LSS-CMB Correlations

Planck collaboration 2013

Antony Lewis
http://cosmologist.info/
CMB-LSS correlations

- $T \Delta_N$
- $TT\Delta_N$, $TT$-CIB
- $TTT$
- $E\Delta_N$, $ETT$
- $T\Delta_b$, $E\Delta_b$
Overdensity: correlated with positive Integrated Sachs-Wolfe (net blueshift)

Underdensity: correlated with negative Integrated Sachs-Wolfe (net redshift)

\[ \Delta T_{\text{ISW}}(\hat{n}) = 2 \int_0^{\chi^*} d\chi \hat{\Psi}(\chi \hat{n}; \eta_0 - \chi) \]
The linear power spectrum of observed source number counts

Anthony Challinor\textsuperscript{1,2} and Antony Lewis\textsuperscript{3,1,*}

\[
\Delta N(\hat{n}, z, m < m_*) = \delta_N(L > L_{ss}) - \frac{1}{\mathcal{H}} \hat{n} \cdot \frac{\partial v}{\partial \chi} + (5s - 2) \left[ \kappa - \frac{1}{\chi} \int_{\eta_A}^{\eta} (\phi + \psi) d\eta \right] \\
+ \left[ \frac{2 - 5s}{\mathcal{H} \chi} + 5s - \frac{\partial \ln[\sigma^3 N(L > L_{ss})]}{\mathcal{H} \partial \eta} + \frac{\mathcal{H}}{\mathcal{H}^2} \right] \left[ \psi + \int_{\eta_A}^{\eta} (\dot{\phi} + \dot{\psi}) d\eta - \hat{n} \cdot \mathbf{v} \right] + \frac{1}{\mathcal{H}} \dot{\phi} + \psi + (5s - 2) \phi.
\]

Full GR calculation of observed galaxy counts as a function of angle and redshift, with bias and magnification bias

- Velocity
- Gravitational potential
- Source evolution
- Lensing
- Correct definition of bias on horizon scales
- Correlation to CMB temperature, polarization
- Numerical code, CAMB sources
  \url{http://camb.info/sources/}

(+linear 21cm, galaxy lensing, and all cross-correlations
+perturbed recombination)

\texttt{arXiv: 1105.5292} \hspace{0.5cm} \texttt{See also Yoo et al, Bonvin \& Durrer.}
CMB temperature – number counts correlation

\[ \Delta T(\mathbf{n}) \approx \int_{\eta_0}^{\eta_A} d\eta e^{-\tau} \left( \hat{\mathbf{n}} \cdot \mathbf{v} + \psi + \phi \right) \times \Delta_N(\mathbf{n}, z, m < m_*) \approx \delta_N - \frac{1}{H} \hat{\mathbf{n}} \cdot \frac{\partial \mathbf{v}}{\partial \chi} - \left( \kappa + \frac{\mathbf{n} \cdot [\mathbf{v} - \mathbf{v}_{\text{obs}}]}{H \chi} \right) (2 - 5s). \]

+ other terms

Z=0.6, \( \sigma_z = 0.05, b = 1, s = 0 \)

Z=3, \( \sigma_z = 0.2, b = 2, s = 0.42 \)

(note: redshift distortion correlation almost exactly cancels)

TT as a probe of Large Scale Structure
Weak lensing of the CMB

\[ \tilde{T}(\hat{n}) = T(\hat{n}') = T(\hat{n} + \alpha) \]
\[ \alpha = \nabla \psi \]
\[ \psi(\hat{n}) = -2 \int_0^{\chi*} d\chi \Psi(\chi\hat{n}; \eta_0 - \chi) \frac{f_K(\chi* - \chi)}{f_K(\chi*)f_K(\chi)} \]
Non-Gaussianity/statistical anisotropy
reconstructing the lensing field

Marginalized over (unobservable) lensing field:

\[ T \sim \int P(T, \psi) d\psi \]

- Non-Gaussian statistically isotropic temperature distribution

For a given lensing field:

\[ T \sim P(T|\psi) \]

- Anisotropic Gaussian temperature distribution
Fractional magnification $\sim$ convergence $\kappa = -\nabla \cdot \alpha/2$

$+ \text{shear modulation}$

\[
\langle \tilde{T}(l_2)\tilde{T}(l_3) \rangle = C_{l_2}^{TT} \delta(l_2 + l_3) \left[ 1 + \kappa \frac{d \ln(l_2^2 C_{l_2}^{TT})}{d \ln l_2} + \hat{l}_2 \hat{l}_2 \frac{d \ln C_{l_2}^{TT}}{d \ln l_2} \right]
\]

e.g. Bucher et al
Variance in each $C_l$ measurement $\propto 1/N_{\text{modes}}$

$N_{\text{modes}} \propto l_{\text{max}}^2$ - dominated by smallest scales

$\Rightarrow$ measurement of angular scale ($\Rightarrow \kappa$) in each box nearly independent

$\Rightarrow$ Uncorrelated variance on estimate of magnification $\kappa$ in each box

$\Rightarrow$ Nearly white ‘reconstruction noise’ $N_{l}^{(0)}$ on $\kappa$, with $N_{l}^{(0)} \propto 1/l_{\text{max}}^2$
Lensing reconstruction information mostly in the *smallest scales* observed

- Need high resolution and sensitivity
- Almost totally insensitive to large-scale $T$ (so only *small-scale* foregrounds an issue)

- Use separate frequencies and check consistency
- Combine (Minimum Variance – MV) for best estimate
- Also cross-check with foreground cleaned maps

Reconstruction Noise $N_l^{(0)}$
Planck full-sky lensing potential reconstruction: map of integrated LSS at $0.5 < z < 6$

Note – about half signal, half noise, not all structures are real: map is effectively Wiener filtered

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Reconstruction noise budget

Lensing maps are reconstruction noise dominated, but maps from different channels are similar because mainly the same CMB cosmic variance.
Power spectrum of reconstruction $TT \times TT \Rightarrow C_{l}^{\psi\psi}$

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Lensing (TT) × LSS

$TT \times \text{counts}$

$TT \times \text{CIB (Planck internal)}$

$\nu=100\ GHz\ (x\ 100)$

$\nu=143\ GHz\ (x\ 100)$

$\nu=217\ GHz\ (x\ 100)$

$\nu=353\ GHz\ (x\ 100)$

$\nu=545\ GHz\ (x\ 10)$

$\nu=857\ GHz\ (x\ 0.1)$

$>50\sigma\ detection$
TTT: Correlation between lenses and CMB temperature, $C_{TT}^{\psi}$?

- The late Integrated Sachs Wolfe effect (late ISW) at low redshift from decaying potentials
- Large-scale modes that span recombination and also act as lenses
- The early Integrated Sachs Wolfe effect (early ISW) due to the transition from radiation to matter domination, and decaying modes
- Lenses close to last-scattering being correlated to density perturbations that have infall giving a Doppler signal in the CMB
- Doppler signal from scattering at reionization
- Lenses at last-scattering that directly correlate perturbations to lensing at the recombination surface
- Non-linear Rees-Sciama signal at low redshift from non-linear gravitational clustering
- Non-linear SZ signal from scattering in clusters
- Correlations due to foreground contaminants

Linear effects, All included in self-consistent linear calculation with CAMB

Non-linear growth effect
- estimate using e.g. Halofit

Potentially important, but frequency dependent
- ‘foregrounds’, e.g. CIB
Contributions to the lensing-CMB cross-correlation, $C_l^{T\psi}$

+ small (but not entirely negligible) $\delta N$ perturbed expansion effect

(note Rees-Sciama contribution is small, numerical problem with much larger result of Verde et al, Mangilli et al.; see also Junk et al. 2012 who agree with me)
Planck lensing bispectrum detection, $C_l^{T\psi}$

Large cosmic variance and reconstruction noise, but ‘detected’ at $\sim 2.5\sigma$.

Table 2. Results for the amplitude of the ISW-lensing bispectrum from the SMICA, NILC, SEVEM, and C-R foreground-cleaned maps, for the KSW, binned, and modal (polynomial) estimators; error bars are 68% CL.

<table>
<thead>
<tr>
<th></th>
<th>SMICA</th>
<th>NILC</th>
<th>SEVEM</th>
<th>C-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>KSW</td>
<td>0.81 ± 0.31</td>
<td>0.85 ± 0.32</td>
<td>0.68 ± 0.32</td>
<td>0.75 ± 0.32</td>
</tr>
<tr>
<td>Binned</td>
<td>0.91 ± 0.37</td>
<td>1.03 ± 0.37</td>
<td>0.83 ± 0.39</td>
<td>0.80 ± 0.40</td>
</tr>
<tr>
<td>Modal</td>
<td>0.77 ± 0.37</td>
<td>0.93 ± 0.37</td>
<td>0.60 ± 0.37</td>
<td>0.68 ± 0.39</td>
</tr>
</tbody>
</table>

- Importance to separate from $f_{NL}$
  $\Delta f_{NL} \sim 7$
CMB Polarization – LSS Correlation?

Quadrupole Anisotropy

Thomson Scattering

Linear Polarization

Hu astro-ph/9706147
Yes, expect E polarization – LSS correlation on large scales

Lewis, Challinor & Hanson (2011),
Number counts at $z < 3$ + CMB lensing gives possible future $\sim 6\sigma$ LSS-CMB polarization correlation
Rayleigh scattering: Rayleigh × CMB correlations
The last-but-one scattering surface: probing baryon LSS at $z \sim 1000$ with multi-tracer CMB

following Takada & Sasaki 1991; Yu, Spergel, Ostriker 2001

\[ \sigma_R(\nu) = \left[ \left( \frac{\nu}{\nu_{\text{eff}}} \right)^4 + \frac{638}{243} \left( \frac{\nu}{\nu_{\text{eff}}} \right)^6 + \frac{1626820991}{136048896} \left( \frac{\nu}{\nu_{\text{eff}}} \right)^8 + \ldots \right] \sigma_T \]

Lee, 2005  \( \nu_{\text{eff}} \equiv \sqrt{8/9cR_A} \approx 3.1 \times 10^6 \text{GHz} \)
Temperature and polarization power spectrum at high frequencies [note detectability of Rayleigh signal only limited by noise (same CMB fluctuations)]

**TT, EE, TE, BB cross-frequency power spectra**

May be detectable with Planck; large-signal with any future Pixie/Core/PRISM-like mission.
Conclusions

• $TT\Delta, TT\phi$ CMB-LSS correlators (bispectra) are significant
  - First full-sky lensing reconstruction from TT with Planck
  - $TT\Delta$ detected at high significance, both counts and CIB
  - TTT Temperature bispectrum mainly from ISW-$\phi$ correlation
    - now detected at $2.5\sigma$
    - important to model accurately for non-Gaussianity studies

• Also $E$- $LSS$ correlators (up to $\sim 6\sigma$ cosmic variance limit), not detected yet

• Frequency dependent Rayleigh $C_\ell$ - may be detectable with Planck, easily in future at high $\sigma$
  - very good consistency check on foreground and recombination modelling/BAO, + lensing separation
Rayleigh scattering from tensor modes