Calibration and Systematics for the CMB-S4 Inflation Survey Small-Aperture Telescopes

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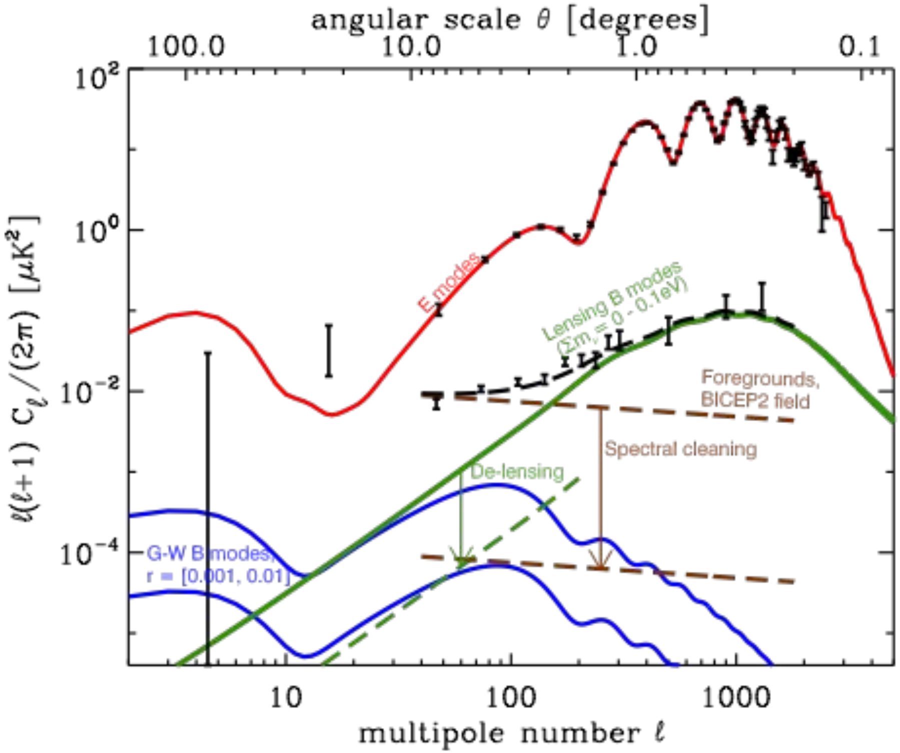
Testing Inflation with the CMB

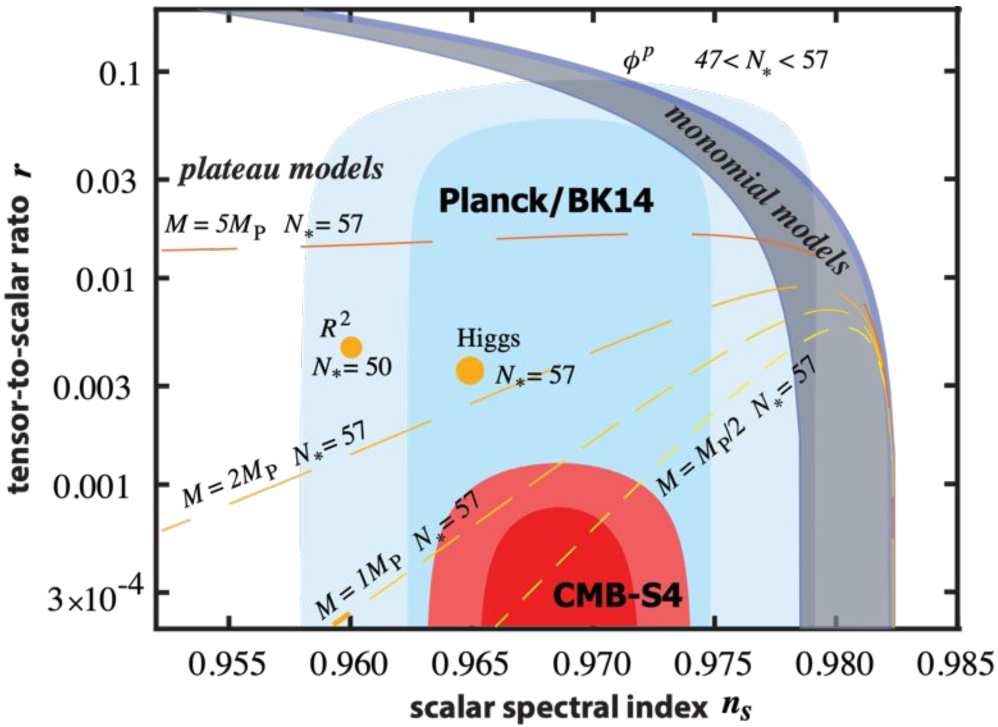
Inflationary gravitational waves produce B-mode polarization in the CMB at degree angular scales. The tensor-to-scalar ratio *r* probes the energy scale of inflation:

$$\text{energy} = 10^{16} \left(\frac{r}{0.01}\right)^{\frac{1}{4}} \text{GeV}$$

Stage 1-3 experiments have made great progress in B-mode measurements (current limit σ(r) = 0.009)... but to reach physically motivated inflationary thresholds we need ~2 orders of magnitude more sensitivity!



Inflation Targets



All inflation models that naturally explain the observed deviation from scale invariance and that also have a characteristic scale equal to or larger than the Planck mass scale predict $r > 10^{-3}$.

A non-detection of *r* at this sensitivity would rule out the leading inflationary models, and motivate alternate models for the origin of the universe.

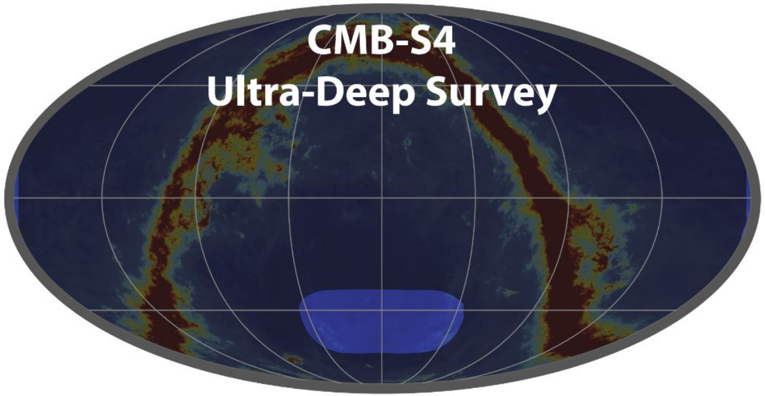
Science Collaboration:

- >350 members
- >110 institutions
- 16 countries
- 2 collaboration meetings/year

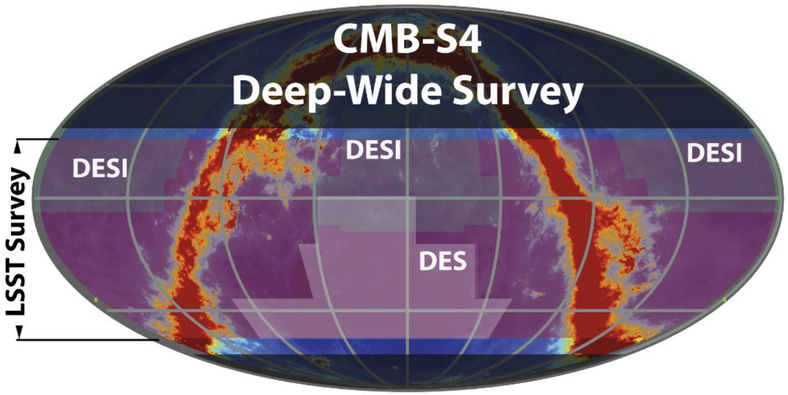
Joint DOE/NSF Project:

- LBNL lead DOE lab
- UChicago lead NSF institution
- 19 institutions so far

CMB-S4 Experimental Strategy



South Pole



Atacama Desert, Chile

Primordial Gravitational Waves and Inflation

<u>CMB-S4 Science Reqt 1.0</u>:

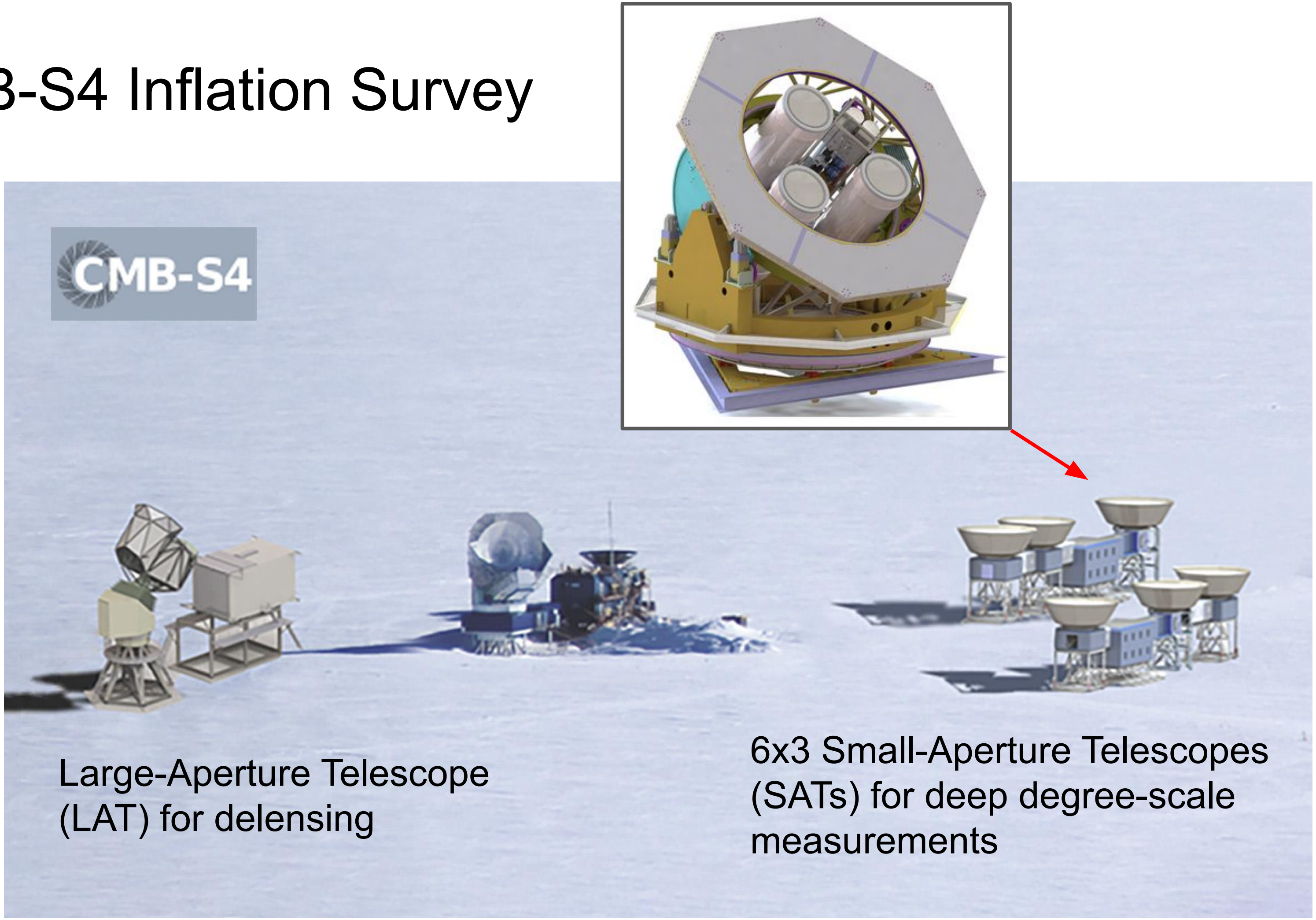
If $r > 0.003$: measure at equivalent 5σ

If $r = 0$: set $r \leq 0.001$ at 95% C.L.

The Dark Universe
Mapping Matter in the Cosmos
The Time-Variable Millimeter-Wave Sky

For more, see Julian's talk on Friday!

CMB-S4 Inflation Survey



Why Small Aperture Telescopes?

Posted B-Mode Sensitivity to r			
Experiment	**arxiv post**	**Bands [GHz]**	**σ(r)**
DASI	0409357	26…36	7.5
BICEP1 2yr	0906.1181	100, 150	0.28
WMAP 7yr	1001.4538	30…60	1.1
QUIET-Q	1012.3191	43	0.97
QUIET-W	1207.5034	95	0.85
BICEP1 3yr	1310.1422	100, 150	0.25
BICEP2	1403.3985	150	0.10
BK13 + Planck	1502.00612	150 + Planck	0.034
BK14 + WP	1510.09217	95, 150 + WP	0.024
ABS	1801.01218	150	0.7
Planck	1807.06209	30...353	~0.2
BK15 + WP	1810.05216	95,150,220+WP	0.020
Polarbear	1910.02608	150 + P	0.3
SPTpol	1910.05748	95 + 150	0.22
Planck/Tristram	2010.01139	30...353	0.07
SPIDER	2103.13334	95 + 150	0.13
BK18 + WP	2110.00483	95,150,220+WP	0.009
Polarbear	2203.02495	150 + P	~0.16

Small-aperture telescopes have historically produced the tightest limits on *r*.

Significant advantages in systematics control:

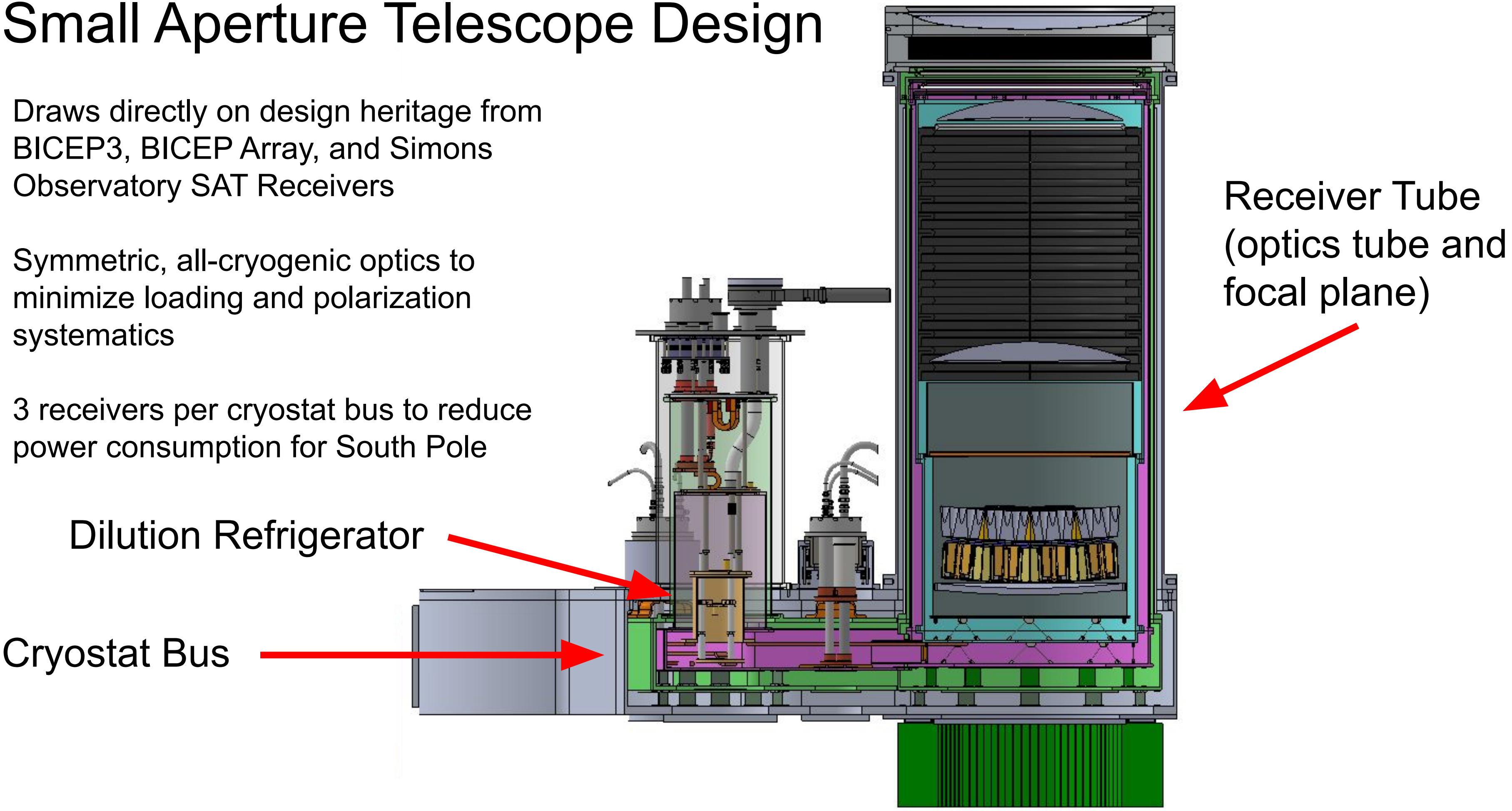
- Ease of shielding
- Aperture-filling calibrators
- Boresight rotation
- Far field is nearby
- Efficient to integrate and deploy

Small Aperture Telescope Design

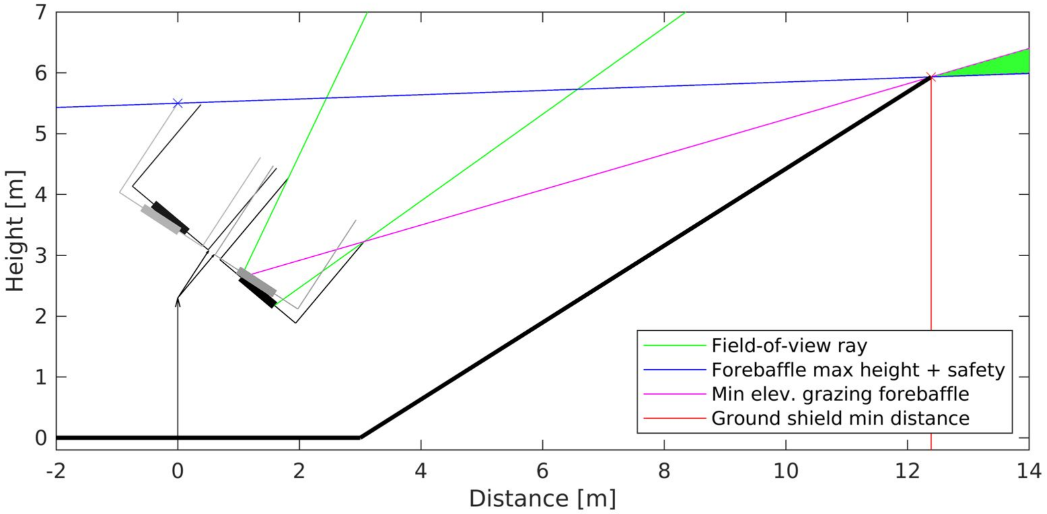
Draws directly on design heritage from BICEP3, BICEP Array, and Simons Observatory SAT Receivers

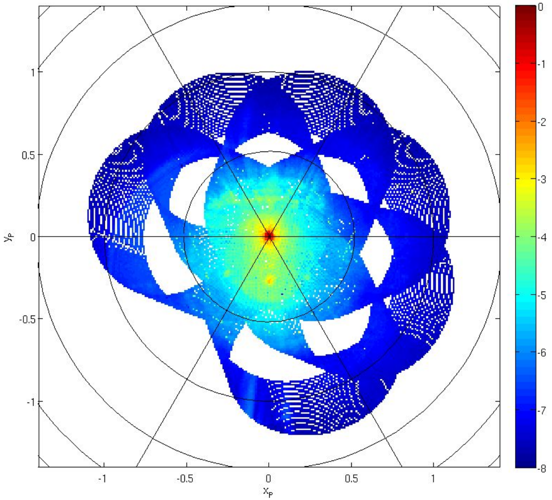
Symmetric, all-cryogenic optics to minimize loading and polarization systematics

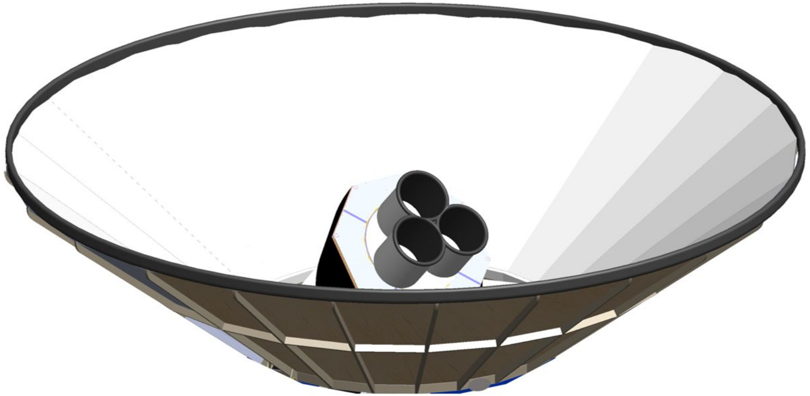
3 receivers per cryostat bus to reduce power consumption for South Pole



Minimizing Systematics in Optical Design



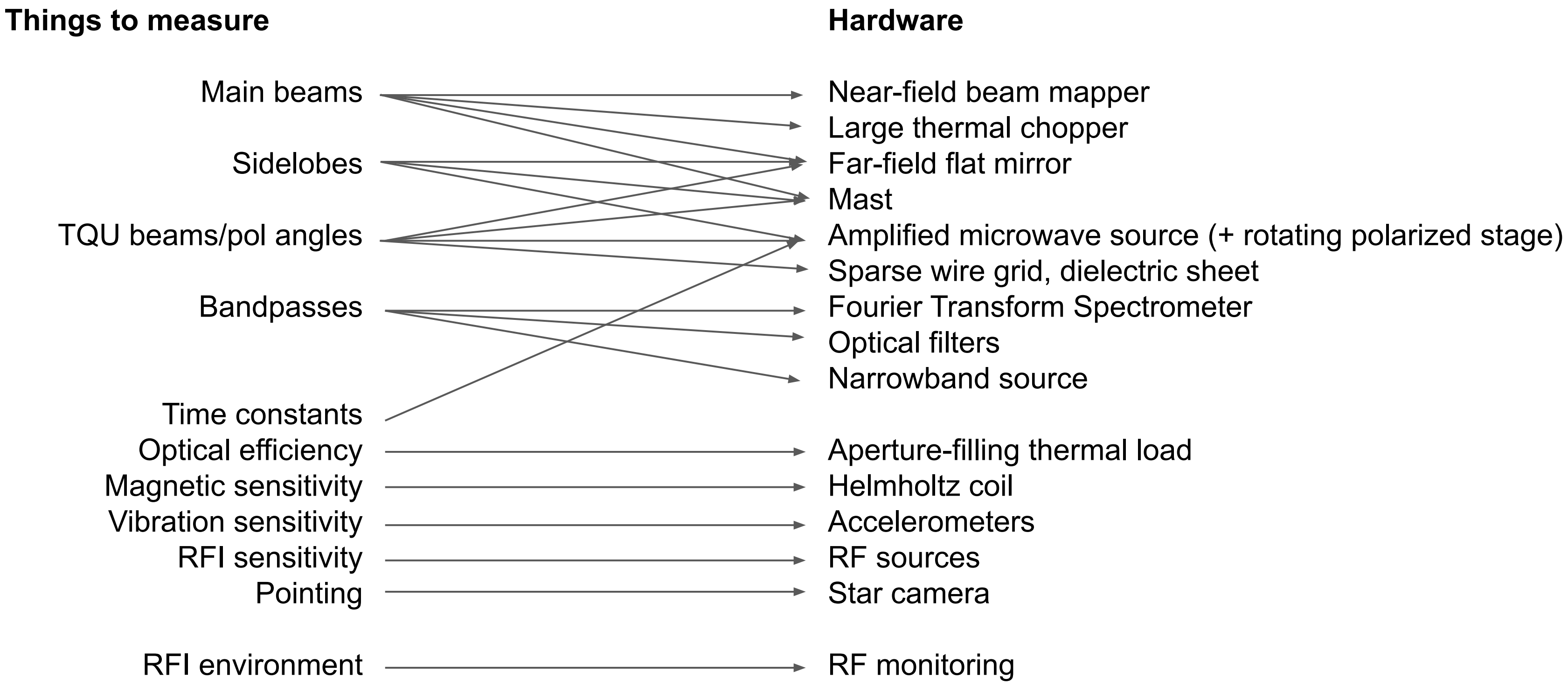




Co-moving forebaffle and fixed ground shield

"Double diffraction" criterion: any ray from the ground must diffract twice (over the forebaffle and ground shield) before entering the window

Aspects of the instrument that could lead to systematics



Calibration Hardware Use Cases

- Testing during cryostat/optics prototyping
  - E.g., optics stack scattering
- Validation of SAT performance during commissioning
  - System-level verification
- Measuring basic instrument parameters to well-defined precision
  - Everything needed to make a CMB map
  - Bandpasses, beam shapes, polarization angles…
- Probing instrumental systematics
  - Everything needed for a robust *r* constraint
  - Deep main beams, sidelobes…

Each use case sets a different requirement on the hardware, e.g., to match or exceed BK performance, the far-field chopper must have an aperture of 24” and spin at 16 Hz.

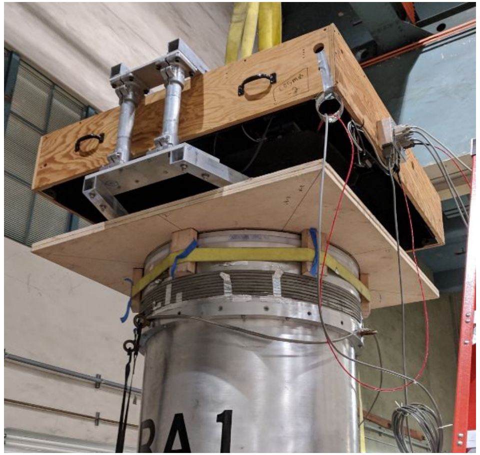
Prototyping and North American/South Pole Integration

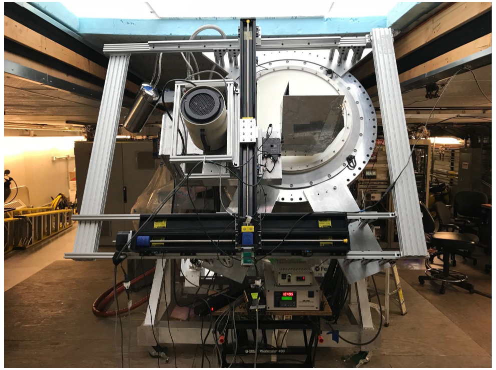
Design work for lab-based equipment beginning now!

- Aperture-filling load
- Near-field beam mapper
- Fourier Transform Spectrometer
- Near-field polarization calibrator

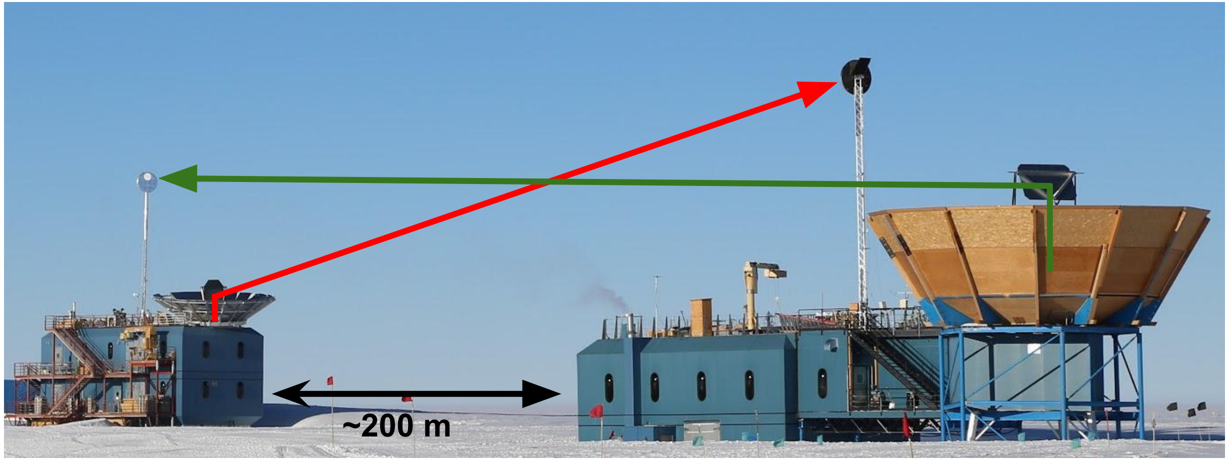
Generally can be straightforwardly adapted from existing BK/SO equipment

Working with lab building/ground shield design team to ensure equipment can be used both in lab and on the mount

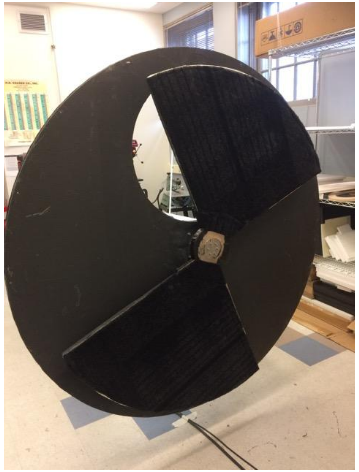




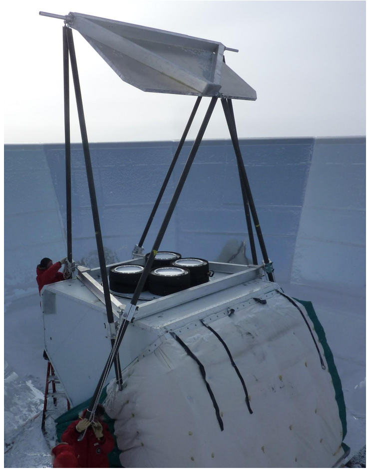
Field-based equipment

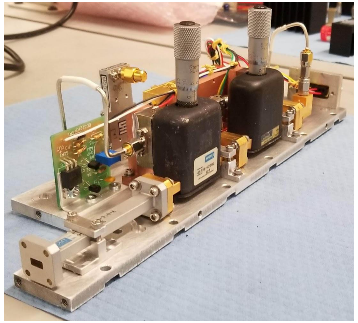


Thermal chopper
24” aperture



Flat redirecting mirror





Amplified microwave source

We have started R&D studies to determine the scale of calibration campaign required to control T→P leakage, sidelobe pickup, etc. to well below CMB-S4 sensitivity

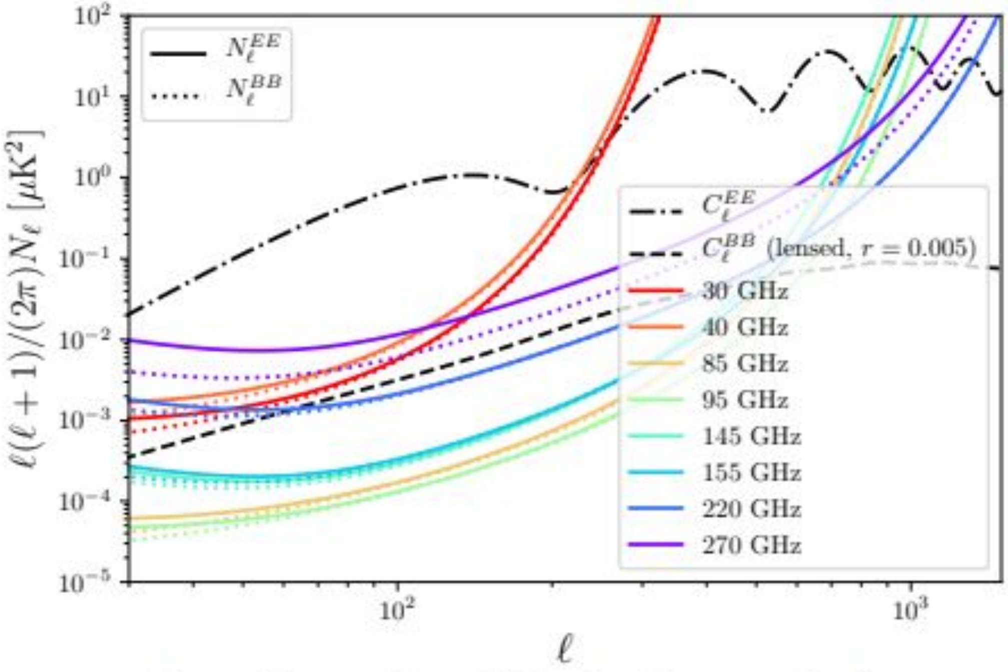
Relies heavily on heritage data from existing experiments (See Clara’s talk yesterday!)

Refining Beam/Calibration Requirements

Science Requirement: Place an upper limit of r < 0.001 at 95% CI

Measurement Requirement: Measure Q/U over 3% of the sky at the following frequencies and noise levels

Integrated SAT System-Level Requirement: Aggregated systematic errors shall be no worse than that achieved by BK



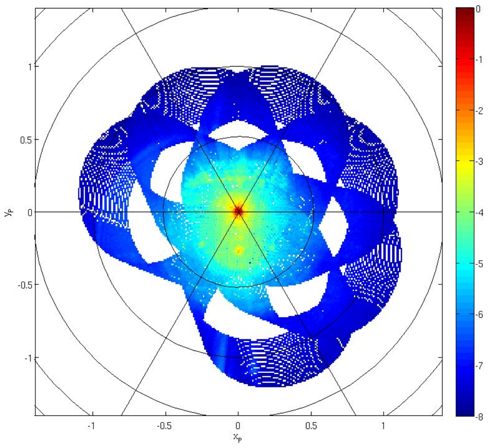
Refining Beam/Calibration Requirements

SAT Subsystem Requirement: Spurious polarized signal power from beams delivered to the detector modules for integrated polarization maps shall not exceed 10% of the final statistical uncertainty on the angular power spectrum at any multipole from 40 to 200.

Break out into specific measurements, e.g.

- **In FOV of instrument**: Leakage from T→P and E→B shall be < XXX
  - Verified by convolution of TQU maps with T/E skies
- **Far sidelobe region**: Total response in T and P shall not exceed XXX [power]; Leakage from T→P and E→B leakage shall be < XXX
  - Verified by convolution of sidelobe TQU maps with ground template, galaxy, etc.

How do we set these requirements and design the calibration strategy to verify them?



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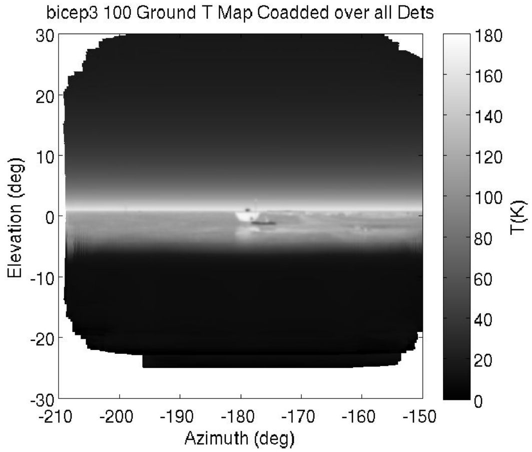

Systematics Sensitivity Forecasting

The CMB-S4 *r* forecasting paper included generic systematics at the power spectrum level.

- Extending to determine impact of calibration precision on systematics estimate
- Assume we have a template of systematic contamination, e.g. from timestream sims. Take the cross spectrum:

Systematic estimate ± measurement uncertainty	**X**	True CMB sky ± statistical noise

For a given CMB map noise level, determine the fidelity needed in the calibration measurement. Take foreground separation into account (different requirements per freq?)

Connect to calibrator design using archival data.

Conclusions

Controlling degree-scale instrumental systematics is critical for achieving the CMB-S4 inflation survey science goals. We rely on the heritage of Stage 1-3 small-aperture telescopes with demonstrated systematics control.

Calibration measurements are a key component of the experiment.

We are now adapting existing BK/SO calibrator designs for use in CMB-S4.

We are setting requirements on calibration precision and connecting them to calibrator designs.