Title: The Piezoaxionic Effect

Speakers: Asimina Arvanitaki

Series: Colloquium

Date: May 25, 2022 - 2:00 PM

URL: https://pirsa.org/22050062

Abstract: Mirror symmetry and time-invariance violating processes were crucial at establishing the Standard Model of fundamental interactions as we know it, their tiny effects eventually measured after enormous experimental effort. Macroscopic material on the other hand can maximally break these symmetries spontaneously. Inside these materials, Dark Matter can exhibit phenomena otherwise impossible in the vacuum. In this talk, I will discuss such a phenomenon that we call the piezoaxionic effect: In crystals whose structure breaks mirror symmetry, which are broadly known as piezoelectric, dark matter candidates called axions will produce a change in the crystals size, i.e. strain. Such a strain can be detected with well-established methods leading to a new observable for this well-motivated class of Dark Matter candidates.

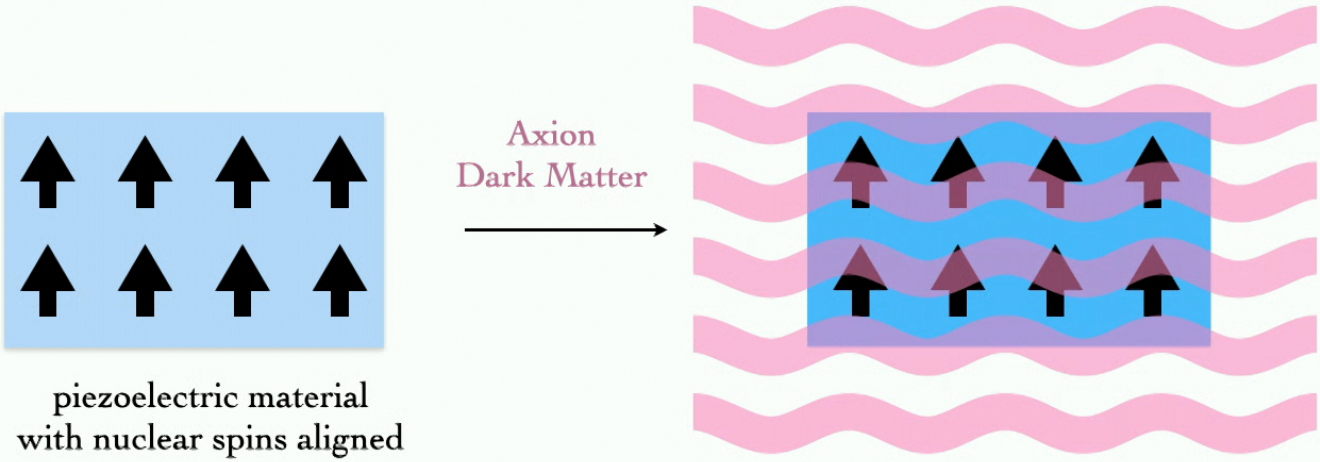
Zoom Link: https://pitp.zoom.us/j/96153495346?pwd=QU1MTENUTzdNOU5sZVc3VzY4NHI1UT09

The Piezoaxionic Effect

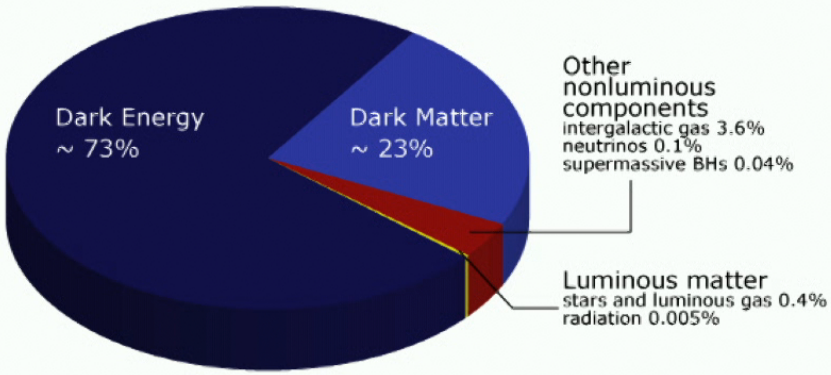
Asimina Arvanitaki
Perimeter Institute For Theoretical Physics

based on work with Amalia Madden,
and Ken Van Tilburg

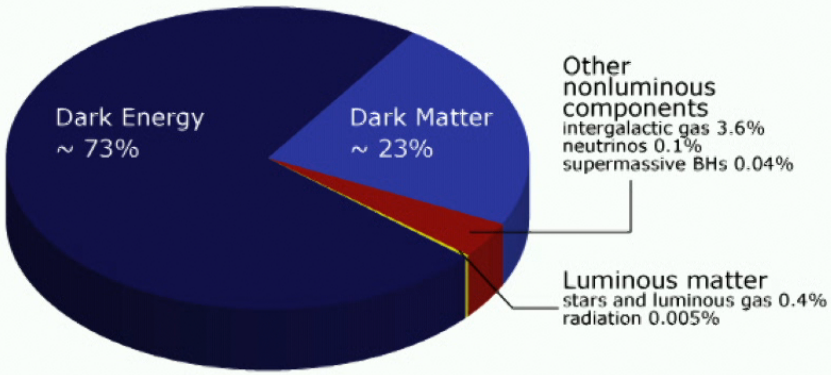
The Piezoaxionic Effect



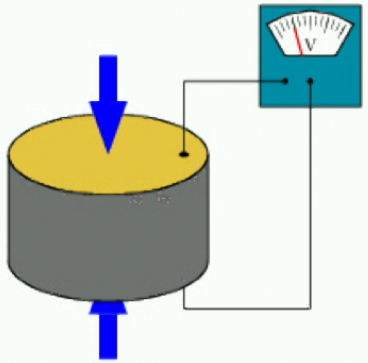
Dark Matter


Dark Energy
~ 73%
Dark Matter
~ 23%
Other
nonluminous
components
intergalactic gas 3.6%
neutrinos 0.1%
supermassive BHs 0.04%
Luminous matter
stars and luminous gas 0.4%
radiation 0.005%

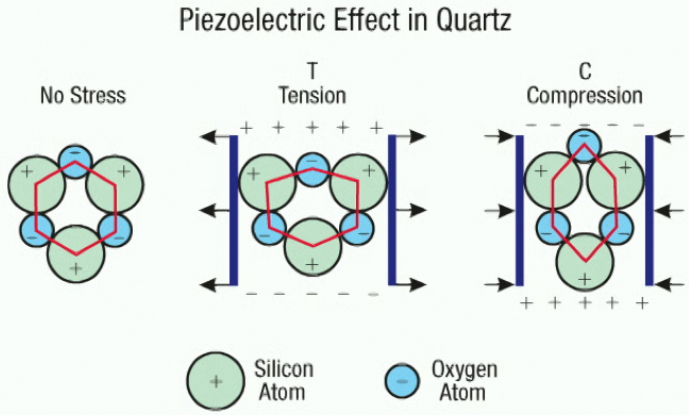
Dark Matter

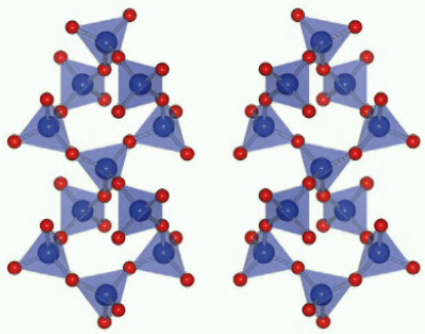


Piezoelectricity



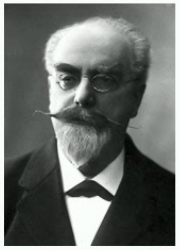
Piezoelectricity in crystals that break mirror (or parity) symmetry





α-quartz left-handed

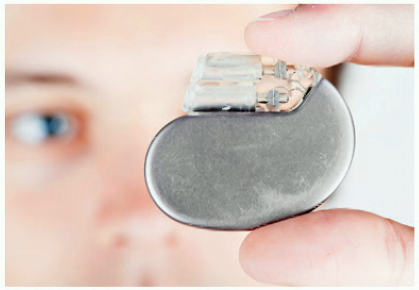
α-quartz right-handed

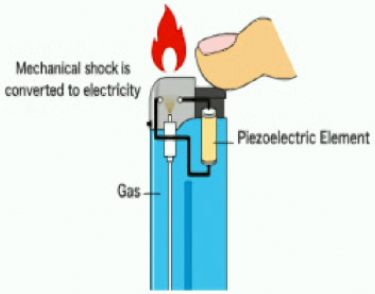


Gabriel Lippmann (1881)

Jacques and Pierre Curie (1880 and 1881)

Piezoelectricity applications

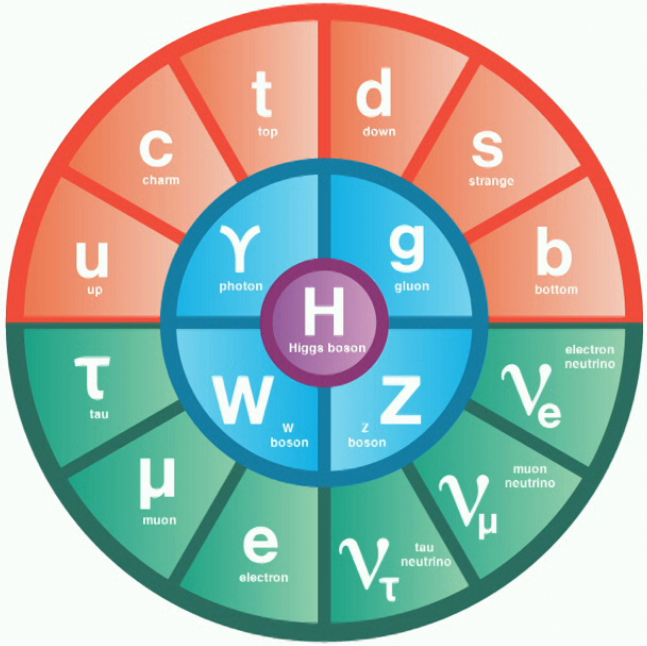




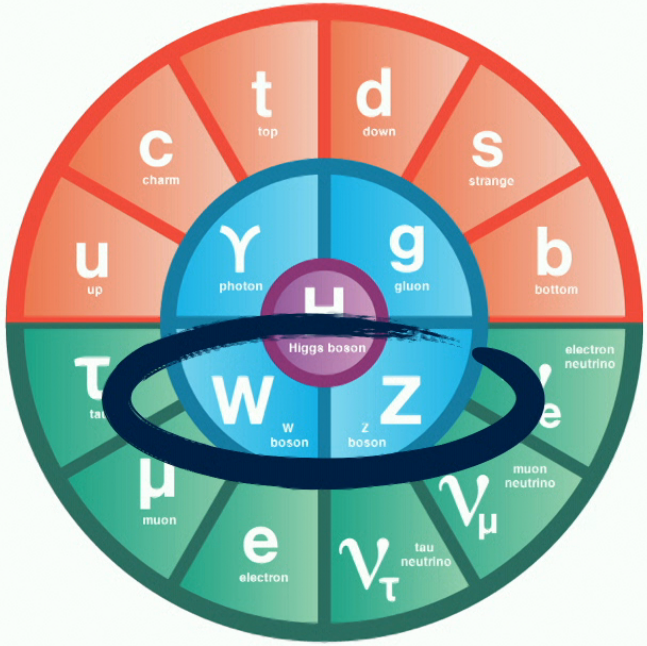
Outline

- Parity violation in the microscopic and macroscopic world
- Axions as parity odd dark matter
- The piezoaxionic effect

Parity violation in the Standard Model

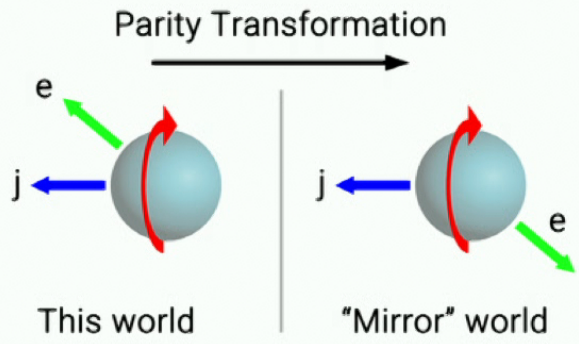


Parity violation in the Standard Model



Weak interactions maximally violate parity symmetry

Discovery of Parity Violation: The Wu Experiment



Decay of Co-60 showed asymmetry between the "front" and "back" emission of electrons

C. N. Yang and Tsung-Dao Lee (1956)

Chien-Shiung Wu (1956)

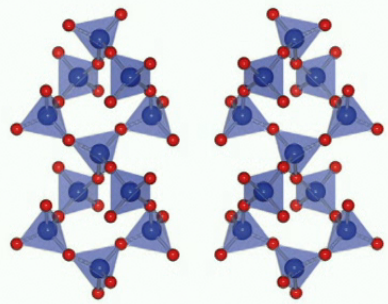
The Wu Experiment and parity violation

- Elementary particles can be assigned parity

- Force responsible for radioactivity is very weak and unimportant at large scales: Why is it that in the everyday world parity is not conserved?

Parity violation in the real world

- At low energies, high-energy symmetries can be spontaneously broken
  - Example: Translational invariance in crystals



α-quartz left-handed α-quartz right-handed

- But, why does nature pick one orientation over the other?
  - For quartz, 99% is right handed
  - Interactions with the environment appear to play a role

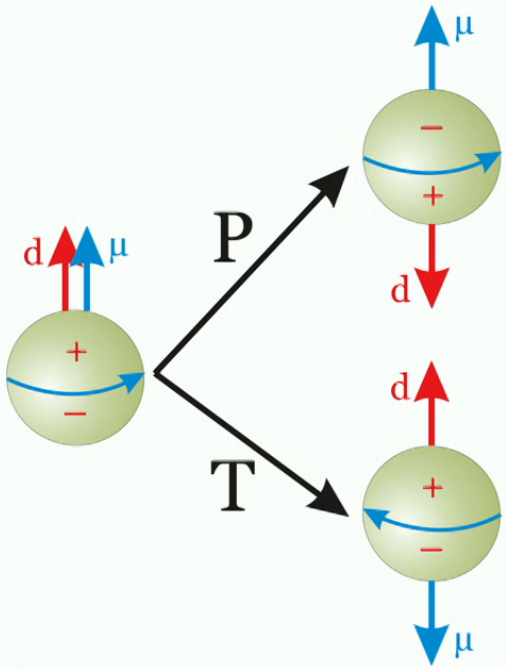
Outline

- Parity violation in the microscopic and macroscopic world
- Axions as parity odd dark matter
- The piezoaxionic effect

Fundamental electric dipole moment

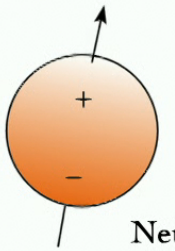
- An electric dipole moment (EDM) for an elementary particle violates both parity and time-reversal symmetries

- 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



Neutron EDM

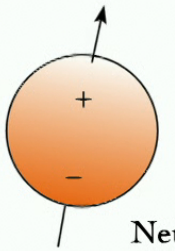
$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

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

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron EDM

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

EDM ~ e fm θ_s

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

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

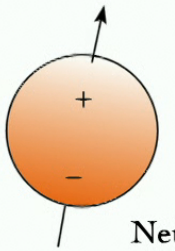
Axion mass from QCD:

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

f_a : axion decay constant

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron EDM

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

EDM ~ e fm θ_s

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

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

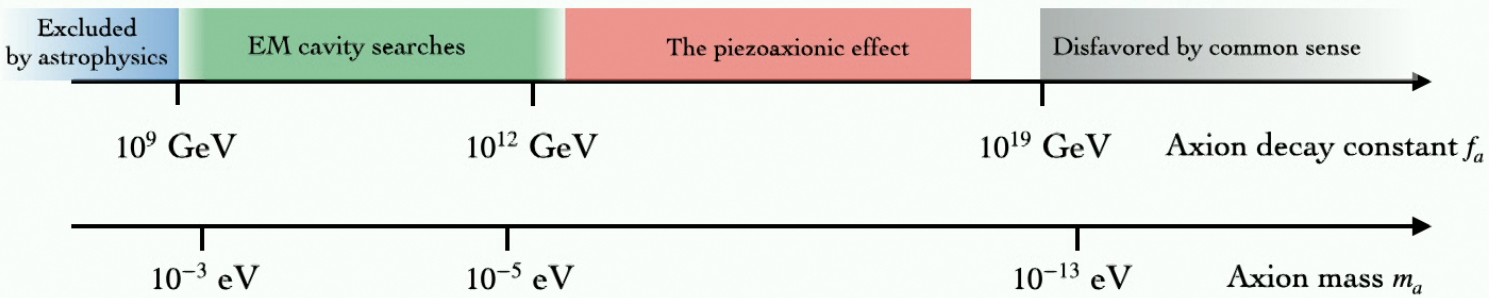
Axion mass from QCD:

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

f_a : axion decay constant

Mediates new forces and can be the dark matter

Parameter Space of the QCD axion



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

String Axiverse

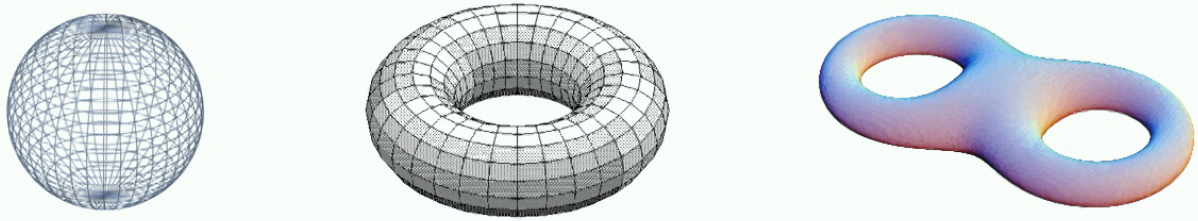
AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

- Extra dimensions

String Axiverse

AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

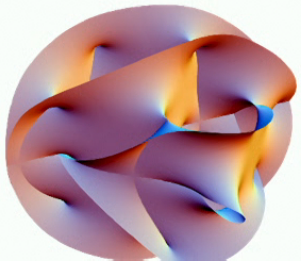
- Extra dimensions
- Gauge fields
- Topology



String Axiverse

AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

- Extra dimensions
- Gauge fields
- Topology



String Axiverse

AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

- Extra dimensions
- Gauge fields
- Topology

Give rise to a plenitude of massless particles in our Universe

Non-trivial gauge configurations

The Aharonov-Bohm Effect

Solenoid

Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

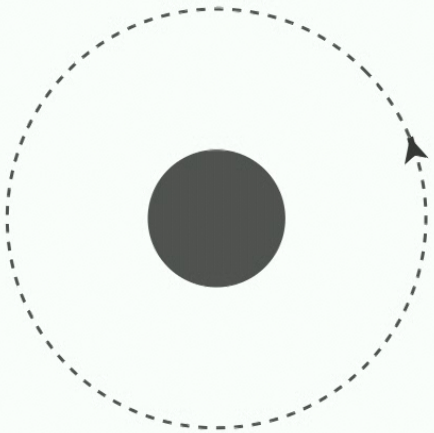
$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Non-trivial gauge configurations

The Aharonov-Bohm Effect



Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

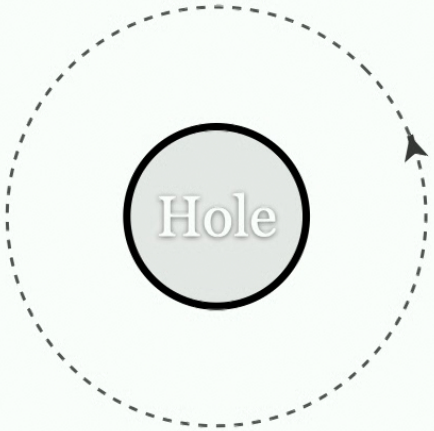
$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Non-trivial gauge configurations

The Aharonov-Bohm Effect



Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

$$\vec{B} = 0$$

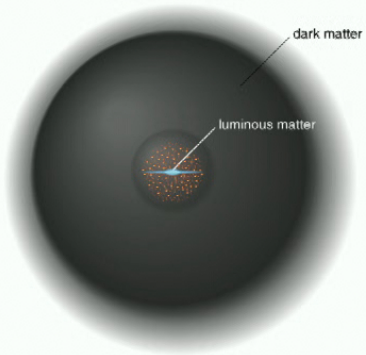
Non-trivial topology:
"Blocking out" the core still leaves a non-trivial gauge, but no mass

String Axiverse

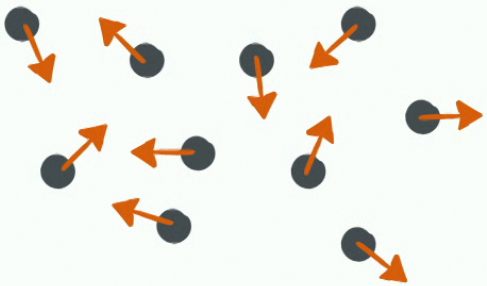
- Axions can mediate new forces
- Axions are constrained from astrophysics
- Axions are excellent DM candidates

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



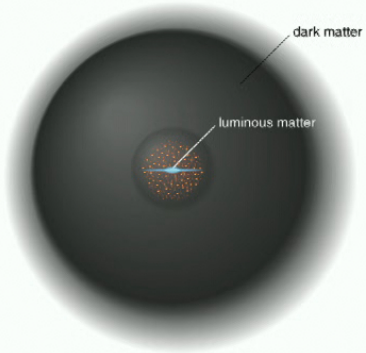
Usually we think of …



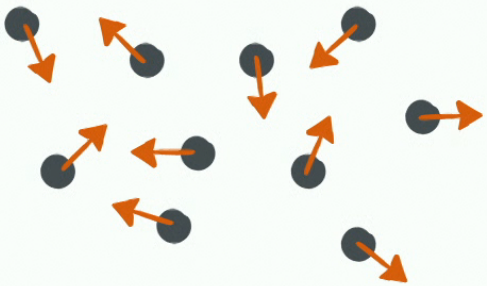
like a WIMP

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

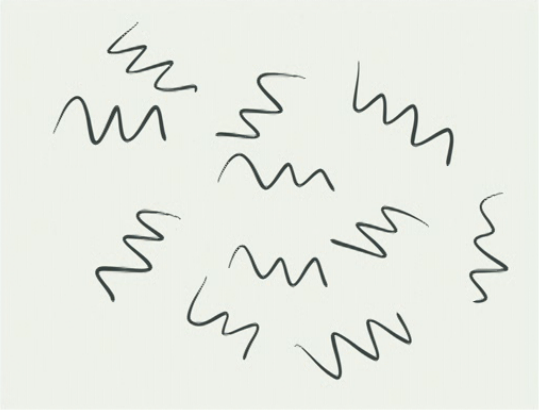


Usually we think of …



like a WIMP

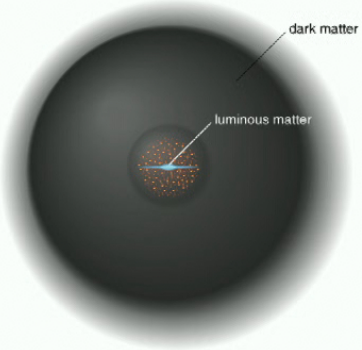
instead of…

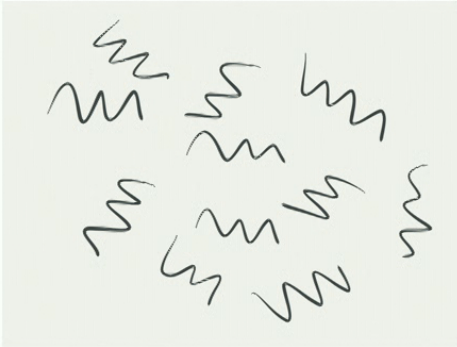


$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy

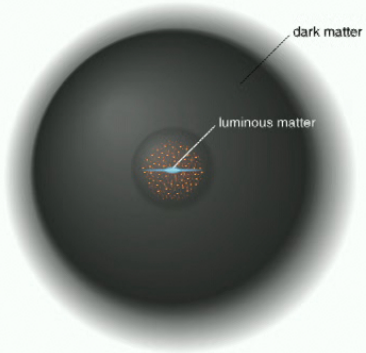


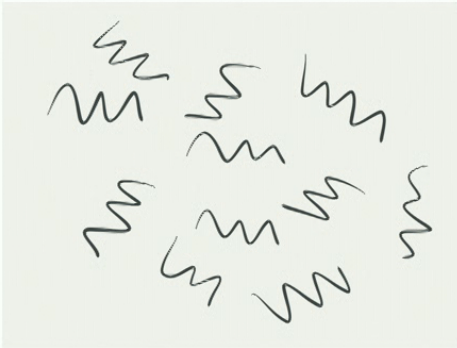


Decreasing DM Mass

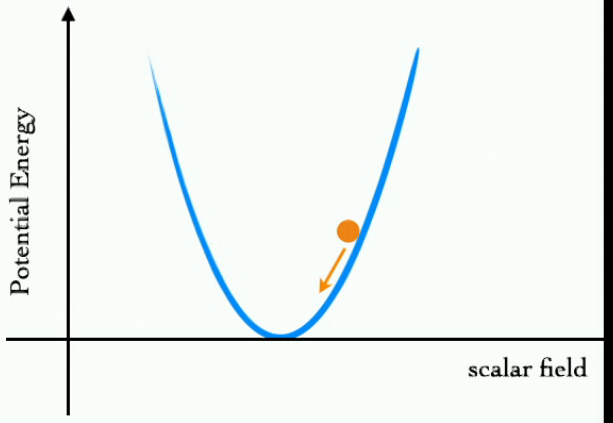
What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy





Decreasing DM Mass



Equivalent to a Scalar Wave

Going from DM particles to a DM "wave"

When $n_{DM} > \frac{1}{\lambda_{DM}^3}$

In our galaxy this happens when $m_{DM} < 1\ eV/c^2$

we can talk about DM a(x,t) and locally

$$a(t) = a_o \cos(\omega_{DM} t)$$

with amplitude

$$a_o \propto \frac{\sqrt{\text{DM density}}}{\text{DM mass}}$$

with frequency

$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

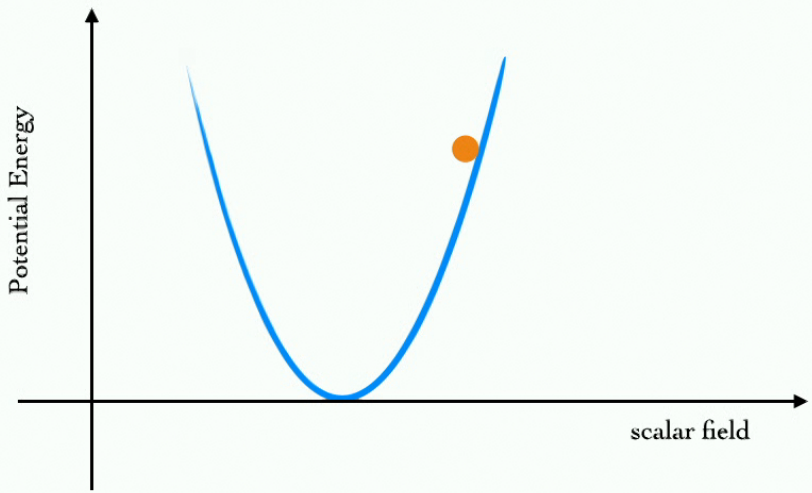
$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

Light Scalar Dark Matter

- Just like a harmonic oscillator

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$$\ddot{x} + \gamma\,\dot{x} + \omega^2 x = 0$$



Frozen when:
Hubble > m_a

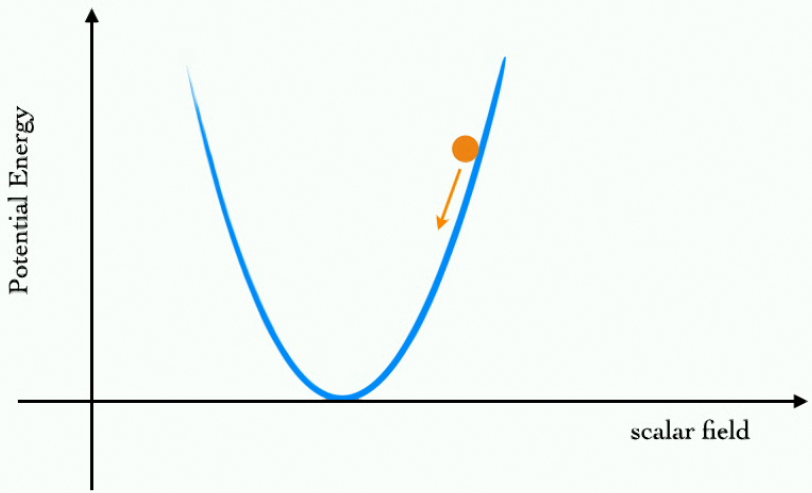
Initial conditions set by inflation

Light Scalar Dark Matter

- Just like a harmonic oscillator

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$$\ddot{x} + \gamma\,\dot{x} + \omega^2 x = 0$$



Frozen when:
Hubble > m_a

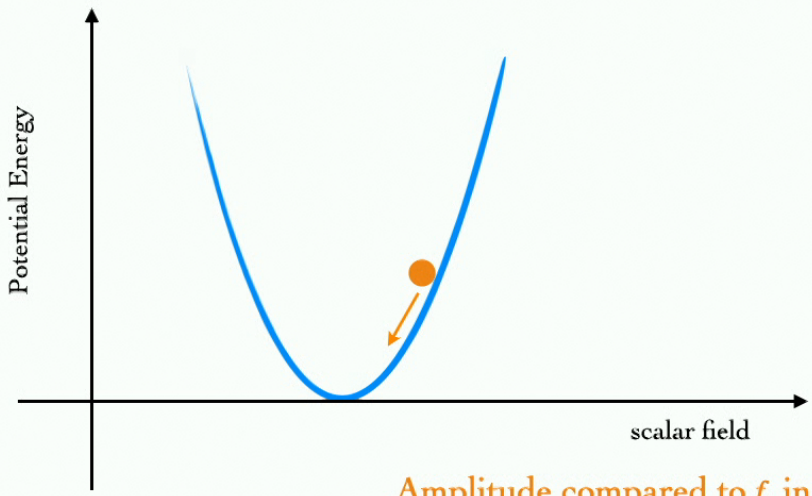
Oscillates when:
Hubble < m_a

ρ_a scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

Light Scalar Dark Matter Today

- If $m_\phi < 1$ eV, can still be thought of as a scalar field today



$m_a{}^2\, a_o{}^2\, \cos^2(m_a\, t) \sim \rho_a$

Coherent for $\upsilon_{vir}{}^{-2} \sim 10^6$ periods

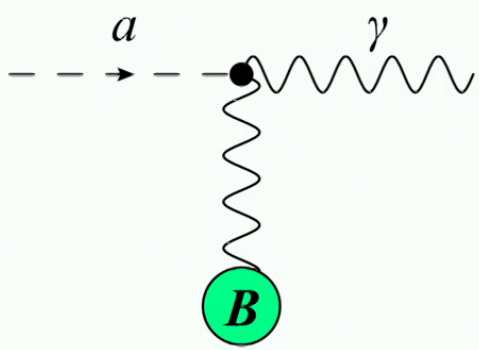
Amplitude compared to f_a in the galaxy:

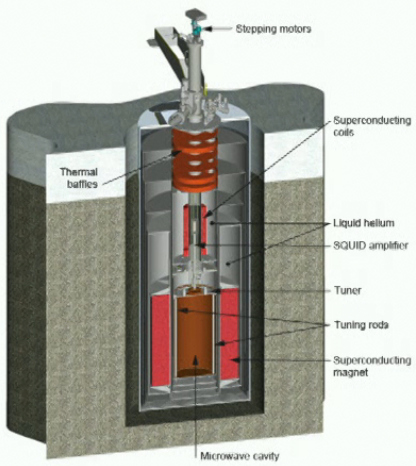
$\frac{a}{f_a} \equiv \bar{\theta} = 4 \times 10^{-19}$ for the QCD axion

Axion Dark Matter

$$\frac{\alpha}{4\pi}\frac{a}{f_a}F\tilde{F}$$

- Axion-to-photon conversion (ex. ADMX)

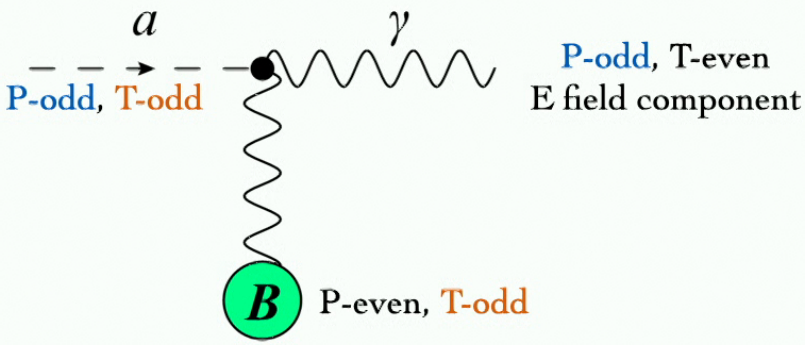




Cavity size = Axion size

New Axion Dark Matter Observable

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



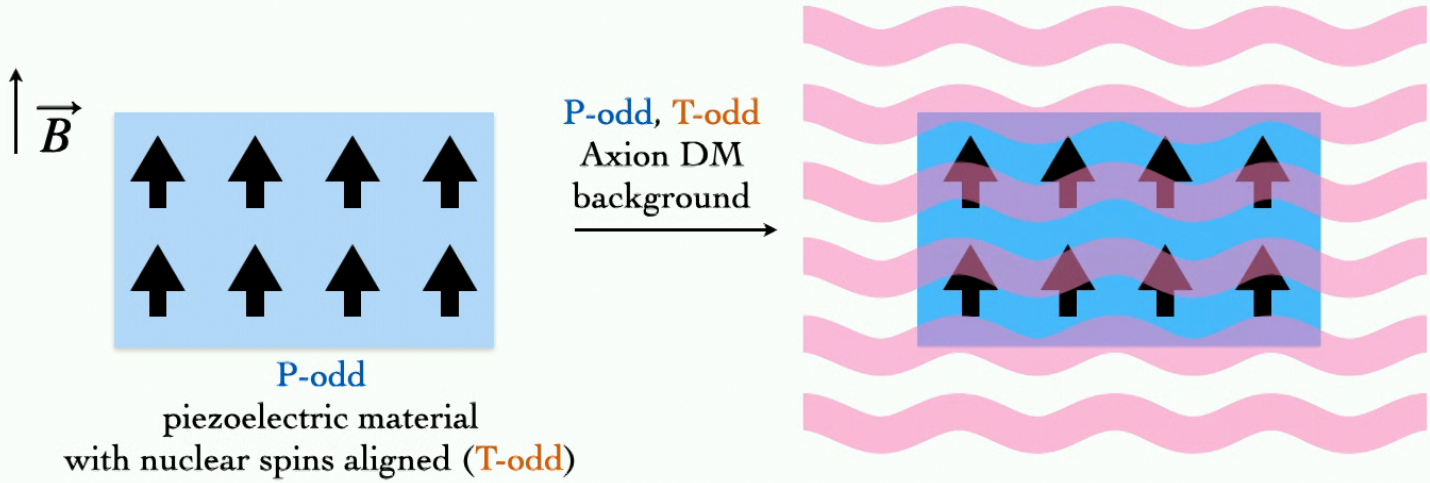
New Axion Dark Matter Observable

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

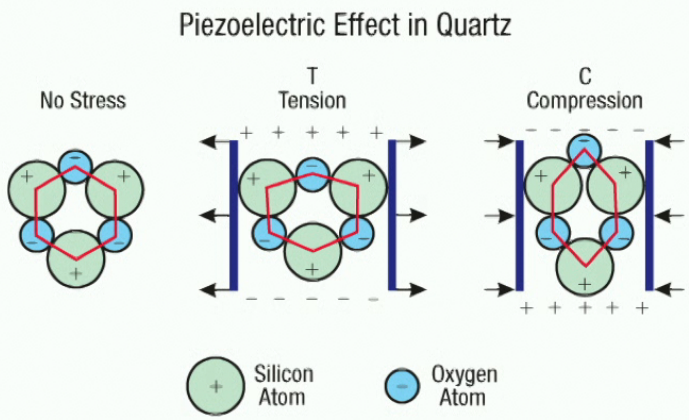
- In piezoelectric material (P breaking) with aligned spins (T breaking), Axion DM results in a stress
  - The most promising coupling is the coupling to gluons

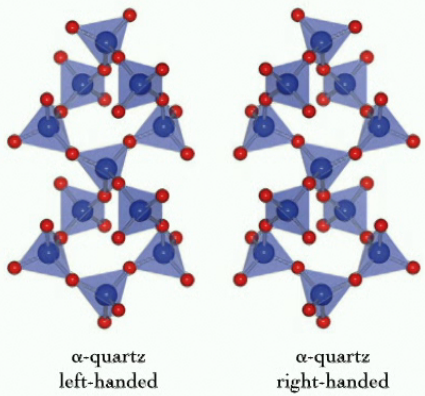
The piezoaxionic effect

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



The piezoaxionic effect

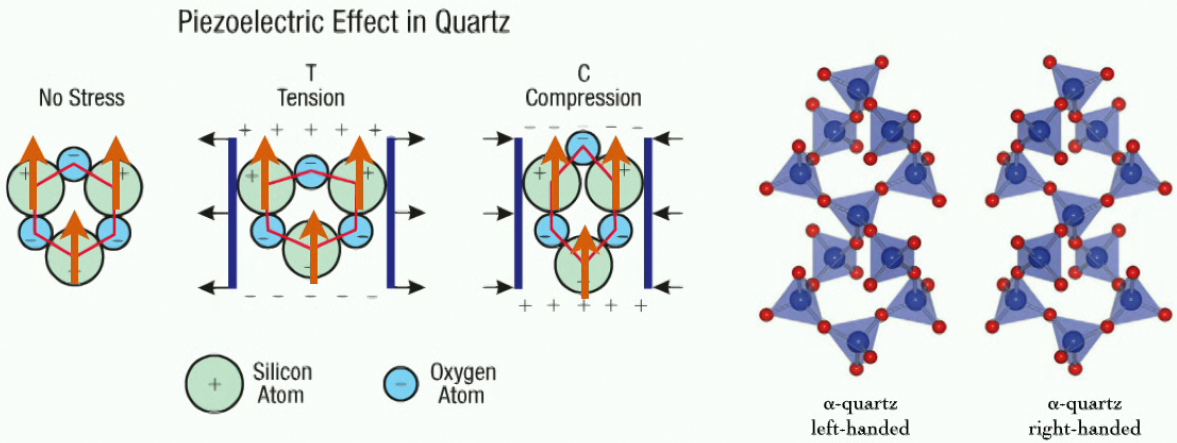




- In a piezoelectric an displacement field (D) leads to stress(T) and strain(S) leads to an electric field (E)

$$T = cS + \boxed{eD}$$
$$E = \epsilon D + \boxed{eS}$$

The piezoaxionic effect



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

$$T = cS + eD - \xi P\theta_a(t) \qquad \xi\text{: Piezoaxionic tensor}$$

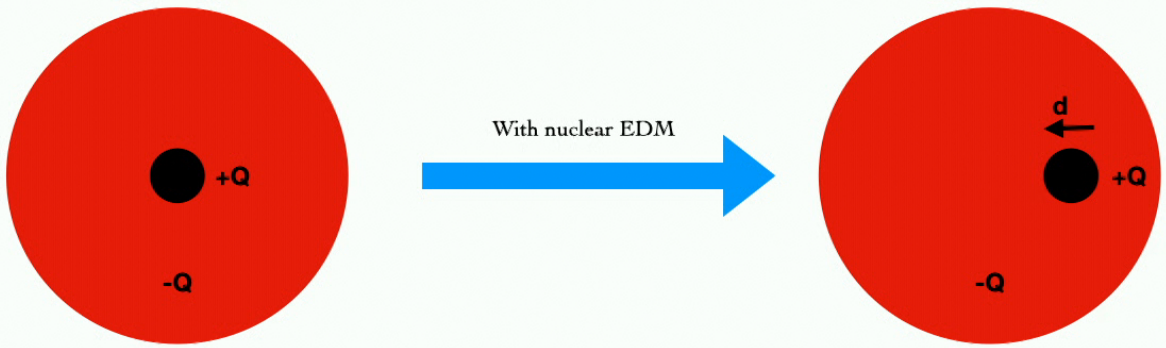
$$E = \epsilon D + eS + \zeta P\theta_a(t) \qquad \zeta\text{ :electroaxionic tensor}$$

- 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

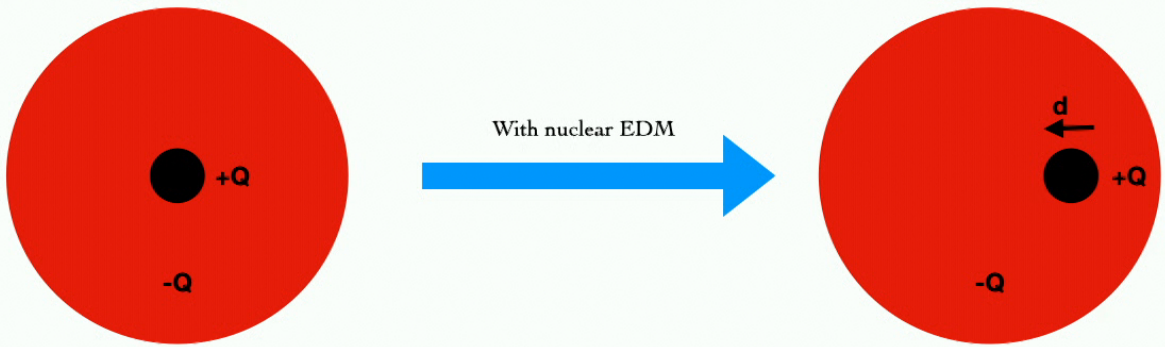


Where does the piezoaxionic constant ξ come from?

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

$$\text{Atomic EDM} \sim \left(\frac{\text{size of the nucleus}}{\text{size of the atom}}\right)^2 \text{EDM of nucleon} \sim 10^{-10}\ \text{EDM of nucleon}$$

- Naively hopeless…



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

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

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

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

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

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

- Schiff Moment interaction with atomic electrons: $\delta H = -4\pi \vec{S} \cdot \vec{\nabla} \delta(r_e)$

- In large atoms, there are relativistic enhancements because the electron sees the unscreened nuclear charge

- Atomic EDM $\propto \left(\frac{\text{size of the nucleus}}{\text{size of the atom}} \right)^2$ EDM of nucleon $\times Z^3 A^{2/3}$

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

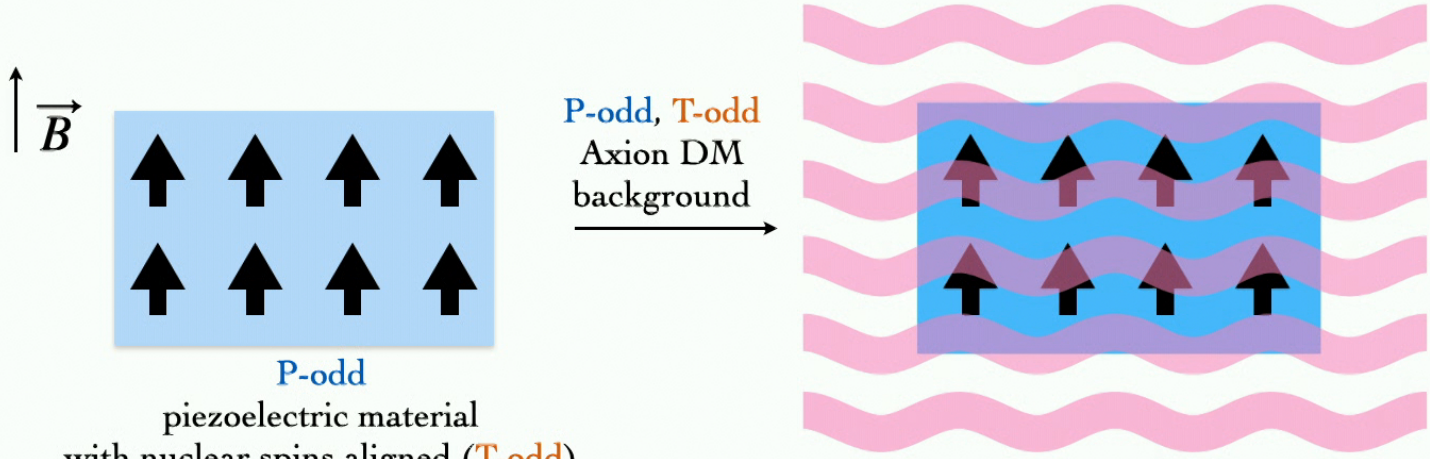
- Piezoaxionic tensor $\sim \frac{\langle \delta H \rangle}{V_{cell}} \times \tilde{\xi}$

- $\tilde{\xi}$ 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

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



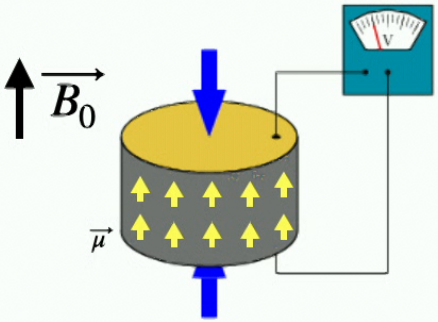
P-odd
piezoelectric material
with nuclear spins aligned (T-odd)

Produces P- and T-even stress and ultimately strain

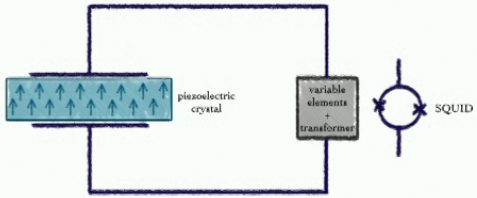
QCD axion equivalent strain:

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

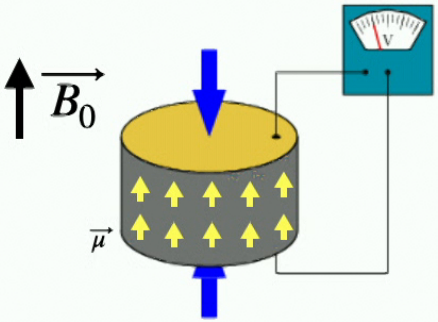
Experimental Set-Up



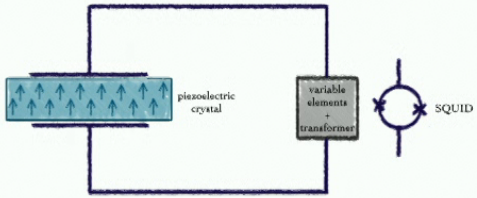
- Piezoelectric material with elements with nuclear spins
- Apply B field to polarize the spins
- Measure the response with well-known techniques



Experimental Set-Up

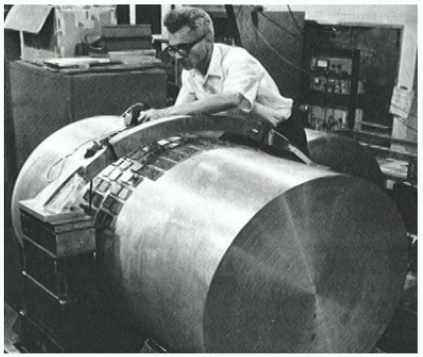


- Piezoelectric material with elements with nuclear spins
- Apply B field to polarize the spins
- Measure the response with well-known techniques



Resonant-Mass Detectors

- In the 1960's: The Weber Bar



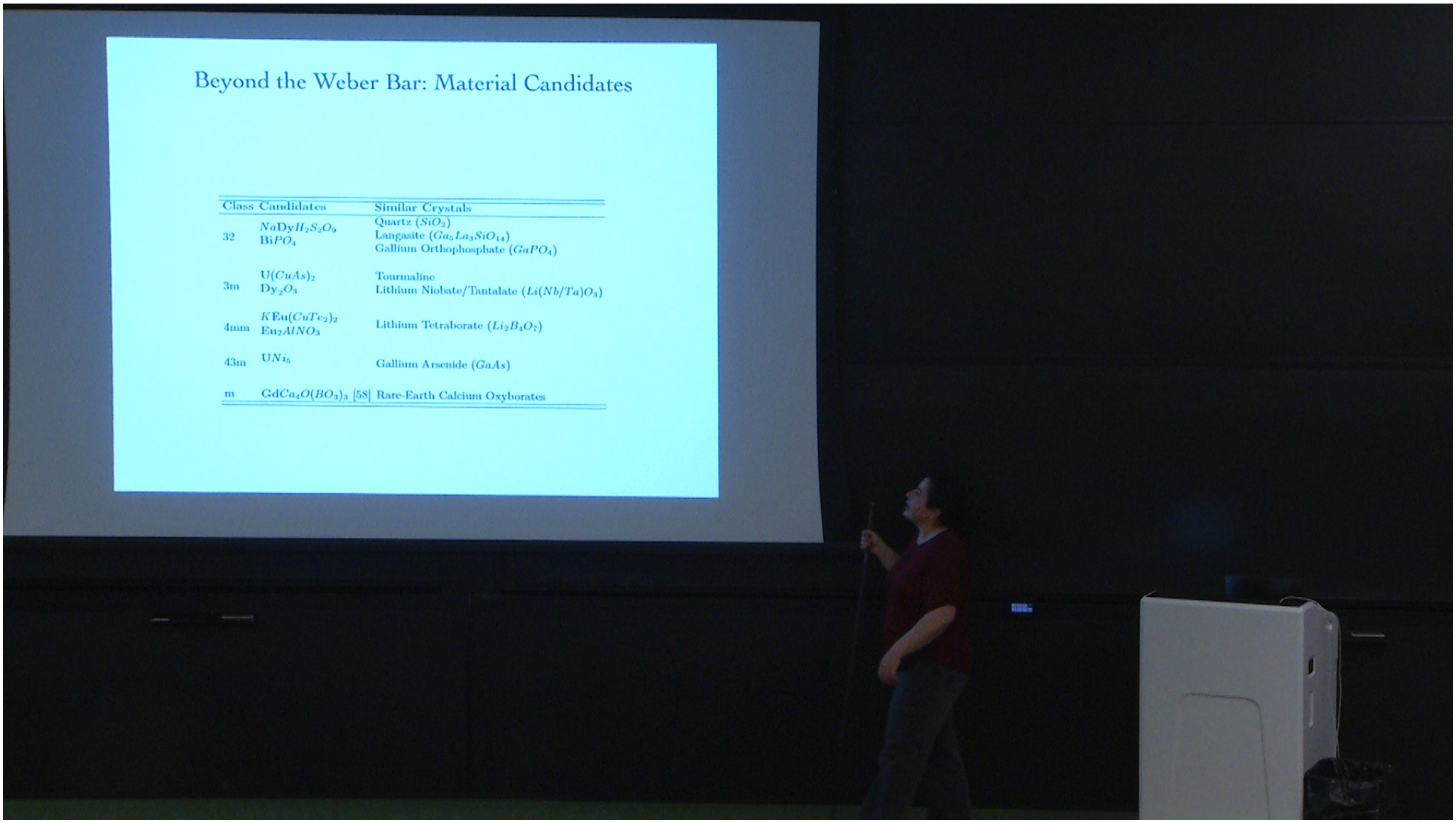
Strain sensitivity $h \sim 10^{-17}$

- Today: AURIGA, NAUTILUS, MiniGrail

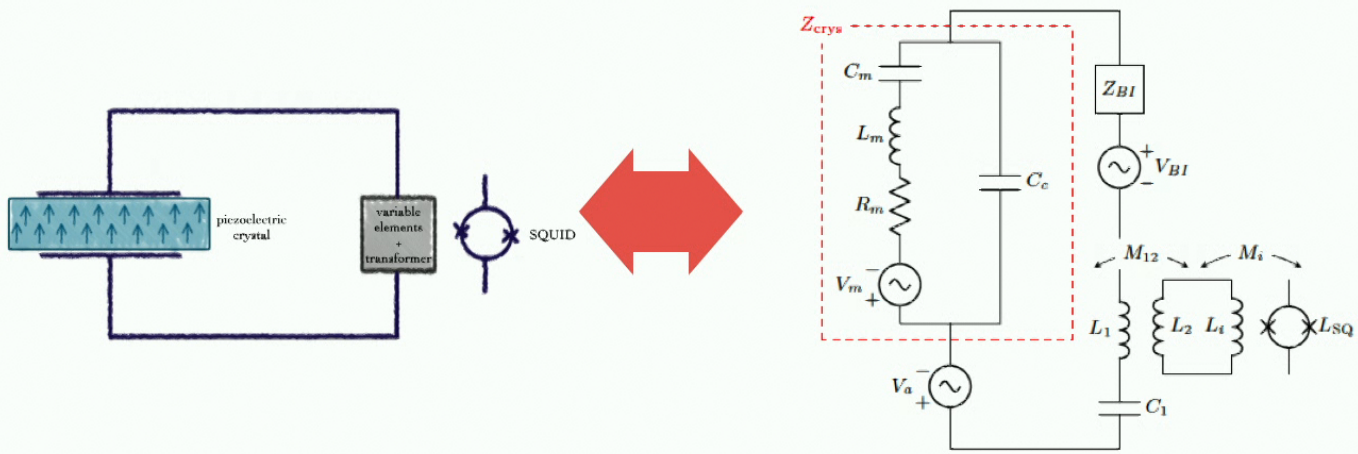
Strain sensitivity $h \sim 10^{-25}$

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 $NaDyH_2S_2O_9$ Quartz (SiO_2)
$BiPO_4$ Langasite ($Ga_5La_3SiO_{14}$)
Gallium Orthophosphate ($GaPO_4$)
3m $U(CuAs)_2$ Tourmaline
Dy_2O_3 Lithium Niobate/Tantalate ($Li(Nb/Ta)O_3$)
4mm $KEu(CuTe_2)_2$ Lithium Tetraborate ($Li_2B_4O_7$)
Eu_2AlNO_3
43m UNi_5 Gallium Arsenide ($GaAs$)
m $GdCa_4O(BO_3)_3$ [58] Rare-Earth Calcium Oxyborates

Beyond the Weber Bar: Frequency scanning

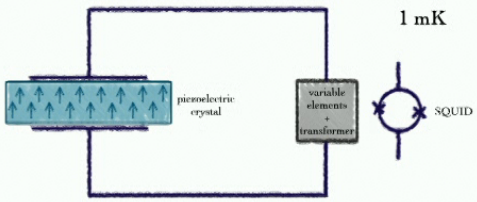


- Monitor all harmonics of a given mode
- Vary resonant frequency with a varying inductor (ex. L_1 and C_1 in the figure)

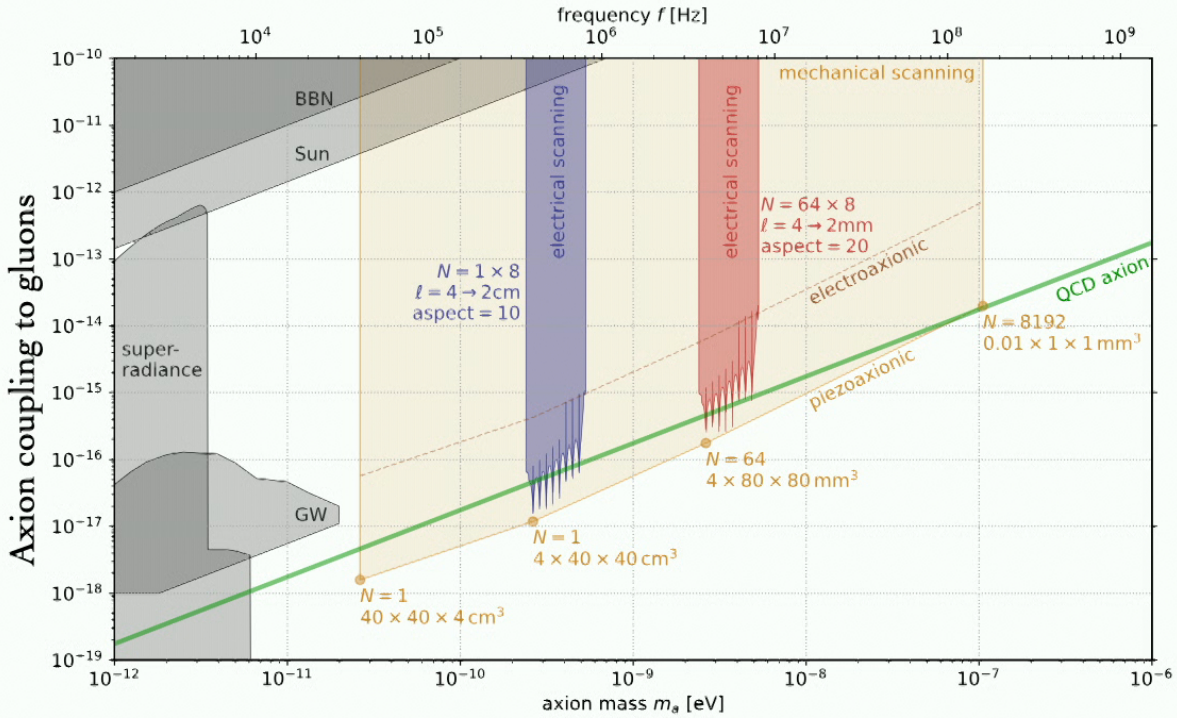
Noise and Systematics

- 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



Things to Do

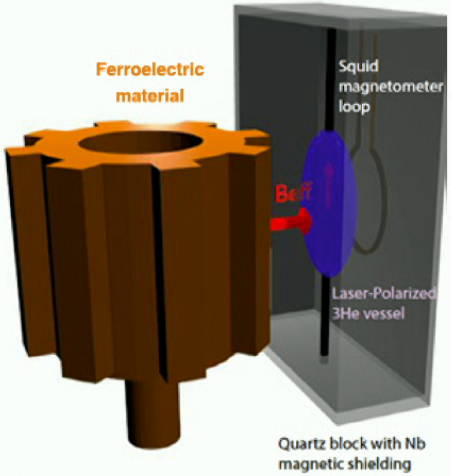
- DFT calculation of piezoaxionic and electroaxionic tensors
- Identify ideal material and optimize setup
- The (inverse) piezoaxionic effect
  - Piezoelectric material can source axions

Ferroaxionic Forces

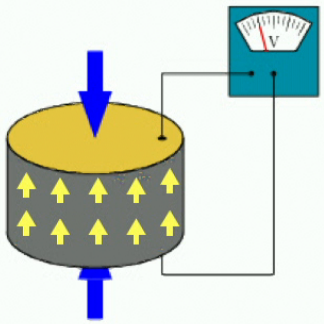
Monopole-Dipole Interaction mediated by the axion

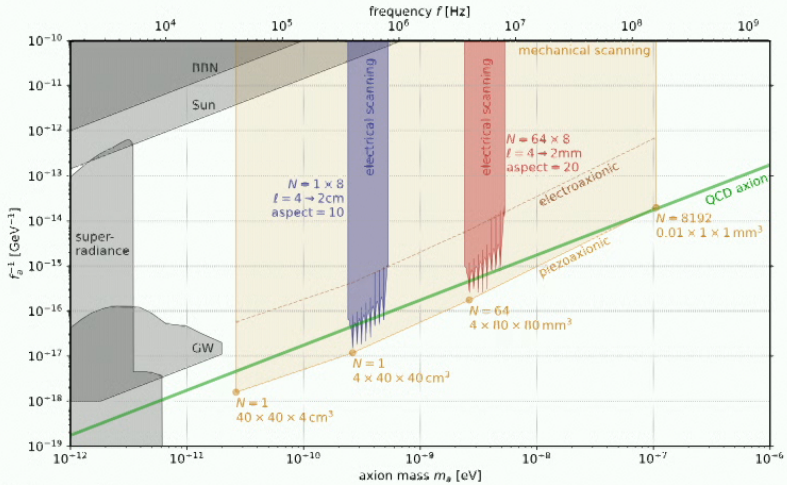
Ferroelectric mass Spin

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



Conclusions

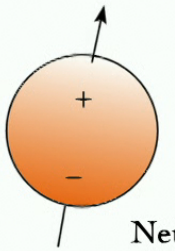




- New observable for the QCD axion
- Piezoelectric material provide a background where P-odd particles can manifest interesting phenomena
- Are there other particles for which such effects are relevant?

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron EDM

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

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:

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

f_a : axion decay constant