Next-Generation Cosmology with Advanced ACTPol

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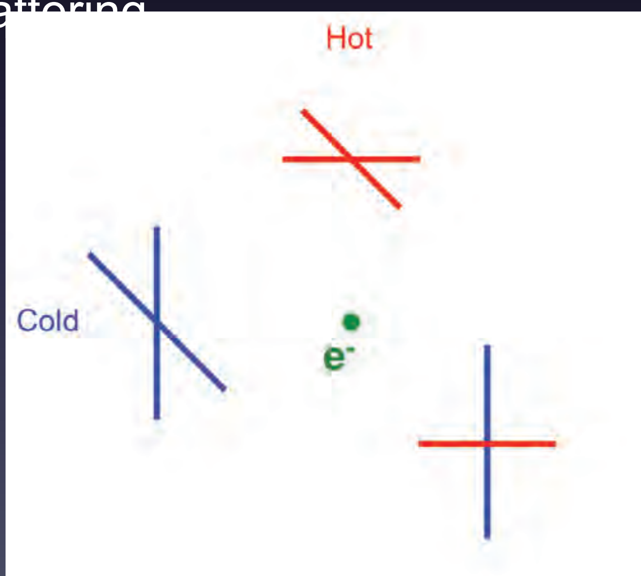
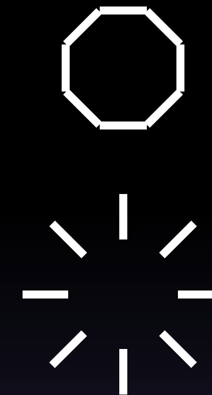
Image by Jon Ward

Polarization in the CMB

CMB linearly polarized at decoupling by Thomson Scattering → Need quadrupolar anisotropy to cause linear polarization



Scalar (Density) Perturbations → E-mode Polarization (Even Parity)



Tensor (G-wave) Perturbations → -mode olarization (Odd Parity)

U. Seljak and M. Zaldarriaga, 1997
M. Kamionkowski, A. Kosowsky, and A. Stebbins, 1997

Inflation and B-modes

Inflation → Produces gravitational waves (tensor perturbations) → Production of E-mode and B-mode polarization

• The E-mode signal is dominated by scalar perturbations, so the primordial B-modes would be compelling evidence for inflation

• The primordial B-mode signal peaks on degree angular scales and its amplitude is expressed in terms of the tensor-to-scalar ratio *r*, which could give the energy scale of inflation

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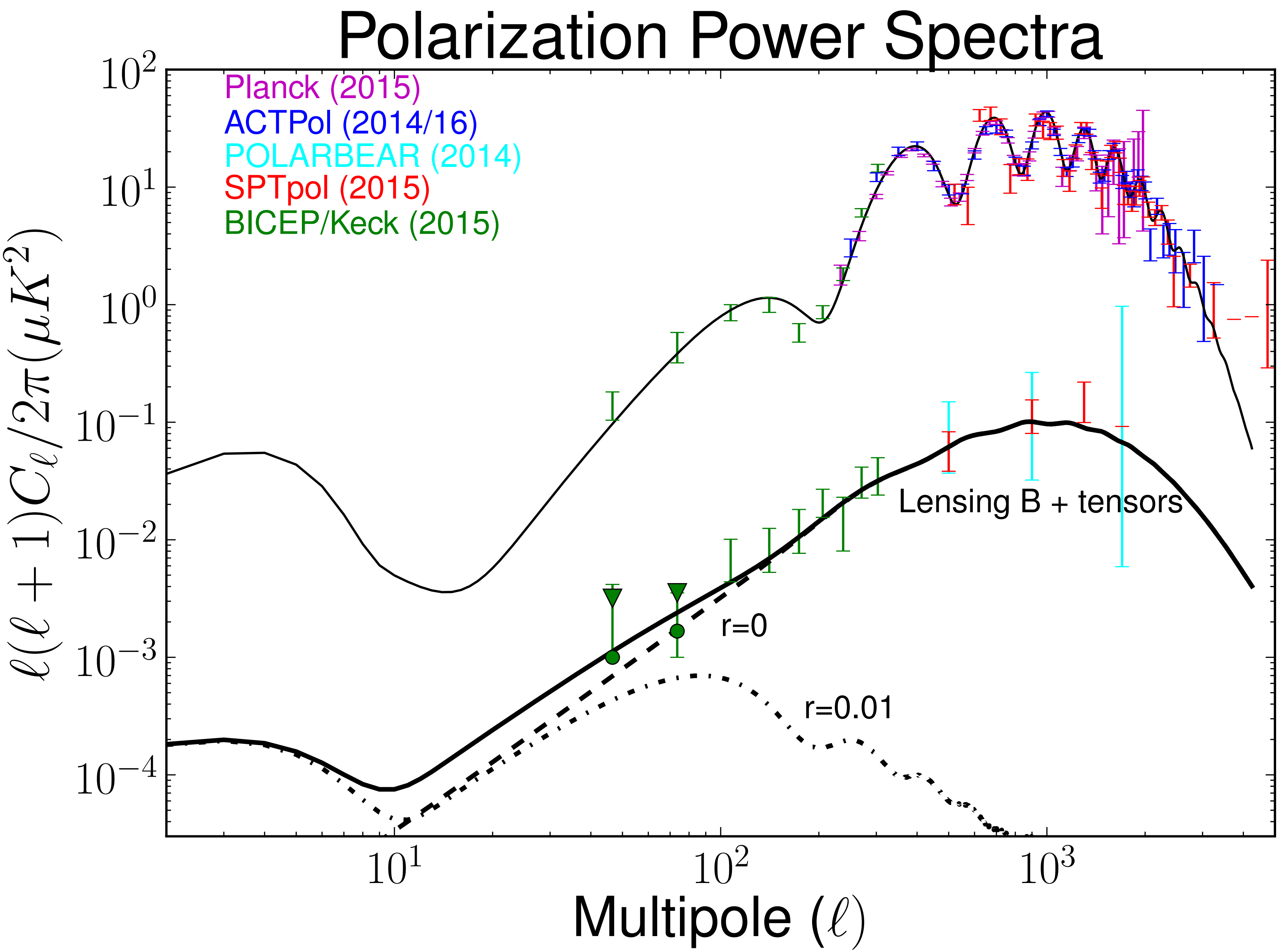


Polarization Power Spectra
Planck (2015)
ACTPol (2014/16)
POLARBEAR (2014)
SPTpol (2015)
BICEP/Keck (2015)
Lensing B + tensors
r=0
r=0.01
$\ell(\ell+1)C_\ell/2\pi(\mu K^2)$
Multipole (ℓ)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{1}
10^{2}
10^{3}

A Few Challenges

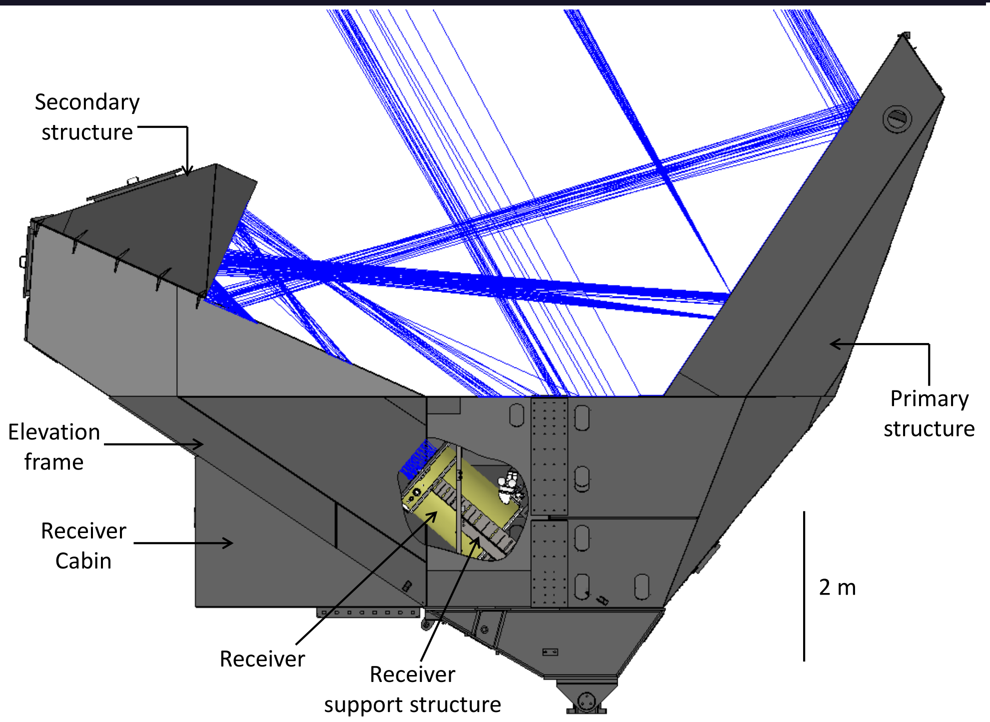
- The amplitude of the B-mode signal is small (r<0.12 at 95% confidence) → Need high sensitivity

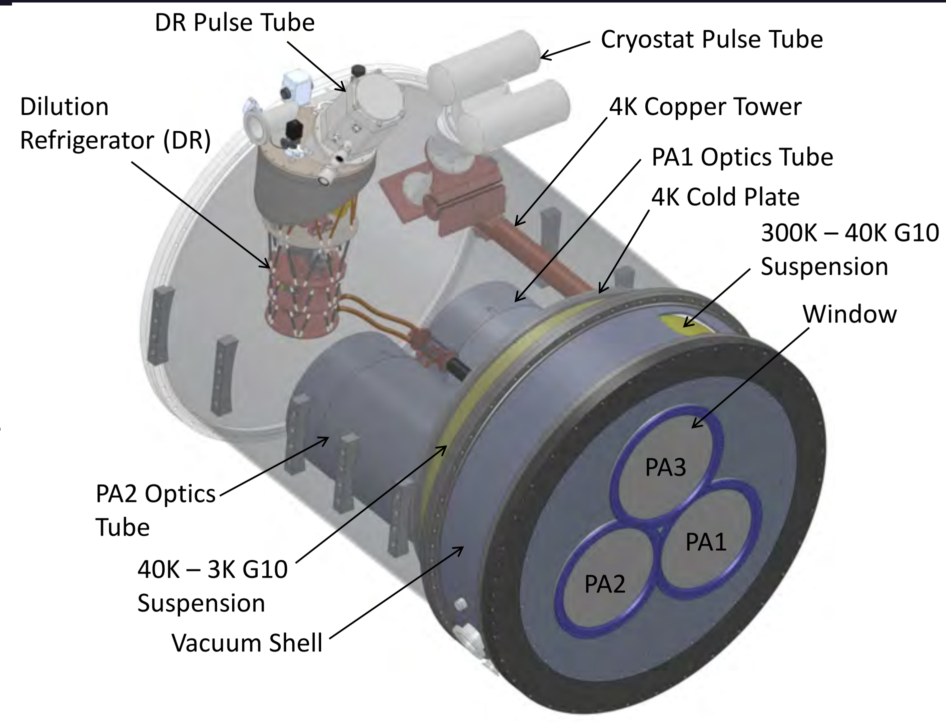
- Polarized foreground contamination from synchrotron and dust emission → Need wide frequency coverage

- Fluctuations in the unpolarized atmosphere, especially on large angular scales → Polarization modulation

The Atacama Cosmology Telescope

- Ground-based, off-axis Gregorian telescope located at elevation of 5200 m in the Atacama Desert in Chile
  - Low moisture, year-round access and observation, access to 20,000 deg^2 of the sky, rotating sky allows for cross-linking

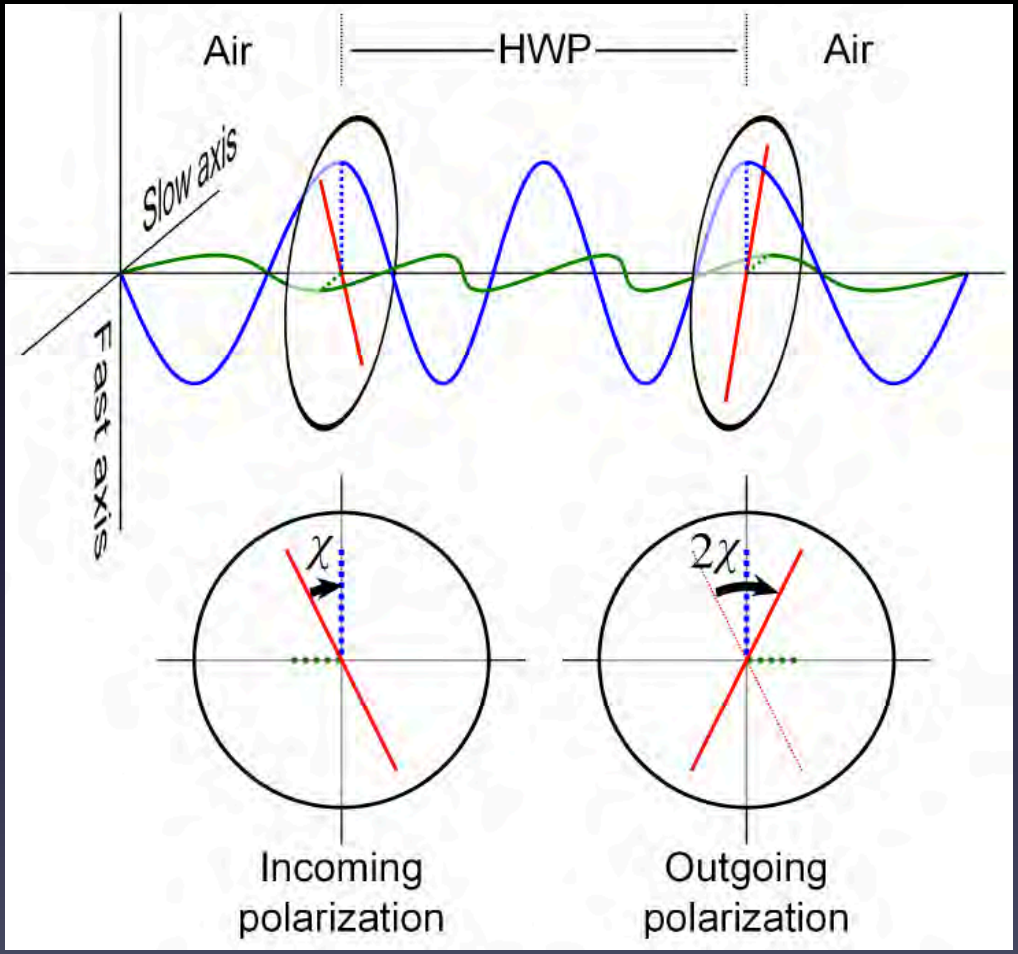




Advanced ACTPol

- Upgraded polarization-sensitive camera for the Atacama Cosmology Telescope (ACT)
- The ACT primary mirror is 6 m, which allows for measurements on small angular scales
- Plan to use half-wave plates (HWPs) for polarization modulation → extend to degree angular scales
- Sequentially fielding four multichroic feedhorn-coupled arrays in three optics tubes operating at 100 mK: one 150/230 GHz, two 90/150 GHz, and one 28/41 GHz → foreground removal and higher detector packing density
- Arrays fabricated on single 150 mm wafer → higher detector packing density

Polarization Modulation with a HWP

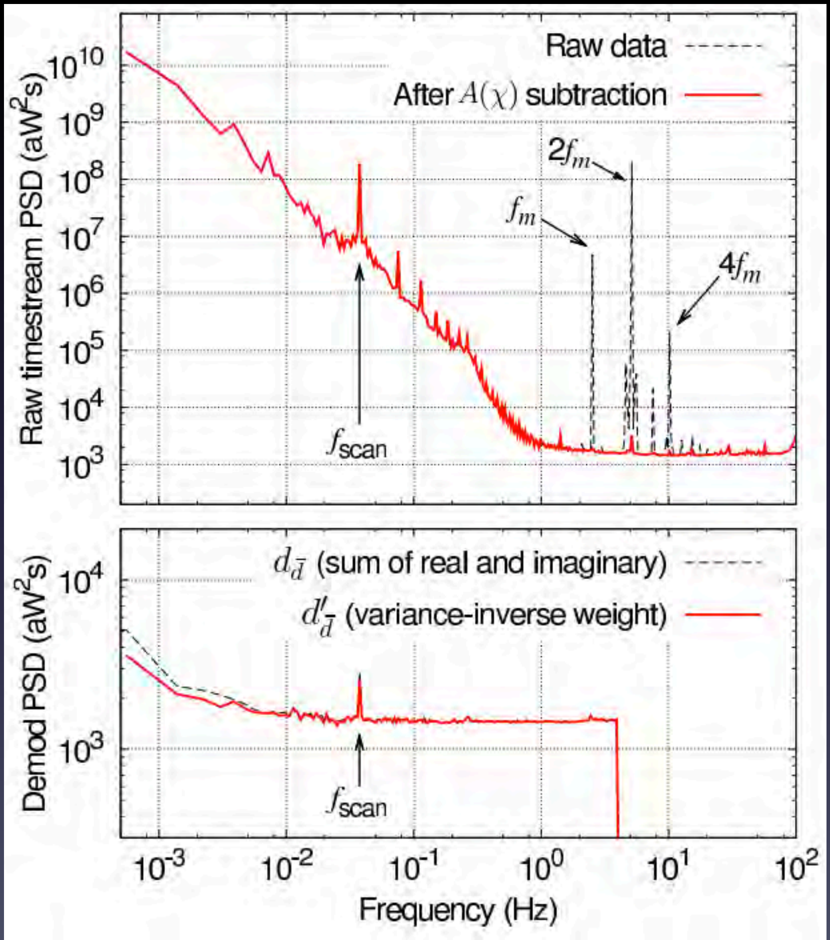


- AdvACT has an ambient-temperature HWP in front of each optics tube
- Ideal HWP rotates linear polarization by 2X (X is angle between incident polarization and fast axis)
- Polarization modulated at 2*f*
- Bolometers only sensitive to power, so pick up signal at 4*f*

A. Kusaka, et al., 2013

HWP Advantages

Separates signal from long time scale atmospheric fluctuations (1/*f* noise)

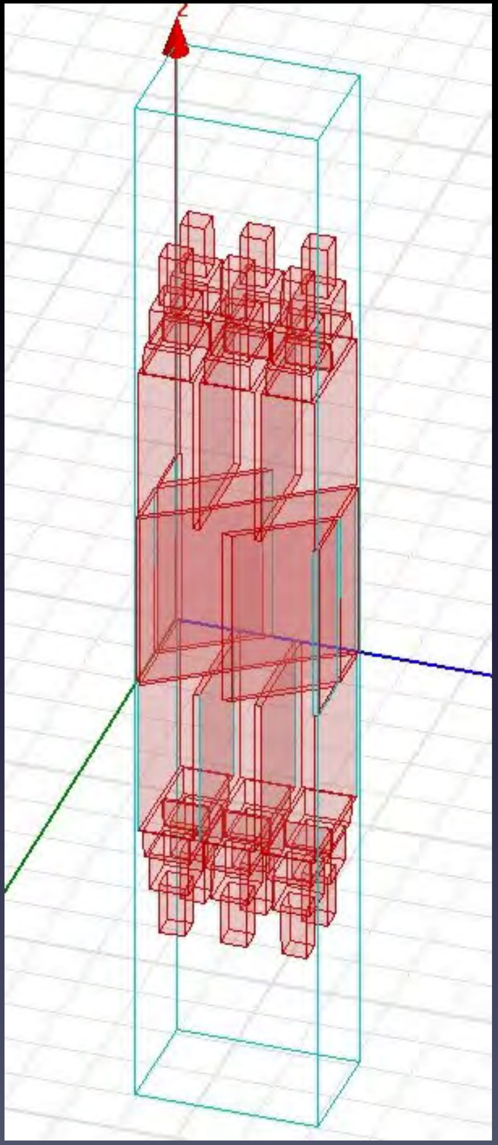


- 1/*f* primarily from fluctuations in unpolarized atmospheric emission, but also temperature drifts, readout electronics, detector responsivity
- Stability on timescales of ~10 minutes→allows for recovery of information large angular scales
- Eliminates need for differencing orthogonal detector pairs for polarization sensitivity
- Mitigates systematic effects with rapid rotation
- Can be made broadband to accommodate multichroic detectors

A. Kusaka, et al., 2013

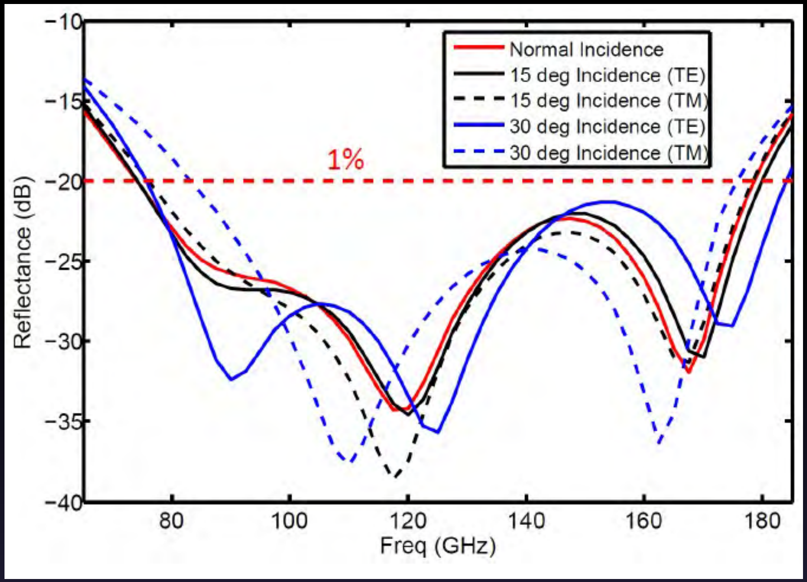
AdvACT HWPs

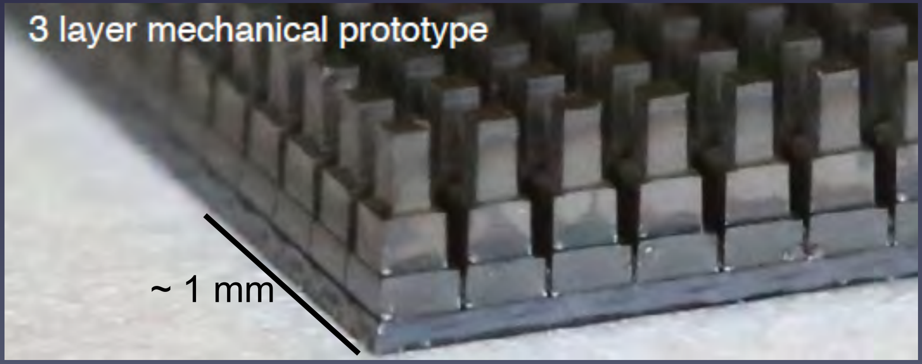
- Stack up several metamaterial Si wafers that together behave as a broadband birefringent material
- Rotated on air bearings for stability in frequency



Lenses

- Use dicing saw to machine metamaterial anti-reflective (AR) coating into silicon lenses
  - Lower loss than plastic AR coatings (loss in each optics tube at 150 GHz ~1% vs. 15% with Cirlex coating)
  - Allows for multichroic optics





Ideal Feedhorn Properties

- To maintain the sensitivity we gain from tightly-packed AdvACT arrays, we need feedhorns with small apertures while maintaining high efficiency
- Maximal symmetry between E-plane and H-plane beams
    - Asymmetry leads to temperature to polarization and E-mode to B-mode leakage
- These features are more easily achieved with a large aperture, so, for the small sizes required for Advanced ACTPol, a compromise between these two is required

Corrugated Feedhorns

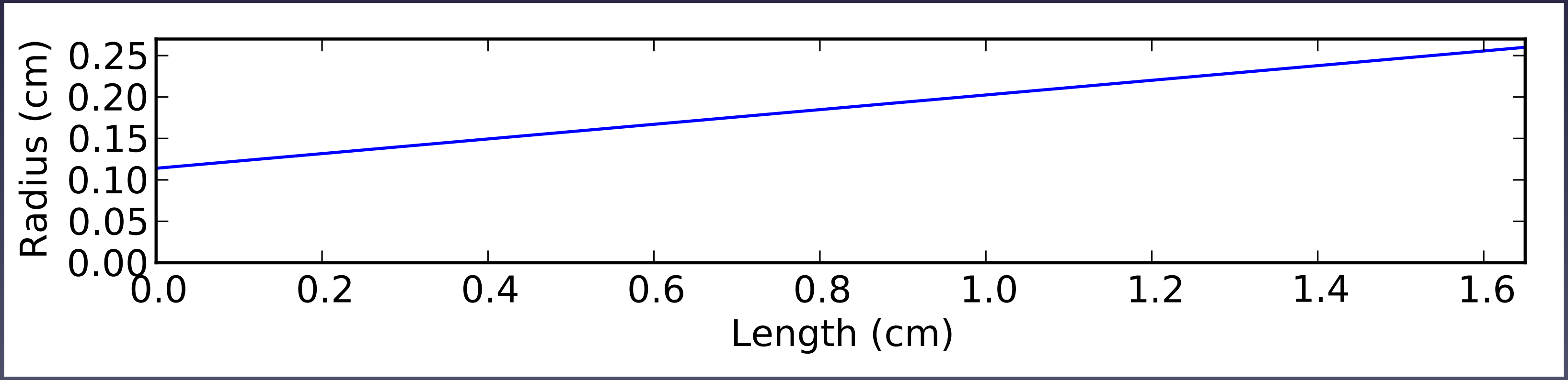
- Corrugated feedhorns approach near ideal beam symmetry between the E-plane and H-plane beams
- Corrugated multichroic feedhorns have been successfully deployed on 90/150 GHz ACTPol array
- Corrugations represent a significant fraction of area required by each feed, which decreases the achievable coupling efficiency

5.2 mm

Aperture size requirement for AdvACT

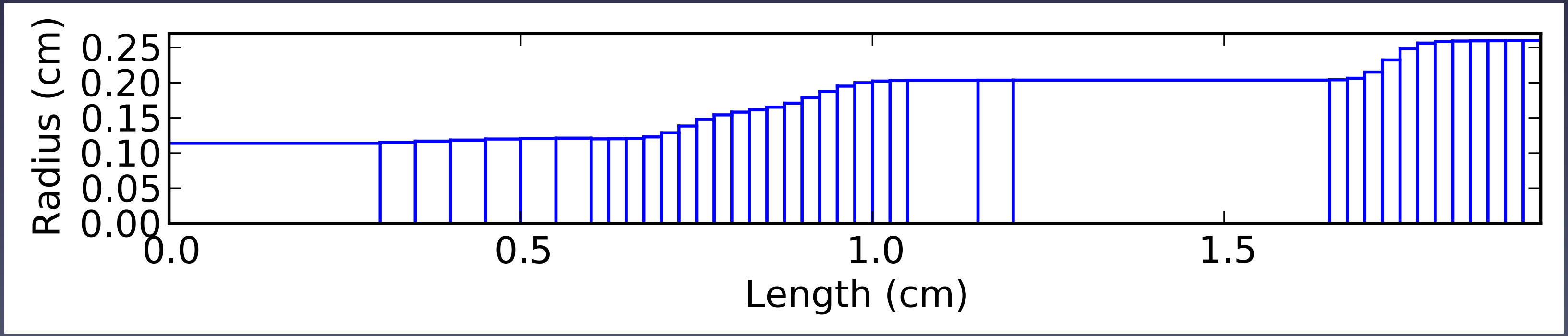
Conical Feedhorns

- High beam coupling efficiency
- But poor symmetry between the E-plane and H-plane beams

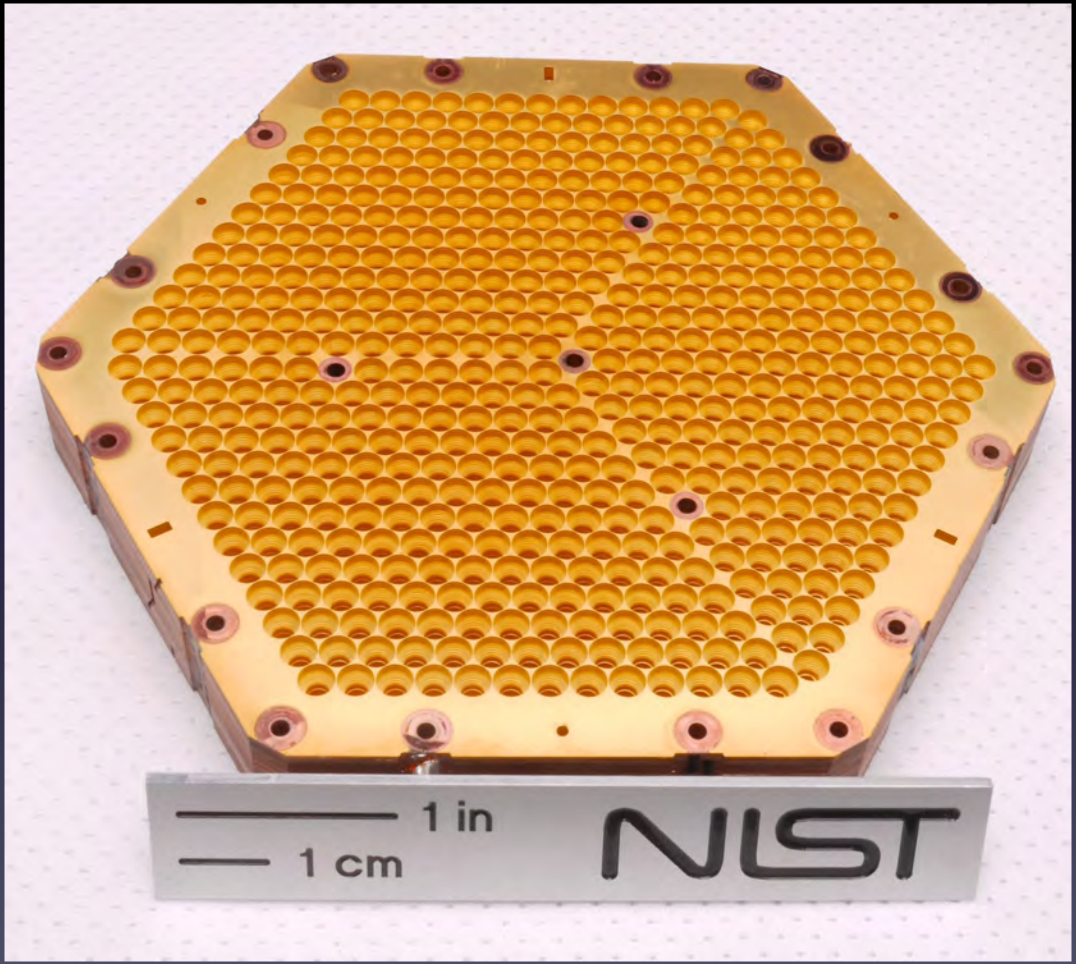


Spline-Profiled Feedhorns

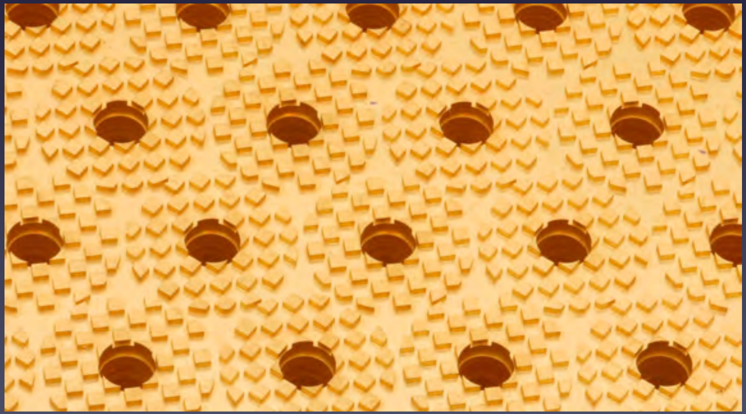
- Compromise between beam symmetry and beam coupling efficiency
- Fabricated in a monolithic feedhorn array by NIST in Boulder out of stacked silicon wafers that are electroplated in copper then gold
- The 90/150 GHz spline-profiled feedhorn array will increase AdvACT's mapping speed by a factor of ~1.8 compared to corrugated ACTPol design
- Use parallel Markov chain Monte Carlo (MCMC) optimizations to minimize the difference between E-plane and H-plane beams within the Lyot stop→design a horn in just a few days



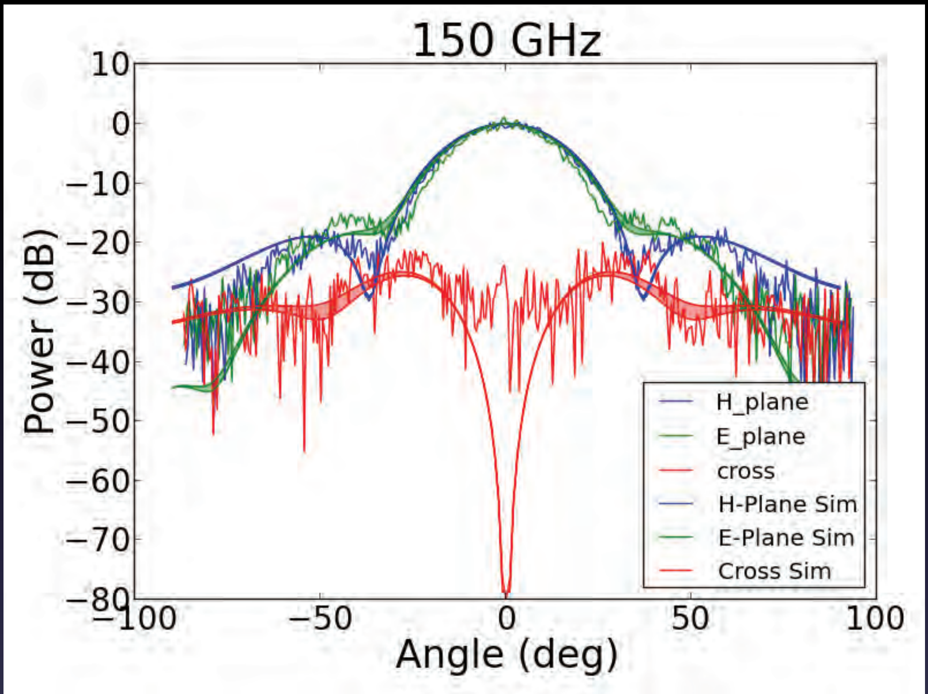
150/230 GHz Feedhorn Array

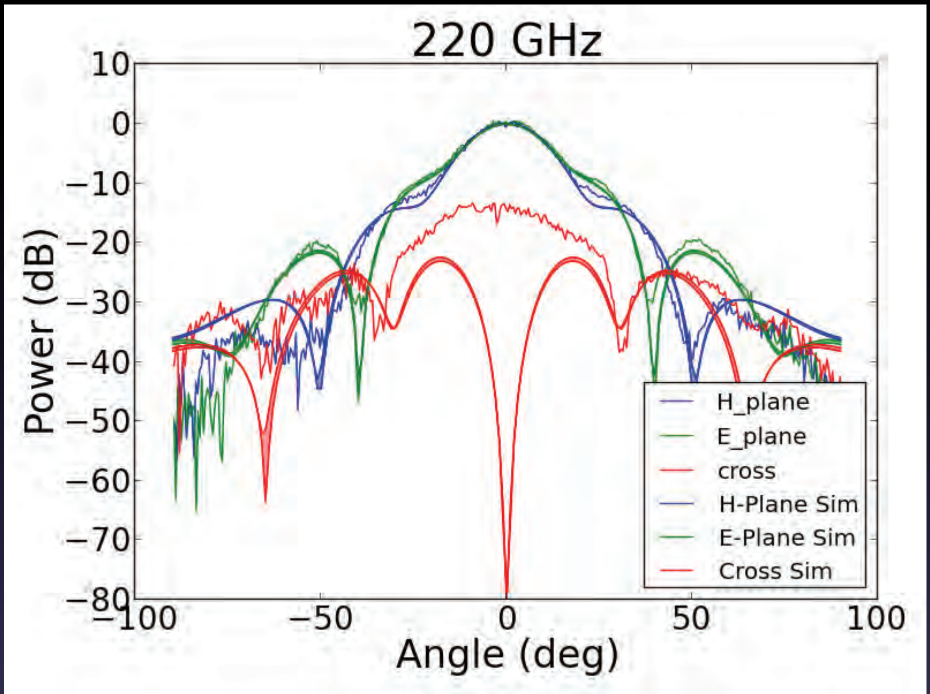


- Photonic choke on detector side to minimize leakage at mechanical coupling to the detectors
- Beam measurements with an ambient temperature vector network analyzer (VNA) are in good agreement with simulated beams from HFSS



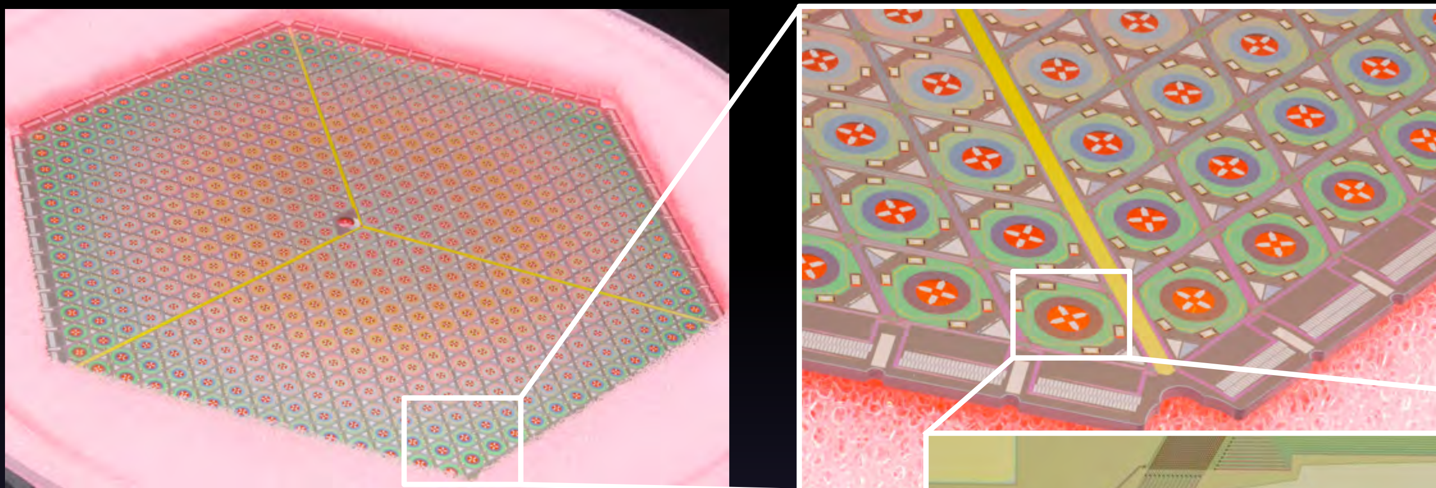
Beam Measurements

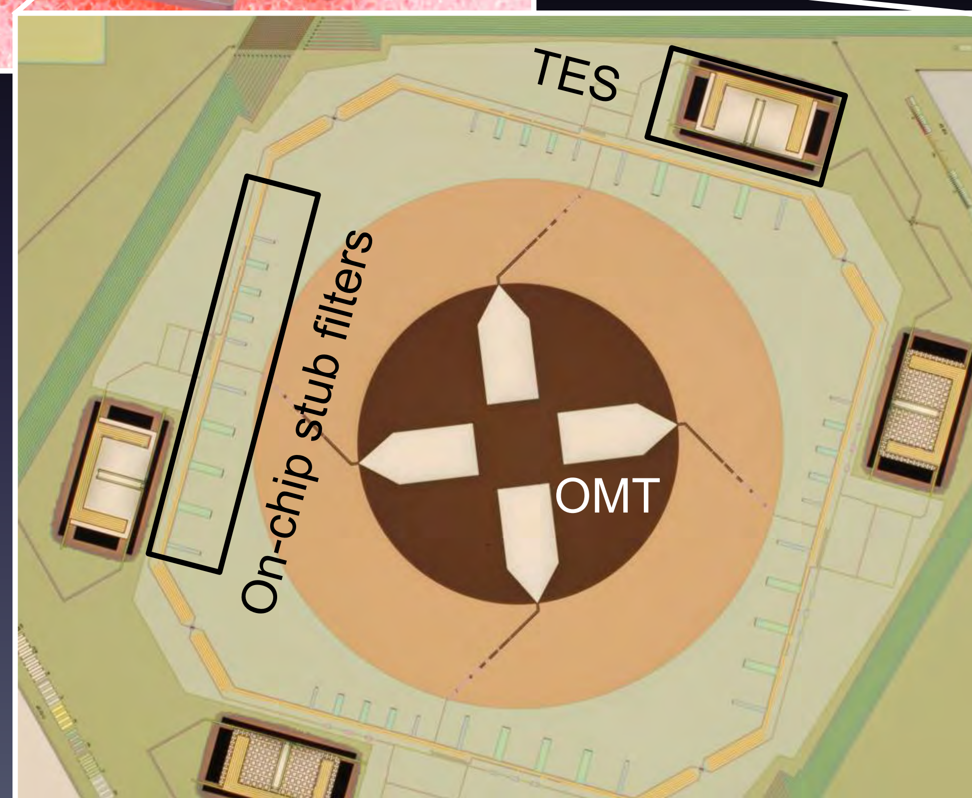




- Beams have been measured every 10 GHz across the observation bands at four positions across the array and are in good agreement with simulations
- Measurements between positions are consistent

Multichroic Detectors





- Fully utilize array area using 150 mm wafers
- Each pixel has two frequencies with two polarizations each (4 detectors/pixel)
- Each detector is a transition-edge sensor (TES) bolometer
- Read out with time-domain multiplexing to reduce number of cryogenic wires

Current Status

- 28/41 GHz array is in development and slated to deploy in early 2018
- Two 90/150 GHz arrays will be deployed in spring 2017
- 150/230 GHz array deployed in August 2016 and currently observing

Thank You

NASA NSF

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NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Polarization Leakage Estimation

- Model co- and cross-polar beams every 10 GHz across the observation bands in HFSS
- Estimate far field polarization signal and leakage beams accounting for Lyot stop and assuming a pair-differenced detector
- Average across each band
- Account for the rest of the ACT optics by scaling the width of the signal beam to the width of a Gaussian beam determined by Code V modeling
- Multiply the signal and leakage window functions by simulations of E-mode and B-mode power spectra to determine the leakage

MCMC Optimization

MCMC wrapper feeds profile into EM simulation program to determine beams

Determine integrated beam symmetry of profile across the observation band with ~20 frequencies (penalty function)

Determine if profile has a lower penalty function than any profiles before

New profile from MCMC code

Determine if random profile to passes criteria (avoids crashes and low efficiency horns)

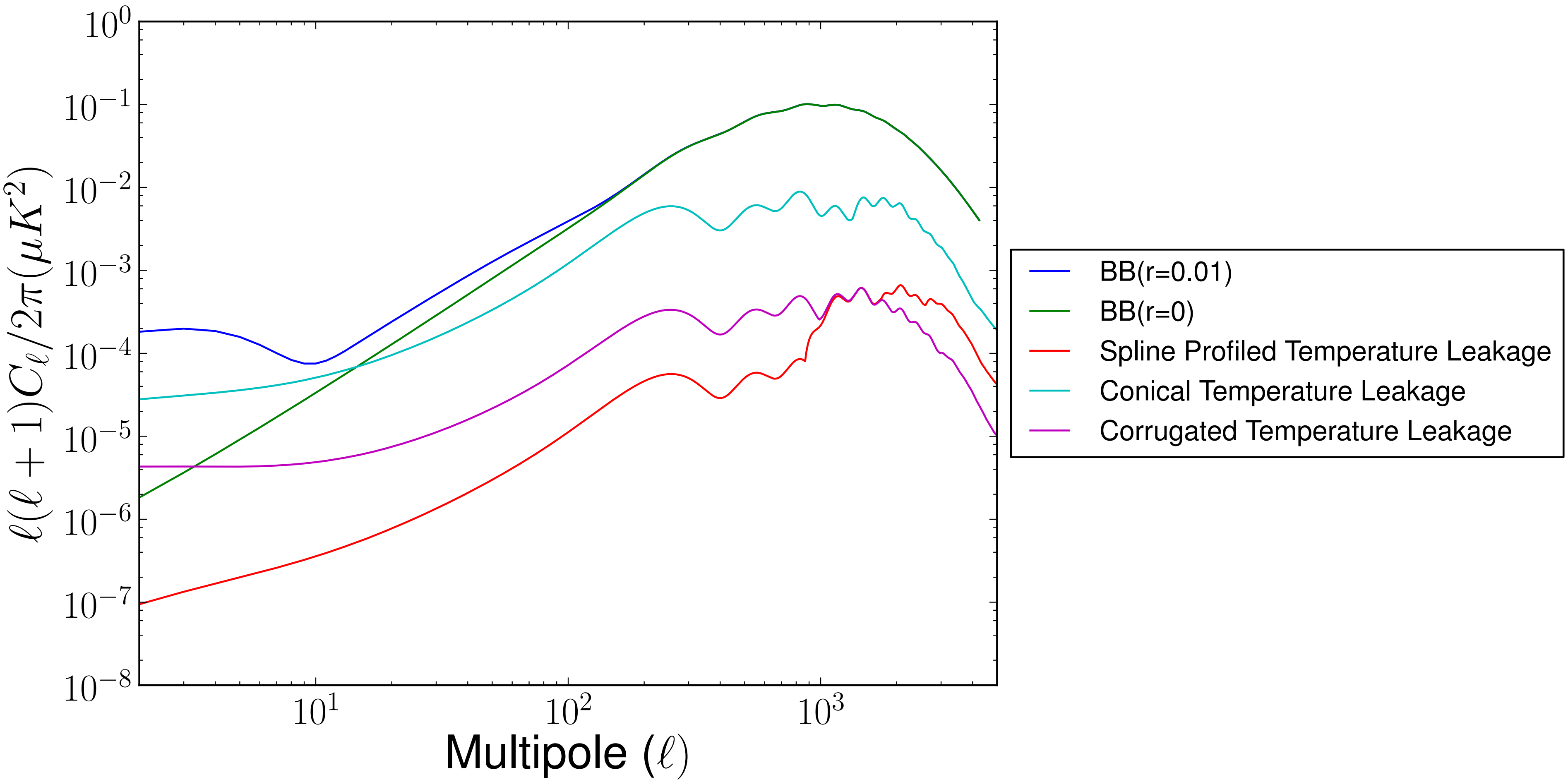
Pass

Fail

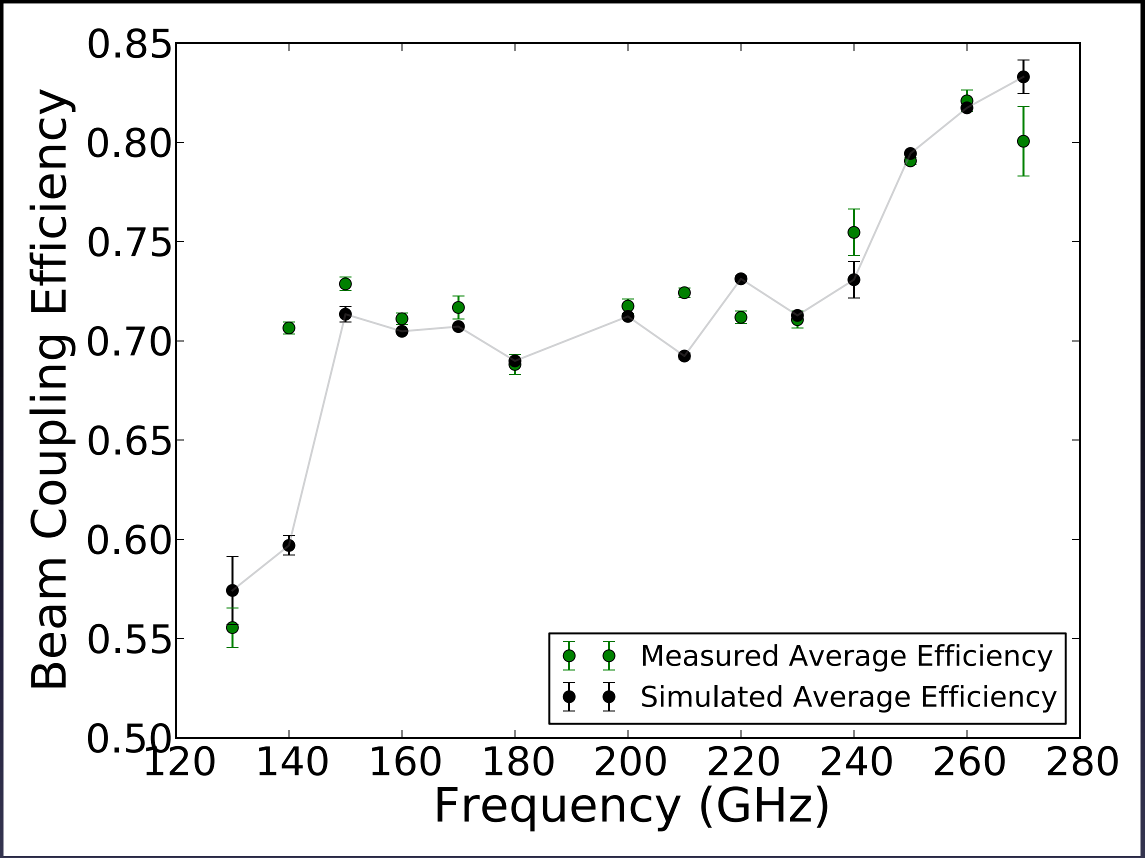
Design Process

- Use parallel Markov chain Monte Carlo (MCMC) optimizations to design a horn in just a few days
    - MCMC minimizes the difference between E-plane and H-plane beams within the Lyot stop
    - Use beam coupling efficiency as a selection criteria after MCMC
- Model the effects of the fabrication tolerances
- Model the feedhorn properties in HFSS
- Estimate the polarization leakages for pair-differenced detector
    - HWP eliminates need for pair-differencing detectors and will thus will significantly mitigate polarization leakage
    - Accounting for beam asymmetries in analysis can further mitigate leakage by an order of magnitude or more

Temperature to Polarization Leakage 230 GHz Band



Beam Coupling Efficiency



- Error bars on simulated values indicate variation between two tolerance models
- Error bars on measured values indicate variation across the array and do not include systematic effects from VNA measurements
- Measured average efficiency in low band is 68% and simulated is 66%
- In high band, both efficiencies are 75%