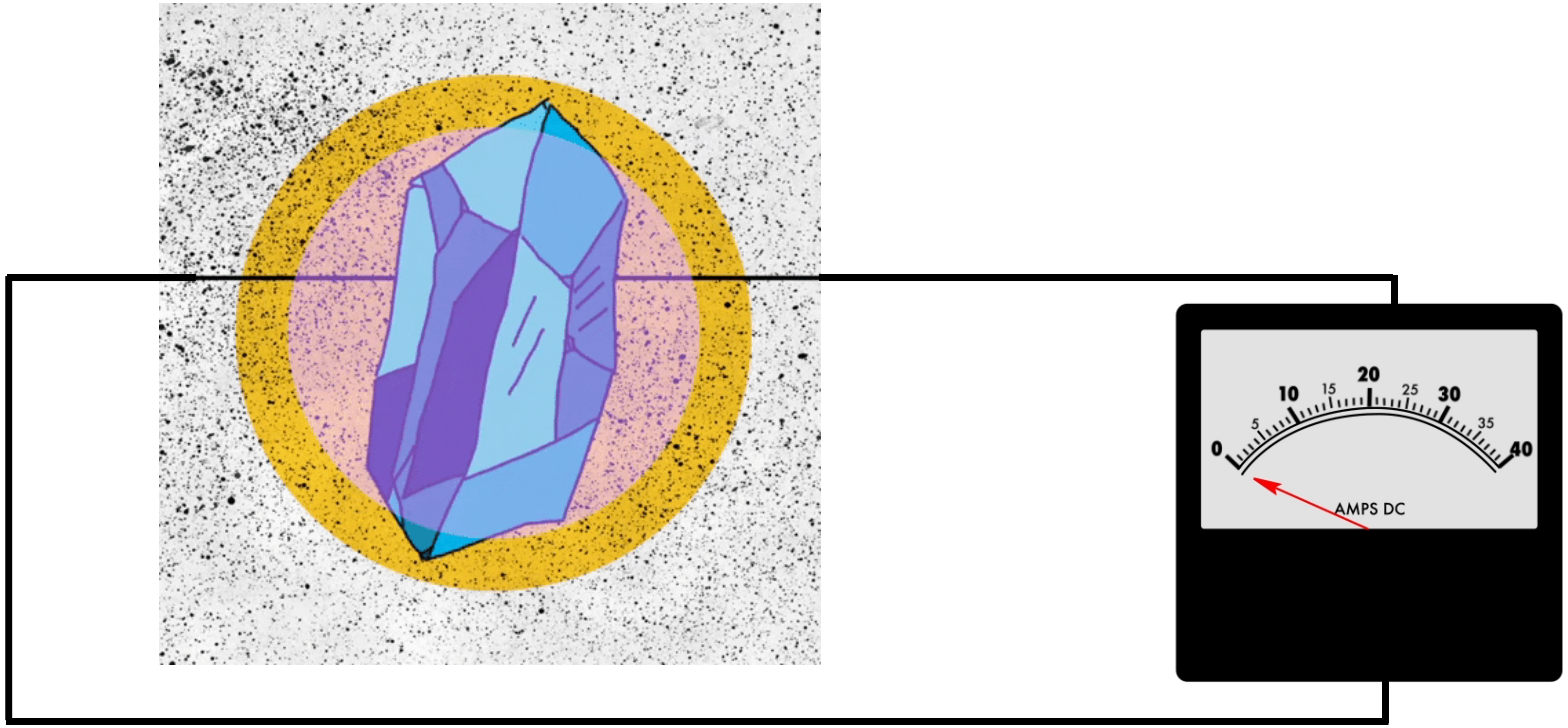
The Piezoaxionic Effect



Amalia Madden
Perimeter Institute for Theoretical Physics

Based on 2112.11466

with Asimina Arvanitaki (Perimeter Institute) and Ken Van Tilburg (NYU & Flatiron Institute)

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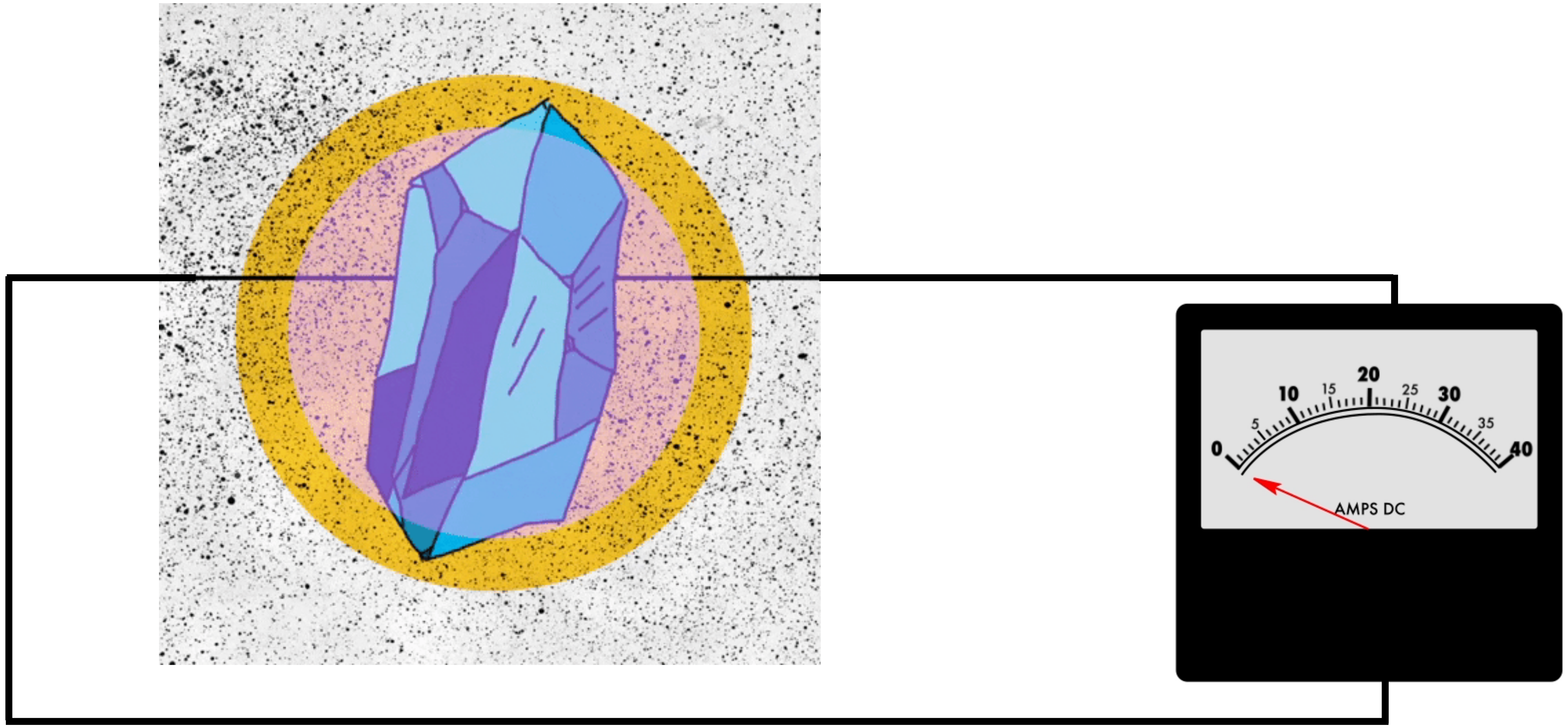

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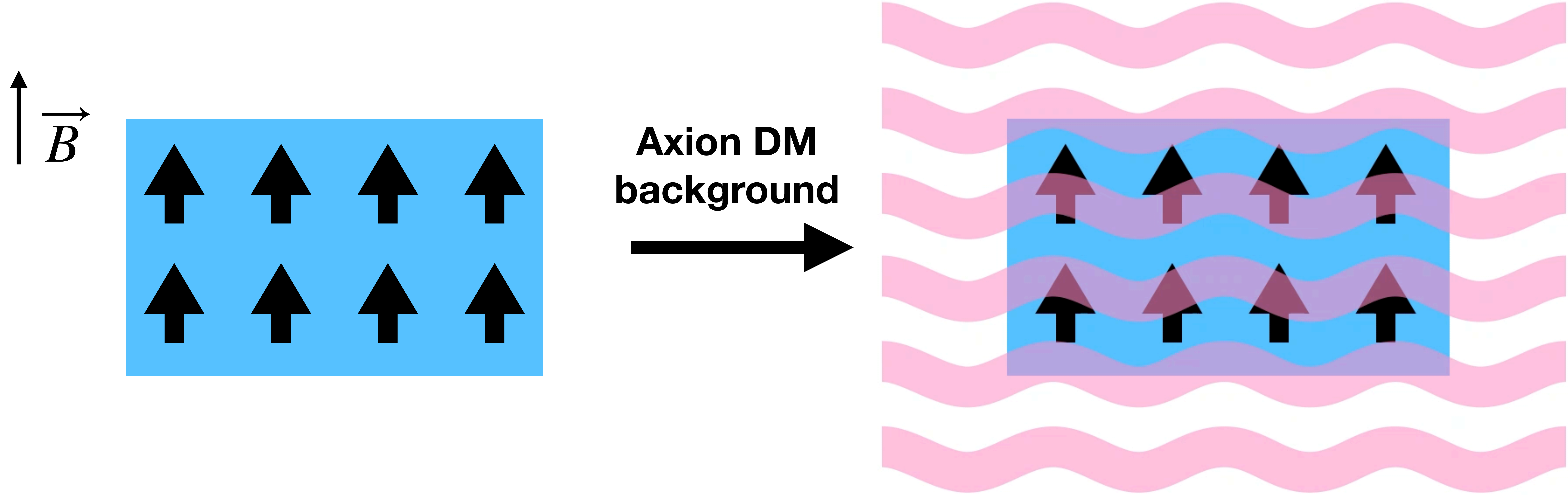
- Amplitude $a_0 \propto \frac{\sqrt{\rho_{DM}}}{m_a}$
- Small frequency spread (coherence)

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

Piezoaxionic effect - a preview

$$\mathscr{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G}$$



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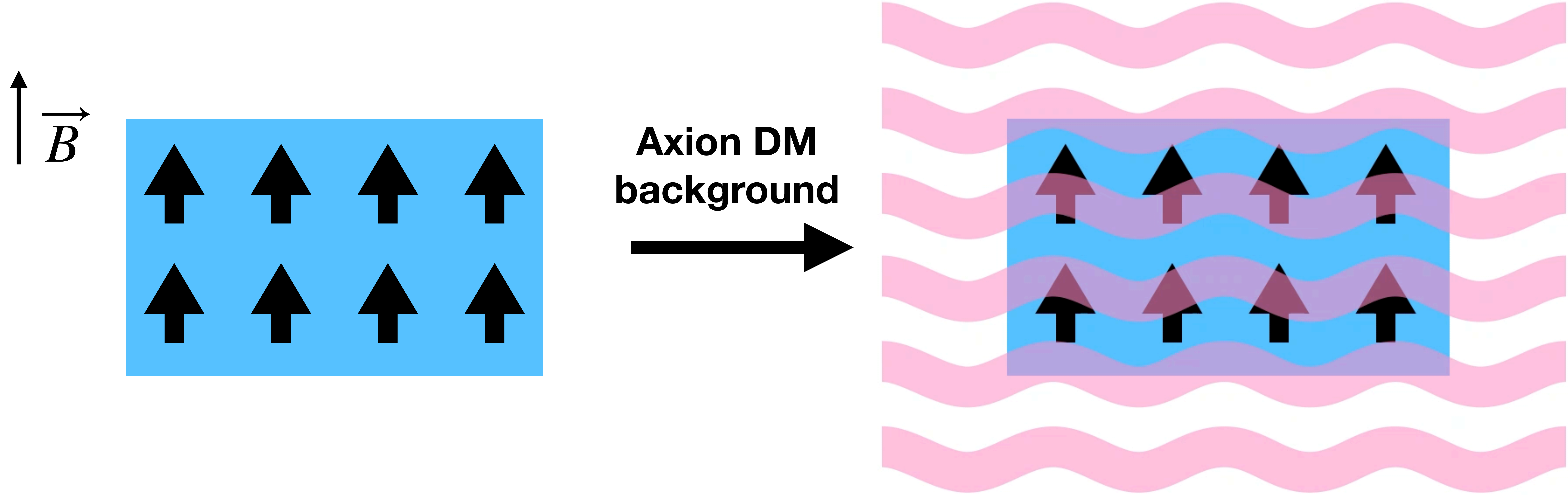


Outline

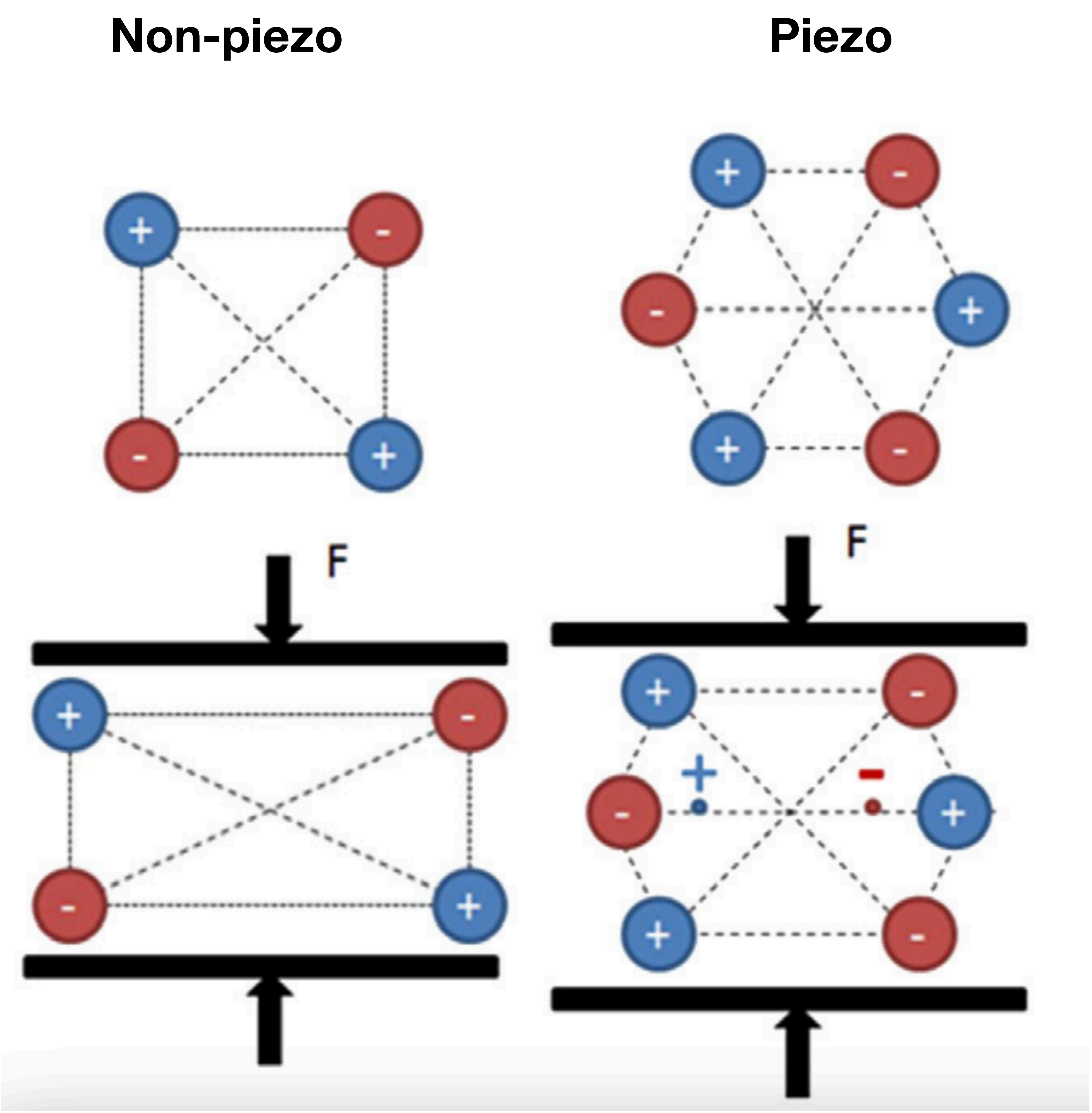
- Parity violation: piezoelectric crystals and axion couplings
- Schiff's theorem: how to detect parity violating nuclear multipole moments
- Resonant mass detectors
- Proposed experimental setup and sensitivity

Piezoelectric Crystals

- Piezoelectric are a large class of materials: 20 out of 32 symmetry groups

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

- Deformation causes net charge across unit cell (and vice versa).



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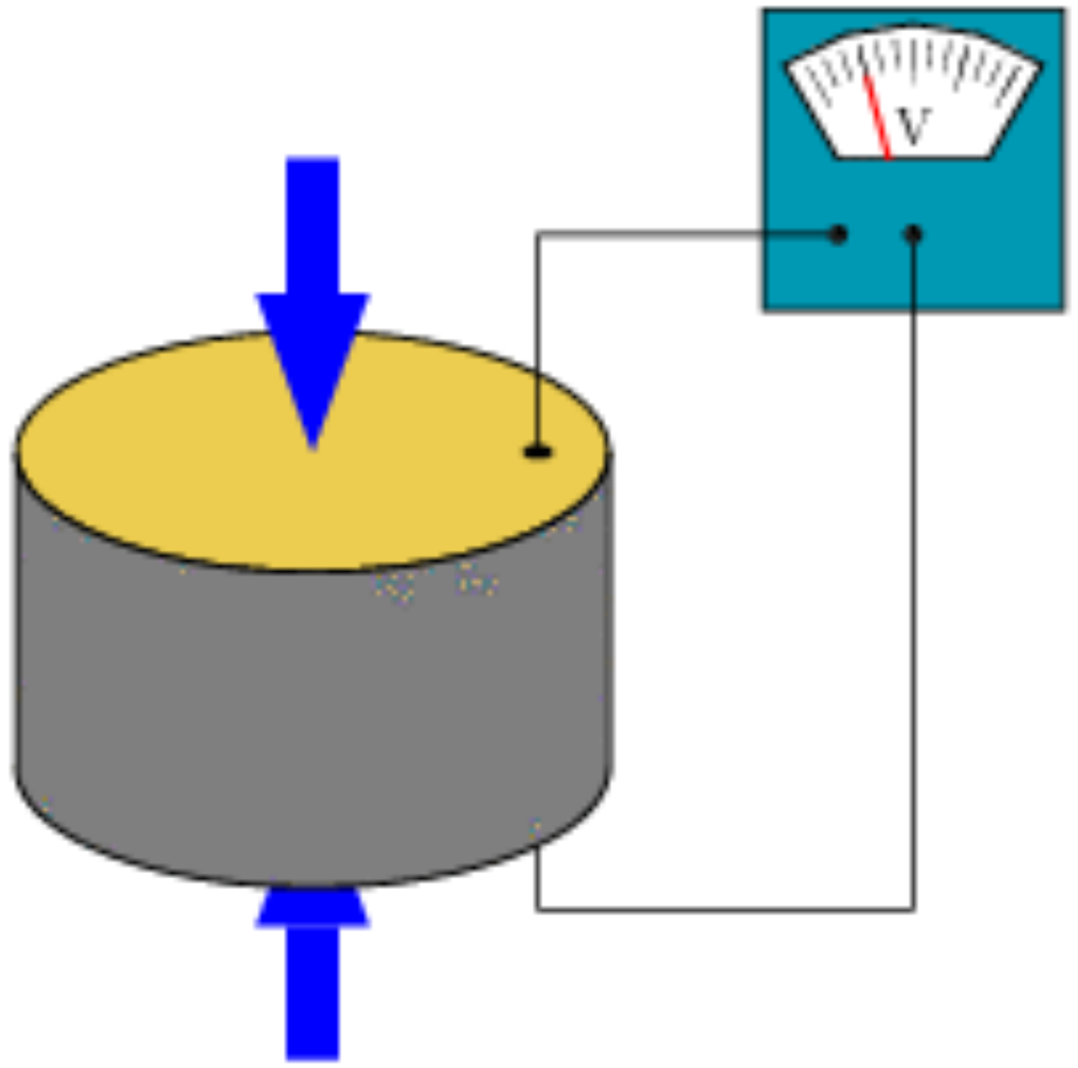

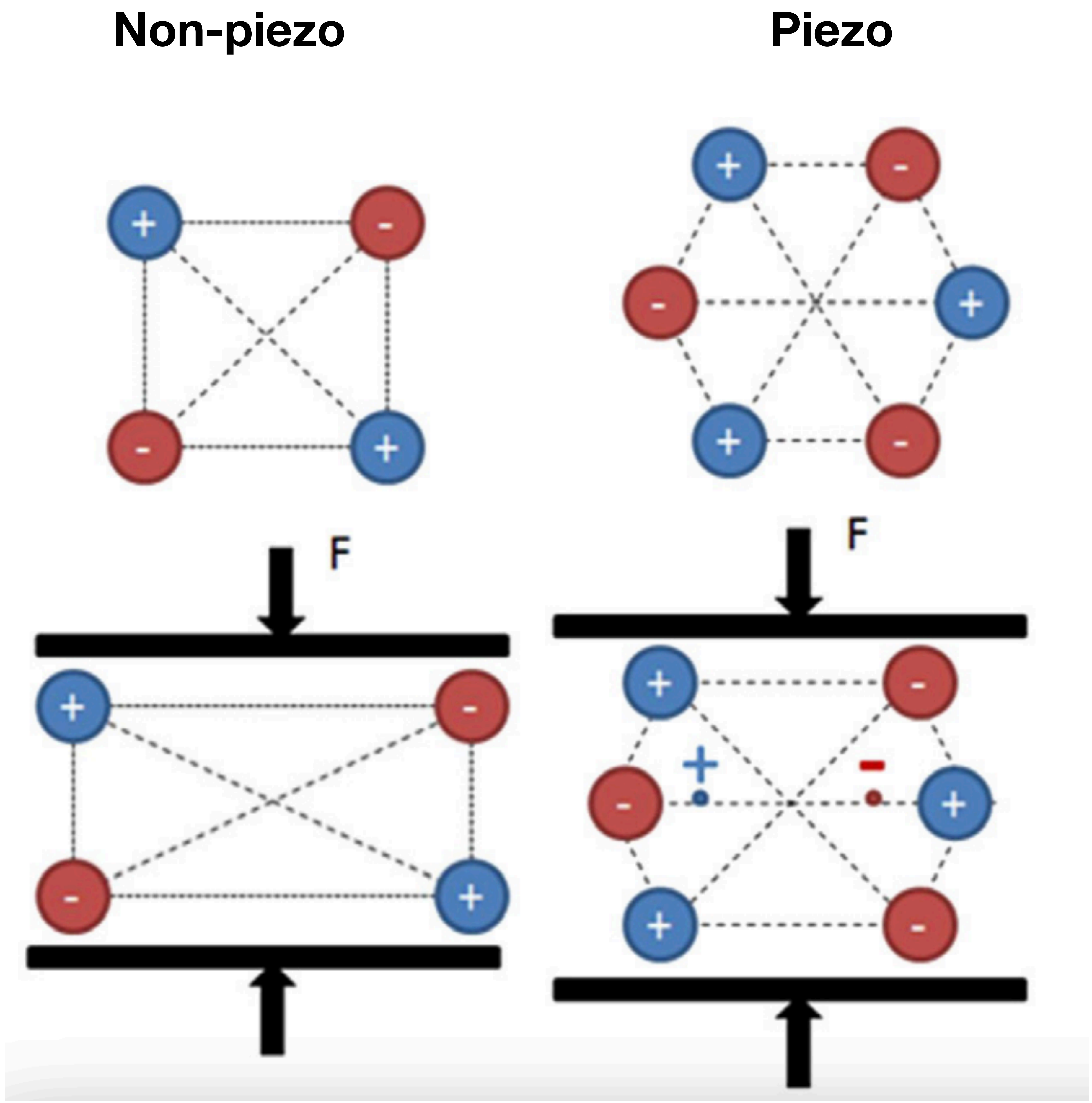

Constitutive Equations for Piezoelectricity

Stiffness ↓ (c) Piezoelectric ↓ (h)

$$\textbf{Stress} = +\, c \cdot \textbf{Strain} - h \cdot \textbf{Electric Displacement}$$

$$\textbf{Electric Field} = -\, h \cdot \textbf{Strain} + \frac{1}{\epsilon} \cdot \textbf{Electric Displacement}$$

↑ Permittivity (ϵ)

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parity even
parity odd

Constitutive Equations for Piezoelectricity

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

Stiffness ↓ Piezoelectric ↓ Piezoaxionic ↓

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

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

↑ Permittivity ↑ Electroaxionic

parity even
parity odd
time-reversal odd

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

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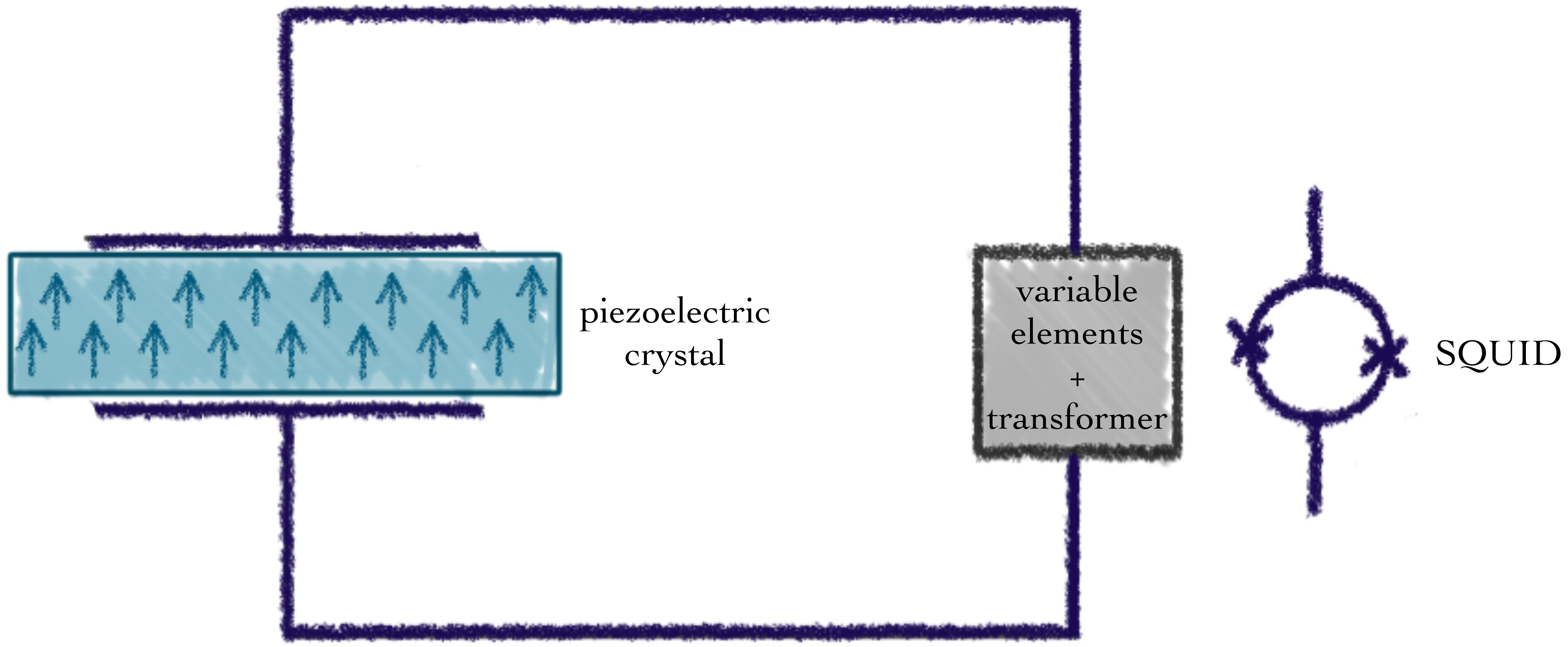
We will focus on ξ in this talk!

Journey from microscopic to macroscopic

START HERE

AXION DM



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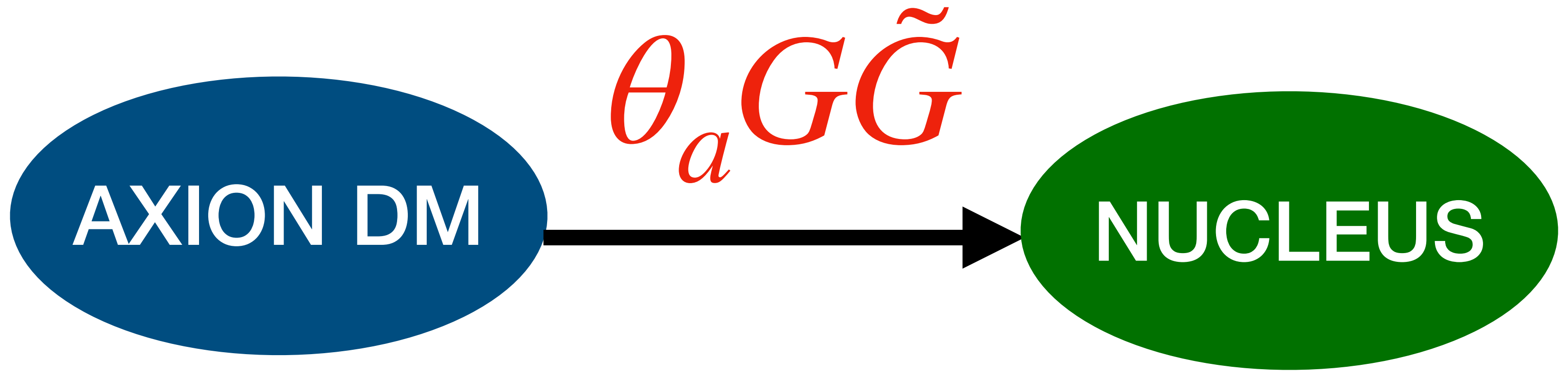

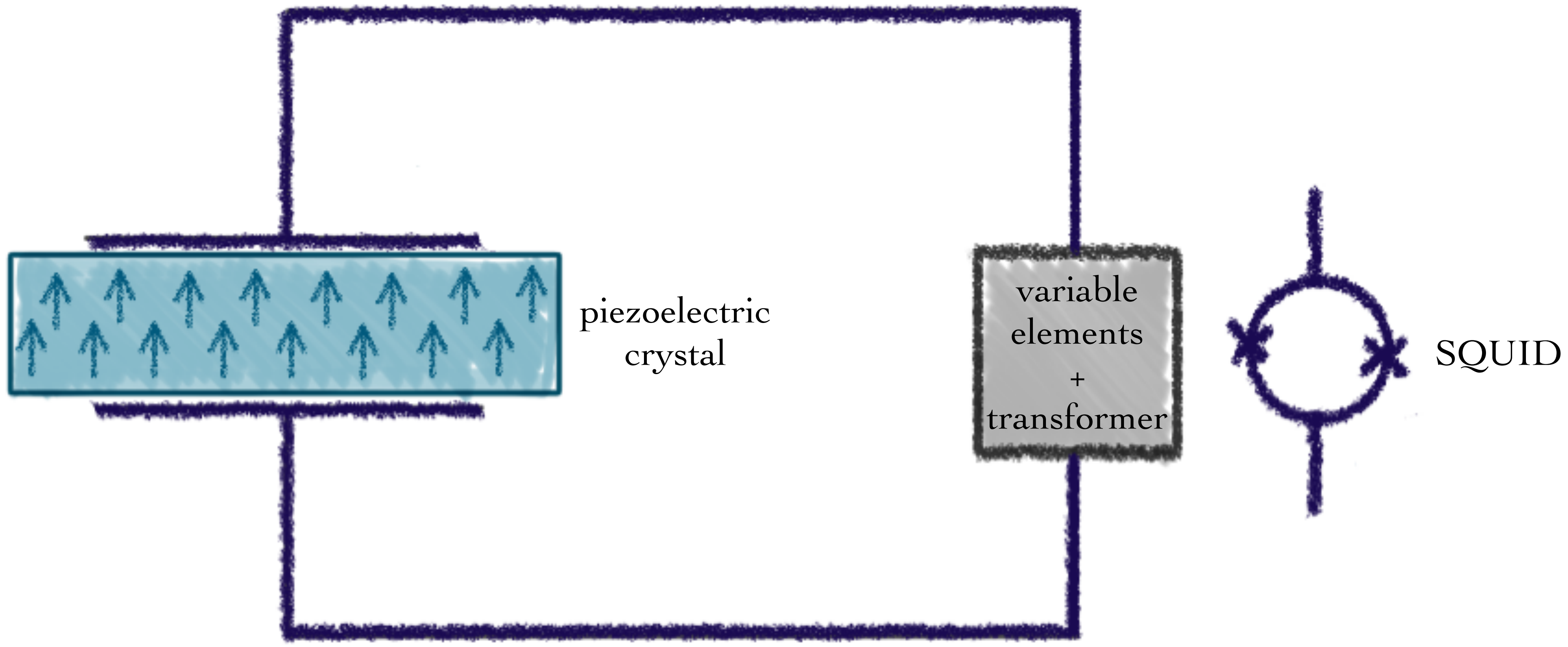

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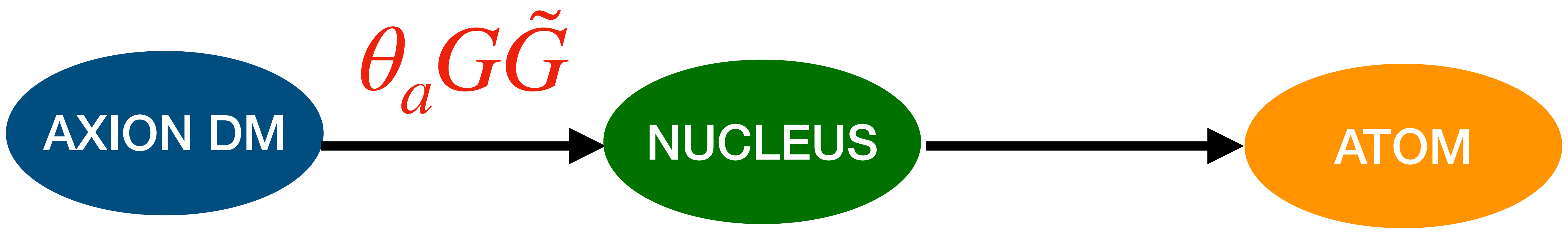

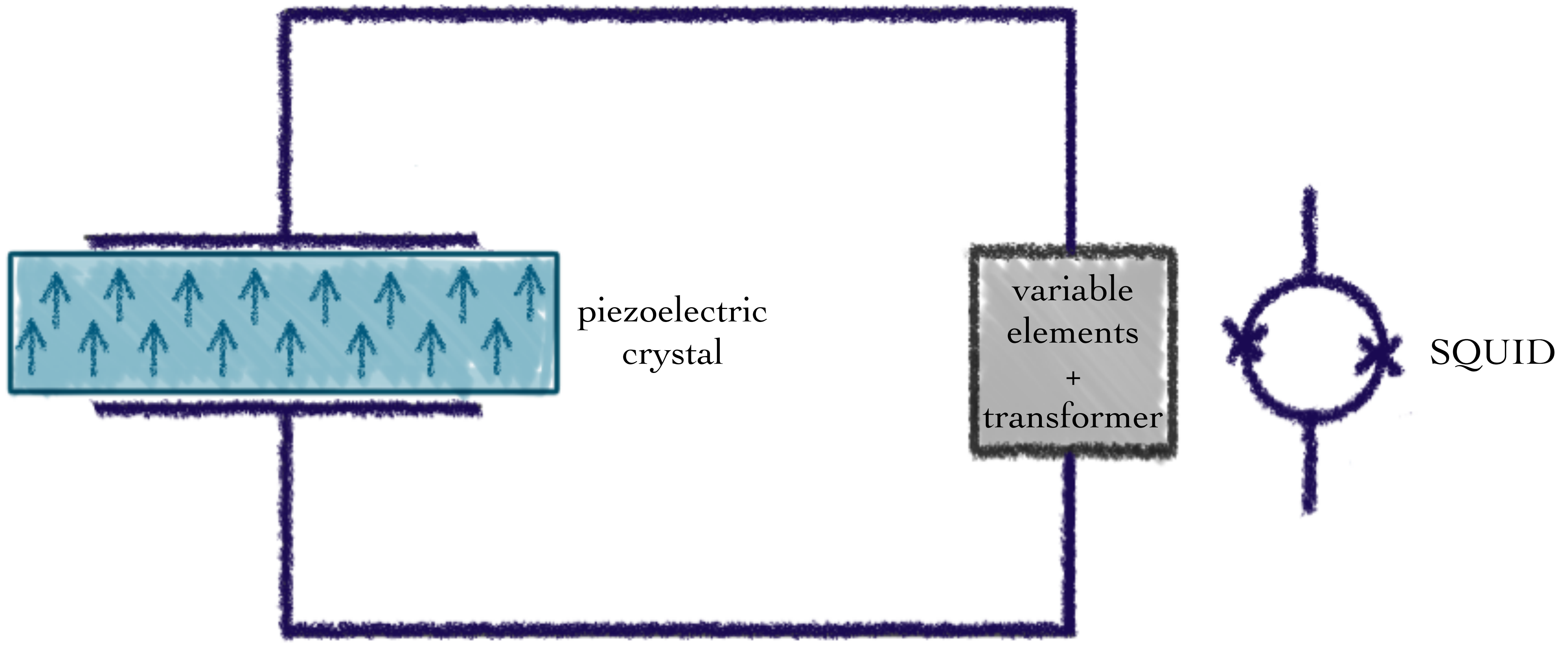

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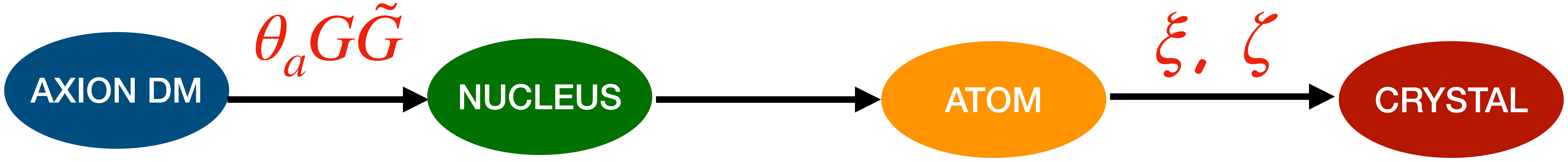

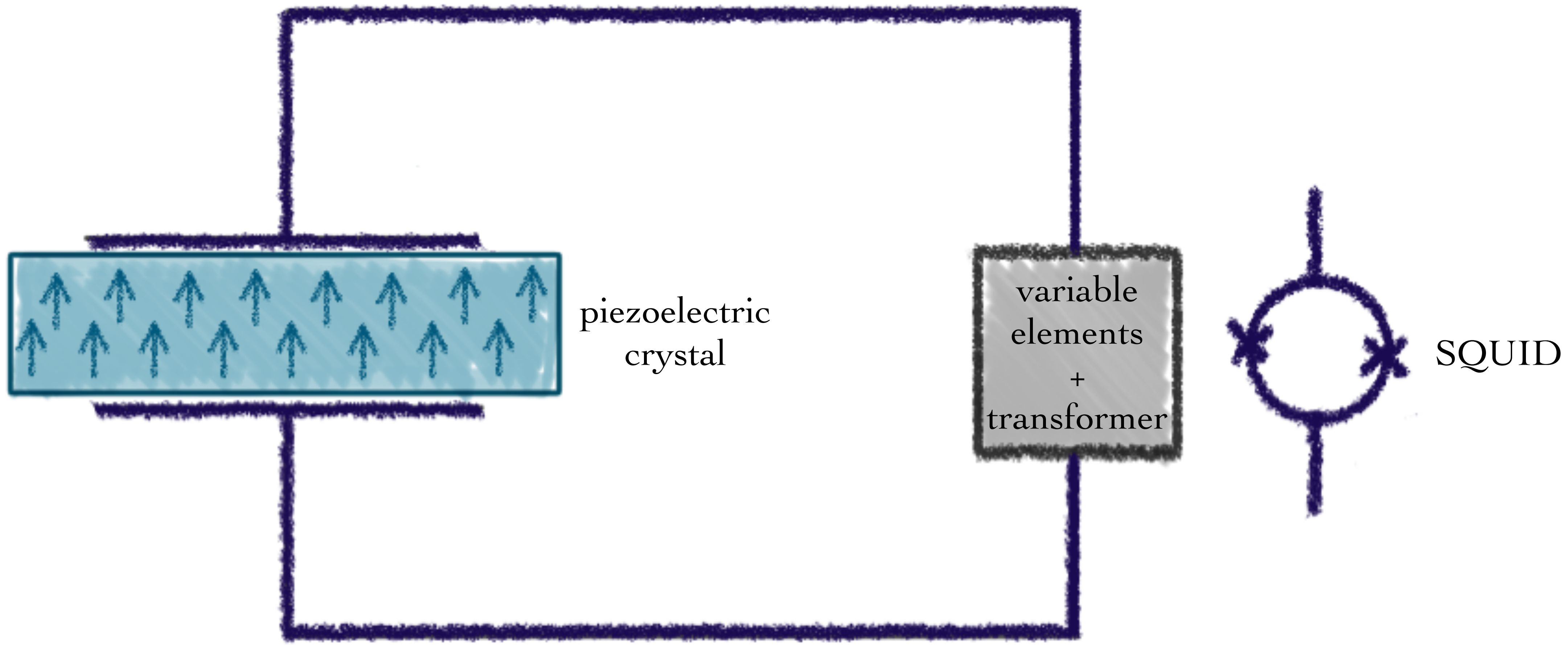

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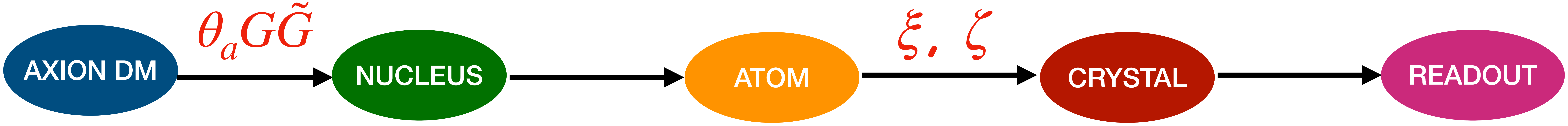
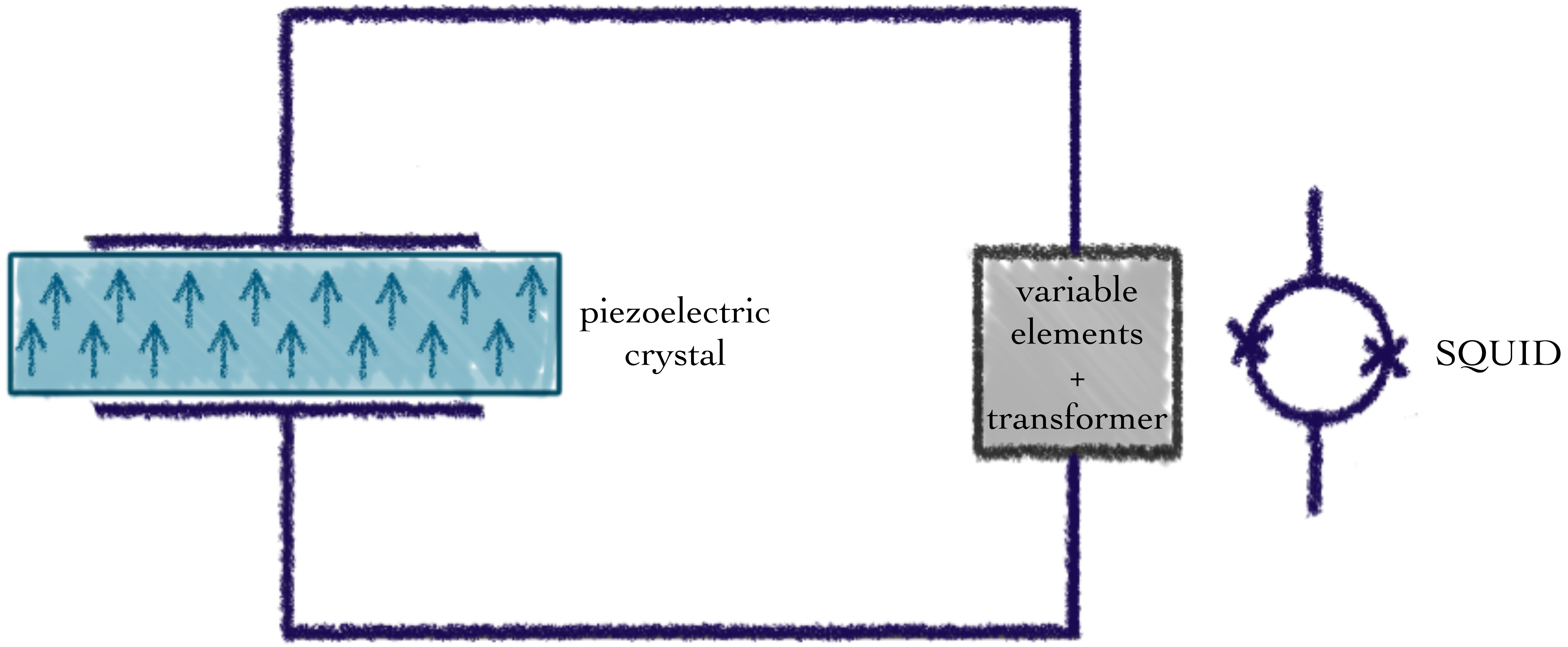
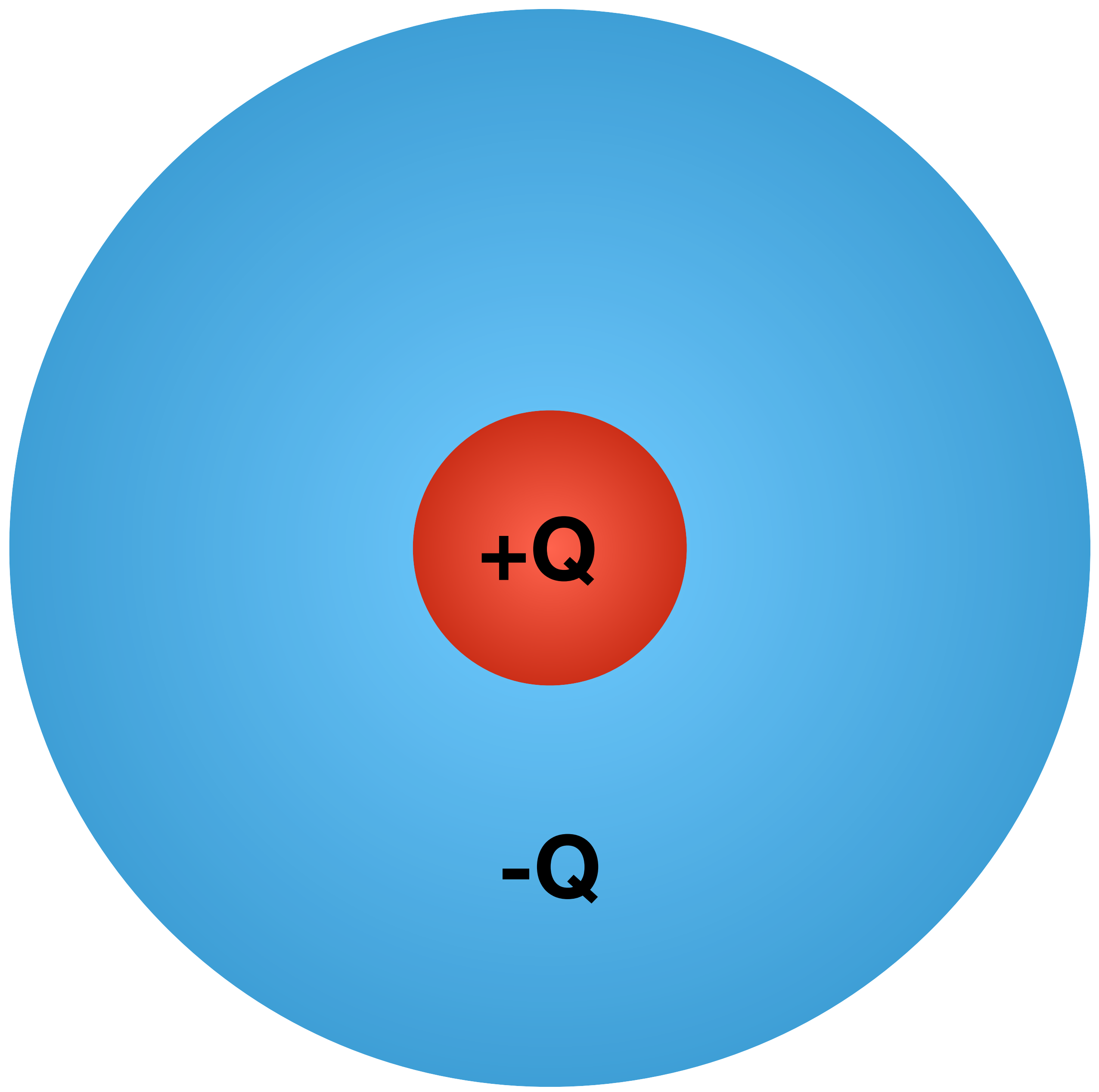




Schiff's Theorem

QCD axion DM induces an ***oscillating*** neutron EDM:

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



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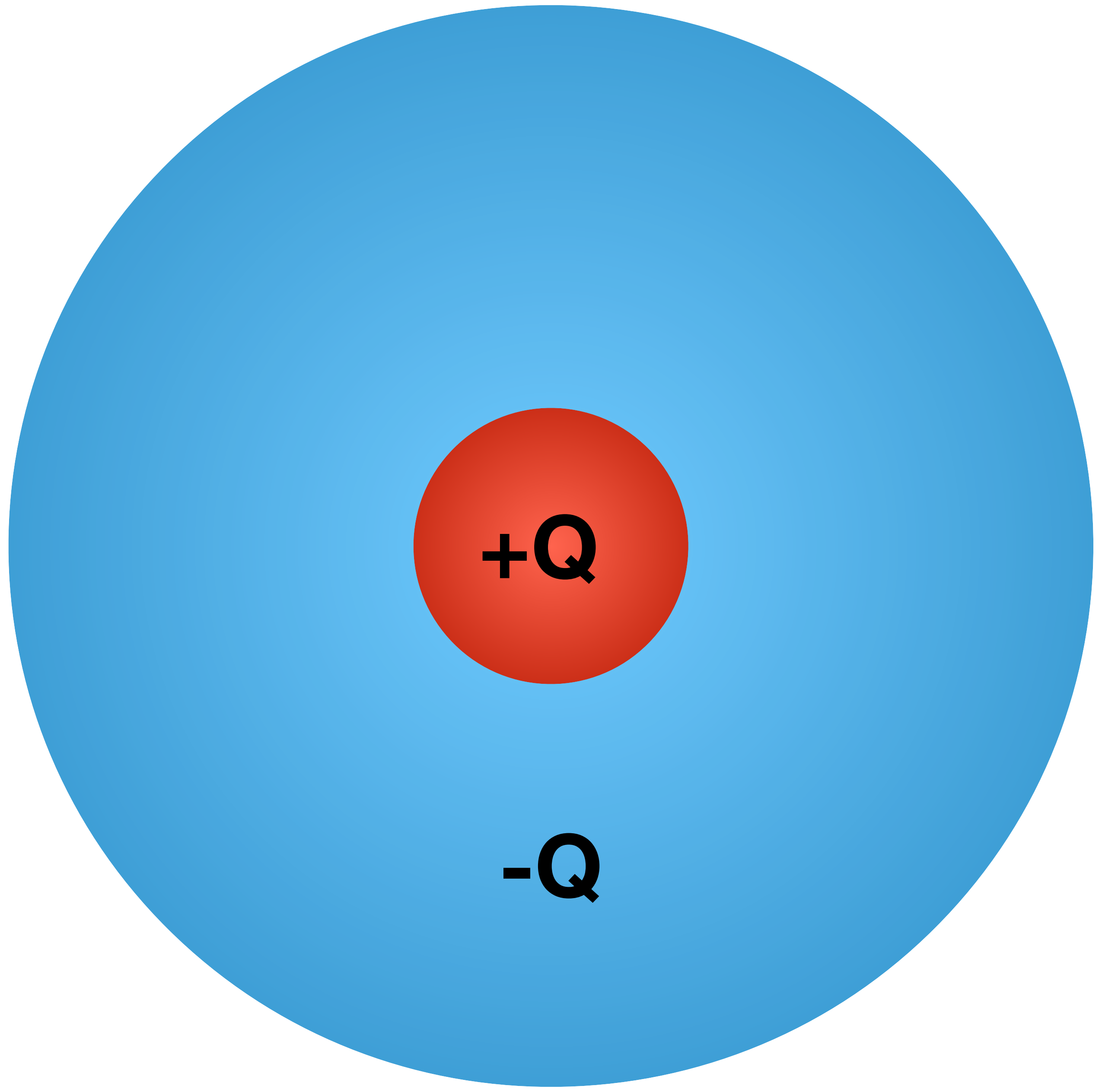

If we treat an atom as a system of *point* particles, nuclear EDM is perfectly shielded by electron cloud [*Schiff* 1963].

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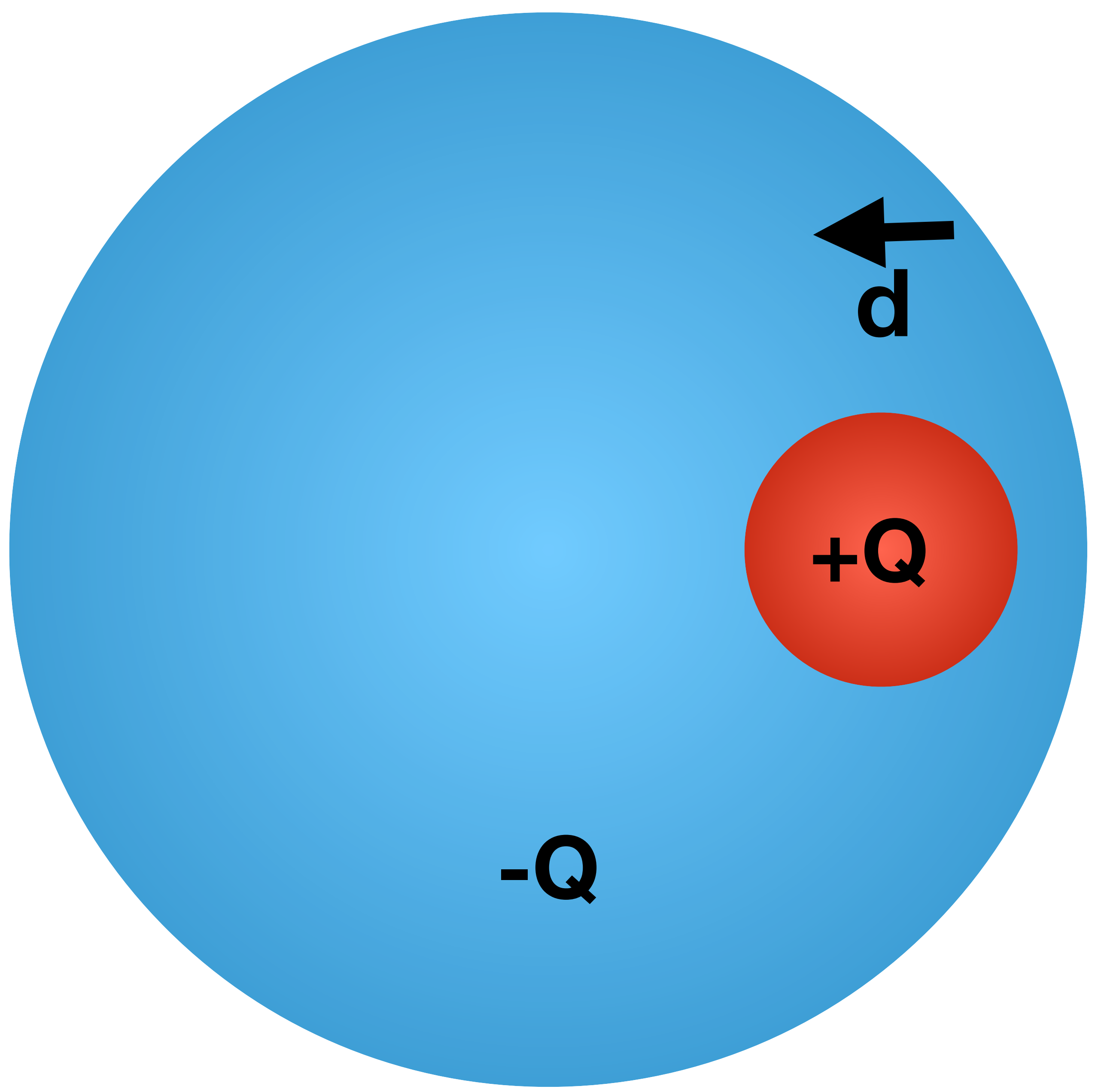

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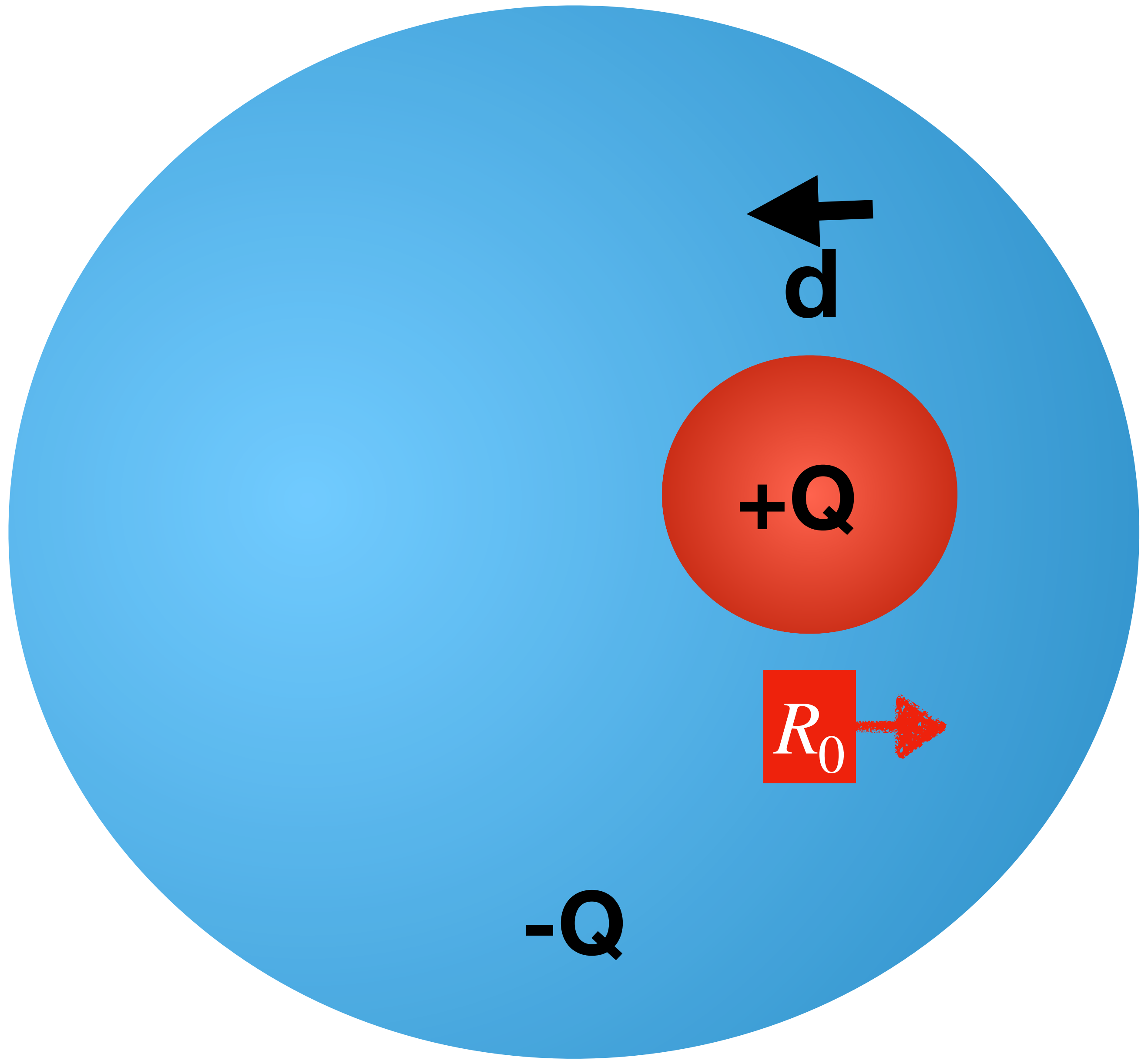
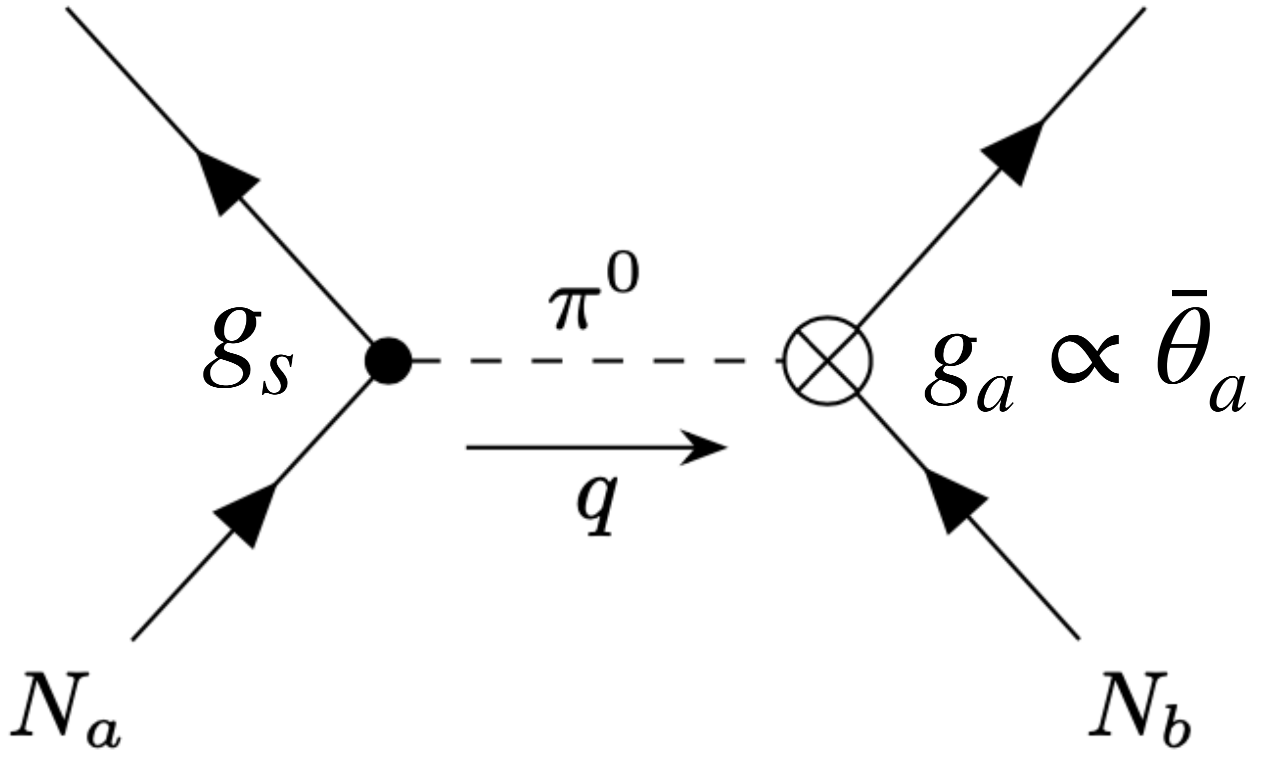
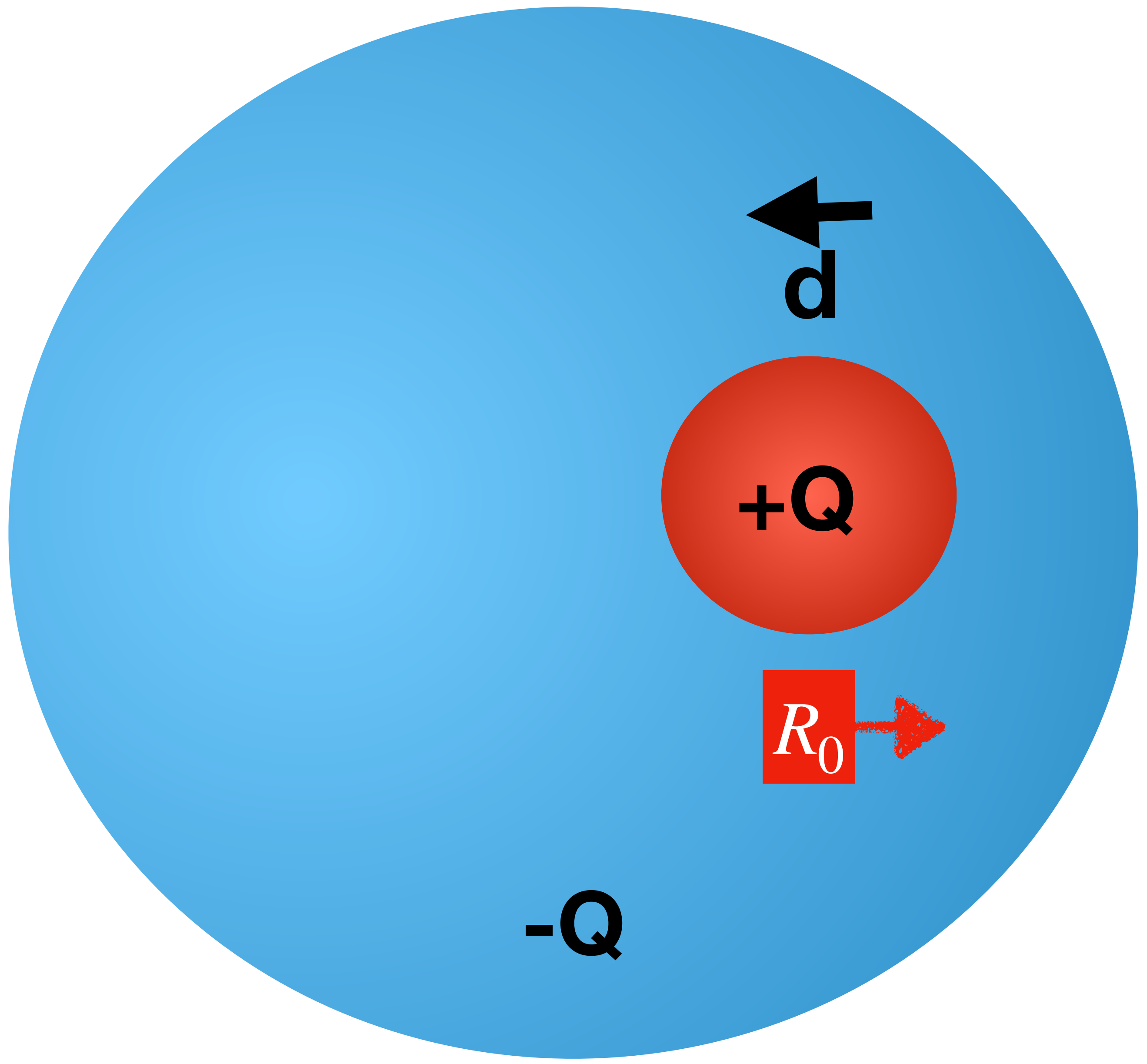

d
+Q
R_0
-Q


g_s
π^0
q
$g_a \propto \bar{\theta}_a$
N_a
N_b

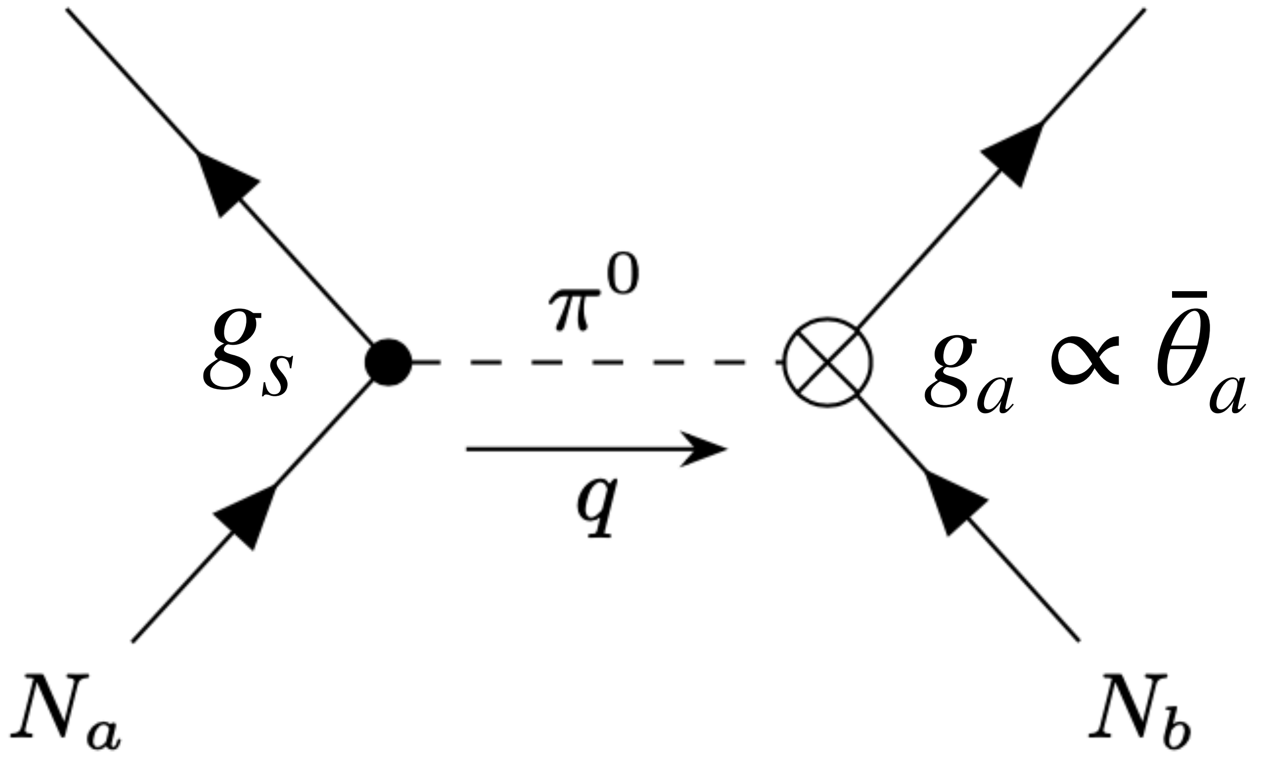

AXION
NUCLEUS
ATOM
CRYSTAL
READOUT

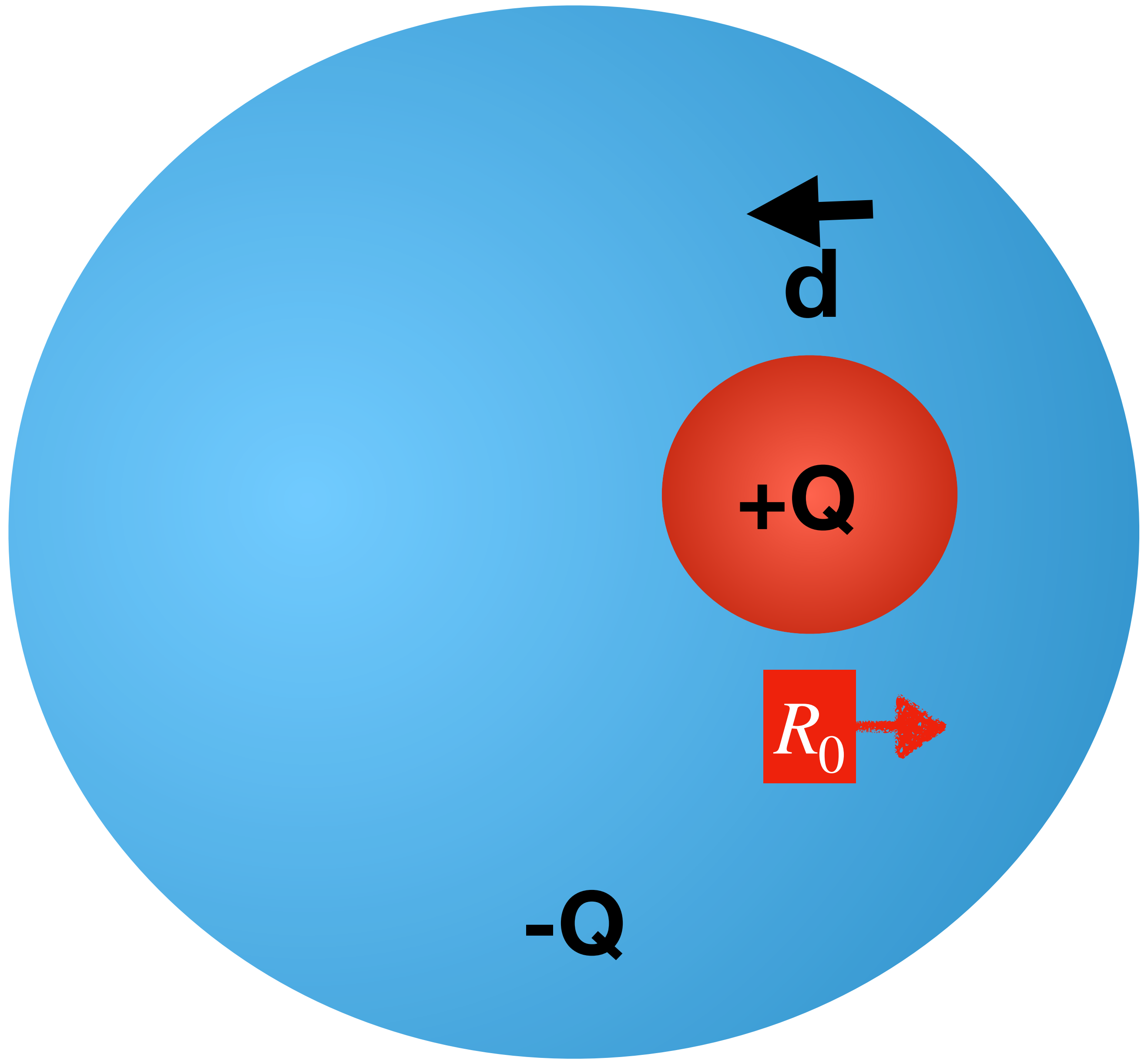


Resolution: Schiff's theorem violated by finite size effects:

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

"Schiff moment $\mathcal{S}$"





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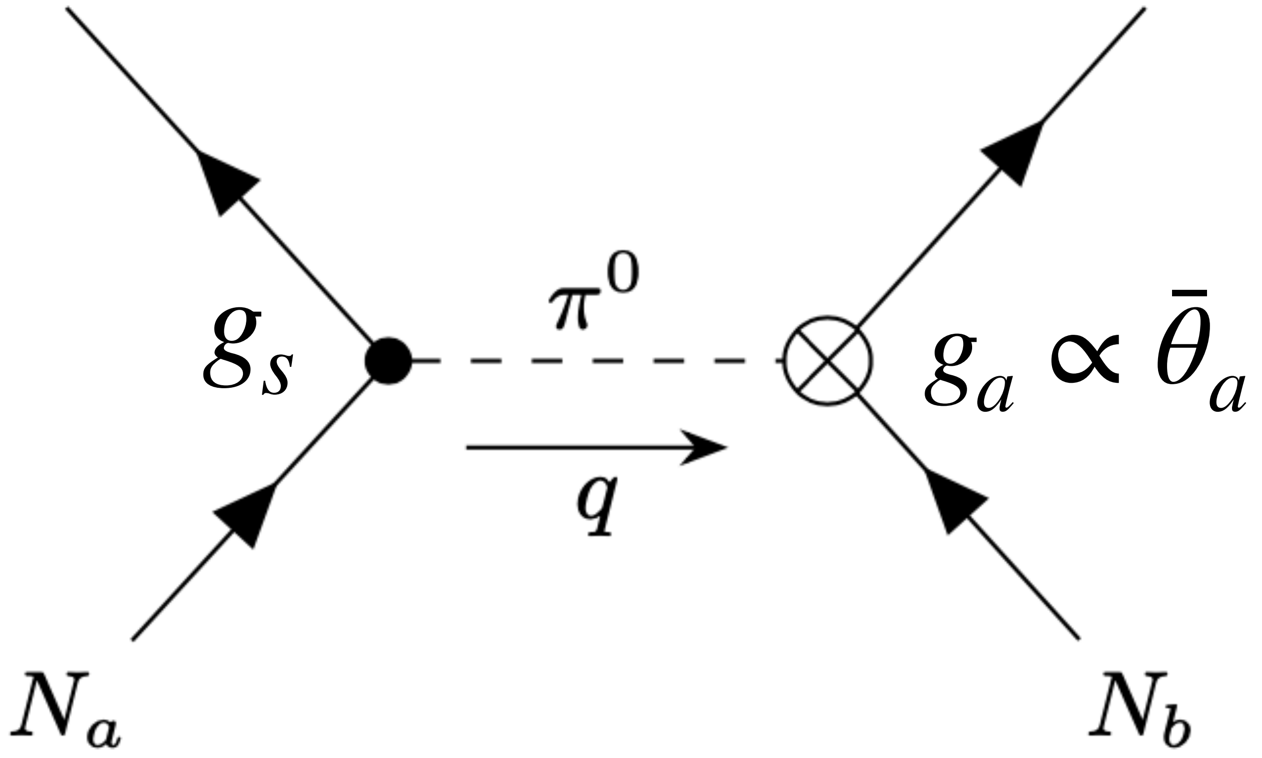
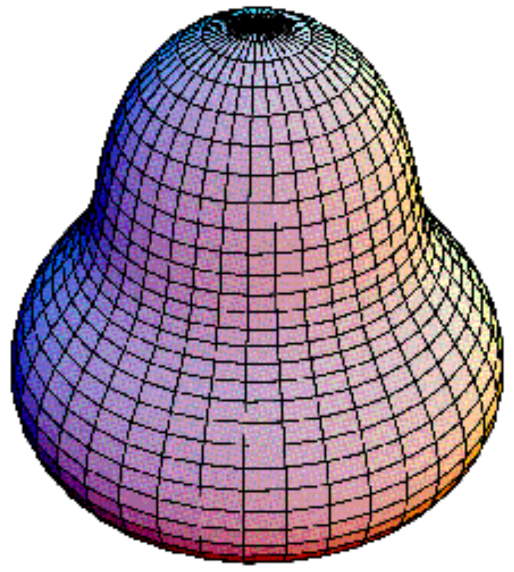
for non-deformed nuclei



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

for deformed (pear shaped) nuclei



- $V_{electrons} = V_{crys} + V_{schiff}$

V_{cell} **= unit cell volume,** $\mathscr{S}$ **= Schiff moment magnitude**

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- V_{crys} mixes s- and p- like electrons in ground state, to give admixtures ϵ_s and ϵ_p. This gives an energy shift:

$$\langle H_{schiff} \rangle \simeq \sum_{s,p} \epsilon_s \epsilon_p^* \langle s | V_{schiff} | p \rangle + c.c$$

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

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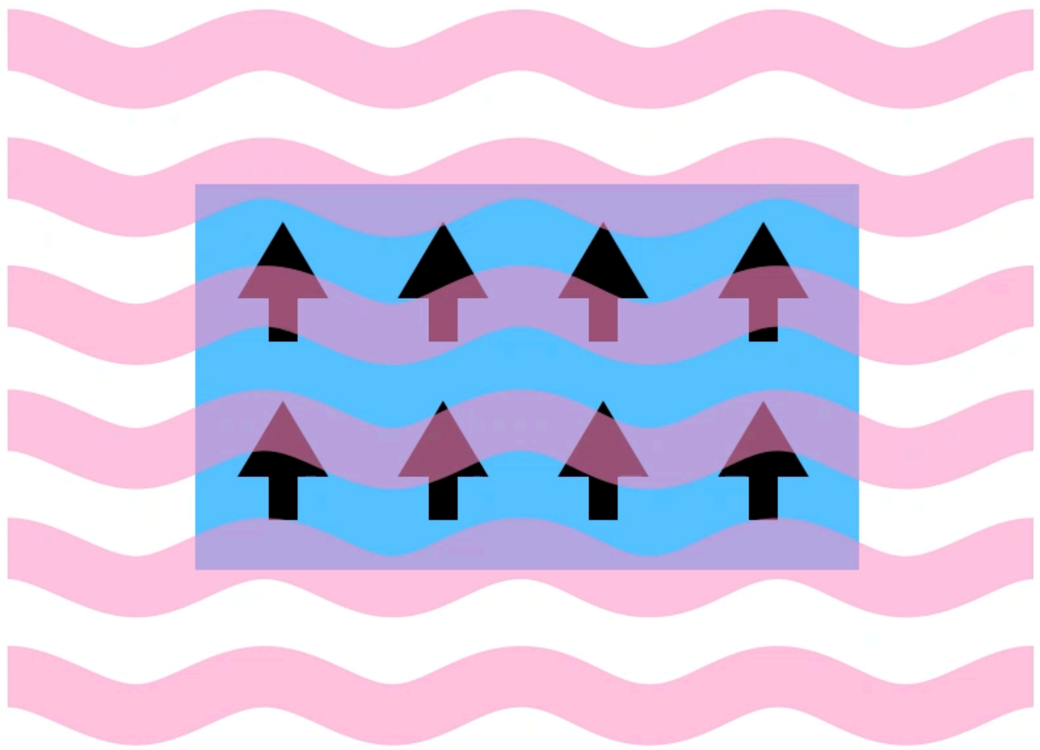
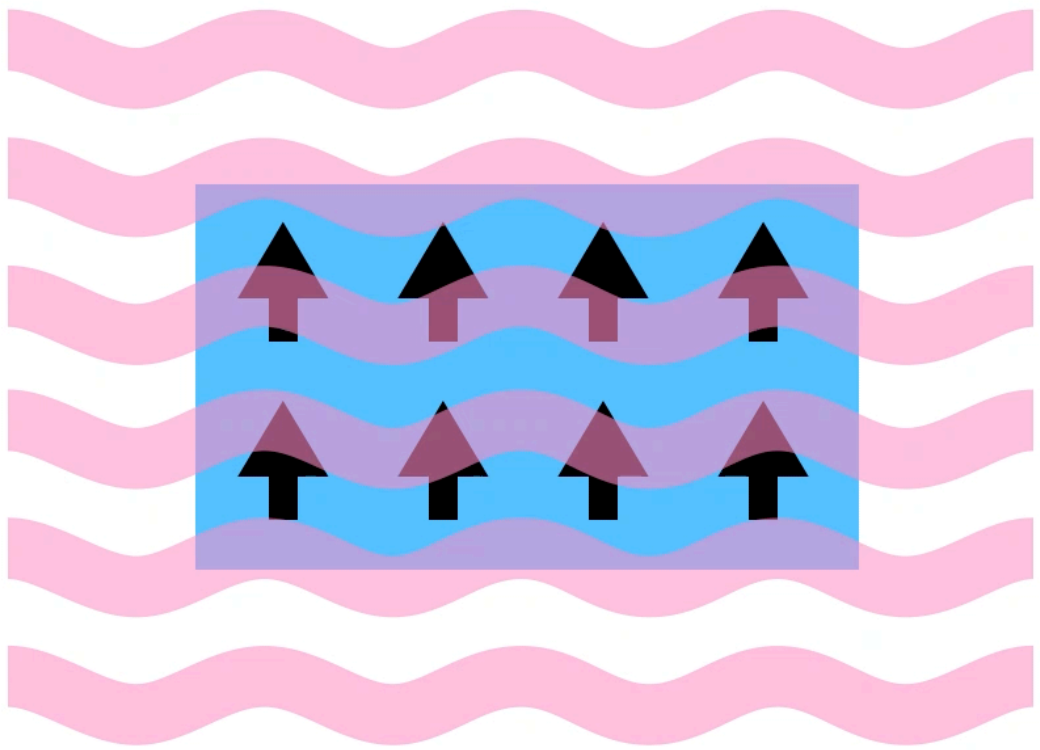
AXION → NUCLEUS → ATOM → CRYSTAL → READOUT



S = **strain** = $\frac{\Delta L}{L}$

$$S = |\xi c^{-1} \hat{I} \bar{\theta}_a|$$



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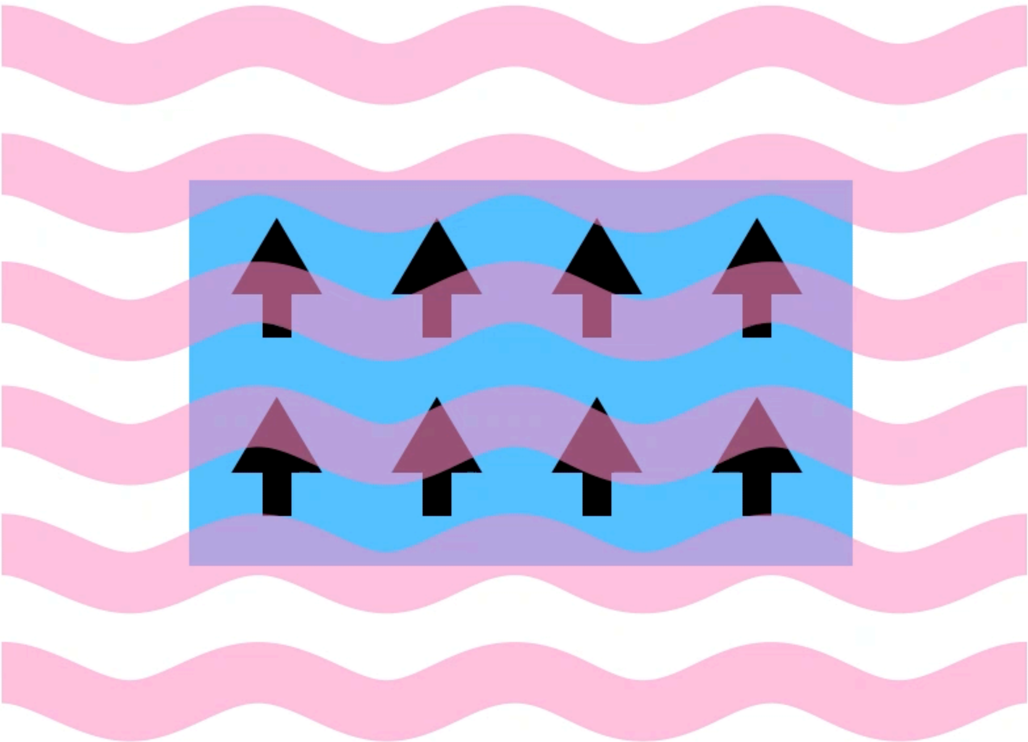

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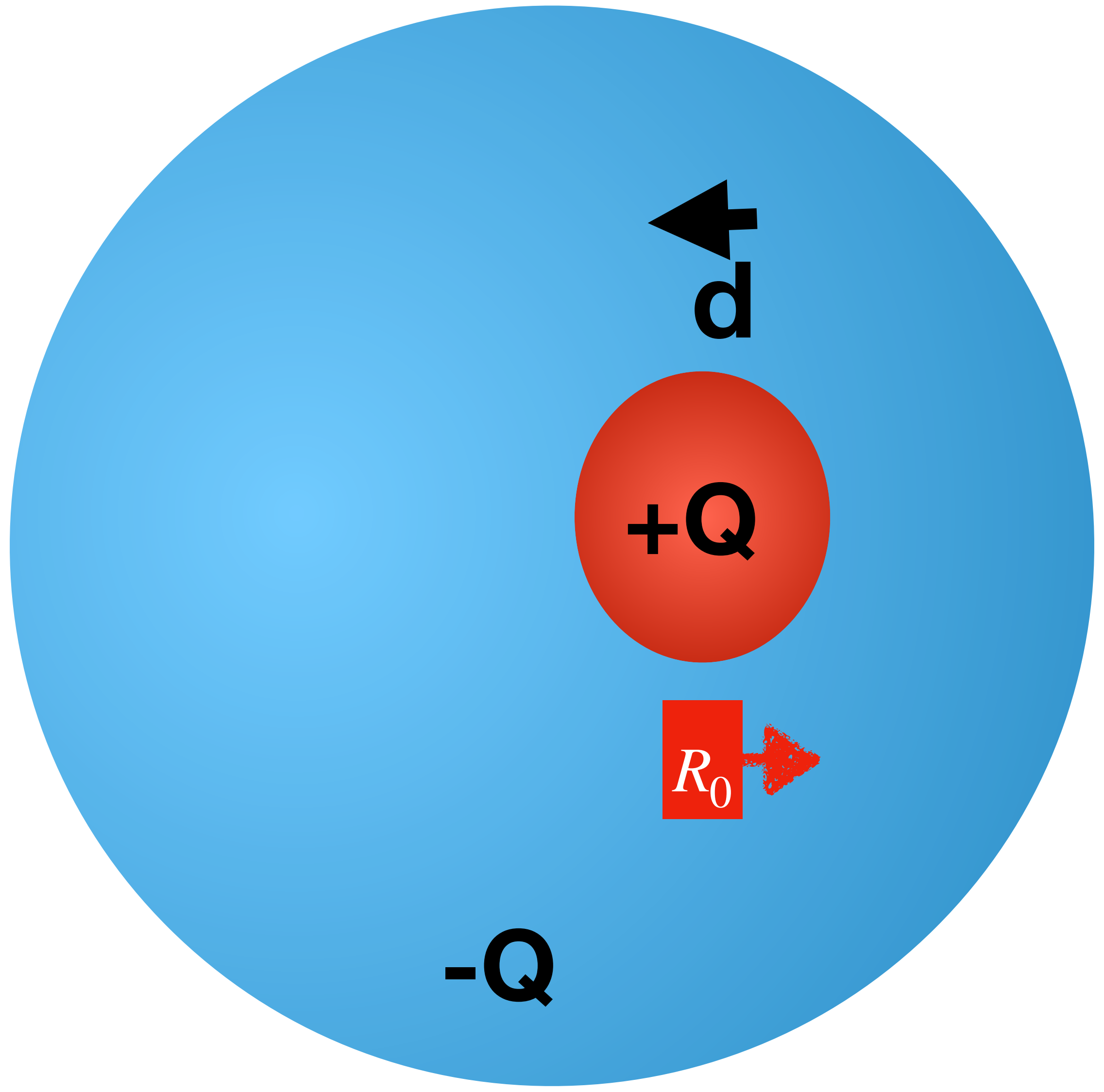
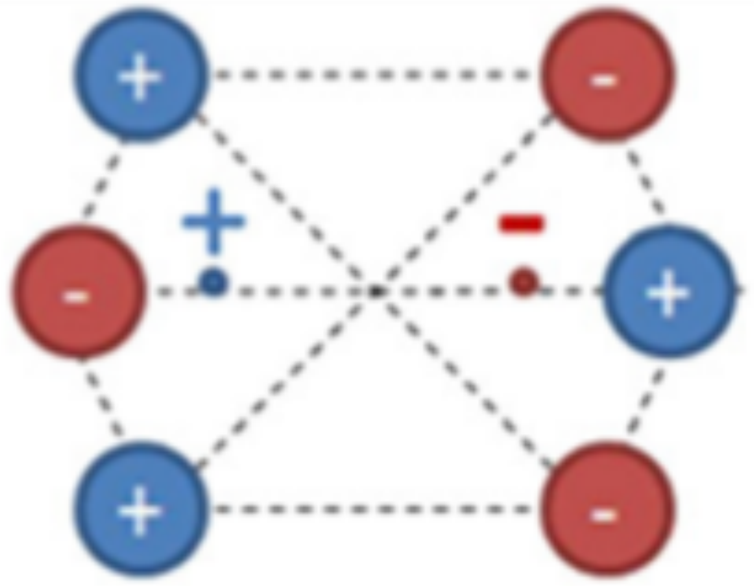
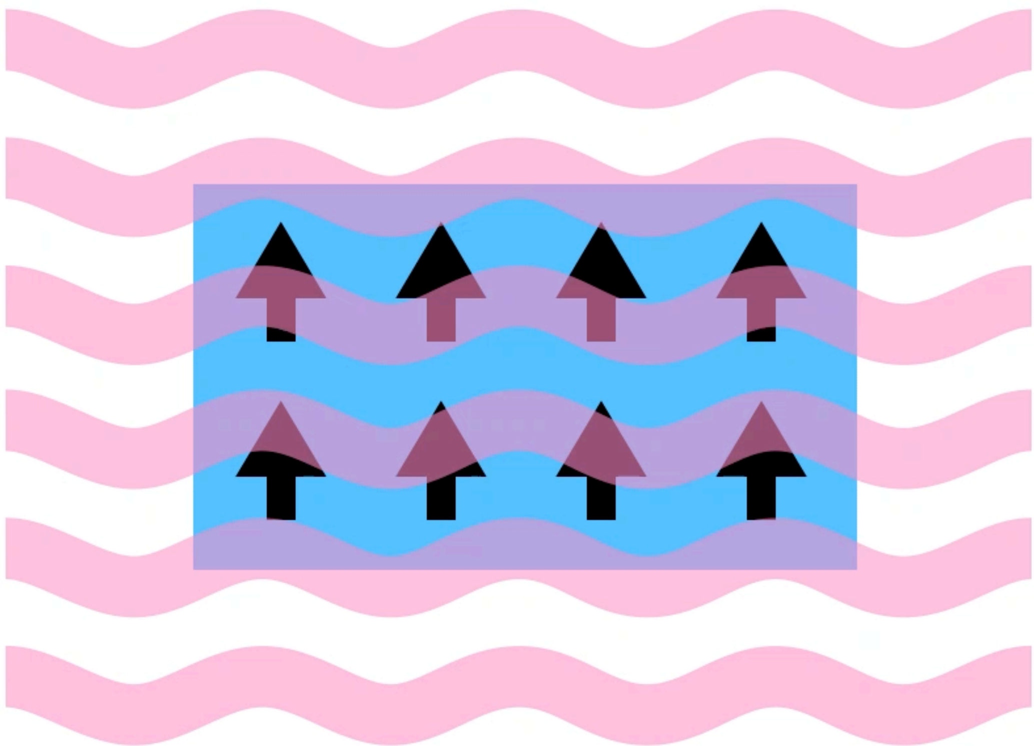


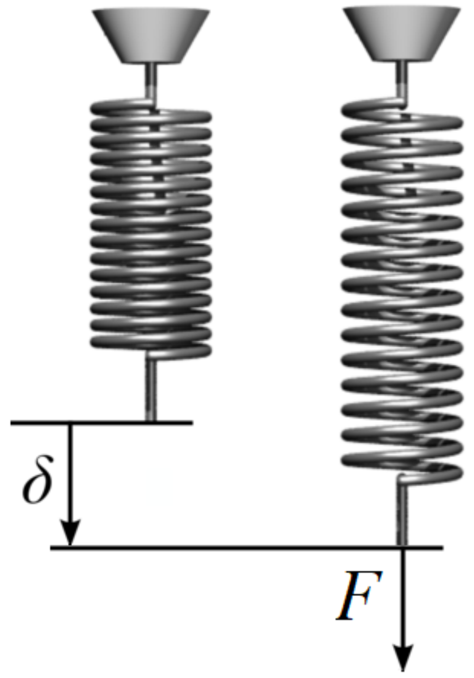
Schiff Moment

$\times$



Piezoelectric Crystal





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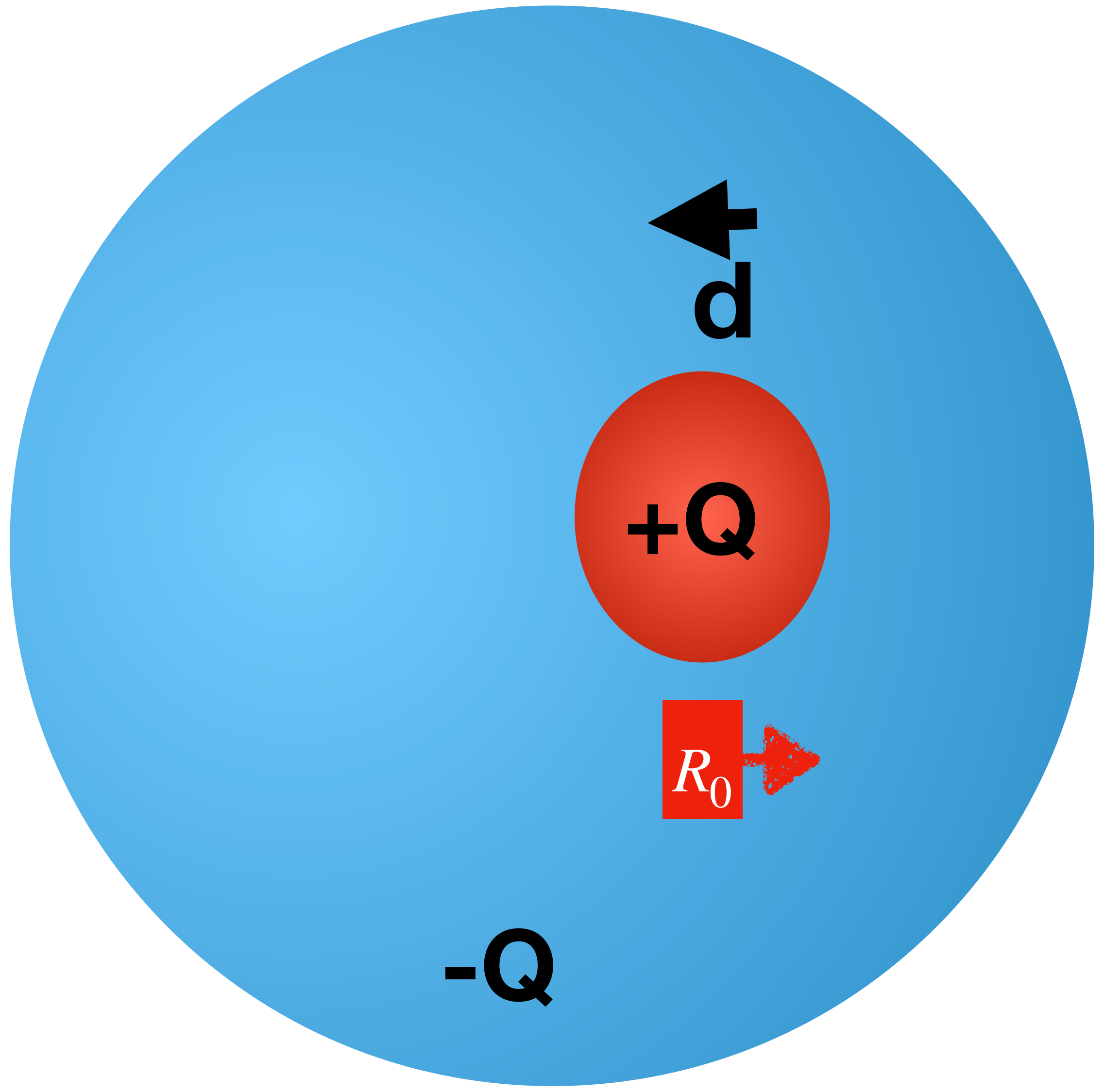

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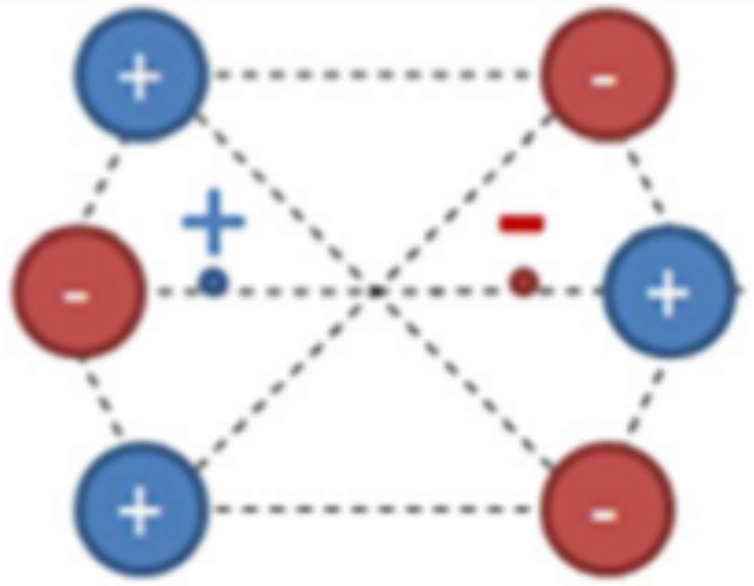

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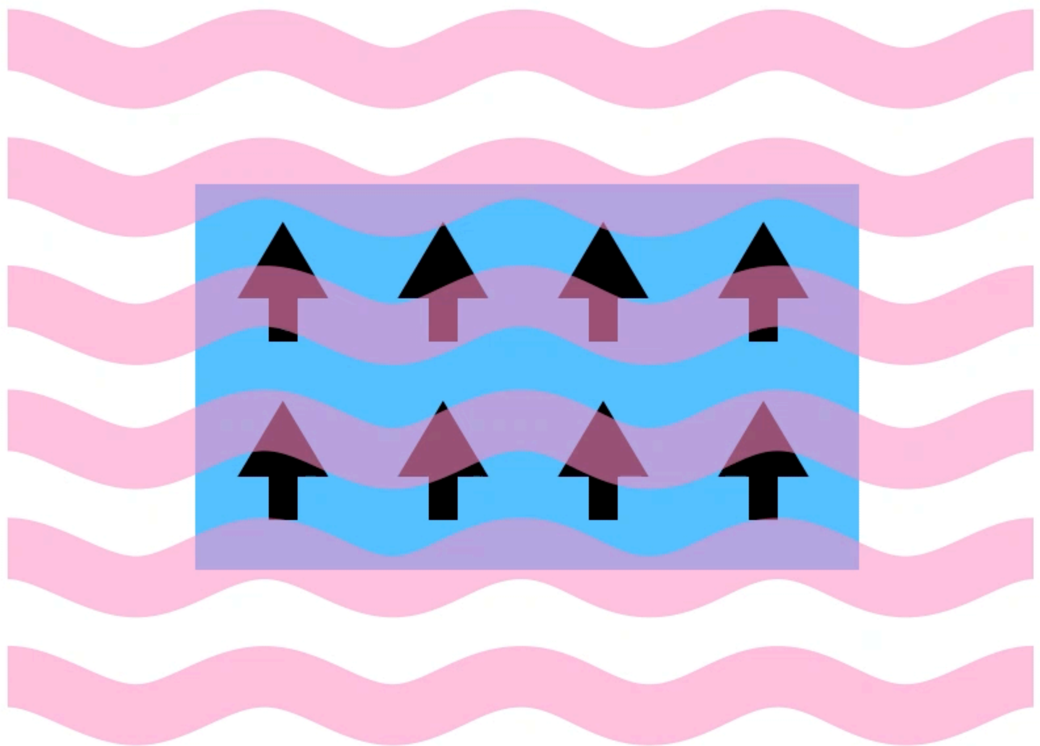

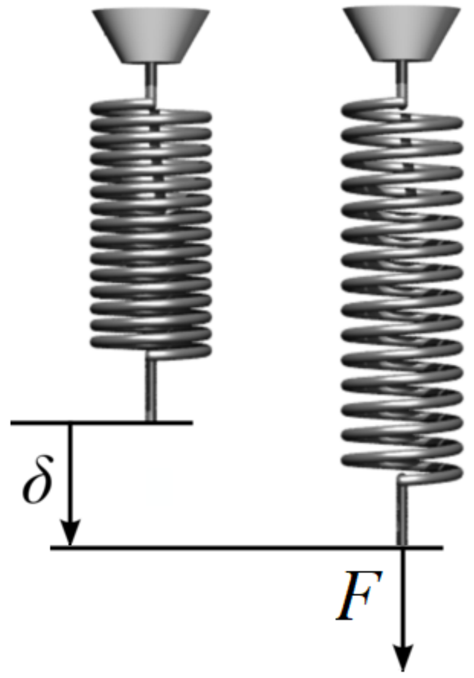

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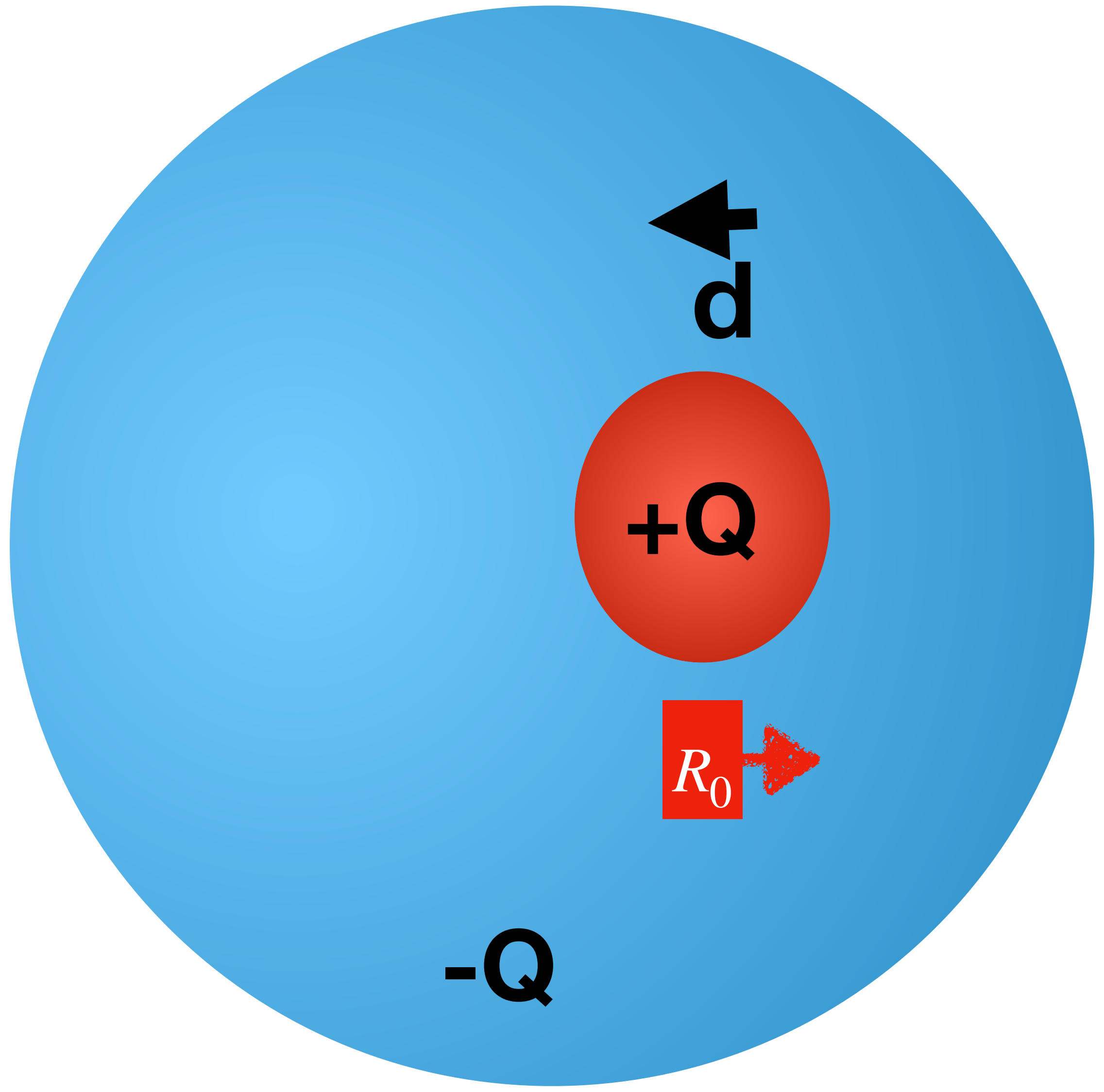
$\hat{I}$ = nuclear spin direction



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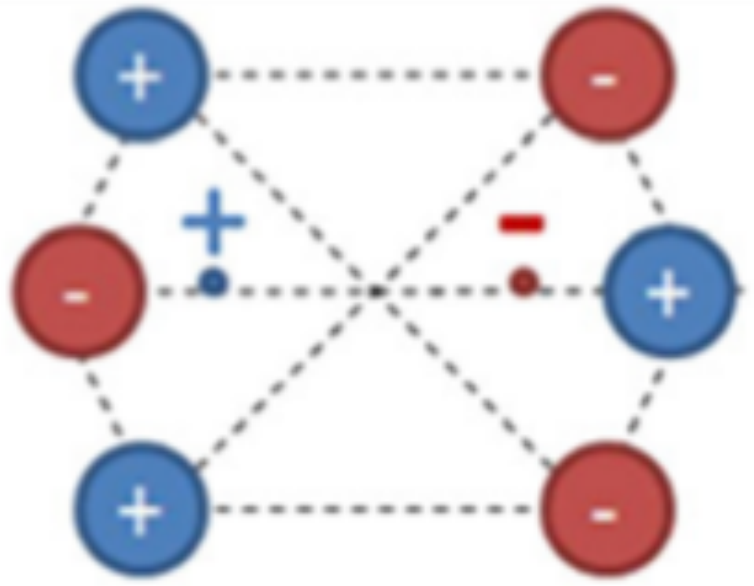

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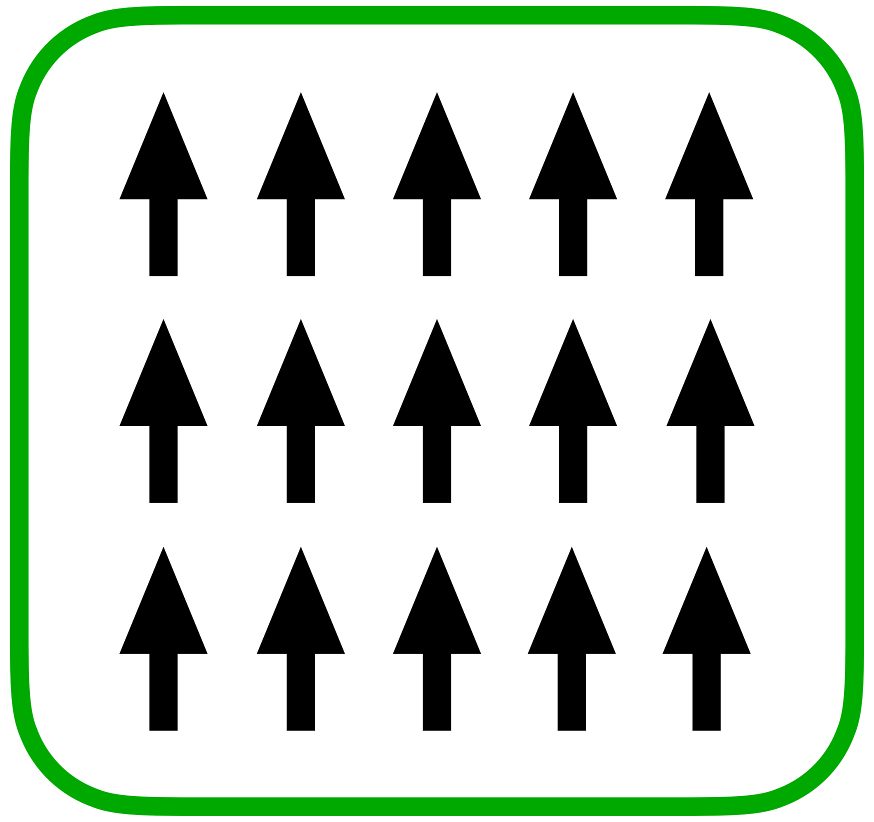

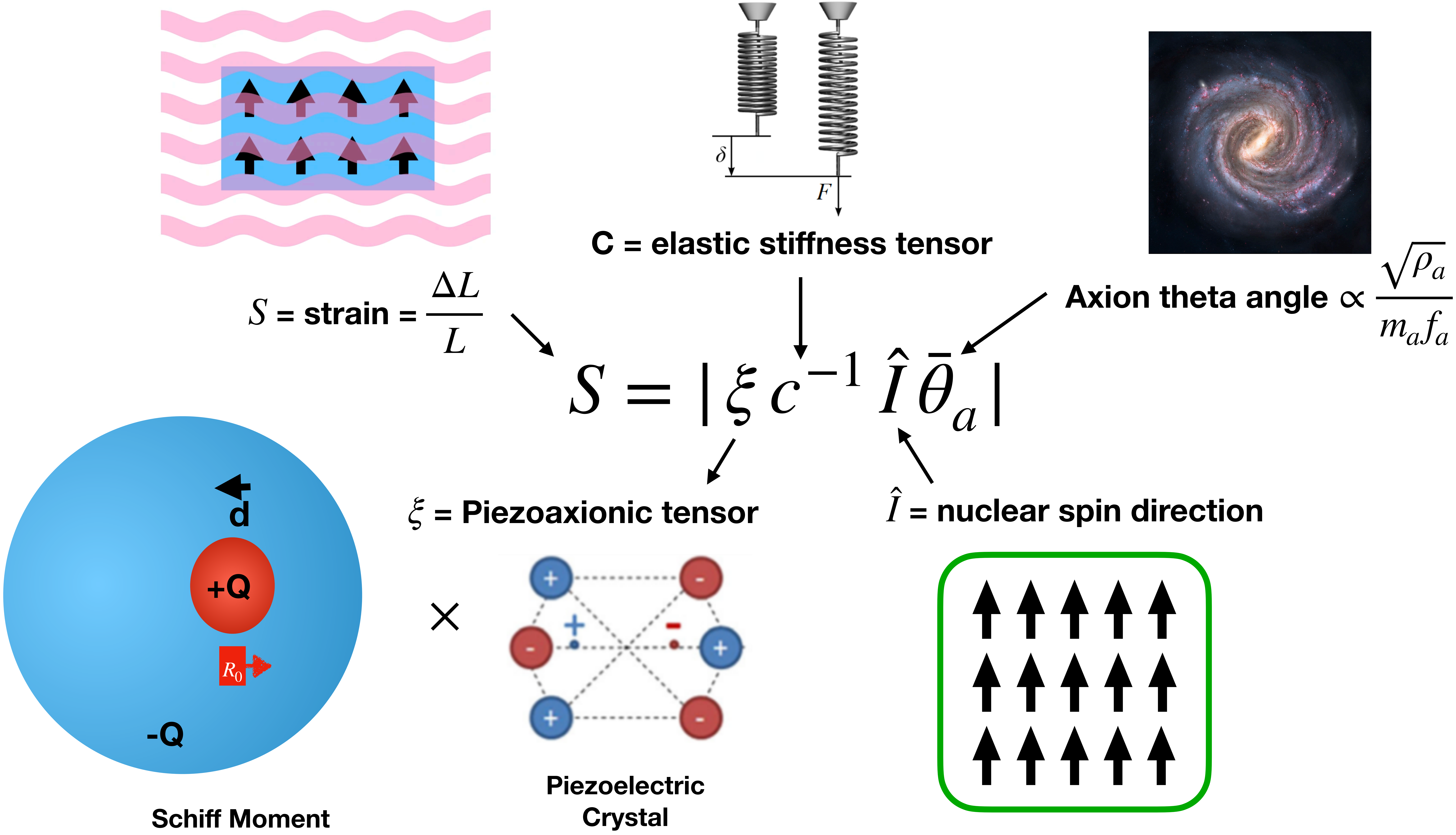

δ
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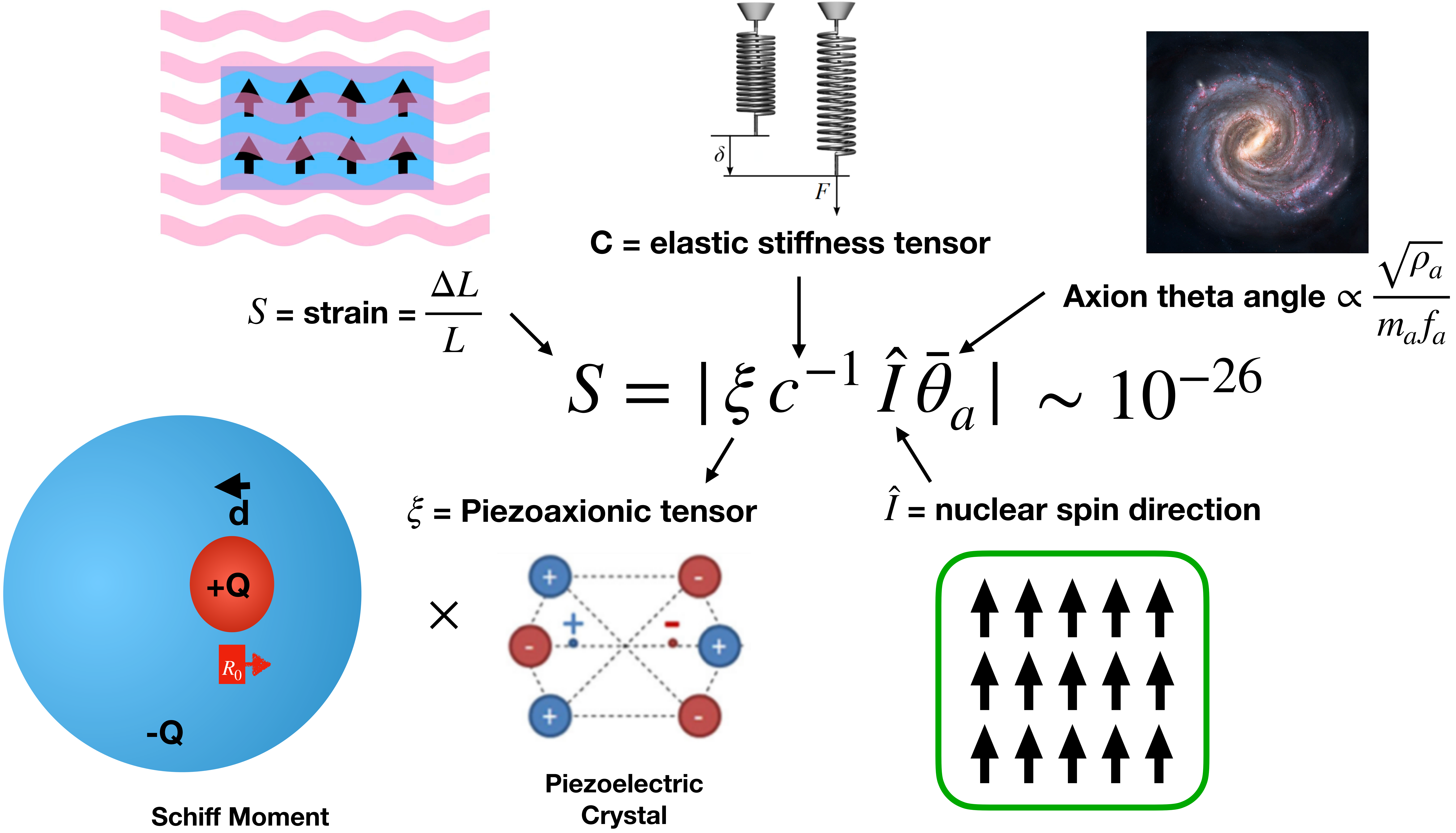

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+Q
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Schiff Moment
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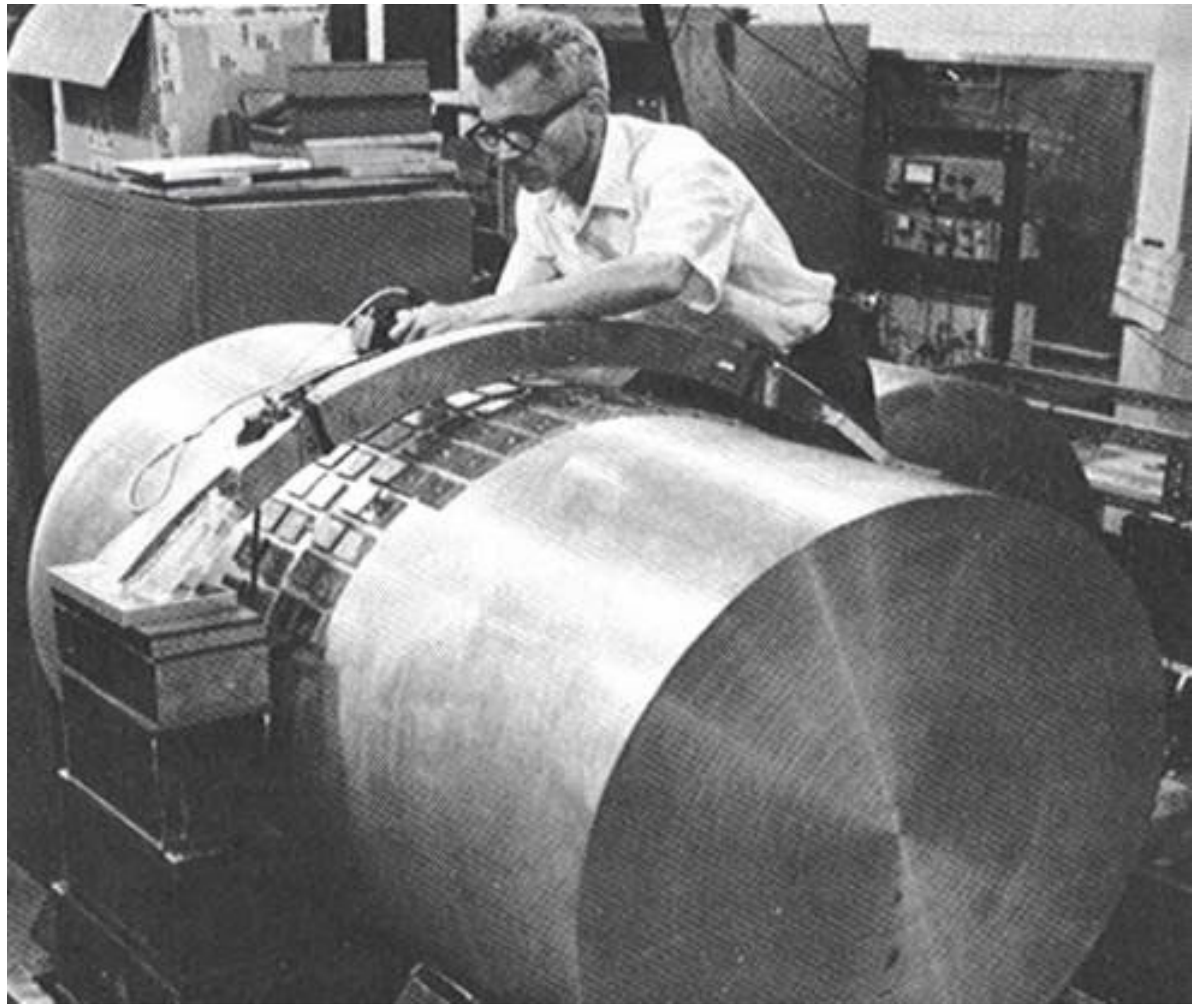
Piezoelectric Crystal

Resonant Mass Detectors



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

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

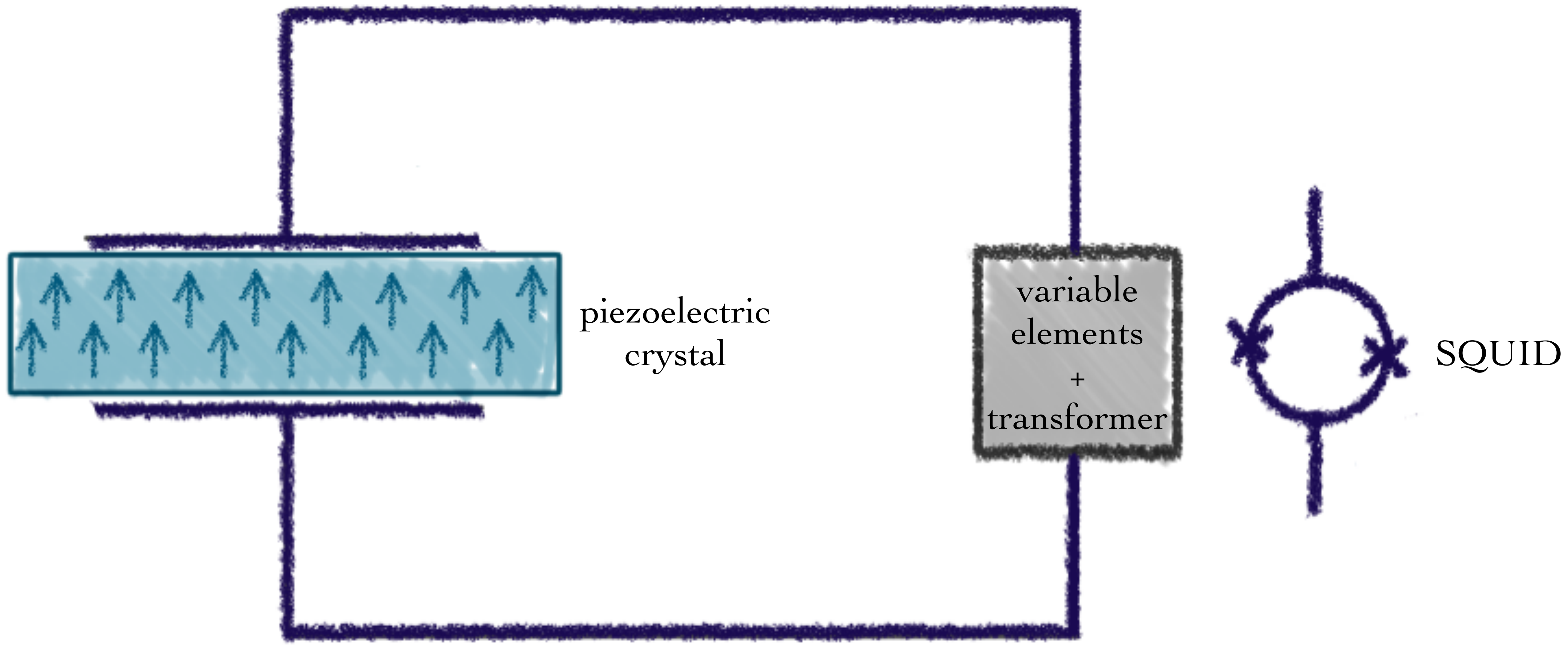
Experimental Setup

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

2. Align nuclear spins using a magnetic field

3. Cool to $\sim 1\, mK$ to reduce thermal noise

4. Oscillating voltage across crystal generates a tiny AC, measured using a SQUID



Backgrounds:

Fluctuating nuclear spins

Small effect, NMR frequency $\neq$ mechanical resonance frequency

Fluctuating magnetic impurities in material

$\lesssim$ppm

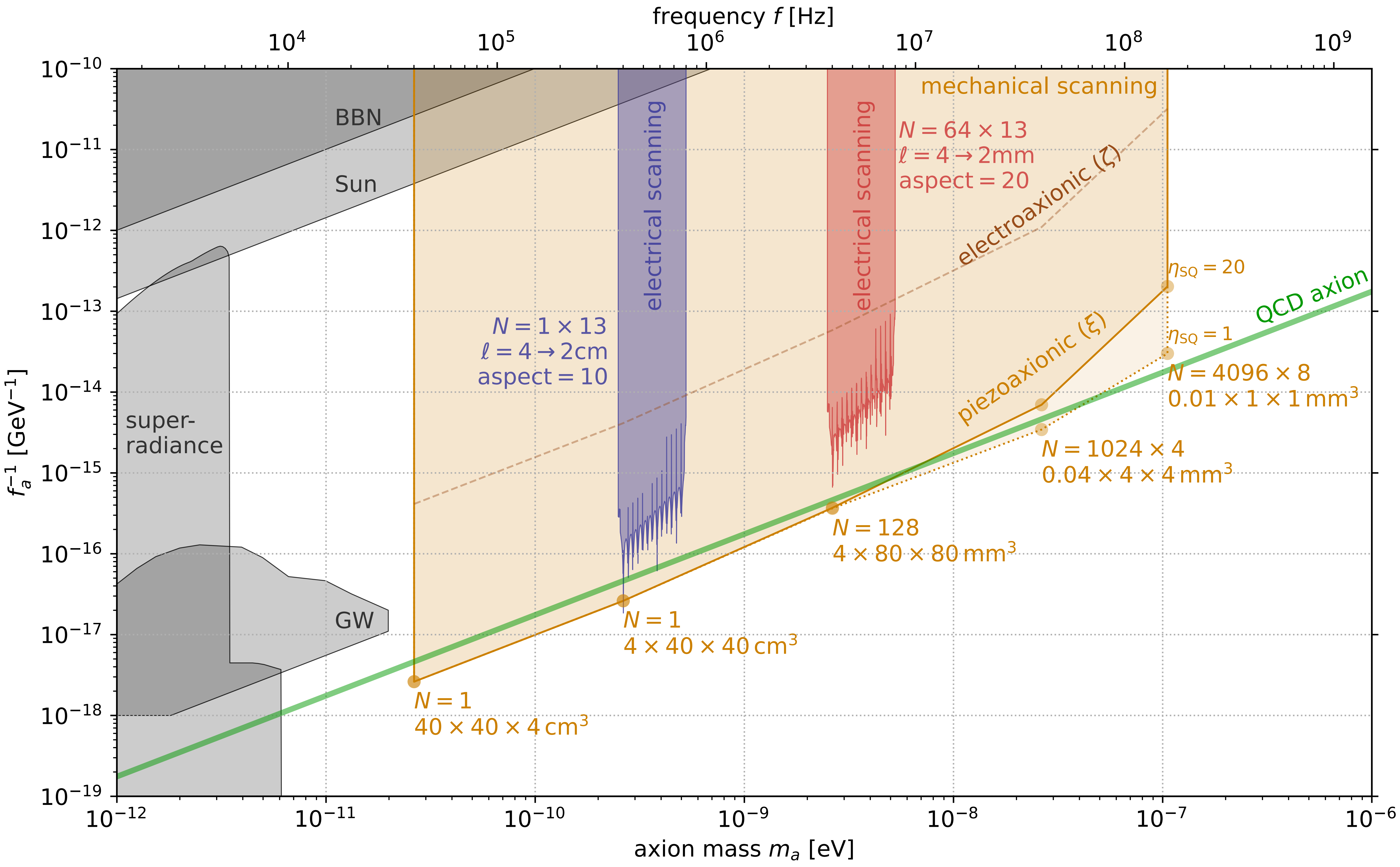
Magnetization noise $\rightarrow$ fictitious EMF

Vibrational noise
Systematic, demonstrated at AURIGA

Noise:

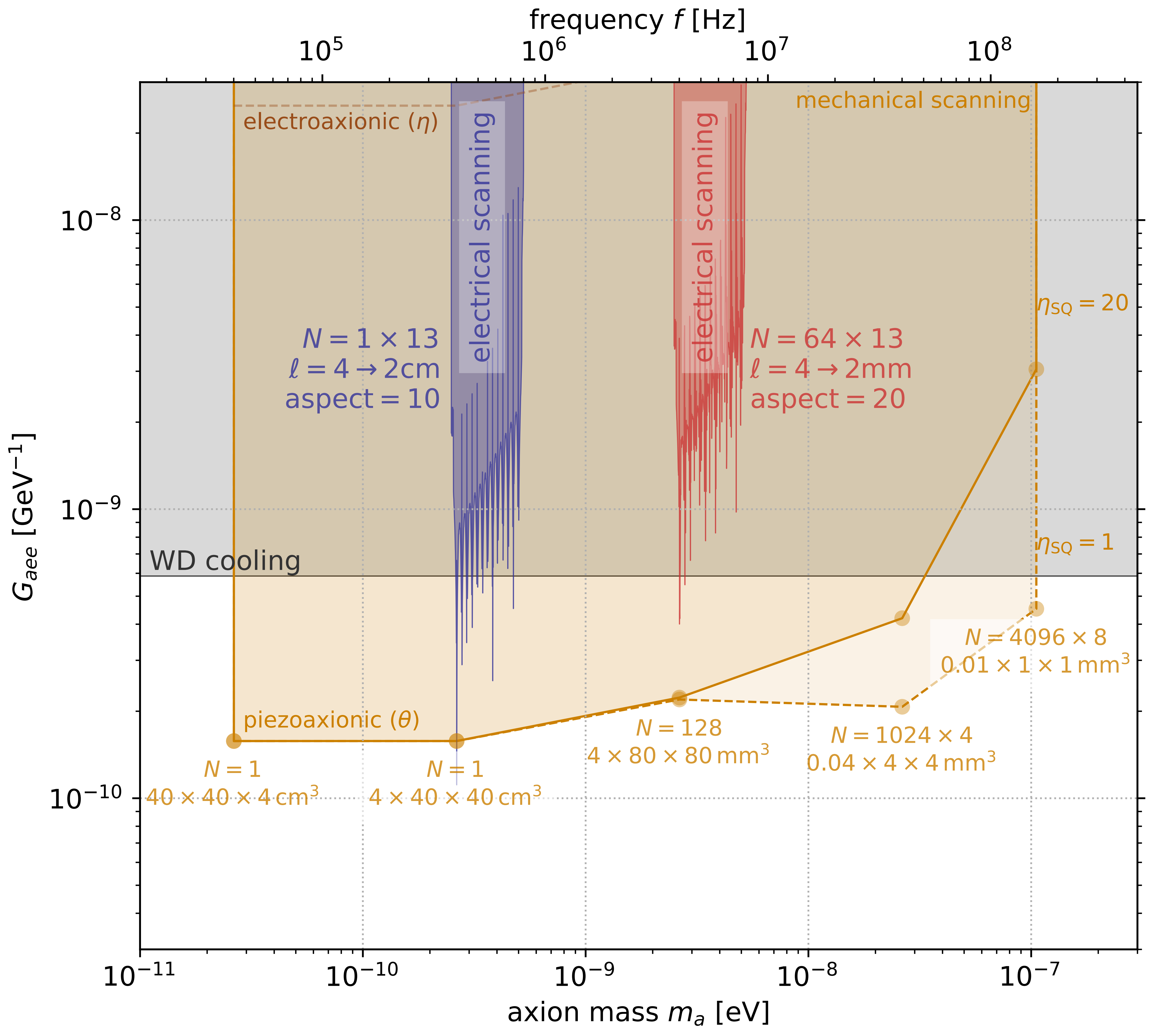
Thermal noise limited, main sources: crystal mechanical noise and SQUID noise

Idealized Forecast



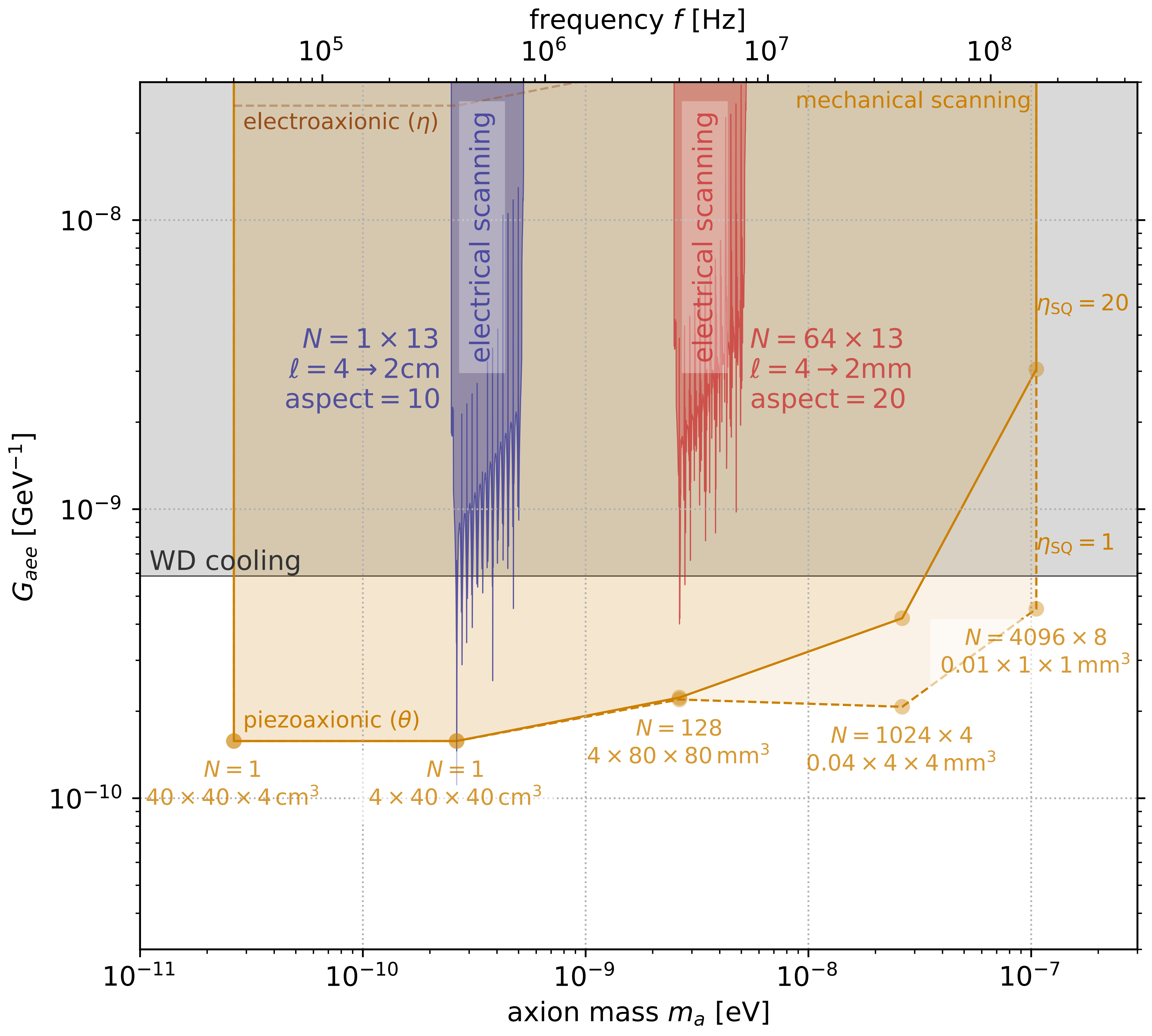
https://github.com/kenvantilburg/piezoaxionic-effect

Axion-Electron Coupling



Axion-Electron Coupling

$$H_f \simeq -\frac{G_{aff}}{2}\sigma_f \cdot \left(\nabla a + \dot{a}\frac{\mathbf{p}_f}{m_f}\right)$$



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P EVEN
T ODD

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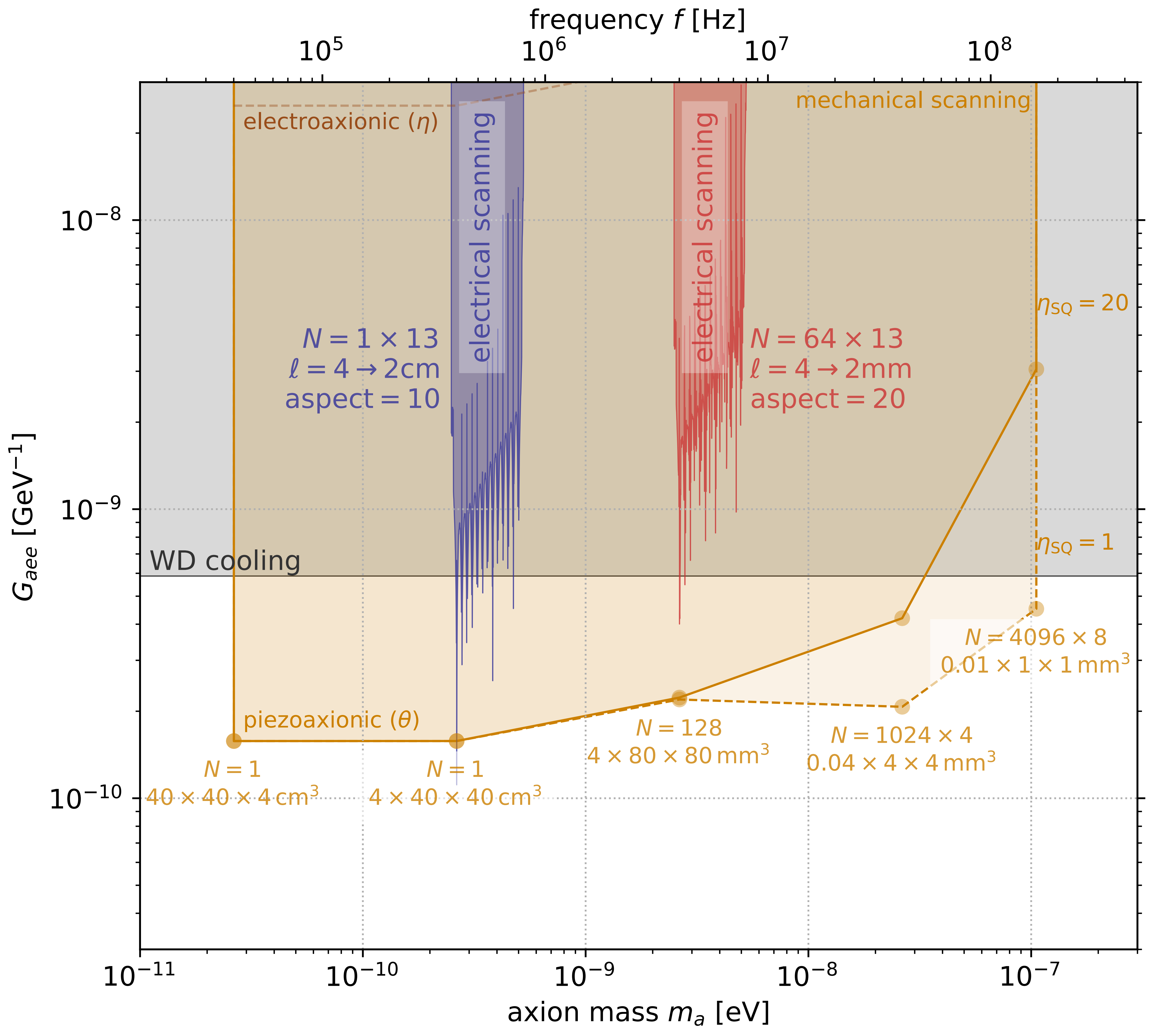
T EVEN



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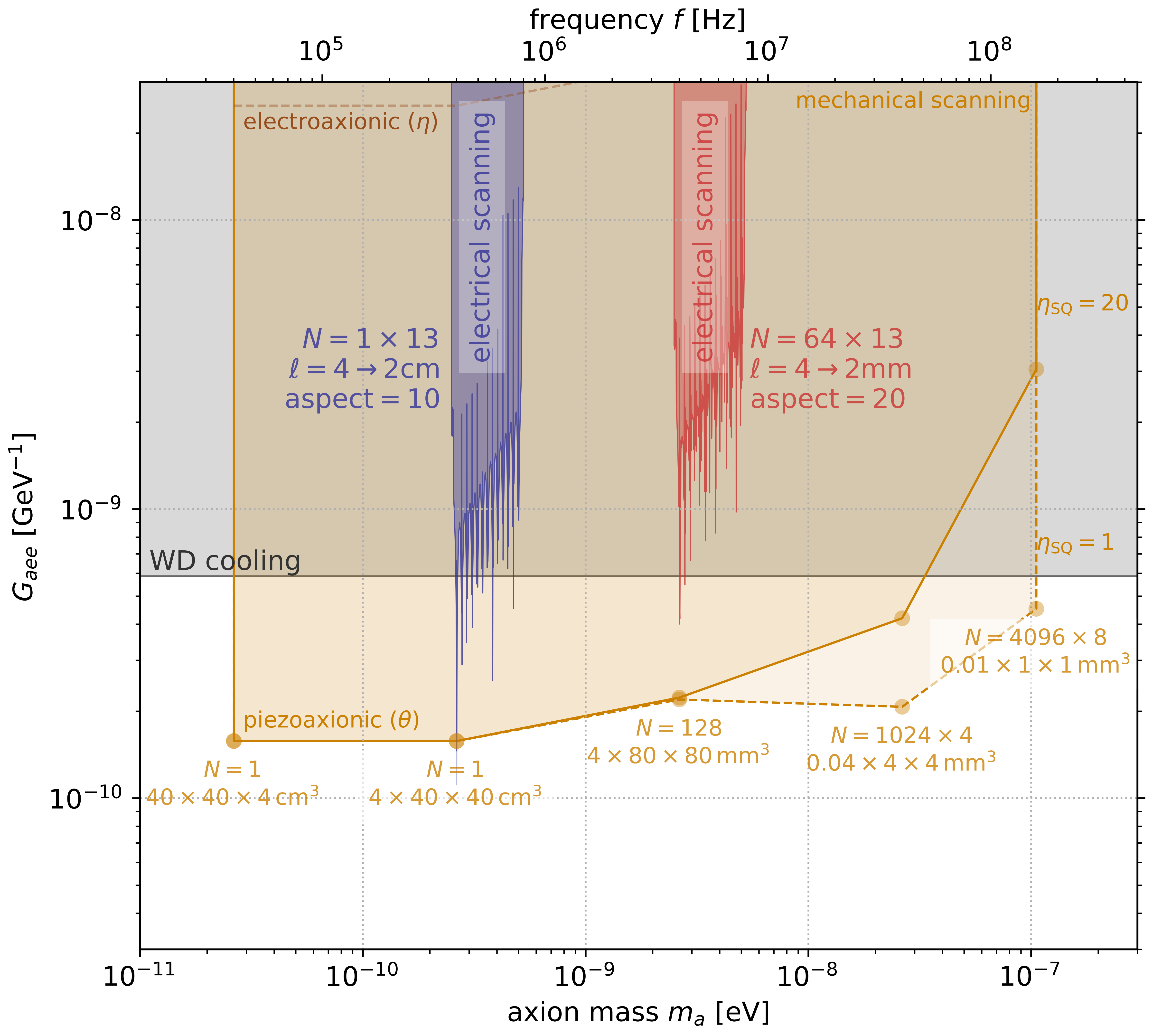
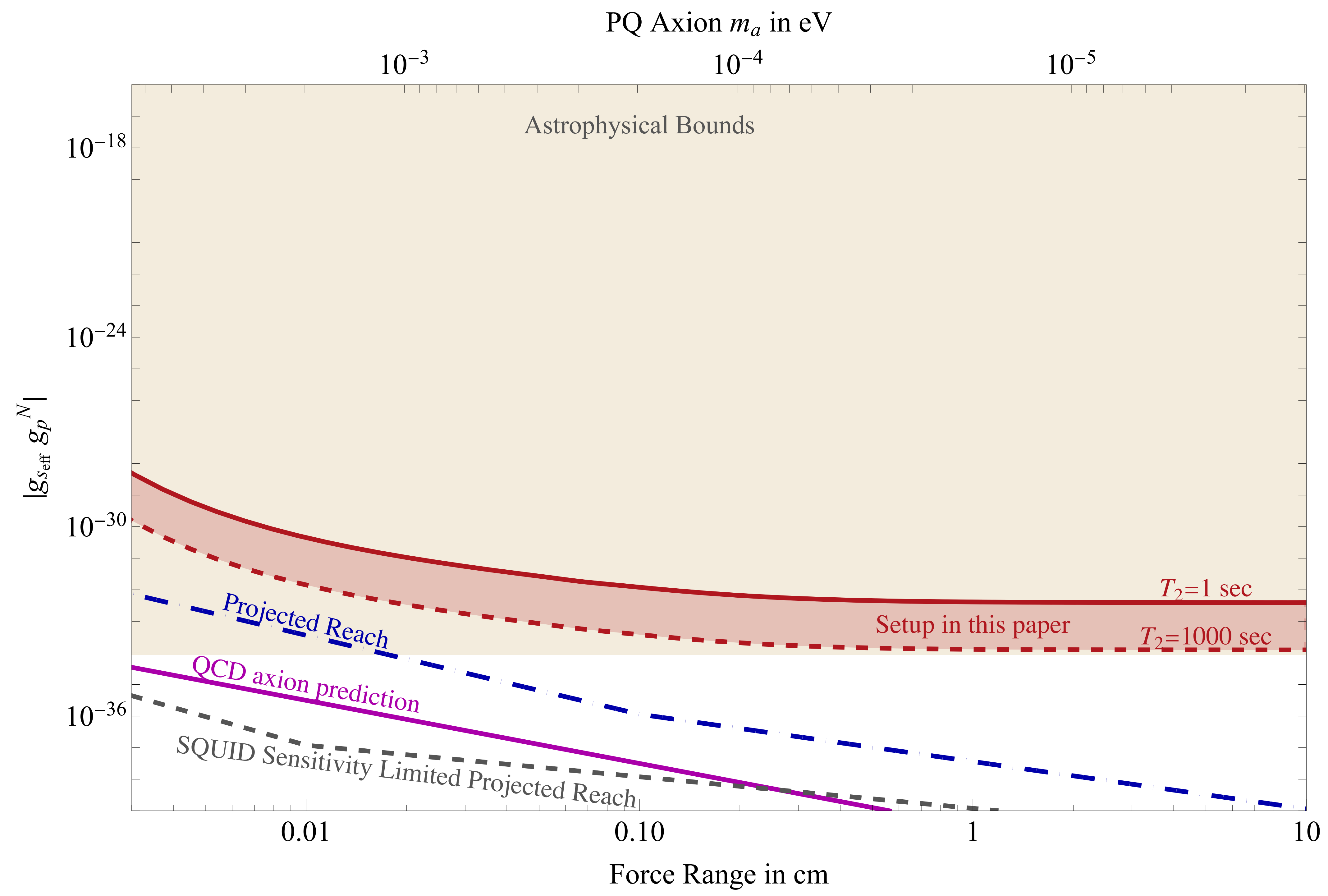
$$U \supset \sum_e \frac{\langle H_e \rangle}{V_c} = -\frac{G_{aee}\,\dot{a}}{2V_c} \sum_e \left\langle \psi_e \middle| \frac{\mathbf{p}_e \cdot \sigma_e}{m_e} \middle| \psi_e \right\rangle$$



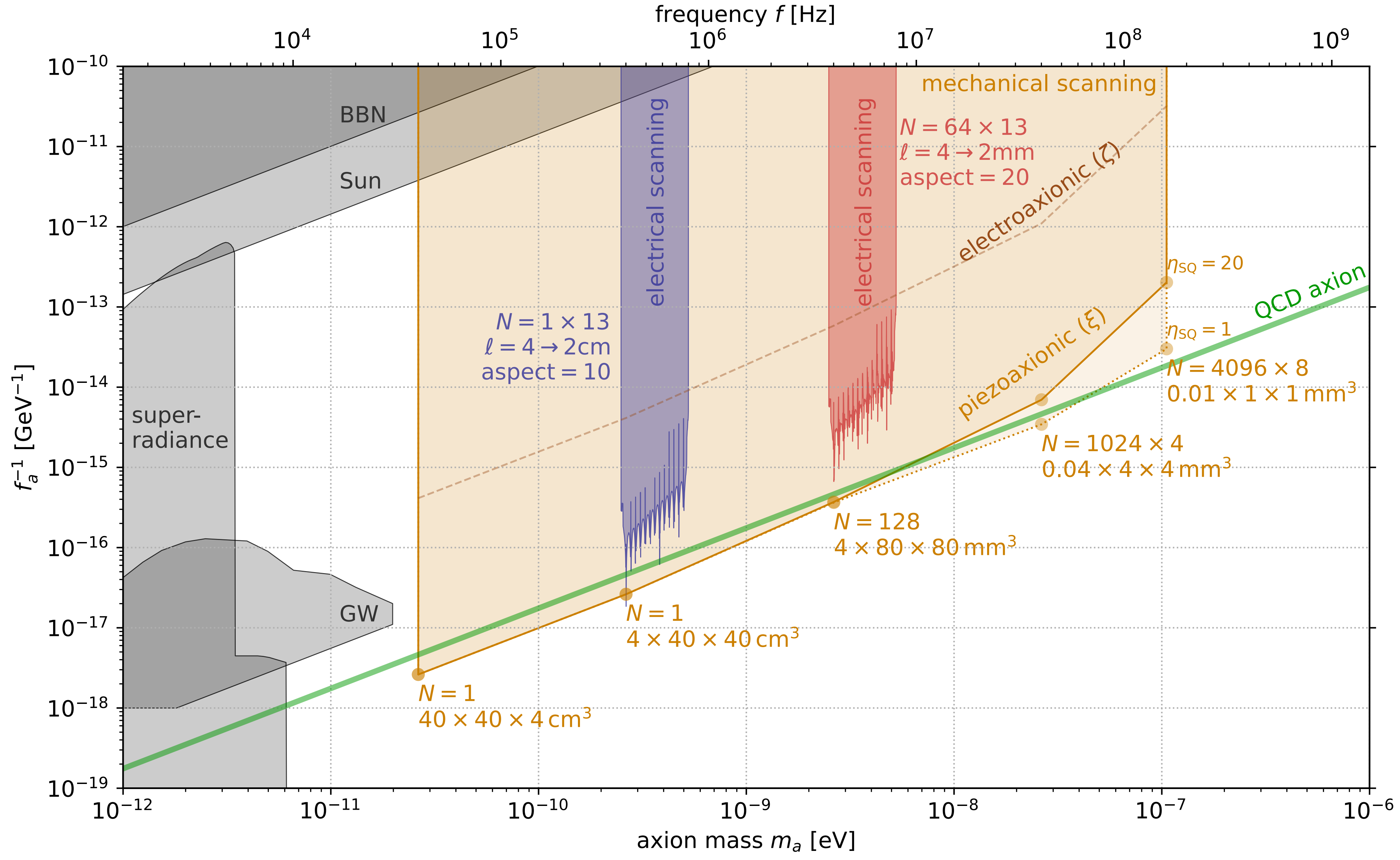
Future Directions

- Precise Schiff moment calculations for stable, octupole deformed nuclei
- Density functional theory (DFT) calculations for ξ and ζ
- Further experimental investigation into suitable materials.
- Axion mediated force experiments from piezoelectric sources (figure)



Summary

- New observable for the QCD axion that probes its model independent coupling
- Experimental set-up with sensitivity for axion masses in range $10^{-11}eV$ to $10^{-7}eV$
- Complementary to cavity experiments



Materials

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

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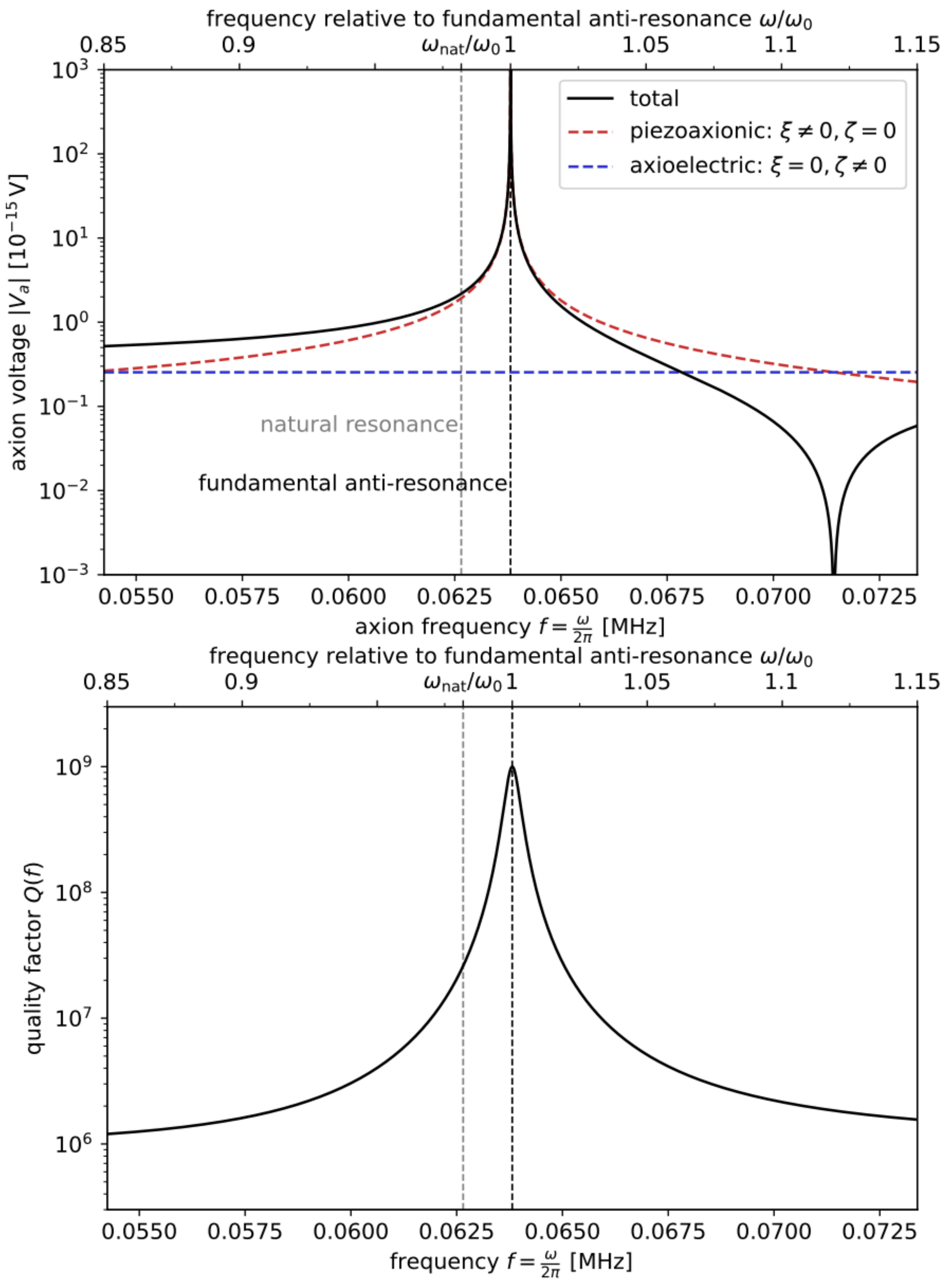
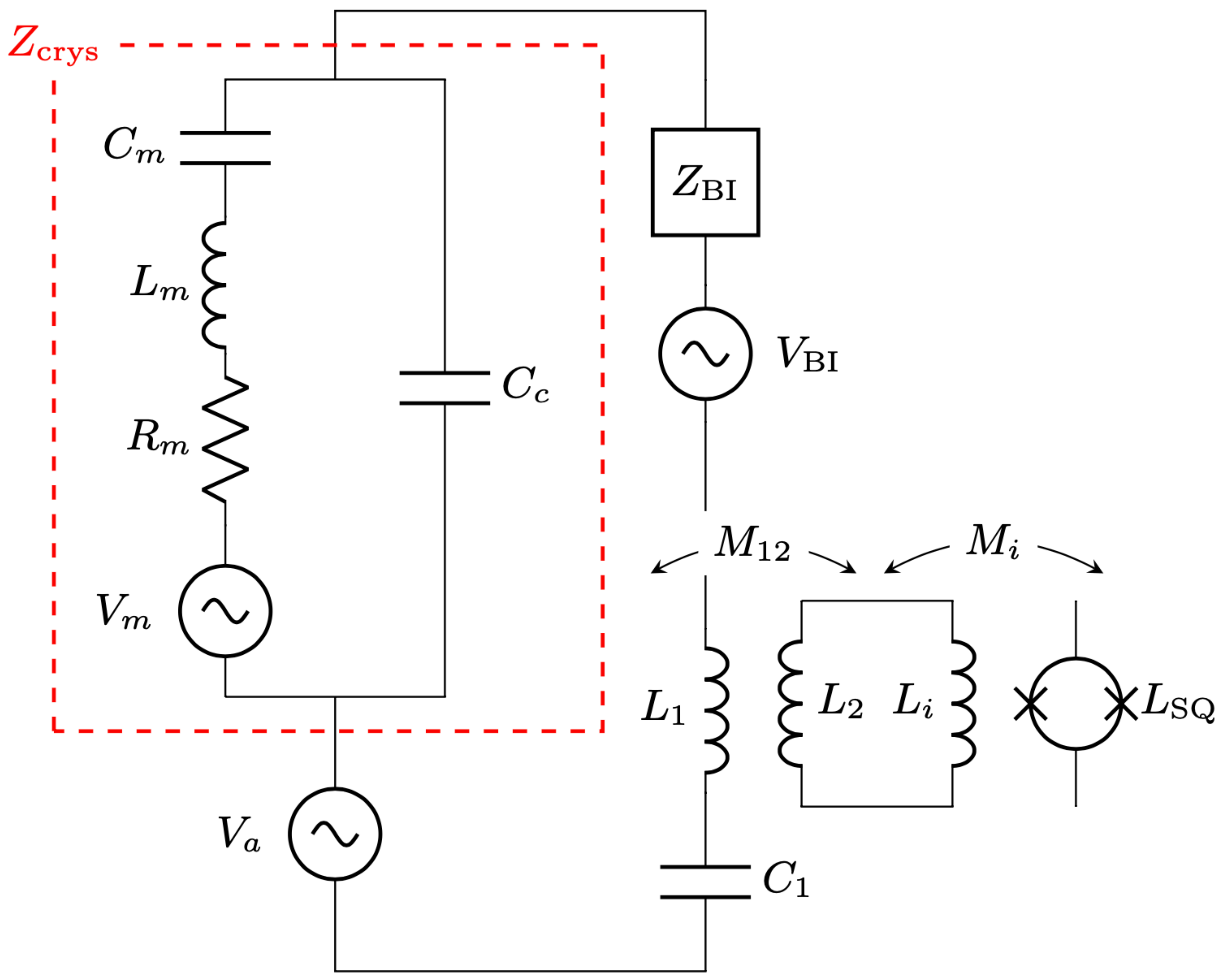
Class	Candidates	Similar Crystals
32	$Na\mathbf{Dy}H_2S_2O_9$	SiO_2 (quartz)
		$Ga_5La_3SiO_{14}$ (langasite)
	$\mathbf{Bi}PO_4$	$GaPO_4$ (gallium orthophosphate)
$\bar{3}$m	$\mathbf{U}(CuAs)_2$	tourmaline
	$\mathbf{Dy}_2SO_2$	$LiNbO_3$ (lithium niobate)
	$\mathbf{Dy}OF$	$LiTaO_3$ (lithium tantalate)
4mm	$\mathbf{Dy}Si_3Ir$	$Li_2B_4O_7$ (lithium tetraborate)
	$\mathbf{Dy}AgSe_2$	
$\bar{4}$2m	$\mathbf{Dy}AgTe_2$	NH_6PO_4 (ADP)
	$\mathbf{Dy}_2Be_2GeO_7$	KH_2PO_4 (KDP)
mm2	$\mathbf{U}CO_5$	$Ba_2NaNb_5O_{15}$ (barium sodium niobate)

Database: https://materialsproject.org/

Scanning





- Monitor all harmonics of a given mode
- Vary electrical resonance frequency using capacitor and inductor