The Sunyaev-Zel’dovich Effect and Large-Scale Structure

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Outline

- Thermal SZ (tSZ) Effect
- Probing LSS and Gastrophysics
- tSZ x Gravitational Lensing
- tSZ Statistics: Power Spectrum and Beyond
- tSZ Stacking: the Y-M Relation
- Future: the tSZ Monopole
Thermal SZ Effect

Change in temperature of CMB photons due to inverse Compton scattering off hot electrons, most of which are in the intracluster medium (ICM) of galaxy groups/clusters.

\[ \tilde{T} = g_v \frac{\sigma_T}{m_e c^2} \int P_e(l) dl \]

Temperature fluctuation  \( \frac{\tilde{T}}{T_{\text{CMB}}} \)

Spectral function  \( g_v \)

Electron pressure profile  \( P_e(l) \)

Line-of-sight integral  \( \int P_e(l) dl \)

Compton-y

SZA Collaboration
Thermal SZ Effect

Unique spectral signature

![Graphs showing intensity vs. frequency and change in intensity with frequency.]

\[\text{ACT}\]

Carlstrom+ (2002)
Thermal SZ Effect

simulation
Probing Large-Scale Structure

tSZ effect in the context of LSS — strongly dominated by halos from N. Battaglia hydro sim.
Probing Large-Scale Structure

tSZ effect in the context of LSS — strongly dominated by halos

from N. Battaglia hydro sim.
Probing Large-Scale Structure
dependence on intracluster medium “gastrophysics”

from N. Battaglia hydro sim.
Probing Large-Scale Structure dependence on intracluster medium “gastrophysics”

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Probing Large-Scale Structure dependence on intracluster medium “gastrophysics”

depending on intracluster medium “gastrophysics” from N. Battaglia hydro sim.

Compton-y \times T_{\text{CMB}} \times -2 (R-J limit)

from N. Battaglia hydro sim.

Cooling+SF - AGN Feedback
Probing Large-Scale Structure
dependence on cosmological parameters (esp. $\sigma_8$)

$\sigma_8=0.834$, $\Omega_m=0.318$

$\sigma_8=0.810$, $\Omega_m=0.272$

McCarthy+ (2014)
tSZ x Lensing
tSZ x CMB Lensing

Probe relationship of hot, ionized gas and matter density

Analysis using Planck 2013 data

\[ \kappa_L = \frac{L(L+1)}{2} \phi_L \]

ILC Compton-y Map

Galactic North

Galactic South

JCH & Spergel (2014)
tSZ x CMB Lensing

$y \times \phi_{\text{CMB}}$

cross-power

$\ell^2 (\ell + 1) C_{\ell}^y \phi / 2\pi$

$\ell$

multipole

JCH & Spergel (2014)

pre-CIB sub.
post-CIB sub.
fiducial (1h)
fiducial (2h)
fiducial (tot)

6.2σ
Interpretation

\[ \sigma_8 (\Omega_m/0.282)^{0.26} = 0.814 \pm 0.029 \]

- Contribution of diffuse, unbound gas
- Halo model
- Hydro sims

\( y \times \phi_{\text{CMB}} \) cross-power

Battaglia, JCH, & Murray (2014)
van Waerbeke, Hinshaw, Murray (2014)
tSZ x CFHTLenS

\[ y \times \phi_{\text{gal}} \]

real-space cross-corr. function

lower $\sigma_8$ preferred, but note points are highly correlated

Battaglia, JCH, & Murray (2014)
Takeaway

• It is extremely difficult to probe “missing baryons” with tSZ measurements, including tSZ x lensing. (instead: kSZ — see Blake Sherwin’s talk + Planck XXXVII (2015))

• However, these measurements are a powerful probe of the ICM electron pressure profile, i.e., of gastrophysical feedback models.

Planck tSZ x S3 CMB lensing, S4 galaxy lensing

| Parameter                              | Error   |
|----------------------------------------|---------|
| $P_0$ (pressure profile amplitude)     | +/- 22% |
| $\beta$ (pressure profile outer slope) | +/- 4%  |
| $\alpha_z$ (z-dependence of amplitude) | +/- 13% |
tSZ Statistics: Power Spectrum and Beyond
tSZ Power Spectrum

Planck 2015 Compton-y map
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**tSZ Power Spectrum**

\[ \ell (\ell + 1) c^2 / 2\pi \]

y-map power spectrum
post-fg subtraction

\[ \text{tSZ amplitude from Planck likelihood} \]

\[ \sigma_8 (\Omega_m / 0.28)^{0.375} = 0.80 \pm 0.01/-0.03 \]
(assuming fixed gas physics/mass bias)

Planck XXII (2015)
tSZ Skewness

Bonus: different tSZ statistics depend differently on cosmology ($\sigma_8$) and astrophysics (ICM pressure profile)

\[ \langle \tilde{T}^3 \rangle = -31 \pm 6 \mu K^3 \pm 14 \mu K^3 \]
\[ \sim \sigma_8^{11-12} \]
\[ \sigma_8 = 0.79^{+0.03}_{-0.03} \]

can break degeneracies (e.g., combine tSZ power spectrum amplitude with skewness)

Wilson, Sherwin, JCH+ (2012); JCH & Sherwin (2013); Crawford+ (2014)
tSZ PDF

- Optimal extension of this idea: measure all the moments (the PDF)
- Probe of non-gaussian structure:
  - For a gaussian field, power spectrum already specifies the PDF
    \[ \sigma^2 = \sum_{\ell=0}^{\infty} \frac{2\ell + 1}{4\pi} C_\ell \]
- Simple observable: histogram of pixel temperature values
- Use information from all clusters in map, including SNR<5
- Optimal cosmological tSZ statistic (very sensitive to \( \sigma_8 \))
- Route to breaking degeneracies between cluster gas physics and cosmological parameters

JCH+ (2014)
tSZ PDF

\[ \chi^2 = 2.0 \text{ (5 eff. d.o.f.)} \]

PTE = 0.85

JCH+ (2014)
\[ \sigma_8 = 0.793 \pm 0.018 \text{ (stat.)} \pm 0.017 \text{ (ICM syst.)} \pm 0.006 \text{ (IR syst.)} \]

~2x smaller than stat. error from tSZ skewness alone (Wilson+12)

data unable to simultaneously constrain ICM (via \( P_0 \)) and \( \sigma_8 \), but ACTPol/AdvACT will
Constraints

Planck CMB
WMAP9 CMB
PSZ Clusters+BAO+BBN
ACT tSZ PDF $\sigma_8\Omega_m^{0.2}$ (raw)

1σ contours

$\sigma_8$

$\Omega_m$

ACT tSZ PDF $\sigma_8\Omega_m^{0.2}$ (ICM marg./IR corr.)
tSZ x X-ray $\sigma_8\Omega_m^{0.26}$ (Hajian)++13
tSZ x CMB lensing $\sigma_8\Omega_m^{0.26}$ (HS14)

JCH+ (2014)
Planck y-map PDF

$p(y)$

Compton-y

$\sigma_8 = 0.77 \pm 0.02 \ (68\% \ C.L.)$ (fixed gas physics model)

major challenge: modeling foreground propagation into y-map

Planck+ XXII (2015)
tSZ Stacking: the Y-M Relation
tSZ Stacking
Planck x SDSS Locally Brightest Galaxies

![Graph showing the tSZ signal and stellar mass relationship](https://example.com/graph.png)

The tSZ signal is well-fit by a power-law Y-M relation: self-similar? (caveat: $M^* \rightarrow M_{500}$)

Planck+ XI (2013)
tSZ Stacking
Planck x SDSS Locally Brightest Galaxies

Planck+ (2013), LeBrun, McCarthy, Melin (2015)
tSZ Stacking
Planck x SDSS Locally Brightest Galaxies Reconsidered

$Y_{\text{cyl}}$ [arcmin$^2$]

$tSZ$ signal

self-similar $Y$-$M$ consistent with data

Greco, JCH+ (2015)
tSZ Stacking
Quasars: Feedback Signal?

Ruan+ (2015) + y-map of JCH & Spergel (2014)
tSZ Stacking
Quasars: Feedback Signal?

A major issue: contamination from the two-halo term?

Ruan+ (2015) + y-map of JCH & Spergel (2014)
The tSZ Monopole

see also Joe Silk’s talk
COBE-FIRAS

CMB spectrum is blackbody to 50 ppm precision

\[ |\langle y \rangle| < 1.5 \times 10^{-5} \] at 95% CL

Fixsen+ (1996); Fixsen (2009)
$\langle y \rangle$ and PIXIE

$>1000\sigma$ detection of mean tSZ signal of the universe

dominated by groups

$\sim 10^{12.5-13.5} \ M_{\odot}$

$\langle y \rangle \sim 1.8 \times 10^{-6}$

groups+clusters $>>$ reionization/primordial ("foreground")

specific intensity

JCH+ (2015)
<y> and PIXIE

30σ detection of relativistic effects in mean tSZ signal

specific intensity

\[(\Delta I_{\text{tSZ,rel}}(\nu) - \langle \Delta I_{\text{tSZ,non-rel}}(\nu) \rangle) \times 10^{25} \text{ [W/m}^2 \text{ /Hz/sr]}\]

- full calculation
- moment approximation
- PIXIE + comp. sep. 1σ
- + cosmic var. 1σ

JCH+ (2015)
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\(<y>\) and \textit{PIXIE}

sub-percent constraints on gastrophysical models

mean τ-weighted electron temperature

\( <k_B T_{e, \text{eff}} > \)

\( <y> \) mean Compton-y

Battaglia, JCH+ (in prep.)
Outlook

- tSZ x CMB lensing and tSZ x CFHTLenS measurements are fit by a consistent gastrophysical model; both prefer $\sigma_8$ values somewhat lower than Planck CMB.

- Current measurements probe gas pressure profile over wide ranges in mass/redshift, but not “missing baryons”.

- tSZ statistics beyond the power spectrum (e.g., PDF) show great promise for cosmological constraints.

- Self-similarity (or not) of Y-M remains an open question.

- *PIXIE* measurement of tSZ monopole will yield sub-percent constraints on gastrophysics.
Extra Slides
Probing Large-Scale Structure
dependence on intracluster medium “gastrophysics”

from N. Battaglia hydro sim. Adiabatic (no cooling, feedback, ...)

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Probing Large-Scale Structure
dependence on intracluster medium “gastrophysics”

from N. Battaglia hydro sim.

Compton-\(y\) \(\times T_{\text{CMB}} \times -2\) (R-J limit)

Adiabatic - AGN Feedback
tSZ x Lensing: Takeaway

- It is extremely difficult to probe “missing baryons” with tSZ measurements, including tSZ x lensing.

fractional contribution to cross-power

Battaglia, JCH, & Murray (2014)
- Wiener-filter ACT Equatorial 148 GHz map — clear non-gaussian tail
- No similar feature seen in identically-processed 218 GHz map
Model

- Thermal SZ PDF: how much sky area is subtended by tSZ (Compton-$y$) values in a given range?
- Simple for a spherical cluster: area between two circles

\[ b \equiv (y_{\text{min}}, y_{\text{max}}) \]

- Then add up such areas for all clusters:

\[
\langle P_b \rangle_{\text{noiseless}} = \int dz \frac{d^2V}{d\Omega} \int dM \frac{dn}{dM} \pi (\theta^2(y_{\text{min}}, M, z) - \theta^2(y_{\text{max}}, M, z))
\]

- volume element
- mass function
- area of annulus

JCH+ (2014)
Model

- Thermal SZ PDF: how much sky area is subtended by tSZ (Compton-y) values in a given range?
- Simple for a spherical cluster: area between two circles

![Diagram with circles and formulas]

Complications:
- non-tSZ contributions in CMB map
- inhomogeneous/correlated noise
- cluster overlaps along line-of-sight

Then add up such areas for all clusters:

\[
\langle P_b \rangle_{\text{noiseless}} = \int dz \frac{d^2V}{dzd\Omega} \int dM \frac{dn}{dM} \pi (\theta^2(y_{\text{min}}, M, z) - \theta^2(y_{\text{max}}, M, z))
\]

- volume element
- mass function
- area of annulus

JCH+ (2014)
Model + Noise

- Observable tSZ PDF:
  - Convolve with noise PDF (measured from splits of data)
  - Convolve with other components (CMB, foregrounds)
  - Account for contributions from zero-tSZ pixels (pure noise)

- Fiducial model: WMAP9 cosmology + Tinker mass function + Battaglia pressure profile

- Noise PDF, Wiener filter, and beam specified to match ACT Equ 148 GHz data analysis

\[ p(T) \]

5\(\sigma\) fluctuation in ACT map

JCH+ (2014)
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Parameter Sensitivity

$P_0 = \text{overall normalized amplitude of } P_e(M,z) \text{ relation}$

$\sigma_8 \sim \Omega_m^{2.5}$

$\sim \sigma_8^{16}$

$\sim \sigma_8^{10}$

$\sim P_0^4$

$\sim P_{0}^{4}$

\(JCH+\ (2014)\)
Contributions

How does the 148 GHz negative tail change as we mask individually detected clusters as a function of their SNR?

\( p(T) \)

ratio w.r.t. unmasked ACT PDF

signal from SNR<5 clusters

JCH+ (2014)
Analysis

- Focus on $\sigma_8$ (most sensitive parameter)
- Fit only $T<0$ 148 GHz PDF (avoids nearly all non-tSZ signals)
- Marginalize over non-tSZ foreground contribution
- Marginalize over parameterized ICM gas physics via $P_0$
- Correct for IR sources “filling in” tSZ decrements at 148 GHz
- Monte Carlo to compute covariance matrix (highly correlated) and validate pipeline

JCH+ (2014)