Discovering the QCD Axion with Polarization Haloscopes

Kevin Zhou

Stanford University

SLAC

PHENO 2023 — May 8, 2023

based on arXiv:2209.12901, with Asher Berlin

Signatures of QCD Axion Dark Matter

$$\mathscr{L} \supset \frac{1}{8\pi f_a}\left(\alpha_s\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu} - \alpha_{\rm EM} C_{a\gamma}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}\right)$$

Defining coupling to gluons, responsible for solving strong CP problem

Yields oscillating CP violating nuclear effects like neutron EDM

$$d_n = g_d\, a \sim (10^{-21}\, e\, \mathrm{fm})\, \cos m_a t$$

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

Signatures of QCD Axion Dark Matter

$$\mathscr{L} \supset \frac{1}{8\pi f_a} \left(\alpha_s \, a \, G^{\mu\nu} \tilde{G}_{\mu\nu} - \alpha_{\rm EM} C_{a\gamma} \, a \, F^{\mu\nu} \tilde{F}_{\mu\nu} \right)$$

Defining coupling to gluons, responsible for solving strong CP problem

Yields oscillating CP violating nuclear effects like neutron EDM

$$d_n = g_d \, a \sim (10^{-21} \, e \, \mathrm{fm}) \cos m_a t$$

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

Coupling to photons can vary by 2 orders of magnitude in simple models

Yields effective currents $\mathbf{J}_{\rm eff} = g_{a\gamma\gamma} \dot{a} \mathbf{B}$ which can be resonantly amplified in GHz frequency cavity haloscopes

This talk: adapt cavity haloscopes to polarization haloscopes, which probe the axion-gluon coupling

Estimating Polarization Currents

QCD axion produces time-varying neutron EDMs $d_n = g_d\, a$ along neutron spin, so a cavity filled 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 the current in a cavity haloscope

Estimating Polarization Currents

QCD axion produces time-varying neutron EDMs $d_n = g_d\, a$ along neutron spin, so a cavity filled with density n_n of spin-polarized neutrons carries a real current

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

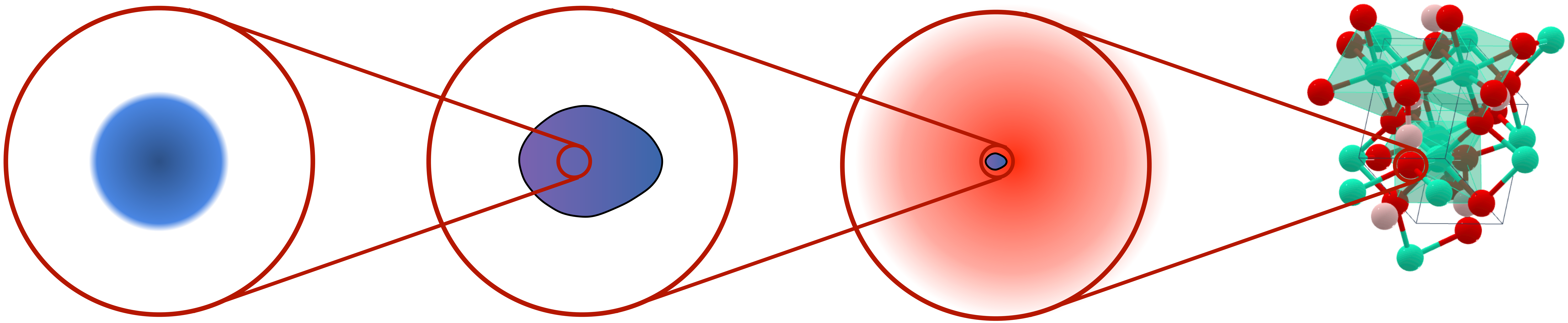
For a typical QCD axion, this is 10^{-3} of the current in a cavity haloscope

Tough but possible to reach in the future, and worth trying, because it:

- probes qualitatively new parameter space
- removes model dependence on photon coupling
- is only known way to verify a cavity haloscope signal is the QCD axion

Refining the Estimate

In reality, microwave cavity is filled with insulating material, not just free neutrons:



neutrons are in nuclei, nuclei are in atoms, atoms are in materials.

Resulting polarization current depends strongly on nucleus and material, but the free neutron estimate can be attained

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 shielded by electrons, leading to no overall atomic EDM d_A and thus no polarization current!

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 shielded by electrons, leading to no overall atomic EDM d_A and thus no polarization current!

- Atomic EDMs come from other axion-induced P, CP-violating nuclear moments:

electric octupole Q_{ijk} magnetic quadrupole M_{ij} Schiff moment $\mathbf{S}$

most promising due to collective enhancement
$S \propto Z$ in octupole-deformed nuclei!

Schiff Moments

	^{161}Dy	^{153}Eu	^{155}Gd
estimated $\langle S_z \rangle$ (e fm^3 θ_a)	4.3	1.0	1.2
estimated $|d_A|$ (10^{-3} e fm θ_a)	1.2	0.25	0.3

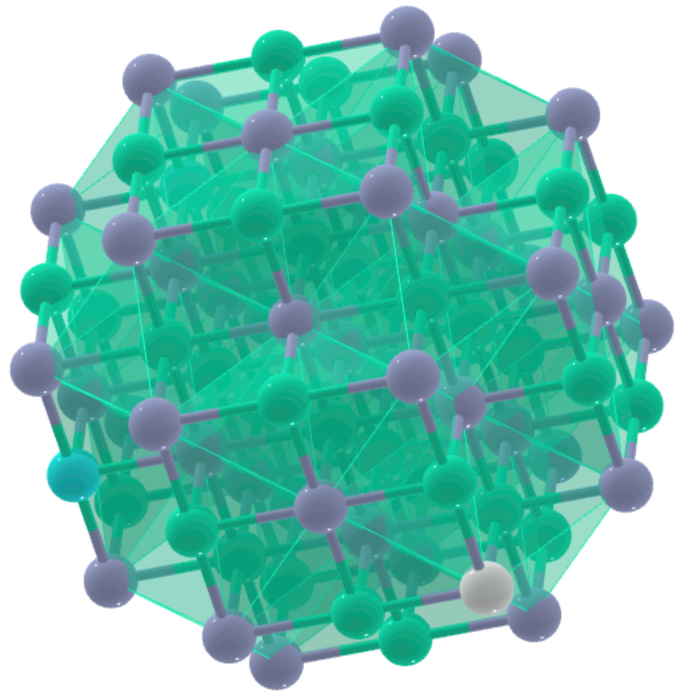
- Octupole deformations can exist in stable, commercially available rare earth nuclei (though more numeric and experimental work needed to verify)

- Can produce significant atomic EDMs of order $d_A \propto Z^2 S \sim d_n$

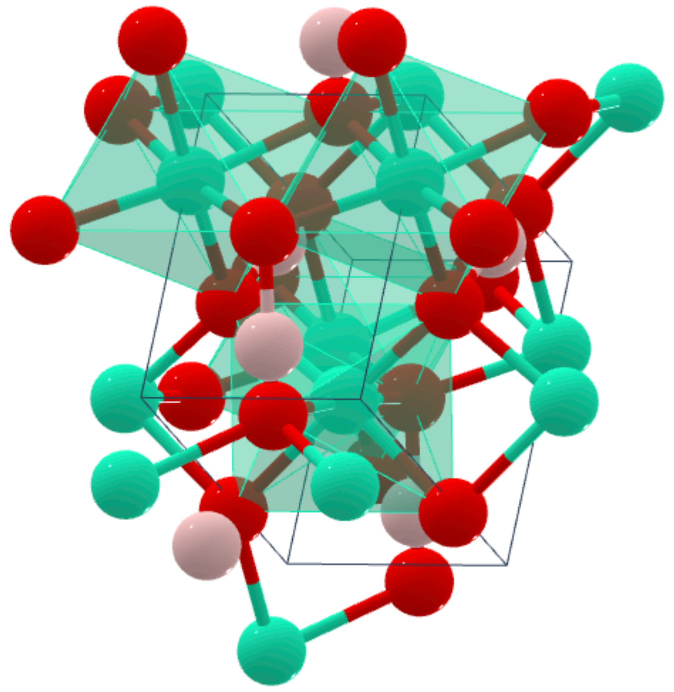
- Can also use magnetic quadrupole moments enhanced by quadrupole deformation: well established, but $\mathcal{O}(1)$ weaker signals

Some Candidate Materials

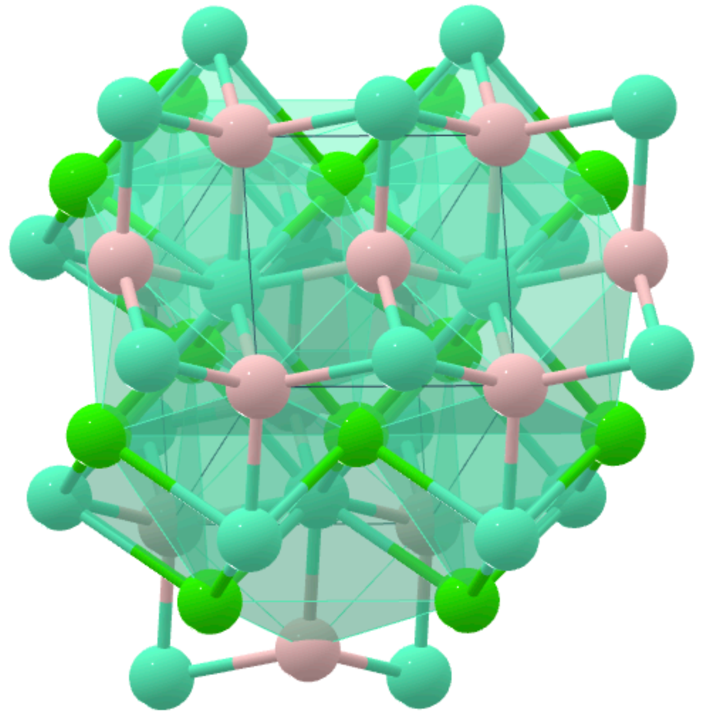
Material only has to be insulating, and have high number density of desired nuclei



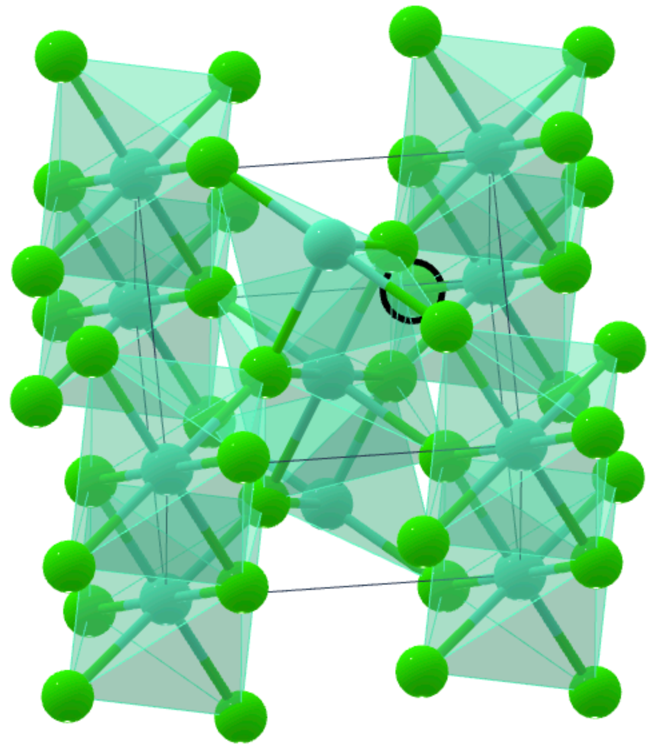
DyN



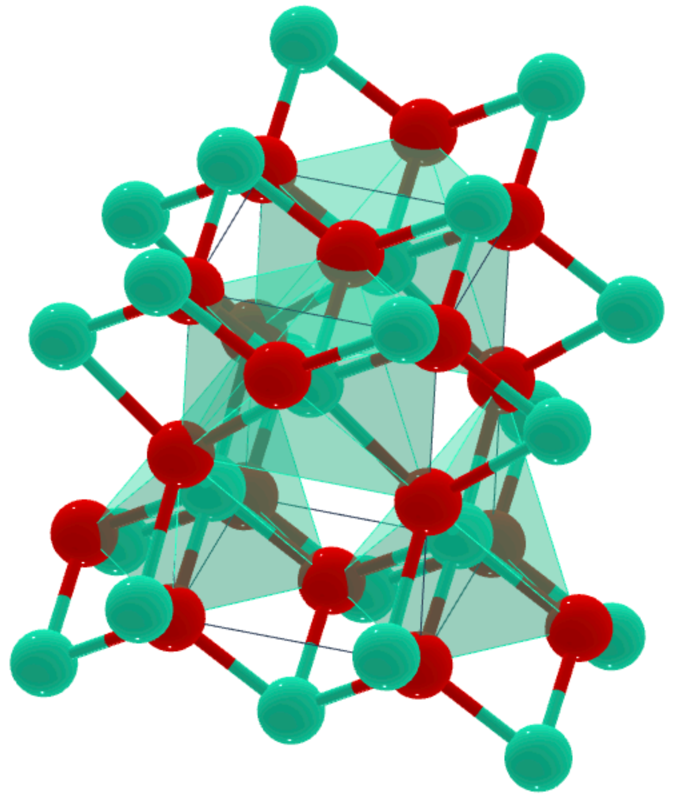
Dy_2O_3



$DyHO_2$



EuHCl



$EuCl_2$

(some simple, stable, commercially available possibilities)

Signal Power

In cavity filled with dielectric material, power in mode on resonance ($\omega_i \simeq m_a$) is

$$P_{\rm sig} \simeq m_a V \, (f_p \, n_0 \, d_A)^2 \, \eta^2 \, \frac{\min(Q_a, Q_0)}{\epsilon}$$

Polarization density of material (fractional nuclear spin polarization f_p)

Signal Power

In cavity filled with dielectric material, power in mode on resonance ($\omega_i \simeq m_a$) is

$$P_{\text{sig}} \simeq m_a V \, (f_p \, n_0 \, d_A)^2 \, \eta^2 \, \frac{\min(Q_a, Q_0)}{\epsilon}$$

Polarization density of material (fractional nuclear spin polarization f_p)

$\mathcal{O}(1)$ geometric form factor: alignment of electric field $\mathbf{E}_i$ with spin polarization (reach higher frequencies with layer structure)

Signal Power

In cavity filled with dielectric material, power in mode on resonance ($\omega_i \simeq m_a$) is

$$P_{\rm sig} \simeq m_a V\,(f_p\, n_0\, d_A)^2\,\eta^2\,\frac{\min(Q_a, Q_0)}{\epsilon}$$

Polarization density of material (fractional nuclear spin polarization f_p)

$\mathcal{O}(1)$ geometric form factor: alignment of electric field $\mathbf{E}_i$ with spin polarization (reach higher frequencies with layer structure)

Dielectrics shield electric fields (order of magnitude penalty)

Signal Power

In cavity filled with dielectric material, power in mode on resonance ($\omega_i \simeq m_a$) is

$$P_{\text{sig}} \simeq m_a V \, (f_p \, n_0 \, d_A)^2 \, \eta^2 \, \frac{\min(Q_a, Q_0)}{\epsilon}$$

Polarization density of material (fractional nuclear spin polarization f_p)

$\mathcal{O}(1)$ geometric form factor: alignment of electric field $\mathbf{E}_i$ with spin polarization (reach higher frequencies with layer structure)

Dielectrics shield electric fields (order of magnitude penalty)

Resonant enhancement, requires high mode Q_0 so low dielectric loss — common at cryogenic temperatures

Maximizing Spin Polarization

In thermal equilibrium in cavity haloscope, $f_p \propto B/T \sim \mathrm{few}\,\%$,
but best sensitivity requires order-one f_p

Many "hyperpolarization" methods considered in literature, such as:

<u>Brute force</u>

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

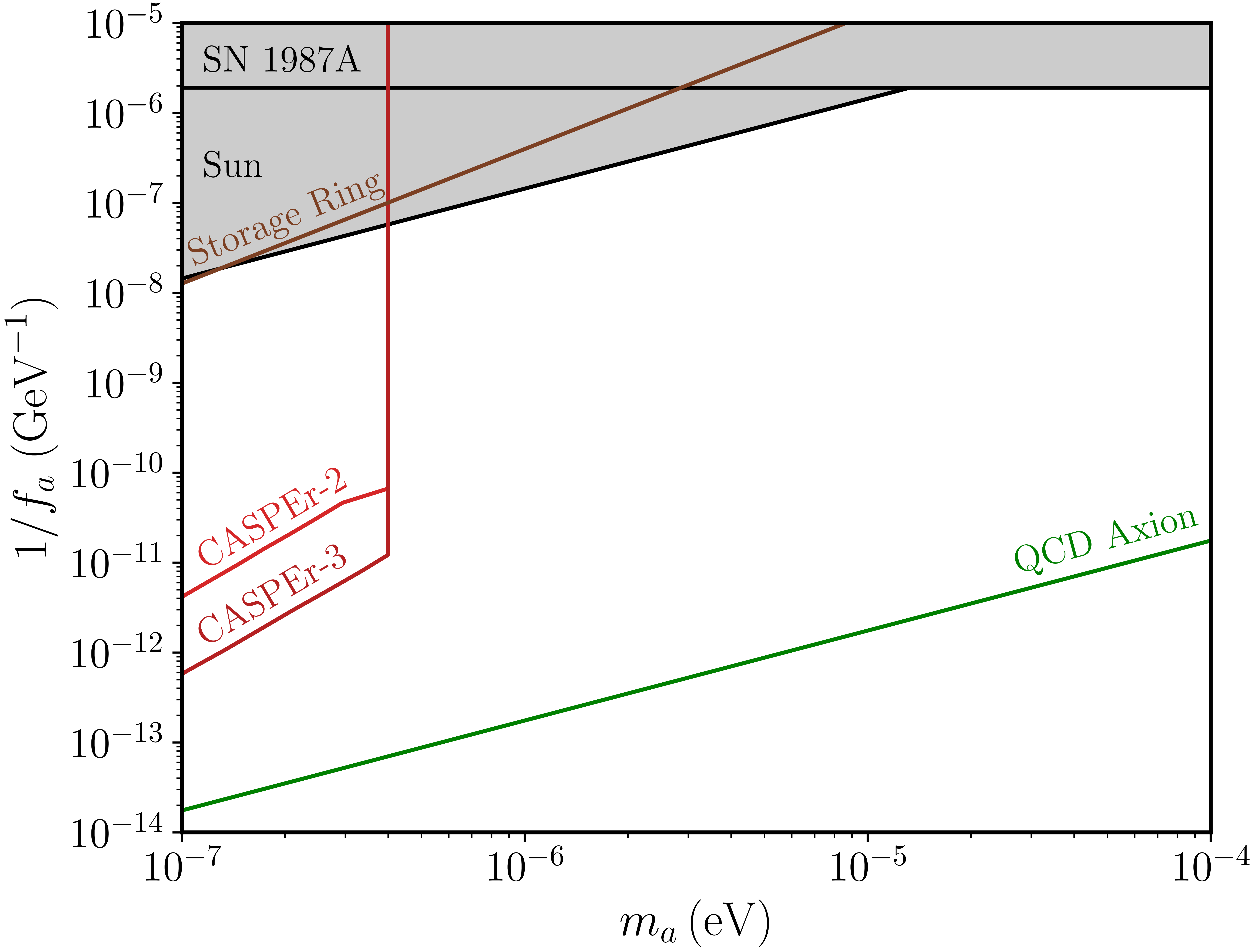
But: thermalization time may be prohibitively long

<u>Frozen spin dynamic nuclear polarization</u>

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

Potential Reach

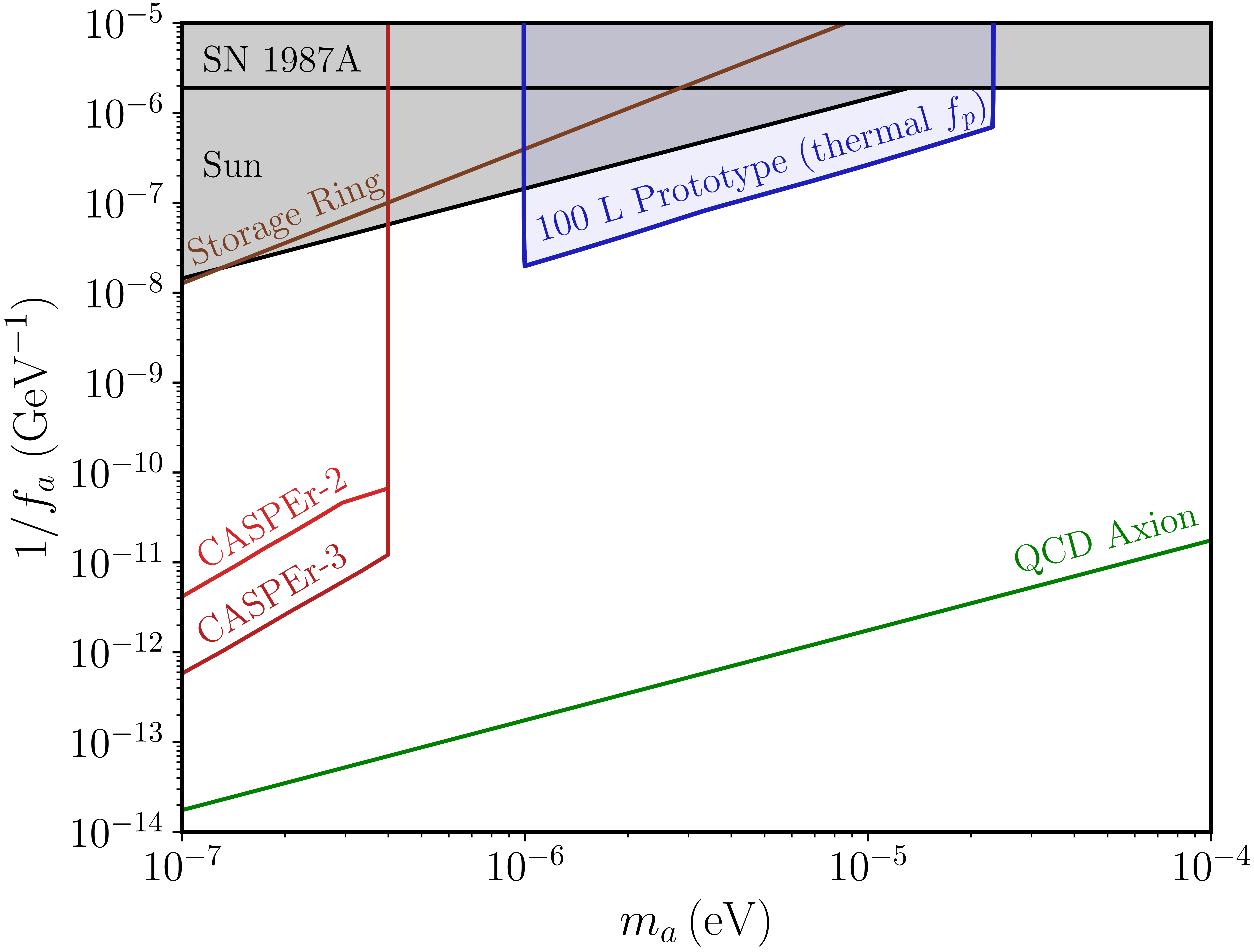


GHz frequencies are unprobed: too high for NMR, mechanical resonance, or static EDM expts

Polarization haloscope naturally targets these frequencies

Reach is easy to estimate: thermal and (quantum limited) amplifier noise dominate

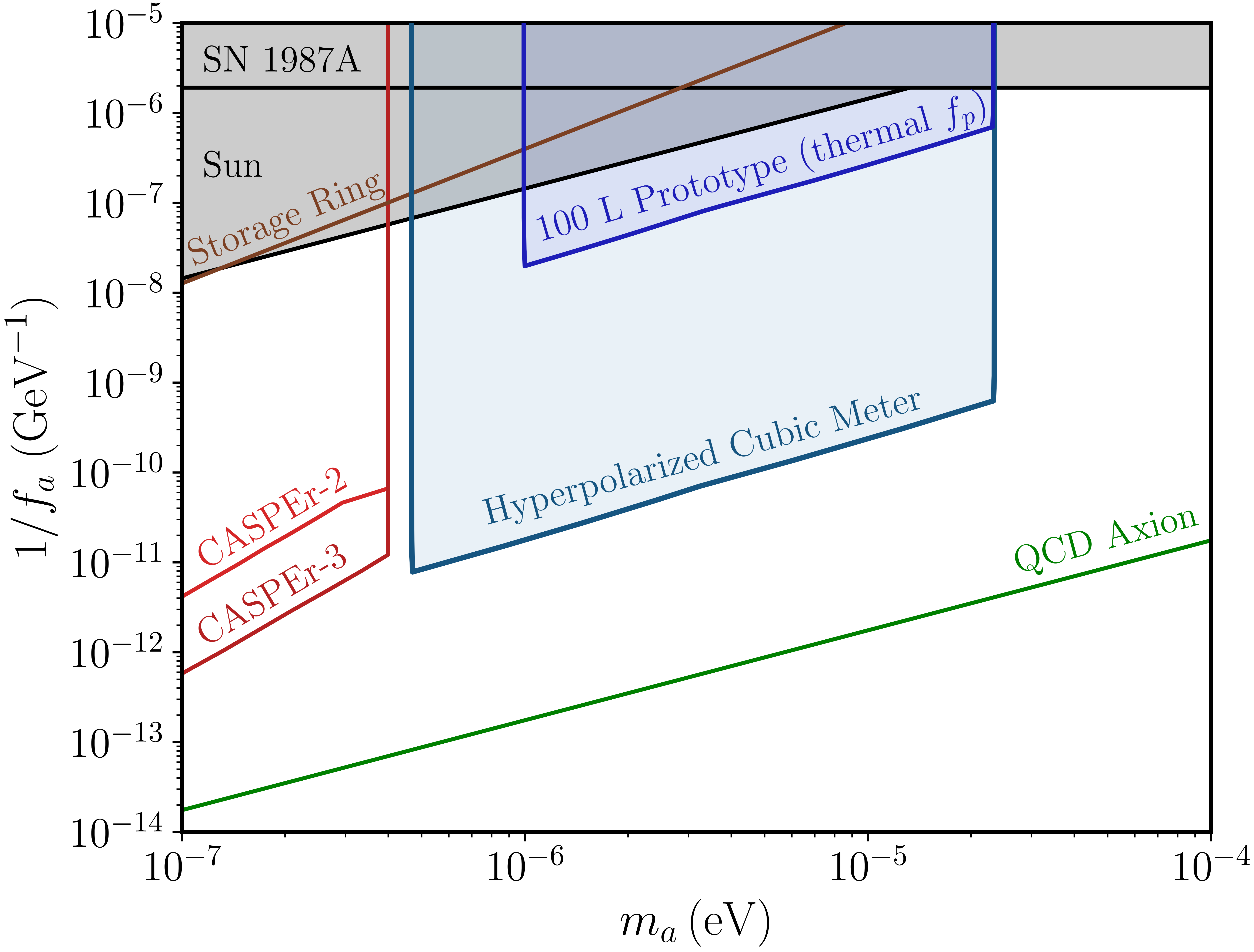
Potential Reach



Modified existing haloscope can probe new parameter space!

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

Potential Reach



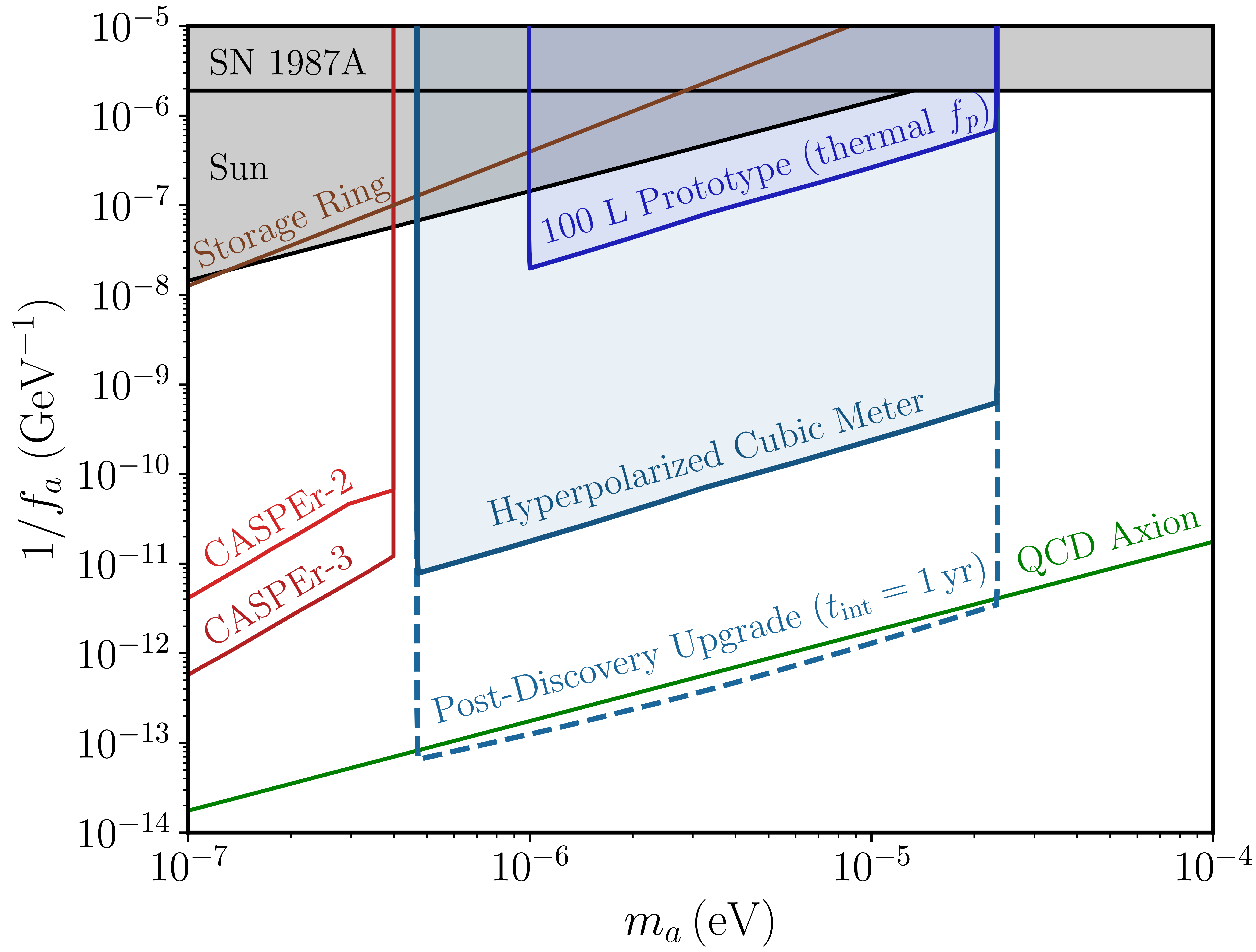
Modified existing haloscope can probe new parameter space!

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

Hyperpolarized sample probes orders of magnitude further

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

Potential Reach



Modified existing haloscope can probe new parameter space!

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

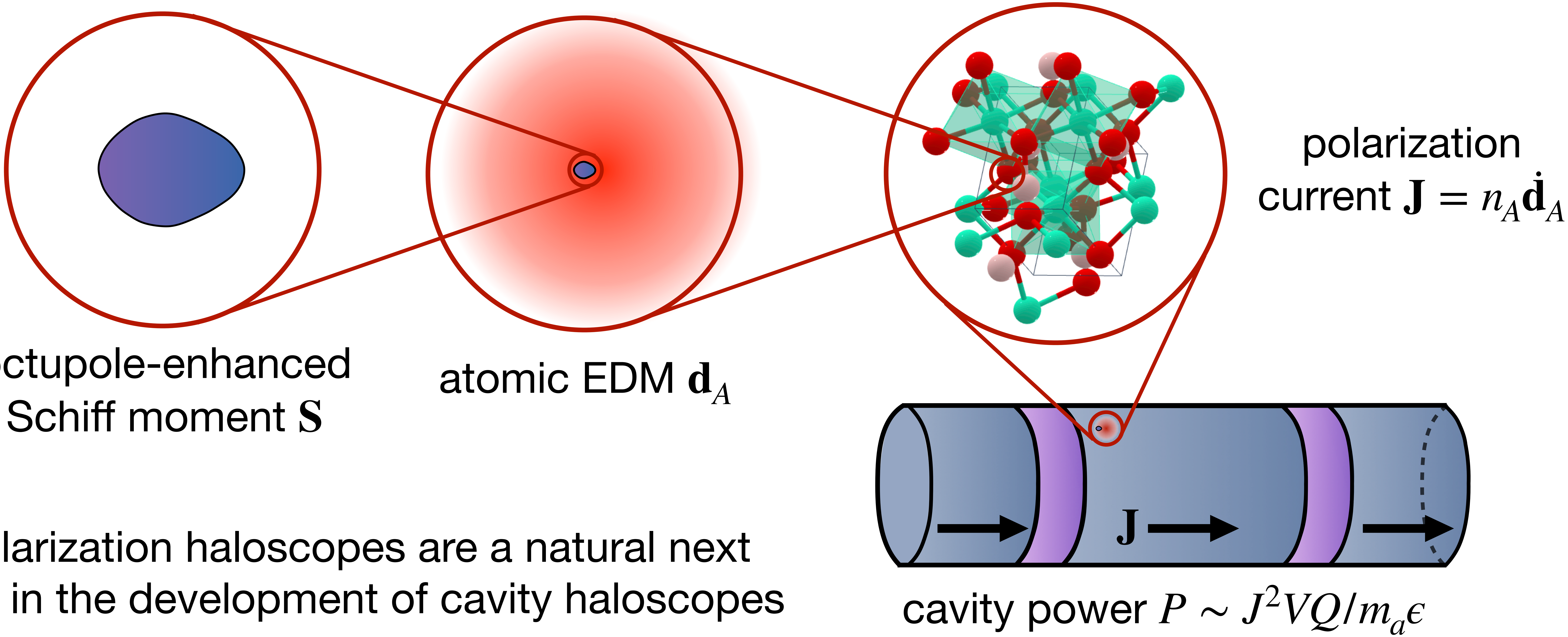
Hyperpolarized sample probes orders of magnitude further

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

Further upgrade can test candidate μeV QCD axion

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

(non-scanning)



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