From SuperMAG to SNIPE Hunt:
Using the Earth to search for ultralight dark matter

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on behalf of the SNIPE Hunt Collaboration

PASCOS 2023

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Based on arXiv:2106.00022, 2108.08852, 2112.09620, 2306.11575, and forthcoming publication

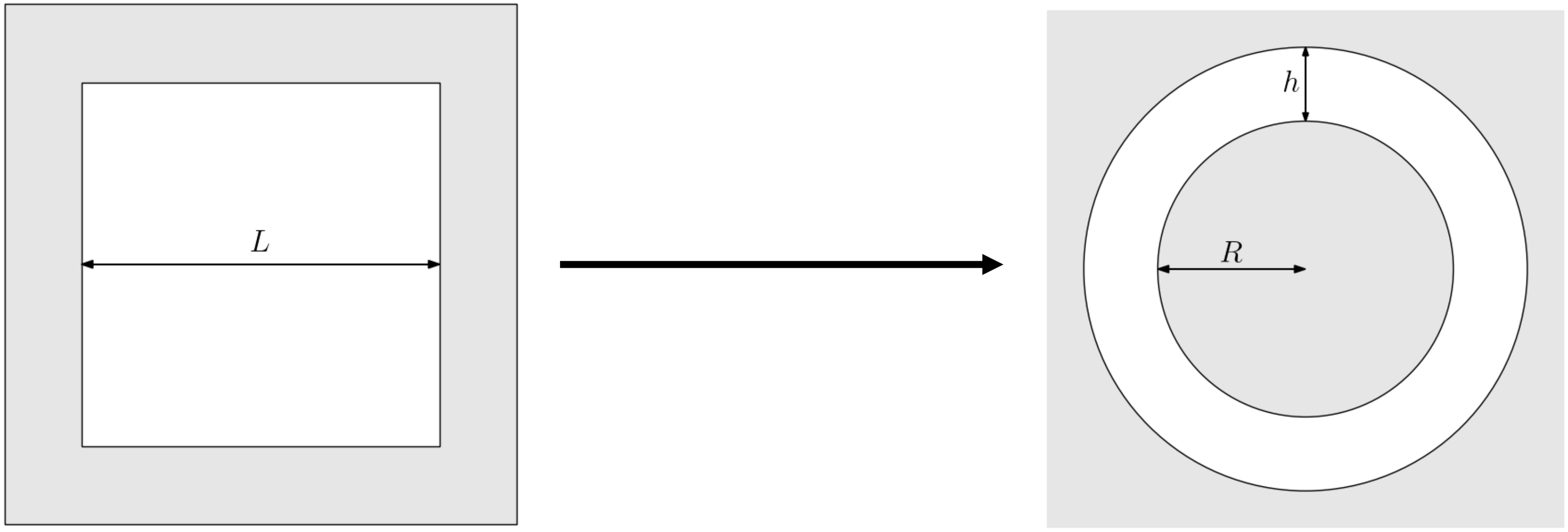
Earth as a transducer

- Shielded/cavity experiments search for ultralight EM-coupled DM:
  - Kinetically mixed dark photon
  - Axionlike particle
- Signal scales with size of apparatus
- DPDM constraints below 10^{-14} eV (sub-Hz) all astrophysical
- We use the Earth as our apparatus/transducer!
- Ultralight DM → oscillating magnetic field at Earth's surface

Earth as a transducer

DM Radio/ADMX

Earth



Earth as a transducer

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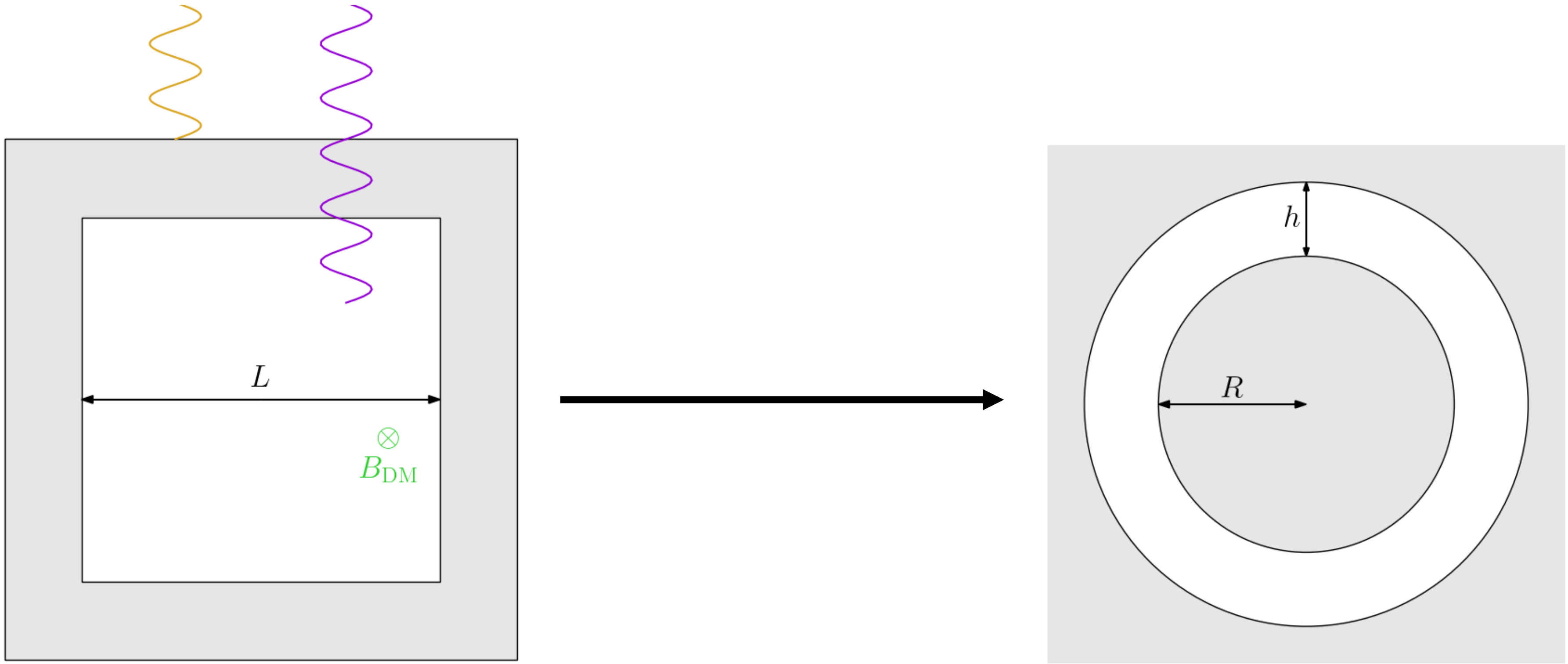
Earth



Earth as a transducer

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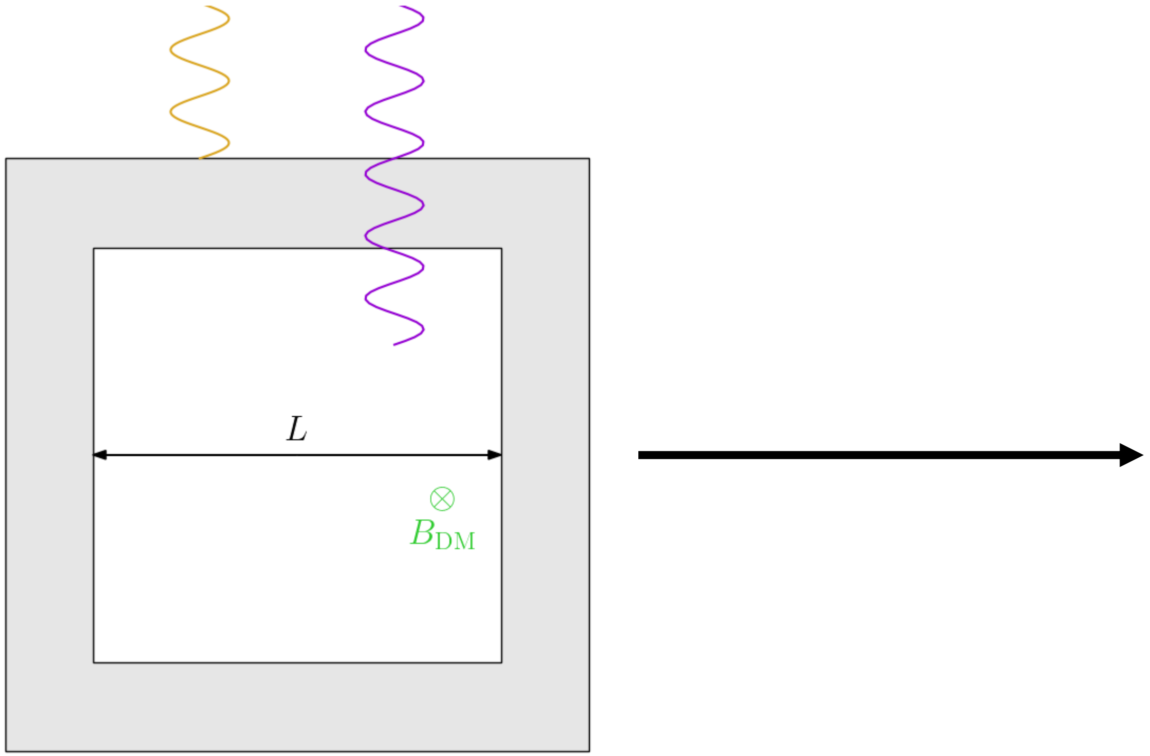
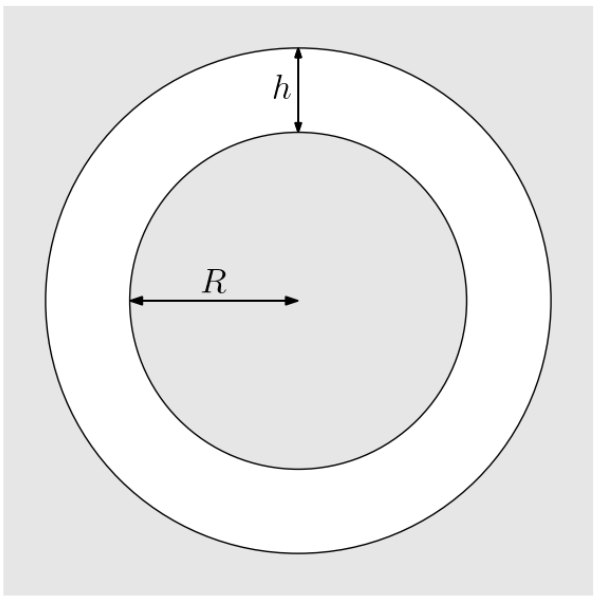


Scales with L

Earth

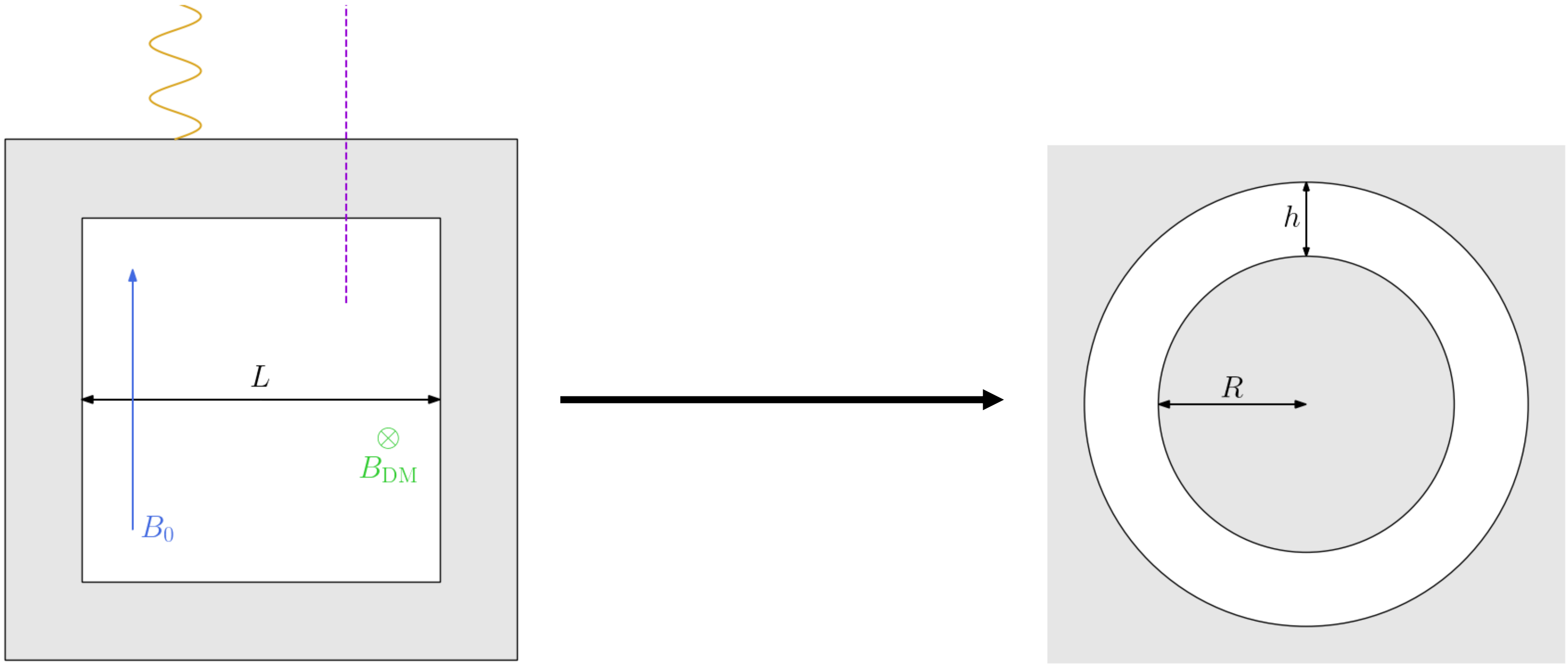


Scales with R

Earth as a transducer

DM Radio/ADMX

Earth

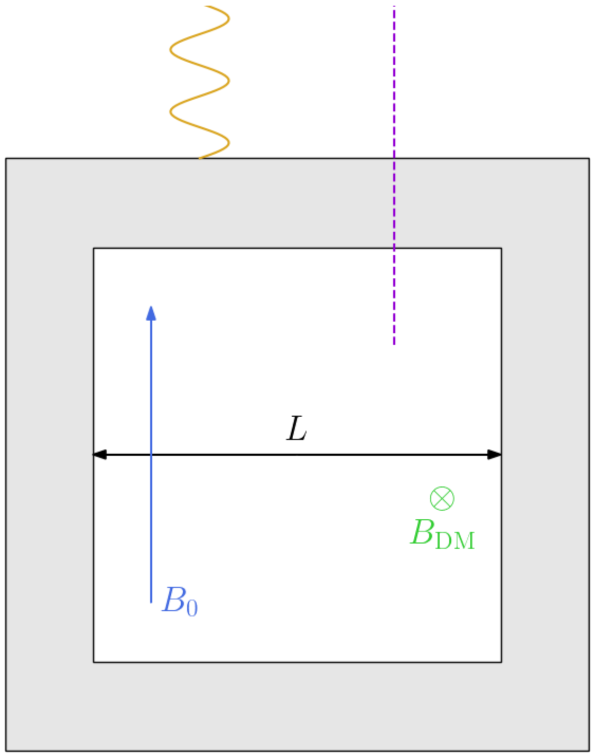


Scales with L

Scales with R

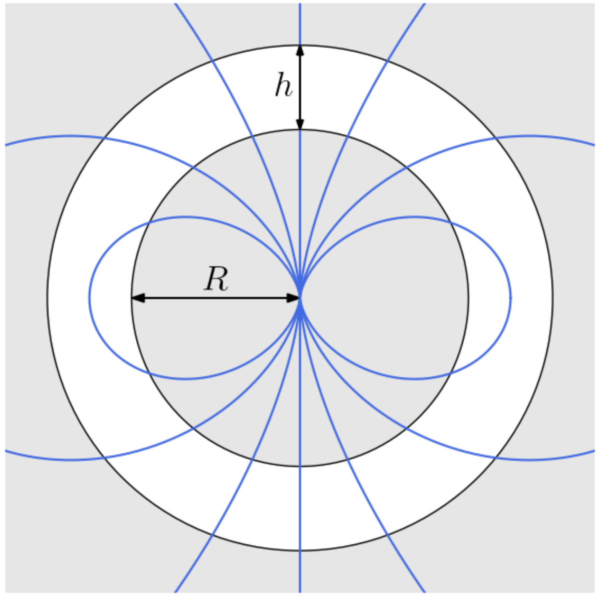
Earth as a transducer

DM Radio/ADMX



Scales with L

Earth



Scales with R

Effective current

- In non-relativistic limit, effects of ultralight DM given by

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J}_{\text{eff}}$$

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- For axionlike dark matter, $\mathbf{J}_{\text{eff}} = i g_{a\gamma} m_a a \mathbf{B}_0$

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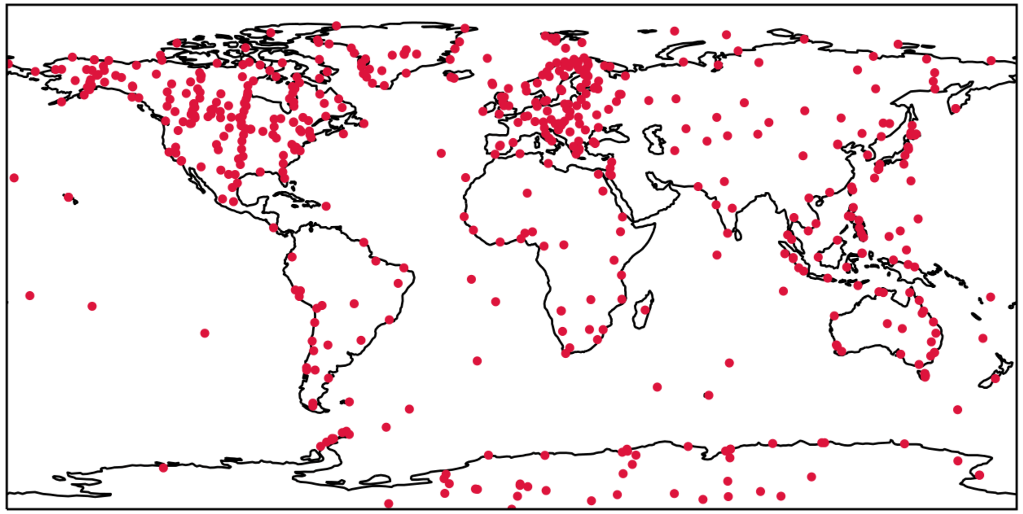
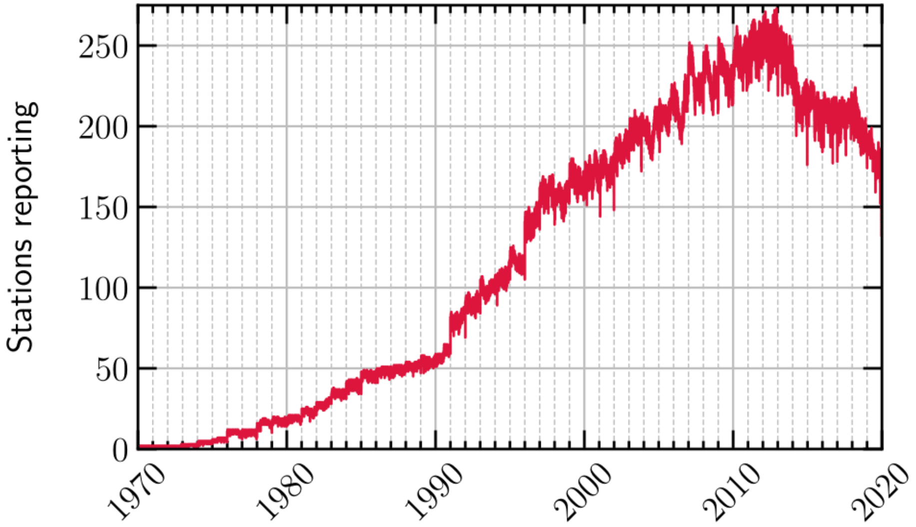
- For axionlike dark matter, $\mathbf{J}_{\text{eff}} = i g_{a\gamma} m_a a \mathbf{B}_0$
- When $\lambda_{\text{DM}} \gg R$, electric field negligible → only magnetic field signal
- Robustness: for arbitrary boundary conditions

$$\mathbf{B} = \mathbf{B}_{\text{sph}} + \text{curl-free}$$

Can project out curl-free part

Search in SuperMAG dataset

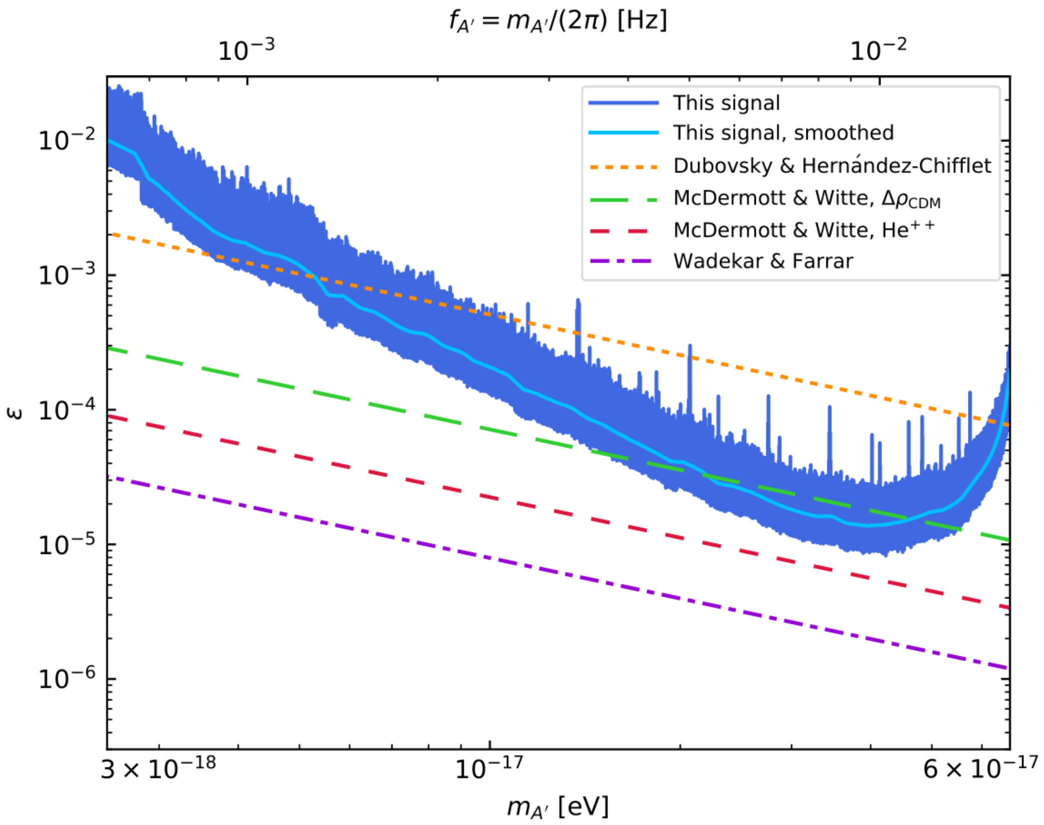




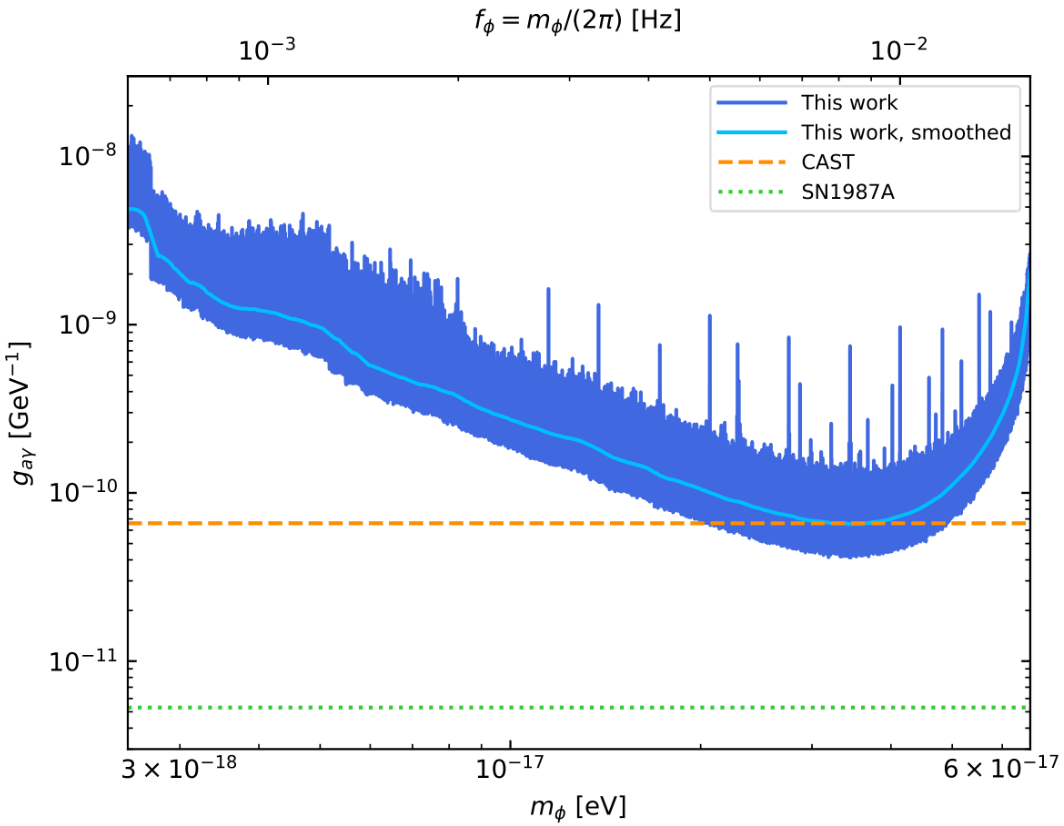
- Signal is spatially coherent → 500+ ground-based magnetometers
- Signal is temporally coherent → 50 years of data
- 1-minute resolution

SuperMAG 1-minute limits

Dark photon



Axion



Going to higher frequencies

- $10^{-2}\,\mathrm{Hz} < f_{\mathrm{DM}} < 1\,\mathrm{Hz}$: SuperMAG 1-second resolution dataset

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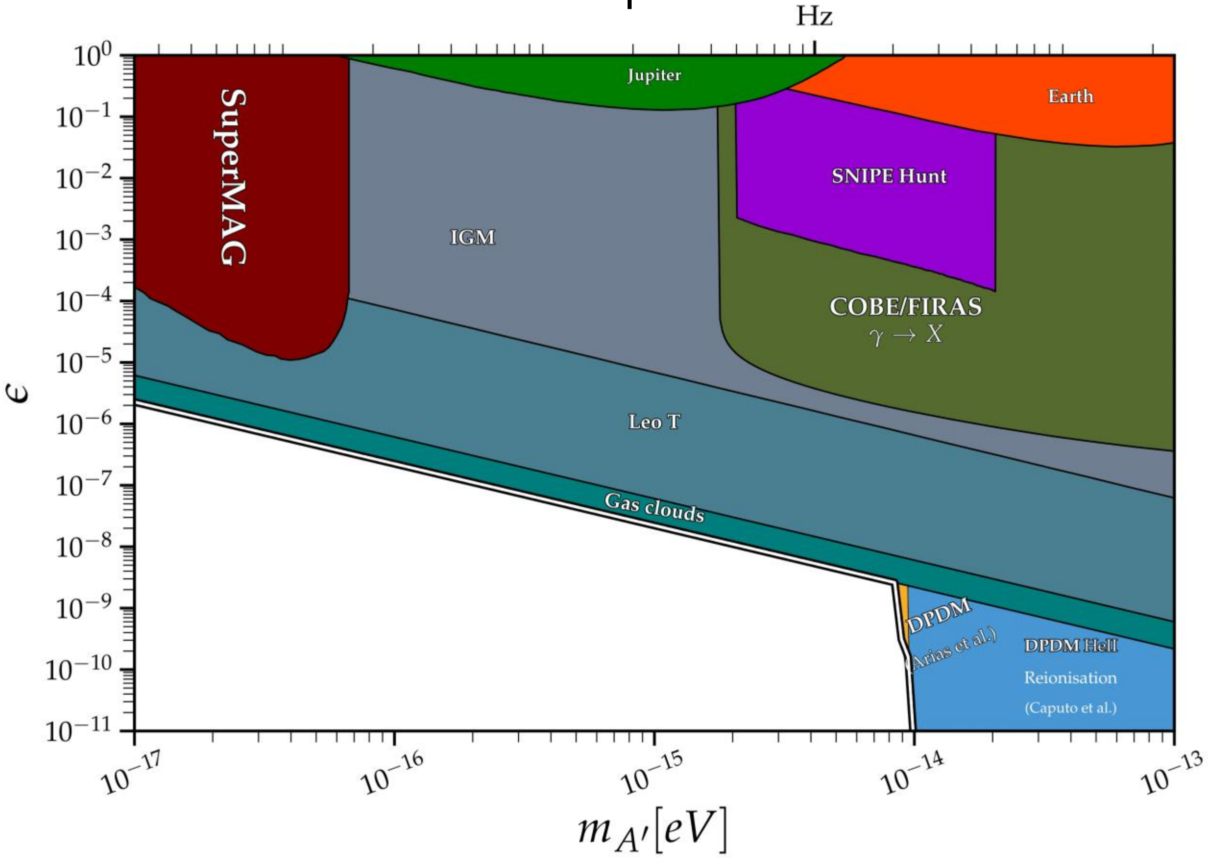
- $10^{-2}\,\mathrm{Hz} < f_{\mathrm{DM}} < 1\,\mathrm{Hz}$: SuperMAG 1-second resolution dataset

- $f_{\mathrm{DM}} > 1\,\mathrm{Hz}$: Search for Non-Interacting Particles Experimental (SNIPE) Hunt
    - Take our own data above 1 Hz
    - Most noise is man-made → go to radio quiet area, e.g. state park
    - SNIPE Hunt summer 2022 run: collected data at three locations (CA, PA, OH) over 2.5 days
    - Magnetometer noise limited

SNIPE Hunt 2022 limits

Dark photon



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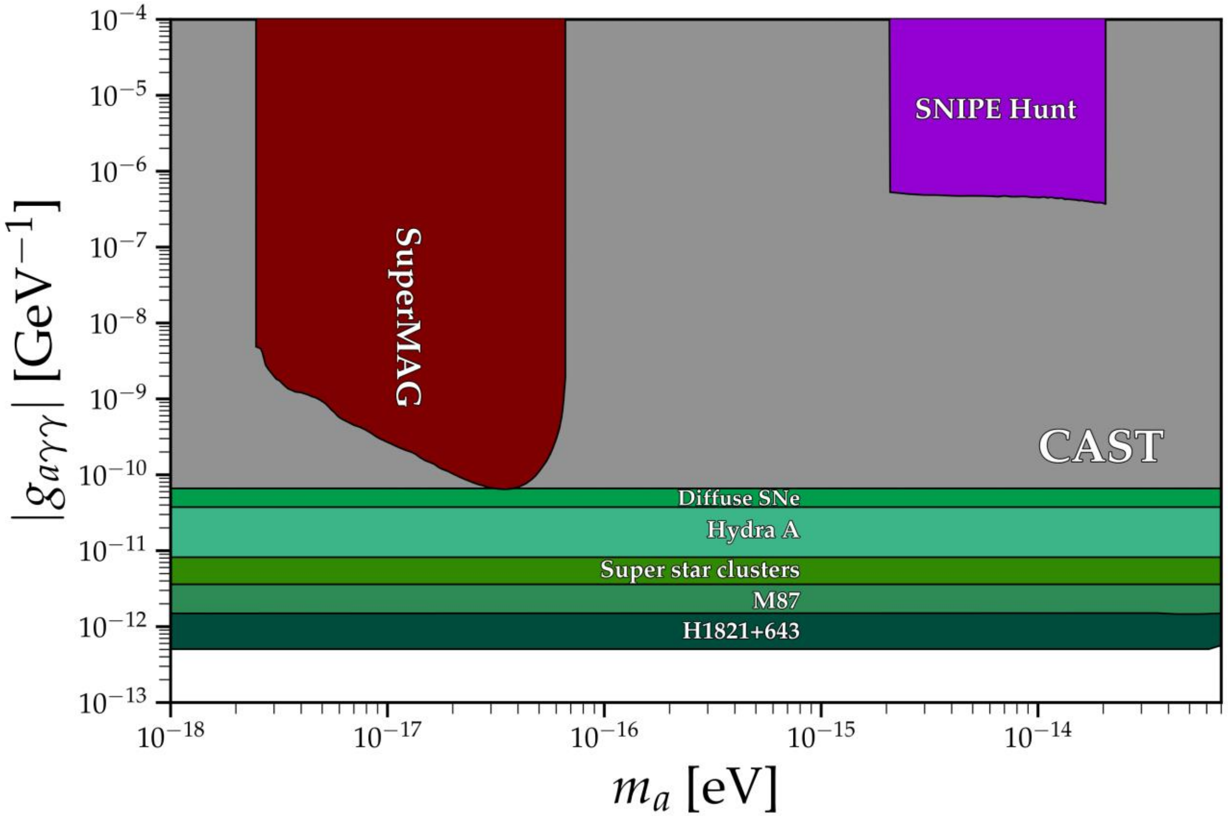

New technique

- Above 5 Hz, $\lambda_{\mathrm{DM}} \lesssim R$ → no robustness, environmental effects relevant
- Ex: Signal diverges at Schumann resonances $m_{\mathrm{DM}}R = \sqrt{\ell(\ell+1)}$
  - Predicted: 11 Hz, 18 Hz, 26 Hz…
  - Measured: 8 Hz, 14 Hz, 20 Hz…
  - Measured widths as low as 2 Hz
  - Small deviations in location of resonance can lead to large discrepancies in signal size!

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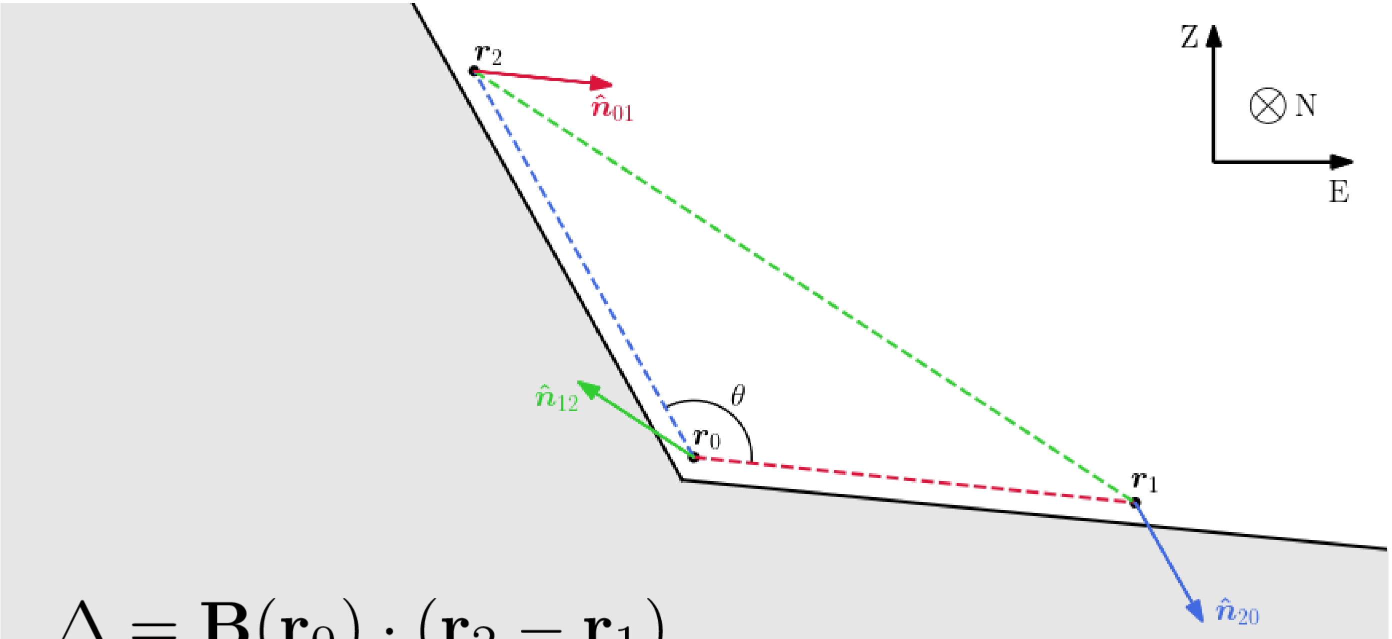
  - Small deviations in location of resonance can lead to large discrepancies in signal size!
- Because the ground is a conductor, we still have $\mathbf{E}_{||} = 0$, so

$$(\nabla \times \mathbf{B})_{||} = \mathbf{J}_{\rm eff,||}$$

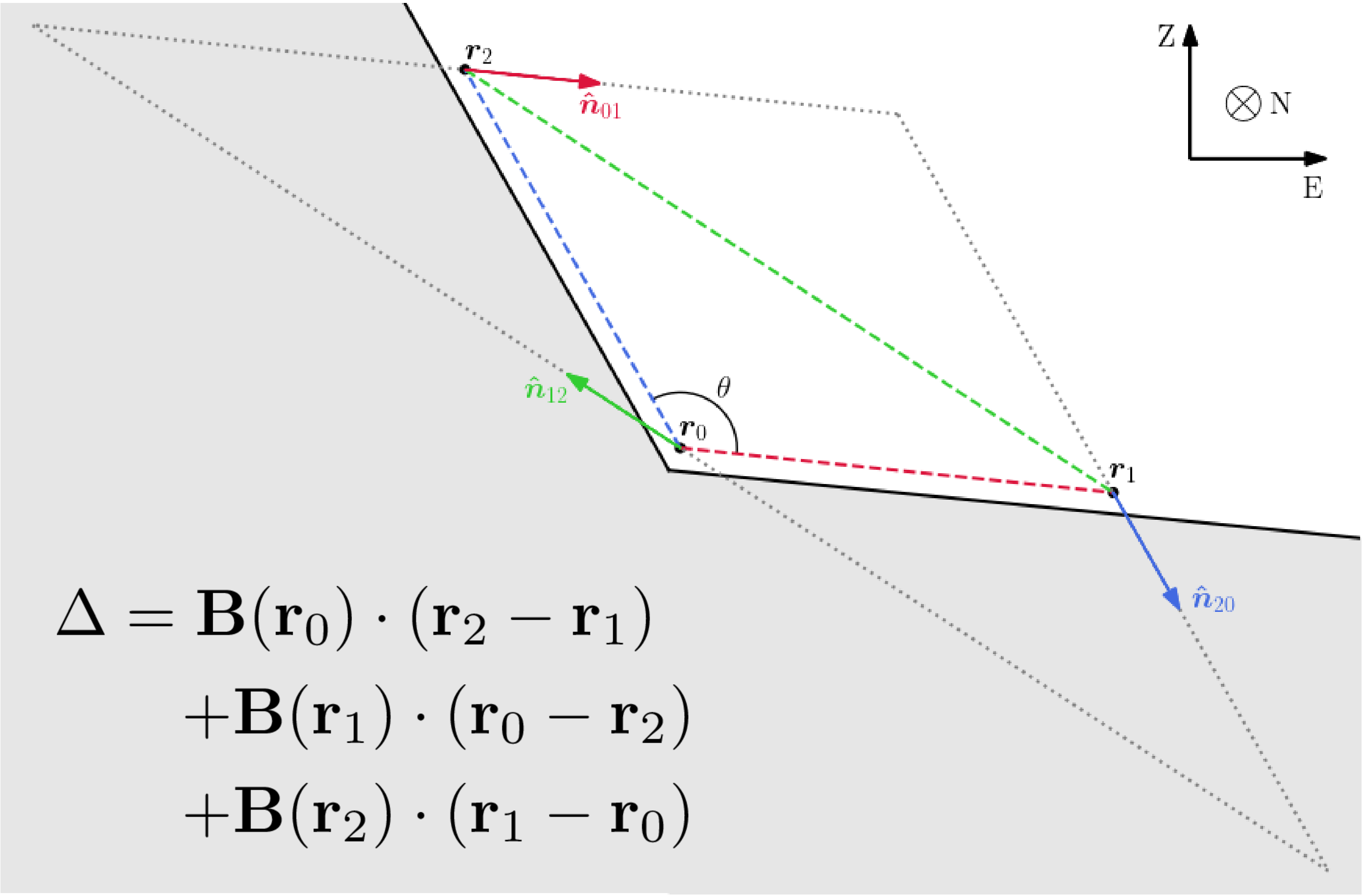
- We can measure $\nabla \times \mathbf{B}$ instead!
- No physical currents in lower atmosphere → background cancellation

Curl measurement scheme



$$\begin{aligned}\Delta = &\mathbf{B}(\mathbf{r}_0) \cdot (\mathbf{r}_2 - \mathbf{r}_1) \\ &+\mathbf{B}(\mathbf{r}_1) \cdot (\mathbf{r}_0 - \mathbf{r}_2) \\ &+\mathbf{B}(\mathbf{r}_2) \cdot (\mathbf{r}_1 - \mathbf{r}_0)\end{aligned}$$

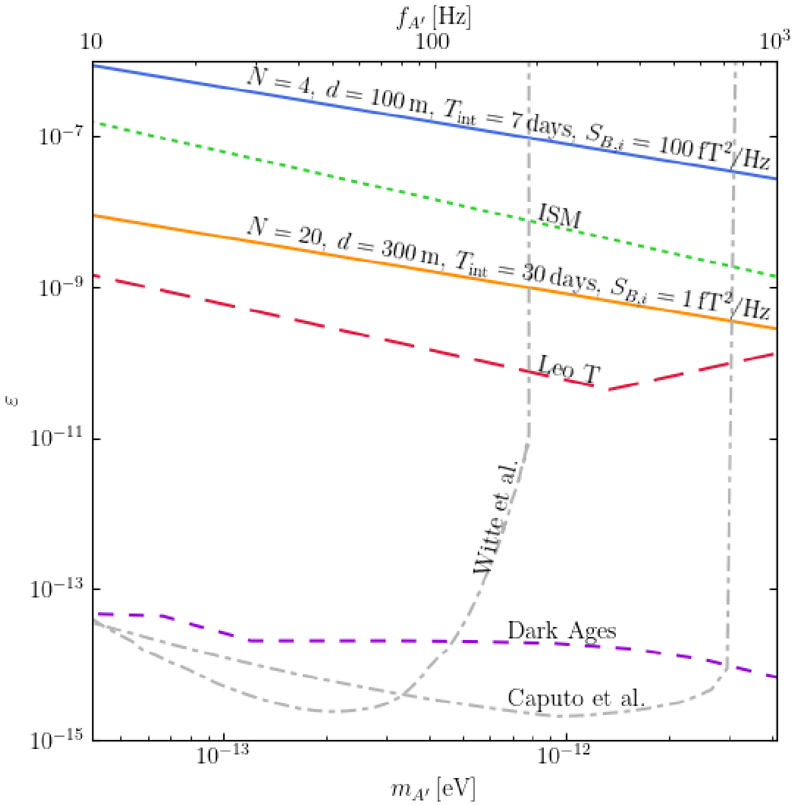
Curl measurement scheme



$$
\begin{aligned}
\Delta = \mathbf{B}(\mathbf{r}_0) \cdot (\mathbf{r}_2 - \mathbf{r}_1) \\
+\mathbf{B}(\mathbf{r}_1) \cdot (\mathbf{r}_0 - \mathbf{r}_2) \\
+\mathbf{B}(\mathbf{r}_2) \cdot (\mathbf{r}_1 - \mathbf{r}_0)
\end{aligned}
$$

Curl scheme projections

Dark photon



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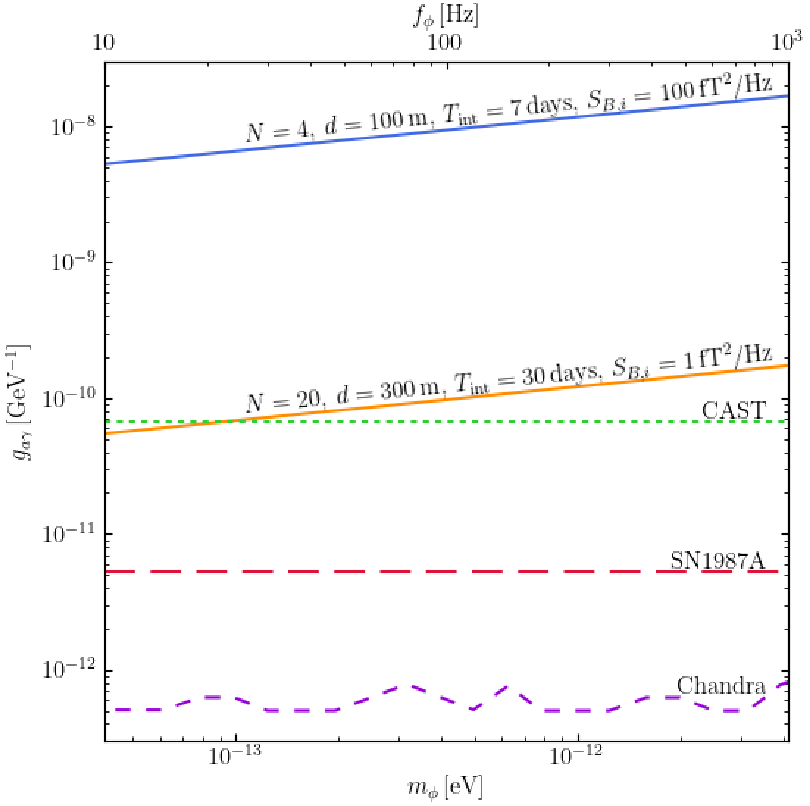

(Assuming we're magnetometer noise limited)

Conclusion

- Ultralight DM sources an oscillating magnetic field at Earth's surface
- Scales with R, high spatial and temporal coherence
- Searched publicly available SuperMAG dataset to set limits for $f_{\mathrm{DM}} < 10^{-2}\,\mathrm{Hz}$
- SuperMAG 1-second analysis will constrain $10^{-2}\,\mathrm{Hz} < f_{\mathrm{DM}} < 1\,\mathrm{Hz}$
- SNIPE Hunt took data in summer 2022 to constrain $1\,\mathrm{Hz} < f_{\mathrm{DM}} < 5\,\mathrm{Hz}$
- Will implement curl scheme in summer 2023 for $f_{\mathrm{DM}} > 5\,\mathrm{Hz}$

SNIPE Hunt Collaboration

- Ariel Arza
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- Andre Li
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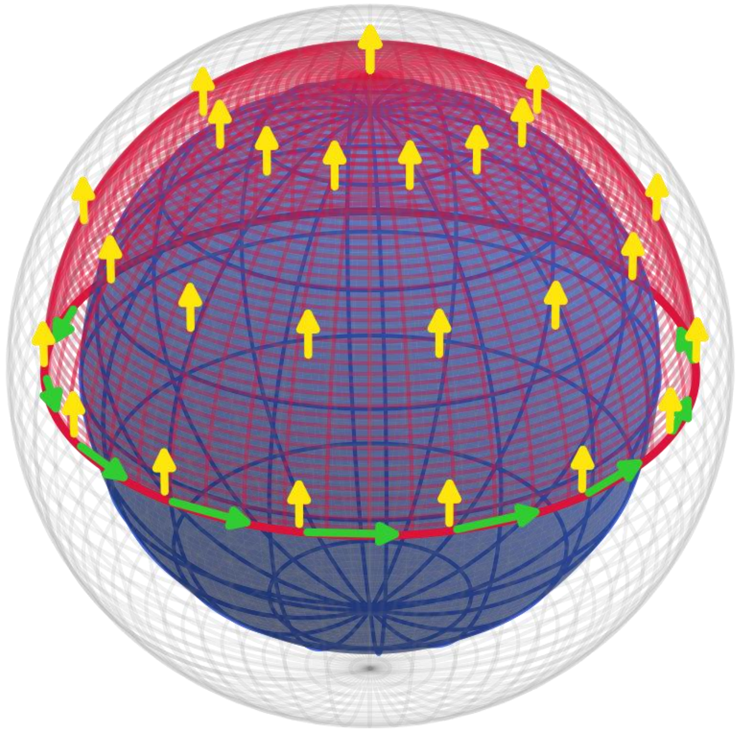
- Ehsanullah Nikfar
- Jason E. Stalnaker
- Ibrahim A. Sulai
- Yicheng Wang

Backup Slides

Ampère's law argument

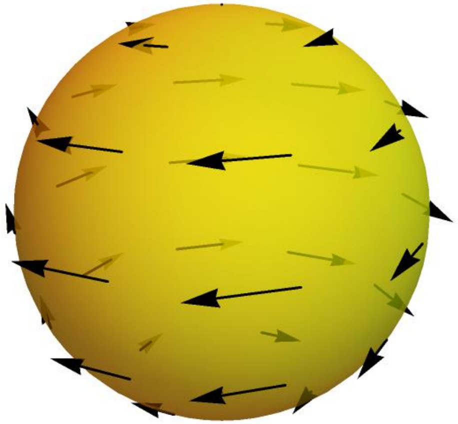


$$BR \sim \oint \mathbf{B} \cdot d\ell = \iint \mathbf{J}_{\text{eff}} \cdot d\mathbf{A} \sim \varepsilon m_{A'}^2 R^2 A'$$

Full solutions

$$\mathbf{B}_{A'}(\Omega, t) = \sqrt{\frac{4\pi}{3}} \cdot \frac{m_{A'}R}{2-(m_{A'}R)^2} \cdot \varepsilon m_{A'} \cdot \mathrm{Re}\left[\sum_{m=-1}^{1} A'_m \mathbf{\Phi}_{1m}(\Omega) e^{-2\pi i (f_{A'} - f_d m)t}\right]$$

$$\mathbf{B}_a(\Omega, t) = g_{a\gamma} a_0 \cdot \mathrm{Im}\left[\sum_{\ell m} \frac{(\ell+1) C_{\ell m} m_a R}{\ell(\ell+1) - (m_a R)^2} \cdot \mathbf{\Phi}_{\ell m}(\Omega) e^{-2\pi i f_a t}\right]$$



$\mathbf{\Phi}_{10}$

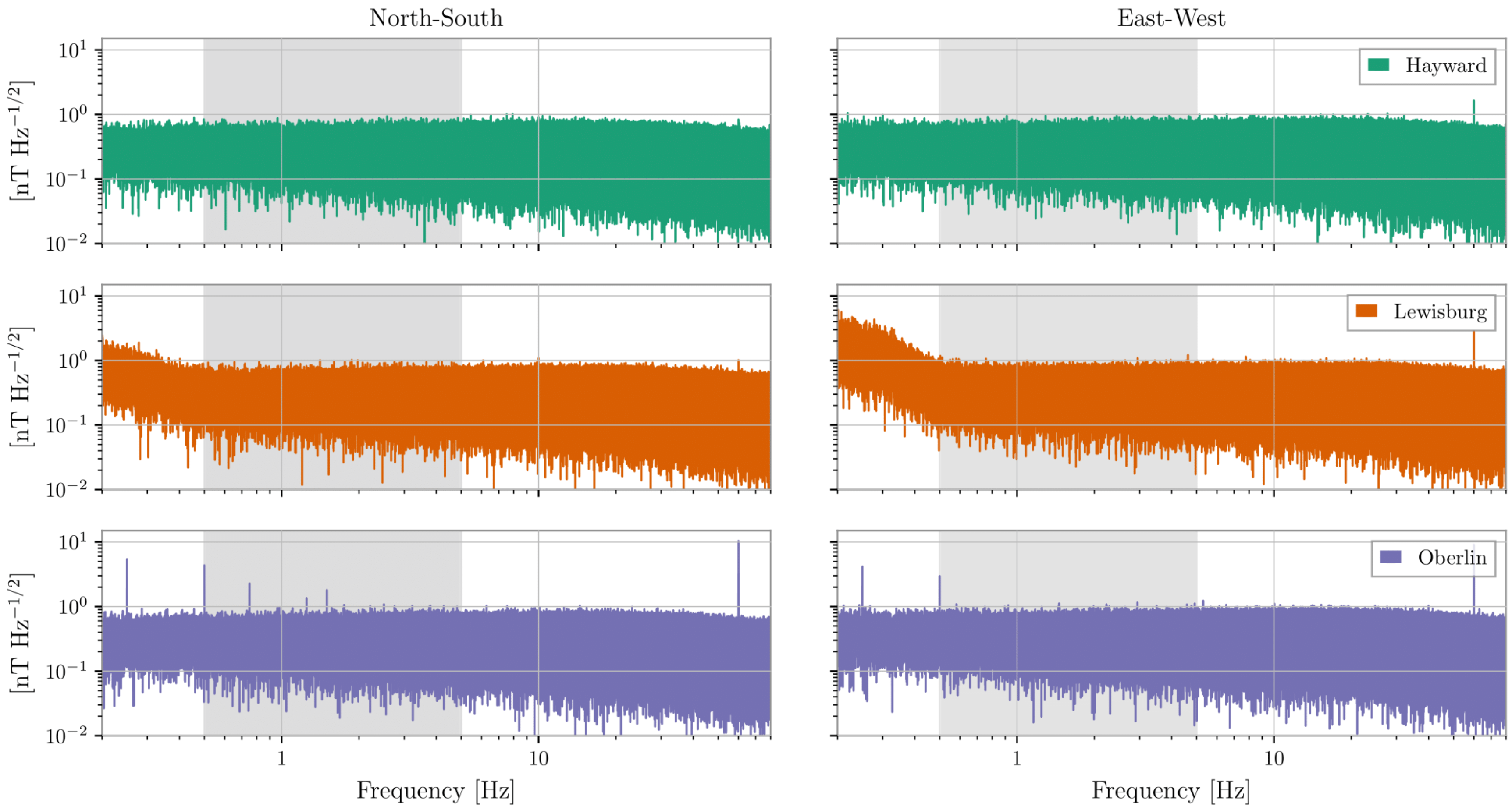
IGRF model

$$\mathbf{B}_\oplus = -\nabla V_0$$

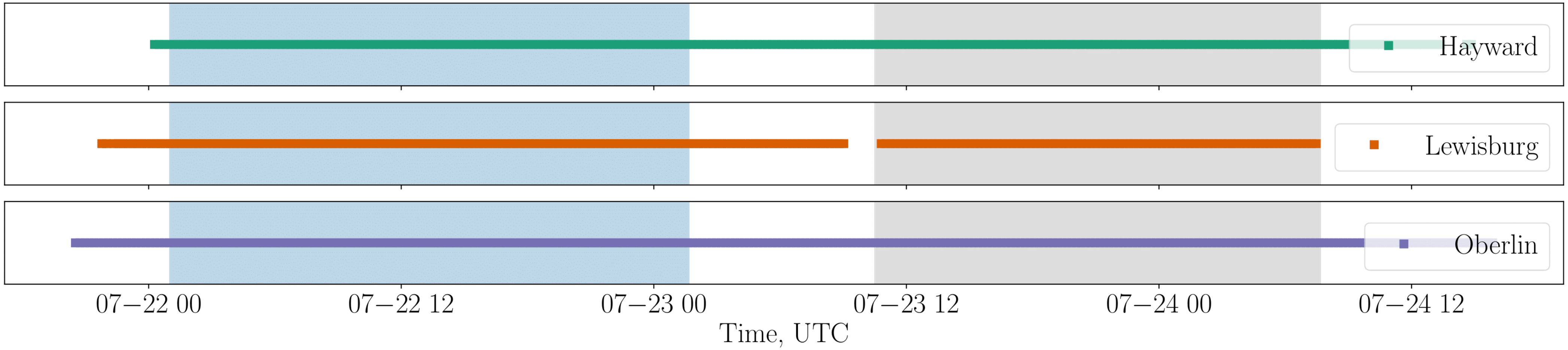
$$V_0 = \sum_{\ell=1}^{\infty} \sum_{m=0}^{\ell} \frac{R^{\ell+2}}{r^{\ell+1}} \left(g_{\ell m} \cos(m\phi) + h_{\ell m} \sin(m\phi)\right) P_\ell^m(\cos\theta)$$

$$C_{\ell m} = (-1)^m \sqrt{\frac{4\pi(2-\delta_{m0})}{2\ell+1}} \frac{g_{\ell m} - i h_{\ell m}}{2}$$

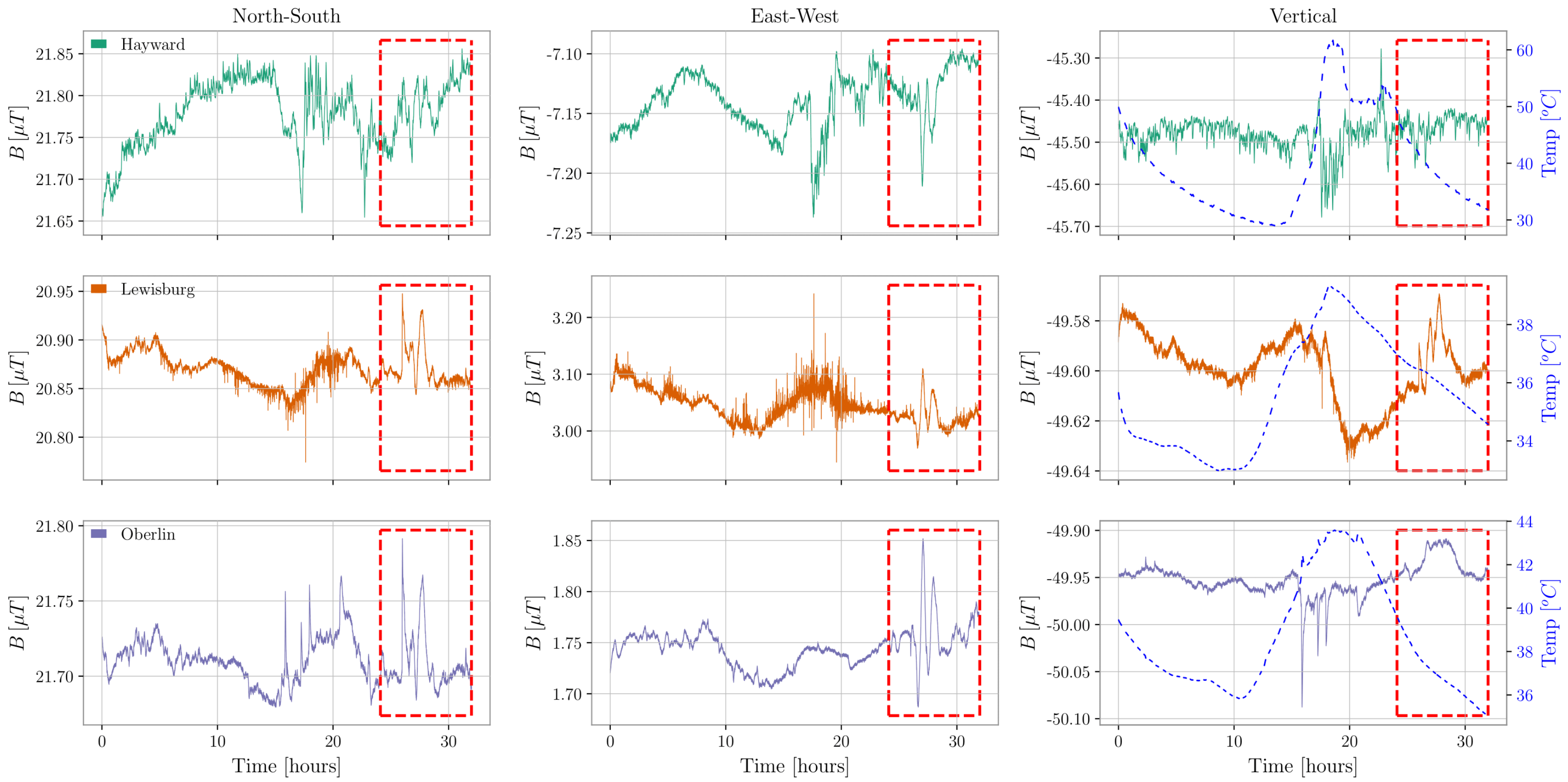
SNIPE Hunt 2022 PSDs



SNIPE Hunt 2022 activity



Geomagnetic storm



Time [hours] from 2022-07-22 00:00:00 UTC (1342483218.0)

Vanishing electric field