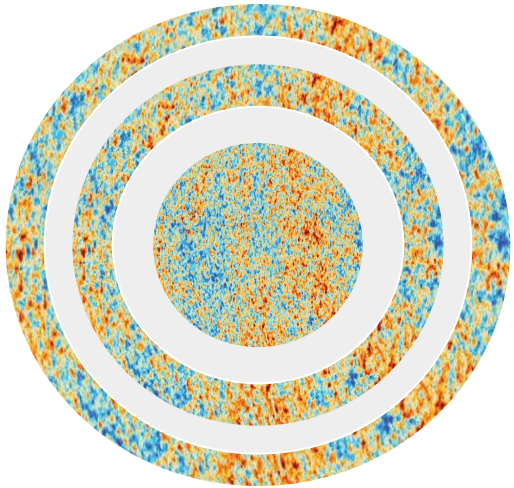


Beam modeling importance & techniques for current and next-generation CMB telescopes

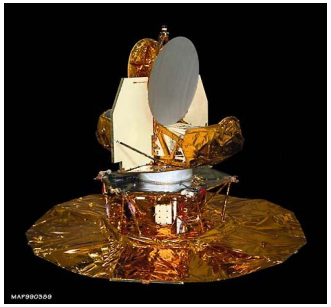
Nadia Dachlythra
July, 2023

(Some of the) CMB experiments

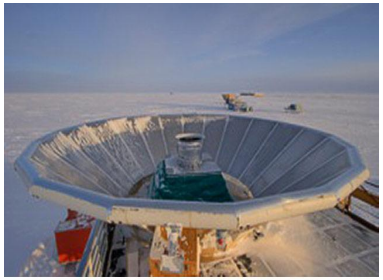
COBE, 1989

BOOMERanG, 1997

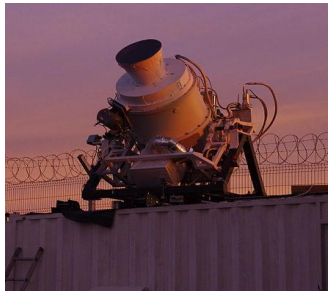
WMAP, 2001



BICEP(1), 2006

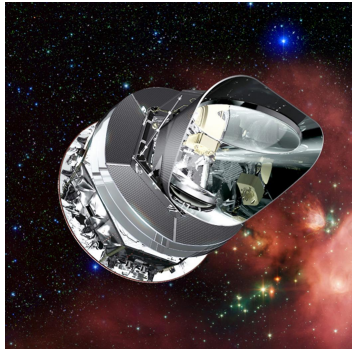


ABS, 2012

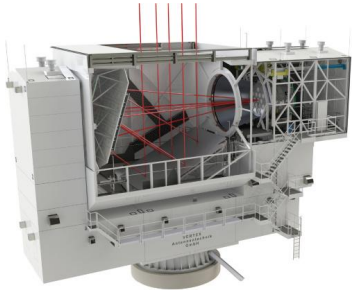


SPIDER, 2015

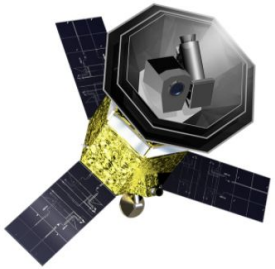
Planck, 2009



The Simons Observatory, LAT and SATs (soon!)

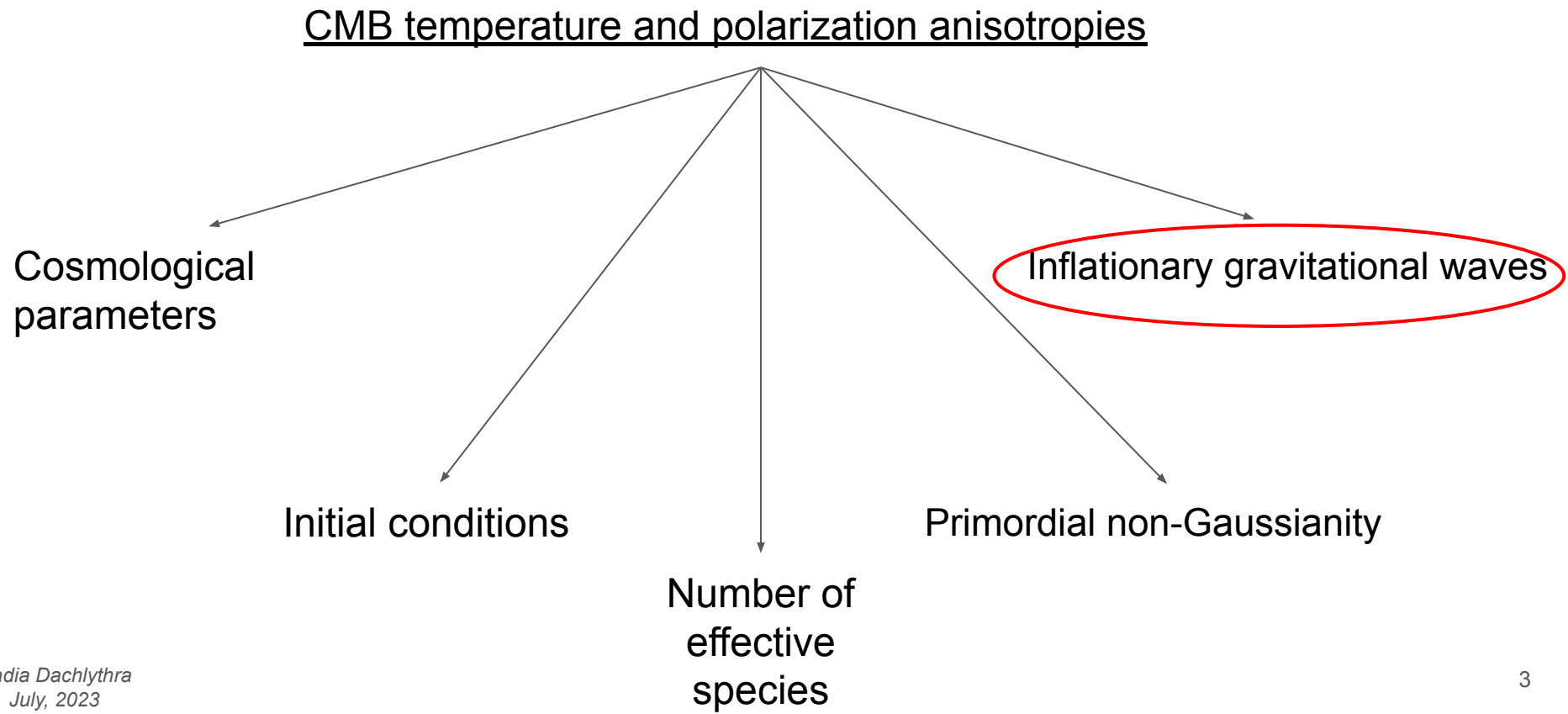


LiteBIRD, $\gtrsim$ 2030



The current LiteBIRD design

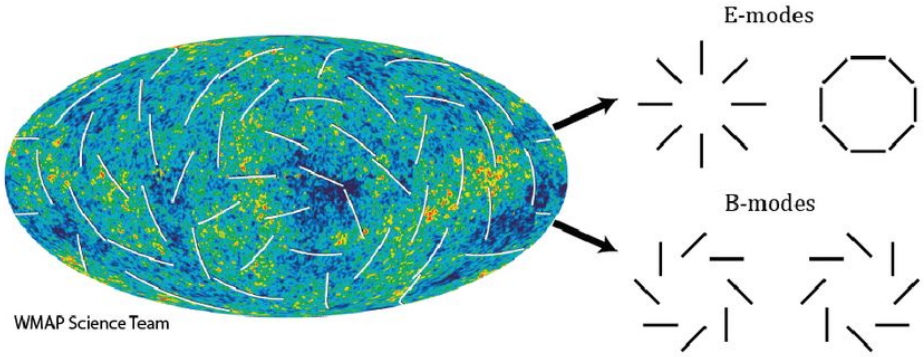
What information can we draw from the CMB?



CMB polarization ~ 10^{-2} · CMB temperature.

- CMB linear polarization: Thomson scattering of photons by free electrons.
- Circular polarization is not expected.
- E-modes:
  - strong, parity-even, curl-free
  - scalar and tensor perturbations
- B-modes:
  - faint, parity-odd, divergence-free
  - only tensor perturbations

- CMB polarization ~ 10^{-2} · CMB temperature.



Credit: Essinger-Hileman et al. 2020, WMAP collaboration

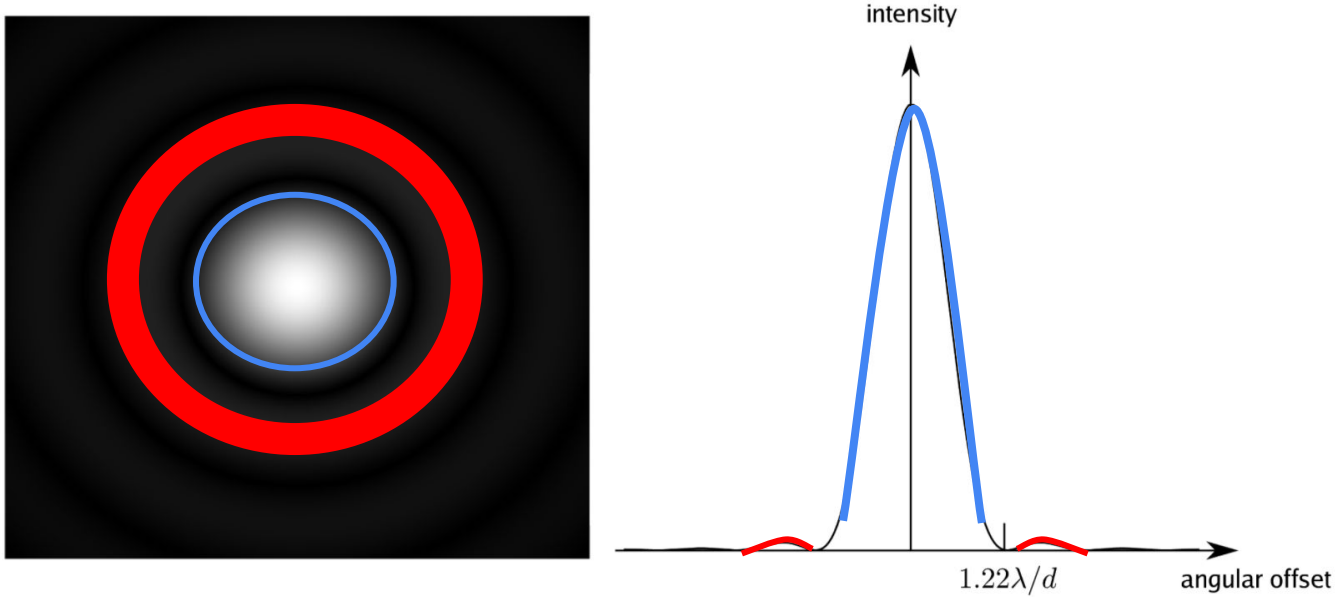
The tensor-to-scalar ratio parameter

- Inflationary gravitational waves → metric tensor perturbations.
- Tensor-to-scalar ratio, **r**: the ratio of the tensor to scalar perturbations amplitude.
- The latest constraints on **r** come from the BICEP/Keck 2018 and Planck PR4 data → ***r*** < 0.032 at a 95% confidence level (*Tristram et al. 2022*).
- The SO telescopes : σ(**r**) ≤ 0.003.
- CMB-S4 and LiteBIRD : **r** > 0.003 detection with a statistical uncertainty σ(**r**) < 0.001.

... it’s beam time!!

What do mean when we talk about beams?

- Instrument's response to a point source.
- Point-Spread-Functions (PSFs): **main lobe** + **sidelobes**.



Credit: D. Buscher, practical-optical-interferometry.

Why do we care?

- Sidelobes: Picking up unwanted parts of the sky (e.g. near the galaxy) or the ground.

- Ellipticity: Beam asymmetry can be problematic for cosmological analysis.

- Unwanted systematic bffs: Beam non-idealities can couple to other types of non-idealities in the experimental setup, as for example to Half-Wave-Plate (HWP) non-idealities (*Duivenvoorden et al. 2021*).

- Beam characteristics are propagated to the beam transfer function.

The importance of the beam transfer function

➢ For the measured CMB power spectra, $\tilde{C}_\ell$:

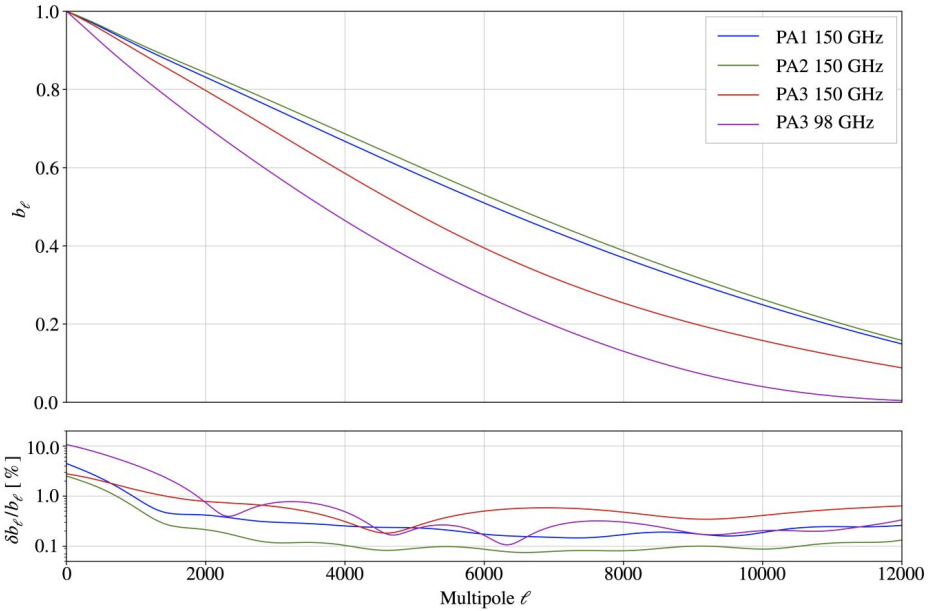
$$\langle \tilde{C}_\ell \rangle = \sum_{\ell'} M_{\ell\ell'} F_{\ell'} B^2_{\ell'} \langle C_{\ell'} \rangle + \langle \tilde{N}_{\ell'} \rangle$$

C_ℓ : true power spectra,

F_ℓ : filter function,

N_ℓ : Fourier transform of the noise covariance matrix

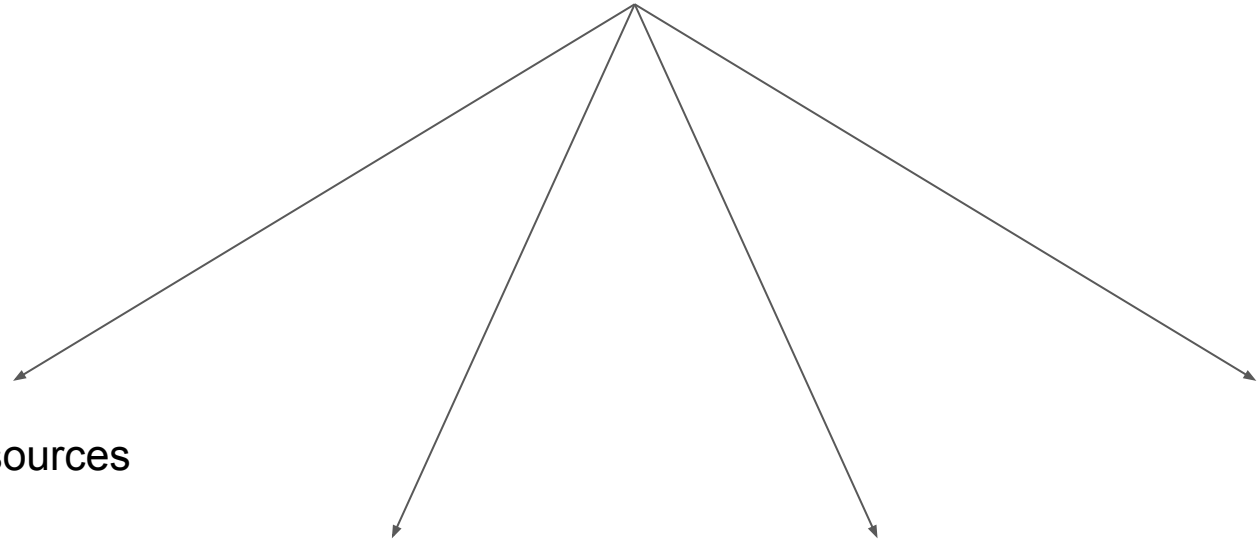
$M_{\ell\ell'}$: is the mode-mixing kernel.



Beam transforms from Uranus simulations of the ACT DR4 release.

Credit : Lungu et al., 2021

Beam calibration



Astrophysical sources

On the field

Artificial sources

On the field

Near-field measurements

In the lab

Holography

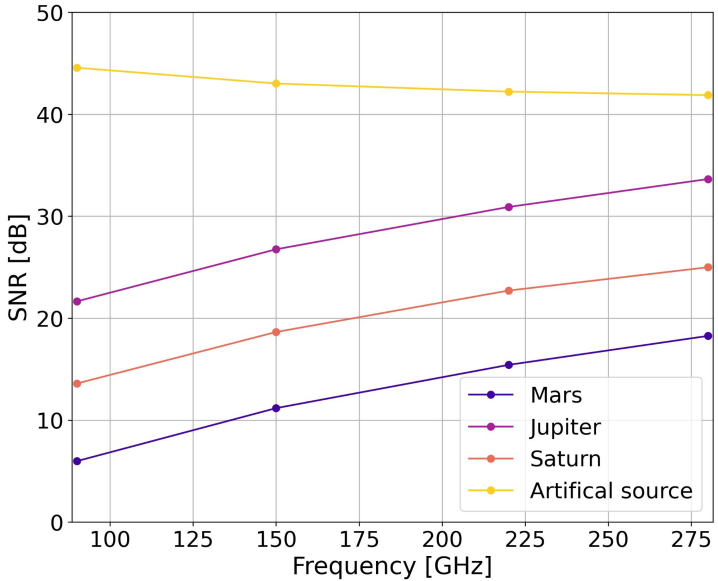
In the lab

Astrophysical sources

- Planets are common candidates for beam calibration (*Weiland et al. 2011*, *The Planck Collaboration VII et al. 2013*, *Hasselfield et al. 2013*, *Lungu et al. 2022*).
- The Moon is also a promising candidate for calibrating beam sidelobes but can saturate the telescope's detectors (*Xu et al. 2020*).
- Planets are not always available for observations when it comes to ground experiments.
- Not all planets are bright enough to calibrate the beam response of every CMB telescope.
- Not as many natural candidates for polarization calibration → Tau A has been used in the past (Kusaka et al. 2018).

Artificial sources

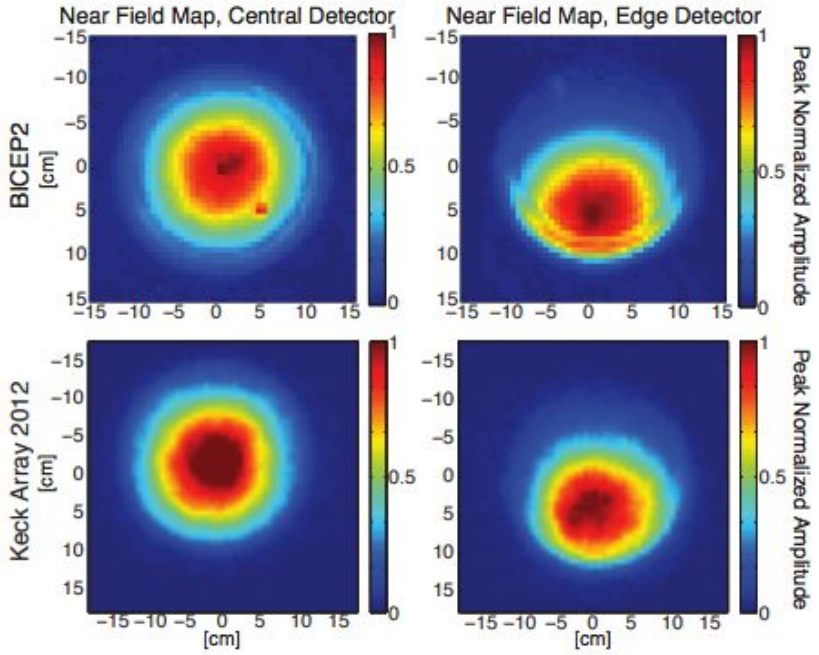
- Sources mounted on tall structures, balloons, satellites, drones (*Masi et al. 2006, Johnson et al. 2015, Nati et al. 2017, Ade et al. 2019, Dunner et al. 2021*).
- Not subject to availability issues.
- Can be tuned to achieve a higher Signal-to-Noise Ratio (SNR) as compared to planets.
- Promising solution to calibrate the instrument's polarized response (*Dunner et al. 2020*).
- May be subject to technical constraints (*Coppi et al. 2022*).



Credit: Dachlythra et al. 2023

Near-field measurements

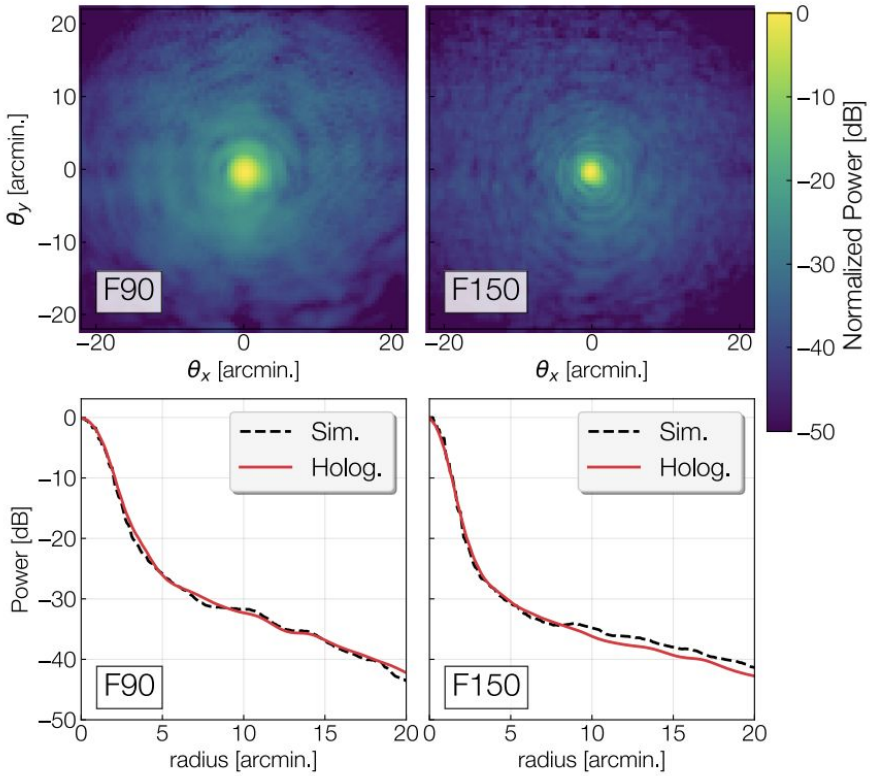
- Measurements at the aperture plane.
- Thermal sources → blackbody emission spectrum.
- No phase information.
- Track internal reflections / provide feedback into optics fabrication process.



Credit: The BICEP2/ Keck Array Collaboration IV, 2015

Holography

- Near-field measurements with a coherent source.
- Map single frequencies within a frequency band.
- Amplitude + phase information.
- Obtain far-field maps:
  - Multiplying with fields produced by distant point source simulations.
  - Integrating over the focal plane.
  - Rotate the telescope → full beam maps.



Credit: Chesmore et al. 2022

Conclusion

- Beams are important for CMB analysis.

- Beam analysis is (~) cool…

* *Please let me know if there are any questions.*
** *Thanks for watching the talk.*