The Earth as a transducer for dark-photon dark-matter detection

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based on arXiv:2106.00022 and arXiv:2108.08852

with Michael A. Fedderke, Peter W. Graham, Derek F. Jackson Kimball

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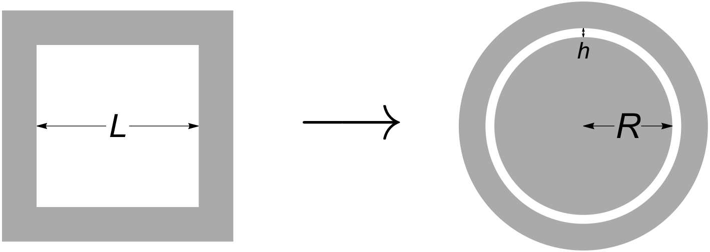
Introduction

- Need big apparatus to detect ultralight dark photons
- Current constraints below 10^{-14} eV (sub-Hz) all astrophysical
- We use the Earth as our apparatus/transducer!
- Dark photons $\longrightarrow$ magnetic field at Earth's surface

Introduction

ADMX/DM Radio Earth



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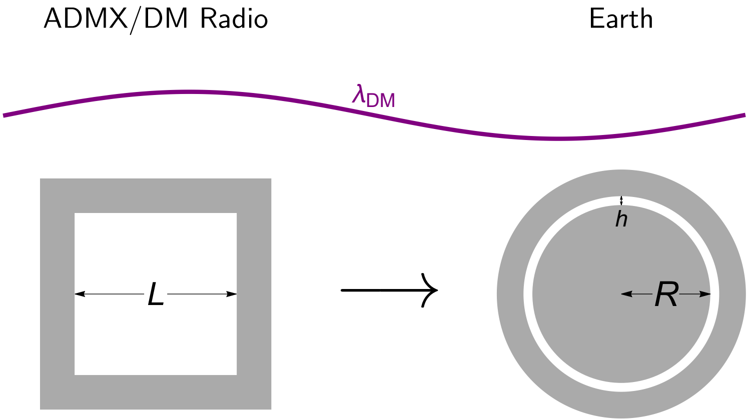

$\boldsymbol{B}$ suppressed by $\frac{L}{\lambda_{DM}} \sim m_{DM} L$

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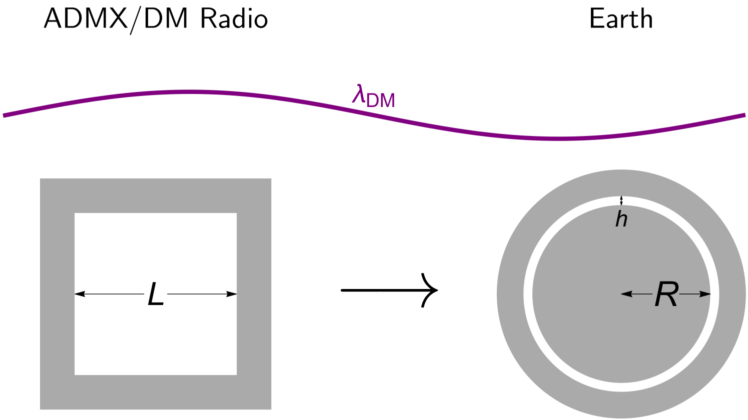

B suppressed by $\frac{L}{\lambda_{\text{DM}}} \sim m_{\text{DM}} L$

B suppressed by $m_{\text{DM}} R$!

Outline

1. Dark Photon Physics
2. Earth Signal
3. Analysis of SuperMAG Data

Coupled Photon–Dark-Photon System

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \varepsilon m_{A'}^2 A'^\mu A_\mu - J^\mu_{\mathrm{EM}} A_\mu$$

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  - The observable fields are E and B (no contribution from E' and B')
- One massless and one massive (mass $m_{A'}$) propagation state
- A and A' are not propagation states in vacuum!
  - Mixing (and all observable effects) are proportional to $m_{A'}$
  - A and A' *are* propagation states in conductor $\rightarrow$ mixing at boundary

Effective Current Approach

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \varepsilon m_{A'}^2 A'^\mu A_\mu - J^\mu_{\text{EM}} A_\mu$$

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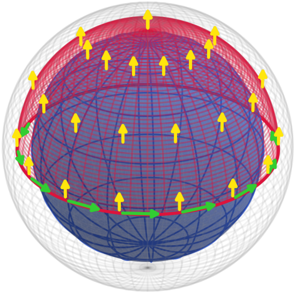
- Just a single-photon EM problem with a background current!

Ampère's Law Argument



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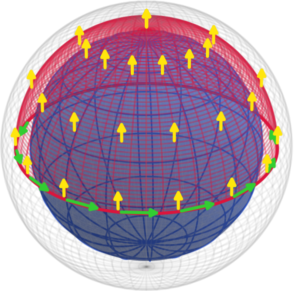

$$BR \sim \oint \boldsymbol{B} \cdot d\boldsymbol{\ell} = \iint \boldsymbol{J}_{\text{eff}} \cdot d\boldsymbol{A} \sim \varepsilon m_{A'}^2 R^2 A'$$

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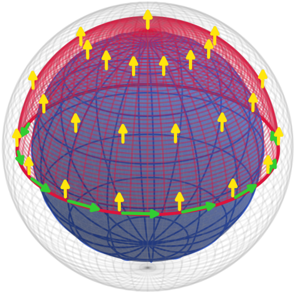

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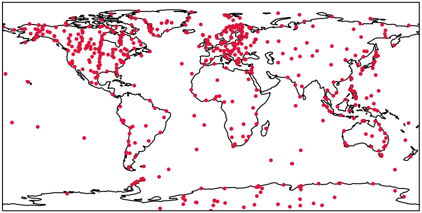
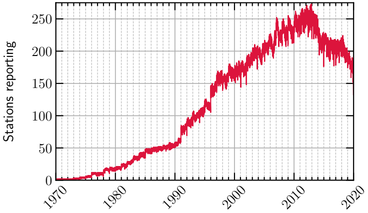
$$B \sim \varepsilon m_{A'}^2 R A' \sim \varepsilon m_{A'} R \sqrt{\rho_{\text{DM}}}$$

Signal Properties

- Observable magnetic field at Earth's surface
- Large: suppressed by $m_{A'}R$ not $m_{A'}h$
- Spatially coherent: global spatial pattern (along latitudes)
- Temporally coherent: sharply peaked in frequency with $Q \sim 10^6$
- Robust: relevant component of signal is unaffected to leading order by boundary conditions!

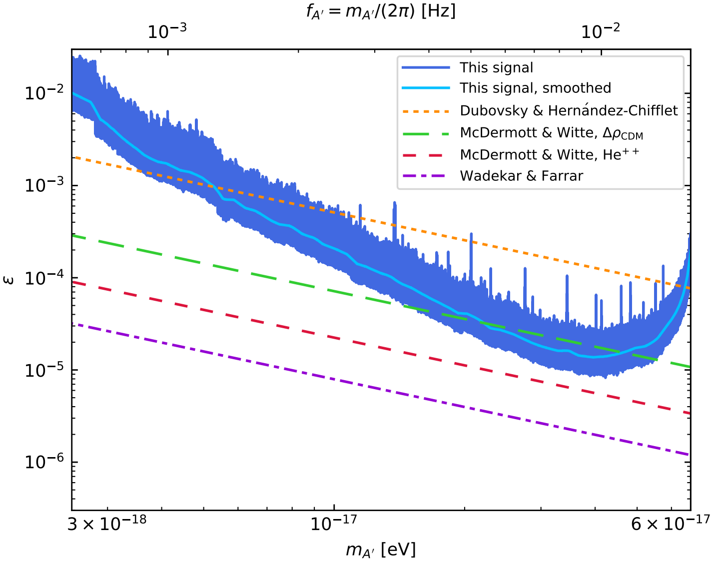
SuperMAG





- Collaboration of over 500 ground-based magnetometers
- Data collected over 50 years
- 1-minute time resolution

Results


$f_{A'} = m_{A'}/(2\pi)$ [Hz]
10^{-3}
10^{-2}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ε
3×10^{-18}
10^{-17}
6×10^{-17}
$m_{A'}$ [eV]
This signal
This signal, smoothed
Dubovsky & Hernández-Chifflet
McDermott & Witte, $\Delta\rho_{CDM}$
McDermott & Witte, He^{++}
Wadekar & Farrar

Future Prospects

- SuperMAG is also releasing 1-second resolution data, which would probe higher masses.
- If $1/f$ noise continues, then our bound scales better than others at higher masses.
- Other possible ways to improve:
  - Noise modeling
  - Better statistical analysis
  - Better magnetometers
  - More and/or higher frequency data
- Similar signal for axions?

Summary

- We demonstrated a novel mechanism to probe ultralight dark photons using the Earth as a transducer.
- It utilizes the natural conductivity environment near the Earth.
- Our signal is not suppressed by the height of the atmosphere!
- It is highly spatially and temporally coherent, and robust to environmental details.
- We set complementary bounds on dark photon parameter space.
- With further research, our results will become even better!

Mixing in Medium

- Consider (transverse) modes of frequency ω

	In vacuum		In good conductor ($\sigma \gg m_{A'}^2/\omega$)	
State	$A - \varepsilon A'$	$A' + \varepsilon A$	A	A'
Propagation	Massless	Mass $m_{A'}$	Damped	Mass $m_{A'}$

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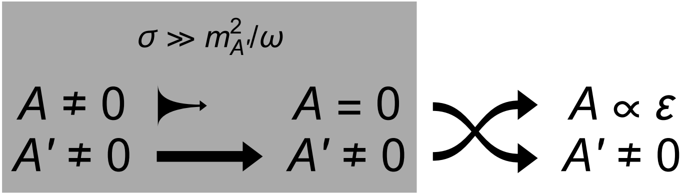

Solving the wave equation with a current

$$(\nabla^2 - \partial_t^2)\boldsymbol{E} = \partial_t \boldsymbol{J}_{\text{eff}}$$

$$\boldsymbol{E} = \boldsymbol{E}_{\text{DM}} + \boldsymbol{E}_{\text{response}}$$

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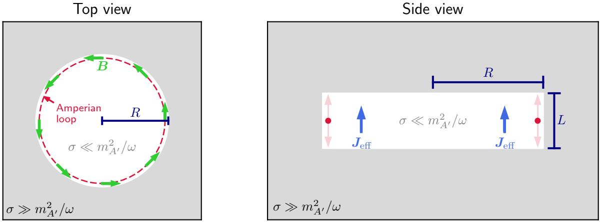
$$\boldsymbol{E} = \boldsymbol{E}_{\text{DM}} + \boldsymbol{E}_{\text{response}}$$

$\boldsymbol{E}_{\text{DM}}$ (specific)	$\boldsymbol{E}_{\text{response}}$ (homogeneous)
$(\nabla^2 - \partial_t^2)\boldsymbol{E}_{\text{DM}} = \partial_t \boldsymbol{J}_{\text{eff}}$	$(\nabla^2 - \partial_t^2)\boldsymbol{E}_{\text{response}} = 0$
Field “sourced by” DM	Cavity response to cancel $\boldsymbol{E}_{\parallel}$ at boundary
Constant in space	(Slowly) varying with $k = m_{A'}$
$\boldsymbol{B}_{\text{DM}} = 0$	$\boldsymbol{B}_{\text{response}} \neq 0$

ADMX/DM Radio Ampère's Law Argument



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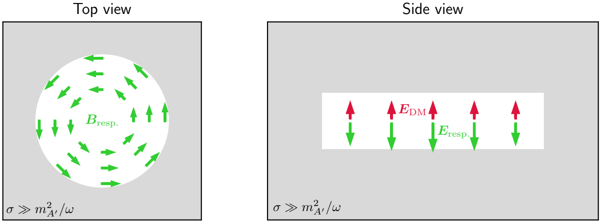
ADMX/DM Radio Solution

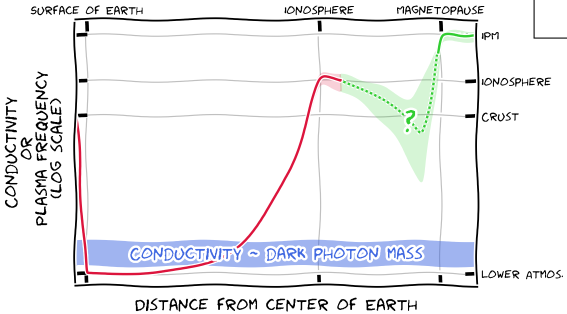


$$\boldsymbol{E} = \boldsymbol{E}_{\rm DM} + \boldsymbol{E}_{\rm response} \propto m_{A'}^2 (R^2 - r^2)$$

$$\boldsymbol{B} = -\frac{i}{m_{A'}} \nabla \times \boldsymbol{E} \propto m_{A'} r$$

Earth Conductivity Profile

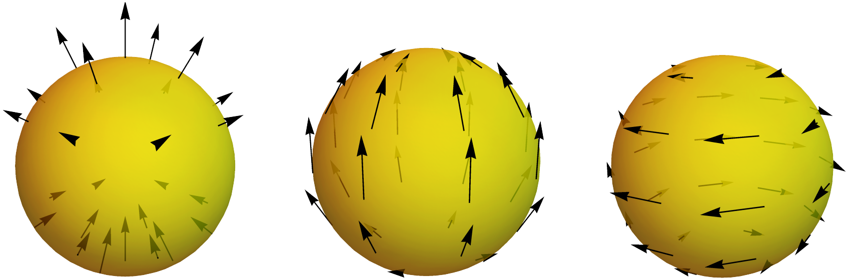
$m_{A'} \sim 10^{-18}$ eV
$f \sim 10^{-4}$ Hz



	Core	Lower Atmosphere	Ionosphere $\sigma_{\parallel}$	Ionosphere $\sigma_{\perp}$	IPM
σ (ω_p) [eV]	100	10^{-18}	10^{-2}	10^{-8}	10^{-10}
h [km]	3000	5	100		3×10^5
δ [km]	0.03	10^8	2	1000	2
Shield?	Yes	No	???		Yes

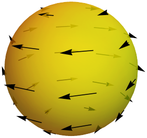
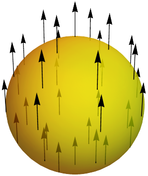
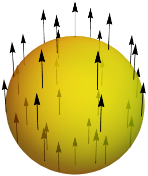
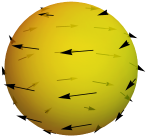
Vector Spherical Harmonics

- Three types of vector spherical harmonics: $\boldsymbol{Y}_{\ell m}$, $\boldsymbol{\Psi}_{\ell m}$, $\boldsymbol{\Phi}_{\ell m}$
- Only $\ell = 1$ relevant for us
- Real and imaginary parts of $m = \pm 1$ oriented along x- and y-axes



$\boldsymbol{Y}_{10}$ $\boldsymbol{\Psi}_{10}$ $\boldsymbol{\Phi}_{10}$

Spherical Modes

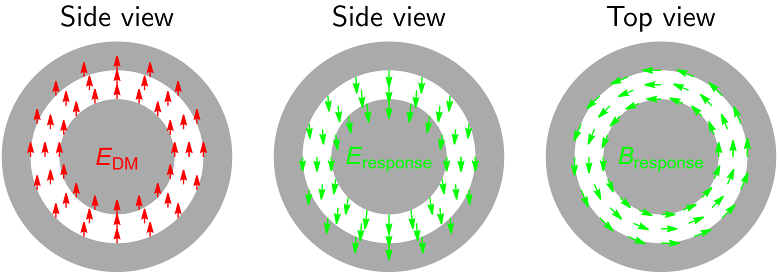
Transverse Electric (TE)	Transverse Magnetic (TM)
$\boldsymbol{E}_{\text{TE}} \sim \boldsymbol{\Phi}_{\ell m}$	$\boldsymbol{E}_{\text{TM}} \sim \boldsymbol{Y}_{\ell m} + \boldsymbol{\Psi}_{\ell m}$
	
$\boldsymbol{B}_{\text{TE}} \sim \boldsymbol{Y}_{\ell m} + \boldsymbol{\Psi}_{\ell m}$	$\boldsymbol{B}_{\text{TM}} \sim \boldsymbol{\Phi}_{\ell m}$
	

Full TM Modes

$$\boldsymbol{E}_{\mathrm{TM}} = \sum_{\ell m} \left(-\frac{\ell(\ell+1) g_{\ell m}(m_{A'} r)}{m_{A'} r} \boldsymbol{Y}_{\ell m} - \left(g'_{\ell m}(m_{A'} r) + \frac{g_{\ell m}(m_{A'} r)}{m_{A'} r} \right) \boldsymbol{\Psi}_{\ell m} \right) e^{-i m_{A'} t}$$

$$\boldsymbol{B}_{\mathrm{TM}} = -i \sum_{\ell m} g_{\ell m}(m_{A'} r) \boldsymbol{\Phi}_{\ell m} e^{-i m_{A'} t}$$

Earth Signal

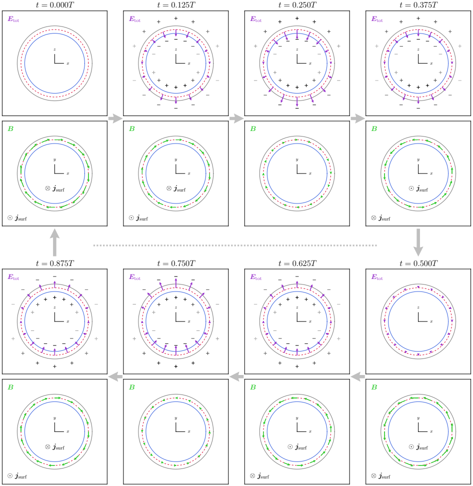


- Only TM modes necessary!

$$B \propto \sum_{m=-1}^{1} (\varepsilon m_{A'}^2 R A'_m) \mathbf{\Phi}_{1m}$$

- Has particular $\mathbf{\Phi}_{1m}$ spatial pattern that we can search for!

Earth Field Oscillations



Earth Signal with Rotation

- Earth signal without rotation:

$$B = \sqrt{\frac{\pi}{3}} \varepsilon m_{A'}^2 R \sum_{m=-1}^{1} A'_m \mathbf{\Phi}_{1m} e^{-i m_{A'} t}$$

- Since $\mathbf{\Phi}_{1m} \propto e^{im\phi}$, can account for rotation of earth as

$$B = \sqrt{\frac{\pi}{3}} \varepsilon m_{A'}^2 R \sum_{m=-1}^{1} A'_m \mathbf{\Phi}_{1m} e^{-i(m_{A'} - 2\pi f_d m)t},$$

where $f_d = 1/(\text{sidereal day})$.

Robustness to Boundary Conditions

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	$\boldsymbol{E}_{\text{response,TE}}$	$\boldsymbol{E}_{\text{response,TM}}$	$\boldsymbol{B}_{\text{TE}}$	$\boldsymbol{B}_{\text{TM}}$
LO	✗	✓		
NLO	✗	✗		
NNLO	?	?		
NNNLO	?	?		

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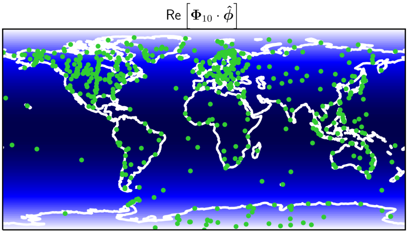
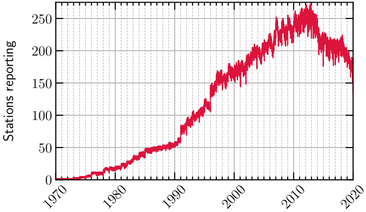
- $\boldsymbol{B}_{\text{TM}}$ *higher* order than $\boldsymbol{E}_{\text{TM}}$, but $\boldsymbol{B}_{\text{TE}}$ *lower* order than $\boldsymbol{E}_{\text{TE}}$

- As long as our search projects onto Φ_{1m}, we can just look for $\boldsymbol{B}_{\text{TM}}$!

Analysis Difficulties





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  - Project onto $\mathbf{\Phi}_{1m}$ modes
  - Fourier transform
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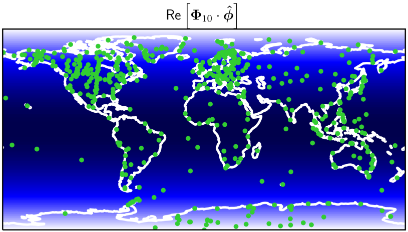
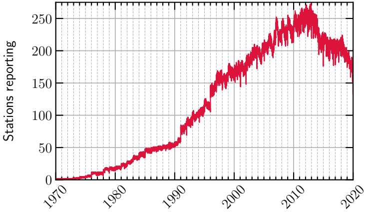
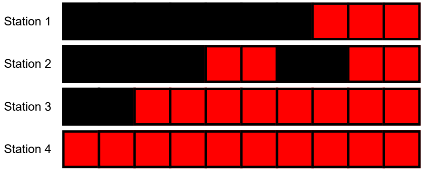




- What we'd like to do:
  - Project onto Φ_{1m} modes — Noise variations/correlations
  - Fourier transform — Active stations highly variable
  - Look for single-frequency peak — Total time > coherence time

Time Series Construction



- Combine data from active stations into new time series
- Weight by inverse noise and Φ_{1m} (different m's will be correlated)
- Do same for signal and just work with time series

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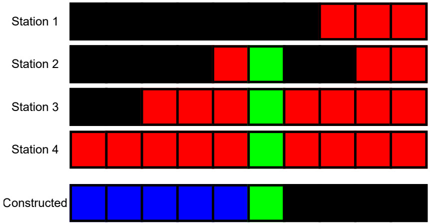

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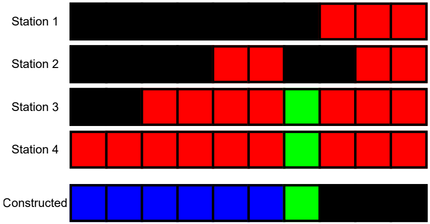

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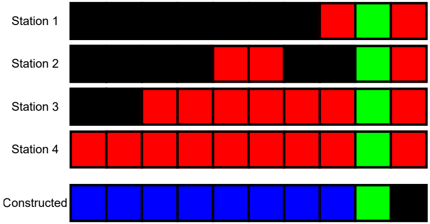

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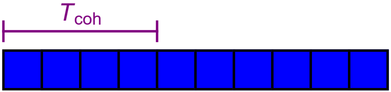
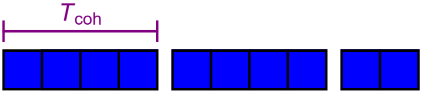
Time Series Partitioning



- Split time series into chunks of length T_{coh}
- Find single-frequency signal size z_k in each chunk k separately
- Combine results incoherently, i.e. $\sum_k |z_k|^2$
- Utilize Bayesian framework to derive posterior for ε

Time Series Partitioning



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Bayesian Analysis

- Analysis variables:

$$z_{ik} \sim \frac{\text{Data}}{\sqrt{\text{Noise}}} \qquad s_{ik} \sim \frac{\text{Signal}}{\sqrt{\text{Noise}}}$$

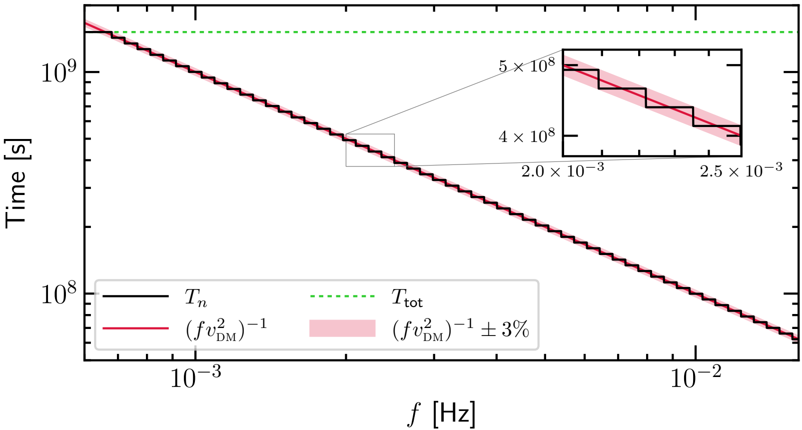
- Likelihood of data z_{ik} given coupling ε

$$\mathcal{L}(\{z_{ik}\}|\varepsilon) \propto \prod_{i,k} \frac{1}{3+\varepsilon^2 s_{ik}^2} \exp\left(-\frac{3|z_{ik}|^2}{3+\varepsilon^2 s_{ik}^2}\right)$$

- Definition of bound $\hat{\varepsilon}$ (using Jeffreys prior $p(\varepsilon)$)

$$\int_0^{\hat{\varepsilon}} d\varepsilon \; \mathcal{L}(\{z_{ik}\}|\varepsilon) \cdot p(\varepsilon) = 0.95$$

Coherence Time Approximation



Candidate Rejection

- Identified 30 signal candidates by comparing $\sum_{i,k} |z_{ik}|^2$ to χ^2-distribution
- Tested candidates with resampling analysis
  - Reran analysis with 4 subsets of time and saw if z_{ik} consist with signal
  - Also with 4 subsets of stations
- All failed one, the other, or joint resampling (except two near Nyquist frequency $f = 1/(2\text{ min})$)