The Atacama Cosmology Telescope (ACT) has mapped the microwave sky to arcminute scales. We present constraints on parameters from the observations at 148 and 217 GHz respectively by ACT from three years of observations. Efficient map-making and spectrum-estimation techniques allow us to probe the acoustic peaks deep into the damping tail, and allow for confirmation of the concordance model, and tests for deviations from the standard cosmological picture. We fit a model of primary cosmological and secondary foreground parameters to the dataset, including contributions from both the thermal and kinetic Sunyaev-Zel'dovich effect, Poisson distributed and correlated infrared sources, radio sources and a term modeling the correlation between the thermal SZ effect and the Cosmic Infrared Background. We will describe the multi-frequency likelihood for the ACT data, and present constraints on a variety of cosmological parameters using this complete dataset, and put these results in context with the recent results from the Planck satellite.
The microwave sky on small scales: and what it means for you.

Renée Hlozek
Princeton
Pontificia Universidad Católica de Chile
University of Oxford
Stony Brook University
West Chester University of Pennsylvania
National Aeronautics and Space Administration
god...
The Cosmic Microwave Background

\[ T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n}) \]

\[ c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2 \]

Linear theory \(\Rightarrow\) ‘clean physics’

Basic elements well understood \(\Rightarrow\) numerical codes
Planck Power Spectrum

Multipole moment, ℓ

Image credit: Erminia Calabrese

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ACT probes new scales

Sudeep Das for the ACT collaboration  
Renée Hlozek - Frontiers
Atacama Cosmology Telescope
ACTxPlanck

Louis et al. 2013 in prep.
Where is ACT's power?

Silk damping regime: peaks 3-7 probed by ACT

Image credit: Erminia Calabrese

Renée Hlozek - Frontiers
Where is ACT's power?

Silk damping regime: peaks 3-7 probed by ACT

Image credit: Erminia Calabrese
We need careful modelling of the foreground emission.
The ACT multi-frequency spectra

Sievers, Hlozek, Nolta et al. 2013

Multipole $\ell$

Renée Hlozek - Cosmological Frontiers
Multi-frequency likelihood

\[
\ell(\ell + 1)C_{\ell}^{th,ij}/2\pi = B_{\ell}^{th,ij} = B_{\ell}^{\text{CMB}} + B_{\ell}^{\text{sec,ij}}
\]

\[
B_{\ell}^{\text{sec,ij}} = B_{\ell}^{\text{tSZ,ij}} + B_{\ell}^{\text{kSZ,ij}} + B_{\ell}^{\text{CIB-P,ij}} + B_{\ell}^{\text{CIB-C,ij}} + B_{\ell}^{\text{SZ-CIB,ij}} + B_{\ell}^{\text{rad,ij}} + B_{\ell}^{\text{Gal,ij}}
\]

Dunkley, Calabrese, Sievers, et al. 2013

Renée Hlozek - Frontiers
Marginalised CMB-only likelihood

\[ C_{\ell}^{\text{th,ij}} = C_{\ell}^{\text{CMB}} + C_{\ell}^{\text{sec,ij}}(\theta) \]

\[ p(C_b^{\text{CMB}} | C_b) = \int p(C_b^{\text{CMB}}, \theta | C_b) p(\theta) d\theta. \]

Restricting the range \( \ell < 3500 \) where the \( C_b \)s are Gaussian – marginalise over the secondary parameters!

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

Dunkley, Calabrese, Sievers, et al. 2013
Effective relativistic species

\[ r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[ \frac{R^2 + \frac{16}{15} (1 + R)}{6(1 + R^2)} \right] \]

\[ r_s = \int_0^{t_*} c_s \, dt/a = \int_0^{a_*} \frac{c_s \, da}{a^2 H} \]

\[ R = 3 \rho_b / (4 \rho_{\gamma}) \]

\[ \rho_R = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_{\gamma} \]

Hou, Keisler, Knox et al. 2011

Renée Hlozek - Frontiers
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Effective relativistic species

Calabrese, Hlozek et al., 2013

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Calabrese, Hlozek et al. 2013
Relativistic species and neutrinos

\[ \Sigma m_\nu < 0.3 \ (\text{WMAP7 + ACT + ACTSkewness + BAO} + H_0) \]

Effective relativistic degrees of freedom not strongly correlated with neutrino mass.

Sievers, Hlozek, Nolta et al. 2013

Renée Hlozek - Frontiers
Relativistic species and neutrinos

\[ \Sigma m_\nu < 0.3 \ (\text{WMAP7} + \text{ACT} + \text{ACTSkewness} + \text{BAO} + H_0) \]

Effective relativistic degrees of freedom not strongly correlated with neutrino mass given current small-scale data.

Renée Hlozék - Frontiers
Primordial Helium

Sievers, Hlozek, Nolta et al. 2013

\[ Y_p = 0.225 \pm 0.034 \text{ (WMAP7 + ACT)} \]

More \( Y_p \) decreases electrons available for recombination, leading to suppression of power.

\[ Y_p = 0.266 \pm 0.021 \text{ (68%; Planck+WP+highL)} \]

Consistency relation is tested, rather than applied.

\[ Y_p = 0.2485 + 0.0016 \left[ (273.9 \Omega_b h^2 - 6) + 100(S - 1) \right]; \]
\[ S = \sqrt{1 + (7/43)(N_{\text{eff}} - 3)} \]

Renée Hlozek - Frontiers
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Sievers, Illozeg, Nolta et al. 2013

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Renée Illozeg - Frontiers
Inflationary parameters

Sievers, Illozck, Nolta et al. 2013

$r = \Delta^2_R(k_0)/\Delta^2_R(k_0)$

$r < 0.19$ (WMAP7 + ACT + BAO + $H_0$, 95% CL)

$r_{0.002} < 0.11$ Planck

Renée Illozck - Frontiers
Inflationary parameters

\[ \Delta^2_R(k) = \Delta^2_R(k_0) \left( \frac{k}{k_0} \right)^{n_s(k_0) - 1 + \frac{1}{2} \ln(k/k_0) \frac{dn_s}{d\ln k}} \]

\[ \frac{dn_s}{d\ln k} = -16\epsilon\eta + 24\epsilon^2 + 2\xi_t^2. \]

Sievers, Hlozek, Nolta et al. 2013
Inflationary parameters

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\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_0) \left(\frac{k}{k_0}\right)^{n_s(k_0) - 1 + \frac{1}{2} \ln(k/k_0) \frac{dn_s}{d \ln k}}
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Sievers, Hlozek, Nolta et al. 2013
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Sievers, Hlozek, Nolta et al. 2013

Renée Hlozek - Frontiers
Inflationary parameters

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\[ \frac{dn_s}{d\ln k} = -16\epsilon + 24\epsilon^2 + 2\xi_i^2. \]

Sievers, Hlozek, Nolta et al. 2013
Primordial power

Hlozek et al. 2011
see Dan Green’s talk tomorrow

Hlozek et al. 2011

Mass Variance $\Delta M / M$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$

$10^1$

$10^2$

$10^3$

$10^4$

$10^5$

$10^6$

$10^7$

$10^8$

$10^9$

$10^{10}$

$10^{11}$

$10^{12}$

$10^{13}$

$10^{14}$

$10^{15}$

$10^{16}$

$10^{17}$

$10^{18}$

$10^{19}$

$10^{20}$

$10^{21}$

$10^{22}$

$10^{23}$

Mass scale $M$ [Msolar]

SDSS DR7 (Reid et al. 2010)

LyA (McDonald et al. 2006)

ACT CMB Lensing (Das et al. 2011)

ACT Clusters (Sehgal et al. 2011)

CCCP II (Vikhlinin et al. 2009)

BCG Weak lensing (Tinker et al. 2011)

ACT+WMAP spectrum (this work)
Signatures of Inflation

- Energy scale of inflation

\[ V^{1/4} = 1.06 \times 10^{16} \text{ GeV} \left( \frac{r_*}{0.01} \right)^{1/4} \]

![Graph showing energy scale and tensor temperature](image)
Tensor modes

Planck B modes
→ \( r < 0.05 \)
(see Martin’s talk)

Host of ground and space-based missions ongoing/planned.
\[ \frac{k^3 P_R(k_0)}{2\pi^2} = A_s = \frac{1}{2\epsilon} \left( \frac{H_I/M_{pl}}{2\pi} \right)^2 \]

\[ \frac{\alpha_a}{1 - \alpha_a} = \frac{8\epsilon}{(\phi_{0,i}/M_{pl})^2} \]

\[ \left( \frac{\phi_{0,i}}{M_{pl}} \right)^2 \approx \frac{6 \times 10^4 \Omega_\alpha h^2}{m_a^2 a_{osc}^3} \]

**Axion isocurvature**

\[ \alpha < 0.036 \text{ (Planck)} \]

\[ H_{inf} \leq 0.87 \times 10^7 \text{ GeV} \left( \frac{f_a}{10^{11} \text{ GeV}} \right)^{0.408} \]

Marsh, Grin, Hlozek, Ferreira 2013
Gravitational Lensing of the CMB

Intervening large-scale potentials deflect CMB photons and distort the CMB.

The rms deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.
First detection of CMB lensing

\[ AL = 1.06 \pm 0.23 \]

Das, et al. 2013

\[
\frac{\ell^2}{4} C_{\ell}^{dd} = \int_0^{\eta_*} d\eta \underbrace{W^2(\eta)}_{\text{geometry}} \left( \frac{k = \ell + 1/2}{d_A(\eta), \eta} \right) \]

\[ P \]

\[ \text{matter} \]
Planck lensing

Angular scale (degrees)

Planck lensing. 2013
Planck lensing. 2013
The CMB alone prefers $\Lambda$

$\Lambda$CDM model favored at $3.2\sigma$ over best model with no $\Lambda$

Sherwin et al. 2011
The Sunyaev-Zel’dovich effect

\[ p_{\text{pair}}(r) \equiv \langle (\mathbf{p}_i - \mathbf{p}_j) \cdot \hat{r}_{ij} \rangle \]
The Sunyaev-Zel’dovich effect

\[ p_{\text{pair}}(r) \equiv \langle (\mathbf{p}_i - \mathbf{p}_j) \cdot \hat{\mathbf{r}}_{ij} \rangle \]

\[ \tilde{p}_{\text{pair}}(r) = \frac{\sum_{i<j} (\mathbf{p}_i \cdot \hat{\mathbf{r}}_i - \mathbf{p}_j \cdot \hat{\mathbf{r}}_j) c_{ij}}{\sum_{i<j} c_{ij}^2} \]

\[ c_{ij} \equiv \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2} = \frac{(r_i - r_j)(1 + \cos \theta)}{2 \sqrt{r_i^2 + r_j^2 - 2r_i r_j \cos \theta}} \]

\[ \tilde{p}_{\text{ksz}}(r) = -\frac{\sum_{i<j} [(T_i - T(z_i)) - (T_j - T(z_j))] c_{ij}}{\sum_{i<j} c_{ij}^2} \]
What next?
Polarisation

![Graph showing polarisation](image)

- **Angular scale**: 10°, 1°, 0.1°
- **Temperature**: Various measurements
  - ACBAR, ACT
  - BICEP, BOOMERANG
  - CAPMAP, CBI, DASI
  - MAXIPOL QUAD
  - QUIET SPT
  - WMAP

- **E-mode**, **B-mode**, **Lensing**, **Primordial**

**Legend**:
- Dashed horizontal line: limits on B-modes
- Dashed vertical line: measurements of T and E

**Figure**: Mike Niemack

- **Smoking gun of inflation?**
- **Neutrino mass via LSS**
- **Inflationary potential**
- **Early Dark Energy**
Small-scale polarisation with ACTPol

Renée Hlozek
ACTPol

Foregrounds much less polarized (1-2% compared to ~17% for temperature)

Renée Hlozek - Frontiers