Tracing Ionized Gas over cosmic time with the Sunyaev-Zel’dovich Effect

Shaw et al. (09,10)
Shirokoff et al. (10)

Collaborators: D. Nagai, D. Rudd (Yale), G. Holder (McGill), Suman Bhattacharyya (LANL), O. Zahn (Berkeley), O. Dore (CITA/Caltech), SPT team.
My lucky-to-be-alive car
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Outline

1. Small-scale CMB overview
   ★ thermal & kinetic SZ power spectrum
   ★ foregrounds

2. SPT measurements of tSZ power spectrum

3. Improved modelling of the tSZ power spectrum

4. Constraining the Epoch of Reionization with SPT and Herschel
Primary CMB Anisotropies

Rapid progress in resolution and sensitivity of observations

Planck
(25 papers on astro-ph today!)
Current CMB Power Spectrum

- Completely consistent with standard $\Lambda$-CDM models

$D_\ell = \ell(\ell + 1)C_\ell / 2\pi$

\[P_{\nu}(\mu K^2)\]

sound waves

baryon loading

photon diffusion

initial conditions

Planck measurements of primary CMB anisotropies will be cosmic-variance limited to $\ell l \sim 2500$

Reichardt et al. 2008
Falling down the damping tail

WMAP7, Larson et al. (10)

ACBAR, Reichardt et al. (08)

10'

5'

4'

Planck

Smaller angular scales (<5’) are still to be explored experimentally

Secondary Anisotropies!
The South Pole Telescope (SPT)

Sub-millimeter Wavelength Telescope:

- 10 meter telescope (1’ FWHM beam at 150 GHz)
- Off-axis Gregorian optics design
- 1 sq. deg FOV
- Observe in 3 bands: 90, 150, 220 GHz

Principle Science Goals

- discovery of ~1000 clusters out to high-redshift
- cosmological constraints via cluster abundance
- measure cmb temperature anisotropies to \( l = 10,000 \)
- detection CMB lensing
- detect high-redshift, star-forming galaxies

Final survey area will be 2500 deg\(^2\) by end of 2011 (currently ~3/5 complete)
Small scale signals in the mm band

![Graph showing power spectrum for 150 GHz with different contributions labeled: Sky total, CMB, tSZ, kSZ + patchy reionization, clustered point sources, Poisson point sources. The graph highlights the impact of various physical processes on the power spectrum and includes annotations for primary CMB (lensed) and clustering of DSFGs.]
The tSZ Effect
CMB photons provide a backlight for structure in the universe.

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

- Surface Brightness of the SZ effect independent of redshift

\[ \frac{\Delta T_{\text{cmb}}}{T_{\text{cmb}}} = f_\nu(x)y = \left( \frac{k_B \sigma_T}{m_e c^2} \right) \int n_e(l) T_c(l) dl \]
Statistical detection of SZ by searching for anisotropy power at small angular scales

tSZ is the dominant source of CMB anisotropy power for $\ell > 3000$ in the $\mu$m

Sensitive to both the abundance of collapsed structures and astrophysics of intra-group and cluster medium
Cosmology Dependence

Amplitude of SZ power spectrum is particularly sensitive to matter power spectrum normalization

\[ C_\ell \propto \sigma_8^7 (\Omega_b h)^2 \]

Exact cosmological scaling depends on relative mass and redshift contributions of structures and thus astrophysics of ICM
Models / Simulations of tSZ power spectrum

Hydrosimulations
(Mare Nostrum & K. Dolag)

Analytic / Semi-analytic models
Shaw+ (09)
Komatsu & Seljak (02)
Sehgal+ (10)

All normalized to $\sigma_8 = 0.8$

Models typically predict 7 - 10 $\mu K^2$ at $l = 3000$
The kSZ Effect
‘Kinetic’ SZ Effect

Three components:

post-reionization components

– low redshift \((z < 3)\) ‘ksz’ from non-Gaussian structures (clusters)

– linear over-densities at higher redshift, \(3 < z < \sim z_{\text{rei}}\), [also known as the Ostriker-Vishniac effect]

kinetic signal from reionization

– Inhomogeneous (or patchy) reionization
post-reionization kSZ power spectrum

simulated ksz map

10deg

\[ \left( \frac{\Delta T}{T_{CMB}} \right)_{ksz} = -\frac{\sigma_T}{c} \int n_e v_{los} dl \]

does not depend on \( T_{gas} \) -> significant contribution from low-density gas

kSZ signal expected to be a factor of ~5-10 less than tSZ
Astrophysical Foregrounds

Radio Sources
Synchrotron dominated
Flux decreases with frequency

$$\alpha \approx -0.5$$

Dusty star-forming galaxies
Dusty dominated (thermal)
Flux increases with frequency

$$\alpha \approx 3$$

Galactic Stuff
dust emission
debris disks
cold galactic blobs

$$\alpha \approx 3$$

$$S_\nu \propto \nu^\alpha$$
SPT can detect and mask sources > 6 (10) mJy at 150 (220) Ghz

At 150 Ghz, can mask bright radio sources, rest not expected to contribute much power

However, dusty sources are a major contaminant!

\[ C_\ell = \int_0^{S_{cut}} S^3 \frac{dN}{dS} d(lnS) \]
Dusty Star-forming Galaxies

Negative K-correction means that sources over incredibly wide redshift range contribute to signal at 150Ghz.

DSFG’s also expected to be clustered, providing an additional anisotropy signal with similar shape to SZ!

multi-frequency information is crucial to separate clustered dusty sources from SZ signal!

150 Ghz
Hall et al. (2010)
2) SPT measurements of small scale CMB temperature anisotropies
Zoom in on 2 mm map
\( \sim 4 \text{ deg}^2 \) of actual data

\( \sim 15 \text{ sigma SZ cluster} \)

"large-scale" fluctuations are primary CMB

Bright emissive point sources
Dusty star-forming galaxies
AGN / Blazars
Primary CMB measurements

secret preview!

\[ \ell (\ell + 1) C_\ell / 2\pi \ \text{[\mu K}^2] \]

- WMAP7
- SPT
- This work

\[ \ell / 1000 \]
2008 SPT measurements of high-ell spectrum

excellent agreement between experiments

92 sigma detection of small-scale anisotropy power

(200 deg$^2$)

200 deg$^2$ to depth of 18μK-arcmin at 150Ghz and 40μK-arcmin at 220Ghz
Simultaneously fit models for primary and secondary anisotropy signals to multi-frequency data via monte-carlo markov chains.
Interpreting the SZ amplitude

Measured tSZ amplitude is significantly lower than predicted from models and hydro simulations for $\sigma_8 = 0.8$ [Sehgal et al. 10, Shaw et al. 09, Komatsu & Seljak 02, White, Hernquist & Springel 01 Mare Nostrum (pc, Oliver Zahn)].

**Predictions from models and hydro simulations for $\sigma_8 = 0.8$**
[Sehgal et al. 10, Shaw et al. 09, Komatsu & Seljak 02, White, Hernquist & Springel 01 Mare Nostrum (pc, Oliver Zahn)]

**Tsz amplitude at ell = 3000, $<D_{3000}> = 3.5 \pm 1$**

**Measured tSZ amplitude is significantly lower than predicted**
Consequences of low tSZ

**Spatial Correlation**
- Foregrounds
  - If clusters host large numbers of star-forming galaxies at high-z, these would ‘fill in’ the SZ signal.

**tSZ Modelling**
- models overestimate tSZ signal
  - thermal pressure of intra-group and cluster gas lower than predicted

**Cosmology**
- $\sigma_8$ lower
  - $\sigma_8 \sim 0.76$ would be sufficient. This would provide some tension with other probes; measurement of the primary CMB anisotropies find $\sigma_8 = 0.821 \pm 0.025$
Where does SZ power come from?

Low mass, high redshift contribution significant.

Direct Observations

\begin{tabular}{|c|c|}
\hline
\text{z>0.6} & \text{none} & \text{few} \\
\hline
\text{z<0.6} & \text{few} & \text{lots} \\
\hline
\end{tabular}

\begin{equation}
M_{500} = \frac{M_\odot}{h}
\end{equation}
Predicting the tSZ Power Spectrum

• Analytic calculations
  • adopt a halo mass function (e.g. Tinker et al. 08)
  • combine with template gas pressure profile (e.g. Komatsu and Seljak 02)
  • can evaluate uncertainty in tSZ signal as well as cosmological scaling

• Numerical simulations
  • don’t need to ‘assume profiles’ or hydrostatic equilibrium
  • follow detailed hydrodynamical evolution of gas in clusters (+ radiative cooling, star-formation, AGN, ...)
  • Need very big simulation boxes!
Simulations require large volumes

- variance in $c_1$ between fields is non-gaussian
- several times greater than gaussian (cosmic) variance
- additional information contained in trispectrum

Shaw+ (09)
Halo model approach to calculating the tSZ power spectrum

Calculate SZ power spectrum by integrating the mass function over $M$ and $z$, weighted by cluster signal at a given angular scale.

$$C_l = g_\nu^2 \int_{0}^{z_{max}} dz \frac{dV}{dz} \int_{0}^{M_{max}} dM \frac{d\eta(M, z)}{dM} |y_l(M, z)|^2$$

volume integral
cluster mass function
gas thermal pressure profiles in fourier space
Modelling the tSZ Power Spectrum

Simple parameterized model, calibrated to observations and including cosmological scaling [Shaw+ (10)]

★ Gas resides in hydrostatic equilibrium in NFW dark matter halos with polytropic EoS

\[
\frac{dP_{tot}(r)}{dr} = -\rho_g(r) \frac{d\Phi(r)}{dr}
\]

\[P_{tot} \propto \rho_g^\Gamma\]

★ Assume some gas has radiatively cooled + formed stars. Stellar mass fraction constrained by observed relations [Giodini+ (09), Gonzalez+ (07)]

★ Include simple parameterization for energy feedback from AGN. Assume feedback energy proportional to stellar mass

\[E_f = \epsilon_f M_\star c^2\]
Including non-thermal pressure support

Hydrodynamical simulations demonstrate significant levels of bulk/turbulent motions in ICM.

\[
\frac{P_{nt}}{P_{tot}}(z) = \alpha(z) \left( \frac{r}{R_{500}} \right)^{n_{nt}}
\]

where \( \alpha(z) = \alpha_0 (1 + z)^\beta \)

calibrate params with hydro sims

\( \alpha_0 = 0.18, \; \beta = 0.5, \; n_{nt} = 0.8 \)

18% at \( R_{500} \) and \( z = 0 \)

\( P_{nt} \) enhanced at high \( z \), and at larger radii
Comparison with X-ray observations

Good match to pressure profiles measured by XMM

mass - gas fraction relation

increasing feedback

Baryon fraction constrains feedback

increasing non-thermal pressure

$P_e/P_{500}(r/R_{500})^3$

$10^{-2}$

$10^{-1}$

$1$  $2$  $3$  $4$  $r/R_{500}$

blue: Arnaud+ (09)
red: Vikhlinin+ (09)
blue: Sun+ (09)

red: Vikhlinin+ (09)
blue: Sun+ (09)
Impact of cluster physics on the SZ Power Spectrum

- Feedback effects power spectrum on small scales.
- Non-thermal pressure suppresses power principally on large scales.

![Graph showing the impact of feedback on the SZ Power Spectrum with different models and scales.](image)

Shaw+ (10)
Comparison with simulations

Model can reproduce results of hydro-simulations that incorporate different levels of ICM physics
constraints with models

our analytic model

simulations of Battaglia + (10)

\[ A_{tSZ}(\kappa_i) = \frac{D_{tSZ}^{3000}}{\Phi_{tSZ}^{3000}(\kappa_i)} \]

Power Measured

Power Predicted | Cosmology

NB: \( \sigma_8 \) determine entirely from primary CMB signal
Joint Sigma8 plots

\[ \sigma_8 = 0.821 \pm 0.025 \text{ (primary CMB-only)} \]

Importance sample chains imposing prior of \( A_{sz} = 1 \) (+- 10\% sample variance) reduces \( \sigma_8 \) to

- analytic model inc. \( P_{nt} \): \( \sigma_8 = 0.799 \pm 0.014 \)
- hydro simulations inc. AGN: \( \sigma_8 = 0.786 \pm 0.014 \)

Spread of \( \sigma_8 \) values obtained from different templates is equivalent to systematic errors. Account for this by including additional 50\% ‘theory uncertainty’

combined constraint including theory uncertainty: \( \sigma_8 = 0.812 \pm 0.022 \)
Measuring the Epoch of Reionization

_Herschel-SPIRE + SPT deep field_

- SPIRE maps are nearly confusion limited in a single observation.
- SPT 100 deg^2 deep field is the deepest mm map in existence and will remain so for the next decade.
- We have been granted 79 hours to map a 100 deg^2 field. Maps are 8x redundant and fully cross linked.
- The SPT Deep Field will be enable many statistical measurements of large scale structure and the high redshift universe.

The HOTAC called this proposal a "must-do"
Patchy Reionization

At $z \sim 20$ reionized patches begin to form around early galaxies/AGN.

These ‘bubbles’ are moving relative to CMB and thus impart a kSZ signal.

But how long did the epoch of reionization last?
Patchy reionization

The duration of the epoch of reionization increases “patchy power” (although bubble size, bias, radiative efficiency also matter)

Sensitive, high-resolution measurements of CMB can probe physics of reionization!
SPT + Herschel can constrain EoR via kSZ

- Limit from $z \sim 6$ quasars
- Current limit from SPT
- $z_{\text{rei}}$ set by WMAP measure of optical depth
- SPT + Herschel limit

plot by Matt McQuinn
Wrap-Up

• New few years very exciting for CMB physics.

• Precision measurements of primary and secondary anisotropies by Planck/SPT/ACT

  » tsz, ksz, reionization, cmb lensing, polarization

• SPT measurements of tSZ signal found significantly less power than expected by many models and simulations
  – can mitigated by inclusion of non-thermal pressure in models / AGN in hydro-simulations
  – joint tSZ + CMB constraints on sigma8 yield $\sigma_8 = 0.812 \pm 0.022$
    but this is dominated by modeling uncertainty

• Together these provide window onto inflation, initial conditions, growth of structure, reionization, galaxy formation, WHIM, ICM
CMB Temperature Anisotropy for busy people

• Largest scales: super-horizon potential fluctuations on the surface of last scattering.

• Intermediate (~1°) scales: potential fluctuations seed oscillations in tightly coupled matter-radiation fluid.

• Sub-degree scales: coupling not perfect; photon diffusion damps smaller fluctuations.