The CMB Lensed by Star-Forming Galaxies

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on behalf of the Planck Collaboration

Planck 2013 results, XVII, XVIII, XXX
Using Planck CMB channels (mostly 143 and 217 GHz), we can reconstruct a full sky lensing potential map (total SNR of about 25) using a quadratic estimator.

This map is a weighted projection of the gravitational potential over the entire visible Universe, with a peak sensitivity between $z\sim1$ and 3.

The gradient of this map gives the deflection angle.
The CMB Lensing Power Spectrum is Robust

Planck 2013 Results. XVII

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Mining the Cosmic Frontier in the Planck Era, May 2013
CMB Lensing Correlates with Galaxy Surveys

**NVSS Quasars**

\[ b(z) = 1.7 \rightarrow \hat{A}^{g\phi}_{\text{NVSS}} = 1.03 \pm 0.05 \ (\approx 20\sigma) \]

\[ z_{\text{mean}} = 1.1 \]

**SDSS LRGs**

\[ b(z) = 2 \rightarrow \hat{A}^{g\phi}_{\text{LRGs}} = 0.96 \pm 0.10 \ (\approx 10\sigma) \]

\[ z_{\text{mean}} = 0.55 \]

**MaxBCG Clusters**

\[ b(z) = 3 \rightarrow \hat{A}^{g\phi}_{\text{MaxBCG}} = 1.54 \pm 0.21 \ (\approx 7\sigma) \]

\[ 0.1 < z < 0.3 \]

**WISE**

\[ b(z) = 1 \rightarrow \hat{A}^{g\phi}_{\text{WISE}} = 0.97 \pm 0.13 \ (\approx 7\sigma) \]

\[ z_{\text{mean}} = 0.18 \]

- This correlation is an important consistency test.
- It offers an opportunity to measure the galaxy survey \((\text{bias} \times dN/dz)\).
- Our lensing map overlaps with YOUR survey

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Planck Maps Exquisitely (Extra-)Galactic Dust

- At 545 GHz (~550 μm) (and all frequencies above 143 GHz), a large fraction of the signal we are mapping is composed of galactic dust and of the Cosmic Infrared Background (CIB).
- The CIB represents the cumulative emission of high-z, dusty, star forming galaxies.
- Planck produces exquisite maps of the CIB on large scales (provided galactic dust cleaning).
A Bright (Far-)Infrared Sky

- The CIB and the COB have equal contributions, instead of $\sim1/3$ for local galaxies.
  - IR luminosity increases with $z$ faster than optical luminosity because of the increased star formation rate at higher $z$.
- Over half of the energy produced since the surface of last scattering has been absorbed and re-emitted by dust.

Béthermin & Dole in prep.
Arp 220 scaled with Redshift

Dust Emission (modified BB)

Planck bands

Increase with z

$S_\nu$, [mJy]

$\lambda$ [\mu m]

$z = 0.01$
$z = 0.10$
$z = 0.50$
$z = 1.00$
$z = 3.00$
$z = 6.00$

$h=0.71; \Omega_m=0.27; \Omega_\Lambda=0.73$

Courtesy J. Viera
Planck CIB maps at 217, 353, 545 and 857 GHz

- High SNR sub-degree structures at all frequencies.
- Assuming sources at $z \sim 1.5$, we are seeing clustering at $10 \text{ Mpc}/h$ ($k \sim 0.1 \text{ } h/\text{Mpc}$).
- Structures partially correlated across frequencies.
- Clearly of cosmological interest!
CIB Redshift and Mass Dependence

- CIB is the dominant extragalactic foreground at high frequency and is produced by the redshifted thermal radiation from UV-heated dust.
- The CIB is a thus a good probe of the SFR at high redshift.
- This signal was highlighted early on by Partridge & Peebles 67:
  - The monopole was discovered by Puget++96 (FIRAS) and Hauser++98 (DIRBE).
  - Tremendous progress in the last few years mapping correlated fluctuations in Spitzer (Lagache++07), Blast (Viero++09), Herschel (Viero++12), Planck, SPT (Hall++11) and ACT (Das++12).
  - Planck adds low frequencies, i.e., high-z, and large scales (see e.g., Planck Early Results XVIII)
- The fluctuations in this background trace the large-scale distribution of matter, and so, to some extend the clustering of matter at high-z
- This led Song++02 to posit a correlation between CIB and CMB lensing.
\[
\sum_{\ell m} \phi_{\ell m} Y_{\ell m}(x) = \nabla^a \left[ a(x) \nabla_a \beta(x) \right]
\]

\[
\alpha(x) = \sum_{\ell m} \tilde{a}_{\ell m} Y_{\ell m}(x)
\]

\[
\beta(x) = \sum_{\ell m} C_{\ell}^{TT} \tilde{a}_{\ell m} Y_{\ell m}(x)
\]

\[
C_b^{\Phi T} = \frac{1}{N_b} \sum_{l \in b} \sum_{|m| \leq \ell \frac{1}{\ell^2}} \left( \hat{\Phi}_{\ell m} T_{\ell m} \right)
\]

- The correlation of the inverse variance weighted reconstructed lensing potential with the temperature map is equivalent to the optimal bispectra (Smith++08).
Lensing Potential and Temperature are Correlated

- Statistical error bars only.
- Grey boxes correspond to the 143 GHz based lensing potential reconstruction x 143 GHz temperature map as a systematic proxy.
- The colored solid curves correspond to the signal prediction based on the Planck Early paper model.
- Cross-correlation enables the use of a large area of the sky (40%).
Using the CIB to “See” the Lensing of the CMB

- Stacking on 20,000, band-pass filtered, 1 deg. wide patches.
- We see the expected relation between light, matter and deflection angles.
- Incidentally, probably the first detection of lensing by voids (e.g., Krause++12).

Stacking on: 20,000 T extrema 20,000 T minima Random location
Null tests, null tests, and... more null tests...

- Null $T$(half ring) $\times$ $\Phi$
- Null $T$(detset) $\times$ $\Phi$
- Null $T$(survey) $\times$ $\Phi$
- Null $T$(20%-40% mask) $\times$ $\Phi$
- Null $T$(60%-40% mask) $\times$ $\Phi$
- Null $T$(w/ or w/o HI cleaning) $\times$ $\Phi$
- Null $\Phi$(100-143 GHz) $\times$ $T$
- Null $\Phi$(217-143 GHz) $\times$ $T$
- Null $\Phi$(20-40%) $\times$ $T$
- Same results hold at other frequencies

\[ \chi^2 \text{ (dof)} = 9.2 \text{ (15)} \quad \chi^2 \text{ (dof)} = 27.8 \text{ (15)} \quad \chi^2 \text{ (dof)} = 40.5 \text{ (15)} \]

\[ \chi^2 \text{ (dof)} = 12.1 \text{ (15)} \quad \chi^2 \text{ (dof)} = 15.6 \text{ (15)} \quad \chi^2 \text{ (dof)} = 2.6 \text{ (15)} \]

\[ \chi^2 \text{ (dof)} = 25.5 \text{ (15)} \quad \chi^2 \text{ (dof)} = 13.5 \text{ (15)} \quad \chi^2 \text{ (dof)} = 11.8 \text{ (15)} \]
Is SZ Contamination Important?

- Current models suggest SZ contribution is not important.

- To test this with our data nonetheless, we compare a “fit” using a CIB only SED (Fixsen++98 or Gispert++01) to a fit with an added SZ spectra:
  - The CIB only SED, without any fit, is a good match to the measured frequency dependence.
  - The data do not favor the inclusion of an extra SZ component, i.e., no significant $\Delta X^2$. 

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Is the CIB Bispectrum Worrisome?

- CIB bispectrum detected by Crawford++12 but still largely uncertain.
- We use a lensing reconstruction at 545 GHz to set an upper limit on the CIB bispectrum contribution:
  - At $l=400$, the 1700 $\mu$K for $\Phi(545)xT(545)$ leads to a 0.02 $\mu$K signal for $\Phi(143)xT(545)$.
Evaluating Point Source Contamination

Fig. 9. Results from the point source contamination estimator of Eq. (5). The best-fit cross-spectra associated with shot noise are plotted in black. We do not show the best-fit at 545 and 857 GHz since the signal-to-noise ratio is low. The grey line is a prediction for the bias from the CMB lensing - infrared correlation, and has been subtracted from the spectra (plotted as black points). We see that with the subtraction of the bias from CMB lensing, the measured bispectrum-related spectrum is generally consistent either with zero, or with the shape expected for shot noise.

This is well approximated by a Poisson noise term and is thus already addressed by our treatment of point sources in Sect. 5.3.2. The spurious lensing signal will also correlate with other components in our map such as the CIB. However, we ignore these terms since they will be smaller than those that correlate directly with the SZ emission. Additionally, a contribution comes from SZ emission in our CIB map that correlates with the lensing potential itself. The latter is the dominant term and we discuss it in this section.

To measure a contribution from the SZ-lensing correlation we attempt to separate the SZ and CIB emission based on their differing spectral shapes. We consider all frequencies from 100 to 857 GHz, but we will illustrate this procedure by considering only two ` bands: ` = 300–450; and 1200–1450. The first is well inside the linear regime, while the second receives a more important non-linear contribution. However, we have checked that if we consider different `-bins we obtain similar conclusions. We model the signal within each `-band as \( s_\ell = a_1,\ell c_\ell(\nu) + a_2,\ell f_\ell(\nu) \), where \( c_\ell(\nu) \) and \( f_\ell(\nu) \) are, respectively, the CIB frequency dependence (as proposed in Fixsen et al. 1998 or Gispert et al. 2000) and the SZ frequency dependence obtained from Eq. 10. For each `-band, we will solve for \( a_1,\ell \) and \( a_2,\ell \) minimizing the associated \( \chi^2 \) while forcing both amplitudes to be positive. As an approximation to the error in each multipole band we calculate the scatter of the signal within the band and multiply it by 1.2, as discussed in Sect. 5.1.

In Fig. 10 we show the measured frequency spectrum within each `-band, along with the best-fit SZ-lensing and CIB-lensing spectra. For the CIB-only fit with the Gispert et al. (2000) frequency dependence we find a relatively poor fit in the lowest `-bin, \( \chi^2(\text{dof}) = 15.5 (5) \), but an improved fit in the higher `-bin, \( \chi^2(\text{dof}) = 4.15 (5) \). Including the SZ component gives \( \chi^2 = 0.52 \) and 1.34 in the low and high `-bins for one extra degree of freedom. When we use the Fixsen et al. (1998) frequency dependence we find an improved fit, with \( \chi^2(\text{dof}) = 2.25 (5) \) and 5.49 (5) in the low and high `-bins, respectively. Overall, the improvement in the \( \chi^2/\text{dof} \) when including the SZ component does not justify inclusion of the SZ component in the model, with the poor fit driven by the lowest frequency bands where the CIB scaling is rather unconstrained. In fact, our measurements might constitute the first constraints to date on this scaling. From these results we conclude that including the SZ-lensing correlation in...
Summary of Possible Astrophysical Contaminants

- After having excluded substantial instrumental and astrophysics contaminants, we interpret the measured signal as the correlation between the CIB and CMB lensing.

\[ \ell^2 C_\ell^{T\phi} \]

\[ [\mu\text{K.sr}] \]

\[ \nu=100 \text{ GHz} \]
\[ \nu=143 \text{ GHz} \]
\[ \nu=217 \text{ GHz} \]
\[ \nu=353 \text{ GHz} \]
\[ \nu=545 \text{ GHz} \]
\[ \nu=857 \text{ GHz} \]
Modeling the CIB x Lensing Correlation

- We will model jointly the CIB autos and the CIB x Lensing angular spectra.

\[ C^{XY}_\ell = \int_0^{\chi_*} d\chi \ W^X(\chi) W^Y(\chi) \ P_{\delta\delta}(k = \ell / \chi, \chi) \]

\[
W^v(\chi) = b \frac{a j_v(\chi)}{\chi}; \\
W^\phi(\chi) = -\frac{3}{\ell^2} \Omega_m H_0^2 \frac{\chi}{a} \left( \frac{\chi_* - \chi}{\chi_* \chi} \right)
\]

Mean emissivity:

\[
\bar{j}_v(z) = (1 + z) \int_0^{S_{\text{cut}}} dS \ S \ \frac{d^2 N}{dS dz}
\]

- We fix the cosmology to the Planck cosmology as we are dominated by galaxy modeling uncertainties.

- We consider two models:
  - A simple linear bias model with a “Gaussian” emissivity (inspired by Hall+12).
  - A Halo Occupation Density (HOD) model. We solve for two HOD parameters and the mean emissivity per frequency in 3 redshift bins. This is an extension from the Planck Early Paper XVIII analysis.

- A more thorough modeling is presented in the CIB focused Planck 2013 Results. XXX
Best Fit Auto- and Cross-Spectra

Reconstructed emissivities model

Linear bias model with b~2.4
Reconstructed Emissivities and HOD Masses

Each DM halo is populated with $N_{\text{gal}} = N_{\text{cen}} + N_{\text{sat}}$

$$N_{\text{cen}} = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log M - \log M_{\text{min}}}{\sigma_{\log M}} \right) \right]$$

$$N_{\text{sat}} = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log M - \log 2M_{\text{min}}}{\sigma_{\log M}} \right) \right]$$
Constraining the SFR at High Redshift

- Using the Kennicutt 98 law and an effective SED for our sources (Béthermin+12, Magdis+12), we can convert the measured emissivities into star formation densities as a function of z.

<table>
<thead>
<tr>
<th></th>
<th>1 &lt; z ≤ 1.5</th>
<th></th>
<th>1.5 &lt; z ≤ 3</th>
<th></th>
<th>3 &lt; z ≤ 7</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GHz</td>
<td>7.16±5.77</td>
<td>1.96±1.58</td>
<td>3.53±3.05</td>
<td>0.655±0.564</td>
<td>5.49±4.78</td>
<td>0.271±0.236</td>
</tr>
<tr>
<td>143 GHz</td>
<td>12.7±9.60</td>
<td>1.37±0.964</td>
<td>6.82±5.46</td>
<td>0.438±0.351</td>
<td>10.5±9.05</td>
<td>0.178±0.153</td>
</tr>
<tr>
<td>217 GHz</td>
<td>11.9±6.33</td>
<td>0.310±0.165</td>
<td>17.3±7.23</td>
<td>0.282±0.118</td>
<td>36.6±13.8</td>
<td>0.182±0.068</td>
</tr>
<tr>
<td>353 GHz</td>
<td>116±17.1</td>
<td>0.671±0.099</td>
<td>75.5±27.5</td>
<td>0.286±0.104</td>
<td>164±47.3</td>
<td>0.320±0.092</td>
</tr>
<tr>
<td>545 GHz</td>
<td>185±106</td>
<td>0.320±0.183</td>
<td>224±148</td>
<td>0.317±0.210</td>
<td>417±251</td>
<td>0.659±0.396</td>
</tr>
<tr>
<td>857 GHz</td>
<td>193±139</td>
<td>0.144±0.104</td>
<td>354±212</td>
<td>0.317±0.190</td>
<td>609±359</td>
<td>1.37±0.809</td>
</tr>
</tbody>
</table>

j: [Jy/Mpc/sr]  
\( \rho_{\text{SFR}}: [\text{M}_\odot/\text{Mpc}^3/\text{yr}] \)

- Adding the CMB lensing x CIB correlation helps constrain the high z contribution
- Combining these constraints lead to \( \rho_{\text{SFR}} = 0.423 \pm 0.123, 0.292 \pm 0.138 \) and \( 0.226 \pm 0.100 \) \( \text{M}_\odot/\text{Mpc}^3/\text{yr} \) for each z bin.
Star Formation Rate Constraints

\[ \rho_{SFR} \left[ M_{\odot}/\text{yr} \right] \]

\[ 0.01 \quad 0.10 \quad 1.00 \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \]

Redshift

CIB(\( \nu \)) x CMB
Lensing analysis

CIB(\( \nu \)) x CIB(\( \nu' \))
analysis
SPT x Herschel vs Planck x Planck

- 90 sq. deg of overlapping SPT and Herschel observations.
- Leads to a 6.6-8σ detection.
- It will take CCAT to resolve these objects

\[ \nu = 545 \text{ GHz} \times 10 \]

\[ \nu = 857 \text{ GHz} \times 0.1 \]

Point and error bars from Holder++13
(No color correction included)
Summary

- Using Planck data alone, we report a strong correlation between the CMB lensing gravitational potential and all temperature maps at frequencies above 217 GHz, and marginal significance at 100 and 143 GHz.

- This measurement is interpreted as the correlation between the CMB lensing and the CIB.
  - Using an extensive set of null tests, we exclude substantial instrumental systematic effects.
  - Using various masks and frequencies for $\Phi$ and $T$, we exclude any substantial galactic contamination.
  - Using targeted tests for known astrophysical foregrounds, we exclude a strong contamination by the SZ effect, the CIB bispectrum and we remove a small point source contamination.

- The detection levels reach 3.6 (3.5), 4.3 (4.2), 8.3 (7.9), 31 (24), 42 (19), and 32 (16) $\sigma$ statistical (statistical and systematic) at 100, 143, 217, 353, 545 and 857 GHz, respectively.

- We built two models and inferred constraints on the star formation density at high redshift, leading to a measurements in 3 large redshift bins, up to $z<6$.

- The high degree of correlation measured (around 80 %) allows for unprecedented visualization of lensing of the CMB.

- This correlation holds great promise for novel CIB and CMB focused science.
  - CMB lensing appears promising as a probe of the origin of the CIB.
  - The CIB is now established as an ideal tracer of CMB lensing.

- Good consistency with the Hershel (550$\mu$m and 350 $\mu$m) x SPT results from Holder++13.
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
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