Università di Roma
'La Sapienza'

"Cosmic microwave weak lensing data as a test for the dark Universe"

Erminia Calabrese

In collaboration with Alessandro Melchiorri, Anže Slosar, George Smoot and Oliver Zahn, see Calabrese et al, Phys.Rev.D77:123531,2008

SIGRAV International School in Cosmology
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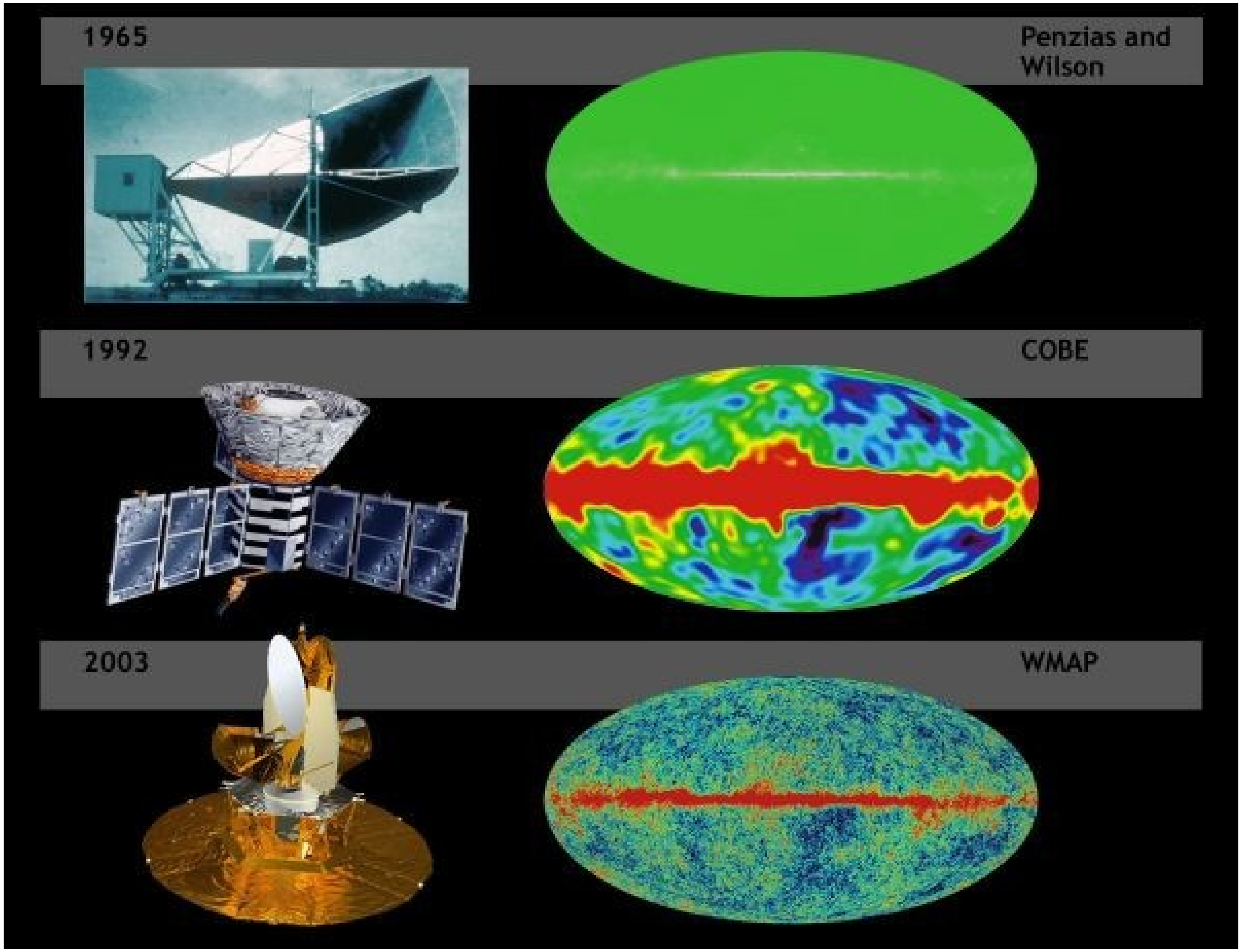
The Cosmic Microwave Background Radiation



$$T_{CMB} = 2.725 \pm 0.002\mathrm{K}$$

$$\left\langle \left(\frac{\Delta T}{T} \right)^2 \right\rangle^{1/2} = 1.1 \cdot 10^{-5}$$

Anisotropies Angular Power Spectrum

In the real space on defines the two points correlation function between two different sky directions as :

$$C(\theta) = \left\langle \frac{\Delta T(\boldsymbol{n})}{T} \frac{\Delta T(\boldsymbol{n}')}{T} \right\rangle = \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} C_l P_l(\cos\theta)$$

It, under the guassianity assumption, holds all the CMB statistical informations :

$$\left\langle \frac{\Delta T}{T}(\boldsymbol{n}) \right\rangle = 0$$

$$\left\langle \frac{\Delta T(\boldsymbol{n})}{T} \frac{\Delta T(\boldsymbol{n}')}{T} \right\rangle = C(\theta)$$

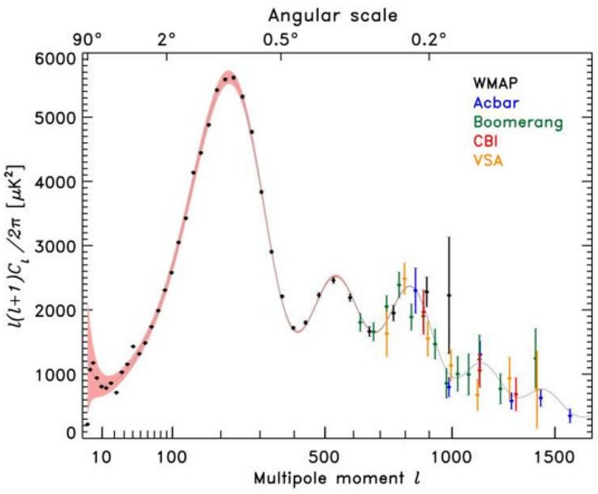
$$C(0) = \sigma^2$$

If we expand the CMB temperature fluctuations in spherical harmonics :

$$\frac{\Delta T}{T}(\boldsymbol{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\boldsymbol{n})$$

We can define the angular power spectrum as :

$$\langle a^*_{l'm'} a_{lm} \rangle = C_{lm} \delta_{ll'} \delta_{mm'} = C_l$$



It describes, in the Legendre space, the contribution of every multipole l to the observed signal

CMB Anisotropies

Primary anisotropies : are produced on the last scattering surface

$$\frac{\Delta T}{T} = \int_0^{\eta_0} \dot{\tau}(\Theta + \Psi + \hat{\boldsymbol{r}} \cdot v) e^{-\tau} d\eta$$

Intrinsic fluctuations

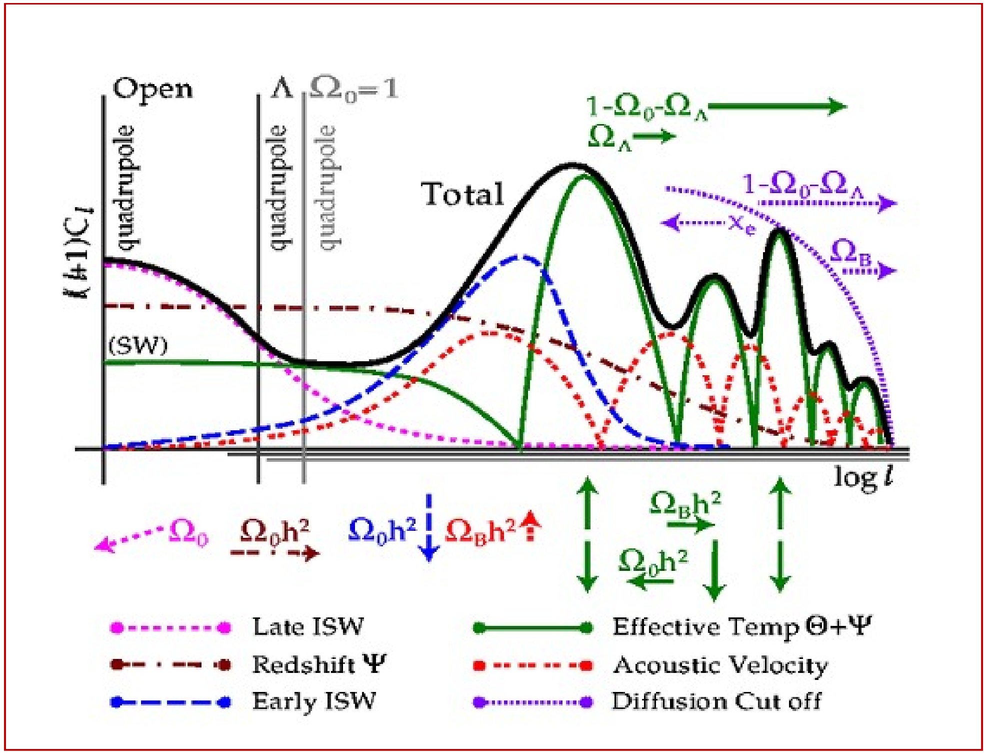
Sachs-Wolfe Effect

Doppler Effect

Secondary anisotropies : are produced while the radiation travels from the last scattering surface to today

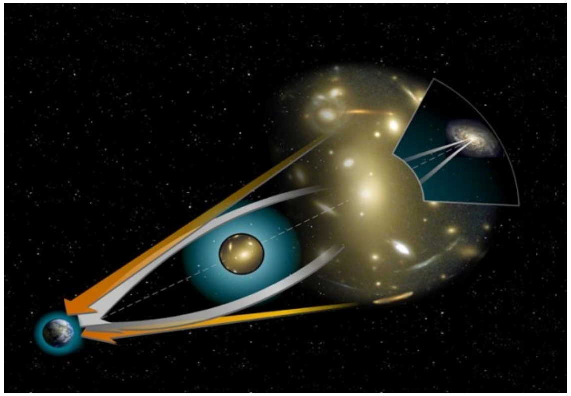
Scattering with electrons: Reionization, SZ

Fluctuations in the gravitational potential: (LSW, Rees-Sciama, Lensing)



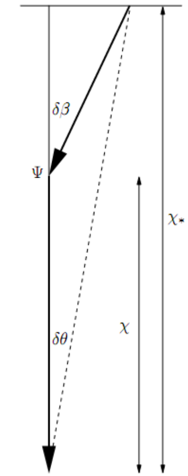
(see e.g. HuW. et al., arXiv:astro-ph/9504057)

Weak Gravitational Lensing



A gravitational source at comoving distance χ creates a deflection :

$$\delta\theta_\chi = \frac{f_K(\chi_* - \chi)\delta\beta}{f_K(\chi_*)} = -\frac{f_K(\chi_* - \chi)}{f_K(\chi_*)} 2\delta\chi \nabla_\perp \Psi$$



observer

Adding up the deflections from all the potential gradients between the observer and the source, we have a total deflection :

$$\boldsymbol{\alpha} = -2\int_0^{\chi_*} \mathrm{d}\chi \frac{f_k(\chi_* - \chi)}{f_k(\chi_*)} \nabla_\perp \Psi(\chi\hat{\boldsymbol{n}}; \eta_0 - \chi)$$

On defines the lensing potential :

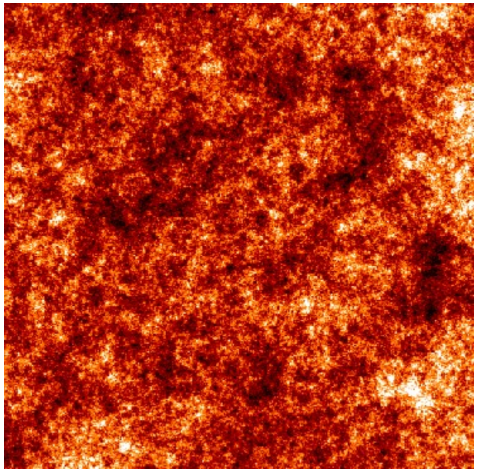
$$\psi(\hat{\boldsymbol{n}}) \equiv -2\int_0^{\chi_*} \mathrm{d}\chi \frac{f_k(\chi_* - \chi)}{f_k(\chi_*) f_k(\chi)} \Psi(\chi\hat{\boldsymbol{n}}; \eta_0 - \chi)$$

$$\boldsymbol{\alpha} = \nabla_{\hat{\boldsymbol{n}}} \psi$$

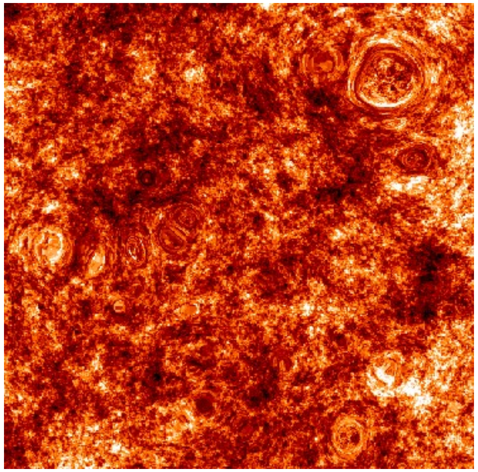
(see e.g. Lewis and Challinor arXiv:astro-ph/0601594 v4)

When the luminous source is the CMB, the lensing effect is essentially to re-maps the temperature field according to :

$$
\begin{aligned}
\tilde{\Theta}(\boldsymbol{x}) &= \Theta(\boldsymbol{x}') = \Theta(\boldsymbol{x} + \boldsymbol{\alpha}) = \Theta(\boldsymbol{x} + \nabla\psi) \\
&\approx \Theta(\boldsymbol{x}) + \nabla^a\psi(\boldsymbol{x})\nabla_a\Theta(\boldsymbol{x}) + \\
&\quad + \frac{1}{2}\nabla^a\psi(\boldsymbol{x})\nabla^b\psi(\boldsymbol{x})\nabla_a\nabla_b\Theta(\boldsymbol{x}) + \ldots
\end{aligned}
$$



unlensed



lensed

(http://www.mpia-hd.mpg.de/
Max Planck Institute for Astronomy at Heidelberg)

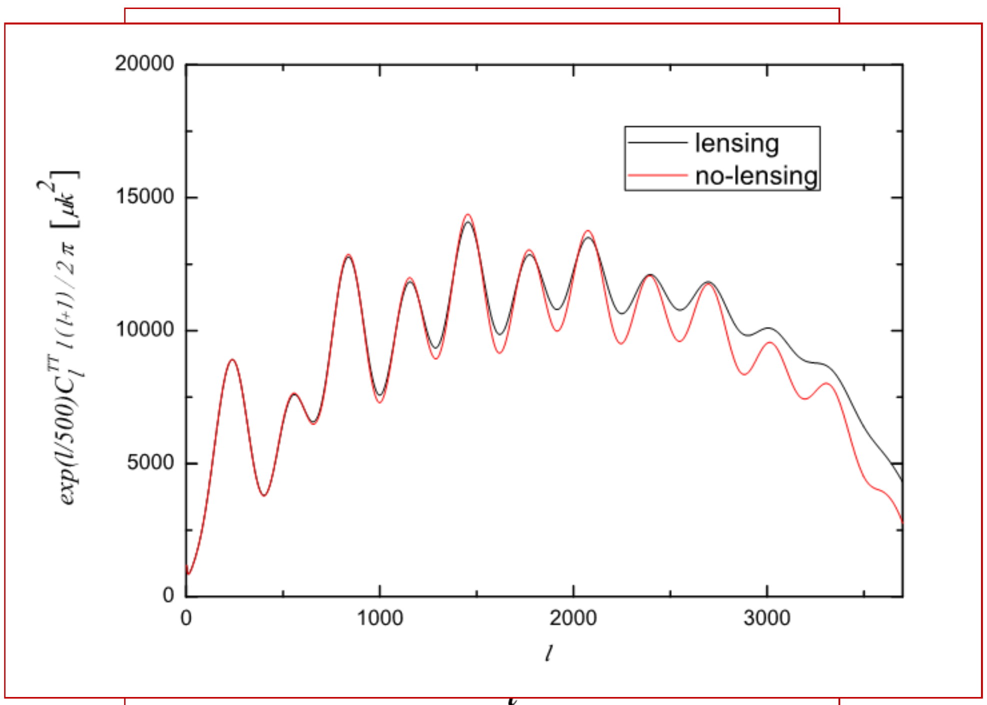
Lensing Effect on Temperature Power Spectrum

We obtain a convolution between the lensing potential power spectrum and the unlensed anisotropies power spectrum:

$$\tilde{C}_l^{\Theta} \approx C_l^{\Theta} + \int \frac{\mathrm{d}^2\boldsymbol{l}'}{(2\pi)^2} \left[\boldsymbol{l}' \cdot (\boldsymbol{l} - \boldsymbol{l}')\right]^2 C^{\psi}_{|\boldsymbol{l}-\boldsymbol{l}'|} C^{\Theta}_{l'} - C_l^{\Theta} \int \frac{\mathrm{d}^2\boldsymbol{l}'}{(2\pi)^2} (\boldsymbol{l} \cdot \boldsymbol{l}')^2 C^{\psi}_{l'}$$

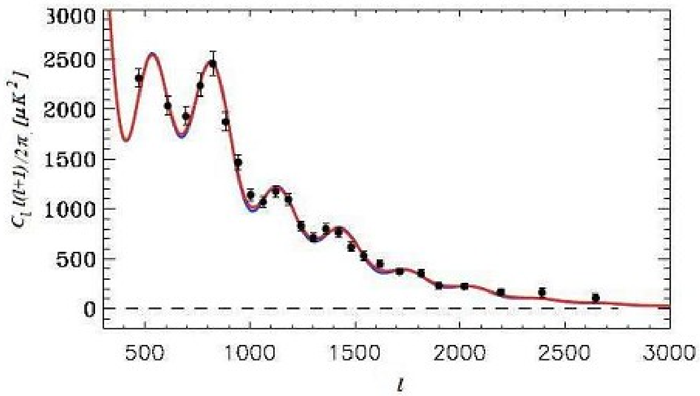
Where the lensing potential power spectrum is given by :

$$C_l^{\psi} = 16\pi \int \frac{\mathrm{d}k}{k} P_{\mathcal{R}}(k) \left[\int_0^{\chi_*} \mathrm{d}\chi T_{\Psi}(k; \eta_0 - \chi) j_l(k_\chi) \left(\frac{\chi_* - \chi}{\chi_* \chi} \right) \right]^2$$



The net result is a 3% broadening of the CMB angular power spectrum acustic peaks

ACBAR Lensing Detection



At the beginning of the last year, the ACBAR (Arcminute Cosmology Bolometer Array Receiver) team claimed a detection of a lensing signal at more than three standard deviations based ONLY on the broadening of the acoustic peaks

Reichardt et al. , arXiv:0801.1491v2 [astro-ph] 10 Jan 2008 :

ABSTRACT

In this paper, we present results from the complete set of cosmic microwave background (CMB) radiation temperature anisotropy observations made with the Arcminute Cosmology Bolometer Array Receiver (ACBAR) operating at 150GHz. We include new data from the final 2005 observing season, expanding the number of detector-hours by 210% and the sky coverage by 490% over that used for the previous ACBAR release. As a result, the band-power uncertainties have been reduced by more than a factor of two on angular scales encompassing the third to fifth acoustic peaks as well as the damping tail of the CMB power spectrum. The calibration uncertainty has been reduced from 6% to 2.2% in temperature through a direct comparison of the CMB anisotropy measured by ACBAR with that of the dipole-calibrated WMAP3 experiment. The measured power spectrum is consistent with a spatially flat, CDM cosmological model. *We see evidence for weak gravitational lensing of the CMB at > 3σ significance by comparing the likelihood for the best-fit lensed/unlensed models to the ACBAR+WMAP3 data.* On fine angular scales, there is weak evidence (1.7σ) for excess power above the level expected from primary anisotropies. The source of this power cannot be constrained by the ACBAR 150GHz observations alone; however, if it is the same signal seen at 30GHz by the CBI and BIMA experiments, then it has a spectrum consistent with the Sunyaev-Zel'dovich effect.

Analysis Method

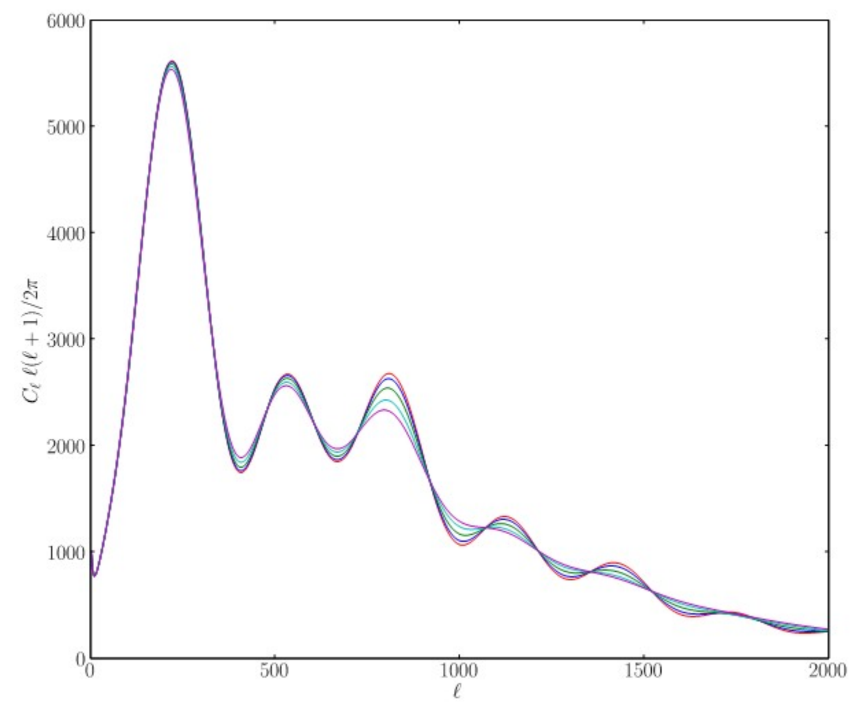
The ACBAR team just compared the best fit value between a model with lensing and a model without lensing, this is a row analysis that doesn't tell us the amount of the measured signal.
We decided to perform a more careful analysis

We phenomenologically uncoupled weak lensing from primary anisotropies by introducing a new parameter AL that scales the lensing potential such as :

$$C_l^{\psi} \rightarrow A_L C_l^{\psi}$$

- AL=0 corresponds to a theory ignoring lensing
- AL=1 corresponds to the standard weak lensing scenario.

AL can also be seen like a fudge parameter controlling the amount of smoothing of the peaks. In fact in this figure we can see that the curves with increasingly smoothed peak structures correspond to analysis with increasingly values of AL (0, 1, 3, 6, 9).



ACBAR and Standard Model Consistence results

· We checked that a model with AL =1 gives cosmological parameters in agreement with the ΛCDM standard model

· AL fixed to 0 and 1, with datasets WMAP3 and ACBAR $\Delta\chi^2 =$ (9,46 according to the ACBAR TEAM)

· Check of outliers in the ACBAR dataset

We calculated the contribution of every data point to the model according to :

$$\Delta\chi_i^2 = ((\vec{d} - \vec{t})^T C^{-1})_i (\vec{d} - \vec{t})_i$$

(where *d* denotes the data vector,
t denotes the theory vector, and *C* is the covariance matrix)

l_{eff}	$\Delta\chi^2$ (lensed)	$\Delta\chi^2$ (unlensed)
225	3.3	3.2
470	2.3	2.0
608	1.4	1.4
695	1.7	2.4
763	$9.5 \cdot 10^{-2}$	$1.3 \cdot 10^{-1}$
823	$3.3 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
884	2.2	2.3
943	1.0	1.8
1003	2.0	4.1
1062	$8.5 \cdot 10^{-2}$	$-1.7 \cdot 10^{-2}$
1122	$6.2 \cdot 10^{-2}$	$1.9 \cdot 10^{-1}$
1183	$6.5 \cdot 10^{-2}$	$2.2 \cdot 10^{-2}$
1243	$1.3 \cdot 10^{-1}$	$-3.6 \cdot 10^{-3}$
1301	$-3.9 \cdot 10^{-3}$	$3.1 \cdot 10^{-1}$
1361	1.7	2.3
1421	$1.2 \cdot 10^{-1}$	$3.4 \cdot 10^{-1}$
1482	4.1	4.9
1541	$1.3 \cdot 10^{-1}$	$4.5 \cdot 10^{-3}$
1618	1.4	3.6
1713	$1.4 \cdot 10^{-2}$	$-3.7 \cdot 10^{-2}$
1814	$3.0 \cdot 10^{-1}$	$3.2 \cdot 10^{-1}$
1898	$2.0 \cdot 10^{-1}$	$-3.5 \cdot 10^{-3}$
2020	$2.3 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$
2194	$2.7 \cdot 10^{-1}$	$5.5 \cdot 10^{-1}$
2391	2.3	2.5
2646	1.1	1.3
total	26.2	34.0

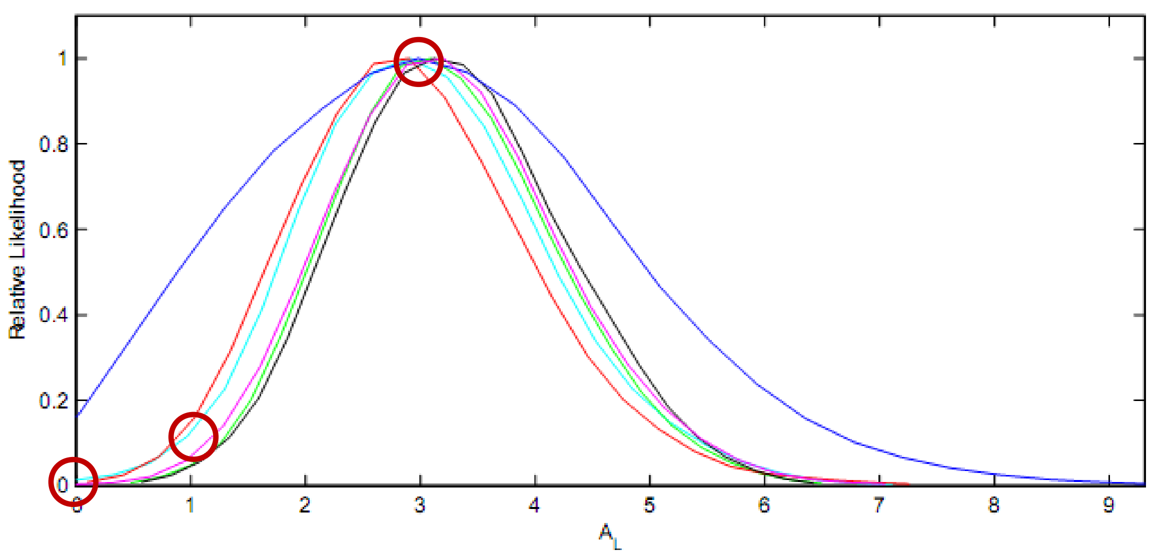
This table shows that there are no significant outliers in the data, as the overall contribution to the χ2 is evenly distributed across the bins.
The signal is coming from a range of scales.

Constraints on Lensing Parameter

Letting AL vary, we did several CosmoMC analysis with different datasets in input (marginalizing over Ω_b, Ω_c, τ, ns, As and θ_s):

Data set	Model	Limits on A_L
WMAP3	Free A_l	$3.1^{+1.6+3.4}_{-1.7-2.8}$
WMAP3 + ACBAR	Free A_L	$3.2^{+1.0+2.1}_{-0.9-1.7}$
WMAP3 + all	Free A_L	$3.3^{+1.0+1.9}_{-0.9-1.8}$
WMAP5	Free A_l	$2.5^{+1.3+2.6}_{-1.2-2.1}$
WMAP5 + ACBAR	Free A_L	$3.0^{+0.9+1.8}_{-0.9-1.6}$
WMAP5 + all	Free A_L	$3.1^{+0.9+1.8}_{-0.8-1.5}$

The results prefer values of AL which are considerably higher than the expected value 1 and they are statistically consistent with unity only at the level of 2 or 3 standard deviations.



(see E. Calabrese et al, Phys.Rev.D77:123531,2008)

ACBAR Claim of a 3 Sigma Lensing Detection Is Gone..

Reichardt et al. , arXiv:0801.1491v3 [astro-ph] (latest revised version):

ABSTRACT
In this paper, we present results from the complete set of cosmic microwave background (CMB) radiation temperature anisotropy observations made with the Arcminute Cosmology Bolometer Array Receiver (ACBAR) operating at 150 GHz. We include new data from the final 2005 observing season, expanding the number of detector-hours by 210% and the sky coverage by 490% over that used for the previous ACBAR release. As a result, the band-power uncertainties have been reduced by more than a factor of two on angular scales encompassing the third to fifth acoustic peaks as well as the damping tail of the CMB power spectrum. The calibration uncertainty has been reduced from 6% to 2.1% in temperature through a direct comparison of the CMB anisotropy measured by ACBAR with that of the dipole-calibrated WMAP5 experiment. The measured power spectrum is consistent with a spatially flat, LambdaCDM cosmological model. *We include the effects of weak lensing in the power spectrum model computations and find that this significantly improves the fits of the models to the combined ACBAR+WMAP5 power spectrum.* The preferred strength of the lensing is consistent with theoretical expectations. On fine angular scales, there is weak evidence (1.1 sigma) for excess power above the level expected from primary anisotropies. We expect any excess power to be dominated by the combination of emission from dusty protogalaxies and the Sunyaev-Zel'dovich effect (SZE). However, the excess observed by ACBAR is significantly smaller than the excess power at ell > 2000 reported by the CBI experiment operating at 30 GHz. Therefore, while it is unlikely that the CBI excess has a primordial origin; the combined ACBAR and CBI results are consistent with the source of the CBI excess being either the SZE or radio source contamination.

The claim of 3 sigma lensing detection is gone...
but too much lensing still there !

Why data suggest a lensing signal three times larger than the expected value?

1. Statistical fluctuation (only 2 sigma evidence), data essentially in agreement with the standard scenario of weak lensing, "Lucky Acbar"

1. 'new physics'

1. Primordial isocurvature barionic modes

1. Additional components

1. Unknown systematics in the ACBAR dataset

Gravitational Slip

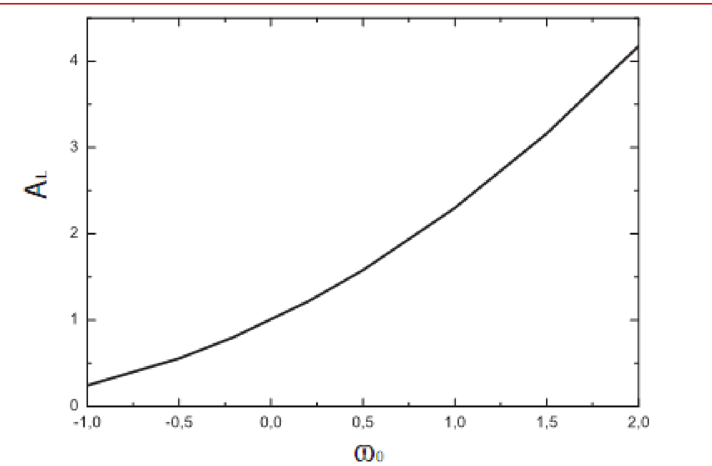
Considering a modified gravity theory in which :

$$\Psi = (1+\bar{\omega}(z))\Phi \qquad \bar{\omega}(z) = \bar{\omega}_0 \frac{\Omega_\Lambda}{\Omega_m}(1+z)^{-3}$$

(Daniel et al., arXiv:0802.1068)

We obtain a relation with the lensing parameter:

$$A_L(\bar{\omega}) = \left(\frac{G_{\bar{\omega}}(z=2)}{G_{\Lambda CDM}(z=2)}\right)^2 \left(\frac{2+\bar{\omega}}{2}\right)^2$$



But if we want AL ≈3 we need values of $\bar{\omega}_0$ *too large*

($\bar{\omega}_0 < 1$ Daniel et al. , arXiv:0901.091)

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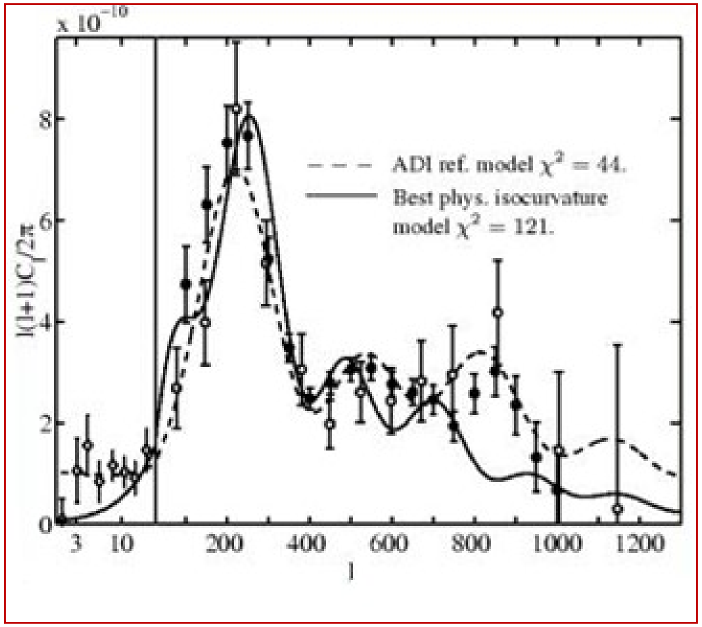
Isocurvature Perturbations

Isocurvature modes usually produce acoustic oscillations opposite in phase with the standard adiabatic fluctuations

- The sum of the two contributions could smooth the angular power spectrum



An analysis with an additional component of isocurvature barionic perturbations gives :

$$A_L = 3.3^{+2.3}_{-2.0}$$

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Additional Components

The possible presence of string or Sunyaev Zel'dovich contributions has been considered:

1. SZ1 is a template expected from the Sunyaev-Zel'dovich effect as given by the analytic model of Komatsu and Seljak (Mon. Not. R. Astron. Soc. 336,1256,2002)

1. SZ2 is a similar template based on smoothed particle hydrodynamics simulations (O. Zahn et al., unpublished)

1. strings template corresponding to the Pogosian and Vachaspati model (Phys. Rev. D 60, 083504,1999)

WMAP3 + ACBAR + strings	$2.9^{+1.3+2.3}_{-1.2-1.8}$
WMAP3 + ACBAR + SZ1	$3.1^{+1.0+2.2}_{-1.0-2.0}$
WMAP3 + ACBAR + SZ2	$3.0^{+1.0+2.3}_{-1.0-1.8}$

- *The effect of these templates on the value of AL is very small.*

We conclude that while the data allow for some amount of extra smooth components, it by no means changes the "detection" of lensing.

Why data suggest a lensing signal three times larger than the expected value?

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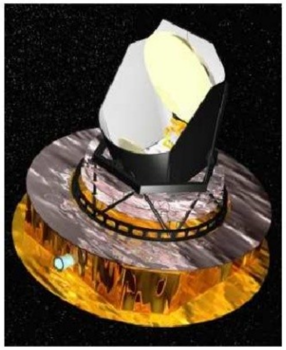
Future constraints

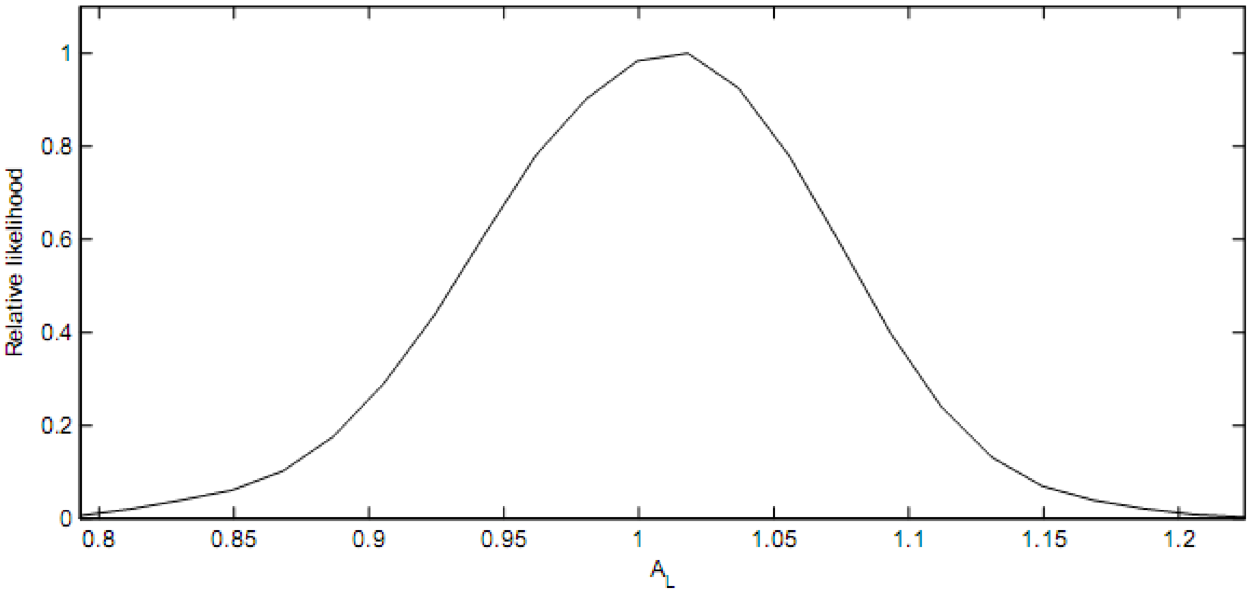
Planck



HFI 143 GHz Channel:

- fsky =1
- Θ=7'
- NoiseVar=3,4·10-4 μK2
- fiducial model with ACBAR+WMAP3 best fit parameters

Letting the lensing parameter vary, the obtained constraints are: $A_L = 1.00^{+0.07+0.12}_{-0.06-0.12}$



Conclusions

- *We introduced a new parameter that uncouples the gravitational lensing from primary CMB anisotropies and that controls the broadening of the angular power spectrum acoustic peaks*

- *We confirmed the claim from the ACBAR team by performing two analysis with AL =0 and AL = 1*

- *Letting AL vary, with different datasets in input, we obtained constraints on it and the results prefer AL ~3 with AL=1 ruled out at 2 sigma level*

- *We searched for some explanations of this inconsistency between the results and the expected values (statistical fluctuations, new physics or wrong ACBAR dataset estimations).*

- *We did a similar analysis simulating a dataset for the Planck HFI 143 GHz channel and we found that with Planck we could constraint AL at a level of 10% . Planck will solve the question (maybe).*

As I showed before larger is the potential and larger is the broadening of the acoustic peaks, so we need to increase :

$$C_l^{\psi} \approx \frac{8\pi^2}{l^3} \int_0^{\chi_*} \chi \mathrm{d}\chi \, \mathcal{P}_\Psi(l/\chi; \eta_0 - \chi) \left(\frac{\chi_* - \chi}{\chi_* \chi} \right)^2$$

And so in the standard scenario we need to modify this relation :

$$\mathcal{P}_\Psi(k;\eta) = \frac{9\Omega_m^2(\eta) H^4(\eta)}{4} \frac{\mathcal{P}_{\bar{\delta}}(k;\eta)}{k^4} = \frac{9\Omega_m^2(\eta) H^4(\eta)}{8\pi^2} \frac{P(k;\eta)}{k}$$