CMB Instrument Primer

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ASTR 448

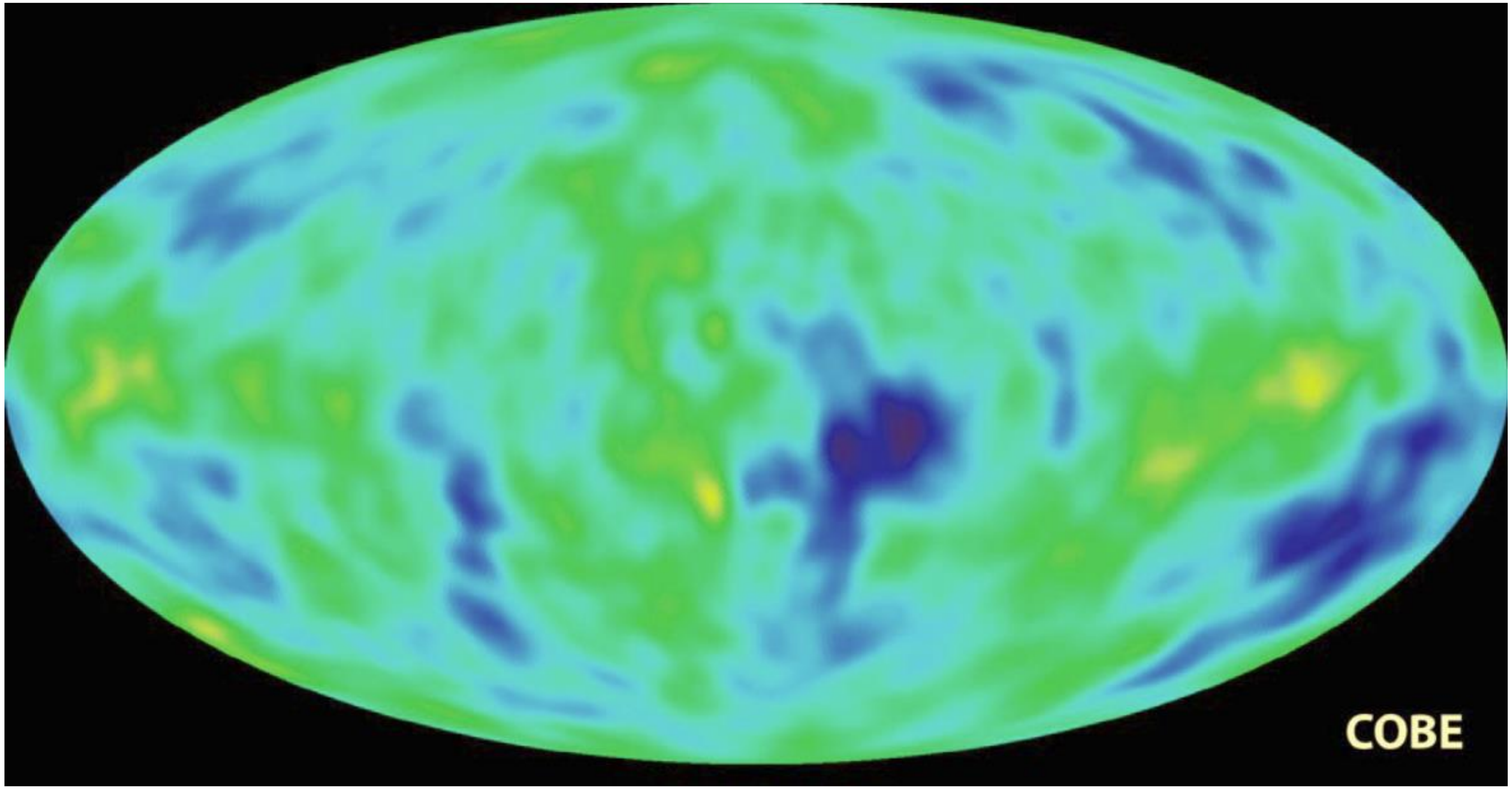
How far we've come…

- An instrument-team's prime-directive is to make the highest quality map that they can.

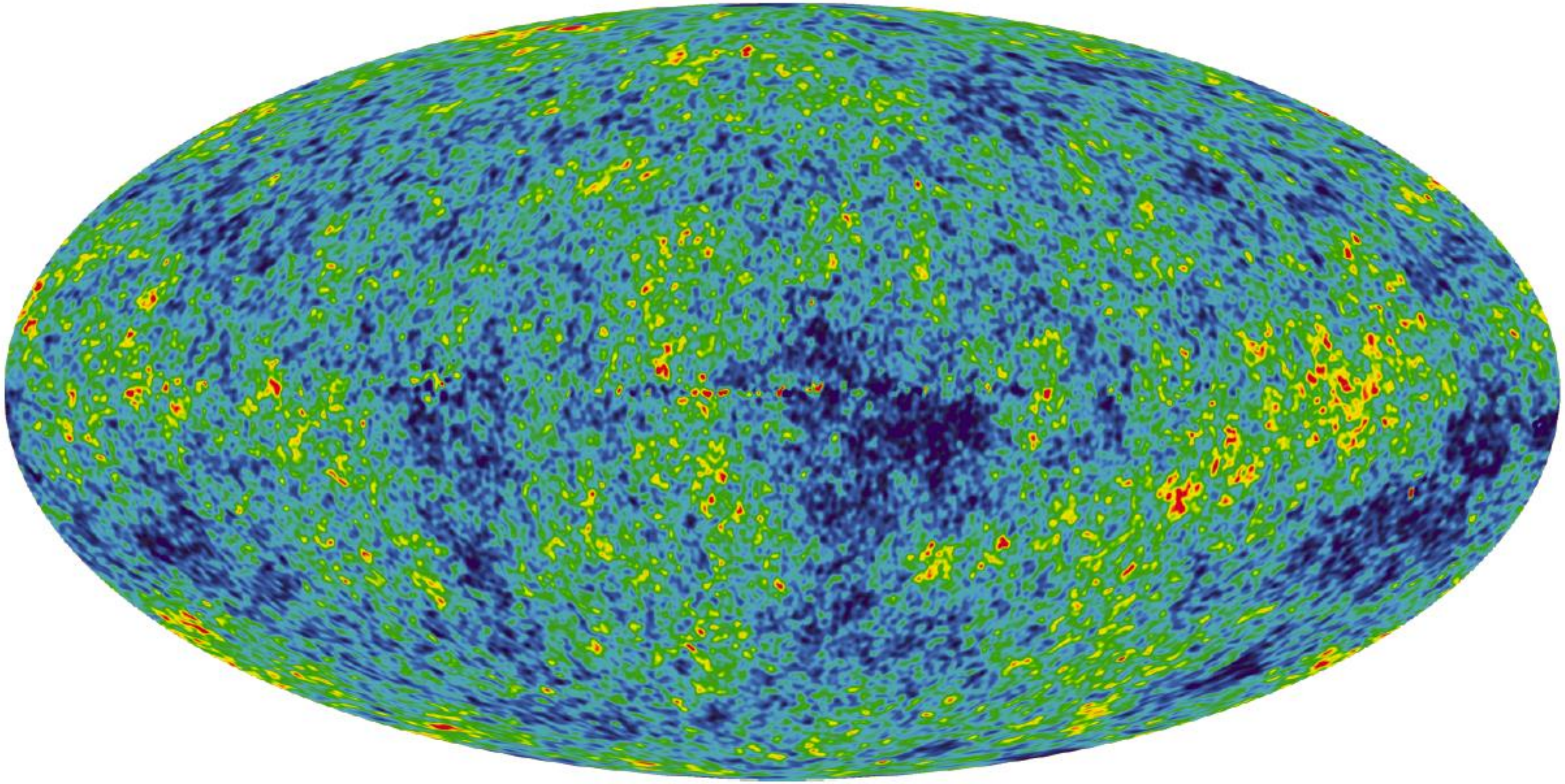
- Metrics by which we judge the quality of the map:
  - Sensitivity
  - Resolution
  - Sky-coverage

- Need to detect ~30 μK intensity fluctuations on a 3 K blackbody.
  - Polarization-fluctuations are even lower…

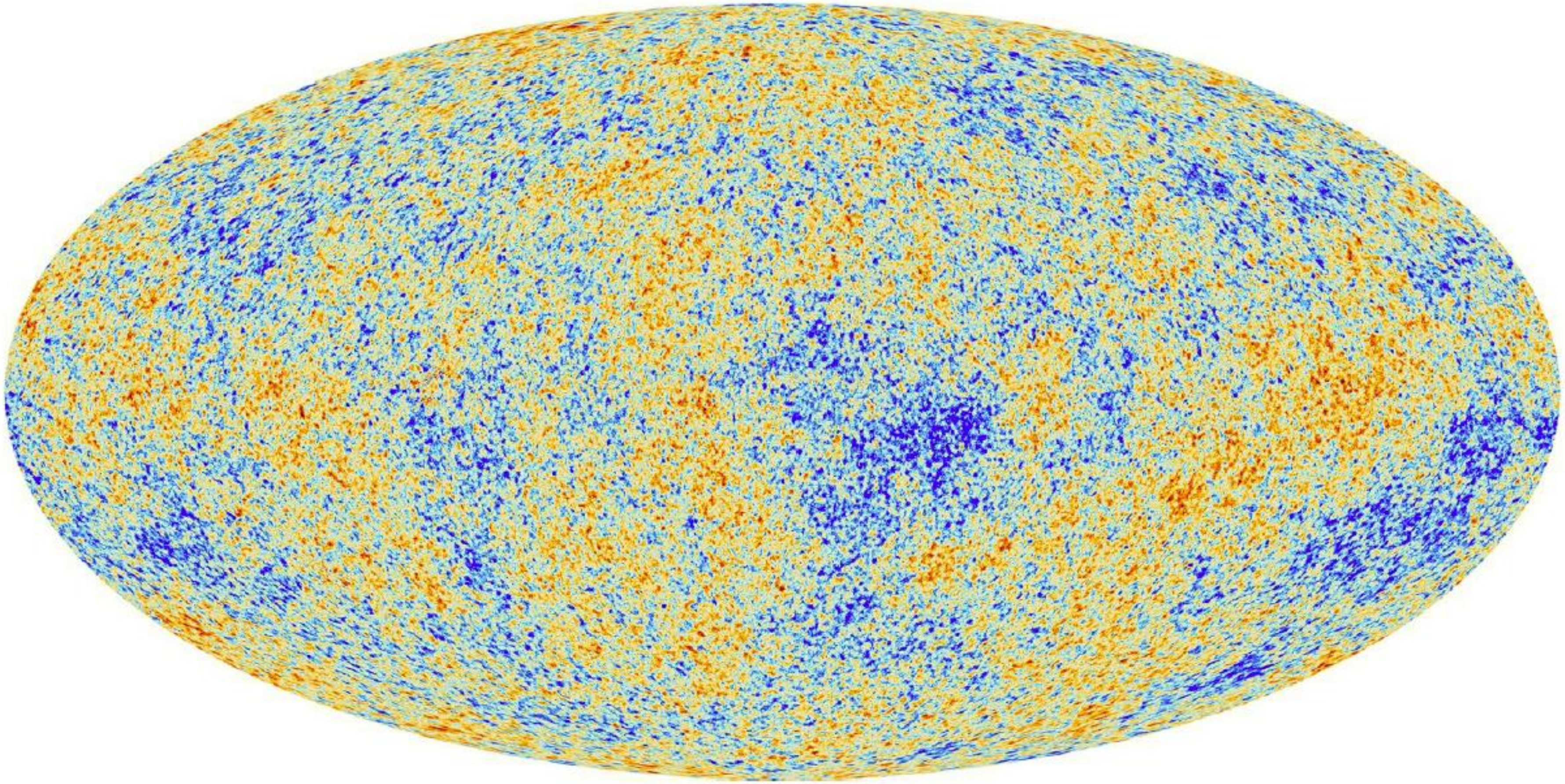
COBE (1992)



WMAP (2004)



Planck (2013)

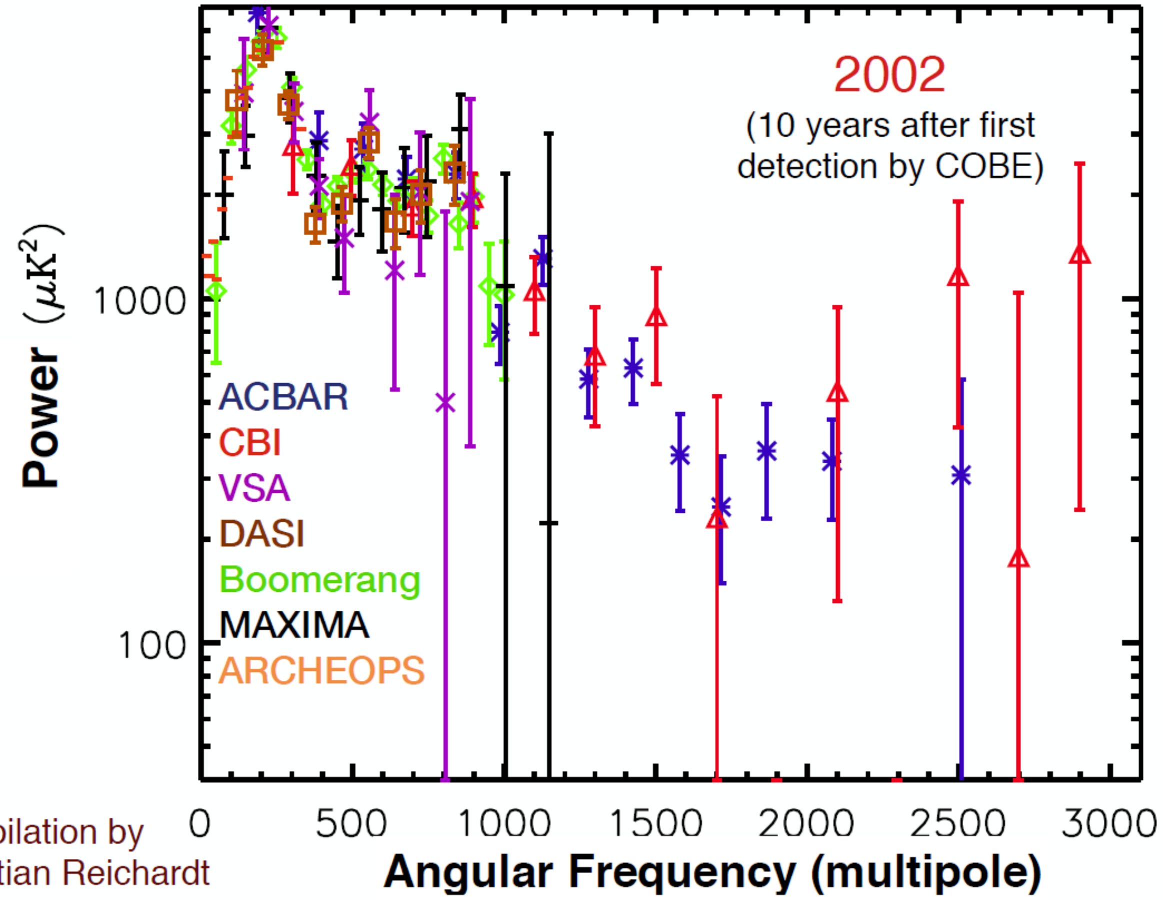


Progress in Power Spectra

- The quality of a map determines the quality (and range) of the power spectra.

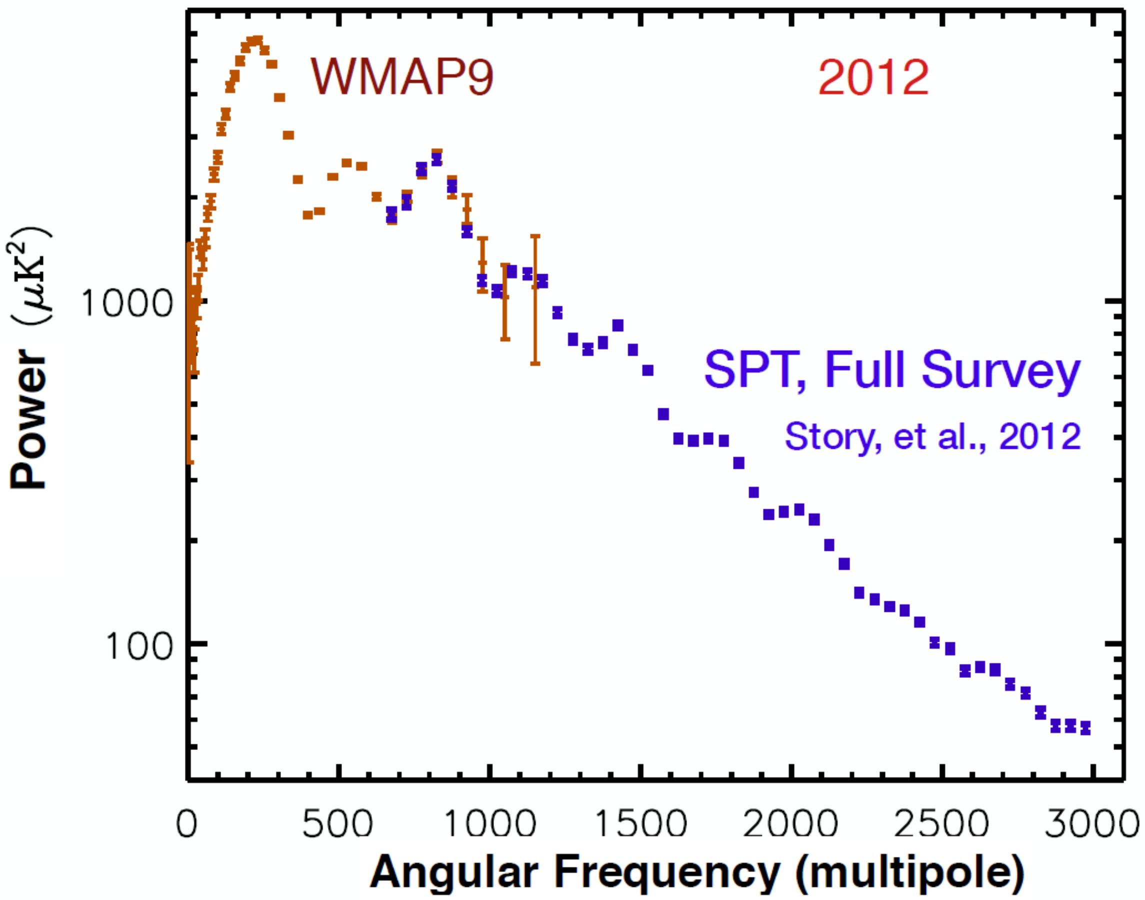
- And as we've been speaking about throughout the course, we can use power spectra (both temperature and polarization), to better constrain our physics & cosmology.

What the CMB looked like 15 years ago…

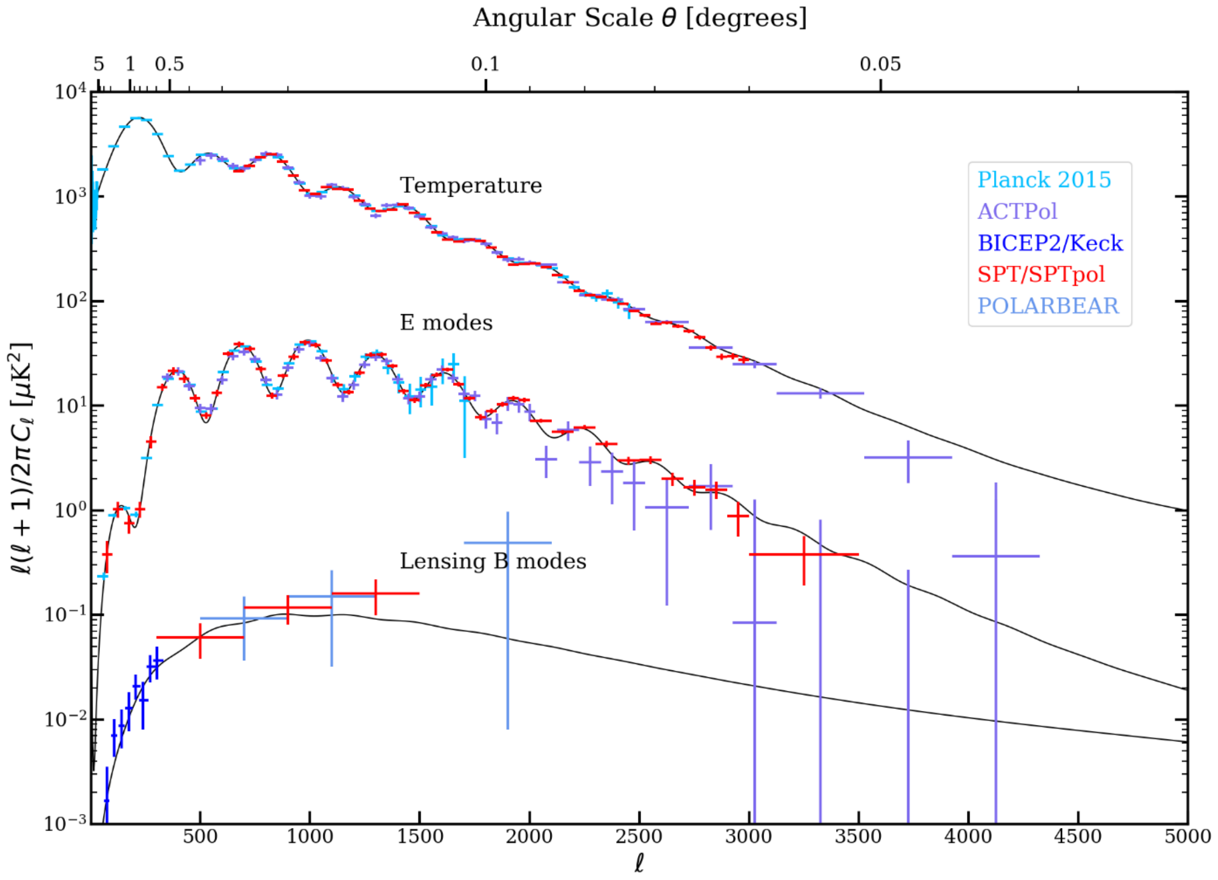


Compilation by
Christian Reichardt

What it looked like 5 years ago…



What it looks like today…

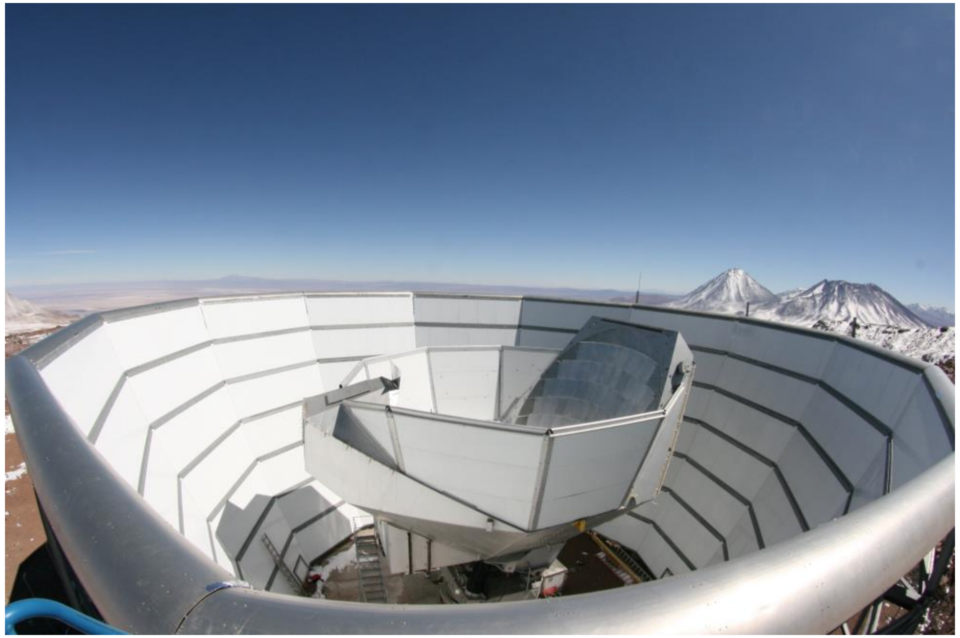


Credit: J Henning (2018)

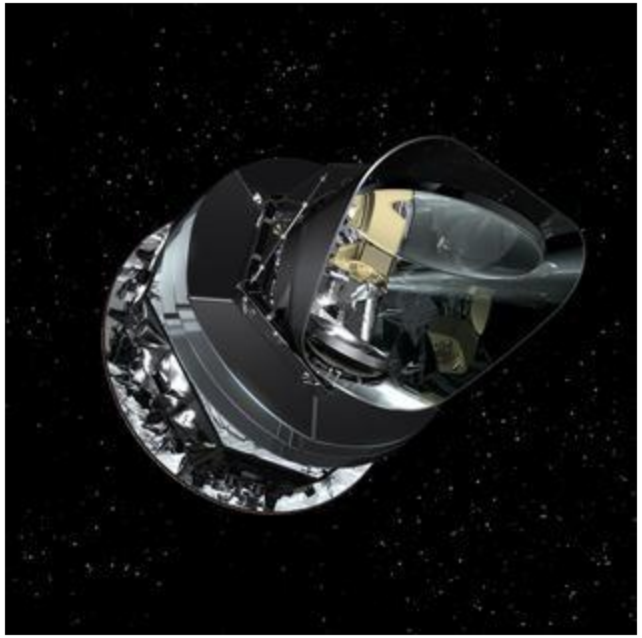
Platforms for Observing the CMB

- Have pursued observation sites by air, land, and ~~sea~~ space…

Long-Duration Balloons

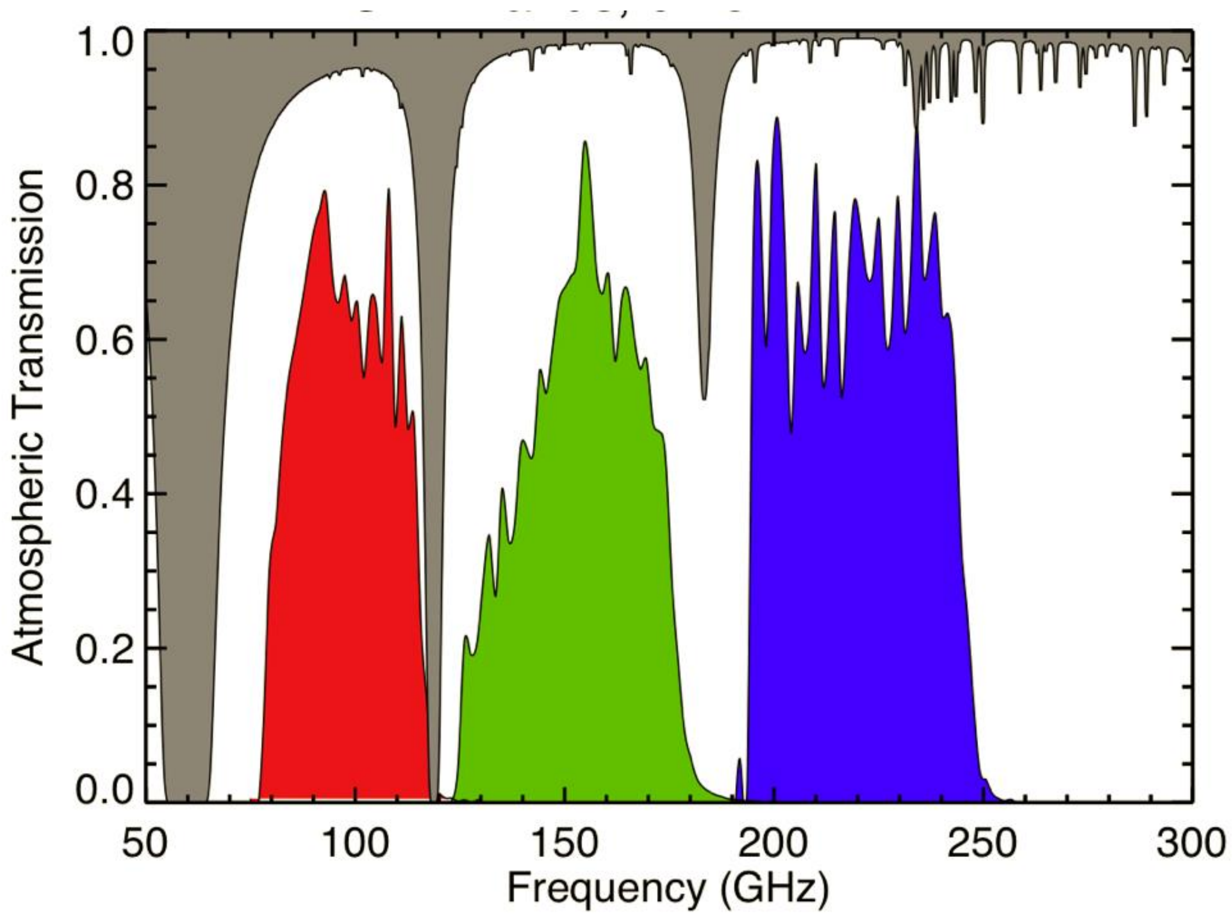


Ground-based Telescopes



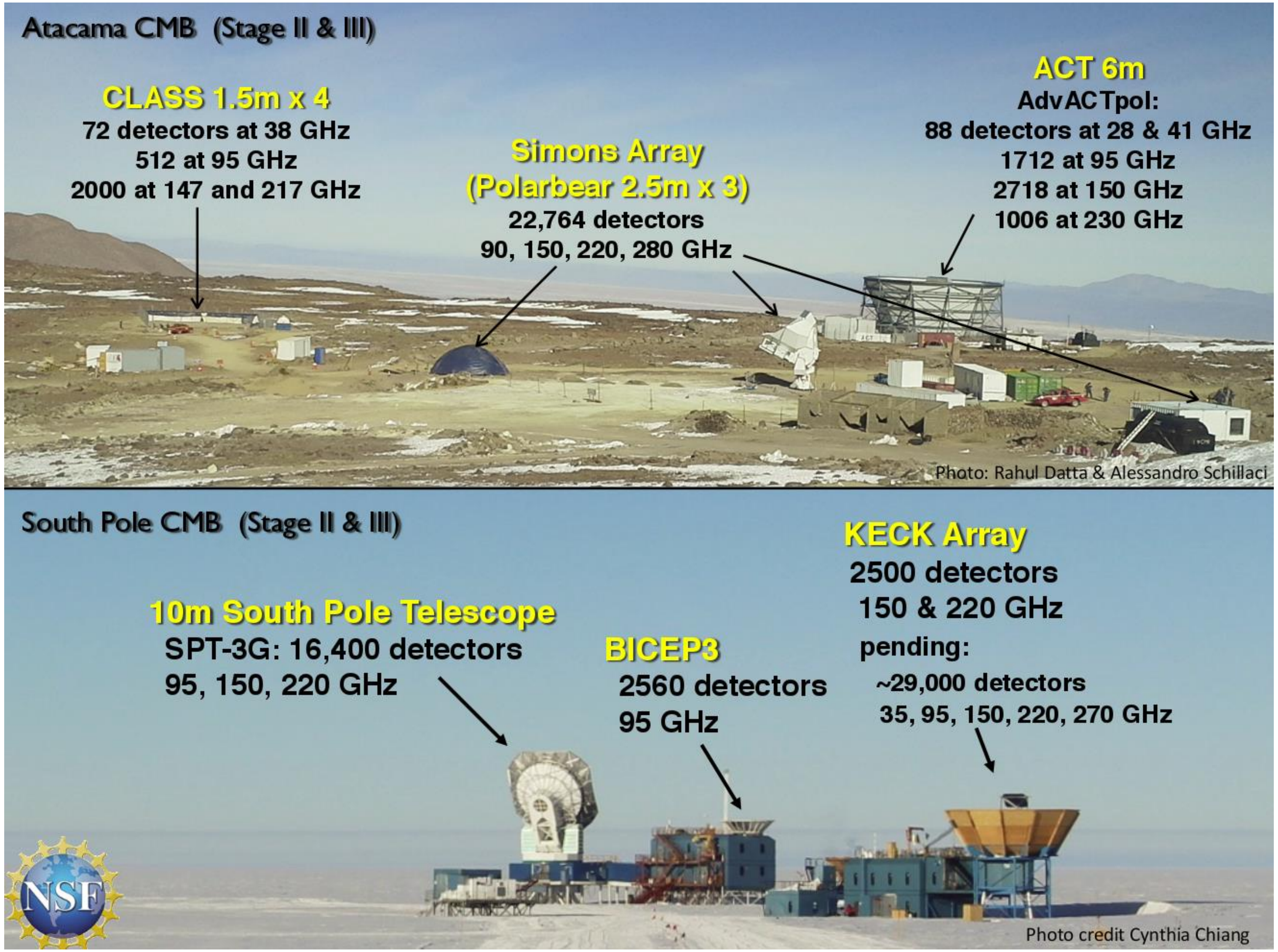
Satellite Missions

Atmospheric Moisture Muddies Observations



(But CMB Intensity conveniently peaks around 150 GHz)

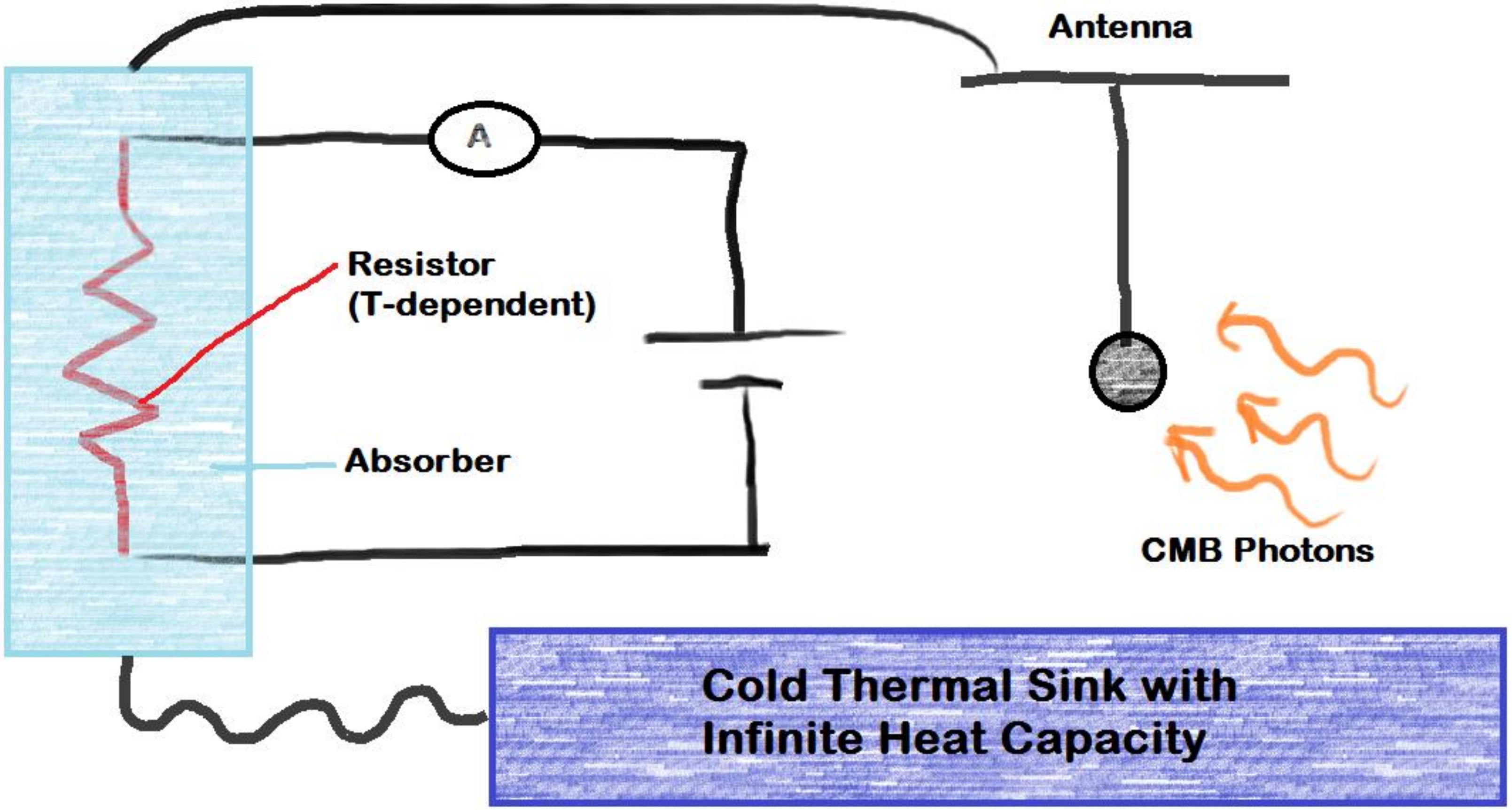
Atacama and the South Pole



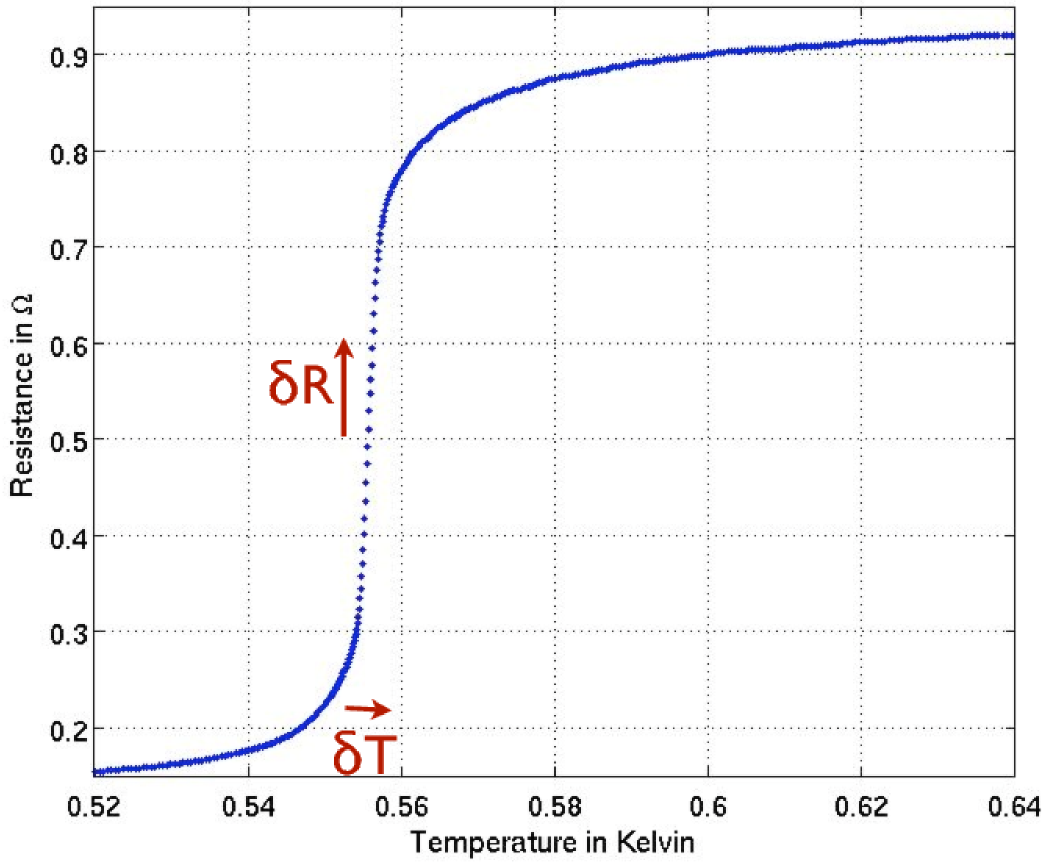
So we’d like to do better… what are the challenges…

- Our receivers need to do a few things, well:
  - Get the light in (Optics)
  - See the light (Detectors)
  - Systematically keep track of the light (Readout)
- These are arguably the 3 big sub-fields of CMB instrument-development, currently.

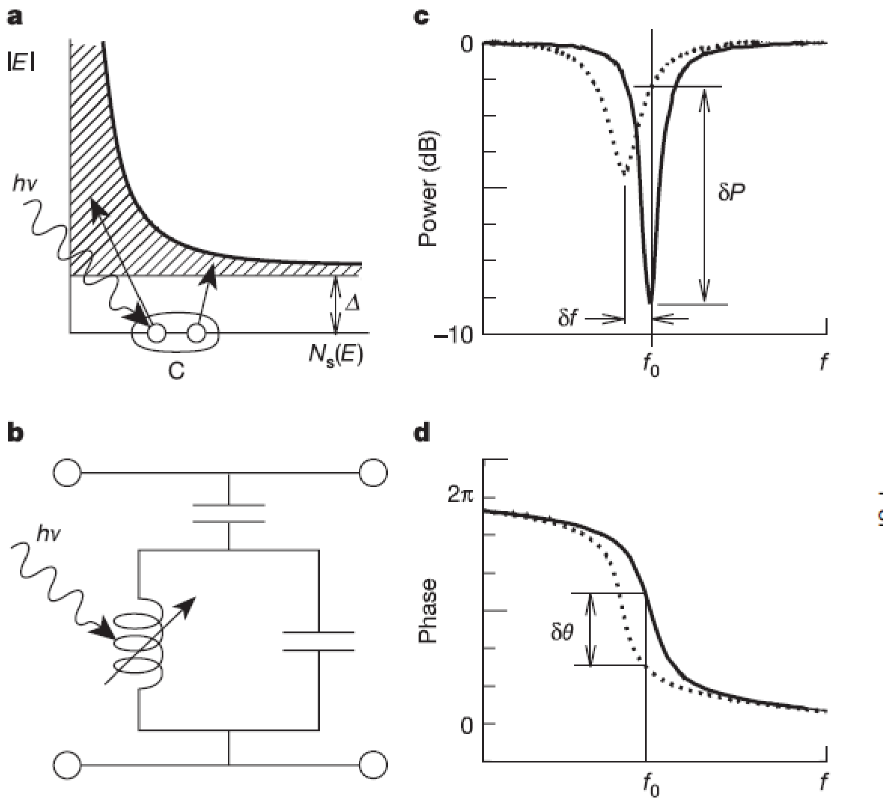
Bolometers 101



Transition-Edge Sensors (TESs)



Kinetic Inductance Detectors (KIDs)



Figures taken from J Zmuidzinas group

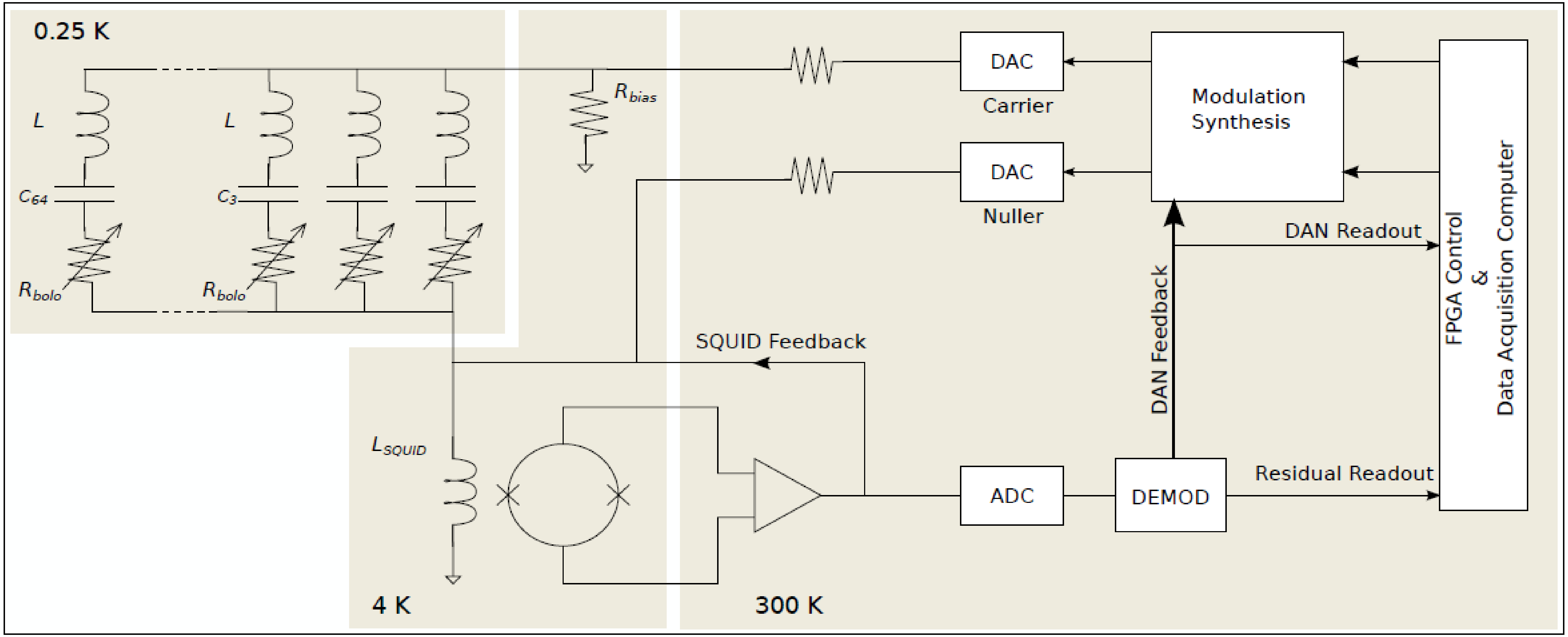
Photon-Noise Limited

- Most CMB experiments today are photon-noise limited (i.e. the random arrival times of the photons we are measuring).
  - Noise in CMB + Noise of Atmosphere > Noise of Detector + Noise of Readout/Instrument

- Designing more sensitive detector-technologies has decreasing utility… but designing instruments that can host more detectors can still significantly improve overall sensitivity.

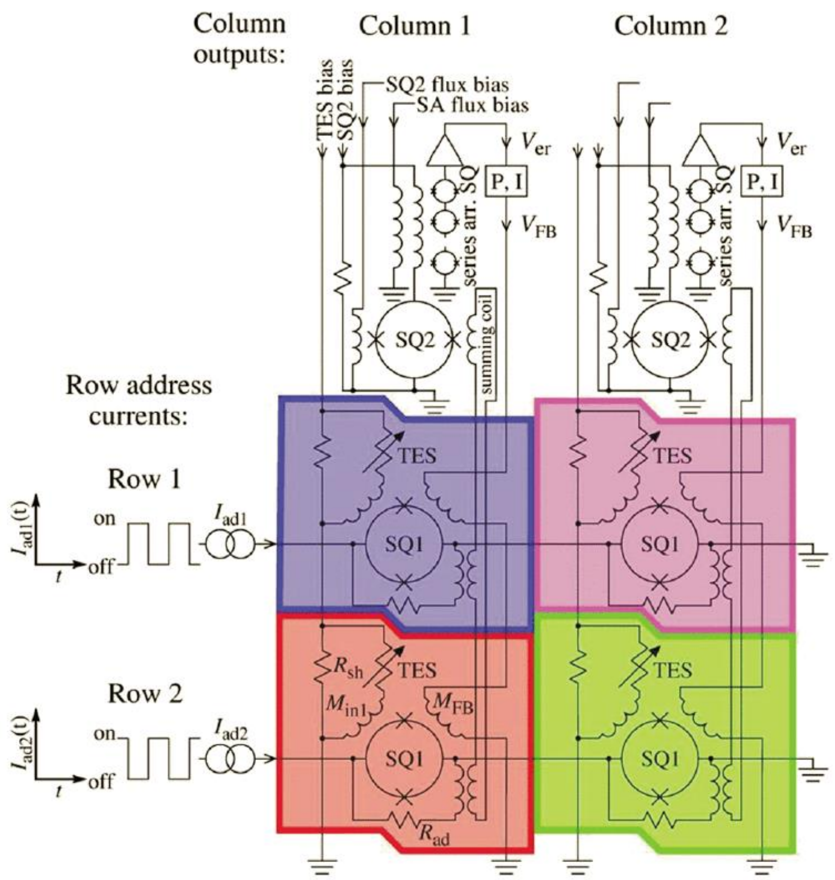
- However, more detectors increases complexity, cost, and cryogenic stresses.
  - Driver for more elegant readout technologies.

Frequency-Domain Multiplexing (FDM/fMux)

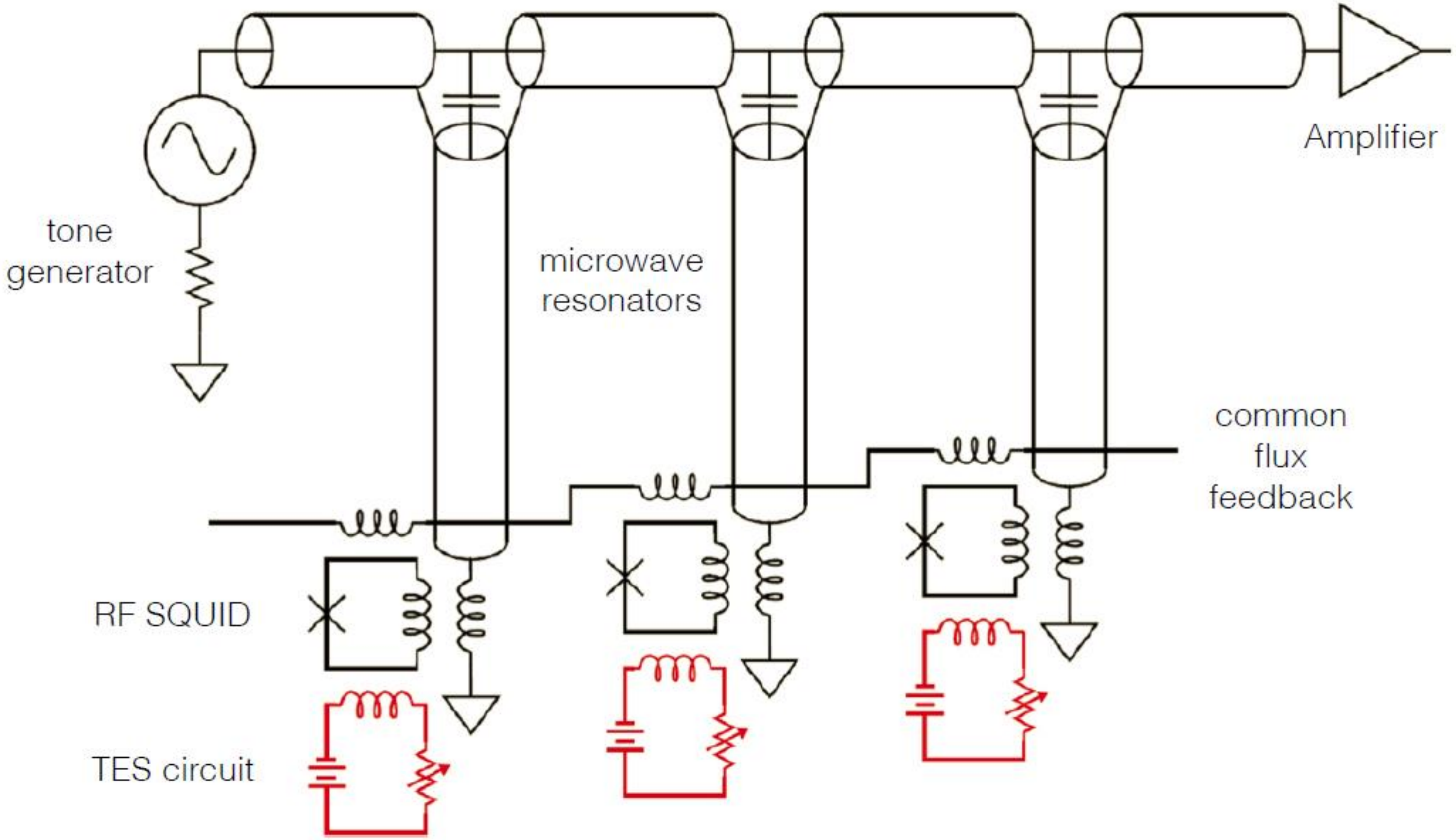


Credit: A Bender

Time-Division Multiplexing (TDM/tMux)



Microwave-Squid Multiplexing (uMux)



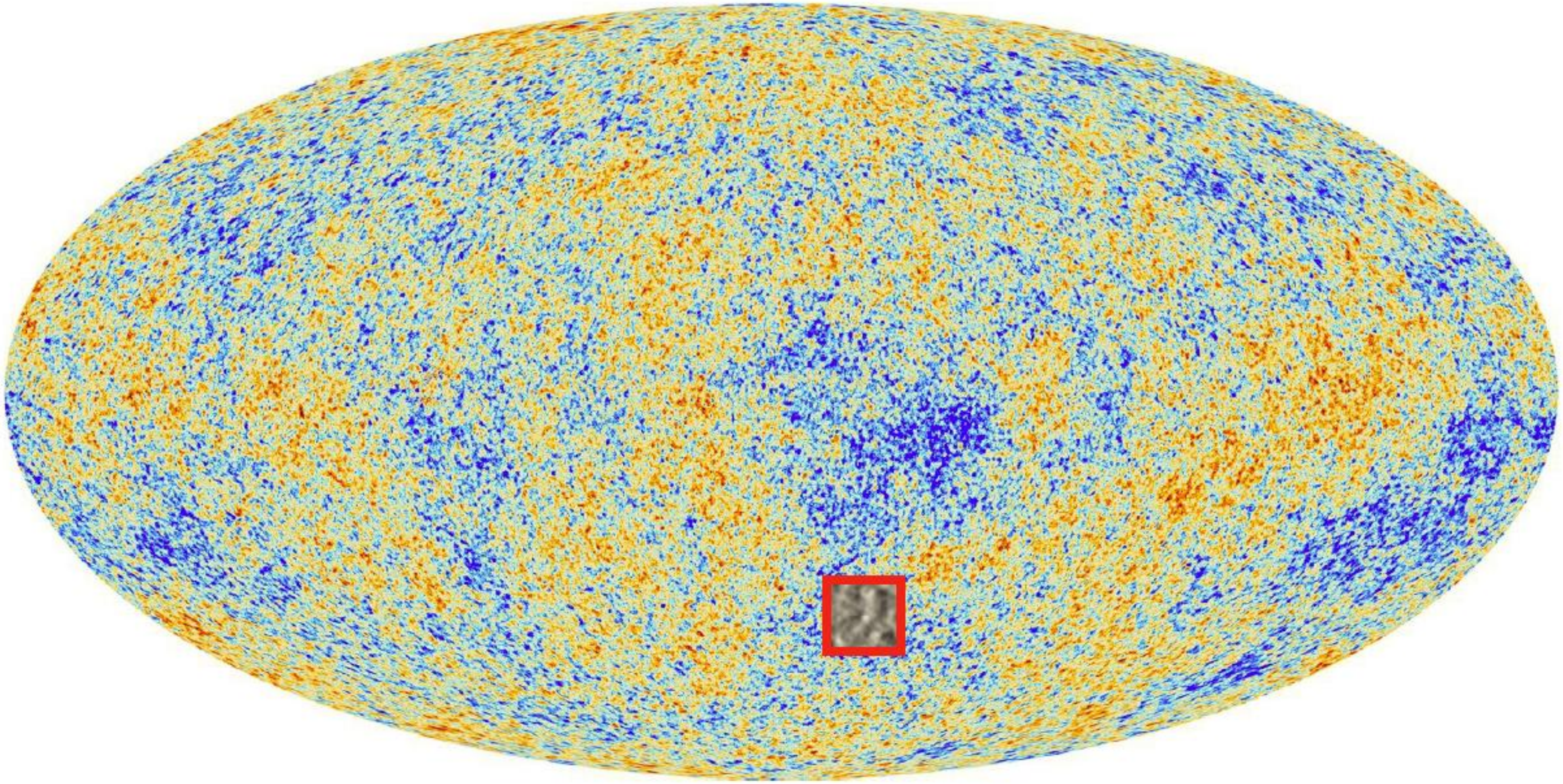
Credit: B Mates

Optics Challenges

- Minimizing and controlling stray reflections
- Minimizing instrument-loading on detectors (and associated cryogenics)
- Filtering
- Antireflective Coatings
- Polarization modulators

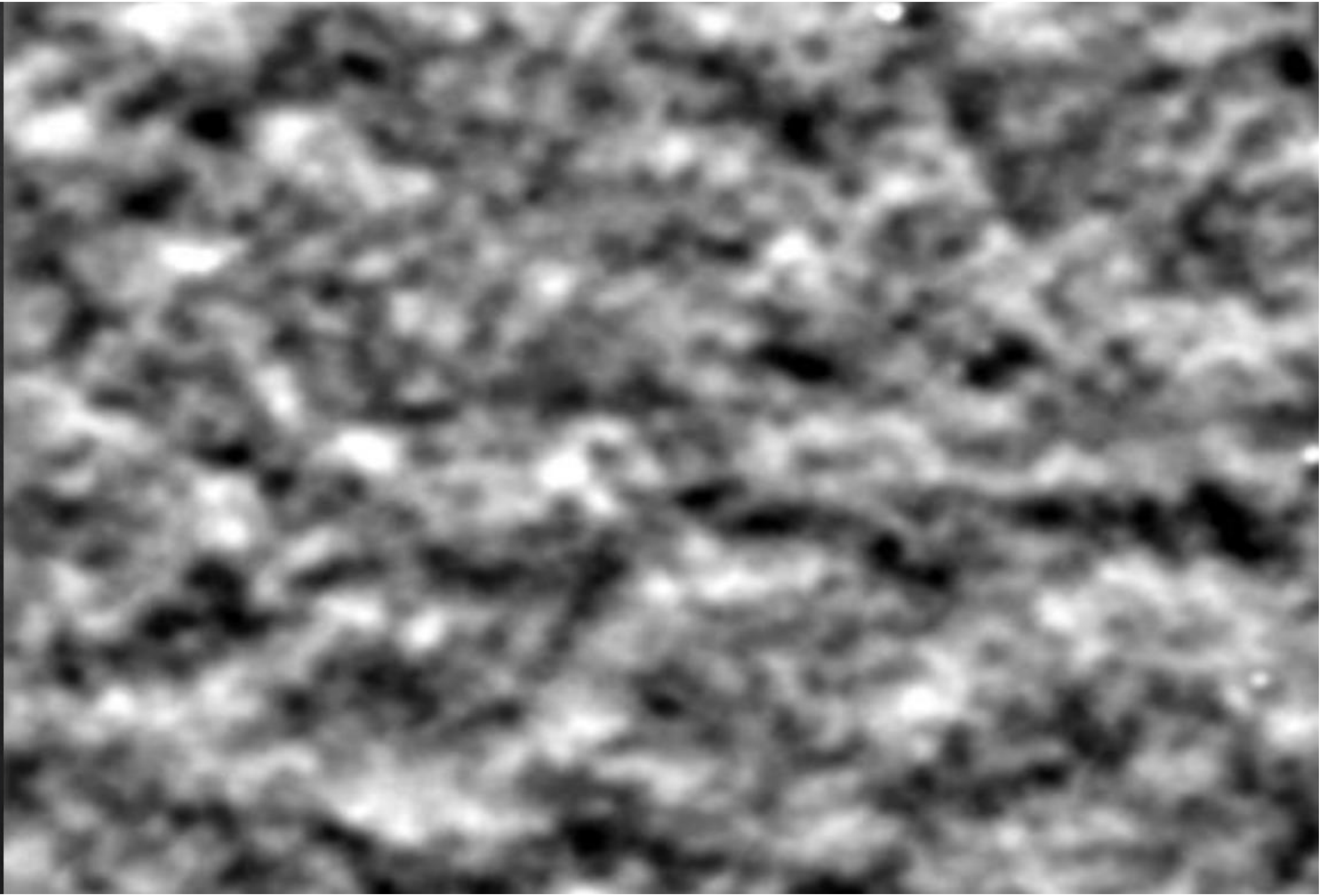
Case Study: The SPT and SPT-3G Receiver

Going back to Planck for a moment…



Planck

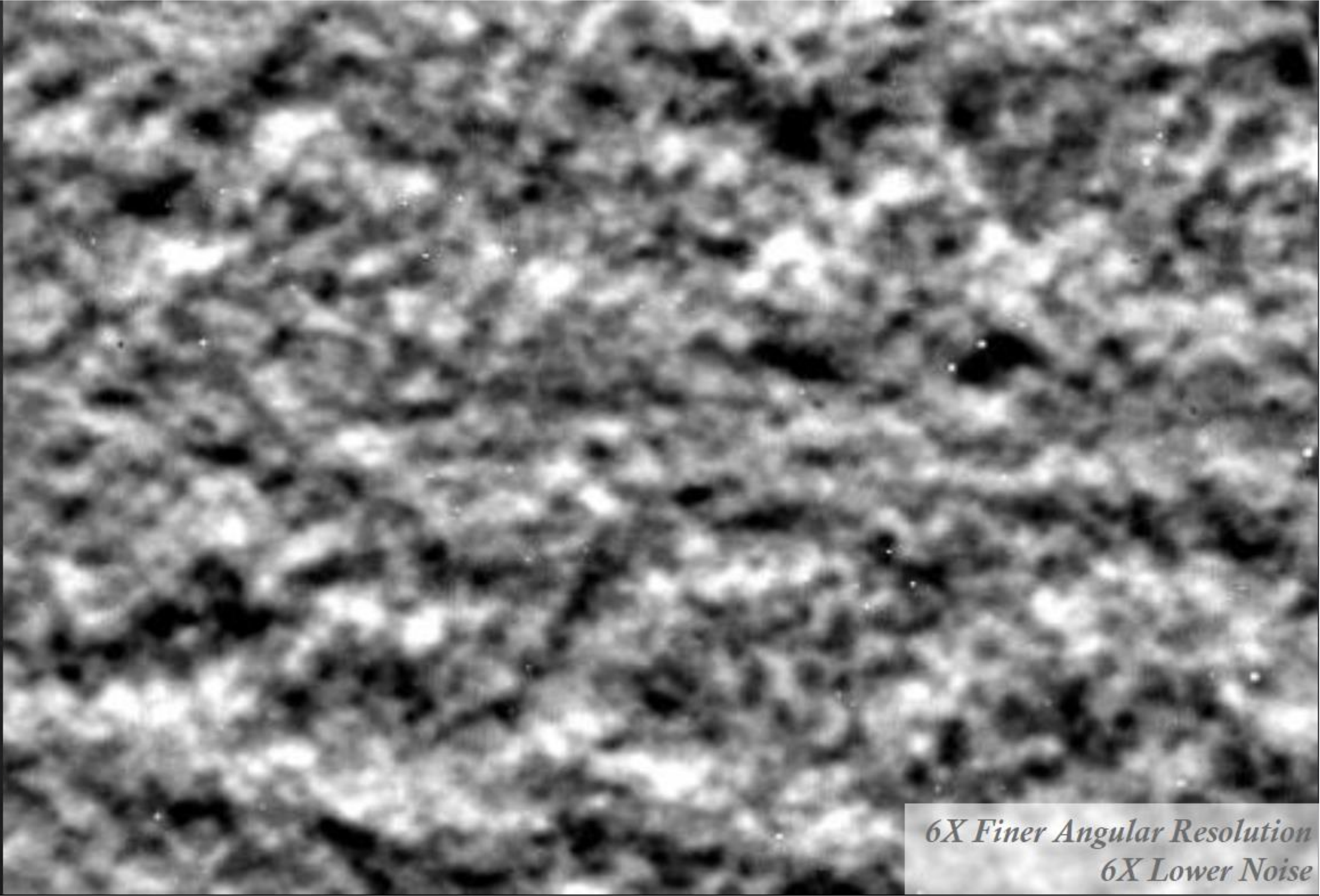
50 deg^2
143 GHz



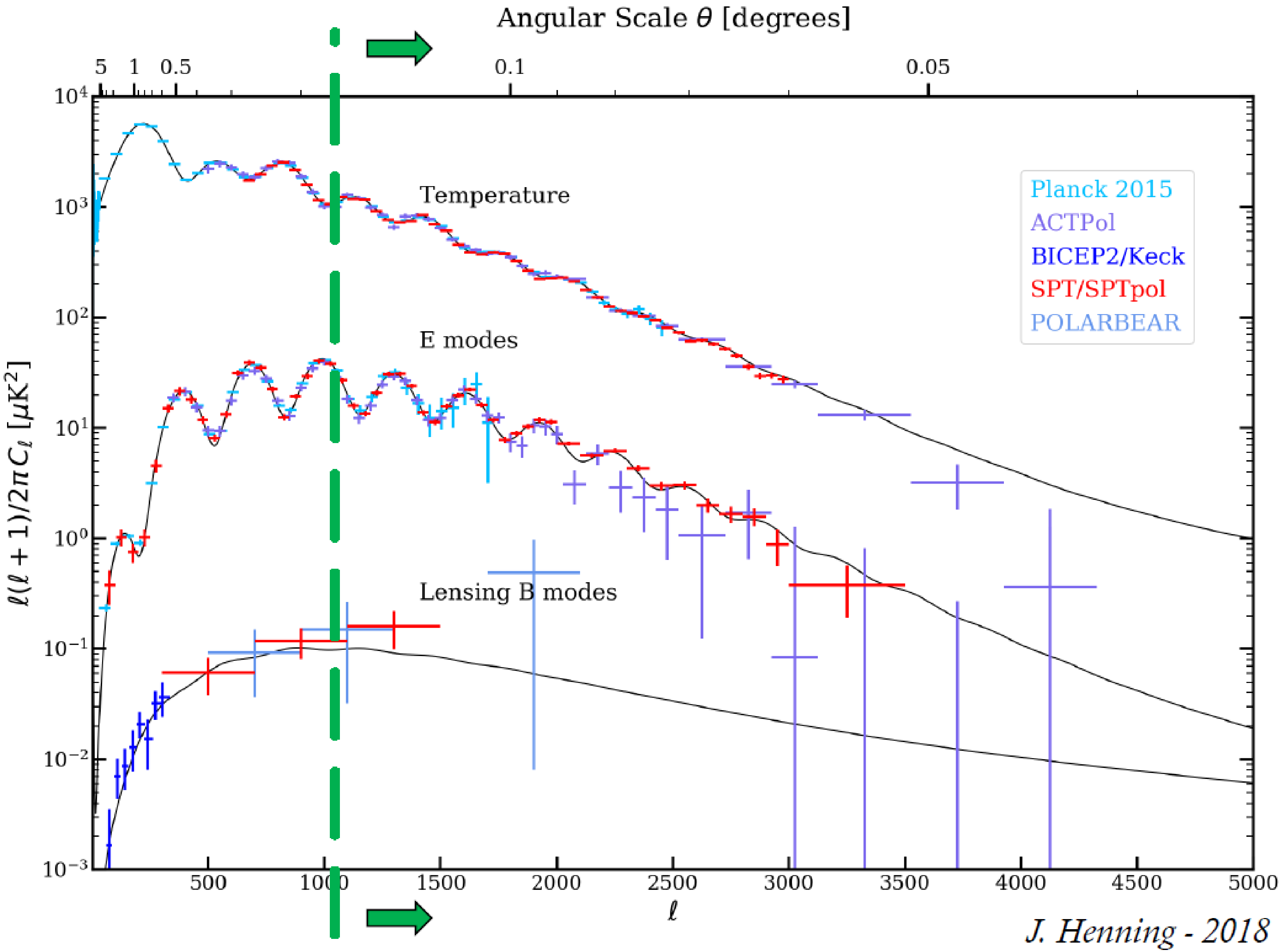
SPTpol

50 deg^2
150 GHz

*SPT provides **deep**, **high-resolution**, maps of the CMB*



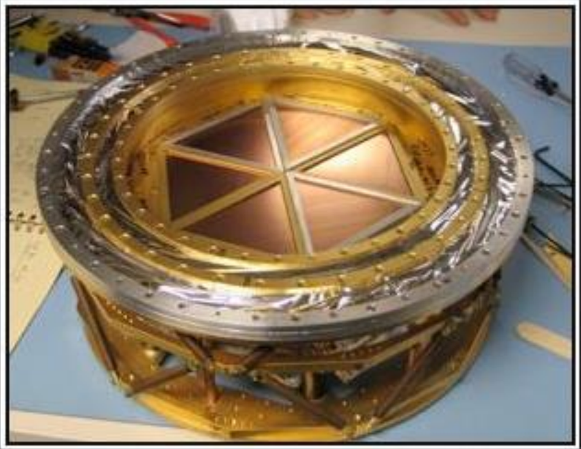
CMB Power Spectra



On arc-minute scales, SPT provides high-sensitivity measurements of CMB temperature- and polarization-anisotropies

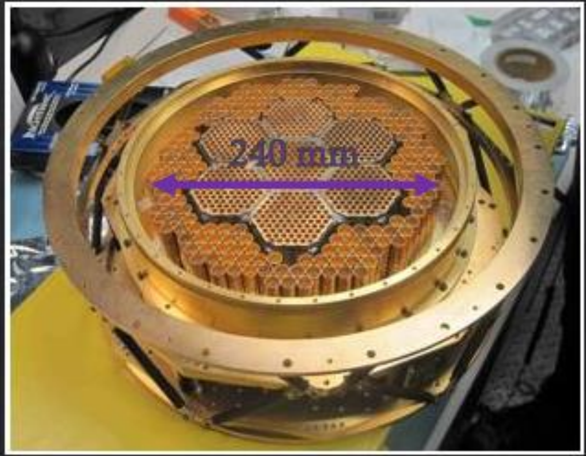
Towards Better Sensitivity…

2007: SPT-SZ
960 Detectors



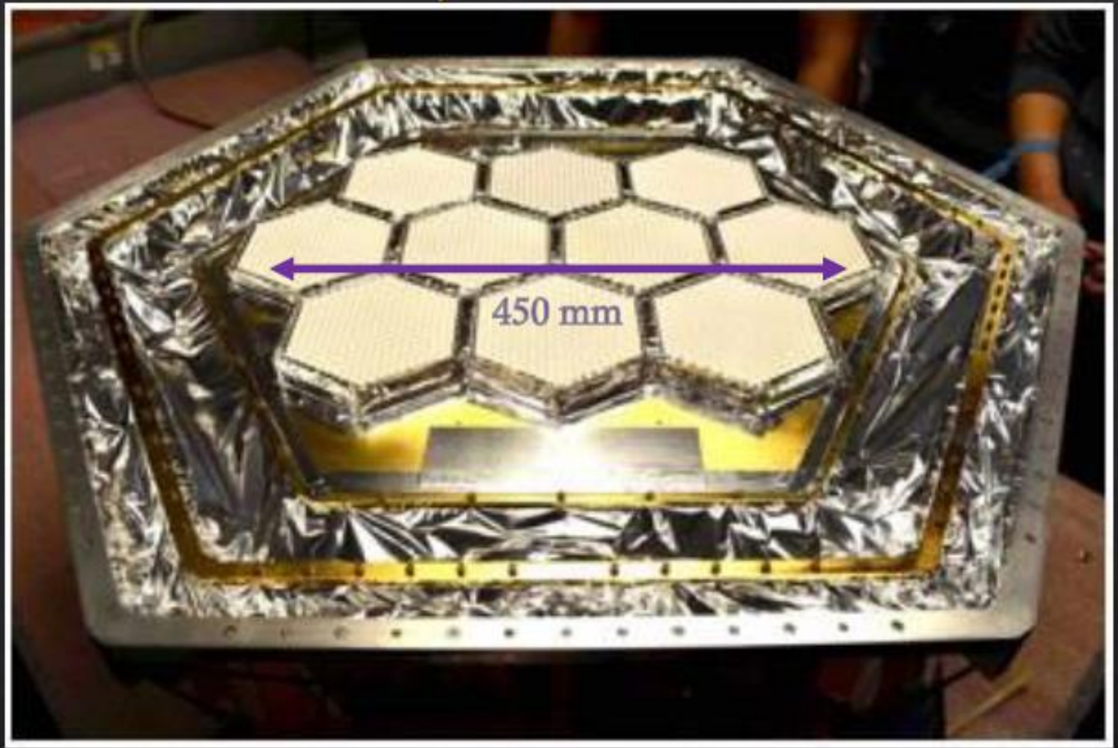
90, 150, 220 GHz

2012: SPTpol
1,500 Detectors



90, 150 GHz + Polarization

2017: SPT-3G
16,000 Detectors



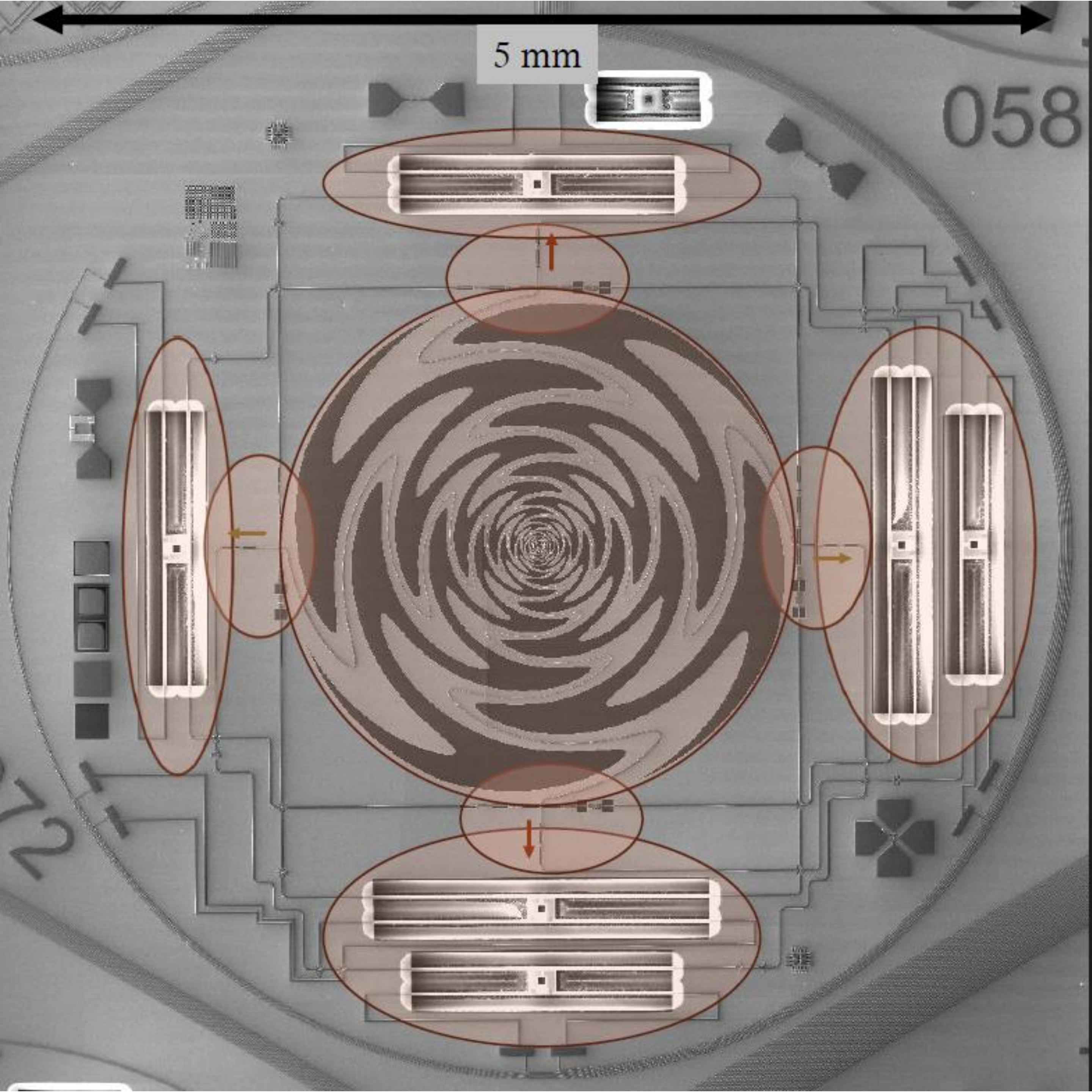
90, 150, 220 GHz + Polarization
(but in every pixel…)

Shot Noise → More Detectors

Foregrounds → More Frequency Coverage

SPT-3G Design Motivations

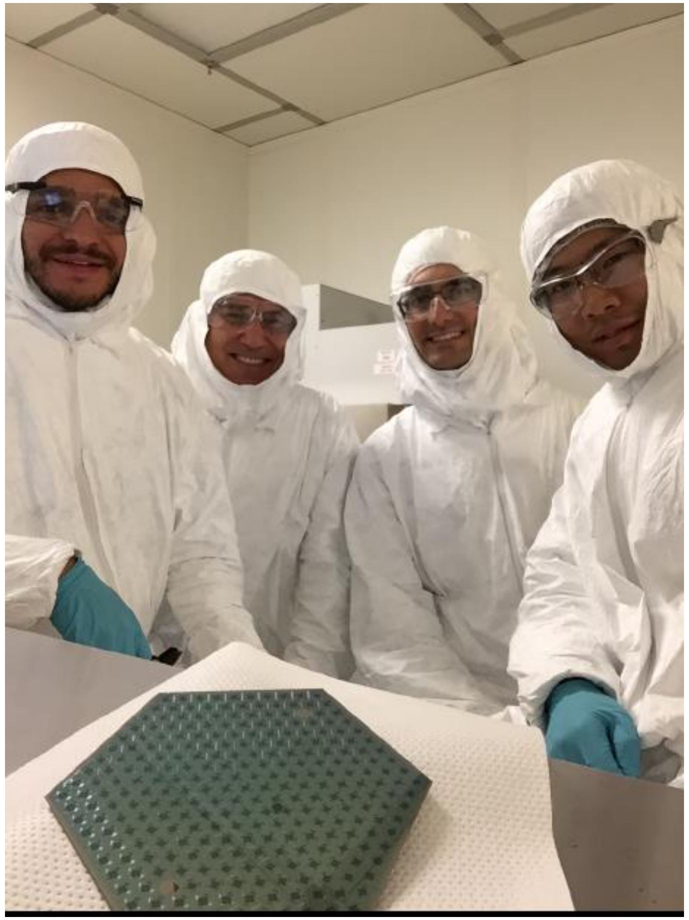
1. **Detectors**: *Tri-chroic dual-polarization pixels*
2. **Readout**: *68x frequency-domain multiplexing*
3. **Optics**: *Larger focal-plane with 3-band frequency coverage*



SPT-3G Pixel Architecture

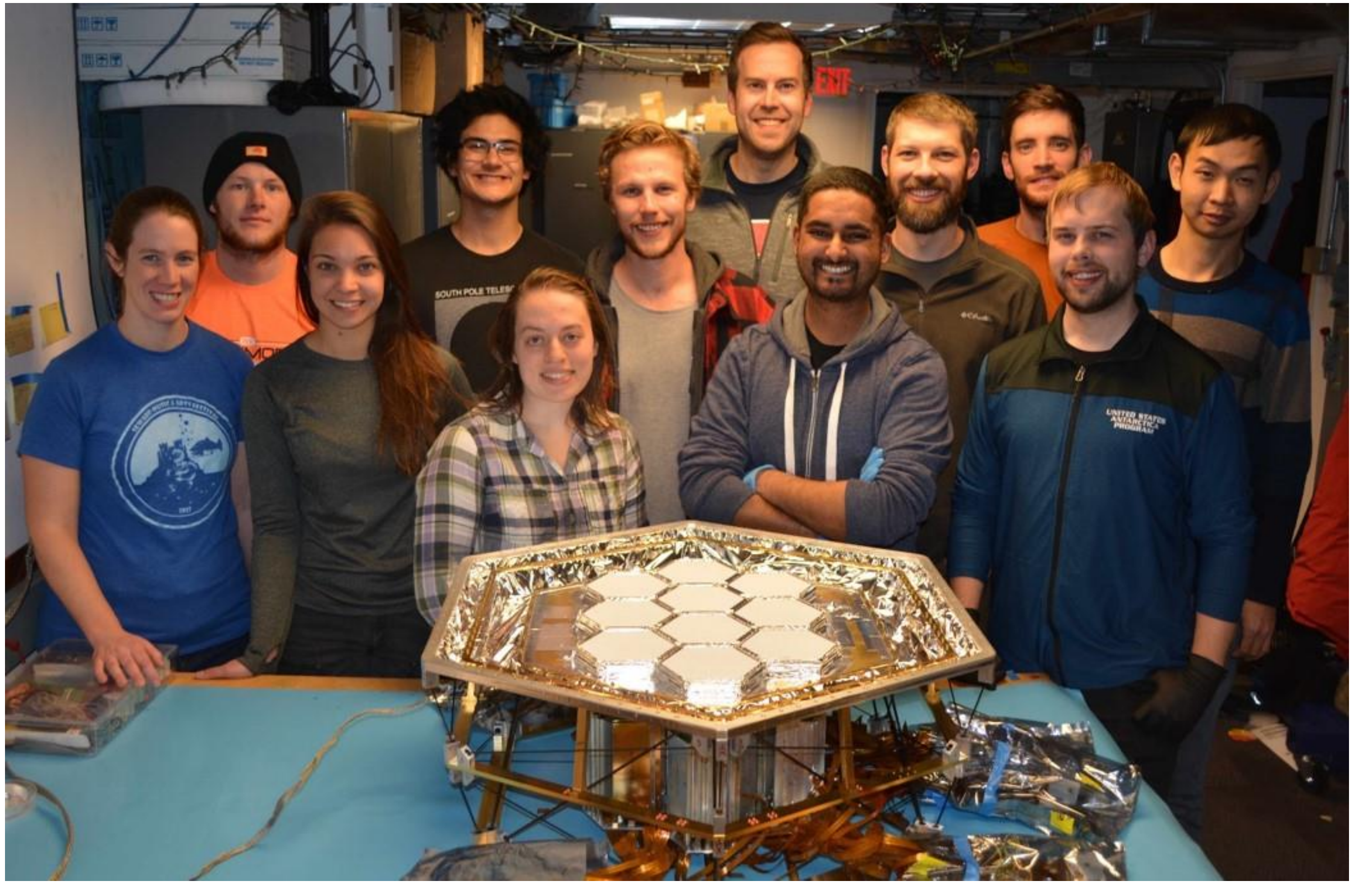
- Broadband Sinuous Antenna
- Superconducting Nb microstrip
- In-line band-defining filters
- 6 TES Bolometers
  - (95, 150, 220 GHz) x (2-Polarizations)
  - Transition-edge at ~500 mK

269 Pixels per Wafer

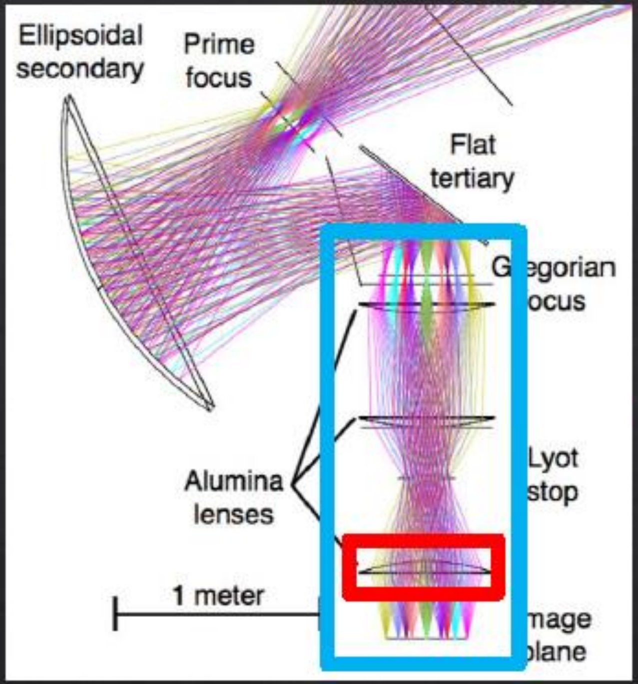


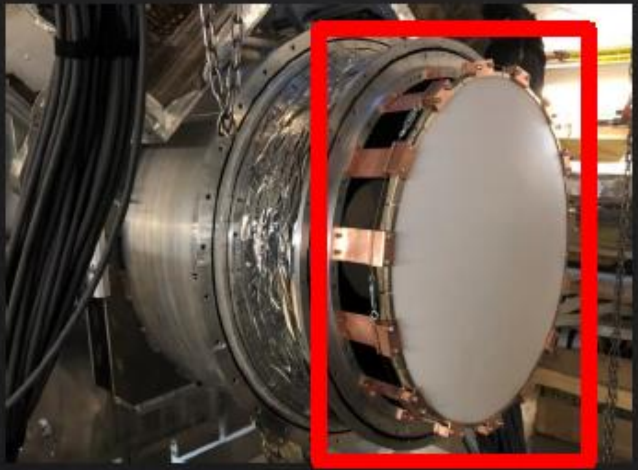
Superconducting LC resonators in-line with each detector

10 detector modules installed across focal plane

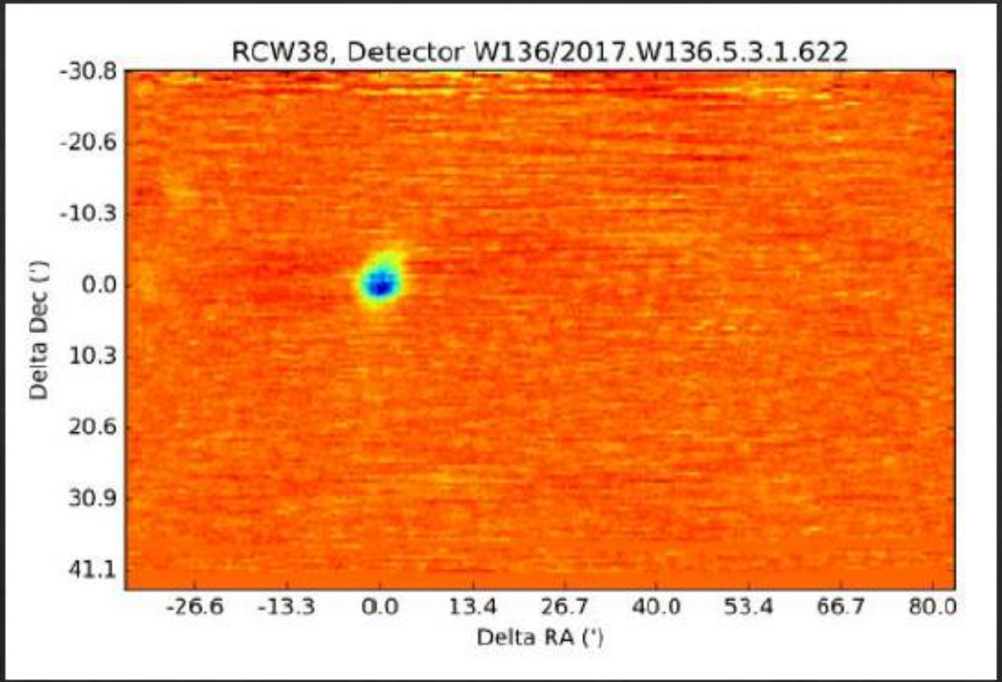


Coupling the Array to the Sky





- 450 mm focal-plane with 1.89 deg field-of-view comprised of arcminute beams
- Cold re-imaging optics consisting of 720 mm alumina elements at 4 K
- Layered Teflon anti-reflective coating designed for low scattering across desired bandpass at low temperatures



Instrument Status

- *SPT-3G First Light – January 30th, 2017*
- *Began 1500 deg^2 survey in February 2018*

Preliminary work indicates that 3G's array mapping speed is several times faster than SPT-Pol for both temperature and polarization!