Dark Energy and the Cosmic Microwave Background

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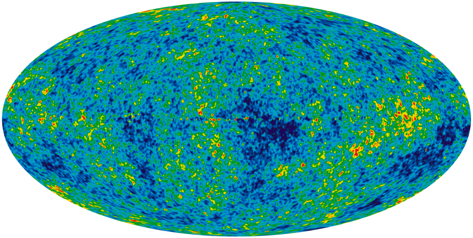
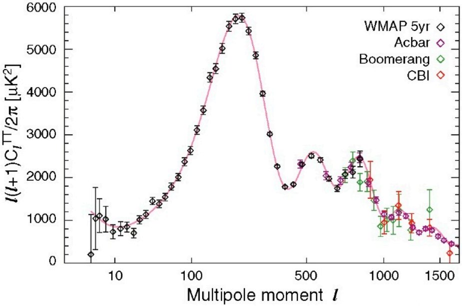
Dark Energy and Simulations   Ringberg June 28, 2012

The CMB data

WMAP 7 year CMB sky



The WMAP Team



Introduction

- The CMB data is precise and well understood.
- Most of it can be calculated within linear perturbation theory to percent accuracy.
- The resulting anisotropy and polarization spectra depend on a few cosmological parameters and a few parameters describing the initial conditions of the fluctuations. Which can also be determined accurately.

Minimal ΛCDM parameters (WMAP 7yr + ACT from Dunkley et al. '11)

Parameter	
$\omega_b \equiv \Omega_b h^2$	0.02214 ± 0.00050
$\omega_c \equiv \Omega_c h^2$	0.1127 ± 0.0054
Ω_Λ	0.721 ± 0.030
n_s	0.962 ± 0.013
τ	0.087 ± 0.014
$10^9 \Delta^2_{\mathcal{R}}$	2.47 ± 0.11

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Introduction

Prominent feature in the CMB: peaks from coherent acoustic oscillations of the baryon photon plasma prior to recombination.

- Scale: sound horizon $r_s(z_*) = (1+z_*)^{-1}\int_0^{t_*}(1+z(t))c_s(t)dt$, depends on $\omega_m, \omega_b, \omega_\gamma$. Angle: $\theta_S = r_s/D_A(z_*)$.
- Amplitude: $\Delta^2_{\mathcal{R}}$, n_s, ω_m.
- Relative amplitude of even and odd peaks: ω_b.
- Damping enveloppe: ω_b, n_s.
- Relative amplitude of 2nd and 3rd peak: ω_m.

Dark energy enters here only over $D_A(z_*)$!

$$\begin{aligned} D_A(z_*) &= \frac{1}{1+z_*}\int_0^{z_*}\frac{dz}{H(z)} \\ &= \frac{h}{H_0(1+z_*)}\int_0^{z_*}\frac{dz}{\sqrt{\omega_r(1+z)^4+\omega_m(1+z)^3+\omega_k(1+z)^2+\omega_{de}(z)}} \end{aligned}$$

$(h/H_0 = 2998\text{Mpc})$.

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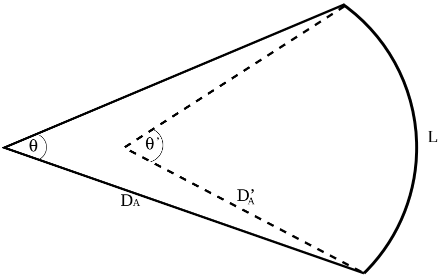
Distance scaling of CMB spectra



(from Vonlanthen, Räsänen & RD '10)

$$\mathcal{C}(\theta) \equiv \langle \Delta T(\mathbf{n}_1)\Delta T(\mathbf{n}_2)\rangle = \frac{1}{4\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\cos\theta)$$

$$= \frac{1}{4\pi}\sum_\ell (2\ell+1)C'_\ell P_\ell(\cos\theta') = \mathcal{C}'(\theta')$$

For $\ell \gtrsim 20$
$$C_\ell = \left(\frac{D'_A}{D_A}\right)^2 C'_{\frac{D'_A}{D_A}\ell}\,.$$

Distance scaling of CMB spectra

In Vonlanthen, Räsänen & RD '10 we have studied how well we can fit the CMB with a cosmological model which is Einstein de Sitter up to last scattering and the distance to last scattering is arbitrary, $D_A = SD_{A,EdS}$.

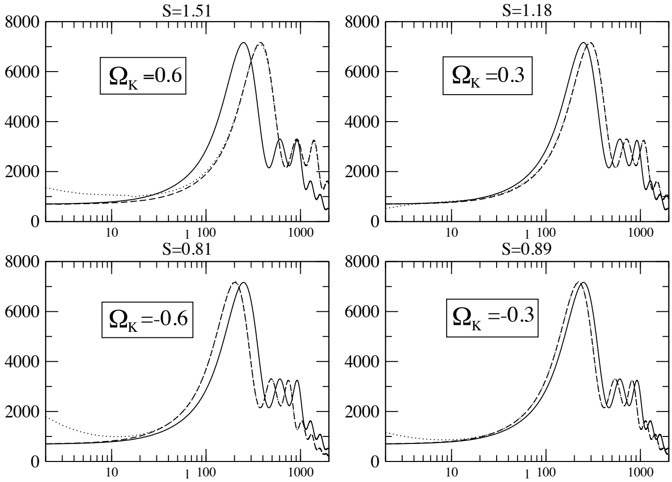
Features on the lss are then simply seen under a different angle,

$$C_\ell = S^{-2} C^{EdS}_{S^{-1}\ell} \ .$$

With this we can fit all present CMB data with $\ell \gtrsim 40$.

$\Rightarrow$ CMB data with $\ell > 40$ measures very precisely ω_b, ω_m, n_s and $D_A(z_*)$ or S, but it cannot determine the nature of dark energy.

Scaled spectra from curved cosmologies



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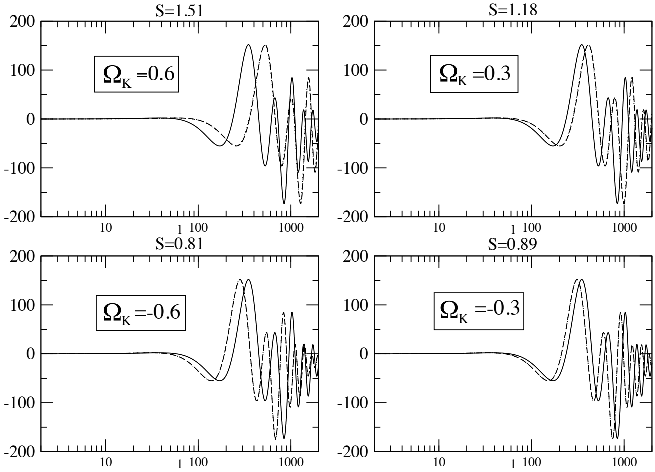

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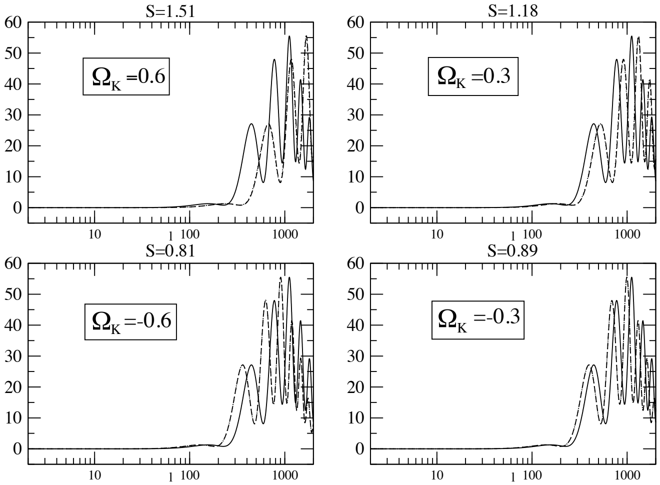

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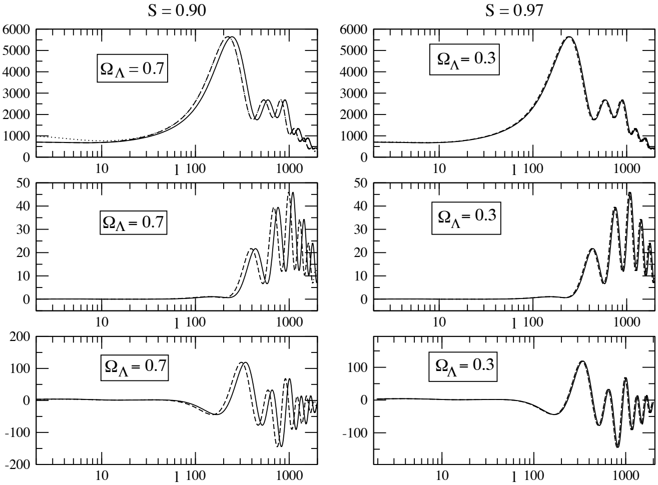

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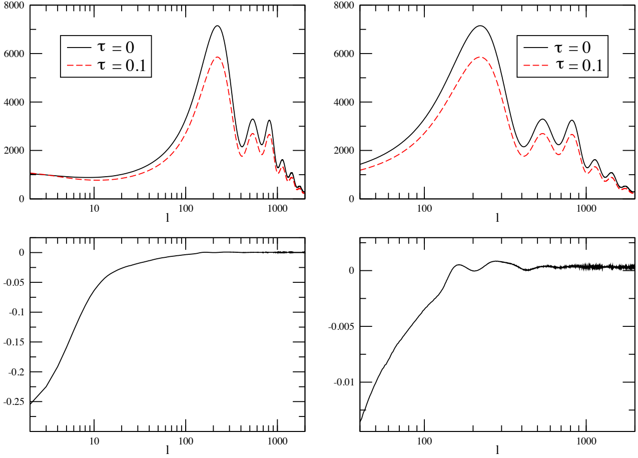
Reionization

TT



$\ell \geq 2$ $\ell \geq 40$

(from Vonlanthen, Räsänen & RD '10)

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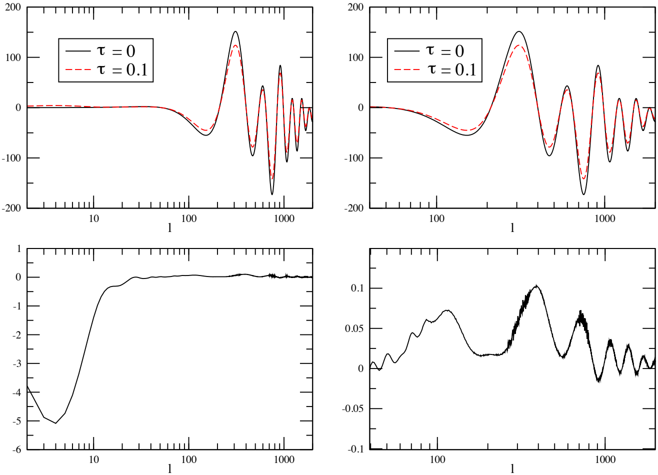

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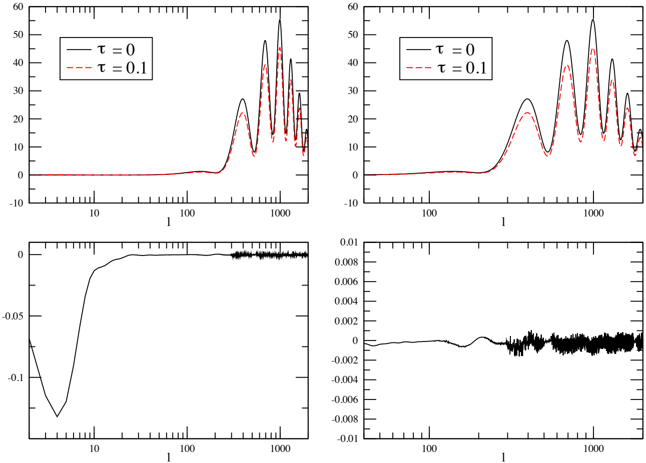
EE



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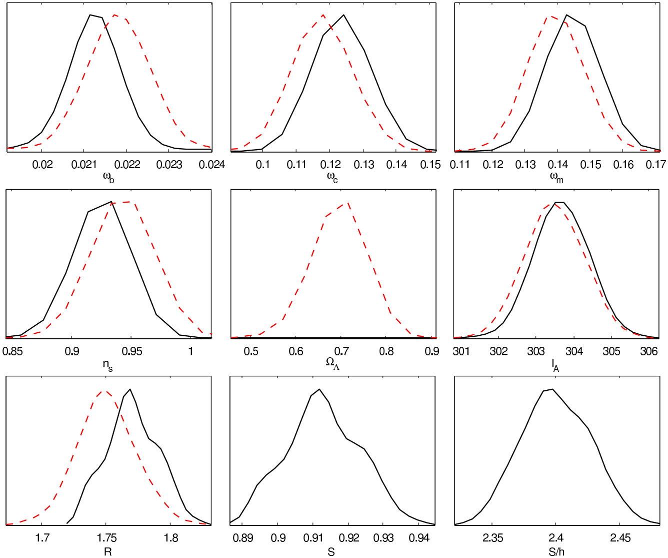
Cosmological parameters



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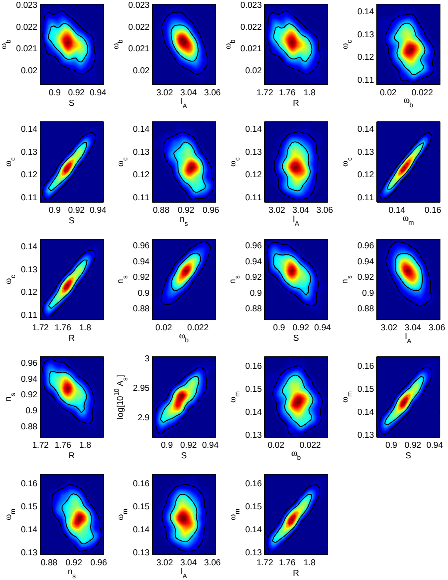

(from
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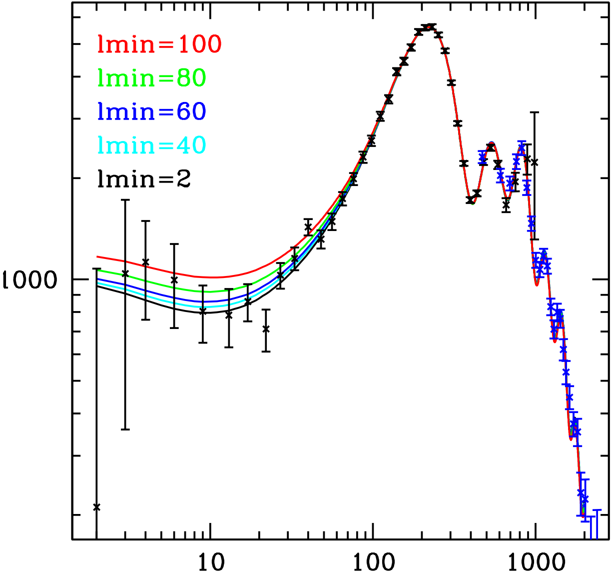
CMB from $\ell \geq l_{min}$



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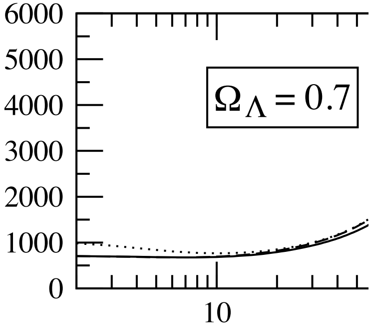
The integrated Sachs Wolfe effect (ISW)

On there way into our telescope CMB photons loose/gain energy if they move through a time-dependent gravitational potential:

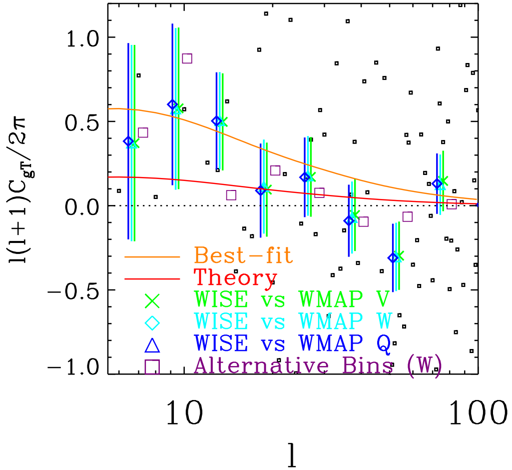
$$\left(\frac{\Delta T}{T}\right)_{ISW}(\mathbf{n}) = \int_{t_0}^{t_*} \partial_t(\Phi + \Psi)(t, \mathbf{x}(t))dt$$

In a flat pure matter Universe $\partial_t \Psi = \partial_t \Phi = 0$. When Λ takes over, the gravitational potentials decay.



ISW from correlation with LSS

Correlation of the WISE (wide field infrared survey explorer) with WMAP 7year.
A 3.1σ detection.

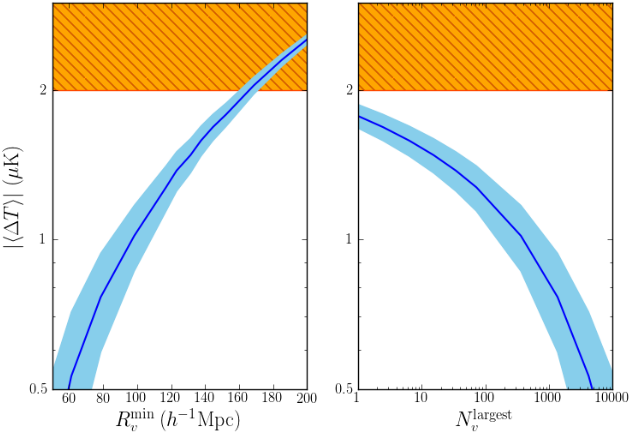


(from Goto, Szapudi & Granett '11)

Is the detected ISW too large?

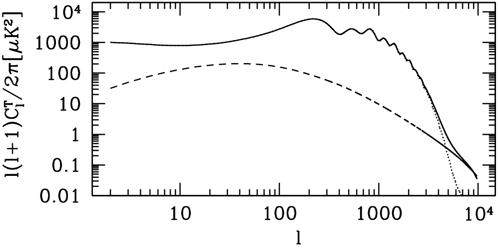
measured ⟹

simulated ⟹

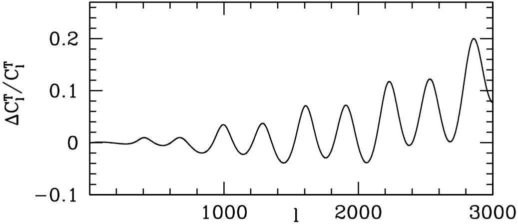


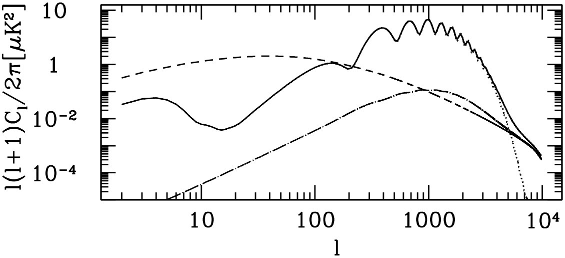
(from Nadatur, Hotschkiss & Sarkar '11

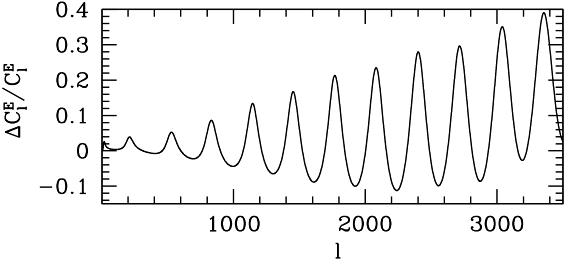
On their path into our antennas, CMB photons are deflected by the gravitational potential of the large scale matter distribution, the lensing potential:



$$\psi(\mathbf{n}) = \int_0^{\eta_0-\eta_*} dr \frac{r_* - r}{r r_*}(\Phi+\Psi)(\eta_0 - r, \mathbf{n}r)$$




$l(l+1)C_l/2\pi[\mu K^2]$
10
1
10^{-2}
10^{-4}
10
100
1000
10^4
l


$\Delta C_l^E/C_l^E$
0.4
0.3
0.2
0.1
0
−0.1
1000
2000
3000
l

Conclusions

- The strongest signal of dark energy in the CMB is via its effect on the distance to the lss, $D_A(z_*)$.
- At present this is the only signal of dark energy safely (more than 5σ significance) detected in the CMB.
- One can fit the observed data perfectly well without dark energy by a simple rescaling of $D_A(z_*)$ for $\ell > 20$. We found $2\Delta \log \mathcal{L} = 22$ (2591 data points) for $\ell_{\rm min} = 2$ and $2\Delta \log \mathcal{L} \lesssim 1$ for $\ell_{\rm min} \geq 20$.
- The ISW expected for ΛCDM is detected at about (3–4)σ by several experiments but it seems rather high.
- CMB lensing is another effect which contains information about dark energy and, especially modified gravity which will be explored in future high precision CMB experiments.

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