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

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N3AS Summer School

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Axions (Axion-Like Particles) and Cosmic Birefringence

- Axion defined for this talk: generic light pseudoscalar ϕ
  - Also sometimes called ‘axion-like particle’
  - Masses of interest: ($m \approx 10^{-19}$-10^{-22} eV)
- Model:

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

- Key observable: cosmic birefringence
  - Rotates linearly polarized light

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

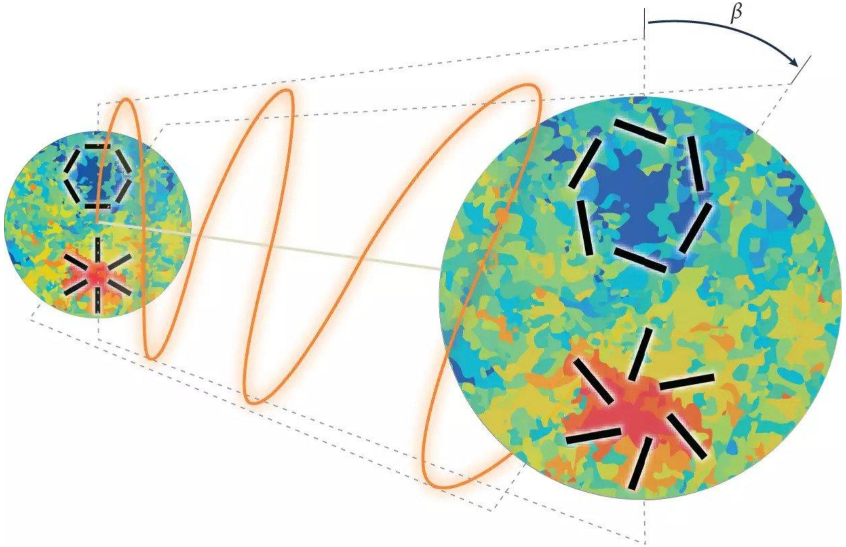


Image: Yuto Minami

Harari & Sikivie, PLB 1992, Carroll 1998

Axions as Fuzzy Dark Matter

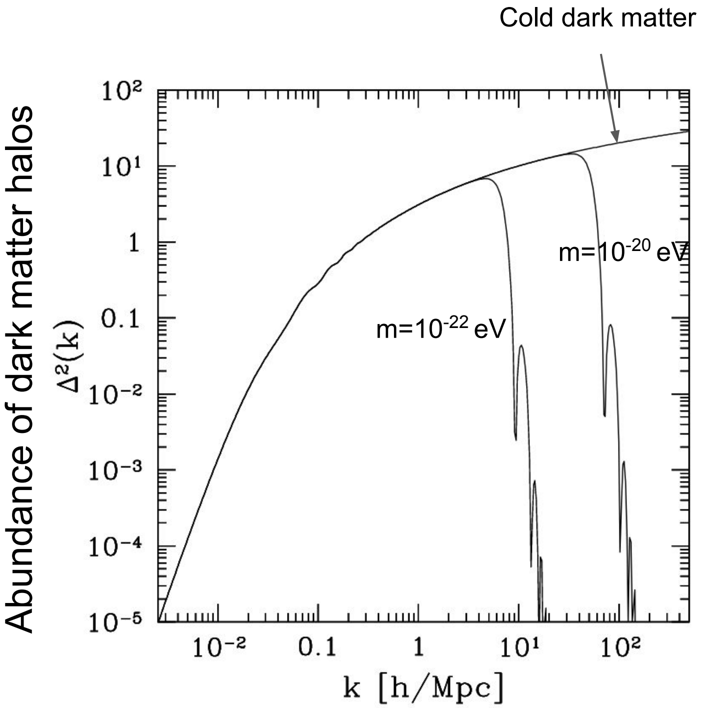
- Cosmological Evolution

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

- Ultralight means large de Broglie wavelength: “Fuzzy dark matter”

$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv} = 0.48\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{250\,{\rm km/s}}{v}\right)$$

- Effects on small scale structure
  - Small halo formation is cut off
  - Smooth density at halo center



Hui, Annu. Rev. Astron. Astrophys. 2021

Axion Signal in the CMB

- Oscillating classical field description:

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

Oscillation period: days-months

- Cosmic birefringence:

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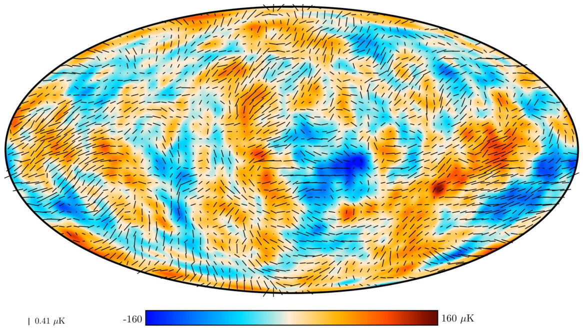
- CMB polarization angle rotation: (Federreke et. al., PRD 2019)

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



ESA/Planck

13.8 billion years

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Averaged out: washout effect

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

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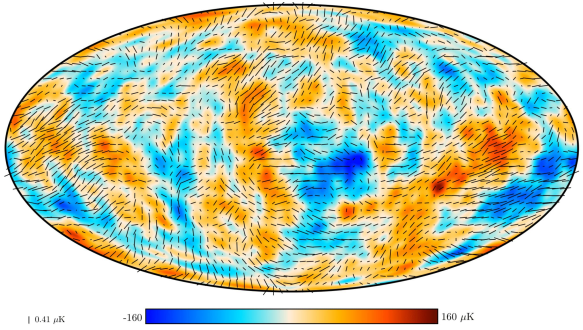
CMB emitted over 10,000's of years



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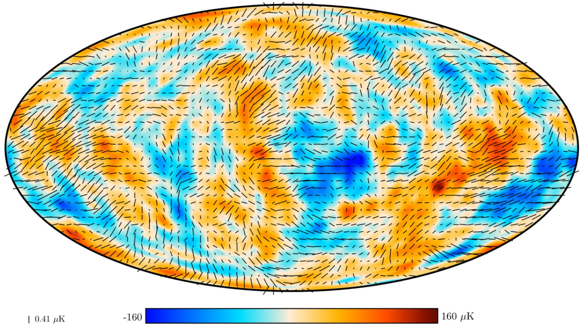
Sinusoidal rotation effect: **this work**



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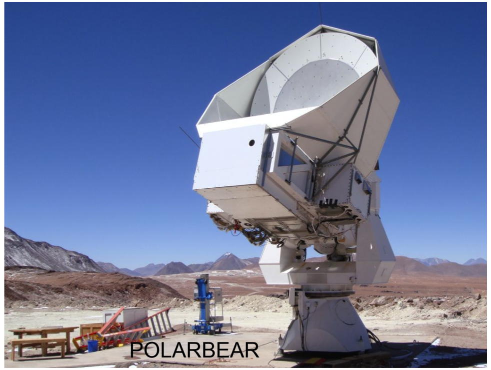
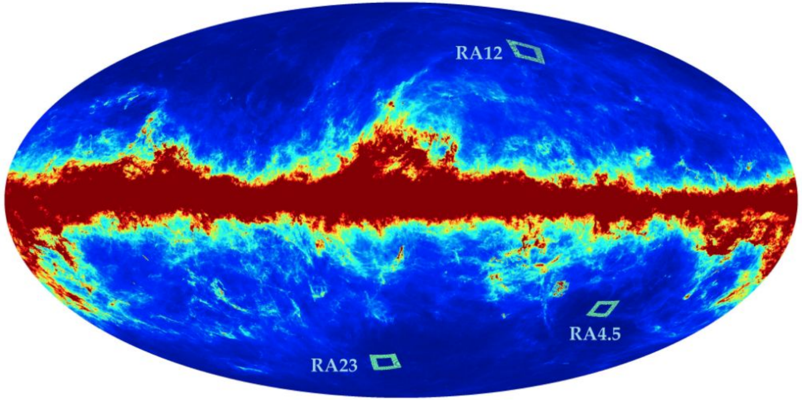
CMB absorbed by POLARBEAR 1

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

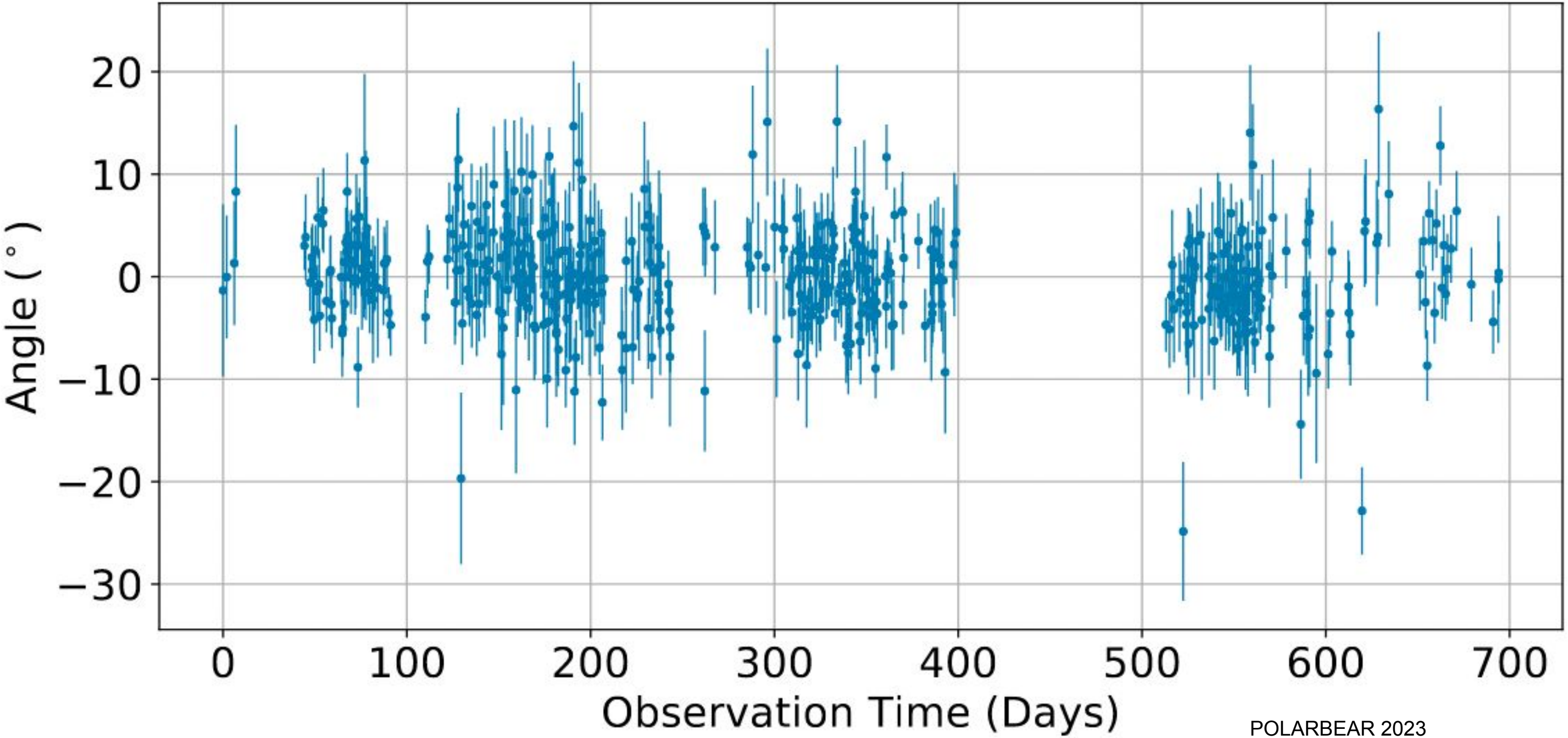




POLARBEAR sky patches

POLARBEAR Ap.J. 2014

Angle Timestream



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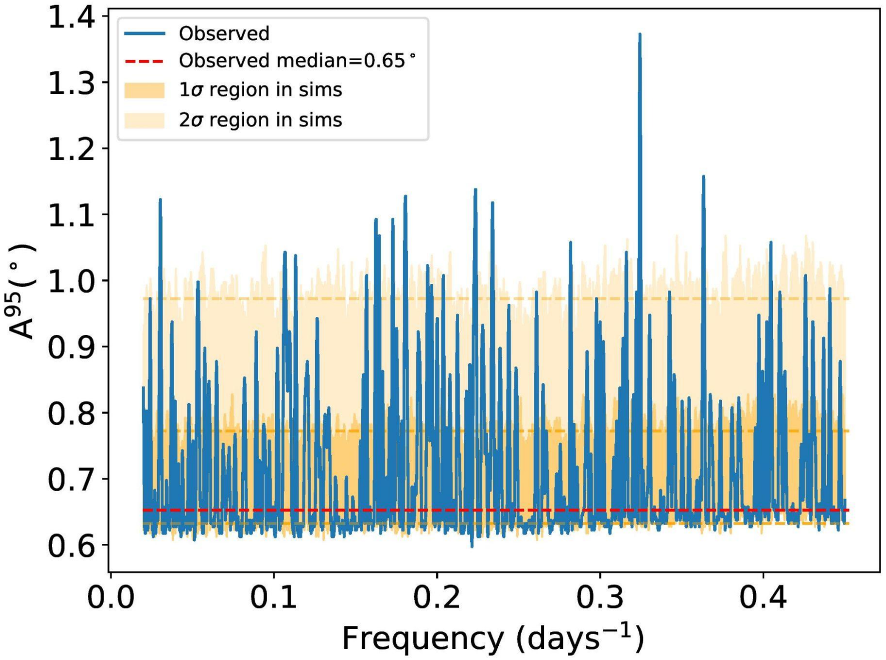
Results: No Detection



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- 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 a simulated distribution
- σ_{PTE} = 1.7: no significant detection
- Place 95% upper confidence limit on sinusoid amplitude A_{95} across frequency range

Stochastic Nature of the Axion Field

Recall:

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

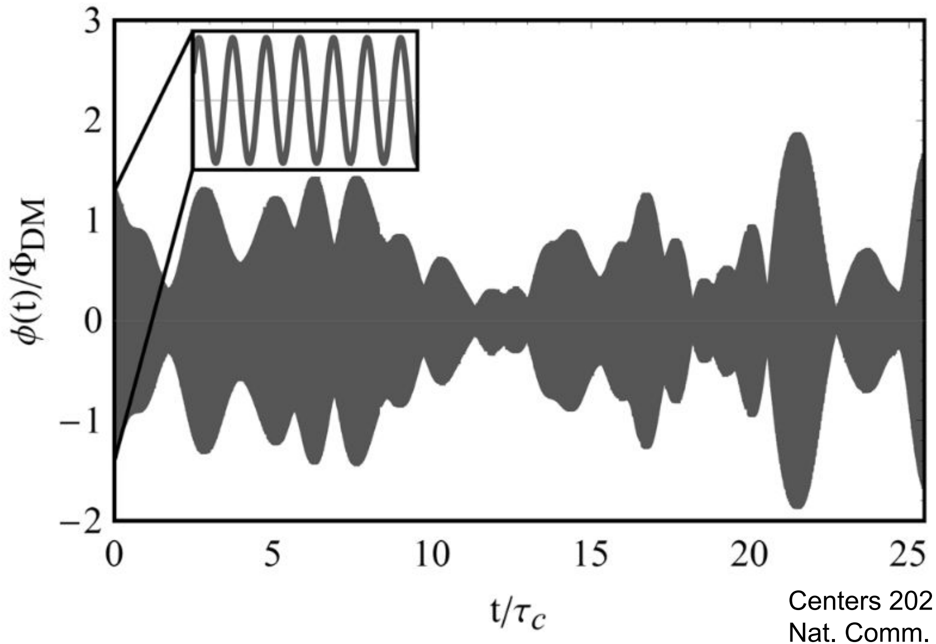
Axion field amplitude at telescope

Problem: ϕ_0 is unknown

- Model as Rayleigh distribution

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

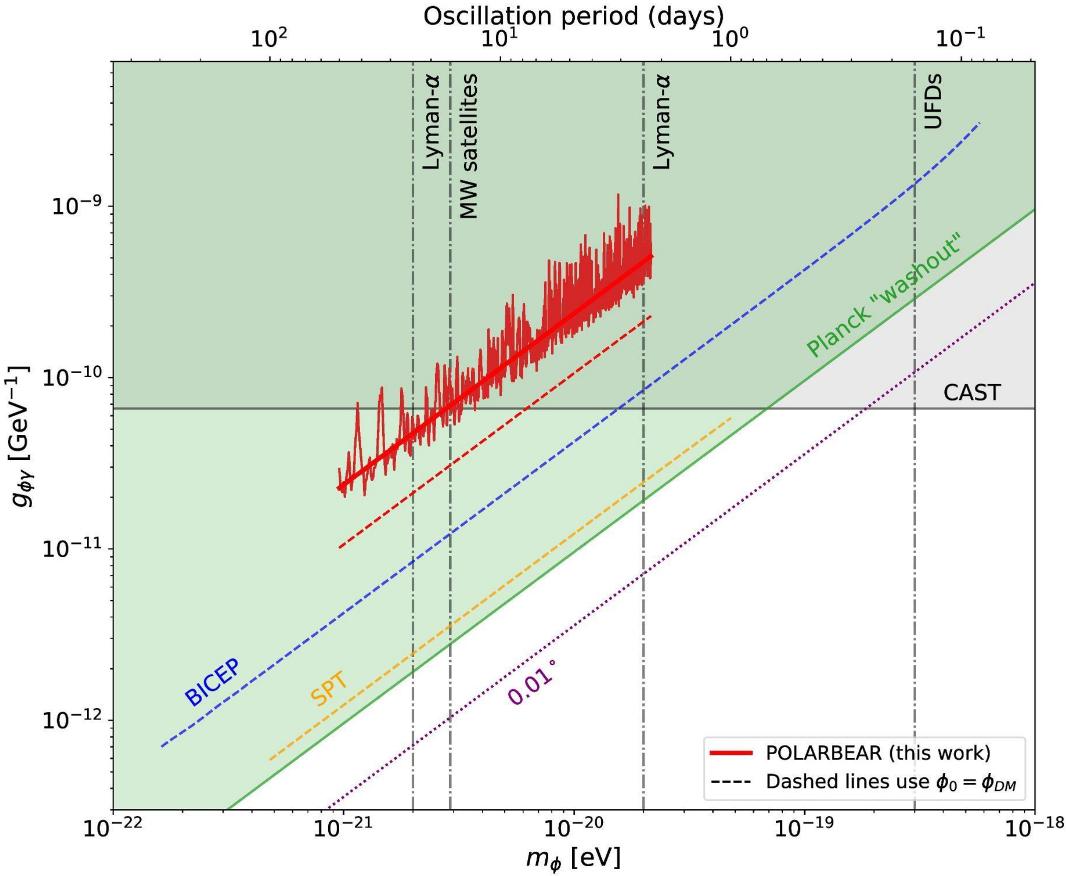
$$\frac{1}{2}\phi_{DM}^2 m_\phi^2 = 0.3\ \mathrm{GeV/cm^3}$$



Centers 2021 Nat. Comm.

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

Constraints on Axion-Photon Coupling



- Marginalize over unknown ϕ_0 amplitude
- Assuming axion is all the DM: median 95% upper confidence limit
- First CMB analysis of this kind to incorporate stochastic effect of local axion field

BACKUP

Estimating an Angle for Each Observation

- Under small rotation angle α, the maps are:

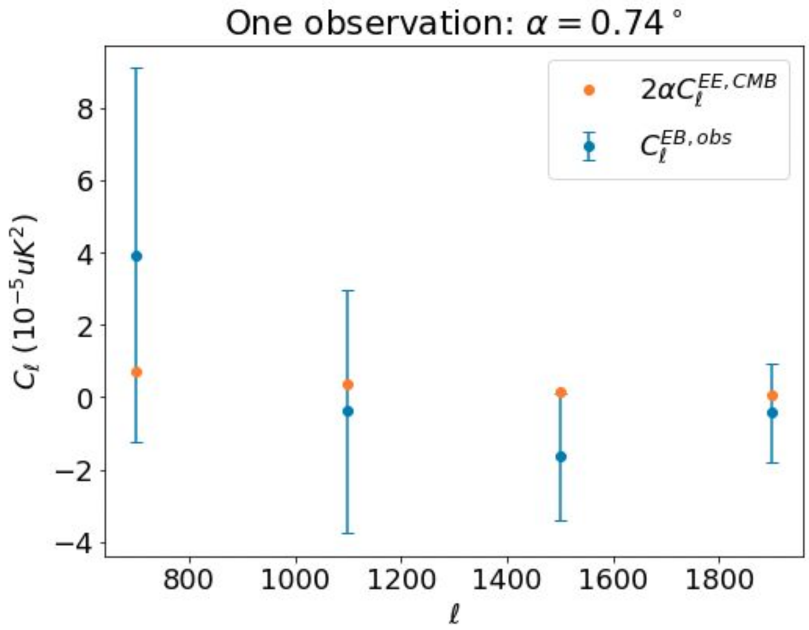
$$E_{\ell m}^{\mathrm{obs}} = E_{\ell m}^{\mathrm{CMB}} - 2\alpha B_{\ell m}^{\mathrm{CMB}}$$

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

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

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

Observed Calculate Known



Estimating an Angle for Each Observation

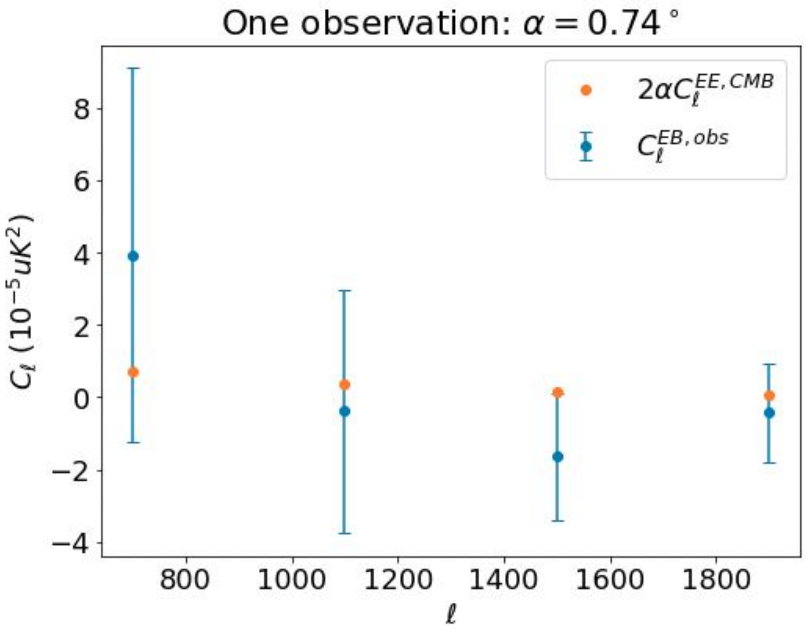
- Under small rotation angle α, the maps are:

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

$$B^{\mathrm{obs}}_{\ell m} = \underbrace{\boxed{2\alpha E^{\mathrm{CMB}}_{\ell m}}}_{\text{carries all the info}} + \cancel{B^{\mathrm{CMB}}_{\ell m}}$$

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

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



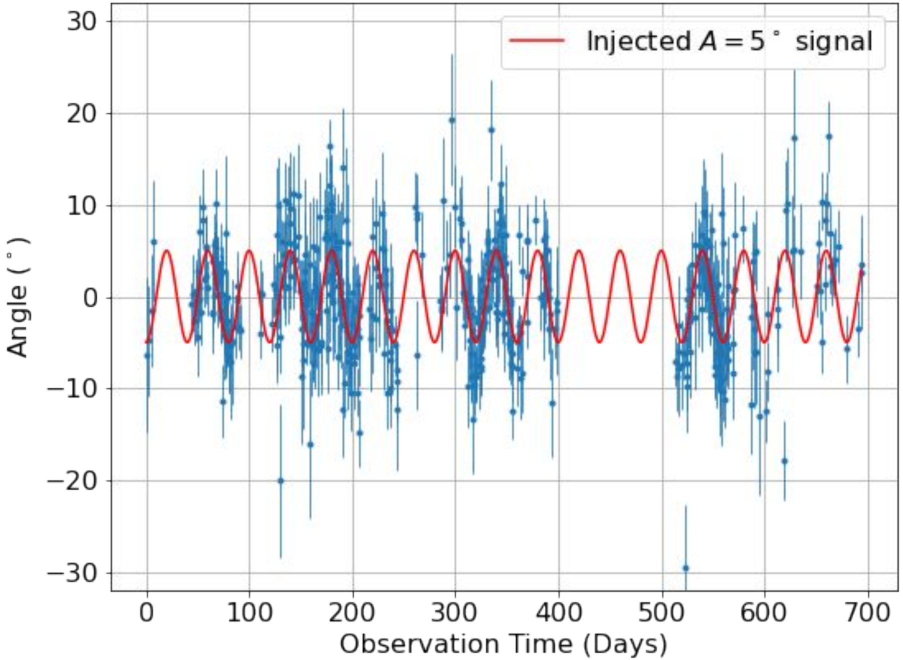
Signal Estimation

- Estimate sinusoidal signal A*sin(2πf + θ) using likelihood:

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

- Frequency range:

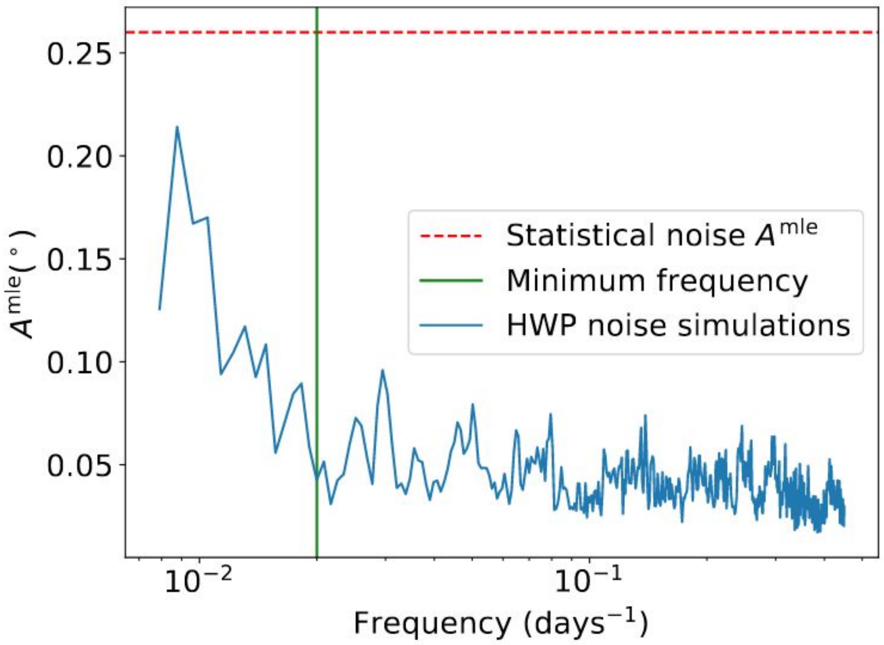
$$\frac{1}{50}\,\text{days}^{-1} \leq f \leq 0.45\,\text{days}^{-1}$$



Large example signal in simulated data

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

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Null Test Results

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

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

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

PTE statistic	Description	PTE
$\max_{t,f} T_{\text{null}}$	Spurious axion signal	0.032
$\sum_{t,f} T_{\text{null}}$	Total chi-square	0.062
$\max_t \sum_f T_{\text{null}}$	Bad test	0.060
$\max_f \sum_t T_{\text{null}}$	Bad frequency	0.246
$\max_t T_{\text{null}}(f=0)$	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
$\text{PTE}_{f,t}(T_{\text{null}})$	Overall	22380	0.128
$\text{PTE}_f(\sum_t T_{\text{null}})$	Per frequency	1492	0.122
$\text{PTE}_t(\sum_f T_{\text{null}})$	Per test	15	0.190

Conclusion

- Axion-photon coupling generates cosmic birefringence
- We searched for a sinusoidal oscillation of the CMB polarization angle using the POLARBEAR telescope.
- No signal found: placed constraints on the coupling vs axion mass in the ($m \approx 10^{-19}$-10^{-22} eV) range