Discovering the QCD Axion with Polarization Haloscopes

Kevin Zhou

Stanford University

SLAC

TRIUMF Theory Seminar — October 19, 2022

Particle Physics Then and Now

Testing the Standard Model
- Electroweak
- QCD
- etc.

Beyond the Standard Model
- Technicolor
- Supersymmetry
- Grand Unification
- etc.

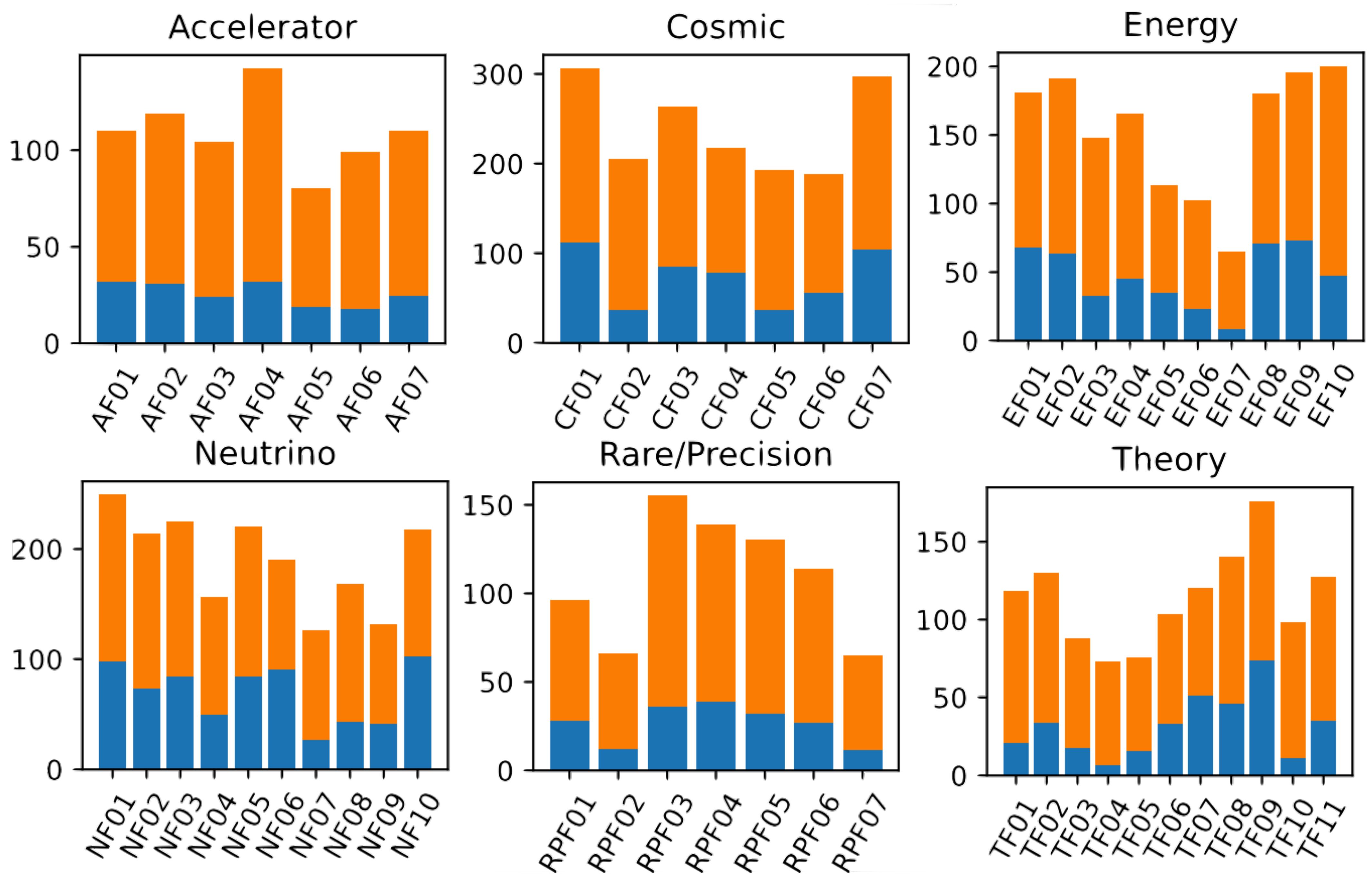
Limits of Accelerator Technology and Novel Accelerator Ideas

Novel Detector Ideas

Snowmass 1982 Summary

DISCOVERY	COMMENTS	ODDS*
Standard Model Higgs	As good as discovered, some say	2–1
Big surprises	Expect the unexpected	2–1
Supersymmetry	Too beautiful to be wrong?	5–1

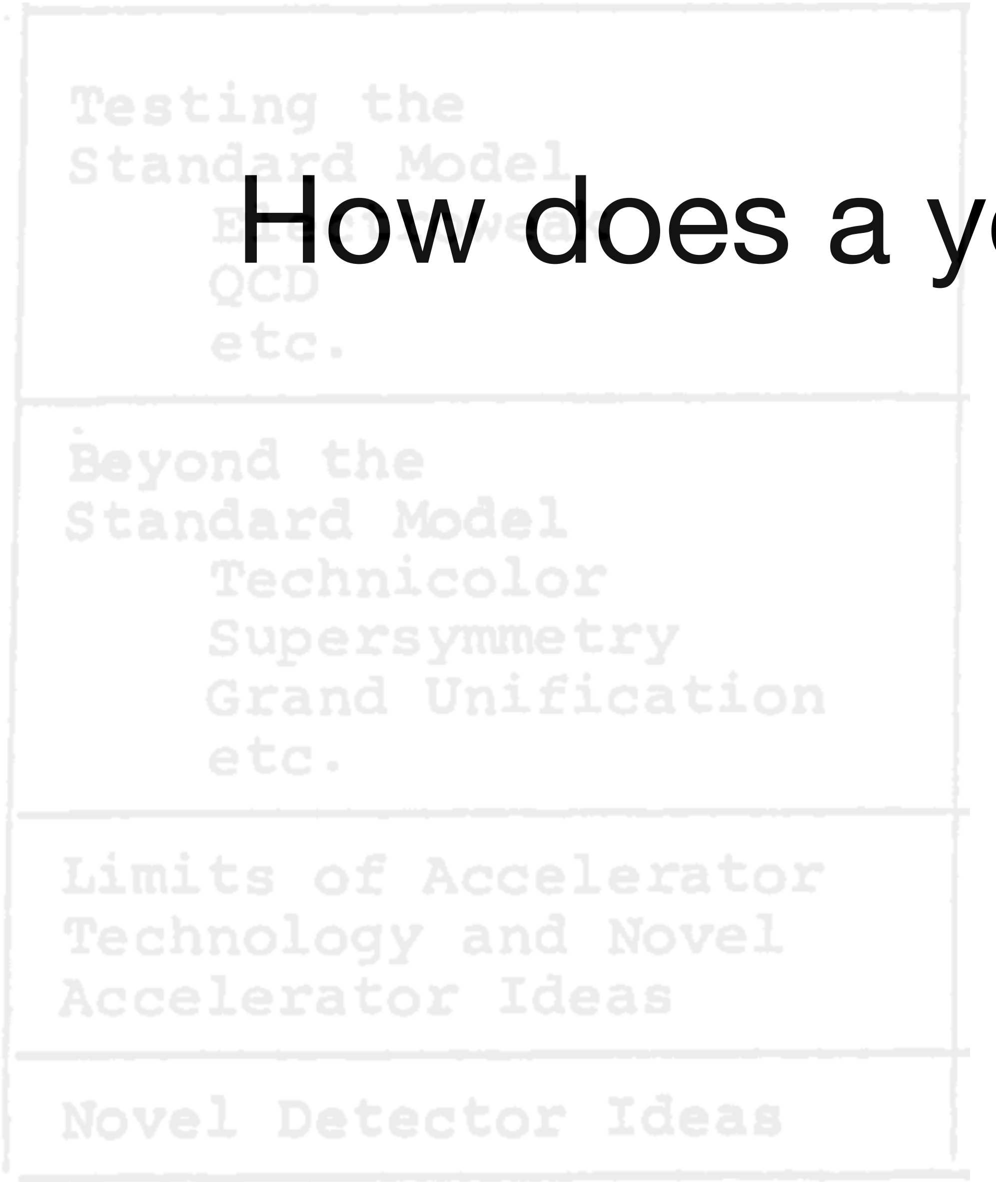
2007 Fermilab survey



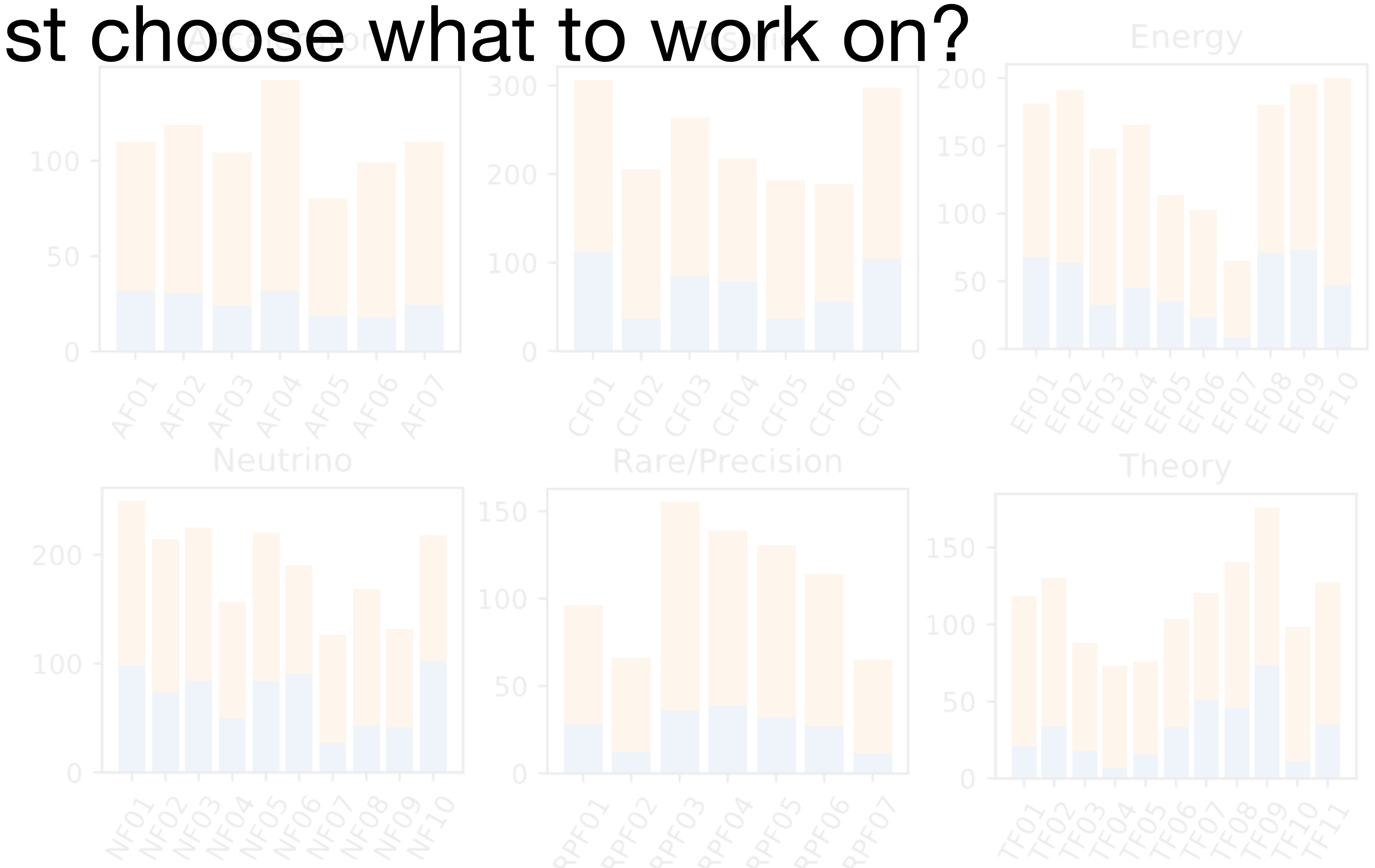
Snowmass 2021 Interest Survey (2203.07328)

Particle Physics Then and Now

How does a young scientist choose what to work on?


Testing the Standard Model
QCD
etc.
Beyond the Standard Model
Technicolor
Supersymmetry
Grand Unification
etc.
Limits of Accelerator Technology and Novel Accelerator Ideas
Novel Detector Ideas

Snowmass 1982 Summary

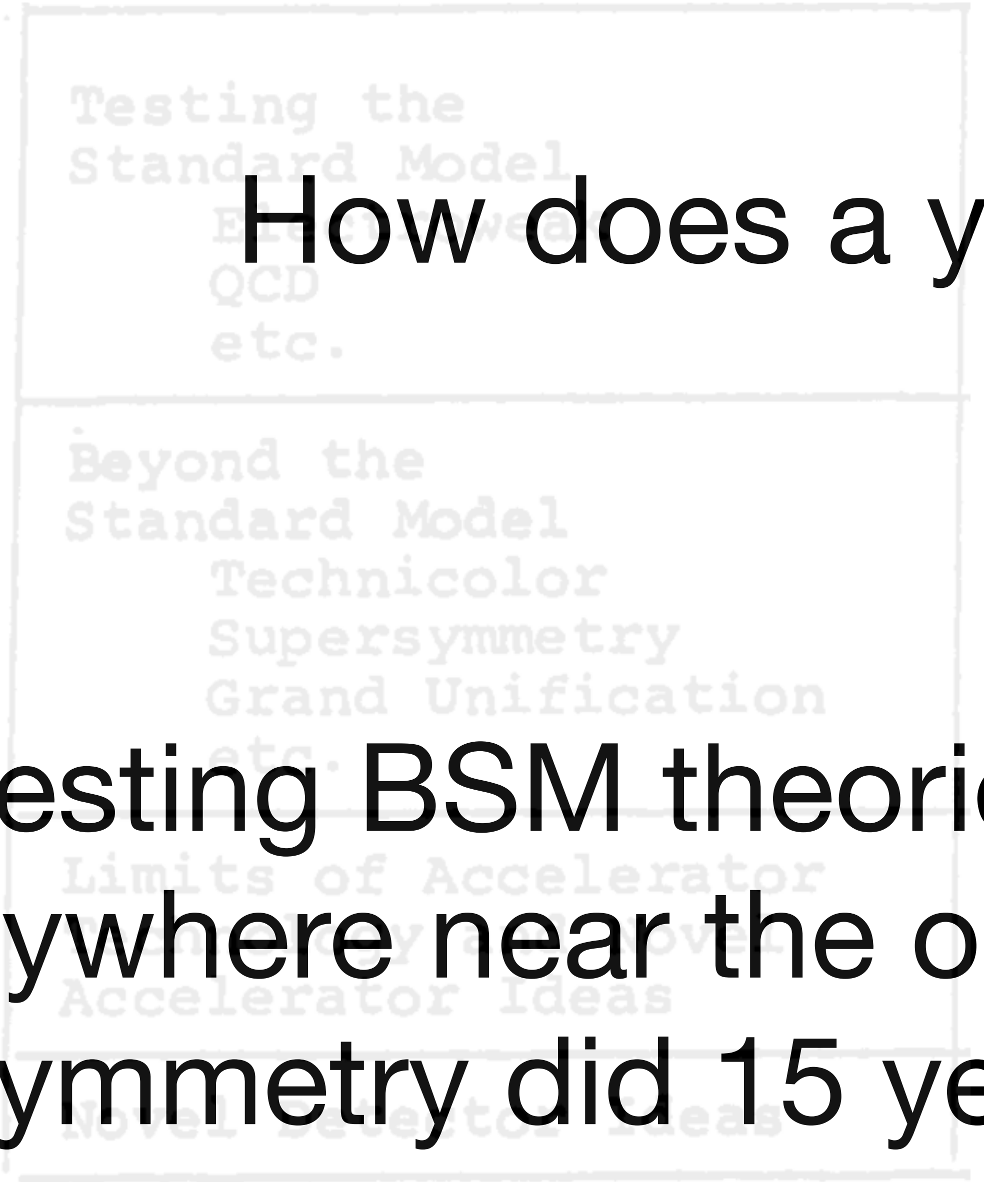


Snowmass 2021 Interest Survey (2203.07328)

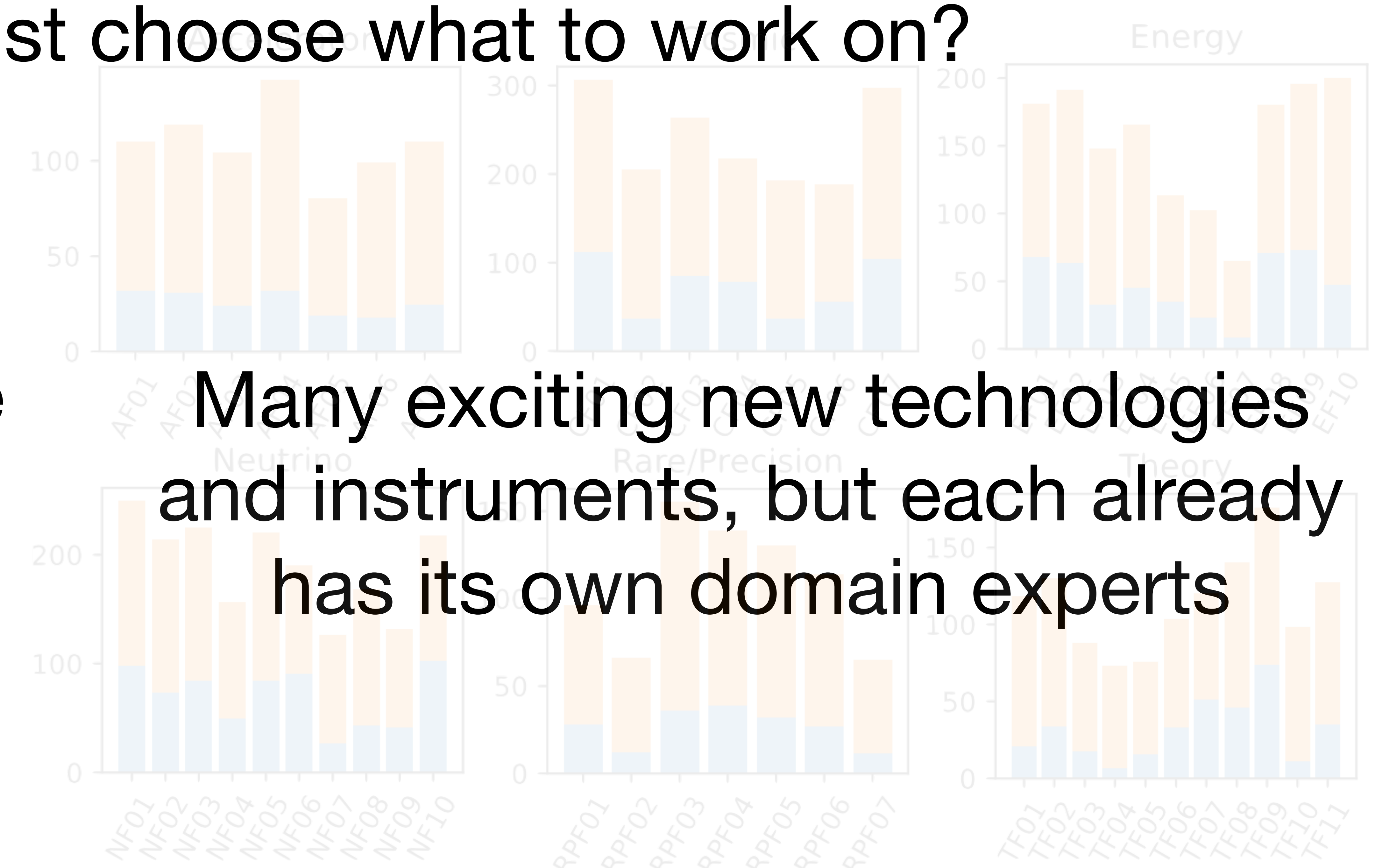
DISCOVERY	COMMENTS	ODDS*
Standard Model Higgs	As good as discovered, some say	2–1
Big surprises	Expect the unexpected	2–1
Supersymmetry	Too beautiful to be wrong?	5–1

2007 Fermilab survey

Particle Physics Then and Now


Testing the
Standard Model
QCD
etc.
Beyond the
Standard Model
Technicolor
Supersymmetry
Grand Unification
Limits of Accelerator
Accelerator Ideas

How does a young scientist choose what to work on?



Many interesting BSM theories, but none has anywhere near the odds that supersymmetry did 15 years ago!

Many exciting new technologies and instruments, but each already has its own domain experts

Snowmass 1982 Summary

DISCOVERY	COMMENTS	ODDS*
Standard Model Higgs	As good as discovered, some say	2–1
Big surprises	Expect the unexpected	2–1
Supersymmetry	Too beautiful to be wrong?	5–1

2007 Fermilab survey

Snowmass 2021 Survey (2203.07328)

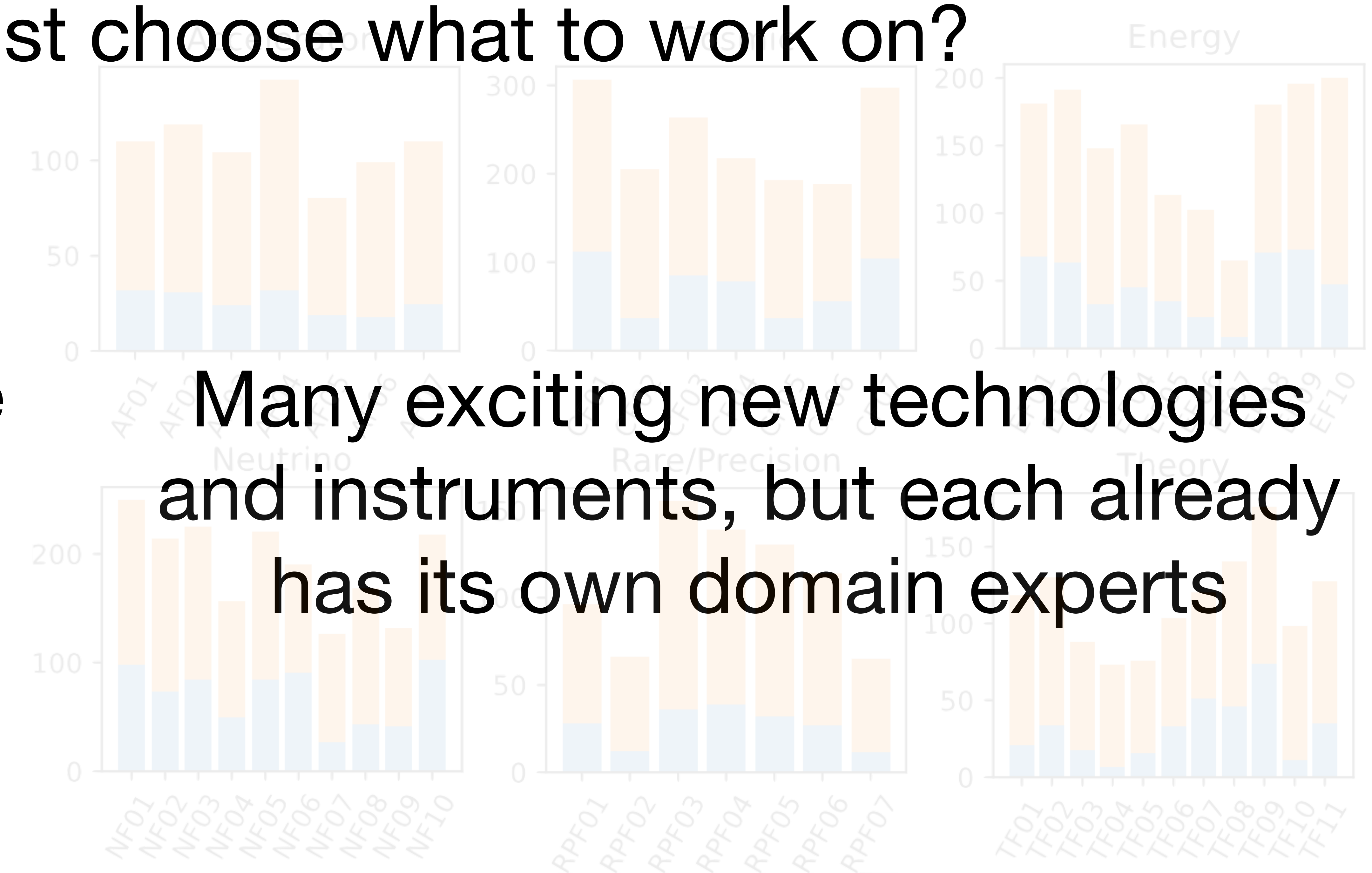
Particle Physics Then and Now

How does a young scientist choose what to work on?

Many interesting BSM theories, but none has anywhere near the odds that supersymmetry did 15 years ago!

Snowmass 1982 Summary

Many exciting new technologies and instruments, but each already has its own domain experts



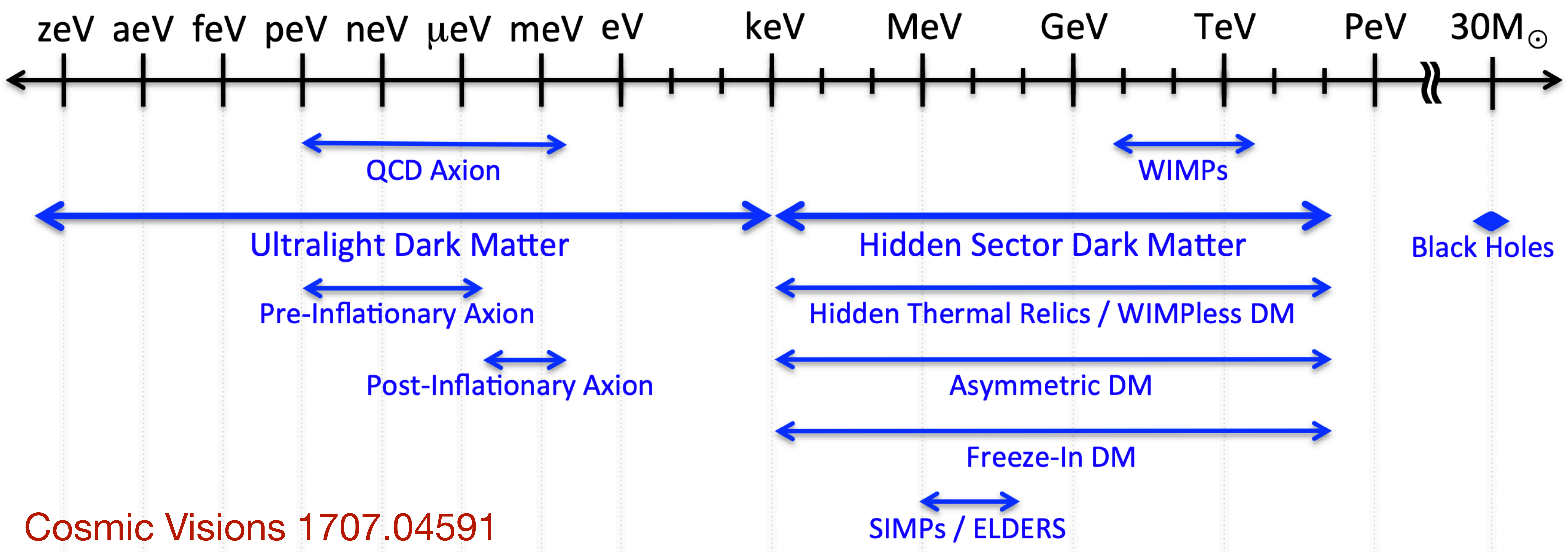
Snowmass 2021 Survey (2203.07328)

Another path: linking theories and the technologies that can test them, across fields

Physics is a big place — many exciting connections have not been made!

2007 Fermilab survey

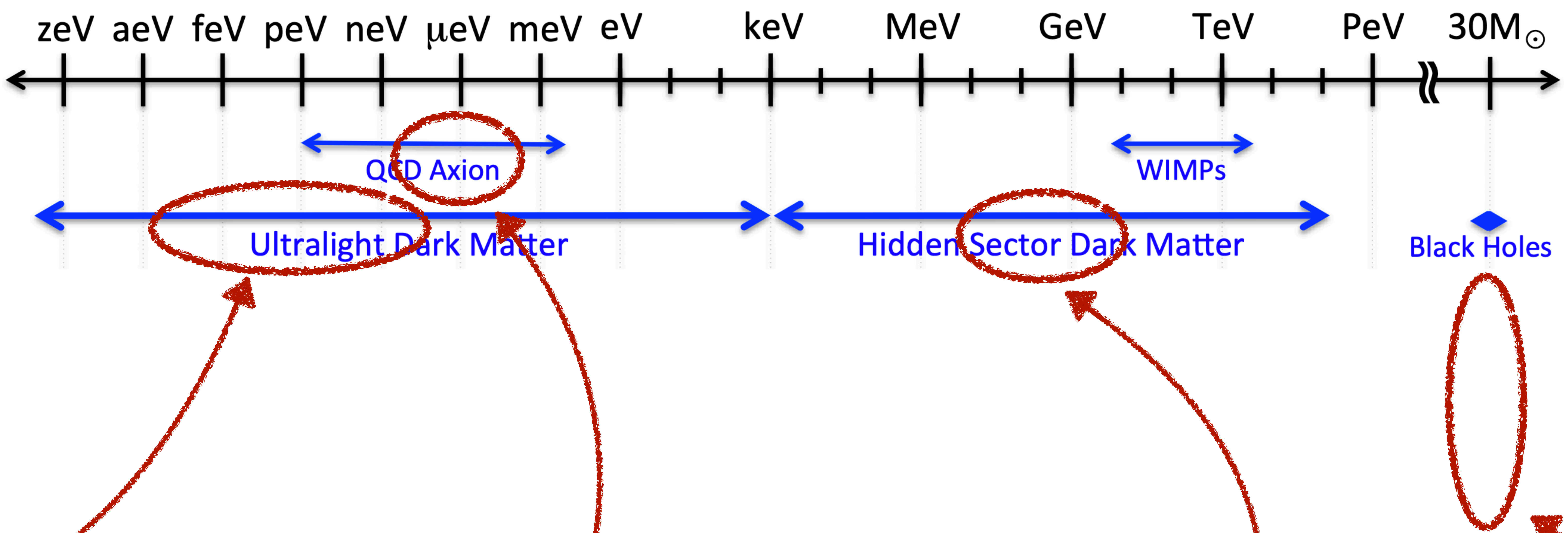
The Search For Dark Matter

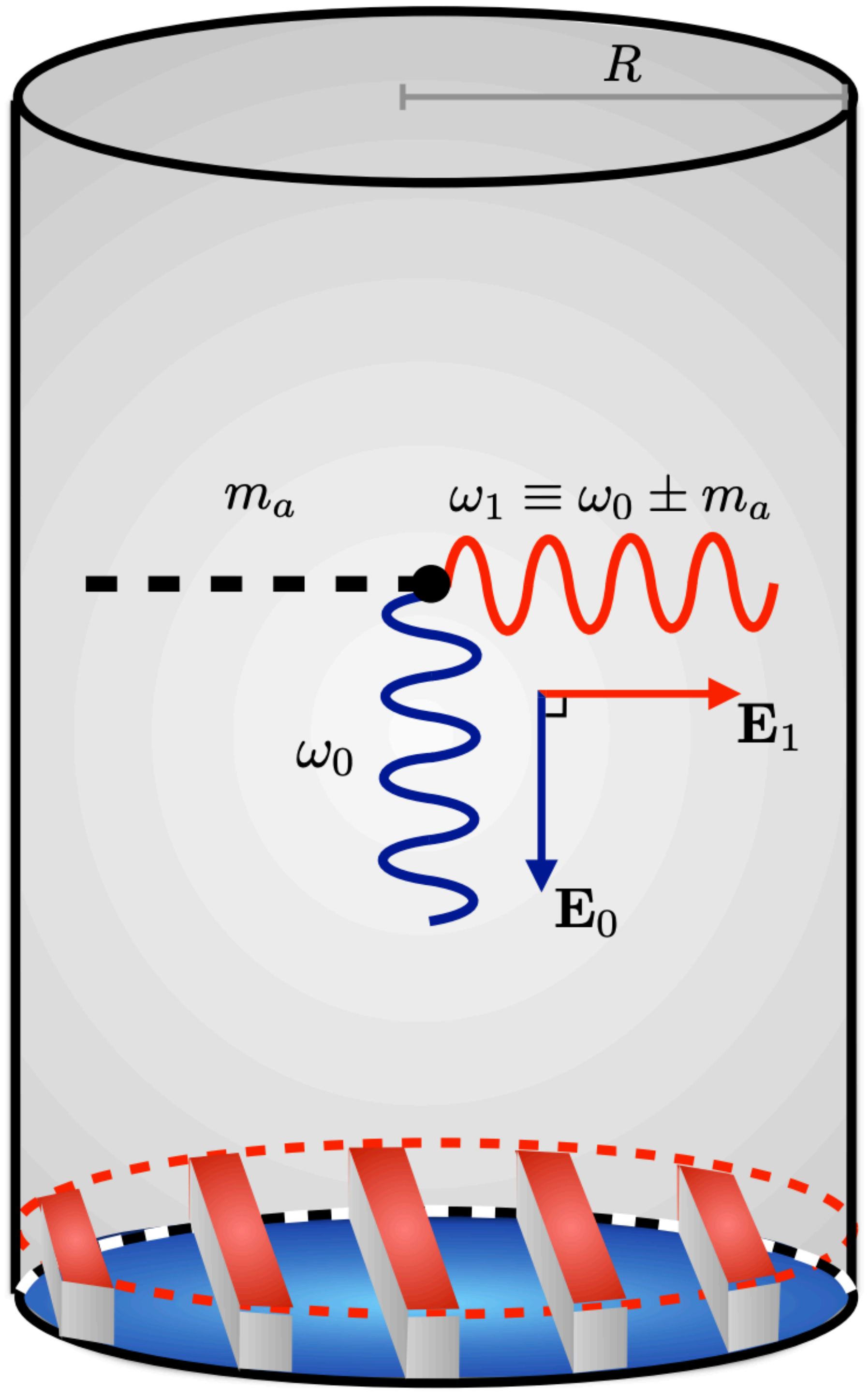


In current situation, we would like to both decisively test canonical models, and probe broadly into underexplored classes of models

New experimental programs can help do both!

The Search For Dark Matter

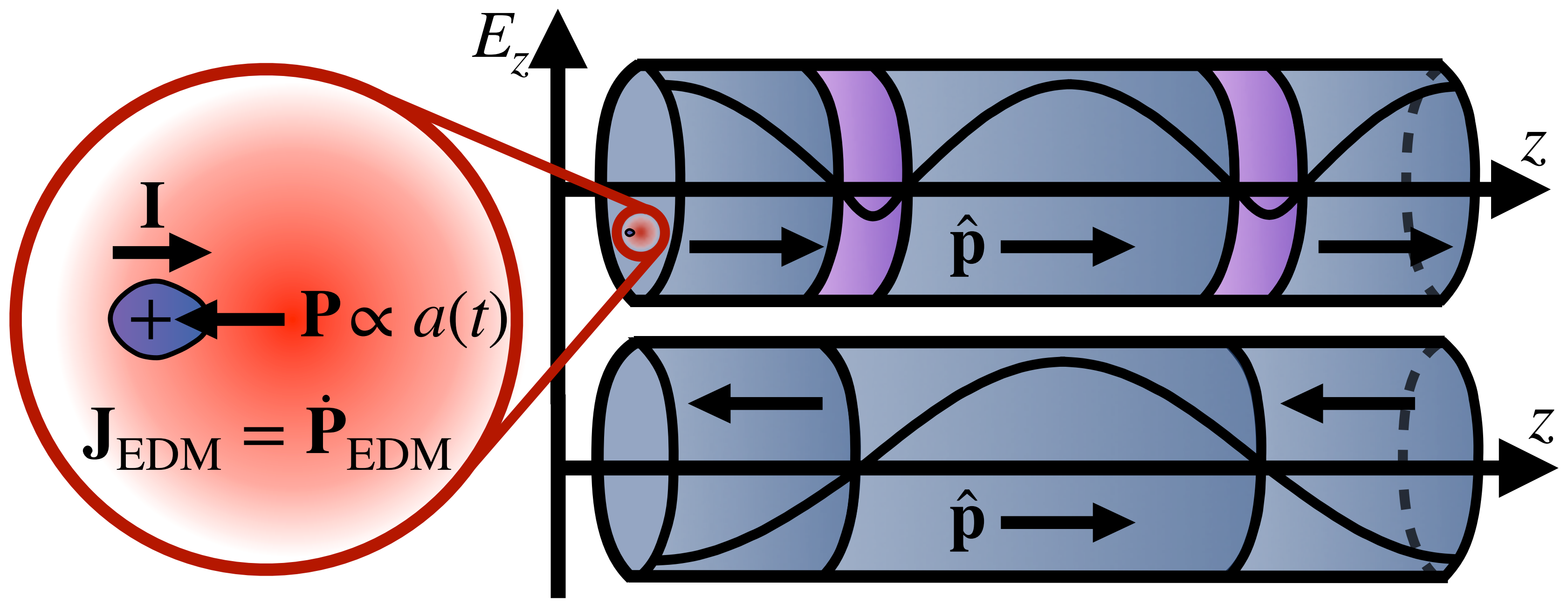




axion upconversion

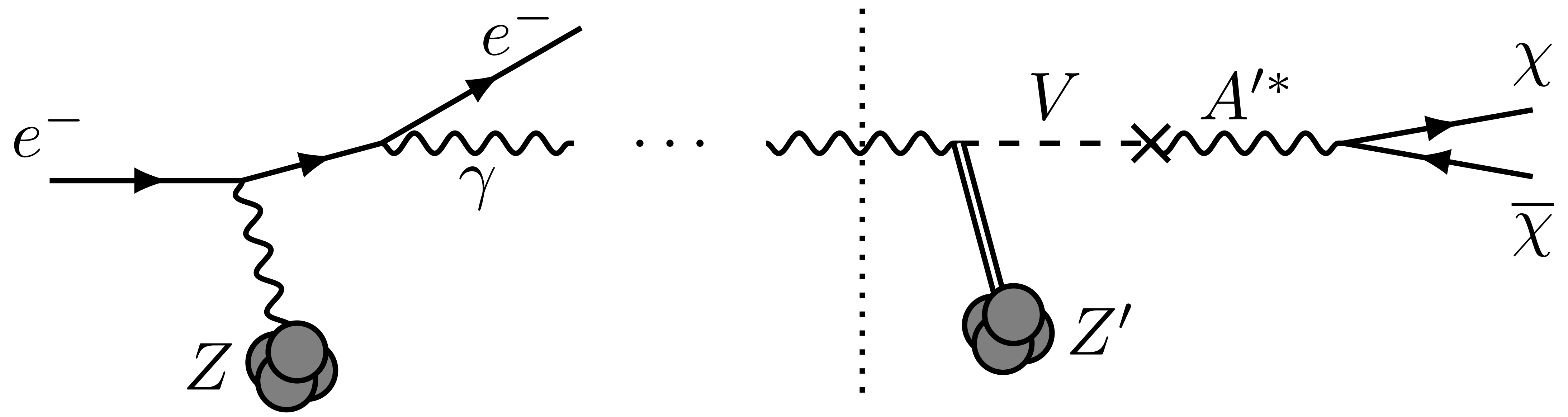
1912.11048, 2007.15656

polarization haloscopes

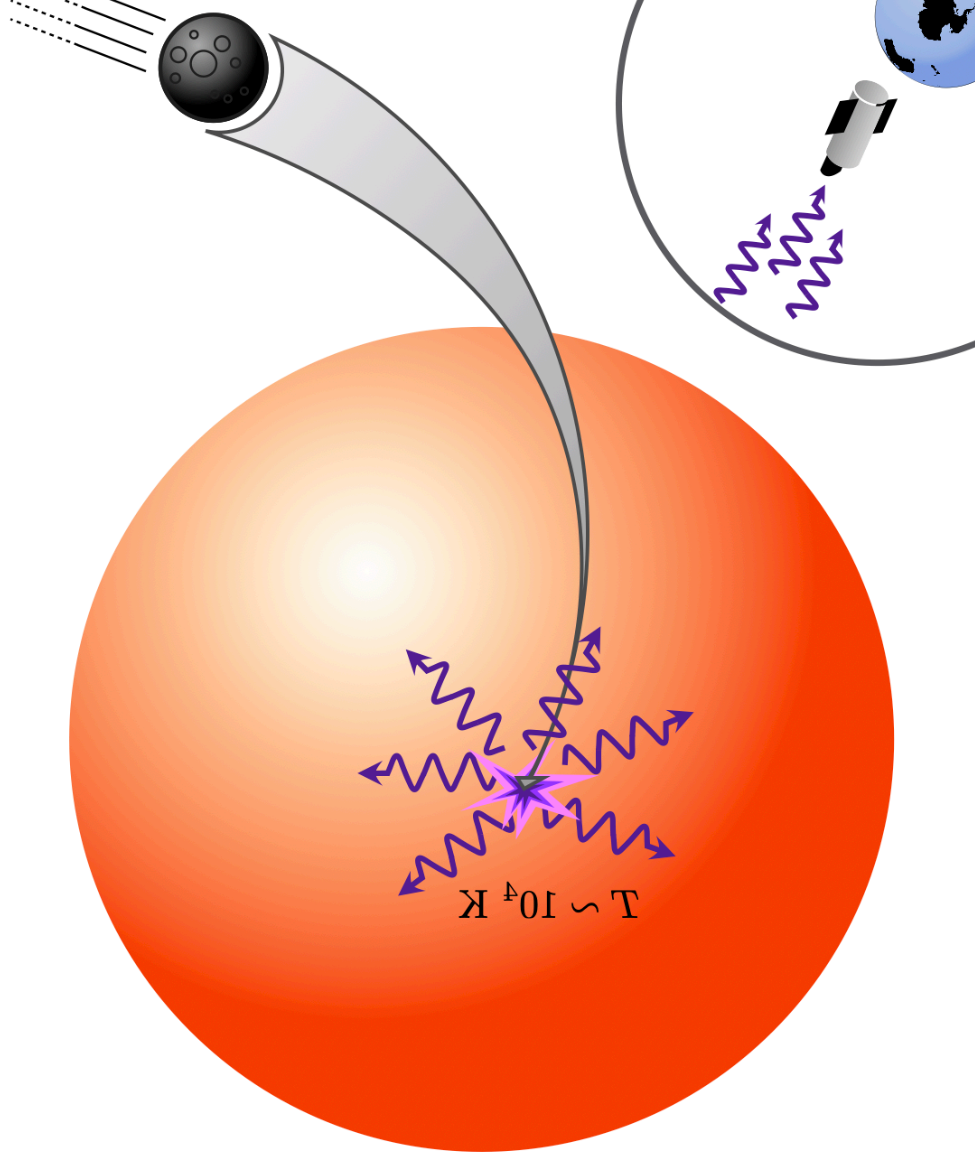


2209.12901

invisible meson decays



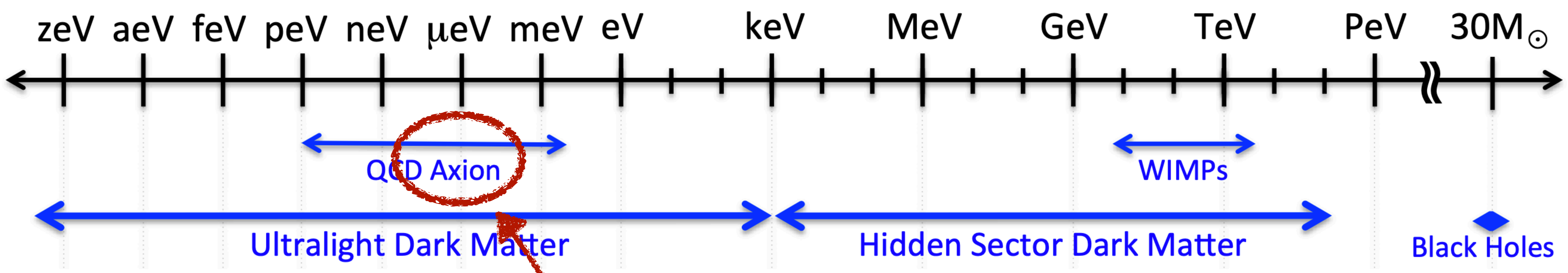
2112.02104



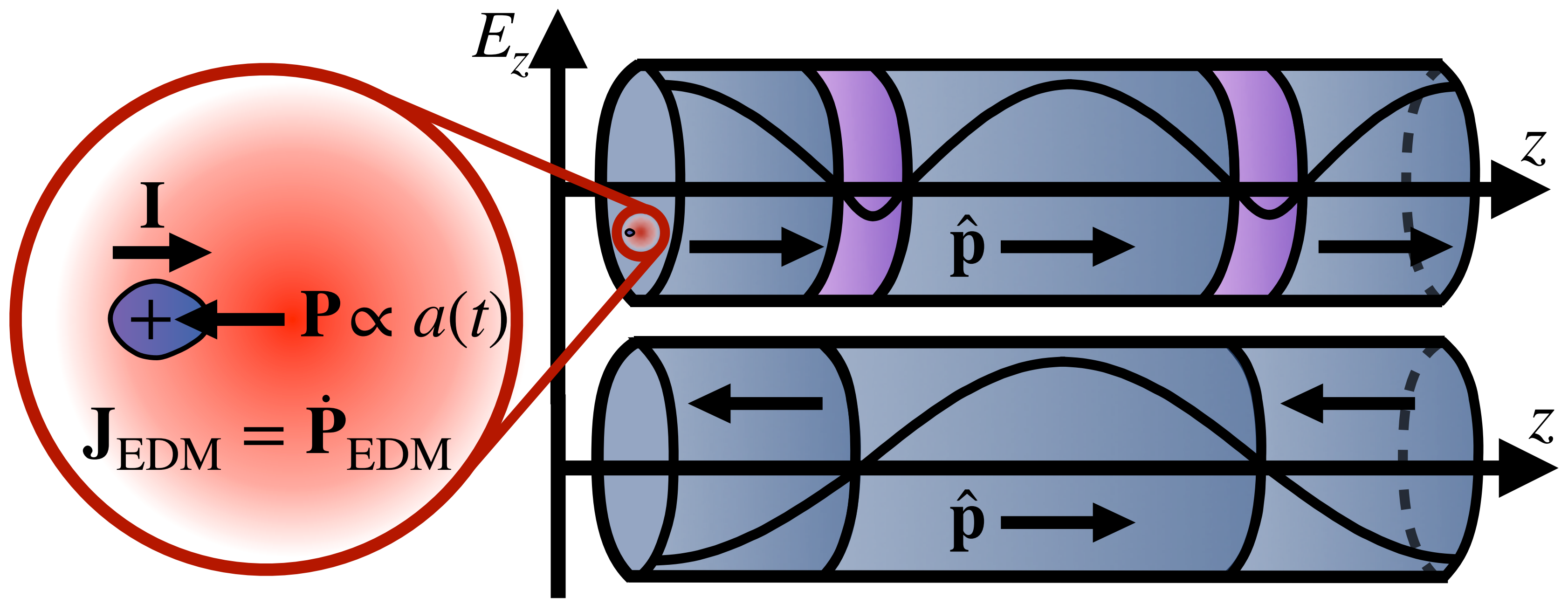
stellar shock transients

2106.09033

The Search For Dark Matter



polarization haloscopes

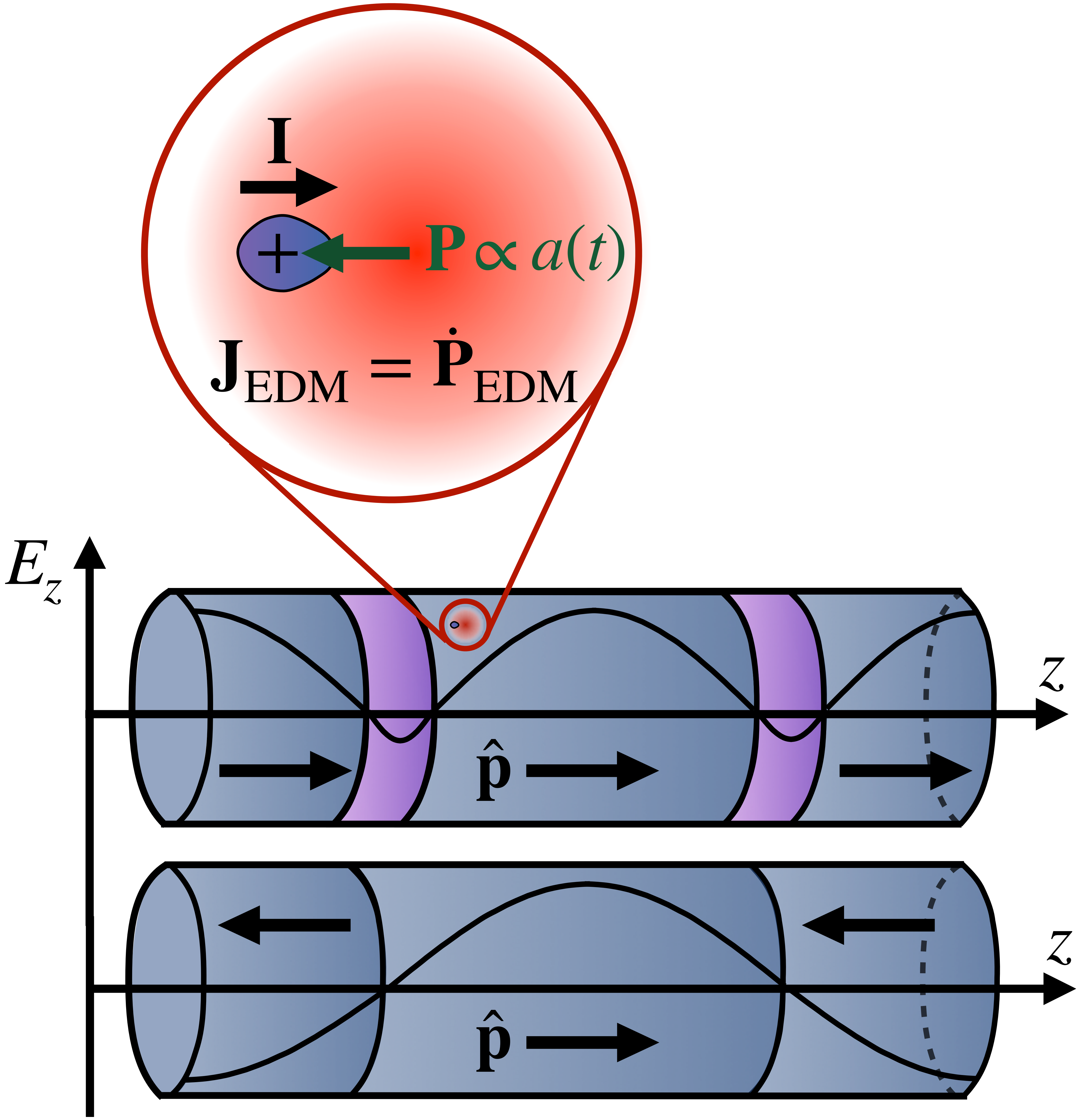


2209.12901

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

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

The QCD Axion

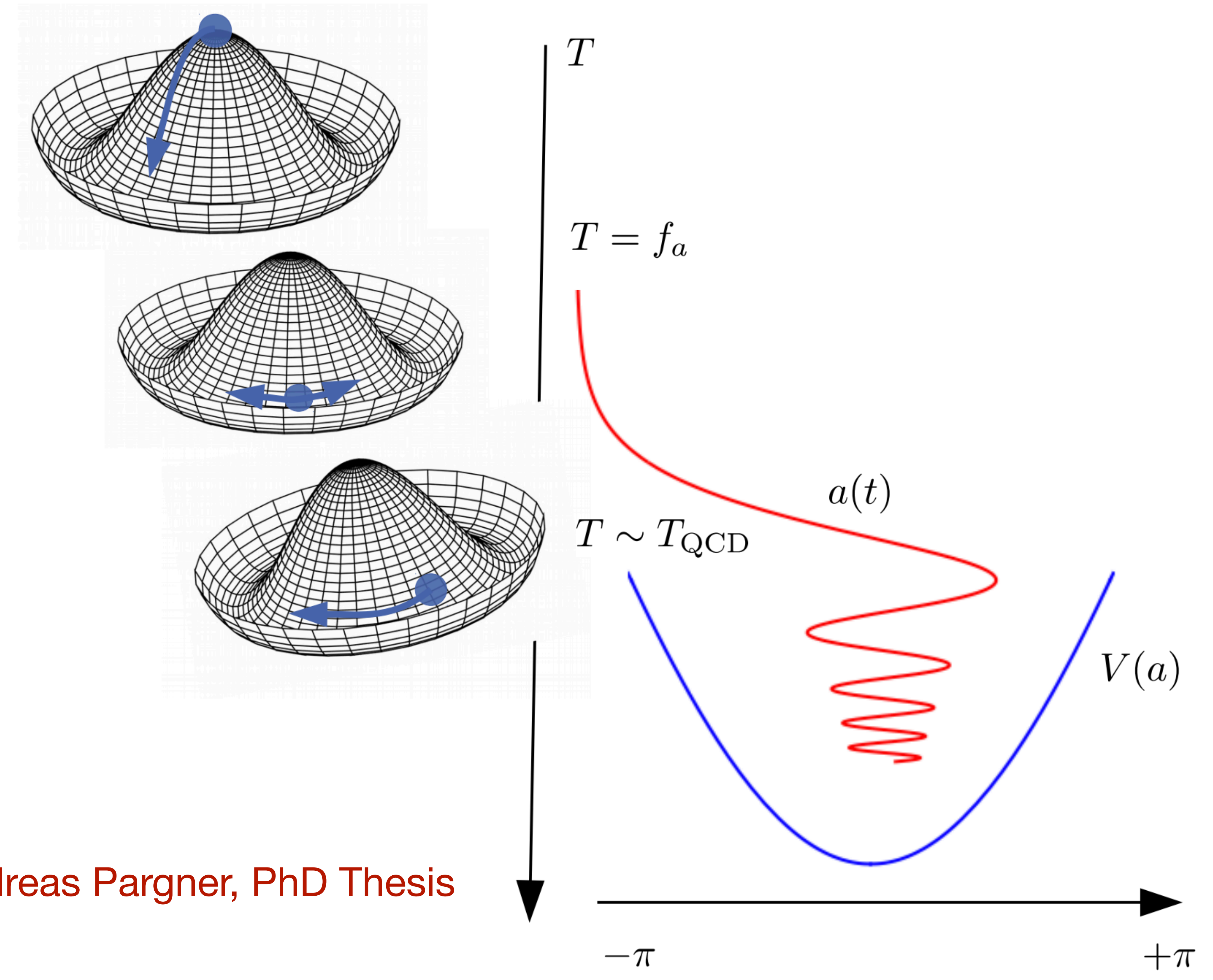
A pseudoscalar field a with defining coupling to gluons

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

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

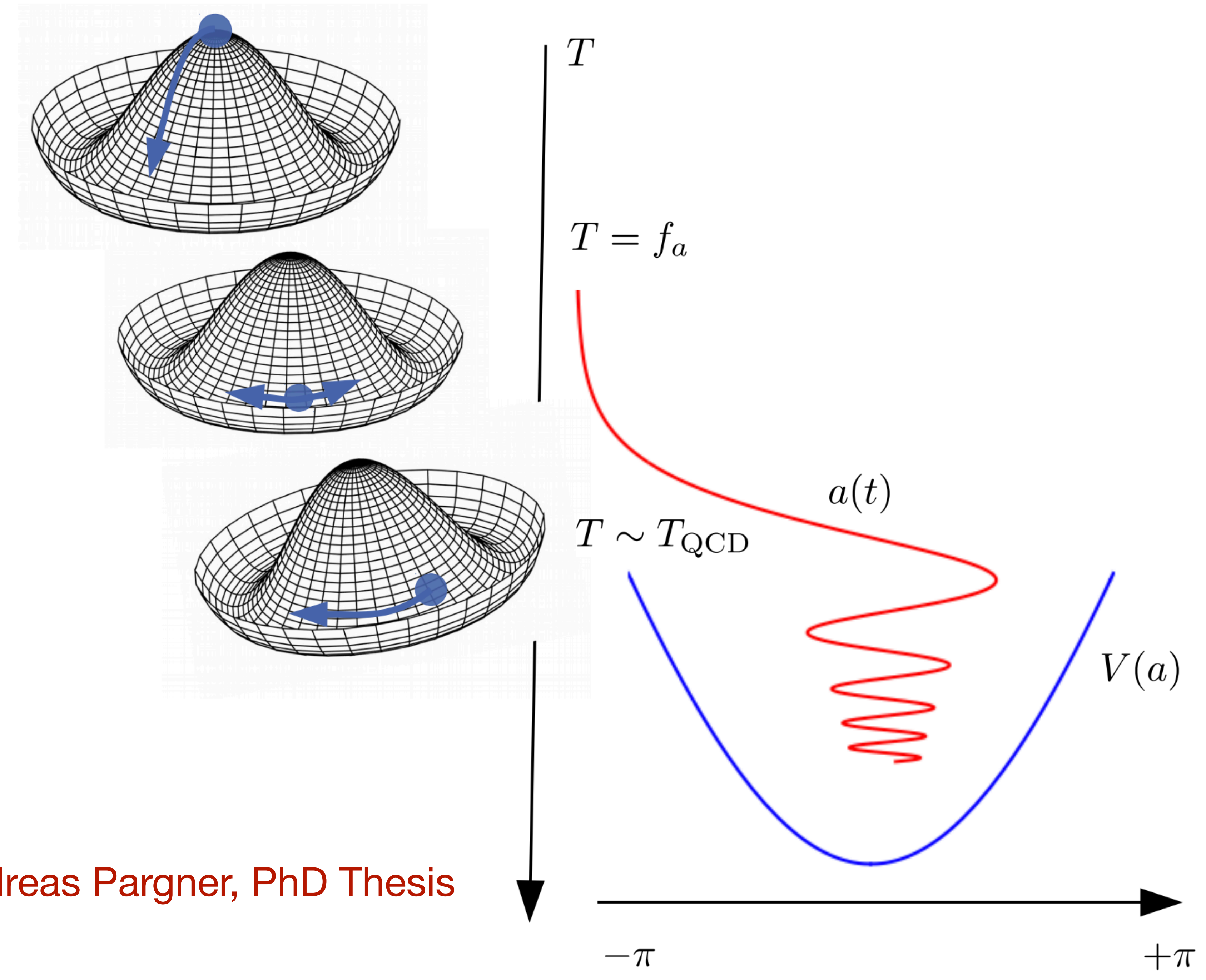
For initial $\theta_a \sim 1$, residual oscillations are dark matter if $m_a \sim (0.5 - 50)\ \mu\text{eV}$

The QCD Axion

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 $U(1)_{\mathrm{PQ}}$
- Generically produced in string compactifications
- Defined by observable interaction!

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 $m_a \sim (0.5 - 50)\ \mu\mathrm{eV}$

Detecting the QCD Axion

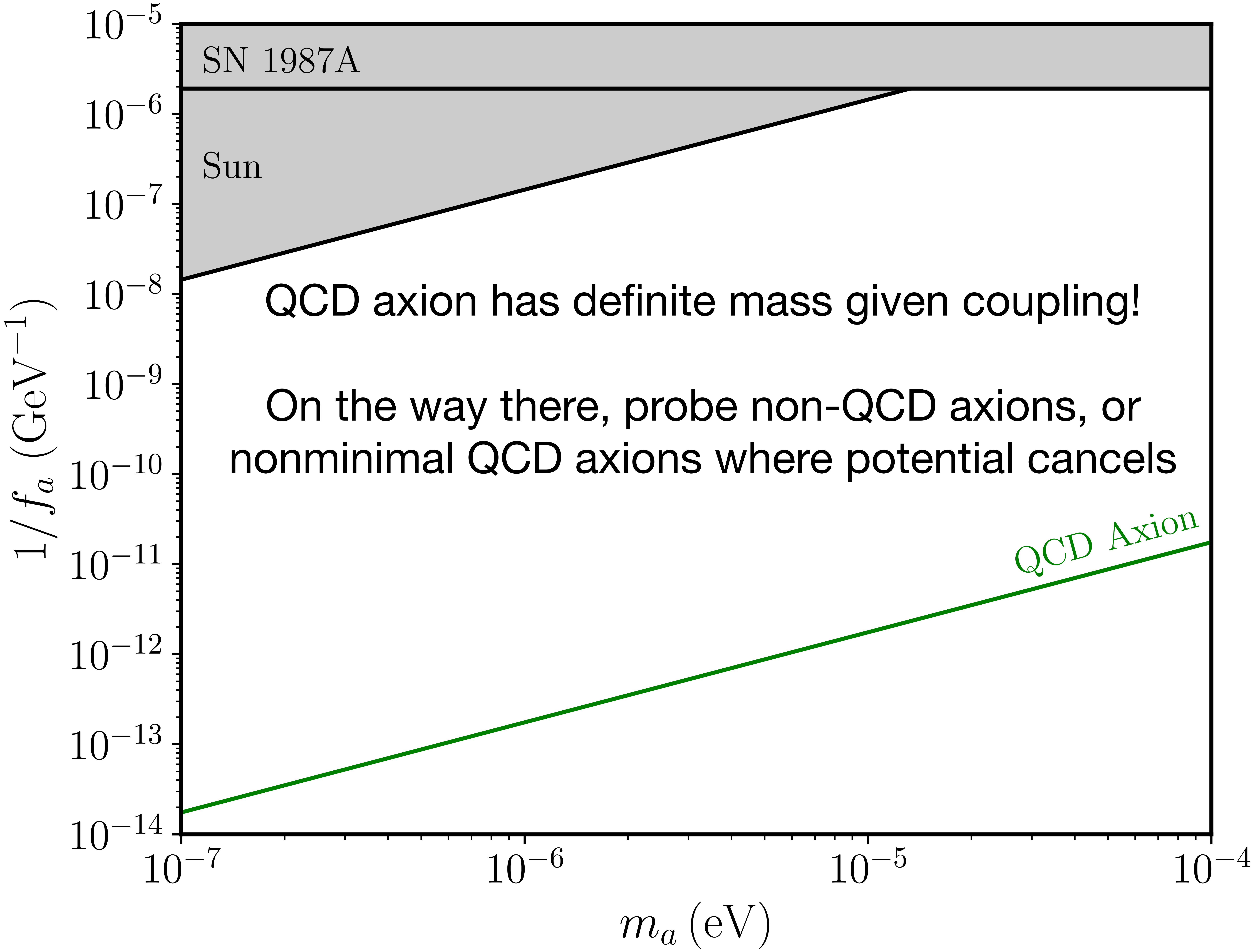
The QCD axion has small residual oscillations about the CP conserving point

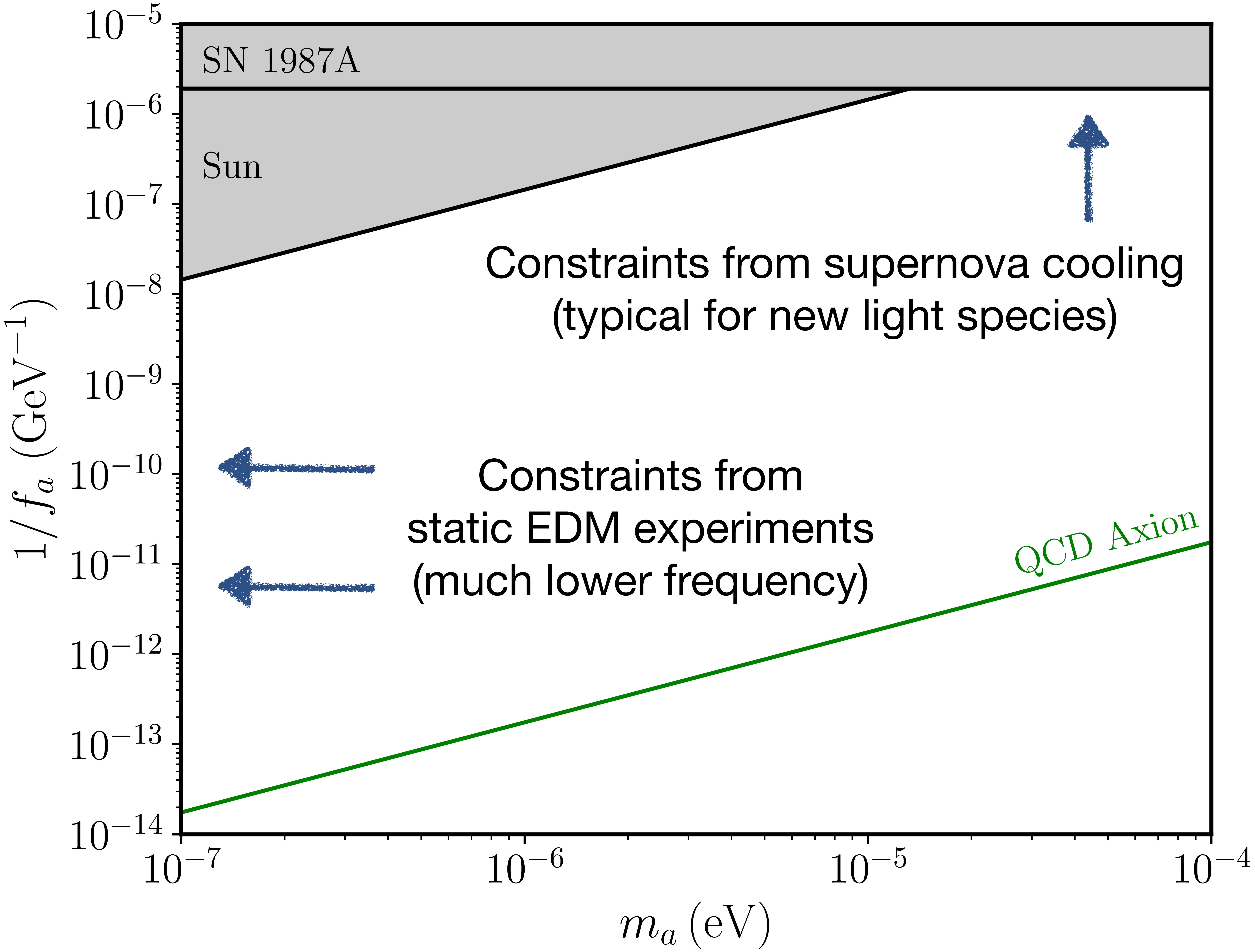
$$\theta_a(t) \simeq \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a f_a} \cos m_a t = 4 \times 10^{-19} \cos m_a t$$

Has <u>defining</u> signature: oscillating CP violating nuclear effects, like neutron EDM

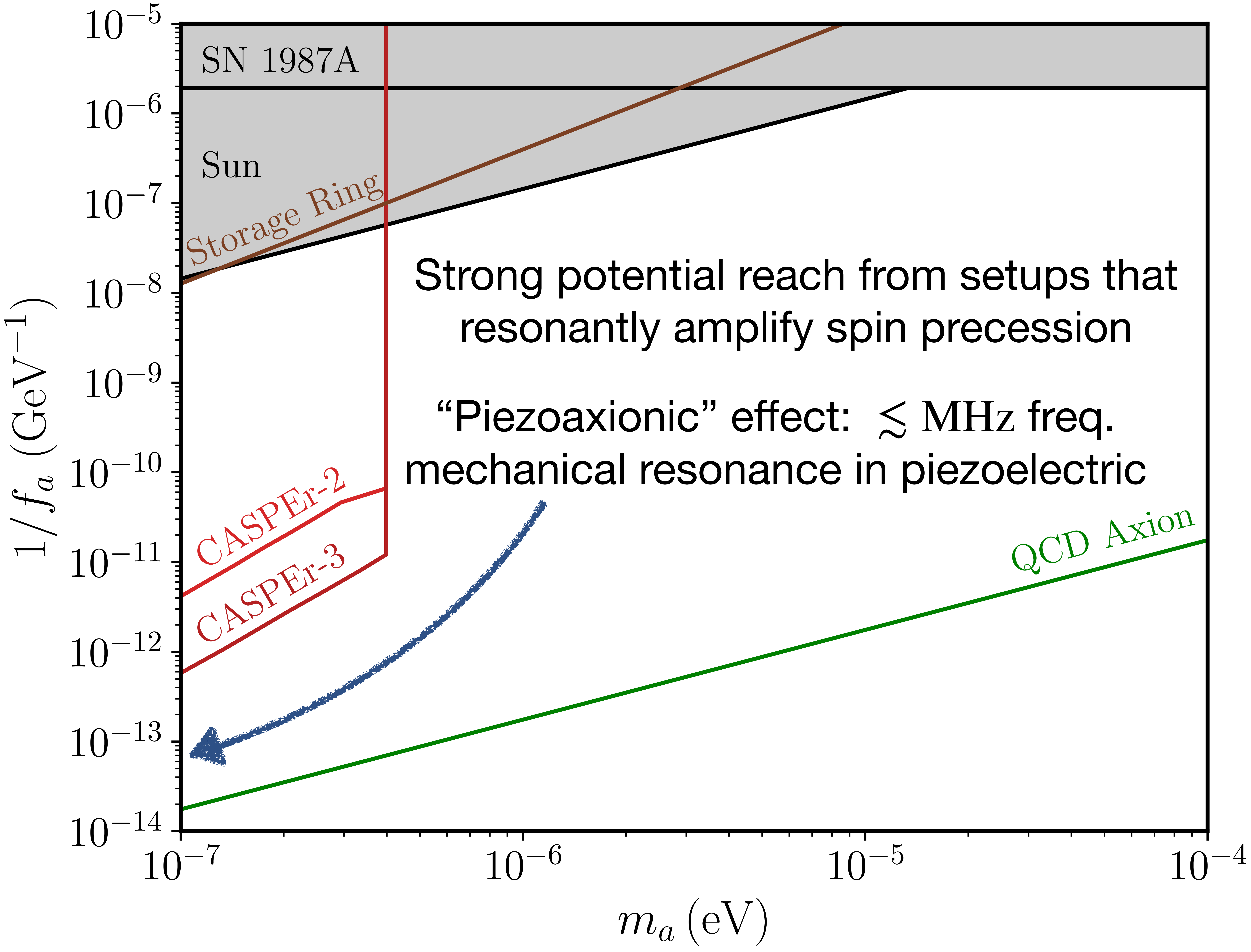
$$d_n = (2.4 \times 10^{-3}\ e\,\mathrm{fm})\,\theta_a \equiv g_d\, a$$

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

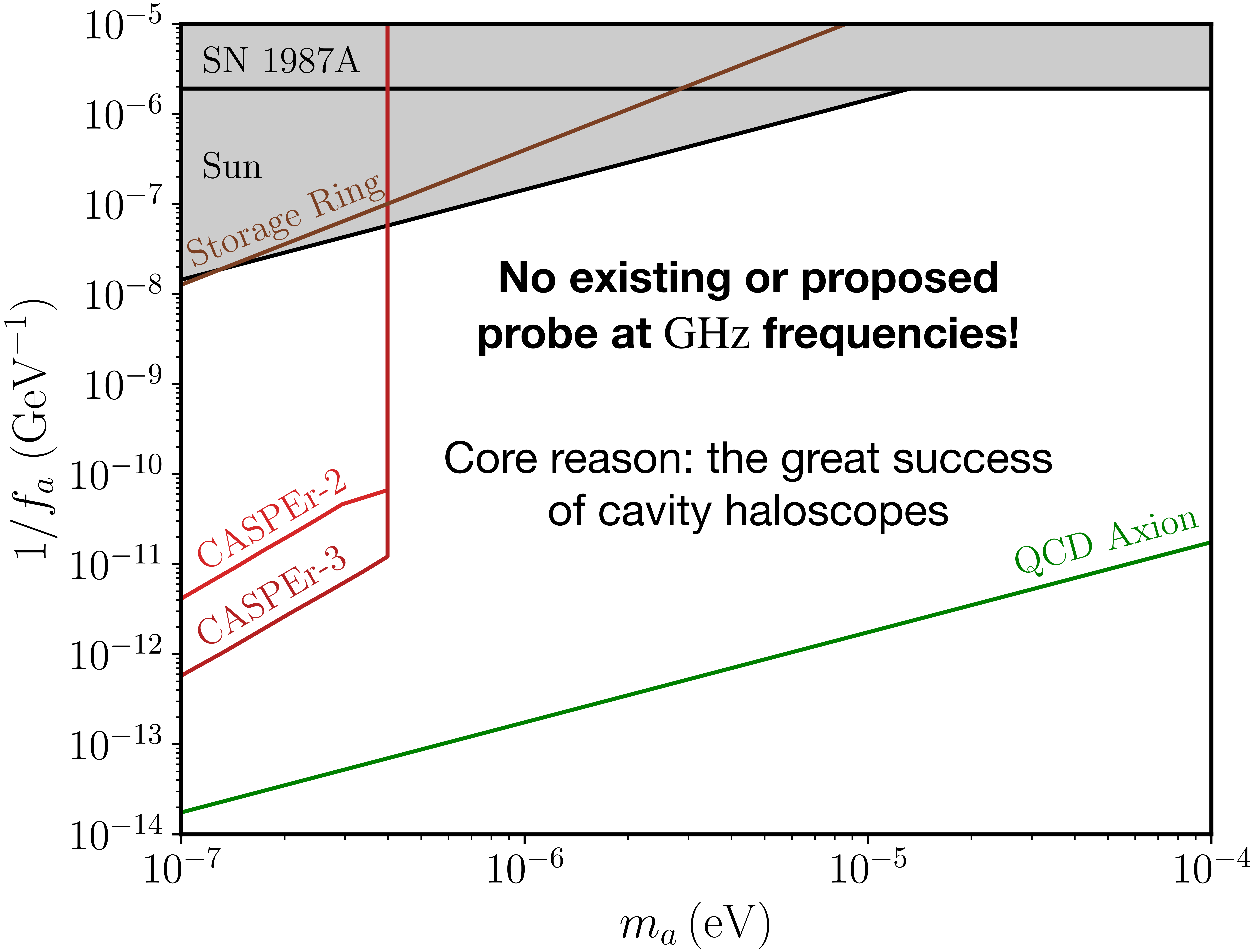

SN 1987A
Sun
QCD axion has definite mass given coupling!
On the way there, probe non-QCD axions, or
nonminimal QCD axions where potential cancels
QCD Axion
$1/f_a\ (\mathrm{GeV}^{-1})$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
$m_a\ (\mathrm{eV})$



SN 1987A
Sun
Constraints from supernova cooling
(typical for new light species)
Constraints from
static EDM experiments
(much lower frequency)
QCD Axion
$1/f_a\ (\mathrm{GeV}^{-1})$
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}
$m_a\ (\mathrm{eV})$



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}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-7}
10^{-6}
10^{-5}
10^{-4}


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

Electromagnetic Axion Detection

Generically, QCD axions have a coupling to electromagnetism

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

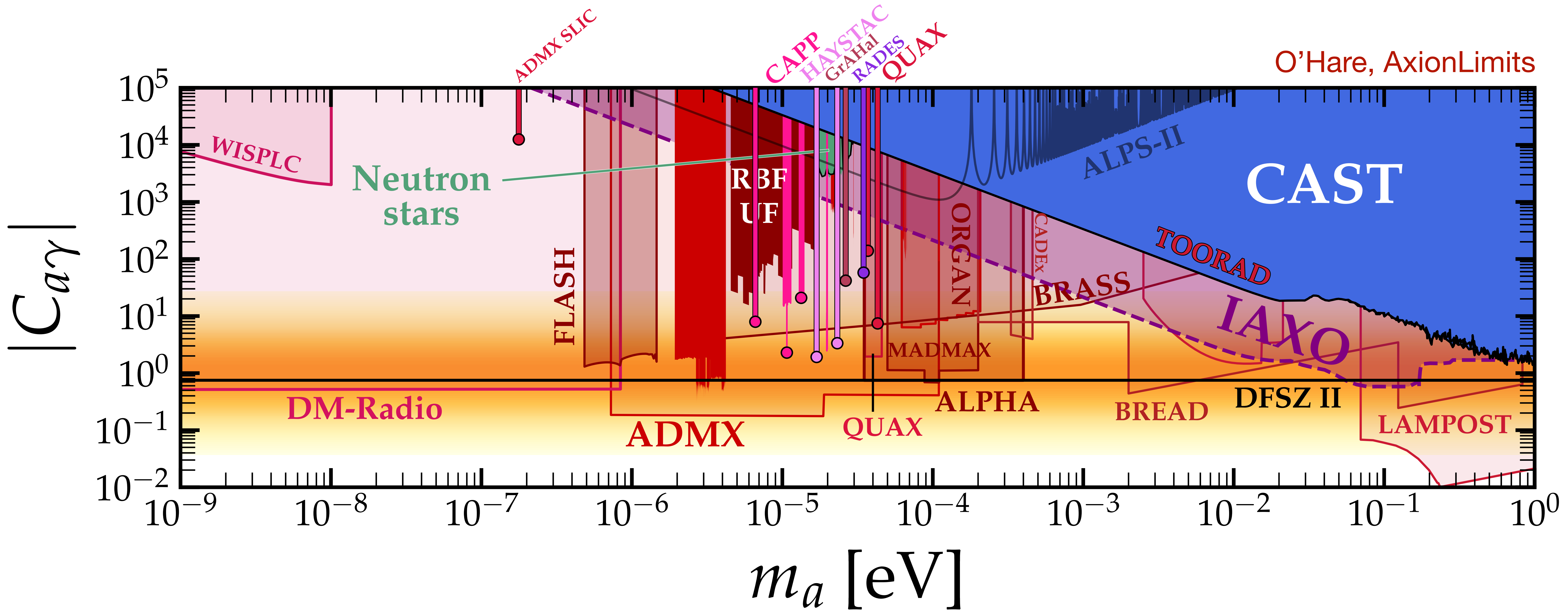
Order-one coefficient $C_{a\gamma}$ varies within 1-2 orders of magnitude for simple models

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

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

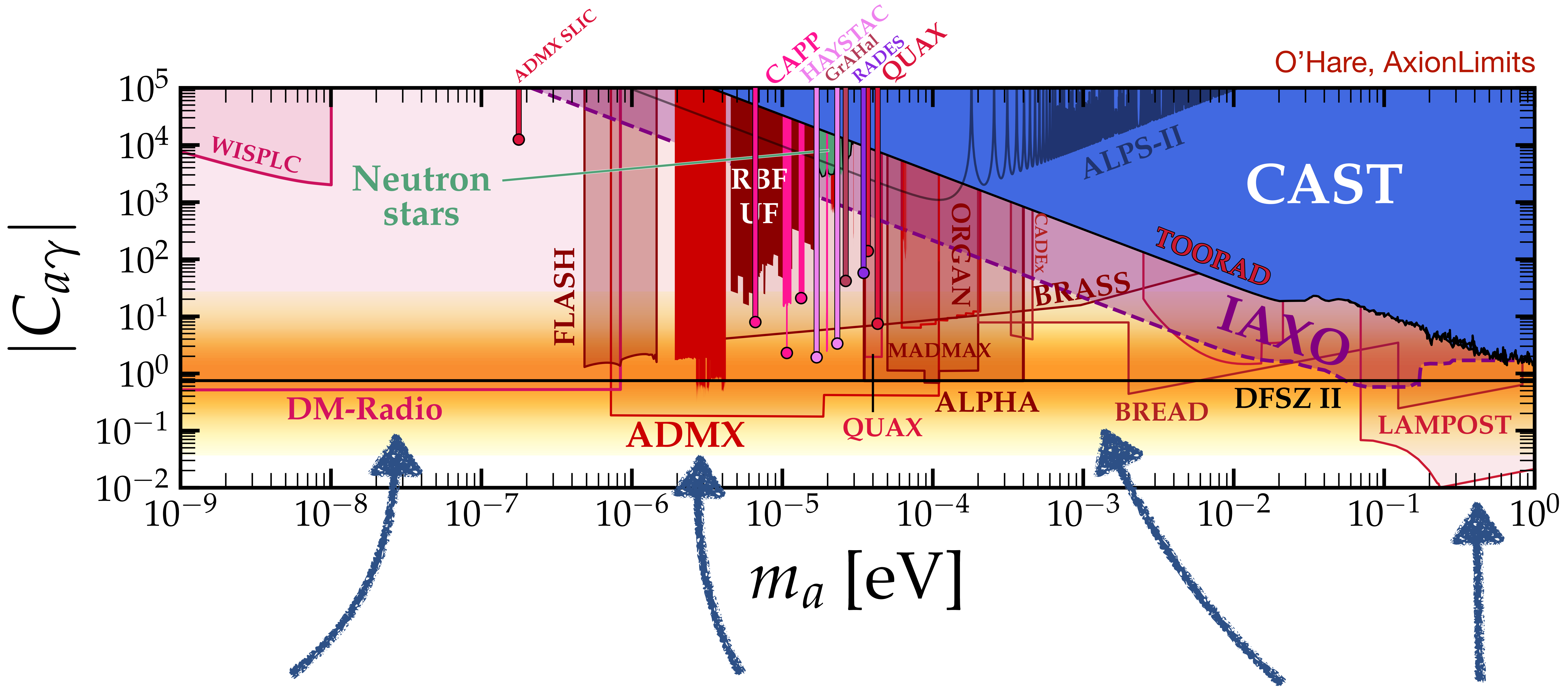
Electromagnetic Axion Detection

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



Electromagnetic Axion Detection

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

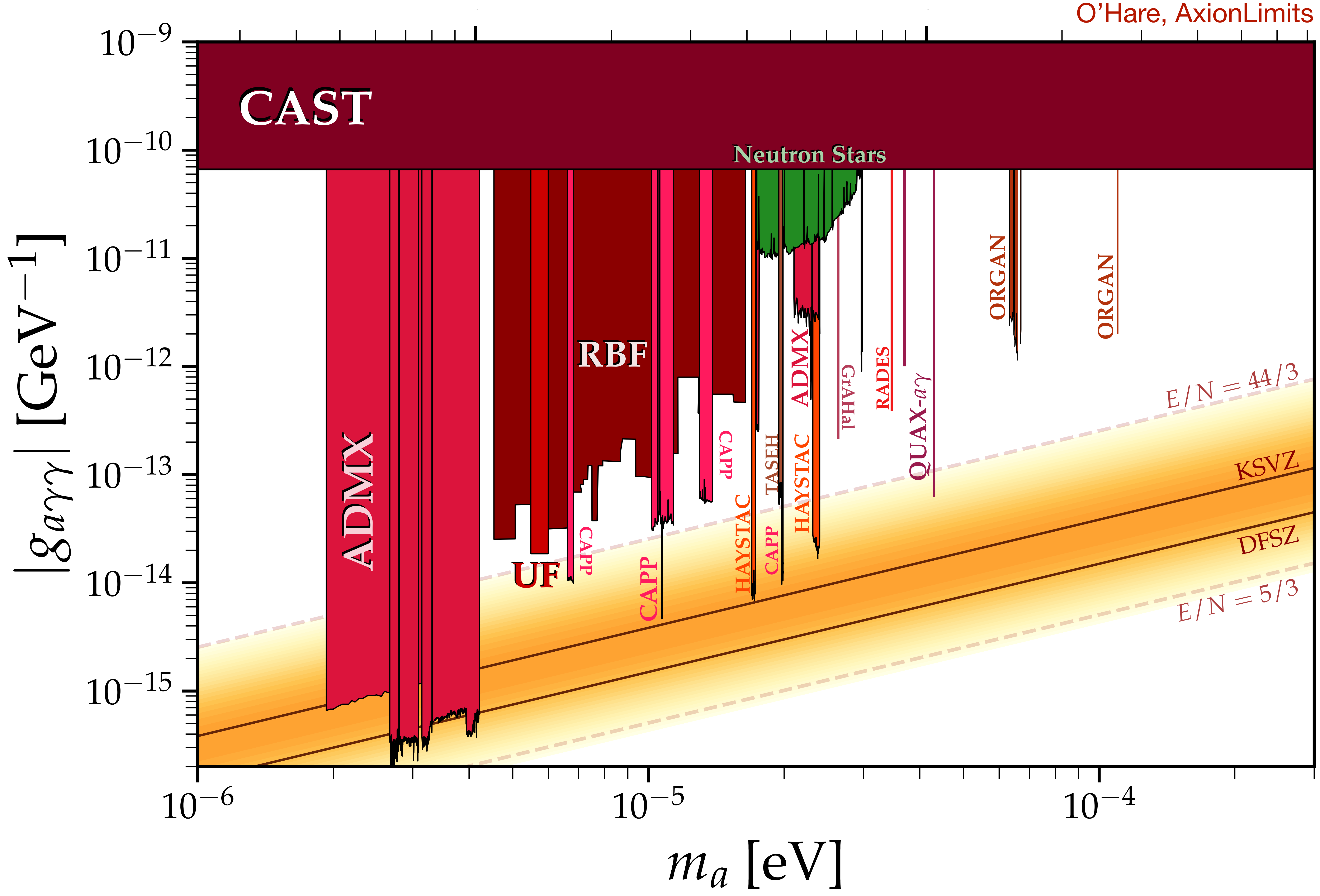


LC circuits or frequency conversion

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

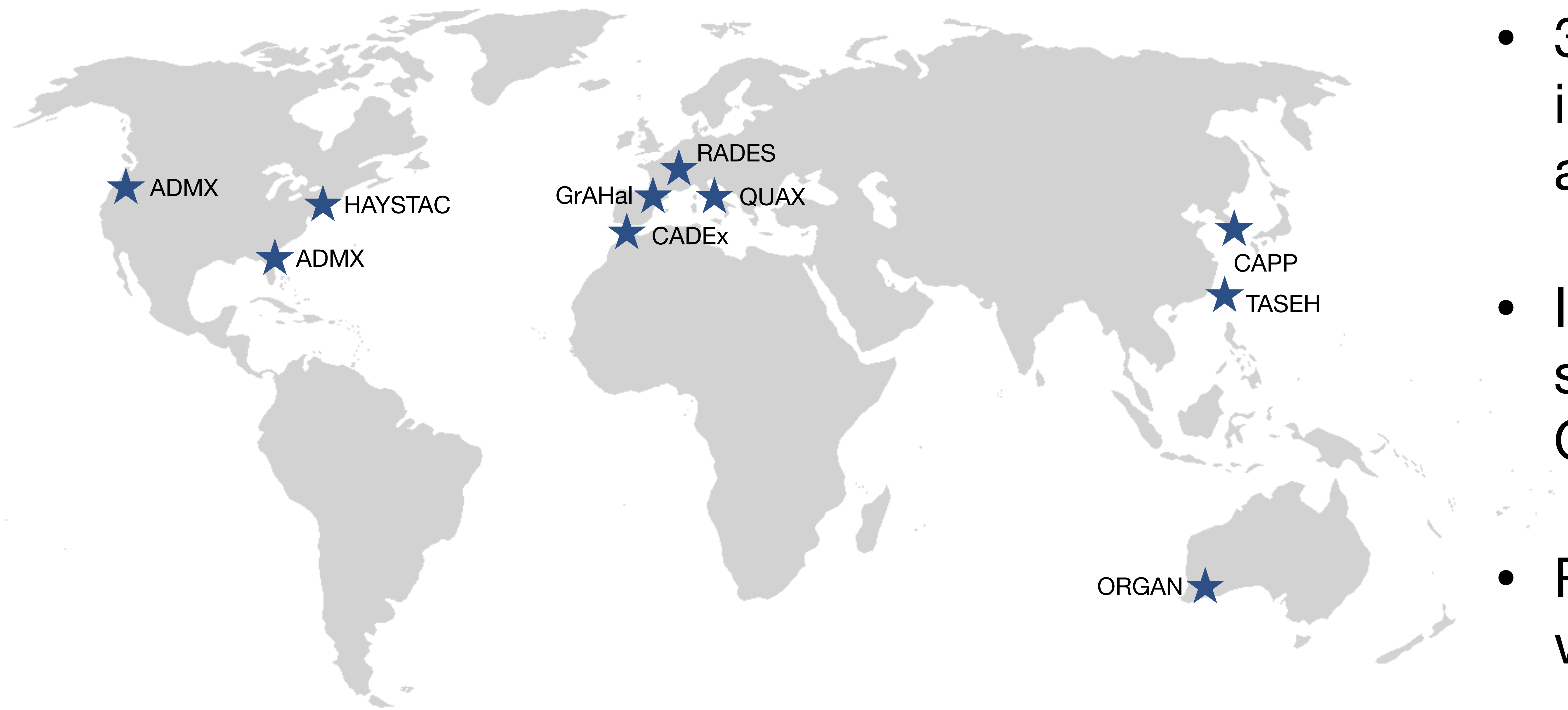
Metamaterials/quasiparticles/ cavity structure/nonresonant

The Cavity Haloscope



- 35 years of steady improvement; account for almost all existing bounds
- In past few years, sensitive to canonical QCD axion models

The Cavity Haloscope

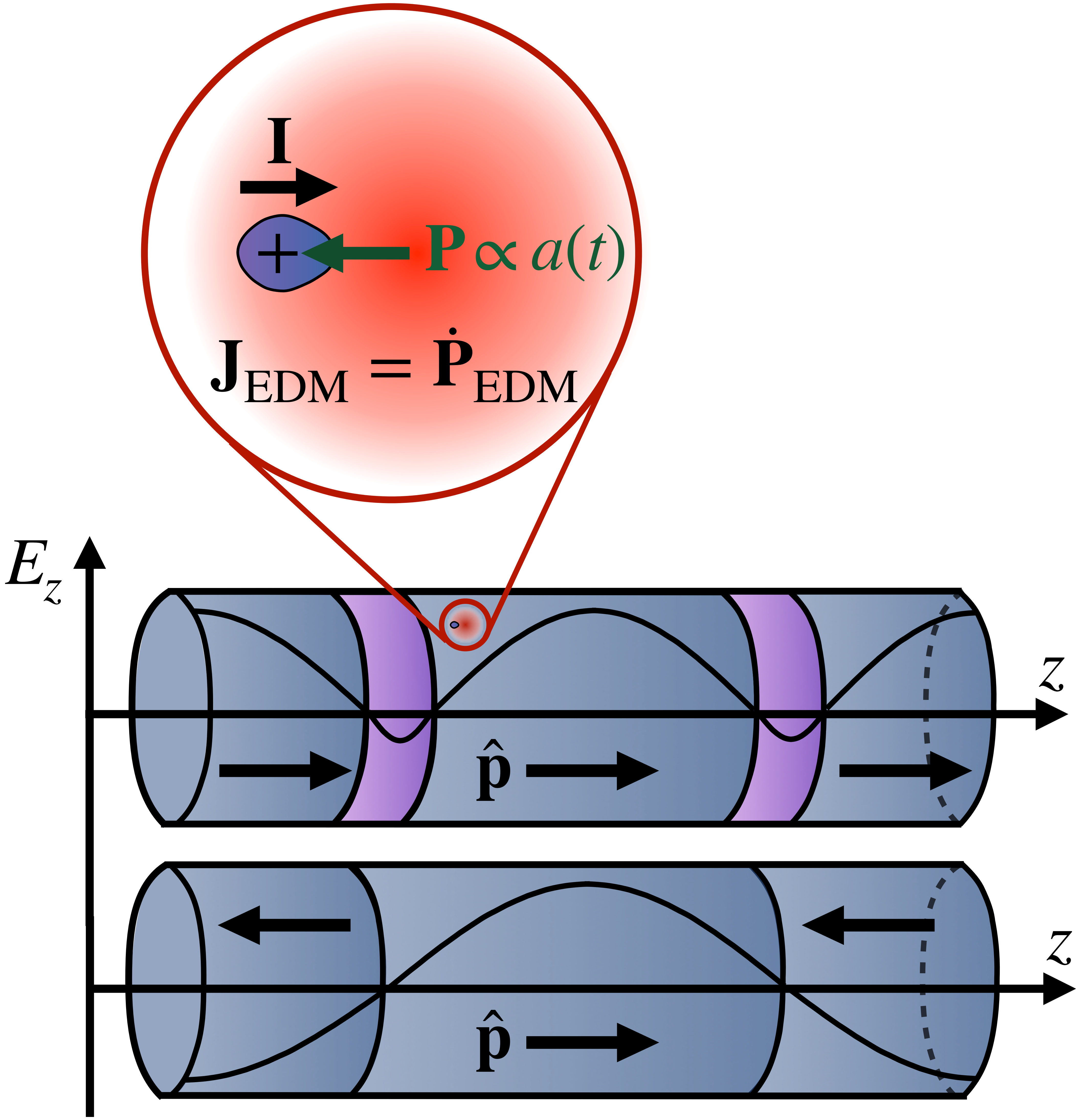


- 35 years of steady improvement; account for almost all existing bounds
- In past few years, sensitive to canonical QCD axion models
- Rapidly growing field, with wide international interest

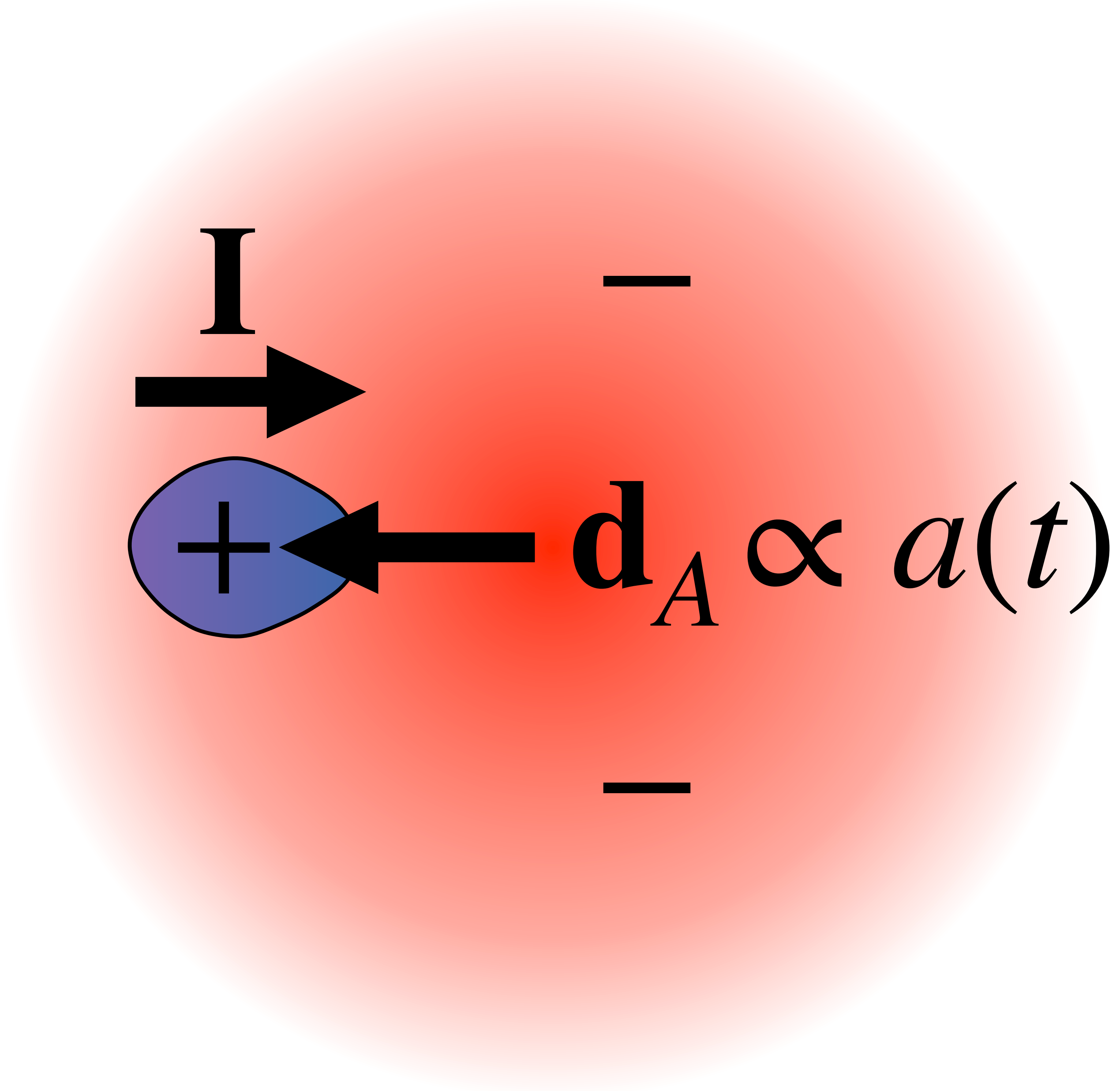
Can translate this success to the axion-gluon coupling with **polarization haloscopes**

Outline

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



Polarization Currents



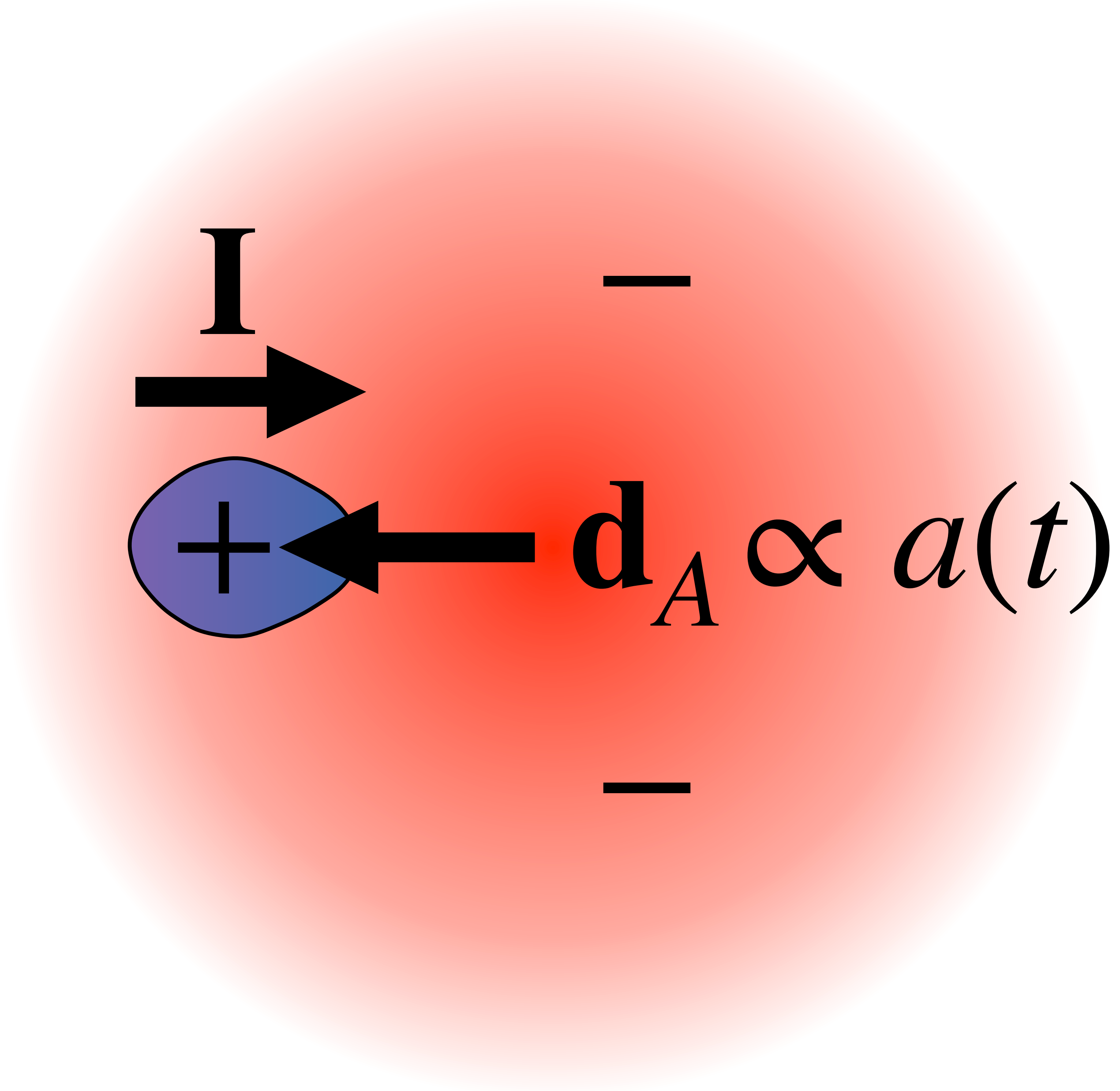
- The QCD axion produces atomic EDMs $\mathbf{d}_A$ parallel to the nuclear spin $\mathbf{I}$
- For a nuclear spin-polarized sample, gives polarization

$$\mathbf{P}_{\mathrm{EDM}} \sim n_A \mathbf{d}_A$$

- Time variation leads to current

$$\mathbf{J}_{\mathrm{EDM}} = \dot{\mathbf{P}}_{\mathrm{EDM}}$$

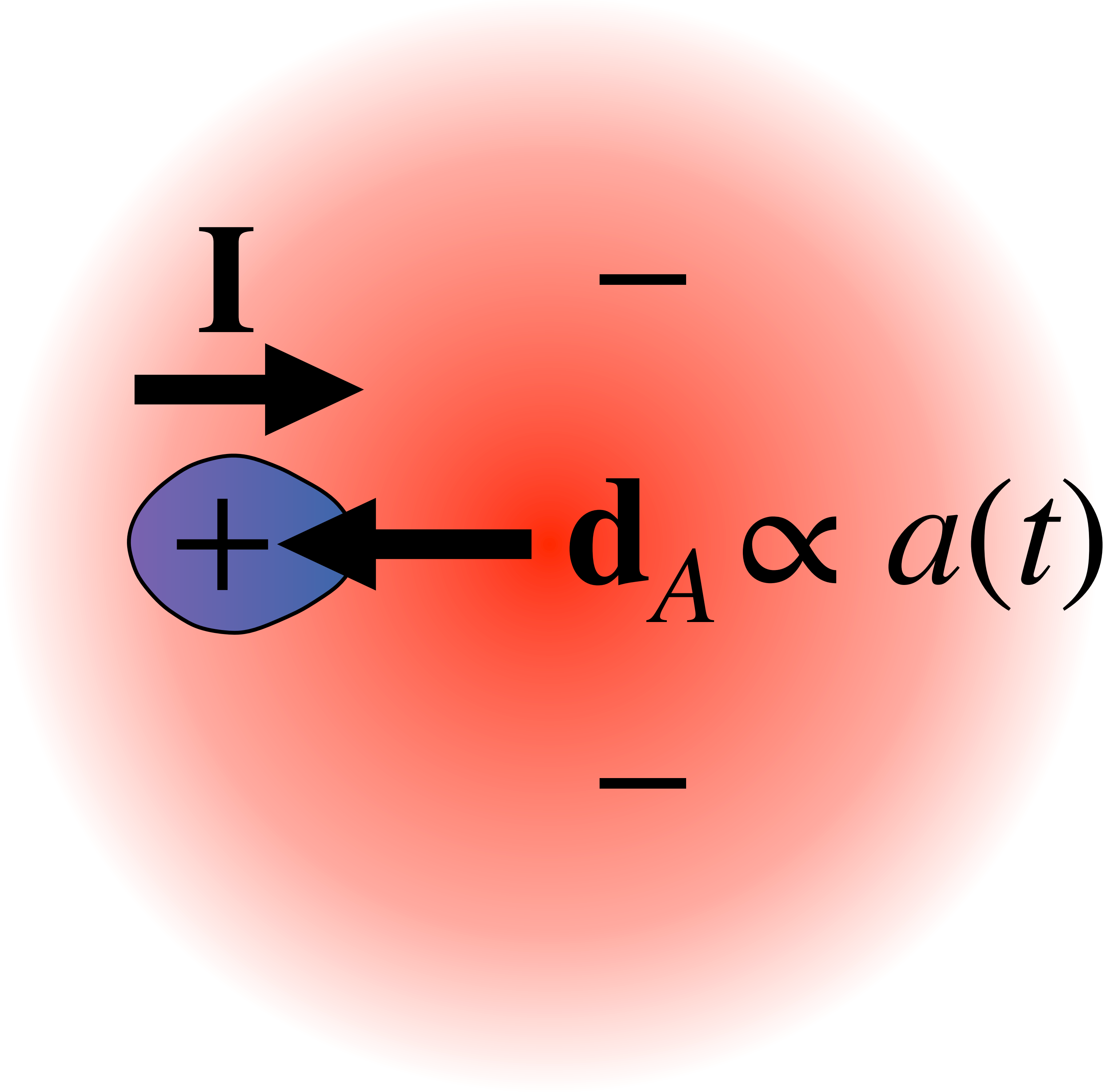
Polarization Currents



To make a polarization haloscope, fill a cavity with nuclear spin-polarized dielectric, yielding

$$\mathbf{J}_{\mathrm{EDM}} = g_d\, \dot{a}\, n_A \frac{d_A}{d_n}$$

Polarization Currents



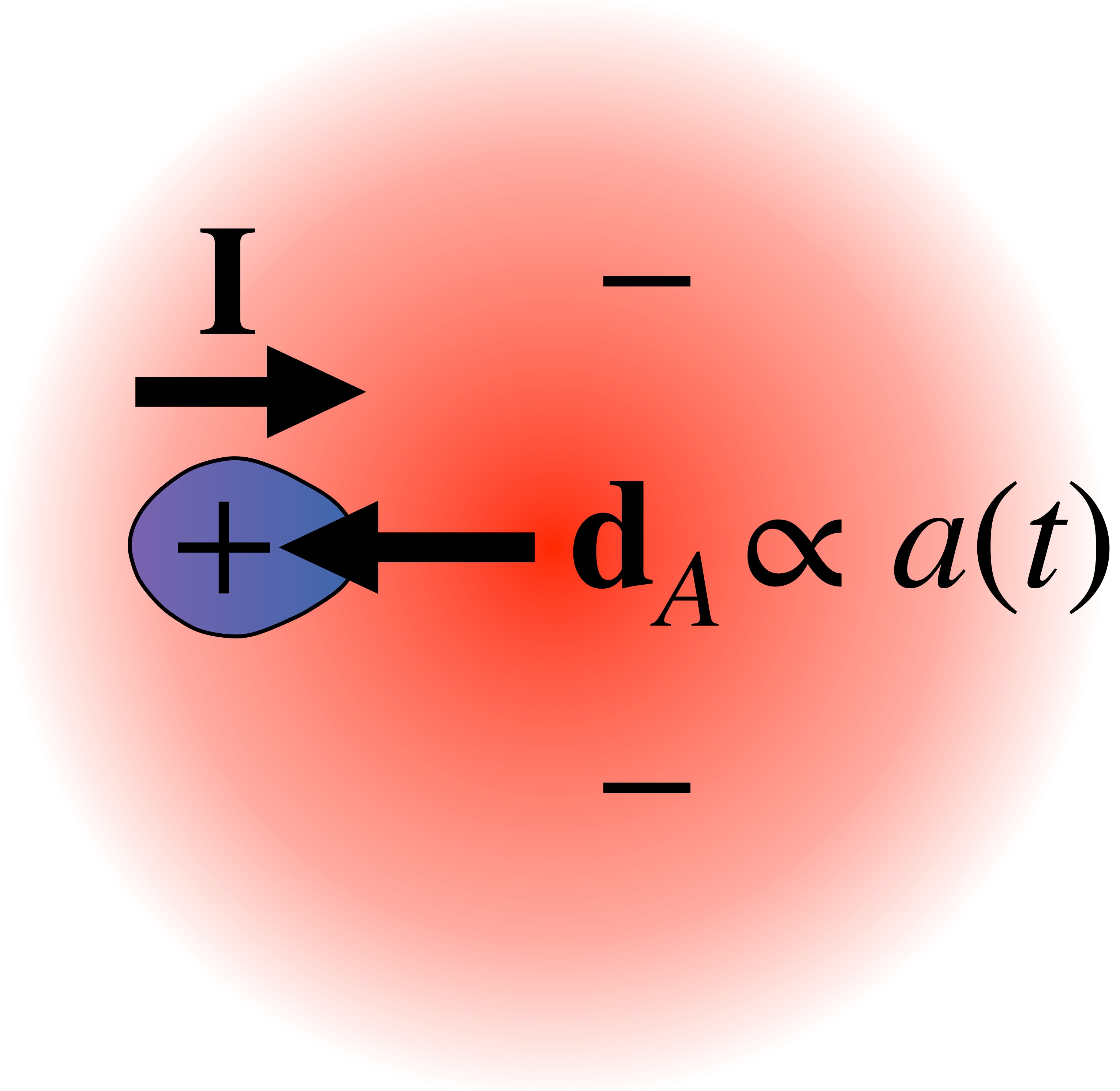
To make a polarization haloscope, fill a cavity with nuclear spin-polarized dielectric, yielding

$$\mathbf{J}_{\mathrm{EDM}} = g_d \, \dot{a} \, n_A \, \frac{d_A}{d_n}$$

For a typical QCD axion:

$$\frac{J_{\mathrm{EDM}}}{J_{\mathrm{eff}}} \simeq 10^{-3} \, \frac{d_A}{d_n} \, \frac{n_A}{5 \times 10^{22} \ \mathrm{cm}^{-3}} \, \frac{8 \ \mathrm{T}}{B}$$

Polarization Currents



$$\frac{J_{\mathrm{EDM}}}{J_{\mathrm{eff}}} \simeq 10^{-3} \, \frac{d_A}{d_n} \, \frac{n_a}{5 \times 10^{22}\ \mathrm{cm}^{-3}} \, \frac{8\ \mathrm{T}}{B}$$

Harder to reach QCD axion this way; why do it?

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

Schiff Moments

- Axions induce P and CP-violating nuclear moments
- Leading effect is nuclear EDM, but electron shielding cancels atomic EDM d_A

Schiff Moments

- Axions induce P and CP-violating nuclear moments
- Leading effect is nuclear EDM, but electron shielding cancels atomic EDM d_A
- Next order effects are electric octupole moment (negligible) and Schiff moment

$$\mathbf{S} = \frac{1}{10}\int d^3\mathbf{x}\,\rho_N(\mathbf{x})\,r^2\left(\mathbf{x} - \frac{5}{3}\frac{\mathbf{d}_N}{Ze}\right)$$

- Acts on electrons to produce atomic EDM with

$$V_S = -\sum_{i=1}^{Z} e\mathbf{S}\cdot\nabla\delta^3(\mathbf{x}_i), \qquad d_A \propto Z^2 S$$

Schiff Moments

- Schiff moments induced by axion-mediated $\hat{P}, \hat{T}$ violating internucleon interaction

$$\langle S_z \rangle \sim \sum_n \frac{\langle n | V_a | 0 \rangle \langle 0 | S_z | n \rangle}{E_n - E_0}$$

- For spherical nuclei, parametric estimate is

$$\langle S_z \rangle \sim 10^{-2} \, \frac{eR_0^2}{m_n} \, \theta_a$$

- Leads to small $d_A \ll d_n$ except for heaviest nuclei, which are unstable

Schiff Moments

- Much higher results for octupole-deformed nuclei with intrinsic Schiff moments,

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

- Suppressed by small octupole deformation, enhanced by Z and small ΔE

$$\langle S_z \rangle \sim 10^{-2} \, \frac{ZeR_0^2}{m_n} \, \theta_a, \qquad |d_A| \sim (\text{few} \times 10^{-3}) \; e \, \text{fm} \times \theta_a \left(\frac{Z}{10^2} \right)^3 \left(\frac{A}{10^2} \right)^{2/3}$$

- Comparable to d_n for rare earths, possibly larger for very heavy nuclei

Schiff Moments

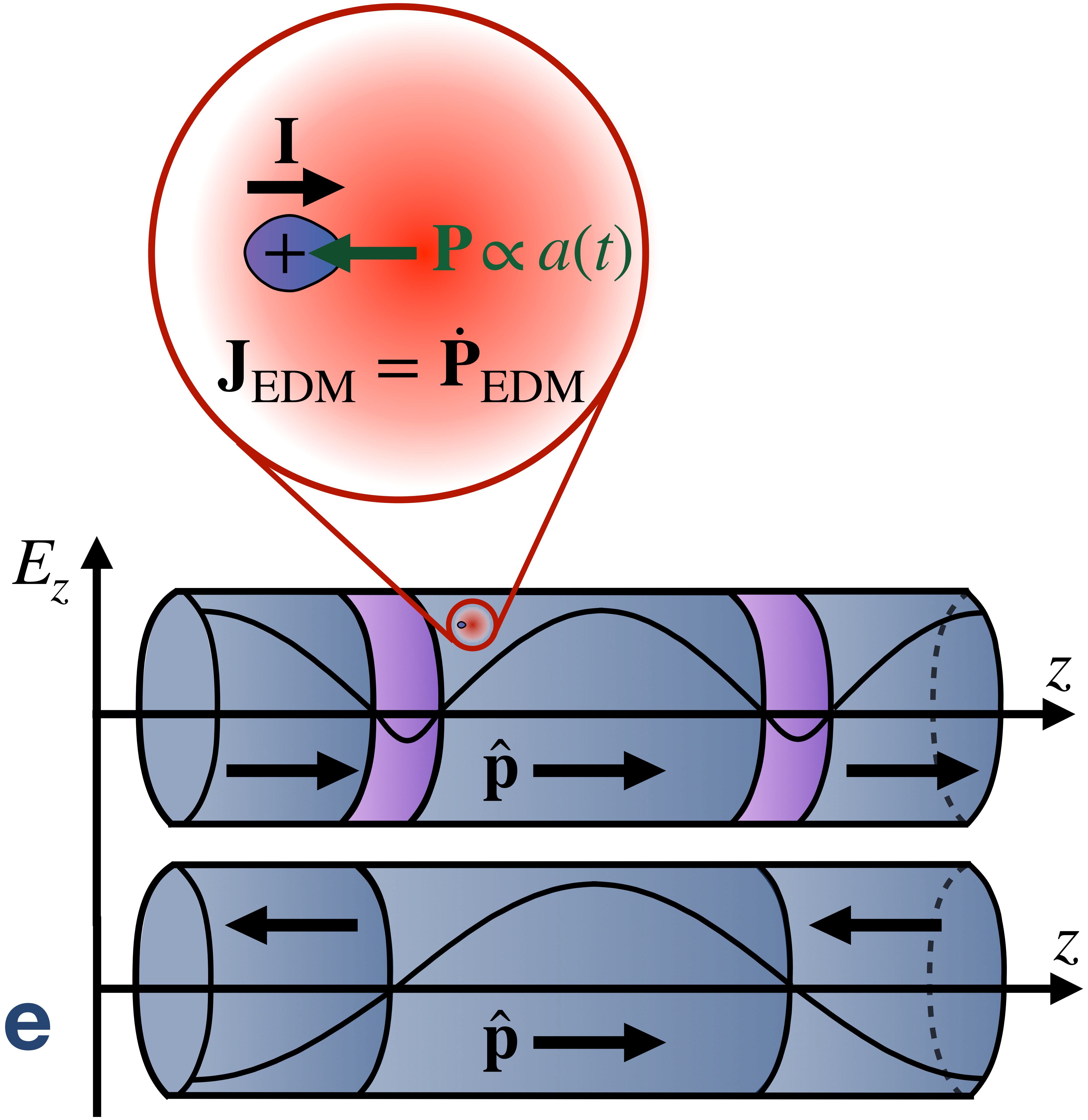
	$^{161}\mathrm{Dy}$	$^{153}\mathrm{Eu}$	$^{155}\mathrm{Gd}$
estimated $\langle S_z \rangle$ (e fm^3 θ_a)	$\lesssim 4$	3.7	~ 1
estimated $\lvert d_A \rvert$ (10^{-3} e fm θ_a)	$\lesssim 0.9$	0.6	~ 0.2
natural abundance	19%	52%	15%
metal price ($/ton)	300 k	30 k	30 k

- Several promising stable, inexpensive rare earth nuclei

- Not all nuclear theorists agree on octopole deformation, more work needed

Outline

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



Signal Power

Analogous to cavity haloscope: for mode with profile $\mathbf{E}_i$ on resonance ($m_a \simeq \omega_i$),

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

Polarization density (fractional nuclear spin polarization f_p)

Resonant enhancement

Signal Power

Analogous to cavity haloscope: for mode with profile $\mathbf{E}_i$ on resonance ($m_a \simeq \omega_i$),

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

Polarization density (fractional nuclear spin polarization f_p)

Resonant enhancement

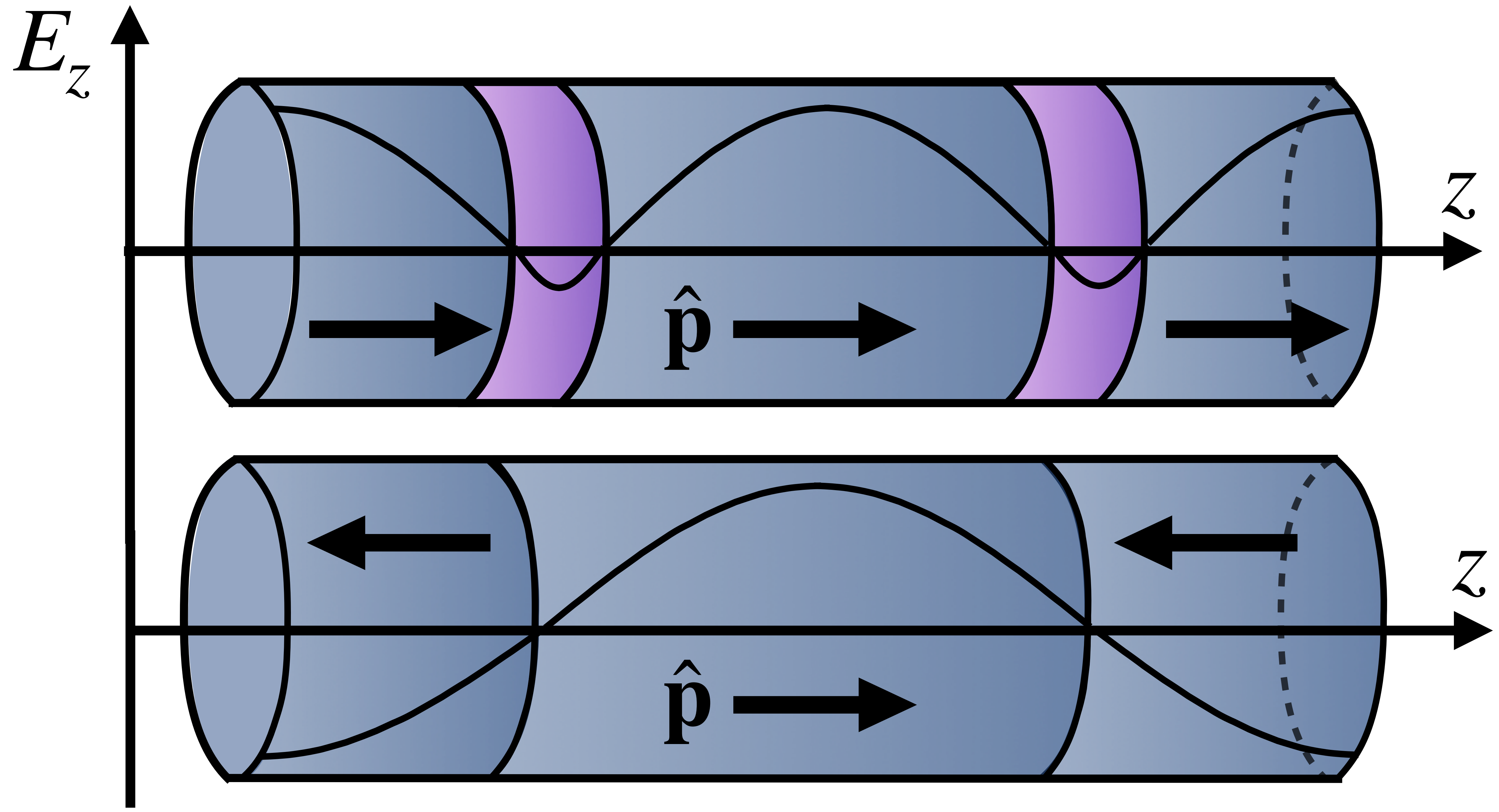
Dielectrics shield electric fields

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

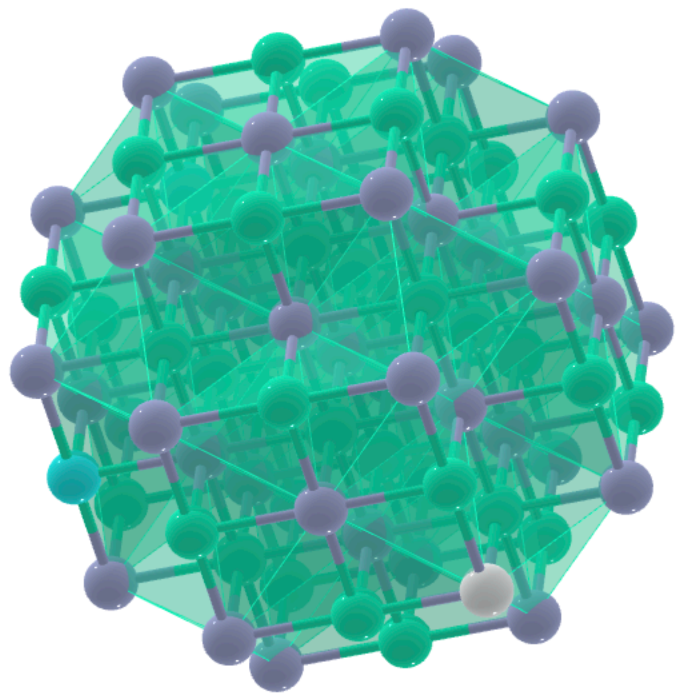
To maximize the geometric form factor, align nuclear spins $\hat{\mathbf{p}}$ with $\mathbf{E}_i$



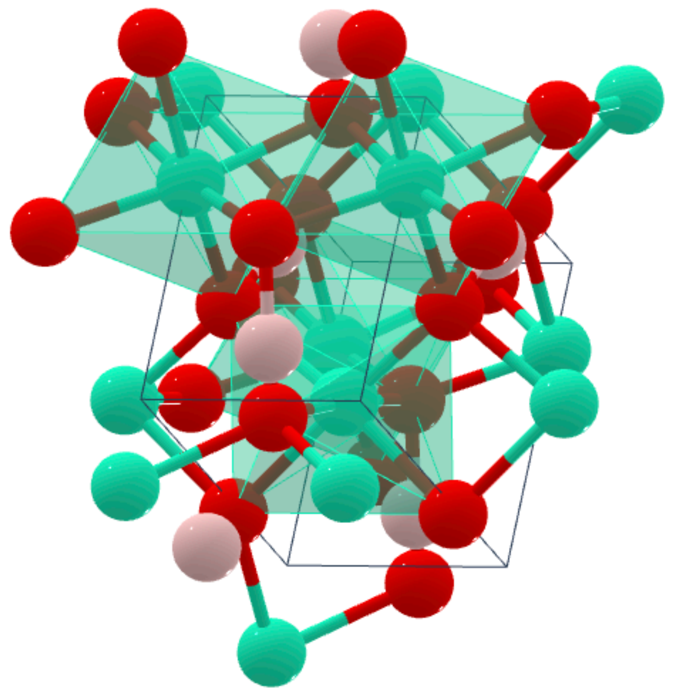
Layers can cover up to $m_a \sim 10^{-5}\,\mathrm{eV}$, but many other approaches possible

Optimizing Material

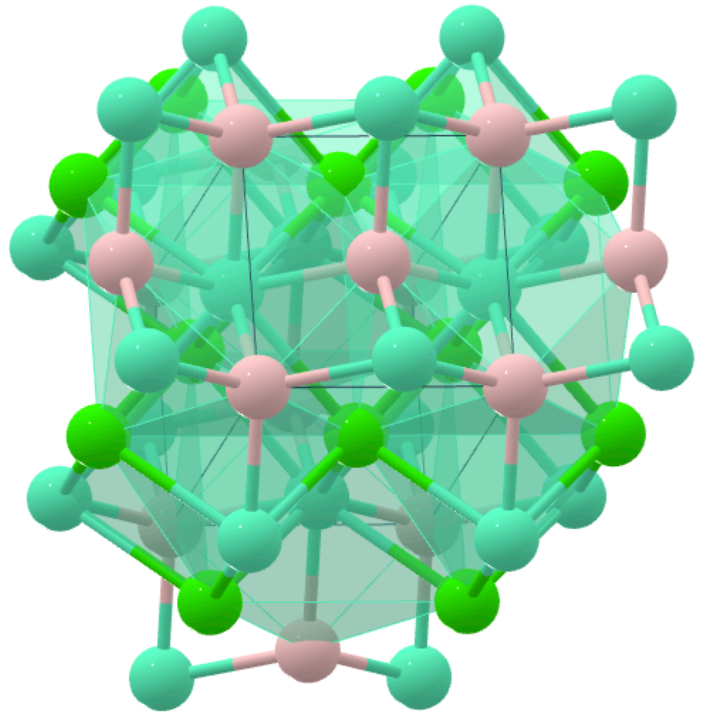
Material only has to be insulating; prefer high n_0, low ϵ



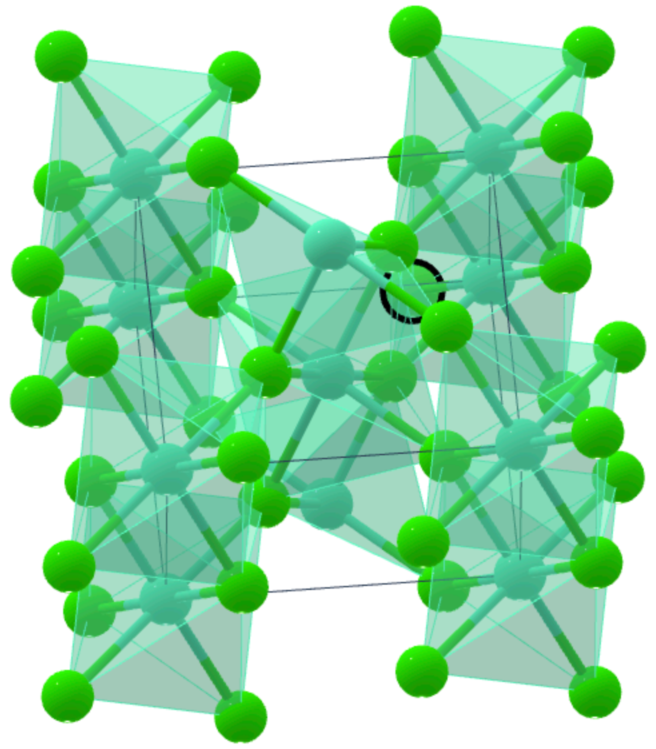
DyN



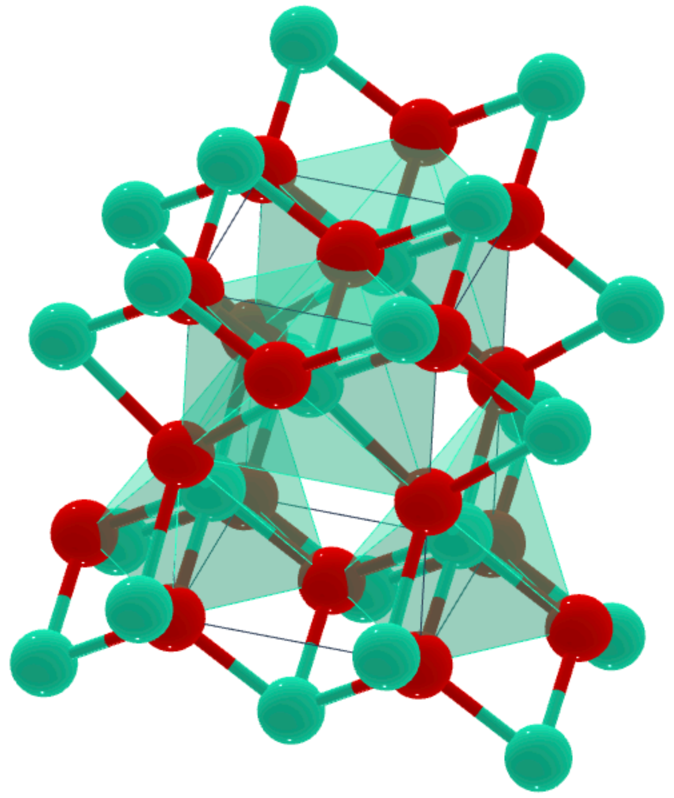
Dy_2O_3



$DyHO_2$



EuHCl



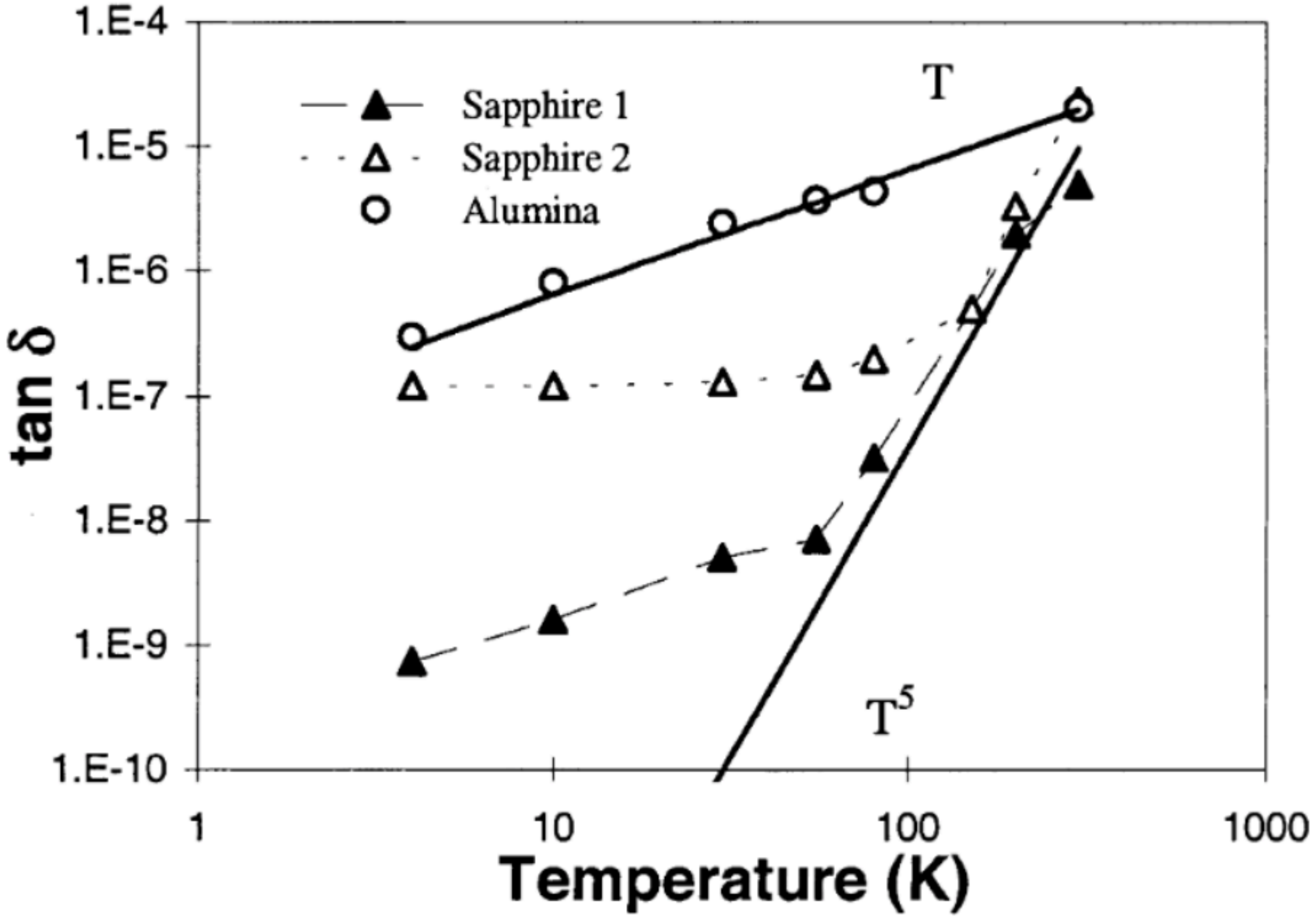
$EuCl_2$

These are simple, stable, and commercially available, but many alternatives exist

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

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

Brute force approach

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

But: thermalization time may be prohibitively long

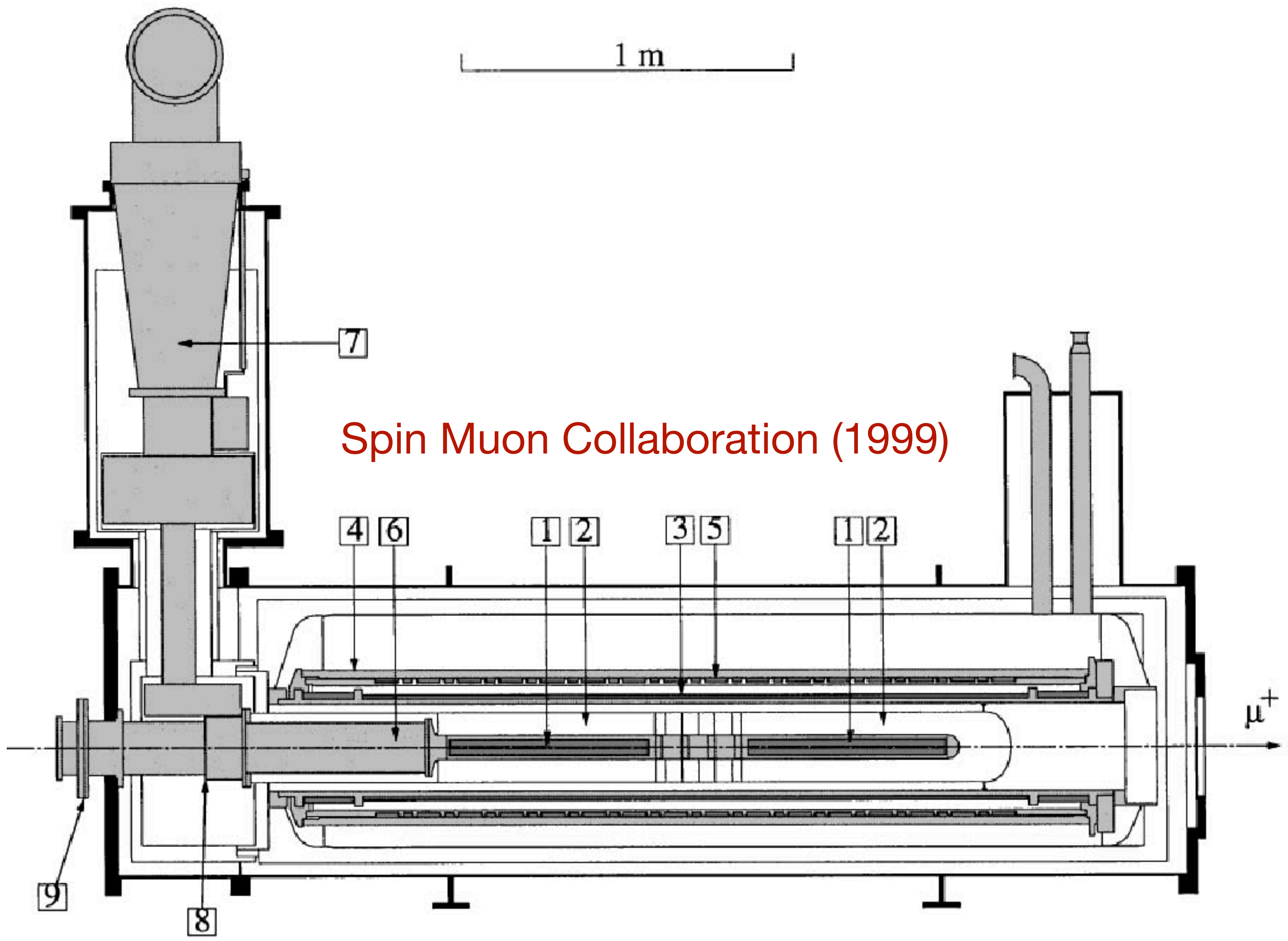
Frozen spin dynamic nuclear polarization

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

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)

<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

Sensitivity Estimate

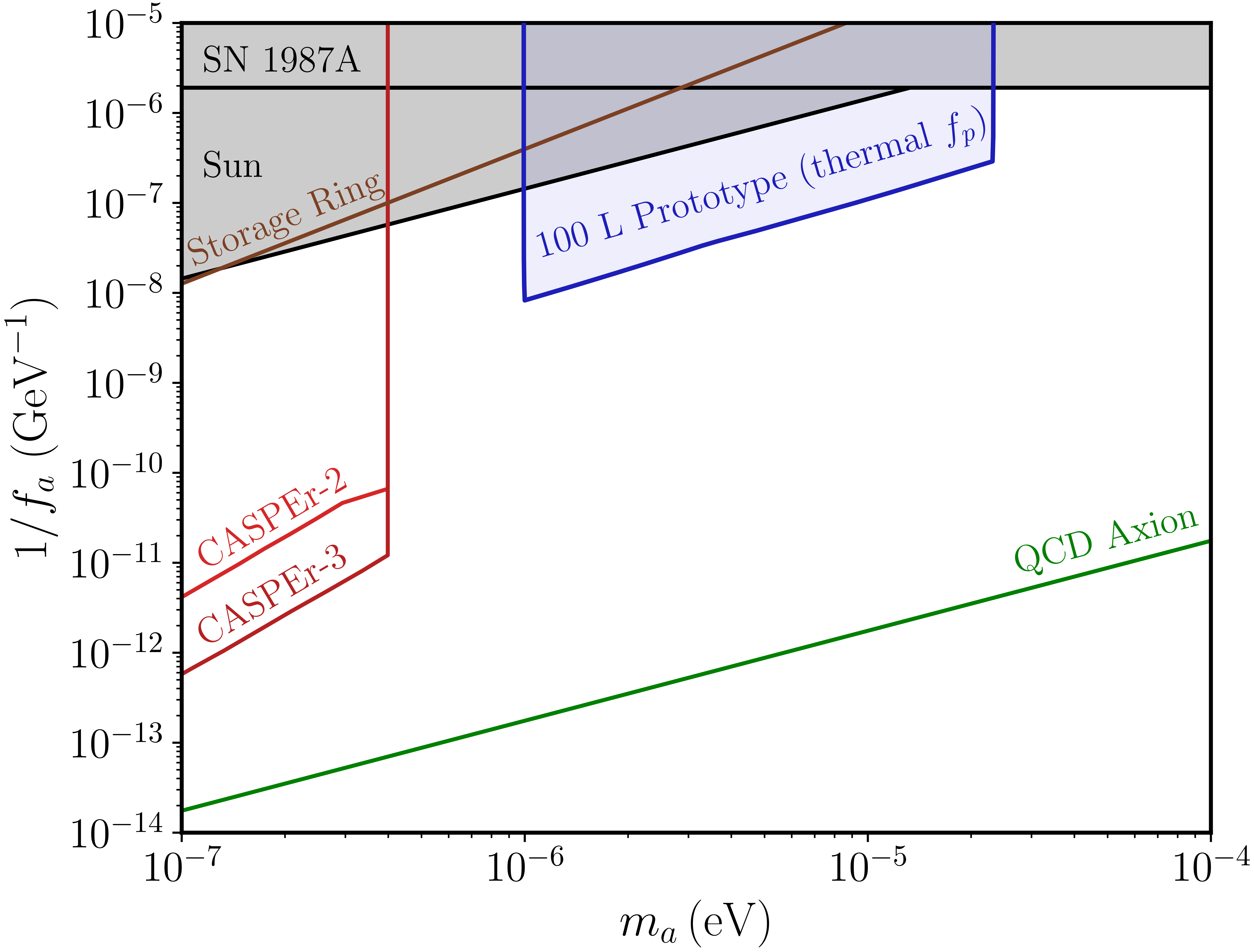
All noise sources besides thermal and amplifier noise vastly subdominant

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

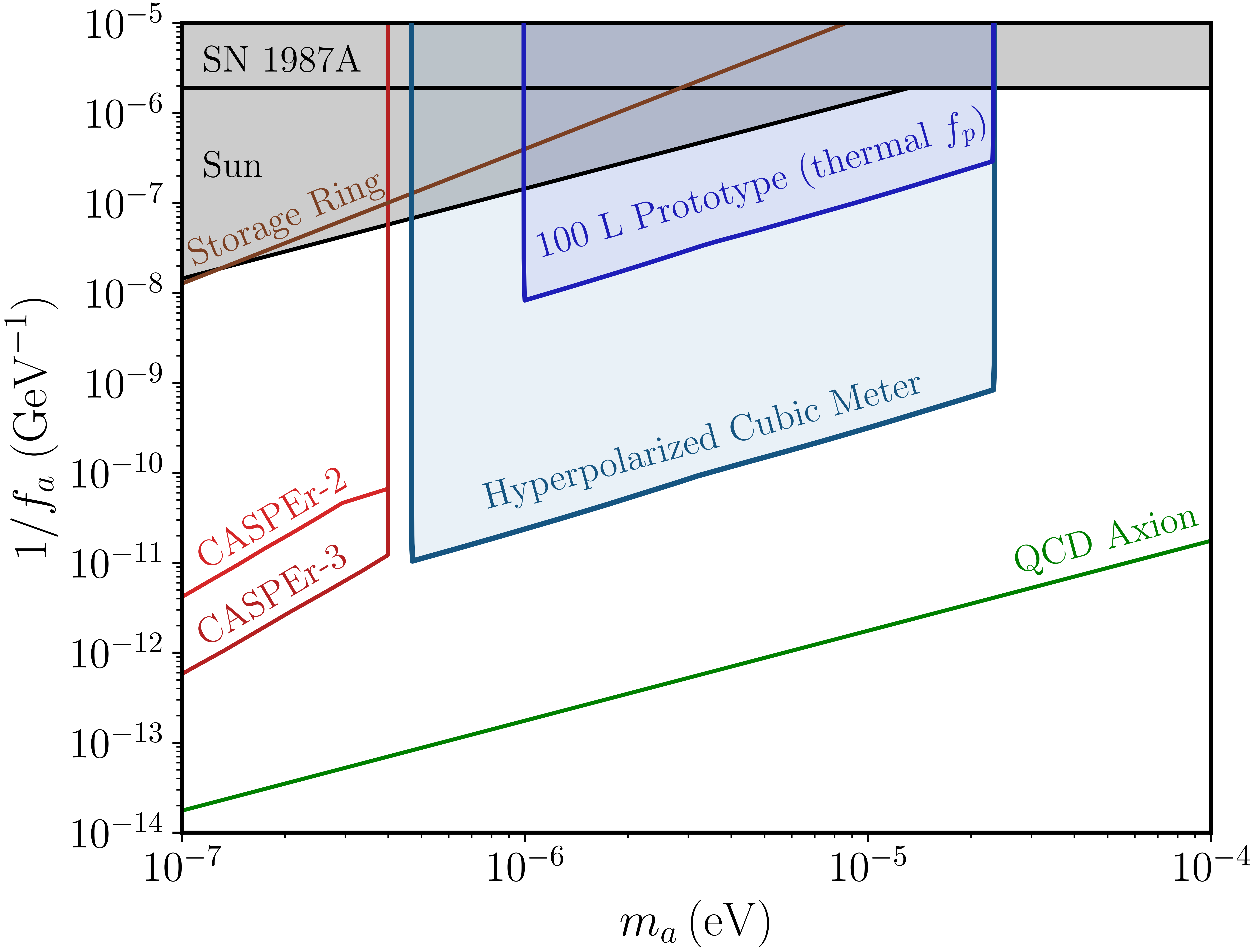
Assume quantum-limited amplifier, $T_{\mathrm{amp}} = m_a$, and usual scanning procedure

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

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

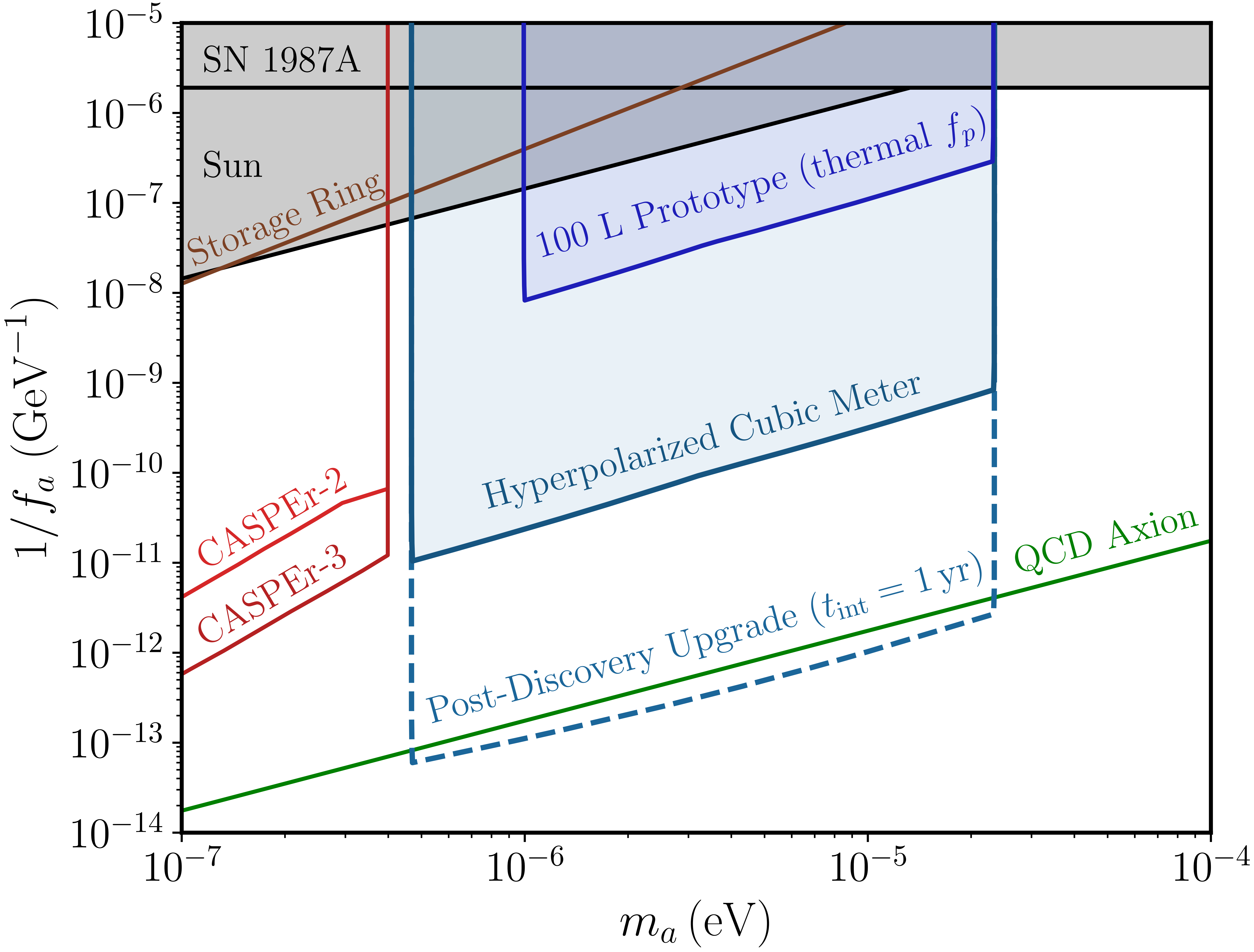


Filling existing haloscope with dielectric probes new parameter space — exciting opportunity!



Filling existing haloscope with dielectric probes new parameter space — exciting opportunity!

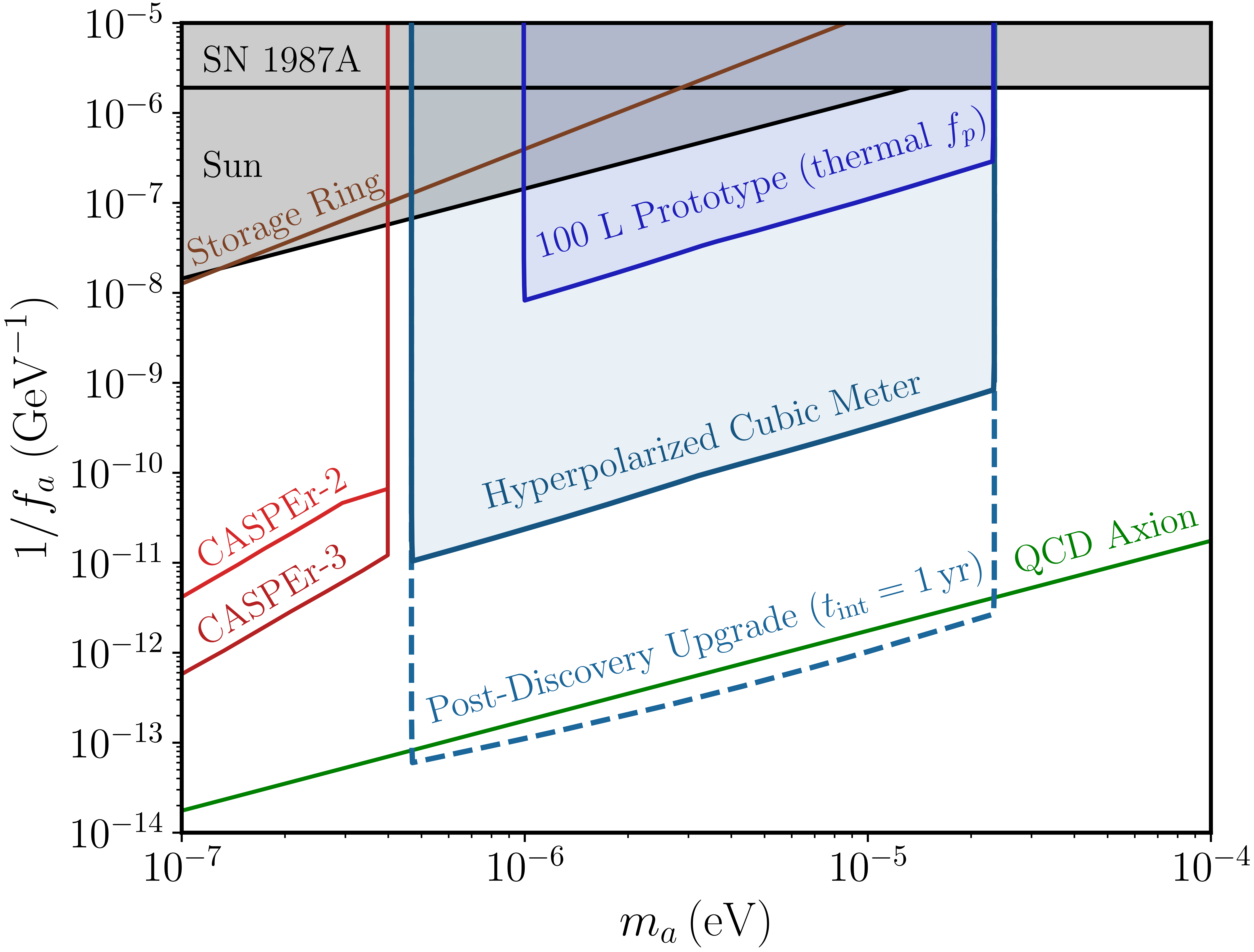
Hyperpolarized sample probes orders of magnitude further



Filling existing haloscope with dielectric probes new parameter space — exciting opportunity!

Hyperpolarized sample probes orders of magnitude further

Upgrade is only known way to confirm a candidate QCD axion



Filling existing haloscope with dielectric probes new parameter space — exciting opportunity!

Hyperpolarized sample probes orders of magnitude further

Upgrade is only known way to confirm a candidate QCD axion

Motivates further investigation into dielectric materials, octupole deformation