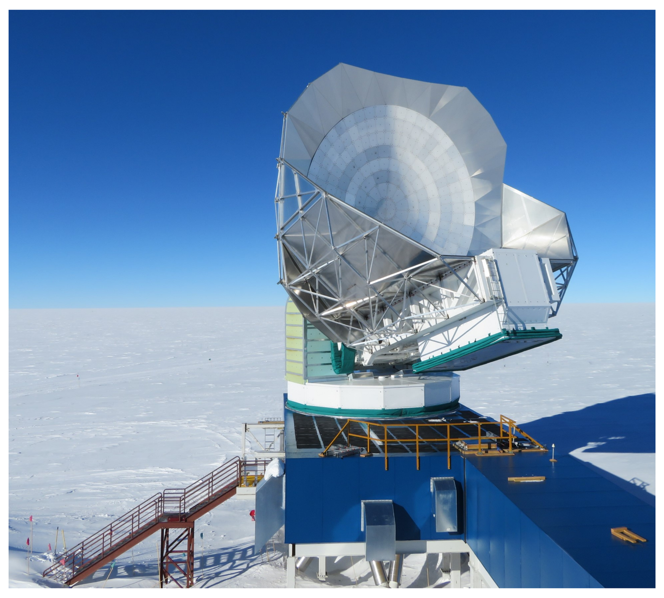
SPT-3G: A New Instrument To Measure the Cosmic Microwave Background On The South Pole Telescope

By Joshua Sobrin for the SPT-3G Collaboration

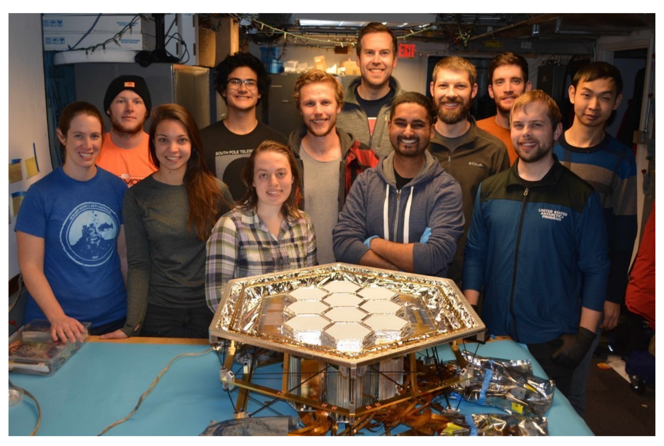
1. Overview

- The South Pole Telescope (SPT) is a 10-meter telescope designed to provide deep, high-resolution, maps of the cosmic microwave background (CMB).
- SPT-3G is the 3rd survey instrument on the SPT, featuring over 16,000 detectors for improved sensitivity.
- Measurements with SPT-3G will improve several cosmological constraints, including the energy scale of inflation, the sum of neutrino masses, and the dark energy equation of state.



10-m SPT located at NSF Amundsen-Scott South Pole Station (Credit: B. Benson)

The order-of-magnitude increase in detector-count over its predecessor, SPTpol, is made possible by…

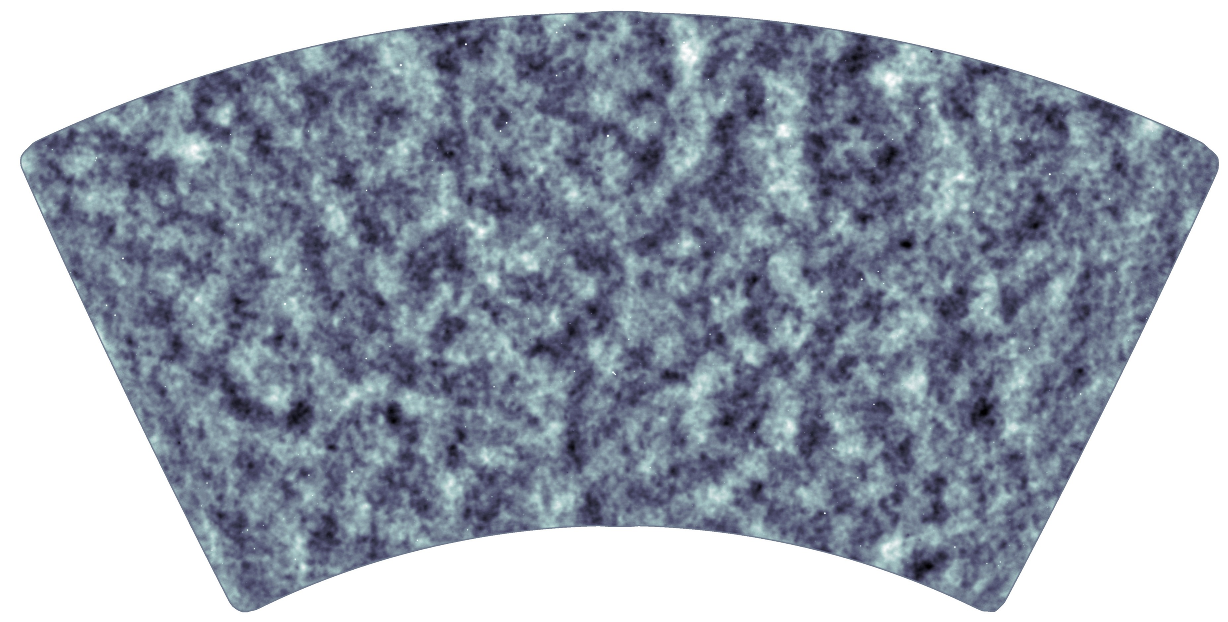


Receiver team stands behind assembled SPT-3G focal plane

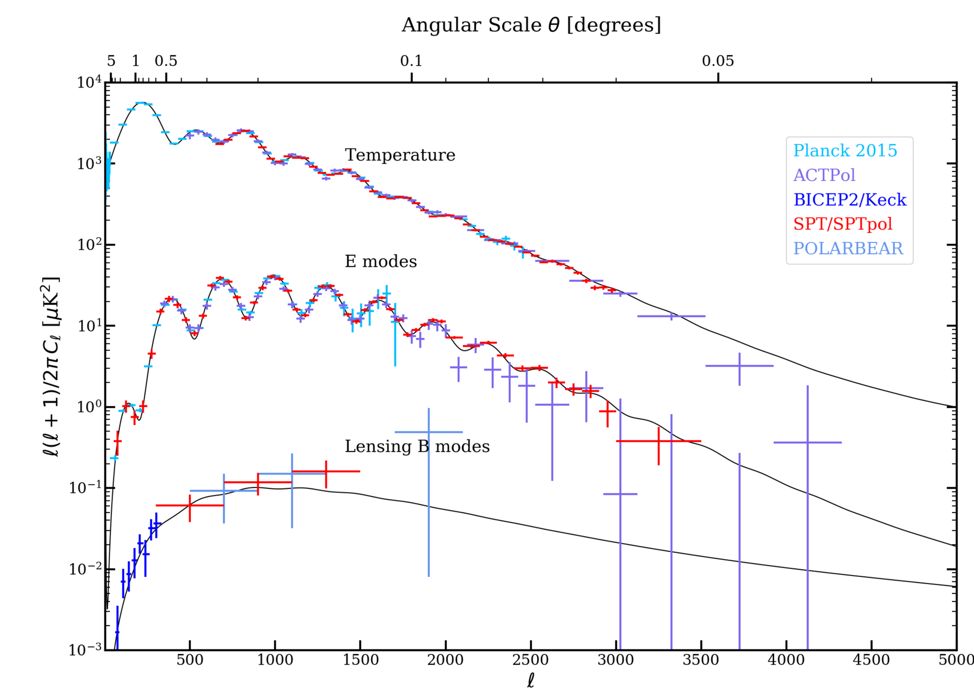
- A revised optics design permitting a broadband 450 mm focal plane with arcminute beams at 150 GHz.
- The fabrication of tri-chroic (95, 150, and 220 GHz) dual-polarization pixels with 6 transition-edge-sensor (TES) bolometers per pixel.
- An improved 68x digital frequency-domain SQUID multiplexing readout system.

2. Science Goals

SPT-3G will survey 1,500 deg² over 4 years to measure the temperature- and polarization-anisotropies of the CMB with unprecedented sensitivity on arcminute scales.



SPTpol (2nd generation) 500 deg² 150 GHz intensity map with point sources and galaxy clusters visible as compact bright and dark spots, respectively



CMB Power Spectra adapted from CMB-S4 Science Book

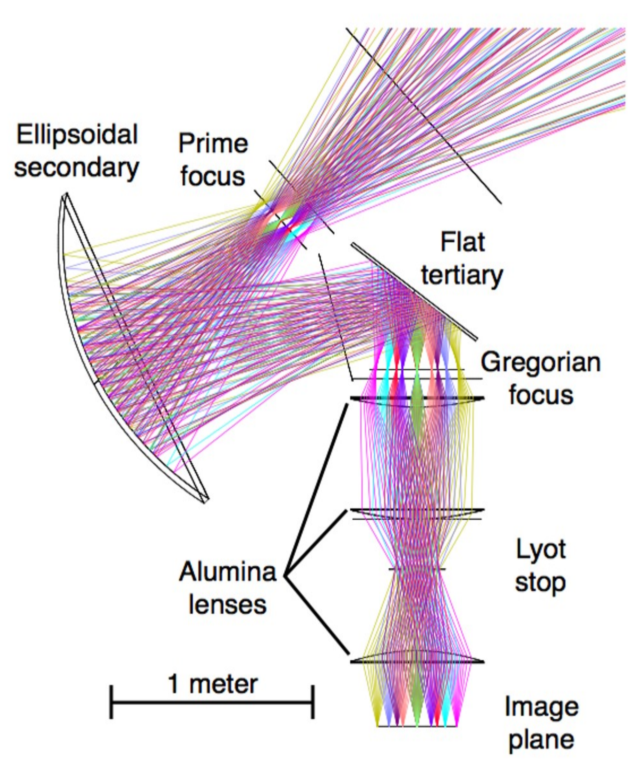
- Constrain inflationary models by using lensing and E-mode power spectrum measurements to de-lens the degree-scale primordial B-mode signal and probe the tensor-to-scalar ratio (***r***). Full overlap with BICEP Array survey will allow for even tighter constraints with joint-analyses.
- Use CMB lensing measurements to probe projected matter distributions and growth of structure to address questions surrounding new light relics (N_{eff}) and neutrino mass (Σm_ν).
- Measure structure formation out to high-redshift using Sunyaev-Zel'dovich effect to detect galaxy clusters and constrain the dark energy equation of state (*w*). Significant overlap with Dark Energy Survey (DES) will allow for a variety of multi-wavelength studies.

Dataset	Cosmological parameter constraints								
	$\sigma(\Omega_b h^2)$ $\times 10^4$	$\sigma(\Omega_c h^2)$ $\times 10^3$	$\sigma(A_s)$ $\times 10^{11}$	$\sigma(n_s)$ $\times 10^3$	$\sigma(h)$ $\times 10^2$	$\sigma(\tau)$ $\times 10^3$	$\sigma(N_{\rm eff})$ $\times 10^1$	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(r)$ $\times 10^2$
Planck	1.93	2.02	5.36	7.07	1.88	4.96	1.39	117	5.72
+ SPT-POL	1.64	1.71	4.92	6.19	1.58	4.95	1.17	96	**2.75**
+ SPT-3G	**1.02**	**1.25**	**4.18**	**4.61**	**1.14**	4.94	**0.76**	**74**	**1.05**
Planck + BOSS	1.34	1.21	4.01	4.54	1.21	4.92	0.74	88	5.72
+ SPT-3G	**0.85**	**0.95**	3.71	3.91	**0.94**	4.90	**0.58**	**61**	**1.05**

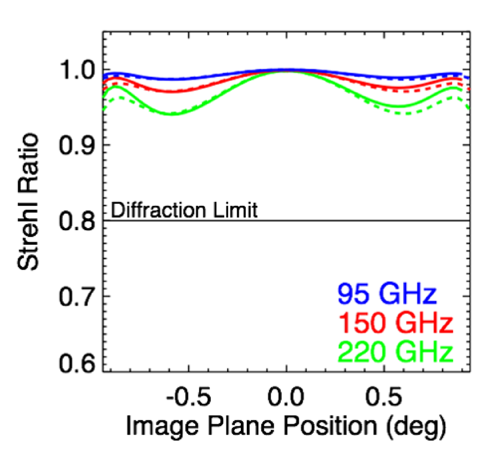
(Further details can be found in B. Benson, et al. *SPT-3G: A Next-Generation Cosmic Microwave Background Poalrization Experiment on the South Pole Telescope*, 2014 arXiv:1407.2973)

3. Optics

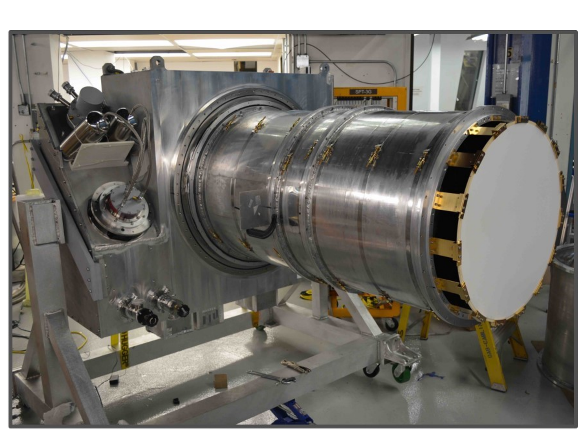
Tight control of instrument loading and broadband anti-reflective technologies were crucial for realizing the high-throughput optics design

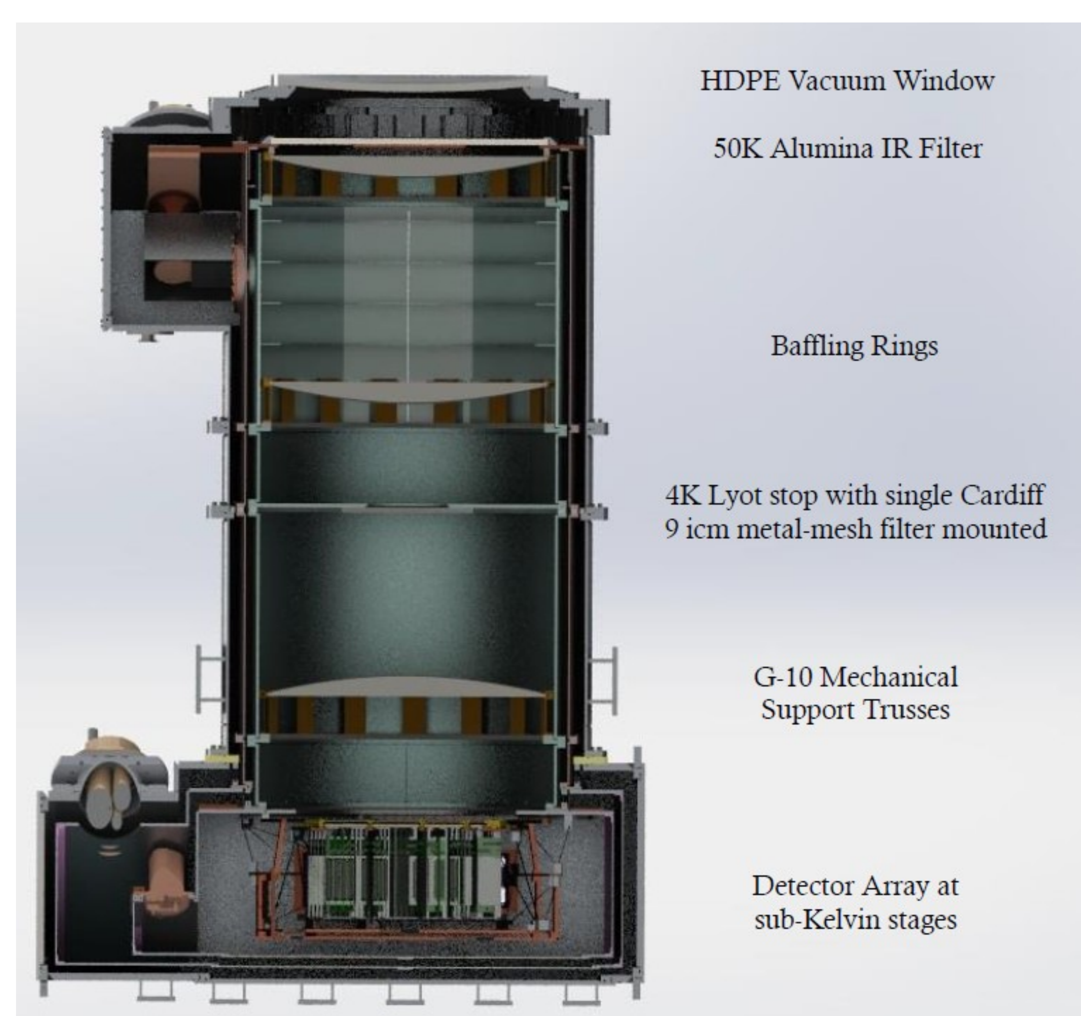


- 10-m off-axis Gregorian design
- 450 mm image plane
- 1.9 deg diameter field-of-view
- Arcminute beams at 150 GHz



- Alumina lenses held at 4 K
  - 720 mm OD
  - Purity = 99.5%
  - n = 3.10
  - tan δ = 1.6 x 10⁻⁴

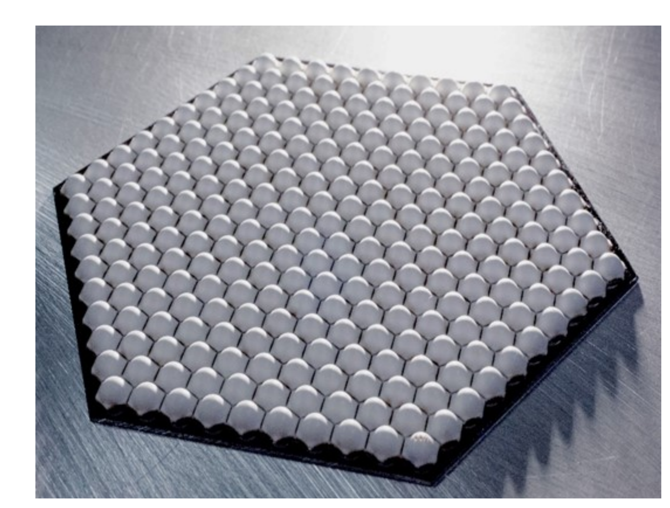




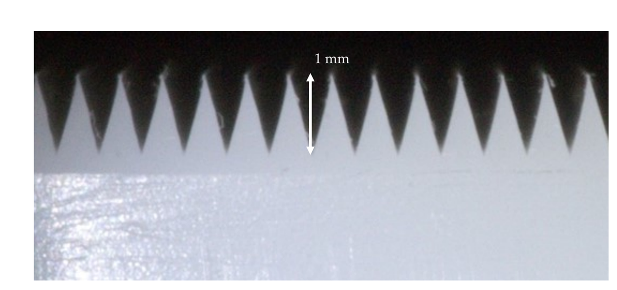
- Receiver design aimed to:
  - Attenuate stray reflections on cold surfaces to control shape of beams
  - Mitigate thermal gradients across receiver to minimize thermal emission onto detectors

- Anti-reflective technologies developed to maximize in-band transmission of signal through receiver window and refractive cold optics.

Ceramic Microsphere Thermal Spray Coating



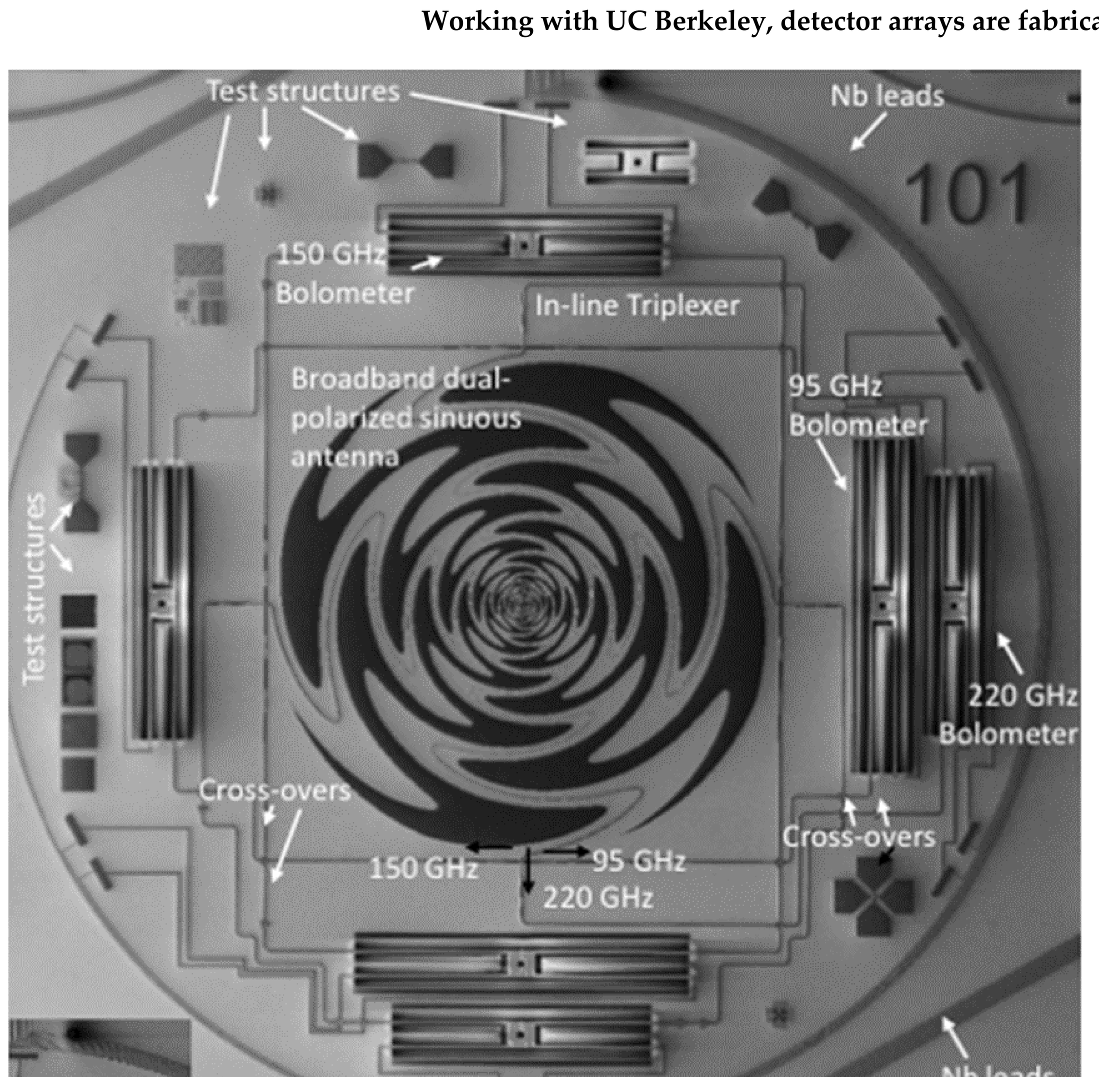
Adhering PTFE-based materials to alumina

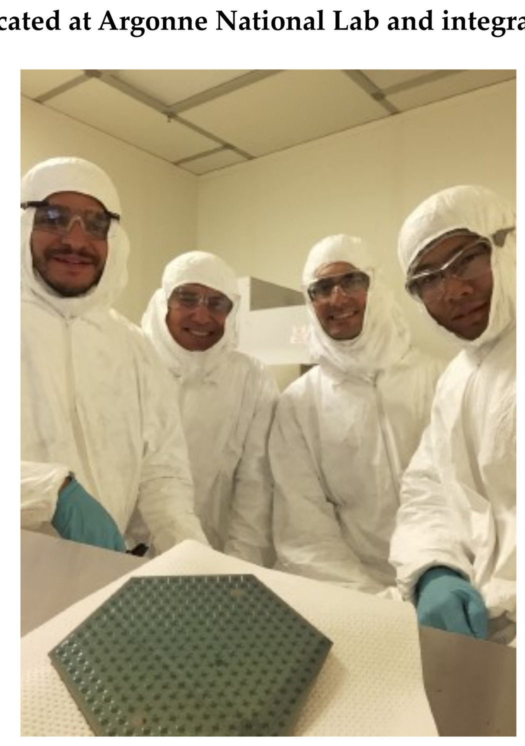


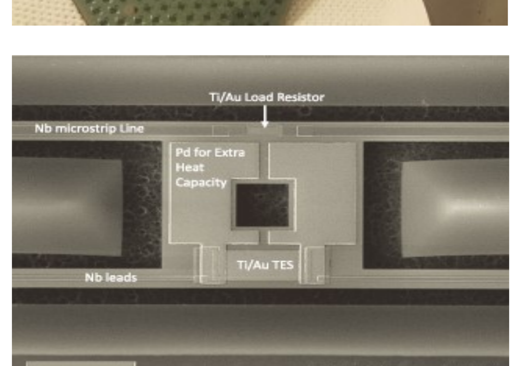
Machining grooves in HDPE

4. Detectors

Working with UC Berkeley, detector arrays are fabricated at Argonne National Lab and integrated at Fermi National Accelerator Lab







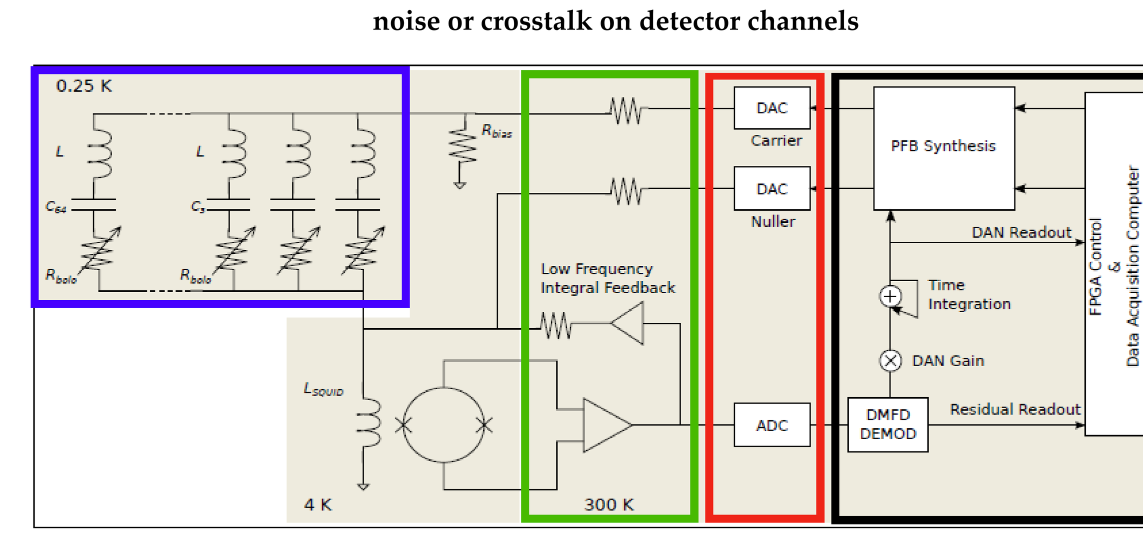
- At Argonne National Lab (ANL), antennas, lumped element filters, microstrip transmission lines, and TES bolometers are patterned repeatedly across silicon wafers to produce CMB-sensitive tri-chroic pixels for the SPT-3G focal plane.

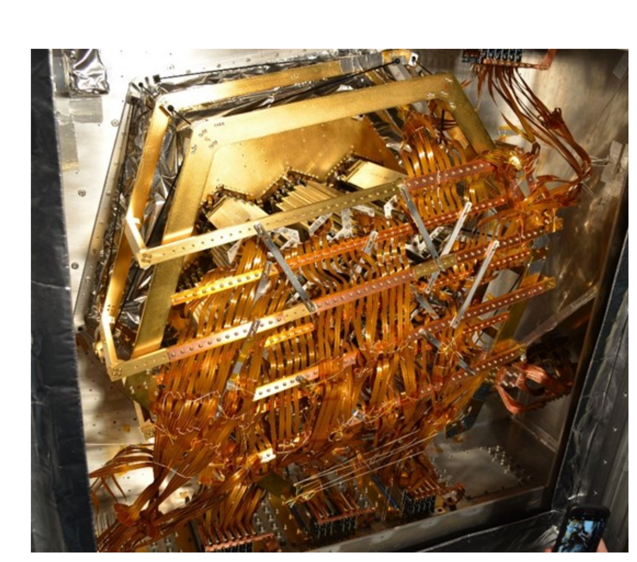
(Further details can be found in C.M. Posada et al. Proc. SPIE 9914 (2016), 9914.)

- At Fermi National Accelerator Lab (FNAL), detector wafers are aligned precisely with lenslet arrays, systematically wirebonded to cryogenic readout cables, and assembled into standalone modules for installation onto focal plane.

5. Readout

Higher multiplexing factor decreases wiring complexity and thermal loading without increasing noise or crosstalk on detector channels





Low-inductance cryogenic wiring with cold DfMUX electronics installed in receiver during integration at South Pole

- Signals from each detector operate in series with an inductor-capacitor LC resonator before being summed and amplified by a SQUID array, allowing multiple detectors to be read out over a single pair of wires.
- An improved DfMUX system achieves 64x multiplexing (1.6—5 MHz) - necessary for the substantial increase in detector count - by adopting a digital feedback system called Digital Active Nulling (DAN), allowing for higher carrier frequencies and longer cryogenic wire lengths.

(Further details can be found in A Bender, et al. *Digital frequency domain multiplexing readout electronics for the next generation of millimeter telescropes,* 2014 arXiv:1407.3161)