Piezoaxionic Detection of Axion Dark Matter with Precessing Nuclear Spins

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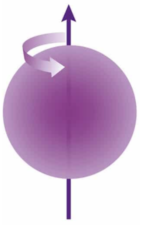
Strong CP Problem and the QCD axion

- No Symmetry prevents having a CP violating term in the SM: $\mathcal{L}_{\rm SM} \supset \frac{\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$
- Weak interactions violate CP through the CKM phase (induces a tiny θ (many-loop suppressed))
- The physical measured topological angle is $\bar{\theta} = \theta + \arg\det \mathcal{M}_q$

- QCD CP violation induces a neutron EDM

$$d_n \sim 10^{-16}\bar{\theta} \cdot e \cdot {\rm cm}$$

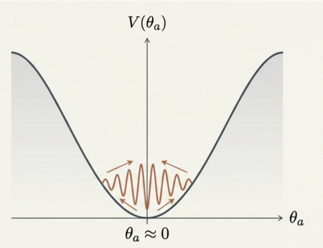
- Experimentally $d_n \lesssim 10^{-26} \cdot e \cdot {\rm cm} \longrightarrow |\bar{\theta}| \lesssim 10^{-10}$
- Why is CP so small in QCD?
- Generic BSM CP violation would instead generate $\theta \sim \mathcal{O}(1)$

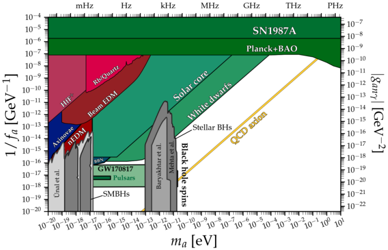


Axion-Gluon Coupling

Solution:

- The axion-gluon coupling: $\mathcal{L} \sim \frac{a}{32\pi^2 f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$
- Promotes the θ term as dynamical axion angle $\mathcal{L} \supset \frac{\alpha_s}{8\pi^2}(\frac{a}{f_a} + \theta)$
- This dynamically solves the Strong CP Problem by relaxing the effective θ to zero





Credit: Amalia Madden

Axion as a DM Background

- As axion interacts very weakly with ordinary matter and light (due to very large PQ scale $f_a \sim 10^9 - 10^{17}$ GeV), they can be a DM candidate.
- Axion is treated as a classical field of monochromatic oscillation (just like CDM)

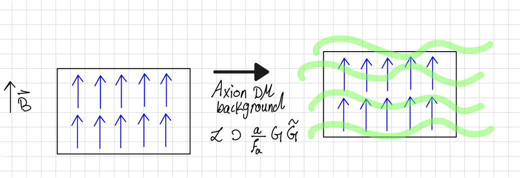
$$a(t) = a_0 \cos(m_a t)$$

  where the amplitude $a_0 \propto \frac{\sqrt{\rho_a}}{m_a f_a}$
  The axion field oscillates at frequency $\omega = m_a$
- More concretely, the axion has a spread in frequencies (due to dispersion of the velocity distribution around the Milky Way) $\frac{\delta\omega}{\omega} \sim 10^{-6}$
- This gives linewidth to the axion field, this gives kHz for a μeV axion

The Piezoaxionic Effect: Physical Idea

Asimina Arvanitaki, Amalia Madden, and Ken Van Tilburg. Piezoaxionic effect. Phys. Rev.D, 109(7):072009, 2024.

- Axion background: P, T violating
- Polarized nuclei: T-odd
- Piezoelectric crystal: P-odd
- Combined, in matter, this coupling induces observable forces



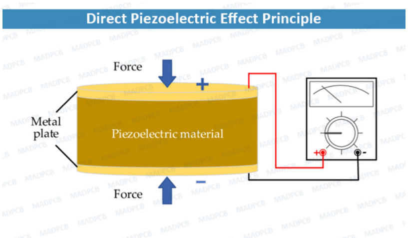
- This axion coupling to nuclear spins acts as a spin-dependent force in matter

$$\mathcal{L} \supset g_{aNN} \nabla a \cdot \mathbf{I}$$

that's why we get a force in piezoelectric crystals

Reminder on Piezoelectricity

- Piezoelectric crystals break parity symmetry spontaneously
- Deformation of the crystal generates an EDM, which generates an Electric field (a voltage difference across)



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

$$T = \underbrace{c^D}_{\text{stiffness}} S + \boxed{hD}$$

$$E = \underbrace{\beta^S}_{\text{impermittivity}} D - \boxed{hS}$$

- Main idea: stress $\leftrightarrow$ electric field

Piezoaxionic Constitutive Equations

- We can incorporate the axion background into the piezoelectric equations.
- In a piezoelectric crystal of polarized nuclear spins $(\hat{I})$, the axion field θ_a also leads to a stress and an electric field E

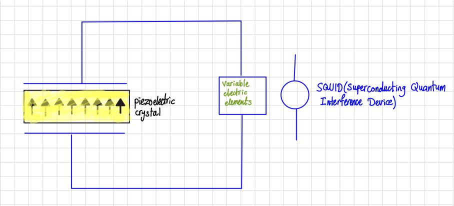
$$T = c^D S - hD - \xi \hat{I} \theta_a , \quad \xi : \text{Piezoaxionic tensor}$$

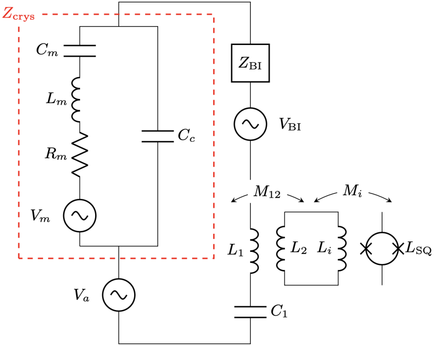
$$E = -hS + \beta^S D + \zeta \hat{I} \theta_a , \quad \zeta : \text{Electroaxionic tensor}$$

- The axion background induces a stress in the piezoelectric crystal; this phenomenon is called *The Piezoaxionic Effect*
- It also induces an electric field directly through the *Electroaxionic Effect* but it is subdominant, which we will see shortly

Setup and Principle of Detection

- Piezoelectric crystal containing a high density of polarized nuclear spins
- External magnetic field aligns the nuclear spins
- Axion dark matter background induces an oscillating stress in the crystal via the axion–gluon coupling
- The piezoelectric effect converts this stress into an oscillating voltage
- The voltage signal is measured with a sensitive readout circuit (amplifier / SQUID)





Resonant Enhancement

Why is this idea interesting?

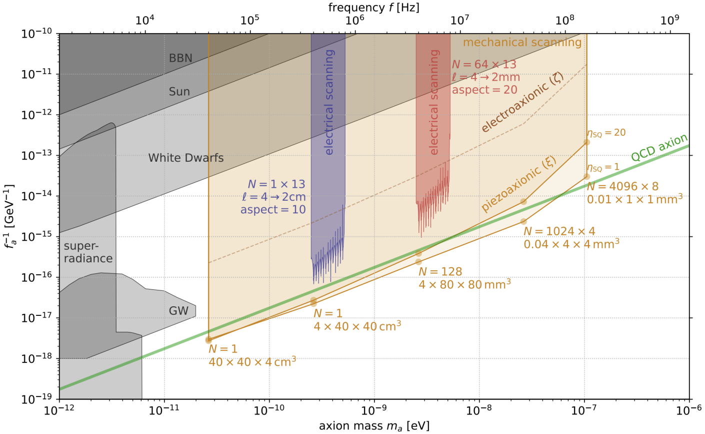
- Each crystal has a resonant acoustic frequency ω_0
- In piezoelectric crystals, this frequency can be pushed to MHz (allows for detecting axion masses in MHz – GHz)
- The idea is that when the axion-induced stress frequency matches the bulk acoustic frequency $m_a \simeq \omega_0$, the signal is enhanced
- This gives a measurable signal!
- Axion Signal Voltage:

$$V_a(\omega) = -\left[\frac{h_{11}\xi_{11}}{c_{11}^D}\frac{2v_D}{\omega}\tan\left(\frac{\omega l_1}{2v_D}\right) + \text{electroaxionic part}\right]\hat{\mathrm{I}}\theta_{\mathrm{a}}$$

- This voltage is obtained by solving the stress and electric field equations and integrating the electric field to obtain the voltage

Projected Sensitivity

- Their parameter space probes closely the QCD axion line.



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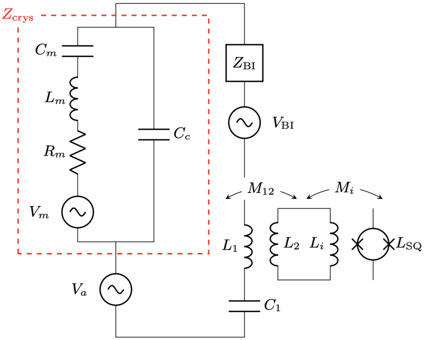
Challenges and Limitations

How do they scan for axion masses?

- Crystal connected to variable capacitance, inductors and resistance
- Varying them changes the impedance of the crystal, and this shifts the **circuit resonance frequency** ω_0
- This method is not very effective because the crystal's geometry limits it and it is too slow



Solution: nuclear spin precession tuning

Our Proposal: Nuclear Spin Precession Tuning

1. Apply a static magnetic field B_0 to polarize the nuclear spins along a chosen axis ($\hat{x}_1$) and wait until steady state ($t \gg T_1$).
2. Apply a short oscillating magnetic pulse perpendicular to the spins

$$\mathbf{B} = B_\perp f(t) \cos(\omega_D t) \hat{x}_\perp$$

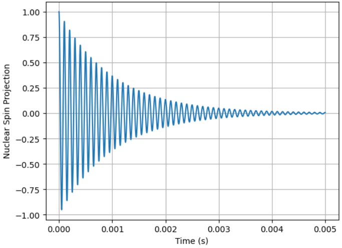
   which rotates the spins by 90°.
3. After the pulse is removed, the spins freely precess at the Larmor frequency

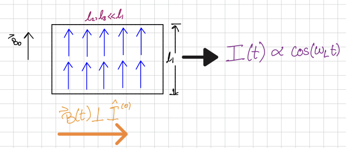
$$\omega_L = \gamma_N B_0.$$

4. The magnetization evolves as

$$I(t) \simeq I^{(0)} \cos(\omega_L t) e^{-t/T_2},$$

   where T_2 is the transverse relaxation time.



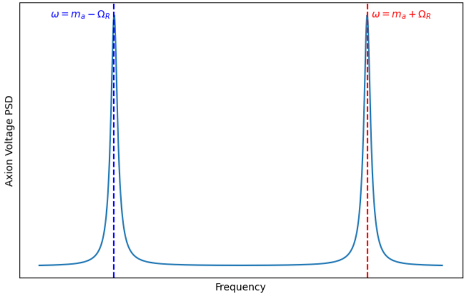


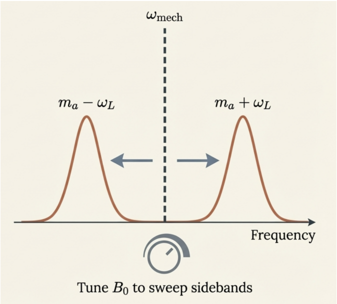
Dynamics

- Incorporating the oscillation of the nuclear spins, this allows for modulation of the axion mass, i.e., this gives us sidebands of $m_a \pm \omega_L$
- The new resonances are the side bands

$$\omega_0 = m_a \pm \omega_L$$

- **Tuning B_0 allows us to scan for axion masses m_a**



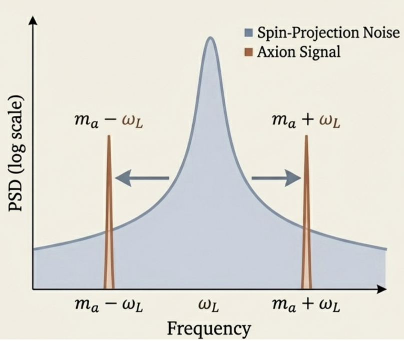


Noise Sources and Backgrounds

- Precessing spins introduce intrinsic quantum fluctuations (spin-projection noise)
- The spin noise induced voltage PSD can be found to be

$$S_{VV}^{\text{spin}} = \frac{l_2 l_3 \mu_N^2 n_N}{8\ell_1 (\beta^S)^2} \frac{T_2 \omega^2}{1 + T_2^2(\omega - \omega_L)^2} \approx 7 \times 10^{-11} (\text{Volts}/\sqrt{\text{Hz}})^2$$

- Dominates at Larmor frequency
- Due to the T_2, it gives a linewidth for the noise of order $\delta\omega \sim$ kHz which sets a lower bound on the axion masses we can probe
- Our heterodyned axion signal sits at $m_a \pm \omega_L$, cleanly avoiding the noise floor



- Solving the new Piezoelectric constitutive equations

$$T = c^D S - hD - \xi \left(\hat{I}^{(0)} \cos(\omega_L\, t)\right) \left(\bar{\theta}_a \cos(m_a\, t)\right),$$
$$E = -hS + \beta^S D + \zeta \left(\hat{I}^{(0)} \cos(\omega_L\, t)\right) \left(\bar{\theta}_a \cos(m_a\, t)\right).$$

- This gives the axion voltage as

$$V_a(\omega) = \underbrace{-\frac{h_{11}\xi_{11}}{c_{11}^D} \frac{2v_D}{\omega} (1 - \frac{i}{2}\delta_c) \tan\left(\frac{\omega l_1}{2v_D}\left(1 - \frac{i}{2}\delta_c\right)\right)}_{\chi(\omega) = \text{Response Function}} \qquad \underbrace{(\tilde{I}_1 * \tilde{\theta}_a)(\omega)}_{\text{Axion−Spin Modulated Signal}}$$

- $\delta_c \sim 10^{-9}$ represents the mechanical losses in the circuit (Very quality factor near mechanical resonance $Q \sim 10^9$)
- Using the found result, we compute the signal power spectral density (Which gives convolutions of Lorentzians) as

$$S_{VV}(\omega) = \underbrace{\left(\frac{h_{11}\xi_{11}}{c_{11}^D}\right)^2 \frac{8v_D^2}{\pi} \frac{1}{(\omega - \omega_n)^2 + (\frac{\delta_c}{2}\omega_0)^2}}_{\text{Detector Response very narrow!}} \times \underbrace{(I_1^{(0)})^2 (\bar{\theta}_a)^2 \sum_{\sigma=\pm} \frac{(1/T_2)}{(1/T_2)^2 + (\omega - (m_a + \sigma\Omega_R))^2}}_{\text{Axion−Nuclear Spin Modulated Signal}}$$

(Very) Preliminary Results (1)

- To synthesize our sensitivity plot, we make use of the Signal-To-Noise-Ratio (SNR), which is defined as

$$\mathrm{SNR} = \sqrt{t_{\mathrm{int}} \int \frac{d\omega}{2\pi} \left(\frac{S_{\mathrm{sig}}(\omega)}{S_{\mathrm{noise}}(\omega)} \right)^2}$$

- We require the SNR ≈ 1 to be able to see the signal
- Near the mechanical resonance $\omega = \omega_0 = m_a \pm \omega_L$ this gives us a sensitivity on f_a^{-1} vs m_a plane, which gives

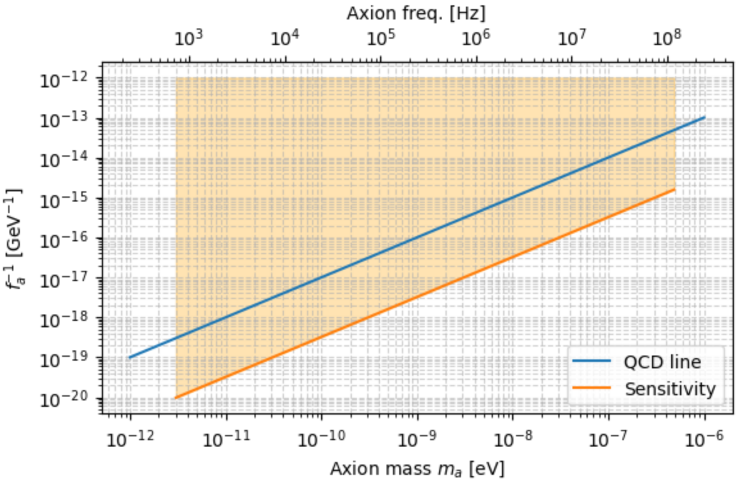
$$\boxed{f_a^{-1} \gtrsim 3 \times 10^{-9} \times \left(\frac{m_a}{1\,\mathrm{eV}} \right) \mathrm{GeV}^{-1}}$$

where the QCD line (Lattice calculations constraints) gives

$$f_a^{-1} \approx 10^{-7} \left(\frac{m_a}{1\,\mathrm{eV}} \right) \mathrm{GeV}^{-1}$$

(Very) Preliminary Results (2)

- Very preliminary sensitivity estimate
- We are still assessing other sources of noises
- We see that our sensitivity approaches the QCD axion band near the mechanical resonance



Summary and Future Work

- QCD axion DM can excite vibrational modes in piezoelectric crystals via its model-independent axion-gluon coupling
- Piezoelectric crystals provide a P violating backgrounds where particles can manifest interesting phenomena (The Piezoaxionic Effect)
- Need to take a deeper look at the thermal noise and mechanical noise, and try to minimize them
- The piezoaxionic effect offers a new, tunable, and noise-resilient path to searching for QCD axion dark matter in the MHz-GHz range

Thank you!

I welcome your questions.