A hunt for magnetic signatures of hidden photon and axion dark matter in the wilderness

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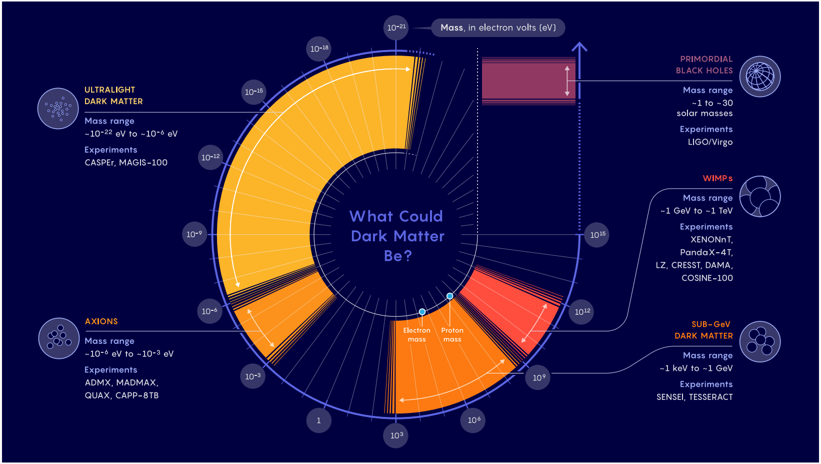
June 9, 2023

Bucknell University

The SNIPE Hunt Collaboration

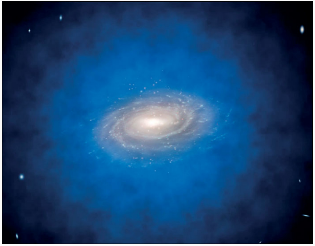
The Dark Matter Landscape

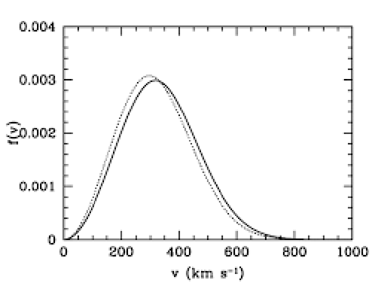


Samuel Velasco/Quanta Magazine

On Axion and Dark Photon Dark Matter

- bosonic S=0 for axion, S=1 for DP
- Have high mode occupation





- Classical wave with frequency $\omega_c = mc^2/\hbar$.
- The standard halo model suggests that $T_{coh} = 1/\Delta\omega \sim 10^6/\omega$

Coupled photon / dark photon system

The SM is extended by a new (kinetically mixed) gauge field.

In the Interaction basis:

$$L \subset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \left(\varepsilon m_{A'}^2 A'^\mu - J^\mu_{EM}\right) A_\mu$$

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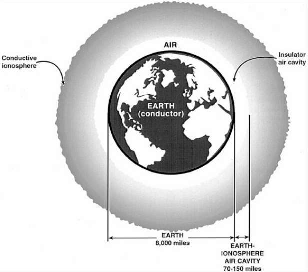
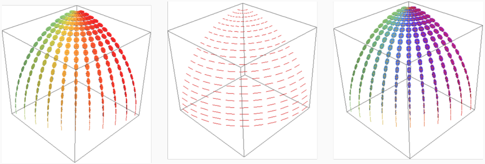
- We have an interacting mode A_μ and a sterile mode A'_μ
- Only the interacting mode A_μ couples with matter
- We can define an effective current $\boldsymbol{J}^\mu_{eff}(\boldsymbol{x}, t) = -\varepsilon m_{A'}^2 \boldsymbol{A}'^\mu(\boldsymbol{x}, t)$

Signal on Earth

Knowing the boundary conditions and the source term, we can solve the modified Maxwell equations to determine the magnetic field pattern over the surface of the Earth!



$$\nabla \times \boldsymbol{B} = \boldsymbol{J}_{\text{eff}}.$$



"Earth as a transducer for dark photon dark matter"
Fedderke et al. Phys. Rev. D 104, 075023 (2021)
Fedderke et al. Phys. Rev. D 104 095032 (2021)

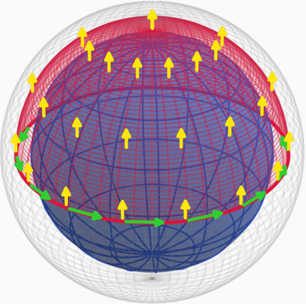
Signal Pattern over Earth

Assume J_{eff} is along the rotation axis of Earth.

Application of Ampere's Law yields

$$BR \sim \oint \mathbf{B} \cdot dl \approx \iint J_{eff} \cdot dA \sim \varepsilon m_{A'}^2 R^2 A'$$

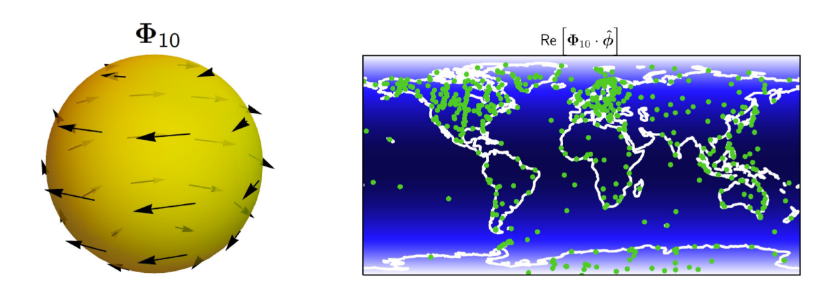
$$B \sim \varepsilon m_{A'}^2 R \sqrt{\rho_{DM}}$$



The Magnitude of the measurable signal goes as R!

Signal Pattern over Earth

would be in $\mathbf{\Phi}_{1,m}$ modes



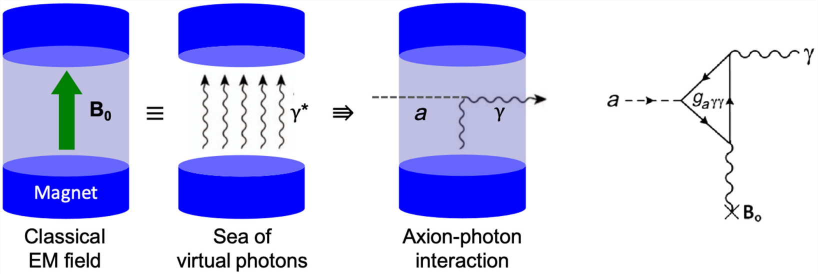
Distribution of magnetometer stations in SuperMag dataset

measured signals are projected onto expected modes

$$\mathbf{B}(\Omega_i, t_j) \cdot \mathbf{B}_i(t_j) \propto Re\left[\sum_m A'_m(t_j)\mathbf{\Phi}_{1m}(\Omega_i) \cdot \mathbf{B}_i(t_j)\right]$$

Phys. Rev. D 104, 075023

On Axions and their detection

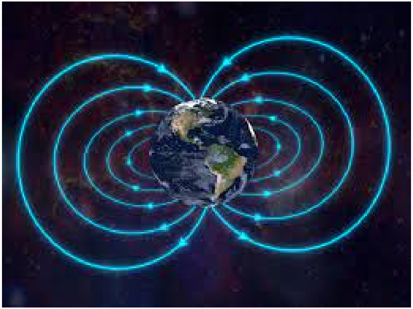


$$\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J} - g_{a\gamma} (\partial_t a) \mathbf{B}$$

$$J_a = i g_{a\gamma} a_0 m_a B_0 e^{-i m_a t},$$

On Axions and their detection



$$J_a = i g_{a\gamma} a_0 m_a B_0 e^{-i m_a t},$$

Earth's field can be modeled and spatial distribution of axion induced mag field on Earth determined.

"Earth as a transducer for axion dark-matter detection"
Arza et al. Phys. Rev. D 105, 095007 (2022)

Search for Non-Interacting Particle Experiment

The SNIPE - Hunt aims to search for DPDM using earth as a transducer over the 1 - 1000 Hz band.

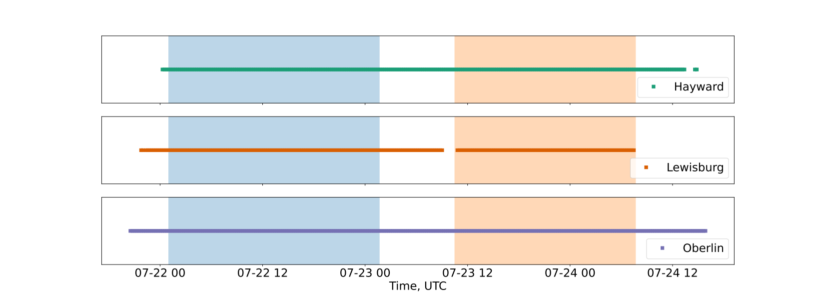
- A purpose built array for DPDM search
- Aims to search over higher frequency band than supermag
- Plans to use more sensitive magnetometers
- Currently 3 stations (Cal-State University East-Bay, Oberlin College, and Bucknell University)
- Proof of principle measurement made last July

Choosing a site

Magnetometers are located away from man-made magnetic noise sources.

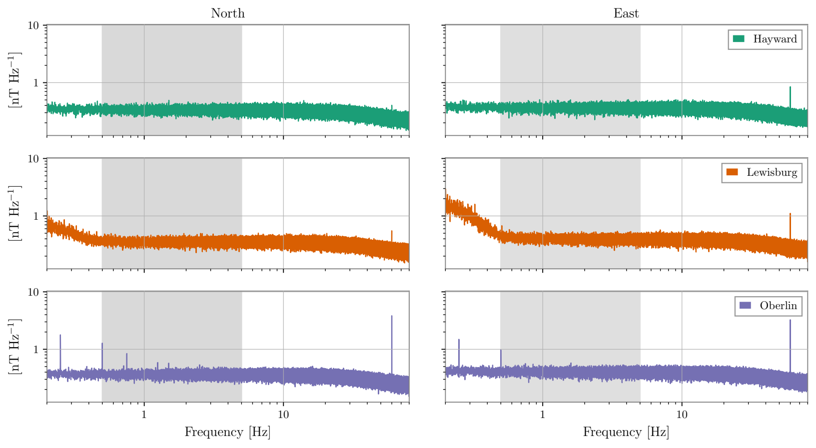
Station Activity

- Measurement campaign over 3 days in July
- Stations located in isolated locations far from man-made noise
- Commercial GMR sensors used (Twinleaf VMR)



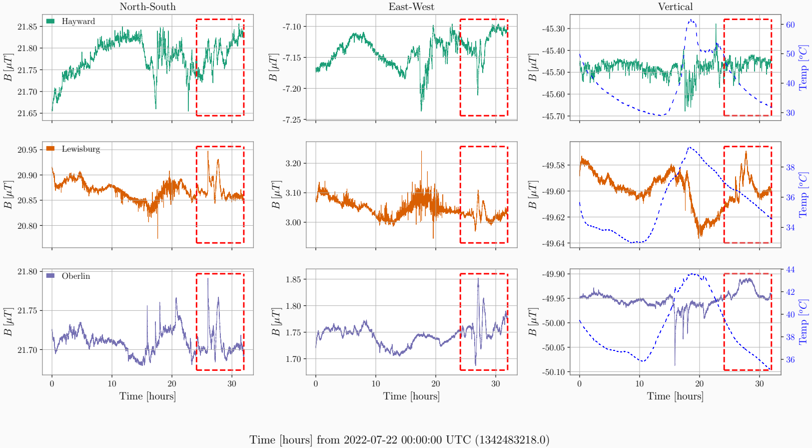
scan-1, scan-2 analyzed independently as a cross-check.

Power Spectra



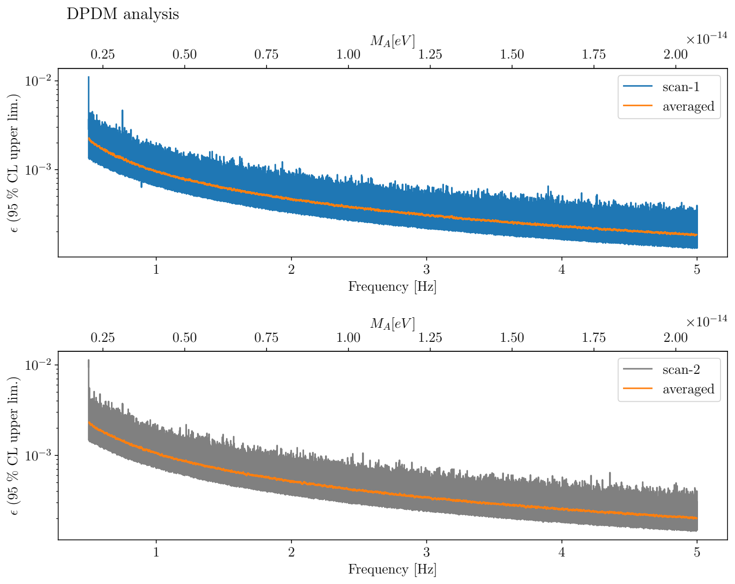
- Sensitivity at the $300pT/\sqrt{Hz}$ level.
- There is plenty of room to improve

Time Series

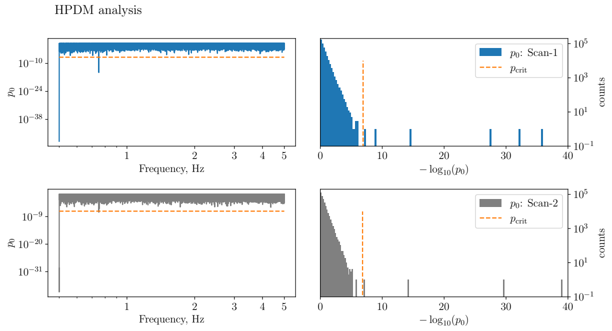


Thunderstorms and geomagnetic storms are clearly evident

Limits on ε

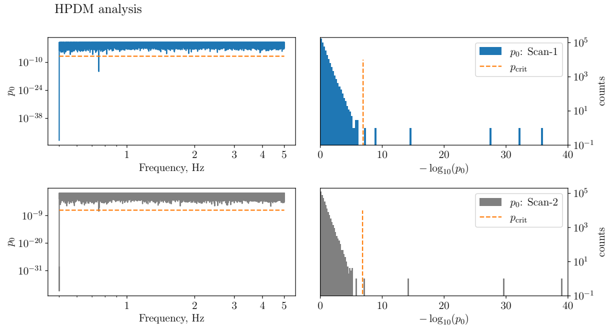


Candidate Events

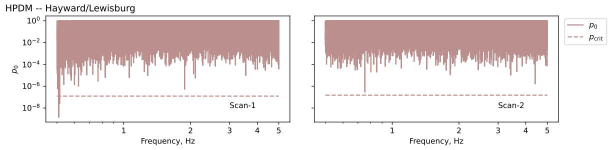


Some frequencies appear significant.

Candidate Events

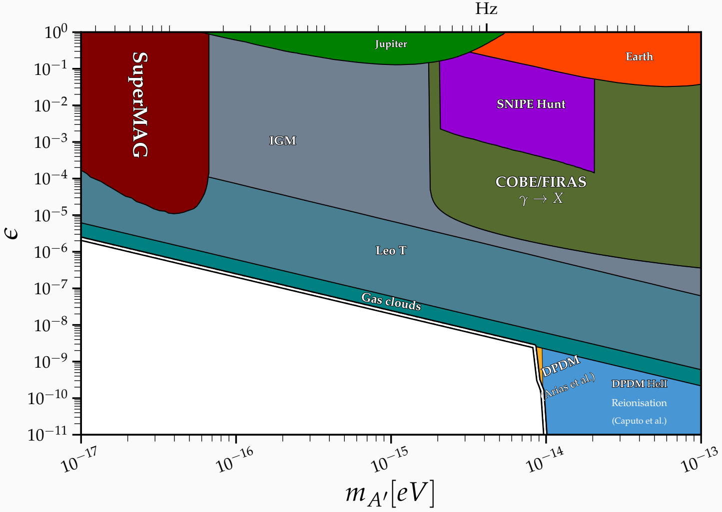


Some frequencies appear significant.



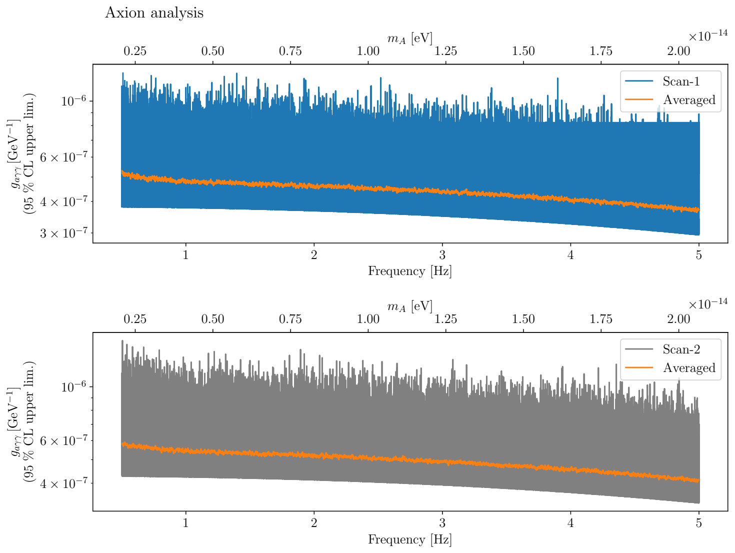
But are artefacts of a single station

Limits

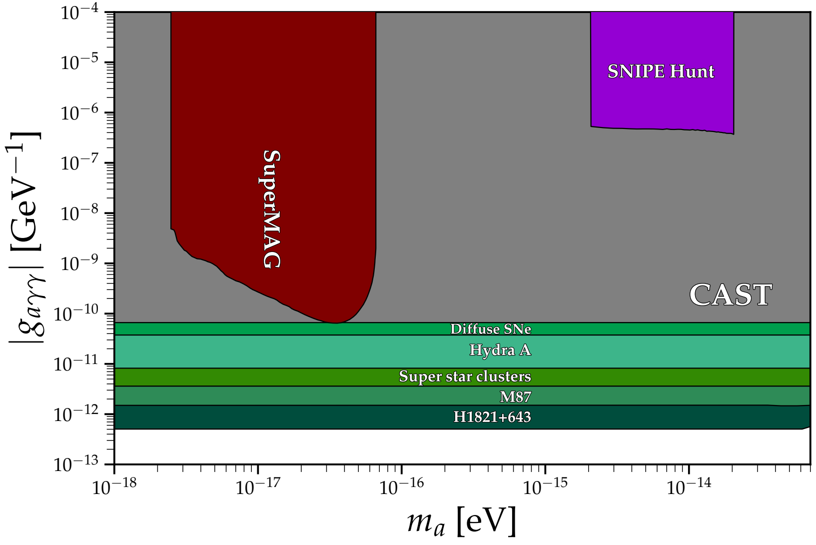


Hz
SuperMAG
Jupiter
Earth
IGM
SNIPE Hunt
COBE/FIRAS
$\gamma \to X$
Leo T
Gas clouds
DPDM
(Arias et al.)
DPDM HeII
Reionisation
(Caputo et al.)
ϵ
$m_{A'}[eV]$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-17}
10^{-16}
10^{-15}
10^{-14}
10^{-13}

Axion Limits



Axion Limits



Next Steps

- Gen - II experiment will use sensors with $fT/\sqrt{Hz}$ sensitivity
  - Atomic Mags – capable but technically challenging
  - $\sim$ meter long 50K turn Induction Coil magnetometers look promising
- Measure $\nabla \times B$ directly to minimize impact of boundary.
- Prelim Measurements planned for Summer 2023

The SNIPE Hunt Team

Theory

Saarik Kalia, Peter Graham, Michael Fedderke, Ariel Arza, Itay Bloch

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