

Searching for Axion Ultralight Dark Matter with Terrestrial Electromagnetic Signals

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What is Dark Matter?

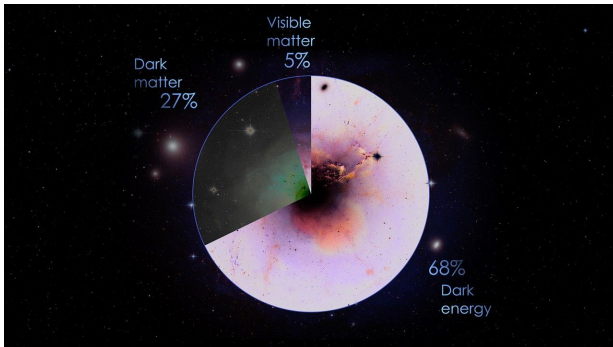
Ultralight Dark Matter and Axions

Earth as a Transducer

Constraining the Axion DM



What is Dark Matter?



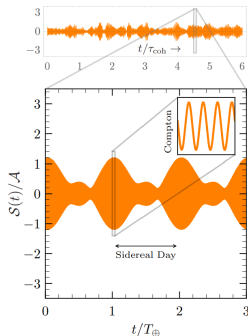
Ultralight Dark Matter and Axions

Why ultralight?

- Huge occupation number
- BOSONS
- Behaves as a coherent waves

AXIONS

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



Dorian W. P. Amaral, Mudit Jain, Mustafa A. Amin, Christopher Tunnell, *Vector Wave Dark Matter and Terrestrial Quantum Sensors*, 2024.



Coupling to Photons

1. Standard Maxwell's eq.

$$\begin{aligned}\nabla \cdot \mathbf{E} &= \rho, \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} + \partial_t \mathbf{B} &= 0, \\ \nabla \times \mathbf{B} - \partial_t \mathbf{E} &= \mathbf{J}.\end{aligned}$$

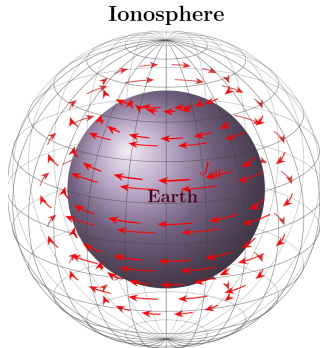
2. Modified Maxwell's eq.

$$\begin{aligned}\nabla \cdot \mathbf{E} &= \underbrace{g_{a\gamma} \nabla a \cdot \mathbf{B}_0}_{\rho_{\text{eff}}}, \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} + \partial_t \mathbf{B} &= 0, \\ \nabla \times \mathbf{B} - \partial_t \mathbf{E} &= \underbrace{-g_{a\gamma} [(\partial_t a) \mathbf{B}_0 + \nabla a \times \mathbf{E}_0]}_{\mathbf{J}_{\text{eff}}}.\end{aligned}$$

$\implies$ We need a background electromagnetic field to induce a signal!



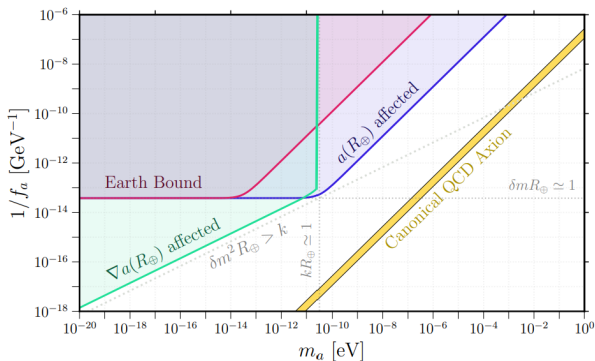
Earth as a Transducer



Arza, A., Fedderke, M. A., Graham, P. W., Jackson Kimball, D. F. & Kalia, S., *Earth as a transducer for axion dark-matter detection*, Phys. Rev. D **105** (2022), doi: 10.1103/PhysRevD.105.095007.



Axion Matter Effects



Banerjee, A., Bloch, I. M., Bonnefoy, Q., *Momentum and Matter Matter for axion Dark Matter matters on Earth,*

JHEP, 2026, doi: 10.1007/jhep06(2026)039.



Computing the Signal: Setup

Background: geomagnetic dipole field ($\ell = 1, m = 0$)

$$\mathbf{B}_0 \simeq B_p \frac{R^3}{r^3} \left(2 \cos \theta \hat{\mathbf{r}} + \sin \theta \hat{\boldsymbol{\theta}} \right), \quad B_p = \frac{g_{10} - i h_{10}}{2}$$

Axion field at the surface (monopole, with matter effects)

$$a(R) = \frac{e^{-ikR} a_0}{-ikR + \beta}, \quad \beta = qR \cot(qR), \quad q^2 = k^2 + \delta m^2$$

- **Cavity:** Earth + ionosphere form a spherical cavity of height h
- **Boundary condition:** $E_{\parallel} = 0$ at $r = R$ and $r = R + h$



Signal Fields at the Surface

Magnetic field

$$|B| \sim g_{a\gamma} |a(R)| B_p \omega R$$

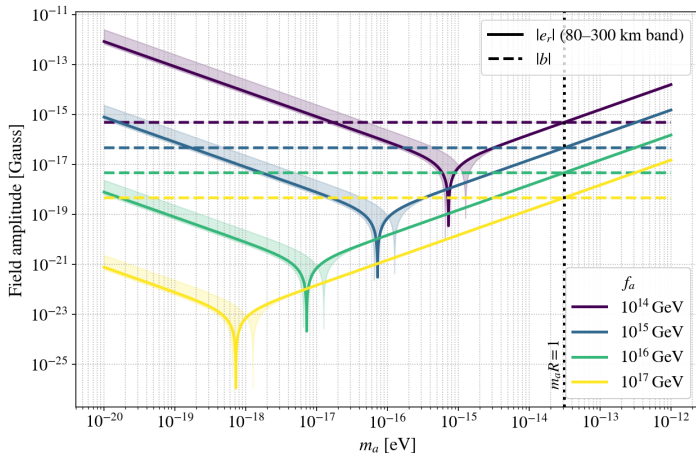
Electric field

$$|E_r| \sim g_{a\gamma} |a(R)| B_p \left[\omega^2 R^2 + \frac{h}{R} (\beta - 1) \right]$$

Red term: new contribution from matter effects
 $\implies$ it can strongly enhance the electric field!



Electric vs. Magnetic Field



E can dominate over B by orders of magnitude for small m_a and f_a .



Searching for the Signal in Real Data

GLOCAEM data: Kakioka Observatory (Japan)

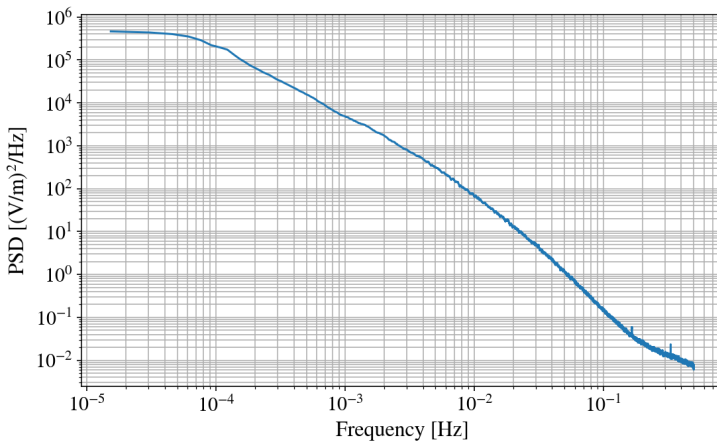
- Electric potential gradient, 1 s sampling, 2021
- Quiet days only: $\text{Var} < 1000 \text{ (V/m)}^2$ (~ 180 of 316 days)
- Power spectral density per day (Welch), then the **median**
- Mass range: $6 \times 10^{-20} \lesssim m_a \lesssim 2 \times 10^{-15} \text{ eV}$

Sensitivity estimate

$$\text{SNR} = \frac{E_{\text{sig}}^2 T_{\text{eff}}}{2 S_N} \sim 1 \implies \text{limit on } g_{a\gamma}$$



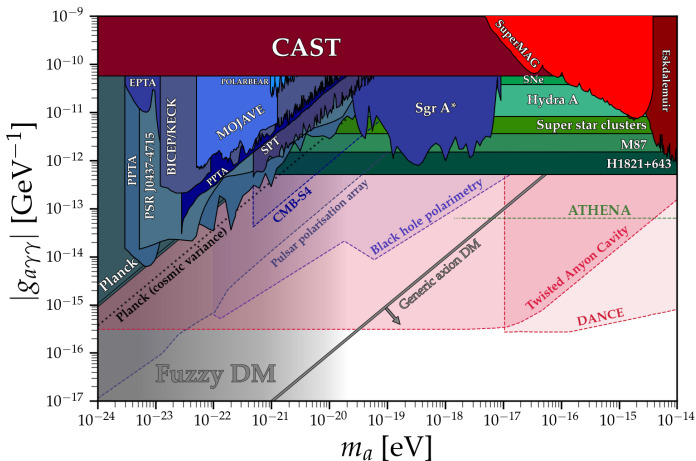
Noise Spectrum of the Electric Field



Median PSD of one year of filtered Kakioka data.



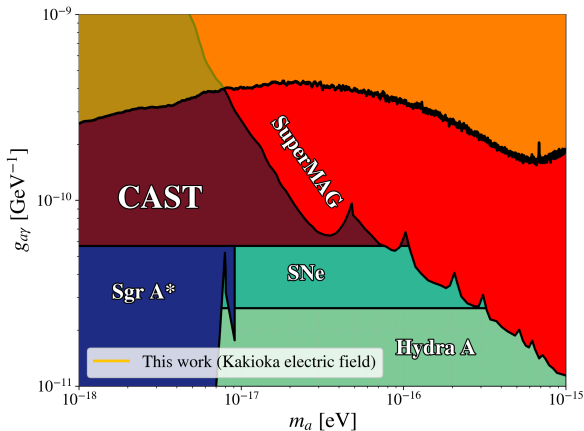
Landscape of UL Axion Searches



Constraints on axion–photon coupling adapted from the community-compiled AxionLimits database (O’Hare, 2020).



Our Results



Complementary to SuperMAG (with different systematics) and potentially leading *terrestrial* constraint beyond astrophysical bounds.



Conclusion and Outlook

What we found

- The Earth acts as a transducer for ultralight axion dark matter
- Matter effects enhance the field gradient and give a sizeable **electric** signal
- First electric-field search: competitive bounds on $g_{a\gamma}$

Next steps

- Include finite conductivity of atmosphere and ionosphere
- More data and more sensitive electric-field measurements



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Thank you! Questions?



Axion Matter Effects

Effective Lagrangian

$$\mathcal{L} = -\sigma_N \bar{N} N \sqrt{1 - \beta \sin^2 \left(\frac{a}{2f_a} \right)} \simeq \frac{1}{2} \frac{z}{(1+z)^2} \sigma_N \bar{N} N \frac{a^2}{f_a^2}.$$

Earth as a uniform sphere $\begin{cases} (\square + m_a^2)a(\mathbf{r}, t) = 0, & r > R, \\ (\square + m_a^2 - \delta m^2)a(\mathbf{r}, t) = 0, & r < R. \end{cases}$

Axion field $\begin{cases} a_\omega^{\text{out}}(r, \theta) = a_0 \sum_{\ell=0}^{\infty} (2\ell+1) i^\ell j_\ell(kr) P_\ell(\cos \theta) + \sum_{\ell=0}^{\infty} c_\ell^{\text{out}} h_\ell^{(1)}(kr) P_\ell(\cos \theta), \\ a_\omega^{\text{in}}(r, \theta) = \sum_{\ell=0}^{\infty} c_\ell^{\text{in}} j_\ell(qr) P_\ell(\cos \theta). \end{cases}$

