Searching for ultralight dark matter from terrestrial magnetic fields

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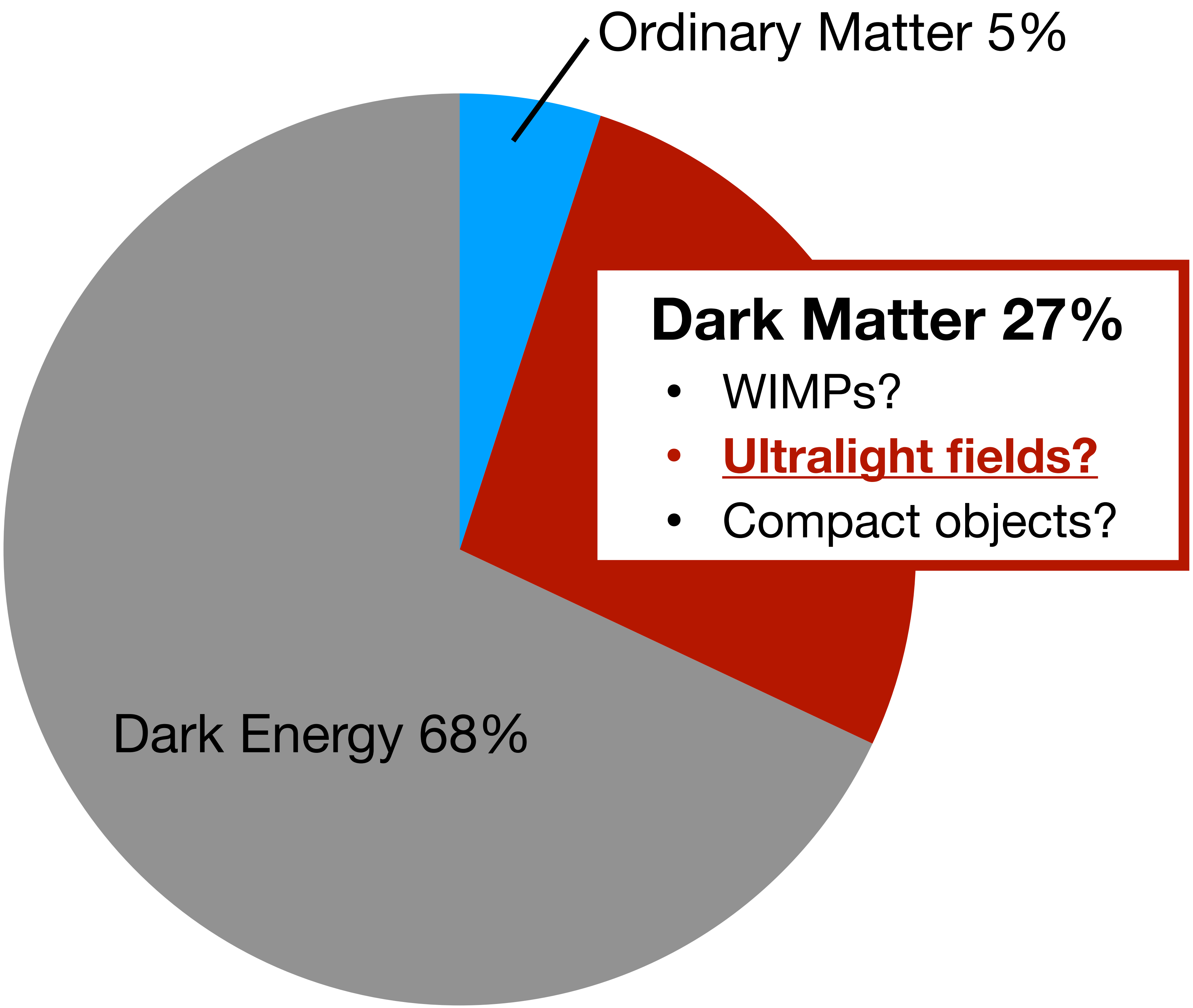
KN, A. Nishizawa, A. Taruya, Y. Himemoto, Phys.Rev.D 113 (2026) 10, L101303,
arXiv:2509.15783

COSMO-26, August 26


Ordinary Matter 5%
Dark Matter 27%
• WIMPs?
• Ultralight fields?
• Compact objects?
Dark Energy 68%

Ultralight DM

Typical velocity in the Galaxy

- **Bosonic fields with masses** $m \sim 10^{-23}$**–**1 **eV**

  de Broglie wavelength $\lambda \sim \dfrac{2\pi}{mv} \sim 10^{8}\,\mathrm{km}\left(\dfrac{10^{-14}\,\mathrm{eV}}{m}\right)\left(\dfrac{10^{-3}}{v}\right)$

  Huge occupation number → Classical waves

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- **Scalar fields ϕ (e.g. axion-like particles)**

$$\ddot{\phi} - (\cancel{\nabla^2} - m_\phi^2)\,\phi = 0 \quad \rightarrow \quad \phi \approx \bar{\phi}\, e^{-im_\phi t}$$

$$f_\phi = \frac{m_\phi}{2\pi} \approx 2.4\,\mathrm{Hz}\left(\frac{m_\phi}{10^{-14}\,\mathrm{eV}}\right)$$

Energy density: $\rho_\phi \approx \dfrac{m_\phi^2\,\bar{\phi}^2}{2}$

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- **Massive vector fields $\mathbf{A}'$ (dark photons)**

$$\ddot{\mathbf{A}}' - (\cancel{\nabla^2} - m_{A'}^2)\,\mathbf{A}' = 0 \quad \rightarrow \quad \mathbf{A}' \approx \bar{\mathbf{A}}'\,e^{-im_{A'}t}$$

$$f_{A'} = \frac{m_{A'}}{2\pi} \approx 2.4\,\mathrm{Hz}\left(\frac{m_{A'}}{10^{-14}\,\mathrm{eV}}\right)$$

Energy density: $\rho_{A'} \approx \dfrac{m_{A'}^2 |\bar{\mathbf{A}}'|^2}{2}$

Coupling to Photons

Axion-like particle a

Axion-photon
coupling constant

$$\mathscr{L}_{\text{int}} = \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Field strength of Standard
Model photons

$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$

Dark photon A'_μ

Kinetic mixing
parameter

$$\mathscr{L}_{\text{int}} = \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

Standard Model photons

Field strength of dark photons

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In the presence of couplings ($g_{a\gamma}$ or ε), dark matter should induce detectable signals in electromagnetic experiments and observations.

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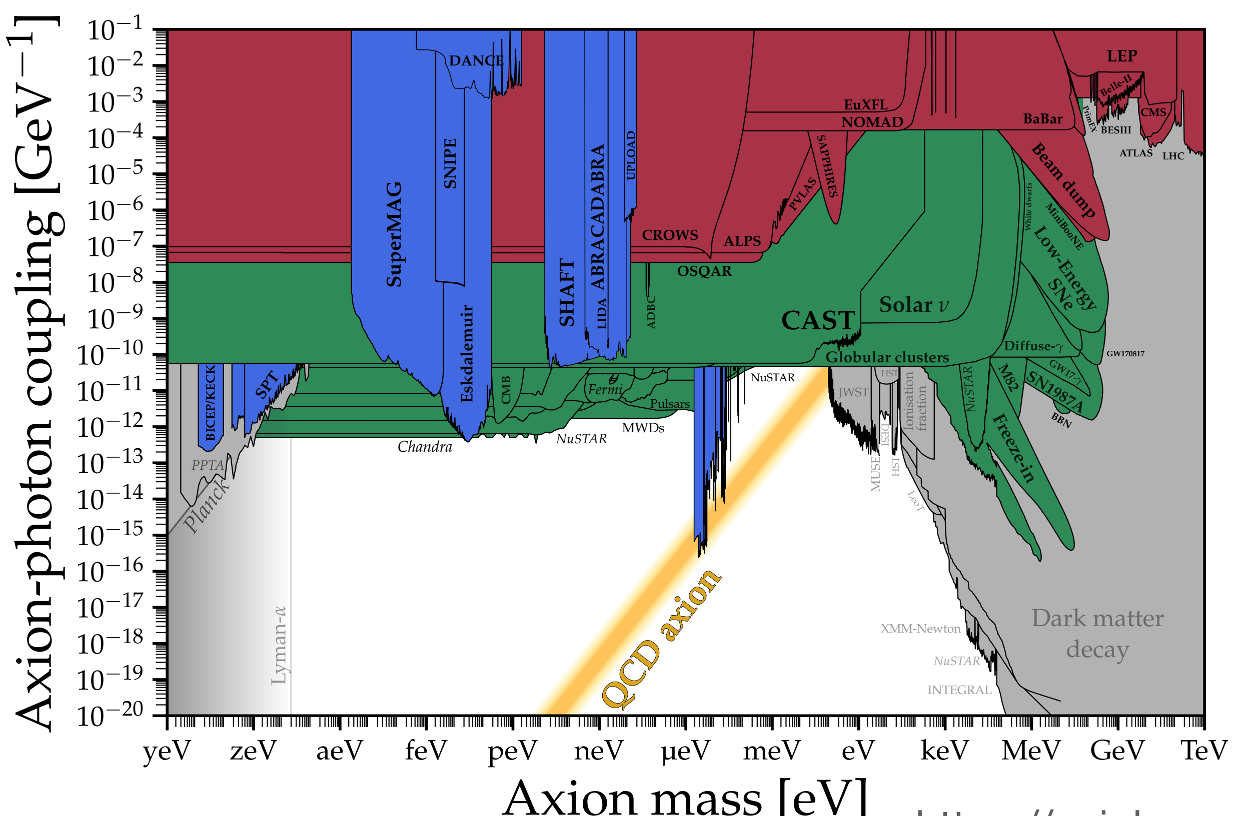
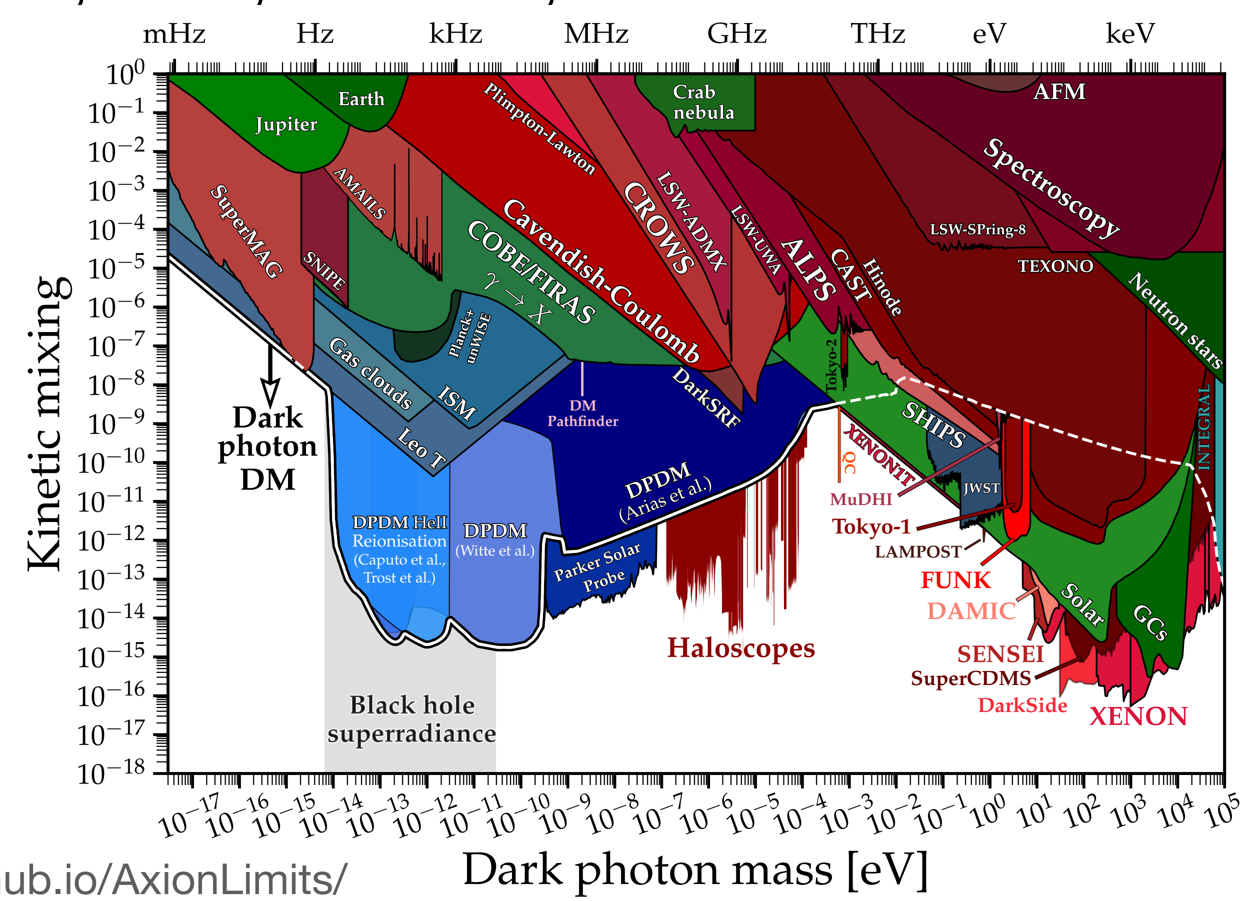




https://cajohare.github.io/AxionLimits/

Key Idea of This Work

Axion or dark-photon dark matter surrounding the Earth can induce magnetic fields at the Earth's surface through its coupling to photons.
→ Terrestrial magnetic-field observations provide a probe of dark matter.

We performed
- **theoretical predictions of the induced magnetic fields,**
- **an analysis of real terrestrial magnetic data.**

- Axion DM: Taruya, Nishizawa, Himemoto, PTEP 2025 (2025) 11, 111E01
  (See also Nishizawa, Taruya, Himemoto, arXiv:2504.07559 & Taruya, Nishizawa, Himemoto, arXiv:2509.14673)
- **Dark-photon DM: KN, Nishizawa, Taruya, Himemoto, PRD 113 (2026) 10, L101303**

Predictions of the Induced Magnetic Fields

Induced Magnetic Fields

Maxwell equations

Kinetic mixing parameter

$$\partial_\nu F^{\nu\mu} = -\,\varepsilon\,\partial_\nu F'^{\nu\mu}$$

Dark-photon DM: $\mathbf{A}' \approx \bar{\mathbf{A}}' e^{-im_{A'}t}$

We consider an atmospheric medium.

Refractive index　　Electric field

Displacement field $\mathbf{D} = n^2\mathbf{E}$

$$\boxed{\begin{gathered}\nabla\cdot\mathbf{D} = 0 \\ \nabla\times\mathbf{B} - \dot{\mathbf{D}} = \underline{\varepsilon\, m_{A'}^2\, \bar{\mathbf{A}}' e^{-im_{A'}t}}\end{gathered}}$$

Effective current $\mathbf{J}_{\rm eff}$

<u>Rough estimate</u>

Integrating $\nabla\times\mathbf{B} \sim \mathbf{J}_{\rm eff}$ over an erea of radius R → $B\,R \sim J_{\rm eff}\,R^2$.

Setting $R \sim$ Earth's radius, we obtain

$$B \sim 0.03\ \mathrm{pT}\left(\frac{\varepsilon}{10^{-8}}\right)\left(\frac{m_{A'}}{10^{-14}\ \mathrm{eV}}\right)\left(\frac{\rho_{A'}}{0.3\ \mathrm{GeV/cm^3}}\right)^{1/2}$$

Induced Magnetic Fields

<u>More accurate treatment</u>

The induced magnetic field $\mathbf{B}$ is expanded in vector spherical harmonics.

Monochromatic

$$\mathbf{B} = -\, i\, \varepsilon\, m_{A'}\, e^{-i m_{A'} t}\, b(x) \sum_{m=-1}^{+1} \bar{A}'_m\, \mathbf{\Phi}_{1,m}(\theta, \phi)$$

$x \equiv m_{A'} r$

$\mathbf{\Phi}_{\ell,m} \equiv \mathbf{r} \times \nabla Y_{\ell,m}$

Only the $\ell = 1$ mode is induced.
(Dipolar nature of dark photon)

The Maxwell equations reduce to a radial equation for the mode function $b(x)$:

$$\left(\frac{d}{dx} \frac{1}{n^2} \frac{d}{dx} + 1 - \frac{2}{n^2 x^2} \right) (x\, b(x)) = -\, i \sqrt{\frac{4\pi}{3}}\, x \frac{d}{dx} \frac{1}{n^2}$$

Boundary conditions

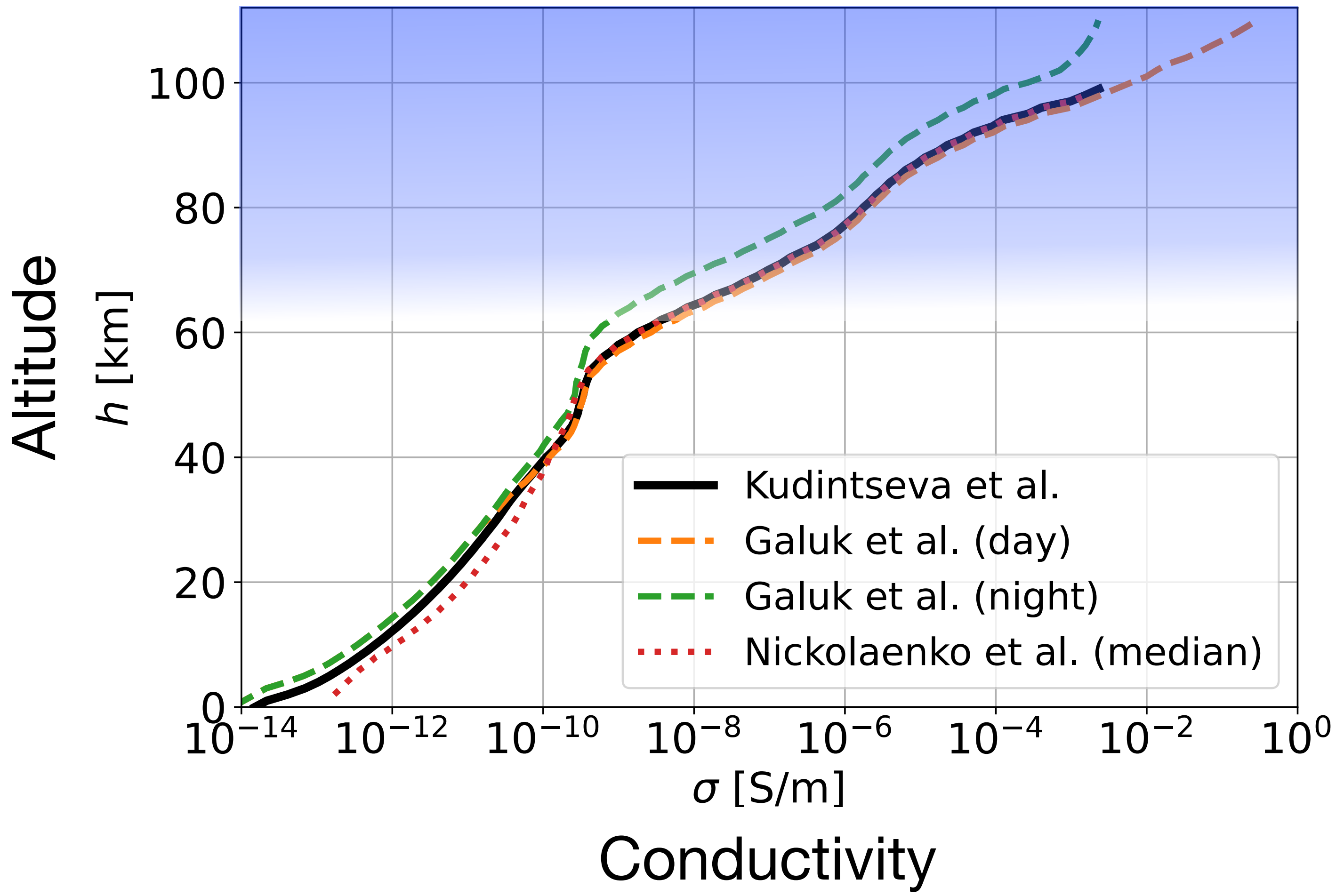
- $\mathbf{E}_{\parallel} = 0$ at the Earth's surface
- Outgoing-wave in the upper atmosphere

Induced Magnetic Fields

Atmospheric conductivity σ is an important factor.

Displacement field $\mathbf{D} = n^2 \mathbf{E}$; Refractive index $n^2 = 1 + i\frac{\sigma}{\omega}$ for $\mathbf{E} \propto e^{-i\omega t}$.

The atmospheric conductivity depends on altitude.



Electromagnetic waves are screened/attenuated by the ionosphere ($h \gtrsim 60$ km).

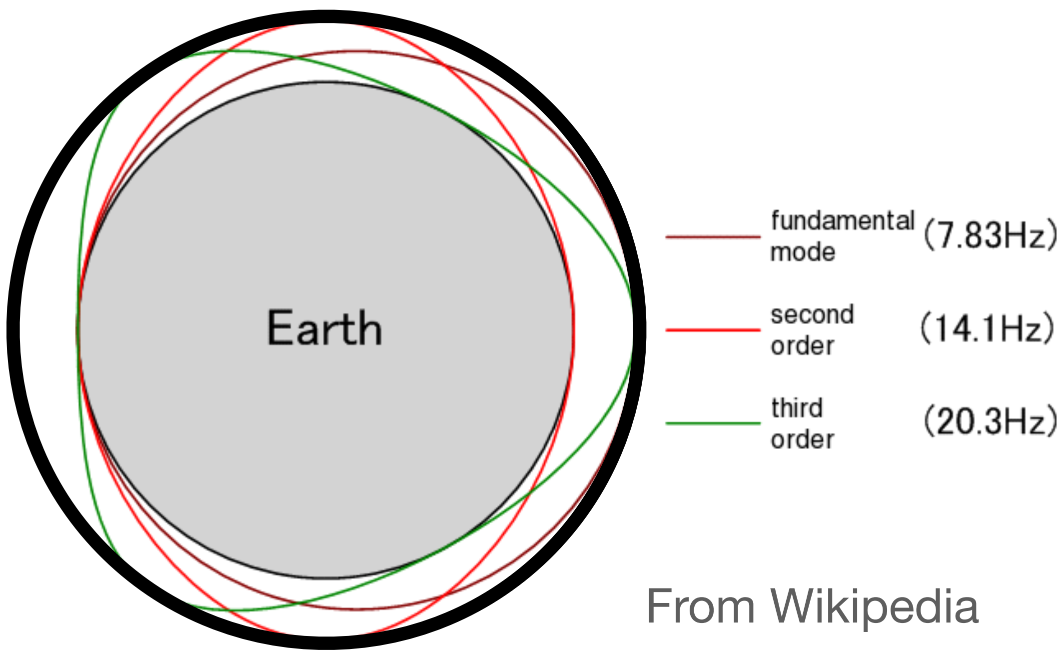
Induced Magnetic Fields

The Earth's surface and the ionosphere act as conducting boundaries.
→ Forming an "Earth-ionosphere cavity."

When the wavelength of electromagnetic waves becomes comparable to the Earth's circumference, resonant modes appear in the Earth-ionosphere cavity: **Schumann resonances.**

[Schumann 1952]

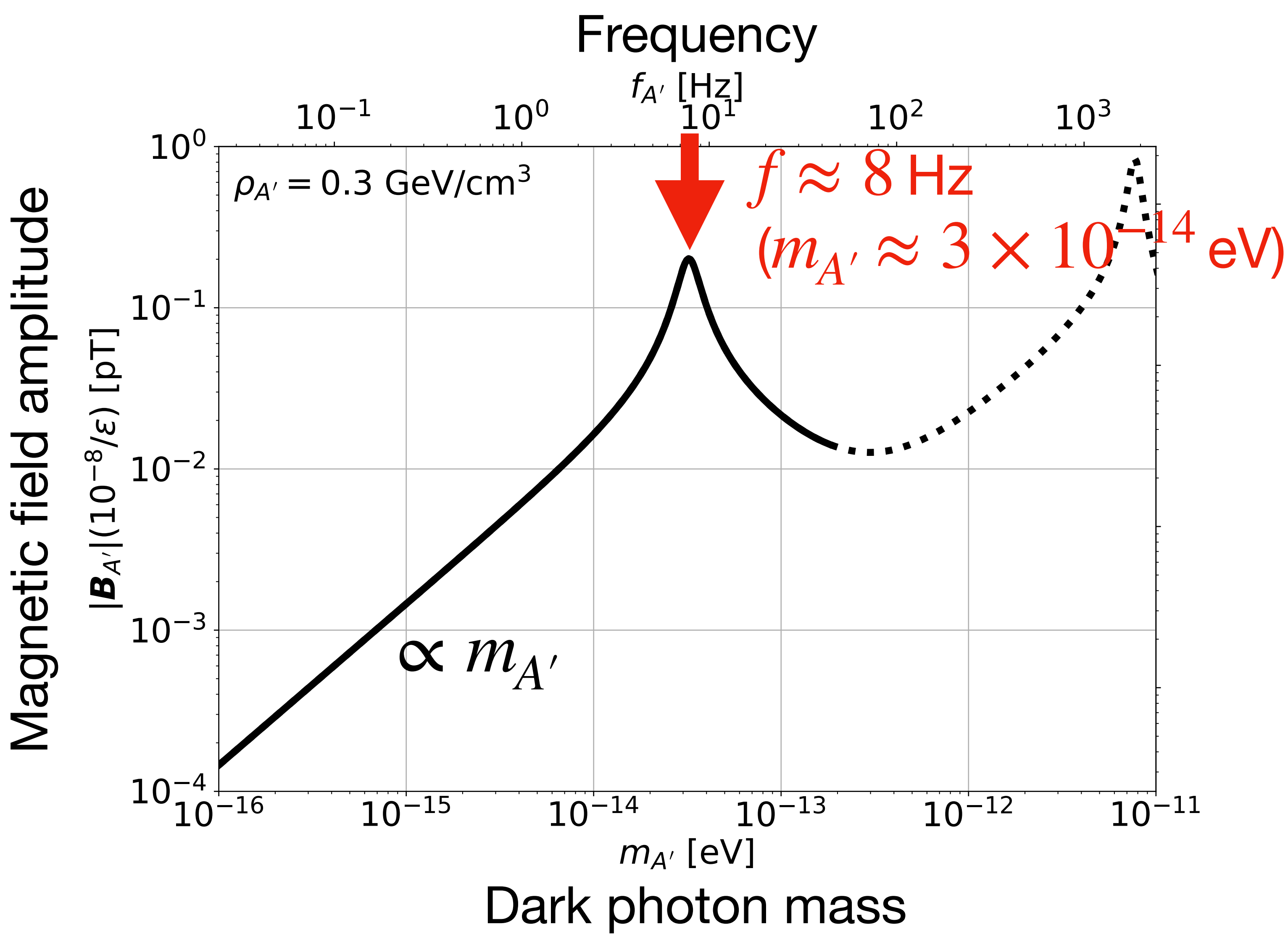
The $\ell = 1$ resonant mode is $f \approx 8$ Hz.



From Wikipedia

Induced Magnetic Fields

We calculated the induced magnetic field using the atmospheric conductivity profile [Kudintseva et al. 2016].



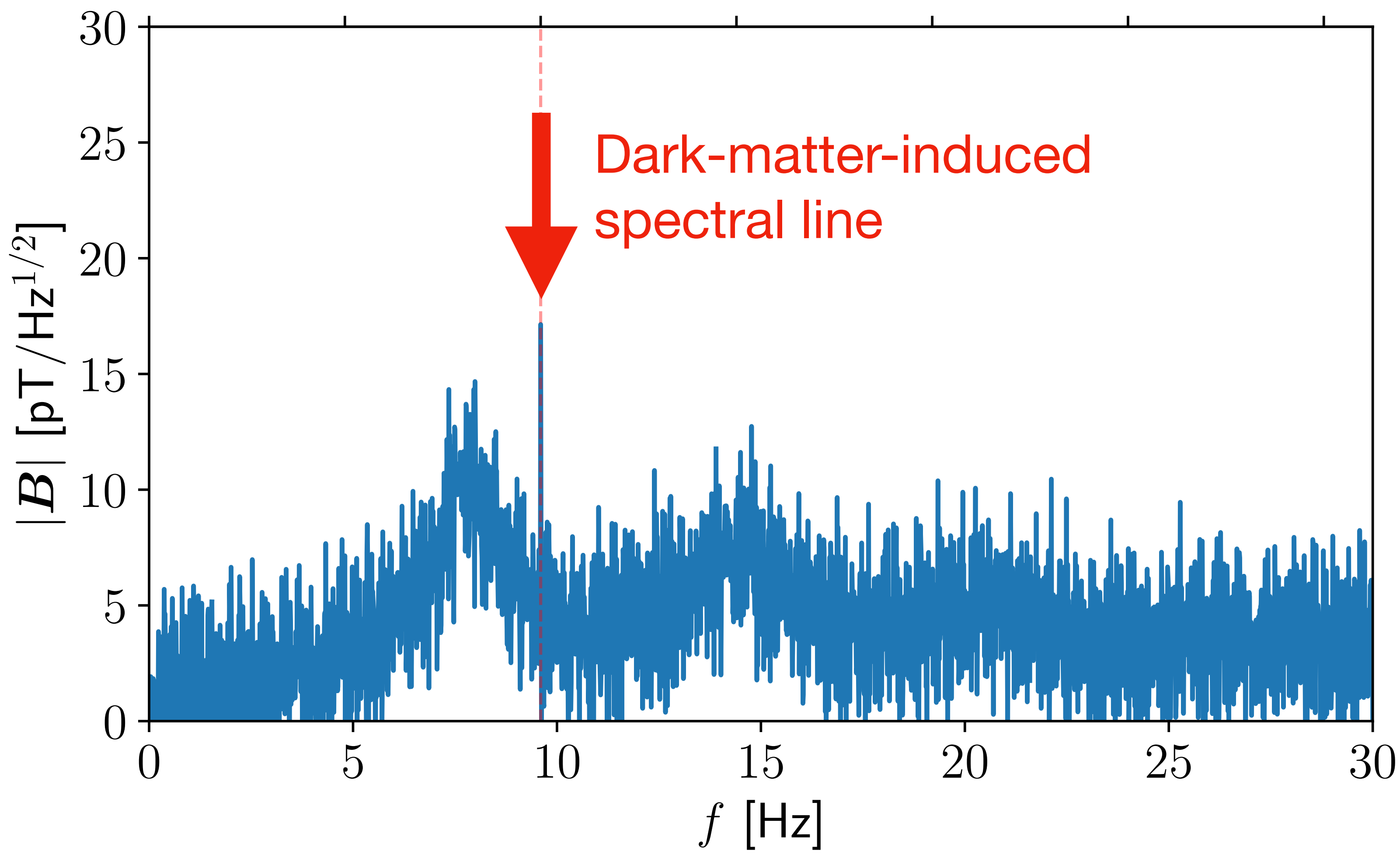
We also checked the robustness of the signal against day-night variations in atmospheric conductivity.

Magnetic-field Data Analysis

Expected Signal

The induced magnetic field oscillates at a nearly monochromatic frequency determined by the dark matter mass.
→ It should appear as a narrow spectral line.

Schematic illustration of the observed spectrum

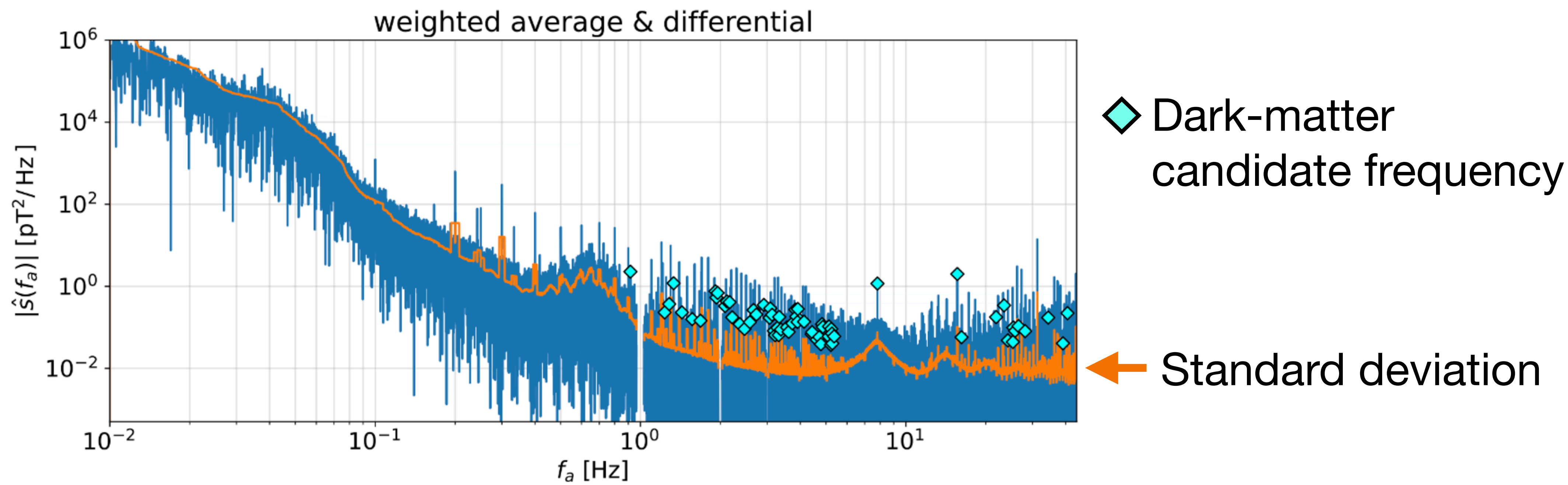


Magnetic-field Data Analysis

We used data from the Eskdalemuir Observatory (UK).

British Geology Survey Data (https://www.bgs.ac.uk/) from 2012—2022,

Sampled at 100 Hz → Sensitive to $m_{\mathrm{DM}} < 2 \times 10^{-13}$ eV.



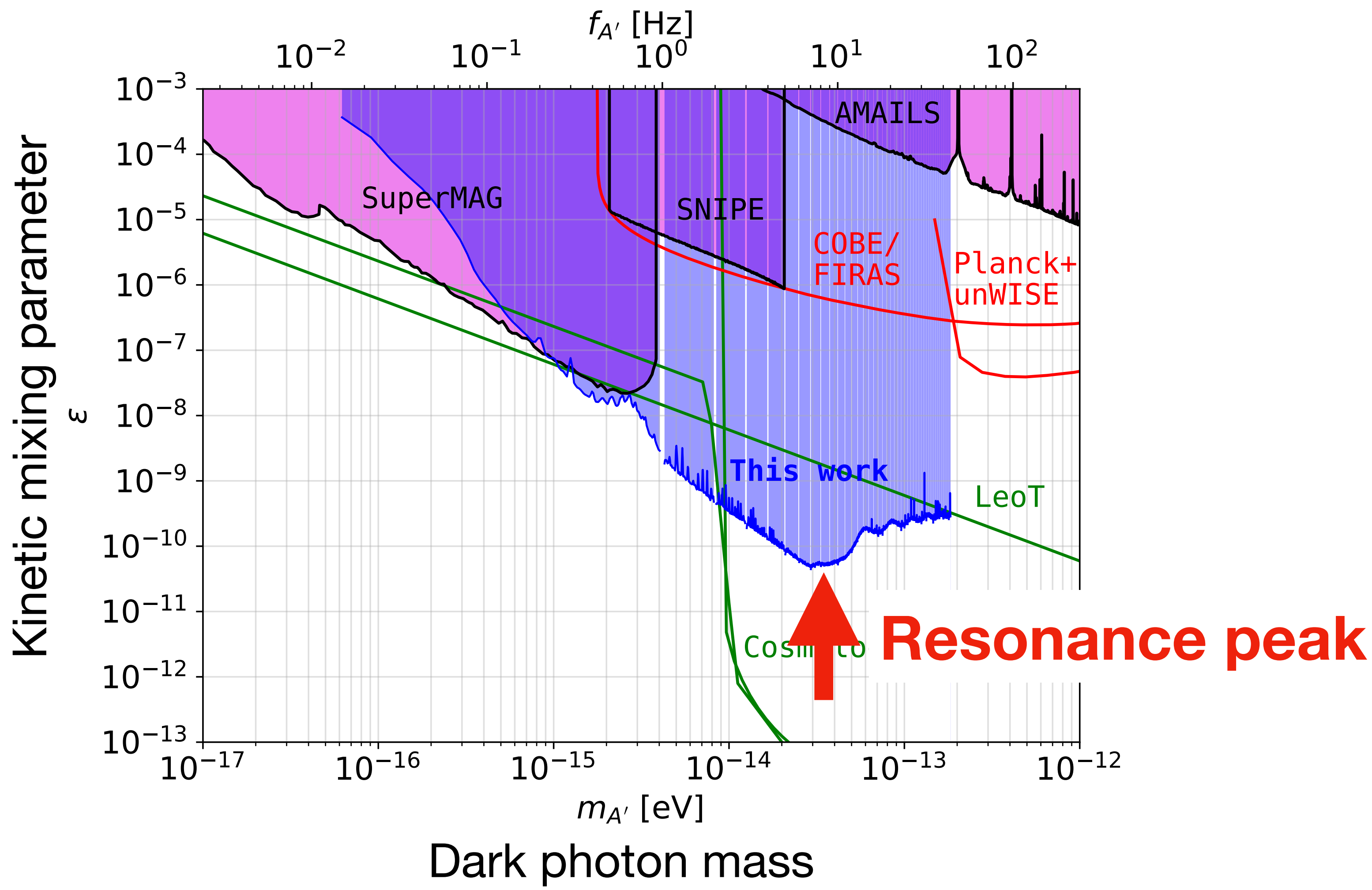
SNR threshold	all years	& persistency	& excluding neat frequencies
SNR > 14	5	5	0
SNR > 13	9	9	1
SNR > 12	14	14	1
SNR > 11	32	31	1
SNR > 10	46	41	1
SNR > 9	60	49	2
SNR > 8	96	74	9
SNR > 7	132	99	13
SNR > 6	183	131	22
SNR > 5	257	172	31
SNR > 4	473	270	50
SNR > 3	821	375	65
SNR > 2	26912	660	342

- We identified 342 candidate frequencies with SNR>2.
- In the present single-site analysis, we cannot distinguish whether the candidates originate from dark photons or axions.
  (Multi-site data may distinguish them through spatial signal patterns.)

Constraints on Photon-Coupling

For frequency bins where no signal candidates are found, we derive upper limits on the dark-photon—photon mixing parameter ε.

(Assuming the DM energy density $\rho_{\mathrm{DM}} = 0.3$ GeV/cm^3)



- Improves upon previous terrestrial experiments for 1×10^{-15} eV $\lesssim m_{A'} \lesssim 2 \times 10^{-13}$ eV.
- Stronger than astrophysical indirect constraints in some mass ranges.

Summary

- Ultralight bosonic dark matter surrounding the Earth can induce magnetic fields at the Earth's surface through its coupling to photons.
  → **Terrestrial magnetic field observations provide a probe of dark matter.**
- We calculated the dark-matter-induced magnetic-field signal, including the resonance peak in the Earth-ionosphere cavity.
- We searched for the magnetic-field signal using terrestrial magnetic field data for dark matter masses $\lesssim 2 \times 10^{-13}$ eV.
  - Multiple candidate spectral lines were found.
    Additional independent observations are needed to further narrow down the signal candidates.
  - Improving existing terrestrial limits on the dark-photon—photon mixing parameter ε for 1×10^{-15} eV $\lesssim m_{A'} \lesssim 2 \times 10^{-13}$ eV.