The Axion-Electron Coupling: Prospects and Pitfalls

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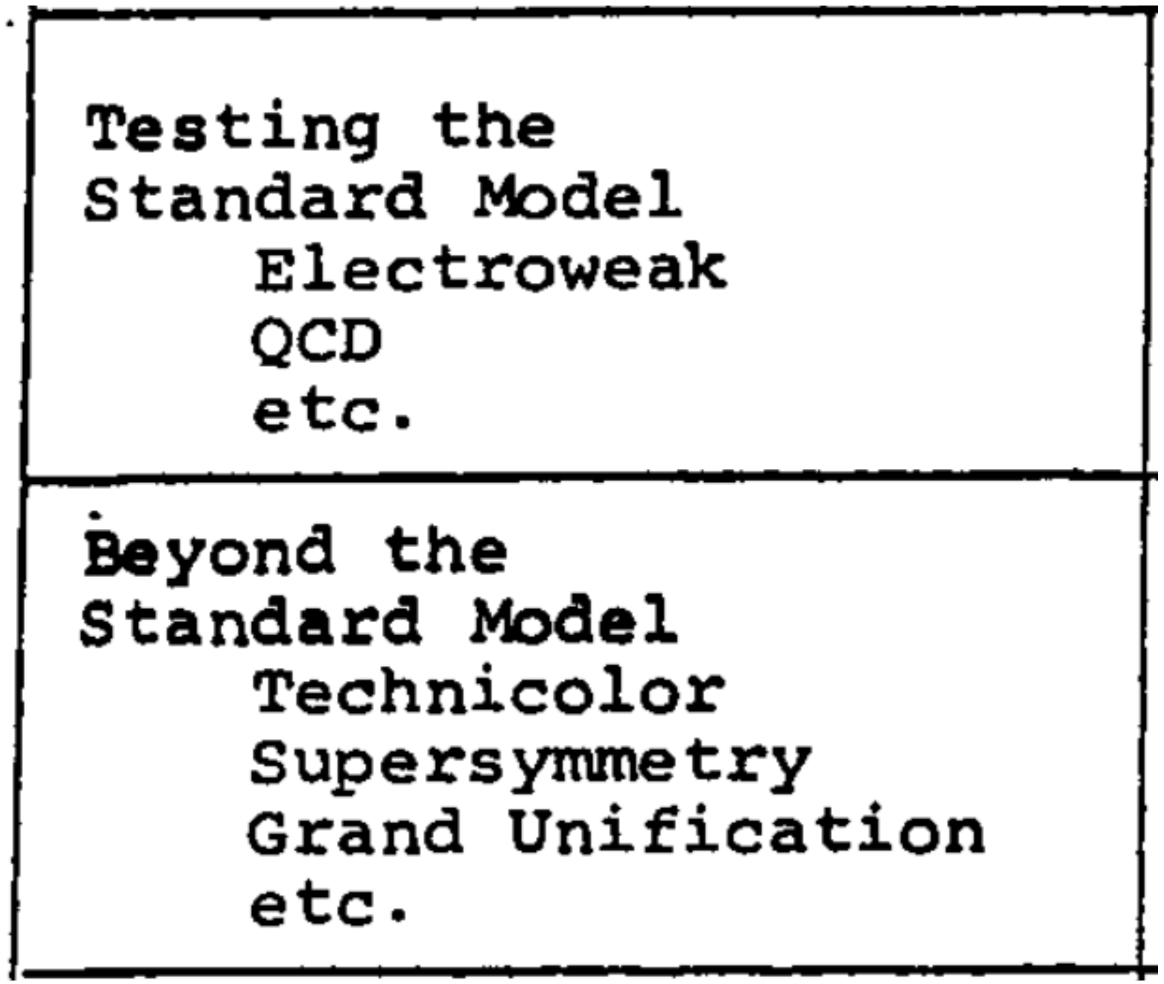
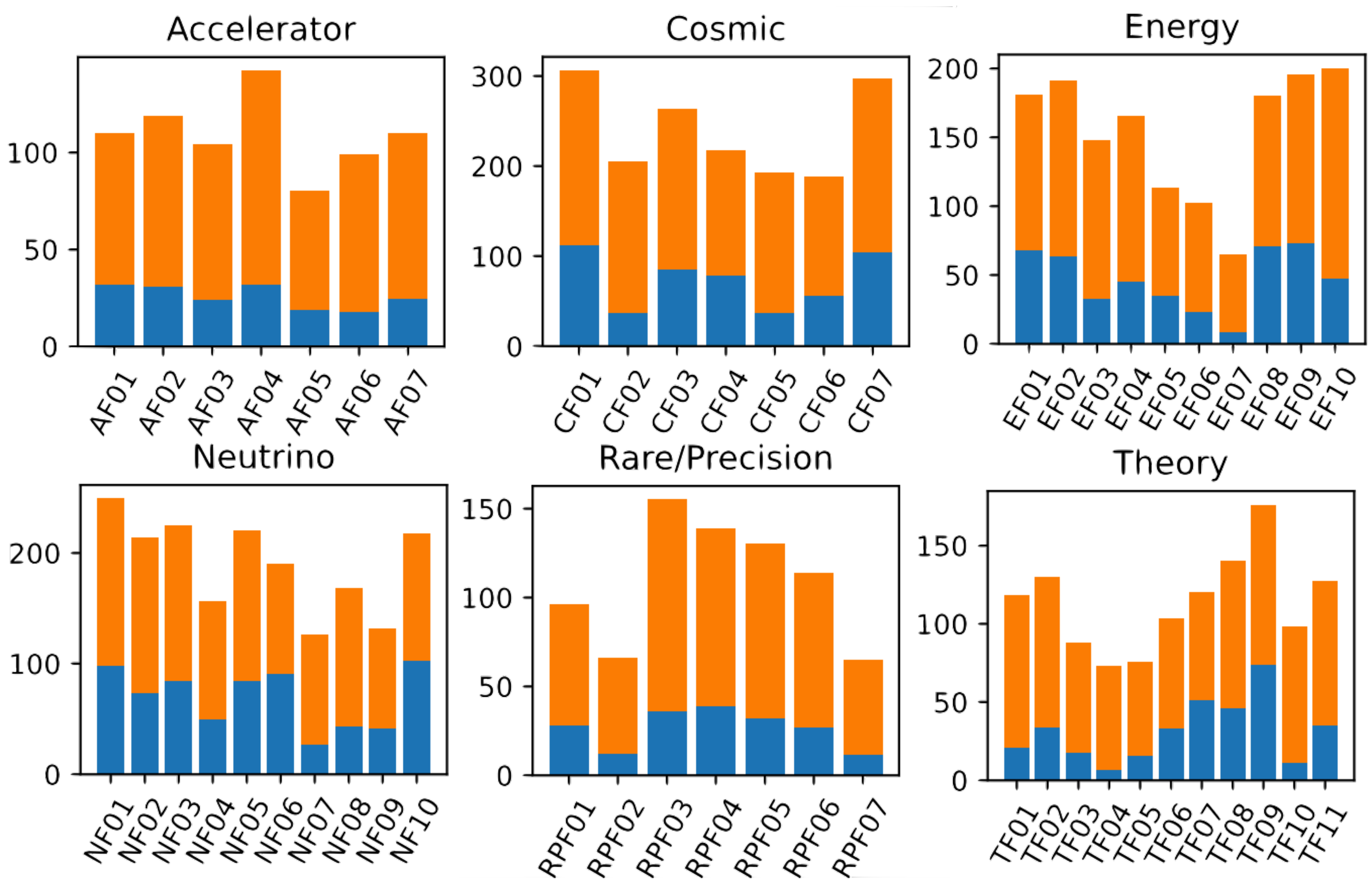
SLAC

SLAC Theory Seminar — November 17, 2023

arXiv:2311.xxxxx, with Asher Berlin, Alex Millar, Tanner Trickle


Testing the
Standard Model
Electroweak
QCD
etc.

Beyond the
Standard Model
Technicolor
Supersymmetry
Grand Unification
etc.



Snowmass 1982

Snowmass 2021

We no longer have a few canonical models to rally the community behind!

But at the same time, technology has advanced substantially…

New experimental programmes allow us to probe wide swaths of unexplored territory

high masses, short distances

known physics

model building

Previously, models of physics beyond the Standard Model valued by:

- Obeying basic principles of relativistic quantum field theory
  - Poincare symmetry, unitarity, gauge invariance…
- Providing a complete picture of reality at all scales
  - Low-energy physics is already completely understood
  - High-energy physics up to $\Lambda \sim 10^{15}\,\mathrm{GeV}$ can be guessed at once
- Having all order-one dimensionless coefficients
- Producing specific predictions at TeV energies

weak coupling

high masses, short distances

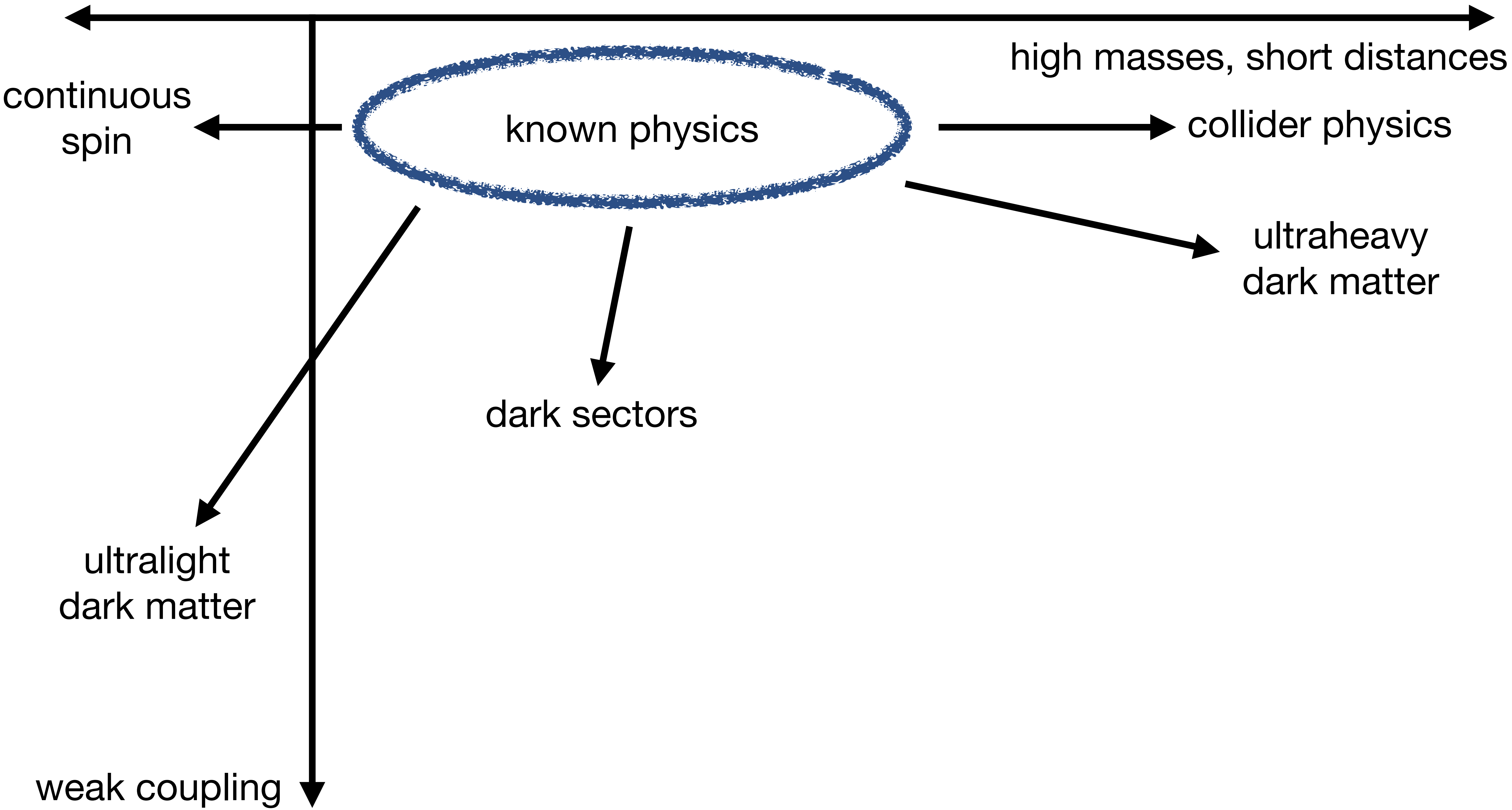
known physics

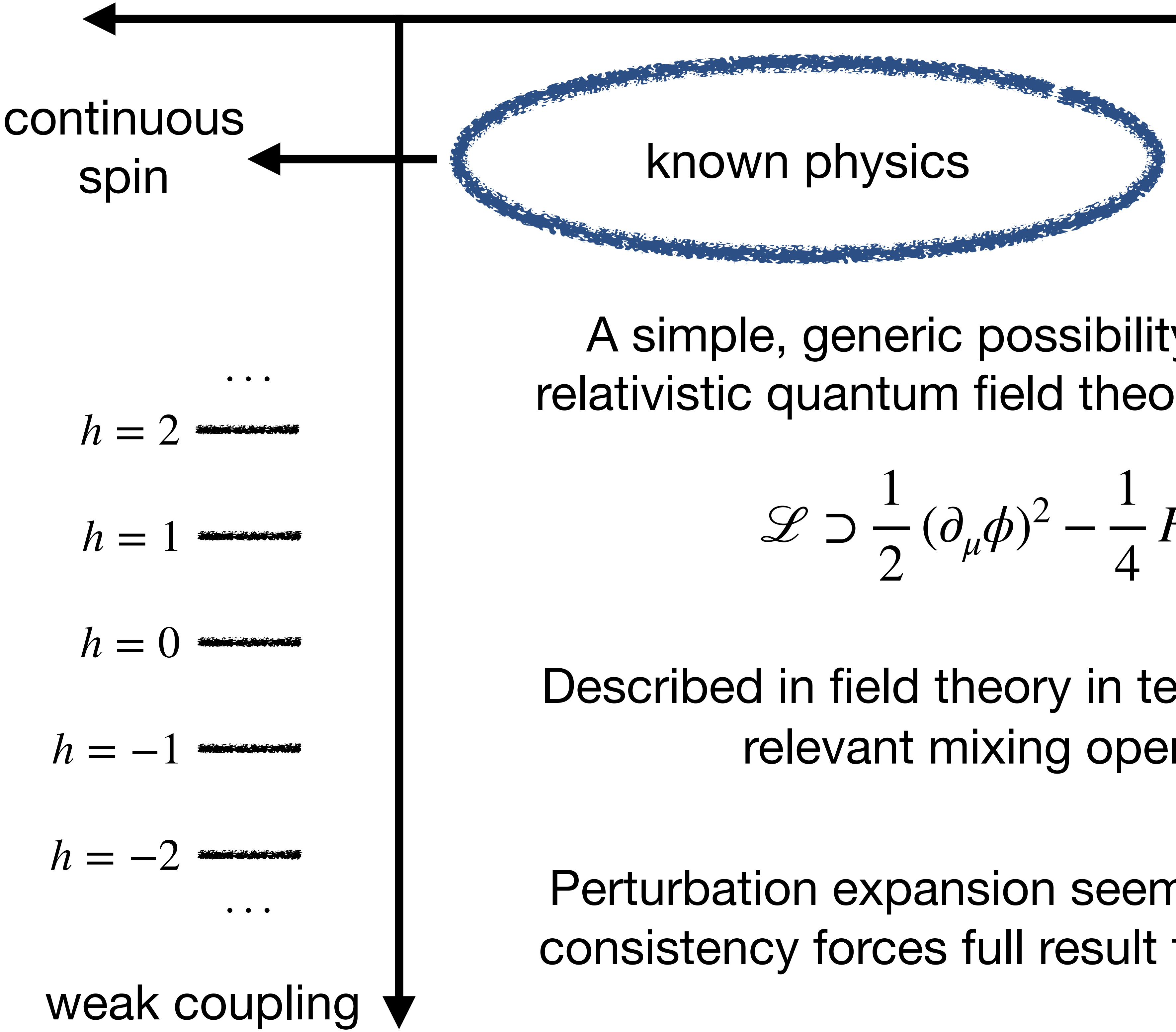
model building

A proposal as we wait for the next collider:

- Obeying basic principles of relativistic quantum field theory
  - Poincare symmetry, unitarity, gauge invariance…
- ~~Providing a complete picture of reality at all scales~~
  - ~~Low-energy physics is already completely understood~~
  - ~~High-energy physics up to $\Lambda \sim 10^{15}\,\mathrm{GeV}$ can be guessed at once~~
- Having **technically natural** values of dimensionless coefficients
- Producing **generic** predictions at **any energy scale**

weak coupling


high masses, short distances
continuous
spin
known physics
collider physics
ultraheavy
dark matter
dark sectors
ultralight
dark matter
weak coupling



A simple, generic possibility, built into the foundations of relativistic quantum field theory, but unexplored for 100 years

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{4}F^2 + \frac{\rho}{\sqrt{2}}(\phi\, \partial^\mu A_\mu) + \ldots$$

Described in field theory in terms of an infinite tower of super-relevant mixing operators, with spin scale ρ

Perturbation expansion seems divergent at $\Lambda \ll \rho$… but self-consistency forces full result to be well-behaved, defying EFT!

high masses, short distances

known physics

ultralight dark matter

weak coupling

Dark matter can be comprised of an ultralight bosonic field, but then cosmology demands it must interact very weakly

Naturally small mass and high cutoff allows only a few leading interactions in effective field theory, independent of UV model:

$$\mathscr{L} \supset \frac{\partial_\mu a}{\Lambda} J^\mu_{\mathrm{SM}}$$	$$\mathscr{L} \supset A'_\mu J^\mu_{\mathrm{SM}}$$
pseudoscalar coupled to CP-odd SM current	vector coupled to CP-even SM current
“axion”	“dark photon”

At low energies, only a small number of axion couplings exist!

$$\mathscr{L} \supset \frac{\partial_\mu a}{\Lambda} K^\mu_{\mathrm{U}(1)_\gamma}$$

axion-photon

$$\mathscr{L} \supset \frac{\partial_\mu a}{\Lambda} K^\mu_{\mathrm{SU}(3)_c}$$

axion-gluon

$$\mathscr{L} \supset \frac{\partial_\mu a}{\Lambda} \bar{\Psi}\gamma^\mu\gamma^5\Psi$$

axion-fermion

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$$\boxed{\mathscr{L} \supset \frac{\partial_\mu a}{\Lambda} K^\mu_{\mathrm{U}(1)_\gamma}}$$

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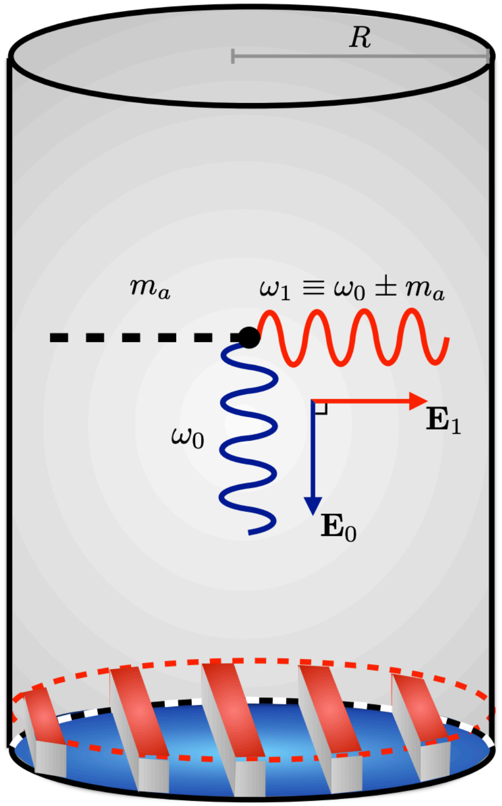

Induces transitions between modes in electromagnetic cavity

Most effective in superconducting cavities developed for accelerators

Three prototypes under construction, including one here

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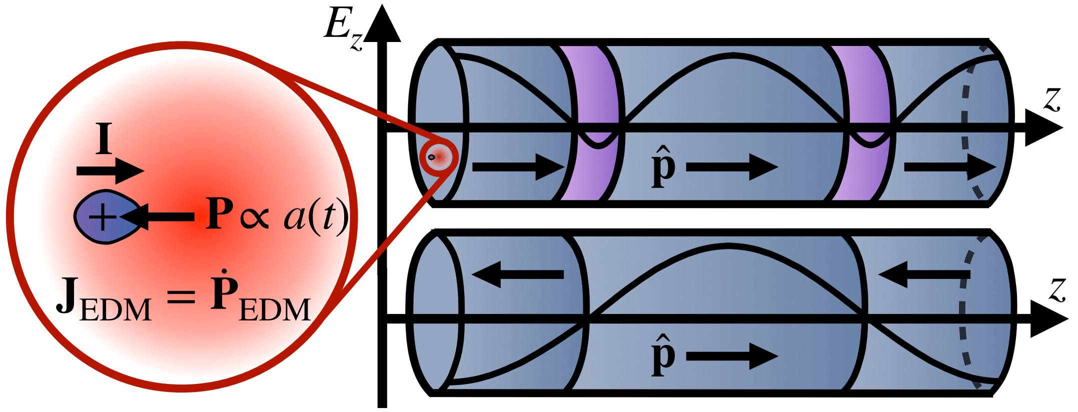

Relaxes vacuum neutron EDM to zero, so axion dark matter produces oscillating EDMs

Corresponds to observable current, but **only** for hyperpolarized samples of quadrupole or octupole deformed nuclei

Needs dedicated experiment with nuclear/atomic physics techniques

At low energies, only a small number of axion couplings exist!

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$$\boxed{\mathscr{L} \supset \frac{\partial_\mu a}{\Lambda} \bar{\Psi}\gamma^\mu\gamma^5\Psi}$$

axion-fermion

Causes spin precession, visible in magnetometers or NMR setups

More general signatures unexplored, and theory situation very unclear
(easy to accidentally derive large parametric enhancements)

$$\mathscr{L} \supset \frac{1}{4}\frac{a}{\Lambda} F\tilde{F}$$

$$\mathscr{L} \supset \frac{1}{4}\frac{a}{\Lambda} G\tilde{G}$$

$$\mathscr{L} \supset \frac{2ma}{\Lambda} \bar{\Psi}i\gamma^5\Psi$$

(common issue in axion physics, arises because of equivalent nonderivative forms)

Outline

- **The axion-fermion coupling**
- Pitfalls: EDMs and energy levels
- Prospects: magnetized multilayers

Understanding the Coupling

The axion-fermion coupling is to fermion's axial vector current: $\mathscr{L} \supset g\,(\partial_\mu a)\,\bar{\Psi}\gamma^\mu\gamma^5\Psi$

It weights the vector current (number density) by γ^5, so it tracks helicity density

To see explicitly, note that in nonrelativistic limit with Dirac gamma matrices:

$$\Psi = e^{-imt}\begin{pmatrix}\psi \\ \bar{\psi}\end{pmatrix} \qquad \bar{\psi} \simeq \frac{(\mathbf{p} - q\mathbf{A})\cdot\sigma}{2m}\,\psi \qquad \bar{\Psi}\gamma^\mu\gamma^5\Psi \simeq \psi^\dagger(\mathbf{v}\cdot\sigma, \sigma)^\mu\,\psi \to (\mathbf{v}\cdot\hat{\mathbf{s}}, \hat{\mathbf{s}})\,\delta^{(3)}(\mathbf{x} - \mathbf{x}_0)$$

The axial vector current of a single nonrelativistic particle is its spin four-vector, so

$$L \supset g\,(\nabla a)\cdot\hat{\mathbf{s}} + g\,\dot{a}\,\mathbf{v}\cdot\hat{\mathbf{s}}$$

where $\hat{\mathbf{s}} = \langle\sigma\rangle$ is classical spin orientation

Understanding the Coupling

$$L \supset g\,(\nabla a)\cdot \hat{\mathbf{s}} + g\,\dot{a}\,\mathbf{v}\cdot\hat{\mathbf{s}}$$

To switch to Hamiltonian, Legendre transform with conjugate momentum:

$$\mathbf{p} = \partial L/\partial \mathbf{v} = m\mathbf{v} + q\mathbf{A} + g\dot{a}\boldsymbol{\sigma}$$

$$H = \mathbf{v}\cdot\mathbf{p} - L \supset -\,g\,(\nabla a)\cdot\boldsymbol{\sigma} - \frac{g}{m}\,\dot{a}\,\boldsymbol{\sigma}\cdot(\mathbf{p} - q\mathbf{A})$$

“axion wind” “axioelectric”

Same result follows more rigorously from writing equation of motion as $i\partial_t\psi = H\psi$

Torques and Forces

$$\mathbf{p} = m\mathbf{v} + q\mathbf{A} + g\dot{a}\sigma \qquad\qquad H \supset -g\,(\nabla a)\cdot\sigma - \frac{g}{m}\,\dot{a}\,\sigma\cdot(\mathbf{p} - q\mathbf{A})$$

Next, compute physical effects with Hamilton/Heisenberg equations of motion:

$$\frac{d\hat{\mathbf{s}}}{dt} = \frac{q}{m}\,\hat{\mathbf{s}} \times \left(\mathbf{B} + \mathbf{B}_{\text{eff}}\right) \qquad\qquad q\mathbf{B}_{\text{eff}} = 2mg\,(\nabla a + \dot{a}\,\mathbf{v})$$

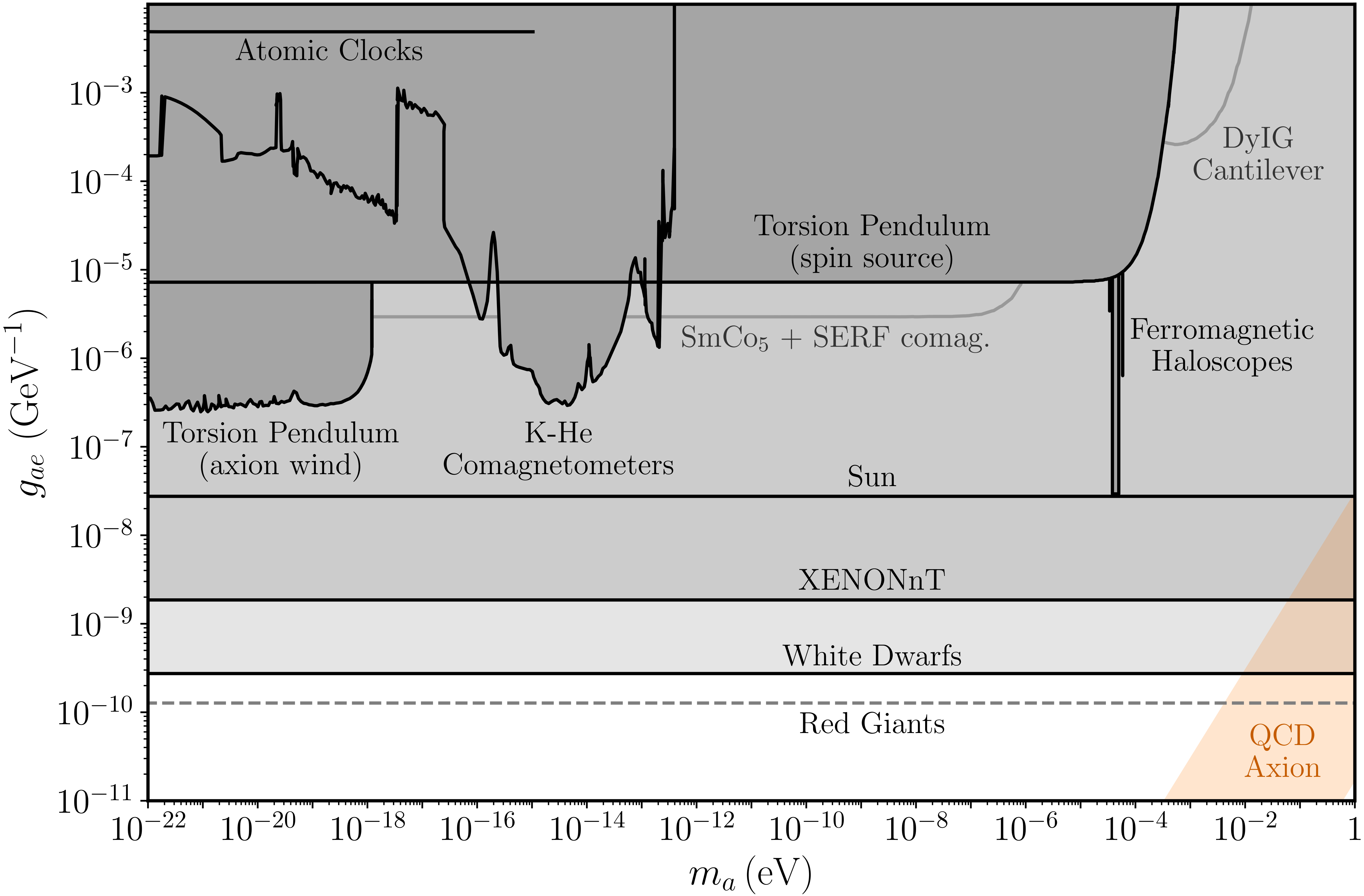
The axion wind term applies a torque to spins, along axion gradient

$$m\frac{d\mathbf{v}}{dt} = (\text{Lorentz}) + q\mathbf{E}_{\text{eff}} \qquad\qquad q\mathbf{E}_{\text{eff}} = -g\,\frac{d}{dt}(\dot{a}\,\hat{\mathbf{s}}) + (\text{subleading})$$

The axioelectric term applies a force parallel to spins

Experimental Signatures

	axion wind	axioelectric
	$q\mathbf{B}_{\text{eff}} = 2mg\,\nabla a$	$q\mathbf{E}_{\text{eff}} = -g\,\dfrac{d}{dt}(\dot{a}\,\hat{\mathbf{s}})$
mechanical $m_a \lesssim 10^{-9}\,\text{eV} \sim \text{MHz}$	torque on spin-polarized object	force on spin-polarized object?
electromagnetic $m_a \lesssim 10^{-3}\,\text{eV} \sim \text{THz}$	spin precession: NMR / FMR / clocks / ?	excites currents? shifts energy levels?
absorption $m_a \gtrsim 10^{-3}\,\text{eV}$	atomic spin flip transitions magnons	ionize atoms phonons electronic excitations?


Atomic Clocks
Torsion Pendulum
(spin source)
DyIG
Cantilever
SmCo$_5$ + SERF comag.
Ferromagnetic
Haloscopes
Torsion Pendulum
(axion wind)
K-He
Comagnetometers
Sun
XENONnT
White Dwarfs
Red Giants
QCD
Axion
g_{ae} (GeV^{-1})
m_a (eV)
10^{-3}
10^{-4}
10^{-5}
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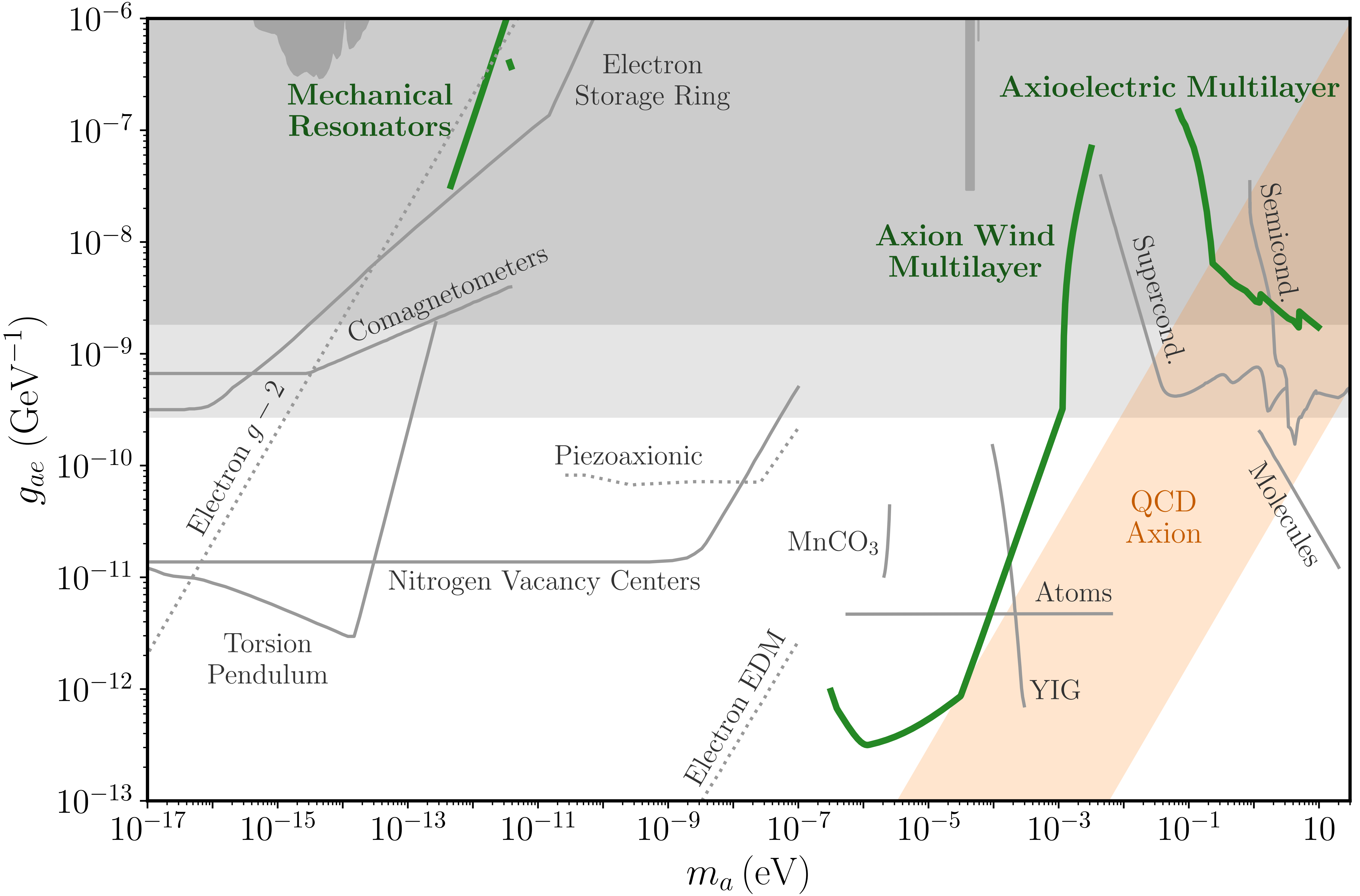
Mechanical Resonators
Electron Storage Ring
Axioelectric Multilayer
Axion Wind Multilayer
Comagnetometers
Supercond.
Semicond.
Electron $g-2$
Piezoaxionic
MnCO$_3$
QCD Axion
Molecules
Nitrogen Vacancy Centers
Atoms
Torsion Pendulum
Electron EDM
YIG
g_{ae} (GeV^{-1})
m_a (eV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
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10^{-12}
10^{-13}
10^{-17}
10^{-15}
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10

Axioelectric Mechanical Effects

$$q\mathbf{B}_{\text{eff}} = 2mg\,\nabla a \qquad\qquad q\mathbf{E}_{\text{eff}} = -g\,\frac{d}{dt}(\dot{a}\,\hat{\mathbf{s}})$$

Compare linear accelerations in spin-polarized object (length L, atoms of mass M)

$$a_{\text{wind}} \sim \frac{\tau L}{I} \sim \frac{(g\,\nabla a)\,L}{ML^2} \qquad\qquad a_{\text{axio-el}} \sim \frac{F}{M} \sim \frac{g\,\ddot{a}}{M}$$

For dark matter axions and precision oscillators, the axioelectric effect is subleading:

$$\frac{a_{\text{axio-el}}}{a_{\text{wind}}} \sim \frac{\ddot{a}}{\nabla a/L} \sim \frac{m_a^2}{m_a v_{\text{DM}}/L} \sim \frac{m_a L}{v_{\text{DM}}} \sim \begin{cases} 10^{-3}\,\frac{L}{1\,\text{m}}\frac{m_a}{1\,\text{kHz}} & \text{in general} \\ c_s\,/\,v_{\text{DM}} & \text{acoustic modes} \end{cases}$$

In addition, signal is not enhanced by L, as for dilatons and gravitational waves

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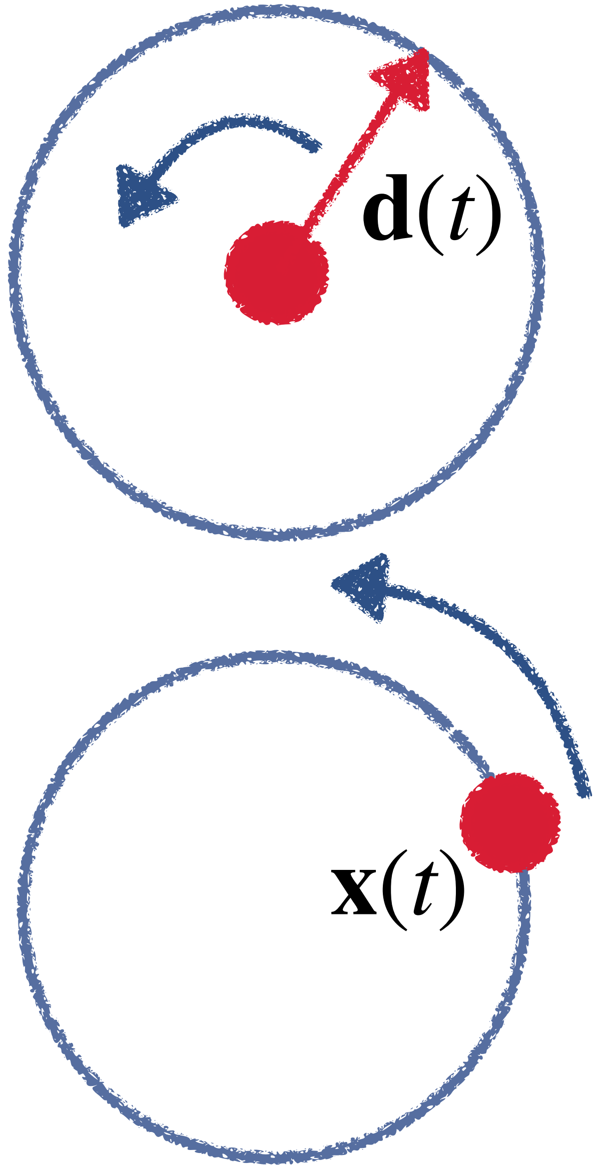
- **Pitfalls: EDMs and energy levels**
- Prospects: magnetized multilayers



Axioelectric Energy Level Shifts

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

Naive estimates of energy level shifts for bound electrons:

$$\Delta E_{\text{wind}} \sim g\,(\nabla a)\cdot\langle\sigma\rangle \sim g\dot{a}v_{\text{DM}}$$

$$\Delta E_{\text{axio-el}} \sim (g\dot{a}/m)\,\langle\sigma\cdot\mathbf{p}\rangle \sim (g\dot{a}/m)(mv_e) \sim g\dot{a}v_e$$

We expect $v_e \sim \alpha \sim 10^{-2}$ which is more than $v_{\text{DM}} \sim 10^{-3}$! But more carefully:

$$\Delta E_{\text{axio-el}} \sim g\dot{a}\,\langle\sigma\cdot\mathbf{v}\rangle \sim g\dot{a}\,\langle\sigma\cdot[iH,\mathbf{x}]\rangle \sim g\dot{a}v_e^3$$

because the leading contributions are from fine structure terms!

Material effects caused by energy level shifts thus overestimated by v_e^2

The Nonderivative Coupling

The axion-fermion coupling can be rewritten by field redefinition:

$$\mathscr{L} \supset \bar{\Psi}(i\partial\!\!\!/ - m)\Psi + g\,(\partial_\mu a)\,\bar{\Psi}\gamma^\mu\gamma^5\Psi \qquad \Psi \equiv e^{-iga\gamma^5}\Psi'$$

$$\mathscr{L} \supset \bar{\Psi}'(i\partial\!\!\!/ - e^{2iga\gamma^5}m)\Psi' = \mathscr{L}_0 - 2mga\,\bar{\Psi}i\gamma^5\Psi + O(g^2)$$

Must leave amplitudes and hence all observables invariant, but doesn't seem to!

$$(i\partial\!\!\!/ - m - q\,A\!\!\!/ - 2imga\gamma^5)\Psi = 0$$

$$(i\partial_t - q\phi)\psi = (\boldsymbol{\pi}\cdot\boldsymbol{\sigma} + 2imga)\bar{\psi},$$

$$(i\partial_t + 2m - q\phi)\bar{\psi} = (\boldsymbol{\pi}\cdot\boldsymbol{\sigma} - 2imga)\psi.$$

$$\bar{\psi} = \frac{1}{2m}\left(1 - \frac{i\partial_t - q\phi}{2m}\right)(\boldsymbol{\pi}\cdot\boldsymbol{\sigma} - 2imga)\psi + \mathcal{O}(1/m^3)$$

$$(i\partial_t - q\phi)\psi \simeq \frac{1}{2m}(\boldsymbol{\pi}\cdot\boldsymbol{\sigma} + 2imga)\left(1 - \frac{i\partial_t - q\phi}{2m}\right)(\boldsymbol{\pi}\cdot\boldsymbol{\sigma} - 2imga)\psi$$

$$\bar{H}_1 \simeq iga\boldsymbol{\pi}\cdot\boldsymbol{\sigma} - \frac{gqa}{2m}\dot{\mathbf{A}}\cdot\boldsymbol{\sigma}$$

$$\bar{H}_2 \simeq -iga\boldsymbol{\pi}\cdot\boldsymbol{\sigma} - g(\nabla a)\cdot\boldsymbol{\sigma} - \frac{gqa}{2m}(\nabla\phi)\cdot\boldsymbol{\sigma} + \frac{ig}{2m}(\nabla\dot{a})\cdot\boldsymbol{\sigma} - \frac{g\dot{a}}{2m}\boldsymbol{\pi}\cdot\boldsymbol{\sigma}$$

$$\bar{H}_3 \simeq -g(\nabla a)\cdot\boldsymbol{\sigma} + \frac{gqa}{2m}\boldsymbol{\sigma}\cdot\mathbf{E} + \frac{ig}{2m}(\nabla\dot{a})\cdot\boldsymbol{\sigma} - \frac{g\dot{a}}{2m}\boldsymbol{\pi}\cdot\boldsymbol{\sigma}$$

$$\int d^3\mathbf{x}\,\Psi^\dagger\Psi = \int d^3\mathbf{x}\,\psi^\dagger\psi + \bar{\psi}^\dagger\bar{\psi} \simeq \int d^3\mathbf{x}\,\psi^\dagger\left(1 + \frac{(\boldsymbol{\pi}\cdot\boldsymbol{\sigma})^2}{4m^2} - \frac{g(\nabla a)\cdot\boldsymbol{\sigma}}{2m}\right)\psi$$

$$\psi_{\rm nr} = M\psi \simeq \left(1 + \frac{(\boldsymbol{\pi}\cdot\boldsymbol{\sigma})^2}{8m^2} - \frac{g(\nabla a)\cdot\boldsymbol{\sigma}}{4m}\right)\psi$$

$$H \simeq \bar{H} + [M, \bar{H}] + i\partial_t M.$$

Two independent, rigorous methods show:

$$H_{\rm alt} \supset -g\,(\nabla a)\cdot\sigma - \frac{g}{2m}\,\dot{a}\,\sigma\cdot(\mathbf{p} - q\mathbf{A}) + \frac{qg}{2m}\,a\,\sigma\cdot\mathbf{E}$$

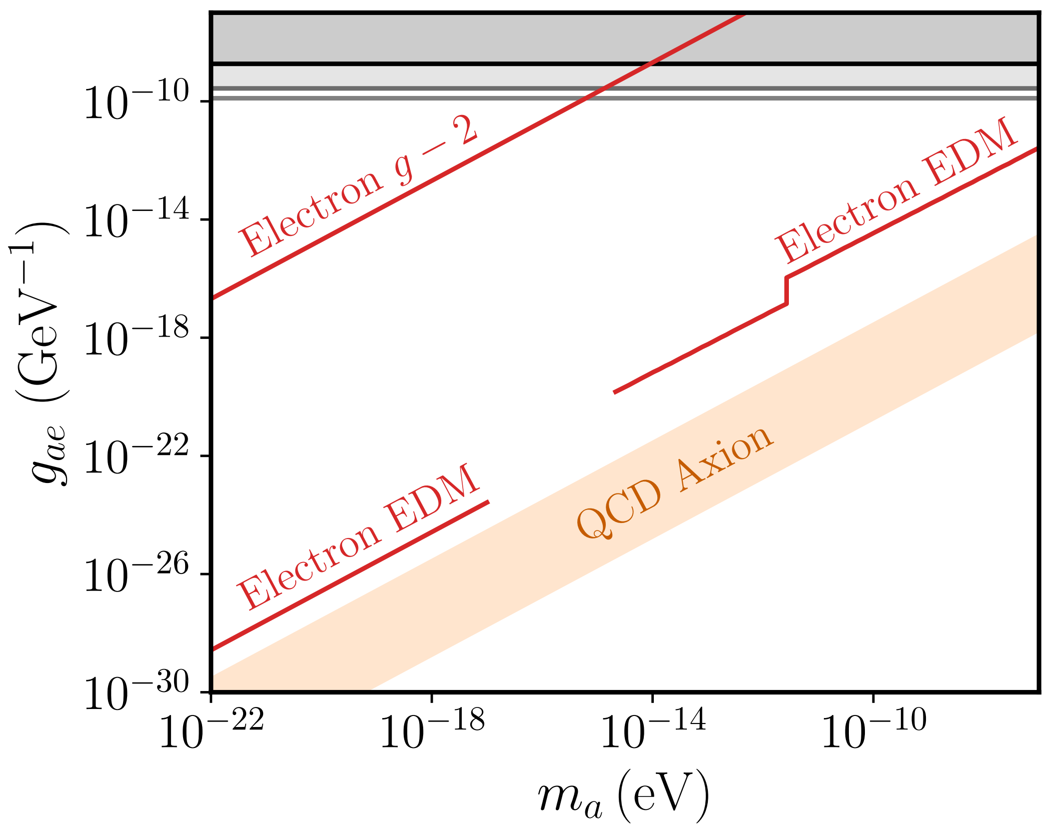
axioelectric term halved!

EDM term appears!

A Pair of Hamiltonians

$$H \supset -\frac{g}{m}\,\dot{a}\,\sigma\cdot(\mathbf{p}-q\mathbf{A}) \qquad\qquad H_{\text{alt}} \supset -\frac{g}{2m}\,\dot{a}\,\sigma\cdot(\mathbf{p}-q\mathbf{A}) + \frac{qg}{2m}\,a\,\sigma\cdot\mathbf{E}$$

If an a-dependent physical effect exists, it implies **extremely** strong sensitivity at low m_a, up to 20 orders of magnitude beyond astrophysical bounds!



Many recent works make such claims:

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)

What's going on? A few logical possibilities:

- One of the Hamiltonians is invalid
- Both can be right; experiment will tell which
- One or both of the Hamiltonians is missing terms

Wisdom From the Past

Physicists encountered a similar problem 75 years ago, because the two forms of the axion-electron coupling are analogous to the two forms of the pion-nucleon coupling:

> At the 1949 APS meeting, Murray Slotnick presented new results, which he had obtained after two years of calculation, concerning the interaction between an electron and a neutron. He had found that the answers for the pseudoscalar theory and the pseudovector theory were different. Oppenheimer asked Slotnick: "Well, what about Case's theorem?" Case had announced that he had proved that the results for both theories were the same. Slotnick answered: "I never heard of Case's theorem!"

Versions of this debate continued into the 1970s!

The details of the resolution are different here, but the tools needed are similar, and readily found in field theory books from before the Peskin and Schroeder era

Unitary Equivalence

Quantum theories are invariant under unitary redefinitions of states and operators:

$$\psi'\rangle = e^{iS} \;\; \psi\rangle \qquad\qquad i\partial_t \;\; \psi\rangle = H \;\; \psi\rangle \qquad\qquad H' = H + i[S, H] - \partial_t S + O(S^2)$$
$$\mathcal{O}' = e^{iS}\mathcal{O}e^{-iS} \qquad\qquad i\partial_t \;\; \psi'\rangle = H' \;\; \psi'\rangle$$

Quantum version of canonical transformation; matrix elements of physical observables and hence all predictions stay same, though detailed time evolution can look different!

The two Hamiltonians are related in precisely this way:

$$S \simeq -\frac{\beta g a}{2m}(\mathbf{p} - q\mathbf{A}) \cdot \sigma \qquad\qquad H(\beta) \supset -(1 - \beta/2)\frac{g\dot{a}}{m}\sigma \cdot (\mathbf{p} - q\mathbf{A}) + \frac{\beta q g a}{2m}\sigma \cdot \mathbf{E}$$

So physical predictions have to be equivalent, even if not obviously so

Rotating The Axioelectric Term Away

$$H(\beta) \supset -(1 - \beta/2)\frac{g\dot{a}}{m}\sigma \cdot \mathbf{p}$$

For neutral particle, we can remove the axioelectric term with no other consequences by just taking $\beta = 2$. Doesn't this imply the axioelectric force is fictitious?

No! Can remove any force this way, by going to that particle's frame. Axioelectric force is genuine because it produces relative acceleration between two particles.

Concrete example: two particles with any interaction

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

$$H(\beta = 2) \supset V(\mathbf{x}_1 - \mathbf{x}_2) - \frac{\beta g a}{2m}(\sigma_1 - \sigma_2) \cdot \nabla_1 V(\mathbf{x}_1 - \mathbf{x}_2)$$

Rotating away axioelectric term just encodes the effect in another term

Rotating The EDM Term In

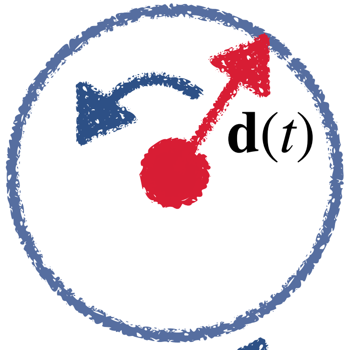
$$H = H_0 \qquad\qquad H' = H_0 - d\sigma \cdot \mathbf{E}$$

When a is constant, we can rotate in an EDM term with arbitrary magnitude

No physical consequences; just redefines how we label the particle's position $\mathbf{x}$

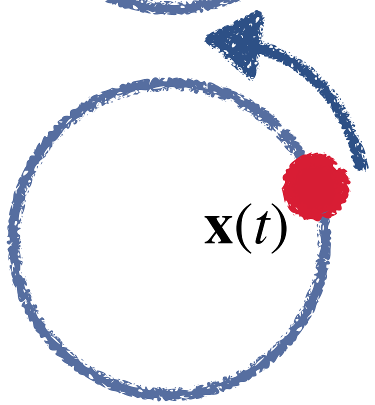
$$\mathbf{x}_q = \mathbf{x} \qquad\qquad \mathbf{x}'_q = \mathbf{x} + (d/q)\sigma$$

Concrete example: place the particle at rest in $\mathbf{B}_0$ to make spin precess



- Particle not moving, but EDM precessing at $\omega_L = qB_0/m$
- Center of charge moves in circle of radius d/q

equivalent descriptions
of same process!



- No EDM, but particle orbits in circle at $\omega_c = qB_0/m$
- Center of charge moves in circle of radius d/q

Measuring Real EDMs

The upshot: all $H(\beta)$ are equivalent, but trying to use $\beta \neq 0$ will induce inconvenient two-particle interactions, and produce a misleading, unphysical EDM term

But if $d\sigma \cdot \mathbf{E}$ is unphysical, what are actual EDM experiments measuring?

In reality, they are sensitive to the relativistic operator

$$H \supset \frac{d}{2}\,\bar{\Psi}\gamma^5\sigma^{\mu\nu}\Psi\,F_{\mu\nu} = d\sigma \cdot \mathbf{E} + \ldots$$

Schiff's theorem: leading term has no effect on nonrelativistic energy levels!

All of the physics of an EDM, like energy level shifts, comes from relativistic corrections — which do not appear in the axion interaction term

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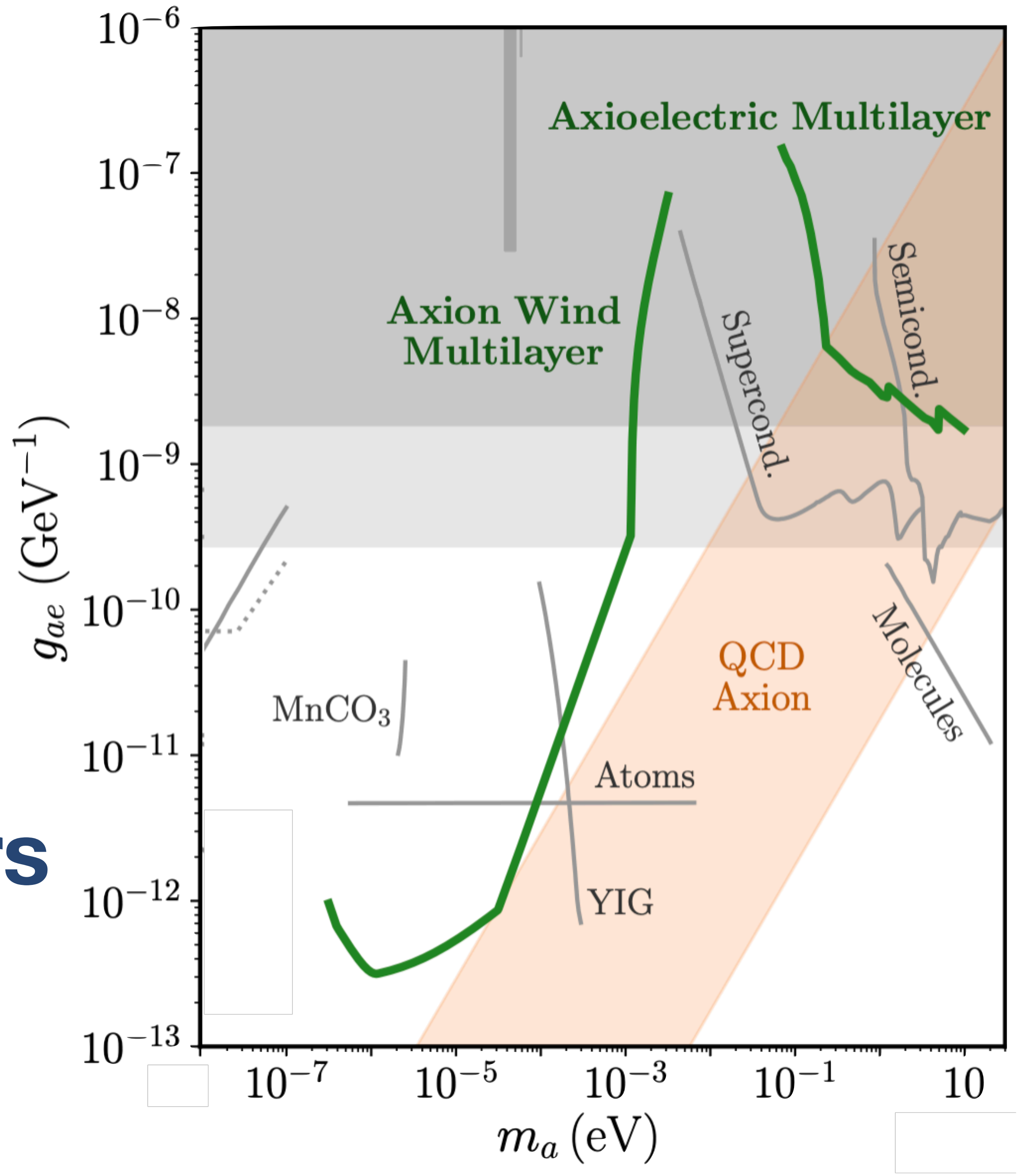
- **Prospects: magnetized multilayers**



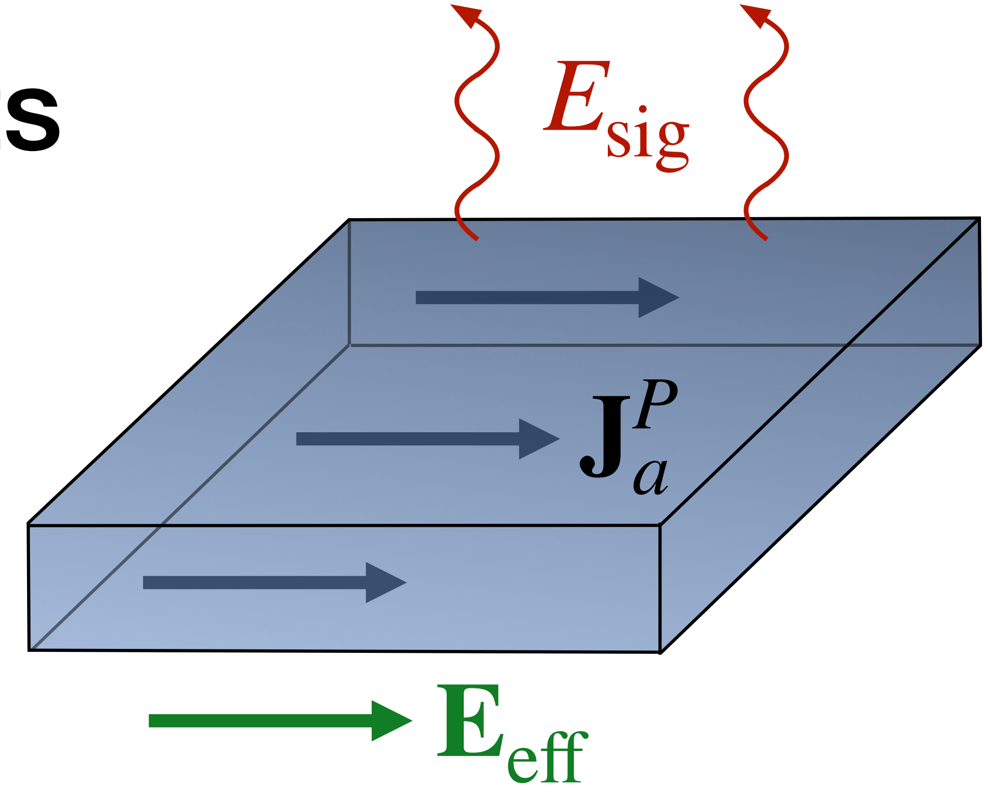
Induced Currents

The axion acts on magnetized mediums to make:

$$\mathbf{P}_a = (\epsilon_\sigma - 1)\mathbf{E}_{\text{eff}} \qquad \mathbf{M}_a = (1 - \mu^{-1})\mathbf{B}_{\text{eff}}$$

"spin-weighted" permittivity, $\epsilon_\sigma \simeq \epsilon$ when fully spin-polarized

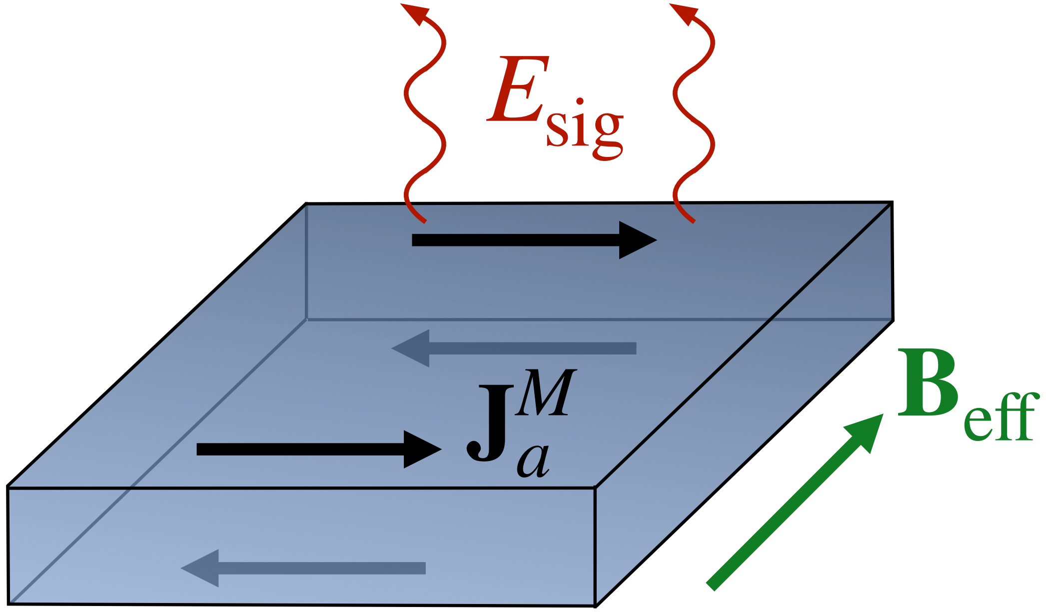
generally small unless the medium is magnetized



Acts as a source in the in-medium wave equation:

$$\nabla \times \nabla \times \mathbf{E} + n^2\, \partial_t^2 \mathbf{E} = -\,\mu\, \partial_t \mathbf{J}_a$$

$$\mathbf{J}_a = \partial_t \mathbf{P}_a + \nabla \times \mathbf{M}_a$$



Bulk polarization current, surface magnetization current

Axioelectric Polarization Current

Do good conductors yield the highest axioelectric effect?

$$\nabla \times \nabla \times \mathbf{E} + n^2\, \partial_t^2 \mathbf{E} = -\,\mu\, \partial_t^2 \mathbf{P}_a \qquad\qquad \mathbf{P}_a \simeq (\epsilon - 1)\mathbf{E}_{\text{eff}}$$

Solving these equations in an infinite medium gives

$$\mathbf{E} = \frac{1-\epsilon}{\epsilon}\,\mathbf{E}_{\text{eff}} \qquad\qquad \mathbf{J} = (\epsilon - 1)\,\partial_t(\mathbf{E} + \mathbf{E}_{\text{eff}}) = \frac{\epsilon - 1}{\epsilon}\,\partial_t \mathbf{E}_{\text{eff}}$$

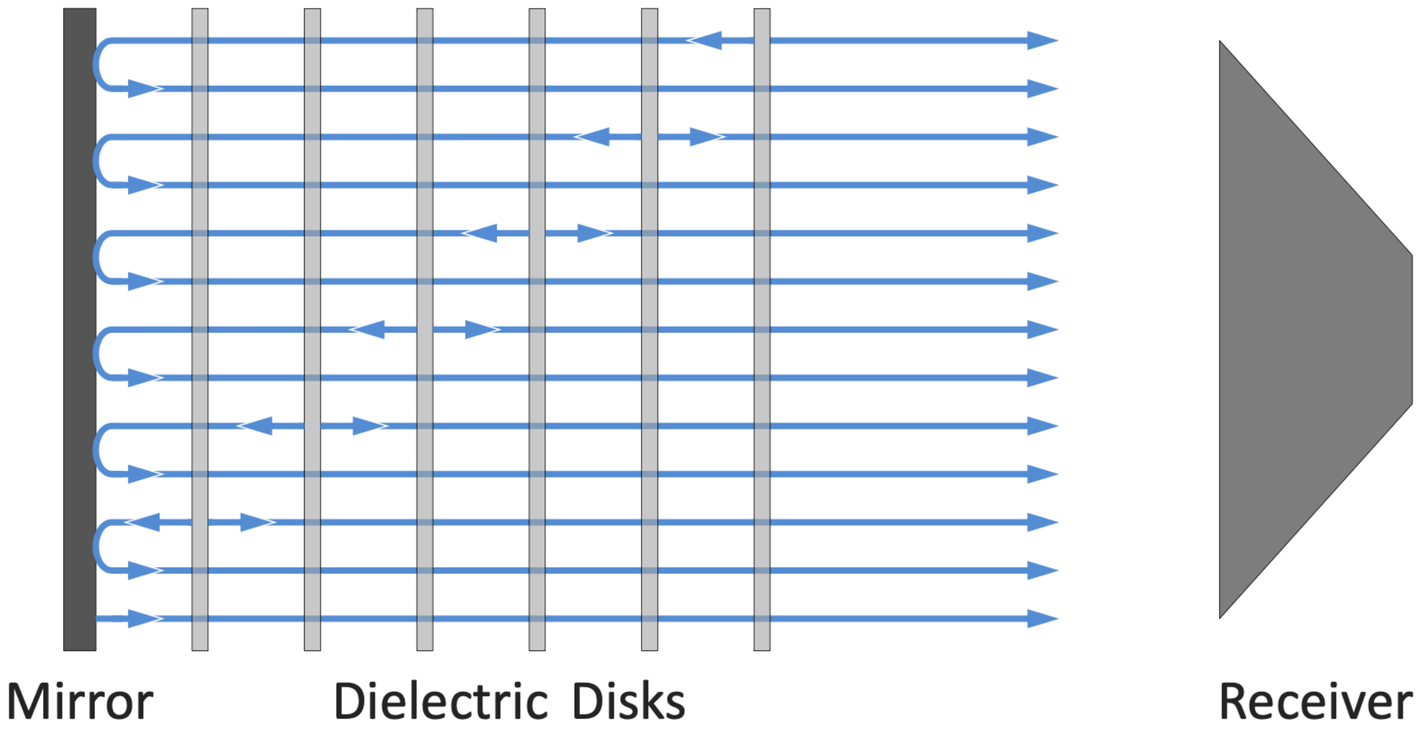
Larger ϵ, like in a good conductor ($\epsilon = 1 + i\sigma/\omega$) does not increase the current!

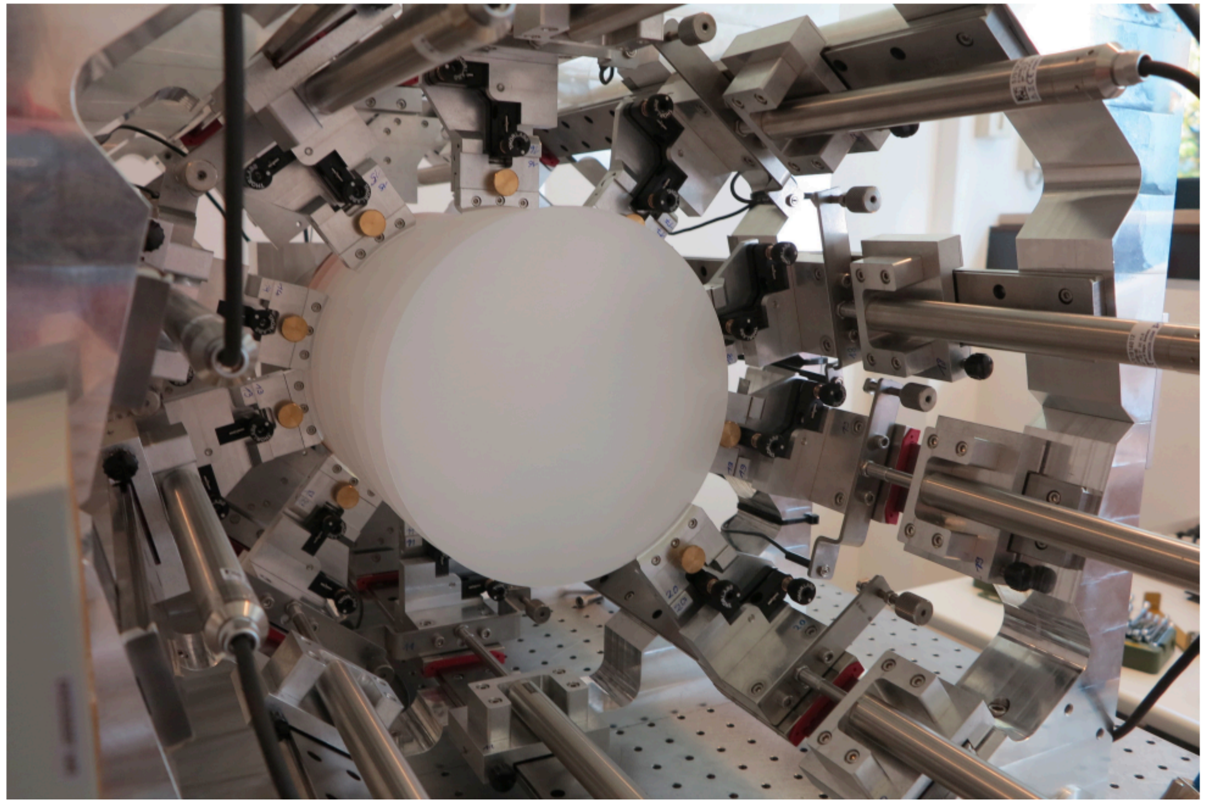
Charges become easier to move, but simultaneously screen the effective field

All materials with $\epsilon \sim O(1)$ are roughly equally good

Magnetized Multilayers

Can search for these currents using magnetized analogues of dielectric haloscopes





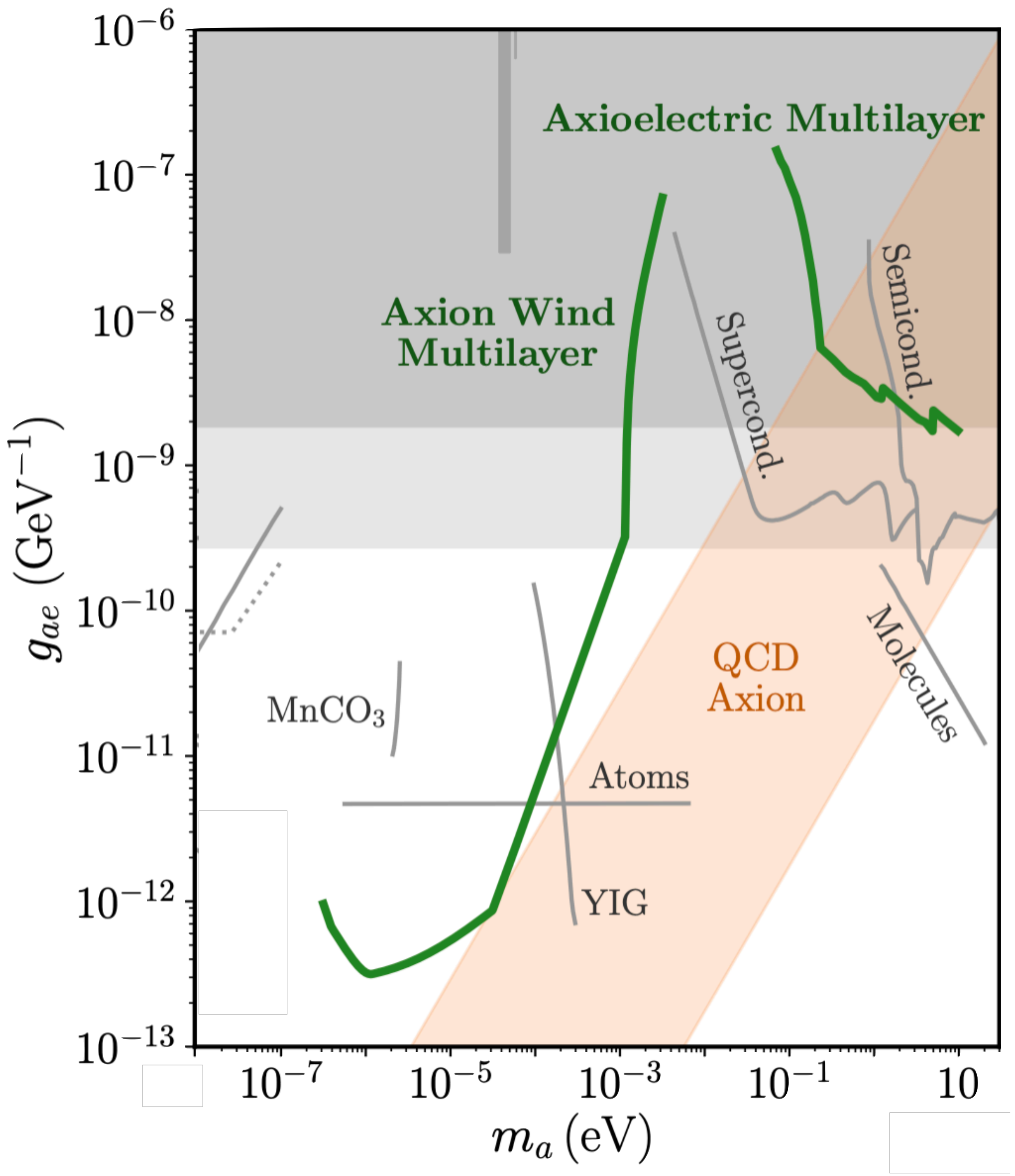
Concept originally designed for axion-photon coupling, prototypes under construction

Constructively interfere the radiation produced by currents in N dielectric disks

Axioelectric Reach

Strongest at the highest axion masses, because $\mathbf{E}_{\text{eff}} \propto \partial_t^2 a \sim m_a^2 a$

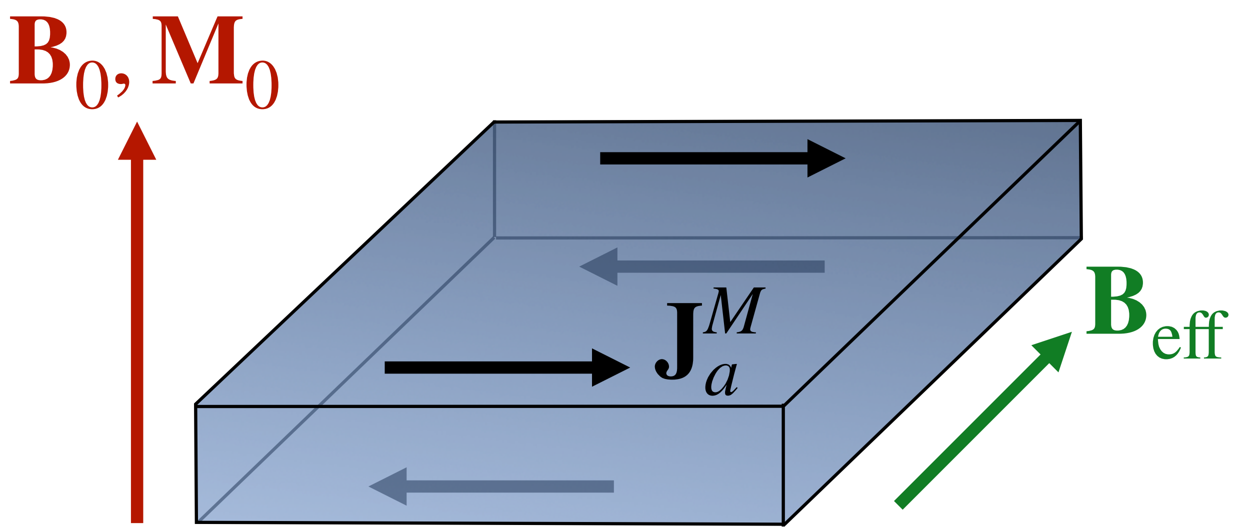
Result is a recasting of a projection for LAMPOST, optical dielectric haloscope



Axion Wind Magnetization Current

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

To understand magnetization current, need a model of μ for magnetic material



Standard result is $M_\pm = \chi_\pm H_\pm$ where

$$\chi_\pm = \frac{\pm\omega_M + i\omega_M/2Q}{\omega \pm \omega_H + i\omega_H/2Q}$$

and $\omega_M = \gamma M_0$, $\omega_H = \gamma H_0$, Q is quality factor

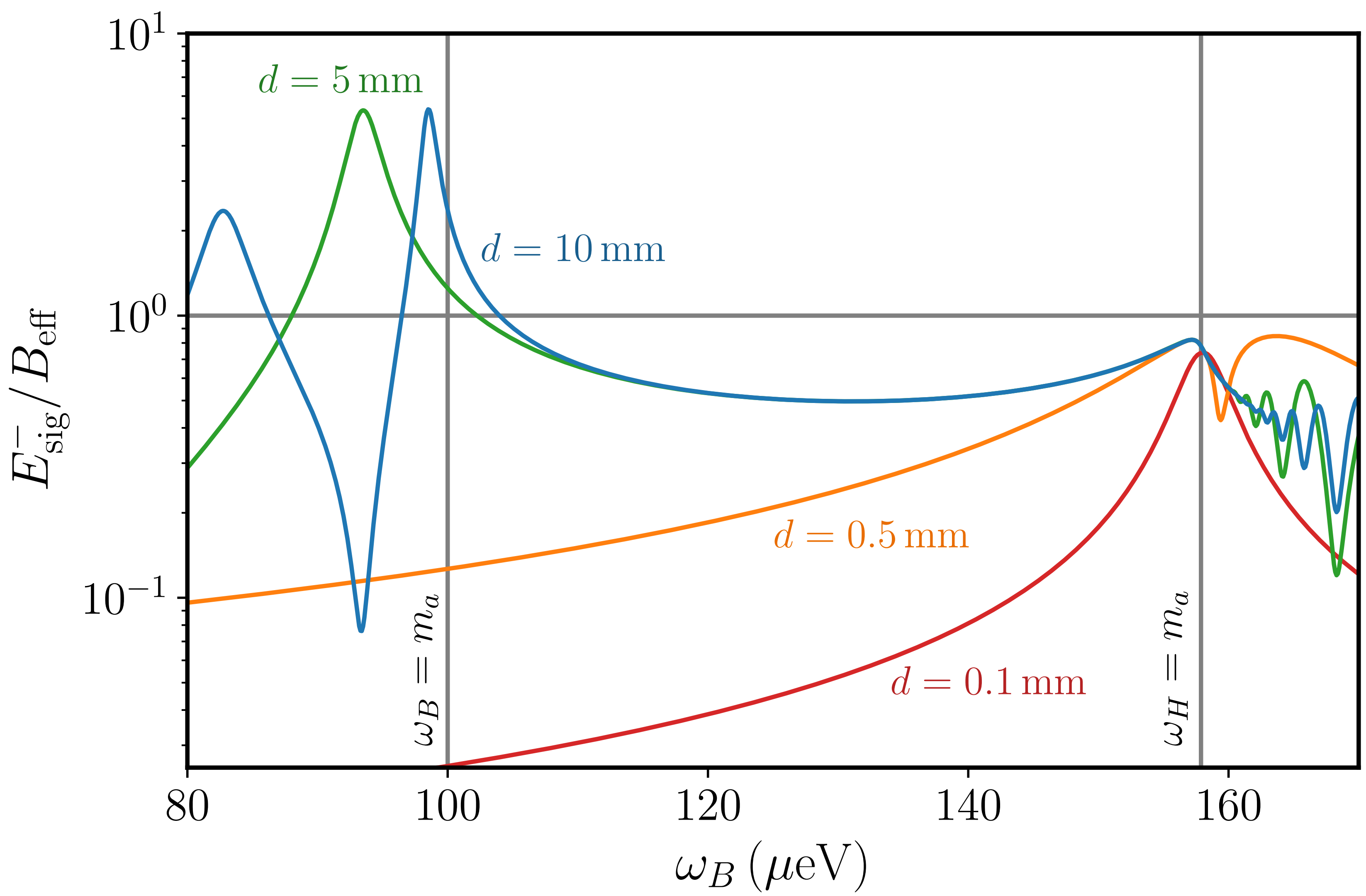
Unlike the case of polarization currents, the M_- response is resonant at a **tunable** frequency, from microwave to far IR ($B_0 \lesssim 10\,\text{T}$ implies $\omega_B \lesssim 10^{-3}\,\text{eV}$)

Optimizing the Applied Field

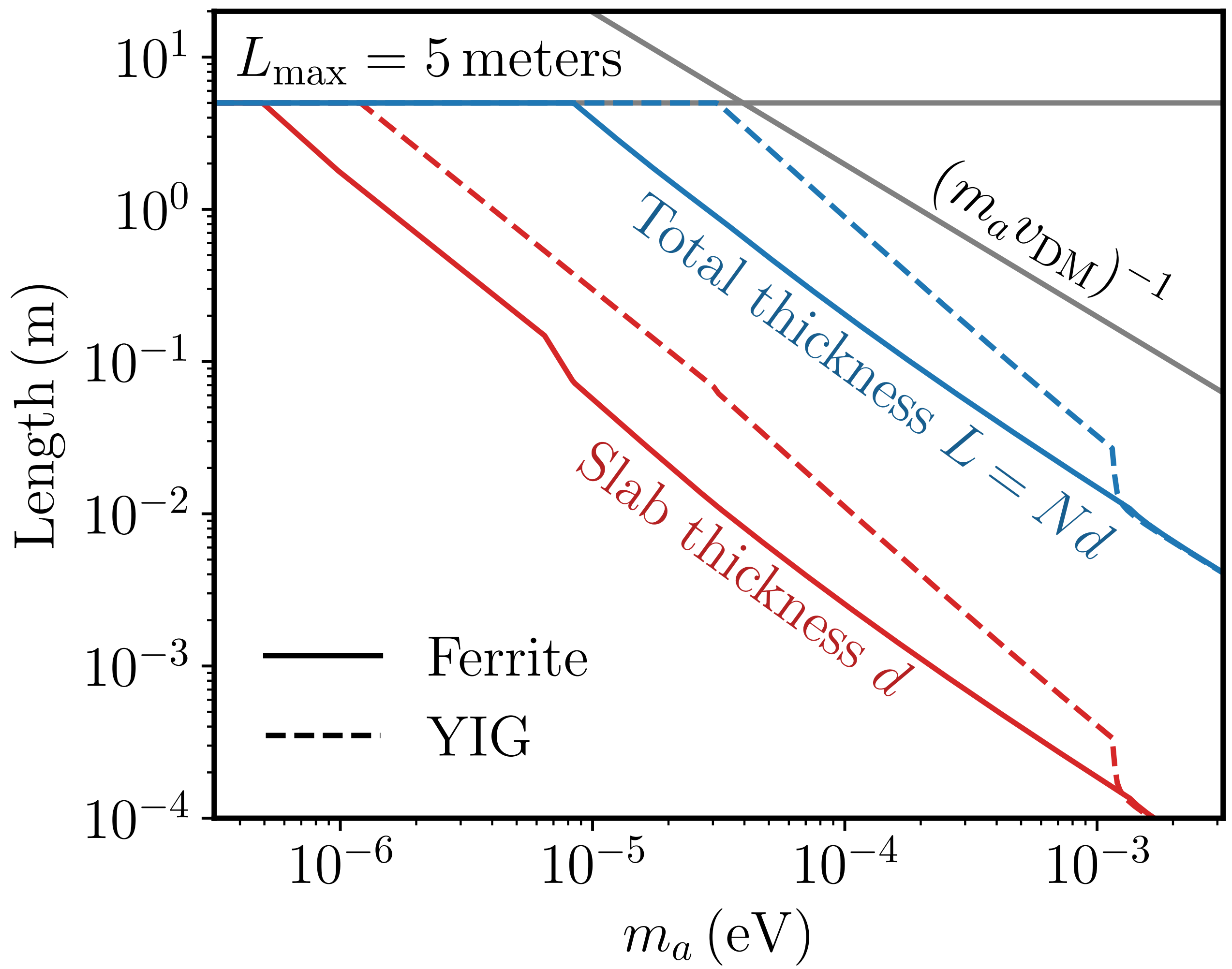
Optimizing $\omega_B = \gamma B_0$ is nontrivial!

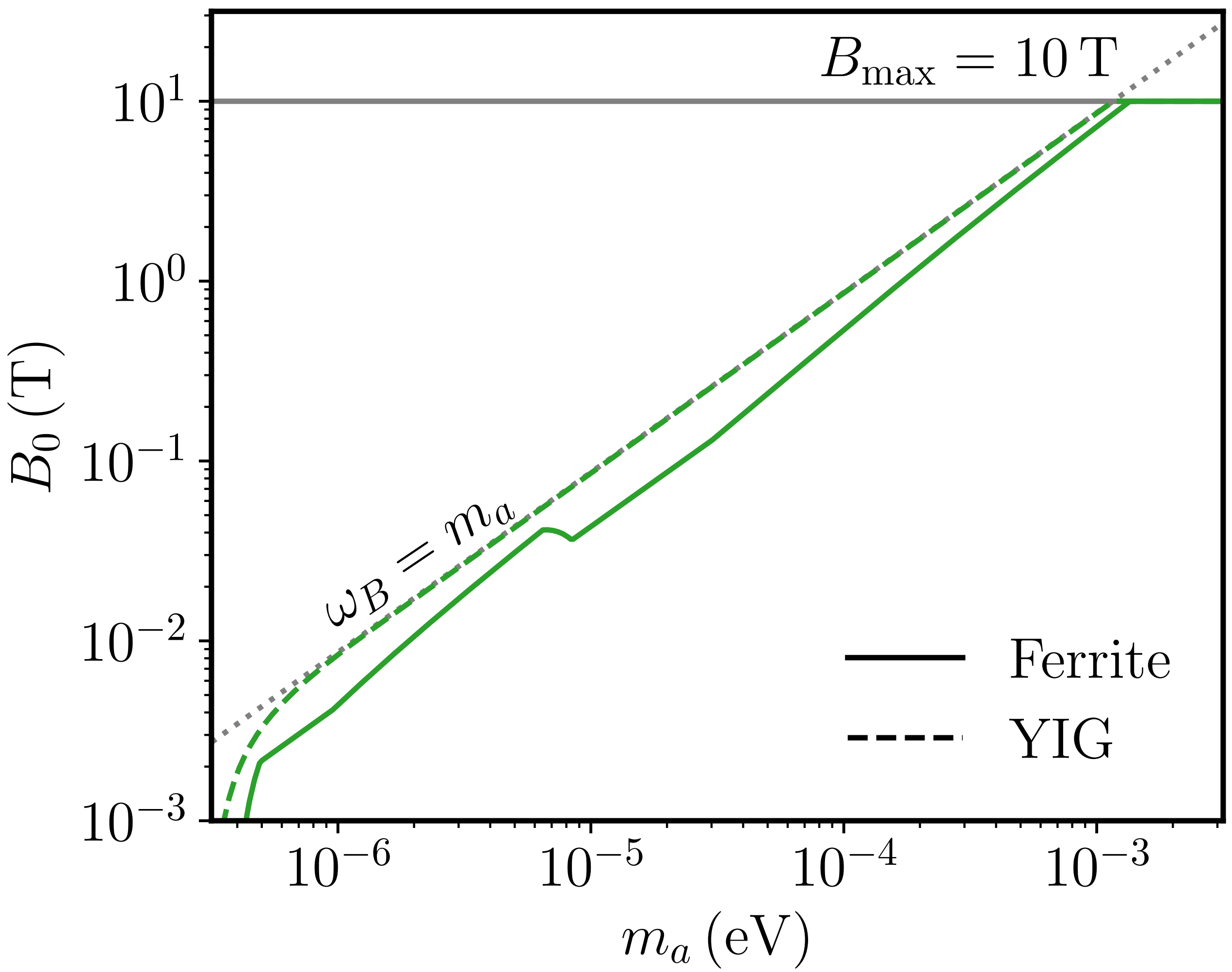
For thin slab, best to set $\omega_H = m_a$ where χ_- vanishes, but response is never resonantly enhanced (radiation loss dominated)

For thick slab, can get resonant enhancement slightly below $\omega_B = m_a$ where μ_- is small, wavelength matches slab thickness



Optimizing the Multilayer





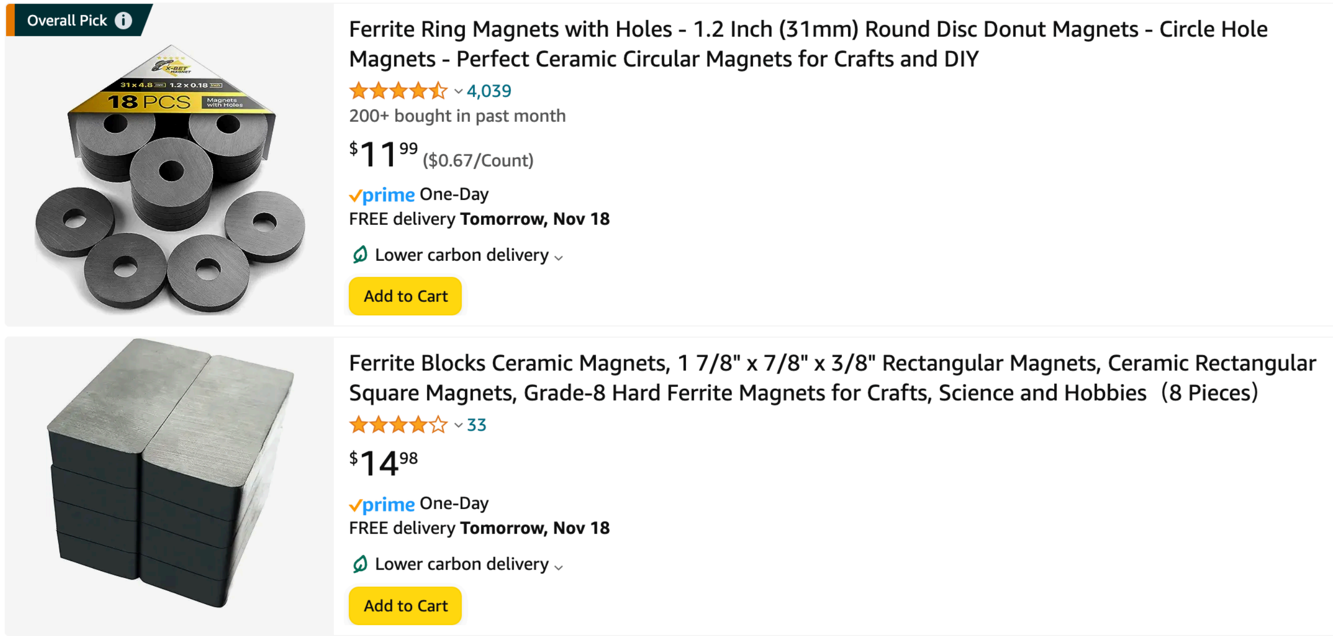
Stack $N \leq 80$ such layers, optimizing B_0 subject to constraints on length and field

Material Benchmarks

	M_S (T)	ω_M (eV)	Q range	fiducial Q	ε	$\tan\delta_\varepsilon$
polycrystalline spinel ferrite	0.5	5.8×10^{-5}	$20 - 10^3$	10^2	15	$\lesssim 10^{-4}$
single crystal YIG	0.25	2.9×10^{-5}	$5 \times 10^3 - 2 \times 10^4$	10^4	15	$\lesssim 10^{-4}$

mass produced, very cheap

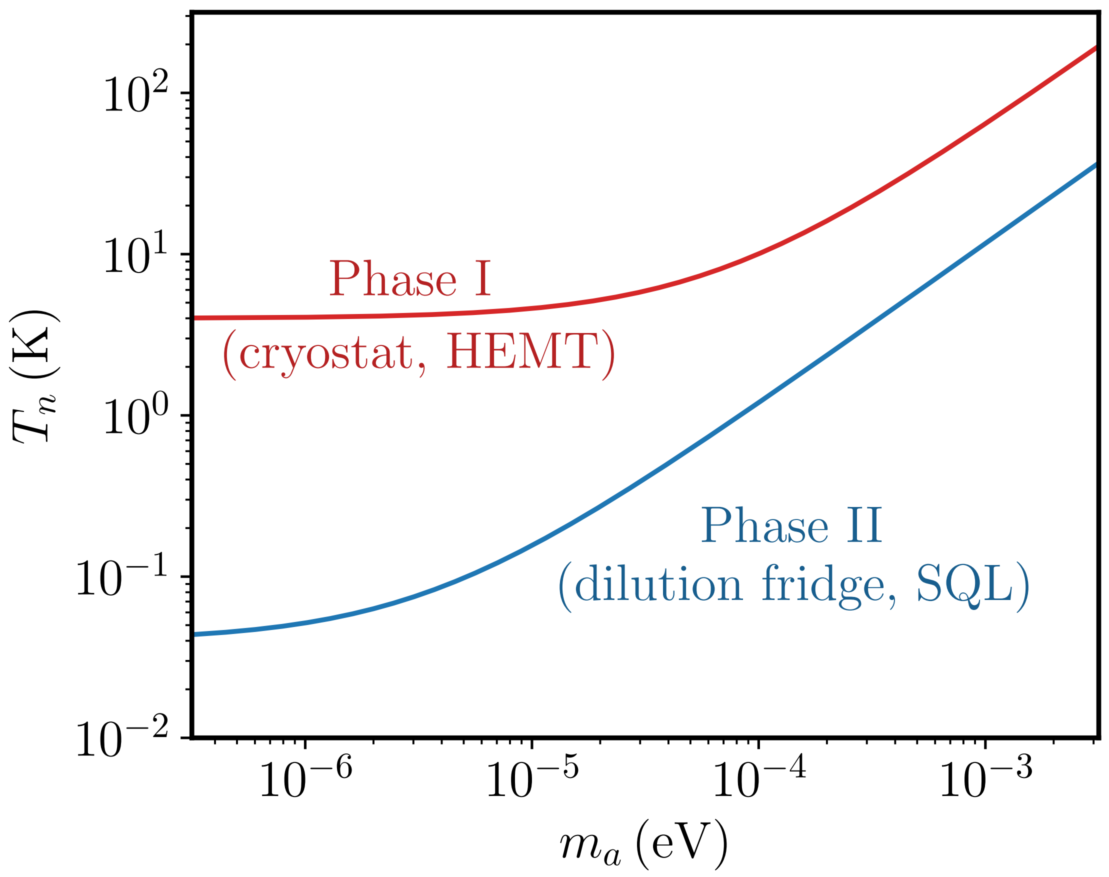
available, but hand-crafted by artisans



Experimental Sensitivity

Unlike most experiments, signal power goes as Q^2 since higher Q allows more layers

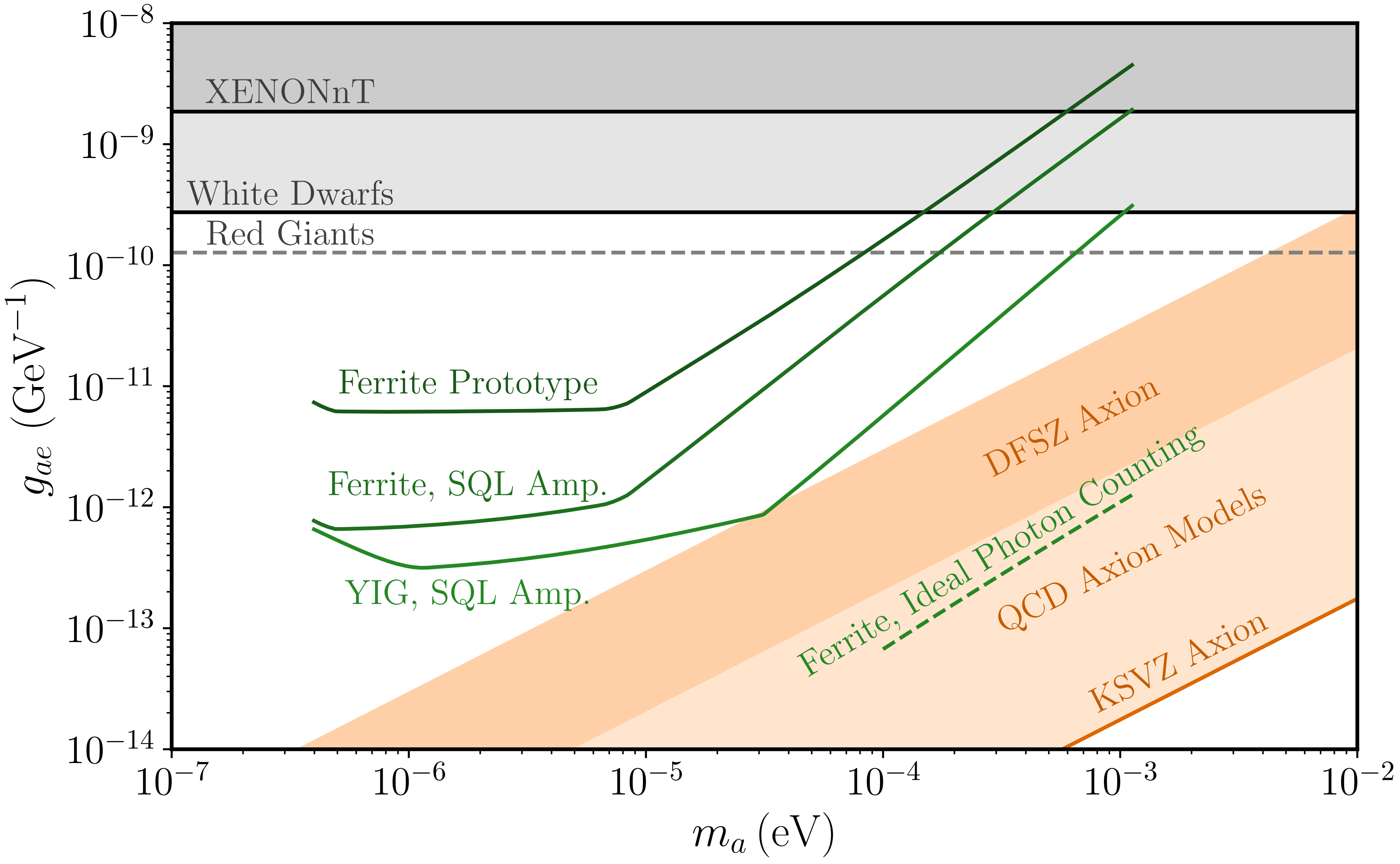
$$P_{\text{sig}} \sim \left(\frac{Q\omega_M}{m_a}\right)^2 B_{\text{eff}}^2 A \qquad A = 1\,\text{m}^2$$



Noise benchmarks: same as ongoing MADMAX experiment

But huge potential improvement from single photon counting at high masses

Can tune by moving layers, like MADMAX, but also by adjusting field



Cheap prototype can reach new parameter space (wins on volume)

Ultimate potential reach well beyond any other proposals in this mass range

Conclusion

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

Theory situation has been unclear, and experimental signatures are underexplored

New ideas are worth investigating and building!