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)
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...
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

**Atacama CMB (Stage II & III)**
- **CLASS 1.5m x 4**
  - 72 detectors at 38 GHz
  - 512 at 95 GHz
  - 2000 at 147 and 217 GHz

- **Simons Array**
  - (Polarbear 2.5m x 3)
  - 22,764 detectors
  - 90, 150, 220, 280 GHz

**ACT 8m**
- AdvAC Tpol:
  - 88 detectors at 28 & 41 GHz
  - 1712 at 95 GHz
  - 2718 at 150 GHz
  - 1006 at 230 GHz

**South Pole CMB (Stage II & III)**
- **10m South Pole Telescope**
  - SPT-3G: 16,400 detectors
  - 95, 150, 220 GHz

- **BICEP3**
  - 2560 detectors
  - 95 GHz

**KECK Array**
- 2500 detectors
- 150 & 220 GHz
- pending:
  - ~29,000 detectors
  - 35, 95, 150, 220, 270 GHz

*Photo credit: Rahul Datta & Alessandro Silich*
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

Resistor (T-dependent)

Absorber

Antenna

CMB Photons

Cold Thermal Sink with Infinite Heat Capacity
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...
SPTpol

50 deg$^2$
150 GHz

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

6X Finer Angular Resolution
6X Lower Noise
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
Preliminary work indicates that 3G’s array mapping speed is several times faster than SPT-Pol for both temperature and polarization!