Prospects for CMB lensing: signal extraction from N-body lensed CMB maps

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Outline

- CMB lensing: present and (near) future
  - first measurements of CMB lensing (ACT, SPT, Planck)
  - phenomenology

- CMB lensing forecast
  - simulated datasets and analysis
  - calibration and priors
  - results

- All sky lensing extraction algorithm
  - testing on lenspix realizations
  - CMB maps lensed by N-body simulations

- Future work

- Highlights
Gravitational Lensing on Cosmic Microwave Background

GL is a phenomenon occurring when the path of a ray of light passes close to a mass and gets deflected by an angle $\alpha$.

A long time after the CMB is emitted, structures collapse and CMB photons get deflected in their path from the last scattering surface to us. CMB lensing is a secondary anisotropy. It has been observed by various collaborations in the T-modes.
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Gravitational Lensing on Cosmic Microwave Background

\[ \tilde{T}(\hat{n}) = T(\hat{n} + \alpha) \]

\[ \alpha = -2 \int_{0}^{\chi'} d\chi \frac{f_K(\chi' - \chi)}{f_K(\chi')} \nabla_\perp \Psi(\chi \hat{n}; \eta_0 - \chi) \]

\[ \psi(\hat{n}) = -2 \int_{0}^{\chi'} d\chi \frac{f_K(\chi' - \chi)}{f_K(\chi')} \Psi(\chi \hat{n}; \eta_0 - \chi) \]

\[ \Rightarrow \alpha = \nabla_\perp \psi \]

\[ \tilde{T}(\hat{n}) = T(\hat{n} + \nabla_\perp \psi) \approx T(\hat{n}) + T'(\hat{n}) \nabla_\perp \psi + \ldots \]

- Lensing generated by structures at large scales (~ cluster of galaxies to hundreds of Mpc) generates a distortion at small scales
- r.m.s. of deflection is ~ 2 arcmin
- Deflections are coherent over several degrees
  (Hanson, Challinor, Lewis 2009)
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  (Hanson, Challinor, Lewis 2009)
First measurements: ACT and SPT

$A_L$: convergence power spectrum amplitude
$A_L = 1 \Rightarrow$ best fit WMAP+ACT LCDM model
4$\sigma$ significance

$$A_L = \frac{C_L^{\text{data}} - N_L}{C_L^{\text{sim}} - N_L}$$

S. Das, B. Sherwin et al. 2011

$A_L = 0.86 \pm 0.16$
6.3$\sigma$ significance

R. Keisler, C. L. Reichardt et al. 2011
A. Van Engelen, R. Keisler et al. 2012
Planck results on lensing

\[ A^\phi_\phi = 0.99 \pm 0.05 \]

Planck+lensing+WMAP+high L
CMB lensing forecast: phenomenology

As a lensing estimator we chose to use only the spectra. Lensing induces small variations in the T and E-modes while it is more effective in modifying the B-modes. Introducing a varying DE modifies the primordial tensors up to 30% at the B-modes peak; this can contaminate the measurement of the parameter \( r \).

Up to now no forecasts for simultaneous constraints were given on a parametric DE and \( r \).
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Simulated datasets and analysis

We simulated data for a standard LCDM Universe from 3 CMB experiments: Planck and 2 upcoming suborbital missions, EBEX and PolarBear. The latter could be able to detect primordial B-modes.

We simulated two datasets: one with no primordial tensor modes ($r=0$) in order to set an expected upper limit and one with $r=0.05$ to estimate the sensitivity of the instruments in a realistic case.

We performed a MCMC analysis with the CosmoMC-CAMB software using different combination of experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Channel</th>
<th>FWHM</th>
<th>$\Delta T/T$</th>
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<td>70</td>
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</tr>
<tr>
<td></td>
<td>100</td>
<td>9.5’</td>
<td>2.5</td>
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<tr>
<td></td>
<td>143</td>
<td>7.1’</td>
<td>2.2</td>
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<td></td>
<td>217</td>
<td>5.0’</td>
<td>4.8</td>
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$f_{sky} = 0.85$

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<td>0.33</td>
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<tr>
<td></td>
<td>250</td>
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<td>0.33</td>
</tr>
<tr>
<td></td>
<td>410</td>
<td>8’</td>
<td>0.33</td>
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$f_{sky} = 0.01$

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<th>PolarBear</th>
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<td>90</td>
<td>6.7’</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>4.0’</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>2.7’</td>
<td>2.93</td>
</tr>
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</table>

$f_{sky} = 0.03$

Table 1. Planck, EBEX and PolarBear performance specifications. Channel frequency is given in GHz, beam FWHM in arcminutes, and the sensitivity for T per pixel in $\mu$K/K. The polarization sensitivity for both E and B—modes is $\sqrt{2}\Delta T/T$. 
Calibration and external priors

To check the consistency of our machinery we performed a few test runs assuming a standard LCDM Universe (fig. on the left) with $r=0$ and $w_0$, $w_a$ fixed, keeping the DE parameters fixed (green) and free to vary (blue) with a combination of Planck+Polarbear. We recover a decrease in constraining power due to the extra degrees of freedom, as expected. Adding an independent measurement at low $z$ such as SNe (fig. on the right) helps reducing the degeneracies significantly (in blue Planck+PolarBear, in green the combination with SNe).
Results I

$r=0$

blue: Planck+priors
red: all experiments

$r=0.05$
Results I

\[ r = 0 \]

\[ \text{blue: Planck with priors, LCDM} \]

\[ r = 0.05 \]

\[ \text{red: all experiments, CPL} \]
Results I

\[ r = 0 \]

\[ r = 0.05 \]

blue: Planck + priors
red: all experiments
Results II

In the case of Planck nominal performance, the constraining power on r is weakened by the inclusion of the extra degrees of freedom, resulting in an increase of about 10% of the upper limits on r as well as a comparable increase in the error bars in models with non-zero tensor power. The inclusion of sub-orbital CMB experiments, capable of mapping the B-mode power up to the angular scales which are affected by lensing, has the effect of making such loss of constraining power vanishing below a detectable level. When using a quadratic estimator for the lensing signal the constraints on DE parameters are degraded. No new degeneracies were detected with this approach.

<table>
<thead>
<tr>
<th>Experiments, fiducial</th>
<th>( r = 0 )</th>
<th>( r = 0.05 )</th>
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<tr>
<td>Planck with priors, ( \Lambda )CDM</td>
<td>( r &lt; 0.029 )</td>
<td>( r = 0.057 \pm 0.022 )</td>
</tr>
<tr>
<td>Planck with priors, CPL</td>
<td>( r &lt; 0.031 )</td>
<td>( r = 0.059 \pm 0.023 )</td>
</tr>
<tr>
<td>all experiments, ( \Lambda )CDM</td>
<td>( r &lt; 0.025 )</td>
<td>( r = 0.057 \pm 0.020 )</td>
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<tr>
<td>all experiments, CPL</td>
<td>( r &lt; 0.025 )</td>
<td>( r = 0.056 \pm 0.020 )</td>
</tr>
<tr>
<td>Planck with priors, CPL</td>
<td>( w_0 = -1.1 \pm 0.2 )</td>
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</tr>
<tr>
<td>all experiments, CPL</td>
<td>( w_0 = -1.1 \pm 0.2 )</td>
<td>( w_0 = -1.1 \pm 0.2 )</td>
</tr>
<tr>
<td>Planck with priors, CPL</td>
<td>( w_a = 0.3 \pm 0.6 )</td>
<td>( w_a = 0.3 \pm 0.6 )</td>
</tr>
<tr>
<td>all experiments, CPL</td>
<td>( w_a = 0.3 \pm 0.6 )</td>
<td>( w_a = 0.2 \pm 0.6 )</td>
</tr>
</tbody>
</table>
Lensing extraction

We are finishing the testing phase of an algorithm of lensing extraction based on the Okamoto-Hu quadratic estimator on flat sky. The aim is to obtain the convergence spectrum from a CMB map obtained by lensing an unperturbed CMB map through N-body simulations targeting the small scales (preliminary study for CMB-galaxy clustering cross correlation).

Y. Fantaye et al. 2012
Lensing extraction testing

Flat sky Okamoto-Hu estimator of the convergence field built with a combination of filtered maps

\[ G(\hat{n}) = \int \frac{d^2l}{(2\pi)^2} \frac{C^U_l}{C^t_l} i l T(l) e^{il\cdot\hat{n}} \]

\[ W(\hat{n}) = \int \frac{d^2l}{(2\pi)^2} \frac{1}{C^t_l} T(l) e^{il\cdot\hat{n}} \]

Use of gnomonic projection on tiling (overlap factor \(~0.5\))

Testing phase: lenspix realizations of lensed CMB maps

Error characterization will exploit the extraction from 100 LENSPIX CMB realizations

S. Plaszczynski et al. 2012
The CoDECS maps

N-body simulations of different interacting dark energy cosmologies on a LCDM background

\[ z_{\text{in}} = 99 \]

1 comoving Gpc/h aside \[ 1024^3 \] CDM and baryon particles hydrodynamics not considered

<table>
<thead>
<tr>
<th>Model</th>
<th>Potential</th>
<th>$\alpha$</th>
<th>$\beta_0$</th>
<th>$\beta_1$</th>
<th>$w_\phi(z = 0)$</th>
<th>$A_s(z_{\text{CMB}})$</th>
<th>$\sigma_8(z = 0)$</th>
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<td>LCDM</td>
<td>$V(\phi) = A$</td>
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<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
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<tr>
<td>EXP001</td>
<td>$V(\phi) = A e^{-\alpha \phi}$</td>
<td>0.08</td>
<td>0.05</td>
<td>0</td>
<td>$\phi(0) = 0$</td>
<td>$A = 0.0219$</td>
<td>$-1.0$</td>
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<td>EXP002</td>
<td>$V(\phi) = A e^{-\alpha \phi}$</td>
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<td>0</td>
<td>$\phi(0) = 0$</td>
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<tr>
<td>EXP003</td>
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<td>0.08</td>
<td>0.15</td>
<td>0</td>
<td>$\phi(0) = 0$</td>
<td>$A = 0.0218$</td>
<td>$-0.992$</td>
</tr>
<tr>
<td>EXP008c3</td>
<td>$V(\phi) = A e^{-\alpha \phi}$</td>
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<td>0.4</td>
<td>0</td>
<td>$\phi(0) = 0$</td>
<td>$A = 0.0217$</td>
<td>$-0.982$</td>
</tr>
<tr>
<td>SUGRA003</td>
<td>$V(\phi) = A \phi^{-\alpha e^{\phi^2/2}}$</td>
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<td>-0.15</td>
<td>0</td>
<td>$\phi(\to \infty) = \sqrt{\alpha}$</td>
<td>$A = 0.0202$</td>
<td>$-0.901$</td>
</tr>
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</table>
CMB maps lensed by N-body simulations with different cosmologies

How to create a light cone populated by structures? The volume until the integration redshift is divided into spherical shells. All the simulation boxes falling into the same shell are randomized in a coherent way. Randomization changes from shell to shell.

C. Carbone et al. 2008

To obtain the lensed CMB maps, the deflection angle $\alpha$ is computed for every direction $\hat{n}$:

$$\alpha(\hat{n}) = -2 \int_0^{r_*} \frac{r_* - r}{r_* r} \nabla_{\hat{n}} \frac{\Phi(r\hat{n}; \eta_0 - r)}{c^2} dr$$

Born approximation:
The change in the comoving separation of CMB light-rays, owing to the deflection caused by gravitational lensing from matter inhomogeneities, is small compared to the comoving separation between the undeflected rays.

$\Rightarrow$ the deflection angle is computed and added along the unperturbed direction of the photon.
The contribution from $l < 350$ is added from the CAMB maps of the lensing potential.
Extraction from CMB maps lensed by N-body simulations.

Aim: extracting and characterizing lensing signal from CoDECS maps obtained with underlying cosmologies to place constraints on the evolution of DE in recent times and quantify the contribution of non-linear scales at high $l$. C. Antolini et al. in preparation...
Constraints on cosmological parameters and local $f_{\text{NL}}$ with CMB-galaxies cross correlation

In the upcoming years, new data with unprecedented sensitivity will be delivered

Planck: CMB T, E, B, $\Psi$
maps

Euclid: $15,000^2$ survey in the visual-infrared bands
$0.7<z<2$

How much “information” can be extracted from measured angular power spectra?

The optimal prediction of the performance (ignoring systematics, foregrounds, unknown degeneracies) is given by the Fisher Matrix approach
Constraints on cosmological parameters and local $f_{NL}$ with CMB-galaxies cross correlation

$$F_{ij} = \sum_{l} \sum_{XX', YY'} \frac{\partial C_{l}^{XY}}{\partial \theta_i} (C_{ovl})^{-1} \frac{\partial C_{l}^{X'Y'}}{\partial \theta_j}$$

where $XX', YY' = TT, EE, TE, T\Psi, \Psi\Psi, gg, g\Psi$

For the $gg, g\Psi$ spectra, the constraints are computed dividing the survey span in redshift shells in order to exploit the differential information in redshift.

Constrained parameters:

- Standard 6 cosmological parameters: $\omega_b, \omega_c, A_s, n_s, H_0, \tau$
- Evolving bias: $b(z)$
- Parametrized DE: $w_0, w_a$
- Local non-gaussianites: $f_{NL}$

Work done in collaboration with W. Percival, L. Samushia
Future work

- Characterization of the error via Monte Carlo approach

- Extract the signal from N-body lensed CMB maps, with and without ray tracing (M. Calabrese et al., in preparation...)

- Place constraints on different cosmological histories using CoDECS maps

- Forecasts on non-standard cosmological parameters using Planck+Euclid

- Cross correlation of CMB lensing signal with simulated galaxy catalogues (preparatory science work for Euclid)
Highlights

- High resolution CMB experiments are posing new challenges to characterize second order effects in cosmology, like CMB lensing

- Late-time and primordial effects compete in the still-to-be-detected anisotropy spectra (B modes)

- The combination of different probes potentially allows for the separation of primordial effects from the evolution of the dark energy component

- The challenges ahead are represented by realistic simulations of the lensing distortion on N-body simulations with various dark energy models, interesting per se and as part of the preparatory work for the Euclid satellite

- In progress: lensing signal extraction from N-body lensed CMB maps

- Next: extraction from N-body maps with different underlying cosmologies and cross correlation with Euclid simulated catalogues
Thanks for your attention!
backup slides
CMB lensing: experiments

EBEX

- balloon experiment
- 1.5 m primary mirror
- 8 arcmin resolution
- 3 channels in frequency
- launch planned this fall
- approx 400 square deg

predictions for 14 days of data taking

foregrounds in frequency channels

P. Oxley, P. Ade 2005
B. Reichborn-Kjennerud, A. M. Aboobaker 2010
CMB lensing: experiments
PolarBear

- ground telescope
- surveying 4 regions $15^\circ \times 15^\circ$
- 3.5 m primary aperture
- 2 (eventually 3) channels in frequency

Could detect BB modes with $r = 0.025$

Engineering run: 3.8 arcmin resolution
Upgrades are planned...

B. Keating, S. Moyerman et al. 2011
The quadratic estimator

We need some tool to extract the deflection from the CMB spectrum to recover the projected gravitational potential.

Okamoto & Hu (2003) performed a full sky calculation to obtain estimators for the deflected power using the measured CMB power spectra.

How to build the quadratic estimator (flat sky):
- Make a filtered gradient map
- Make a high-pass filtered map
- Multiply them in real space
- Take the divergence
- Renormalize to ensure \( \langle \hat{d}(\mathbf{L}) \rangle = L \psi(\mathbf{L}) \) to first order in \( \psi \)

\[
\hat{d}(\mathbf{L}) = -\frac{A_L}{L} \int d^2 \hat{n} \nabla \cdot (W(\hat{n}) G(\hat{n})) e^{-i L \cdot \hat{n}}
\]

\[
\langle \hat{d}(\mathbf{L}_1) \hat{d}(\mathbf{L}_2) \rangle = (2\pi)^2 \delta(\mathbf{L}_1 + \mathbf{L}_2) (L_1^2 C_{L_1}^{\psi \psi} + N_L^{(0)}) + ...
\]

This estimator can be built under certain assumptions:
- the distribution of CMB anisotropies is Gaussian
- small deflection angle
- uncorrelated noise
- Gaussian convergence field
- no anisotropic foreground
CMB lensing: power transfer between scales and modes

\[ R = \frac{1}{4\pi} \int \frac{dl}{l} l^4 C_{l}^{\phi\phi}. \]

\[ \tilde{C}_{l}^{EE} = (1 - l^2 R) C_{l}^{EE} + \frac{1}{2} \int \frac{d^2 l_1}{(2\pi)^2} [(1 - l_1) \cdot l_1]^2 C_{|l_1-l_1|}^{\phi\phi} \]
\[ \times [(C_{l_1}^{EE} + C_{l_1}^{BB}) + \cos(4\varphi_{l_1})(C_{l_1}^{EE} - C_{l_1}^{BB})], \]

\[ \tilde{C}_{l}^{BB} = (1 - l^2 R) C_{l}^{BB} + \frac{1}{2} \int \frac{d^2 l_1}{(2\pi)^2} [(1 - l_1) \cdot l_1]^2 C_{|l_1-l_1|}^{\phi\phi} \]
\[ \times [(C_{l_1}^{EE} + C_{l_1}^{BB}) - \cos(4\varphi_{l_1})(C_{l_1}^{EE} - C_{l_1}^{BB})], \]

\[ \tilde{C}_{l}^{\Theta E} = (1 - l^2 R) C_{l}^{\Theta E} + \int \frac{d^2 l_1}{(2\pi)^2} [(1 - l_1) \cdot l_1]^2 C_{|l_1-l_1|}^{\phi\phi} \]
\[ \times C_{l_1}^{\Theta E} \cos(2\varphi_{l_1}), \quad (45) \]
CMB lensing: power transfer between scales and modes

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\times \left. \left[\left(C_{l_1}^{EE} + C_{l_1}^{BB}\right) + \cos(4\varphi_{l_1})\left(C_{l_1}^{EE} - C_{l_1}^{BB}\right)\right] \right] \]

\[ \tilde{C}_{l}^{BB} = \left(1 - l^2 R\right) C_{l}^{BB} + \frac{1}{2} \int \frac{d^2 l_1}{(2\pi)^2} \left[ \left(1 - l_1 \cdot l\right)^2 C_{l_1}^{\phi \phi} \right. \\
\times \left. \left[\left(C_{l_1}^{EE} + C_{l_1}^{BB}\right) - \cos(4\varphi_{l_1})\left(C_{l_1}^{EE} - C_{l_1}^{BB}\right)\right] \right] \]

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\times \left. C_{l_1}^{\Theta E} \cos(2\varphi_{l_1}) \right], \quad (45) \]
CMB lensing: power transfer between scales and modes

\[ R = \frac{1}{4\pi} \int \frac{dl}{l} l^4 C^\phi_\phi. \]

\[ \tilde{C}_l^{EE} = (1 - l^2 R) C_l^{EE} + \frac{1}{2} \int \frac{d^2 l_1}{(2\pi)^2} [(1 - l_1) \cdot l_1]^2 C^{\phi\phi}_{|l-1|} \times [(C_l^{EE} + C_l^{BB}) + \cos(4\varphi_{l_1})(C_l^{EE} - C_l^{BB})], \]

\[ \tilde{C}_l^{BB} = (1 - l^2 R) C_l^{BB} + \frac{1}{2} \int \frac{d^2 l_1}{(2\pi)^2} [(1 - l_1) \cdot l_1]^2 C^{\phi\phi}_{|l-1|} \times [(C_l^{EE} + C_l^{BB}) + \cos(4\varphi_{l_1})(C_l^{EE} - C_l^{BB})], \]

\[ \tilde{C}_l^{\Theta E} = (1 - l^2 R) C_l^{\Theta E} + \int \frac{d^2 l_1}{(2\pi)^2} [(1 - l_1) \cdot l_1]^2 C^{\phi\phi}_{|l-1|} \times C_l^{\Theta E} \cos(2\varphi_{l_1}), \]

(45)
Previous measurements of Dark Energy eq. of state
SDSS Lyα forest, SDSS galaxy clustering, SNe, WMAP 1 year

<table>
<thead>
<tr>
<th>Parameter</th>
<th>6-p+w</th>
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<td>WMAP+gal+bias+lya</td>
<td>WMAP+gal+bias+lya</td>
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<td>2.33$\pm$0.10 +0.20 +0.32</td>
<td>2.34$\pm$0.09 +0.19 +0.28</td>
<td>2.48$\pm$0.15 +0.29 +0.43</td>
<td>2.33$\pm$0.10 +0.20 +0.32</td>
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<td>$\Omega_m$</td>
<td>0.303$\pm$0.029 +0.061 +0.093</td>
<td>0.282$\pm$0.023 +0.047 +0.074</td>
<td>0.264$\pm$0.028 +0.056 +0.109</td>
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<tr>
<td>$n_s$</td>
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<td>0.981$\pm$0.027 +0.055 +0.080</td>
<td>0.980$\pm$0.026 +0.051 +0.068</td>
<td>1.020$\pm$0.041 +0.080 +0.114</td>
<td>0.978$\pm$0.028 +0.058 +0.084</td>
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<tr>
<td>$\tau$</td>
<td>0.160$\pm$0.082 +0.130 +0.139</td>
<td>0.163$\pm$0.064 +0.121 +0.135</td>
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<td>0.152$\pm$0.067 +0.127 +0.146</td>
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</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.945$\pm$0.089 +0.187 +0.290</td>
<td>0.895$\pm$0.033 +0.067 +0.104</td>
<td>0.920$\pm$0.040 +0.084 +0.12</td>
<td>0.890$\pm$0.030 +0.063 +0.099</td>
<td>0.897$\pm$0.033 +0.068 +0.104</td>
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<tr>
<td>$h$</td>
<td>0.699$\pm$0.027 +0.054 +0.080</td>
<td>0.708$\pm$0.023 +0.046 +0.069</td>
<td>0.736$\pm$0.039 +0.080 +0.119</td>
<td>0.726$\pm$0.025 +0.050 +0.078</td>
<td>0.707$\pm$0.023 +0.046 +0.066</td>
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<tr>
<td>$w$</td>
<td>$-1.009^{+0.096}_{-0.112} +0.18 +0.26</td>
<td>$-0.990^{+0.086}_{-0.093} +0.16 +0.22</td>
<td>$-1.080^{+0.149}_{-0.193} +0.24 +0.31</td>
<td>$-0.908^{+0.077}_{-0.091} +0.14 +0.19</td>
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<td>$w_l$</td>
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<td>0.05$^{+0.63}_{-0.63} +1.92 +2.88</td>
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U. Seljak, A. Makarov et al. 2004
Previous measurements of Dark Energy eq. of state
SDSS Ly$\alpha$ forest, SDSS galaxy clustering, SNe, WMAP 1 year

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<td>WMAP+gal+bias+lya</td>
<td>WMAP+gal+bias+lya</td>
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<tr>
<td>$10^2 \omega_b$</td>
<td>2.36\pm0.13 +0.26 +0.38 -0.11 -0.21 -0.31</td>
<td>2.33\pm0.10 +0.20 +0.32 -0.09 -0.18 -0.27</td>
<td>2.34\pm0.09 +0.19 +0.28 -0.09 -0.16 -0.26</td>
<td>2.48\pm0.15 +0.29 +0.43 -0.13 -0.24 -0.34</td>
<td>2.33\pm0.10 +0.20 +0.32</td>
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<td>$\Omega_m$</td>
<td>0.303\pm0.029 +0.061 +0.093 -0.028 -0.052 -0.072</td>
<td>0.282\pm0.023 +0.047 +0.074 -0.023 -0.044 -0.067</td>
<td>0.264\pm0.028 +0.056 +0.109 -0.022 -0.040 -0.062</td>
<td>0.260\pm0.024 +0.050 +0.077 -0.022 -0.040 -0.056</td>
<td>0.285\pm0.024 +0.047 +0.070</td>
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<tr>
<td>$n_s$</td>
<td>0.987\pm0.041 +0.077 +0.105 -0.030 -0.054 -0.075</td>
<td>0.981\pm0.027 +0.055 +0.080 -0.023 -0.042 -0.062</td>
<td>0.980\pm0.026 +0.051 +0.068 -0.020 -0.038 -0.059</td>
<td>1.020\pm0.041 +0.080 +0.114 -0.037 -0.068 -0.096</td>
<td>0.978\pm0.022 -0.041 -0.059</td>
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<td>0.160\pm0.082 +0.130 +0.139 -0.067 -0.116 -0.153</td>
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<td>0.145\pm0.066 +0.125 +0.152 -0.056 -0.109 -0.142</td>
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<td>0.920\pm0.040 +0.084 +0.12 -0.041 -0.072 -0.093</td>
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$w(z = 1) = -1.03^{+0.21}_{-0.28} +0.39 +0.58 +0.52$

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First measurements: ACT

Analysis made using a flat sky quadratic estimator

$A_L$: convergence power spectrum amplitude

$A_L = 1 \Rightarrow$ best fit WMAP+ACT LCDM model

$4\sigma$ significance

$$A_L = \frac{C_L^{\text{data}} - N_L}{C_L^{\text{sim}} - N_L}$$

S. Das, B. Sherwin et al. 2011

Also, from ACT data the first evidence for DE from CMB alone is recovered adding the ACT lensing data

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B. Sherwin, J. Dunkley et al. 2011
First measurements: SPT

\[ A_L^{0.65} = 0.94 \pm 0.15 \]

\[ A_L = 1 \Rightarrow \text{best fit WMAP+SPT LCDM model} \]

\[ 6\sigma \text{ significance} \]

\[ A_L = \frac{C_L^{\text{data}} - N_L}{C_L^{\text{sim}} - N_L} \]

R. Keisler, C. L. Reichardt et al. 2011
A. Van Engelen, R. Keisler et al. 2012
First measurements: SPT

\[ A_L = 0.86 \pm 0.16 \]

6.3\(\sigma\) significance

\[ A_L = \frac{C_L^{data} - N_L}{C_L^{sim} - N_L} \]

R. Keisler, C. L. Reichardt et al. 2011
A. Van Engelen, R. Keisler et al. 2012