Summary

Beam modeling and implications for *B*-mode polarization

- **Good:** Sort of know what we're up against
- **Bad:** Requires significantly better understanding of instruments
- **Ugly:** Instrument characterization takes time and resources

Beam modeling is no replacement for actual measurements

Instrument and signal/foreground modeling will likely need to happen concurrently

Optical modelling for Simons Observatory Large Aperture Telescope

- Internal baffling (ray tracing)
- Sidelobe pattern (ray tracing)
- Beam properties (physical optics)
- Panel gap diffraction (physical optics)

These simulations describe our expectations, but we are eager to measure realized performance

Modeling optical systematics for the Simons Observatory Large Aperture Telescope

CMB systematics and calibration focus workshop — Dec 2, 2020

Jon Gudmundsson, Stockholm University and the Oskar Klein Centre

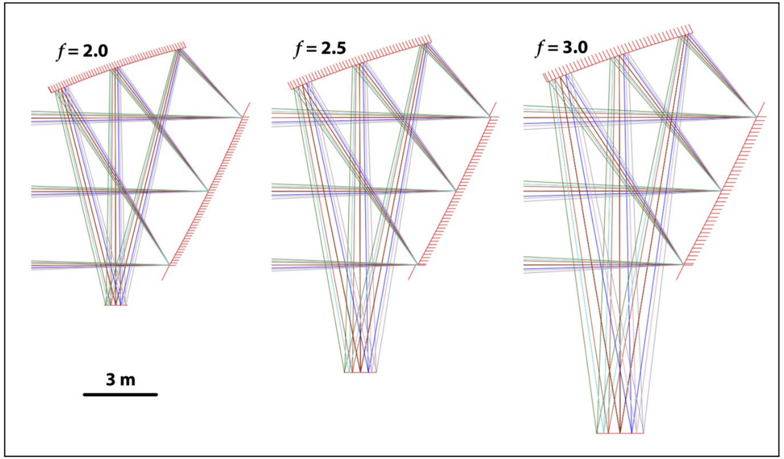
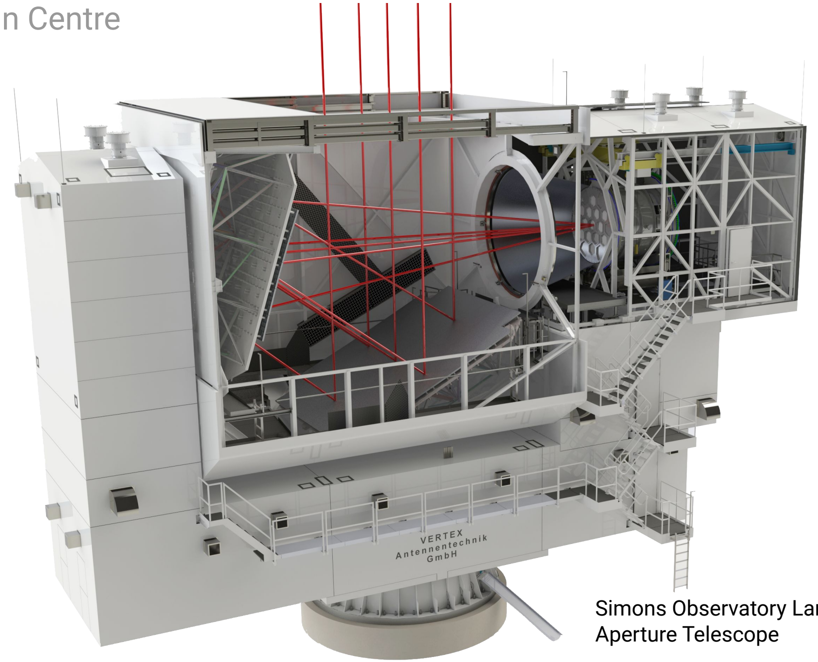


Fig. 1. Three 6 m aperture telescope designs with different f. Plotted rays span the 150 GHz CFOV with Strehl ratios > 0.70.

Niemack, Applied Optics, vol. 55 (2016)



Simons Observatory Large Aperture Telescope

Suggested talk title/topic: *Beam modeling for SO and its implication for the B-mode search*

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10 min

Optical modelling for Simons Observatory Large Aperture Telescope

15 min

From [BeyondPlanck I. Global Bayesian analysis of the Planck Low Frequency Instrument data], Section 1.4:

Indeed, only toward the end of the Planck mission period did it become evident that the ***single most limiting factor for the overall analysis was neither instrumental systematics nor astrophysical foregrounds as such, but rather the interplay between the two****. Intuitively speaking, the problem may be summarized as follows: One cannot robustly characterize the astrophysical sky without knowing the properties of the instrument, and one cannot characterize the instrument without knowing the properties of the astrophysical sky. The calibration and component separation procedures are intimately tied together.*

Framework for analysis of next generation, polarised CMB data sets in the presence of galactic foregrounds and systematic effects — Vergès et al. (2020)

The Simons Observatory: Bandpass and polarization-angle calibration requirements for B-mode searches — Abitbol et al. (2020)

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data — Minami and Komatsu (2020)

A new limit on CMB circular polarization from SPIDER — Nagy et al (2016)

Spin characterisation of systematics in CMB surveys — a comprehensive formalism — McCallum, Thomas, Brown, Tessore (2020)

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BICEP / Keck Array XII: Constraints on axion-like polarization oscillations in the cosmic microwave background — BICEP/Keck Array collaboration (2020)

Instrumental systematics biases in CMB lensing reconstruction: a simulation-based assessment — Mirmelstein, Fabbia, Lewis, and Peloton (2020)

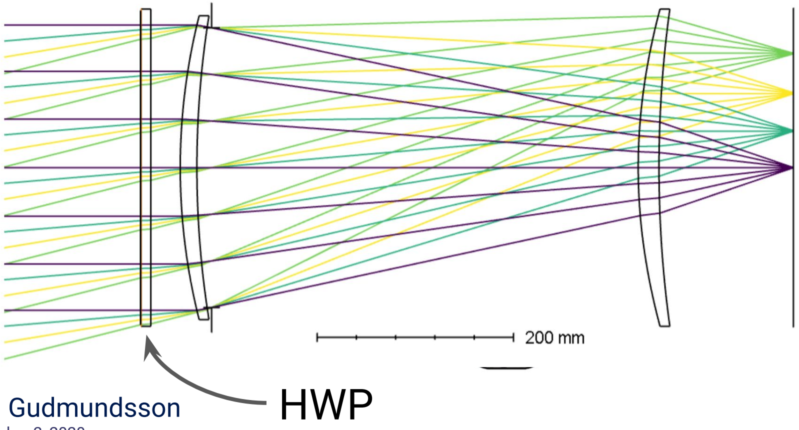
Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth — Planck Collaboration (2016)

Two-year Cosmology Large Angular Scale Surveyor (CLASS) Observations: A Measurement of Circular Polarization at 40 GHz — Padilla et al. (2019)

The Atacama Cosmology Telescope: Constraints on Cosmic Birefringence — Namikawa et al. (2020)

Example: Interplay between HWP and FGs

- Many next-generation CMB experiments using polarization modulators
  - Most common examples are so-called: half-wave plates (HWPs)
  - Improves cross-linking, **signal modulation enables noise modeling**
- HWPs add significant **complexity** to optical system
- Incorporating interactions between HWPs and rest of the optical system not-possible with any existing simulation infrastructure
- Updated version of *beamconv* (https://github.com/AdriJD/beamconv) to be made available in the coming weeks



The HWP induces a polarization dependent phase in incoming light; typically used as the first optical element

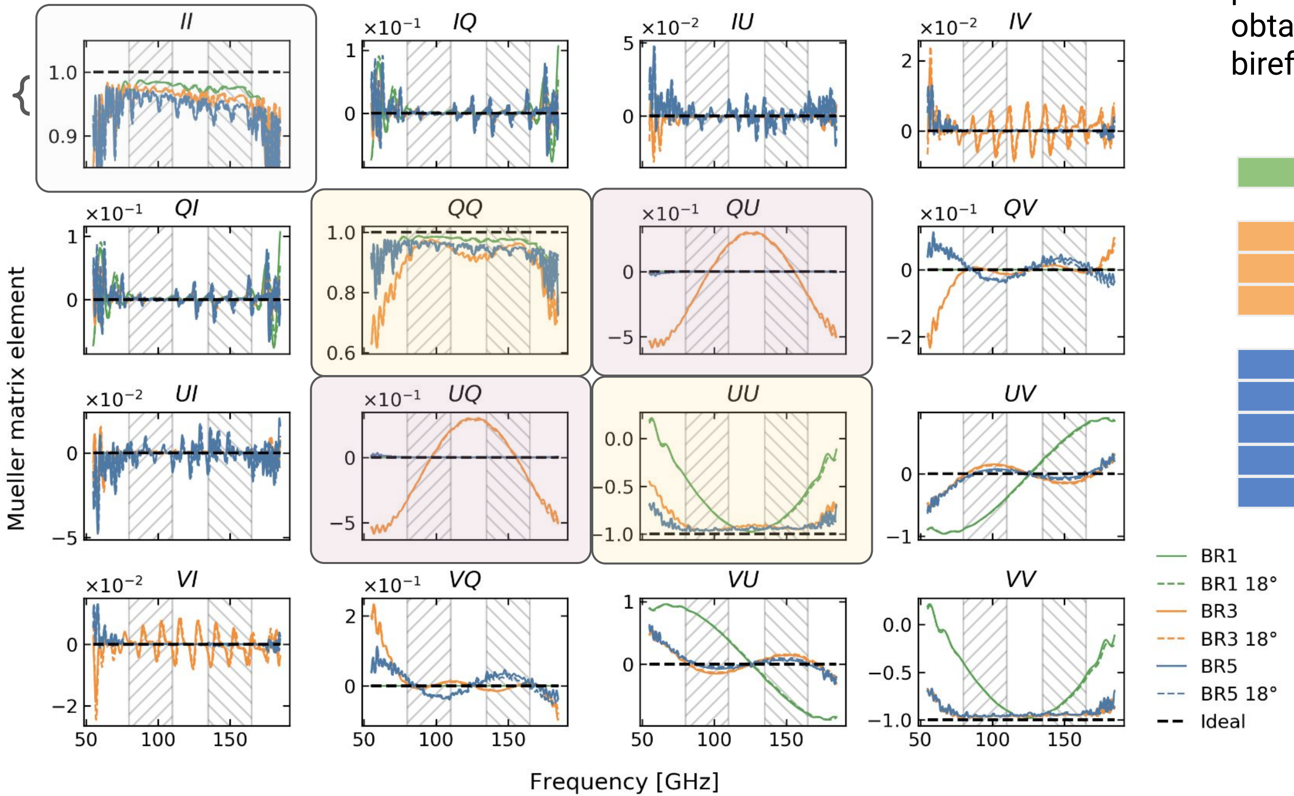
Duivenvoorden SU '19 | A. Adler SU '23 | N. Dachlythra SU '23 | M. Billi U. Bologna '21

HWP Mueller matrices

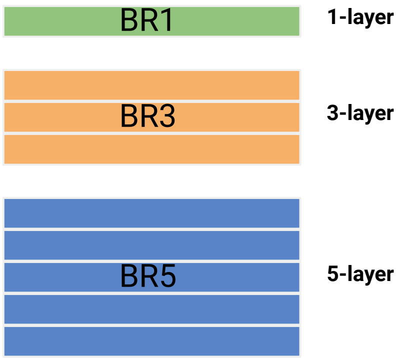
Overall sensitivity

Polarization modulation efficiency (QQ and UU)

Cross-polar leakage (QU/UQ)



Broadband (achromatic) polarization modulators obtained by stacking birefringent plates

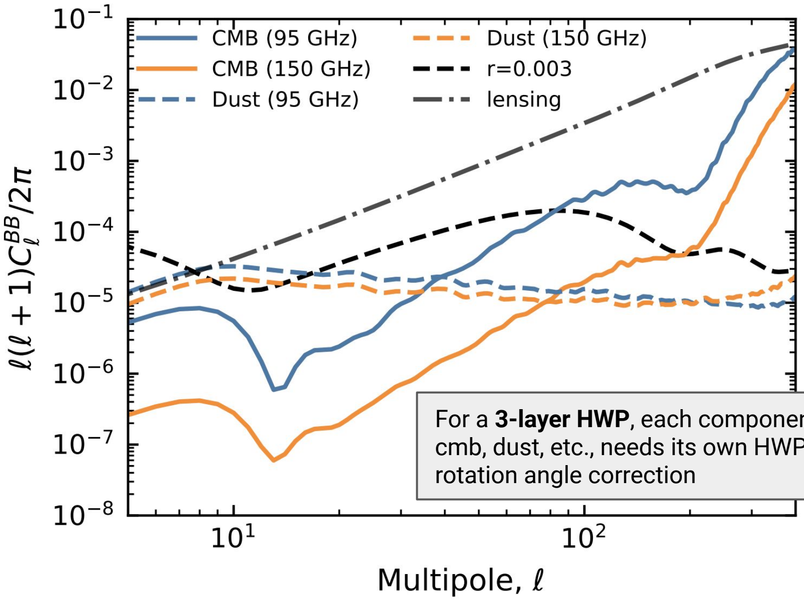


All configurations use the same 3-layer anti-reflection coating

Mueller matrices for arbitrary stacks calculated using T. Hileman's publicly available code: https://github.com/tomessingerhileman/birefringent_transfer_matrix

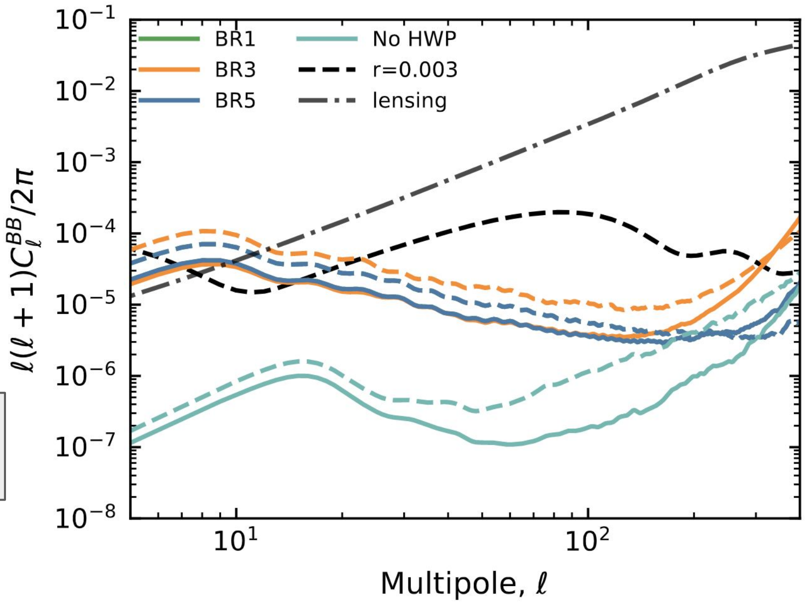
Frequency-dependent phase angle

Incorrect phase angle correction: using phase angle for dust/CMB when observing CMB/dust



For a **3-layer HWP**, each component, cmb, dust, etc., needs its own HWP rotation angle correction

Residual from sidelobe coupling to Galaxy depends on HWP model



Map making will have to account for spectral energy distribution of sources; various foreground models impact *B*-mode residuals differently

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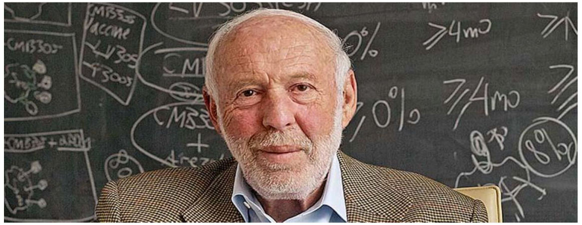
15 min

Simons Observatory (SO)

SIMONS FOUNDATION

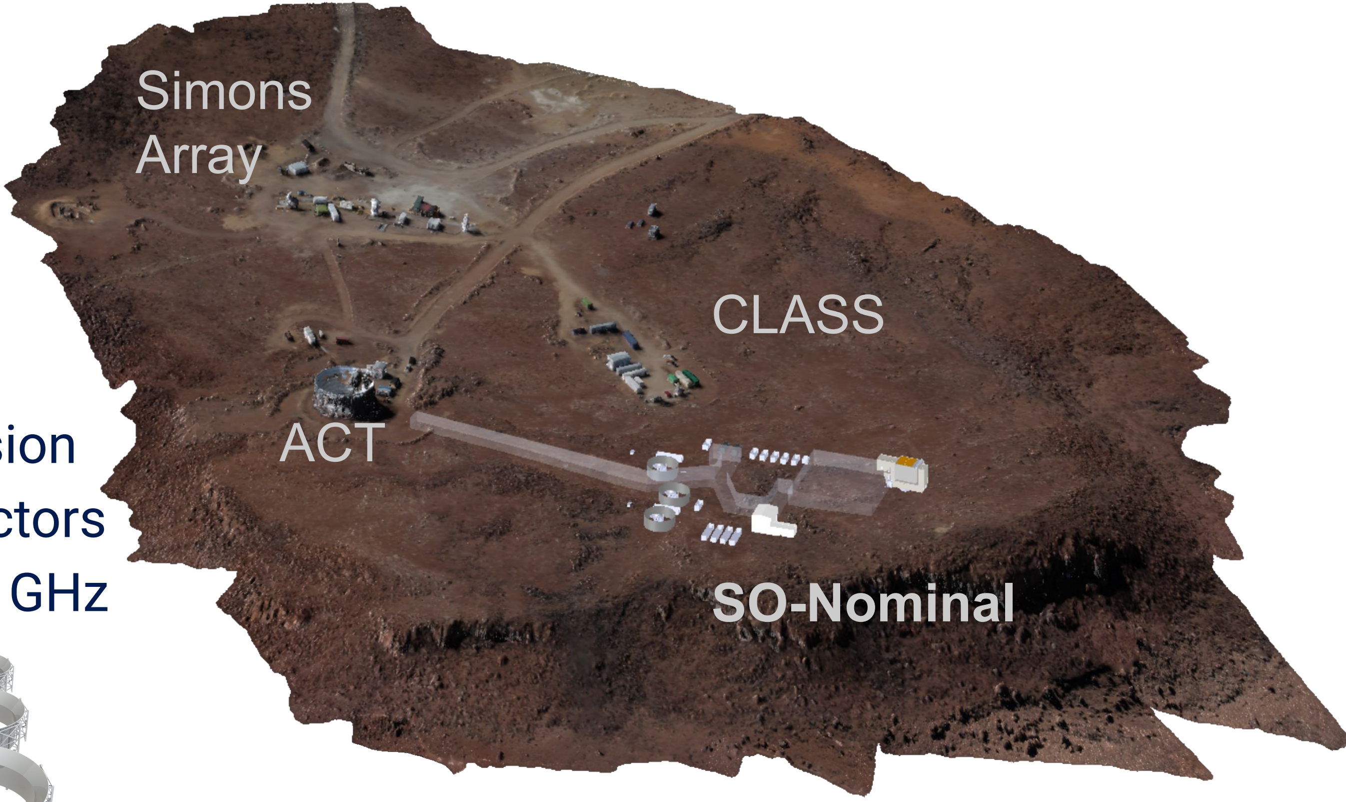
HEISING-SIMONS FOUNDATION

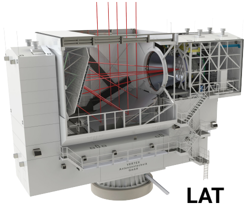


Construction of nominal project is funded privately and has already begun. >200 collaborators

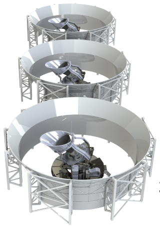
The Simons Observatory — quick recap

- Atacama, Chile
- Altitude: 5200 m
- High and dry
- 23° S latitude
- Established site
- Room for expansion
- Approx 60k detectors spanning 30-270 GHz



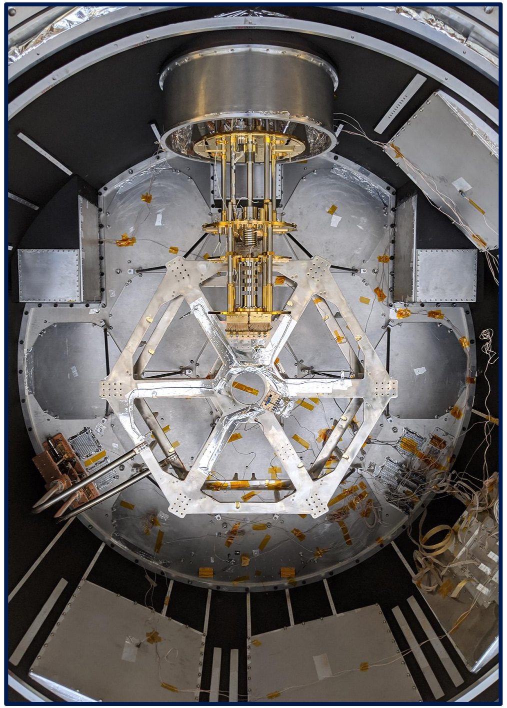


LAT



3x SAT

Recent Progress



Nov ‘19, SO LAT receiver back plate

Dec ‘19, SO LAT receiver close-up

Oct ‘20, SO SAT platform during testing

Oct ‘20, SO LAT under construction

The Large Aperture Telescope

- Crossed-Dragone design
  - Approx 6-m aperture
- Elevation structure with 270° throw
- Co-rotating cryogenic receiver able to support 13 optics tubes
- Baseline:
  - 1xLF (27/39 GHz)
  - 4xMF (90/150 GHz)
  - 2xUHF (220/270 GHz)

The Simons Observatory: Modeling Optical Systematics in the Large Aperture Telescope

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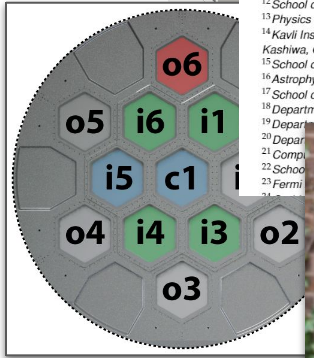


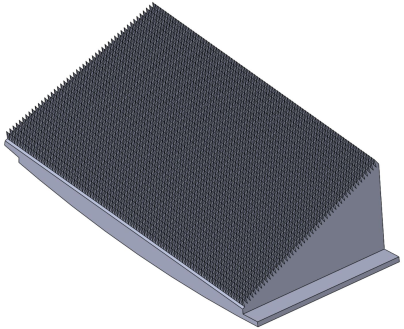

P. Gallardo


R. Puddu

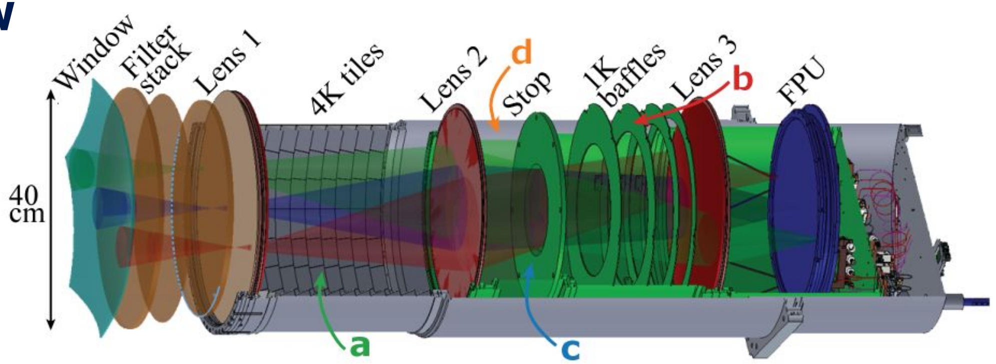

S. Dicker

Internal baffling simulations (ray tracing)

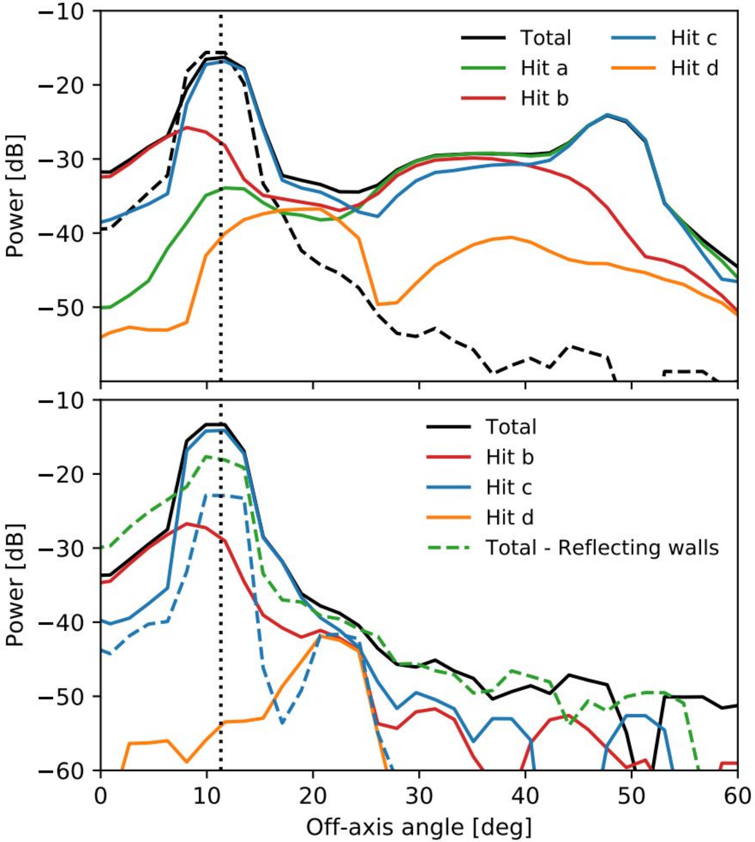
- **Warm spillover a significant concern** for loading
- Other cameras of similar design to the LATR have reported sensitivity to power at angles far larger than the geometric ray tracing would indicate
- **Non-sequential stray light analysis** using Zemax
- Time-reverse sims with a **detector on the sky-side of the vacuum window**
- Generate 10^8 rays and separate based on surface interactions
- Study impact of different coatings (see e.g. tile)



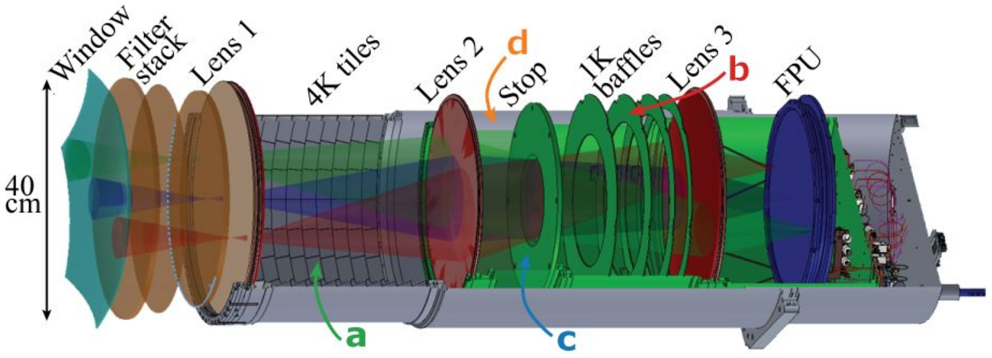
Custom metamaterial AR tiles.
See: Xu, Chesmore et al. (2020)



Internal baffling simulations (ray tracing)

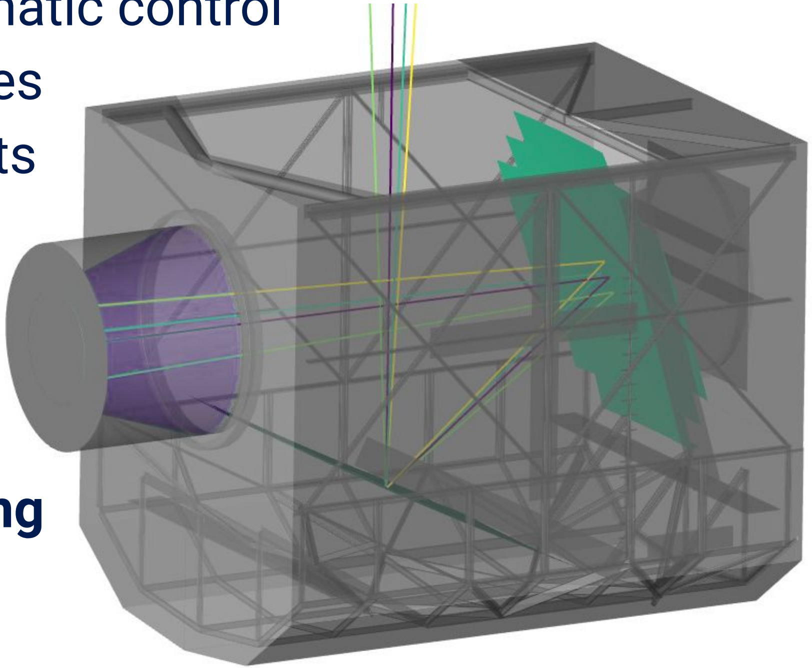


- Top: Carbon black everywhere, large spillover passed secondary (defined by dotted line)
- Bottom: Significant improvements made to tube, spillover reduced



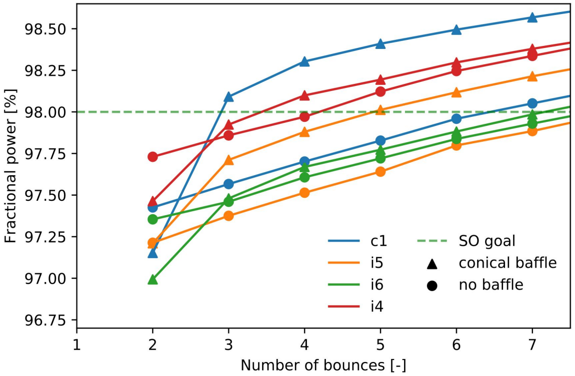
Sidelobes and warm spillover (ray tracing)

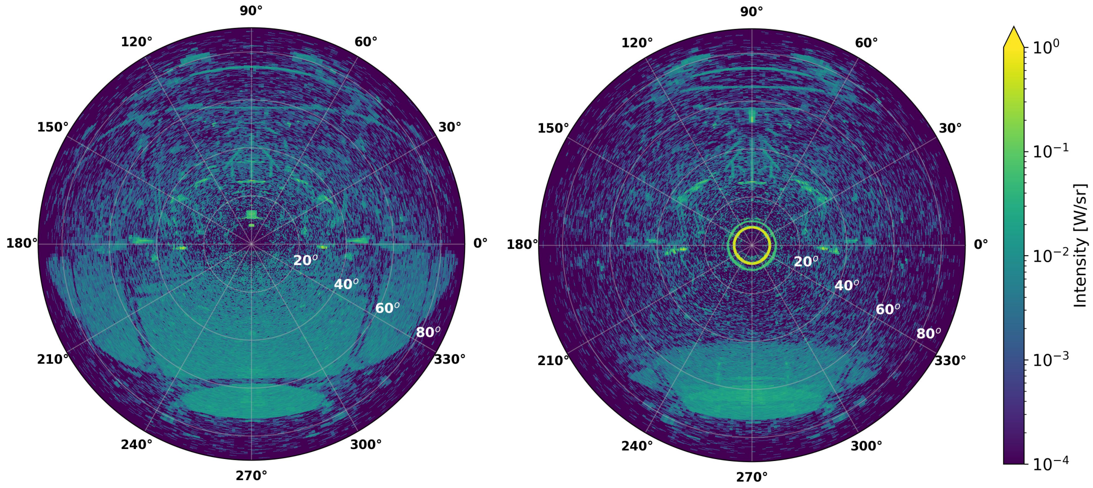
- What if our internal baffling simulations are not adequate?
  - How can we direct rays efficiently to the sky?
- **Prioritize mapping speed** over systematic control
- Predict expected spillover far sidelobes
- Assumptions from ACT measurements
  - See Gallardo et al. (2018)
- Polarization-dependent effects not Included, but work in progress
- A **0.5% reduction in spillover corresponds to 10-15% increase in mapping speed at 150 GHz**



Sidelobes and warm spillover (ray tracing)

- **Reflective baffle** directs power more efficiently to the sky
  - Roughly 0.5% increase in optical power making it out after 3 bounces
- Ray-tracing beam maps, *Left*: No baffle, *Right*: Cone-shaped baffle
  - **Power in large sidelobe reduced by almost factor of 2**
  - Replaced with an **annular feature**



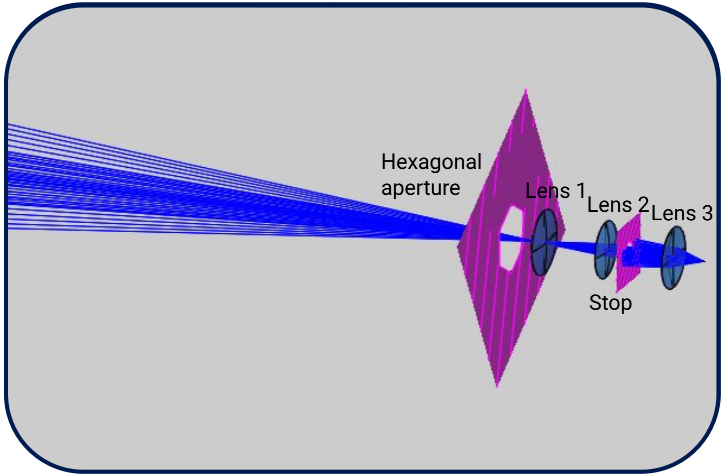


No baffle

Cone baffle

Physical optics (PO) simulations — setup

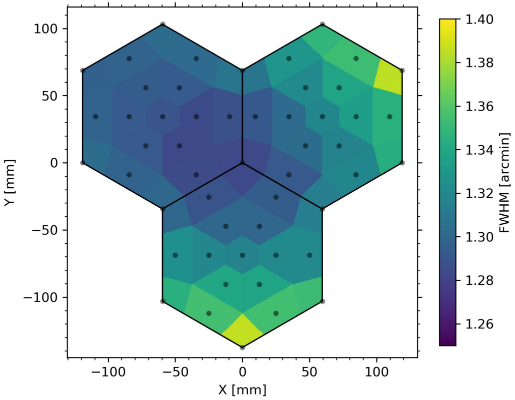
- Electric field **emitted from focal plane** (horn) location and propagated in succession through: 1) lens 3; 2) cold stop; 3) lens 2; 4) lens 1; 5) hexagonal vacuum window; 6) secondary; 7) primary

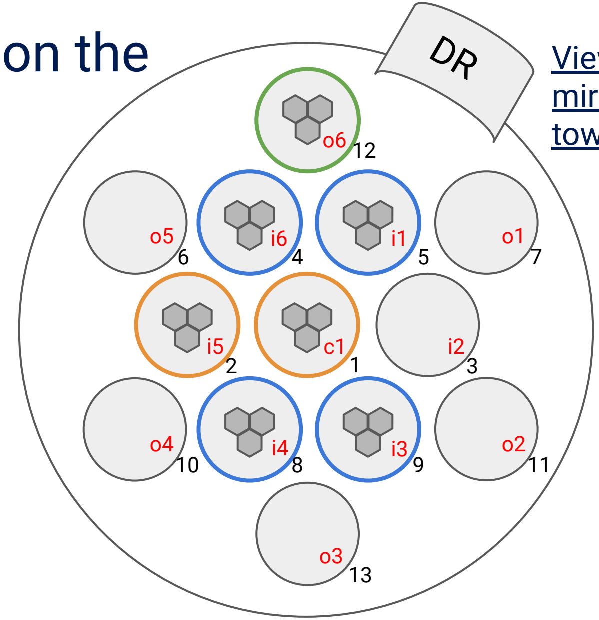


- Filters not included
- No optics tube, internal reflections
- Vacuum window modeled as a hexagonal aperture, not a curved dielectric

Physical optics (PO) simulations — setup

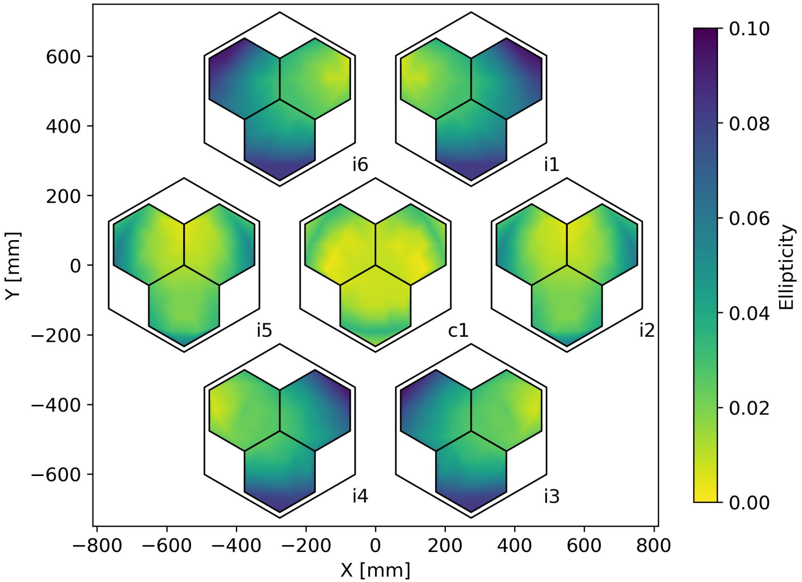
- **Goal**: Provide **quantitative predictions for far-field beam response** that can be used to assess impact on mapping speed and various science efforts
- Electric fields emitted from 52 points on the FPU and propagated through all three lenses
- Run **sims for 90, 150, 220, and 270 GHz**

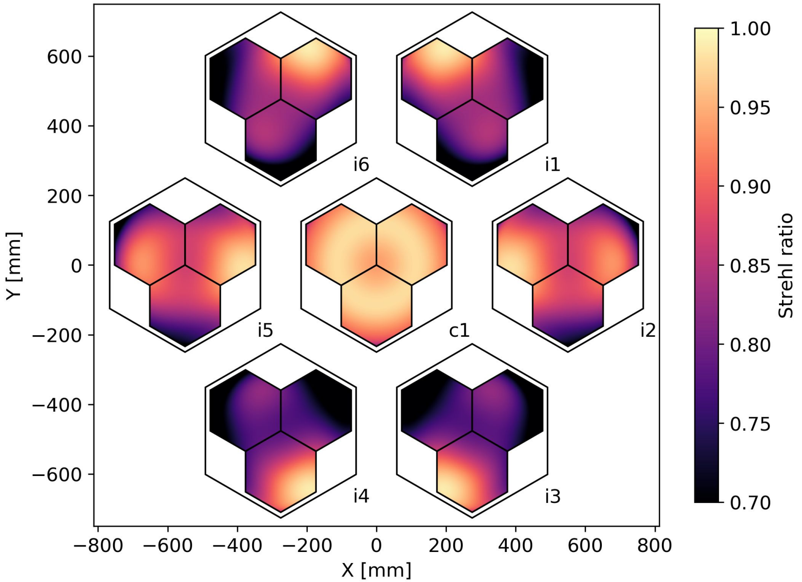




Physical optics sims — Strehl

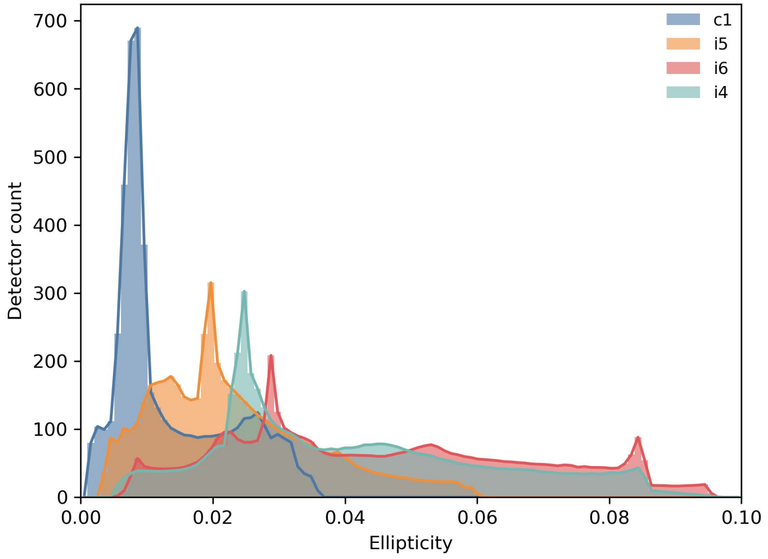
- Beam ellipticity at 150 GHz as predicted by PO sims (left) correlates with Strehl ratio as calculated using ray tracing in Zemax (right)

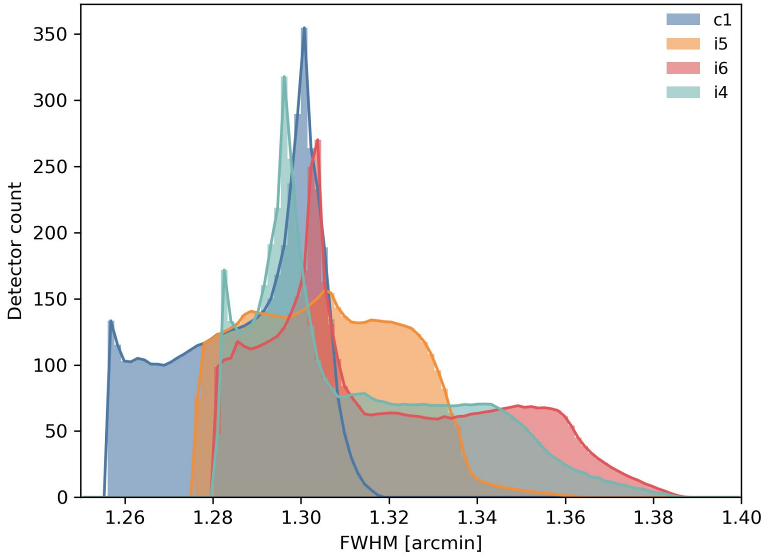




Physical optics sims — performance

- Predict distribution of beam ellipticity and FWHM at 150 GHz





Physical optics sims – panel gaps

- How do the 1.2-mm gaps between the panels in the secondary and primary mirror influence our far field response at 150 GHz?