The Piezoaxionic Effect

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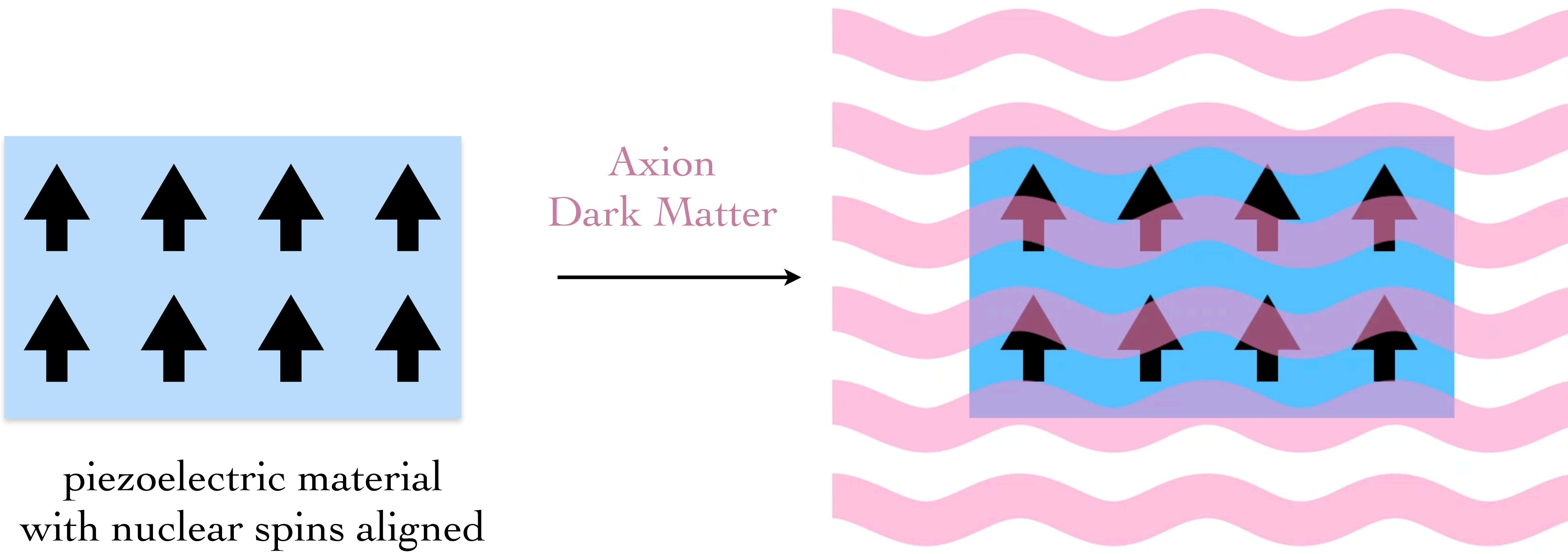
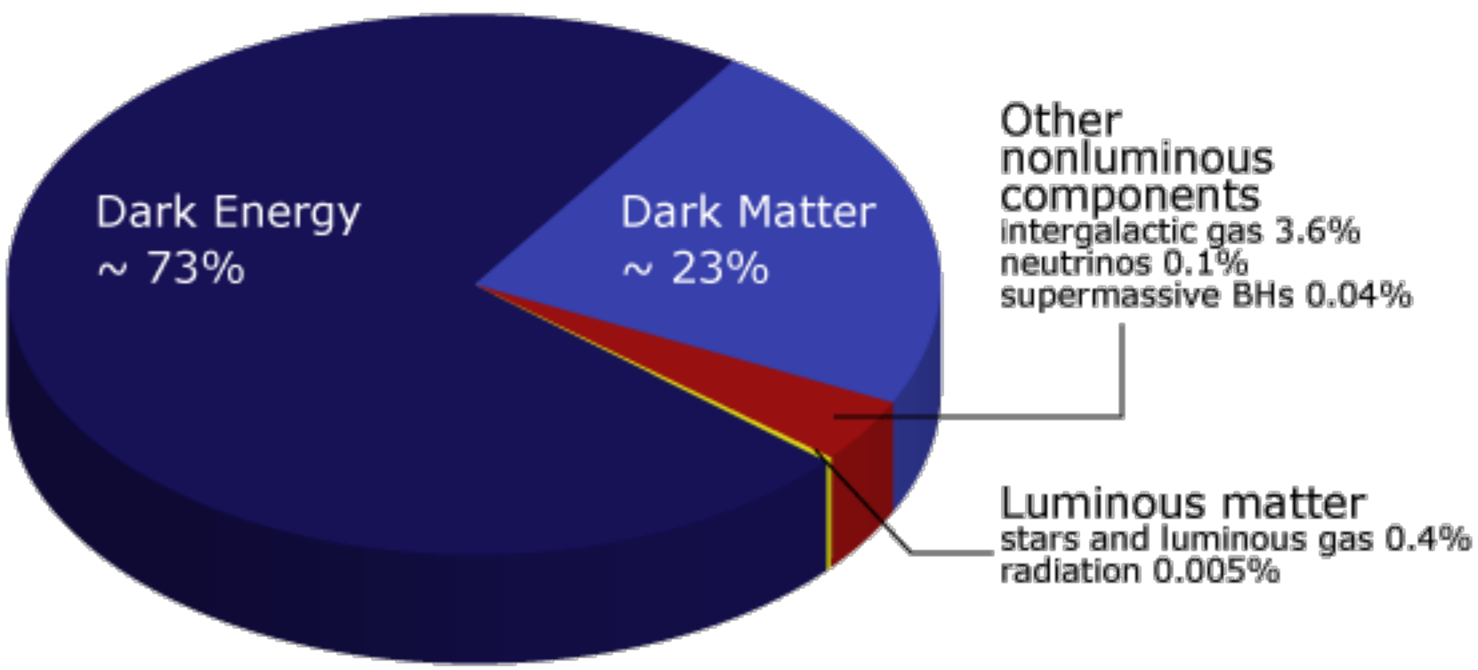
Perimeter Institute For Theoretical Physics

based on work with Amalia Madden,
and Ken Van Tilburg

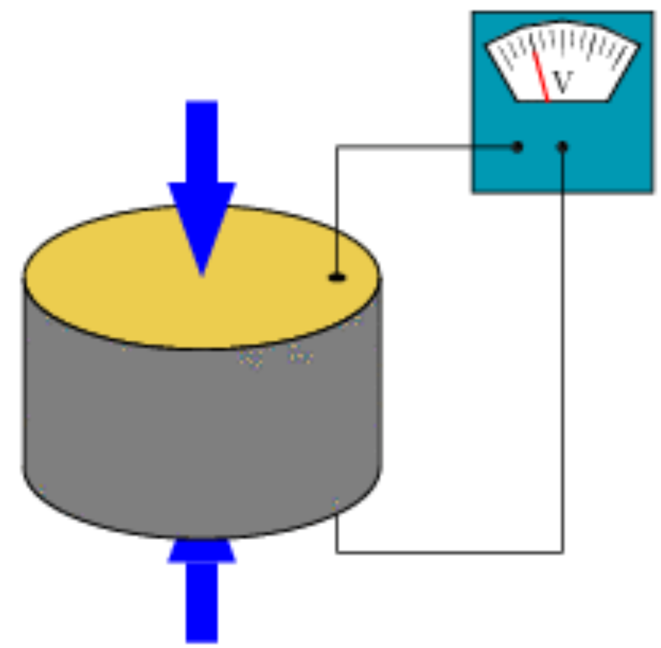
The Piezoaxionic Effect



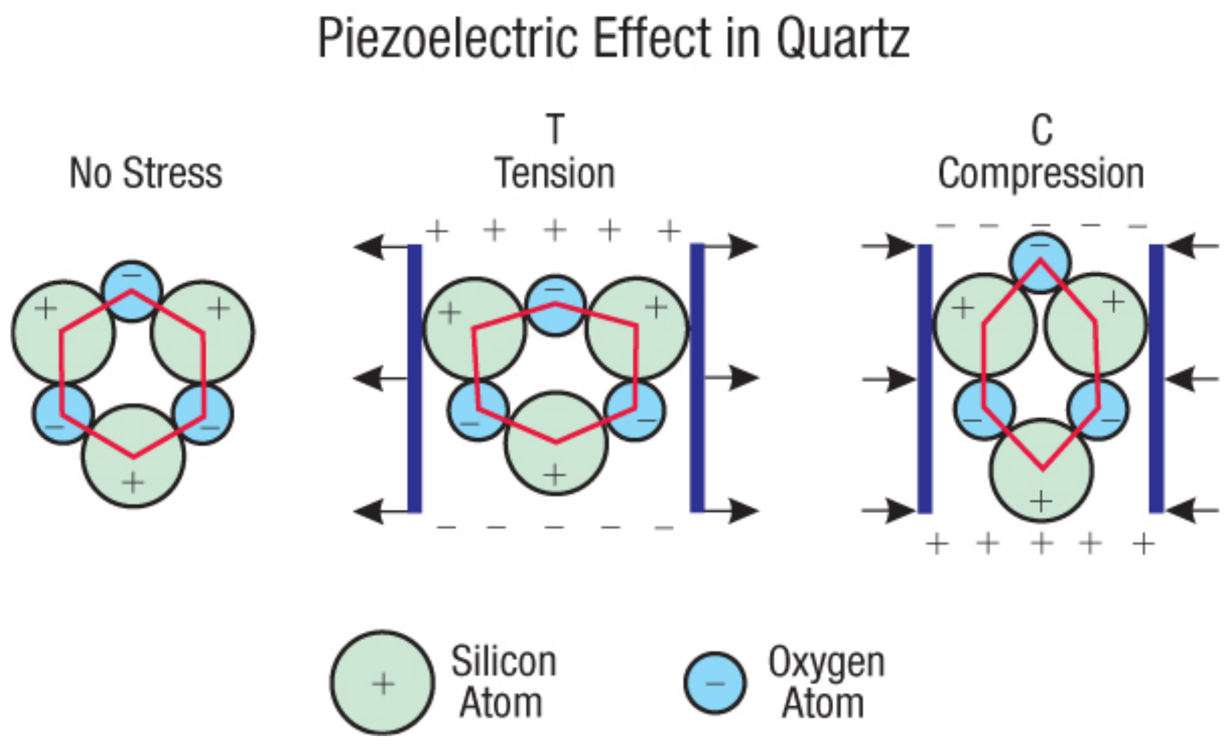
Dark Matter

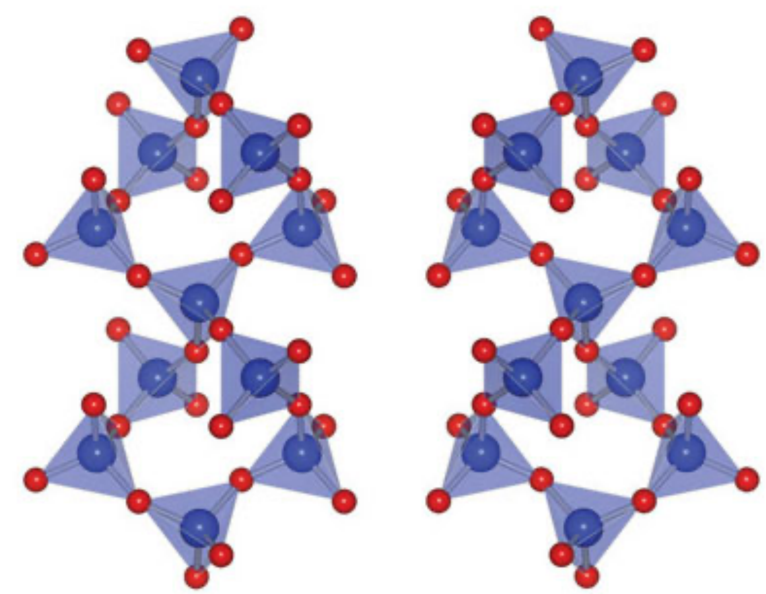


Piezoelectricity



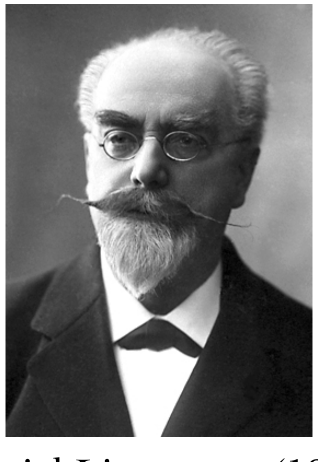
Piezoelectricity in crystals that break mirror (or parity) symmetry





α-quartz left-handed

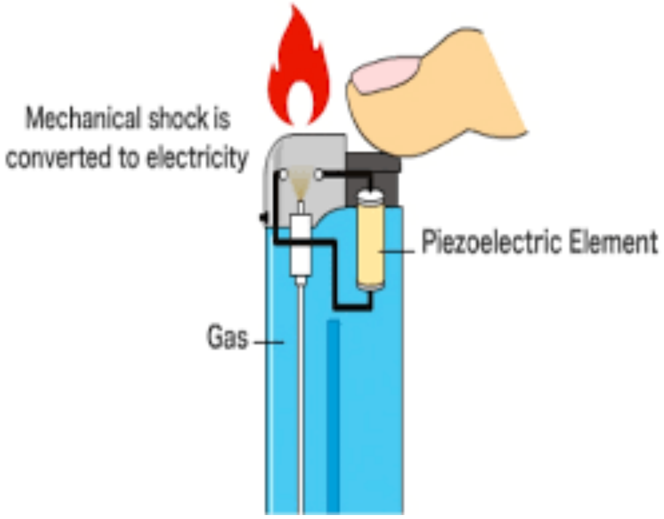
α-quartz right-handed



Gabriel Lippmann (1881)

Jacques and Pierre Curie (1880 and 1881)

Piezoelectricity applications



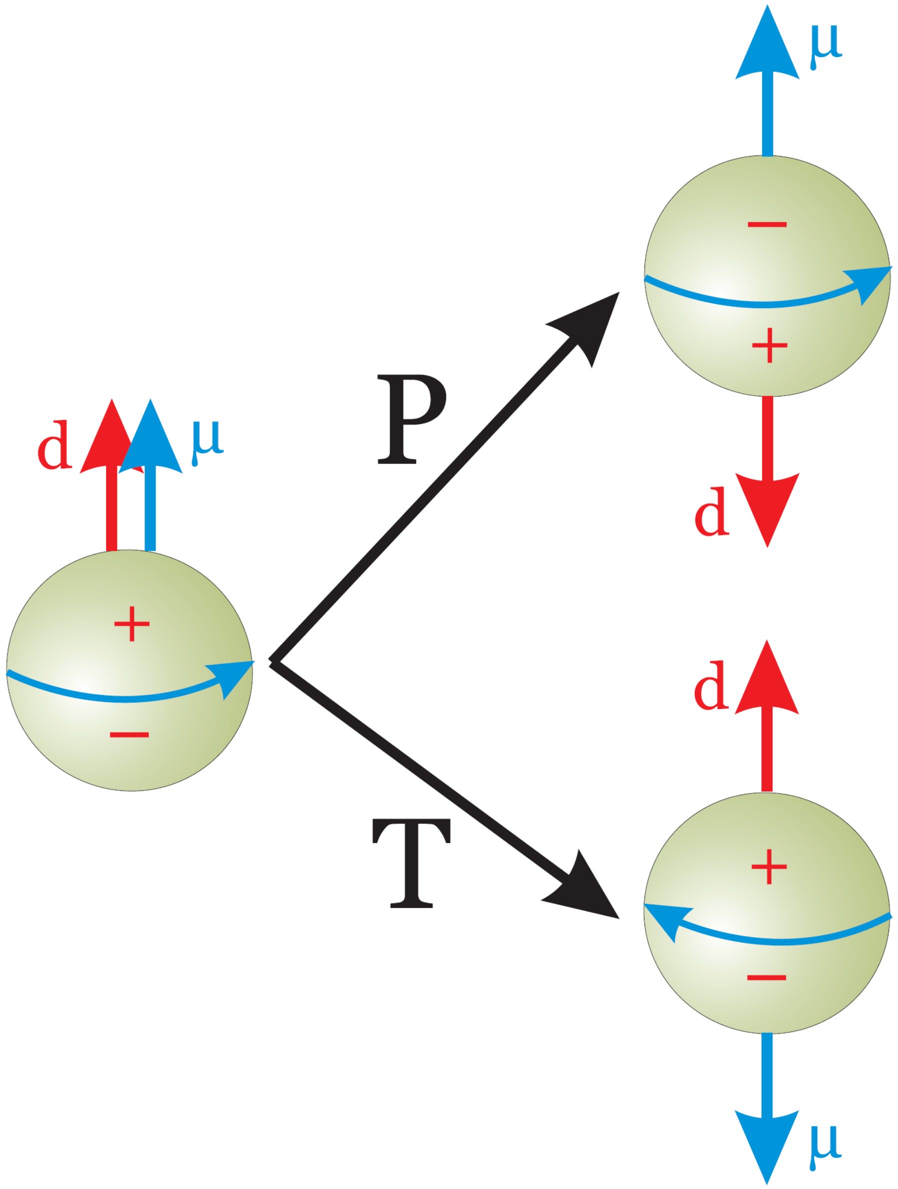
Outline

- Axions as parity odd dark matter
- The piezoaxionic effect

Fundamental electric dipole moment

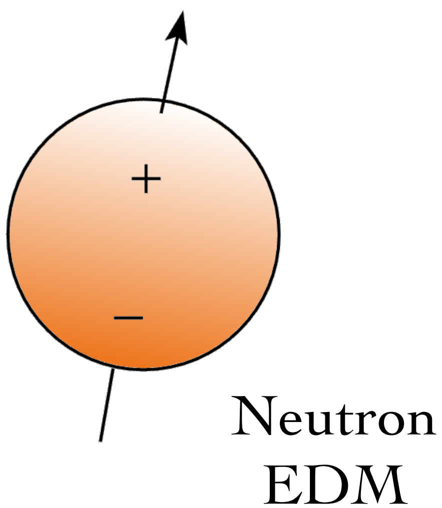
- An electric dipole moment (EDM) for an elementary particle violates both parity and time-reversal symmetries

- In the Standard Model the expectation is that the neutron has an EDM.



Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

Experimental bound: $\theta_s < 10^{-10}$

Solution:
θ_s ~a(x,t) is a dynamical field, an axion

Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-11} \text{ eV } \frac{10^{17} \text{ GeV}}{f_a} \sim (3 \text{ km})^{-1} \frac{10^{17} \text{ GeV}}{\mathrm{f_a}}$$

f_a : axion decay constant

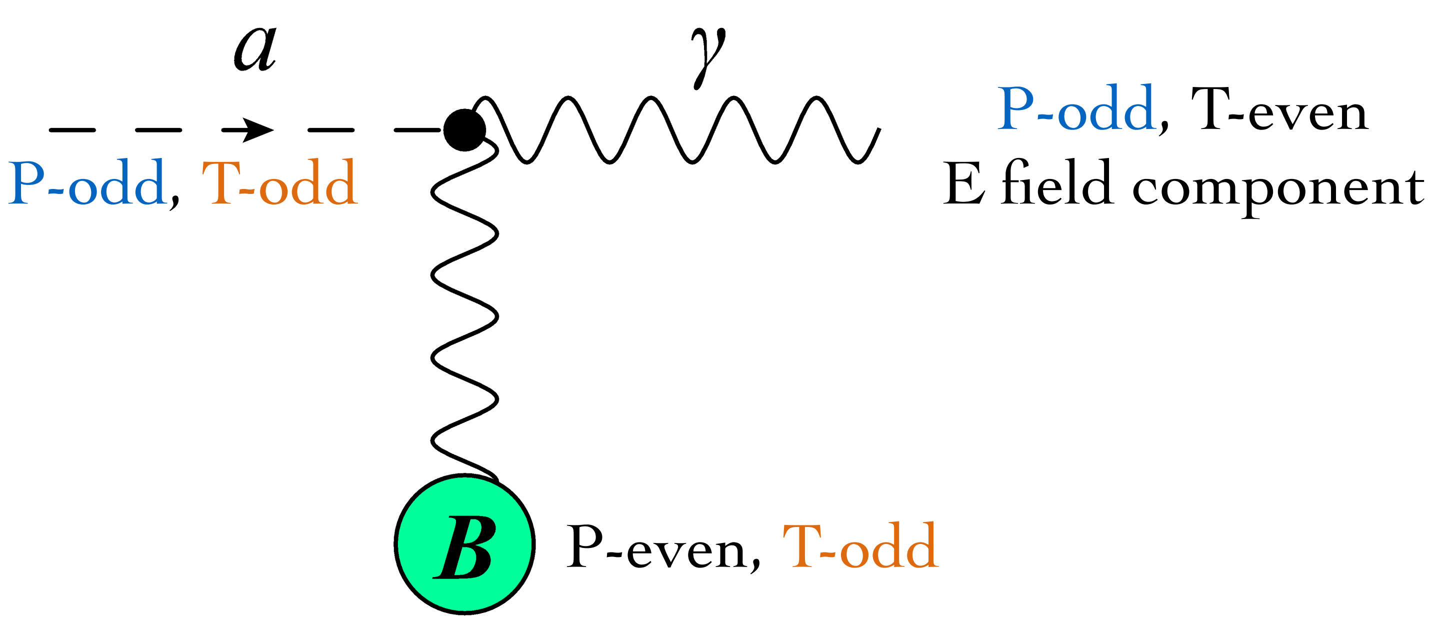
Mediates new forces and can be the dark matter

Symmetry properties of the axion

- The electric dipole moment is a P-odd and T-odd quantity
- The axion is a P-odd and T-odd particle
- Axion dark matter creates a P-odd and T-odd background

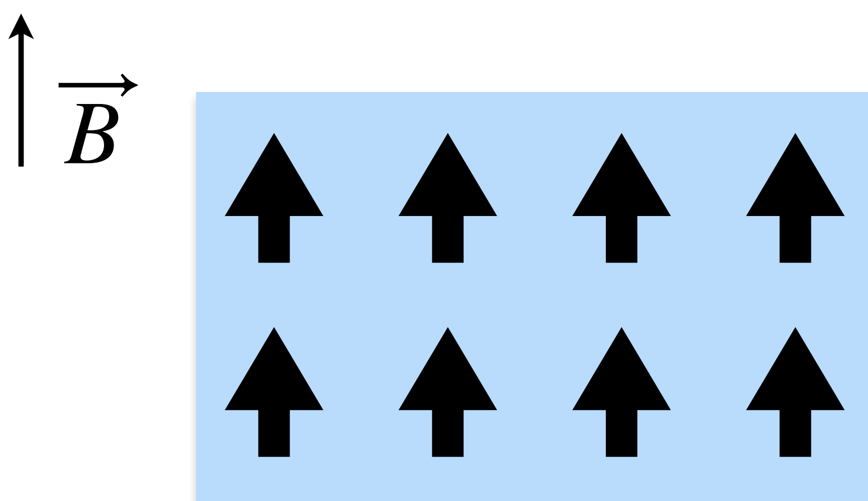
Axion Dark Matter

- Axion DM produces a time-dependent P and T violating background



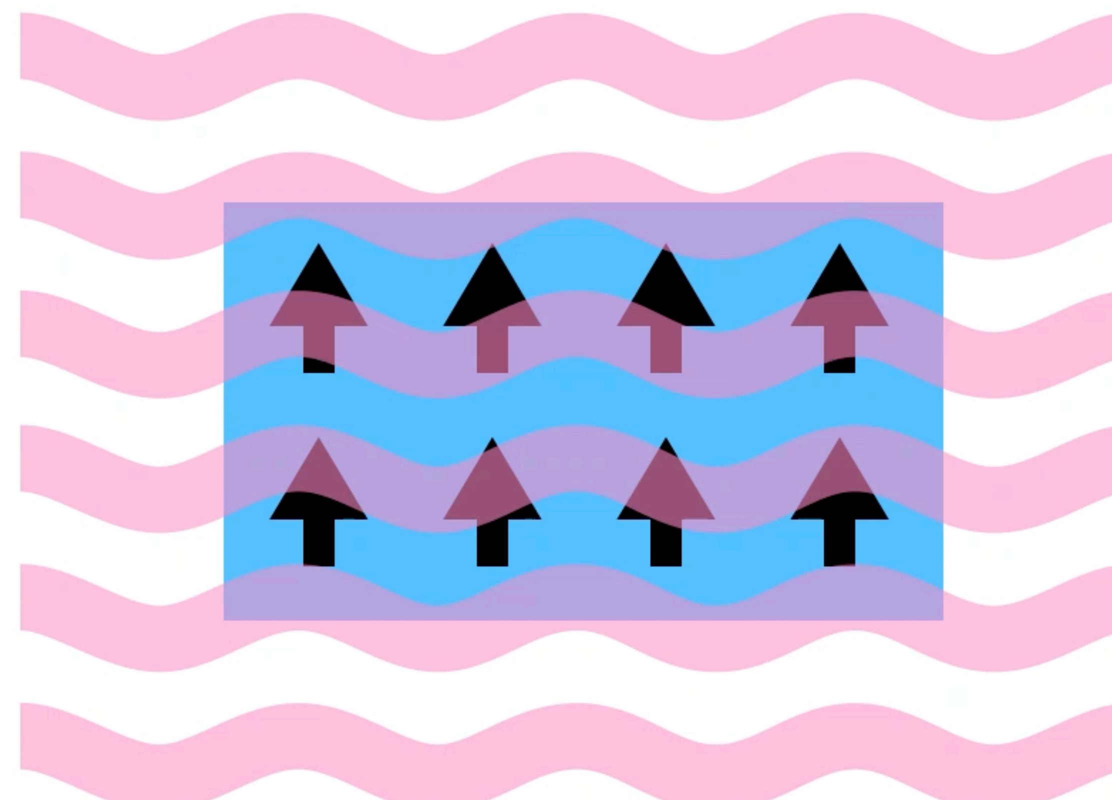
The piezoaxionic effect

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



P-odd
piezoelectric material
with nuclear spins aligned (T-odd)

P-odd, T-odd
Axion DM
background



Produces P- and T-even stress and
ultimately strain

Outline

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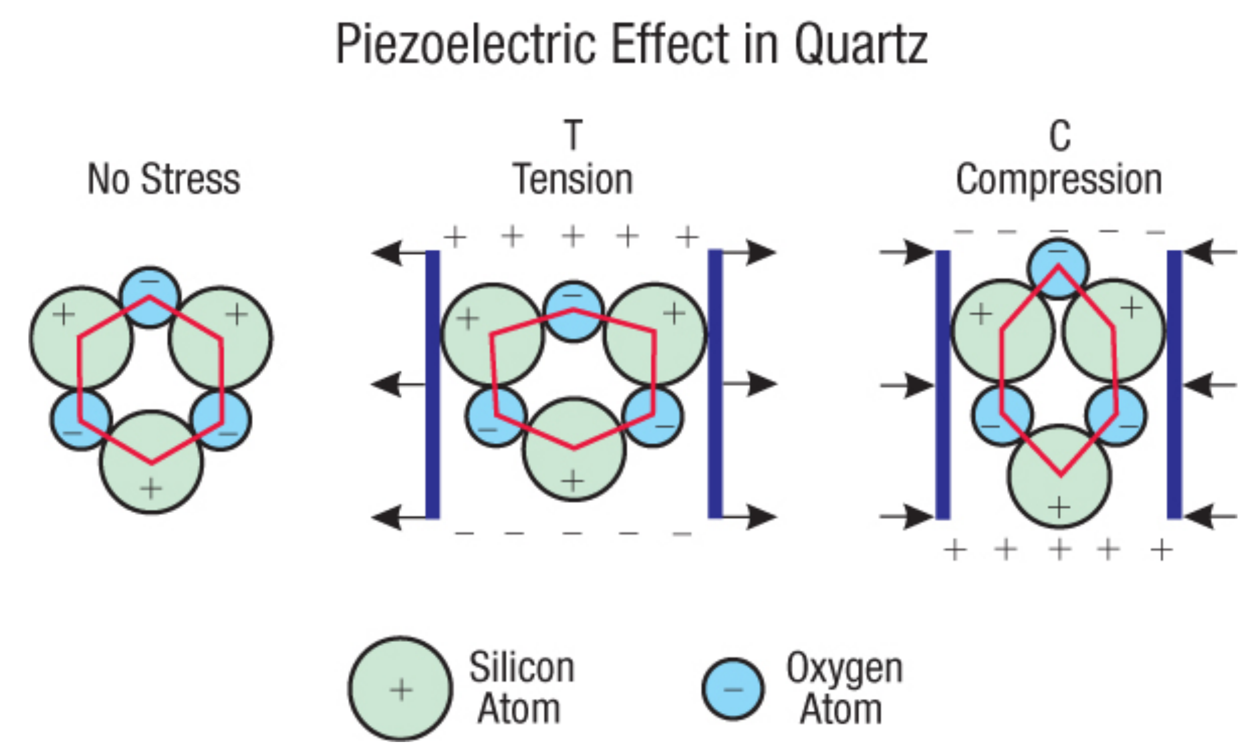
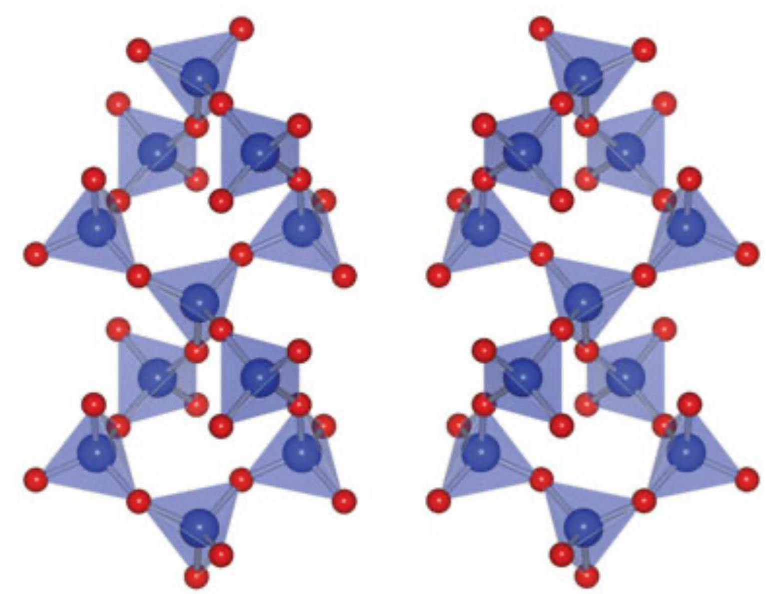
The piezoaxionic effect





α-quartz left-handed

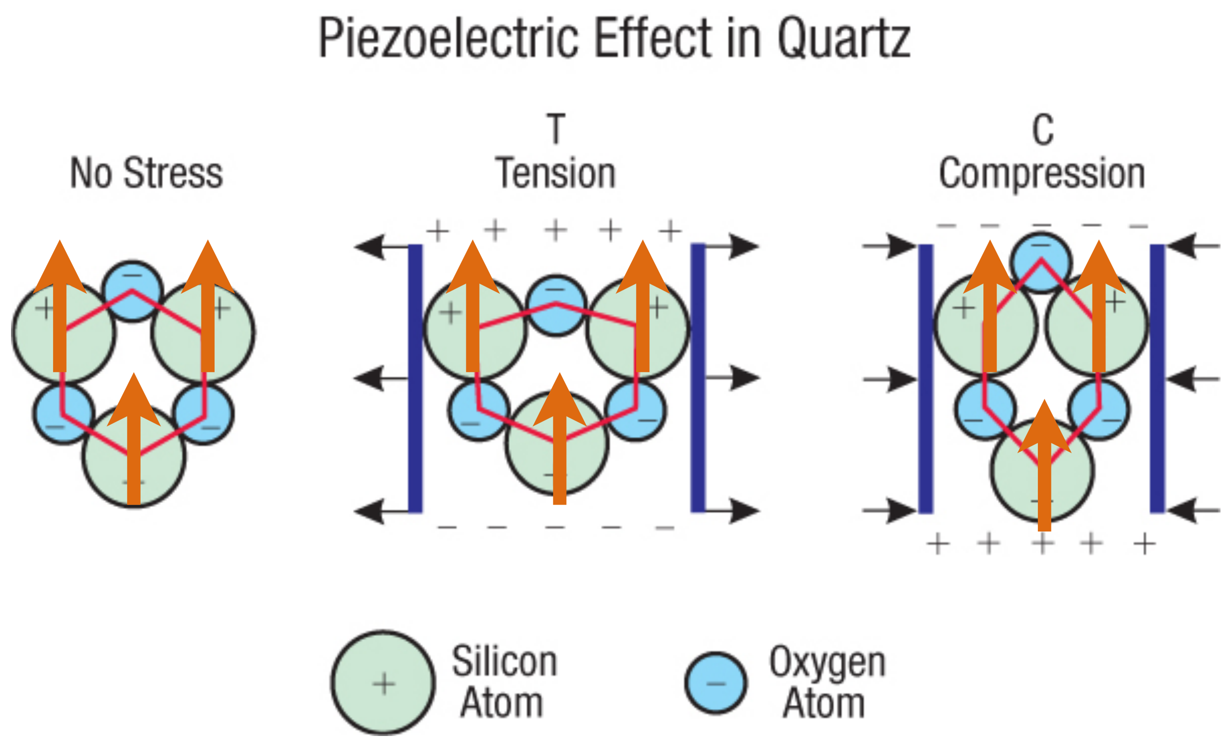
α-quartz right-handed

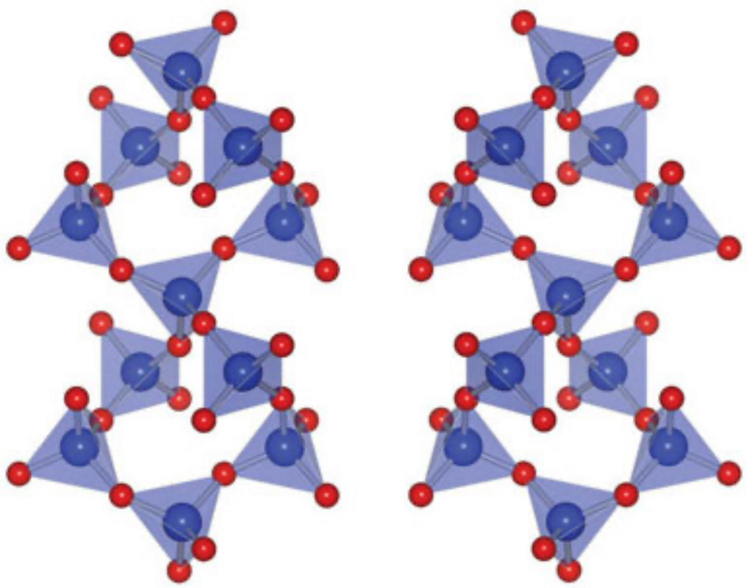
- In a piezoelectric an displacement field (D) leads to stress(T) and strain(S) leads to an electric field (E)

$$T = cS + \boxed{eD}$$

$$E = \epsilon D + \boxed{eS}$$

The piezoaxionic effect





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left-handed

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right-handed

- In nuclear spin polarized (P) piezoelectric material the axion field (θ_a) also leads to stress and an electric field (E)

$$T = cS + eD - \xi P\theta_a(t)$$ ξ: Piezoaxionic tensor

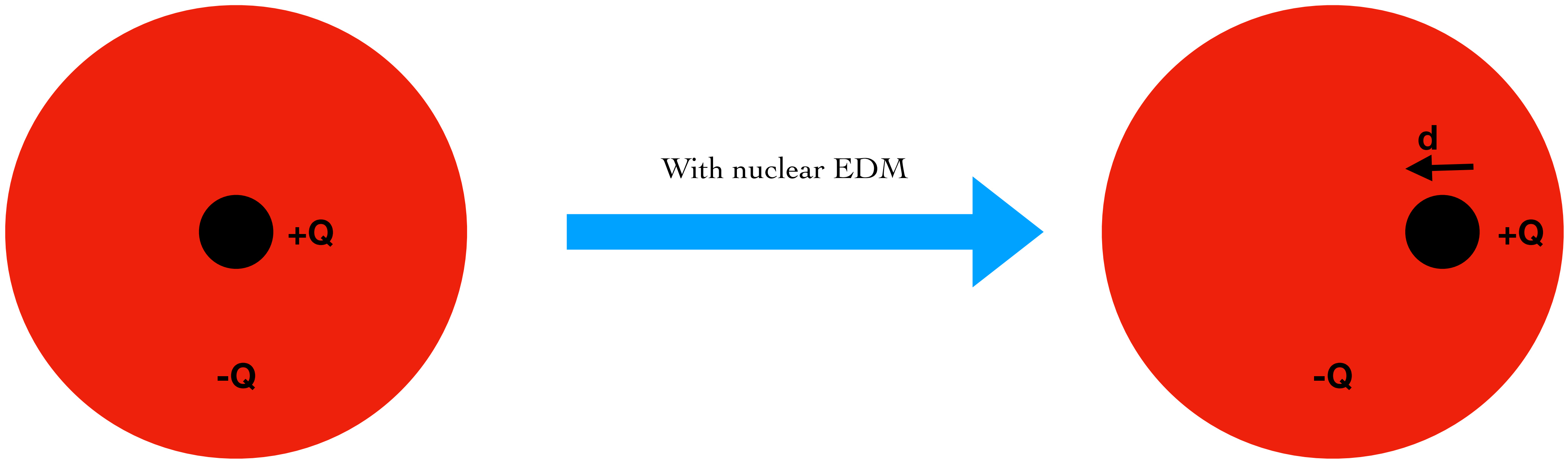
$$E = \epsilon D + eS + \zeta P\theta_a(t)$$ ζ :electroaxionic tensor

- Need the nuclear spins to preserve T-symmetry

How do we go from the nucleons, to the nucleus, then to the atom and eventually to the crystal to calculate ξ?

Where does the piezoaxionic constant ξ come from?

- In an atom, first P and T violating moment: electric octuple moment
  For nuclei, this is the Schiff moment



Where does the piezoaxionic constant ξ come from?

- Schiff moment generated by $\theta_a G\tilde{G}$, i.e. the axion coupling to gluons and is maximized in deformed nuclei

$$S \sim e\theta_a \frac{\eta_N}{m_N} R_0^2 \propto A^{2/3} \quad \text{for non-deformed nuclei}$$

$$S \propto Z\, A^{2/3} \qquad \text{for deformed nuclei}$$

Where does the piezoaxionic constant ξ come from?

- Energy shift for the atom: $\delta H \sim \langle \psi_{\text{atom}} | -4\pi \vec{S} \cdot \vec{\nabla} \delta(r_e) | \psi_{\text{atom}} \rangle$
- For a free atom, ψ_{atom} has fixed parity so $\delta H = 0$
- In a piezoelectric crystal, $|\psi_{\text{atom}}\rangle = \epsilon_s |\text{P-even}\rangle + \epsilon_p |\text{P-odd}\rangle$

$$\langle \delta H \rangle \sim 10^{-26}\ \text{eV}\ \epsilon_s \epsilon_{p_i}\ P^i\ \mathscr{M}\ \frac{\bar{\theta}}{4 \times 10^{-19}} \cos(\omega_a t)$$

ϵ_s :the s-orbital admixture of valence electron

ϵ_{p_i} :the p-orbital admixture of valence electron

P^i :nucleus polarization normalized to 1

$\mathscr{M}$:matrix element involving angular averaging

$\bar{\theta}$: axion displacement angle

From the Atom to the Crystal

- Calculate axion contribution to the the energy density of the crystal, expanding around the ground state

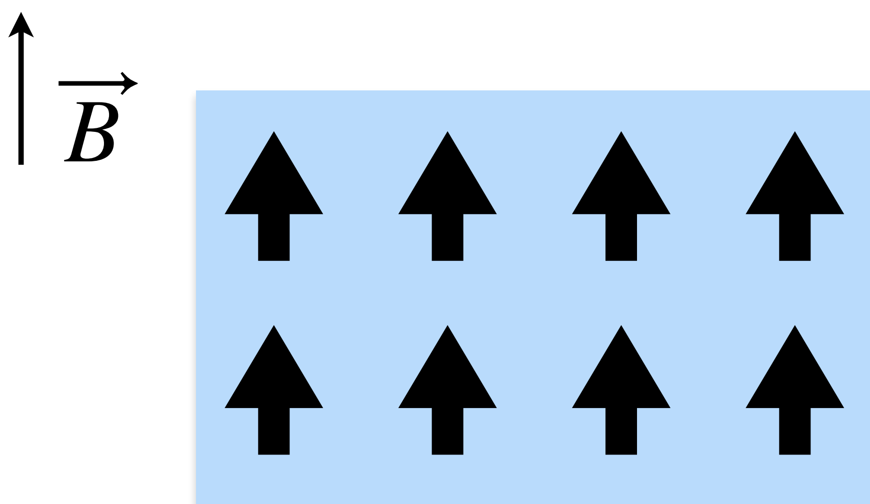
- Piezoaxionic tensor $\sim \frac{\langle \delta H \rangle}{V_{cell}} \times \tilde{\xi}$

- $\tilde{\xi}$ is $\mathcal{O}(1)$, depends crystal properties and is larger for crystal with larger piezoelectric constant

- The piezoaxionic effect is maximized in material that are dense, with large piezoelectric constants, and nuclei with large Schiff moments

The piezoaxionic effect signal

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



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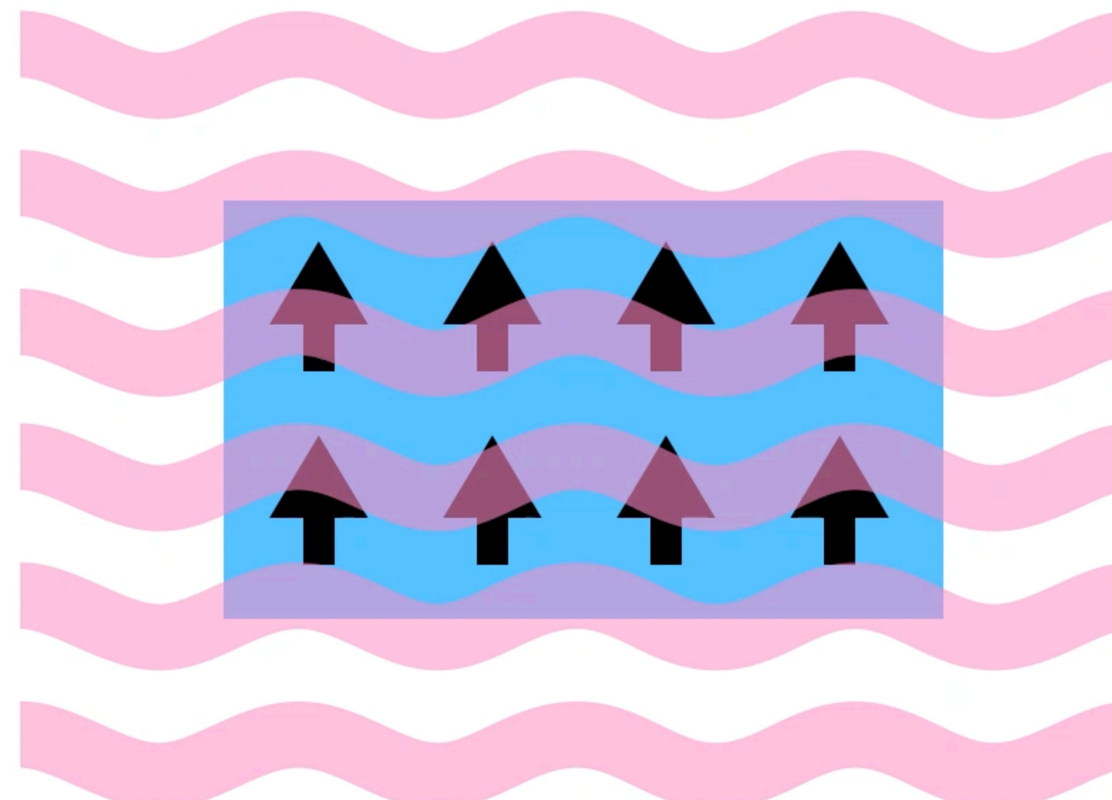


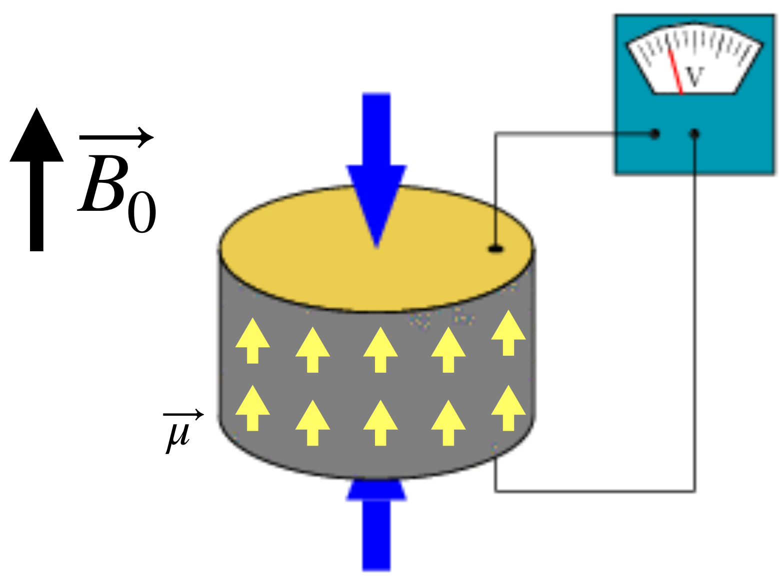
Produces P- and T-even stress and ultimately strain

QCD axion equivalent strain:

$$\sim 3 \times 10^{-26} \frac{S}{\theta_a e \times \mathrm{fm}^3} \frac{\tilde{\xi}}{1} \cos m_a t$$

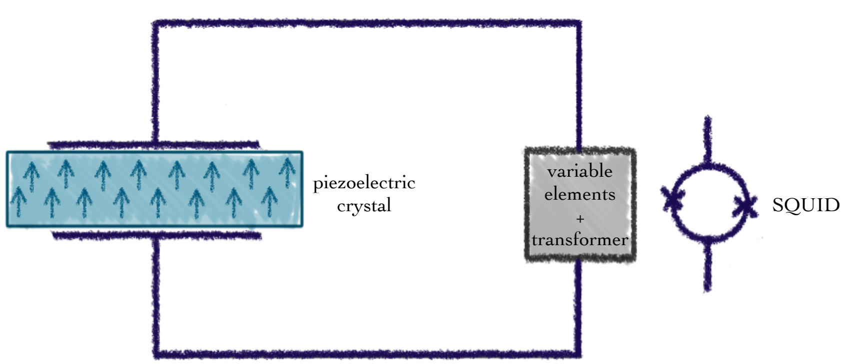
This is really small…

Experimental Set-Up



- Piezoelectric material with elements with nuclear spins

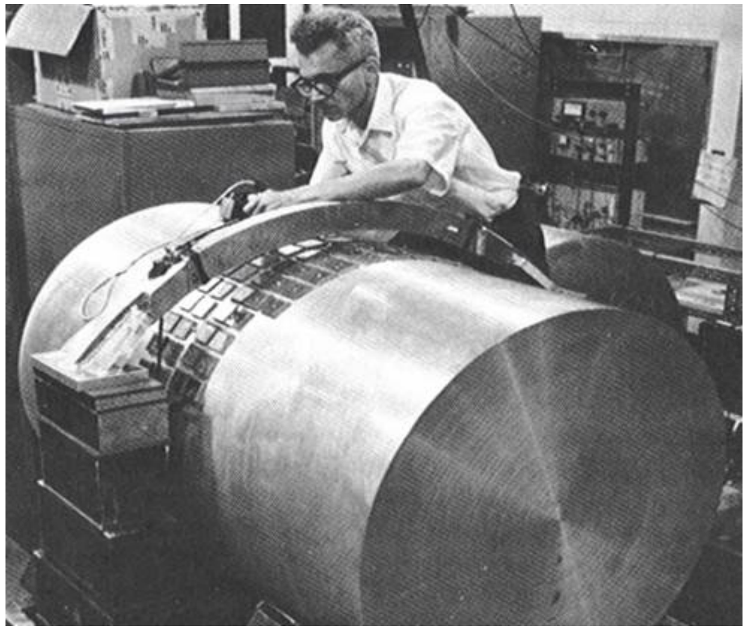
- Apply B field to polarize the spins



- Measure the response with well-known techniques

Resonant-Mass Detectors

- In the 1960's: The Weber Bar



Strain sensitivity h~10^{-17}

- Today: AURIGA, NAUTILUS, MiniGrail

Strain sensitivity h~10^{-25}

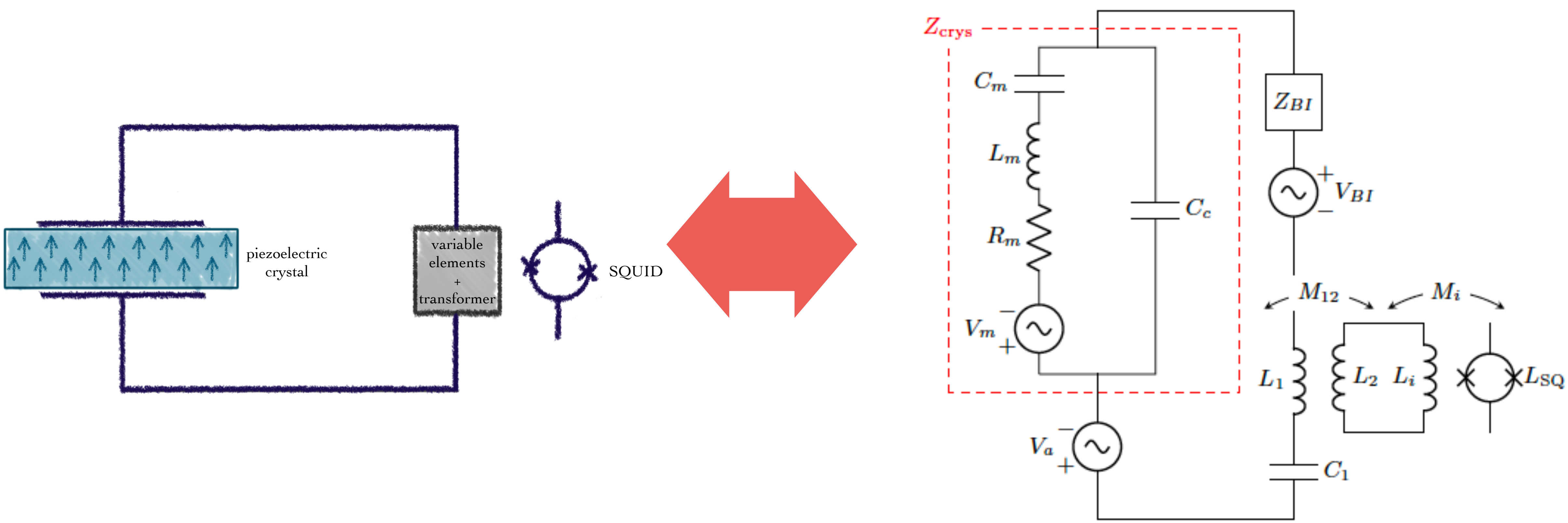
Beyond the Weber Bar: Material Candidates

- Piezoelectricity possible in 20 out of 32 crystal symmetry classes
- Has to contain nuclei with large Schiff moments and low radioactivity: ex. Np, Eu, U, Sm, Nd…
- Has to have a low mechanical losses and a large piezoelectric constant

Beyond the Weber Bar: Material Candidates

Class	Candidates	Similar Crystals
32	$Na\mathbf{Dy}H_2S_2O_9$ $\mathbf{Bi}PO_4$	Quartz (SiO_2) Langasite ($Ga_5La_3SiO_{14}$) Gallium Orthophosphate ($GaPO_4$)
3m	$\mathbf{U}(CuAs)_2$ $\mathbf{Dy}_2O_3$	Tourmaline Lithium Niobate/Tantalate ($Li(Nb/Ta)O_3$)
4mm	$K\mathbf{Eu}(CuTe_2)_2$ $\mathbf{Eu}_2AlNO_3$	Lithium Tetraborate ($Li_2B_4O_7$)
43m	$\mathbf{U}Ni_5$	Gallium Arsenide ($GaAs$)
m	$\mathbf{Gd}Ca_4O(BO_3)_3$ [58]	Rare-Earth Calcium Oxyborates

Beyond the Weber Bar: Frequency scanning



- Monitor all harmonics of a given mode

- Vary resonant frequency with a varying inductor (ex. L_1 and C_1 in the figure)

Noise and Systematics

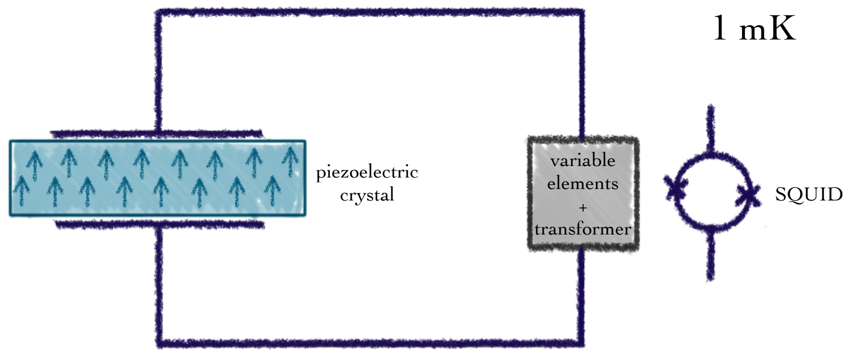
- On resonance limited by thermal noise, off-resonance limited by SQUID

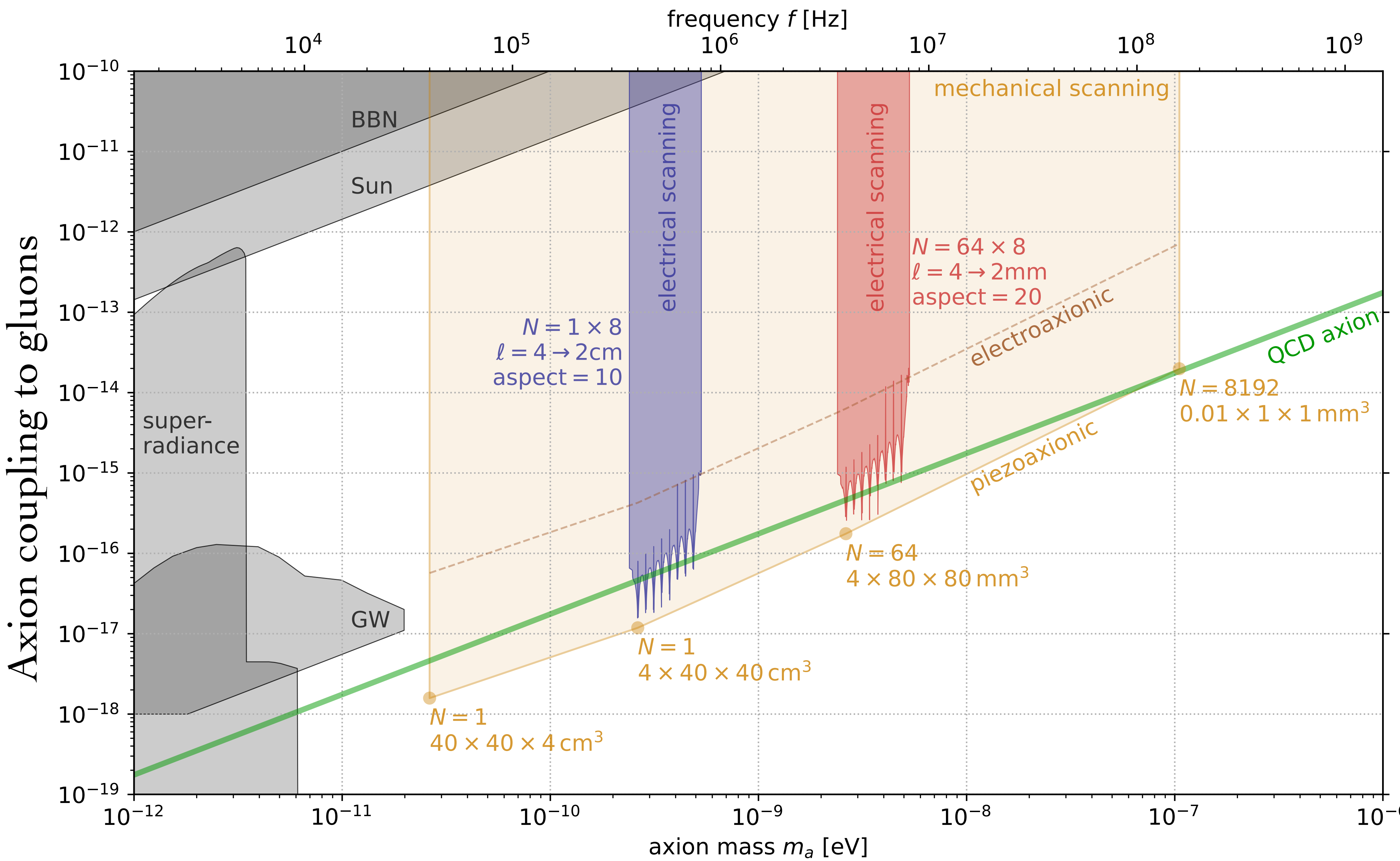
- EMF from magnetic impurities
  (~ppm is enough)

- EMF from fluctuating nuclear spins can be small
  (NMR frequency ≠ mechanical resonance frequency)

Idealized Forecast*

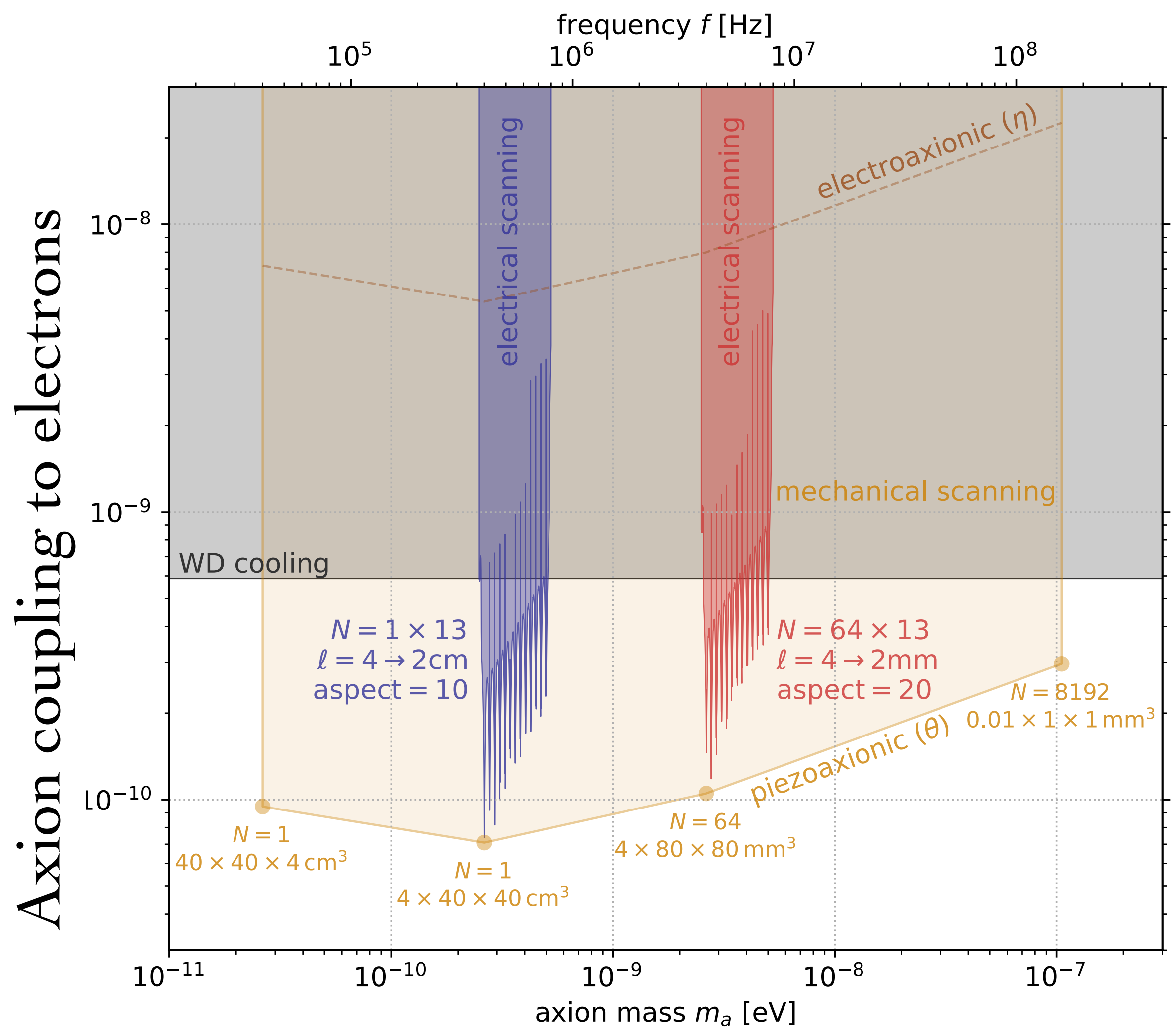
*Should be taken as indicative because it is not optimized





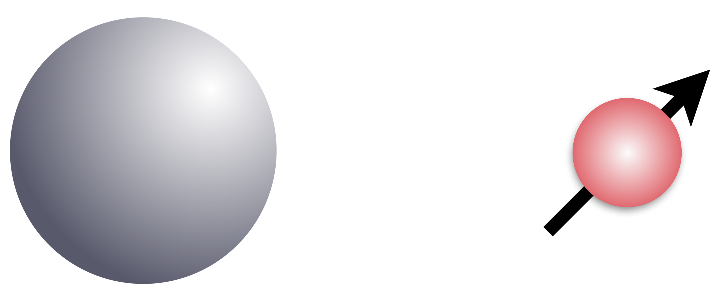
Other Axion Couplings

- Axion coupling to electrons is P-odd and T-even
- Axion DM will produce strain in any piezoelectric material without special nuclei or nuclear spin



Ferroaxionic Forces

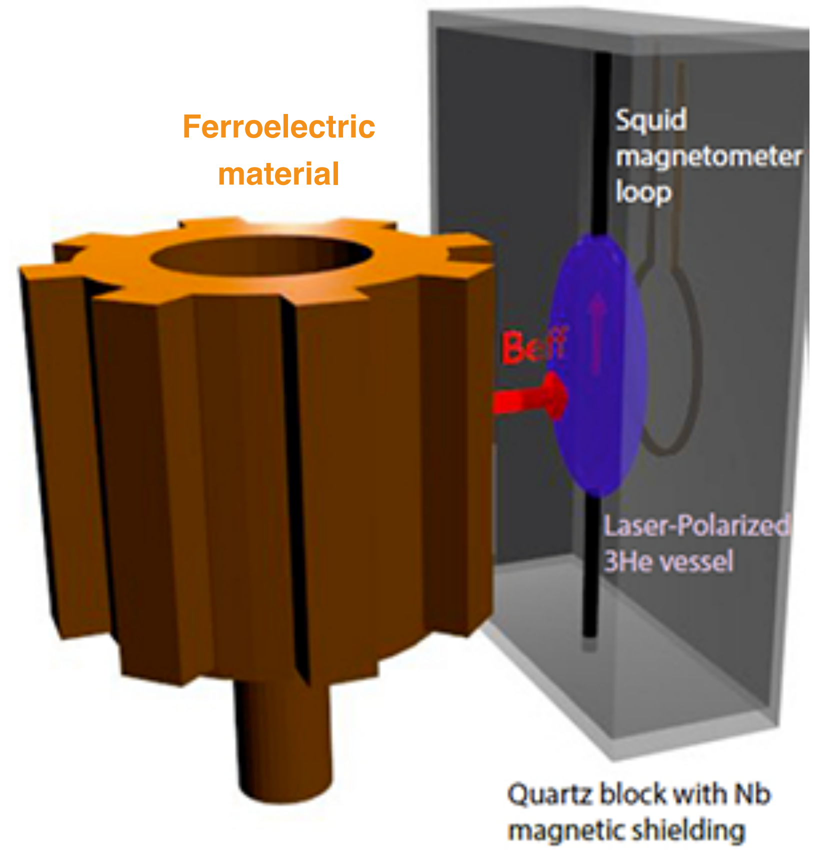
Monopole-Dipole Interaction mediated by the axion



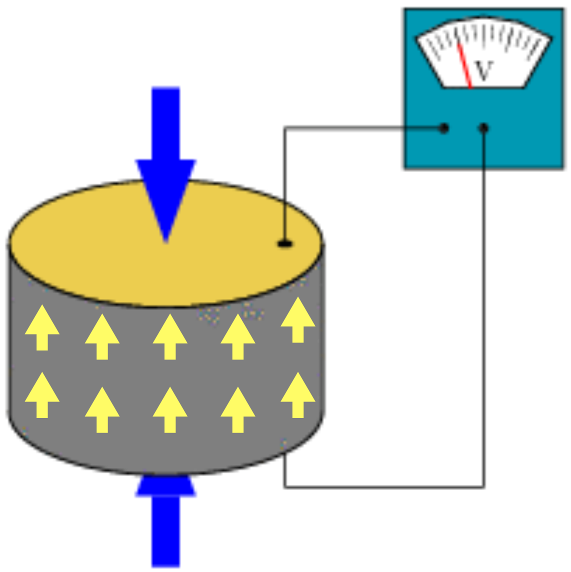
Ferroelectric mass

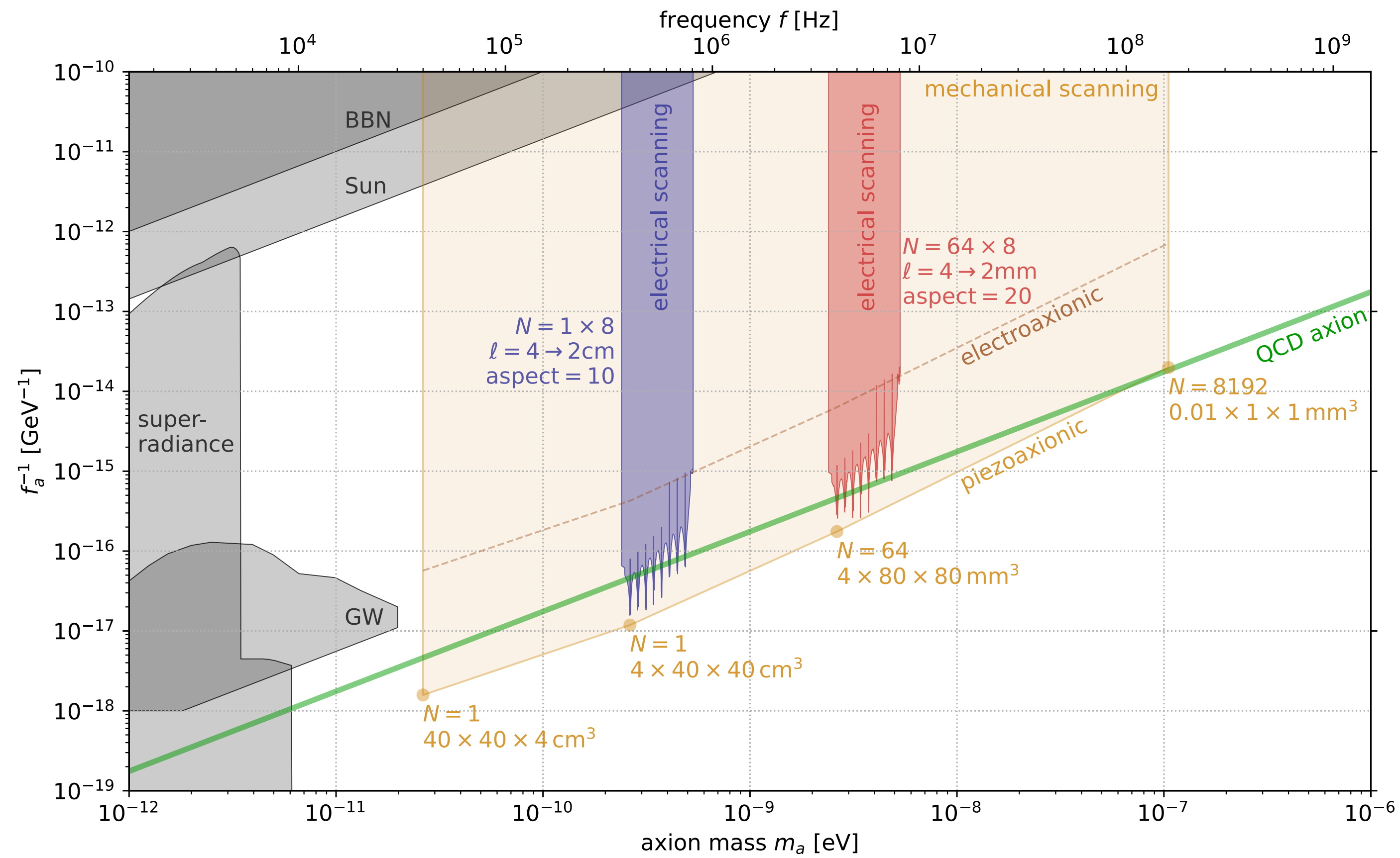
Spin

$$\text{Interaction potential} \propto \frac{e^{-m_a r}}{r^2}$$



Conclusions





- New observable for the QCD axion

- Piezoelectric material provide a background where P-odd particles can manifest interesting phenomena