CMB Measurements Probe Cosmology and Fundamental Physics

1) Inflation
   - Spectral index of fluctuations
   - Non-Gaussianity
   - *Energy-scale of Inflation (10^{16} \text{ GeV})*, from B-mode polarization

2) Neutrinos
   - Measure the relativistic energy density of the Universe, and any "Dark Radiation" (e.g., Sterile Neutrinos)
   - *Sum of the neutrino masses*, through their impact on the growth of structure, CMB lensing and clusters of galaxies

3) Dark Energy
   - "Early" dark energy
   - Clusters of galaxies
   - Tests of General Relativity
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

- 100, 150, 220 GHz
- 1.6, 1.2, 1.0 arcmin resolution

2007: SPT-SZ
960 detectors
100, 150, 220 GHz

2012: SPTpol
1600 detectors
100, 150 GHz
+Polarization

2016: SPT-3G
~16,200 detectors
100, 150, 220 GHz
+Polarization

Funded by:

[Logos of funding bodies]
To deploy in Nov. 2016!

- 16,200 Transition Edge Sensor (TES) bolometers operating at 250 mK
- Multi-chroic pixels sensitive to 95, 150, 220 GHz band

Funded by:

- The SPT-3G Collaboration (Feb. 2016)
- ~70 scientists (~half postdocs and students)
- across ~20+ institutions

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2013: Planck
30\(\mu\)K RMS fluctuations on 3 K background

Credit: ESA (Planck)
Planck
143 GHz
50 deg²

The moon
(for scale)
SPTpol
150 GHz
50 deg²

6x finer angular resolution
6x deeper

The moon (for scale)
Point Sources
Active galactic nuclei, and the most distant, dust-obscured star-forming galaxies

SPTpol
150 GHz
50 deg²

z=2.782
HST-WFC3
ALMA
Clusters of Galaxies

"Shadows" in the microwave background from clusters of galaxies:
The Sunyaev-Zel’dovich (SZ) effect
The CMB implies a Universe dominated by dark matter and dark energy ($\Lambda$CDM model)

Wavelength [Mpc]

- CMB constraints on baryon and cold dark matter density:
  - $\Omega_b h^2 = 0.02207 \pm 0.00027$
  - $\Omega_c h^2 = 0.1198 \pm 0.0026$
  - 40-$\sigma$ offset between the amount of matter ($\Omega_c$) and baryons ($\Omega_b$)!

Fluctuation Power [$\mu$K$^2$]

$l =$ oscillations per 360 degrees
Dark Energy and Sunyaev-Zel’dovich (SZ) Effect Discovered Clusters

- First SZ-discovered clusters found in 2008 (SPT, Staniszewski+2008), now >1000 SZ-identified clusters
- SZ uniquely provide “clean” samples of the most massive, high-redshift clusters of galaxies

(SPT) Bleem et al. 2014
**ACT-CL/SPT-CL J0102-4915: “El-Gordo”**

“**Rarest** cluster in universe;** At** $z=0.87$ with mass, $M_{200}$, $\sim 3 \times 10^{15} \, M_{\text{sun}}$, above this mass and redshift only 1 cluster expected in Universe.

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**Chandra (X-ray)**

**Galaxy Density**

Clusters provide complementary constraints to other DE probes (BAO, SNe)

Combined constraint on DE equation of state \( w = -1.02 +/- 0.04 \)

Clusters measure structure growth

Combined cosmological constraint on sum of the neutrino masses of 0.14 +/- 0.08 eV

(SPT) de Haan et al. 2016
Synergy with Dark Energy Survey (DES)

- DES originally motivated as optical follow-up survey for SPT
- 4000 deg² of overlap between SPT and DES surveys.
- Strong synergy between CMB and Optical surveys (e.g., SPT+DES, CMB-S4+LSST).
- Cross correlation of observables can contain additional information, control systematics:
  - CMB lensing
  - SZ maps
  - Galaxy and cluster density
  - Optical lensing
Synergy with Dark Energy Survey (DES)

- Cross correlation of CMB lensing and galaxy density can probe evolution of structure (i.e., $\sigma_8(z)$)
- **Powerful test of the physics of dark energy and general relativity**

Omuri, Simard, Chown, Holder (SPT,DES)

Bocquet (SPT,DES)
Detector sensitivity has been limited by photon “shot” noise for last ~15 years; further improvements are made only by making more detectors!
**SPT-3G: A New Camera for the SPT**

- **To deploy in Dec. 2016!**
- 16,260 transition edge sensor (TES) bolometers at 250 mK
- Using lenslet coupled, 3-band (95, 150, 220 GHz) sinuous antenna coupled TES detector design from UCB (Suzuki et al, 1210.8256)
- 4-year survey (2017-2020) to cover 2500 deg$^2$
SPT-3G: A New Camera for the SPT

- Camera Cryostat Integration at Fermilab
- Alumina Lenses cooled to 4 K in Optics Cryostat
- Detectors cooled to 250 mK in SPT-3G Cryostat
**SPT-3G Survey (2017-2020)**

**EE-Spectrum**

- Planck
- SPTpol
- SPT-3G

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**BB-Spectrum**

- SPTpol
- SPT-3G (delens)

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**SPT-3G Survey:**

- 4-year survey, over 2500 deg$^2$ sky area:
- 150-σ detection of CMB lensing,
- Detect 10,000 clusters via the Sunyaev-Zel’dovich (SZ) effect,
- Constrain cosmology (see table)
- Overlap with BICEP/KECK survey, to provide CMB “de-lensing” to improve “r” constraints

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<table>
<thead>
<tr>
<th>(with Planck priors)</th>
<th>SPT-3G (2019)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(r)$</td>
<td>0.011</td>
</tr>
<tr>
<td>$\sigma(N_{\text{eff}})$</td>
<td>0.058</td>
</tr>
<tr>
<td>$\sigma(\Sigma m_\nu)$</td>
<td>0.061 eV*</td>
</tr>
</tbody>
</table>

*Includes BOSS prior

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8/6/2016  Bradford Benson | The South Pole Telescope
Summary

• High-angular resolution and depth of SPT-SZ, SPTpol data has provided new constraints on CMB power spectrum, CMB lensing, abundance of massive clusters.

• Strong synergies between optical and CMB surveys probing structure growth (e.g, DES+SPT).

• SPT-3G to deploy in Dec. 2016, and will improve SPT mapping speed by an order of magnitude.

• SPT data has provided new constraints on dark energy, neutrino mass; future measurements will provide new, powerful test of LCDM paradigm