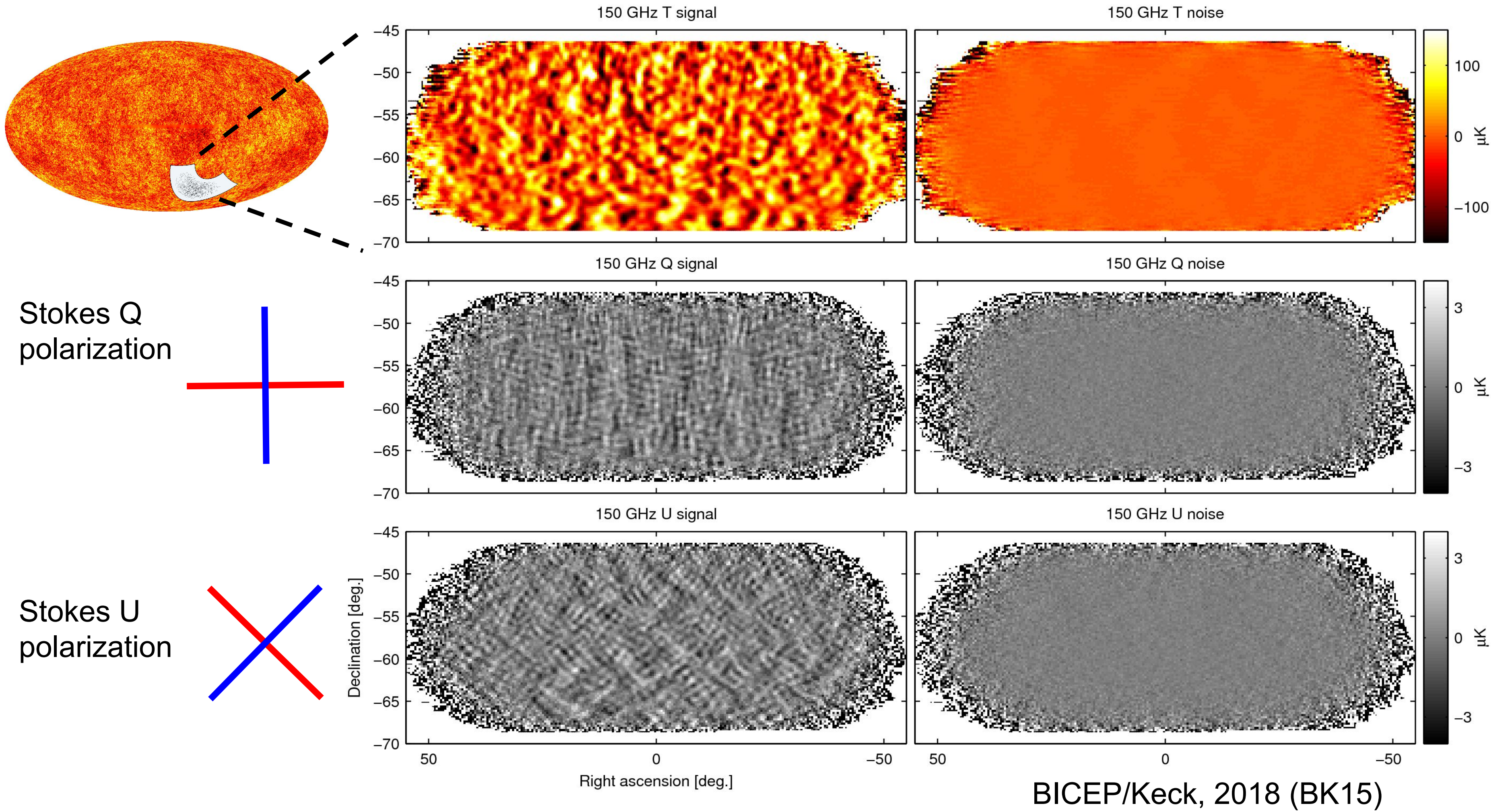
The oscillating sky
Detecting axion dark matter with the CMB

Ari Cukierman (Stanford University)

APEC seminar, Kavli IPMU
Nov. 19, 2020



Stokes Q
polarization
Stokes U
polarization
150 GHz T signal
150 GHz T noise
150 GHz Q signal
150 GHz Q noise
150 GHz U signal
150 GHz U noise
Declination [deg.]
Right ascension [deg.]
μK
BICEP/Keck, 2018 (BK15)

CMB experiments for dummies

Build very sensitive microwave receivers in remote locations

Make repeated observations of the same patch of sky

Average away instrumental noise and atmospheric fluctuations

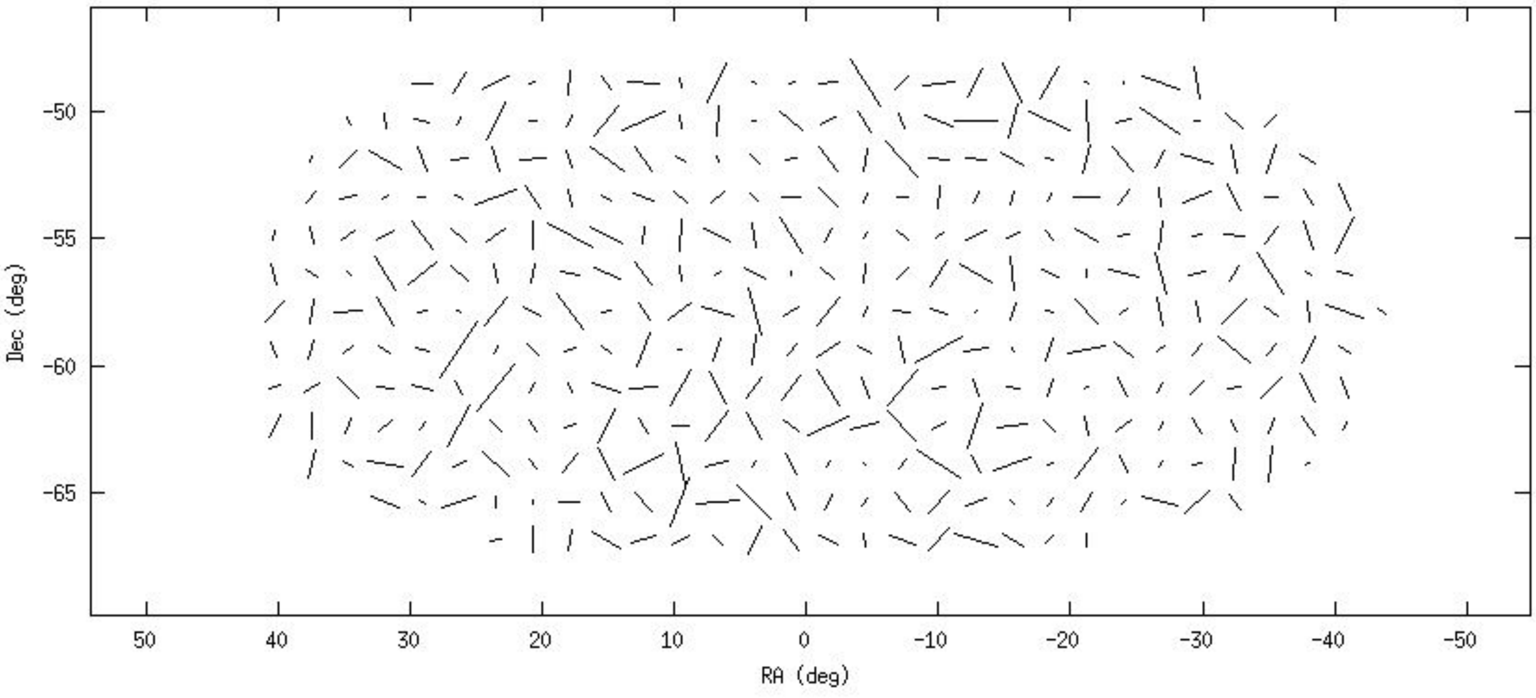
What remains is the CMB**

Implicit assumption: the CMB is unchanging

**With about a million caveats

Local axion-like dark matter produces time-variability in CMB polarization

The oscillating sky



Axions

~~Axions~~ Axion-like particles

~~Axions Axion-like particles~~ Axions

Light bosons, similar SM couplings to QCD axion

- This talk targets 1e-22 - 1e-18 eV

“Fuzzy dark matter”

- Astrophysical de Broglie wavelengths

Birefringence for opposite-helicity photons

- Linear polarizations are rotated

Polarization rotations

Depends only on axion field at the *endpoints*

Independent of trajectory

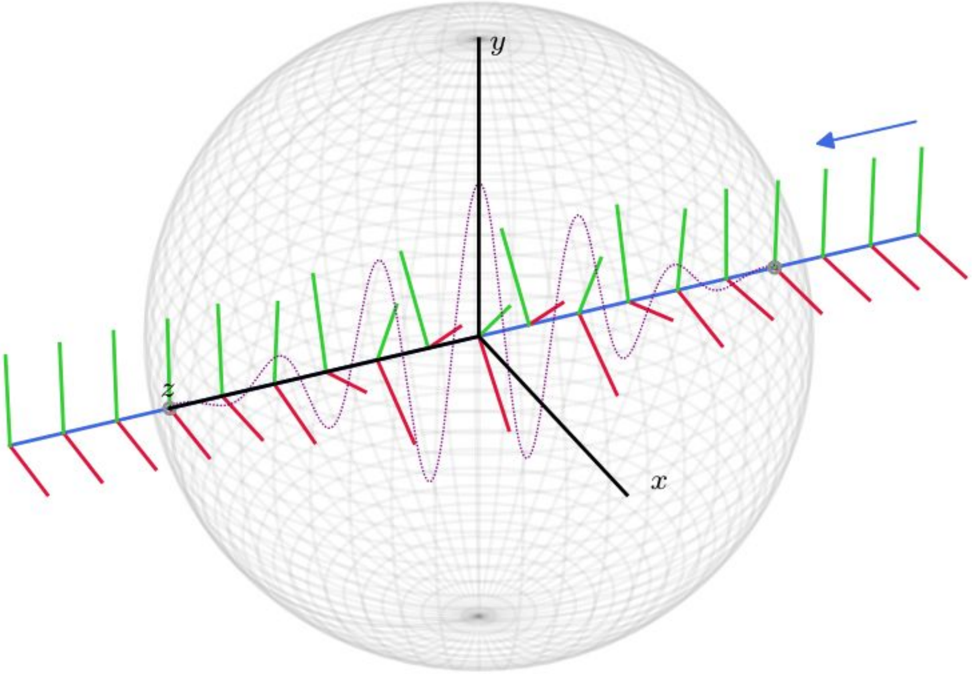


Fig. credit: M. Fedderke

Two more ingredients...

Axion field amplitude evolves in time

- Hubble expansion, structure formation

Axion field **oscillates** with frequency **m/(2π)**

- 1e-22 - 1e-18 eV → periods of hours to years

Axions and the CMB

See **Fedderke, Graham, Rajendran, 2019**

Observables:

1. Washout
   a. Suppression of CMB polarization relative to ΛCDM
   b. Largest effects on EE and TE
2. AC oscillation
   a. All-sky coherent oscillation of CMB polarization with frequency **m/(2π)**

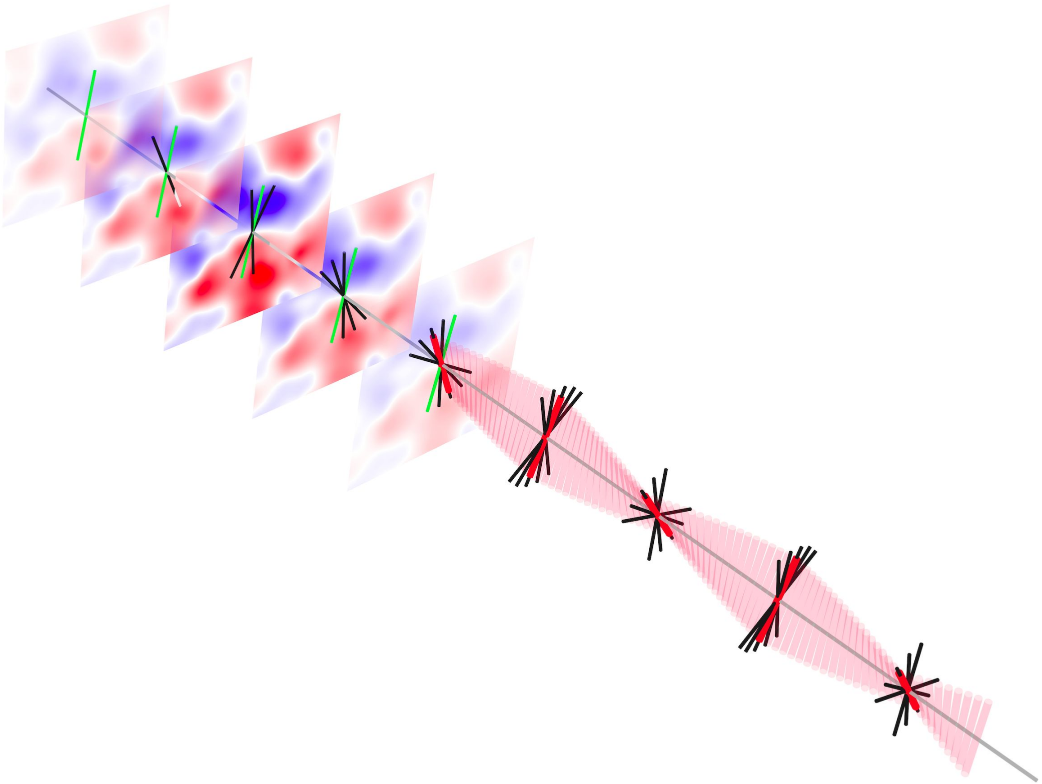


Fig. credit: M. Fedderke

The oscillating sky

Avg. axion field amplitude at recombination

Axion-photon coupling constant

Local axion field amplitude *today*

Axion mass

Arbitrary phase

$$\begin{pmatrix} Q(t) \\ U(t) \end{pmatrix} = J_0(g_{\phi\gamma}\langle\phi_*\rangle) \begin{pmatrix} 1 & -g_{\phi\gamma}\phi_0 \cos(m_\phi t + \alpha) \\ g_{\phi\gamma}\phi_0 \cos(m_\phi t + \alpha) & 1 \end{pmatrix} \begin{pmatrix} Q_0 \\ U_0 \end{pmatrix}$$

Time-variable polarization

Stokes Q/U mixing = polarization-angle oscillation

- "AC oscillation"
- sinusoidal and coherent

Polarization in decoupled limit

Washout (overall suppression of polarization)

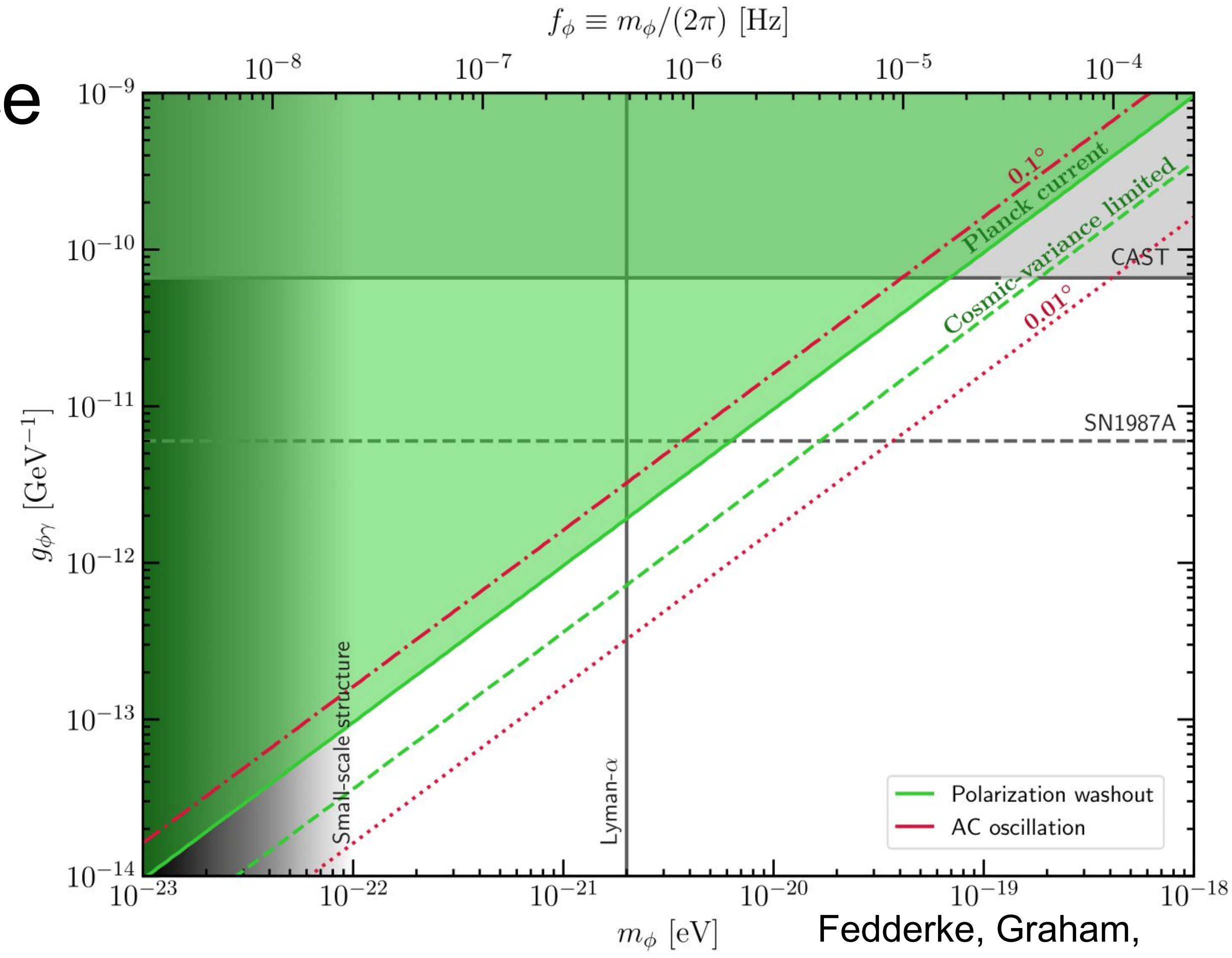
Parameter space

Washout

- Close to cosmic-variance limit with *Planck*

AC oscillation

- Current limits equivalent to ~0.1-deg. amplitude
- <u>No cosmic variance</u>



Fedderke, Graham, Rajendran, <u>2019</u>

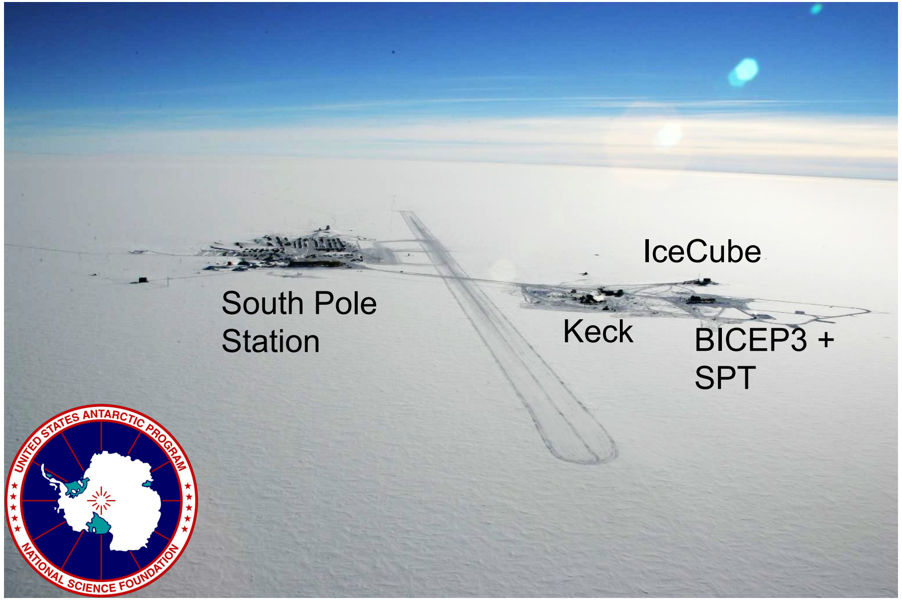
BICEP and the *Keck Array*

2006 - present, South Pole

- 30-300 GHz

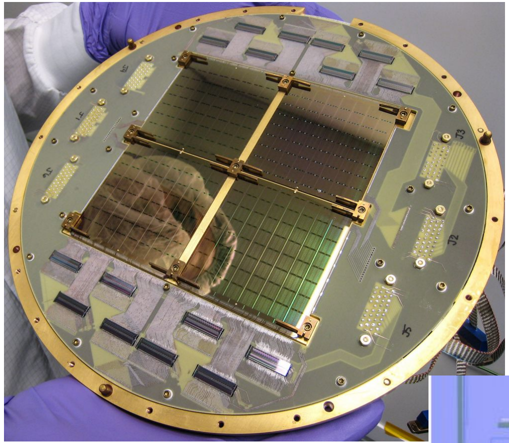
Designed to measure CMB B-modes

- Primordial gravitational waves
  - Testing inflationary cosmologies
- Gravitational lensing of CMB



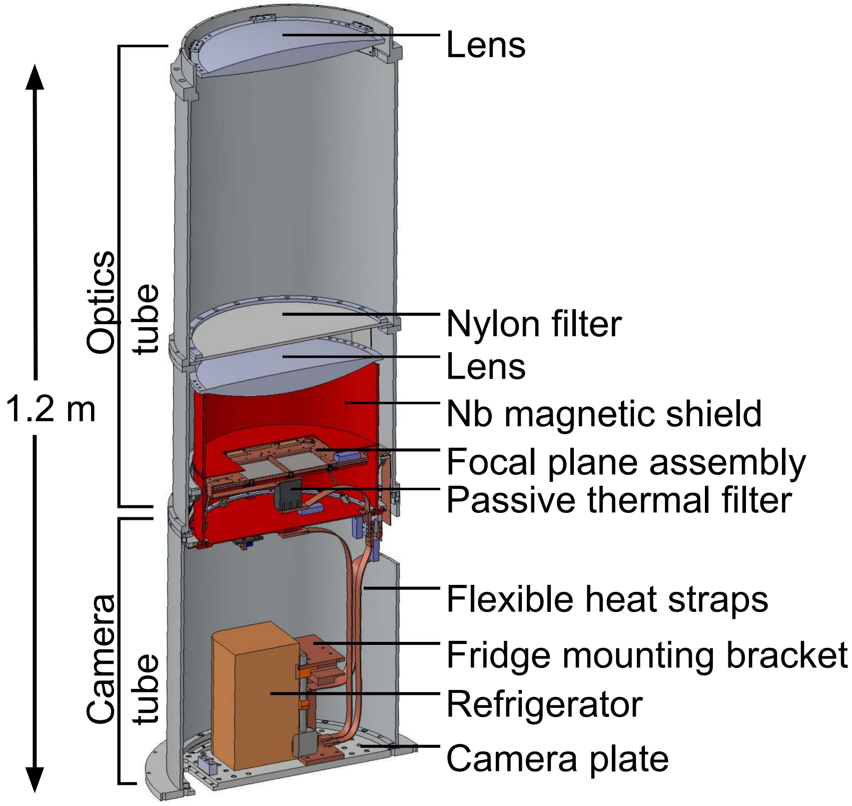
Keck Array (2012-2019)

BICEP and the *Keck Array* (cont'd)



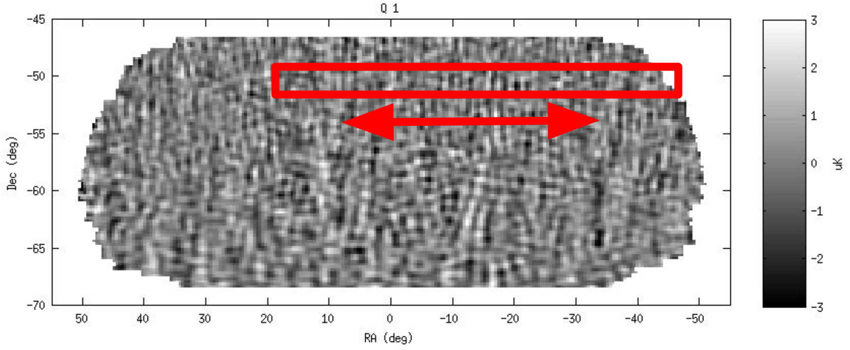
Keck focal plane
(250 mK)

Slot antennas +
transition-edge
sensors (TESs)



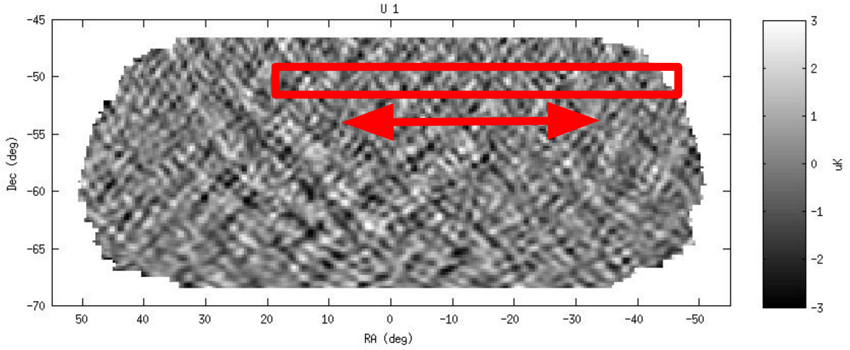
Scan strategy

Q



Constant-elevation scans every hour *relentlessly* for years...

U



Search strategy

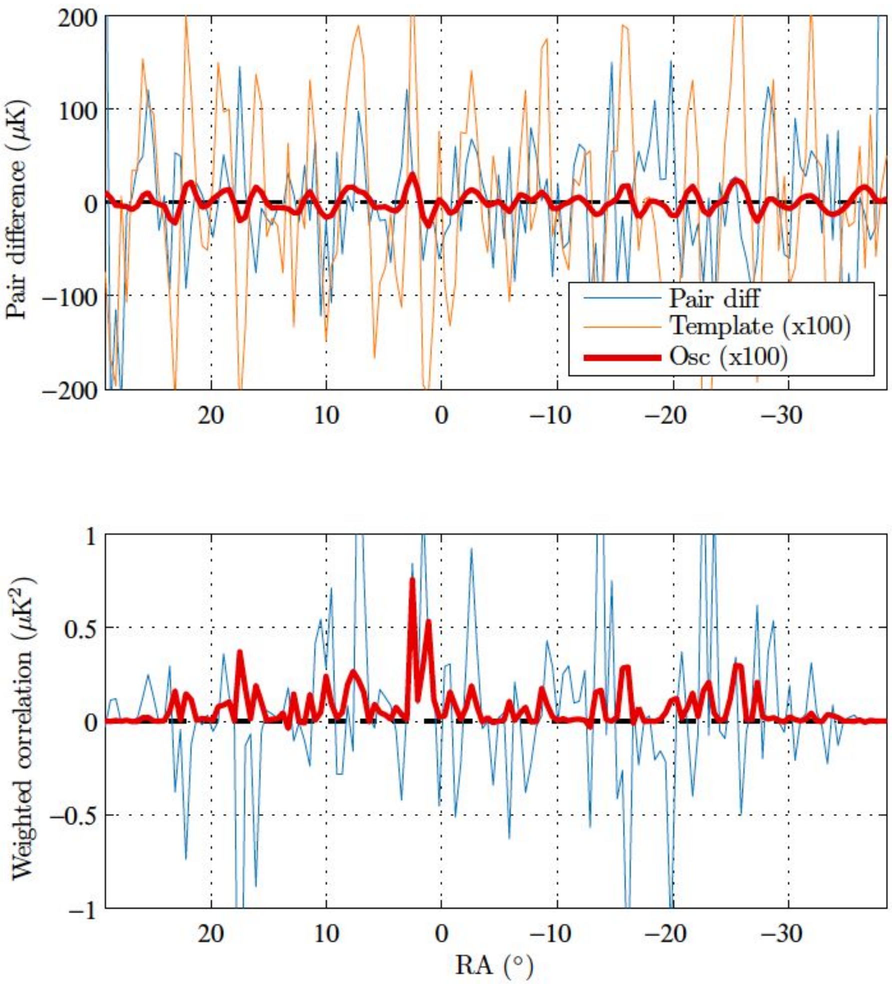
Find correlations between data and template

Oscillation hidden under atmospheric fluctuations

Correlations:

High-variance but mean zero for atmosphere

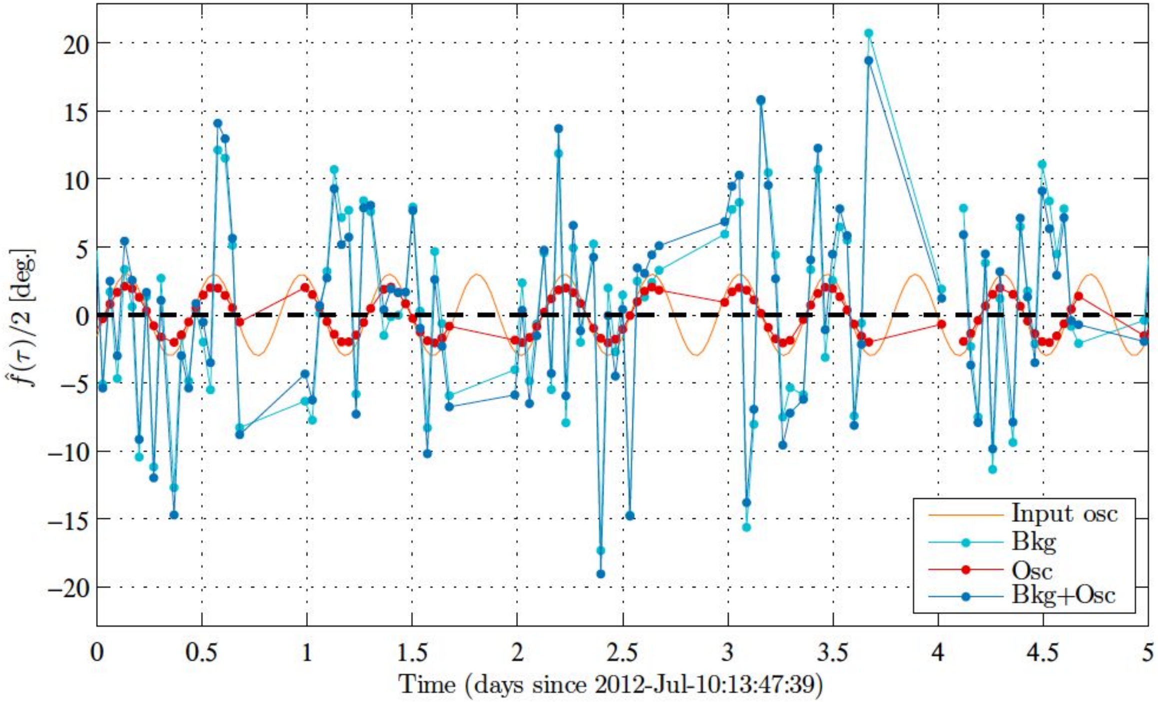
Positive for oscillation



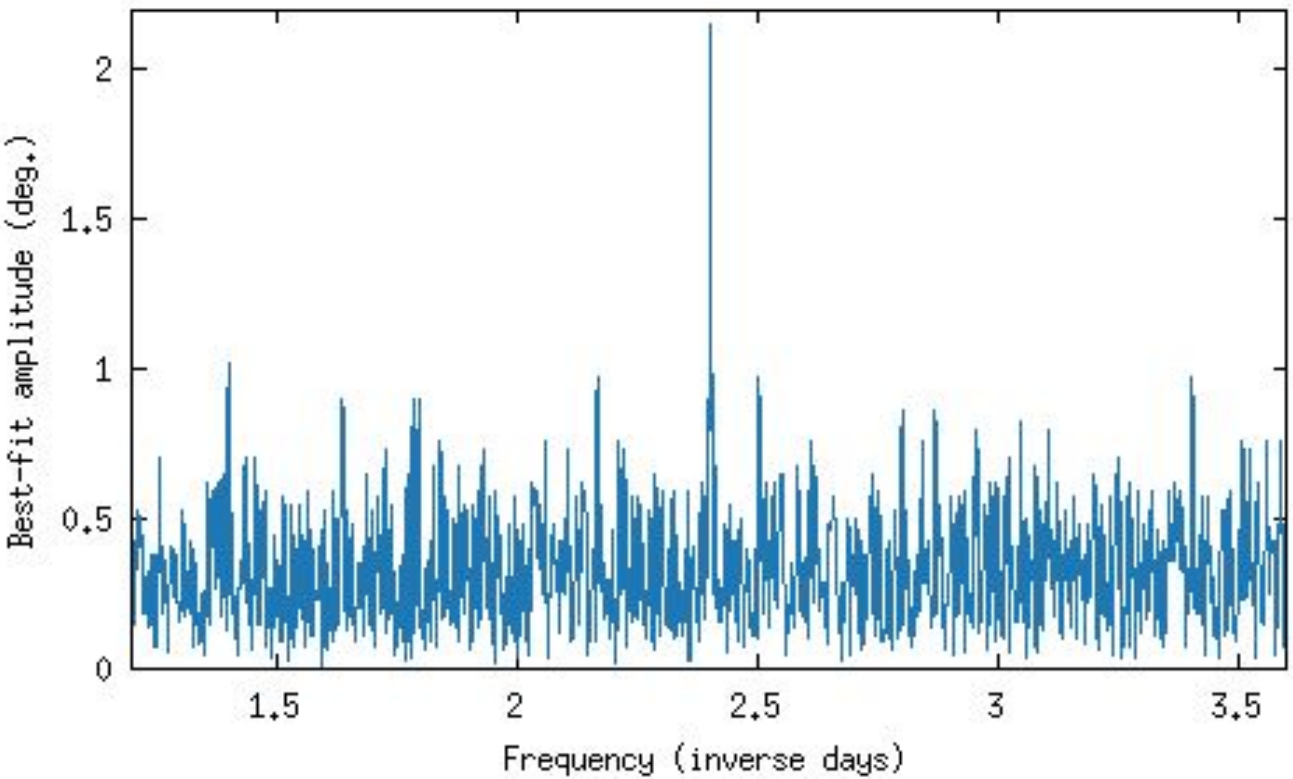
Time series

Combine 1000s of detectors to suppress noise

Combine 1000s of observations to search for oscillation



Frequency space



Background +
oscillation

Method and first demonstration

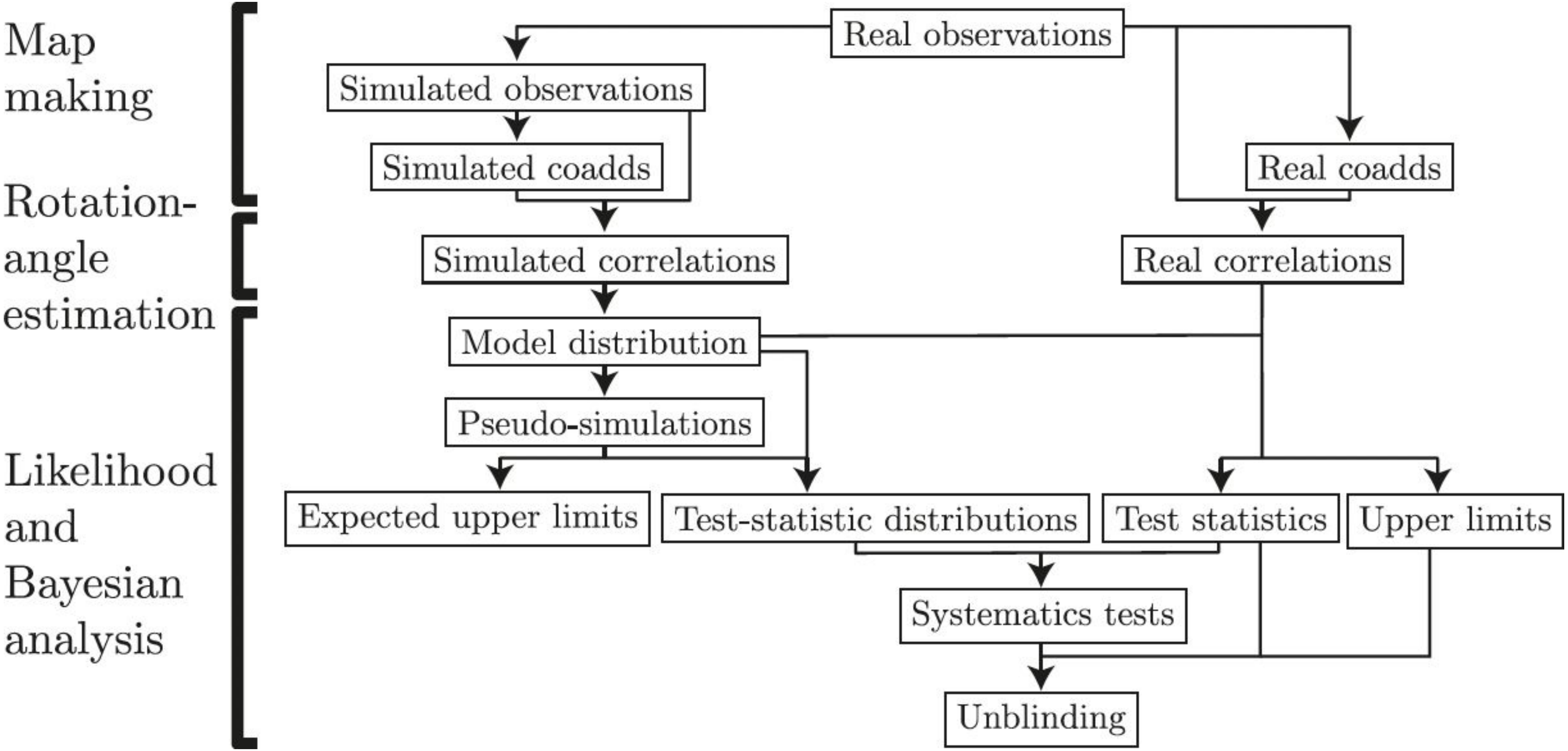
On the arXiv *last week*: “**BICEP / Keck Array XII: Constraints on axion-like polarization oscillations in the cosmic microwave background**” (https://arxiv.org/abs/2011.03483)

Method to extract oscillation signal and estimate statistical significance

First demonstration with *Keck Array* 2012 observations

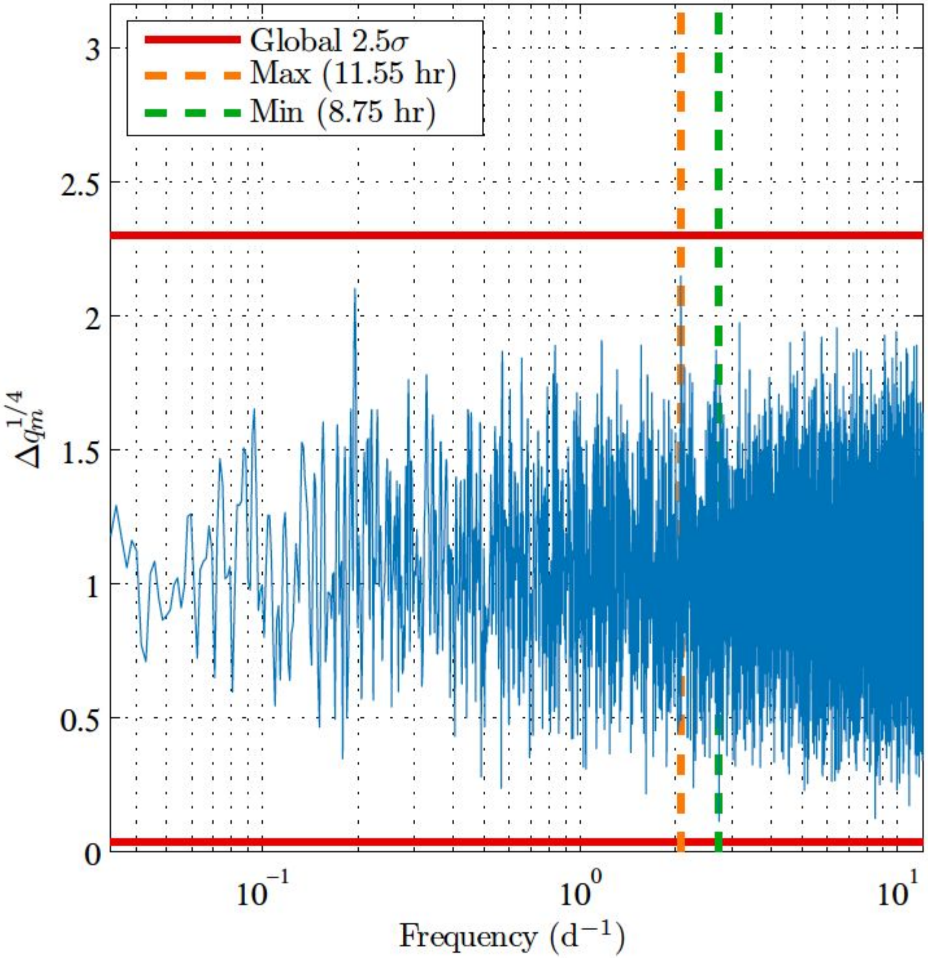
- Restricted dataset for computational speed
- Full BICEP dataset is >10x larger

Oscillation pipeline



Background consistency

Keck 2012 results are consistent with background

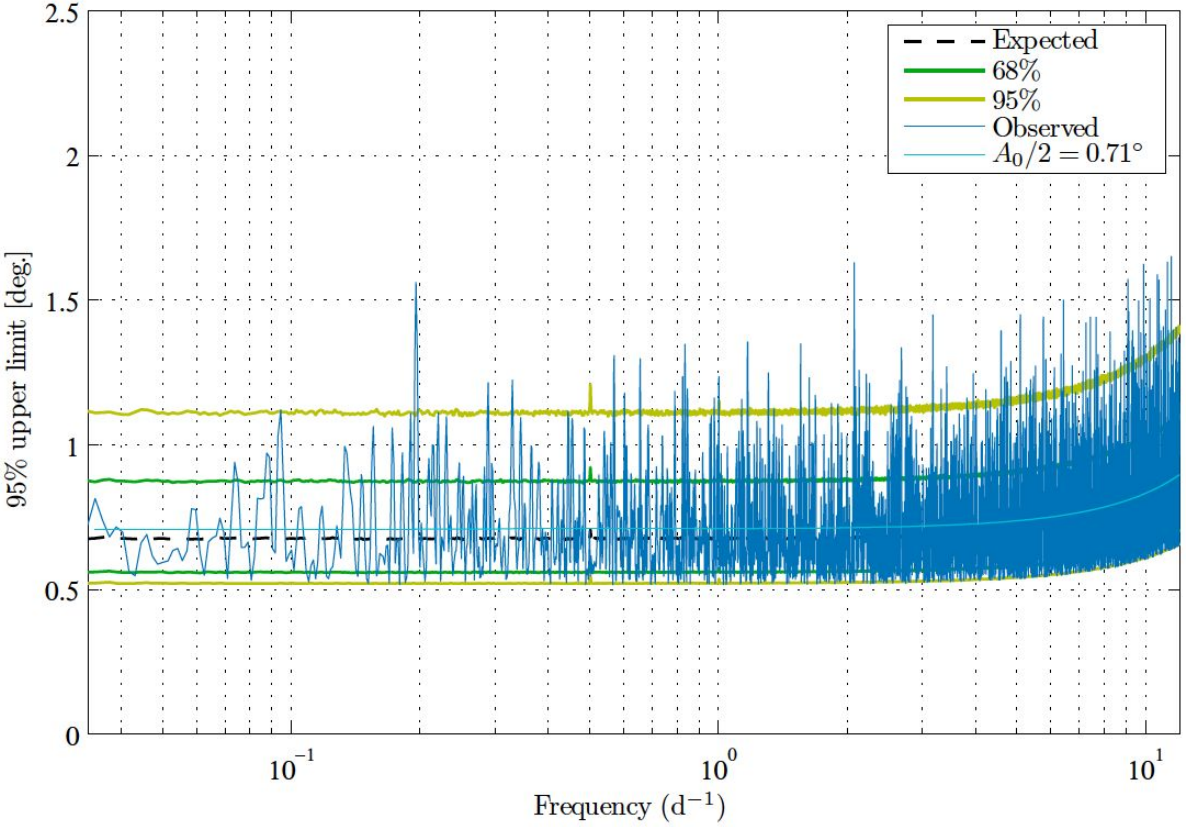


Upper limits -- rotation amplitude

Uniform Bayesian priors on rotation amplitude and phase

Periods longer than 24 hr: 95% upper limit ~ 0.7 deg.

Observations binned by hour → degradation at shorter periods



Upper limits -- axion-photon coupling constant

Oscillation sensitive to $g_{\phi\gamma}\phi_0$

Axion-photon coupling constant

Local axion field amplitude *today*

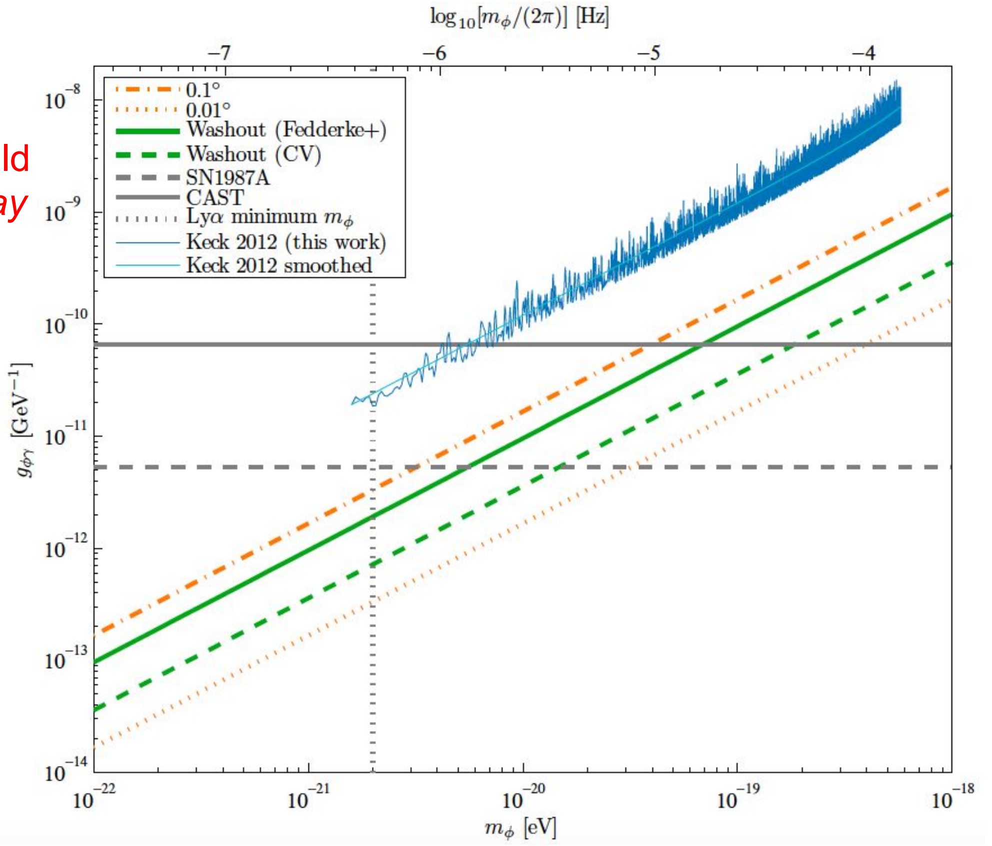
Limits scale as $g_{\phi\gamma} \propto m_\phi / \sqrt{\rho_\phi}$

Axion mass

Local dark-matter density

Assume dark matter is all axion-like particles with single mass

****Keck 2012 is a small fraction of total CMB dataset *already on disk***



What’s next?

South Pole Observatory (SPO)

South Pole Telescope (SPT)

BICEP3

Dark Sector Laboratory (DSL), South Pole
(photo credit: Dan Van Winkle)

SPT-3G (2017 - present)

10-m aperture → arcmin resolution

Sinuous antennas + TESs

- 90, 150, 220 GHz

Less observing time and depth than BICEP but **more polarization modes**

- Combine datasets for systematics check

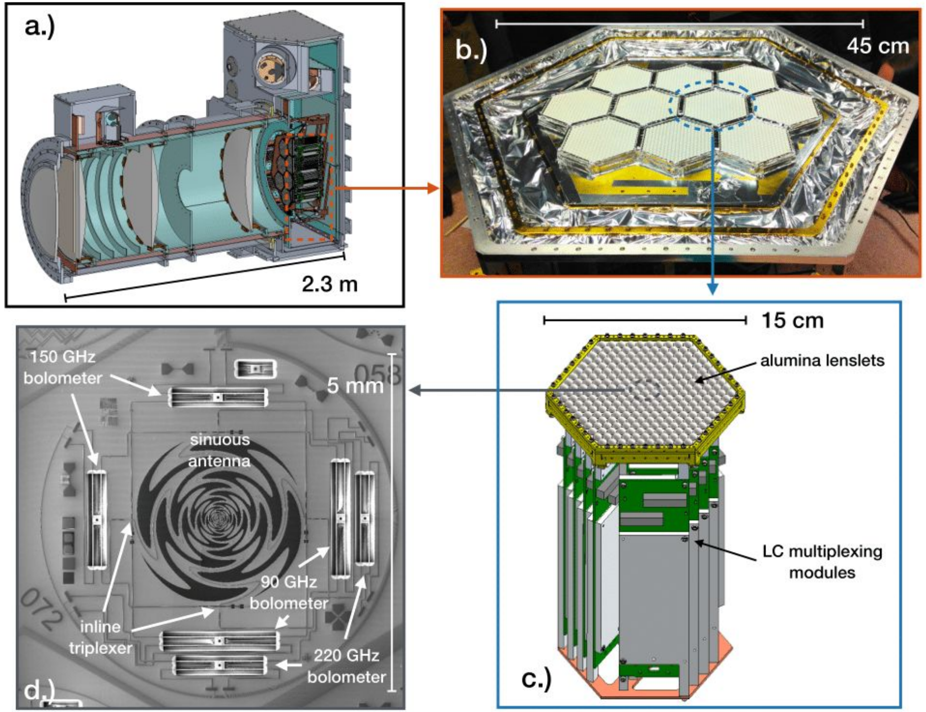


Fig. credit: Anderson et al., 2018

South Pole outlook

Axion analyses underway for BICEP/Keck and SPT-3G

SPT-3G continues observations

BICEP Array replacing Keck Array

- 4 BICEP3-scale receivers
- 30/40-GHz receiver already deployed
- 90, 150 and 220/270 receivers to follow

CMB Stage 4 to follow...

BICEP Array, Jan. 2020

CMB Stage 4

Next-generation DOE/NSF CMB experiment at **South Pole and Atacama Desert**

~500,000 detectors

Broad range of mm-wave science: inflation, large-scale structure, neutrino physics, light relics, astrophysical transients, etc.

Non-Antarctic CMB efforts

Simons Observatory

- Large- and small-aperture telescopes
- Atacama (2021 -)

LiteBIRD

- Satellite telescopes (small aperture)
- JAXA led with NASA/ESA contributions
- Late 2020s

Future

Axion-oscillation constraints are *free* for CMB polarimeters

- No change to scan strategy
- No change to low-level data processing

CMB-based limits will probe unexplored regions of parameter in the next decade

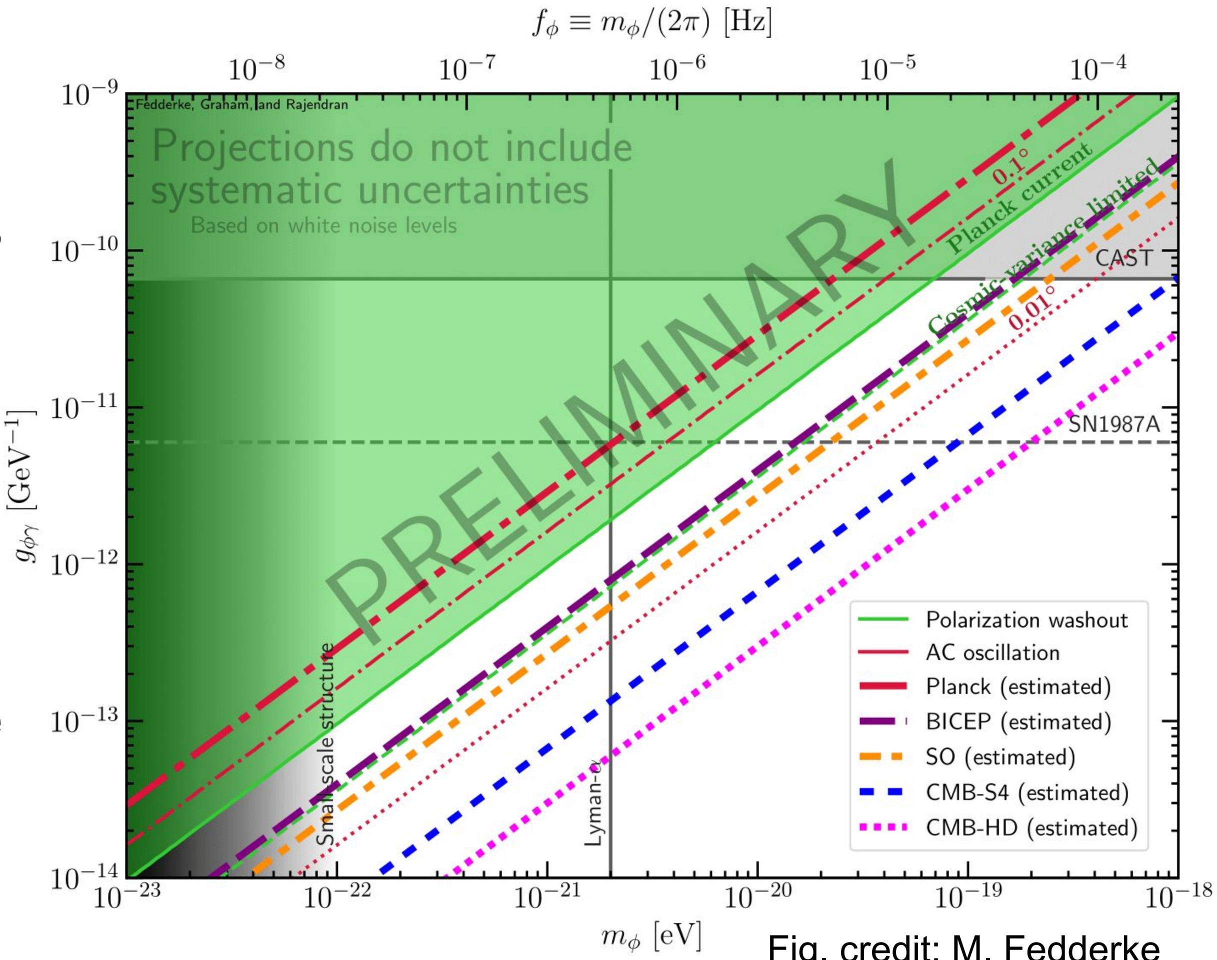


Fig. credit: M. Fedderke

Questions