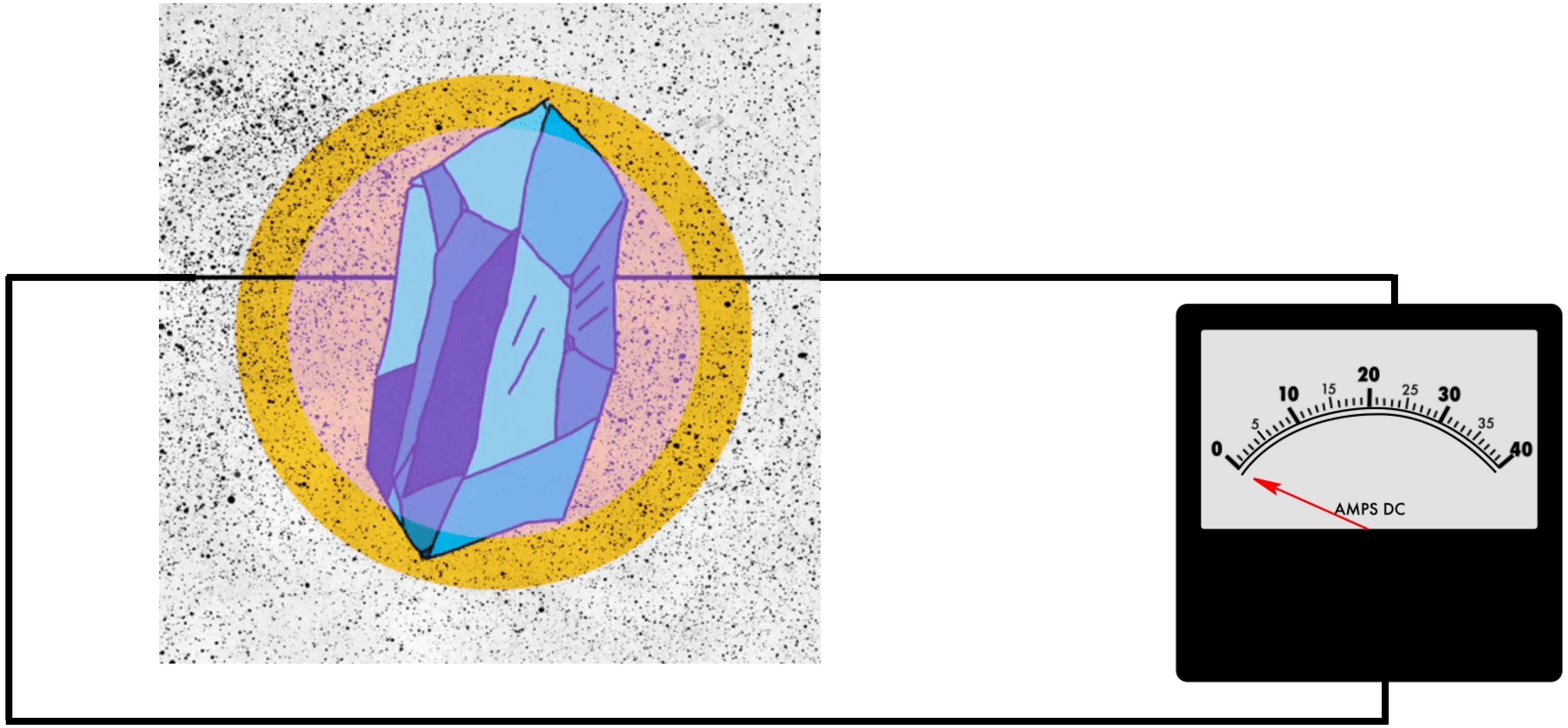
The Piezoaxionic Effect



Amalia Madden - Perimeter Institute for Theoretical Physics

Based on work w/ Asimina Arvanitaki (PI) and Ken Van Tilburg (NYU)

Outline

- **Motivation**

    The QCD axion

- **The Piezoaxionic Effect**

    P and T violation in nuclei, atoms and crystals

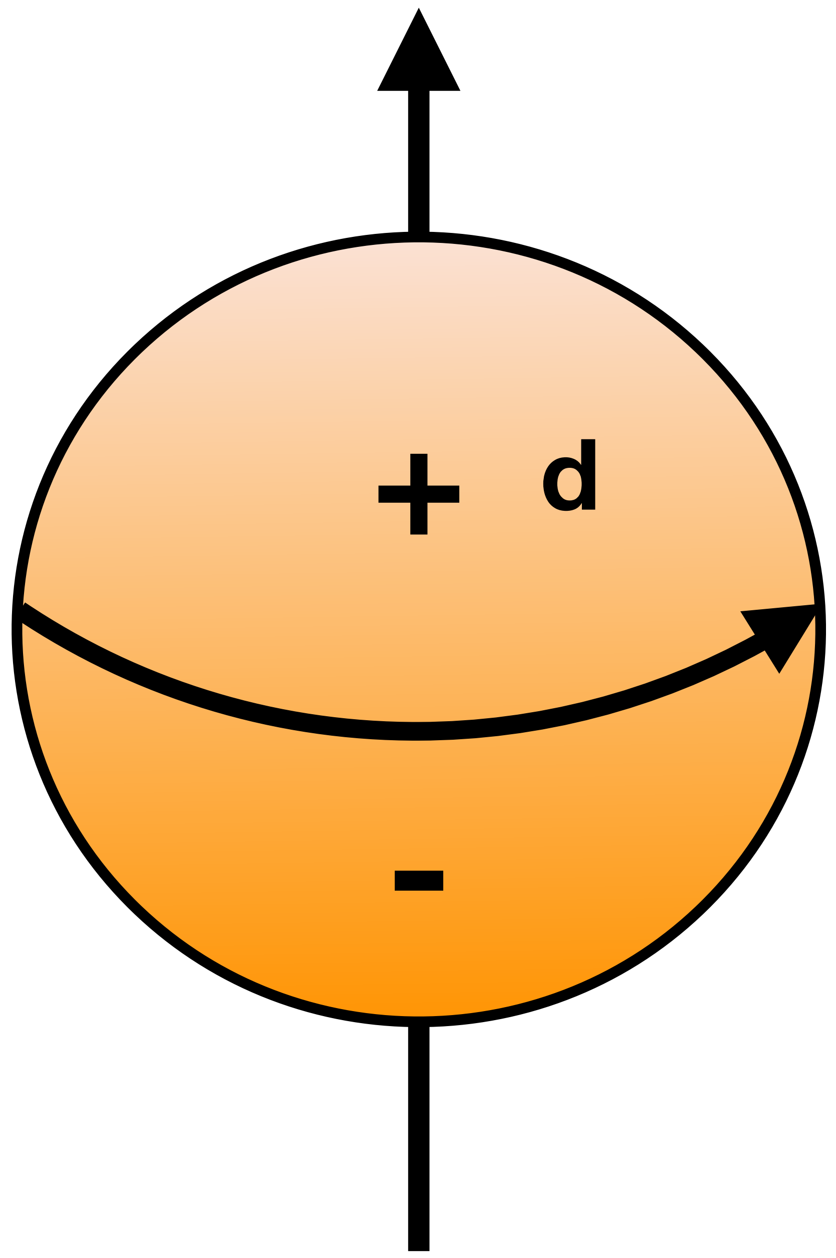
    Proposed experimental setup and sensitivity

- **The Ferroaxionic Effect**

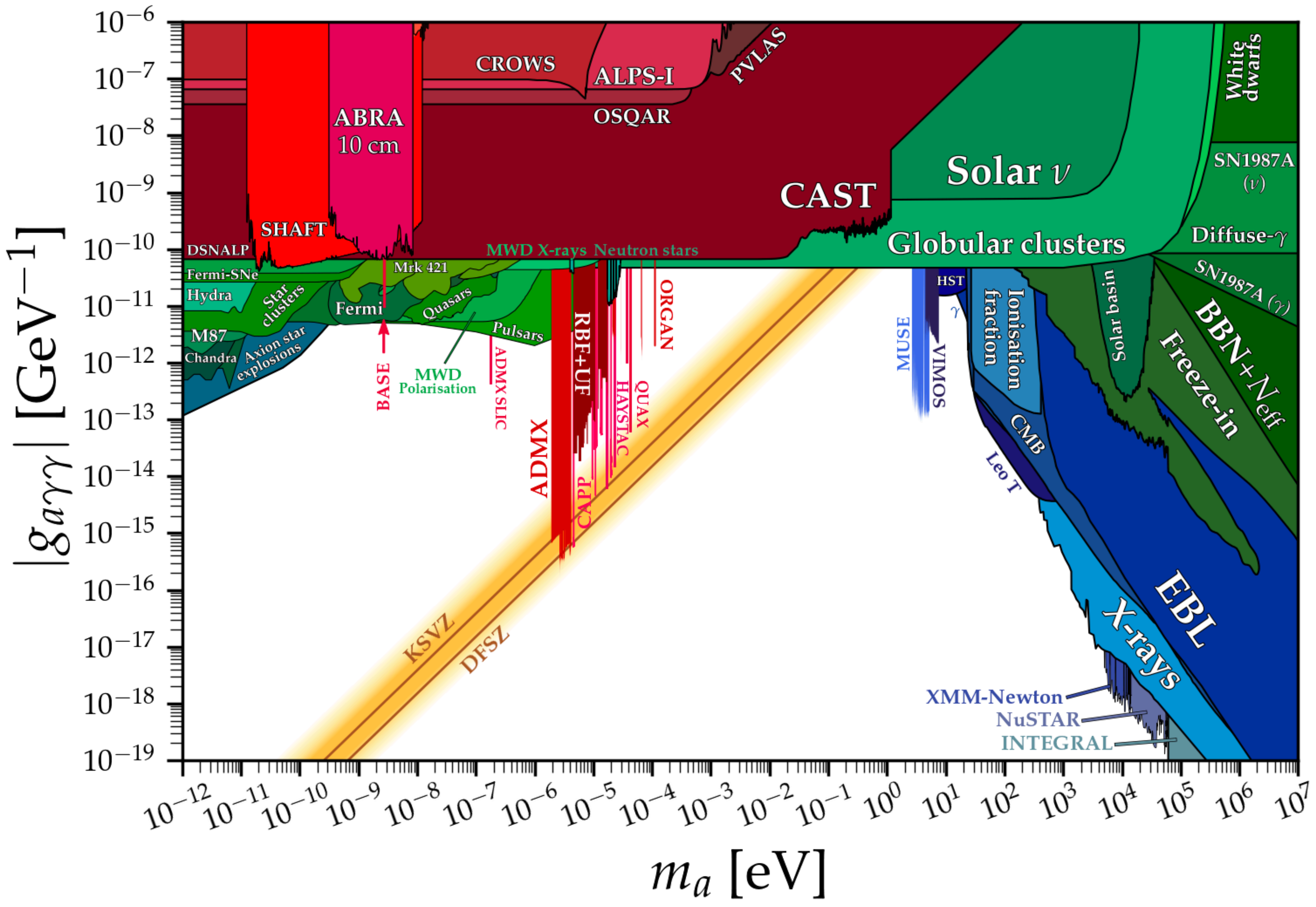
    Axion-mediated forces

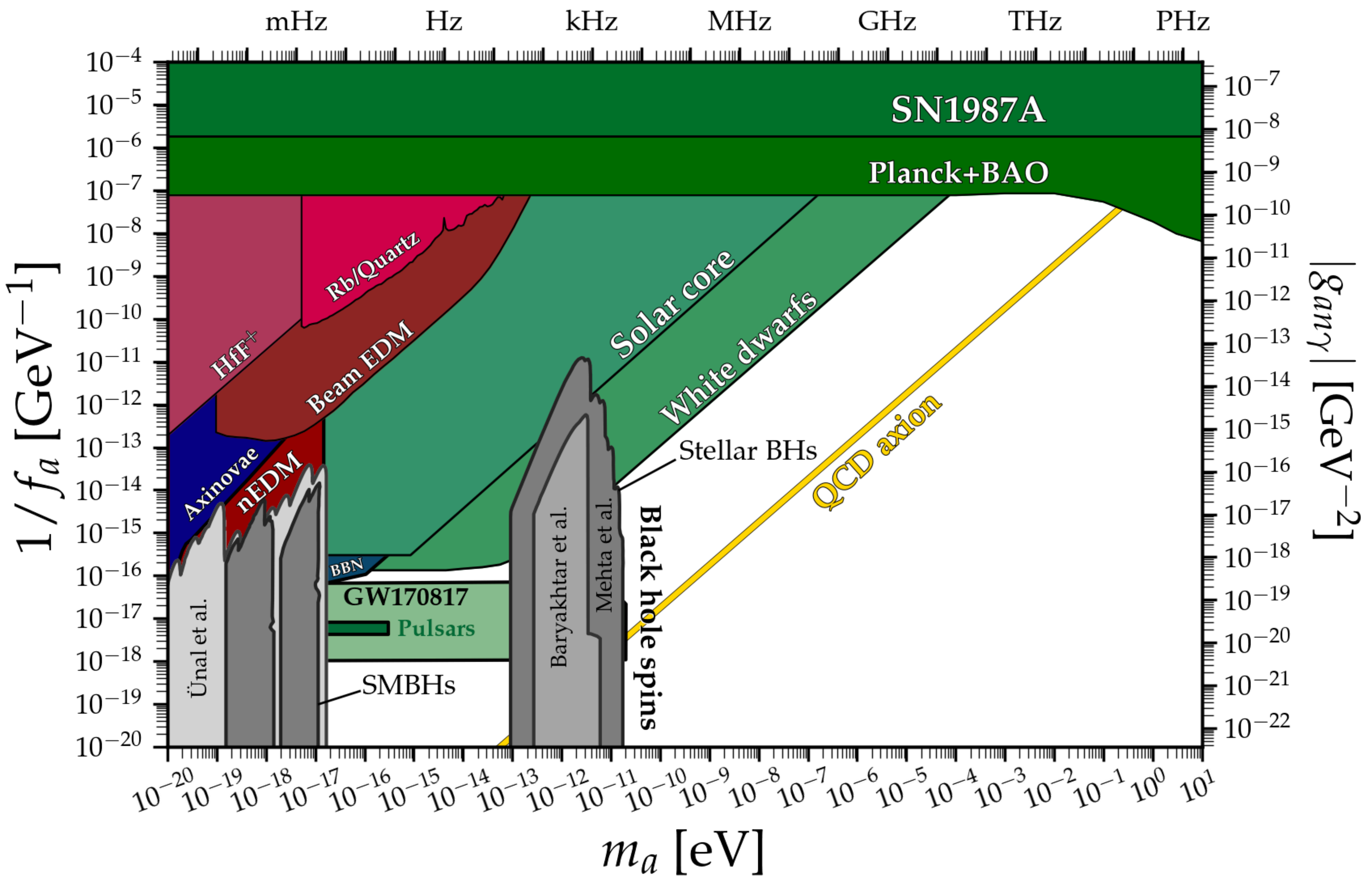
Strong CP Problem

- $\mathscr{L}_{SM} \supset \frac{\theta_0}{32\pi^2} \operatorname{tr} G\tilde{G}$
- Physical angle $\bar{\theta} = \theta_0 + \arg\det[M_q]$
- Neutron EDM of size $d_n \sim \bar{\theta} \cdot 10^{-16} \cdot e \cdot \text{cm}$
- Experimentally, $d_n \lesssim 10^{-26} \cdot e \cdot \text{cm} \implies |\bar{\theta}| < 10^{-10}$
- $\mathscr{L} \supset \frac{a}{32\pi^2 f_a} \operatorname{tr} G\tilde{G}$ dynamically solves strong CP problem



Photon vs Gluon Couplings





https://cajohare.github.io/AxionLimits/

Wavy Dark Matter

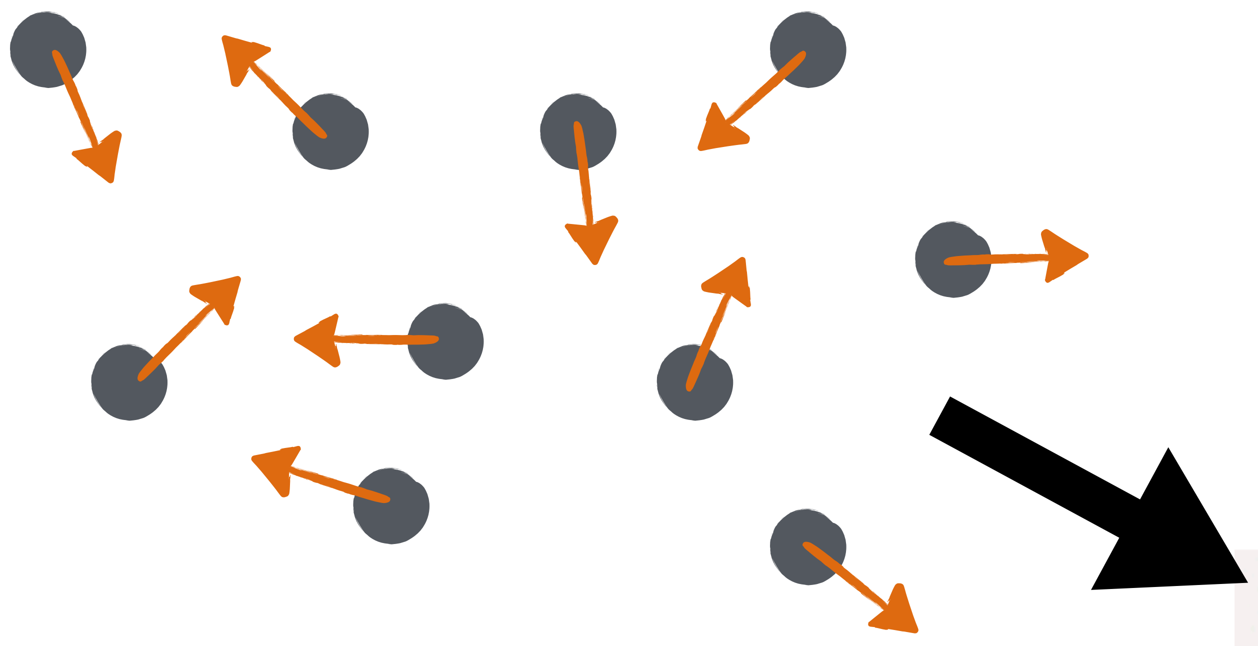
Bosonic DM has wave-like properties when $n_{DM} > \frac{1}{\lambda_{DM}^3}$. In our galaxy: $m_{DM} < 1eV$.

- Locally, $a(t) \approx a_0 \cos \frac{m_a c^2}{\hbar} t$

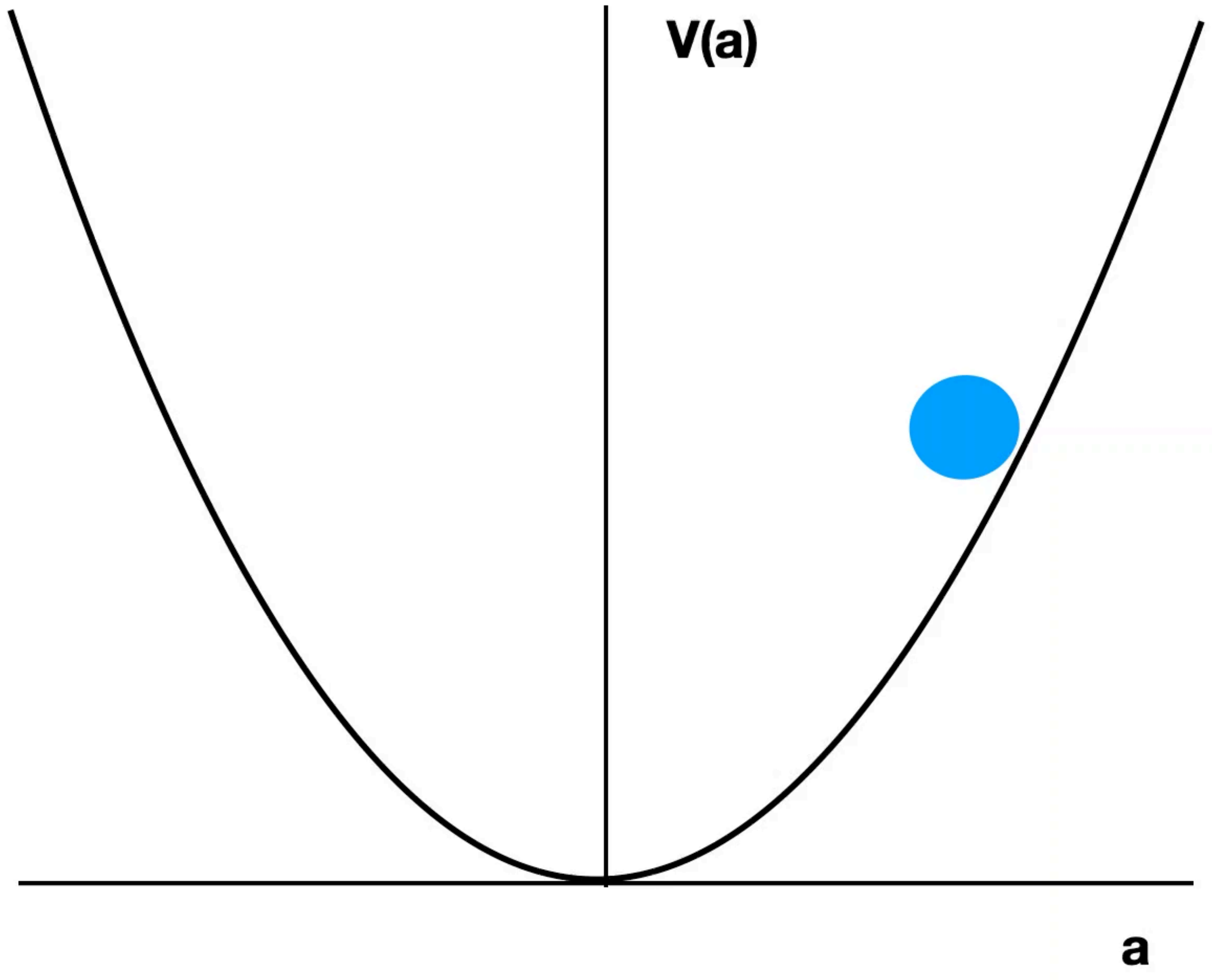
- Amplitude $a_0 \propto \frac{\sqrt{\rho_{DM}}}{m_a}$

- Small frequency spread (coherence)

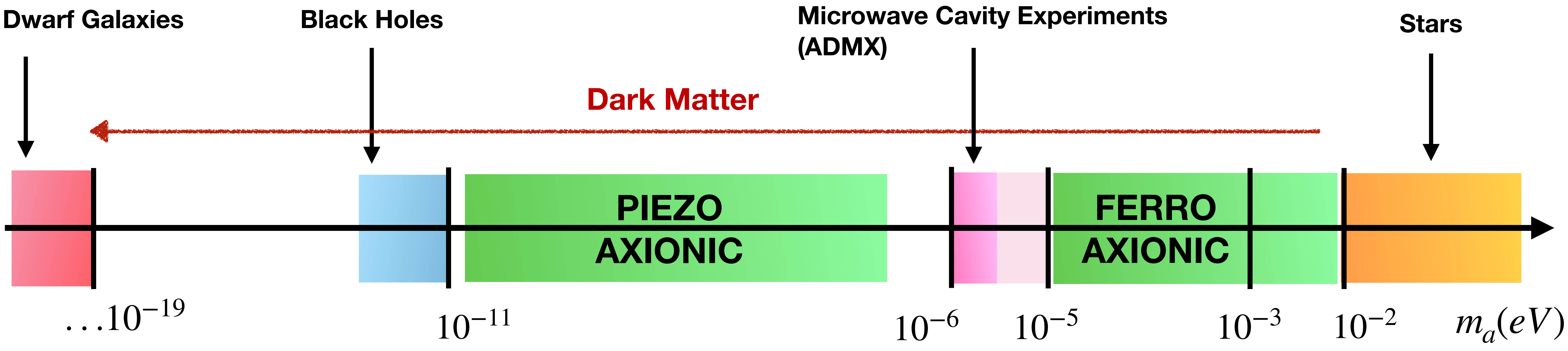
$$\delta\omega_a \approx \frac{v^2}{\hbar}\omega_a \approx 10^{-6}\,\omega_a$$



Dark matter production

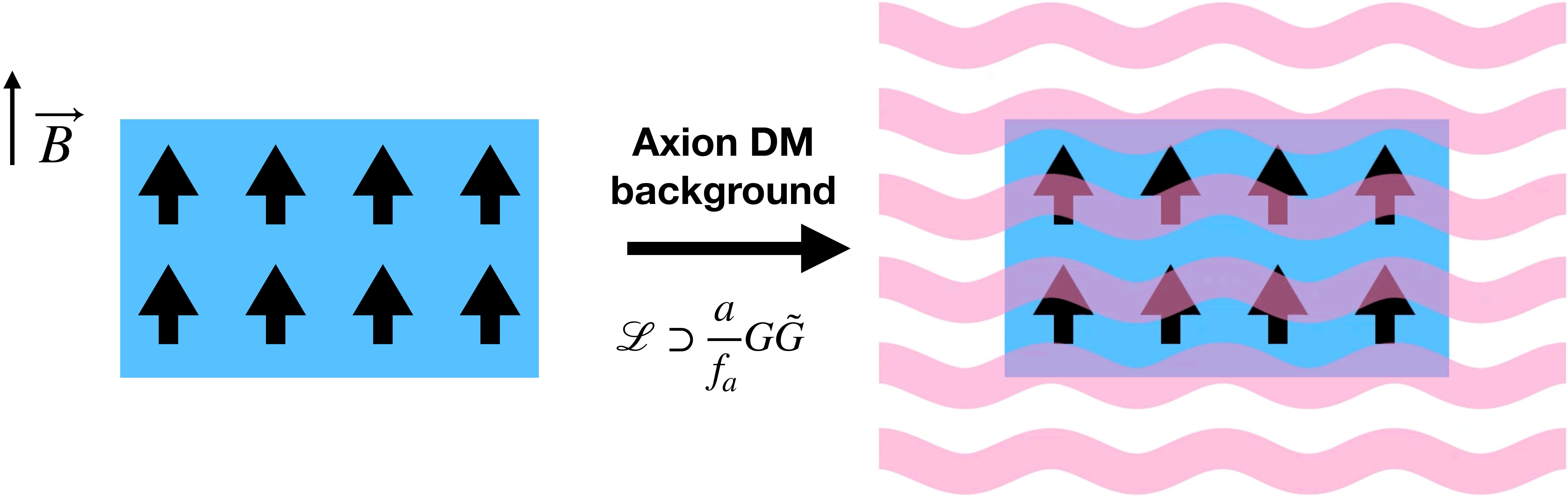


- $\ddot{a} + 3H(T)\dot{a} + m^2 a = 0$
  (H = Hubble parameter)
- $m < 3H$: frozen
- $m > 3H$: oscillates around minimum
- $\frac{\rho_a}{\rho_{total}} = 0.25 < \theta^2_{initial} > \left(\frac{f_a}{5 \times 10^{12}\text{GeV}}\right)^{7/6}$
  and scales as a^{-3}



$$m_a \sim 6 \times 10^{-11} eV \left(\frac{10^{17} GeV}{f_a} \right)$$

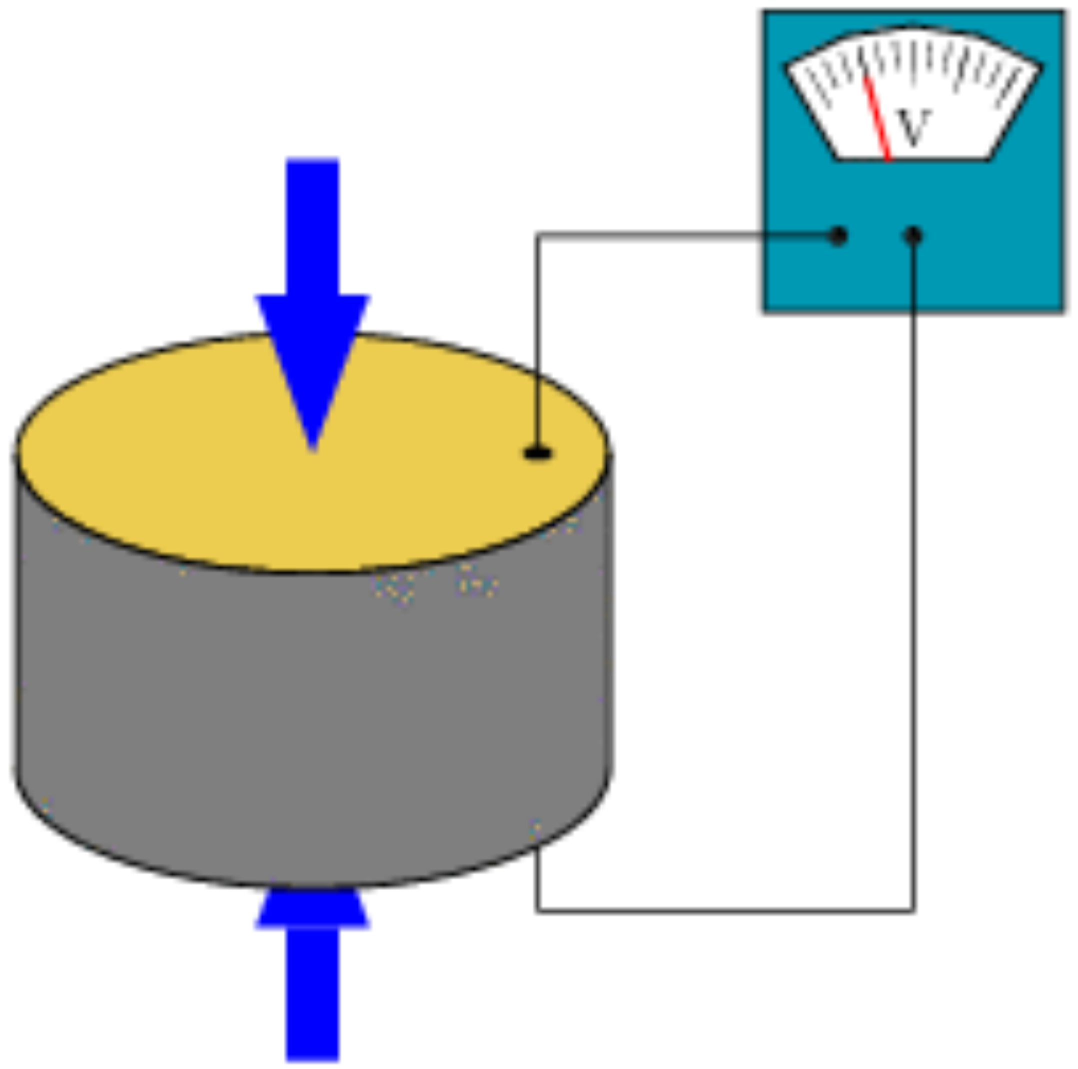
The Piezoaxionic Effect

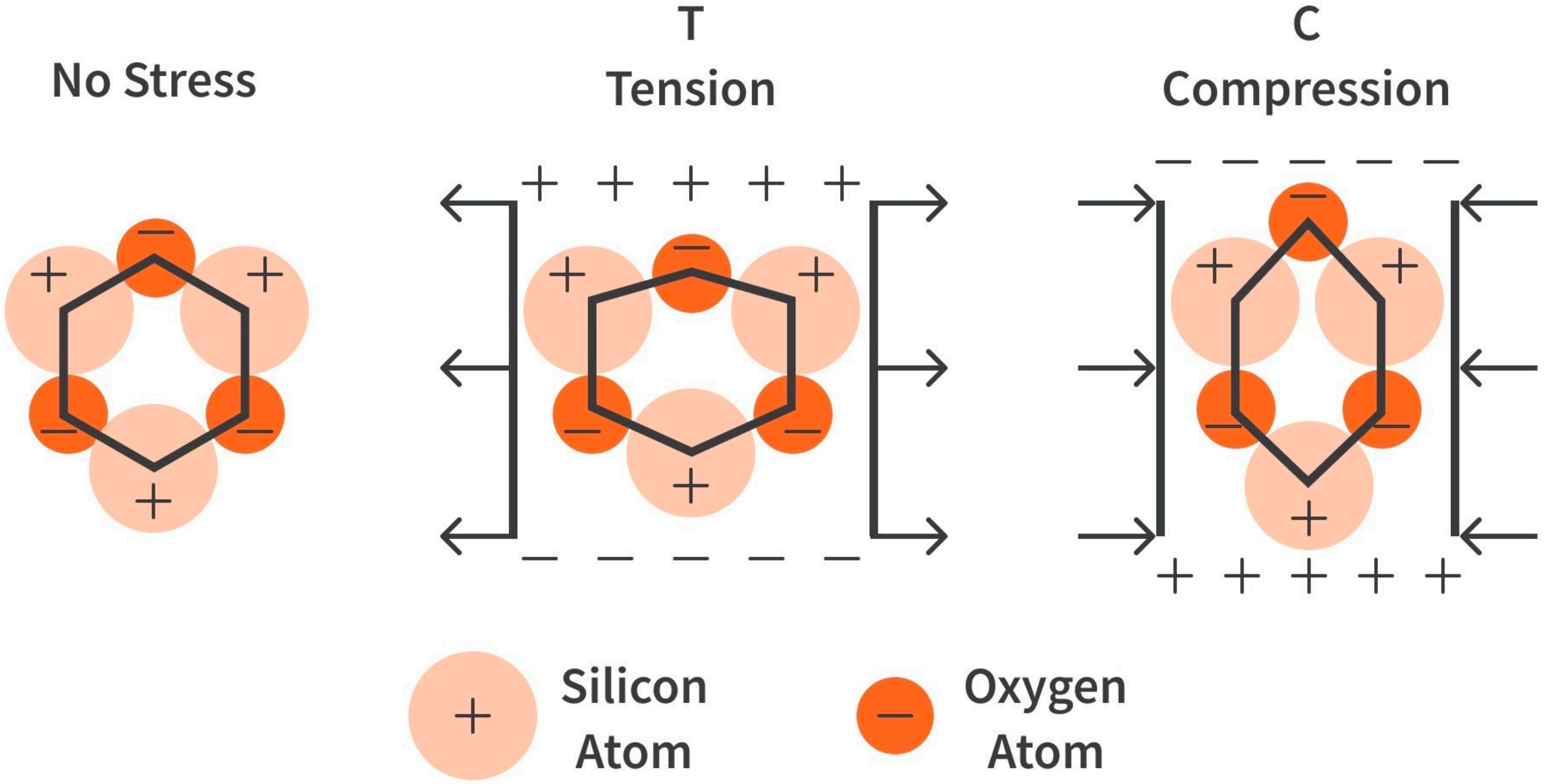


Piezoelectric Crystals

- Crystal structure breaks parity symmetry
  $(x, y, z) \neq (-x, -y, -z)$

- Deformation causes electric dipole moment across unit cell (and vice versa).





Constitutive Equations for Piezoelectricity

$$\theta_a(t) \equiv \frac{a(t)}{f_a}$$

$$\text{Stress} = +\underbrace{c}_{\text{Stiffness}} \cdot \text{Strain} - \underbrace{h}_{\text{Piezoelectric}} \cdot \text{Electric Displacement} - \underbrace{\xi}_{\text{Piezoaxionic}}\, \theta_a(t) \cdot \text{Nuclear Spin Direction}$$

$$\text{Electric Field} = -h \cdot \text{Strain} + \underbrace{\frac{1}{\epsilon}}_{\text{Permittivity}} \cdot \text{Electric Displacement} - \underbrace{\zeta}_{\text{Electroaxionic}}\, \theta_a(t) \cdot \text{Nuclear Spin Direction}$$

parity even
parity odd
time-reversal odd

The piezoaxionic tensor ξ is **ODD** under parity, and can only be present in piezoelectric materials.

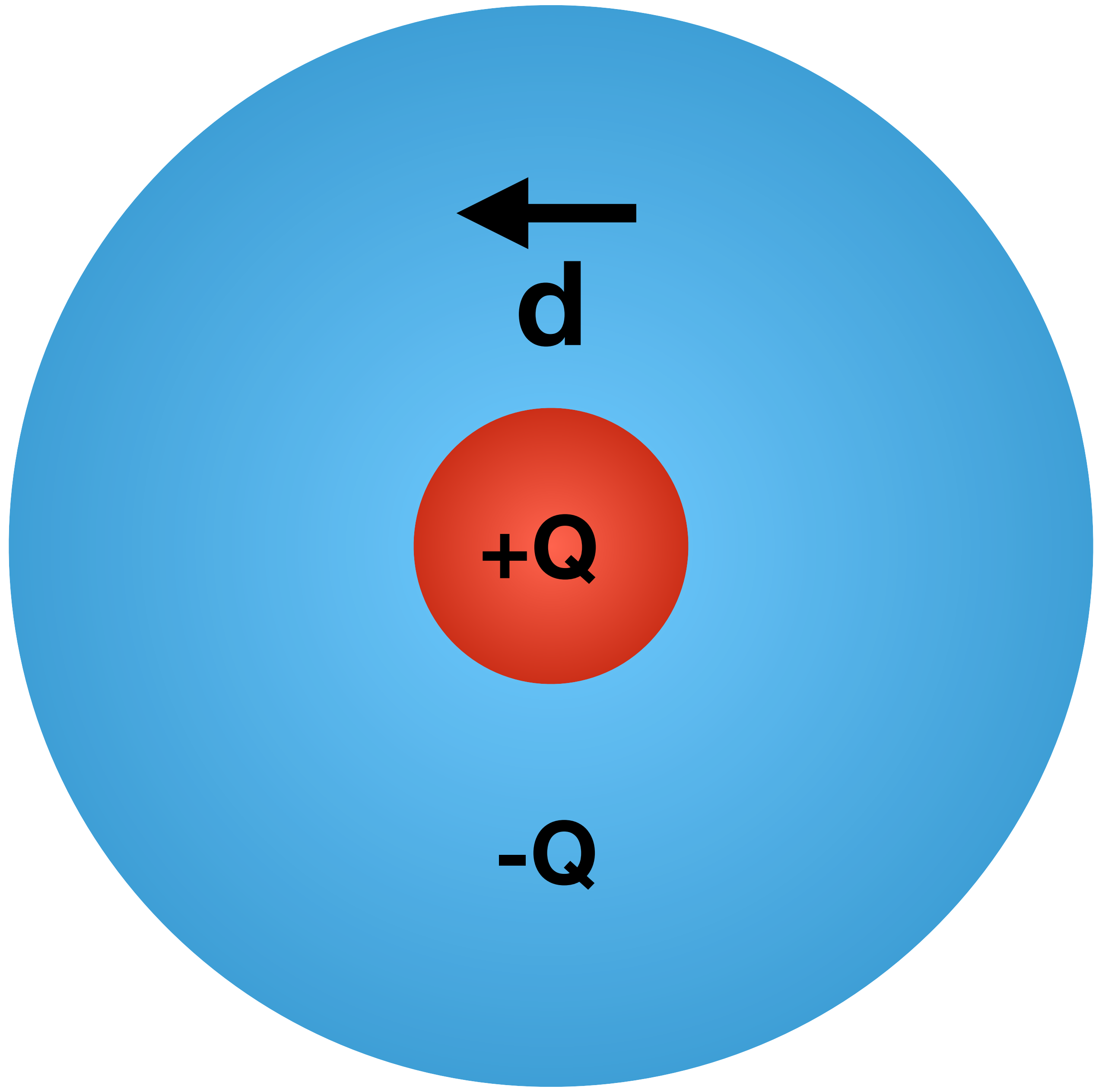
The electroaxionic tensor ζ is **EVEN** under parity, and can be present in all dielectrics.

We will focus on ξ in this talk!

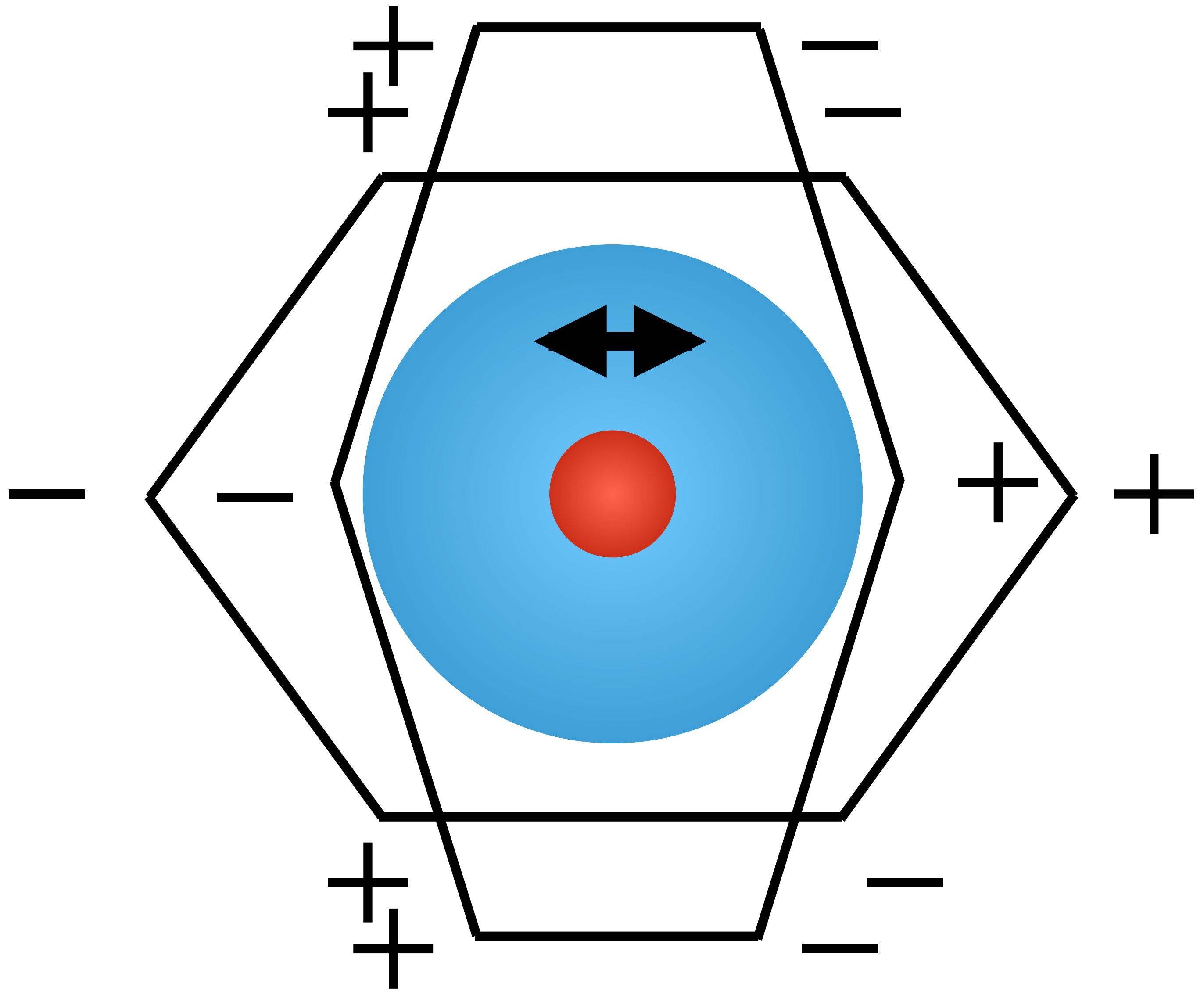
How big is the piezoaxionic effect?

QCD axion dark matter induces an ***oscillating*** nuclear electric dipole moment (EDM):

$$d_n \sim 10^{-16} \frac{\sqrt{\rho_{DM}}}{m_a f_a} \cos m_a t \cdot \mathrm{e} \cdot \mathrm{cm}$$

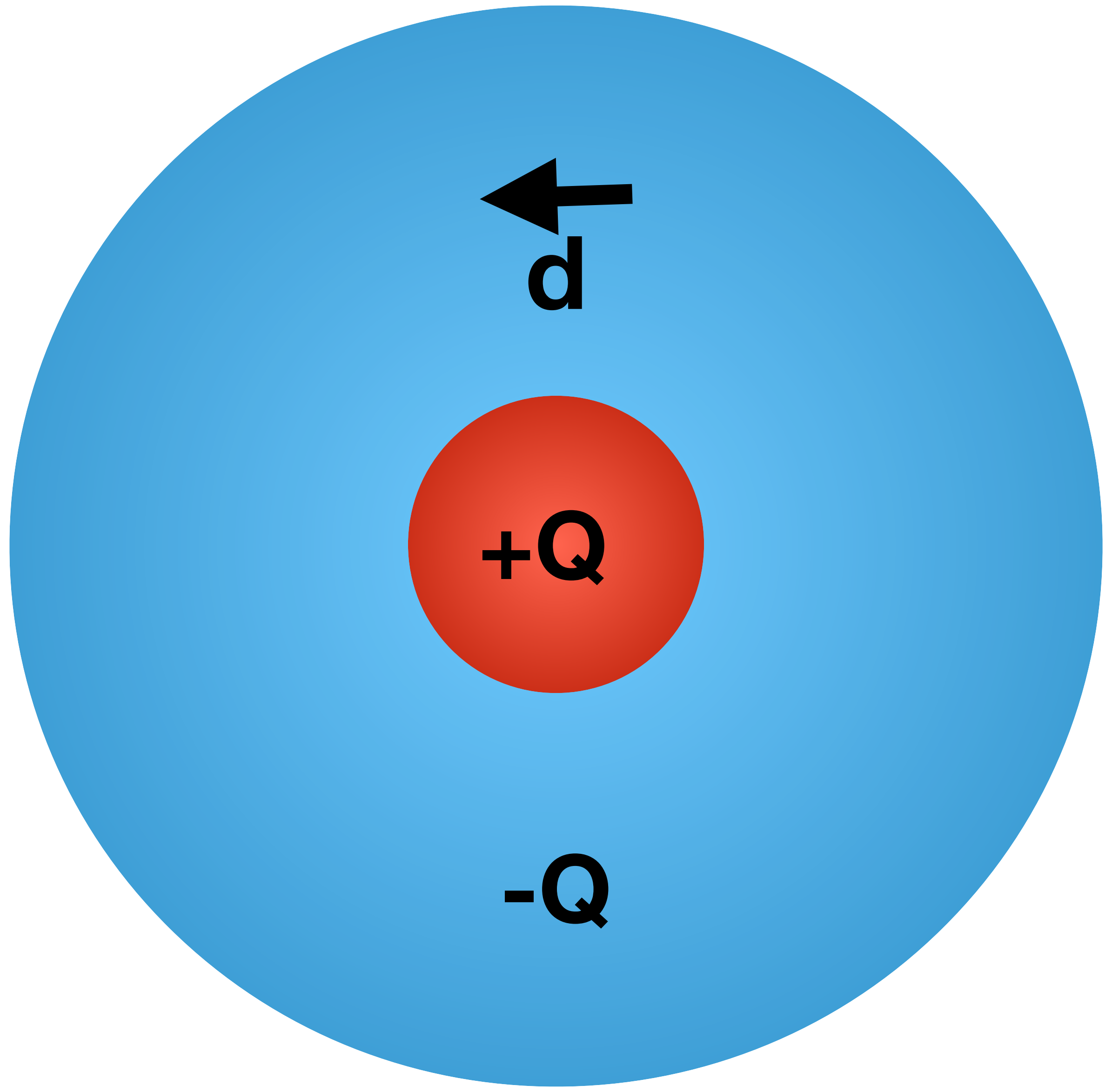


EDM generates an oscillating stress on unit cell:



Schiff Suppression

If we treat an atom as a system of **static**, **point-like** particles, nuclear EDM is perfectly shielded by electron cloud [*Schiff* 1963].



Resolution: Schiff's theorem violated by finite size effects:

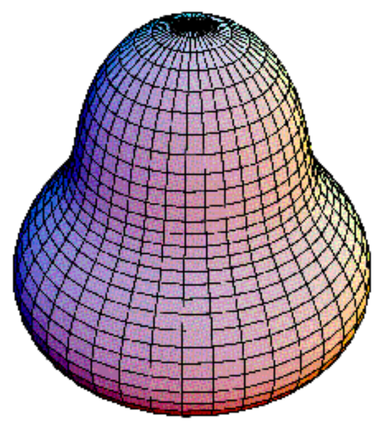
$$V_e = 4\pi e \, \mathcal{S} \cdot \nabla(\delta_e(\mathbf{r}))$$

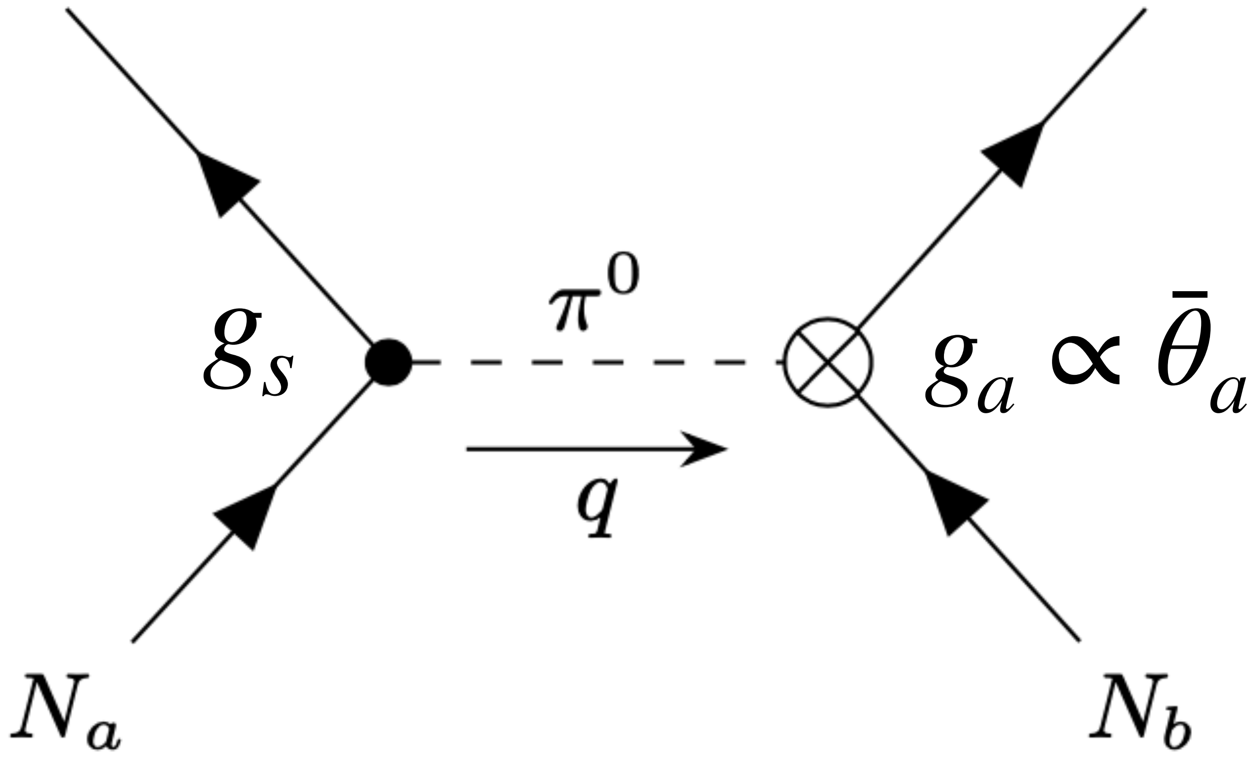
$$\mathcal{S} \sim e\frac{\bar{\theta}_a}{m_N} R_0^2 \propto A^{2/3}$$

non-deformed nuclei

$$\mathcal{S} \sim eZ\frac{\bar{\theta}_a}{m_N} R_0^2 \propto Z \, A^{2/3}$$

pear shaped nuclei





- In a piezoelectric crystal, the ground state electron wave function is a mixture of opposite parity orbitals ϵ_s and ϵ_p:

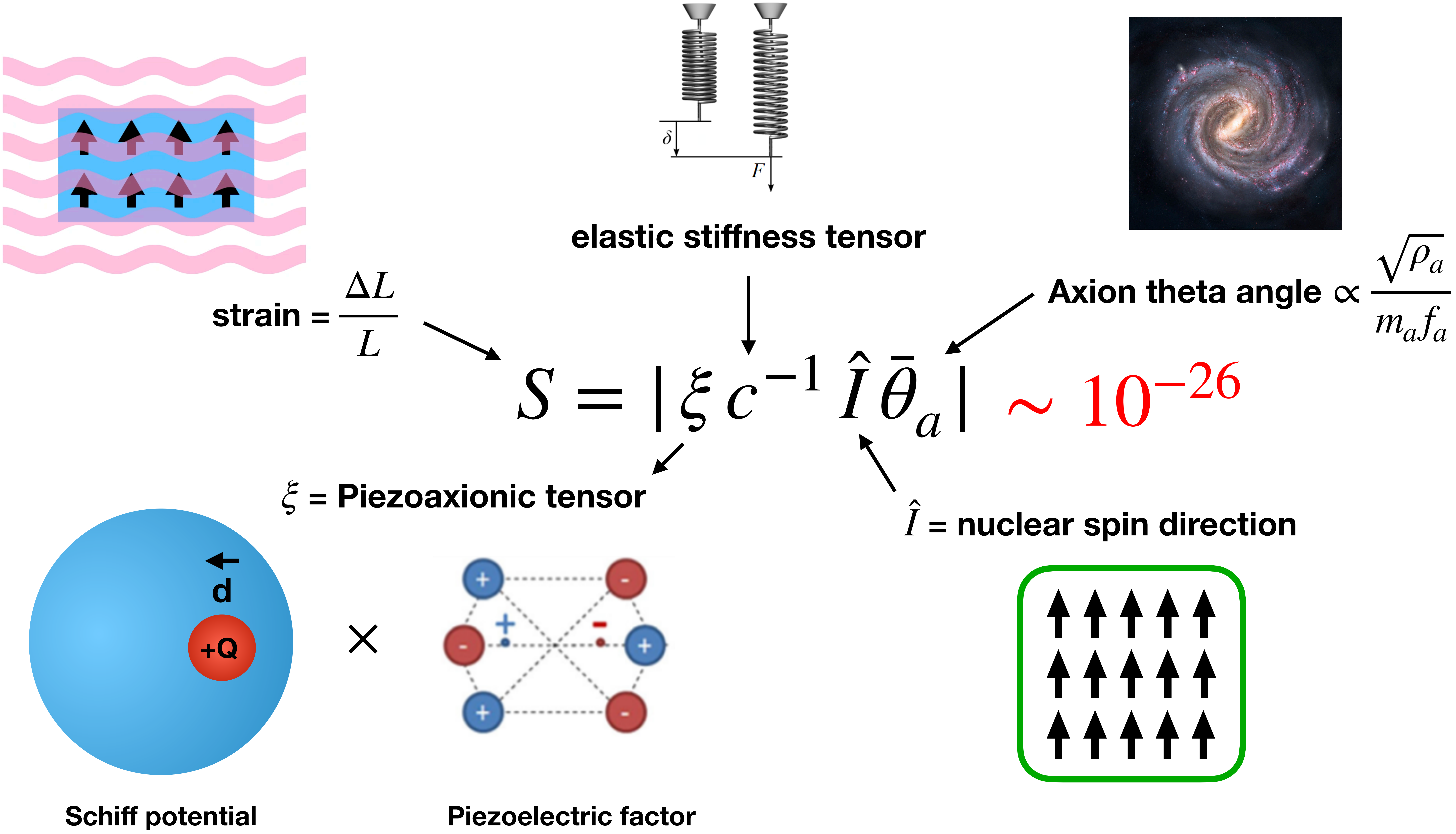
$$|\psi\rangle_e = \epsilon_s\,|\,s\rangle + \epsilon_p|p\rangle$$

- The piezoaxionic tensor can be estimated as:

$$\xi \sim \partial_{Strain}\frac{\langle H_{Schiff}\rangle}{V_{cell}} \simeq \frac{Z^2}{a_0^4}\frac{d\mathcal{S}}{d\theta_a} \times \frac{N_{\mathcal{S}}}{V_{cell}}\frac{\partial(\epsilon_s\epsilon_p^*)}{\partial_{Strain}}$$

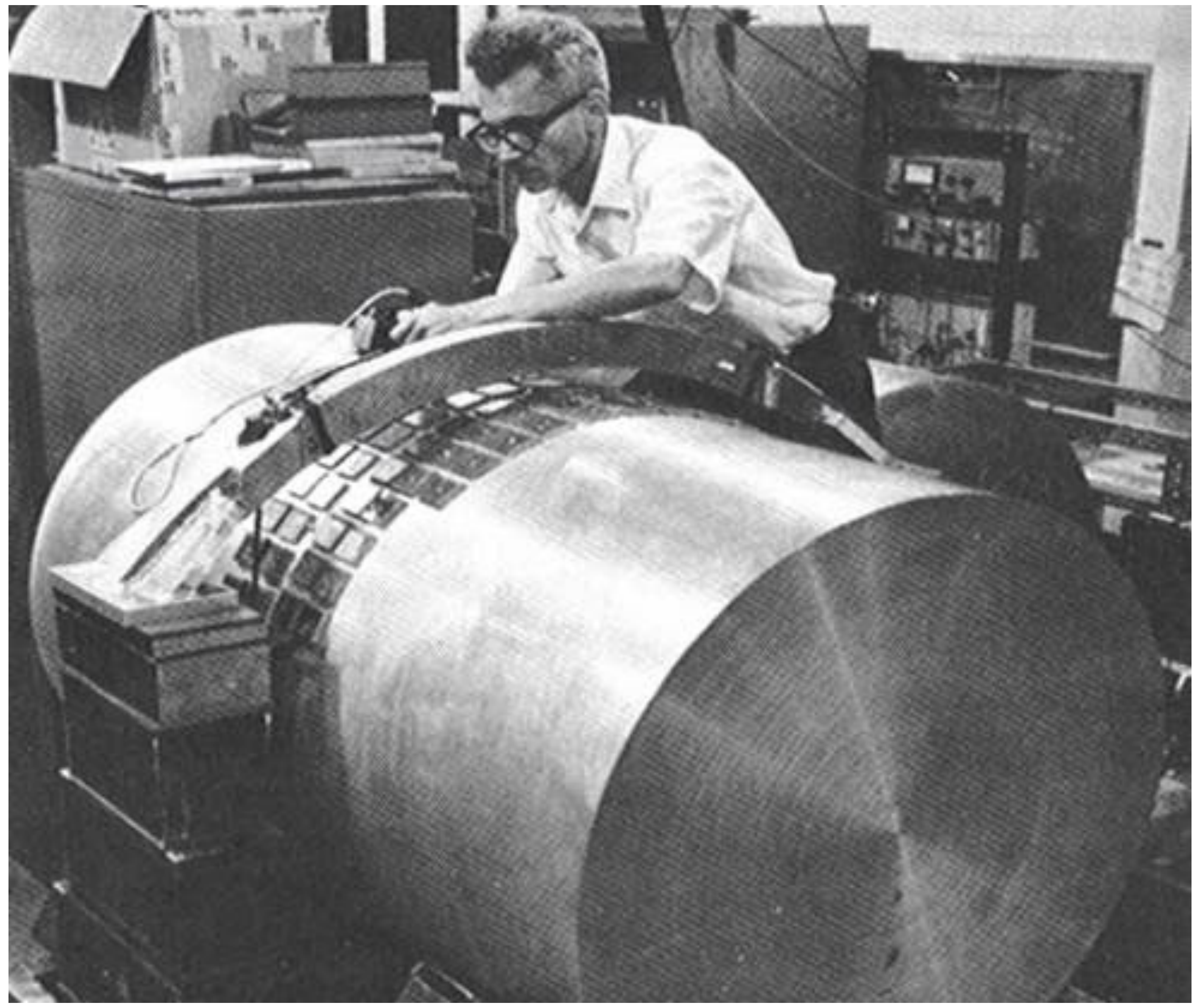
$\sim \mathcal{O}(1)$ factor

Bigger in strongly piezoelectric materials



elastic stiffness tensor
strain = $\frac{\Delta L}{L}$
Axion theta angle $\propto \frac{\sqrt{\rho_a}}{m_a f_a}$
$S = |\xi c^{-1} \hat{I} \bar{\theta}_a| \sim 10^{-26}$
ξ = Piezoaxionic tensor
$\hat{I}$ = nuclear spin direction
d
+Q
×
Schiff potential
Piezoelectric factor

Resonant Mass Detectors



In the 1960's:
Weber Bar, $S \sim 10^{-17}$

AURIGA, NAUTILUS,
MiniGrail, $S \sim 10^{-25}$

Goryachev et al. 2014
$S \sim 10^{-22}$

$0.1 - 1kHz$

$MHz - GHz$

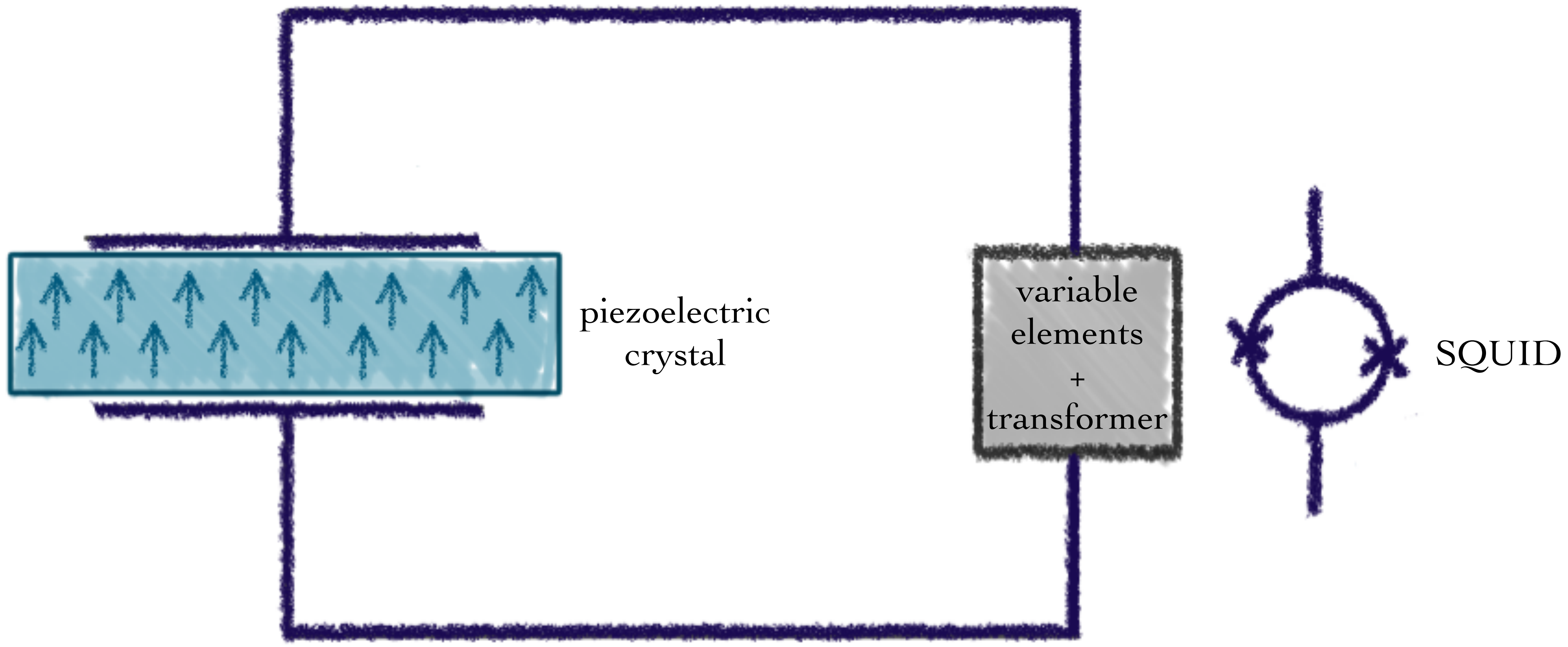
Experimental Setup

1. Find a piezoelectric material with low mechanical noise and big Schiff moments

2. Cool to $\sim\ mK$

3. Align nuclear spins using a magnetic field

4. Measure tiny oscillating voltage using a SQUID



Materials

Piezoelectric make up a large class of materials - 20 out of 32 symmetry groups!

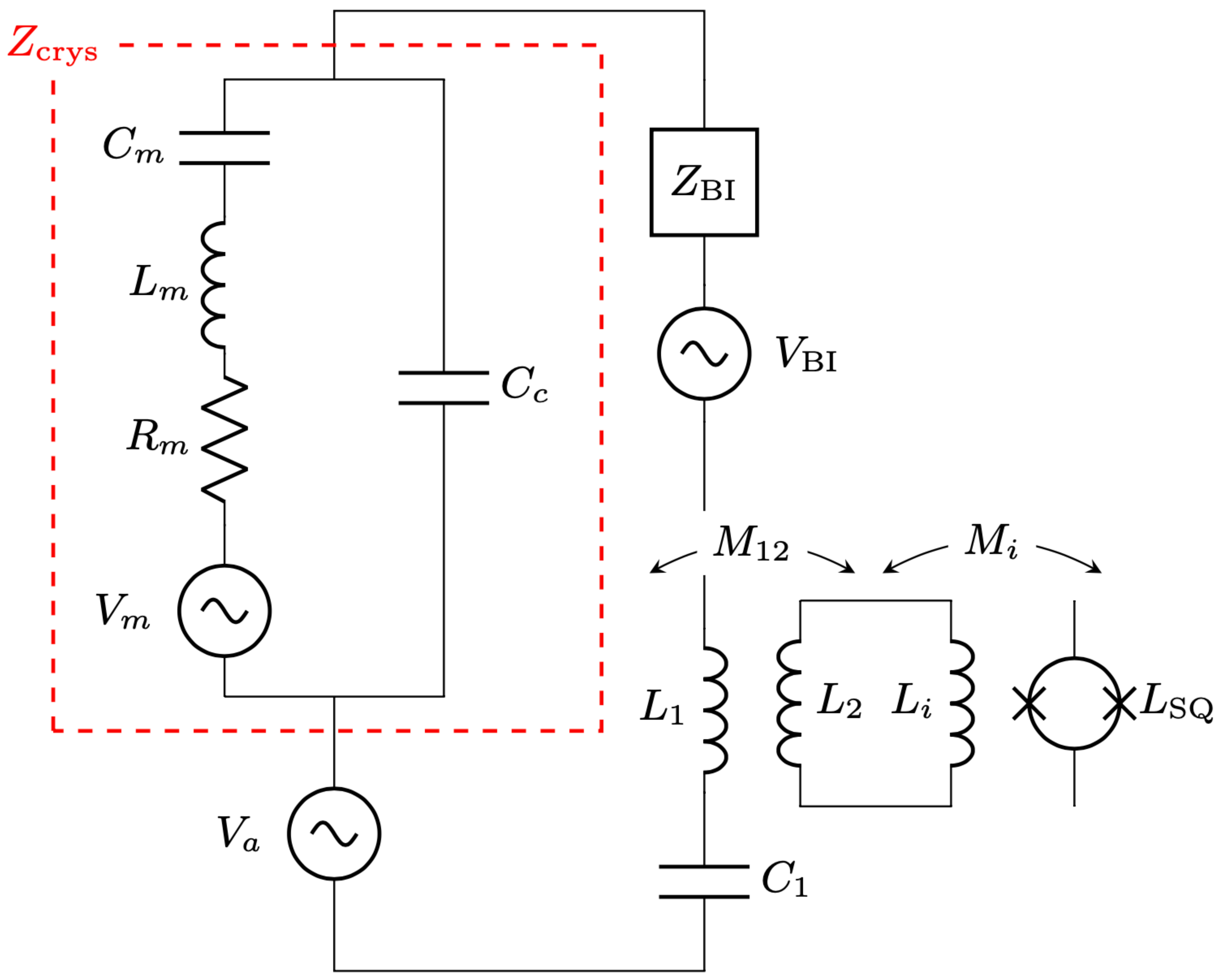
- High density of nuclei with large Schiff moments and low radioactivity
- Good acoustic properties (high Q-factor)
- Strong piezoelectric properties
- Structural similarity to well-known resonator crystals.

Class	Candidates	Similar Crystals
32	Na**Dy**$H_2S_2O_9$	SiO_2 (quartz)
		$Ga_5La_3SiO_{14}$ (langasite)
	BiPO_4	$GaPO_4$ (gallium orthophosphate)
3m	**U**OF_4	tourmaline
	UCd	$LiNbO_3$ (lithium niobate)
4mm	**Dy**Si_3Ir	$Li_2B_4O_7$ (lithium tetraborate)
	Dy$AgSe_2$	
$\bar{4}2m$	**Dy**$AgTe_2$	NH_6PO_4 (ADP)
	$\mathbf{Dy}_2Be_2GeO_7$	KH_2PO_4 (KDP)
mm2	**U**CO_5	$Ba_2NaNb_5O_{15}$ (barium sodium niobate)

Candidate materials collected from the database at https://materialsproject.org/

Scanning

- Grow a series of crystals of different thicknesses
- Vary *electrical* resonance frequency using capacitor and inductor



Backgrounds:

Fluctuating nuclear spins

Small effect

Fluctuating magnetic impurities in material

$\lesssim$ppm

Magnetization noise → fictitious EMF

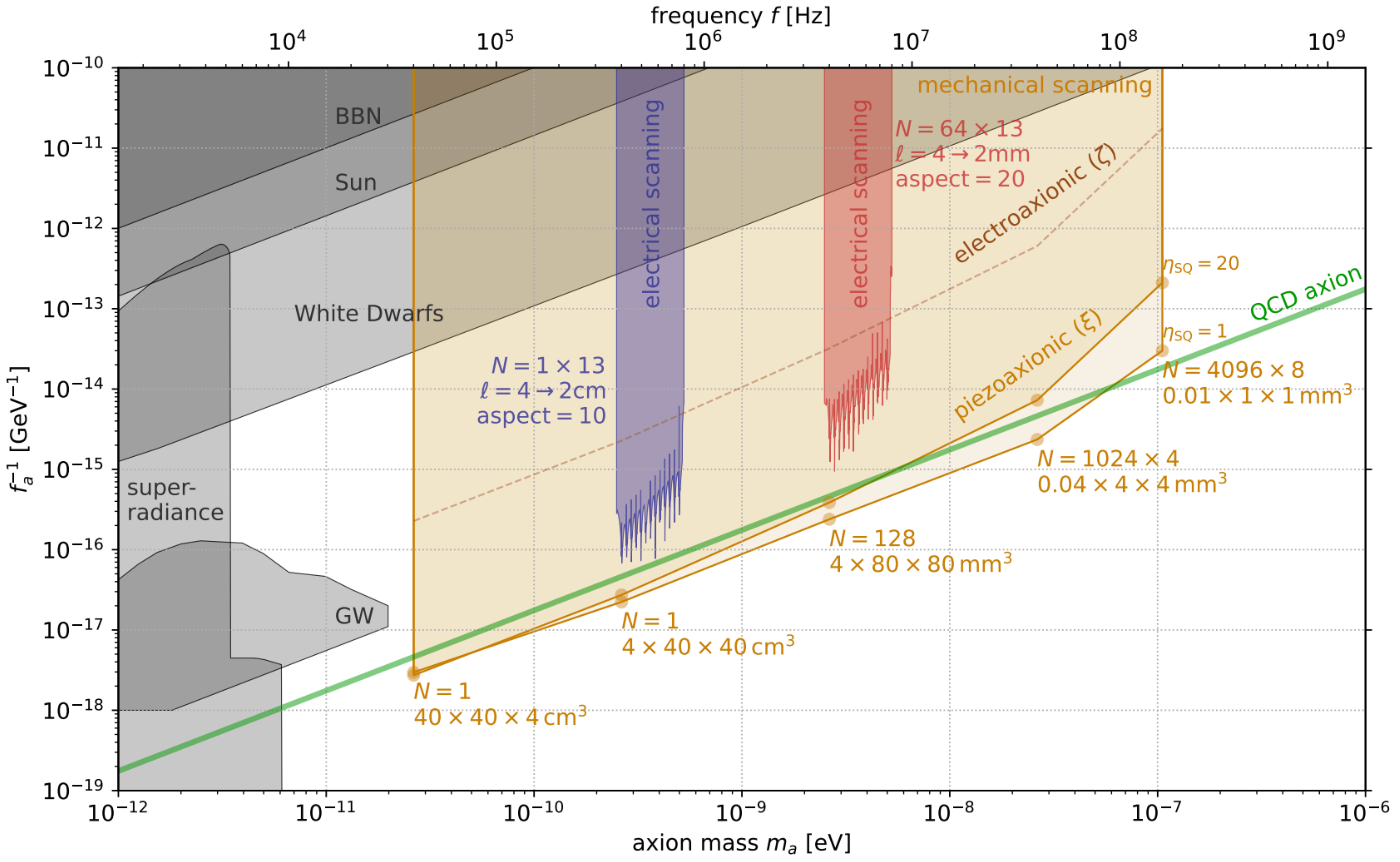
Vibrational noise

Systematic, demonstrated at AURIGA

Noise:

Thermal noise limited, main sources: crystal mechanical noise and SQUID noise

Idealized Forecast



BBN: K. Blum, R. T. D'Agnolo, M. Lisanti, B. R. Safdi (2014)

Sun: A. Hook, J. Huang (2018)

WDs: R Balkin, J Serra, K Springmann, S Stelzl, A Weiler (2022)

Superradiance: A. Arvanitaki, S. Dubovsky (2011)

GWs: J. Zhang, Z. Lyu, J. Huang, M. C. Johnson, L. Sagunski, M. Sakellariadou, H. Yang (2021).

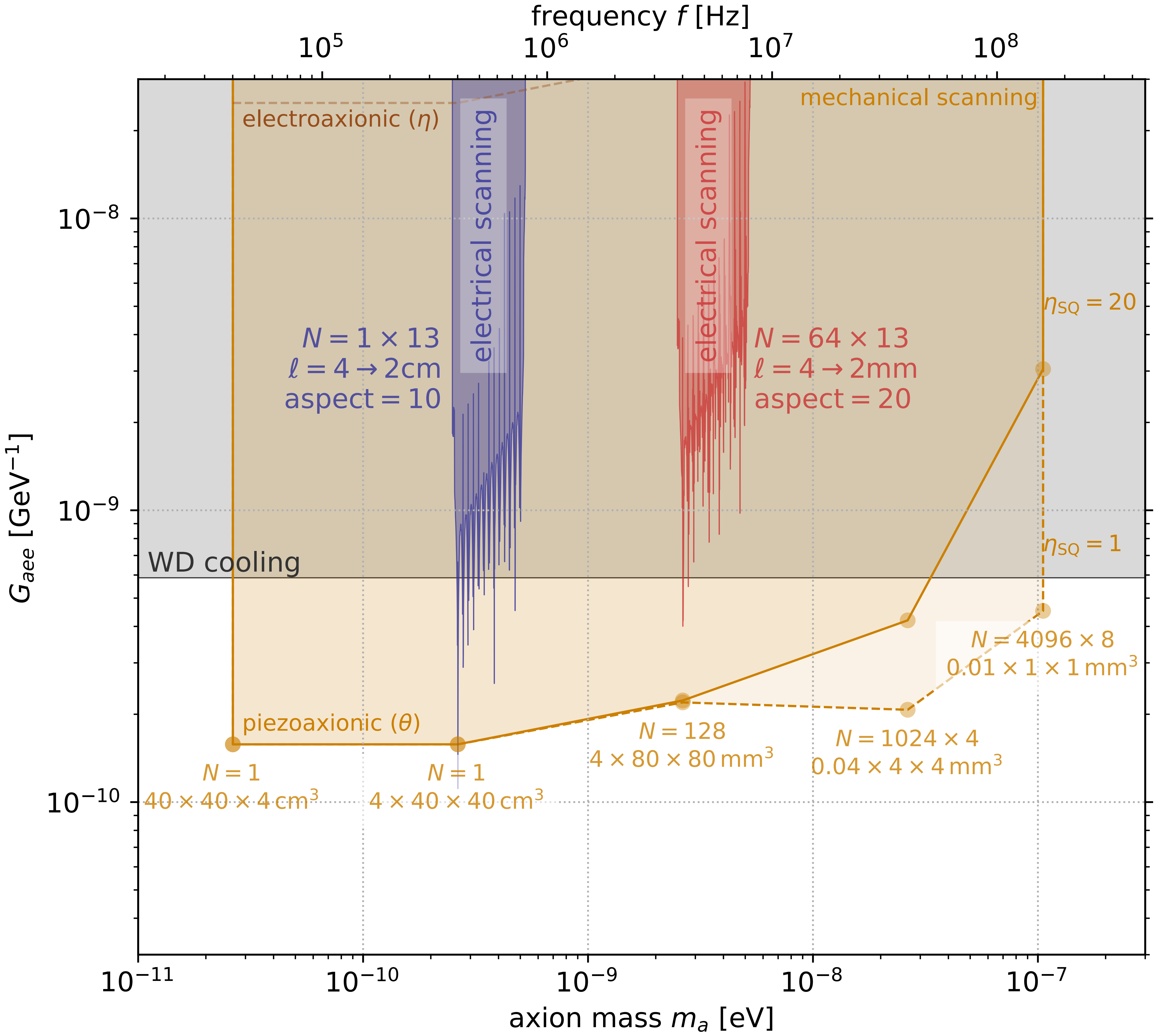
***parameter space above QCD axion line tuned in mass and vacuum alignment**

Axion-Electron Coupling

$$H_{aee} \simeq -\frac{G_{aee}}{2}\sigma_e \cdot \left(\nabla a + \dot{a}\frac{\mathbf{p}_e}{m_e}\right)$$

P EVEN
T ODD

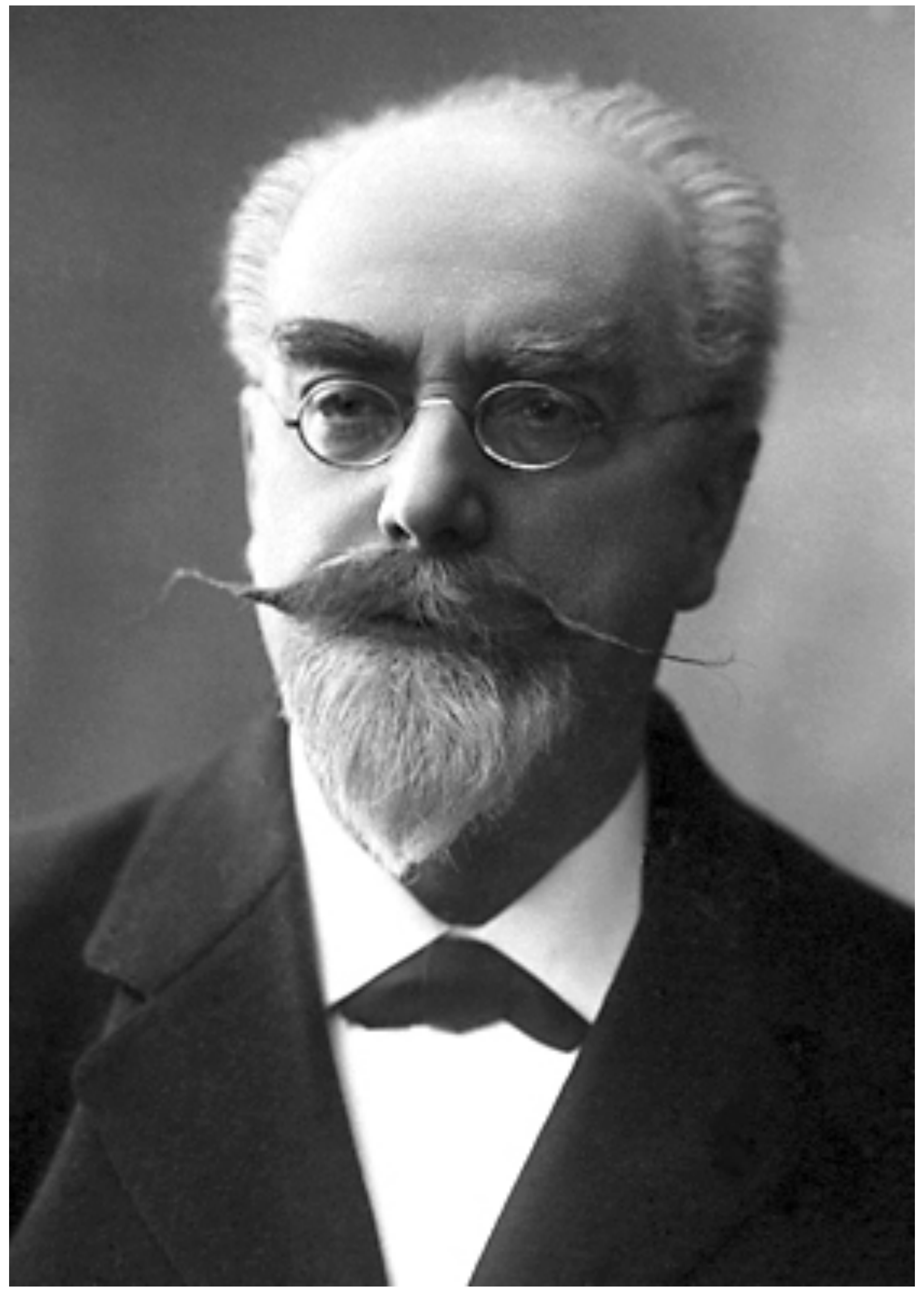
P ODD
T EVEN



Future Directions

- Precise Schiff moment calculations for stable, octupole deformed nuclei
- Density functional theory (DFT) calculations for ξ and ζ
- Experimental investigation of suitable materials

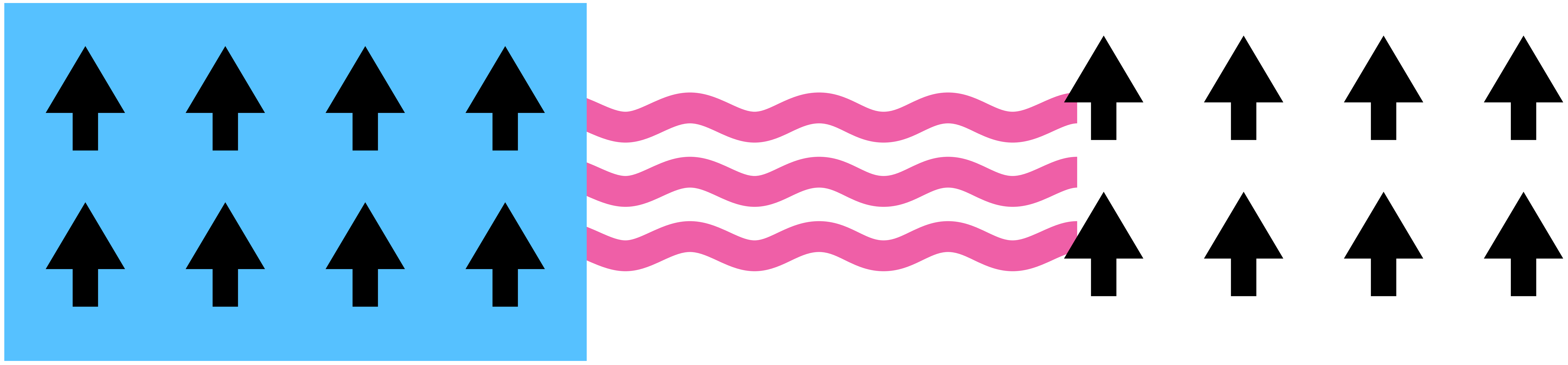
1880: Curie brothers discover “direct” piezoelectric effect
Stress -> Charge



1881: Gabriel Lippman predicts “converse” effect from thermodynamics
Charge->Stress

Curie brothers experimentally verify

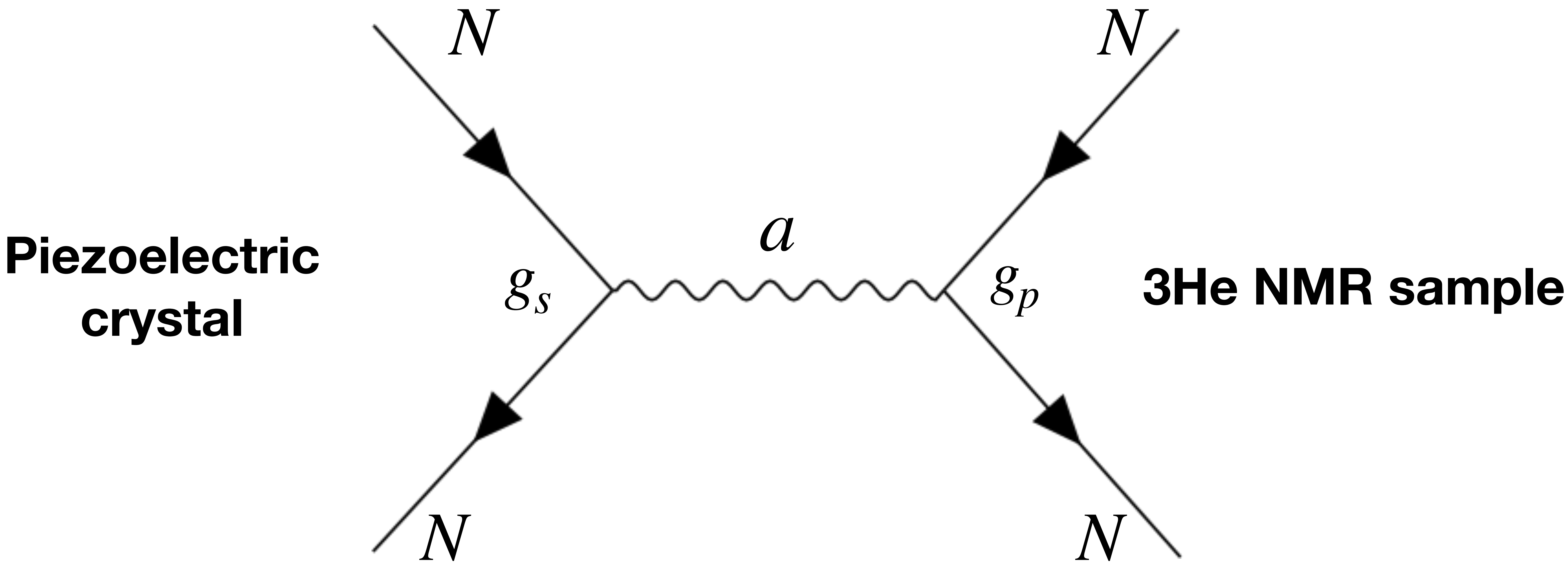
Ferroaxionic effect



$$\mathscr{L} \supset \frac{a}{f_a} G\tilde{G}$$

$$\mathscr{L} \supset G_{aNN} \nabla a \cdot \sigma_N$$

(As seen yesterday in Andy Geraci's talk!)



Monopole-dipole potential:

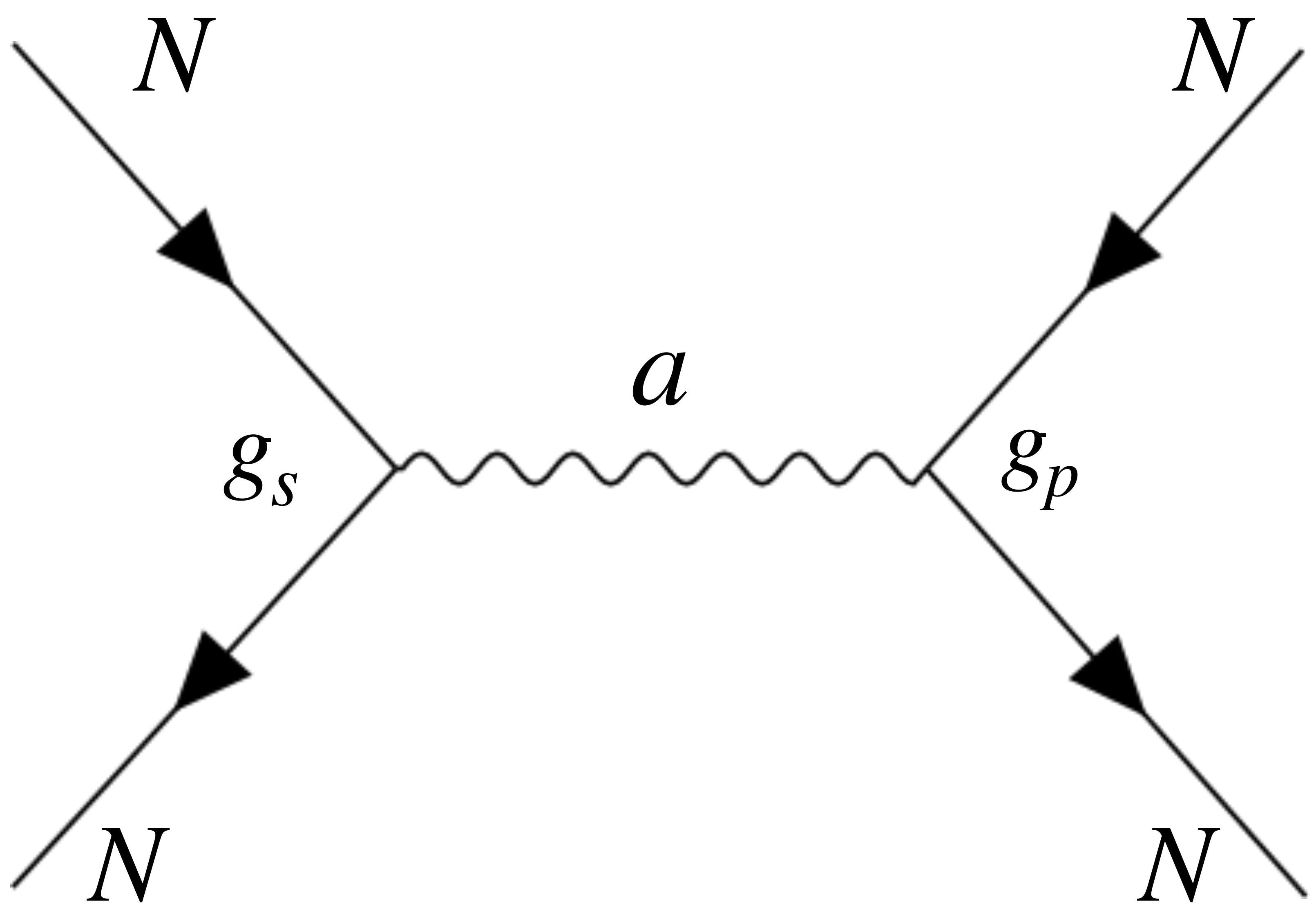
$$U_{s,p}(r) = \frac{g_s\, g_p}{m_N}\left(\frac{m_a}{r} + \frac{1}{r^2}\right) e^{-m_a r}\,(\hat{r}\cdot\hat{\sigma})$$

$$= \gamma \overrightarrow{B}_{eff} \cdot \hat{\sigma}$$

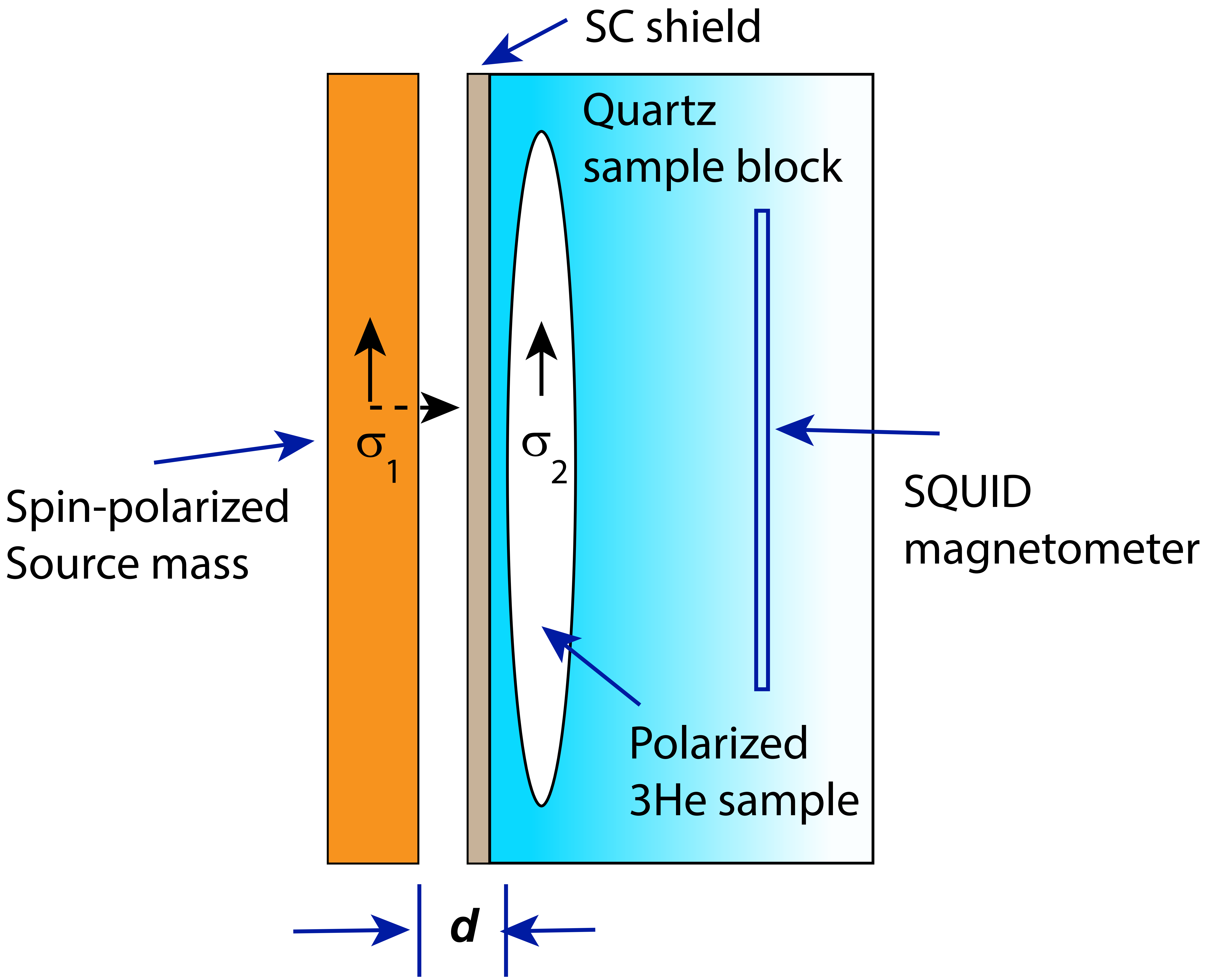
$$\left(\Box + m^2\right) \underline{a} = \underline{g_s}\, n_N$$

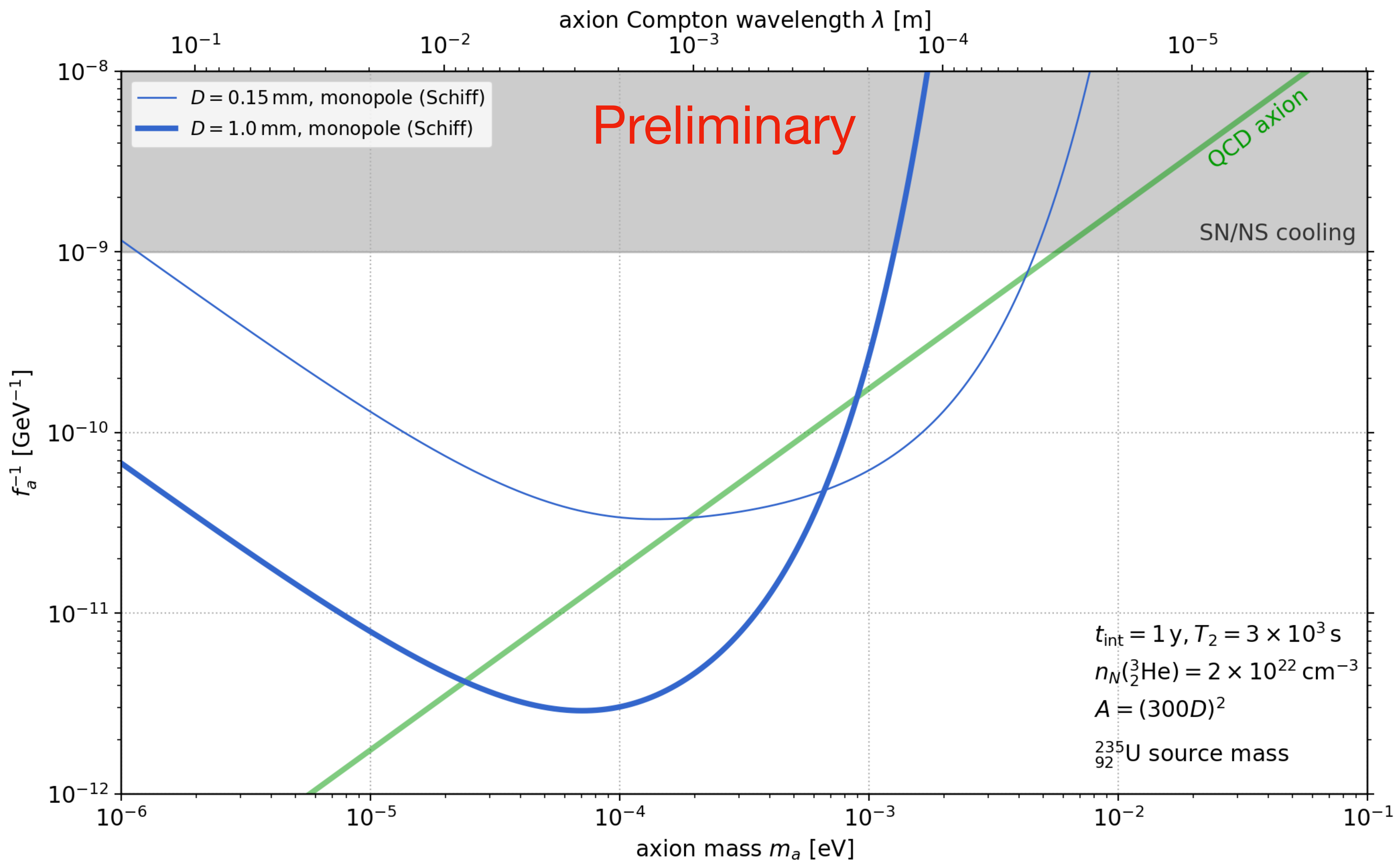
$$\underline{g_s} \simeq \frac{4\pi e}{A f_a} \frac{\partial \mathcal{S}}{\partial \theta_a} \underline{\mathscr{M}}_{\mathbf{e}} \cdot \underline{\mathbf{I}}$$

parity odd
time-reversal odd



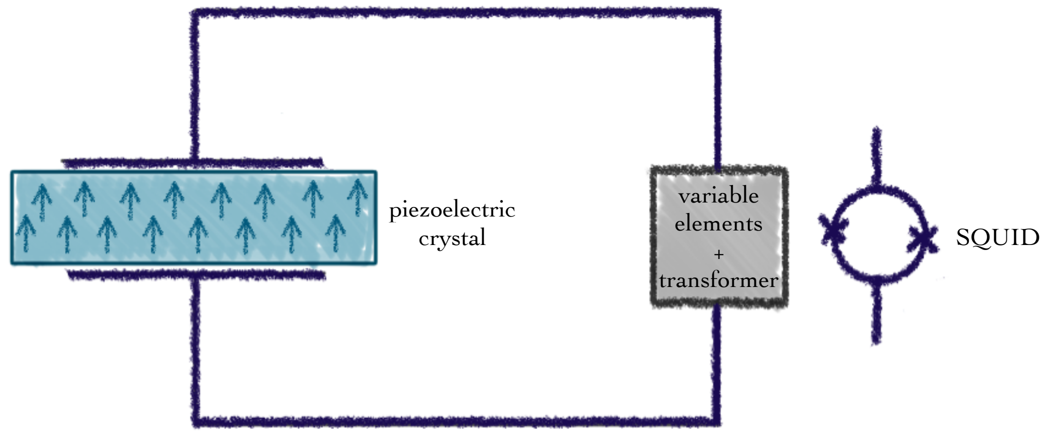
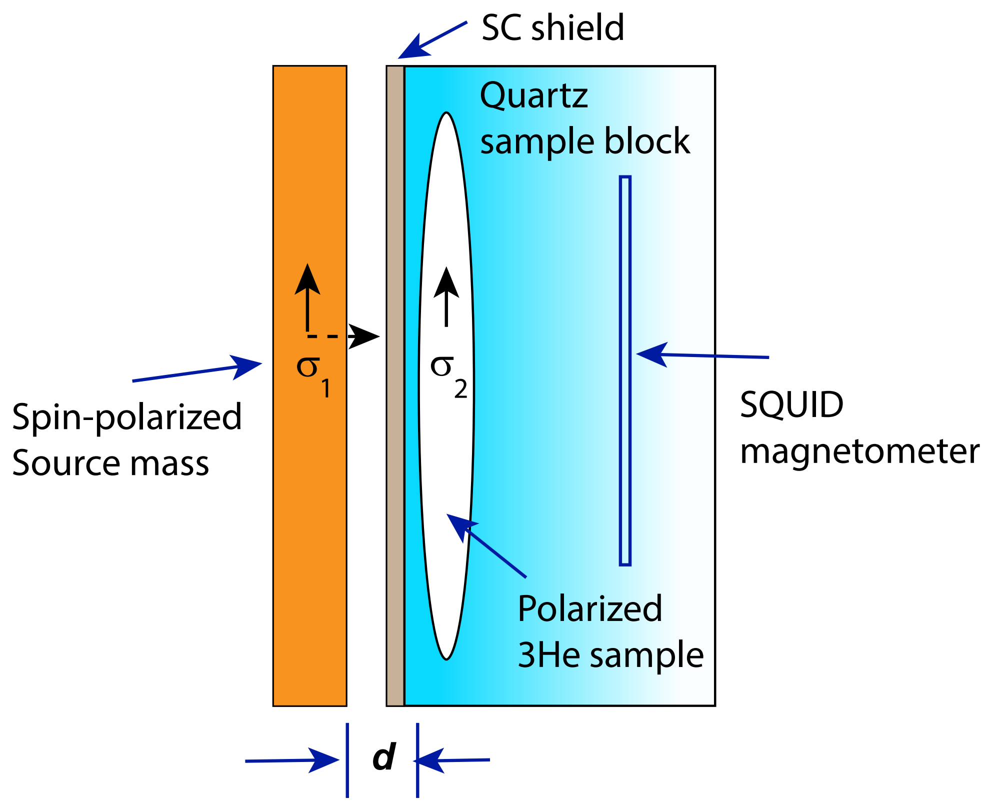
$\mathscr{M}_e$, the electronic matrix element, inherits its direction from the electric polarization vector of the ferroelectric


SC shield
Quartz
sample block
σ_1
σ_2
Spin-polarized
Source mass
SQUID
magnetometer
Polarized
3He sample
d



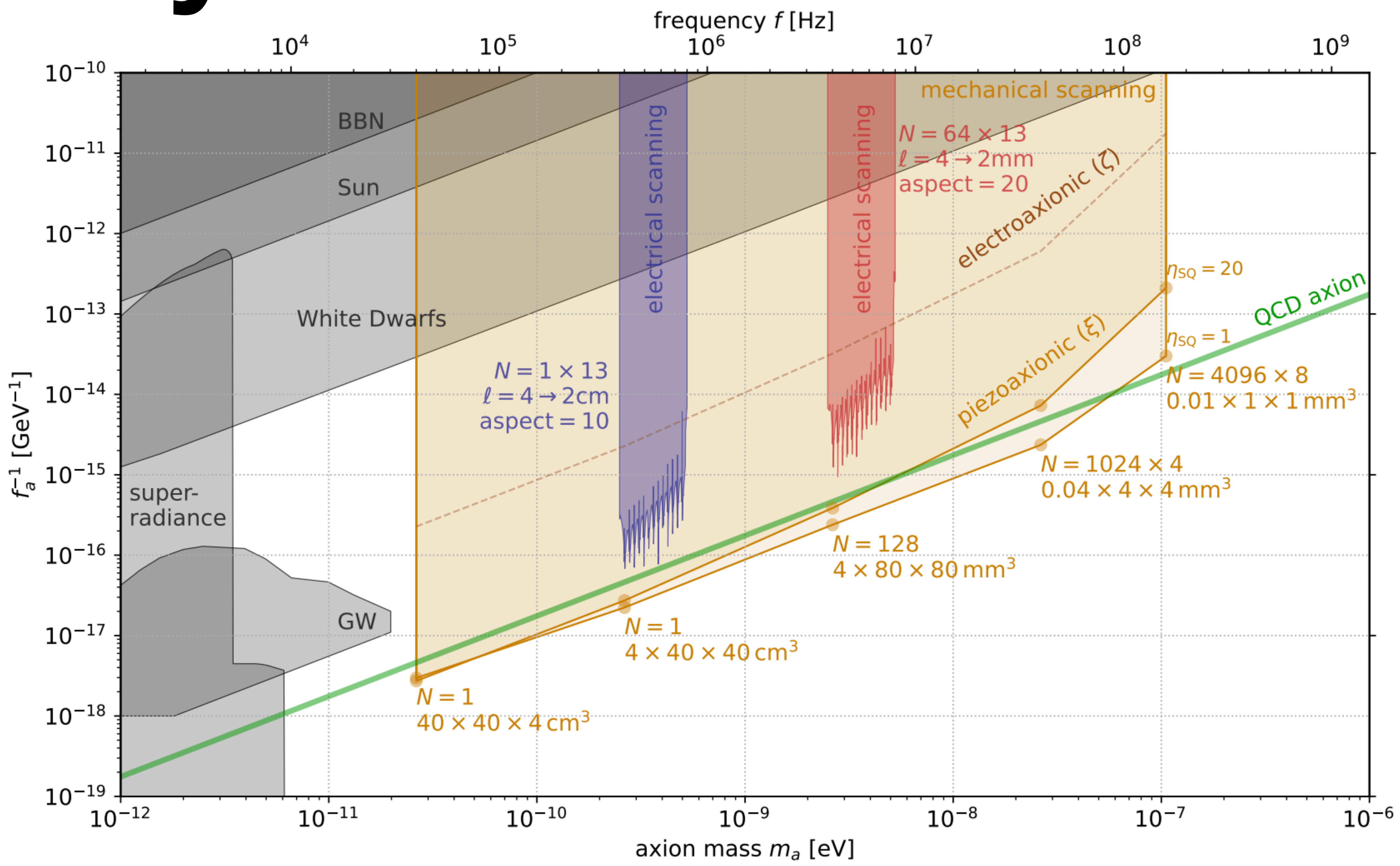
axion Compton wavelength λ [m]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$D = 0.15$ mm, monopole (Schiff)
$D = 1.0$ mm, monopole (Schiff)
Preliminary
QCD axion
SN/NS cooling
f_a^{-1} [GeV^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$t_{\rm int} = 1$ y, $T_2 = 3 \times 10^3$ s
$n_N({}^3_2\text{He}) = 2 \times 10^{22}$ cm^{-3}
$A = (300D)^2$
${}^{235}_{92}$U source mass
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
axion mass m_a [eV]

Summary

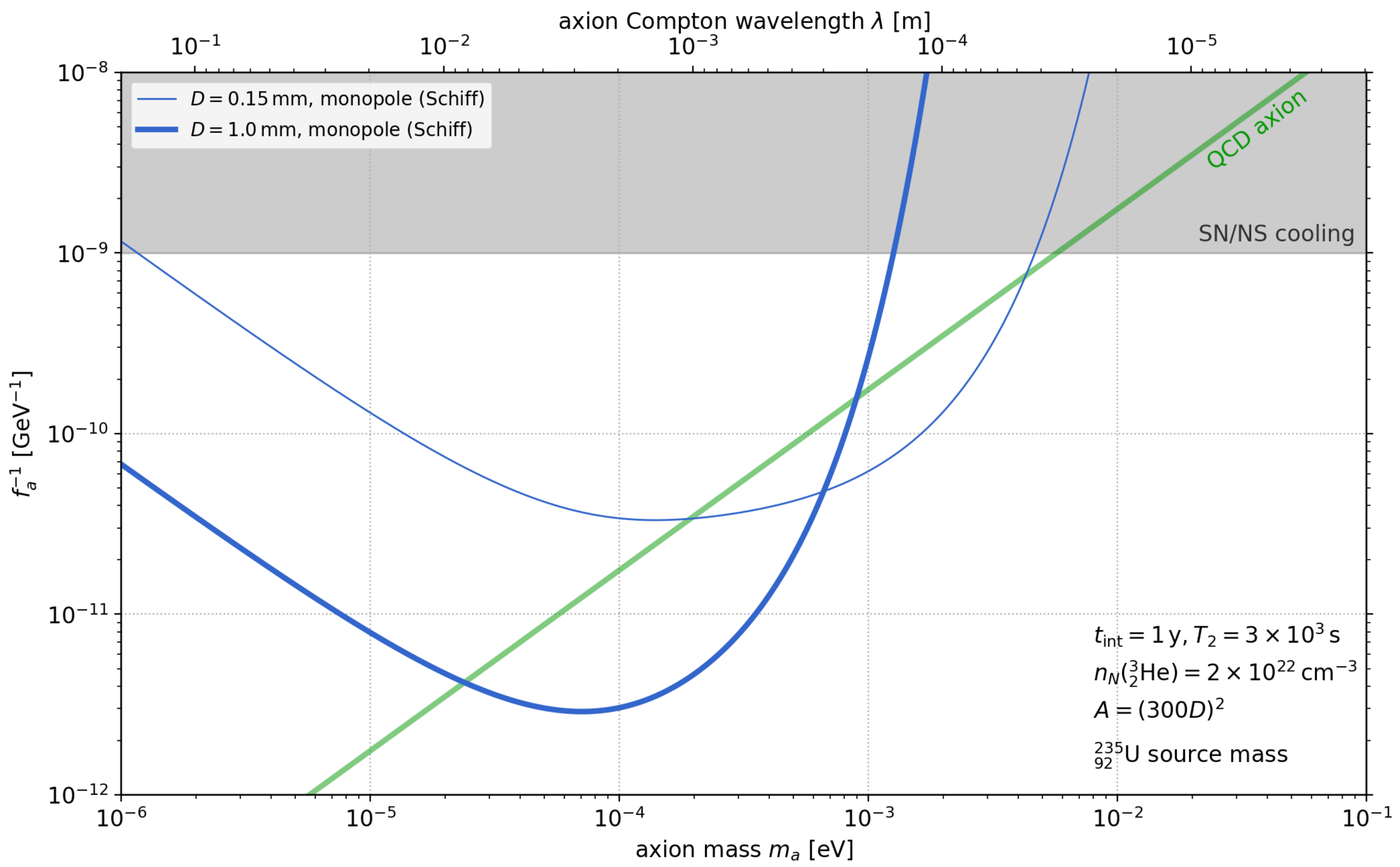
	$\frac{a}{f_a} G\tilde{G}$ $G_{aee}\, \sigma_e \cdot \dot{a} \frac{\mathbf{p}_e}{m_e}$	$10^{-11} eV$ to $10^{-7} eV$	**Must be DM**
	$\frac{a}{f_a} G\tilde{G}$ $G_{aNN} \nabla a \cdot \sigma_N$	$10^{-5} eV$ to $10^{-2}\, eV$	**Doesn't need to be DM**

Summary

- QCD axion DM can excite vibrational modes in piezoelectric crystals via its model-independent coupling to gluons.



- Ferroelectric crystals can source QCD axion mediated forces, that could be detected using an NMR sample.



- Complimentary to cavity experiments