CMB power spectrum results from the South Pole Telescope

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Photo: Keith Vanderlinde
Outline

• The South Pole Telescope & survey
• Primary CMB results
• SPT cluster cosmology
Overview

The South Pole Telescope (SPT):

- 10 meter telescope - 1 arcmin resolution at 150 GHz
- 1 deg FOV
- 960 feed-horn coupled, background-limited detectors
- Observe simultaneously in 3 bands - 95, 150, 220 GHz - with modular focal plane

Funded by NSF

Receiver cryostat (250 mK)

Secondary mirror cryostat (10 K)
Overview

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SPT Focal Plane

Modular design: 960 pixels fabricated on six silicon wafers

Incoming radiation is:
- Low-pass filtered (capacitive mesh)
- Coupled to waveguide via smooth-walled conical feedhorns
- High-pass filtered by circular waveguide
- Confined to an integrating cavity
- Absorbed by detector

Erik Shirokoff
Why the South Pole?

- Atmospheric transparency and stability:
  - Extremely dry and cold (average winter temperature below -60 C).
  - High altitude ~ 10,500 feet.
  - Sun below horizon for 6 months.
- Unique geographical location:
  - Observe the clearest views through the Galaxy 24/7/52 “relentless observing”
  - Clean horizon.
- Excellent support from existing research station.
The SPT Survey

- Finish 3-frequency survey of 6% of the sky this November
- Area chosen based on galactic dust and observable elevations
- Active optical & X-ray followup program
- Full DES coverage
What a map looks like

Full survey: 2500 deg$^2$
Noise: 40, 18, 65 μK-arcmin at 95, 150, 220 GHz
Zoom in on 150 GHz map
~4 deg$^2$ of actual data

CMB anisotropies and foregrounds
Galaxy clusters
Point sources
A Brief History of the Universe

Cosmic Microwave Background (CMB) Radiation

~90% photons straight from (easy to model) early universe

Lever arm on geometry

(image modified from NASA/WMAP)
±200 µK

CMB and cosmology

(primary anisotropy)
A dark energy dominated Universe

Komatsu et al 2010

SN BAO CMB

Percival et al 2009

Riess et al 2007

CMB BAO SN

Atoms 4.6%

Dark Energy 72%

Dark Matter 23%
Maps to bandpowers

Beam + Calibration
+ 800 deg$^2$ Map

Pseudo-$C_l$ methods

Power Spectrum
“Pseudo-CI” Analysis

Direct Fourier transform:

\[
\tilde{a}_{\ell m} = \int d\hat{n} \left[ \Delta T^i(\hat{n}) W(\hat{n}) \right] Y_{\ell m}(\hat{n})
\]

\[
\tilde{C}^{ii}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |\tilde{a}_{\ell m}|^2
\]

Need to explicitly account for:
• Experimental beam shape

\[
< \tilde{C}^{ii}_\ell > = B^2_{\ell} < C_{\ell'} >
\]
“Pseudo-Cl” Analysis

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Need to explicitly account for:
• Experimental beam shape
• Filtering of timestream data
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Need to explicitly account for:

- Experimental beam shape
- Filtering of timestream data
- Masking for unwanted sources

\[
< \tilde{C}_{\ell}^{ii} >= \sum_{\ell'} M_{\ell\ell'}[W] F_{\ell'} B_{\ell'}^2 < C_{\ell'} >
\]
“Pseudo-Cl” Analysis

Direct Fourier transform:

\[ \tilde{a}_{\ell m}^{i} = \int d\hat{n} \left[ \Delta T^{i}(\hat{n})W(\hat{n}) \right] Y_{\ell m}(\hat{n}) \]

\[ \tilde{C}_{\ell}^{ii} = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |\tilde{a}_{\ell m}^{i}|^2 \]

Need to explicitly account for:
- Experimental beam shape
- Filtering of timestream data
- Masking for unwanted sources
- Biases introduced by noise

\[ < \tilde{C}_{\ell}^{ii} > = \sum_{\ell'} M_{\ell \ell'} [W] F_{\ell'} B_{\ell'}^2 < C_{\ell'} > + < N_{\ell} > \]
SPT - both primary & secondary CMB

SPT “low ell”
(dominated by primary CMB anisotropy)

SPT “high ell”
(thermal and kinetic SZ cosmic infrared background)
Primary CMB

- Reduces uncertainties by >2 across damping tail
SPT modestly improves 6 "vanilla" cosmo parameters

\[ ns = 0.9663 \pm 0.0112 \text{ (3.0-sigma from 1.0)} \]
CMB Lensing

Introduce $A_{\text{lens}}$ which smoothly scales lensing potential power spectrum:

$$C_\ell^\psi \rightarrow A_{\text{lens}}C_\ell^\psi$$

(lensing smoothes out acoustic peaks)

- $(A_{\text{lens}})^{0.65} = 0.94 \pm 0.15$
- Consistent with $A_{\text{lens}} = 1$.
- 5-6$\sigma$ rejection of $A_{\text{lens}} = 0$.
- Predict 30 $\sigma$ detection for full spt survey & lensing analysis.
- Constrain neutrino mass, early dark energy, modified gravity.
Extensions beyond LCDM

- **Inflation** - *Running* and *Tensor* modes (normally=0, allow to be free)

- **Primordial Helium** (normally determined by BBN, a tight function of $\Omega_b h^2$. Allow to be free).

- **Number of relativistic species** (think neutrinos) (normally 3.046, allow to be free)
Initial conditions

• Tightest constraints on tensor-scalar ratio ($r$), running and $n_s$
• $r<0.21$ (95%), SPT+WMAP7
• $r<0.17$ (95%), SPT+WMAP7+H0+BAO
Primordial Helium

- $Y_p = 0.296 \pm 0.030$ (SPT+WMAP7)

- $7.7\sigma$ rejection of $Y_p=0.$

- $Y_p = 0.296 \pm 0.030$ (SPT+WMAP7)
Number of Relativistic Species

- $N_{\text{eff}} = 3.85 \pm 0.62$ (SPT+WMAP7)
- $N_{\text{eff}} = 3.86 \pm 0.42$ (SPT+WMAP7+$H_0$+BAO)

7.5σ rejection of $N_{\text{eff}} = 0$. 

- $N_{\text{eff}} = 3.85 \pm 0.62$ (SPT+WMAP7)
- $N_{\text{eff}} = 3.86 \pm 0.42$ (SPT+WMAP7+$H_0$+BAO)
One result from the damping tail paper is that the ratio of the damping scale to the sound scale is directly related to $N_{\text{eff}}$. Modulo the small variation in $Y_p$ caused by $\Omega_{\text{Bh}2}$, this says that there is a one-to-one relationship between $N_{\text{eff}}$ and this ratio of angles. To estimate our constraint on $N_{\text{eff}}$, you just need to know our constraint on the angle ratio. It makes sense that SPT can improve upon the measurement of this ratio, because we measure the damping scale much better than WMAP alone, and therefore improve upon $N_{\text{eff}}$. In fact our constraint on $N_{\text{eff}}$, 1-sigma=0.6, can be totally explained by our constraint on this ratio. Hou et al. 2011

\[
\frac{\theta_d}{\theta_s} \approx 0.24(1 + 0.227\ N_{\text{eff}})^{0.22} \frac{1}{\sqrt{1 - Y_p}}
\]
Number of neutrinos

- \( N_{\text{eff}} \):
  - \( > 2.7 \) (WMAP)
  - \( 3.85 \pm 0.62 \) (WMAP+SPT)
Tension with measures of structure

Data prefers $N_{\text{eff}} > 3$ (1.8-sigma)

Such models need high $\sigma_8$

- $N_{\text{eff}}$: $3.42 \pm 0.34$ (WMAP+SPT+BAO+Clusters)
Hold on - massive neutrino’s

- Can have a lower and “more reasonable” $\sigma_8$, like 0.8, if you allow for Sum of $m_{\nu} \sim 0.3$ eV.
Allowing for (not very) massive neutrinos decorrelates $N_{\text{eff}}$ and $\sigma_8$, at no expense to $N_{\text{eff}}$ constraint.
Take Away #1

- SPT has mapped out the CMB damping tail, in order to detect gravitational lensing, and measure the number of relativistic species (among other things).

Read more in astro-ph/1105.3182
Probing dark energy with galaxy clusters

Counting dark spots (galaxy clusters) to probe dark energy

Back to the SPT map
Sunyaev-Zel’dovich Effect:
CMB photons provide a backlight for structure in the universe.

- **Thermal**: 1-2% of CMB photons traversing galaxy clusters are inverse Compton scattered to higher energy

- **Kinetic**: Doppler shift from motion of cluster
SZE Surveys

Use SZE as a Probe of Structure Formation and to provide nearly unbiased cluster sample

- Surface brightness independent of redshift
- Total flux proportional to the total thermal energy of cluster (expected to be good mass proxy)
Cosmology with Galaxy clusters

Cluster Abundance, $\frac{dN}{d\Omega dz}$

$$\frac{dN}{d\Omega dz} = n(z) \frac{dV}{d\Omega dz}$$

Growth

Volume

Cluster $dN/dZ$ with Mass $> M$

eRosita future x-ray limit

Chris Greer
Cosmology with Galaxy clusters

Cluster Abundance, dN/dz

\[ \frac{dN}{d\Omega dz} = n(z) \frac{dV}{d\Omega dz} \]

Growth

Depends on:
Matter Power Spectrum, \( P(k) \)
Growth Rate of Structure, \( D(z) \)

Volume

Depends on:
Rate of Expansion, \( H(z) \)

\[ \rho(z) = \rho_0 (1+z)^{3(1+w)} \]
where \( w = \rho/p \) is eqn. of state

\[ \frac{dN}{dz} \]

Credit: Joe Mohr
SPT cluster sample

- Over 300 optically confirmed candidates
  - ~80% new discoveries
  - Confirmed 95% purity at >5 sigma
- High redshift, <z> ~0.5 - 0.6
- $M_{500}(z=0.6) = 3\times10^{14} M_o / h_{70}$ (lower at higher z)
Early results from SPT

Vanderlinde+, 2010

- Only 21 clusters!
- Constraints limited by mass calibration (but early days)
SPT significance as a Mass Proxy

- $Y_{sz}$ should have low (~7%) scatter with mass (Kravstov, Vikhlinin, Nagai 2006)
- However, poor constraints on cluster amplitude and angular size with low significance detections
- Signal-to-noise in spatial filtered map is mass proxy (Vanderlinde et al 2010)
- Use simulation based priors on this scaling relation (~25% one-sigma prior on mass calibration)
Multi-wavelength Observations: Mass Calibration

SZ-mass scaling relation needs precise and unbiased mass calibration *AT ALL REDSHIFTS.*

Multi-wavelength mass calibration campaign, including:

- X-ray with Chandra and XMM (PI: Benson, Andersson, Vikhlinin)
- Weak lensing from Magellan (0.3 < z < 0.6) and HST (z > 0.6) (PI: Stubbs, High, Hoekstra)
- Dynamical masses from NOAO 3-year survey on Gemini (0.3 < z < 0.8); VLT at z > 0.8
SPT Cosmological Constraints with X-ray

- Developing full cosmological MCMC to jointly fit cosmology, $Y_x-M$, $\xi-M$ relations, using priors from Vikhlinin et al (2009)

- X-ray measurements reduce mass uncertainty from 25% to 10%

- Improves 21 cluster cosmological constraints on $\sigma_8$ by $\sim50\%$ and $w$ by $\sim30\%$
Future constraints with SPT+Xray

SPT 2500 deg² survey with ~450 clusters at 5 sigma
X-ray based mass calibration with 5% mean from 80 clusters - Chandra XVP

Constrain $\sigma_8$ to 1.2%; $w$ to 4.6%

Independent of geometric constraints (SN/BAO)
Note: 3.3% systematic uncertainty in $w$ due to mass calibration
Take Away #2

- SPT has discovered hundreds of real, massive clusters. Observations underway will accurately determine the mass calibration at all redshifts, enabling strong constraints on dark energy.
SPTPol: CMB polarization

- Building 760 pixel polarimeter for SPT
- Scheduled to deploy this winter
- 3x mapping speed of current receiver

600 deg$^2$

SPTpol 3 year projections:
- $\sigma(\Sigma m_\nu) = 0.15$ eV (from ps)
- 2$\sigma$ detection limit of $r = 0.023$

Deploy in 2011
Snow sculpture at the South Pole

The End