Constraints on axion-like polarization oscillations in the cosmic microwave background with POLARBEAR

Based on arxiv 2303.08410

Jake Spisak

N3AS News Session

April 4th, 2023

Introduction to Axions

- Original QCD axion: solution to strong CP problem
- Here: a generic light pseudoscalar ‘ϕ’
  - Also sometimes called ‘axion-like particle’
  - Motivation: string theory
  - Masses of interest: ($m \approx 10^{-20}$-10^{-22} eV)
- Model:

Small EM coupling

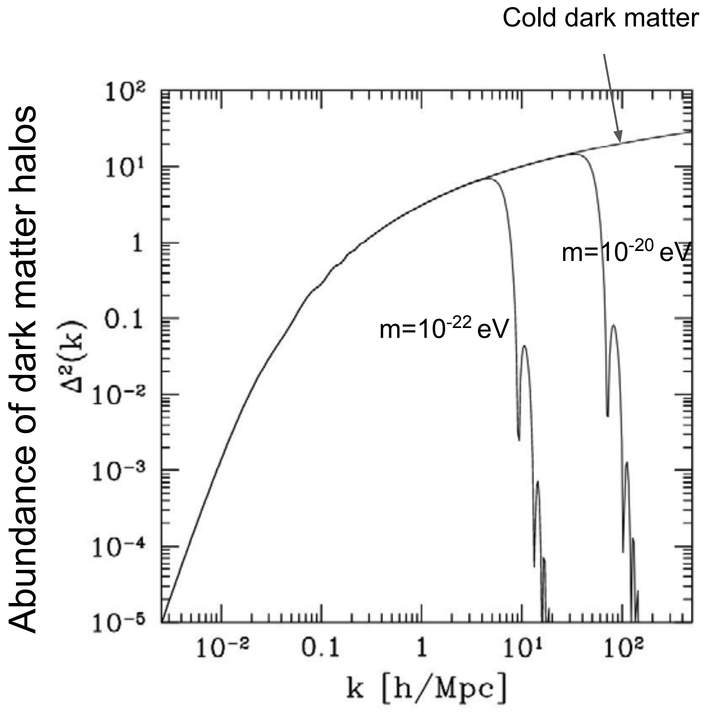
$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{g_{\phi\gamma}}{4} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Cosmological evolution:

$$\ddot{\phi} + 3H\dot{\phi} + m^2 \phi = 0$$

Axions as Fuzzy Dark Matter

- Ultralight ($m \approx 10^{-20}$-10^{-22} eV) means huge ($\gtrsim$kpc) de Broglie wavelength
- Addresses issues with cold dark matter halos
  - Too many small halos
  - Density at halo center too high



Hui, Annu. Rev. Astron. Astrophys. 2021

Axion-EM Coupling: Rotation of Polarized Light

- Coupling $\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ modifies the EM field equations

- Rotates linearly polarized light: ‘cosmic birefringence:

σ=±1 photon helicity

$$A_\sigma(\eta, z) = A_\sigma(\eta', z') \times \exp\left[-i\omega(\eta-\eta') + ik(z-z') + i\sigma\boxed{\frac{g_{\phi\gamma}}{2}\Delta\phi(\eta, z; \eta', z')}\right]$$

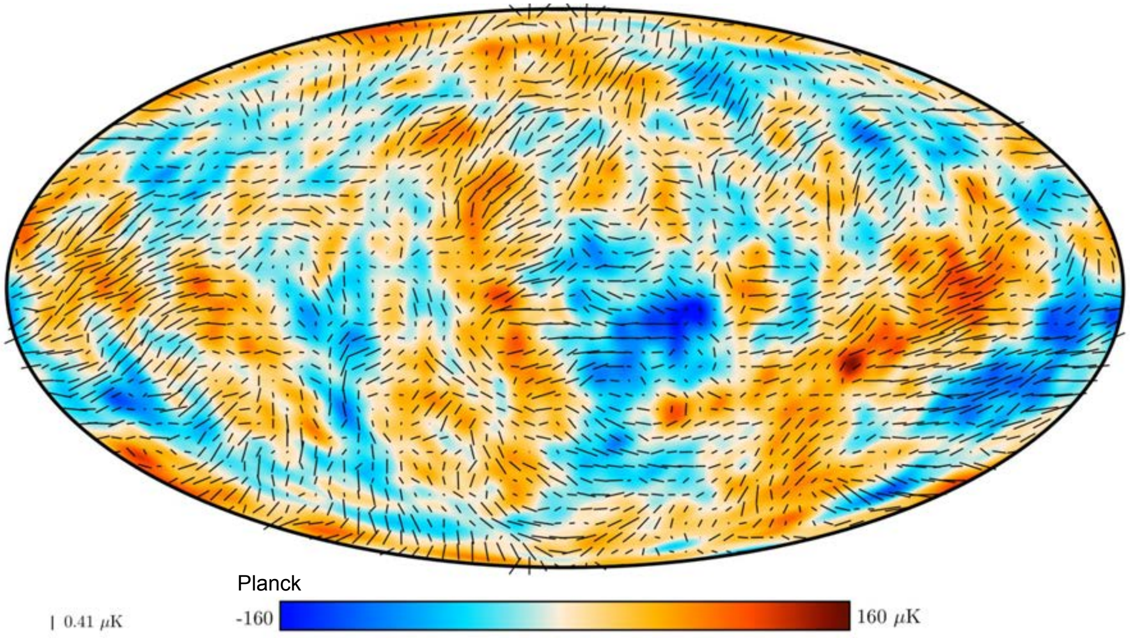
Rotation angle

Δϕ: difference between ϕ at emission and absorption

The Cosmic Microwave Background (CMB)

- Relic light from early universe plasma
- Released ~300,000 years after big bang
- Extremely isotropic 2.73K blackbody
- Tiny anisotropies: early universe perturbations
- Slight linear polarization

Sky map of temperature & polarization anisotropies:



Axion Signal in the CMB

- Axion acts like an oscillating scalar field:

$$\phi(\vec{x},t) = \phi_0(\vec{x},t)\sin\left(m_\phi t + \theta(\vec{x})\right)$$

Oscillation period: days-months

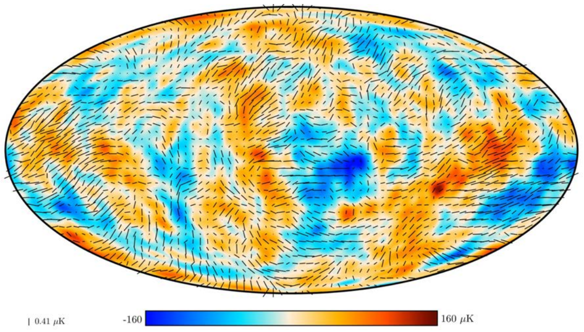
- Coupling to EM field rotates polarized light:

$$\beta = \frac{g_{\phi\gamma}}{2}\left(\phi(\vec{x}_{\mathrm{abs}}, t_{\mathrm{abs}}) - \phi(\vec{x}_{\mathrm{emit}}, t_{\mathrm{emit}})\right)$$

- CMB polarization angle rotation: (Federreke, PRD 2019)

$$\beta_{\mathrm{CMB}}(t) = \frac{g_{\phi\gamma}\phi_0}{2}\sin(m_\phi t + \theta)$$

CMB emitted over 10,000’s of years



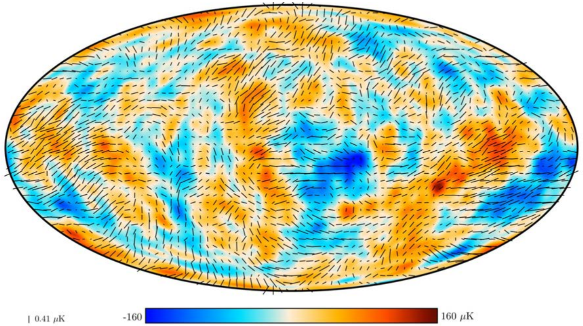
ESA/Planck

13.8 billion years

CMB absorbed by POLARBEAR 1

Axion Signal in the CMB

CMB emitted over 10,000's of years



ESA/Planck

- Axion acts like an oscillating scalar field:

$$\phi(\vec{x},t) = \phi_0(\vec{x},t)\sin\left(m_\phi t + \theta(\vec{x})\right)$$

Oscillation period: days-months

- Coupling to EM field rotates polarized light:

$$\beta = \frac{g_{\phi\gamma}}{2}\left(\phi(\vec{x}_{\text{abs}}, t_{\text{abs}}) - \cancel{\phi(\vec{x}_{\text{emit}}, t_{\text{emit}})}\right)$$

Averaged out

- CMB polarization angle rotation: (Federreke, PRD 2019)

Field at telescope

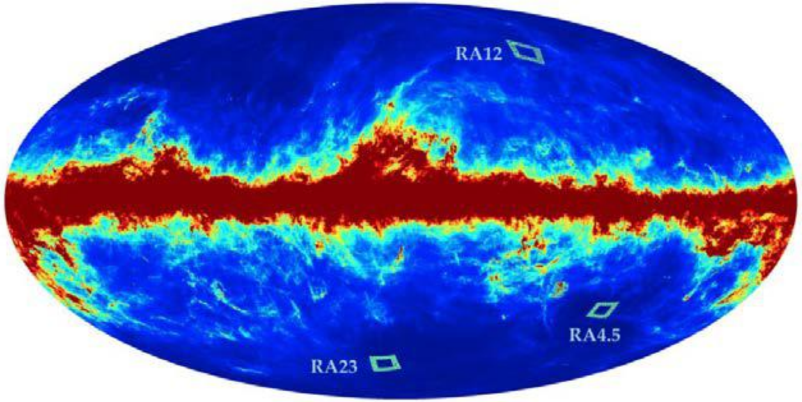
$$\beta_{\text{CMB}}(t) = \frac{g_{\phi\gamma}\phi_0}{2}\sin(m_\phi t + \theta)$$

13.8 billion years

CMB absorbed by POLARBEAR 1

POLARBEAR-1 Observations

- POLARBEAR-1: CMB telescope in Atacama Desert
    - 150 GHz
    - 3.5 arc-min resolution
    - Took data 2012-2016
- Use 2 years of data: 2012-2014
- 3 small patches:
    - ‘Observation’: staring at 1 patch, up to 8 hours long
- 515 total observations

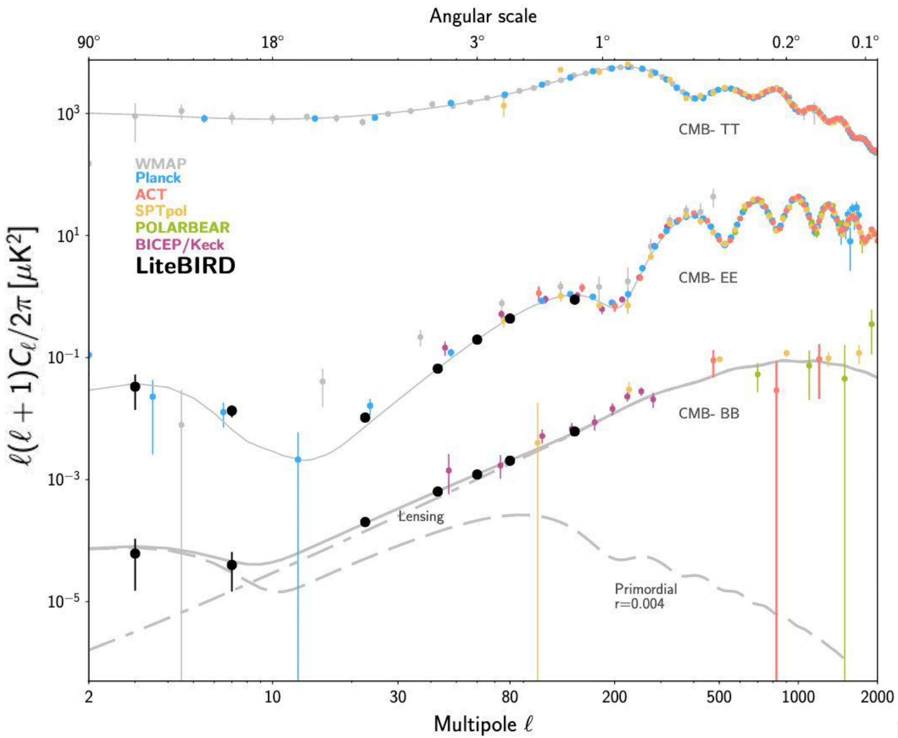


POLARBEAR sky patches

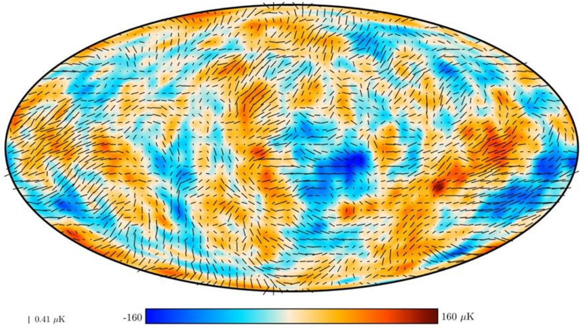
POLARBEAR Ap.J. 2014

CMB Power Spectrum

Power spectrum "C_ℓ": Correlate two points on the sky



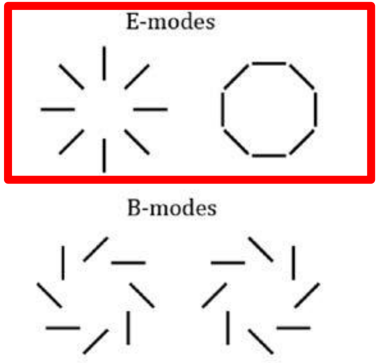
LiteBIRD PTEP 2022



ESA/Planck

Two types of polarization

Dominant in CMB



Estimating an Angle for Each Observation

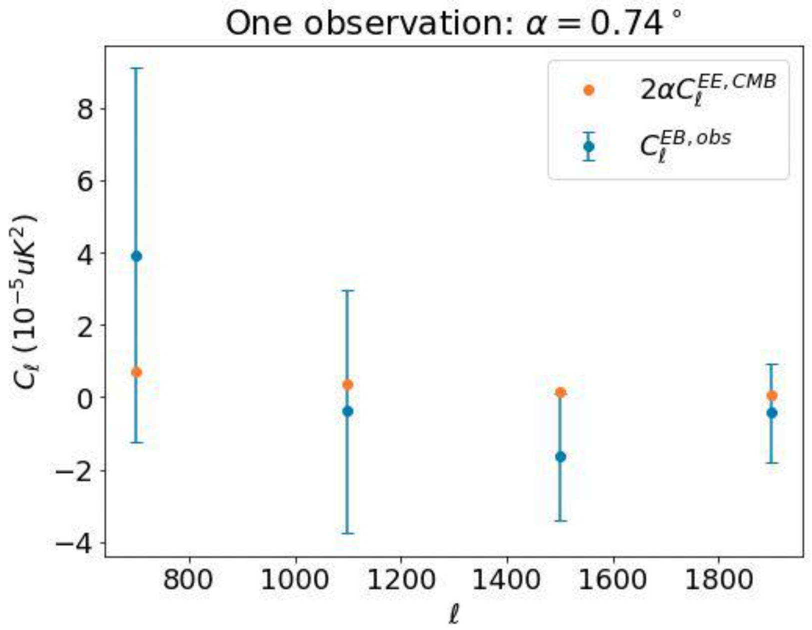
- Under small rotation angle α, the maps are:

$$E_{\ell m}^{\text{obs}} = E_{\ell m}^{\text{CMB}} - 2\alpha B_{\ell m}^{\text{CMB}}$$

$$B_{\ell m}^{\text{obs}} = 2\alpha E_{\ell m}^{\text{CMB}} + B_{\ell m}^{\text{CMB}}$$

- Correlate single observation B map with coadded E maps to estimate angle

$$\underbrace{C_{\ell,obs}^{EB}}_{\text{Observed}} = 2\underbrace{\alpha_{obs}}_{\text{Calculate}}\underbrace{C_{\ell,CMB}^{EE}}_{\text{Known precisely}} + \mathcal{O}(\alpha^2)$$



Estimating an Angle for Each Observation

- Under small rotation angle α, the maps are:

$$E^{\text{obs}}_{\ell m} = E^{\text{CMB}}_{\ell m} - \cancel{2\alpha B^{\text{CMB}}_{\ell m}}$$

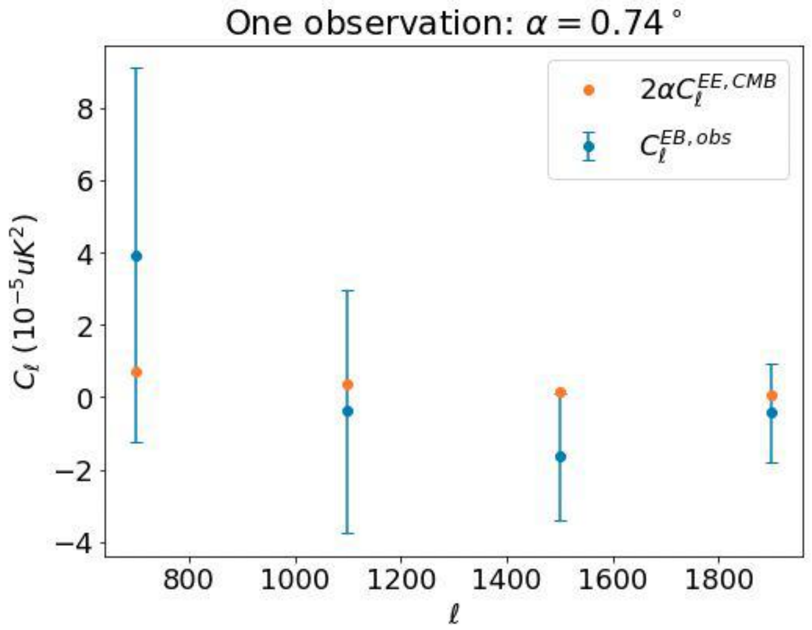
$$B^{\text{obs}}_{\ell m} = \boxed{2\alpha E^{\text{CMB}}_{\ell m}} + \cancel{B^{\text{CMB}}_{\ell m}}$$

carries all the info

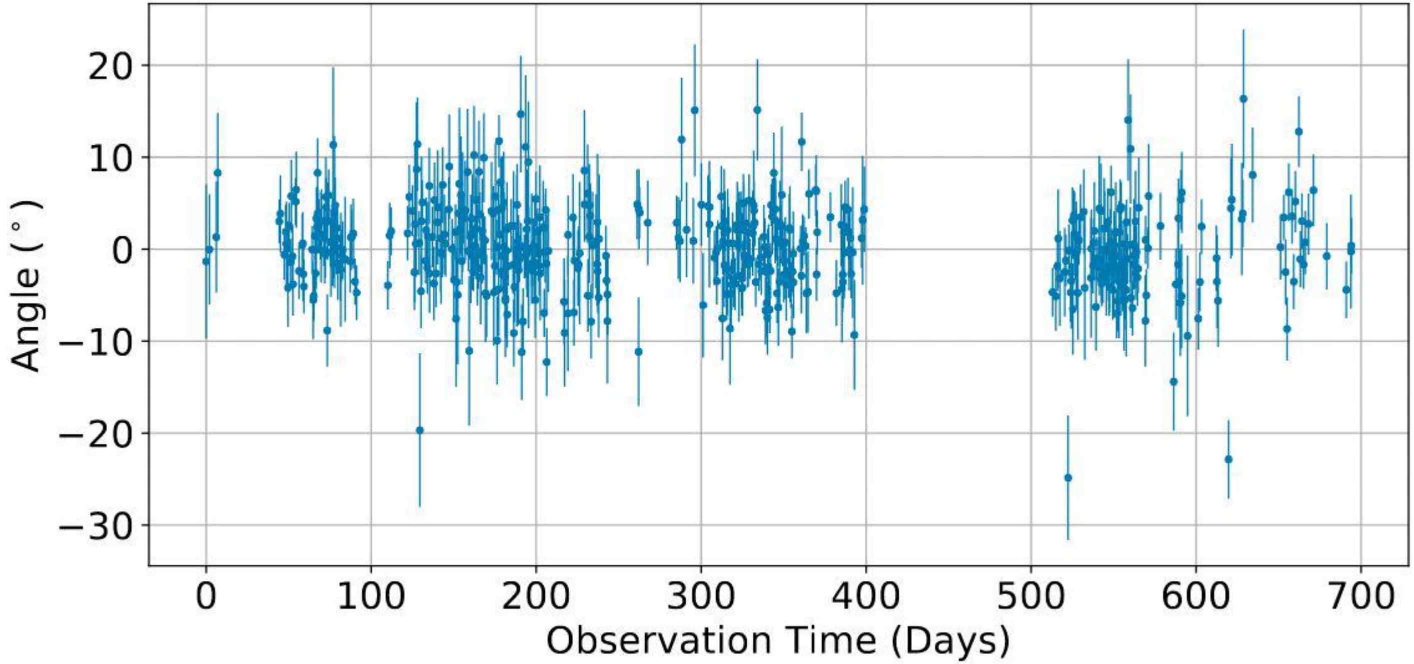
- Correlate single observation B map with coadded E maps to estimate angle

$$\underbrace{C^{EB}_{\ell,obs}}_{\text{Observed}} = 2\alpha_{obs}\underbrace{C^{EE}_{\ell,CMB}}_{\text{Known precisely}} + \mathcal{O}(\alpha^2)$$

Calculate



Angle Timestream



POLARBEAR 2023

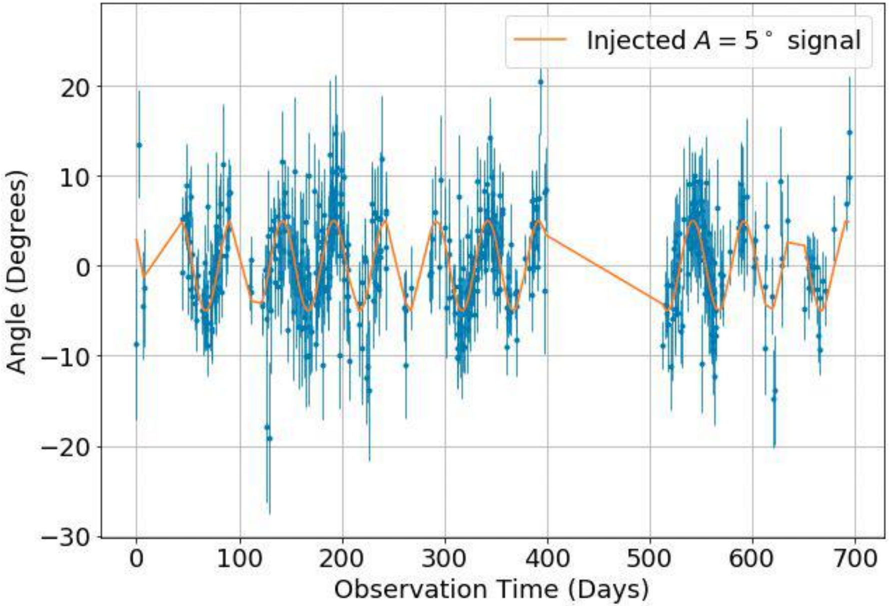
The Axion Signal

- The signal is averaged over the ~4-8 hour observation period
  - <3% effect for sinusoid periods considered here
- Estimate signal using likelihood:

$$\mathcal{L}(A, f, \theta) \propto e^{-\frac{1}{2}\chi^2(A,f,\theta)}$$

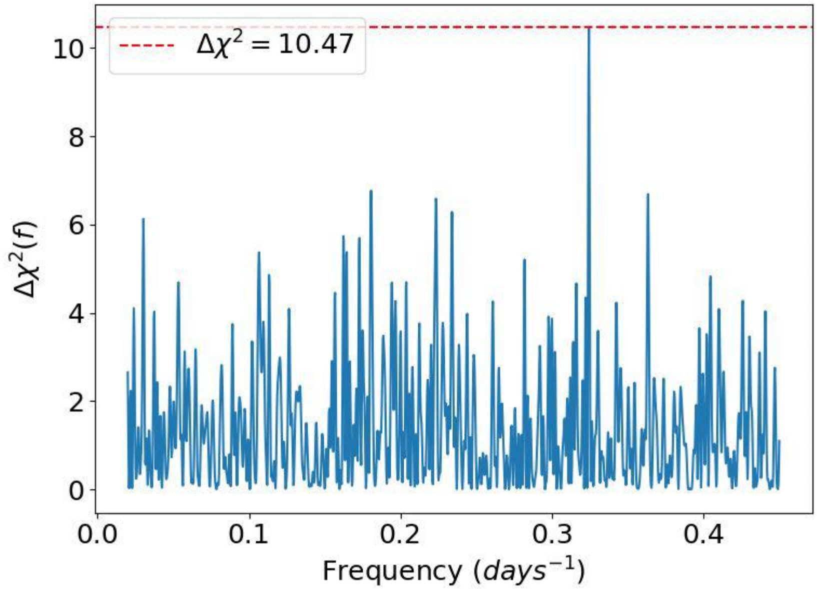
- Frequency range:

$$\frac{1}{50}\,\mathrm{days}^{-1} \leq f \leq 0.45\,\mathrm{days}^{-1}$$



Large example signal in simulated data

Results: No Detection



POLARBEAR 2023

- Test for presence of signal:

$$\Delta\chi^2 \equiv \chi^2(A=0) - \chi^2(A^{\mathrm{mle}}, f^{\mathrm{mle}}, \theta^{\mathrm{mle}})$$

- Compare to simulated distribution of Δ□^{2} values
- σ_{PTE} = 1.7: no detection claimed
- 5σ sensitivity to signals with amplitude > 1.43°

Constraints on Axion-Photon Coupling

Recall:

$$A = \frac{g_{\phi\gamma}\phi_0}{2}$$

Axion field amplitude at telescope

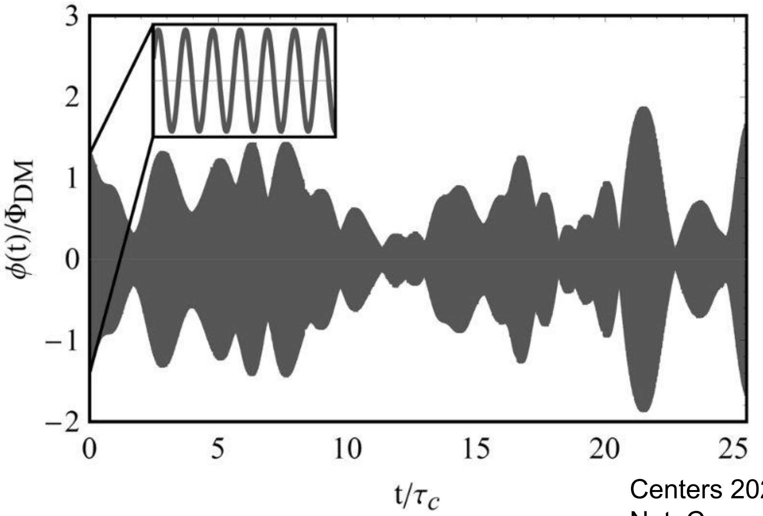
Problem: ϕ_0 value is **stochastic**

- Governed by Rayliegh probability distribution

$$P(\phi_0) = \frac{2\phi_0}{\phi_{\rm DM}^2} e^{-\frac{\phi_0^2}{\phi_{\rm DM}^2}}$$

Average value from local Milky Way DM density:

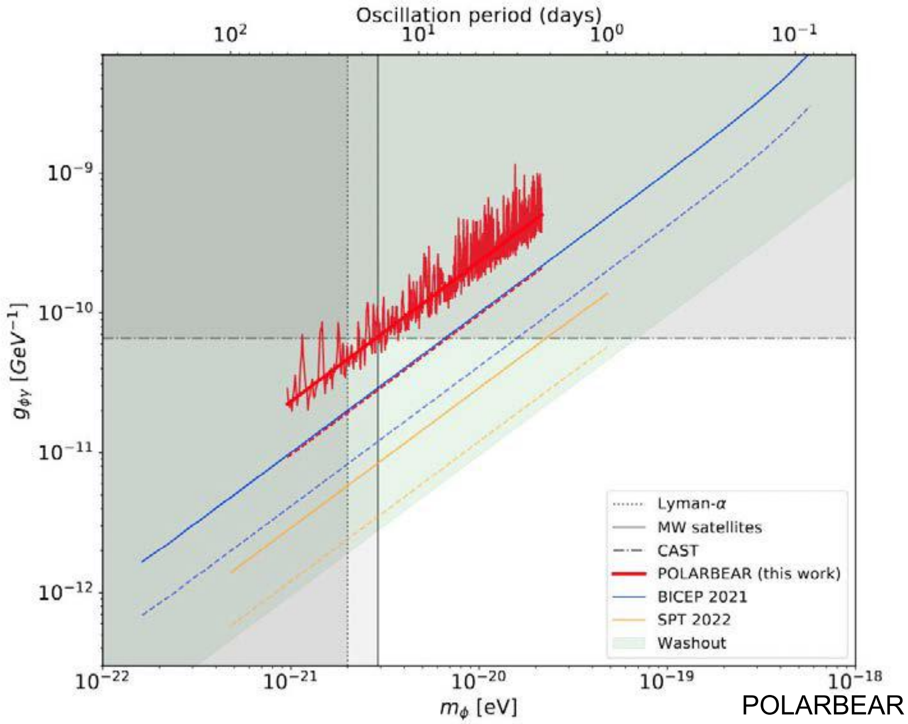
$$\frac{1}{2}\phi_{DM}^2 m_\phi^2 = \rho_{\rm local}$$



Centers 2021 Nat. Comm.

Local axion field amplitude variation vs. coherence time $\tau_c \gtrsim$ 6000 years

Constraints on Axion-Photon Coupling



POLARBEAR 2023

Solid red line: POLARBEAR constraint

Dashed lines: constraint using $\phi_0 = \phi_{DM}$ instead

- Marginalize over unknown ϕ_0 amplitude
- 95% upper confidence limit:

$$P(g^{\rm mle} \leq g^{\rm mle}_{\rm obs} | g^{95})(f) = 0.05$$

- Median upper limit

$$g_{\phi\gamma} < (2.4 \times 10^{-11}\,{\rm GeV}^{-1}) \times \left(\frac{m_\phi}{10^{-21}\,{\rm eV}}\right)$$

- First CMB analysis of this kind to incorporate stochastic effect of local axion field

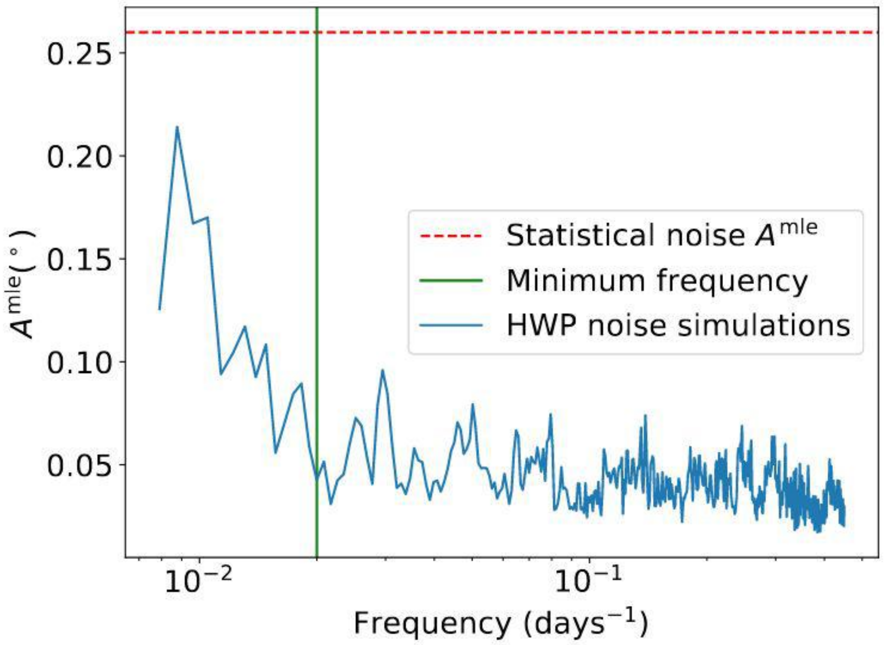
Conclusion

- Axions (ultralight $m \approx 10^{-20}$-10^{-21} eV spin-0 fields) are a promising dark matter candidate.
- Axion-photon coupling causes the linear polarization of the Cosmic Microwave Background to oscillate in time.
- We searched for this effect with data from the POLARBEAR telescope.
- No signal found, placed constraints on the coupling vs axion mass

BACKUP

Largest Systematic Issue: Half Wave Plate Noise

- Half wave plate (HWP): rotates polarization of incoming light
- HWP was rotated in 11.25° increments between observations during 1st year
- Error at each increment: $\sigma_{HWP} = 0.56°$
- Causes low-frequency noise
- **Mitigation: minimum frequency used is 1/50 days^{-1}**



Estimated HWP Noise

Null Test Results

$$T_{\rm null}(f) \equiv \frac{|A_{\rm null}(f)|^2}{\sigma\left(\Re(A_{\rm null}(f))\right)^2} \tag{17}$$

where

$$A_{\rm null}(f) \equiv (A_1^{\rm mle} e^{i\theta_1^{\rm mle}} - A_2^{\rm mle} e^{i\theta_2^{\rm mle}})(f). \tag{18}$$

TABLE I. The five null test PTE values used in the pass criteria #1.

PTE statistic	Description	PTE
$\max_{t,f} T_{\rm null}$	Spurious axion signal	0.032
$\sum_{t,f} T_{\rm null}$	Total chi-square	0.062
$\max_t \sum_f T_{\rm null}$	Bad test	0.060
$\max_f \sum_t T_{\rm null}$	Bad frequency	0.246
$\max_t T_{\rm null}(f=0)$	Mean angle offset	0.192

TABLE II. The three null test PTE values used in the pass criteria #2.

Axion KS Test inputs	Description	Number of inputs	PTE
$\mathrm{PTE}_{f,t}(T_{\rm null})$	Overall	22380	0.128
$\mathrm{PTE}_f(\sum_t T_{\rm null})$	Per frequency	1492	0.122
$\mathrm{PTE}_t(\sum_f T_{\rm null})$	Per test	15	0.190