Title: TBA

Speakers: Adam Anderson

Series: Particle Physics

Date: June 16, 2020 - 1:00 PM

URL: http://pirsa.org/20060000


CMB with SPT-3G: Recent Results and Constraining Axions with CMB Polarization Rotation
Adam Anderson
Fermilab
16 June 2020
Perimeter Seminar
photo: Geoff Chen
1
Adam Anderson

Outline

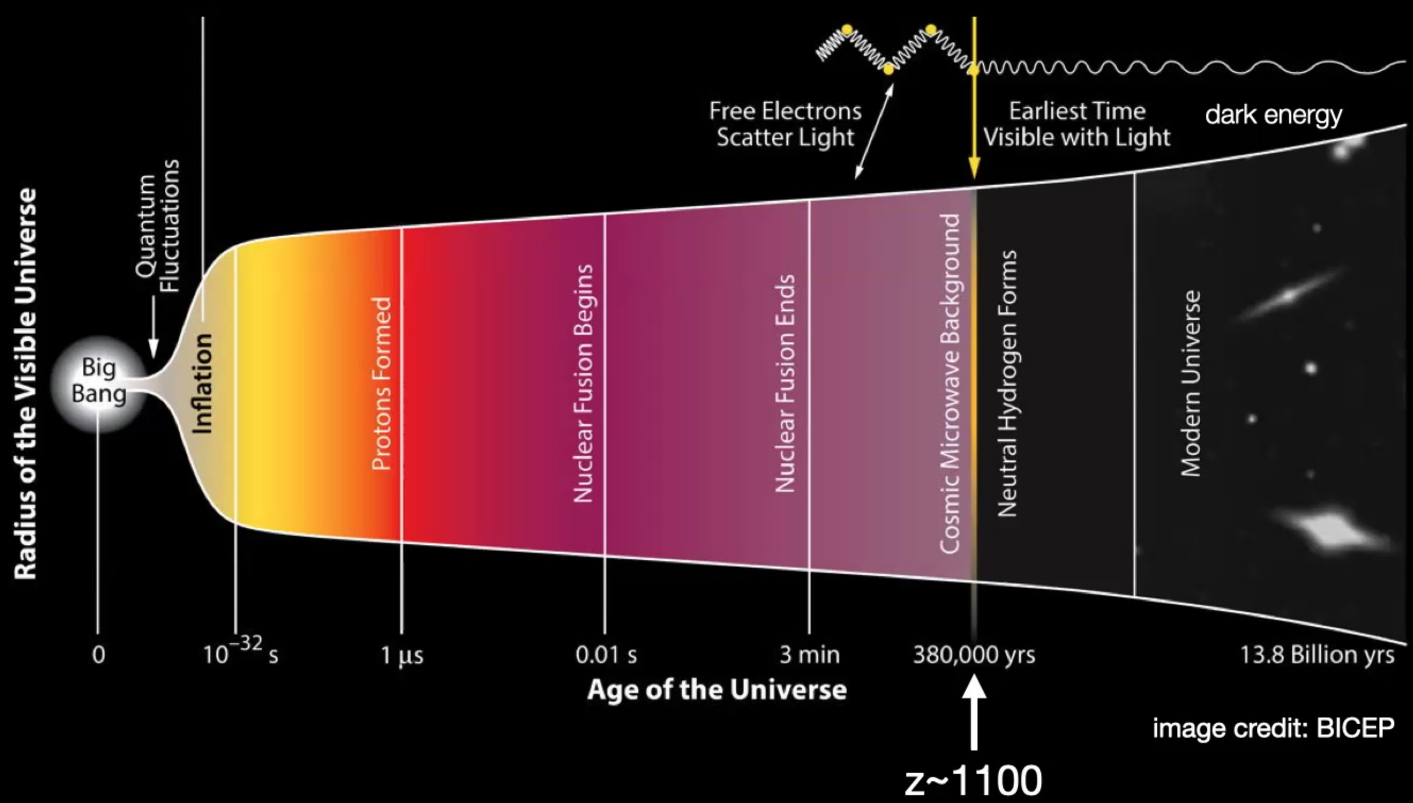
1. Why more CMB experiments?

2. SPT-3G and upcoming results

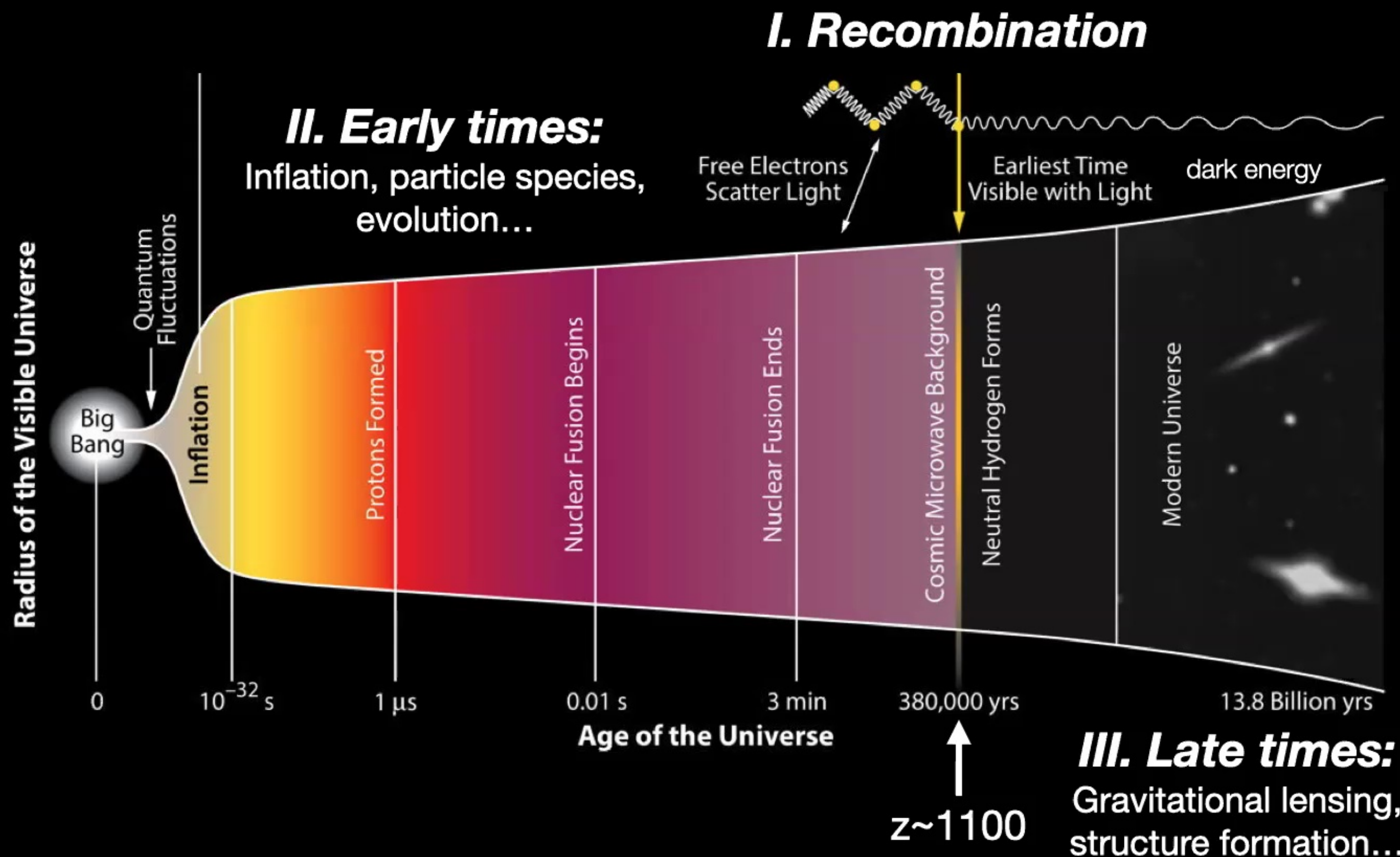
3. Searching for time-varying polarization rotation

2

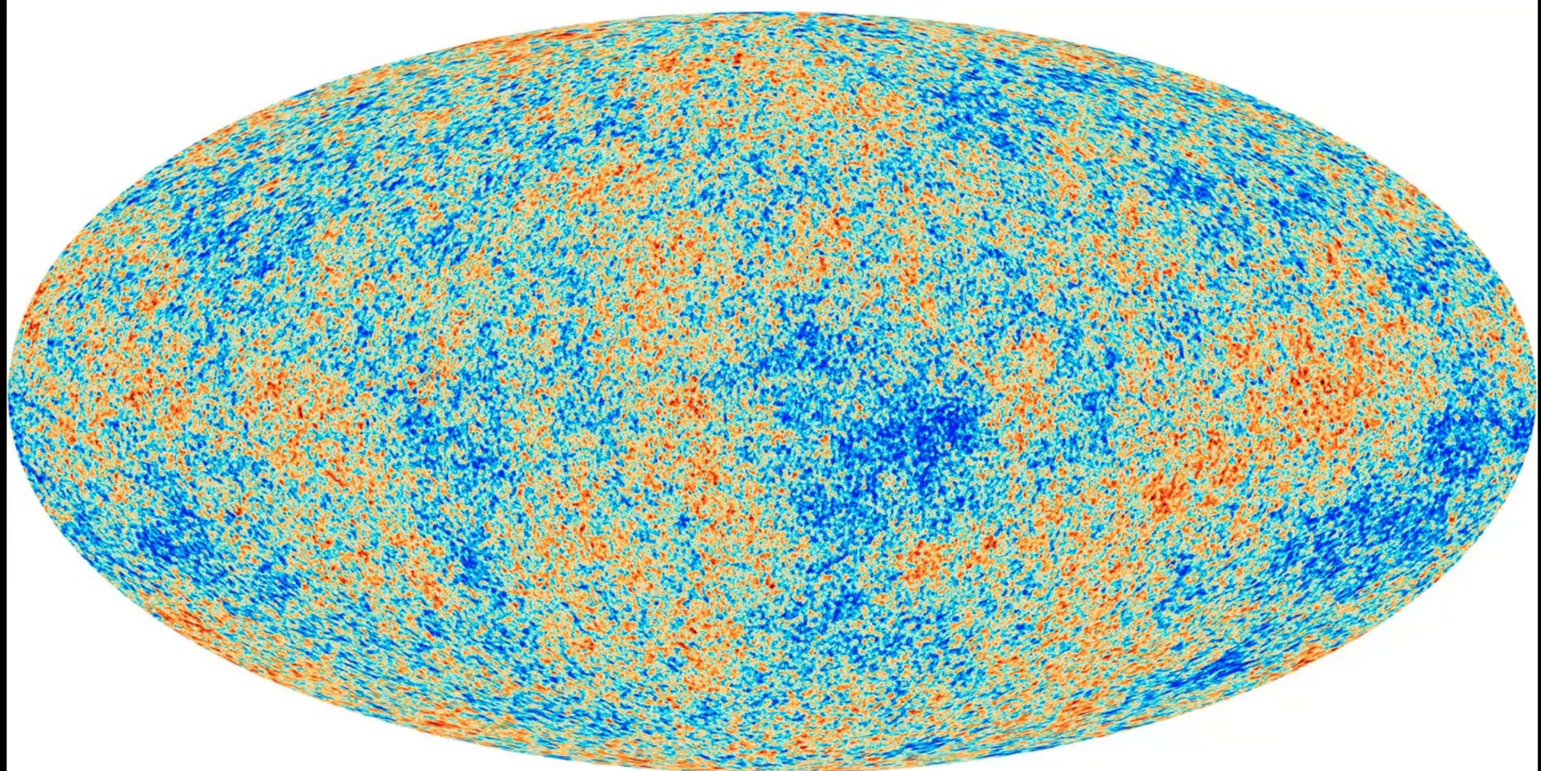
CMB and the Cosmic Timeline



CMB and the Cosmic Timeline



Modern CMB Maps: Planck



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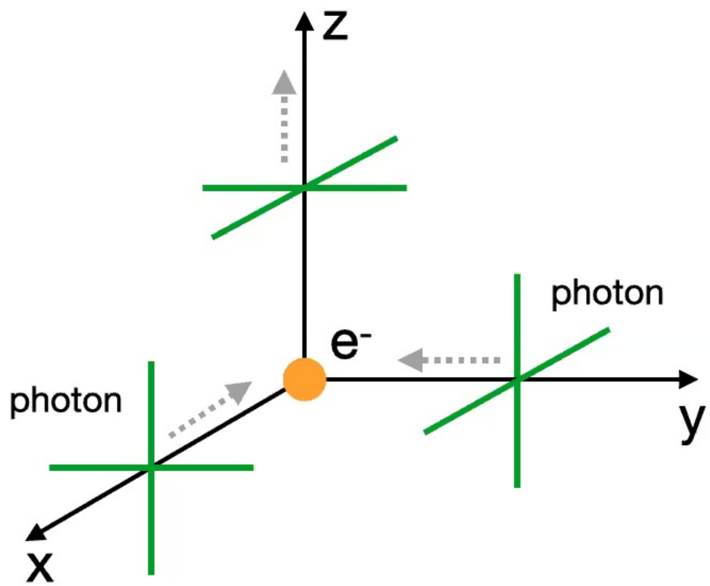
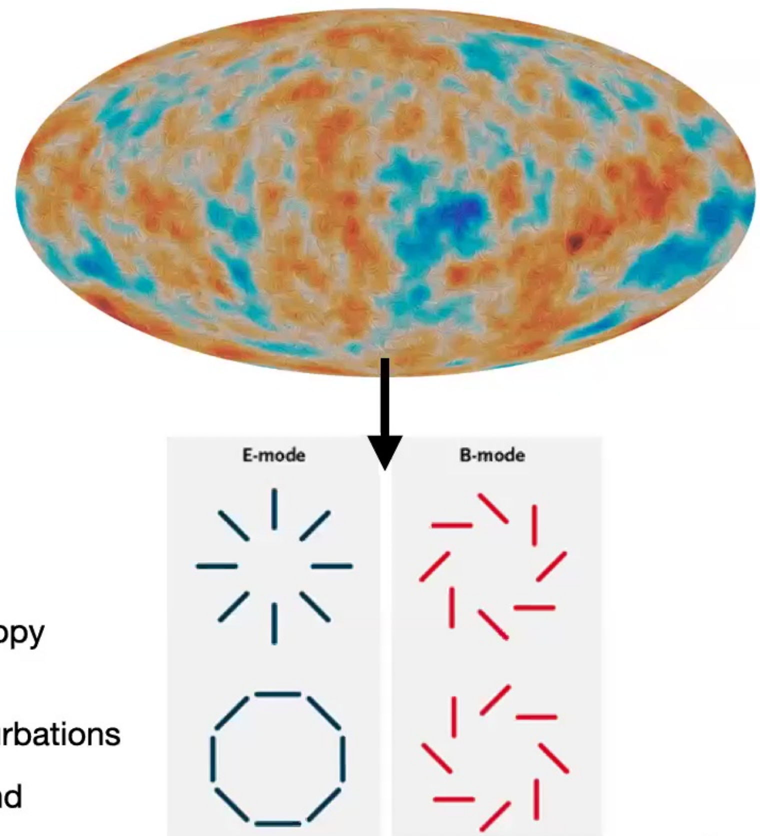
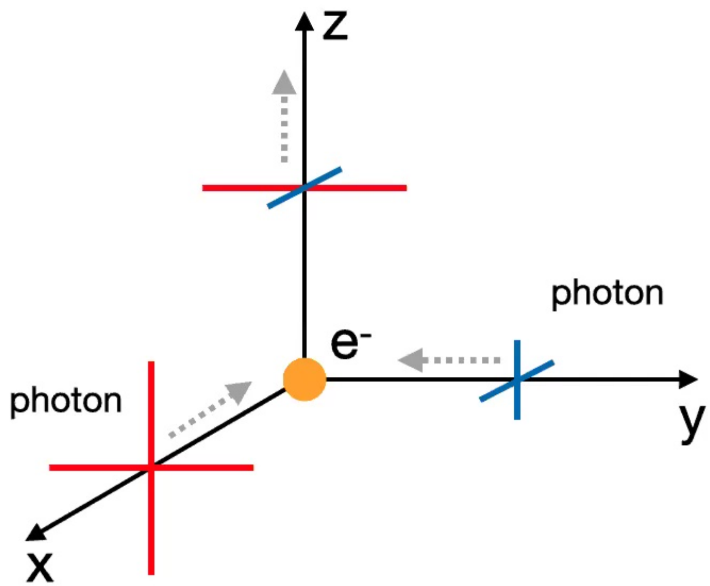
CMB Polarization

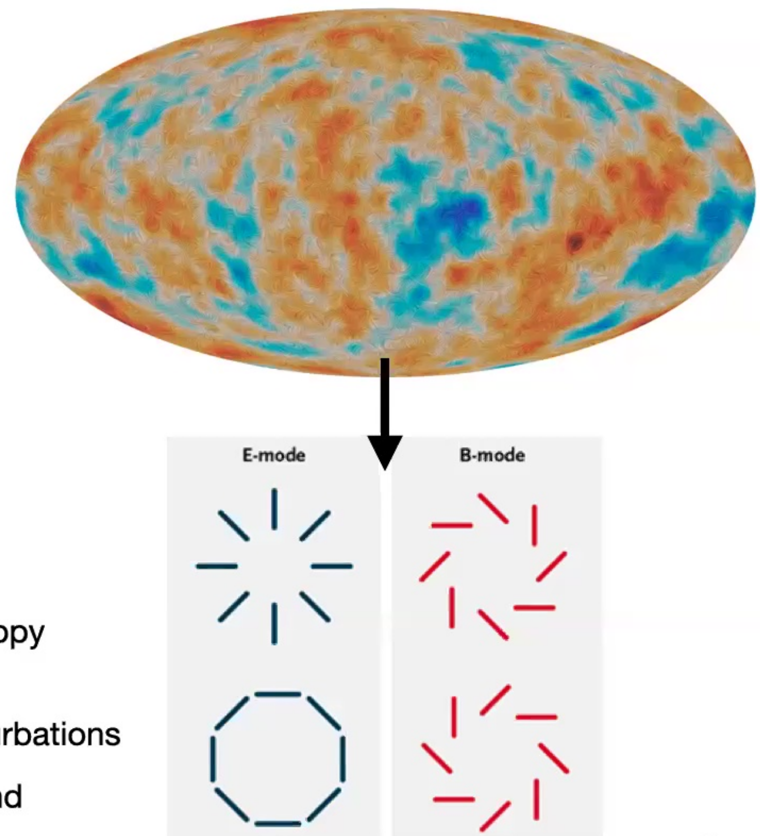




- Thomson scattering with quadrupole anisotropy produces polarization
- **E-modes:** sourced primarily by density perturbations
- **B-modes:** sourced by gravitational waves and lensing of E modes into B modes

CMB Polarization





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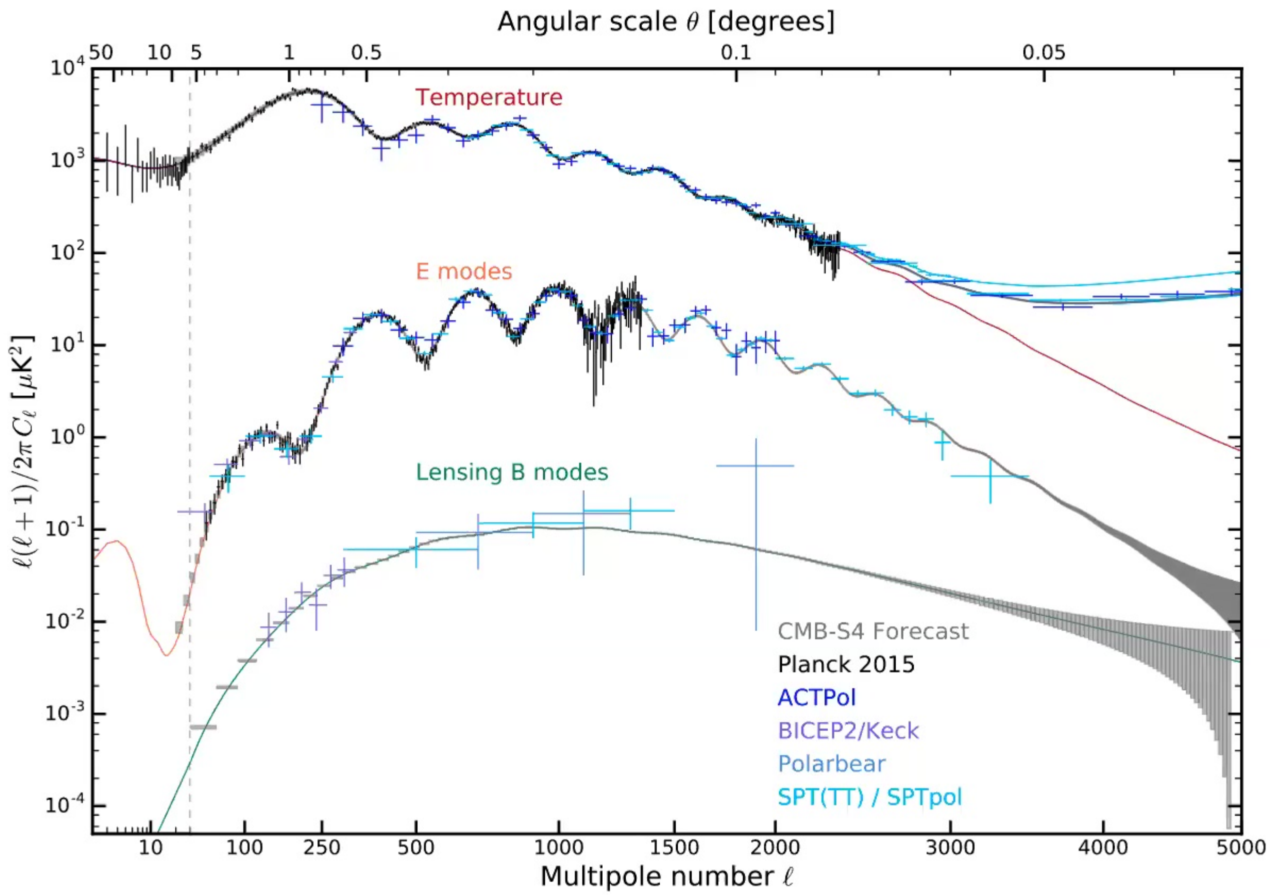
Polarization Power Spectrum



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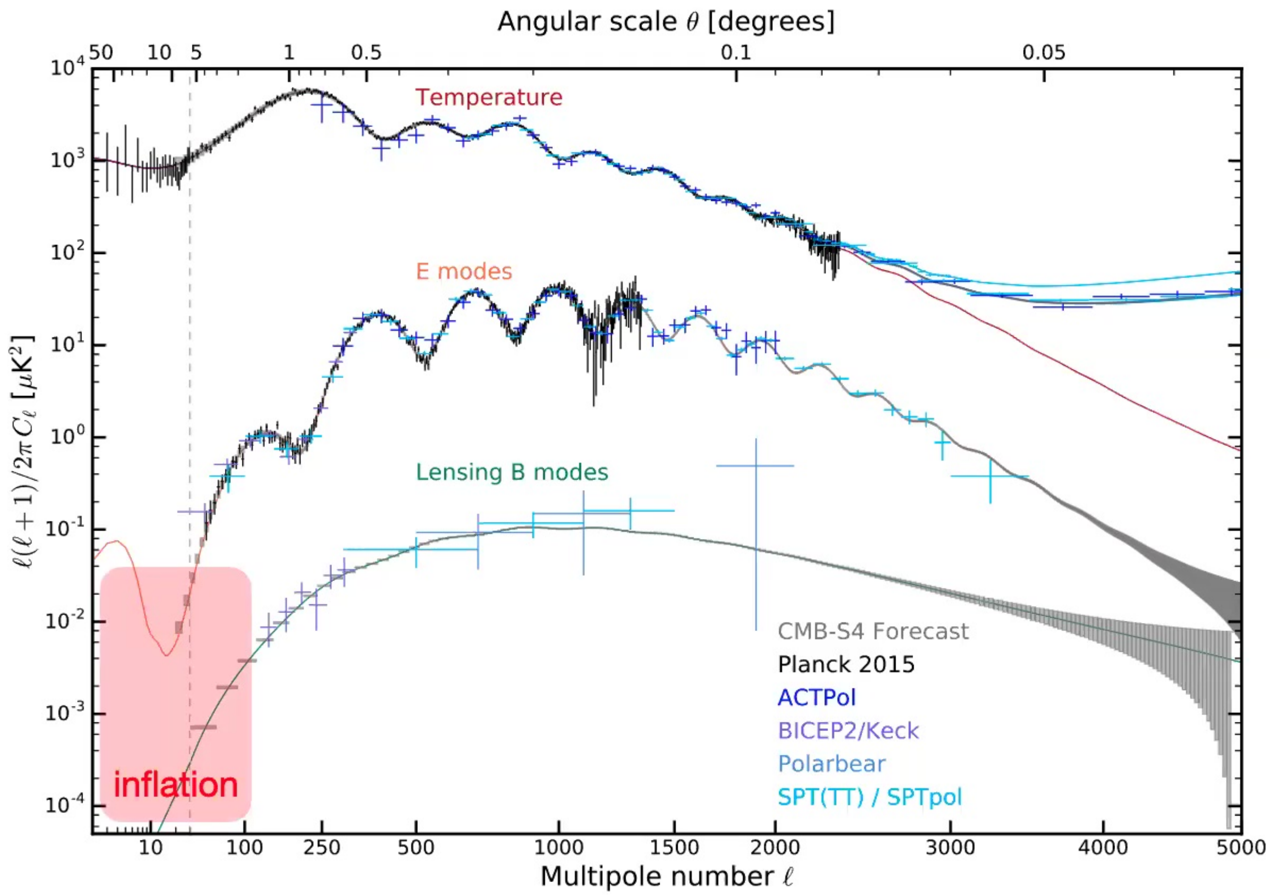
Polarization Power Spectrum



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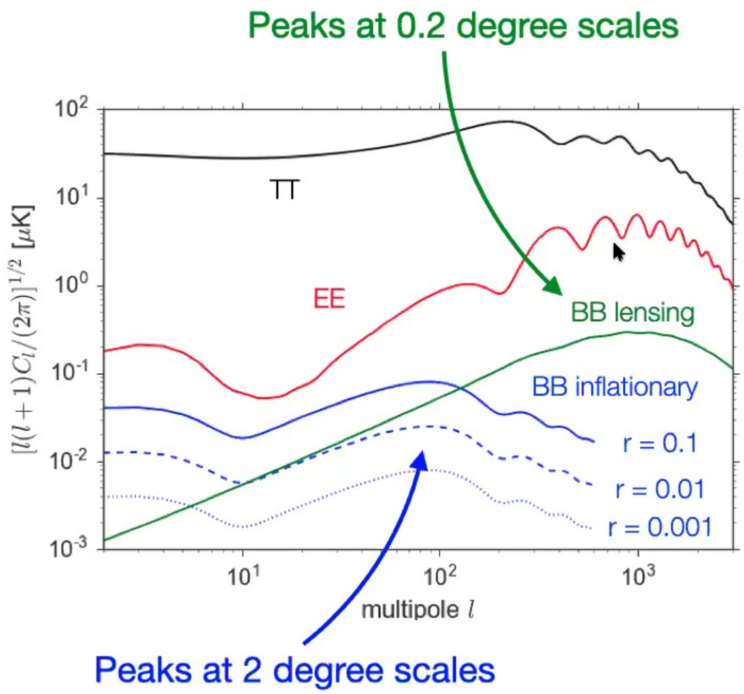
Primordial B Modes

- Inflation produces a background of gravitational waves that persist through recombination
- Signals peaks on degree scales with amplitude proportional to *r* "tensor-to-scalar" ratio
- ***Only*** mechanism for producing "primordial" B modes
- Unambiguous evidence for inflation
- "Lensing B modes" produced by gravitational lensing that distorts E modes into B modes



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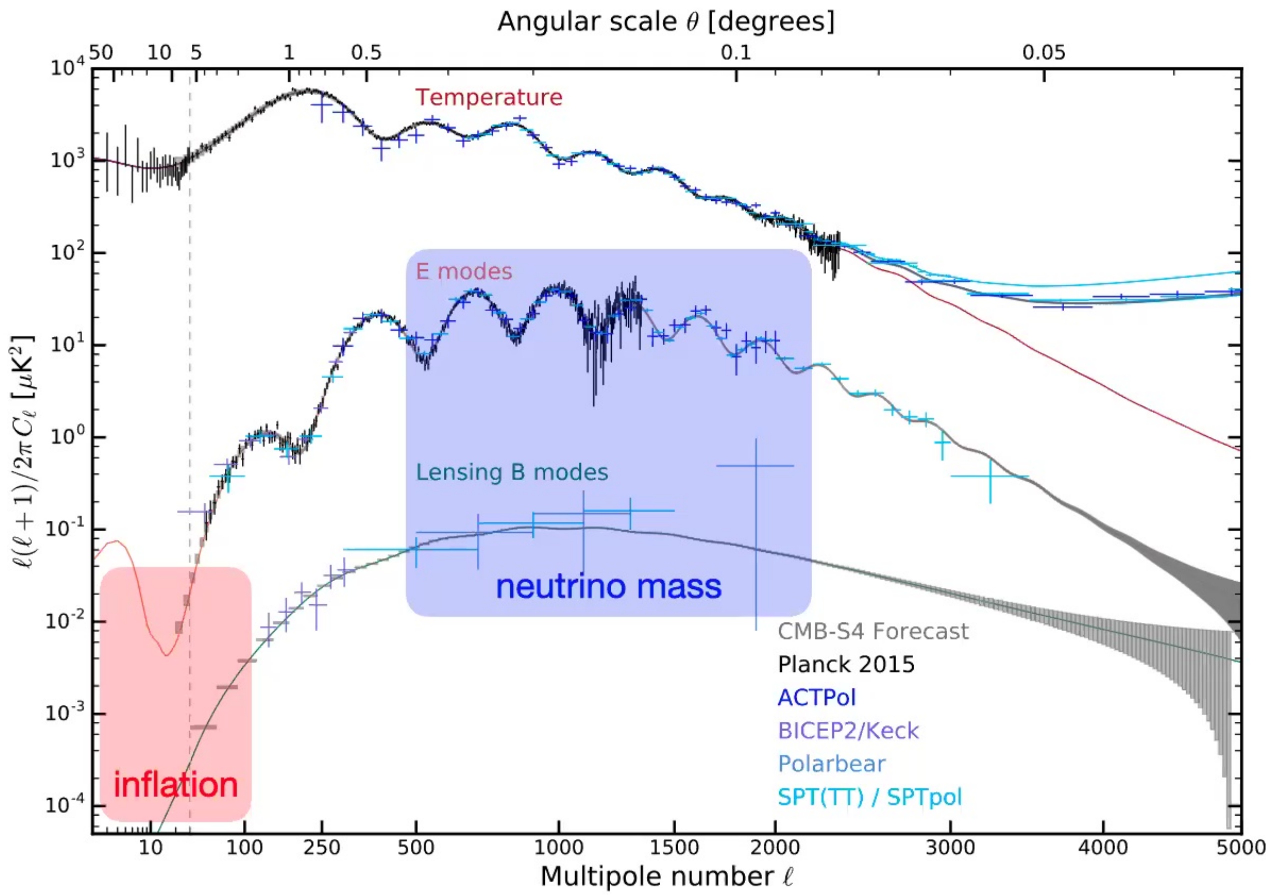
Polarization Power Spectrum



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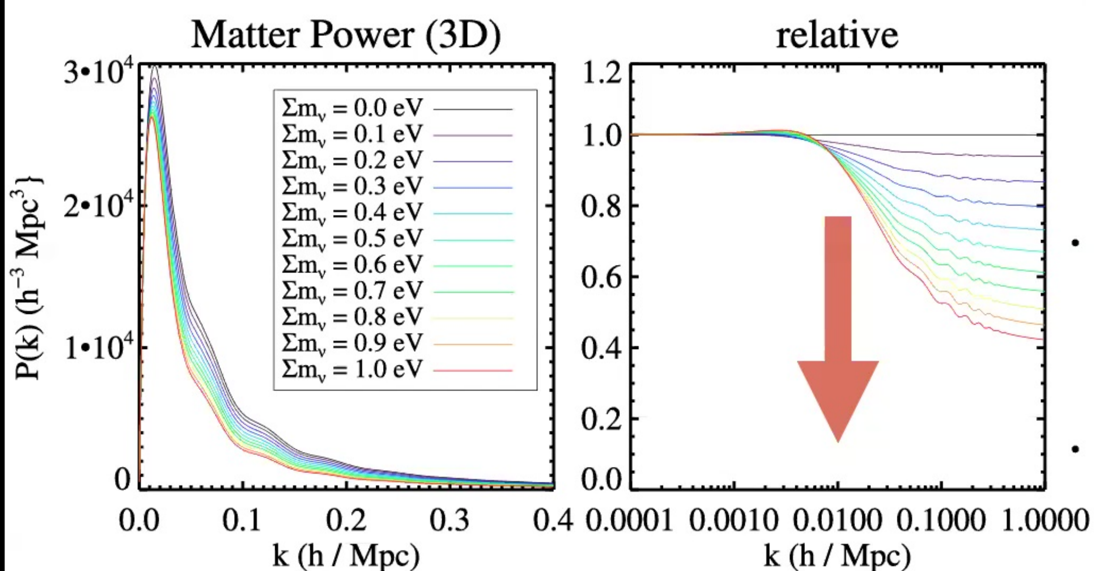
Neutrino Mass: Matter Power Spectrum



CMB-S4 science book

- ***Sum of neutrino masses affect growth of structure in universe***
- Clustering of matter suppressed at scales < 100 MPc
- ~5% suppression per 0.1eV in total mass
- ***Lower*** limit from oscillations:

oscillations depend on squared mass differences, not absolute mass scale → $\sum m_\nu > 0.06\text{eV}$

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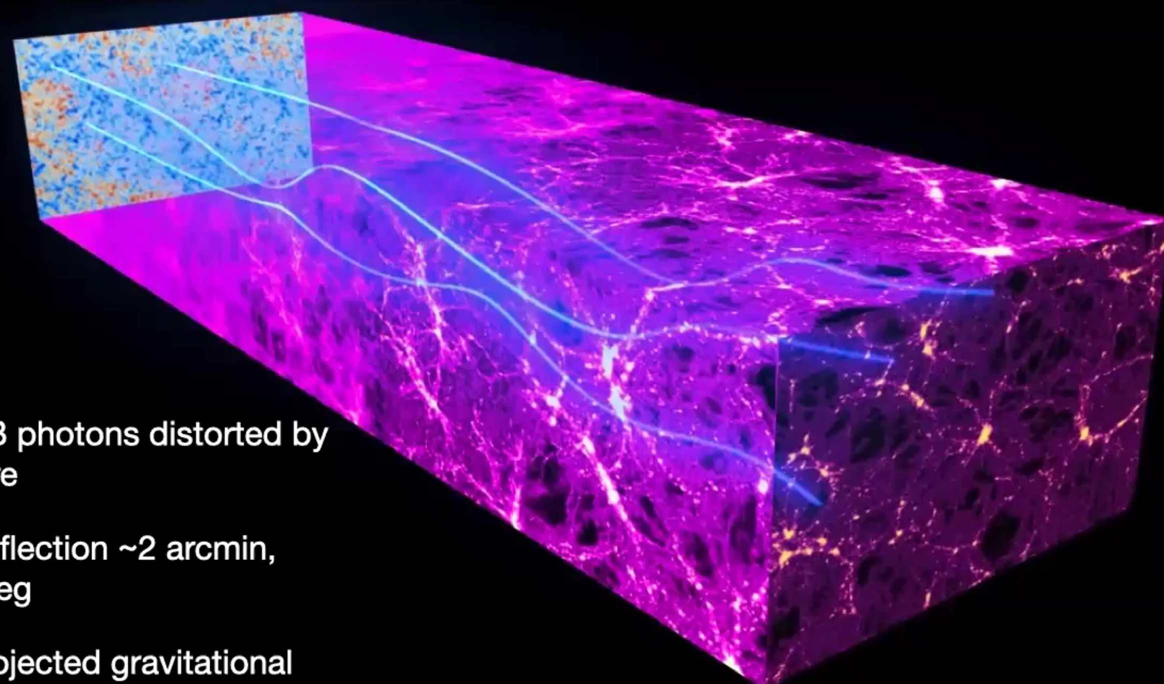
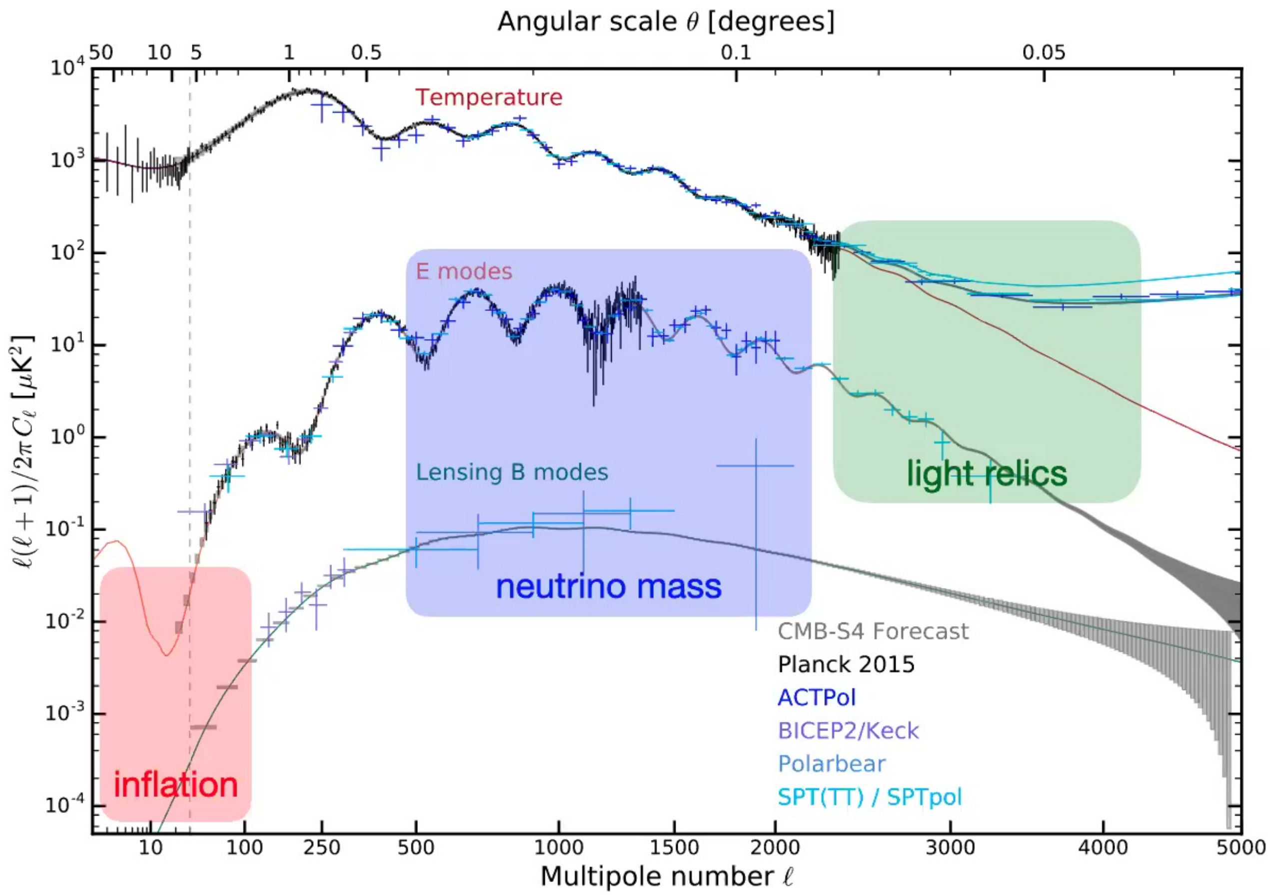
Neutrino Mass and Gravitational Lensing



- Trajectories of CMB photons distorted by large-scale structure
- Angular scale of deflection ~2 arcmin, coherent over ~2 deg
- Reconstruct the projected gravitational potential between us and CMB

CMB probes matter power spectrum and neutrino mass

Polarization Power Spectrum



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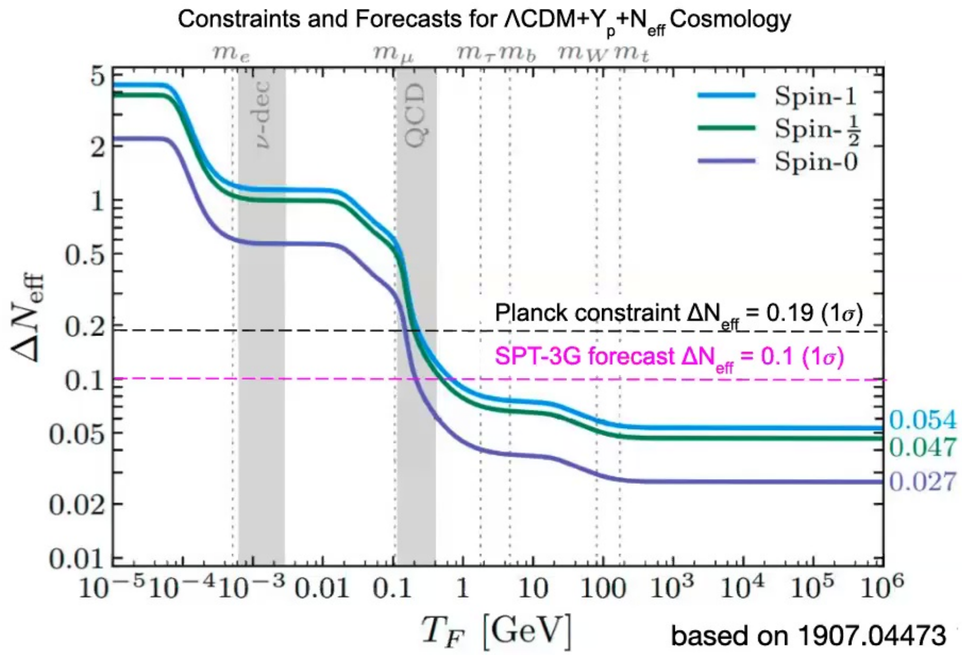
N_{eff} Constraints

- ***Any*** light particle in thermal equilibrium contributes to relativistic energy density (~N_{eff})
- After decoupling, contribution is diluted relative to active neutrinos as Standard Model particles annihilate
- Light sterile neutrinos with large mixing angles excluded
- 5-year constraint: $\sigma(\Delta N_{\text{eff}}) = 0.1$



based on 1907.04473

freeze-out temperature

← *late times* *early times* →

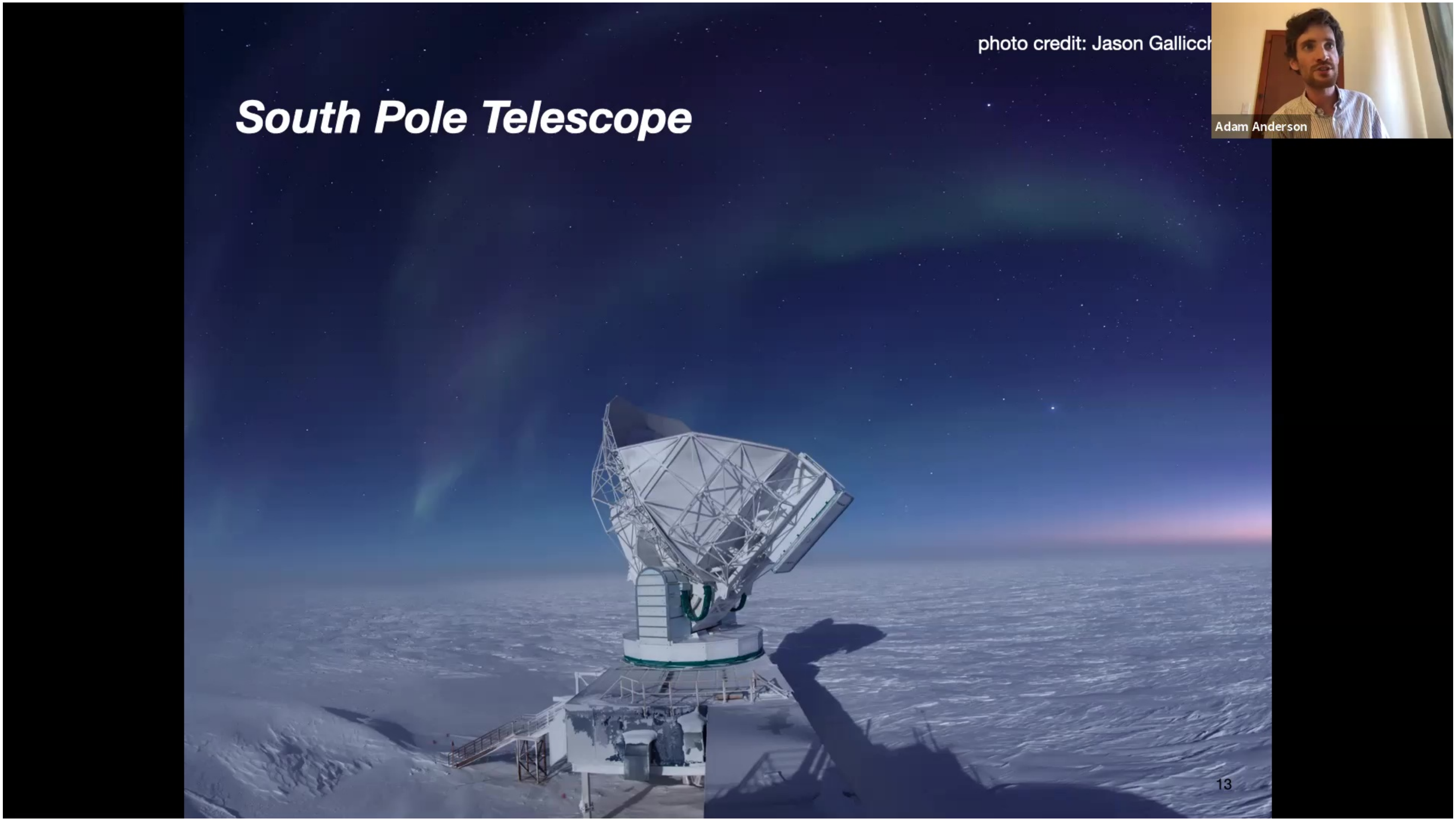


photo credit: Jason Gallicc
South Pole Telescope
Adam Anderson
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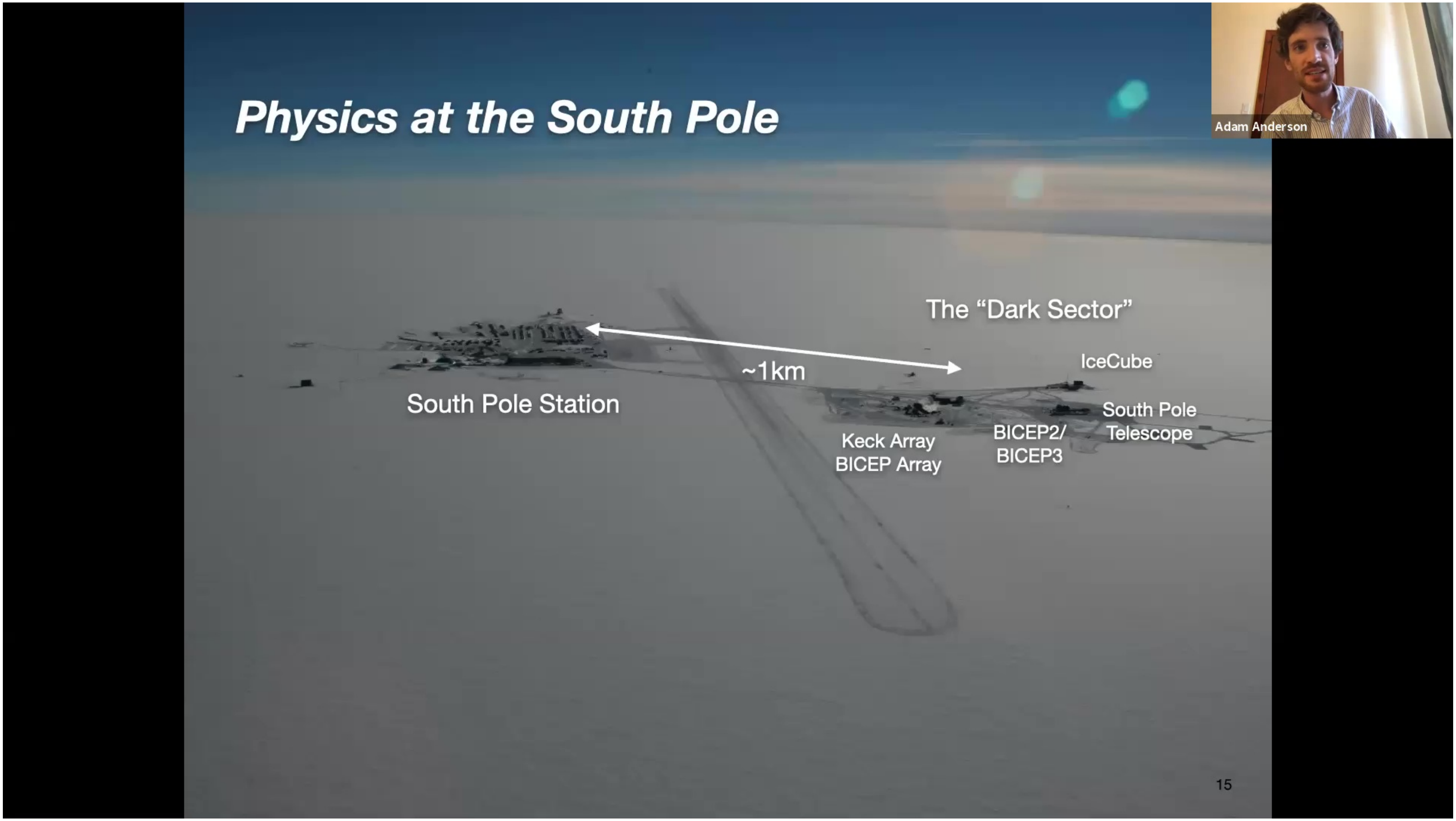
SPT-3G Collaboration


Physics at the South Pole
The "Dark Sector"
~1km
IceCube
South Pole Station
South Pole
Telescope
Keck Array
BICEP Array
BICEP2/
BICEP3
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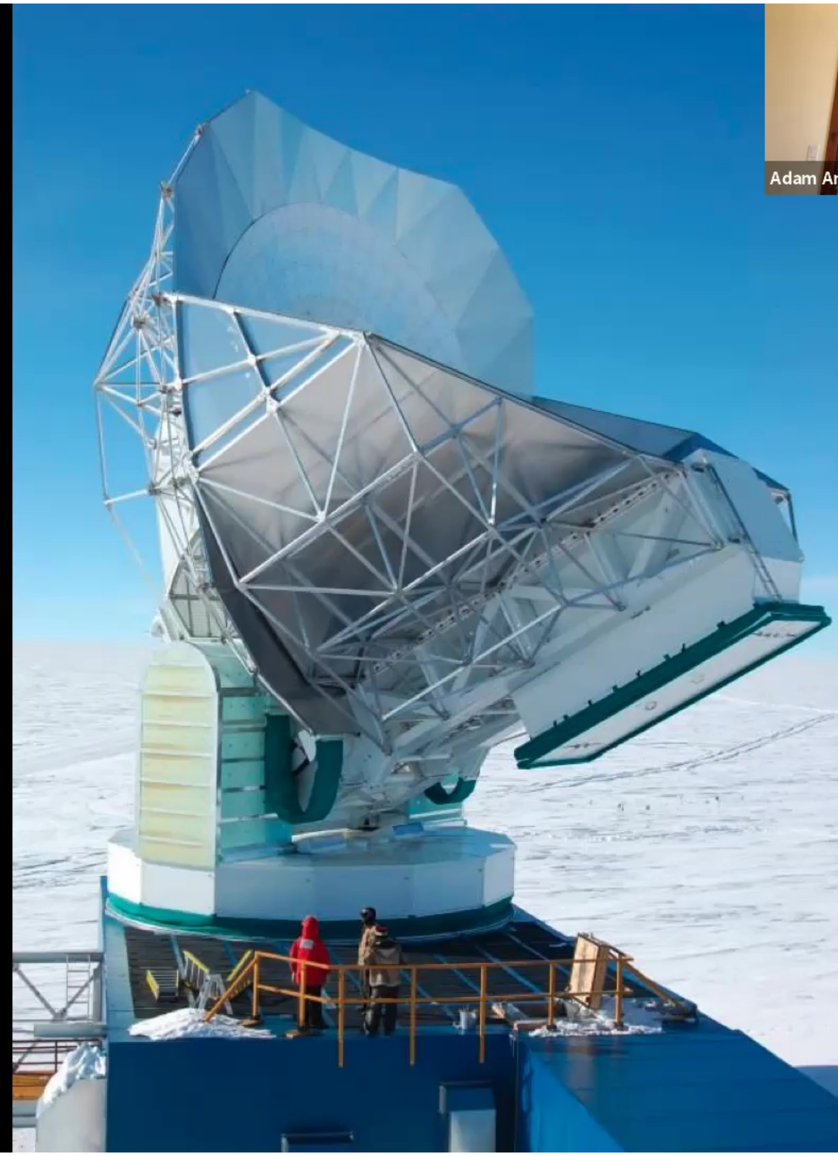
Adam Anderson

The South Pole Telescope (SPT)

- Unique 10 m primary mirror, largest of its kind
- resolution of ***1.0 to 1.5 arcmin***, highest resolution CMB maps
- South Pole is an excellent site:
    - dry (winter PWV ~4x less than Chile)
    - extremely stable atmosphere (6mo night, laminar winds)
    - 24/7 access to the same clean patches of sky ("relentless" observing)



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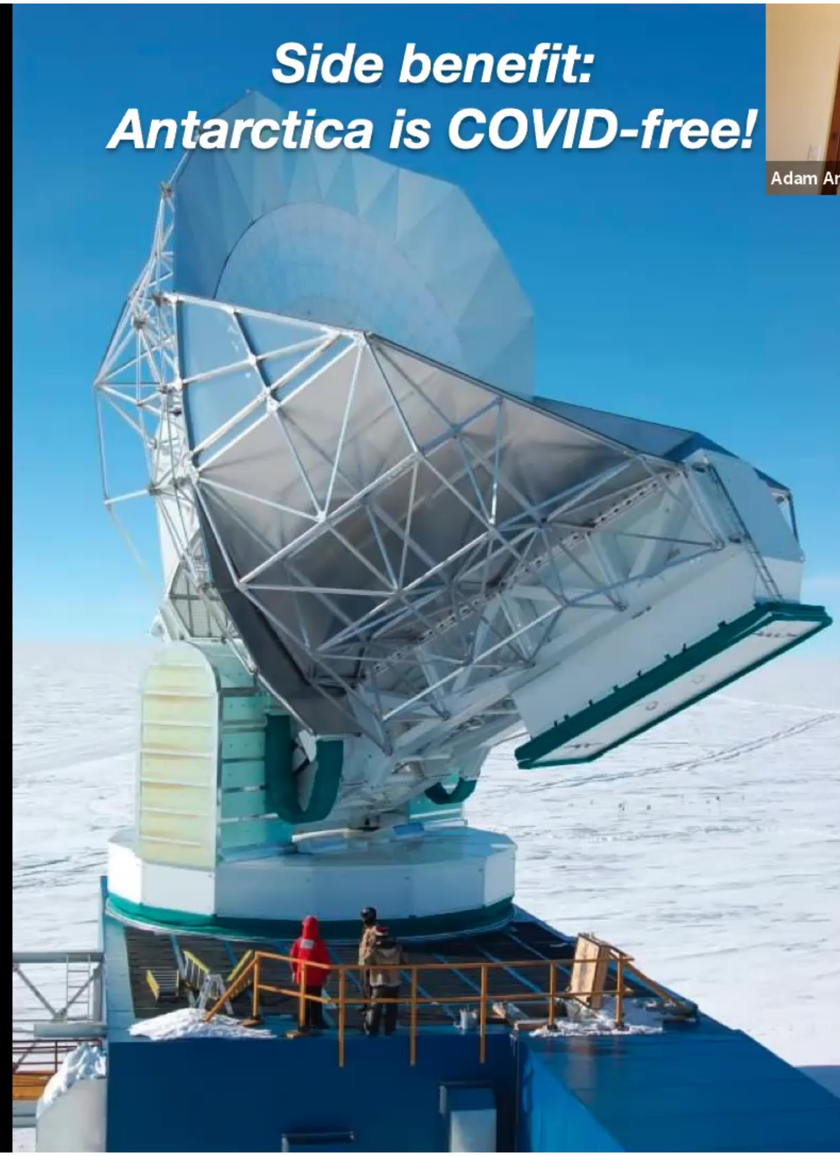

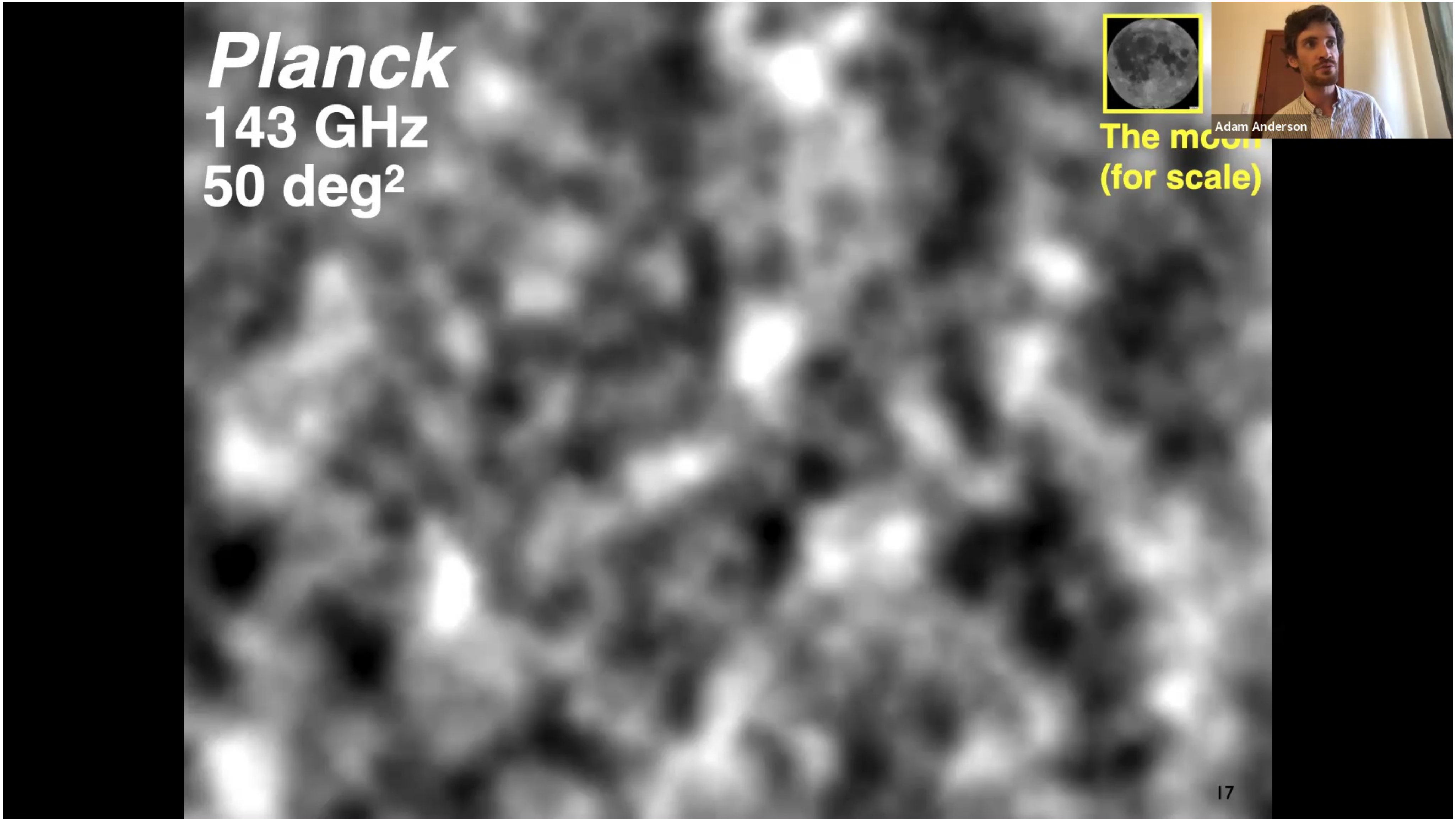
Planck
143 GHz
50 deg²
The moon
(for scale)
Adam Anderson
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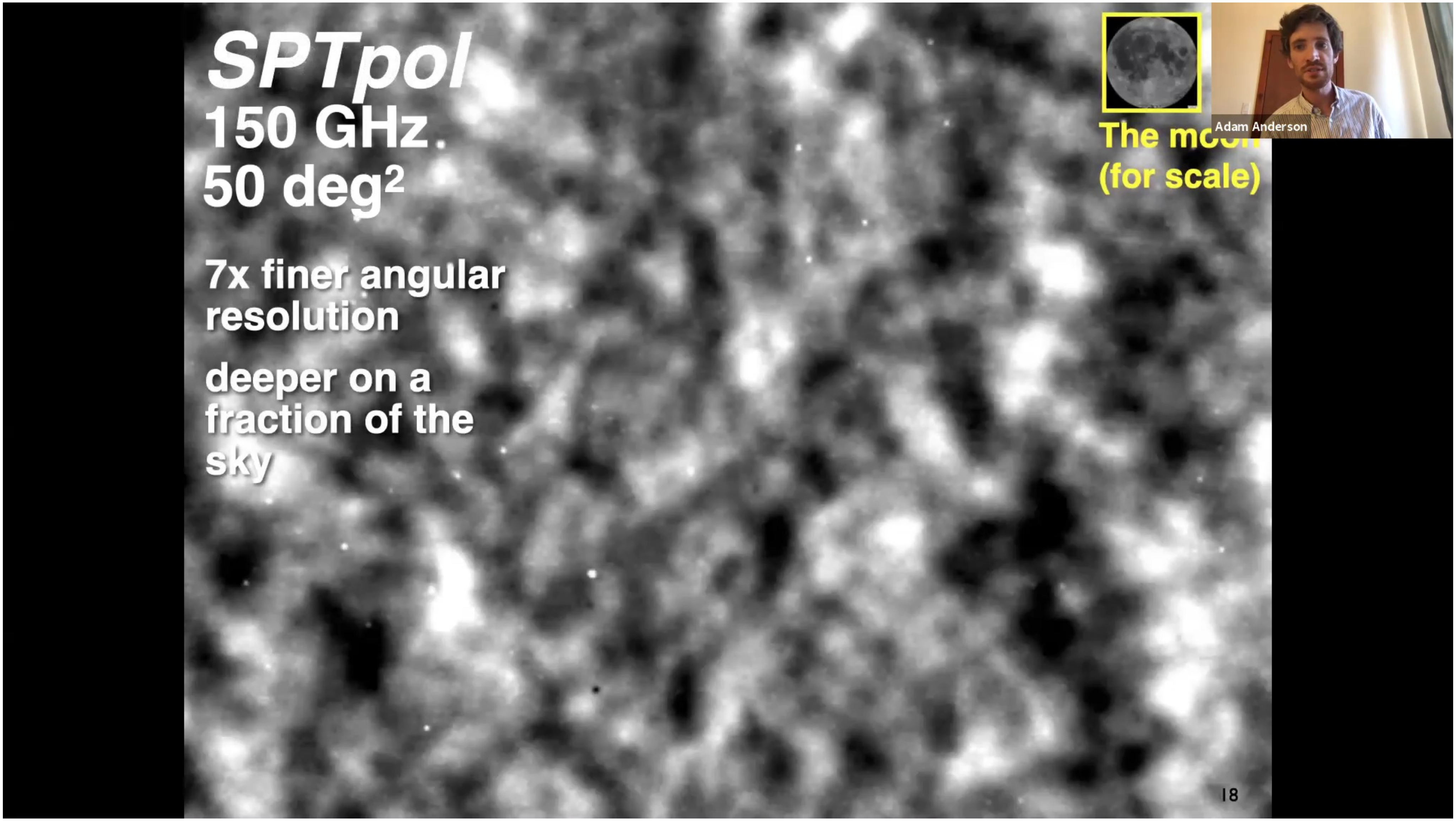
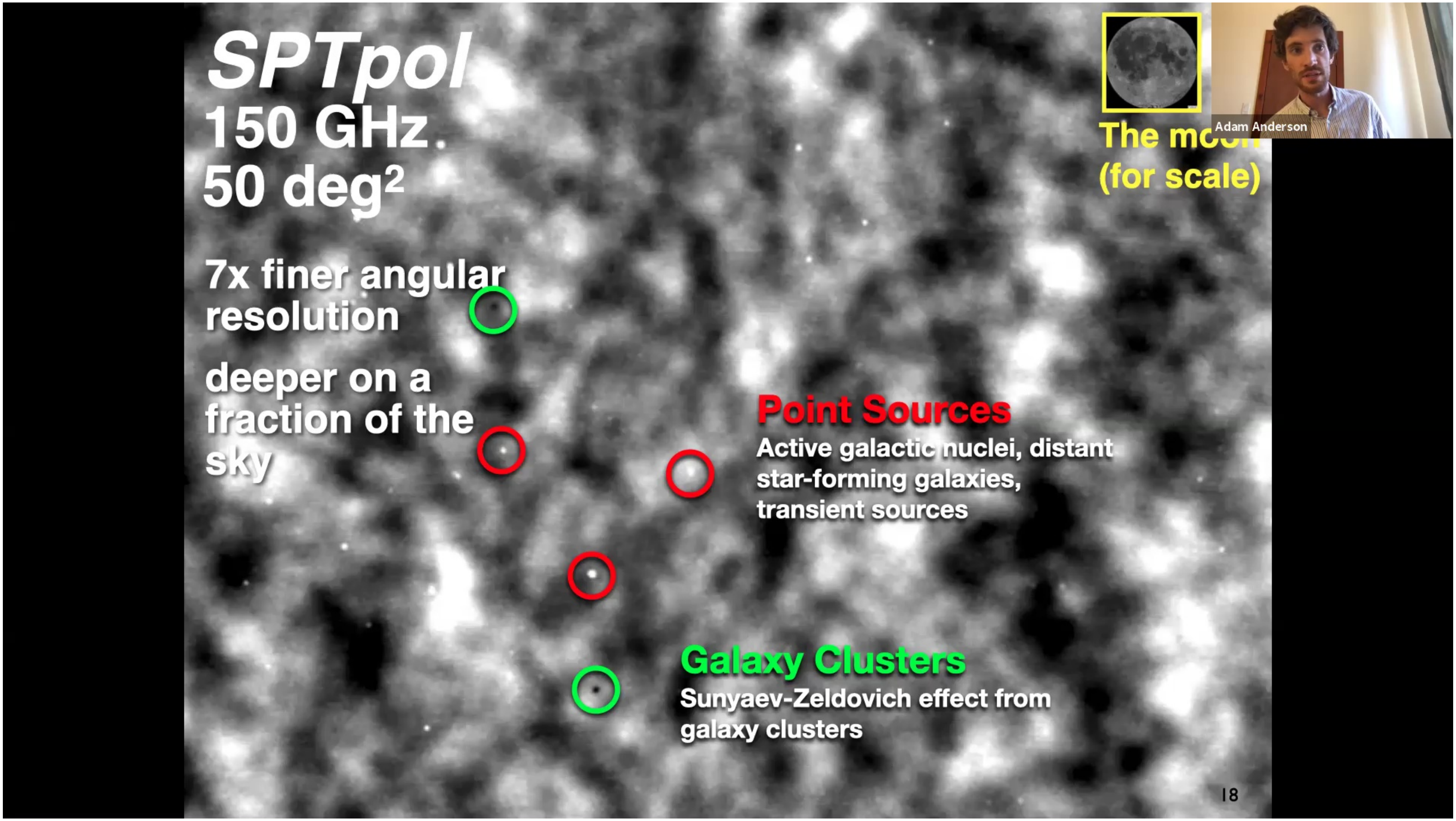

SPTpol
150 GHz
50 deg²
7x finer angular resolution
deeper on a fraction of the sky
The m
(for scale)
Adam Anderson
18



SPTpol
150 GHz
50 deg²
7x finer angular resolution
deeper on a fraction of the sky
The moon (for scale)
Adam Anderson
Point Sources
Active galactic nuclei, distant star-forming galaxies, transient sources
Galaxy Clusters
Sunyaev-Zeldovich effect from galaxy clusters
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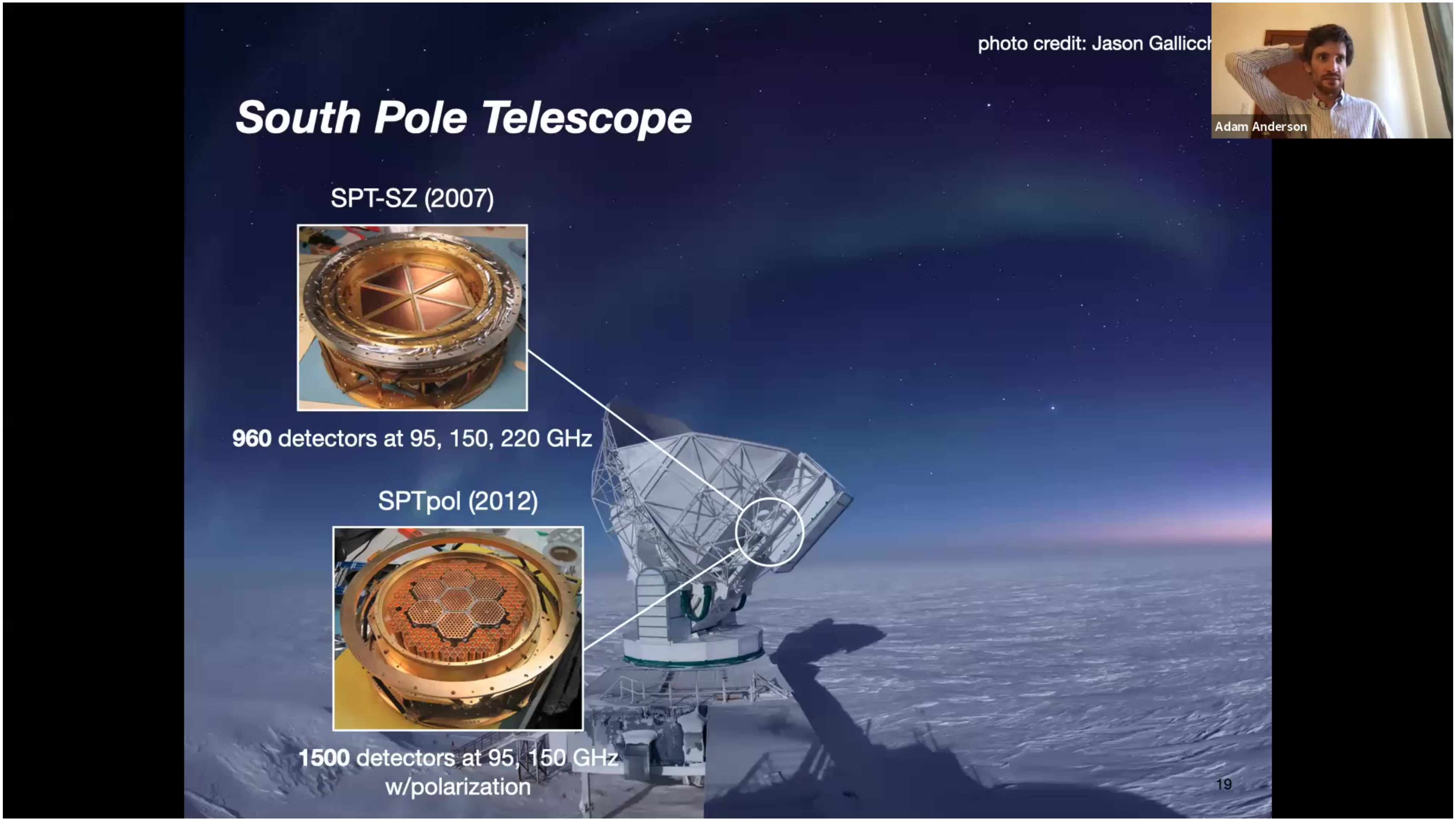
photo credit: Jason Gallicch
Adam Anderson
South Pole Telescope
SPT-SZ (2007)
960 detectors at 95, 150, 220 GHz
SPTpol (2012)
1500 detectors at 95, 150 GHz
w/polarization
19

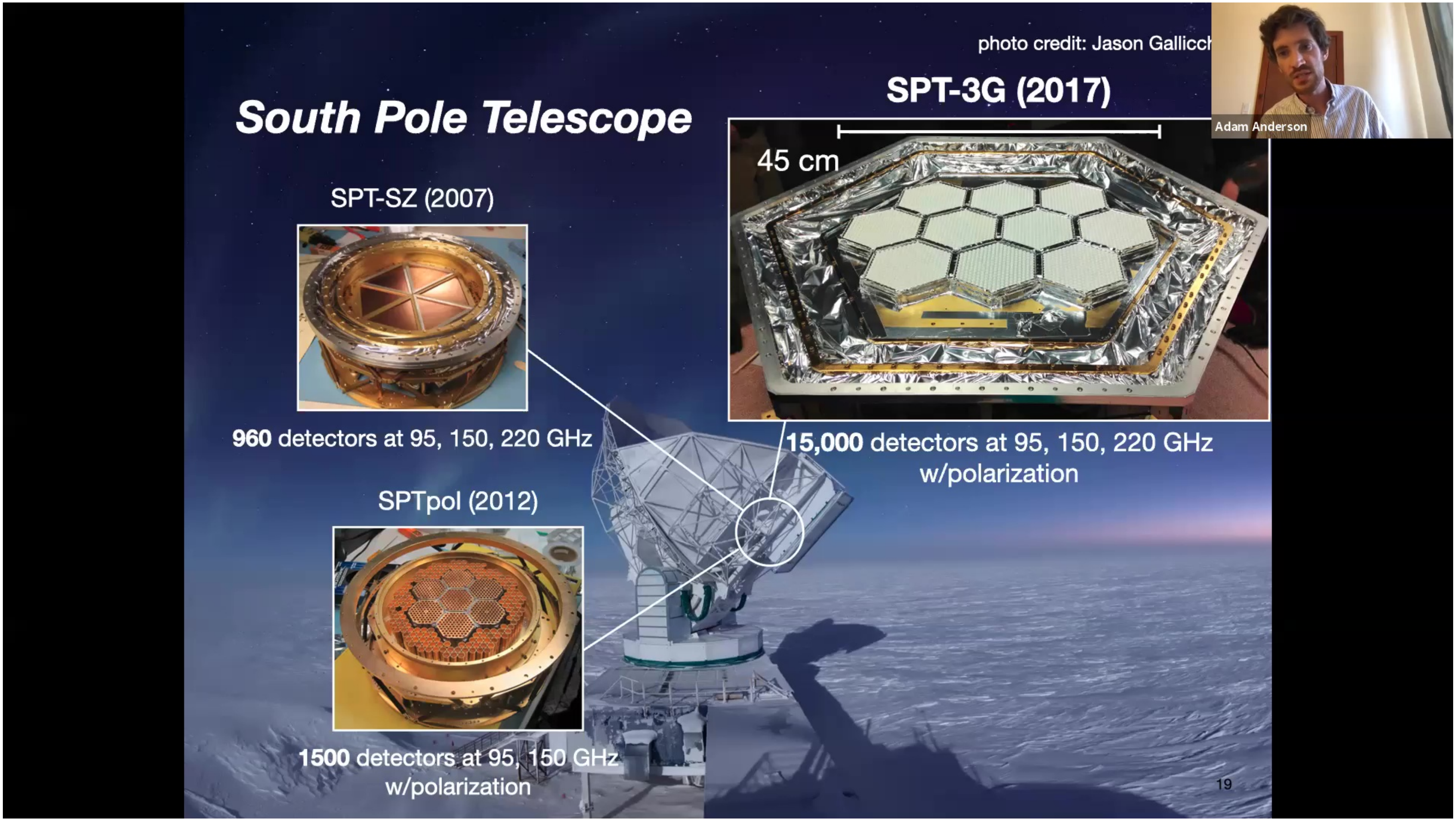

photo credit: Jason Gallicch
SPT-3G (2017)
South Pole Telescope
45 cm
SPT-SZ (2007)
960 detectors at 95, 150, 220 GHz
15,000 detectors at 95, 150, 220 GHz
w/polarization
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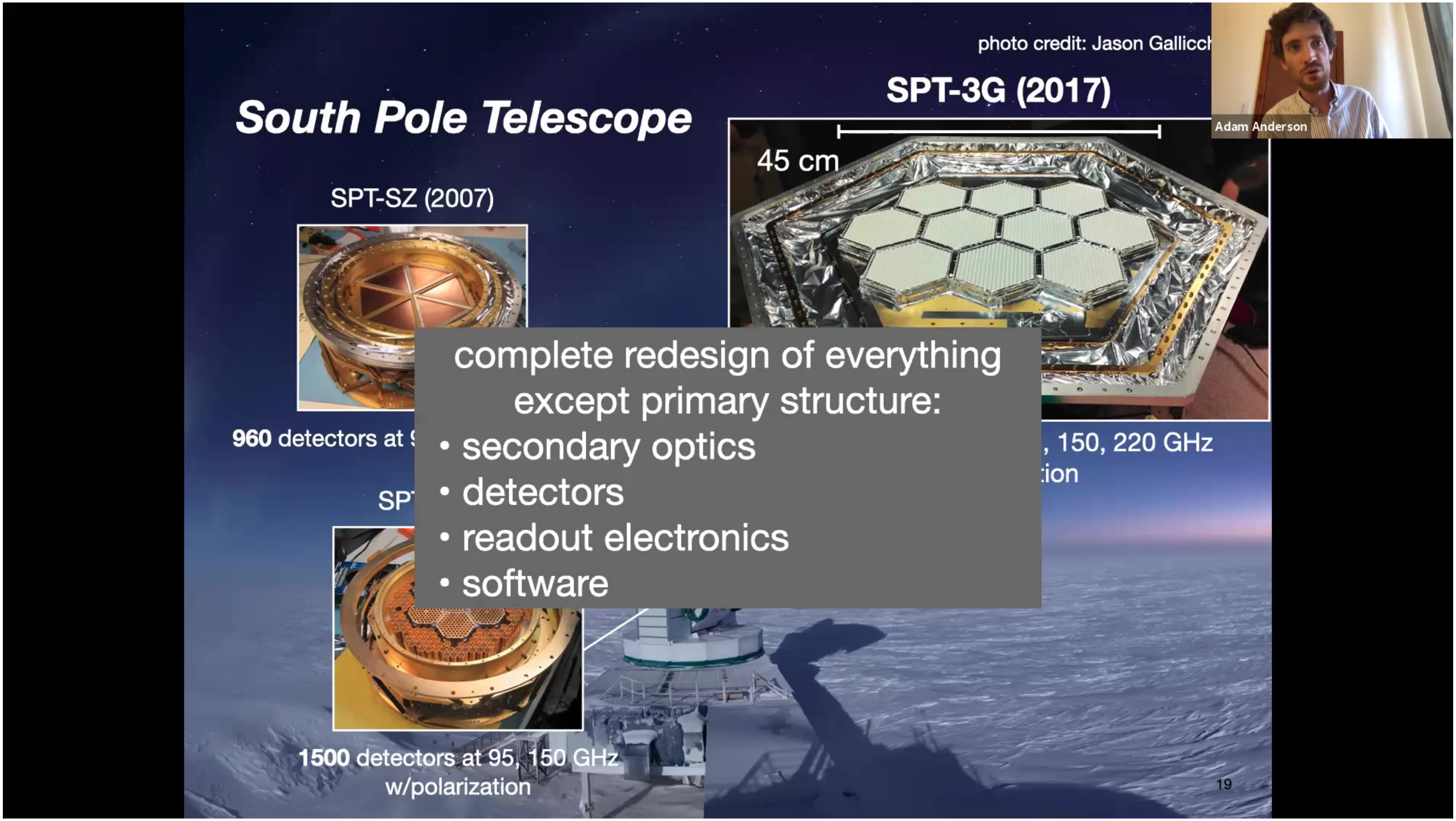
19
Adam Anderson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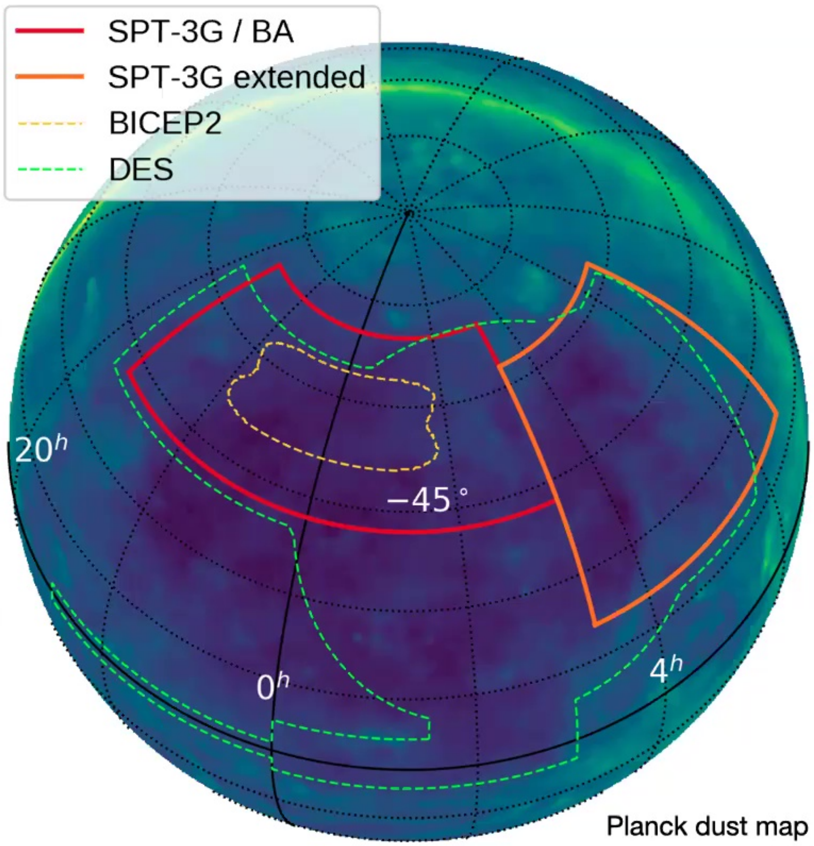
South Pole Telescope
SPT-SZ (2007)
SPT-3G (2017)
45 cm
960 detectors at 9
, 150, 220 GHz
tion
SPT
complete redesign of everything except primary structure:
• secondary optics
• detectors
• readout electronics
• software
1500 detectors at 95, 150 GHz w/polarization
19
Adam Anderson

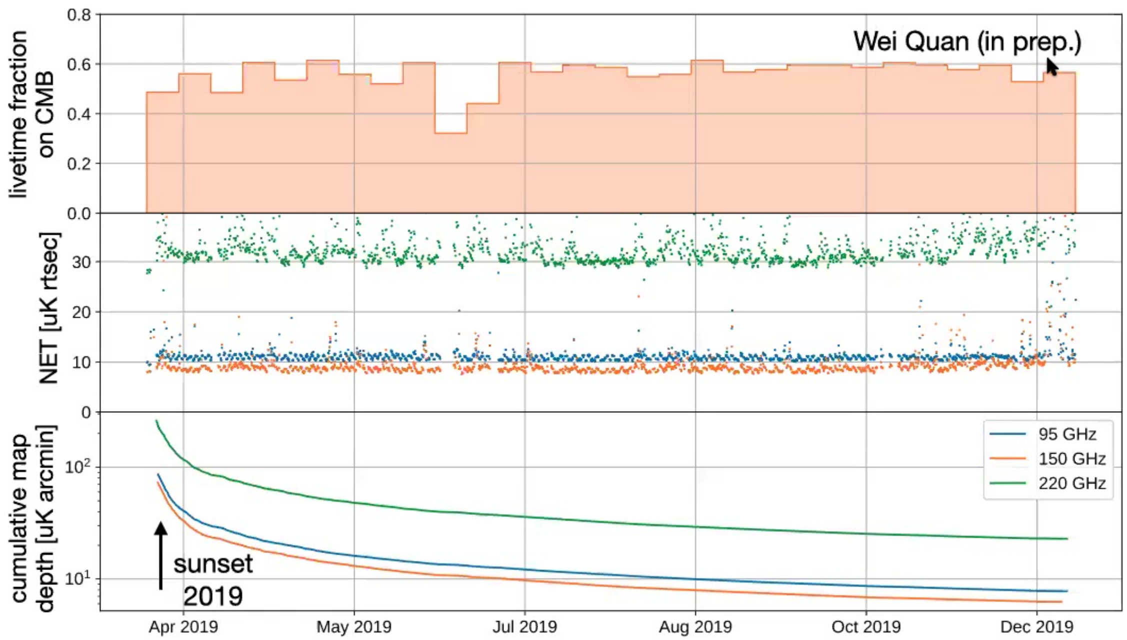
SPT-3G Surveys



Planck dust map
(A&A 594, A10 (2016))

	Obs. Years	Area (deg2)	95 GHz (uK-arcmin)	150 (uK-arcmin)	220 (uK-arcmin)
SPT-SZ	2007-11	2500	40	17	80
SPTpol-Main	2012-16	500	13	5	-
SPTpol-Deep	2012-16	100	10	3.5	-
SPT-3G	***2019-2023***	***1500***	***~3***	***~3***	***~10***

2019 Survey Status and Performance



~60% observing efficiency in 9-month observing season

Daily camera sensitivity is stable over season

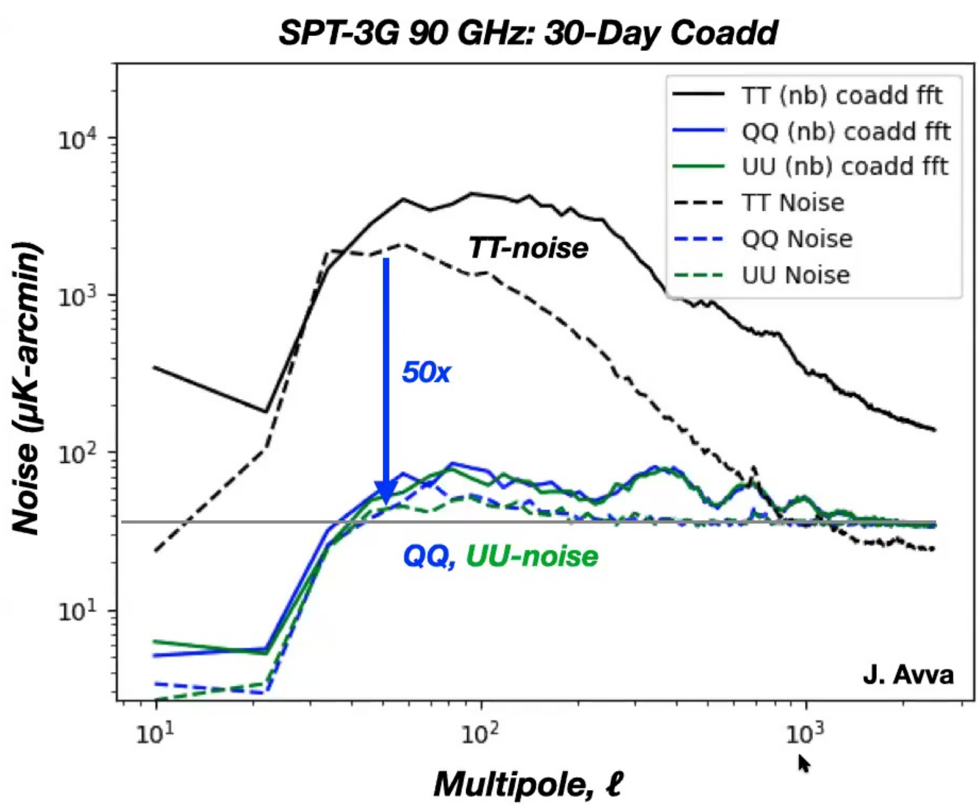
SPT-3G Temp. Noise (uK-arcmin)

Freq. (GHz)	95	150	220
2018 Season	19	14	50
2019 Season	**8**	**6**	**23**
Full survey (2023)	~3	~3	~10

← Approx. Simons Observatory "goal" survey depth (f_{sky} = 0.4)

← Approx. CMB-S4 wide survey depth (f_{sky} = 0.7)

Low-Ell Noise Performance



- South Pole atmosphere has relatively low-fluctuation power and is unpolarized
- SPTpol low-ℓ noise was limited by temperature sensitivity of electronics
- SPT-3G has improved low-ℓ performance:
  - Electronics ℓ_{knee}=24 (Bender et al, 2019; arxiv: 1907.10947)
  - ***1500d survey QU-noise has low ℓ_{knee}***
  - (Using out-of-box RCW38 calibration, 1 deg/sec scanning, no additional modulation)

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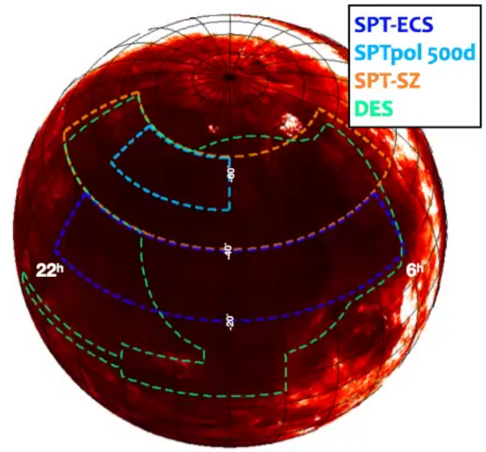
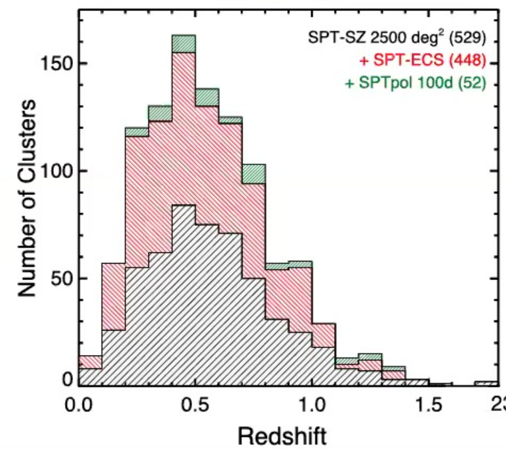
SPT-3G Extended Survey

- Main field is sun-contaminated during summer, but >1500 sq. deg. of additional clean sky available
- Concept demonstrated with SPTpol Extended Cluster Survey (Bleem, et al. 1910.04121): 500 clusters
- ***SPT-3G Extended:*** shallow survey for 4 summers 2019-2023, 3mo/year to improve cosmological constraints and detect clusters
- ***Finished first season at end of March***
- Reduces error bars on Σm_ν and N_{eff} by 30-40%



	Obs. Years	Area (deg2)	95 GHz (uK-arcmin)	150 (uK-arcmin)	220 (uK-arcmin)
SPTpol-ECS	2013-15	2770	43 - 80	25 - 40	-
3G Extended	2019-...	1500	11 - 22	10 - 24	35 - 90



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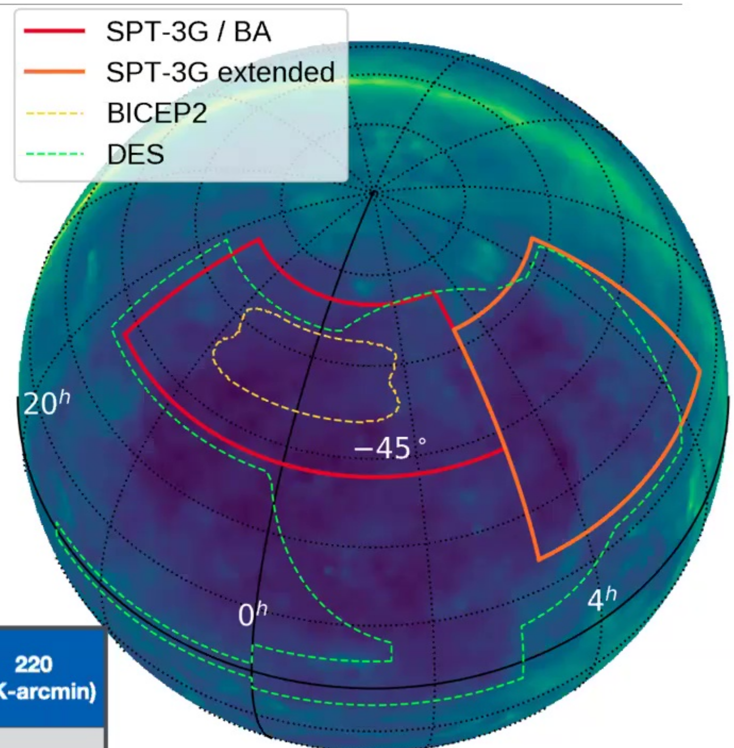

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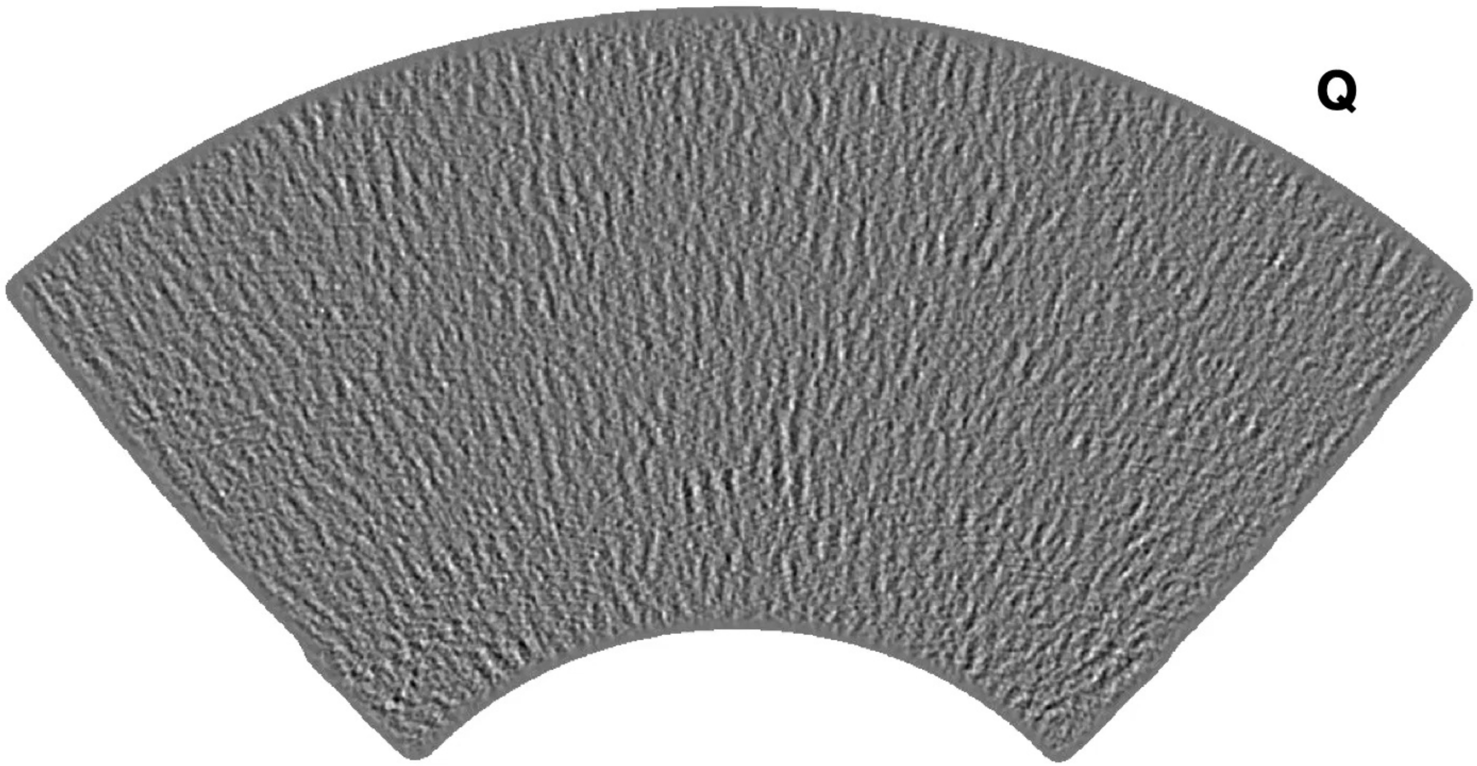
SPT-3G 2018 E Modes



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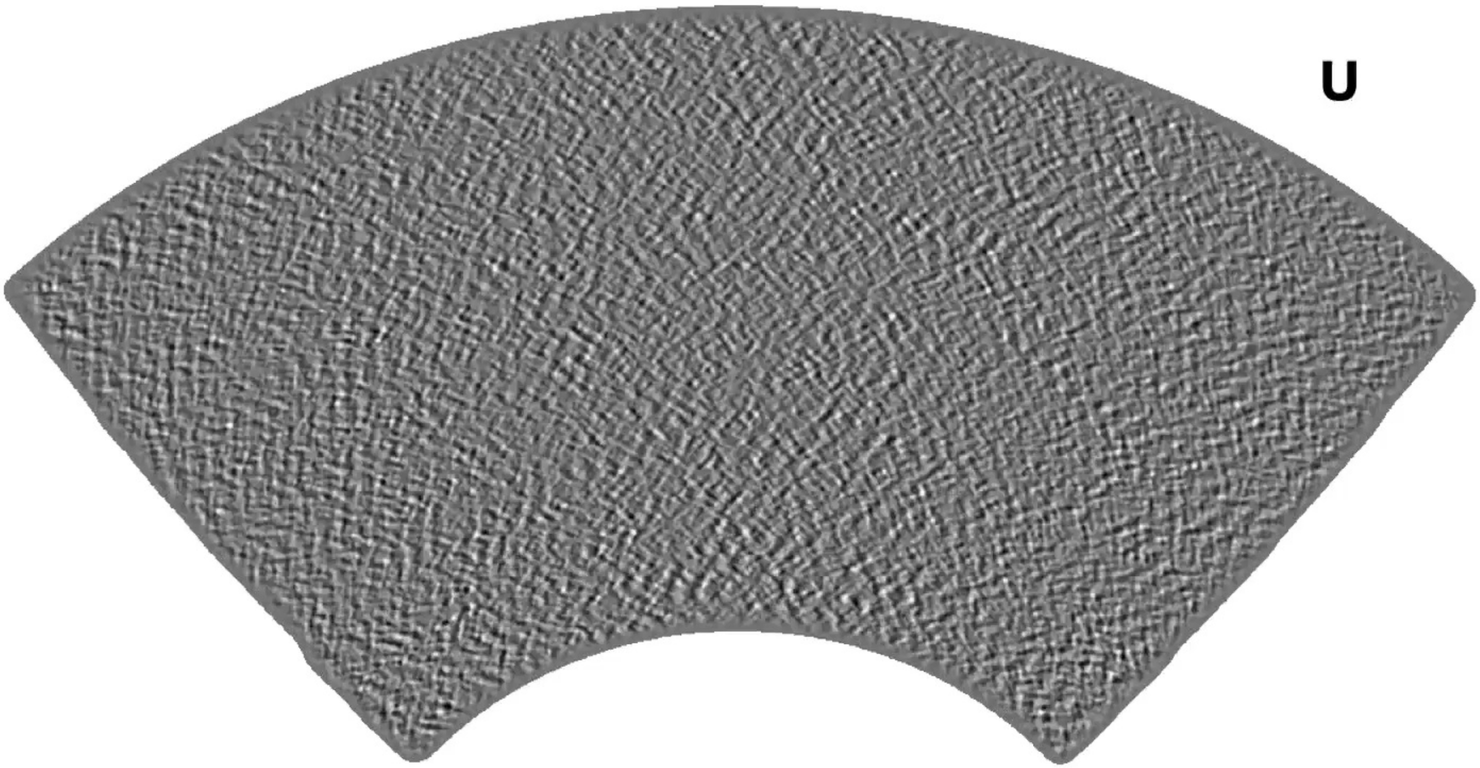
SPT-3G 2018 E Modes



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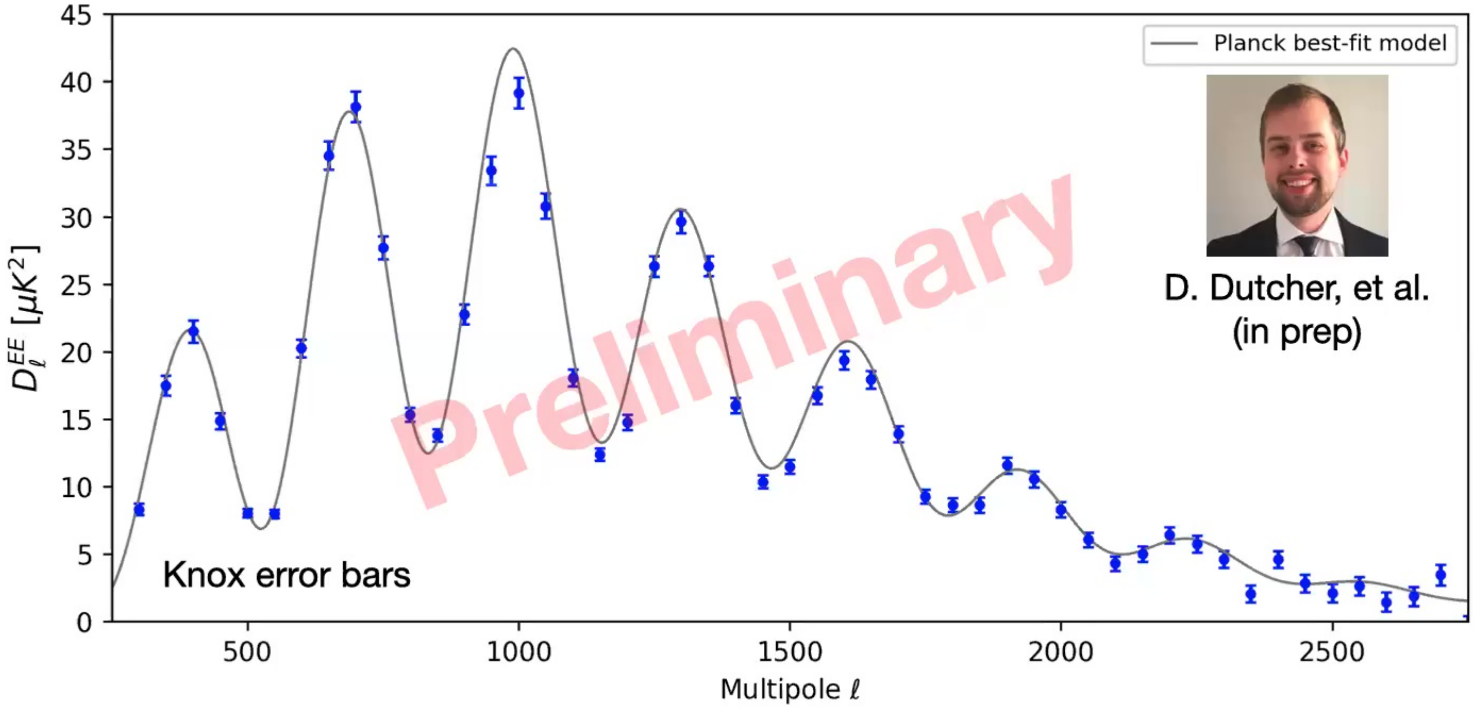
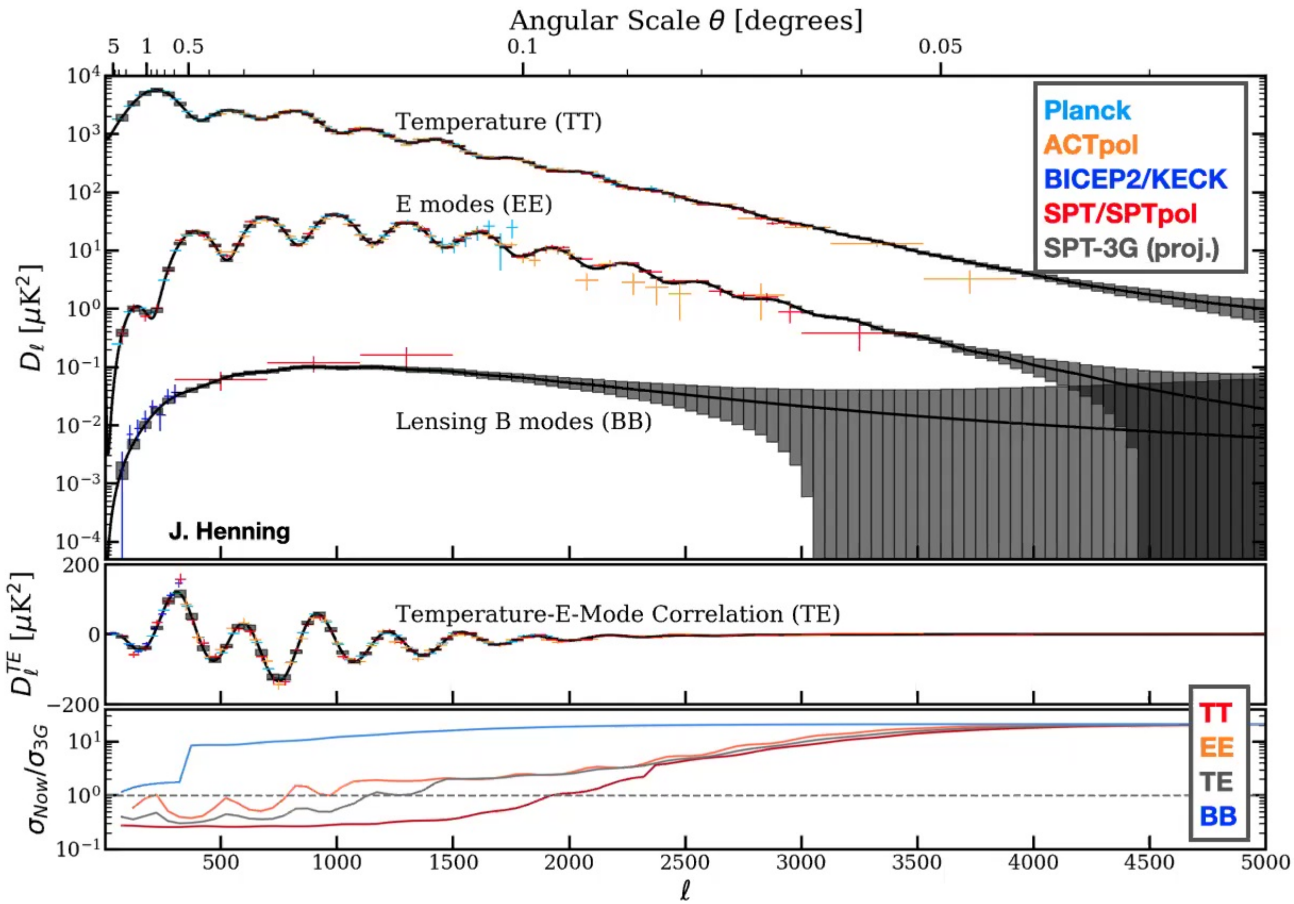
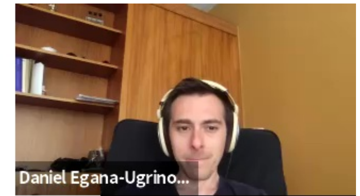
SPT-3G 2018 E Modes



- Work in progress! To-Dos: point source masking, mode-coupling, beam, improvements in filter transfer function from simulations, etc.
- *Most sensitive measurement of E mode power spectrum over* $700 < \ell < 1700$

SPT-3G Power Spectra Forecast





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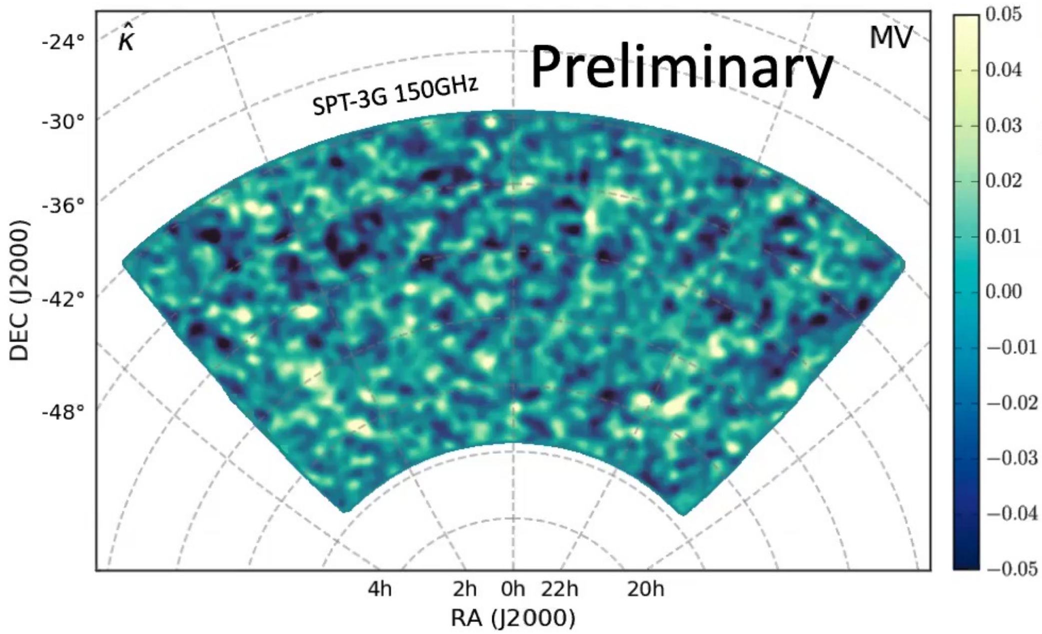
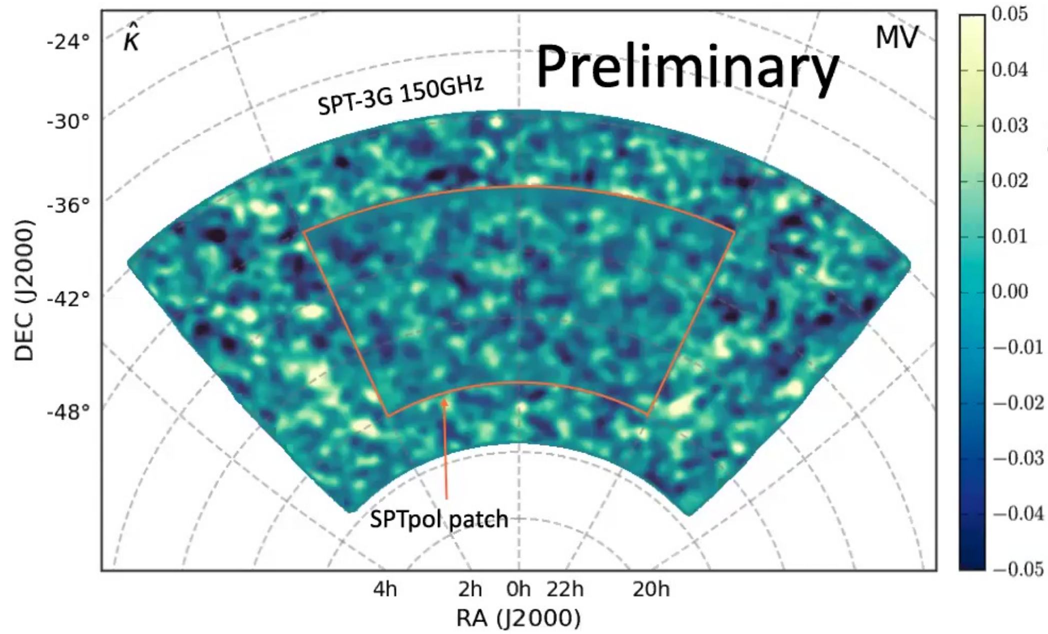
SPT-3G 2018 Lensing



Z. Pan, et al. (in prep)

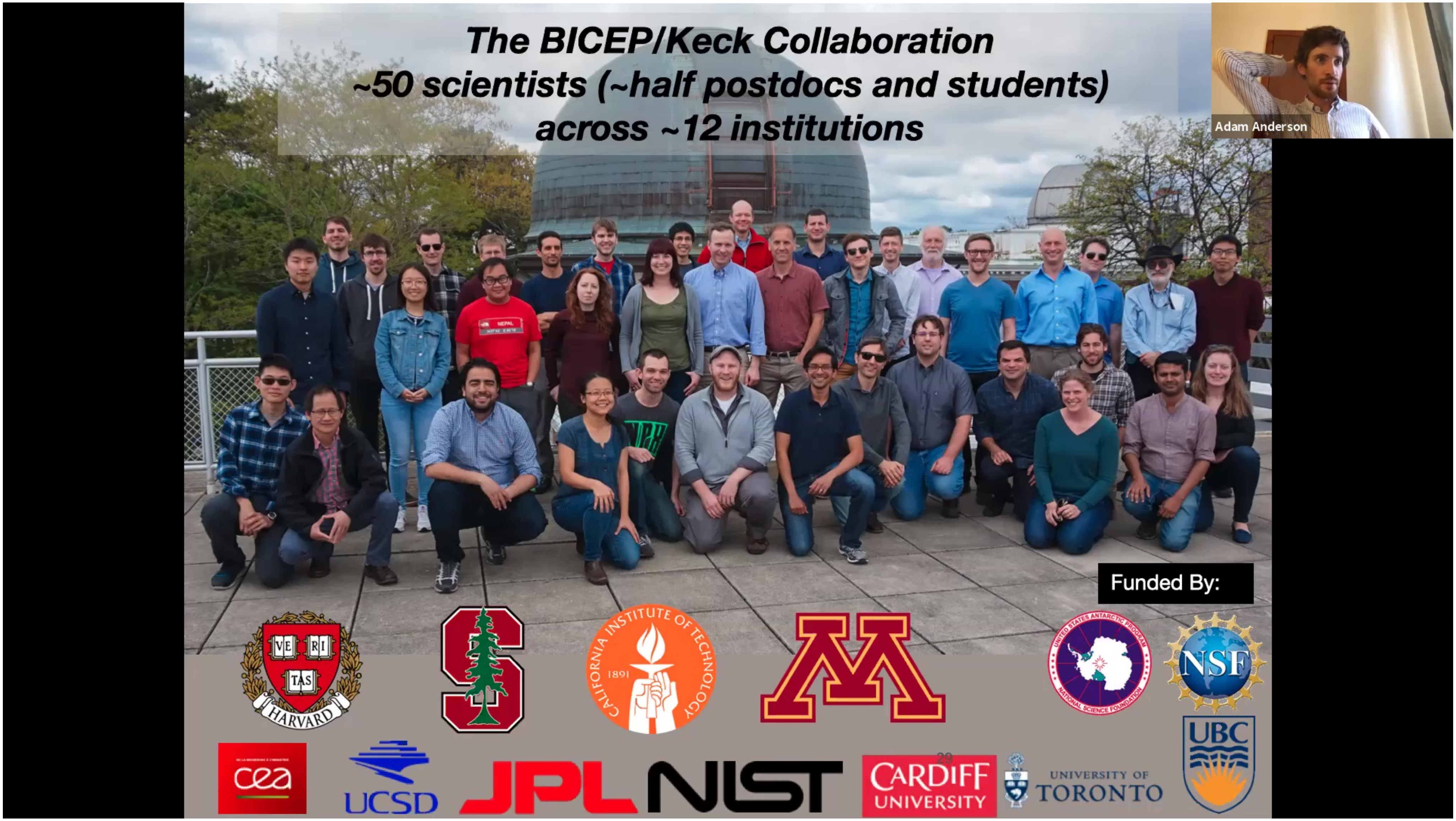
- Minimum variance combination of T, E, B using quadratic estimator

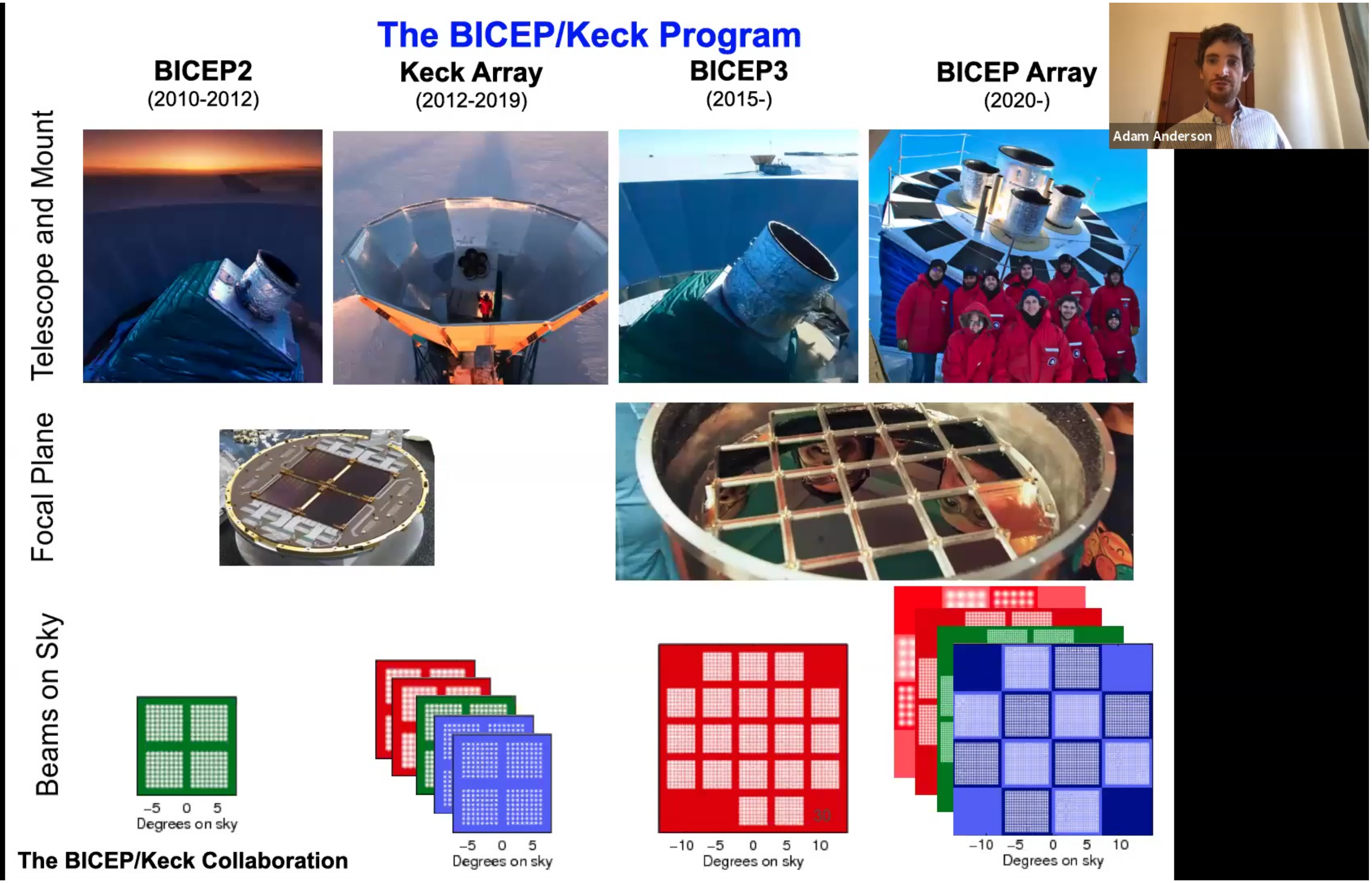
SPT-3G 2018 Lensing



Z. Pan, et al.
(in prep)

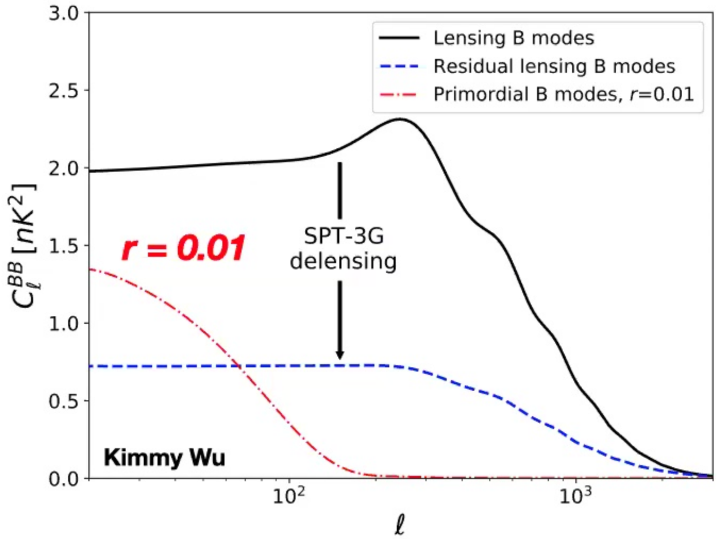
- Good agreement with SPTpol lensing map (K. Wu, et al. (2019) 1905.05777)
- 3G is slightly higher noise than SPTpol, but 3x more area, x3 bands (95, 150, 220 GHz)


The BICEP/Keck Collaboration
~50 scientists (~half postdocs and students)
across ~12 institutions
Adam Anderson
Funded By:

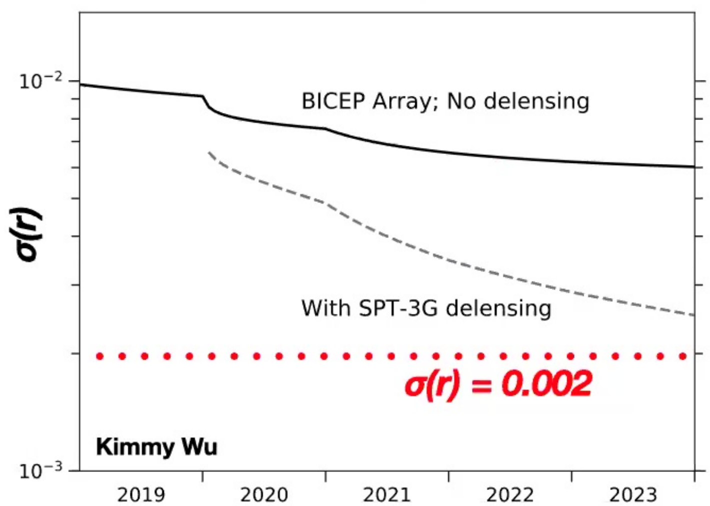

The BICEP/Keck Program
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2015-)
BICEP Array
(2020-)
Adam Anderson
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 −5 0 5 10
Degrees on sky
The BICEP/Keck Collaboration

Delensing with BICEP Array and SPT-3G

SPT-3G internal



BICEP Array + SPT-3G



- SPT-3G will be able to internally remove 2/3 of the B-mode signal due to gravitational lensing
- BICEP Array will be strongly limited by lensing B modes; ***requires a delensing survey*** to significantly improve constraint on *r*

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BICEP/Keck + SPT = South Pole Observatory

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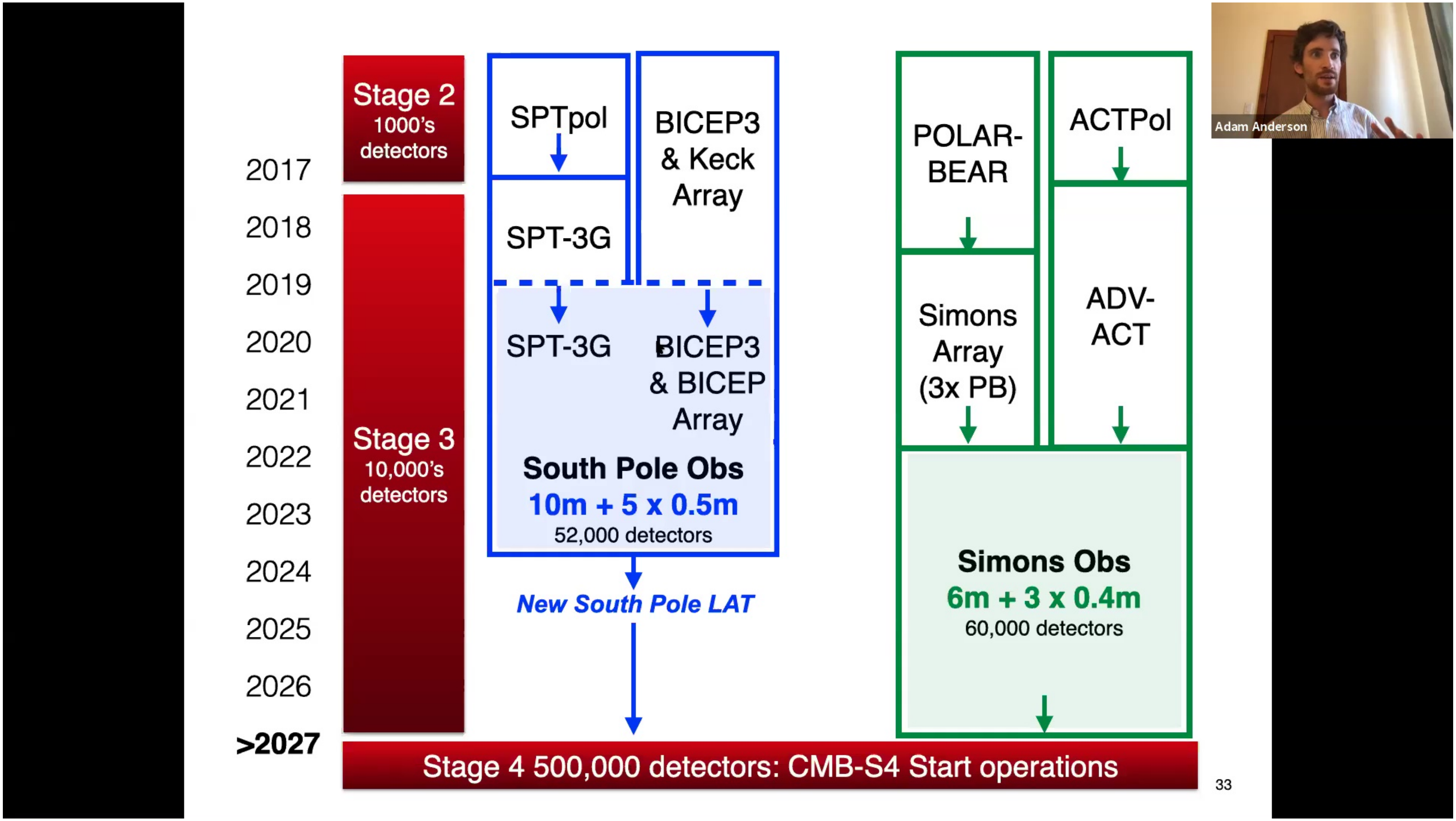
Stage 2
1000's detectors
Stage 3
10,000's detectors
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
>2027
SPTpol
SPT-3G
BICEP3 & Keck Array
SPT-3G
BICEP3 & BICEP Array
South Pole Obs
10m + 5 x 0.5m
52,000 detectors
New South Pole LAT
POLAR-BEAR
Simons Array (3x PB)
ACTPol
ADV-ACT
Simons Obs
6m + 3 x 0.4m
60,000 detectors
Stage 4 500,000 detectors: CMB-S4 Start operations
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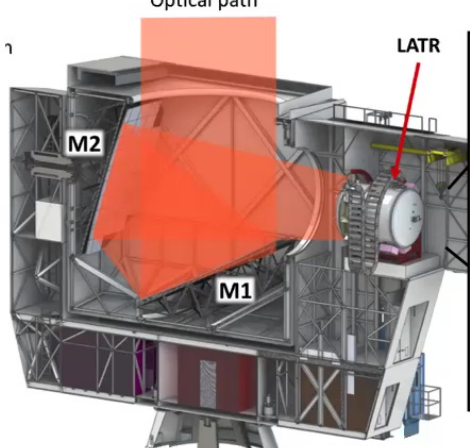
Adam Anderson

The CMB-S4 Concept

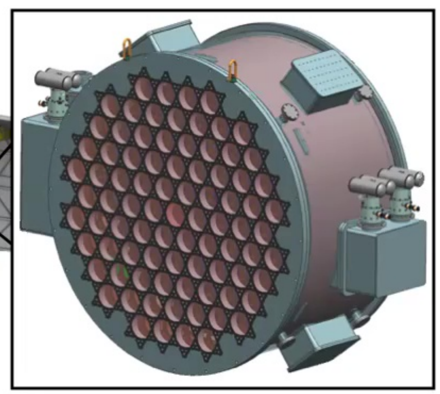
- Achieved DOE CD-0 in 2019. First light in 2026-2027.
- **Concept:**
  - **~500,000 detectors** split between 3x 6m-aperture, ~18x 0.5m-aperture telescopes
  - **Two sites:** Split between South Pole and Atacama in Chile
  - **Two surveys:** Inflation survey on 3-8% sky, neutrinos and cross-correlation on 40% sky
  - **~7 frequency bands:** 20, 30, 40, 95, 150, 220, 270 GHz for foreground characterization

Large aperture: delensing, neutrinos, high-resolution science

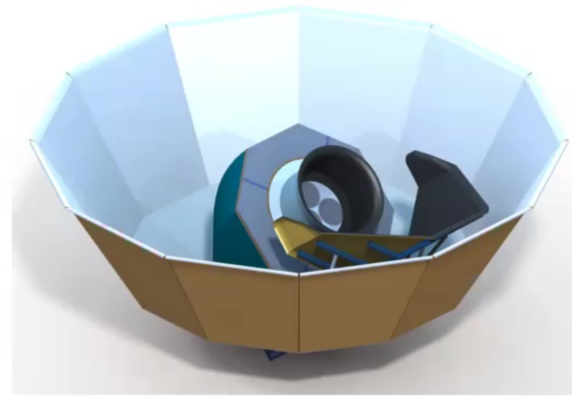
Small aperture: inflationary B modes



Simons Observatory LAT



85-tube cryostat concept



BICEP Array

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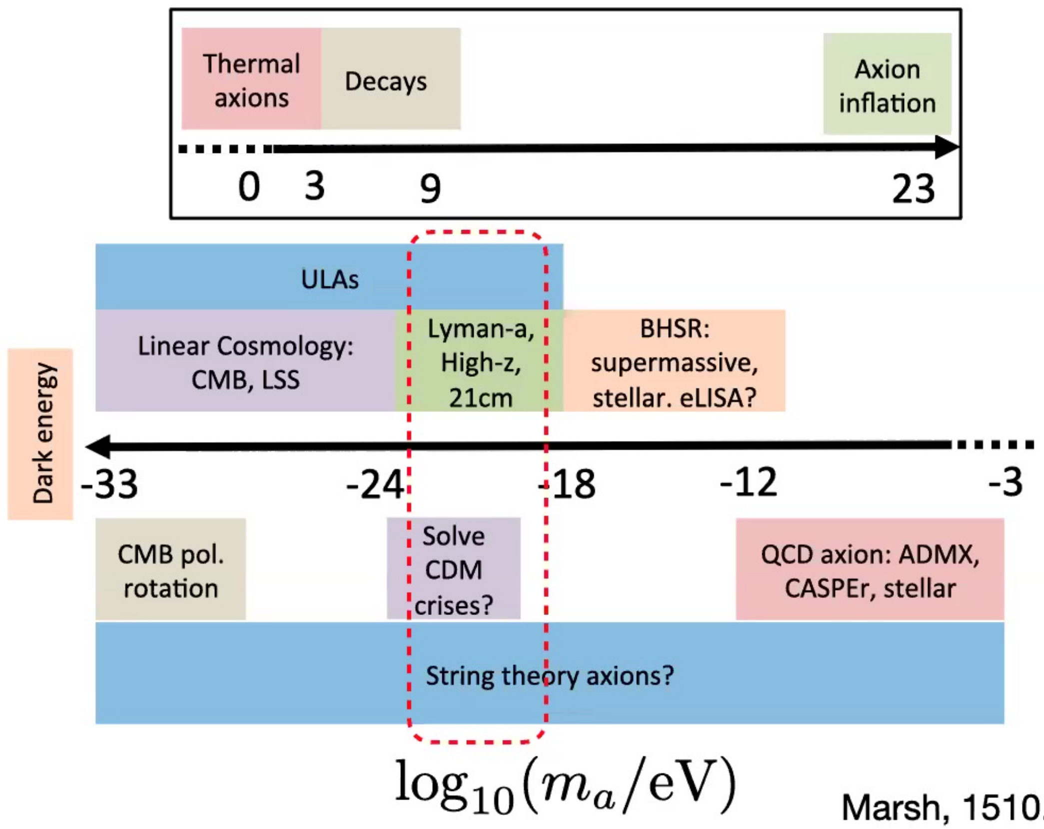
CMB-S4 Science

	Stage 2	Stage 3	Stage 4	Top level goal for S4
Inflation: σ_r	≤ 0.1; single field slow roll	≤ 0.01	≤ 0.001	Detect or rule out the most natural class of inflationary models
Light Relativistic Species: $\sigma_{N_{eff}}$	0.14; Minimum ΔN_{eff}	0.06	0.027	Detector rule out all light relativistic species with spin
Neutrino Masses: $\sigma_{\Sigma M\nu}$	0.15eV; lower limit Σm_ν	0.06eV	0.015eV	>3σ detection of neutrino mass, potential to determine the neutrino mass hierarchy
Dark Energy: FOM	~180	~300-600	~1250	Improve tests of modified gravity and tests for new dynamical fields

+ much more ancillary science!

Axion-like Particles



Marsh, 1510.07633v2 36

Birefringence due to ULAs

- Axion-photon coupling modifies Maxwell's equations. Fields satisfying free wave equation are:

$$\mathbf{D} = \mathbf{E} + \frac{g_{\phi\gamma}}{2}\phi\mathbf{B}$$
$$\mathbf{H} = \mathbf{B} - \frac{g_{\phi\gamma}}{2}\phi\mathbf{E}$$

- Produces rotation of plane of linear polarization (birefringence) that depends only on difference in axion field between absorption and emission:

$$\Delta\theta = \frac{g_{\phi\gamma}}{2}\left[\phi(\eta_{\rm abs}, \mathbf{x}_{\rm abs}) - \phi(\eta_{\rm emit}, \mathbf{x}_{\rm emit})\right]$$

- Basis for much previous work, various sources:
  - Radio sources (1811.10997)
  - Anisotropic polarization rotation in CMB (POLARBEAR, ACTpol, SPTpol (see 2006.08061!))

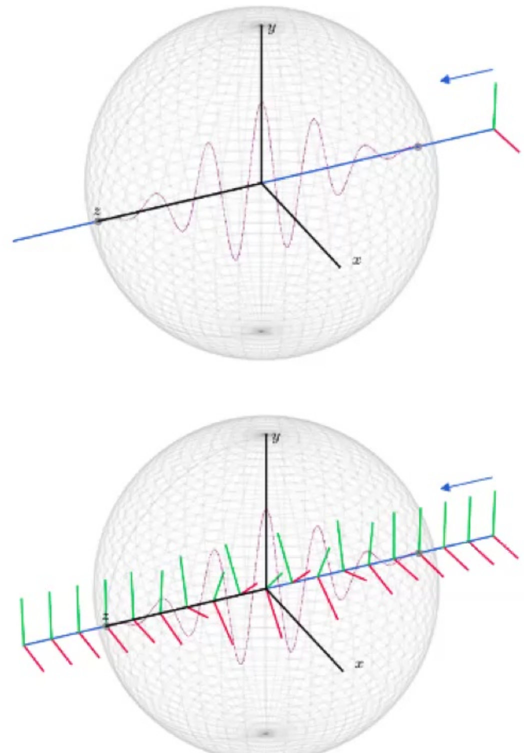


Fig. credit: M. Fedderke

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Using the CMB As a Source

- CMB is an ideal source to search for effect due to axion dark matter
- Fedderke, et al. (1903.02666) point out:
  - *Local* oscillation of axion field at earth produces time-dependent polarization rotation
  - Oscillation of axion field faster than CMB visibility function results in "average" source rotation
  - Rotation variation is *coherent* across sky and *common* to all observers

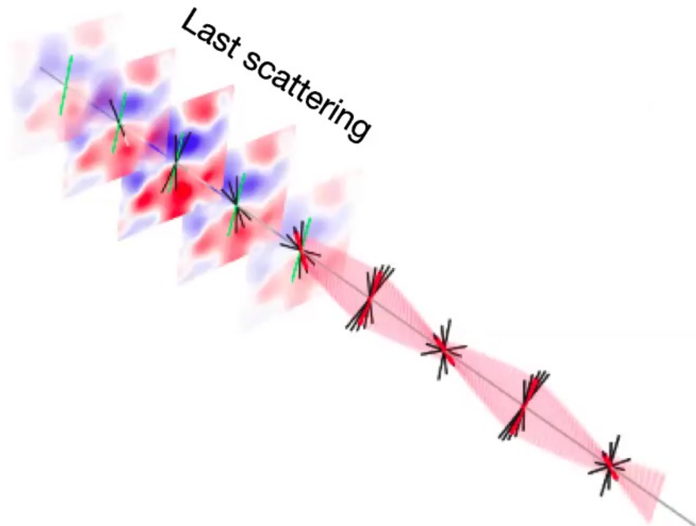
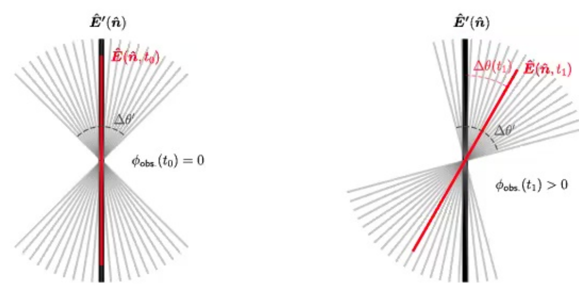


Fig. credit: M. Fedderke



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Effect 1: Polarization "Washout"

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = J_0\left(g_{\phi\gamma}\langle\phi_*\rangle(\hat{\boldsymbol{n}})\right) \exp\left[\pm 2i\left(\frac{g_{\phi\gamma}}{2}\phi_0 \cos(m_\phi t + \alpha)\right)\right](Q \pm iU)_0(\hat{\boldsymbol{n}})$$

polarization "washout" effect

Stokes's parameters for linear polarization

- Polarization is overwhelmingly due to E-mode polarization
- Washout results in suppression of amplitude of E-mode power spectrum
- Degeneracies:
  - Not easily mimicked by adjusting base 6 parameters in LCDM (1903.02666)
  - Polarization calibration / efficiency

$$C_{TT,\ell} \rightarrow C_{TT,\ell}$$
$$C_{TE,\ell} \rightarrow J_0(g_{\phi\gamma}\langle\phi_*\rangle)C_{TE,\ell}$$
$$C_{EE,\ell} \rightarrow [J_0(g_{\phi\gamma}\langle\phi_*\rangle)]^2 C_{EE,\ell}$$

Effect 2: Polarization Angle Oscillation

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = J_0\left(g_{\phi\gamma}\langle\phi_*\rangle(\hat{\boldsymbol{n}})\right) \exp\left[\pm 2i\left(\frac{g_{\phi\gamma}}{2}\phi_0 \cos(m_\phi t + \alpha)\right)\right](Q \pm iU)_0(\hat{\boldsymbol{n}})$$

slow oscillation

Stokes's parameters for linear polarization

- Mixing of Q and U Stokes parameters, global polarization angle rotation, *sinusoidal in time*
- Equivalent to mixing of E modes into B modes
- *Amplitude:* set by axion-photon coupling
- *Frequency:* set by axion mass
- *Phase:* arbitrary
- Polarization rotation is due to *local* axion field at Earth, so coherent over full sky, and seen with same phase by all observers

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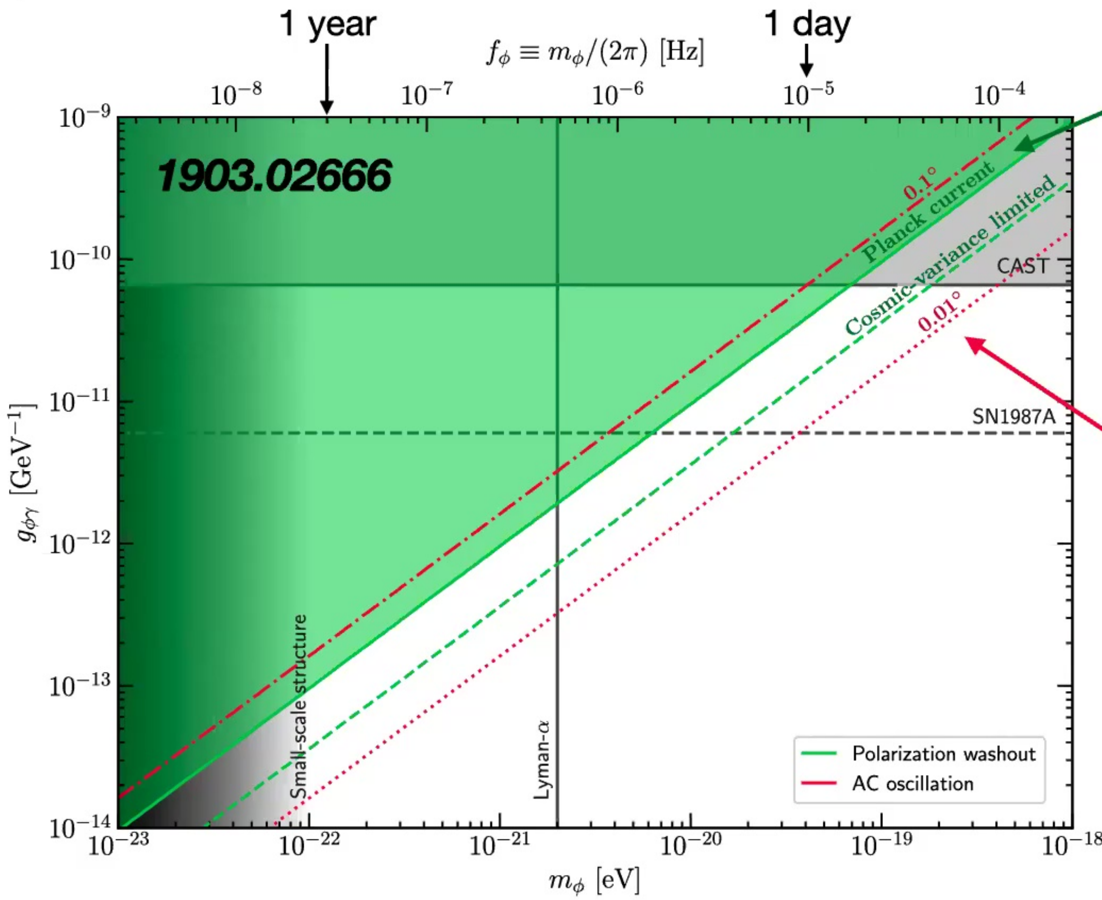
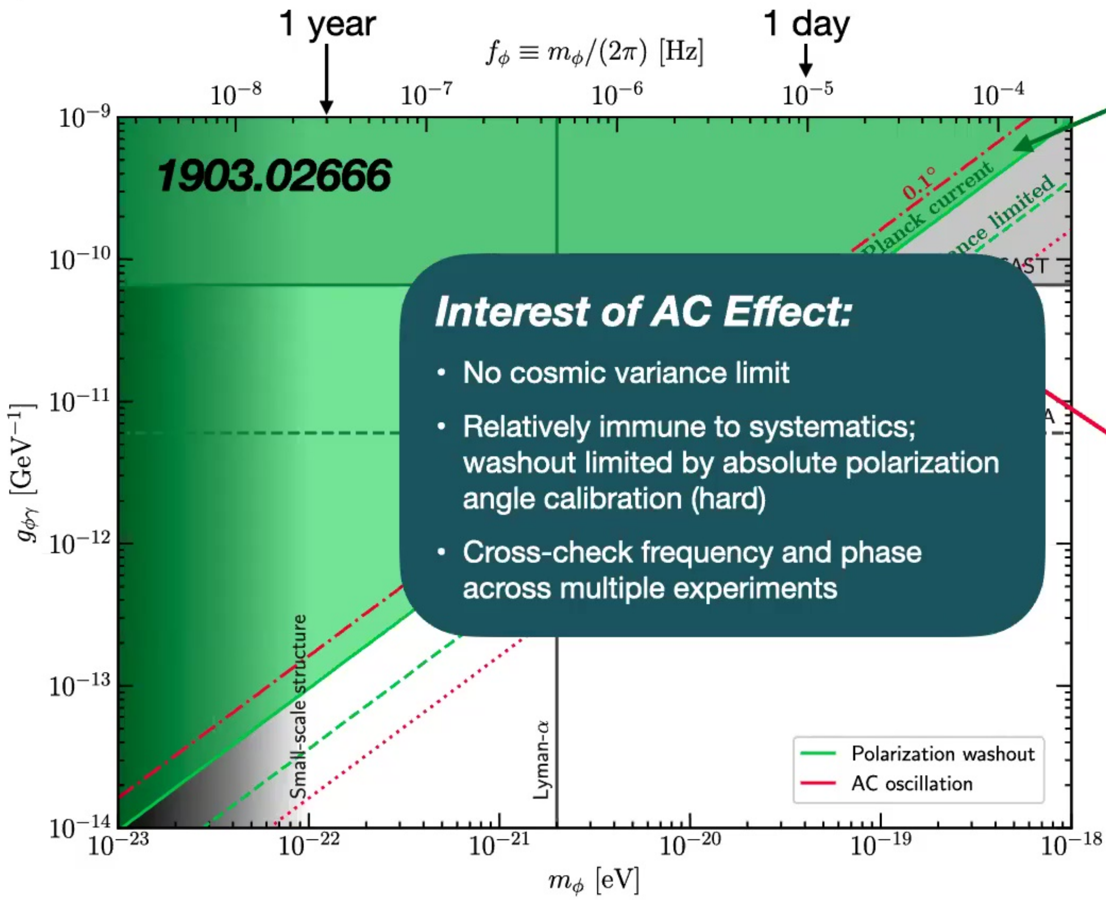
Existing Bounds



from polarization suppression effect

AC modulation effect; no existing experimental limits!

Existing Bounds



Interest of AC Effect:

- No cosmic variance limit
- Relatively immune to systematics; washout limited by absolute polarization angle calibration (hard)
- Cross-check frequency and phase across multiple experiments

from polarization suppression effect

AC modulation effect; no existing experimental limits!

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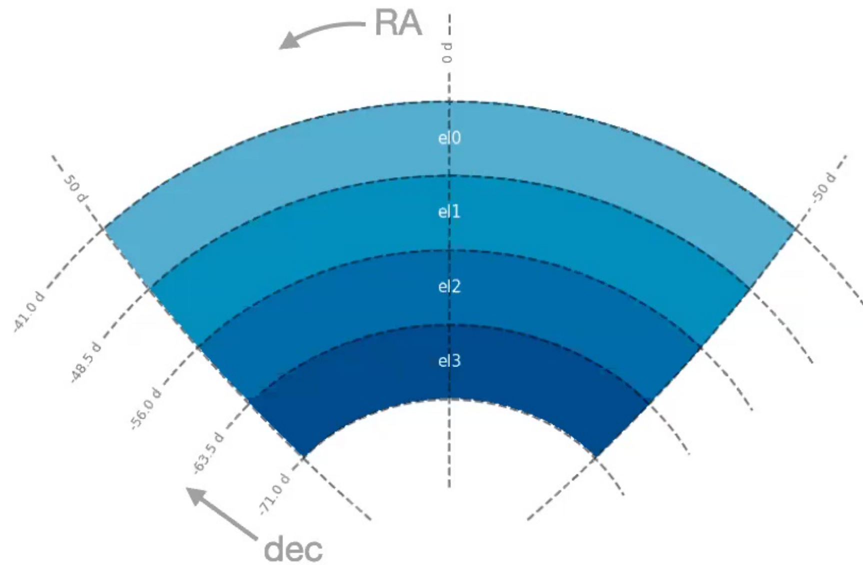
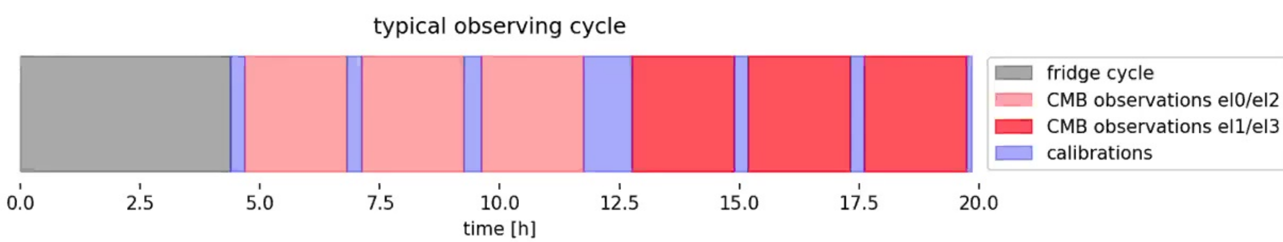
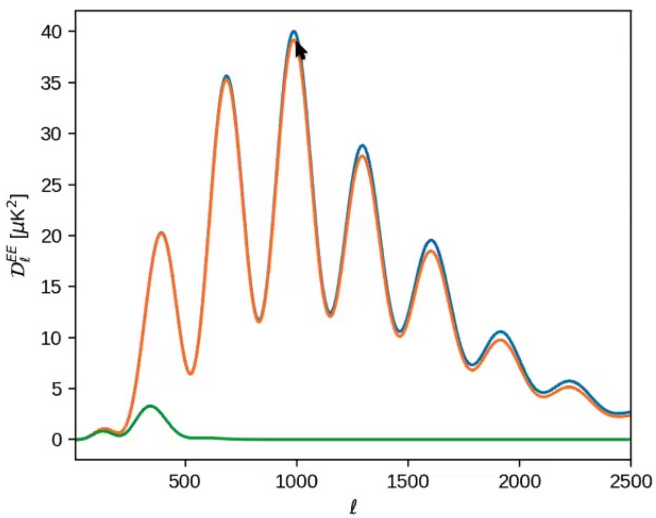
SPT Observing Cadence

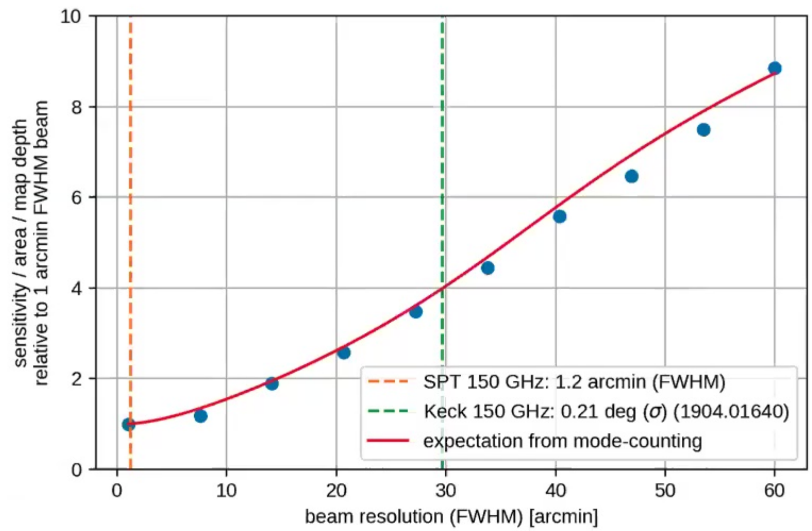
- 1500d field divided into 4 subfields, observed ~2h at a time
- Repeated 20h cycle of calibrations, CMB observations, and cryogenic cycle
- High-cadence re-observation of common field is well matched to axion analysis





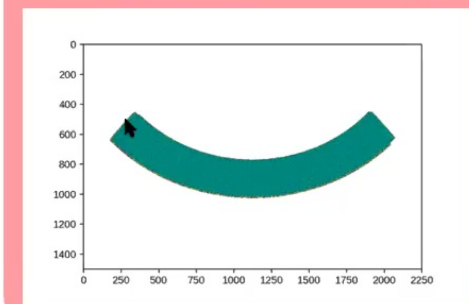
Small Beam Advantage: SPT vs. BICEP/Keck



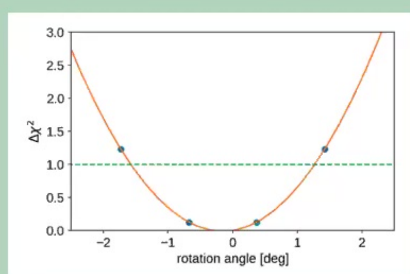


Analysis Overview

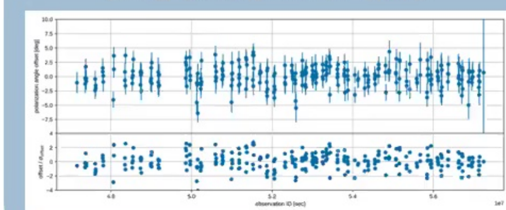
“single observation” maps



real-space estimate of polarization angle

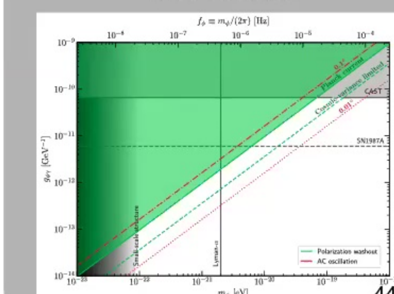


polarization angle as a function of time



null tests for systematics

set limits



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Analysis with Real-space Estimator

- Use simple real-space chi-square statistic, with linear polarization rotation

$$\chi^2(\rho) = \sum_{pq,ij} \left(P_{pi} - P_{pi}^{\mathrm{model}}(\rho)\right) \left(\Sigma^{-1}\right)_{pq,ij} \left(P_{qj} - P_{qj}^{\mathrm{model}}(\rho)\right)$$

$$P_{Qi}^{\mathrm{model}}(\rho) = Q_{0,i} - \rho U_{0,i}$$
$$P_{Ui}^{\mathrm{model}}(\rho) = U_{0,i} + \rho Q_{0,i}$$

Unrotated templates from coadd

- Assume diagonal covariance, and approximate entries using weights matrix:

$$W_{pqj} = \sum_{d,t} N_d^{-1} M_{pqd} P_{jdt}, \qquad (\Sigma^{-1})_{pq,ij} = W_{pqi}\delta_{ij}\frac{2\Delta f}{f_s}$$

weights; noise; Mueller matrix; pointing; diagonal by fiat; weights bandwidth; sampling rate

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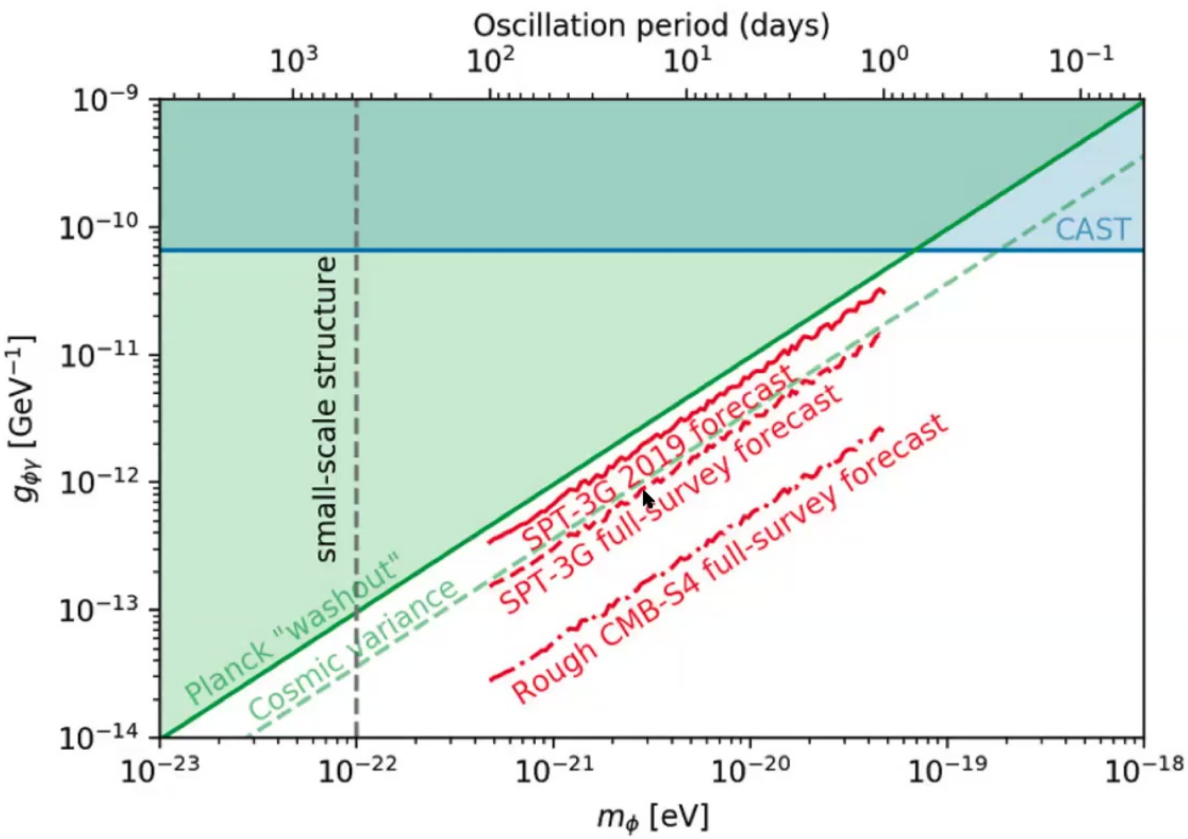
Sensitivity Projections



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Joint Effort with BICEP: SPO

- Similar search underway with BICEP/Keck data (Ari Cukierman - Stanford)
- BK has more data + lower noise, SPT has better resolution
- Combination provides potential systematics cross-checks

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Questions?
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Junwu Huang