Discovering the QCD Axion with Polarization Haloscopes

Kevin Zhou

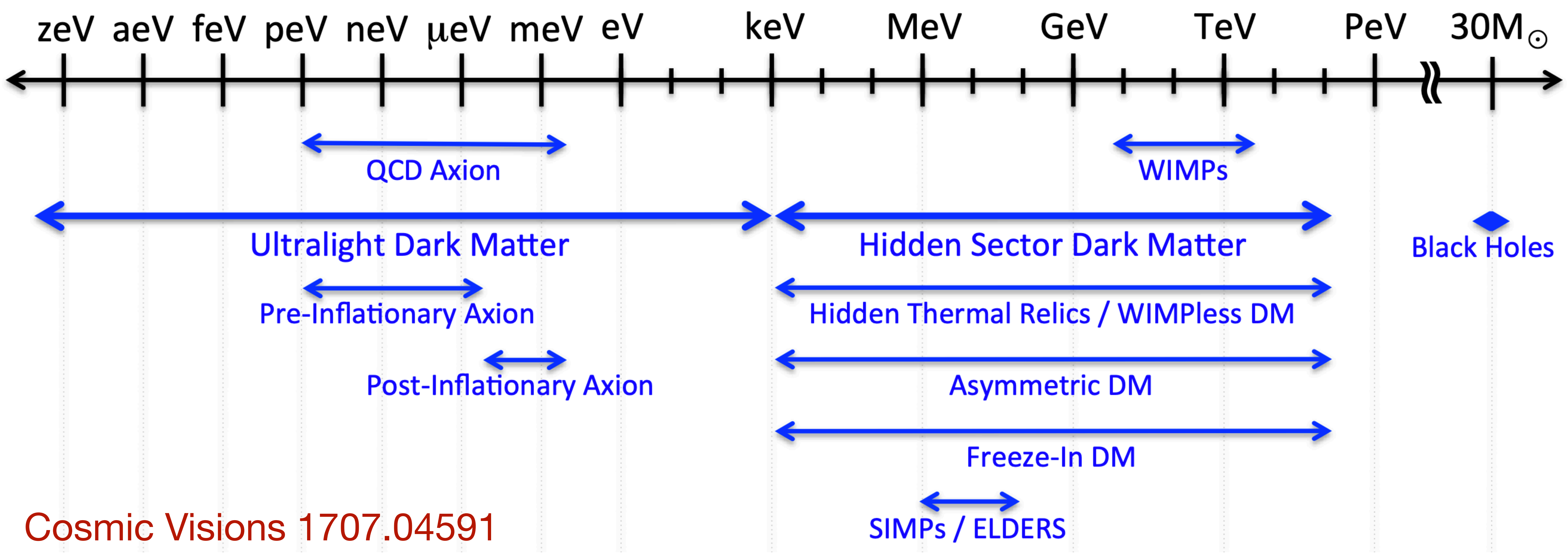
Stanford University

SLAC

Fermilab Theory Seminar — April 13, 2023

based on arXiv:2209.12901, with Asher Berlin

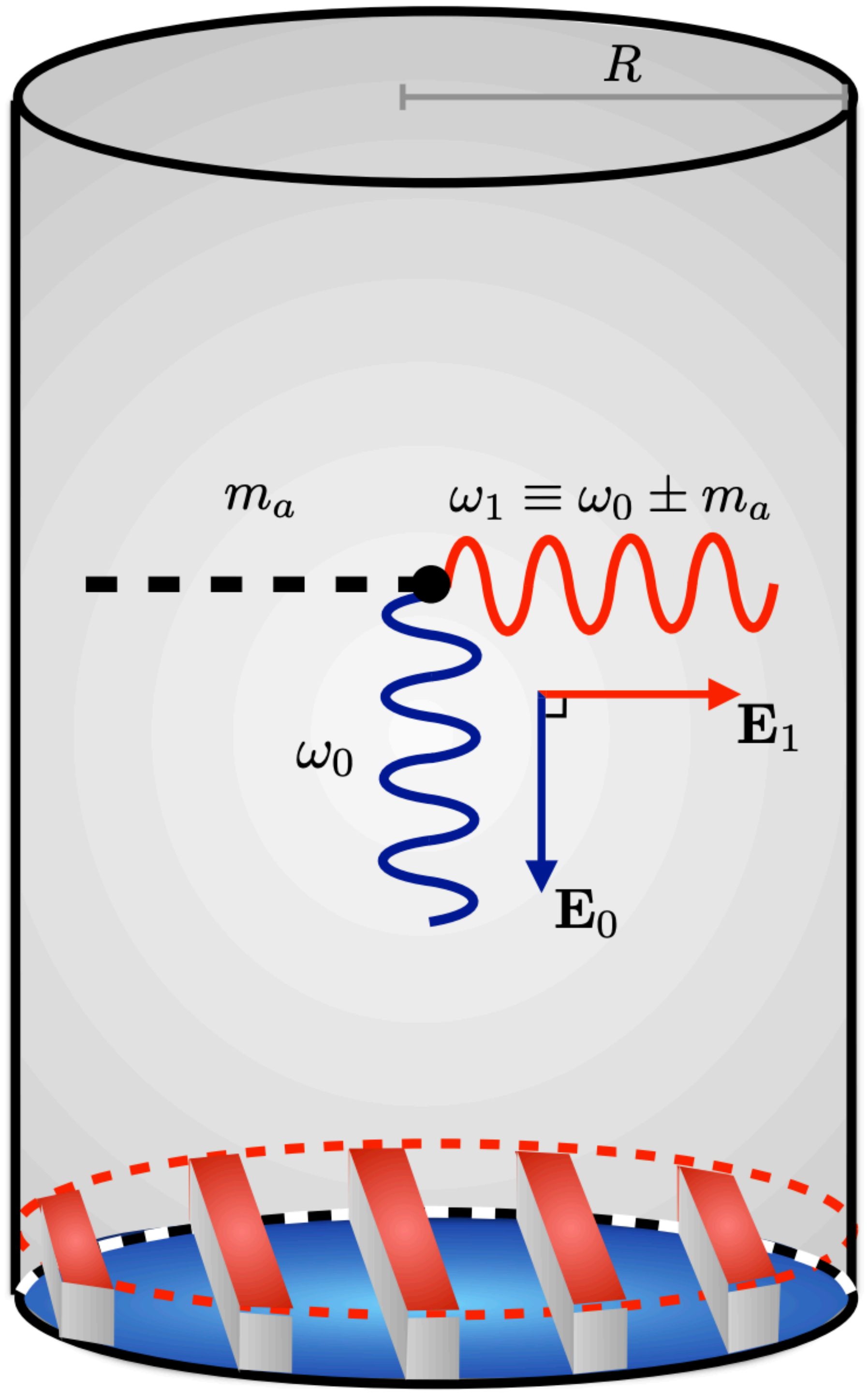
The Search For Dark Matter

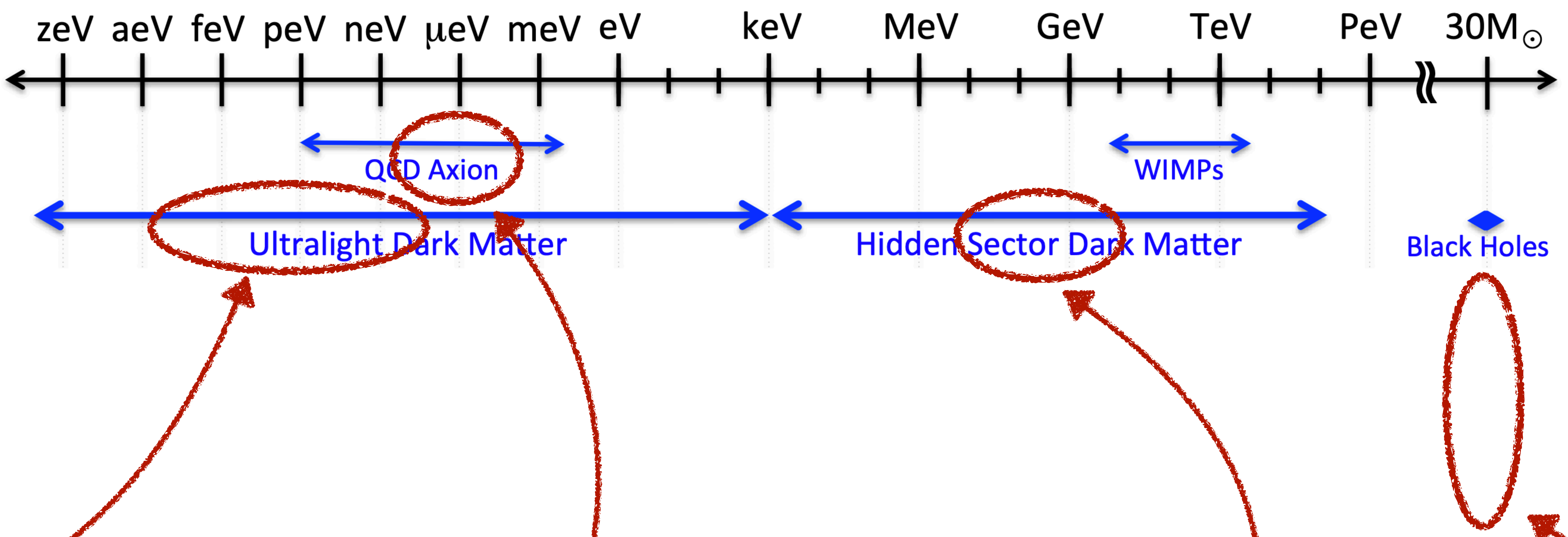


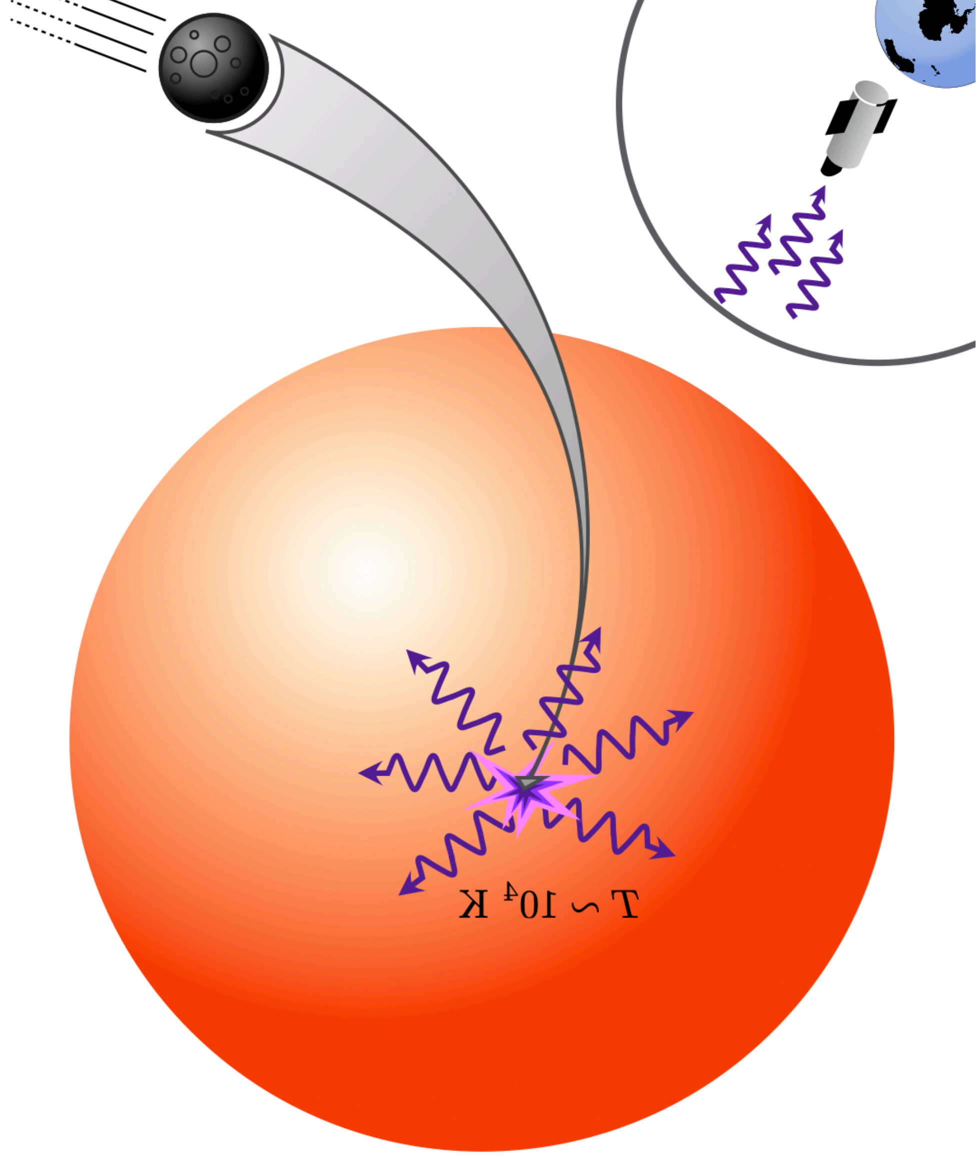
In current situation, we would like to both decisively test canonical models, and probe broadly into underexplored classes of models

New experimental programs can help do both!

The Search For Dark Matter







stellar shock transients

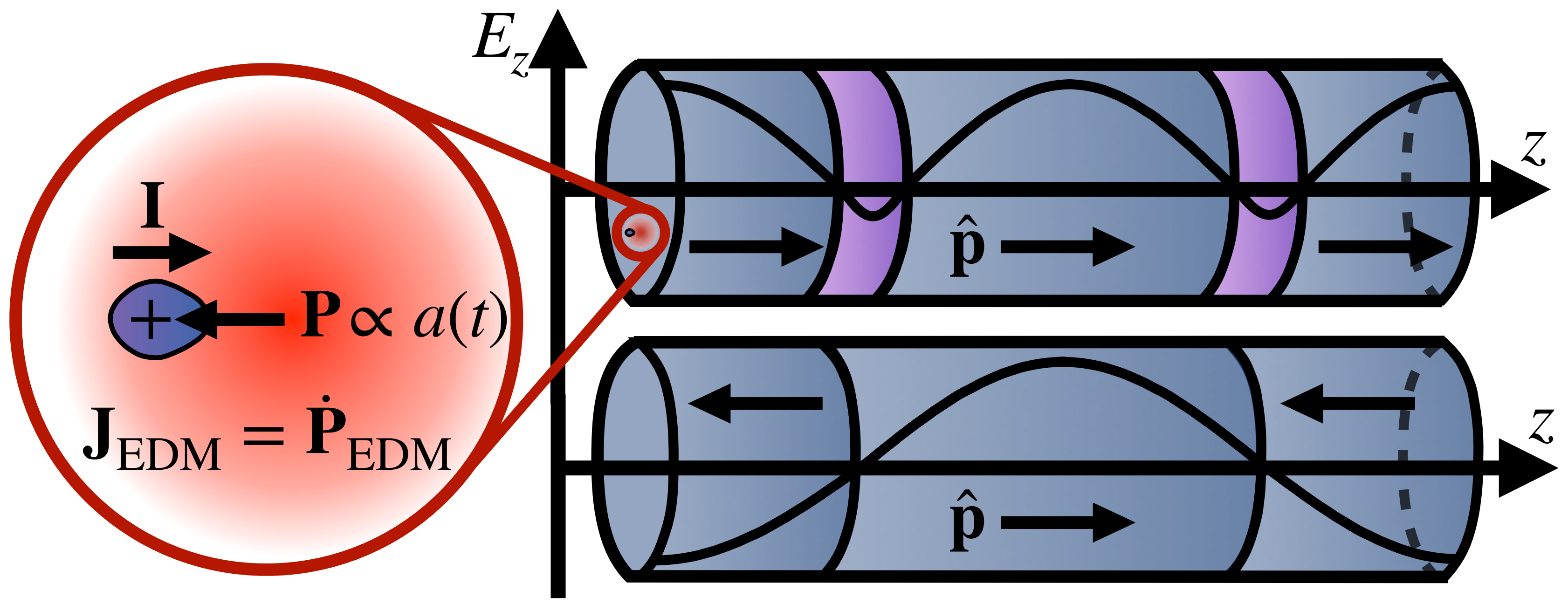
2106.09033

axion upconversion

1912.11048, 2007.15656

polarization haloscopes

invisible meson decays



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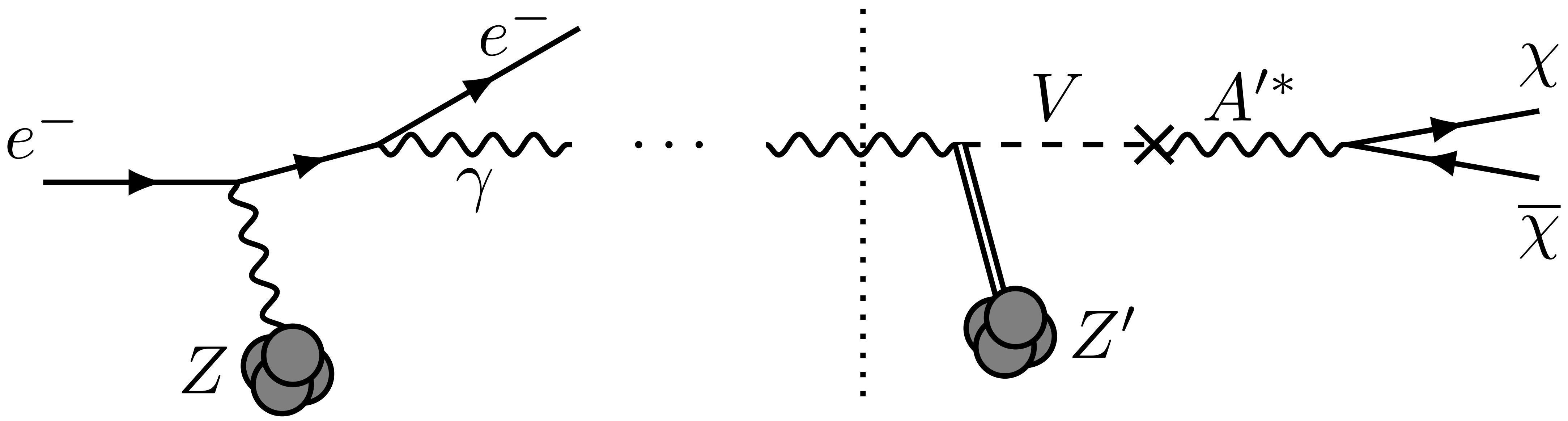

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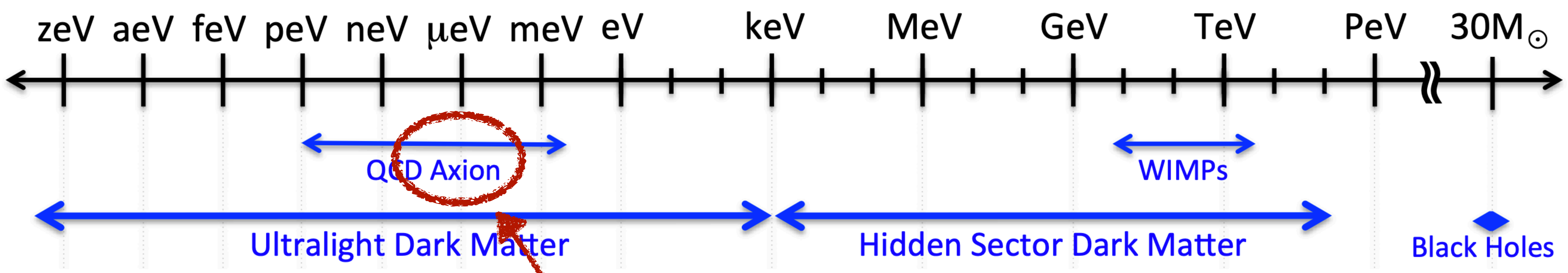
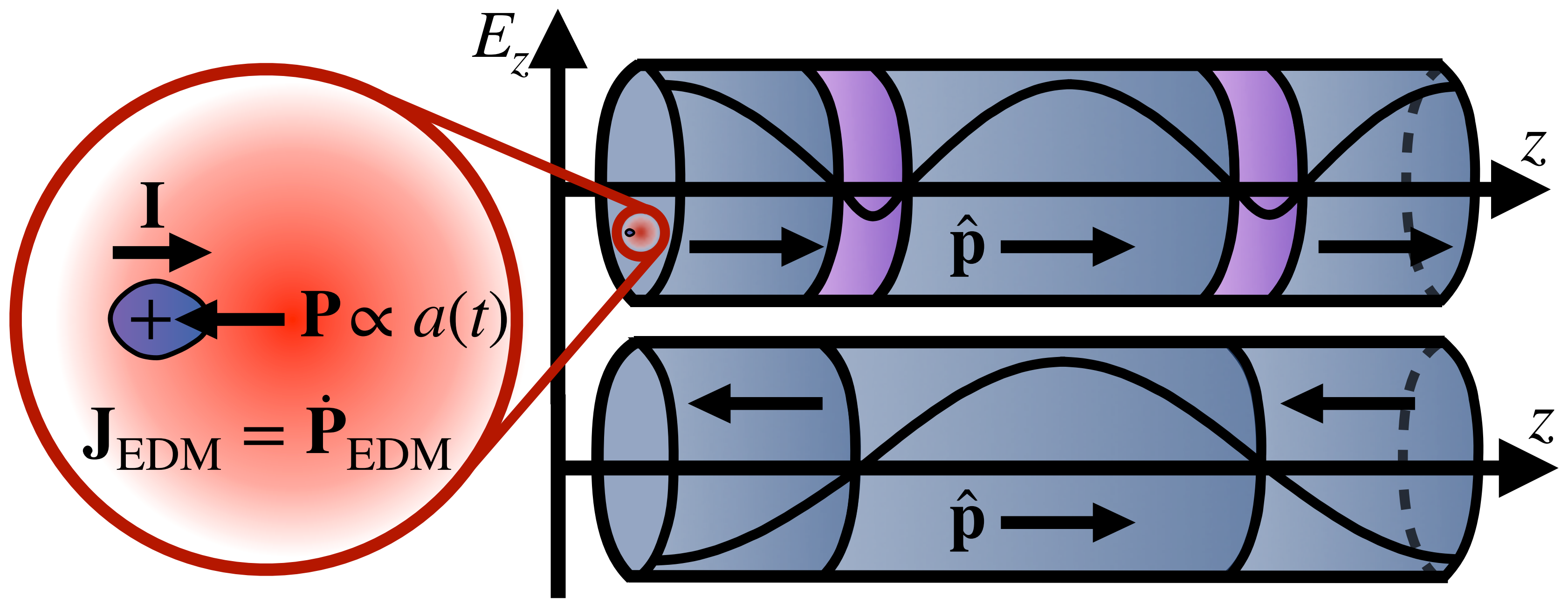
The Search For Dark Matter



polarization haloscopes

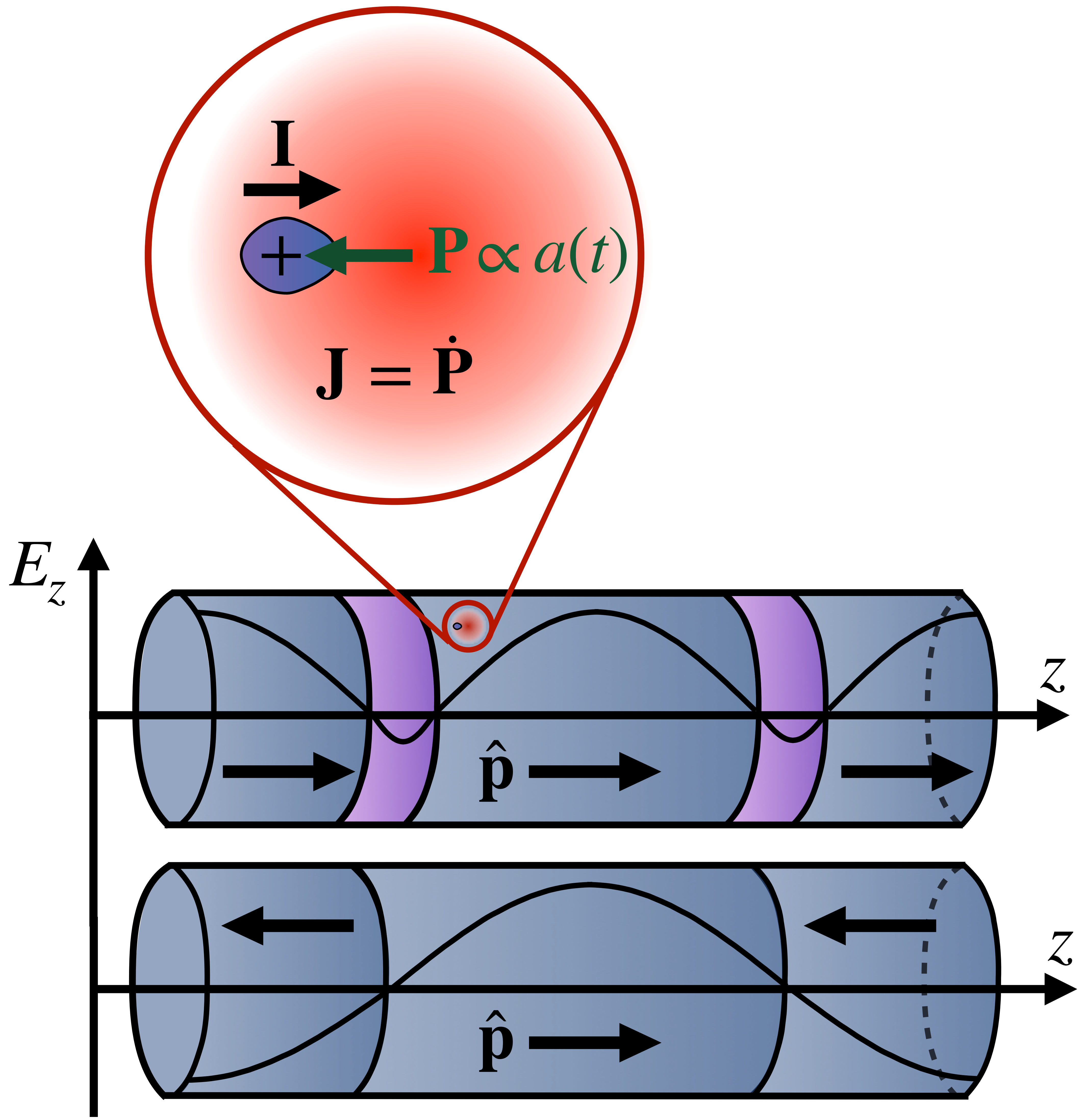


2209.12901

This talk: a new way to decisively probe one of the most long-standing, well-motivated dark matter candidates

Outline

- **The QCD axion**
- Axion-induced polarization
- Making a polarization haloscope



The QCD Axion

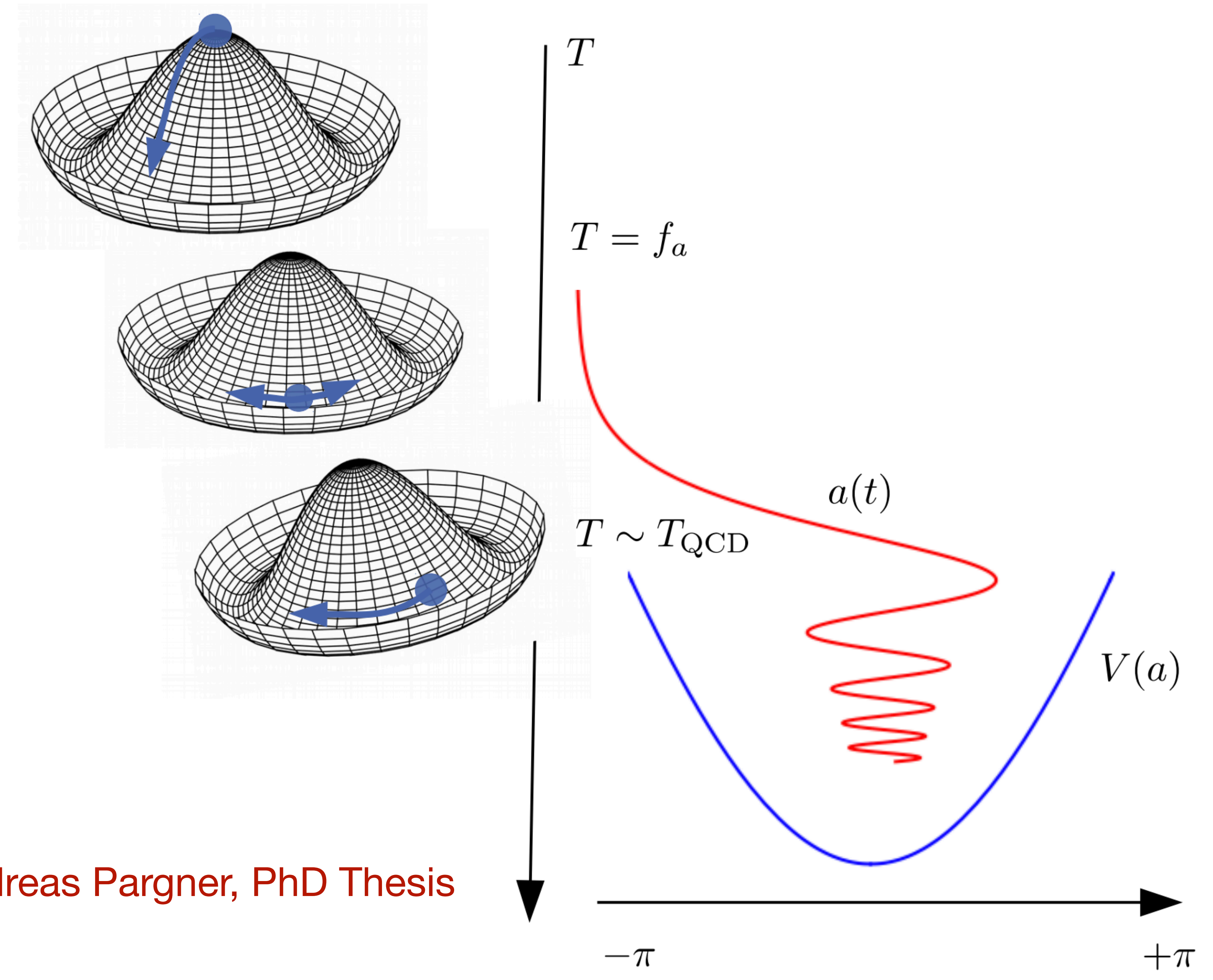
A pseudoscalar field a with defining coupling to gluons

$$\mathscr{L} \supset \theta_a \frac{\alpha_s}{8\pi} G^{\mu\nu}\tilde{G}_{\mu\nu} \qquad \theta_a = \frac{a}{f_a}$$

Nonperturbative QCD effects produce potential minimum at strong CP-conserving point, and mass

$$m_a = 5.7\ \mu\text{eV}\ \frac{10^{12}\ \text{GeV}}{f_a}$$

Explains lack of strong CP violation by relaxation over cosmological time



Andreas Pargner, PhD Thesis

For initial $\theta_a \sim 1$, residual oscillations are dark matter if $m_a \sim (0.5 - 50)\ \mu\text{eV}$

The QCD Axion

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Theoretically appealing:

- One of the simplest possible couplings to new light fields, motivated by effective field theory
- Simple UV completions in theories with spontaneously broken $U(1)_{\text{PQ}}$
- Axions generically produced in string compactifications
- QCD axion defined by observable interaction!

Detecting the QCD Axion

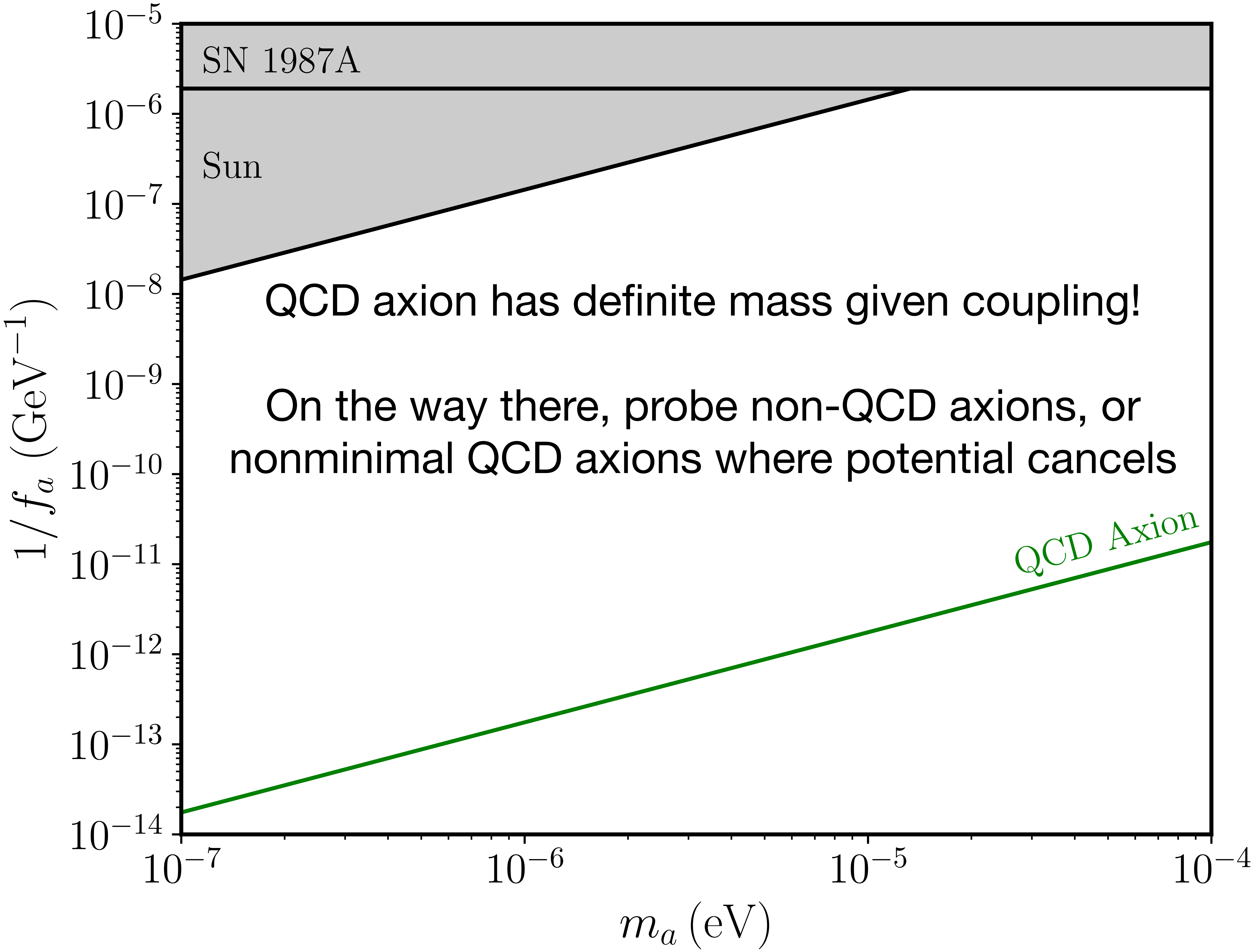
The QCD axion has small residual oscillations about the CP conserving point

$$\theta_a(t) \simeq \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a f_a} \cos m_a t = 4 \times 10^{-19} \cos m_a t$$

Defined by an observable signature: oscillating CP violating nuclear effects, like

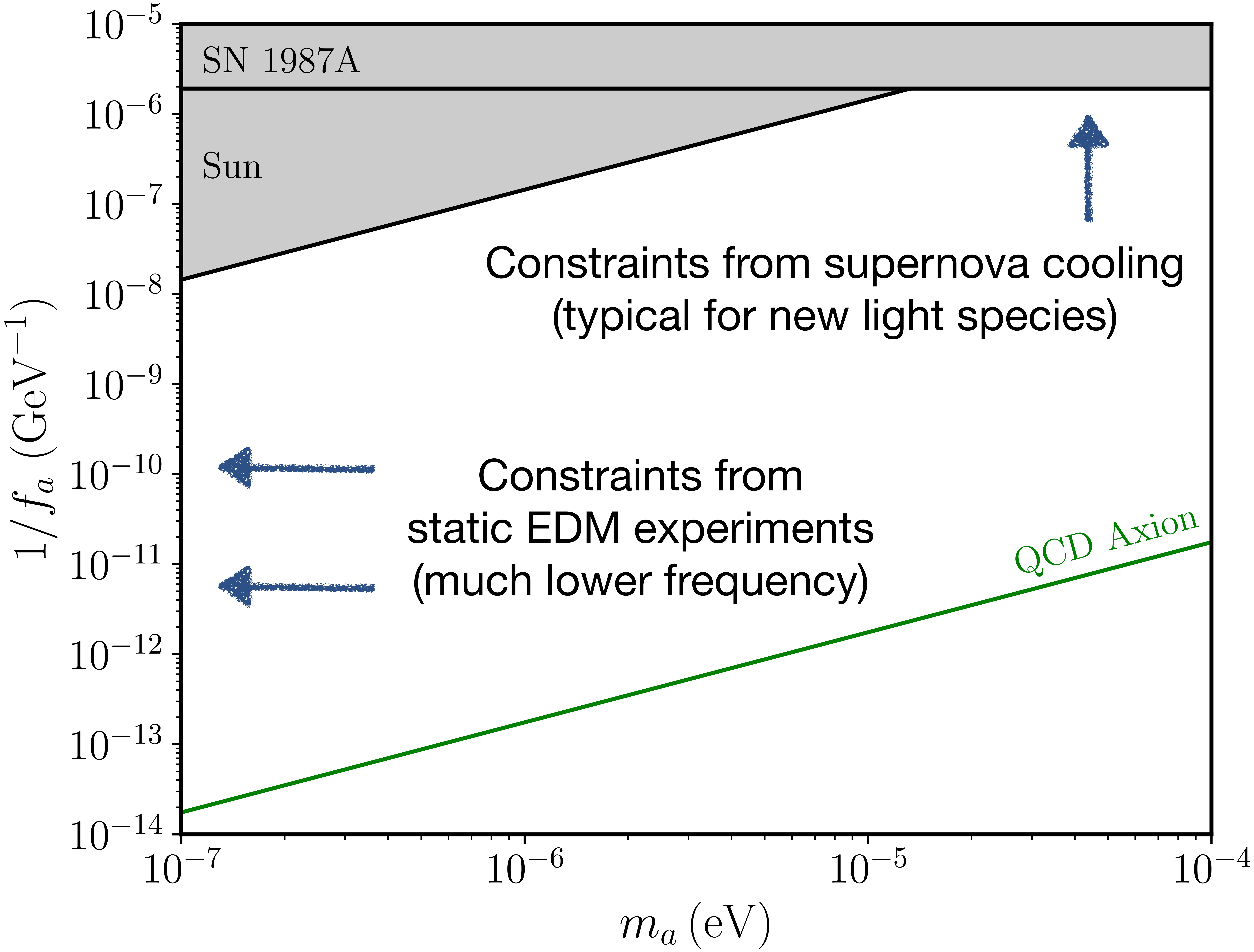
$$\text{neutron EDM } d_n = (2.4 \times 10^{-3}\, e\,\mathrm{fm})\,\theta_a \equiv g_d\, a$$

Tiny effect hard to measure, especially at GHz axion frequencies ($m_a \sim \mu\mathrm{eV}$)

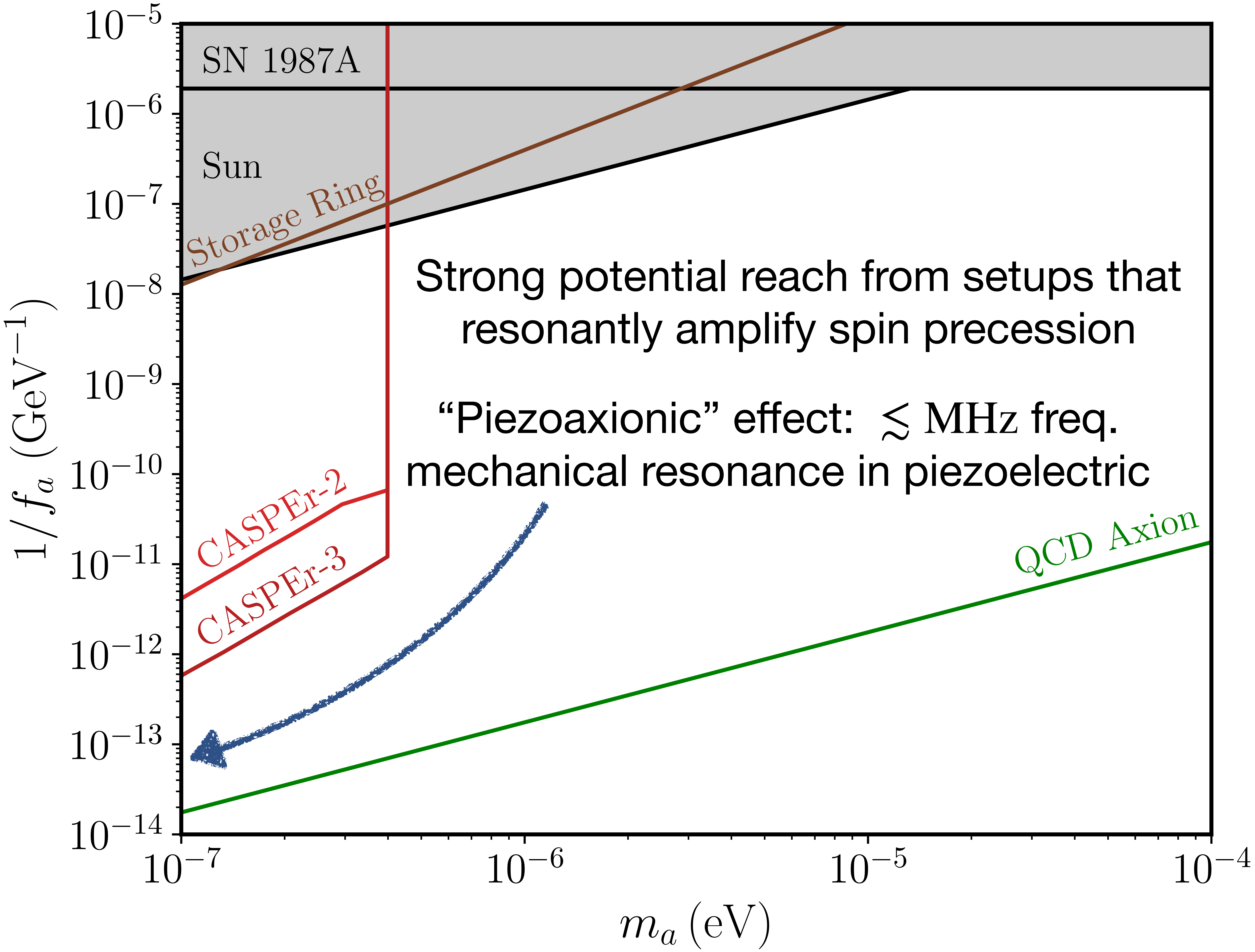


QCD axion has definite mass given coupling!

On the way there, probe non-QCD axions, or nonminimal QCD axions where potential cancels



SN 1987A
Sun
Constraints from supernova cooling
(typical for new light species)
Constraints from
static EDM experiments
(much lower frequency)
QCD Axion
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$1/f_a\ (\mathrm{GeV}^{-1})$
10^{-7}
10^{-6}
10^{-5}
10^{-4}
$m_a\ (\mathrm{eV})$


SN 1987A
Sun
Storage Ring
Strong potential reach from setups that resonantly amplify spin precession
"Piezoaxionic" effect: $\lesssim$ MHz freq. mechanical resonance in piezoelectric
CASPEr-2
CASPEr-3
QCD Axion
$1/f_a\ (\mathrm{GeV}^{-1})$
$m_a\ (\mathrm{eV})$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
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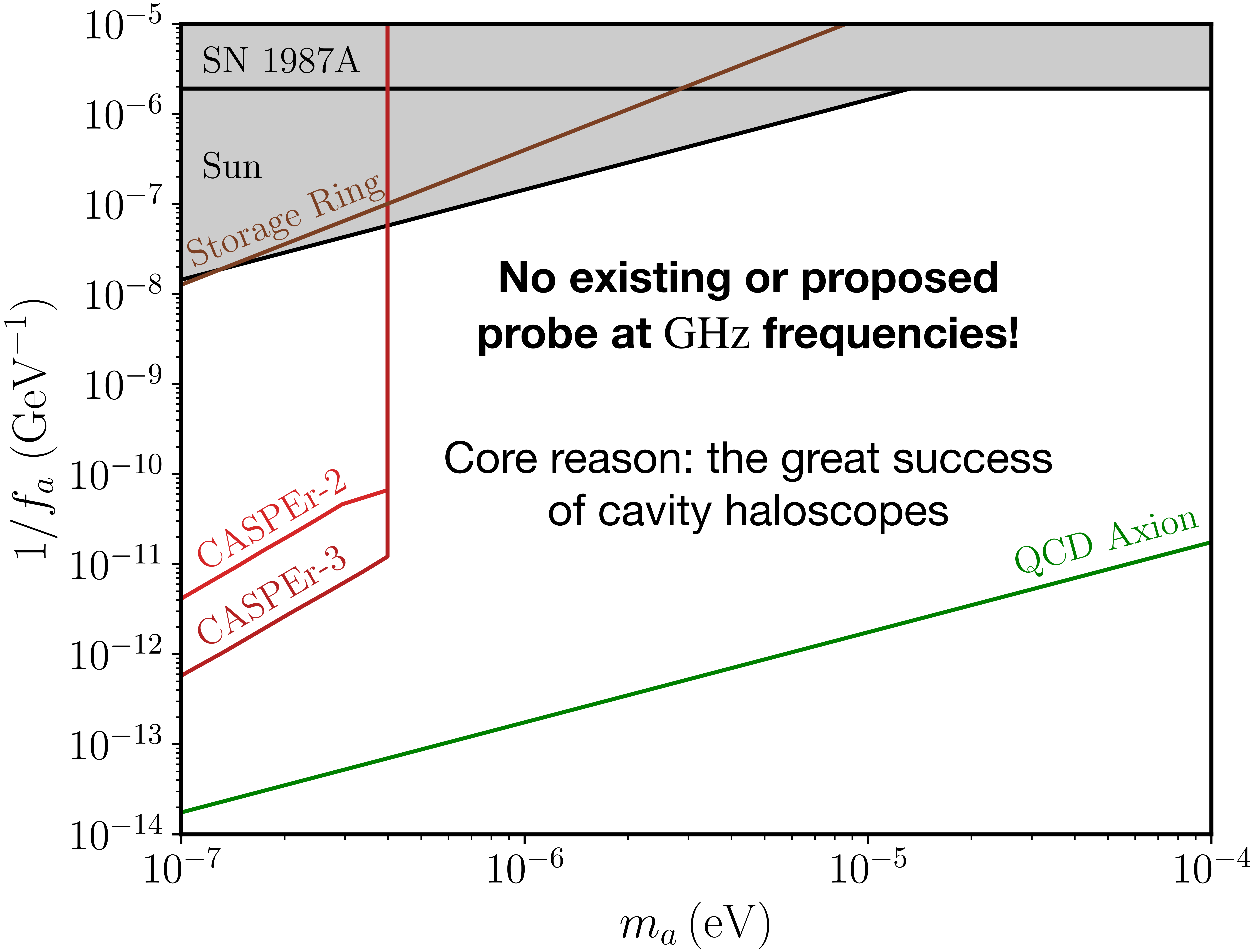
10^{-5}
10^{-4}



SN 1987A
Sun
Storage Ring
CASPEr-2
CASPEr-3
QCD Axion
No existing or proposed probe at GHz frequencies!
Core reason: the great success of cavity haloscopes
$1/f_a\ (\mathrm{GeV}^{-1})$
$m_a\ (\mathrm{eV})$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-7}
10^{-6}
10^{-5}
10^{-4}

Electromagnetic Axion Detection

Generically, QCD axions have a coupling to electromagnetism

$$\mathscr{L} \supset -\frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}, \qquad g_{a\gamma\gamma} = \frac{\alpha C_{a\gamma}}{2\pi f_a}$$

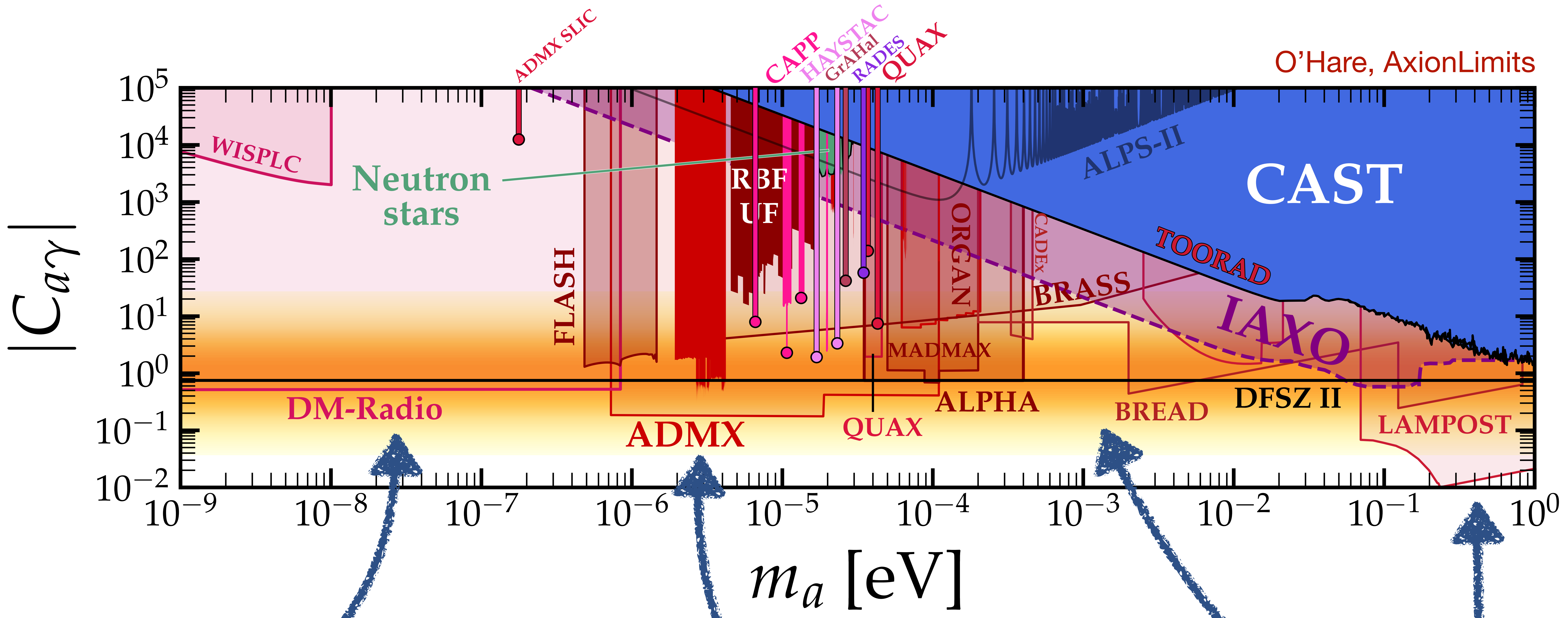
Order-one coefficient $C_{a\gamma}$ varies within 1-2 orders of magnitude for simple models

Leading signature: modifies Ampere's law to include effective current

$$\nabla \times \mathbf{B} = \mathbf{J} + \mathbf{J}_{\text{eff}}, \qquad \mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\dot{a}\mathbf{B}$$

Electromagnetic Axion Detection

Most proposed approaches apply a large $\mathbf{B}$ and resonantly amplify $\mathbf{J}_{\text{eff}}$

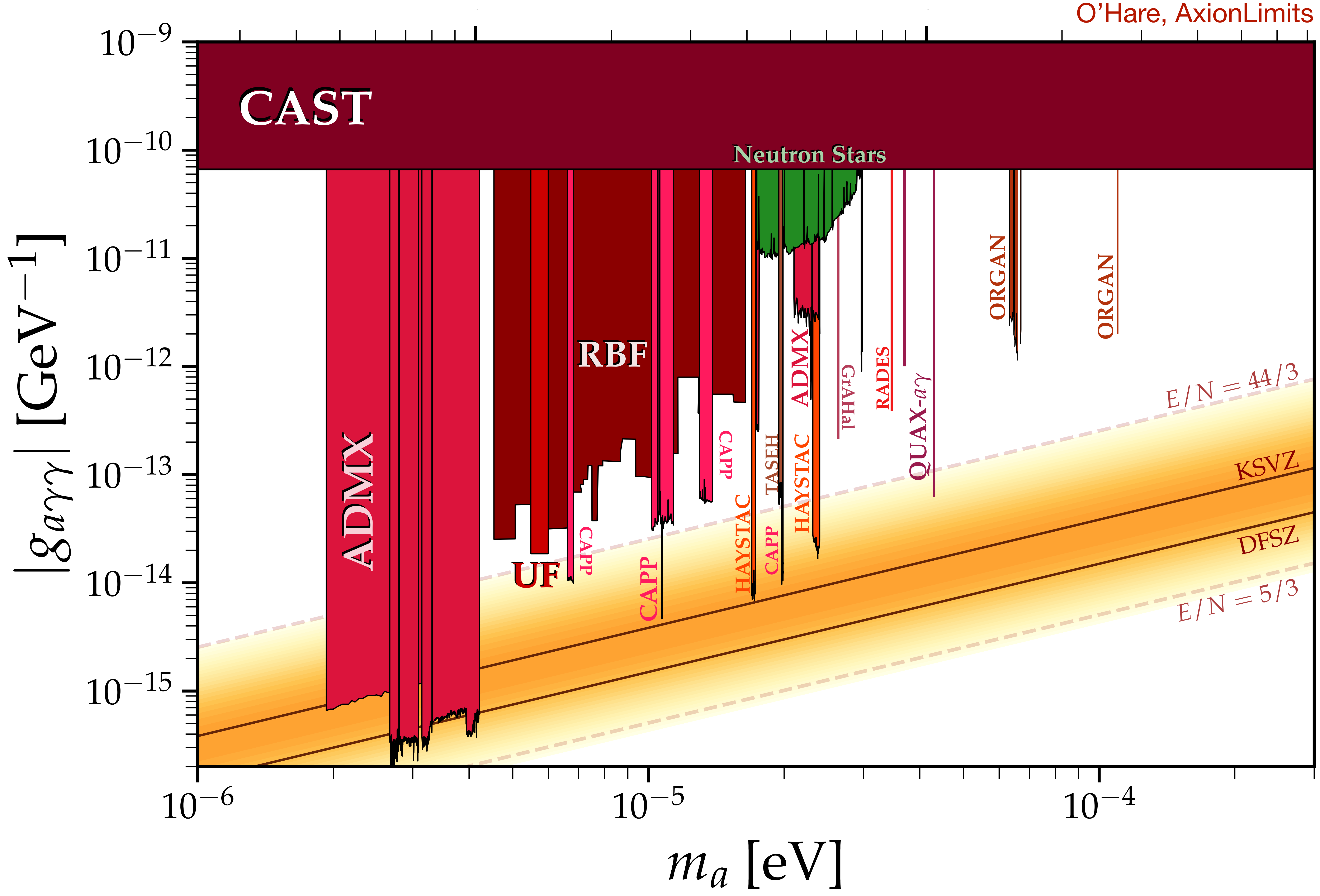


LC circuits or frequency conversion

<u>Meter-scale microwave cavities</u>

Metamaterials/quasiparticles/ cavity structure/nonresonant

The Cavity Haloscope



- RF cavity resonantly amplifies $\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\dot{a}\mathbf{B}$ from coupling to photons
- After 35 years, finally sensitive to canonical QCD axion models

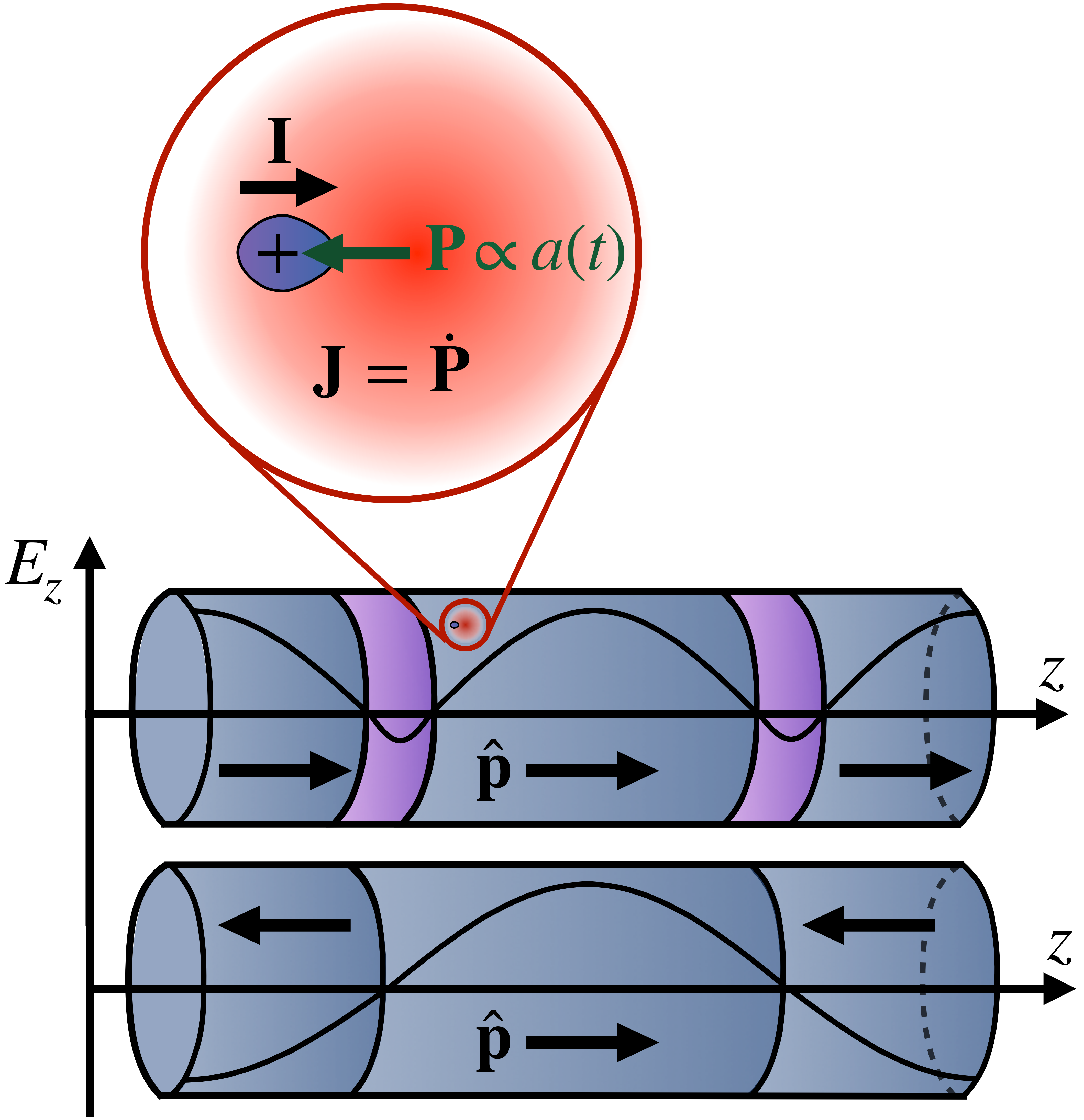
The Cavity Haloscope

- RF cavity resonantly amplifies $\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\dot{a}\mathbf{B}$ from coupling to photons
- After 35 years, finally sensitive to canonical QCD axion models
- Rapidly growing field, with wide international interest

Can translate this success to the axion-gluon coupling with **polarization haloscopes**

Outline

- The QCD axion
- **Axion-induced polarization**
- Making a polarization haloscope



Polarization Currents

QCD axion produces neutron EDMs $d_n = g_d\, a$ along spin, so we can estimate a sample with density n_n of spin-polarized neutrons carries a real current

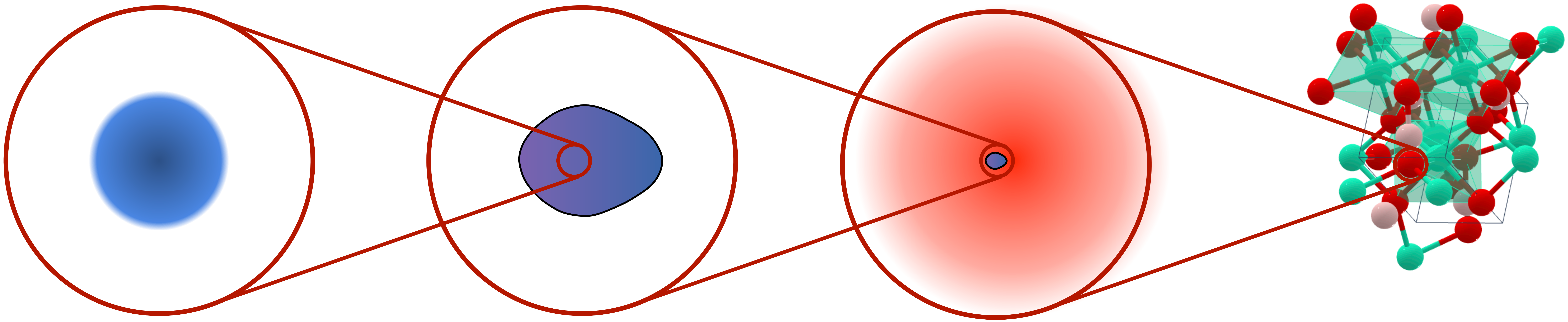
$$\mathbf{J}_{\mathrm{EDM}} = \dot{\mathbf{P}} = g_d\, \dot{a}\, n_n$$

For a typical QCD axion, this is 10^{-3} of $J_{\mathrm{eff}} = g_{a\gamma\gamma}\dot{a}\mathbf{B}$ in a cavity haloscope! But:

- Probes qualitatively new parameter space
- Removes model dependence on photon coupling
- Only known way to verify a cavity haloscope signal is the QCD axion

Refining the Estimate

The previous estimate treats neutrons as separate particles, but:



neutrons are in nuclei nuclei are in atoms atoms are in materials

The estimate turns out to be okay, but only for appropriate nuclei and materials!

Inducing Atomic EDMs

- The QCD axion induces a nuclear EDM, both directly through nucleon EDMs and indirectly by P and CP violating modifications to internucleon interactions

- But in the nonrelativistic limit, a nuclear EDM is completely shielded by electrons, leading to zero overall atomic EDM d_A (Schiff's theorem)

- Next most relevant P and CP-violating nuclear moments induced by the axion:

    - Electric octupole moment (subdominant)

    - <u>Schiff moment</u> (focus of this talk)

    - Magnetic quadrupole moment (potentially also competitive)

Schiff Moments

- The Schiff moment is a "radius-weighted" dipole moment:

$$\mathbf{S} \sim \int d^3\mathbf{x}\, \rho_N(\mathbf{x})\, r^2\, \mathbf{x}$$

- Describes an internal electric field in the nucleus, which acts on electrons by

$$V_S = -\sum_{i=1}^{Z} e\mathbf{S} \cdot \nabla \delta^3(\mathbf{x}_i)$$

- This P and CP violating contact interaction yields atomic EDM $d_A \propto Z^2 S$

Schiff Moments

- For spherical nuclei, Schiff moments induced by internucleon interaction are

$$\langle S_z \rangle \sim \sum_n \frac{\langle n | V_a | 0 \rangle \langle 0 | S_z | n \rangle}{E_n - E_0} \sim 10^{-2} \, \frac{eR_0^2}{m_n} \, \theta_a$$

- Small nuclear size R_0 yields small atomic EDMs except for heavy unstable nuclei

- More promising: octupole-deformed nuclei with intrinsic Schiff moments,

$$\langle S_z \rangle = S_{\text{int}} \langle n_z \rangle, \qquad S_{\text{int}} \propto ZeR_0^3, \qquad \langle n_z \rangle \sim \sum_n \frac{\langle n | V_a | 0 \rangle \langle 0 | n_z | n \rangle}{E_n - E_0}$$

- For strongly deformed nuclei, final result is Z-enhanced: $\langle S_z \rangle \sim 10^{-2} \, \dfrac{ZeR_0^2}{m_n} \, \theta_a$

Schiff Moments

	$^{161}\mathrm{Dy}$	$^{153}\mathrm{Eu}$	$^{155}\mathrm{Gd}$
estimated $\langle S_z \rangle$ (e fm^3 θ_a)	4.3	1.0	1.2
estimated $\lvert d_A \rvert$ (10^{-3} e fm θ_a)	1.2	0.25	0.3
natural abundance	19%	52%	15%
metal price ($/ton)	300 k	30 k	30 k

- Octupole deformations can exist in rare earth nuclei, which are stable and cheap
- Can produce atomic EDMs of order $d_A \sim d_n$, validating earlier estimate
- More numeric and experimental work needed to verify octupole deformation
- Can also use magnetic quadrupole moments enhanced by quadrupole deformation: well established, $\mathcal{O}(1)$ weaker signals

Outline

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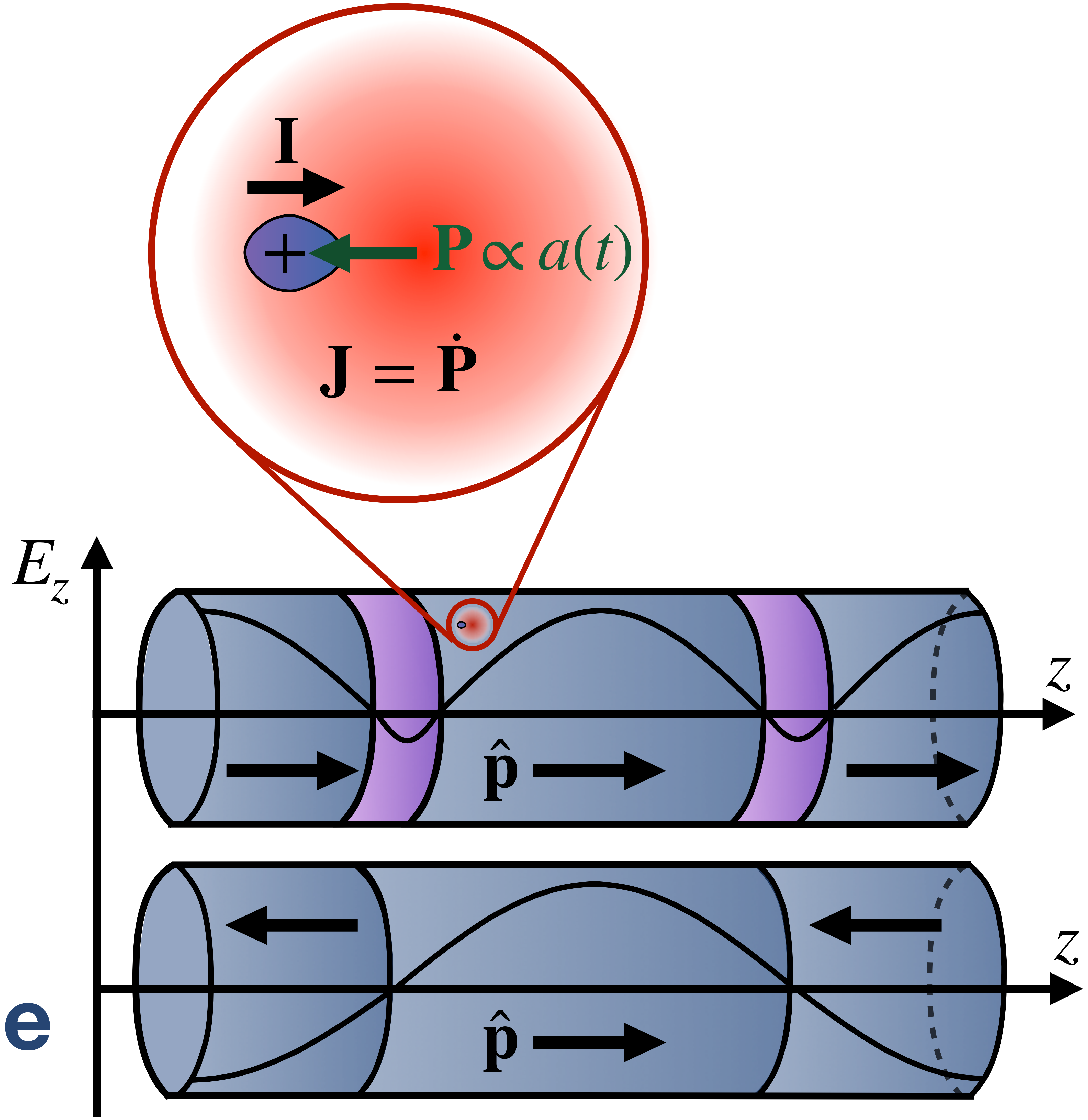


Signal Power

Power in mode with profile $\mathbf{E}_i$ on resonance ($m_a \simeq \omega_i$) is

$$P_{\text{sig}} \simeq m_a \, (f_p \, n_0 \, d_A)^2 \, \frac{V}{\bar{\epsilon}} \, \eta_i^2 \;\; \min(Q_a, Q_i)$$

Polarization density (fractional nuclear spin polarization f_p)

Resonant enhancement

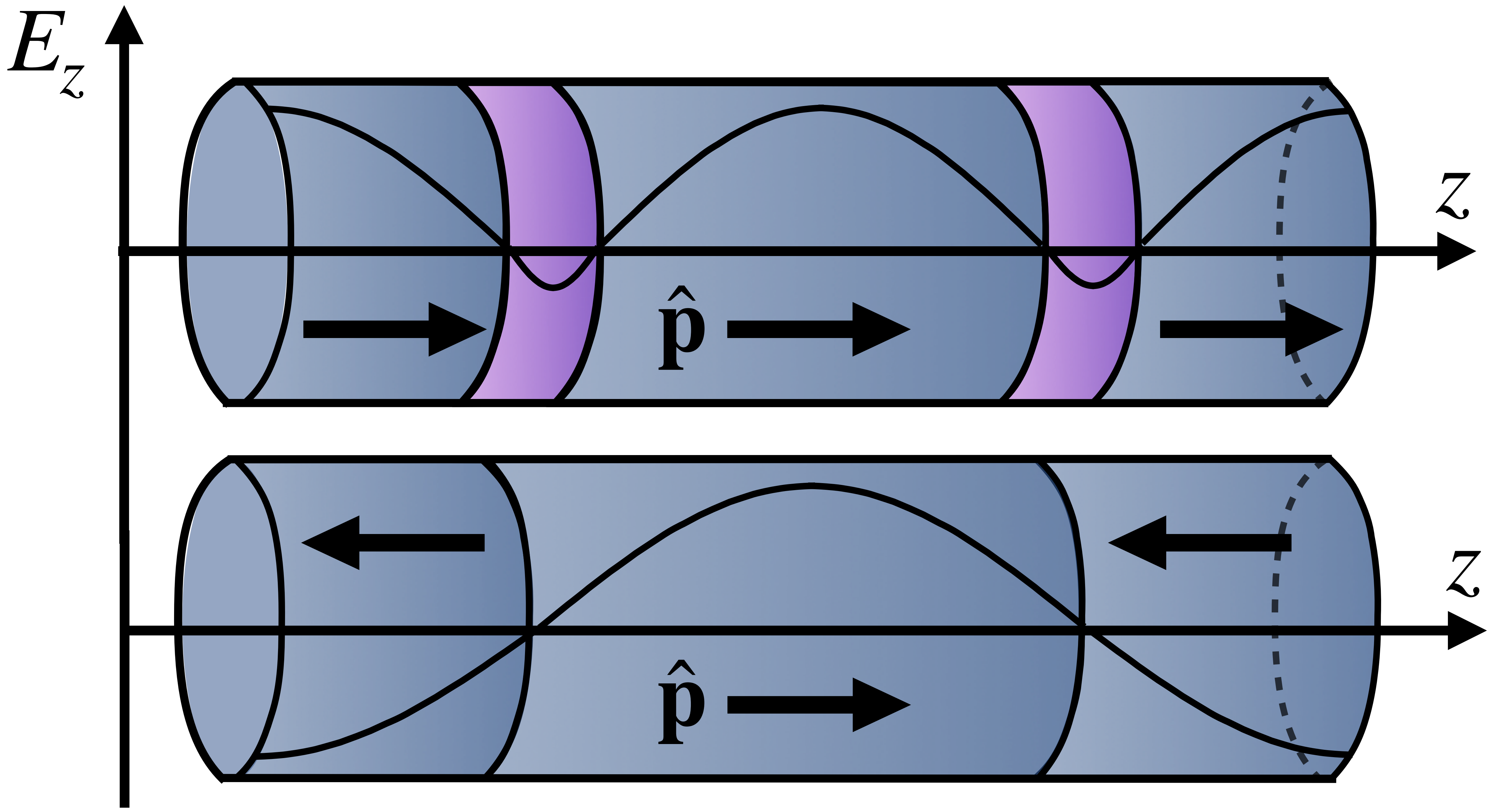
Dielectrics shield electric fields

Geometric form factor

$$\eta_i = \frac{\left| \int_{V_p} d^3\mathbf{x} \, \mathbf{E}_i \cdot \hat{\mathbf{p}} \right|}{\sqrt{V \int_V d^3\mathbf{x} \, (\epsilon/\bar{\epsilon}) \, E_i^2}} \lesssim 1$$

Optimizing Geometry

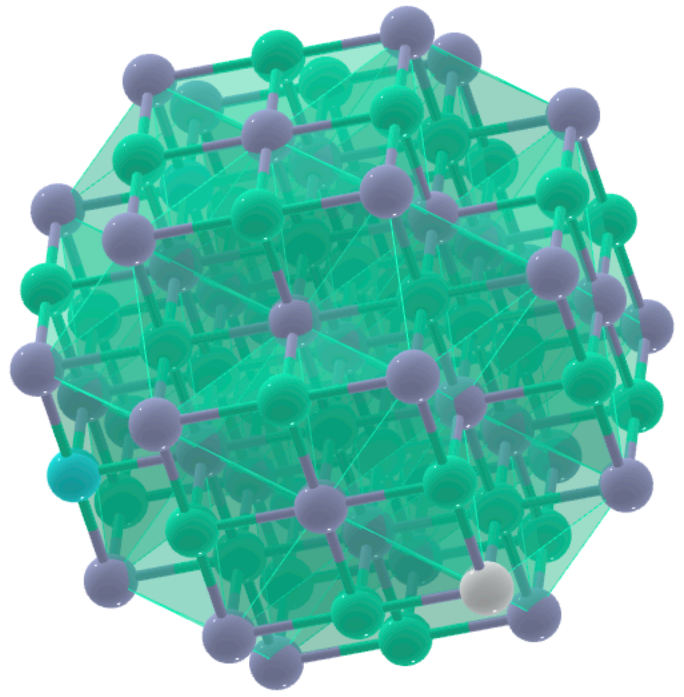
To maximize the geometric form factor, align nuclear spins $\hat{\mathbf{p}}$ with $\mathbf{E}_i$



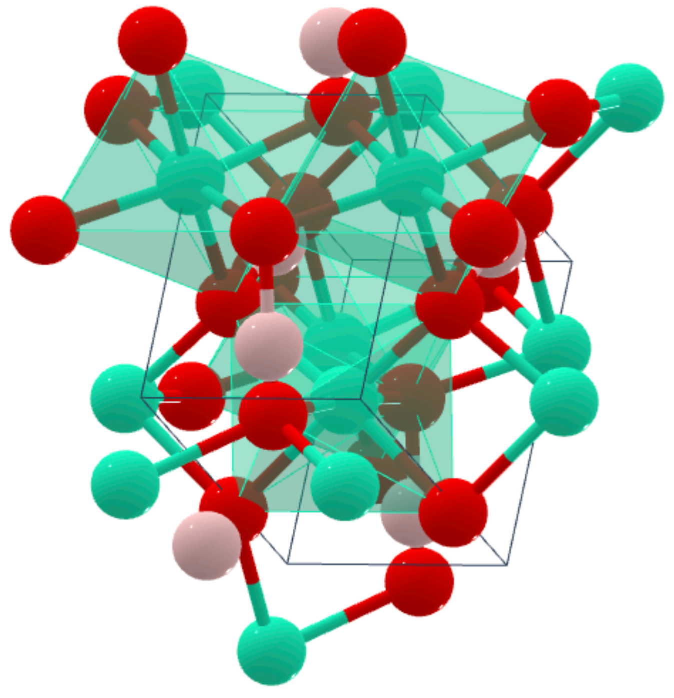
Layers can cover up to $m_a \sim 10^{-5}\,\mathrm{eV}$, but many other approaches possible

Optimizing Material

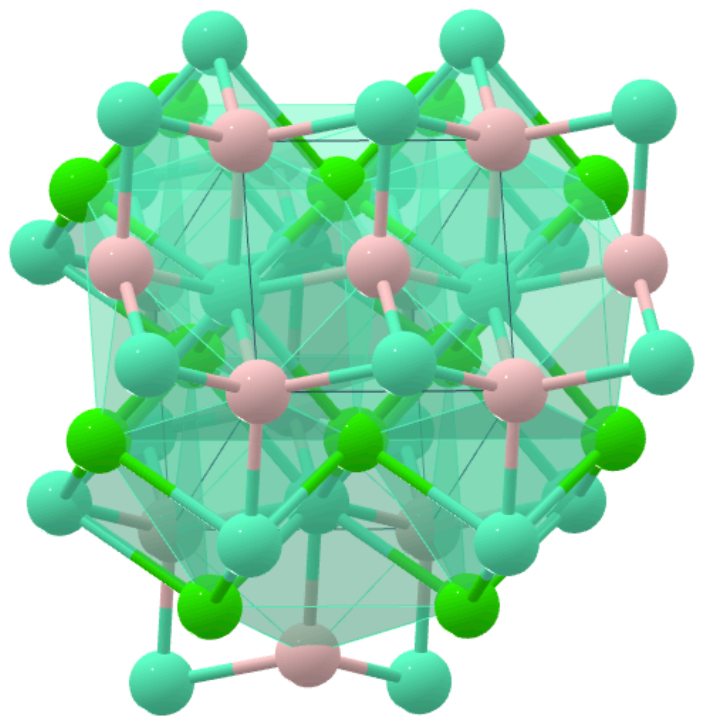
Material only has to be insulating, and have high number density of desired nuclei



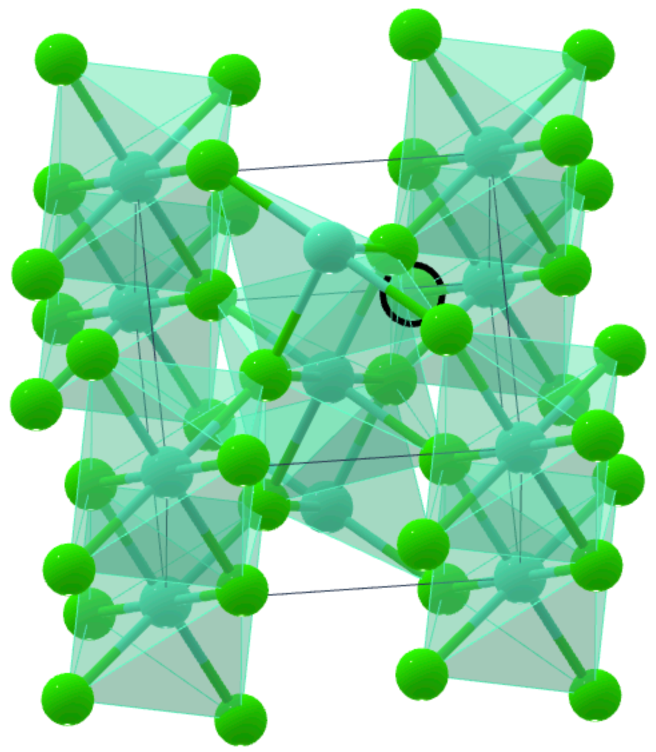
DyN



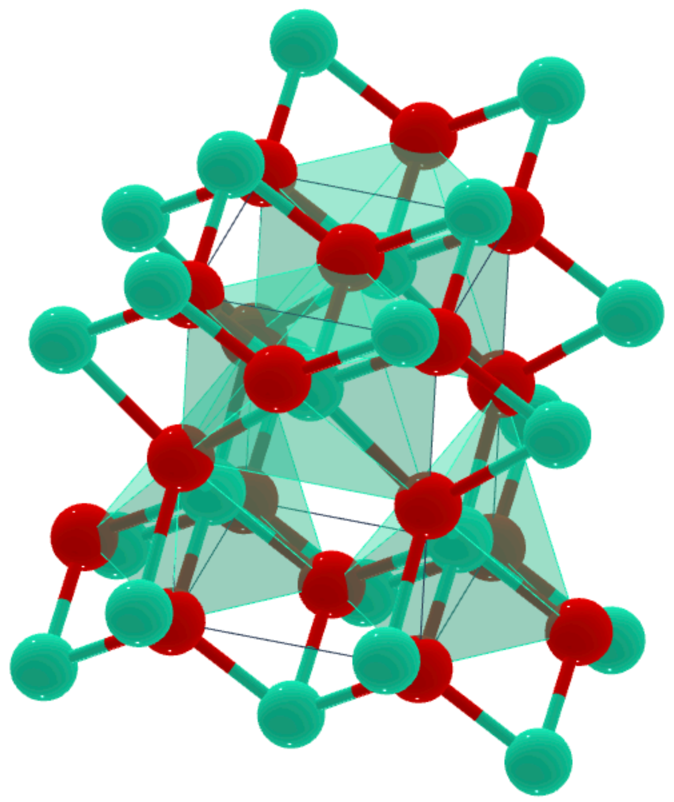
Dy_2O_3



$DyHO_2$



EuHCl



$EuCl_2$

some simple, stable, commercially available possibilities

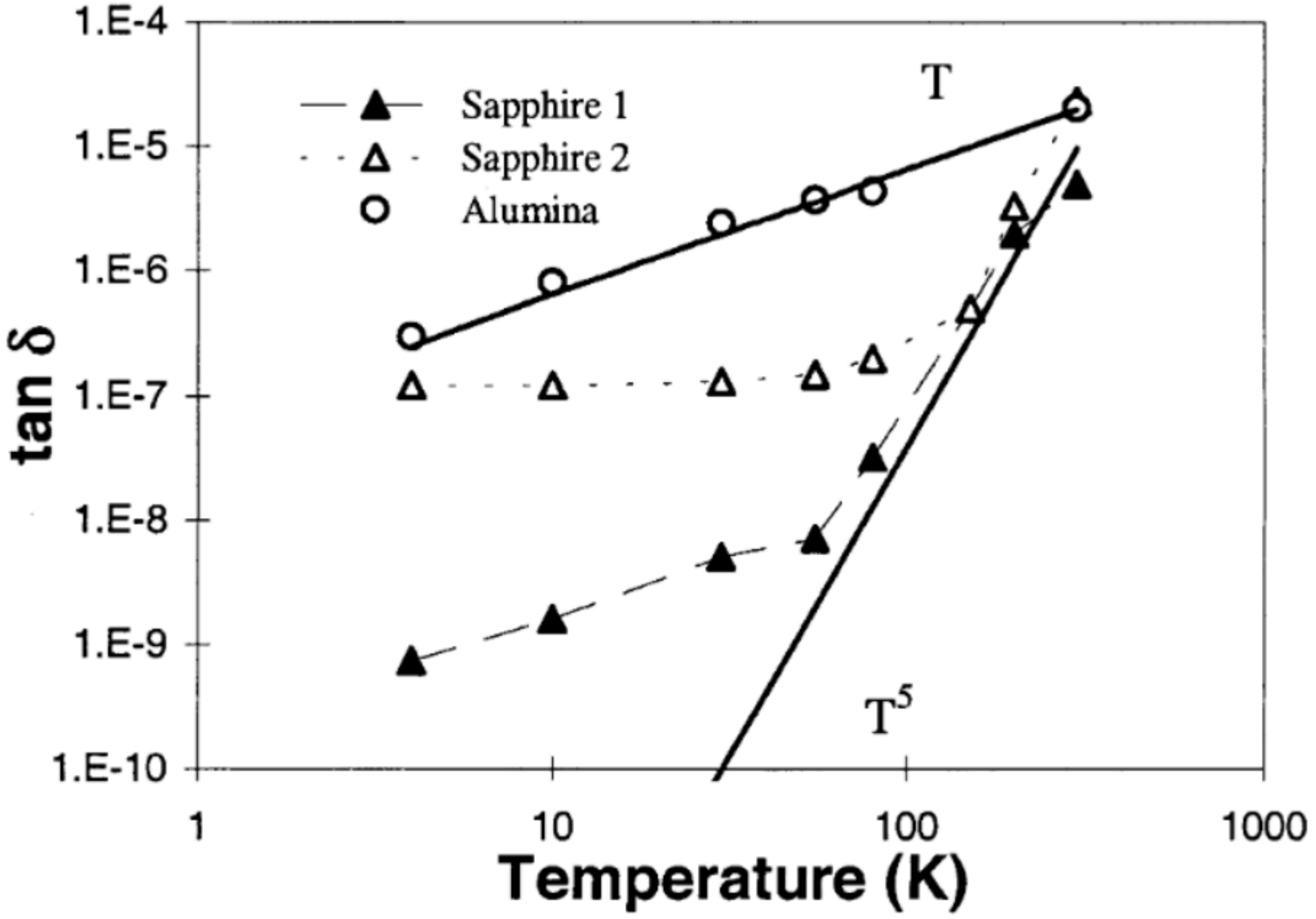
We account for the most important material effect: dielectric shielding by $\epsilon \sim 10$

(modifications of atomic orbitals inside solid are $\sim 25\,\%$ effect,
but require many body simulation to compute)

Dielectric Loss

- Need low dielectric loss tangents $\tan\delta \lesssim 10^{-6}$
- Intrinsic losses fall rapidly as T decreases, so extrinsic losses dominate at low T
- Losses depend on T, ω, and applied field; need dedicated measurements
- But loss tangents far below 10^{-6} observed for high quality crystals

Alford et al. (2001)



Spin Polarization

Thermal spin polarization depends on B/T, is $\sim 1\%$ at typical haloscope conditions

Like other approaches, achieving best sensitivity requires order-one f_p

<u>Brute force approach</u>

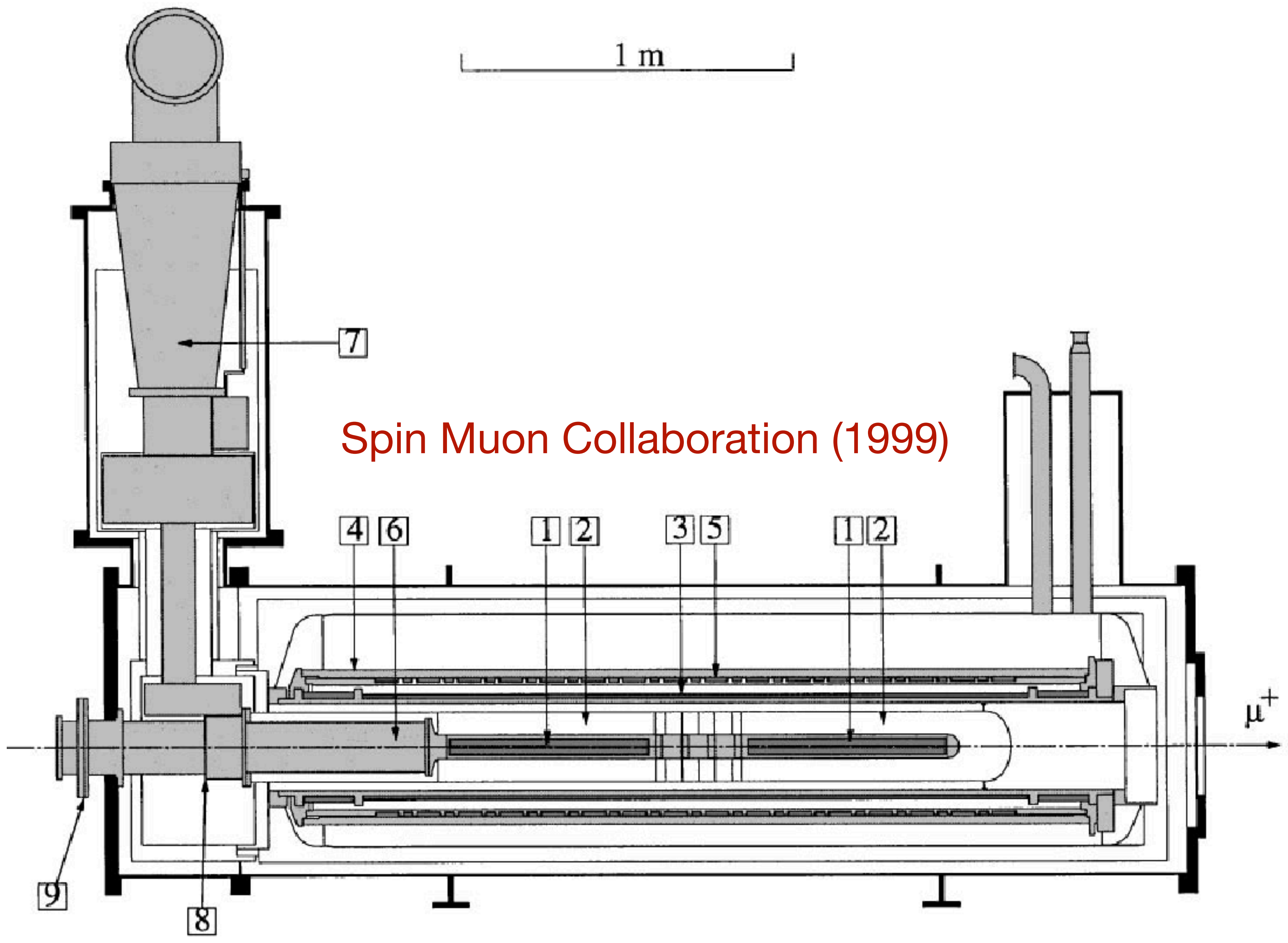
Apply $B \gtrsim 10\,\mathrm{T}$ at $T \sim 2\,\mathrm{mK}$

But: thermalization time may be prohibitively long

Spin Polarization

Thermal spin polarization depends on B/T, is $\sim 1\%$ at typical haloscope conditions

Like other approaches, achieving best sensitivity requires order-one f_p



Spin Muon Collaboration (1999)

Frozen spin dynamic nuclear polarization

Polarize electron spins, transfer to nuclei with microwave radiation, and "freeze" result by lowering T

More elaborate instrumentation, but meter-scale targets realized at CERN

Sensitivity Estimate

All noise sources besides thermal and amplifier noise vastly subdominant

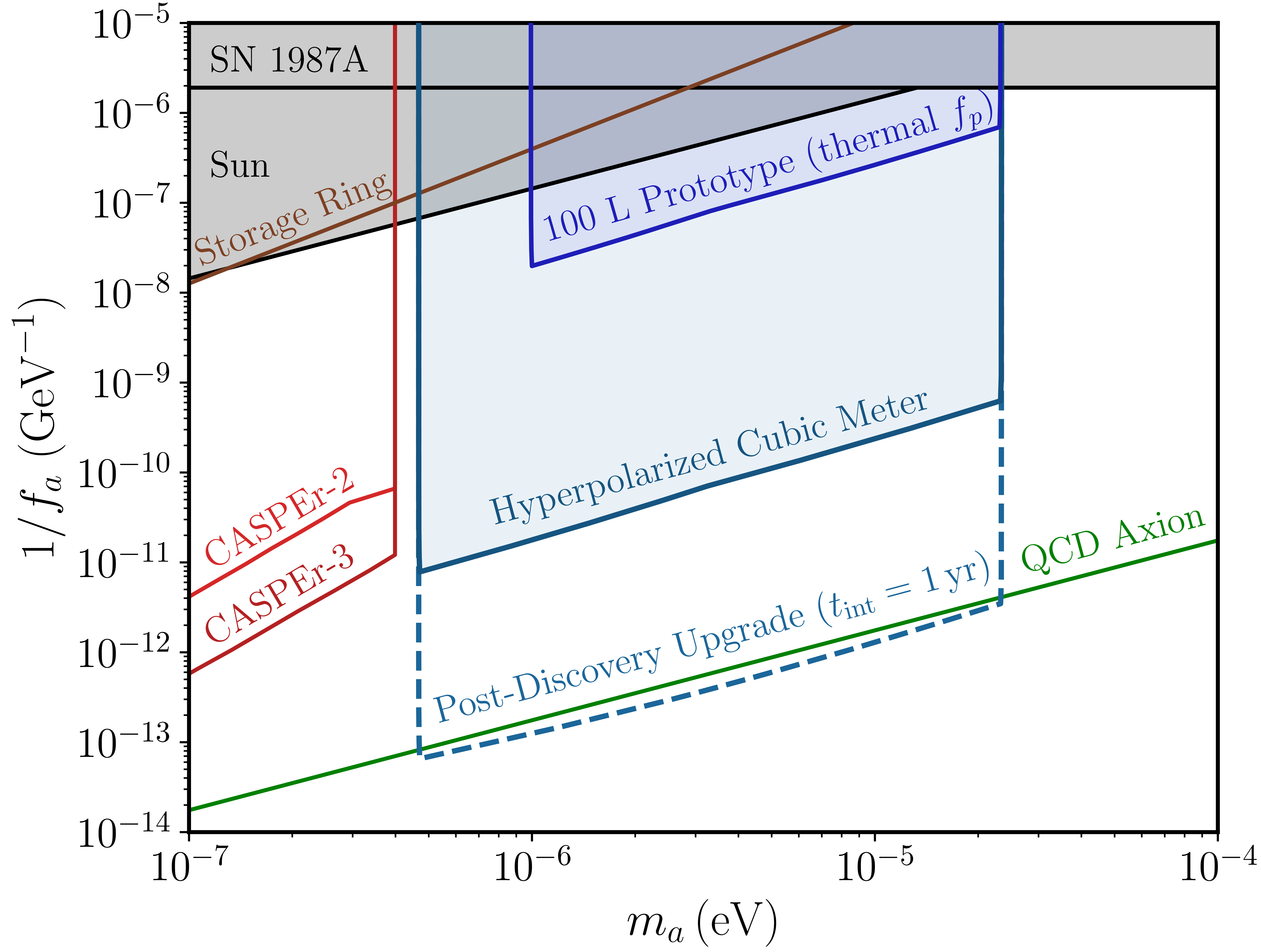
$$\mathrm{SNR} \simeq \frac{P_{\mathrm{sig}}}{T_n} \sqrt{\frac{t_{\mathrm{int}}}{\Delta \nu_s}}, \qquad T_n = T + T_{\mathrm{amp}}$$

Assume quantum-limited amplifier, $T_{\mathrm{amp}} = m_a$, and usual scanning procedure

$$\Delta \nu_s = \frac{m_a}{2\pi \, \max(Q, Q_a)}, \qquad t_{\mathrm{int}} = \frac{t_e}{\min(Q, Q_a)}$$

which implies $\mathrm{SNR} \propto \sqrt{Q \, Q_a \, t_e}$ (overcoupling enhances by $\sqrt{T/m_a}$)

Potential Reach



Existing haloscope with dielectric probes new parameter space!

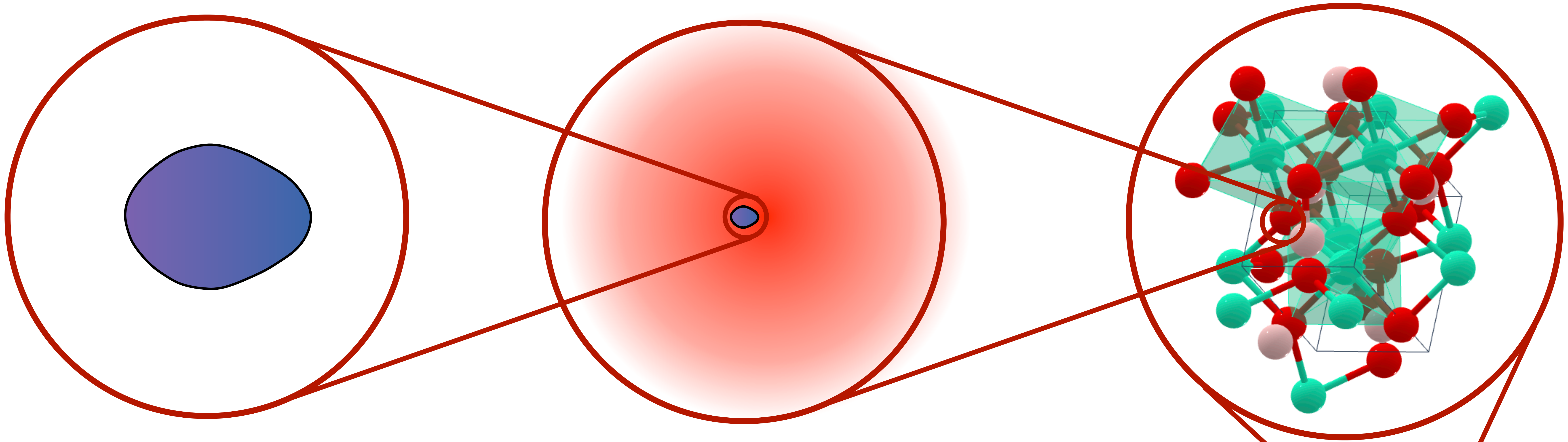
$(Q, V, f_p, T) = 10^5, 0.1\,\mathrm{m}^3, 5\,\%\,, 40\,\mathrm{mK}$

Hyperpolarized sample probes orders of magnitude further

$(Q, V, f_p, T) = 10^6, 1\,\mathrm{m}^3, 100\,\%\,, 40\,\mathrm{mK}$

Mild further upgrade can test candidate μeV QCD axion

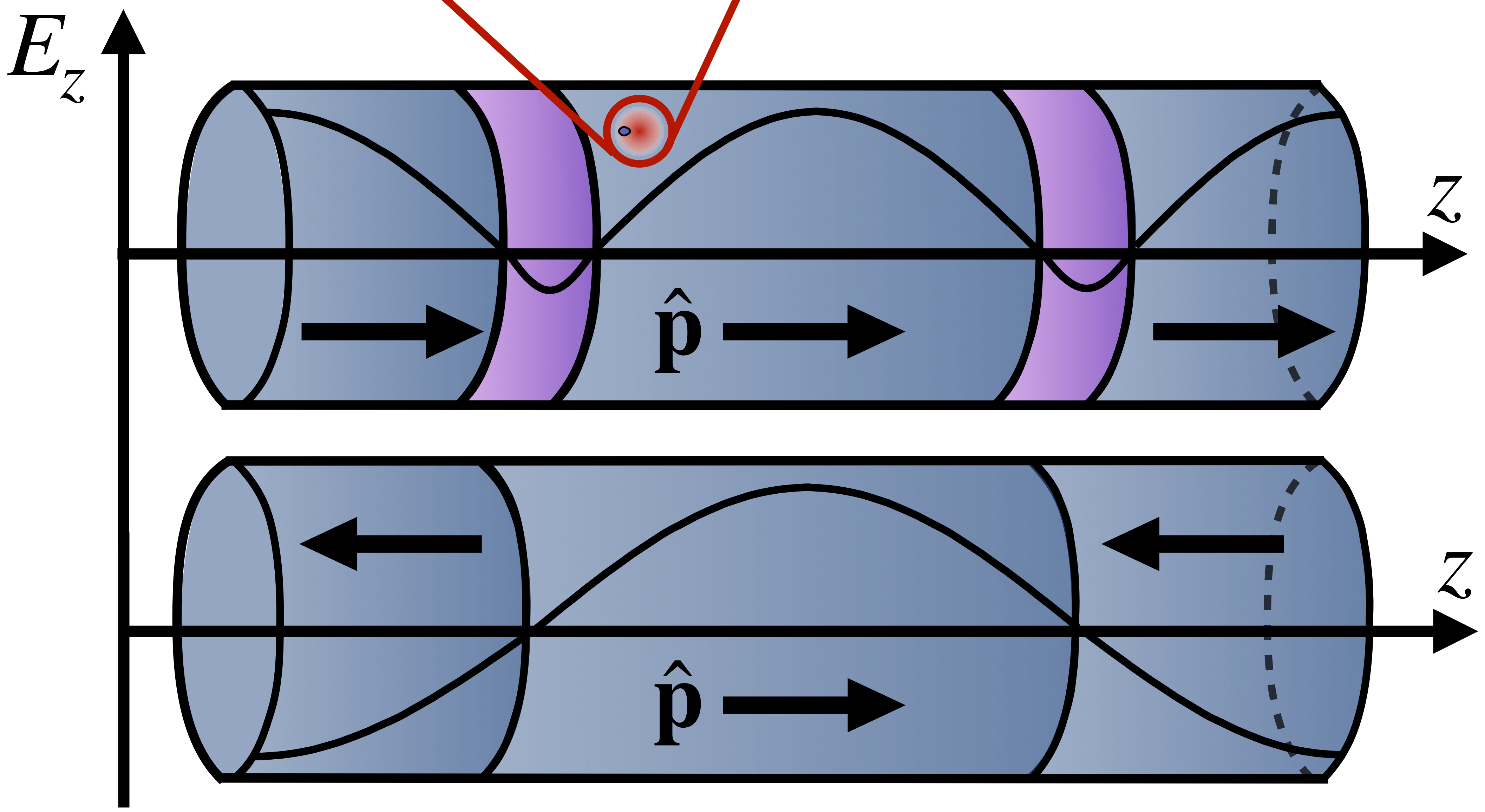
$(Q, V, f_p, T) = 10^8, 1\,\mathrm{m}^3, 100\,\%\,, 10\,\mathrm{mK}$



polarization current $\mathbf{J} = n_A \dot{\mathbf{d}}_A$

octupole-enhanced Schiff moment $\mathbf{S}$

atomic EDM $\mathbf{d}_A$



cavity power $P \sim J^2 V Q / m_a \epsilon$

Polarization haloscopes are a natural next step in the development of cavity haloscopes

In near term, motivates investigation of axion-induced EDMs and appropriate materials

In long term, only way to test if an axion is the QCD axion