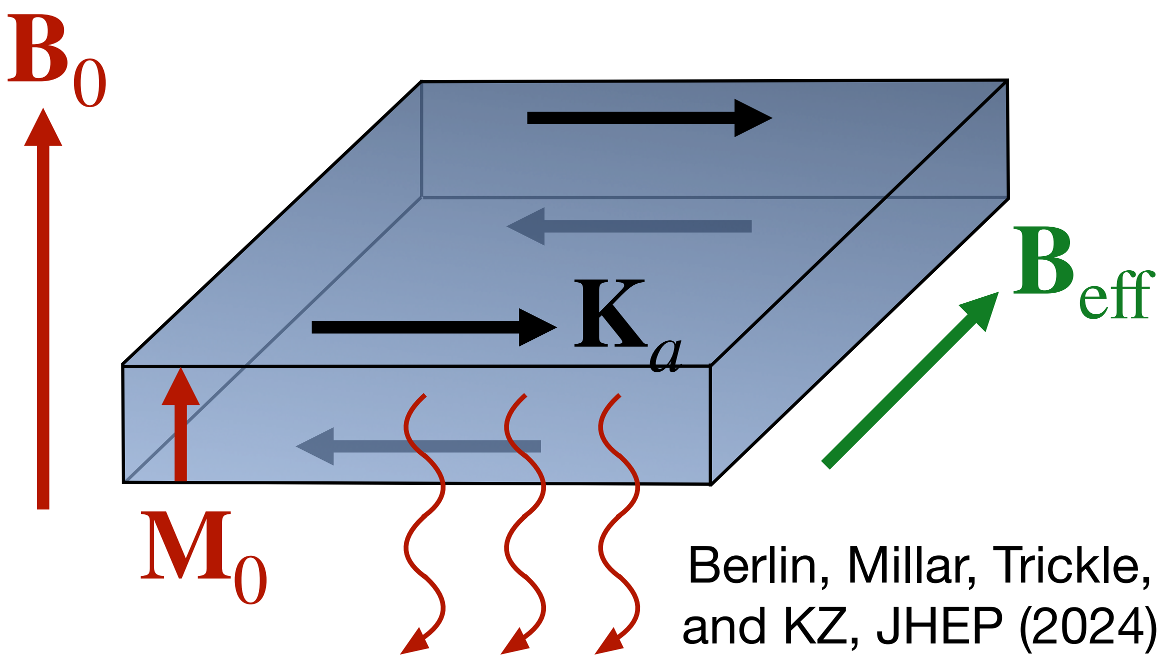
$a\, \bar{N}\sigma_{\mu\nu}\gamma^5 N\, F^{\mu\nu}$

axion-EDM



Exerts electron spin torque $\tau = \hat{\mathbf{s}} \times \mathbf{B}$ through effective magnetic field $\mathbf{B}_{\text{eff}} = g_{ae}\, \nabla a$

Stronger signals than nuclear case, but electron spins are "messier"



Berlin, Millar, Trickle, and KZ, JHEP (2024)

Most experiments amplify with ferromagnetic resonance, so sample excites a microwave cavity

New concept: emit radiation from "magnetic multilayer", substituting scale for resonance

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

axion-photon

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

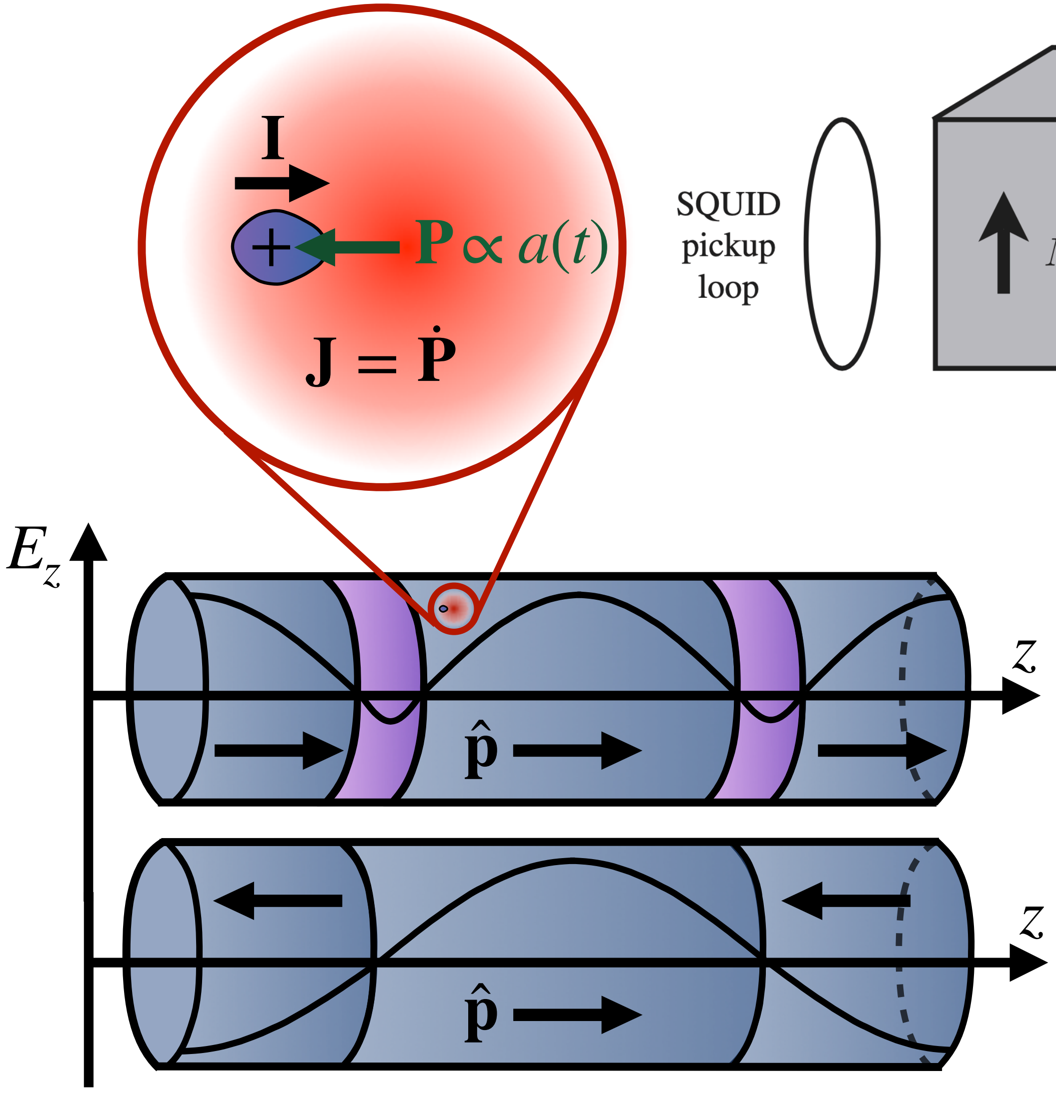
axion-nucleon

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

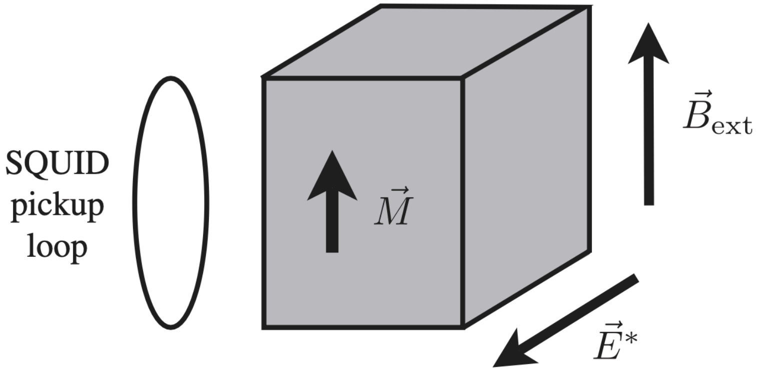
axion-electron

$\boxed{a\, \bar{N}\sigma_{\mu\nu}\gamma^5 N\, F^{\mu\nu}}$

axion-EDM



Berlin and KZ, PRD (2023)



Leads to time-dependent nuclear and atomic electric dipole moments

Traditional EDM experiments don't work, as the EDM oscillates rapidly in time

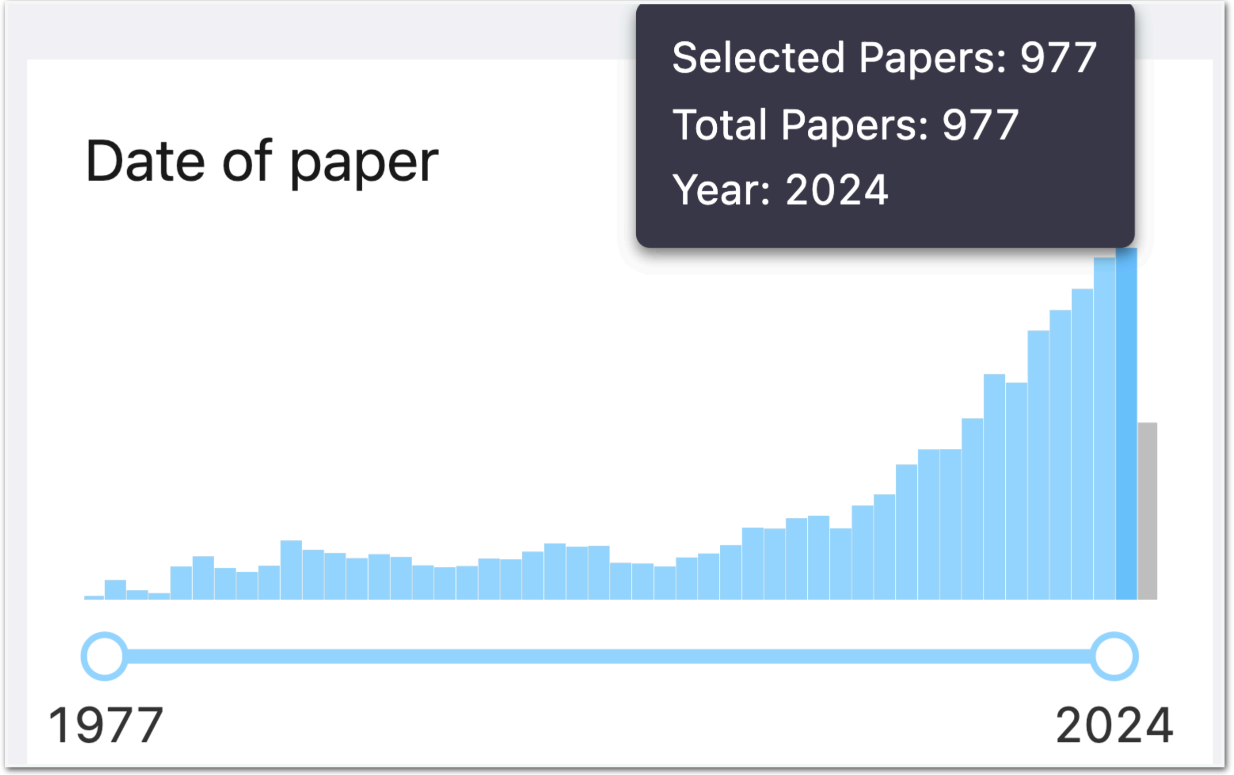
Below GHz: in sample with background $\mathbf{E}$, amplify with nuclear magnetic resonance

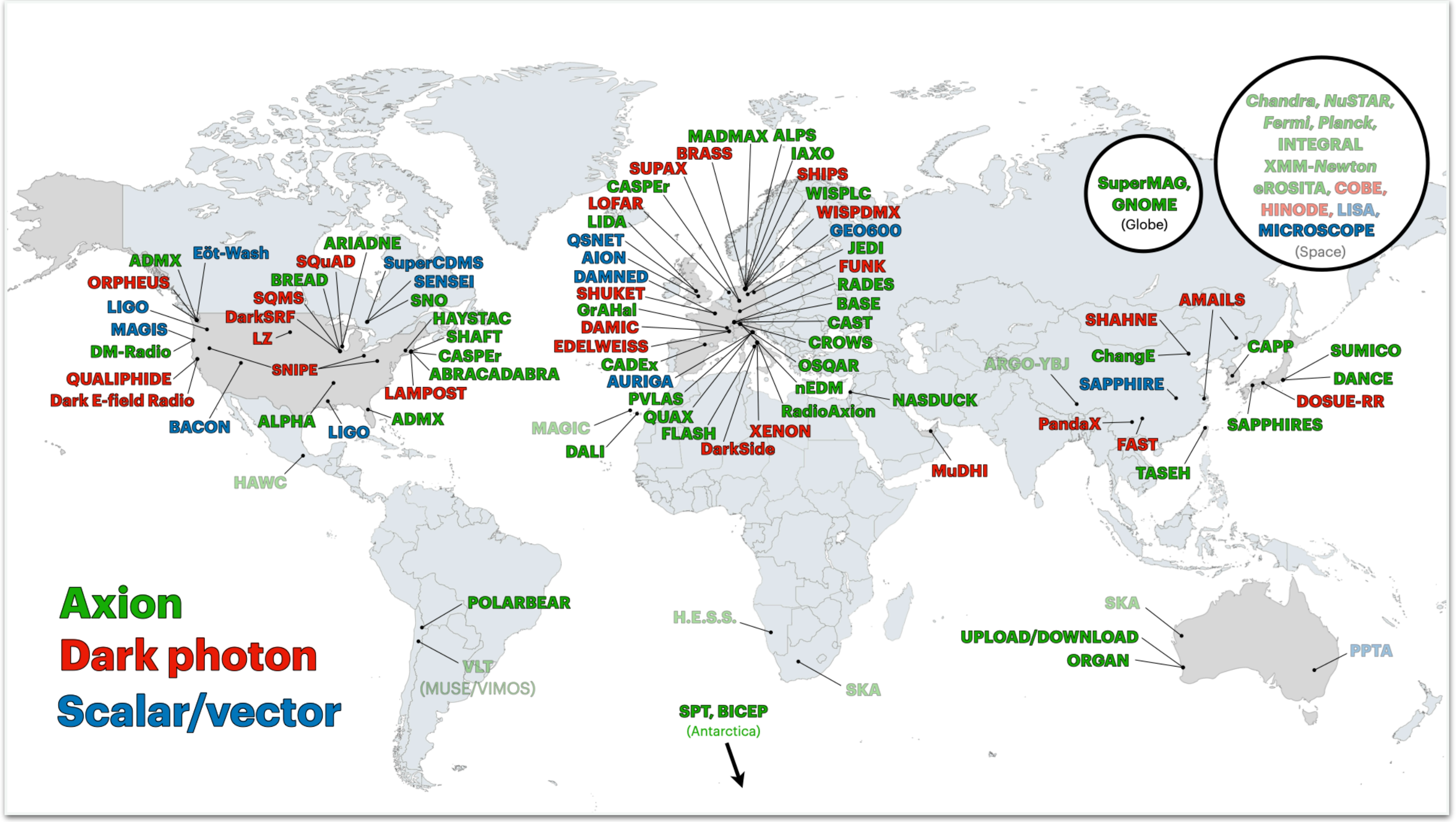
Above GHz: use oscillating current $\mathbf{J} = d\mathbf{P}/dt$ to excite a resonant microwave cavity

Both quite difficult, better for "post discovery"

Axion Searches: Theory and Practice

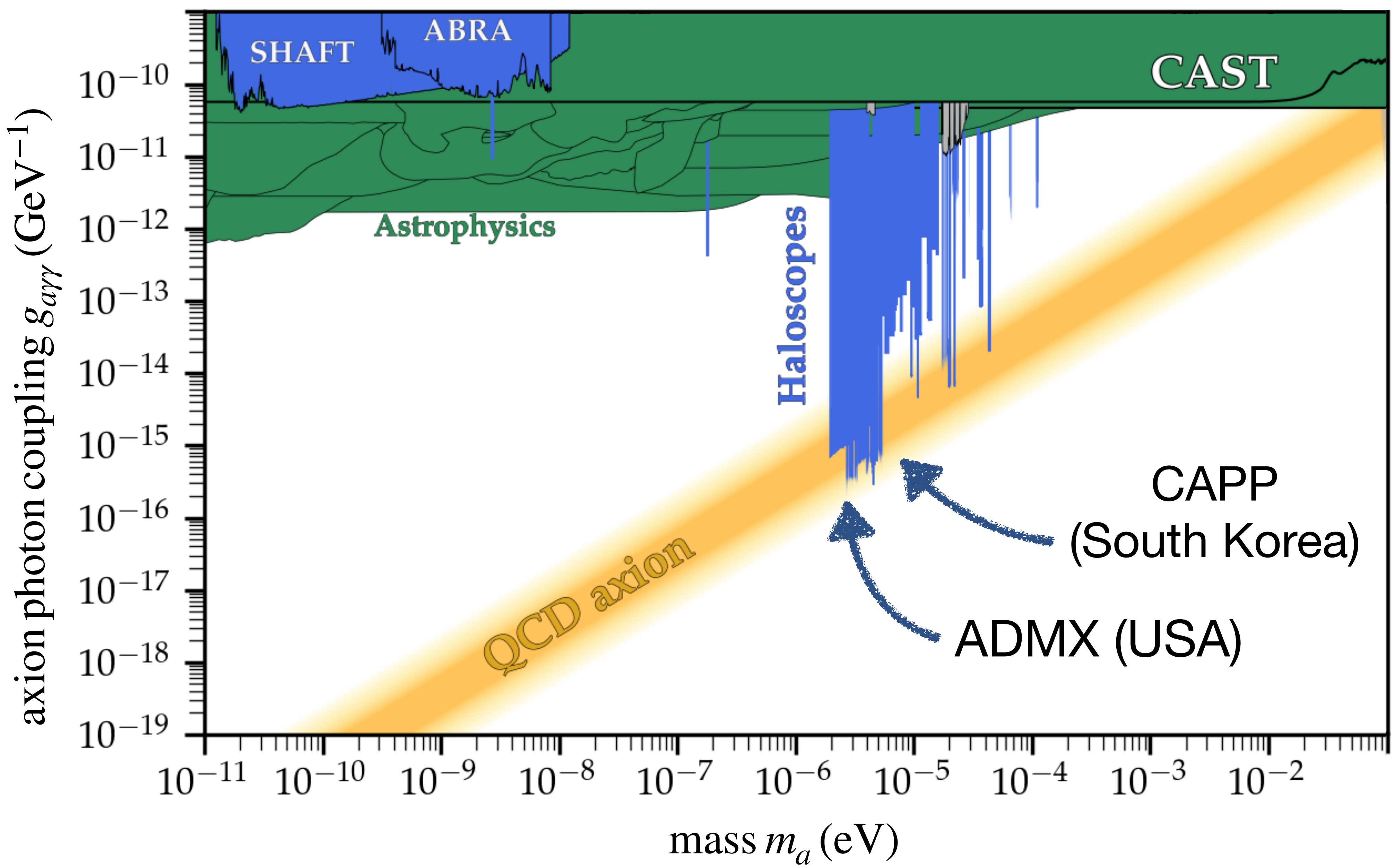
Many papers have been written, and many experimental collaborations formed





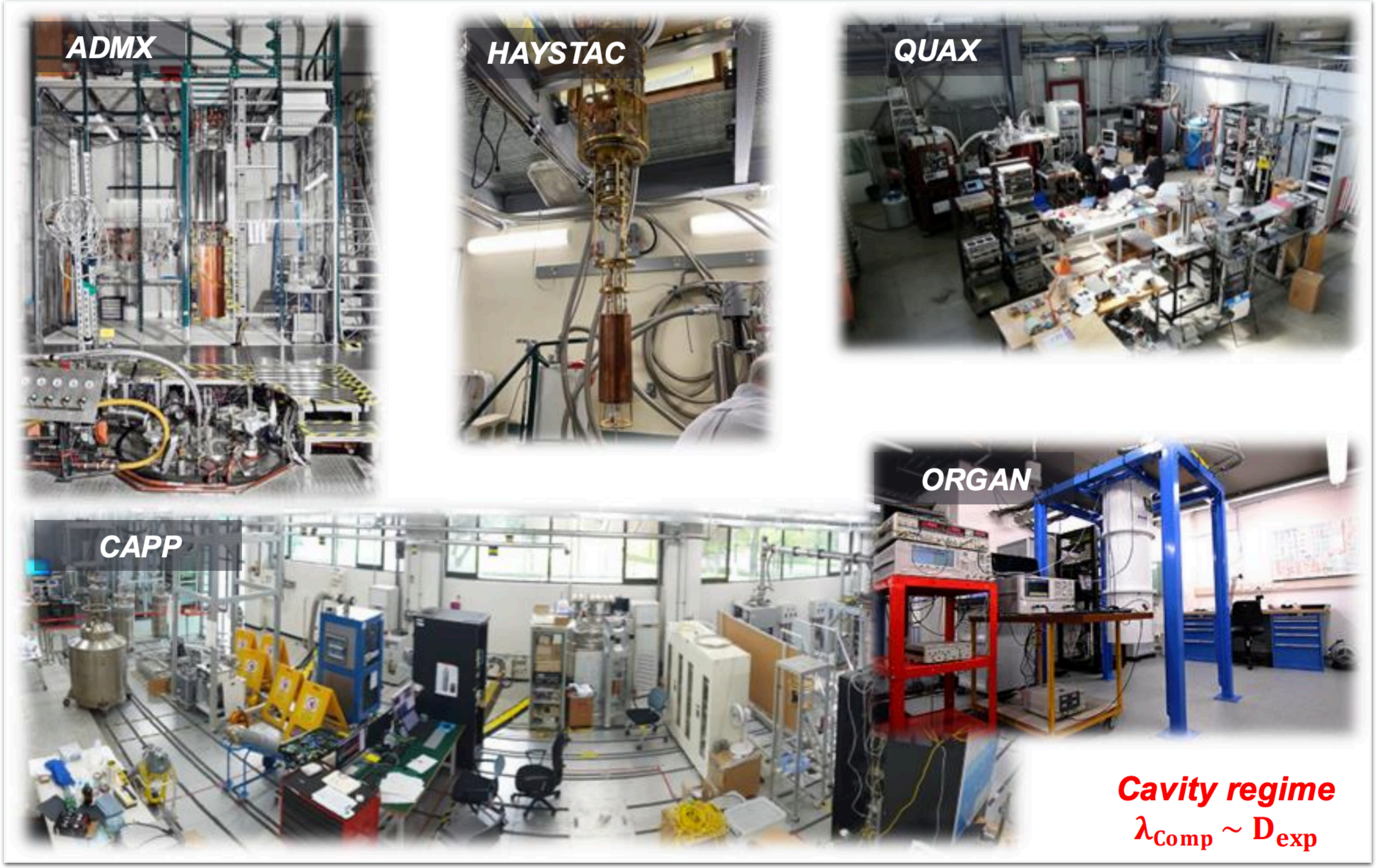
But many sensitivity projections from theorists are overly optimistic,
and many experiments only aim for very low sensitivity

Axion Searches: Theory and Practice



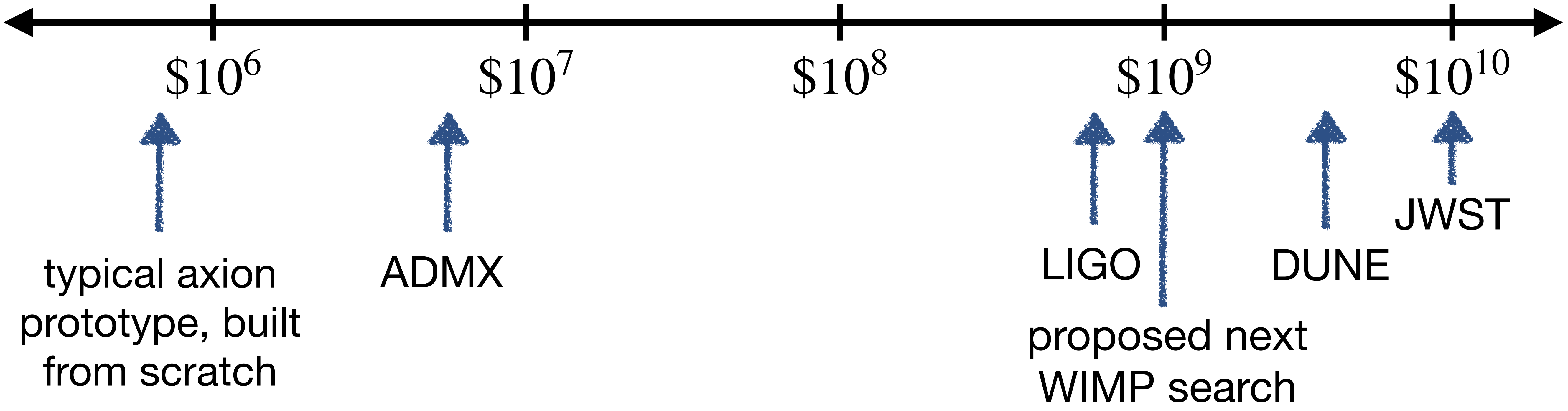
Currently, only the axion-photon coupling has been probed significantly, and largely by just two experiments, both cavity haloscopes

Cavity Haloscopes in the Lab



(slide by Sungwoo Youn, present director of CAPP)

Axion Searches: Theory and Practice



Axion experiments are “small scale” science

Achieving strong sensitivity costs more than an average graduate student, but fits within the scale of a university lab

A decisive next-generation axion experiment would still be a very small fraction of a national particle physics budget

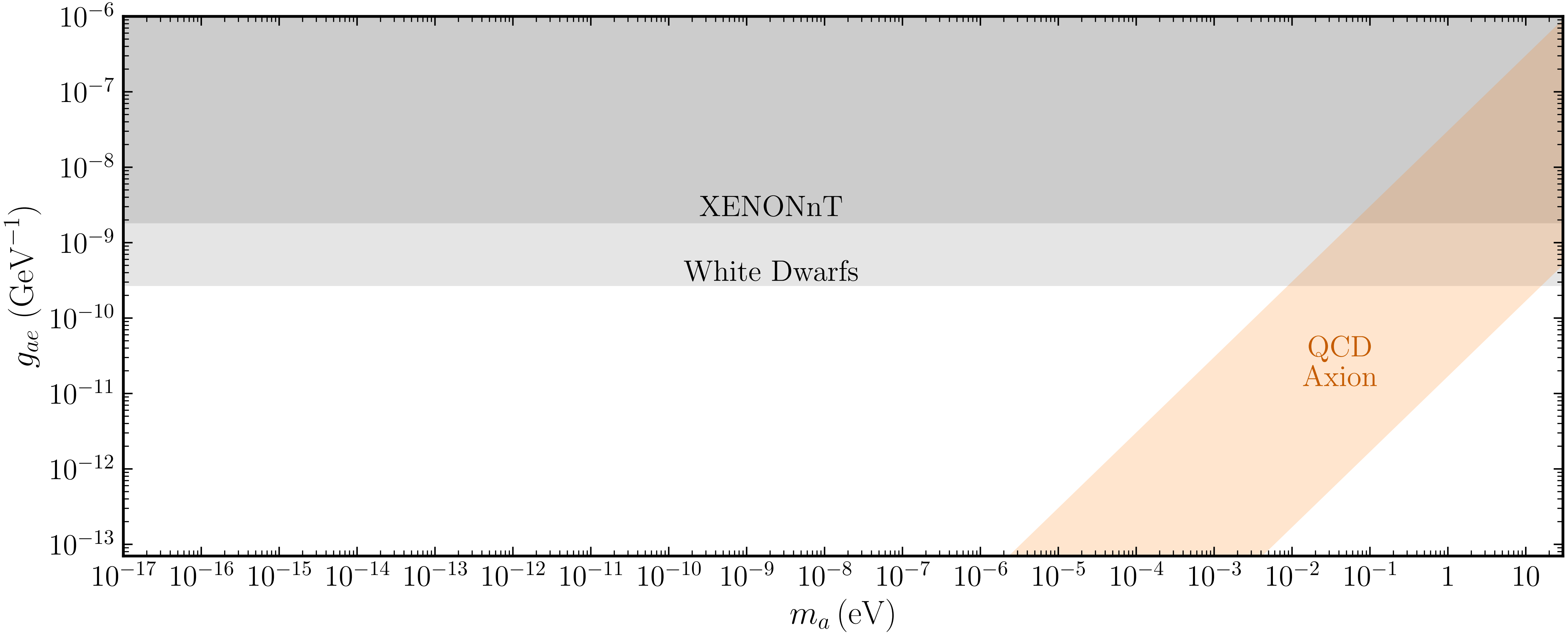
$(\partial_\mu a)\, K^\mu_{\mathrm{EM}}$
axion-photon

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

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

$a\, \bar{N}\sigma_{\mu\nu}\gamma^5 N\, F^{\mu\nu}$
axion-EDM

This talk explains: what will and won't work to probe the axion-electron coupling



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

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

"axioelectric" term

both terms oscillate with the axion field, at $f \sim (m_a/\mu\mathrm{eV})$ 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 $\mathbf{E}_{\text{eff}} = (g/q)\,\ddot{a}\,\sigma$?

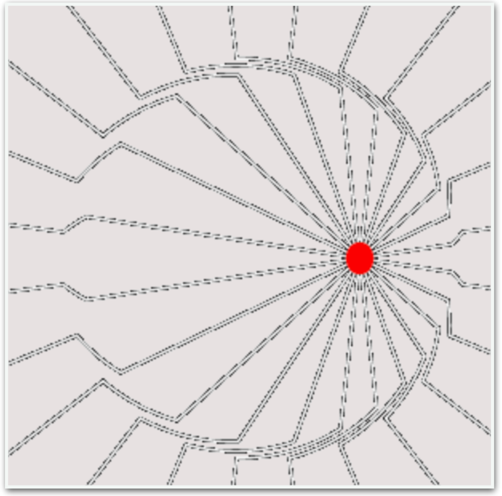
In a spin-polarized dielectric, we have: $\mathbf{J}_a = \dot{\mathbf{P}}_a = (\epsilon - 1)\,\dot{\mathbf{E}}_{\text{eff}}$

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

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

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 $\mathbf{J}_{\text{tot}} \sim \dot{\mathbf{E}}_{\text{eff}}$ even when $|\epsilon| \gg 1$!

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

Estimating the Axioelectric Current

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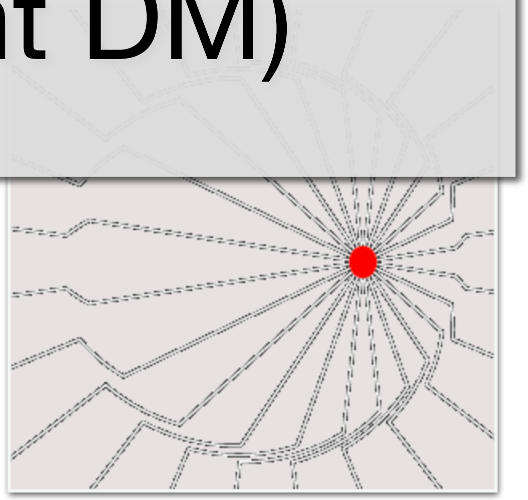
But material also creates electric field: $\cancel{\nabla \times \nabla \times \mathbf{E}} + \epsilon\ddot{\mathbf{E}} = -\dot{\mathbf{J}}_a$

Takeaway: can't just treat electrons as free.

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

Material shielding effects can be very important.
(also applies to other forms of ultralight DM)

$1 - \omega_p^2/\omega^2$ ideal superconductor



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

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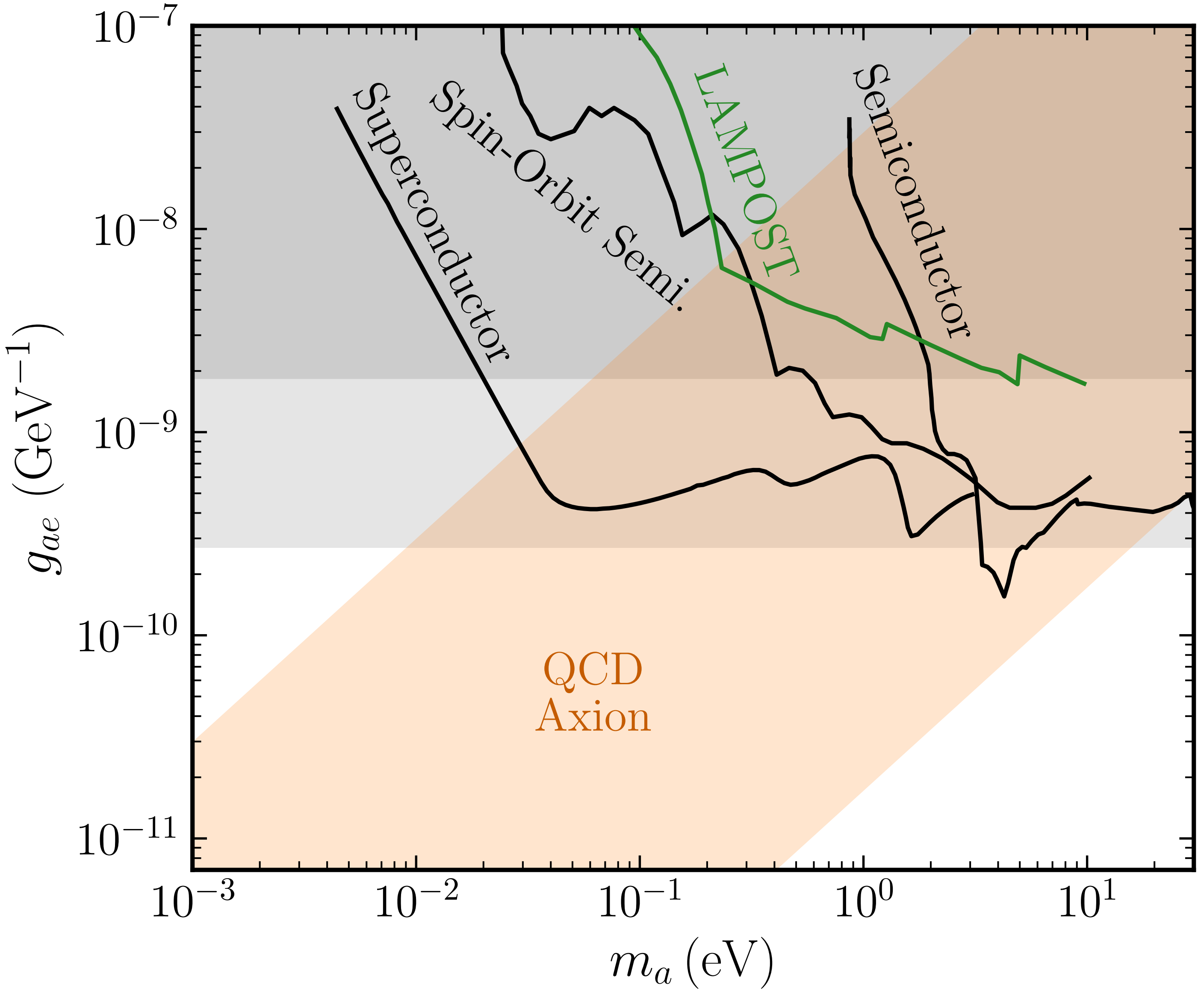
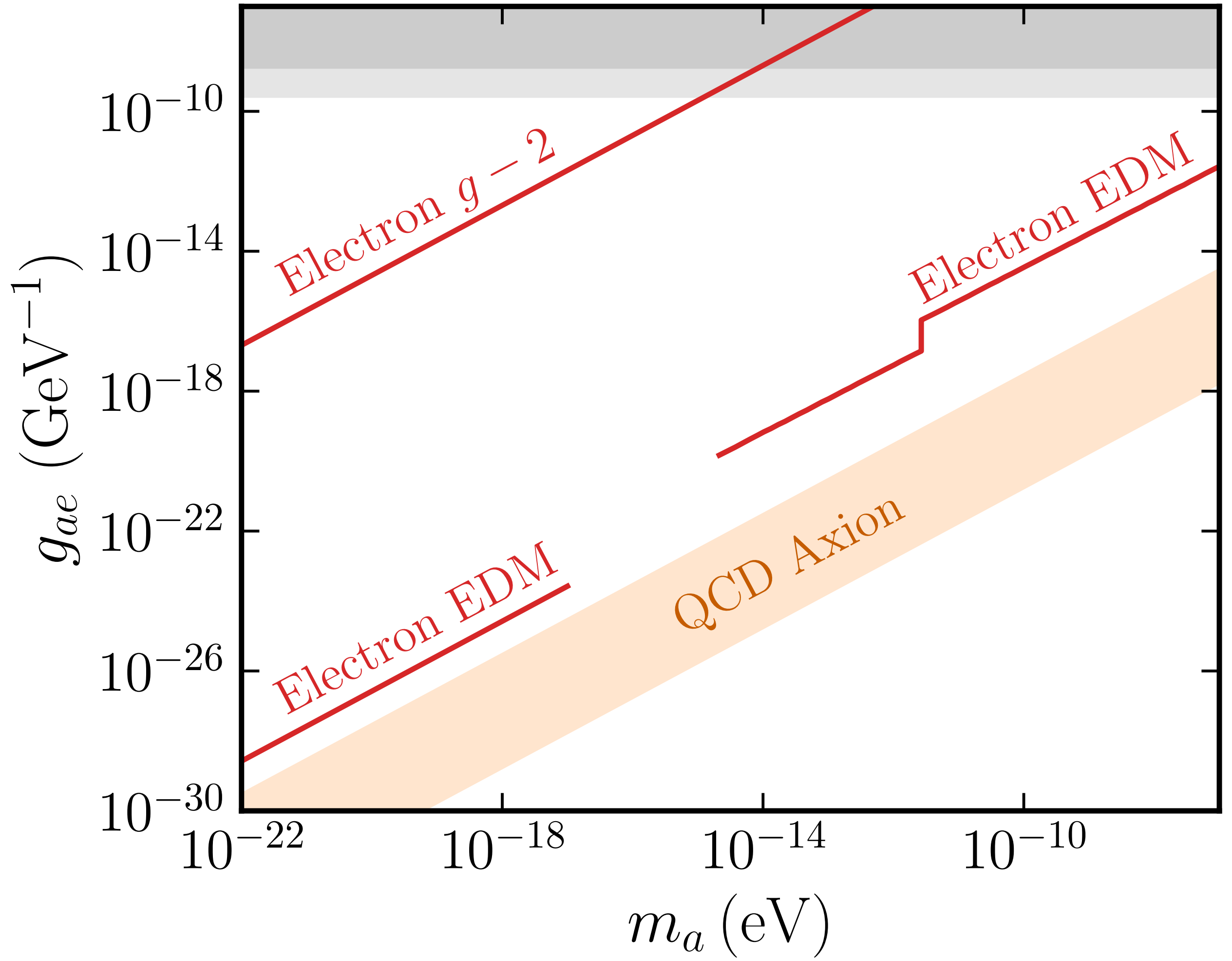
Axioelectric Reach vs. Other Projections



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

1702.01459, 1904.10543, 2102.04669, 2302.01142, 2308.16135, 2308.05375, 2410.10715, 2412.14664



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

The EDM Controversy

The axion-electron coupling has two equivalent forms

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

which have different nonrelativistic limits

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

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

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

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

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

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

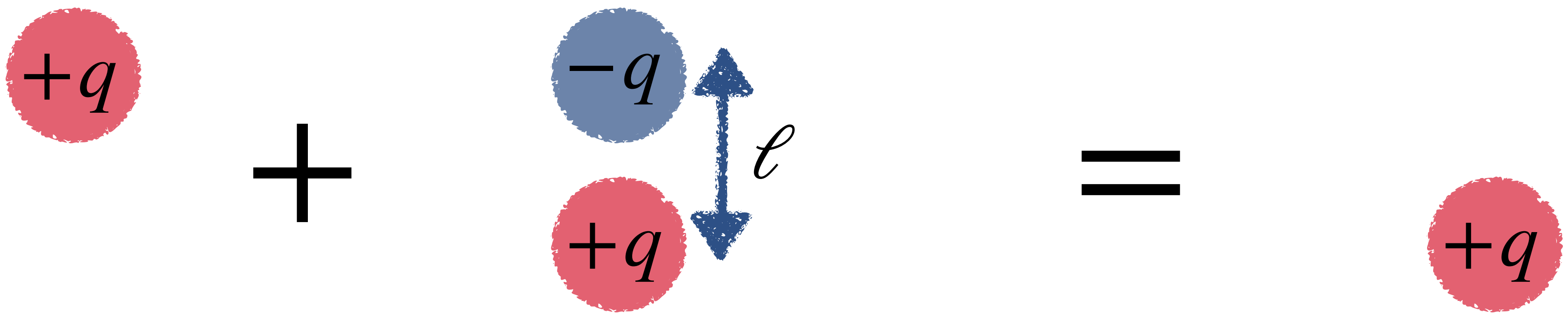
Shifting the axioelectric coefficient adds other terms with same physical effect

True and Spurious EDMs

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

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

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



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

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 $\sim (m_a/\mathrm{eV})^2$)
Stadnik and Flambaum (2014)

True and Spurious EDMs

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

Takeaway: large terms in H or $\mathscr{L}$ don't always imply large physical effects.

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

Can be artifacts of using wrong "reference frame"

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)

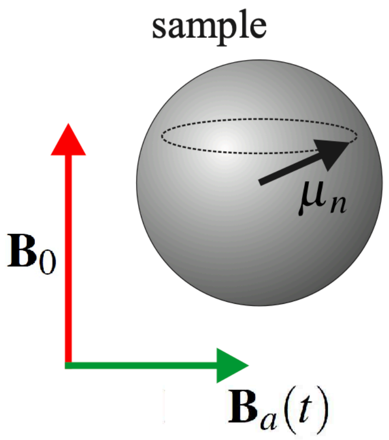
Takeaway: for derivatively coupled axion, beware of any claimed effect that persists as $m_a \to 0$

Almost always results from unphysical assumption!

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

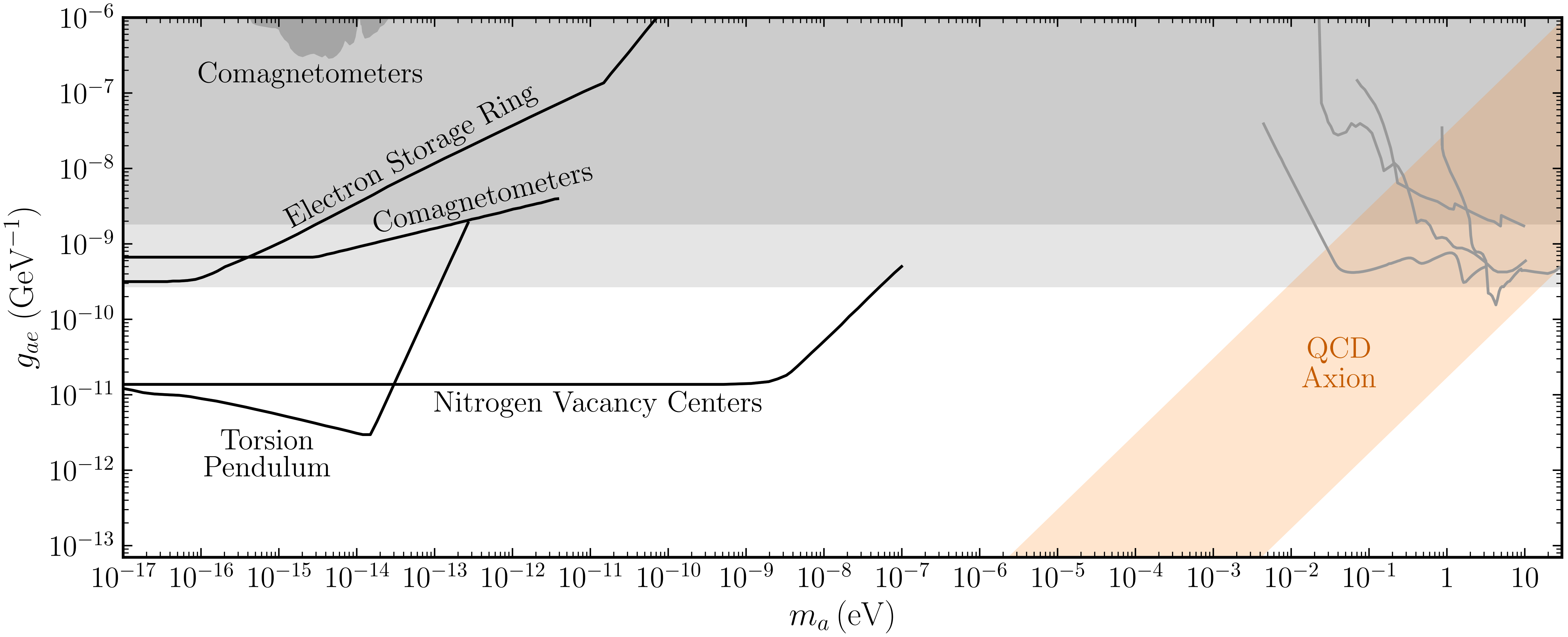
Naturally probes $m_a \sim \mathrm{meV}$ but interactions prevent very high Q

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

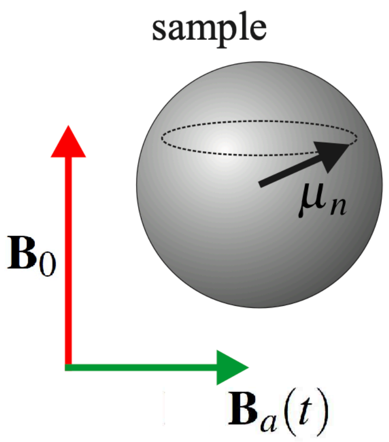


Separated electrons: comagnetometer vapor, storage ring bunch, NV centers (but much lower number density results in limited sensitivity)

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

Probing the Axion Wind Torque

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



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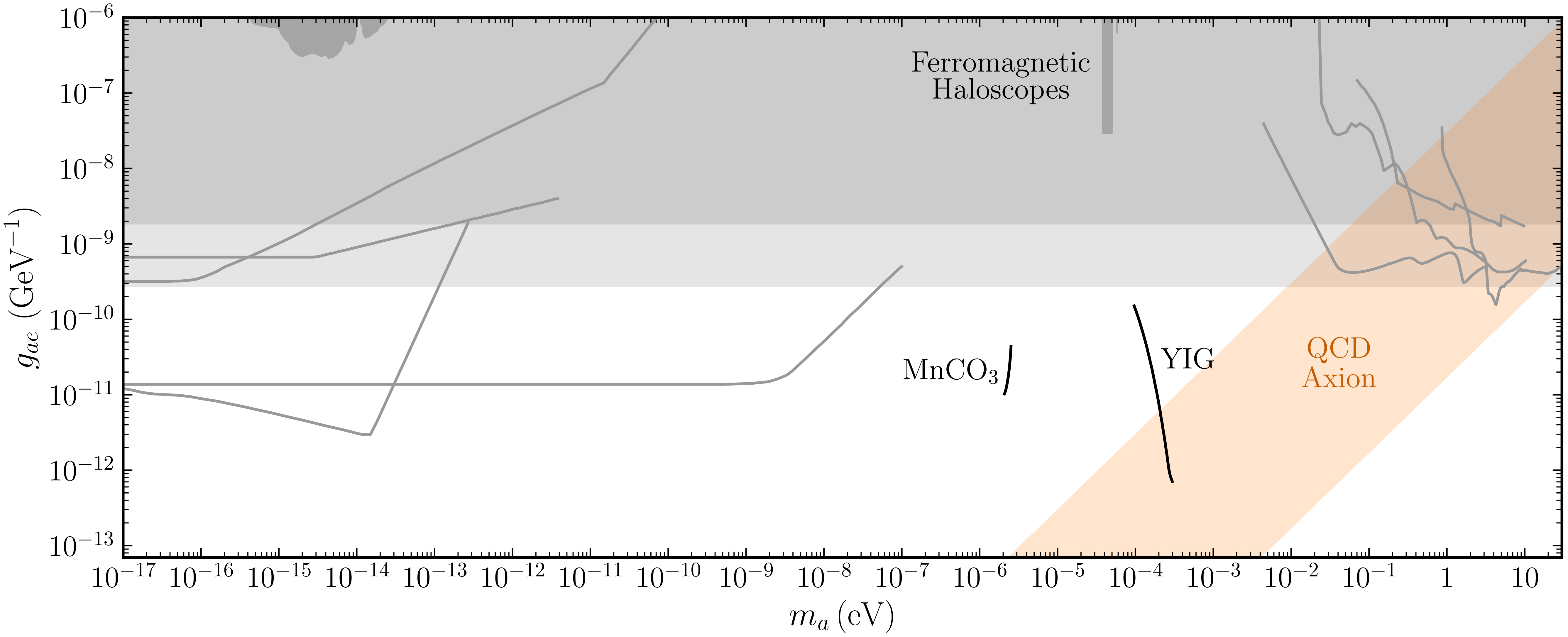
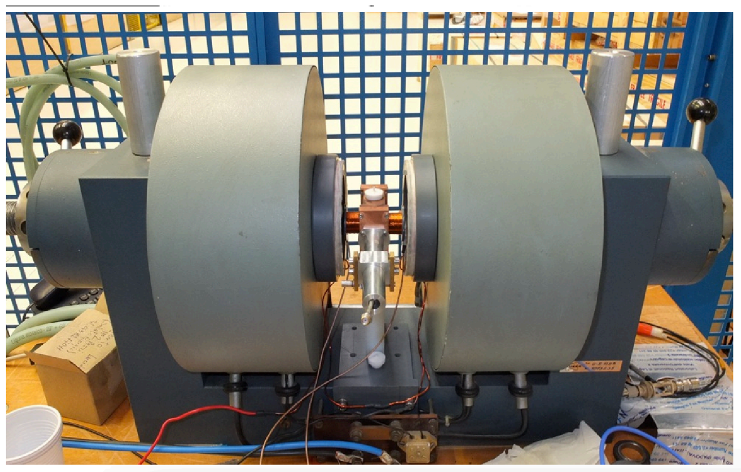
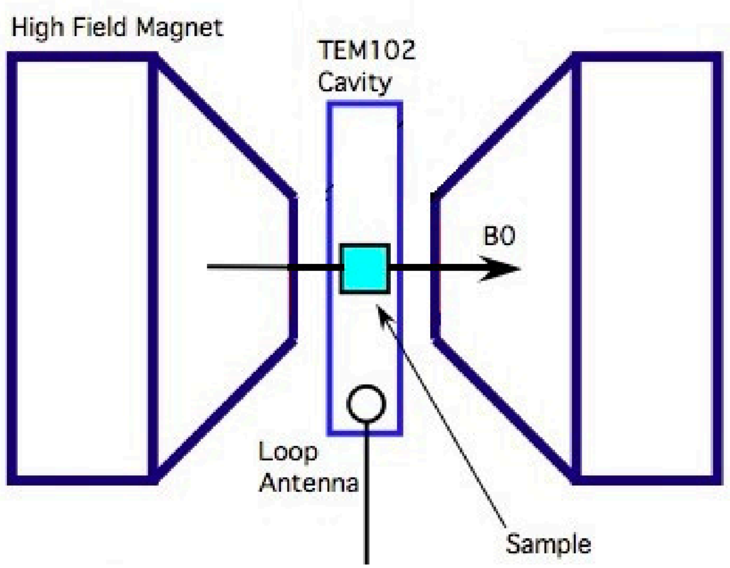




Before our work, all existing and proposed experiments used the "ferromagnetic haloscope" concept

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

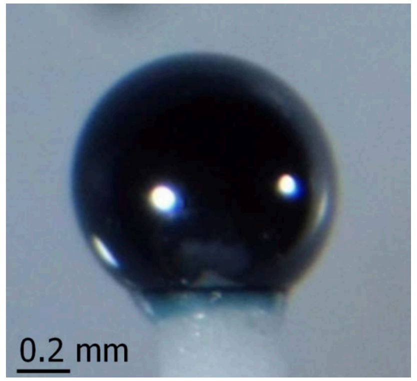
$$\mathbf{B}_{\text{eff}} = \frac{g_{ae}}{\mu_B} \nabla a$$

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

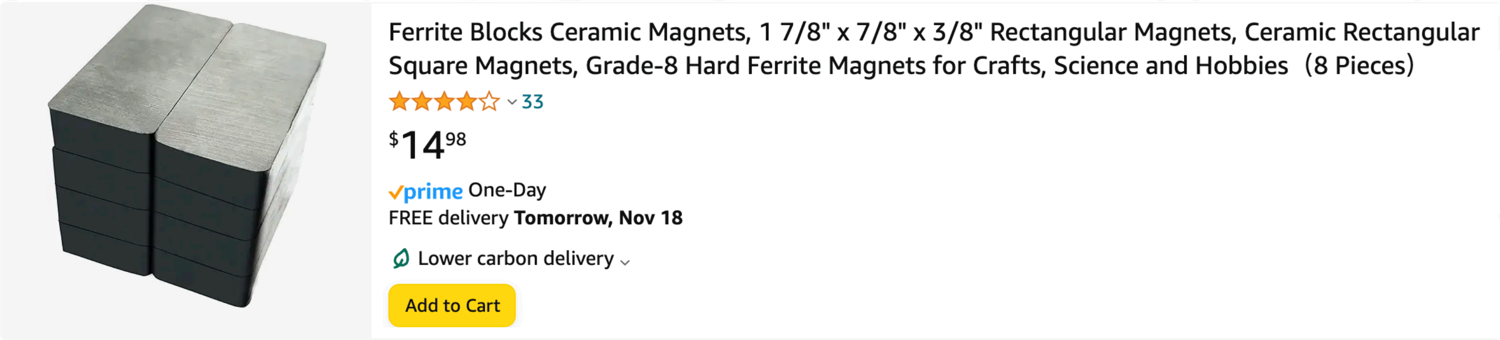
Single crystal YIG made very slowly, in mm spheres, at cost of over $\$10^7/\text{kg}$

Crescini 2017

The Ferromagnetic Haloscope

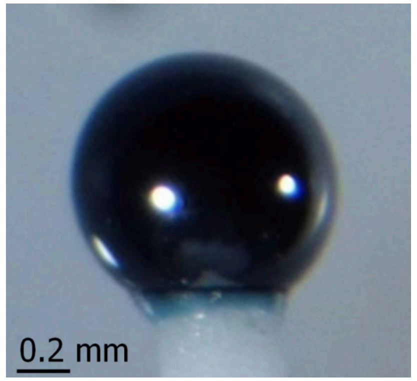
Alternative idea: replace strong resonant enhancement with overall scale

Polycrystalline spinel ferrites are cheap and mass produced



M_0 double that of YIG

$$Q_m \sim 10^2$$



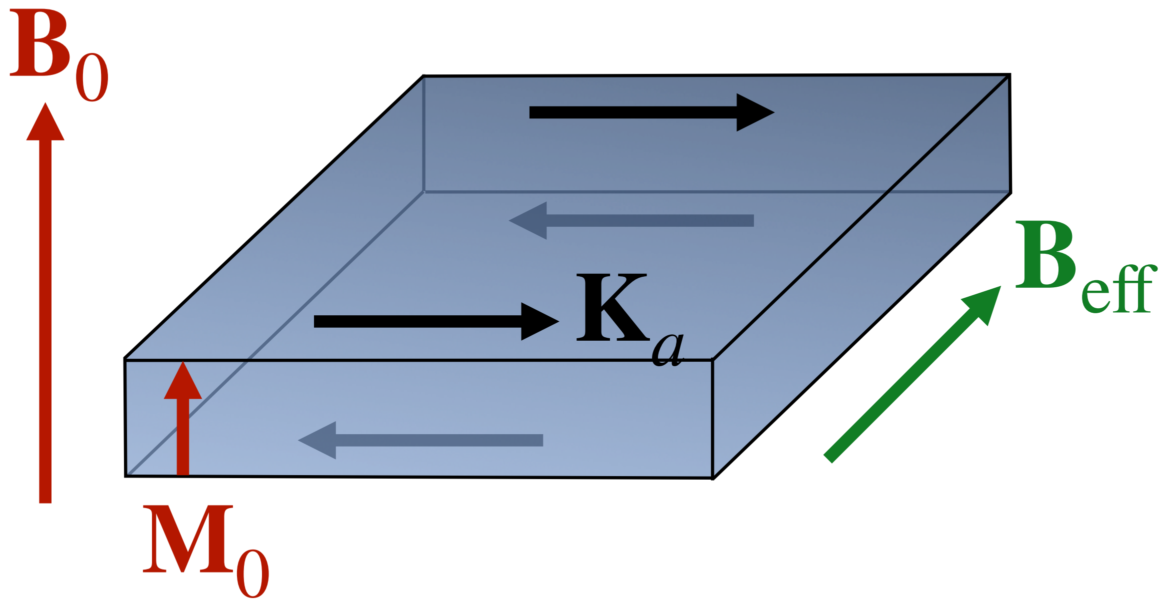
$$V \sim \begin{cases} 0.005\,\mathrm{cm}^3 & \text{QUAX (2018)} \\ 0.01\,\mathrm{cm}^3 & \text{Flower et al. (2019)} \\ 0.1\,\mathrm{cm}^3 & \text{QUAX (2020)} \\ 100\,\mathrm{cm}^3 & \text{QUAX target} \end{cases}$$

Main issue: scaling sample volume

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

Crescini 2017

Radiation From a Slab



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

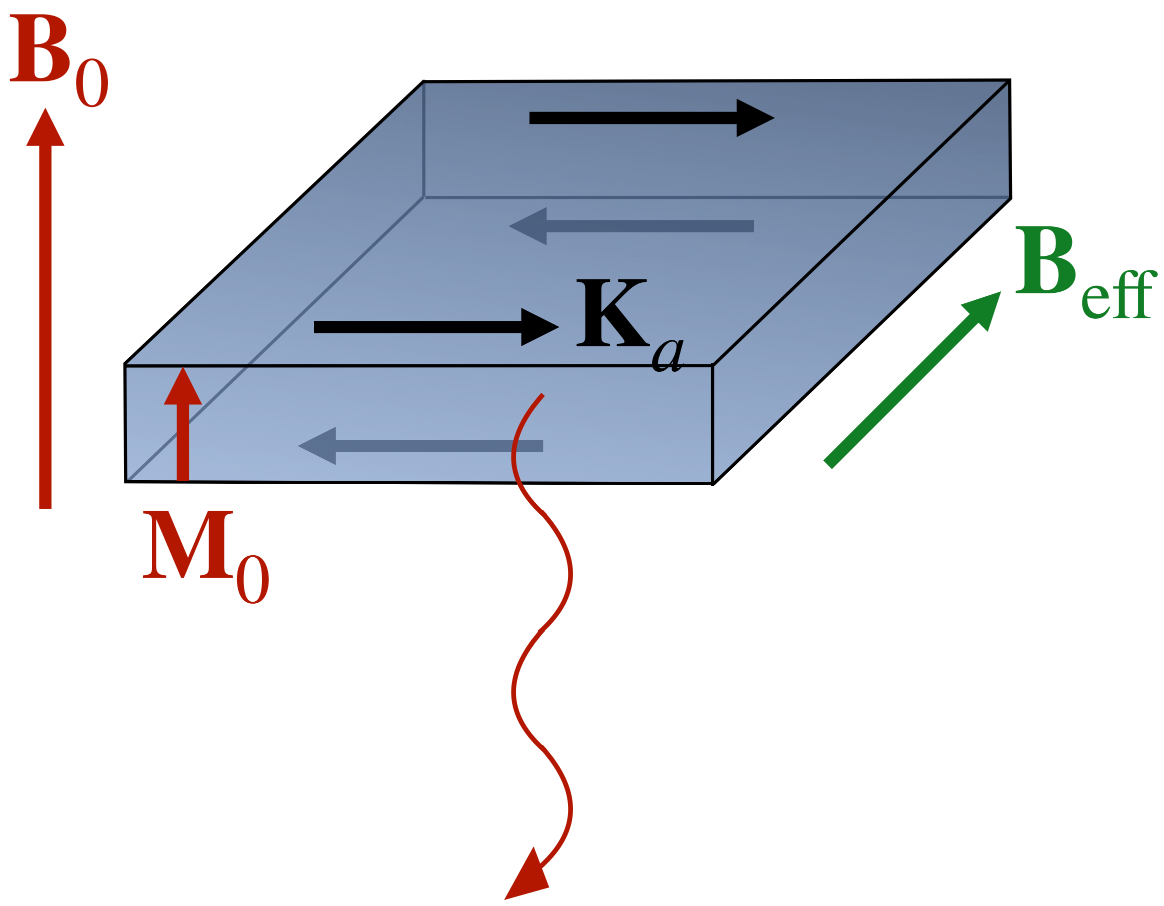
Magnetized slab carries surface currents

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

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

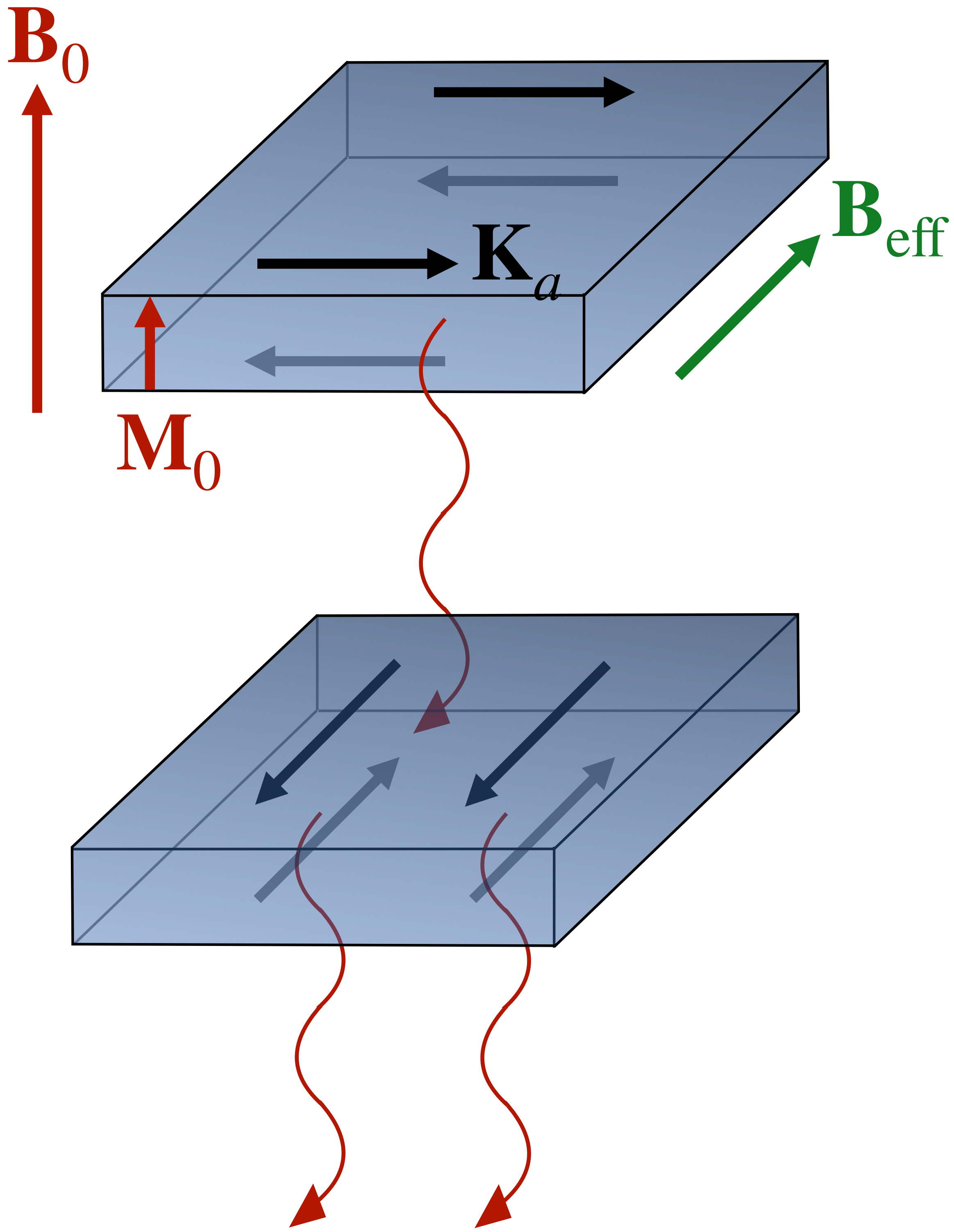
Magnetized slab carries surface currents

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

Power deposited in slab maximized on resonance, at tunable frequency

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

Radiation From a Slab



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

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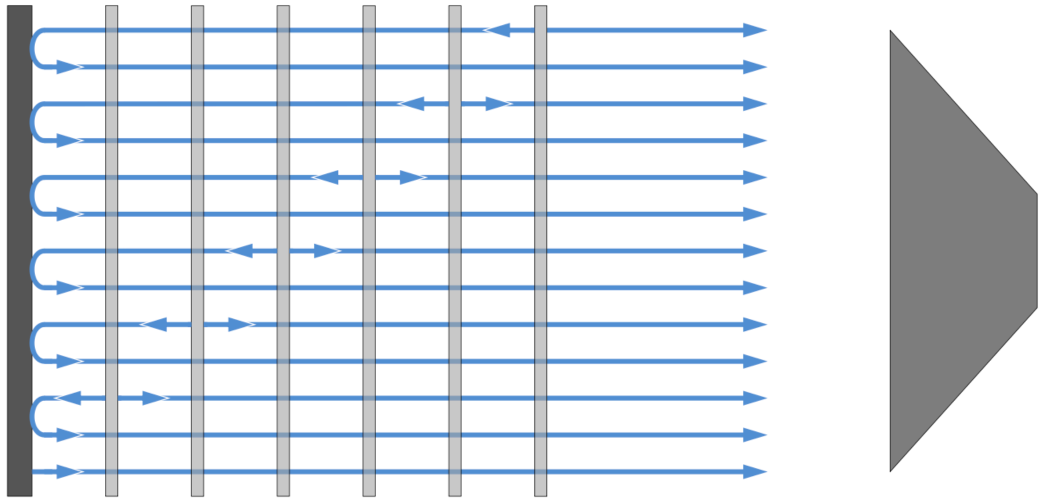
Power deposited in slab maximized on resonance, at tunable frequency

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

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

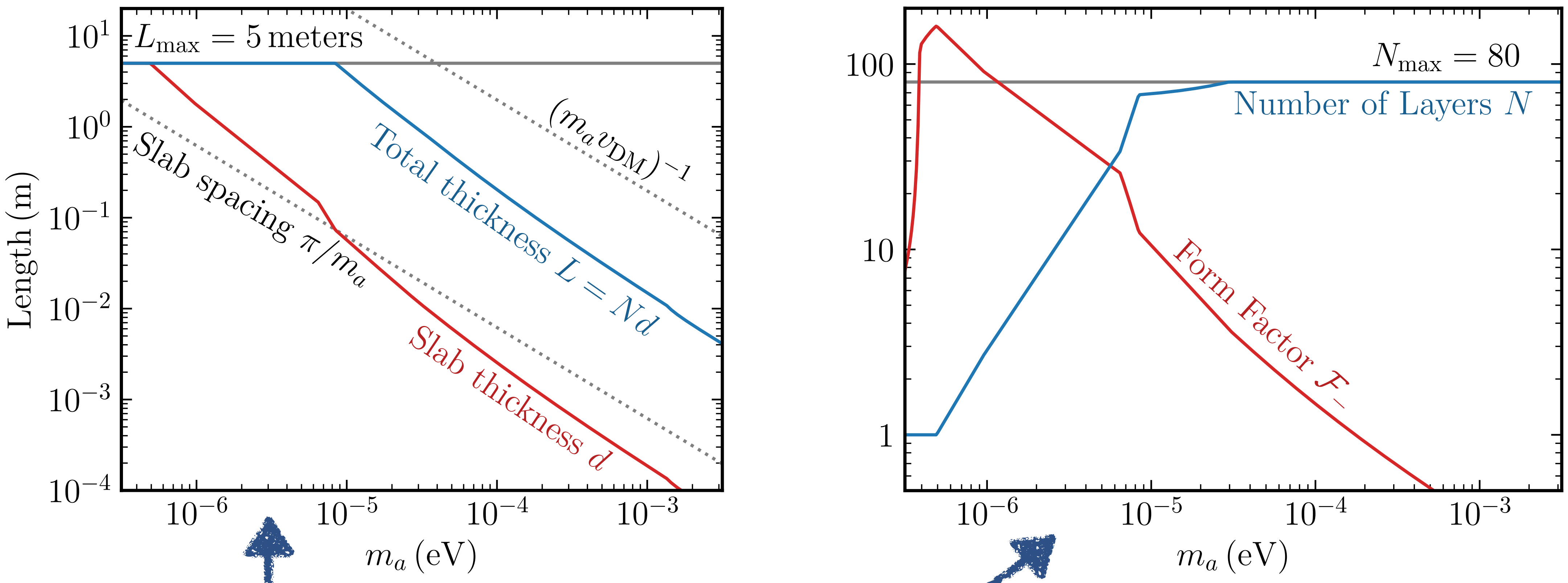
For simplicity, we consider the “transparent mode” setup:

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	slab area	number of layers
$\mathscr{F} \sim 1 - \mu^{-1}$	$A = 1\,\mathrm{m}^2$	$N \leq 80$
(+ material loss effects)		$N \leq \mathrm{Re}(n)/(\pi\,\mathrm{Im}(n))$

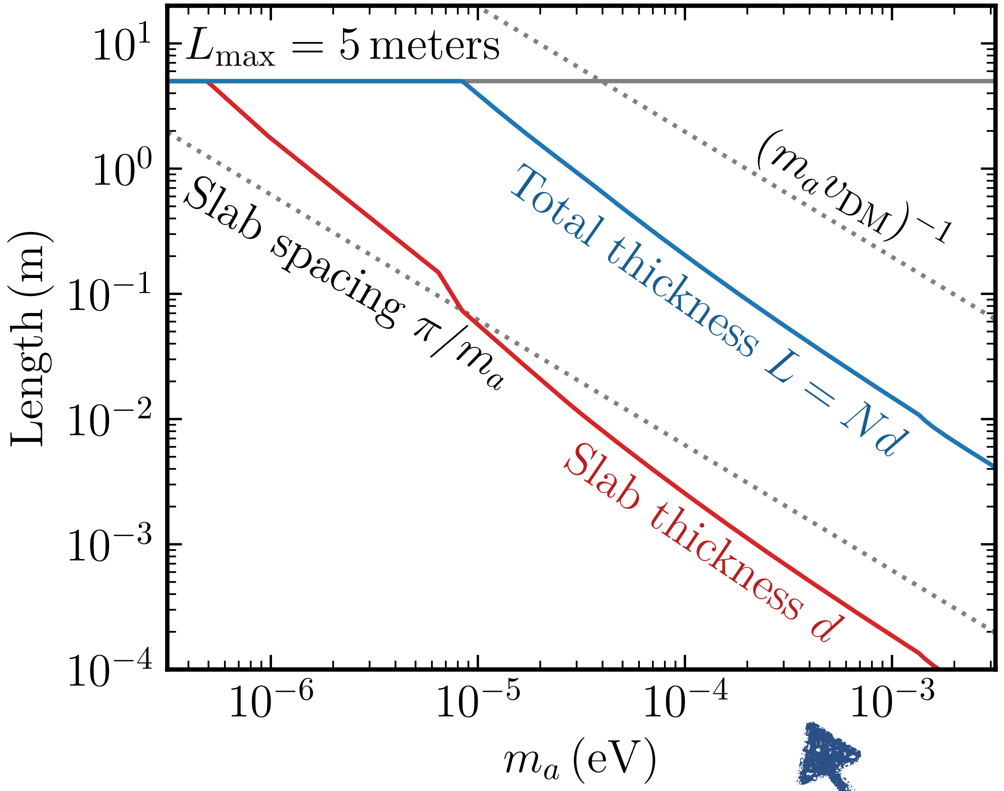
Optimizing a Magnetized Multilayer

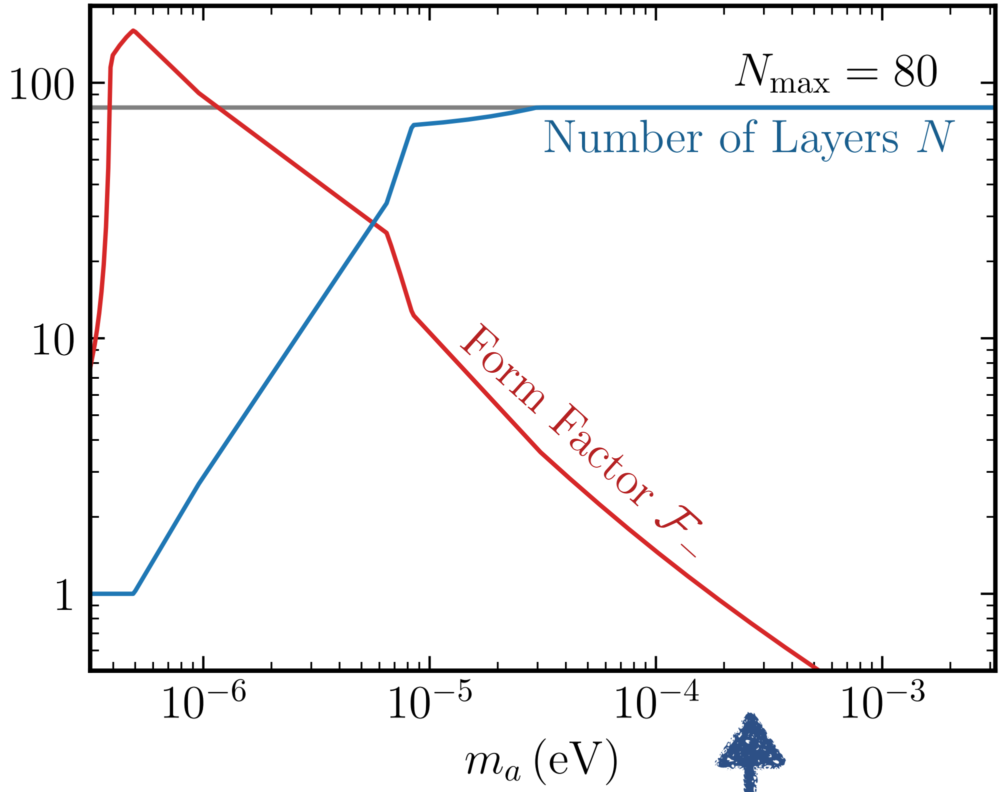


Low mass

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

Optimizing a Magnetized Multilayer





Low mass

High mass

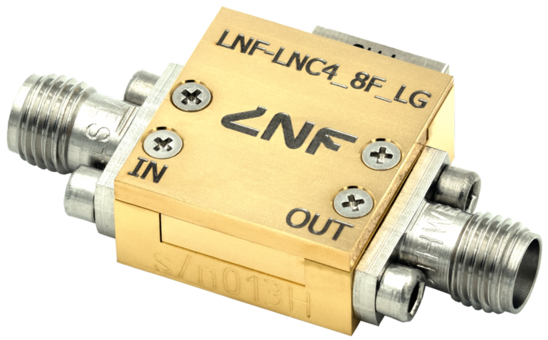
A few thick slabs tuned close to resonance; large volume needed, but only low magnetic field

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

Benchmark Reach

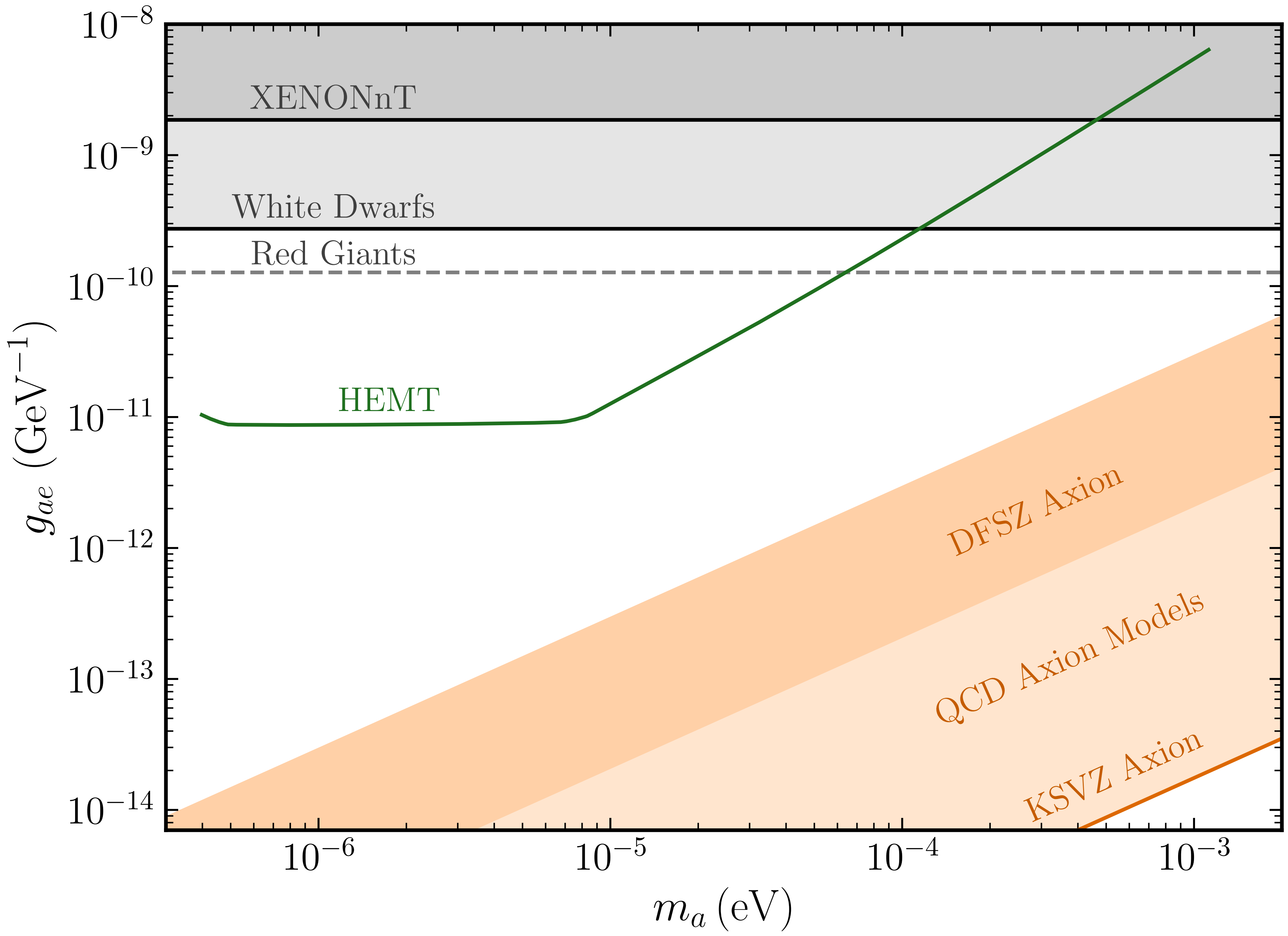
$$\mathrm{SNR} \simeq \frac{P_{\mathrm{sig}}}{T_n}\sqrt{\frac{t_{\mathrm{int}}}{\Delta\nu_a}}$$

Standard HEMT amplifier



Helium cryostat cooling

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



Benchmark Reach

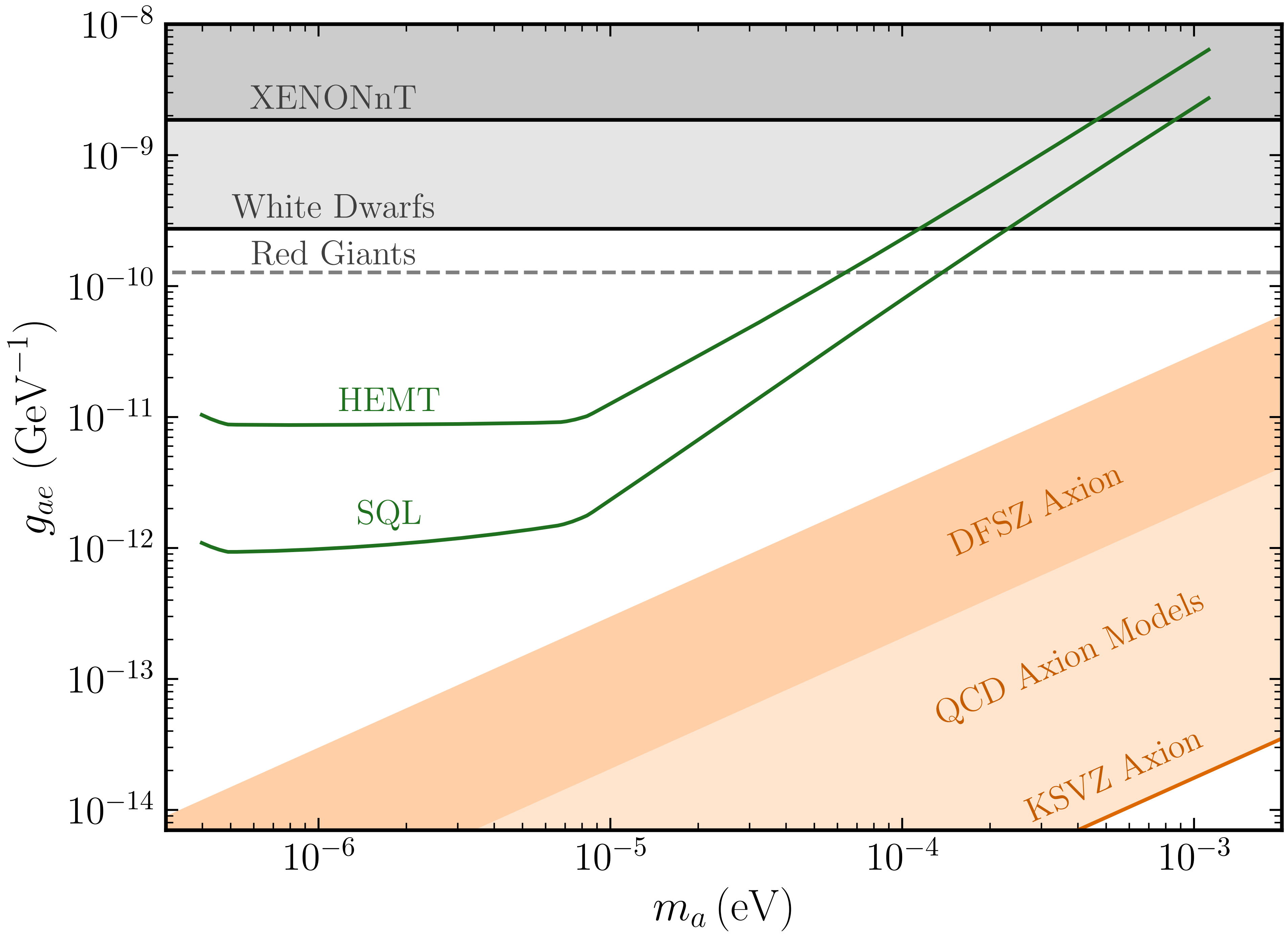
$$\mathrm{SNR} \simeq \frac{P_{\mathrm{sig}}}{T_n}\sqrt{\frac{t_{\mathrm{int}}}{\Delta\nu_a}}$$

Standard quantum limited amplification

Dilution fridge cooling

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

More challenging, but realized in several expts



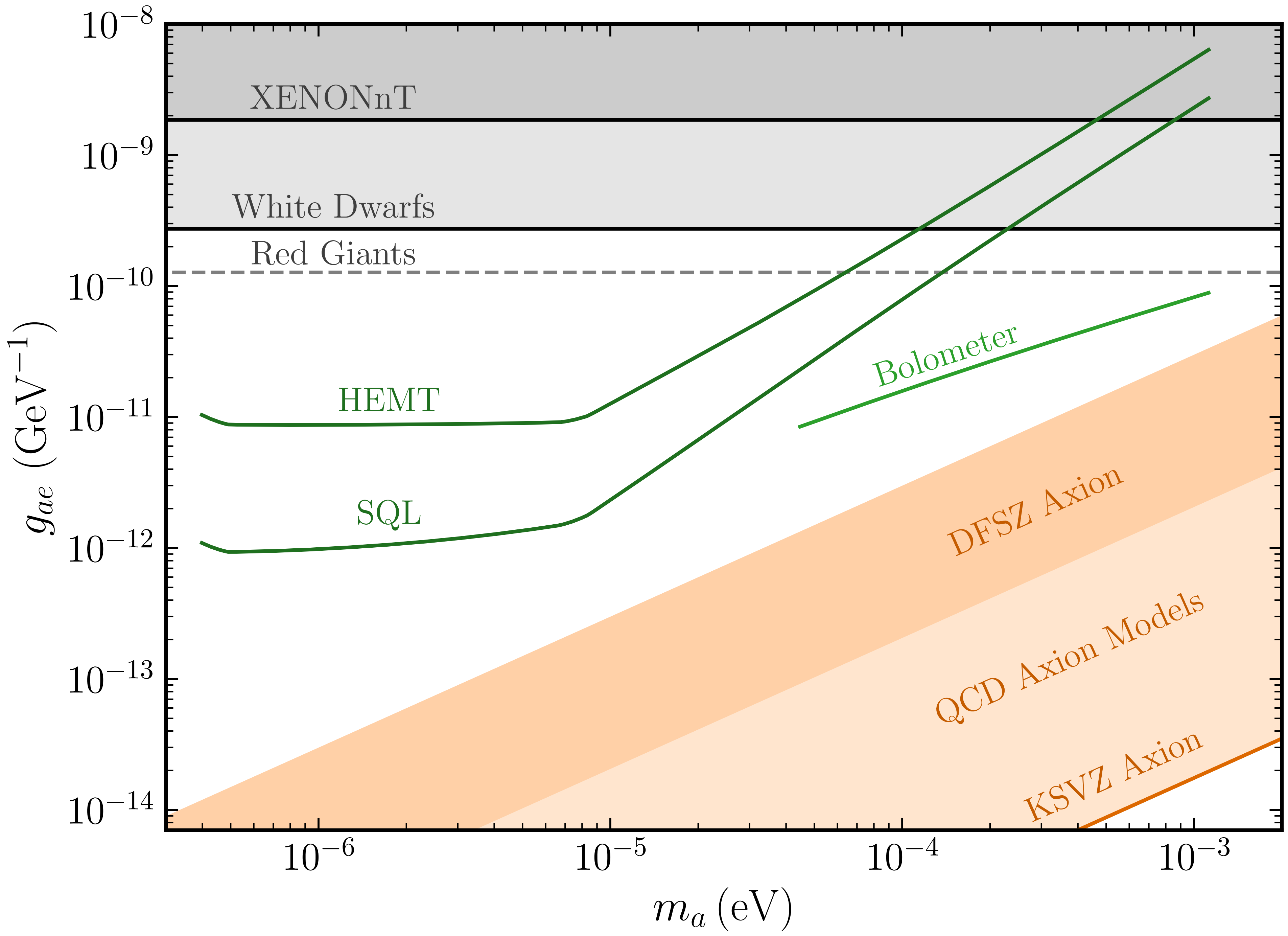
Benchmark Reach

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

Frequency insensitive bolometer

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

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



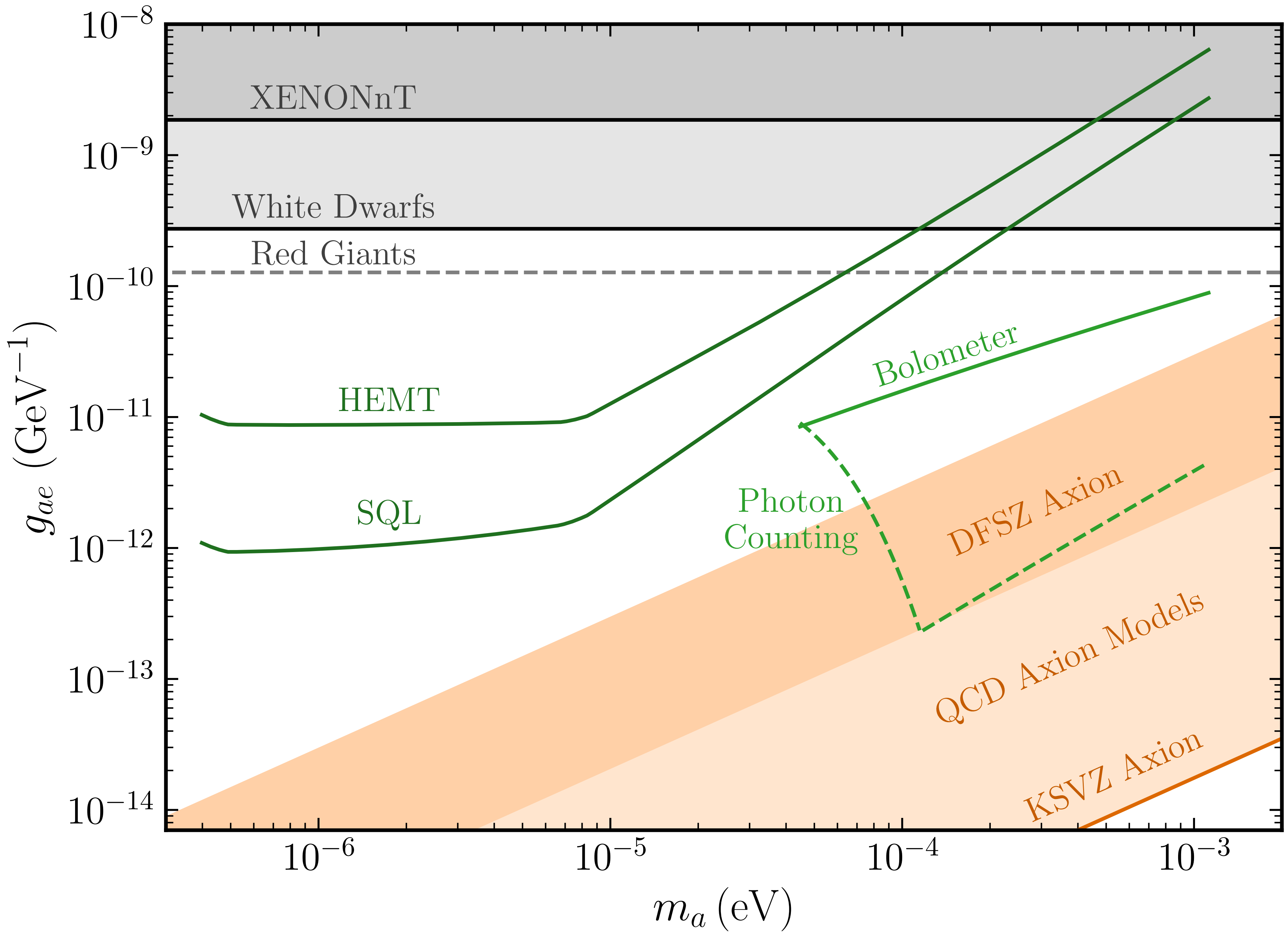
Benchmark Reach

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

Thermal limited photon counting

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

Challenging, but some prototypes at meV, with improving dark count rates



Conclusion

- The axion is minimal and generic: promising search target
- Its physical effects are simple, but can be subtle to compute
- Experiments are moving forward with proven concepts, while new ideas may allow even stronger sensitivity