Title: N-body lensed CMB maps: lensing extraction and characterization

Date: Nov 15, 2013 11:00 AM

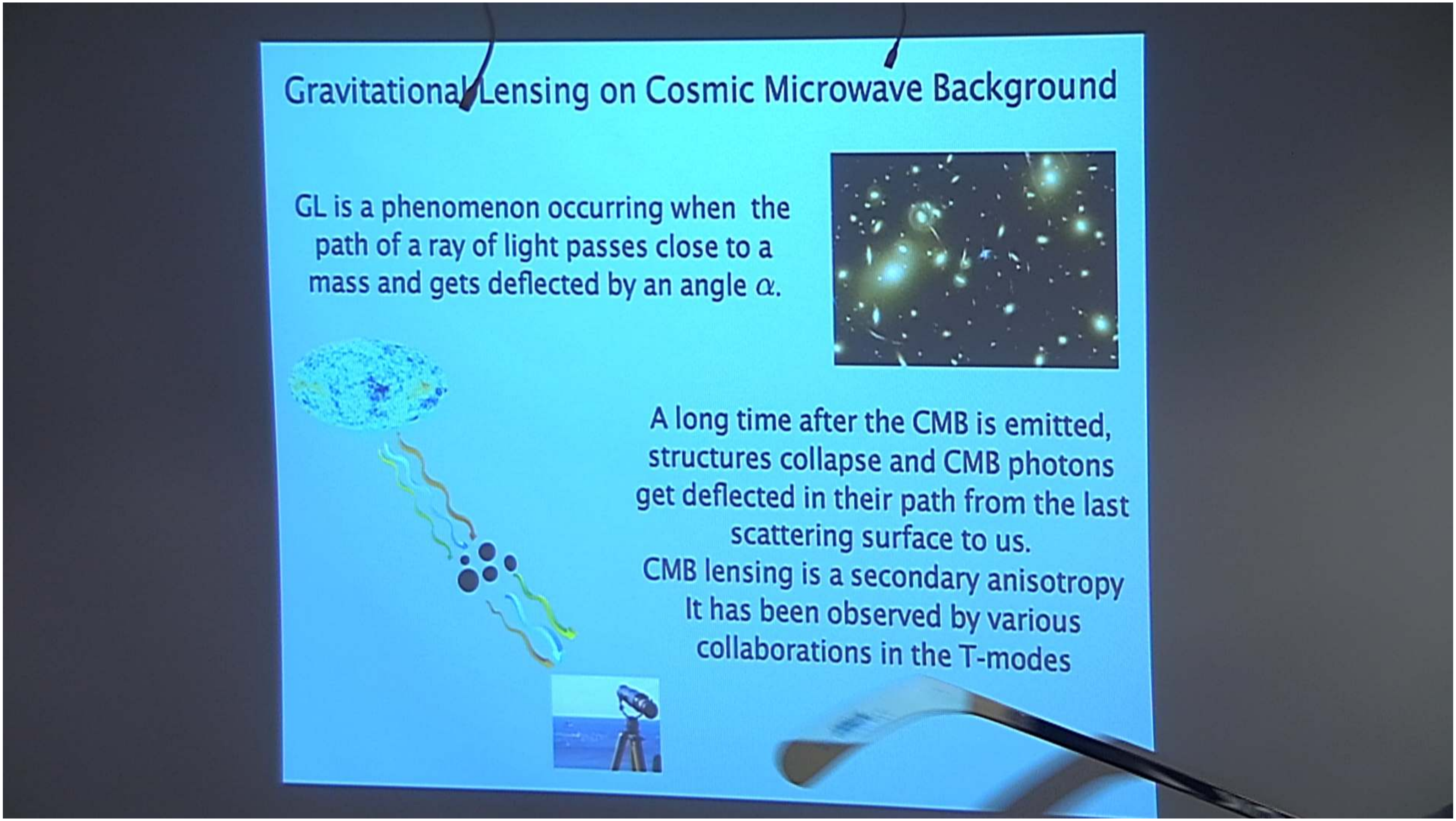
URL: http://pirsa.org/13110088

Abstract: After multiple high precision detections (ACT, SPT, Planck) gravitational lensing has become a new source of relevant cosmological information: combining it with other probes (e.g. the large scale structure) can give significant insight on the evolution of the Dark Energy component. Developing new algorithms of estimate of this signal will allow the community to exploit this observable as a new and independent probe in cosmology. In my talk I will present the reconstruction of the lensing shear pattern and its angular power spectrum from total intensity and polarised CMB maps obtained using Born approximated ray-tracing through N-body simulated structures.The recovered spectra are in agreement with predictions of the underlying Î›CDM with no visible bias, on a scale interval which extends from the arcminute to several degrees over the sky. This demonstrates the feasibility of CMB lensing studies based on large scale simulations of cosmological structure formation in the context of the upcoming large observational campaigns.

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 α.

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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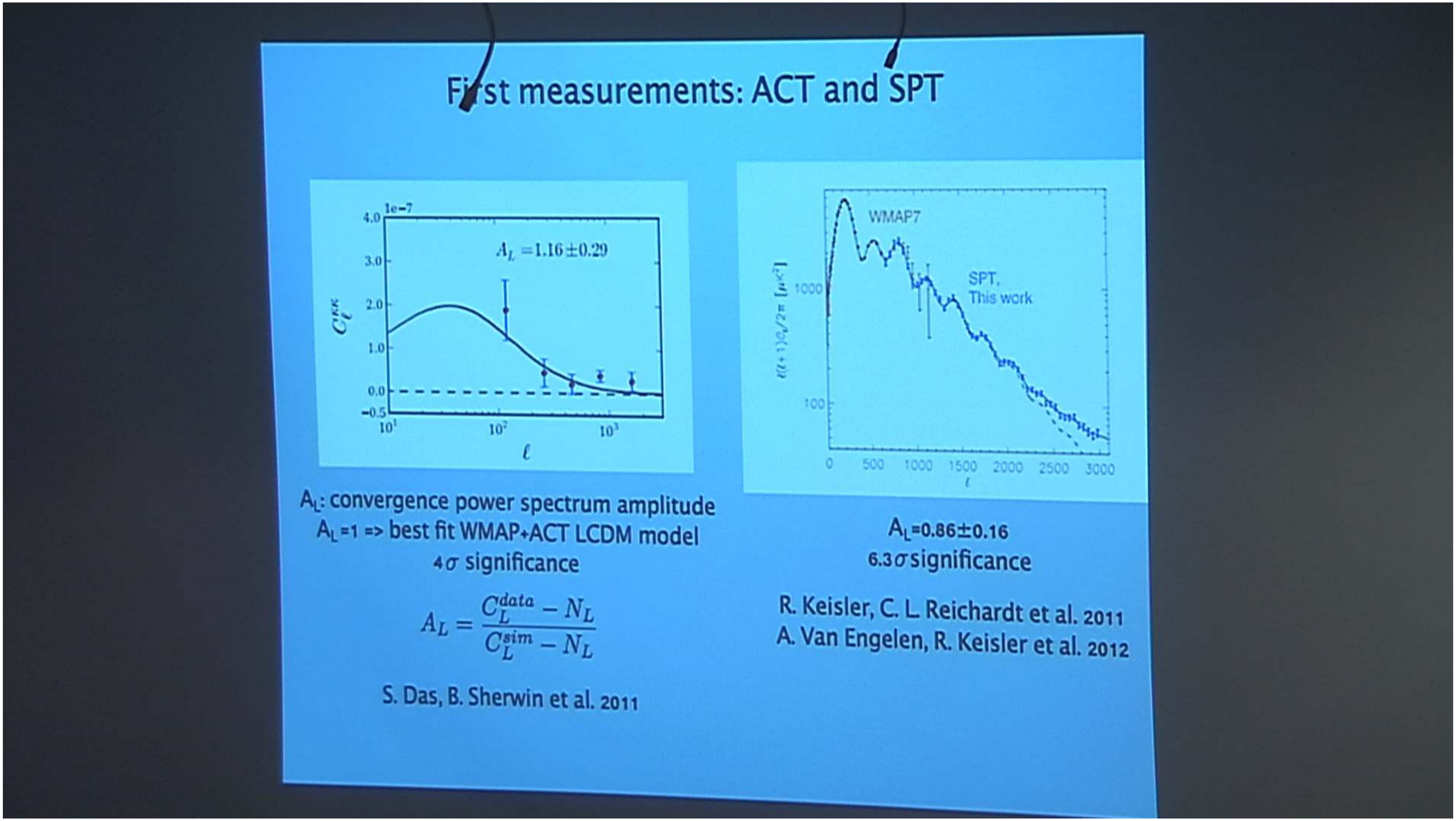
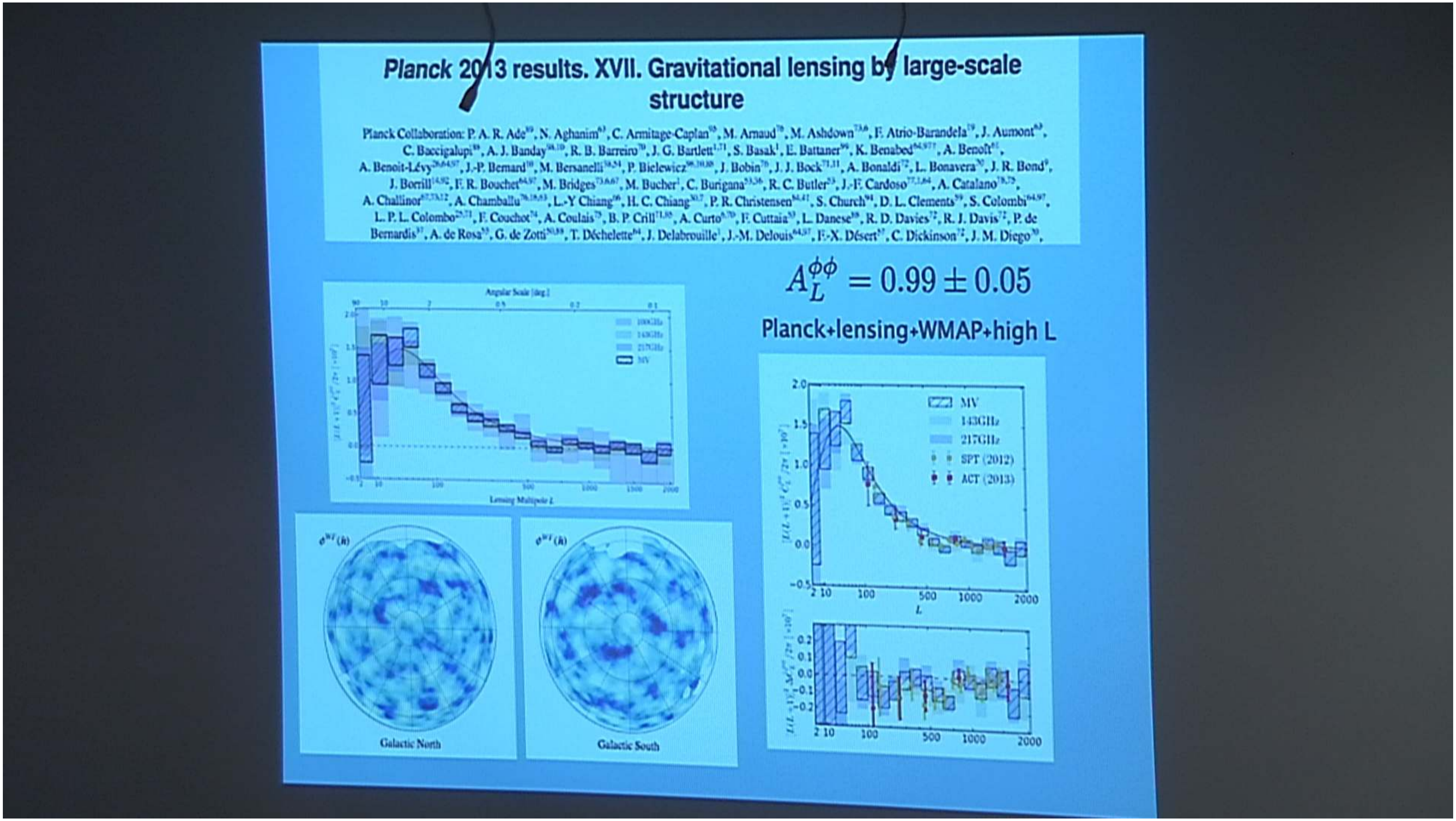

First measurements: ACT and SPT
$A_L = 1.16 \pm 0.29$
$C_\ell^{\kappa\kappa}$
1e−7
ℓ
WMAP7
SPT,
This work
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
A_L: convergence power spectrum amplitude
A_L=1 => best fit WMAP+ACT LCDM model
4σ significance
$$A_L = \frac{C_L^{data} - N_L}{C_L^{sim} - N_L}$$
S. Das, B. Sherwin et al. 2011
A_L=0.86±0.16
6.3σ significance
R. Keisler, C. L. Reichardt et al. 2011
A. Van Engelen, R. Keisler et al. 2012

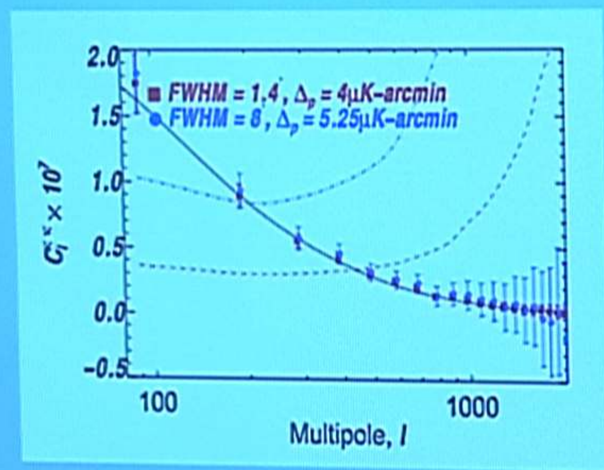

Planck 2013 results. XVII. Gravitational lensing by large-scale structure
Planck Collaboration: P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, S. Basak, E. Battaner, K. Benabed, A. Benoît, A. Benoit-Lévy, J.-P. Bernard, M. Bersanelli, P. Bielewicz, J. Bobin, J. J. Bock, A. Bonaldi, L. Bonavera, J. R. Bond, J. Borrill, F. R. Bouchet, M. Bridges, M. Bucher, C. Burigana, R. C. Butler, J.-F. Cardoso, A. Catalano, A. Challinor, A. Chamballu, L.-Y Chiang, H. C. Chiang, P. R. Christensen, S. Church, D. L. Clements, S. Colombi, L. P. L. Colombo, F. Couchot, A. Coulais, B. P. Crill, A. Curto, F. Cuttaia, L. Danese, R. D. Davies, R. J. Davis, P. de Bernardis, A. de Rosa, G. de Zotti, T. Déchelette, J. Delabrouille, J.-M. Delouis, F.-X. Désert, C. Dickinson, J. M. Diego,
$A_L^{\phi\phi} = 0.99 \pm 0.05$
Planck+lensing+WMAP+high L
Angular Scale [deg.]
Lensing Multipole L
MV
143GHz
217GHz
SPT (2012)
ACT (2013)
L
Galactic North
Galactic South

CMB lensing: power transfer between scales and modes

$$R = \frac{1}{4\pi} \int \frac{dl}{l}\, l^4 C_l^{\phi\phi}\,.$$

$$\tilde{C}_l^{EE} = \left(1 - l^2 R\right) C_l^{EE} + \frac{1}{2} \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} [(\mathbf{l} - \mathbf{l}_1) \cdot \mathbf{l}_1]^2 C^{\phi\phi}_{|\mathbf{l}-\mathbf{l}_1|}$$
$$\times [(C_{l_1}^{EE} + C_{l_1}^{BB}) + \cos(4\varphi_{l_1})(C_{l_1}^{EE} - C_{l_1}^{BB})]\,,$$
$$\tilde{C}_l^{BB} = \left(1 - l^2 R\right) C_l^{BB} + \frac{1}{2} \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} [(\mathbf{l} - \mathbf{l}_1) \cdot \mathbf{l}_1]^2 C^{\phi\phi}_{|\mathbf{l}-\mathbf{l}_1|}$$
$$\times [(C_{l_1}^{EE} + C_{l_1}^{BB}) - \cos(4\varphi_{l_1})(C_{l_1}^{EE} - C_{l_1}^{BB})]\,,$$
$$\tilde{C}_l^{\Theta E} = \left(1 - l^2 R\right) C_l^{\Theta E} + \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} [(\mathbf{l} - \mathbf{l}_1) \cdot \mathbf{l}_1]^2 C^{\phi\phi}_{|\mathbf{l}-\mathbf{l}_1|}$$
$$\times C_{l_1}^{\Theta E} \cos(2\varphi_{l_1})\,, \qquad (45)$$

Lensing extraction



Y. Fantaye et al. 2012

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 targetting the small scales (preliminary study for CMB-galaxy clustering cross correlation).

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 ψ

$$\mathbf{G}(\hat{\mathbf{n}}) = \int \frac{d^2\mathbf{l}}{(2\pi)^2} \frac{C_l^U}{C_l^t} i\mathbf{l}T(\mathbf{l}) e^{i\mathbf{l}\cdot\hat{\mathbf{n}}}$$

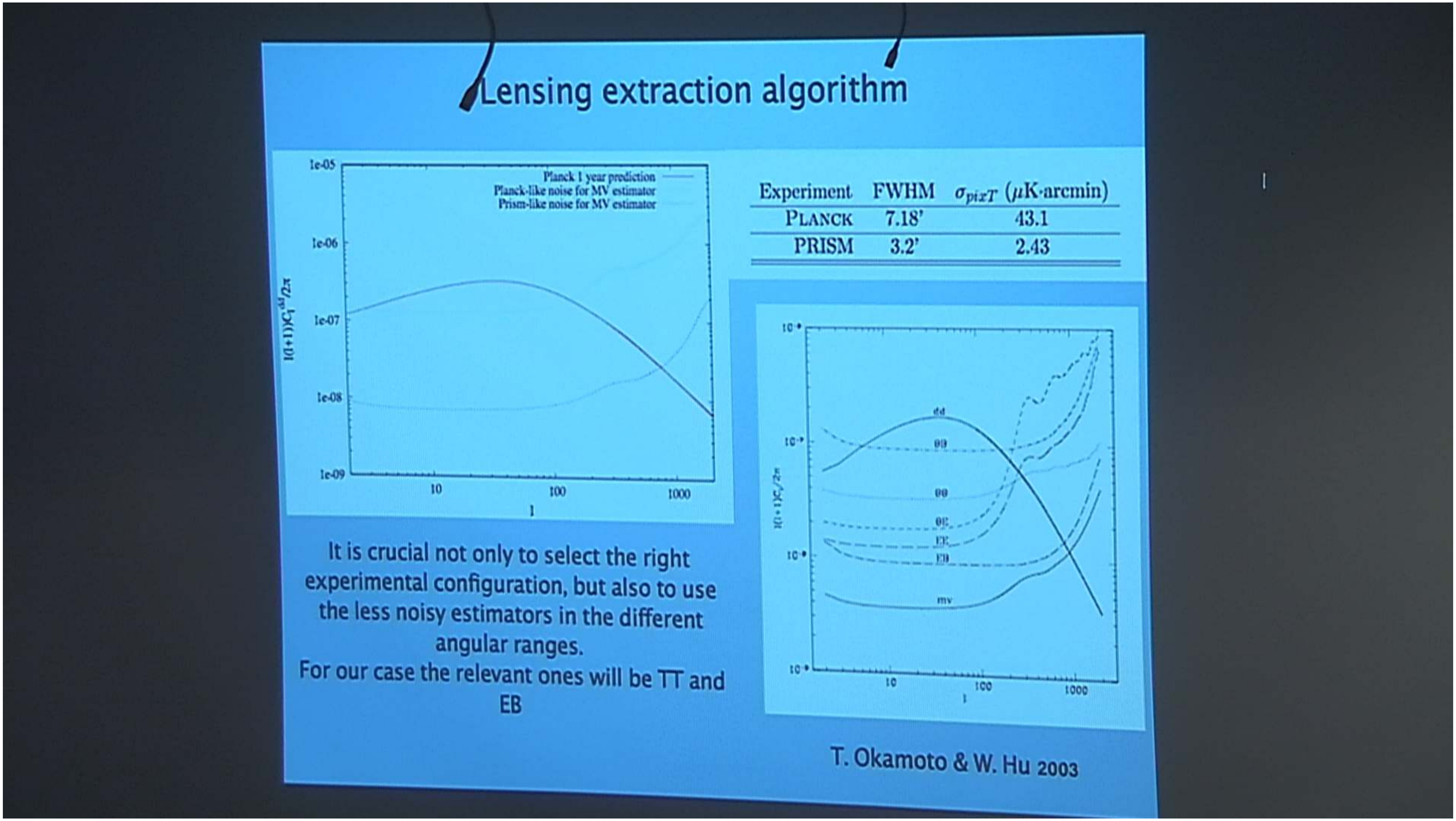
$$W(\hat{\mathbf{n}}) = \int \frac{d^2\mathbf{l}}{(2\pi)^2} \frac{1}{C_l^t} T(\mathbf{l}) e^{i\mathbf{l}\cdot\hat{\mathbf{n}}}$$

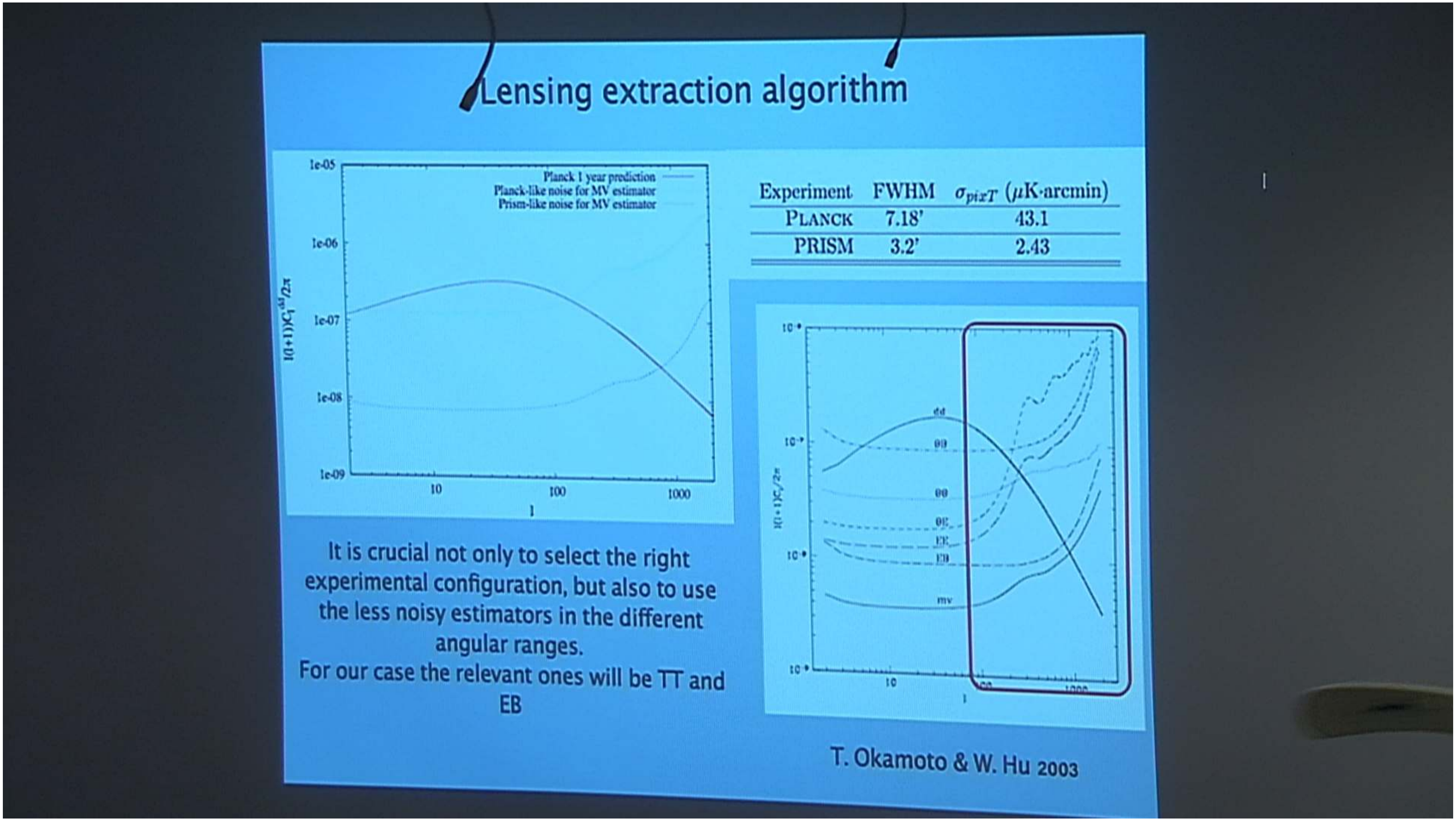
$$\mathbf{L} = \mathbf{l_1} + \mathbf{l_2}$$

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

$$\langle \hat{d}(\mathbf{L_1}) \hat{d}(\mathbf{L_2}) \rangle = (2\pi)^2 \delta(\mathbf{L_1} + \mathbf{L_2}) ({L_1}^2 C_{L_1}^{\psi\psi} + N_L^{(0)}) + ...$$

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


Lensing extraction algorithm
Planck 1 year prediction
Planck-like noise for MV estimator
Prism-like noise for MV estimator
1e-05
1e-06
1e-07
1e-08
1e-09
10
100
1000
l
Experiment FWHM σpixT (μK·arcmin)
PLANCK 7.18' 43.1
PRISM 3.2' 2.43
dd
θθ
EB
mv
It is crucial not only to select the right experimental configuration, but also to use the less noisy estimators in the different angular ranges.
For our case the relevant ones will be TT and EB
T. Okamoto & W. Hu 2003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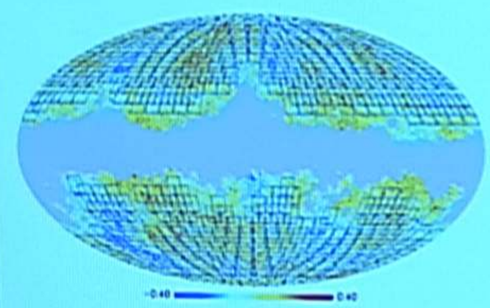

Fig. 4. Example of the tiling of the map shown on Fig. 1 with overlapping 10° × 10° patches, that do not intersect the Galactic masked region.

S. Plaszczynski et al. 2012

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

$$\mathbf{G}(\hat{\mathbf{n}}) = \int \frac{d^2\mathbf{l}}{(2\pi)^2} \frac{C_l^U}{C_l^t} i\mathbf{l}T(\mathbf{l}) e^{i\mathbf{l}\cdot\hat{\mathbf{n}}}$$

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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

CMB maps lensed by N-body simulations with different cosmologies

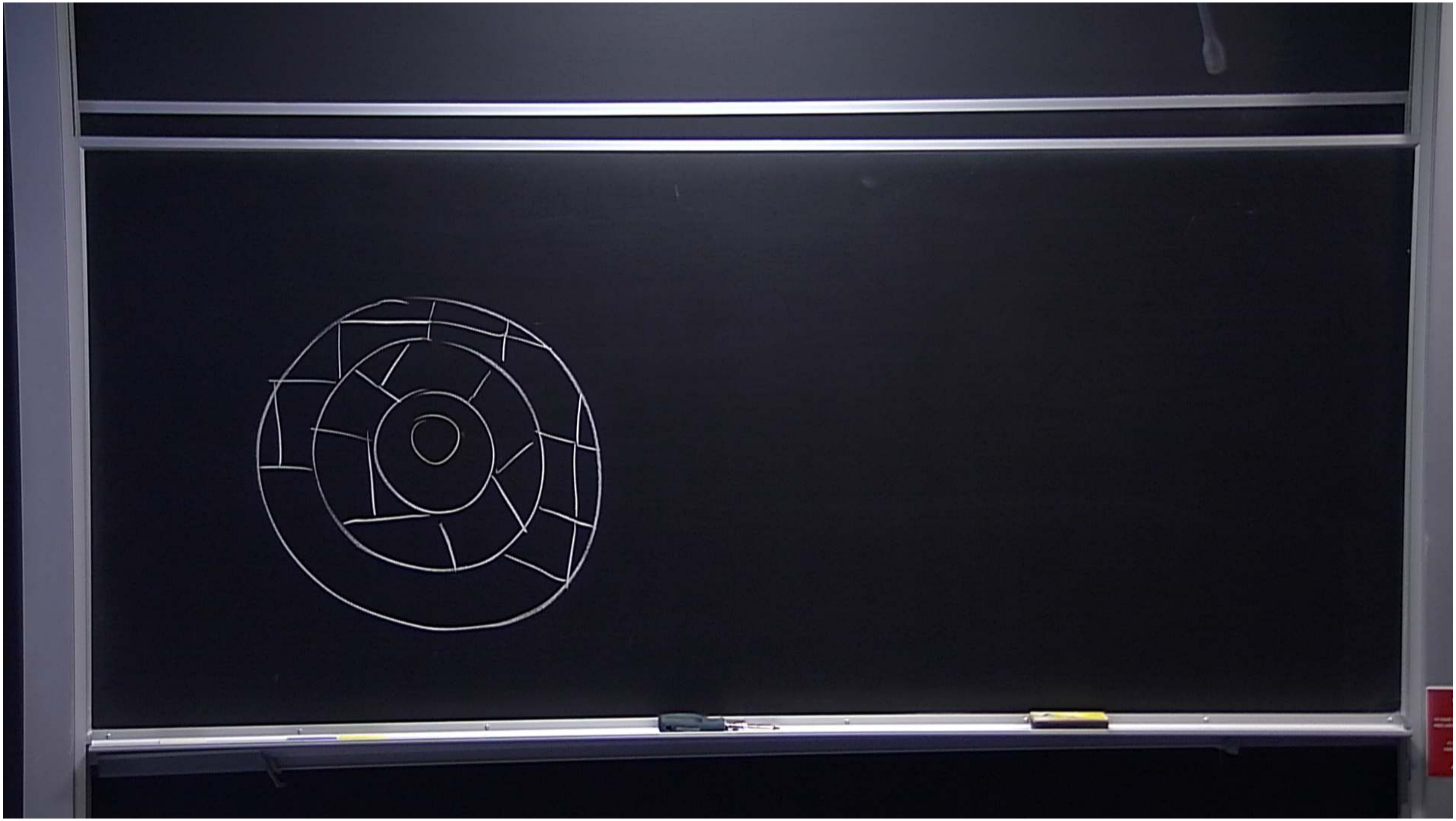
How to create a light cone populated by structures? The volume until the integration redshift is divided into spherical shells. All the simulation boxes falling into the same shell are randomized in a coherent way. Randomization changes from shell to shell

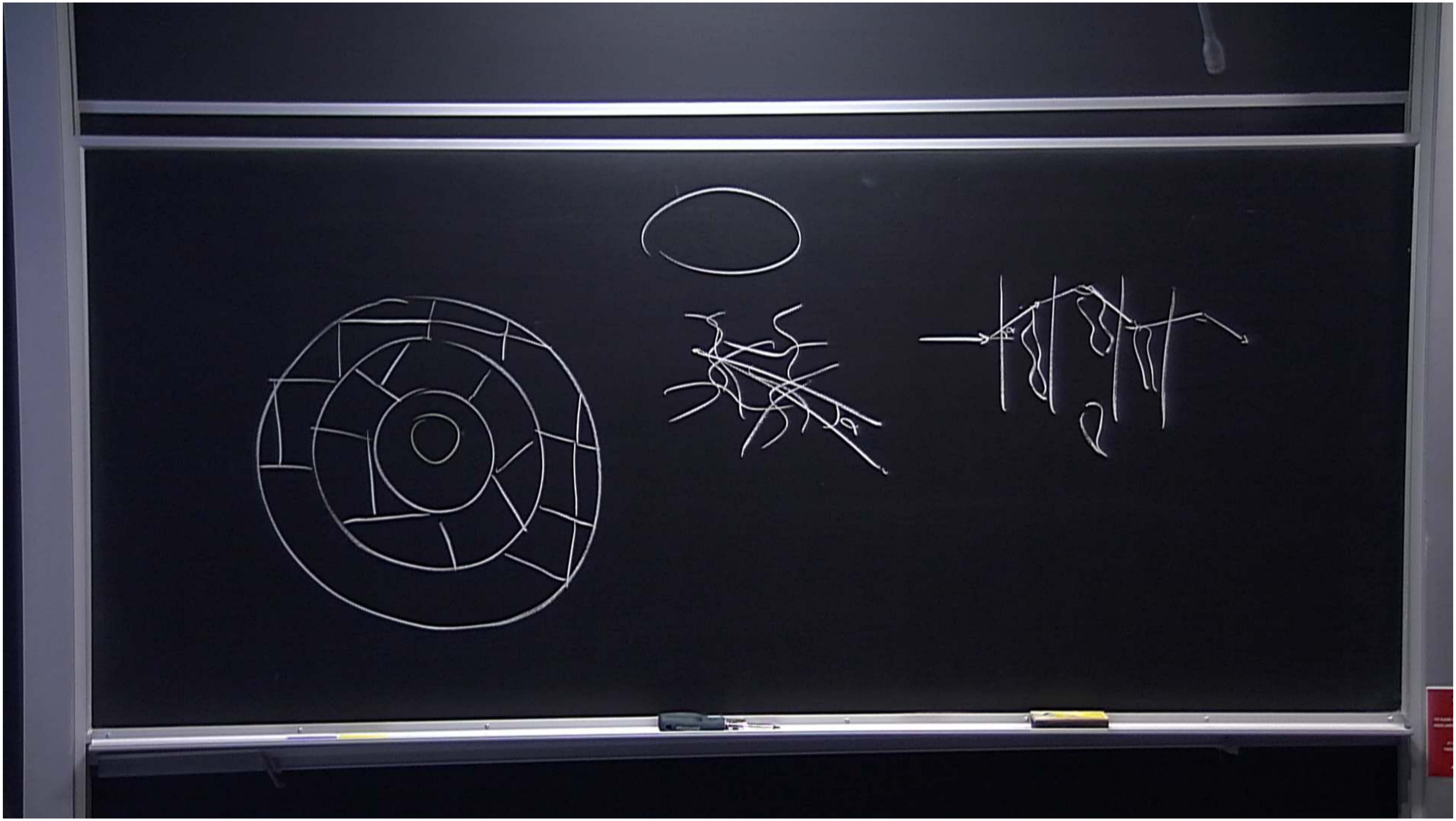
C. Carbone et al. 2008
M. Calabrese et al. 2013

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

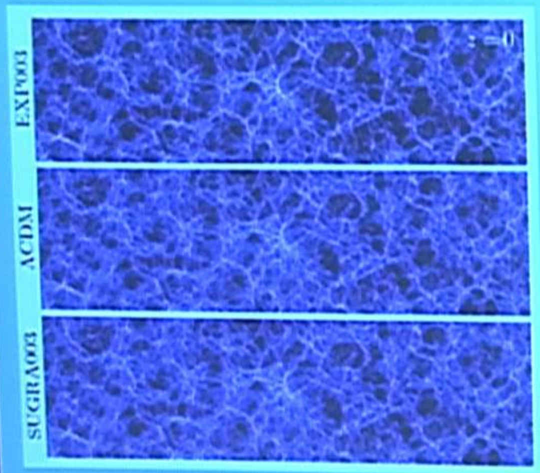
$$\alpha(\hat{\mathbf{n}}) = -2 \int_0^{r_*} \frac{r_* - r}{r_* r} \nabla_{\hat{\mathbf{n}}} \frac{\Phi(r\hat{\mathbf{n}}; \eta_0 - r)}{c^2} dr$$

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





The CoDECS maps



M. Baldi 2012

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

Parameter	Value
H_0	$70.3\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$
Ω_{CDM}	0.226
Ω_{DE}	0.729
$\mathcal{A}_s$	2.42×10^{-9}
Ω_b	0.0451
n_s	0.966

$Z_{in}=99$

1 comoving Gpc/h aside

1024^3 CDM and baryon particles

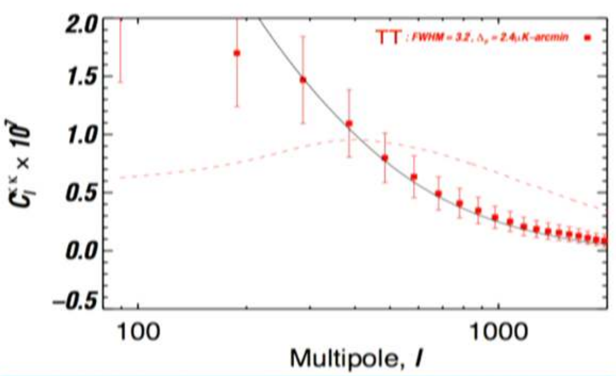
hydrodynamics not considered

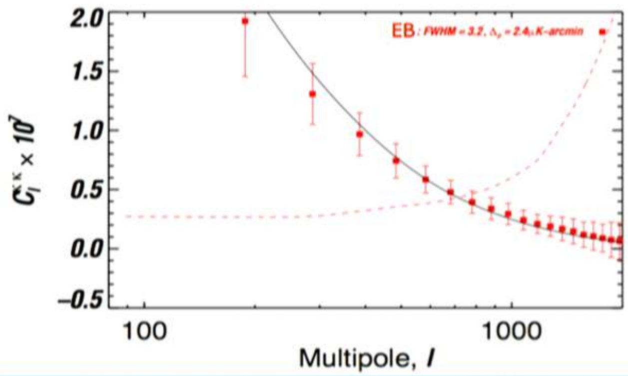
Model	Potential	α	β_0	β_1	Scalar field normalization	Potential normalization	$w_\phi(z=0)$	$\mathcal{A}_s(z_{CMB})$	$\sigma_8(z=0)$
ΛCDM	$V(\phi)=A$	–	–	–	–	$A=0.0219$	-1.0	2.42×10^{-9}	0.809
EXP001	$V(\phi)=Ae^{-\alpha\phi}$	0.08	0.05	0	$\phi(z=0)=0$	$A=0.0218$	-0.997	2.42×10^{-9}	0.825
EXP002	$V(\phi)=Ae^{-\alpha\phi}$	0.08	0.1	0	$\phi(z=0)=0$	$A=0.0218$	-0.995	2.42×10^{-9}	0.875
EXP003	$V(\phi)=Ae^{-\alpha\phi}$	0.08	0.15	0	$\phi(z=0)=0$	$A=0.0218$	-0.992	2.42×10^{-9}	0.967
EXP008e3	$V(\phi)=Ae^{-\alpha\phi}$	0.08	0.4	3	$\phi(z=0)=0$	$A=0.0217$	-0.982	2.42×10^{-9}	0.895
SUGRA003	$V(\phi)=A\phi^{-\alpha}e^{\phi^2/2}$	2.15	-0.15	0	$\phi(z\to\infty)=\sqrt{\alpha}$	$A=0.0202$	-0.901	2.42×10^{-9}	0.806

Extraction from CMB maps lensed by N-body simulations

Validation:

A LensPix simulated map is created with Planck 1 year parameters
Once the map is projected on 15 degree side patches the signal is extracted using the TT and EB estimators.
The deflection signal recovered is well compatible with the CAMB prediction.

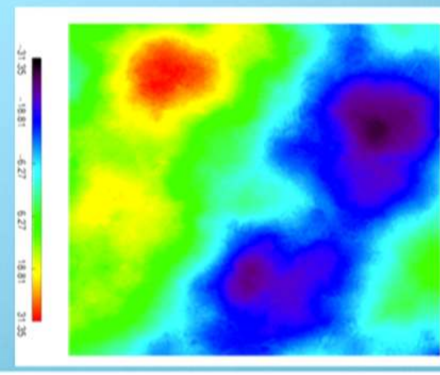


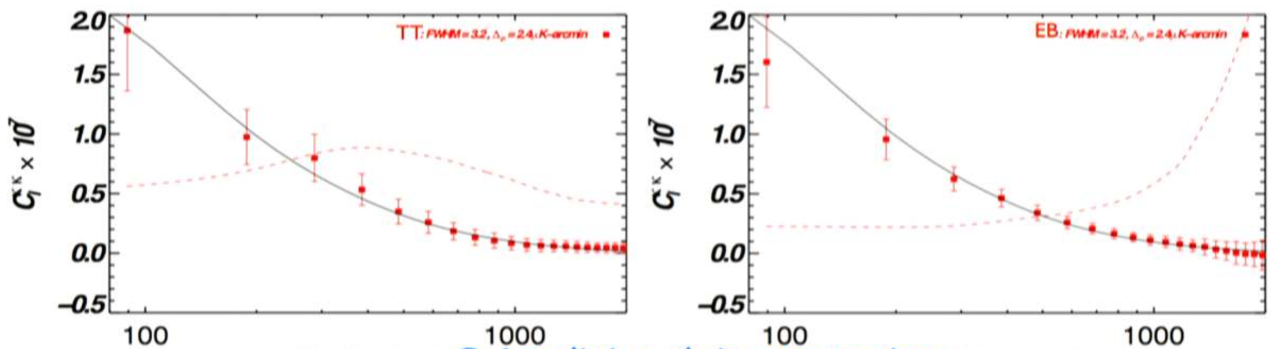


Extraction from CMB maps lensed by N-body simulations

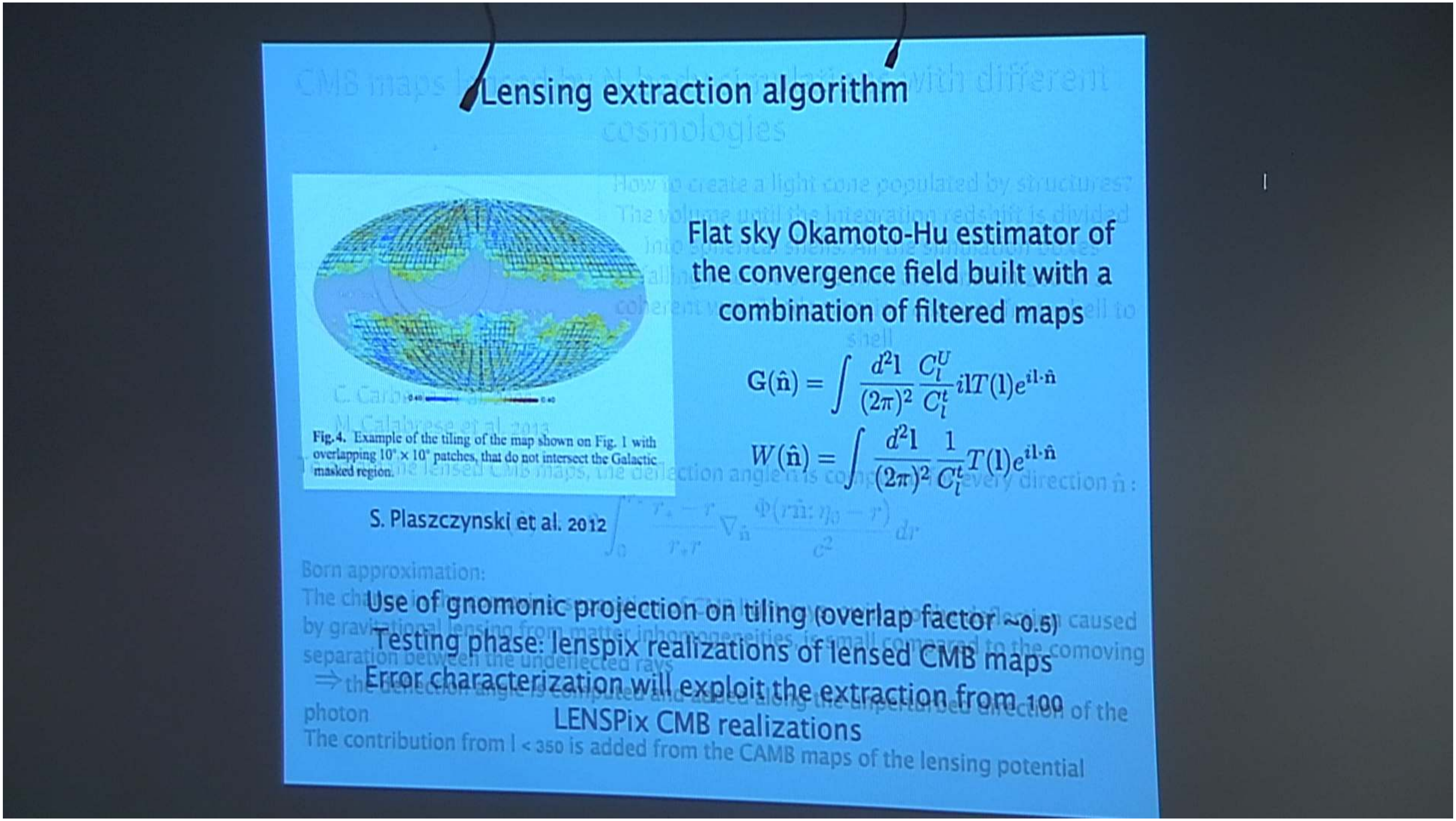
Results:

The N-Body lensed CMB shows a very good agreement with the theoretical prediction. For the Prism-like case, the fine structures of the signal can be studied down to $l \simeq 2000$. The stacked shear map is reconstructed as well.





C. Antolini et al., in preparation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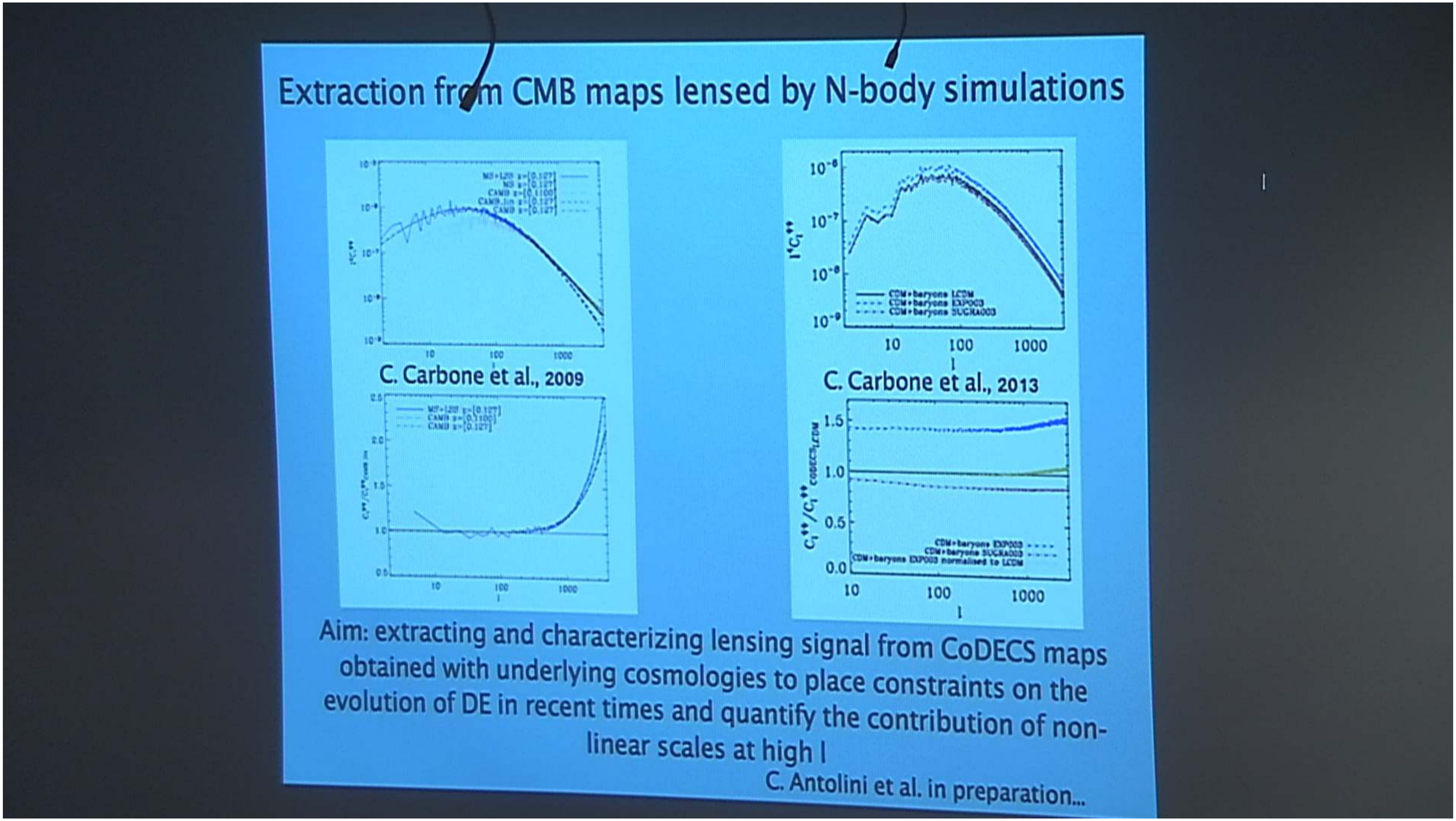
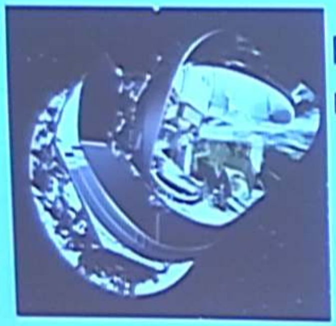

Extraction from CMB maps lensed by N-body simulations
C. Carbone et al., 2009
C. Carbone et al., 2013
Aim: extracting and characterizing lensing signal from CoDECS maps obtained with underlying cosmologies to place constraints on the evolution of DE in recent times and quantify the contribution of non-linear scales at high l
C. Antolini et al. in preparation...

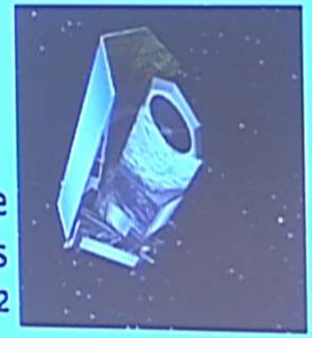
Constraints on cosmological parameters and local f_{NL} with CMB-galaxies cross correlation

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



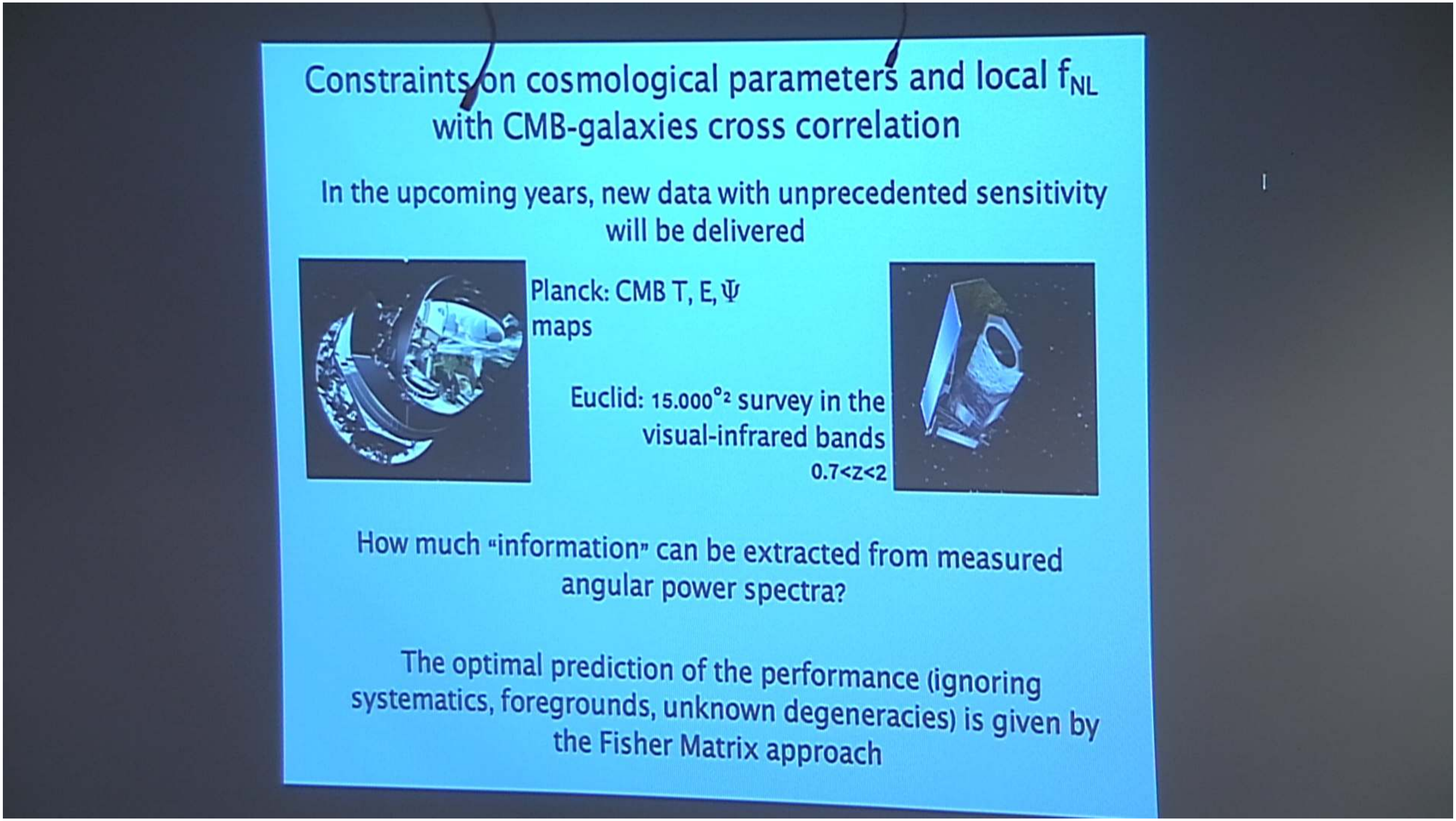
Planck: CMB T, E, Ψ maps

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



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Constraints on cosmological parameters and local f_{NL} with CMB-galaxies cross correlation

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

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	$\omega_b \quad \omega_c \quad A_s \quad n_s \quad H_0 \quad \tau$
Evolving bias	$b(z)$
Parametrized DE	$w_0 \quad w_a$
Local non-gaussianites	f_{NL}

Work in progress with W. Percival, L. Samushia

ICG Portsmouth

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

- Out soon: lensing signal extraction from N-body lensed CMB maps