Weak Lensing with Planck

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esa

planck

cnes

agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

ISTITUTO NAZIONALE DI ASTROFISICA INAF

Science & Technology Facilities Council

CSIC

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

Aalto University

APC

ioa

Kavli Institute for Cosmology Cambridge KICC

CAVENDISH ASTROPHYSICS

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

irfu cea saclay

CEFCA

CESR

CITA–ICAT

IASF

cnrs INSU Observer & comprendre

cnrs IN2P3 Les deux infinis

ipac

HELSINKI INSTITUTE OF PHYSICS

INSTITUTO DE ASTROFISICA DE CANARIAS

IFCA Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

NÉEL institut

IPAG

ISDC

JPL

LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

l'Observatoire de Paris LERMA

LPSC Grenoble

MANCHESTER 1824
The University of Manchester

MilliLab

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF OSSERVATORIO ASTRONOMICO DI PADOVA

UNIVERSITY OF OXFORD

SAPIENZA Università di Roma

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Università degli Studi di Roma TOR VERGATA

OSSERVATORIO ASTRONOMICO TRIESTE

UBC

UC UNIVERSIDAD DE CANTABRIA

UCSB

SISSA

ALMA

ESO

US University of Sussex

HAVERFORD

esa

UNIVERSITY OF HELSINKI

UNIVERSITÉ DE GENÈVE

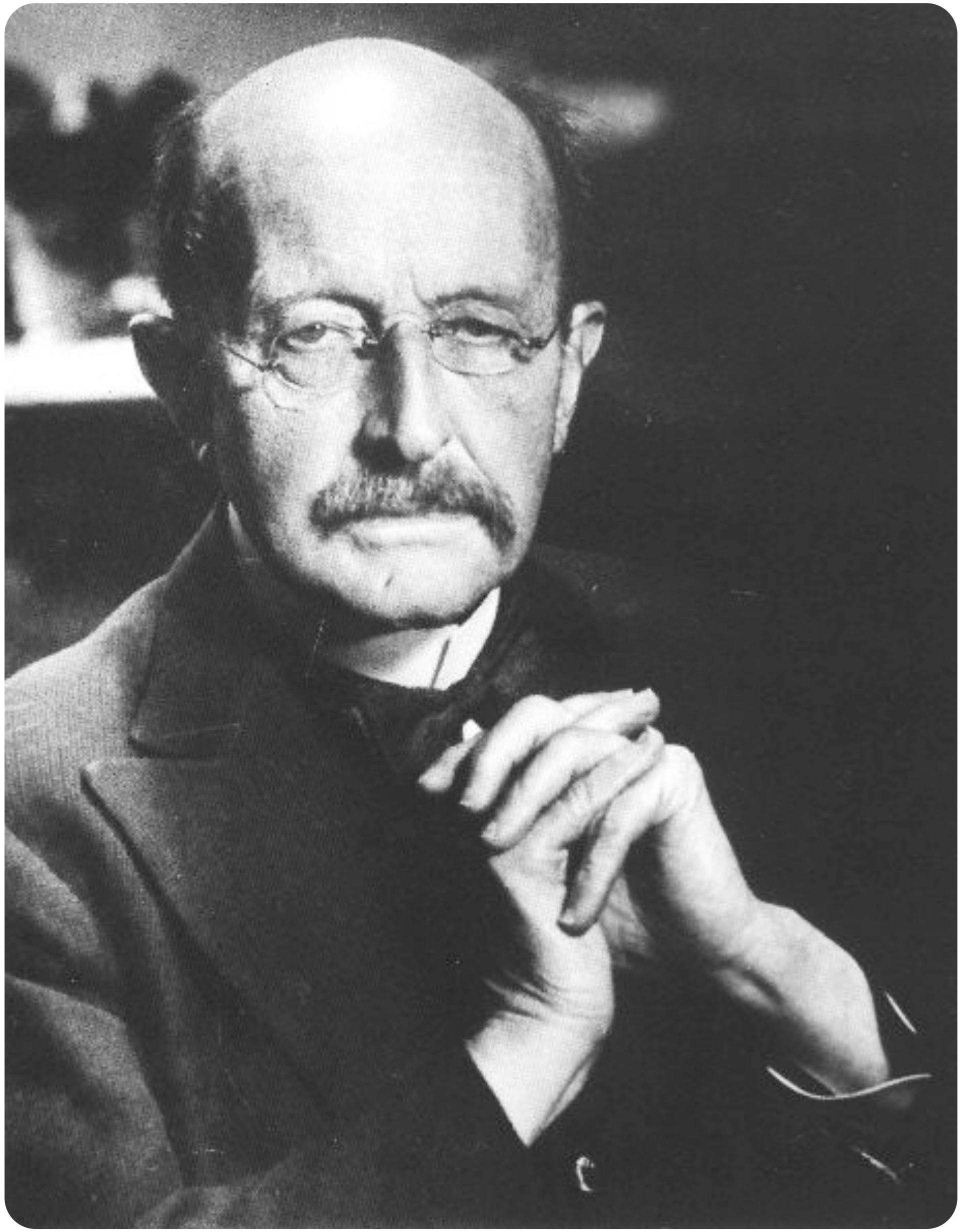
UNIVERSITY OF TORONTO

UNIVERSITÉ DE PARIS-SUD XI

ISTITUTO DI SCIENZA E TECNOLOGIE DELL'INFORMAZIONE "A. FAEDO"

asdc ASI Science Data Center

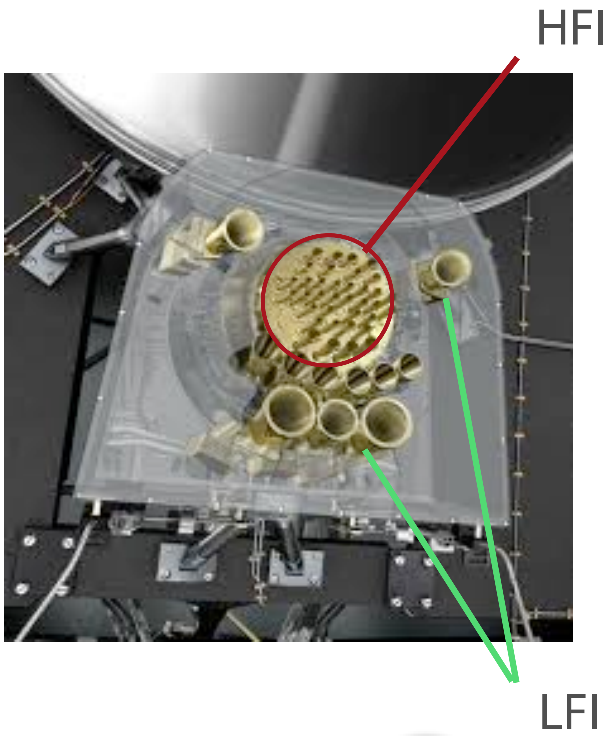
Max Planck (1858-1927)

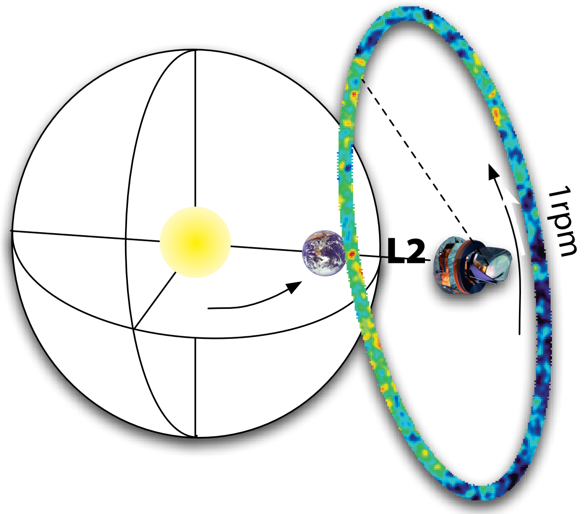


Planck (1993-23/10/2013)

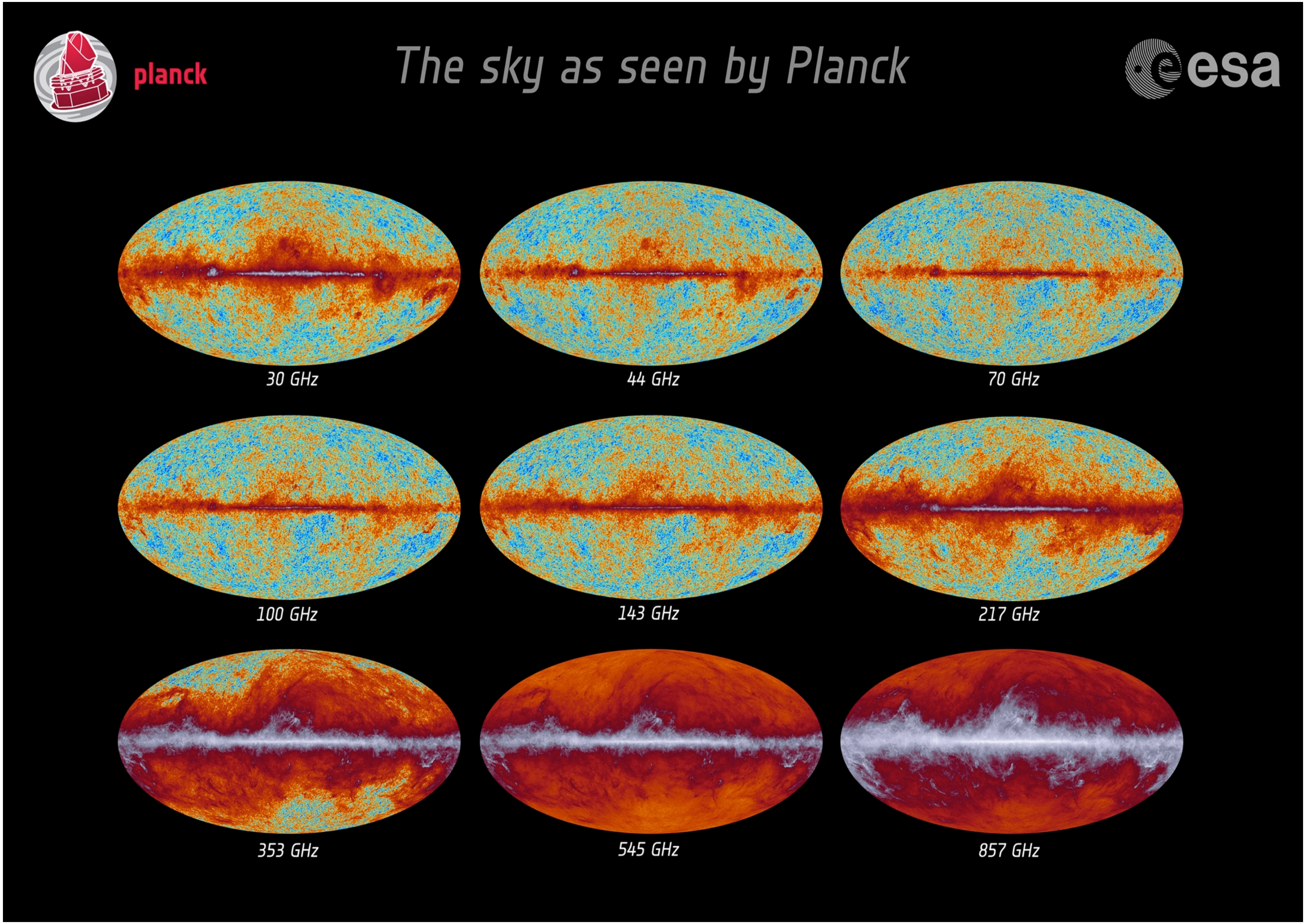

Ariane 5 ECA Launch • HERSCHEL – PLANCK - May 14, 2009

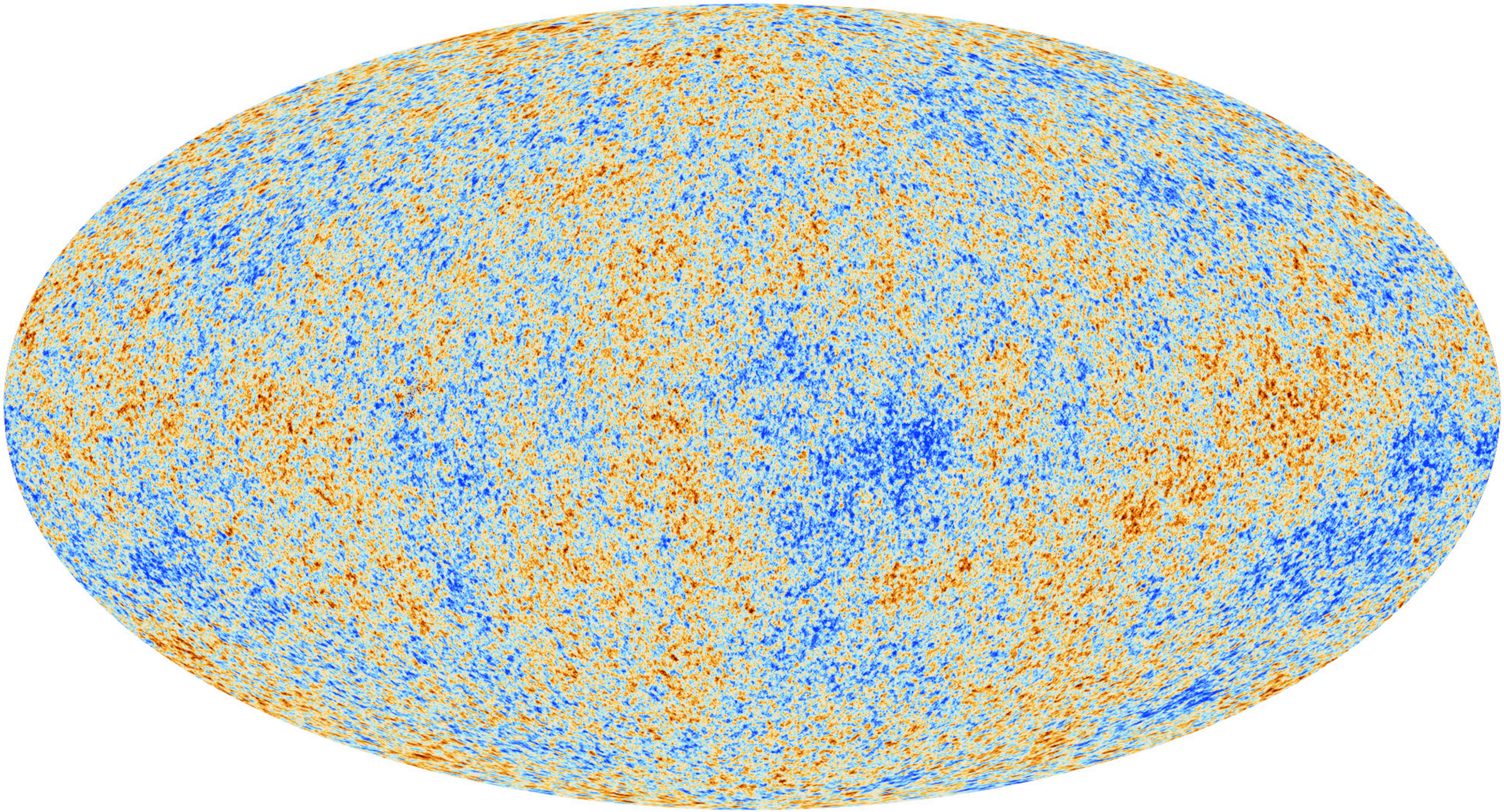
Planck





- **Driving goal : The definitive Temperature anisotropies measurement**
- Primary 1.5m
- 2 instruments
  - LFI : 3 bands, 22 radiometers
  - HFI : 6 bands, 50 bolometers
- 4 stage cooler down to 0.1K
  - Last stage is a He3/He4 dilution cooler
- Operated flawlessly since launch
  - HFI (and the dilution cooler) stopped Jan 2012
- ~5 independent surveys (nominal mission 2 surveys)


planck
The sky as seen by Planck
esa
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

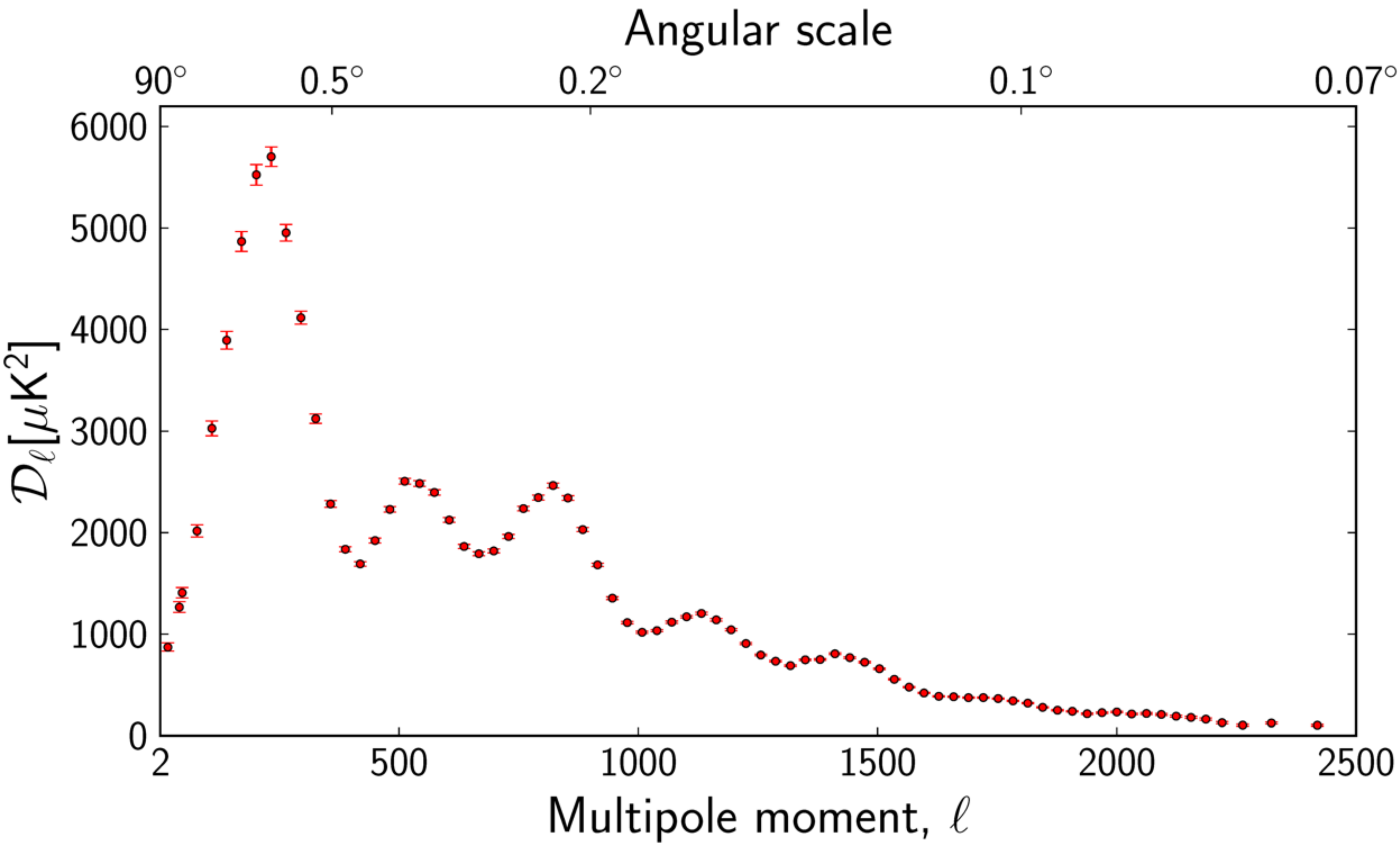


First Planck (almost) full sky CMB Temperature Map

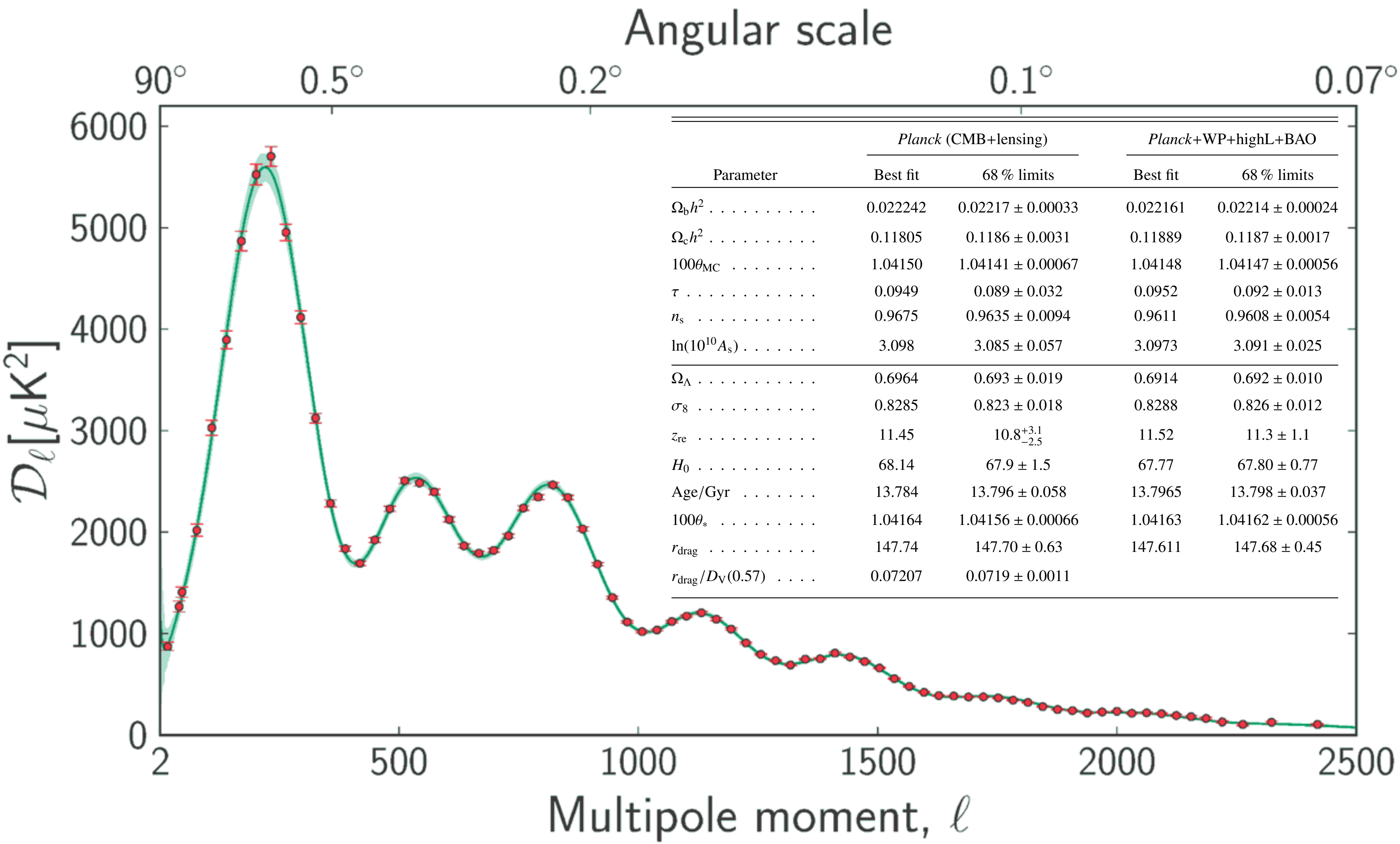
Released March 2013, along with 28 articles

Data available : first year maps and map characterisation

http://pla.esac.esa.int/pla/aio/planckProducts.html



Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ



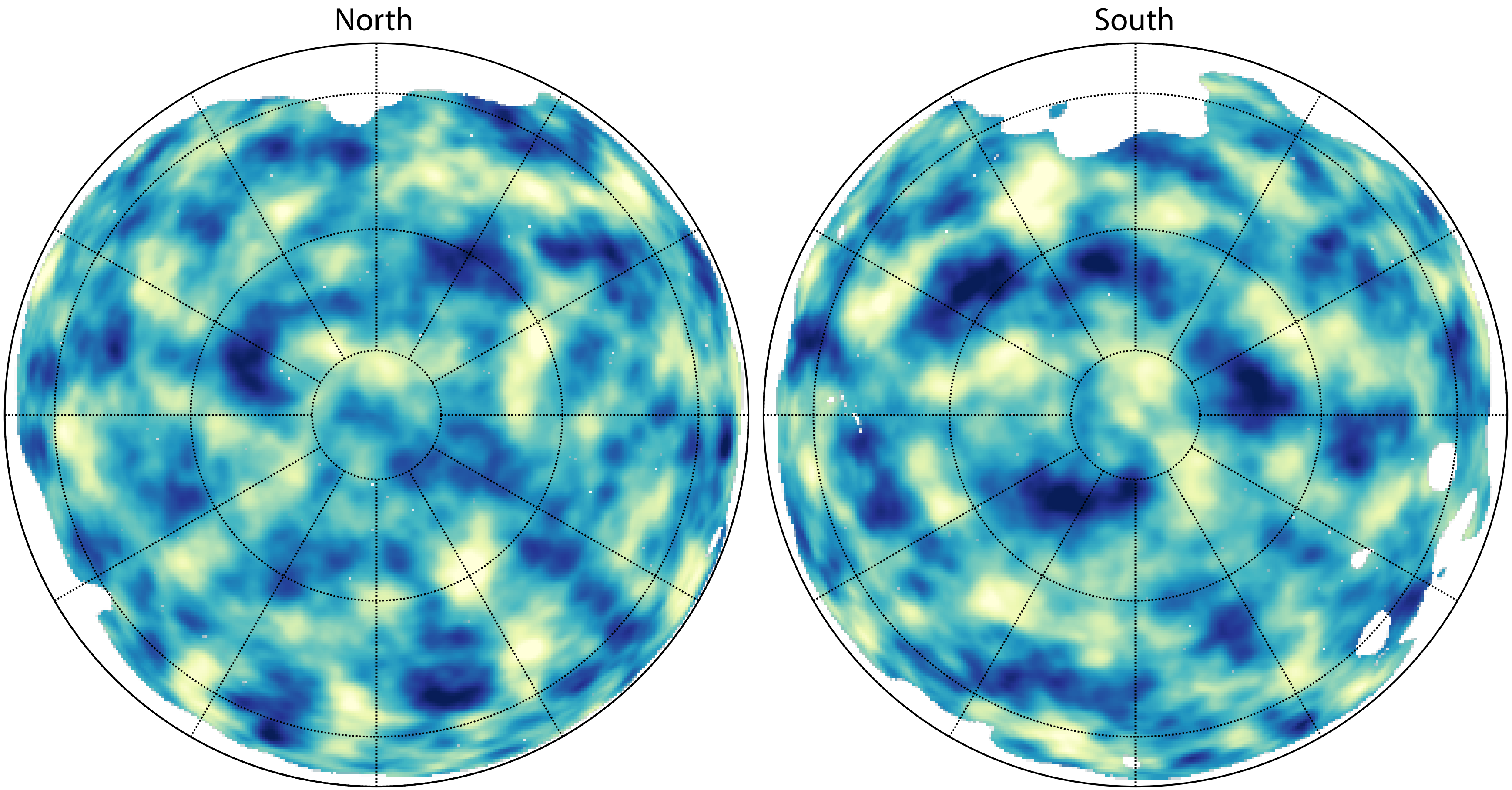
Parameter	*Planck* (CMB+lensing)		*Planck*+WP+highL+BAO	
	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Amazing fit to the theory
6 parameter model !

Planck as a Matter tracer machine

- Planck is the first full sky mission capable of measuring secondary anisotropies & small scale foregrounds
  - Tracer of the large scale structure at lower redshift
- Dark matter and baryons
  - **Weak lensing**
  - ISW
  - SZ clusters
  - CIB

Planck map of the large scale structures

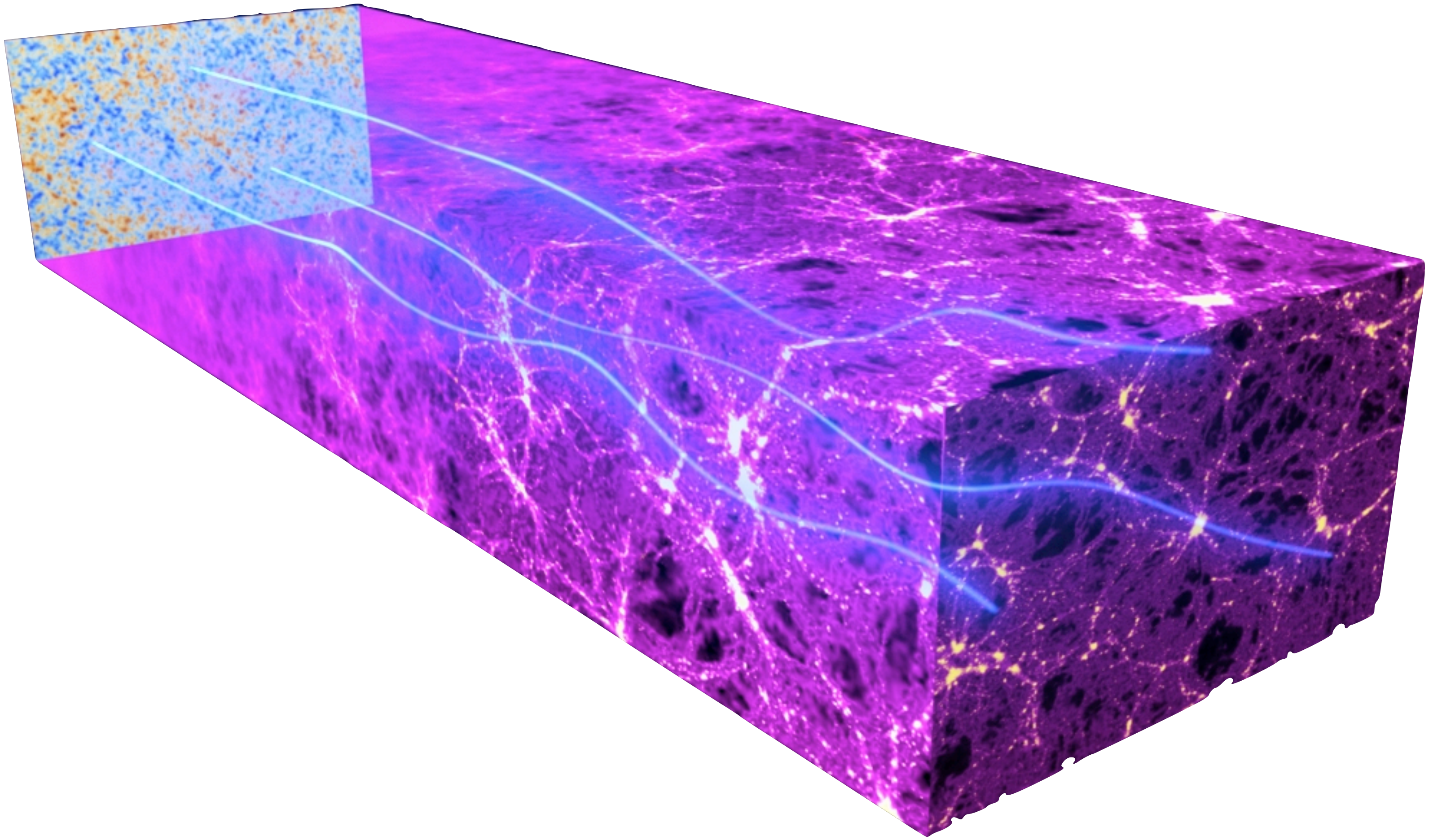


According to our reconstruction of the lensing effect

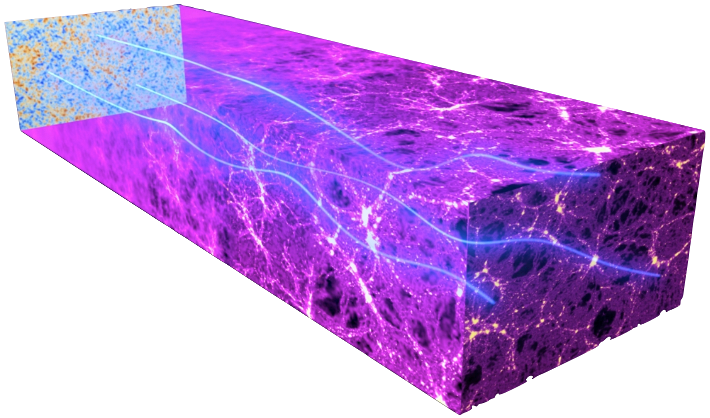
25sigma detection

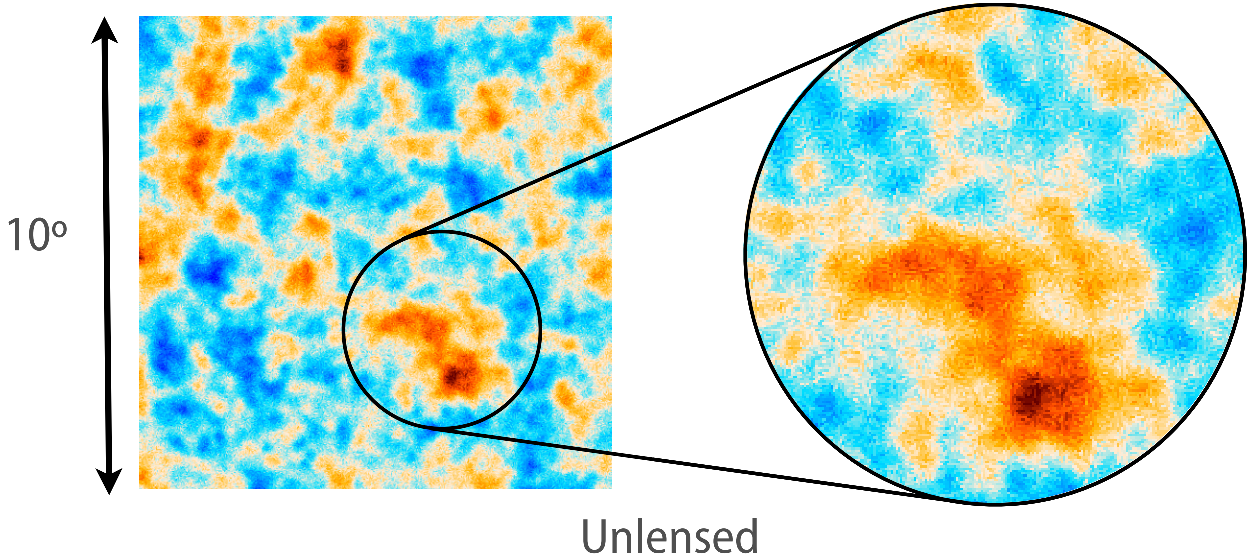
Almost full sky map of LSS at z~2

CMB lensing reconstruction

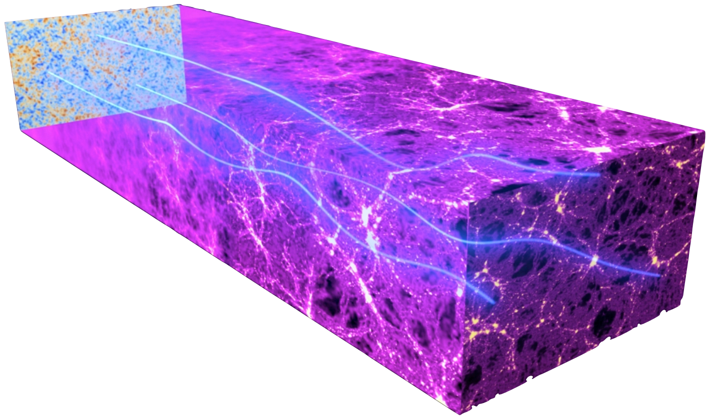


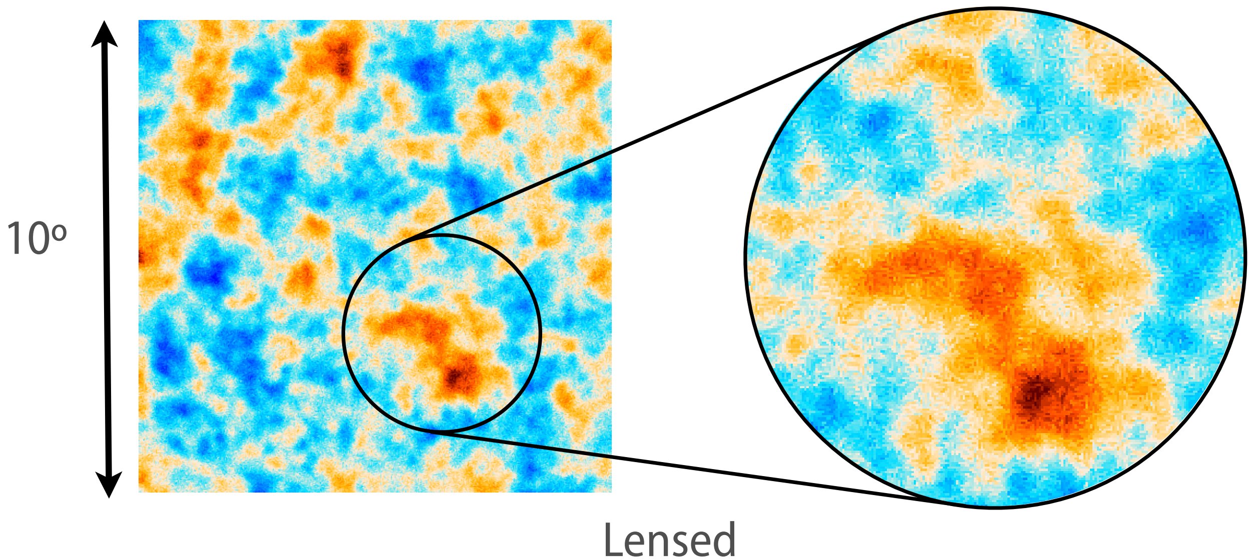
CMB lensing reconstruction



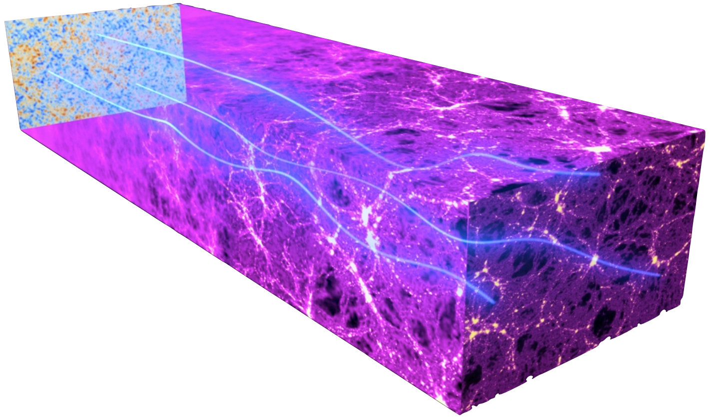


CMB lensing reconstruction

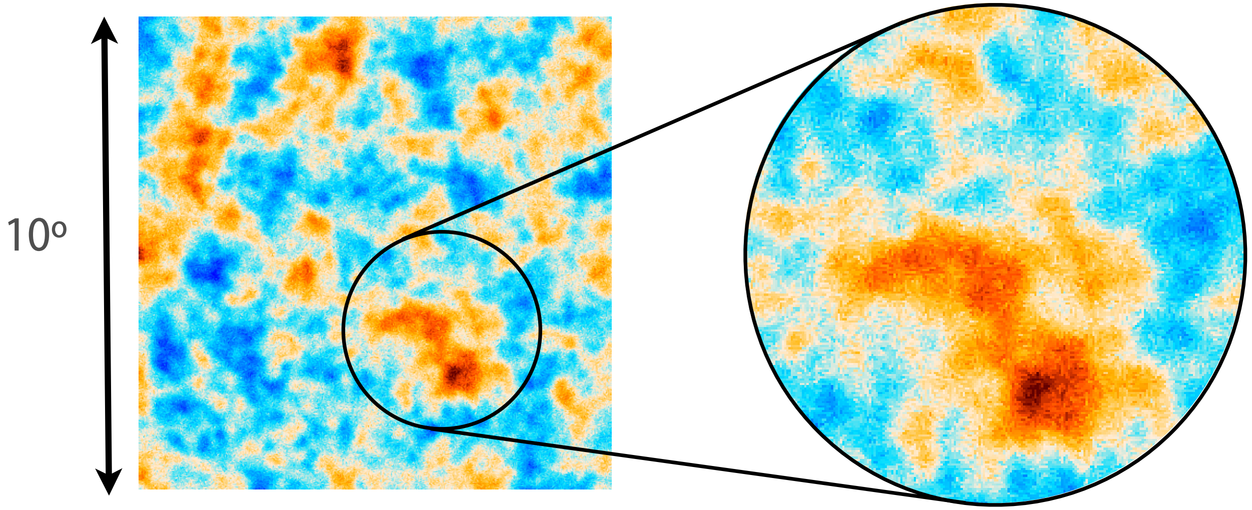




CMB lensing reconstruction

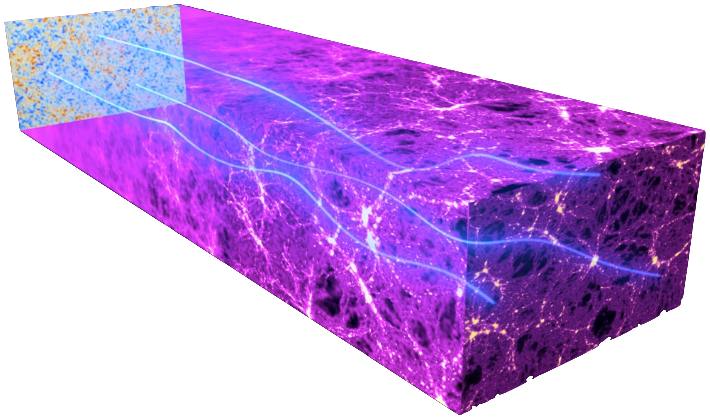


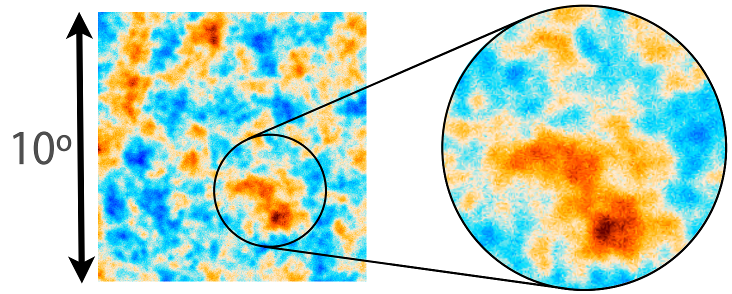
Displacement is 0.3 arcmin scale.
HFI beam is 5 arcmin at best



Lensed

CMB lensing reconstruction

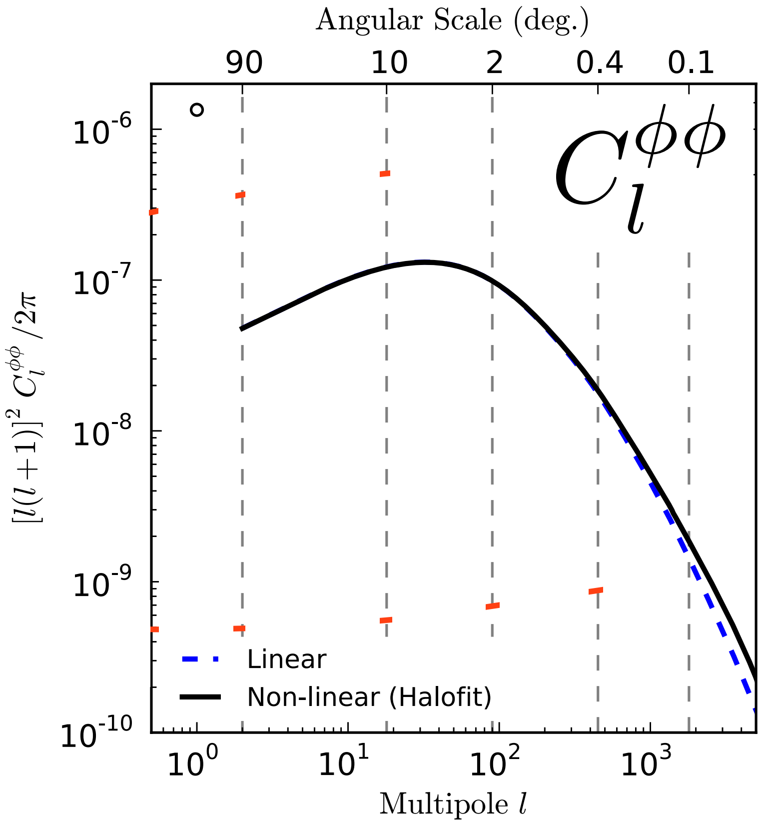




Lensing on CMB is small BUT

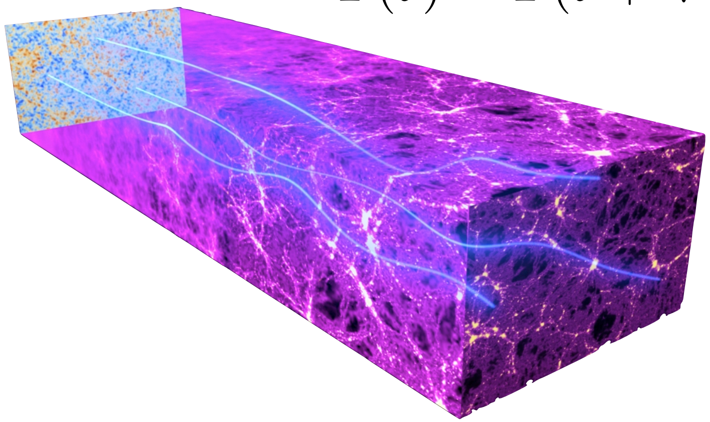
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \dots$$

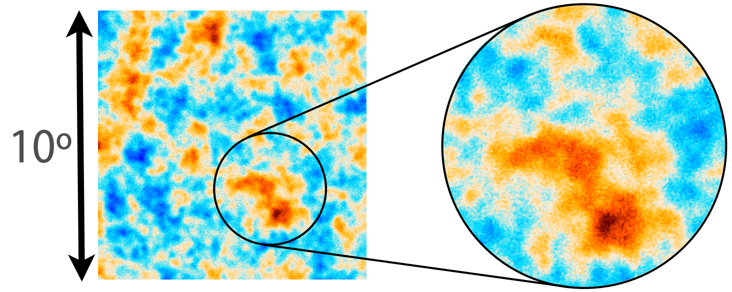
It couples the Temperature anisotropies field with its gradient. And it's coherent on degree scales



CMB lensing reconstruction

$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$





A quadratic estimator to measure the specific NG signature.

$$\Delta\langle T_{\ell_1 m_1} T_{\ell_2 m_2}\rangle = \sum_{LM} \sum_{\ell_1 m_1, \ell_2 m_2} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W^{\phi}_{\ell_1 \ell_2 L} \phi_{LM},$$

$$W^{\phi}_{\ell_1 \ell_2 L} = -\sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2L+1)}{4\pi}} \sqrt{L(L+1)\ell_1(\ell_1+1)} \times C^{TT}_{\ell_1} \left(\frac{1+(-1)^{\ell_1+\ell_2+L}}{2}\right) \begin{pmatrix} \ell_1 & \ell_2 & L \\ 1 & 0 & -1 \end{pmatrix} + (\ell_1 \leftrightarrow \ell_2). \quad (6)$$

$$\hat{\phi}^x_{LM} = \frac{1}{\mathcal{R}^{x\phi}_L} \left(\bar{x}_{LM} - \bar{x}^{MF}_{LM}\right).$$

$$\mathcal{R}^{x\phi,(1)(2)}_L = \frac{1}{(2L+1)} \sum_{\ell_1 \ell_2} \frac{1}{2} W^x_{\ell_1 \ell_2 L} W^{\phi}_{\ell_1 \ell_2 L} F^{(1)}_{\ell_1} F^{(2)}_{\ell_2}.$$

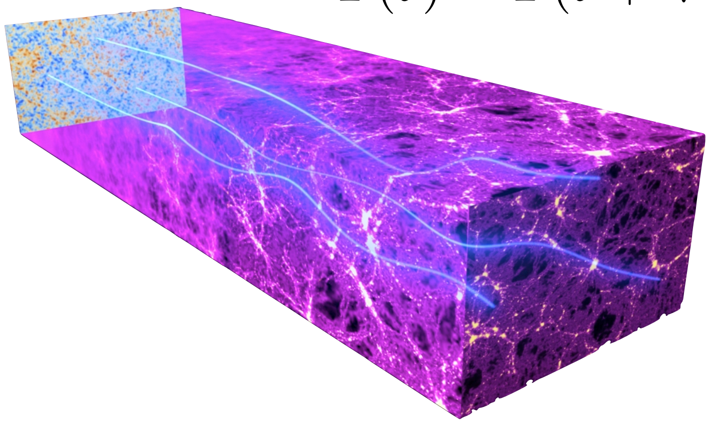
$$\bar{x}_{LM} = \frac{1}{2} \sum_{\ell_1 m_1, \ell_2 m_2} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W^x_{\ell_1 \ell_2 L} \bar{T}^{(1)}_{\ell_1 m_1} \bar{T}^{(2)}_{\ell_2 m_2}.$$

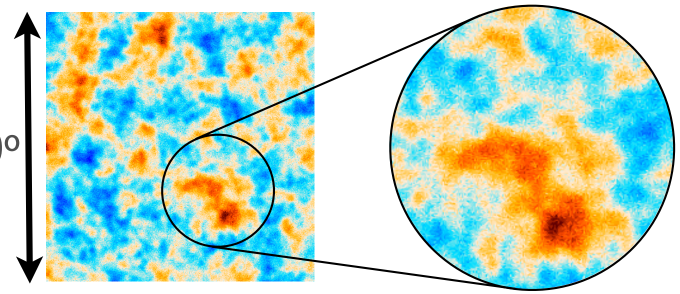
$$\bar{x}^{MF}_{LM} = \frac{1}{2} \sum_{\ell_1 m_1, \ell_2 m_2} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W^x_{\ell_1 \ell_2 L} \langle \bar{T}^{(1)}_{\ell_1 m_1} \bar{T}^{(2)}_{\ell_2 m_2} \rangle.$$

$$\bar{T}_{\ell m} = [S+N]^{-1} T_{\ell m} \approx [C^{TT}_{\ell} + C^{NN}_{\ell}]^{-1} T_{\ell m} = F_{\ell} T_{\ell m}$$

CMB lensing reconstruction

$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \dots$$





A quadratic estimator to measure the specific NG signature.

$$\bar{\phi} = \Delta^{-1}\vec{\nabla}\cdot \left[C^{-1}T\ \vec{\nabla}(C_\ell \otimes C^{-1}T)\right]$$

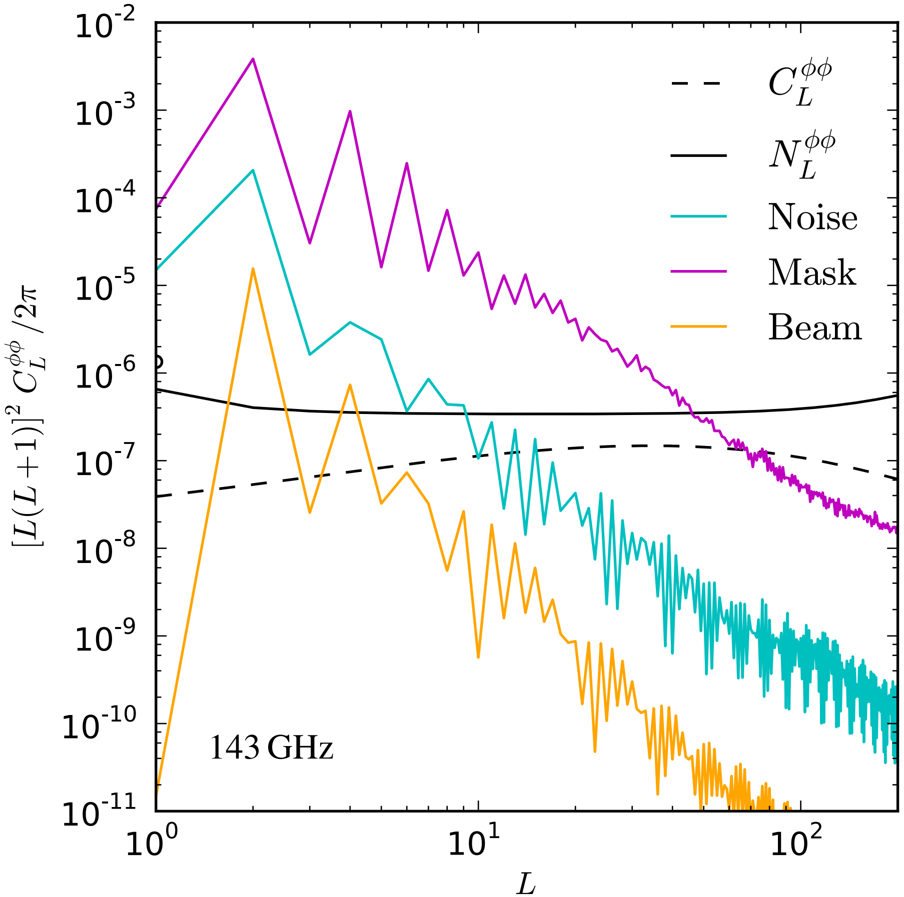
$$W^{\phi}(l_1, l_2) = C^{TT}_{|l_1|}\, l_1 \cdot L + C^{TT}_{|l_2|}\, l_2 \cdot L.$$

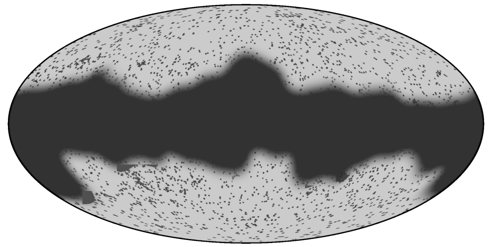
- Take two temperature maps and inverse variance filter them.
- Differentiate one and filter it by the temperature power spectrum
- Multiply with the other inverse variance filtered map
- Normalize to get unbiased estimator

$$R_L^{x\phi,(1)(2)} = \frac{1}{(2L+1)} \sum_{\ell_1 \ell_2} \frac{1}{2} W^x_{\ell_1\ell_2 L} W^{\phi}_{\ell_1\ell_2 L} F^{(1)}_{\ell_1} F^{(2)}_{\ell_2}.$$

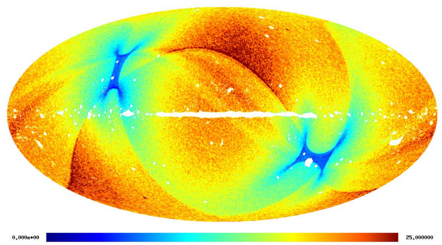
$$\bar{T}_{\ell m} = [S+N]^{-1} T_{\ell m} \approx [C_\ell^{TT} + C_\ell^{NN}]^{-1} T_{\ell m} = F_\ell T_{\ell m}$$

Biases at the map level

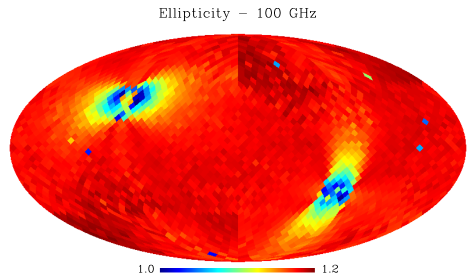




Mask



noise RMS



Beam ellipticity

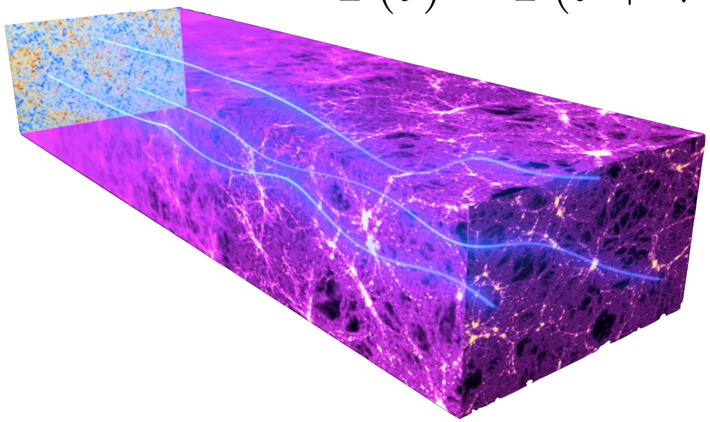
Due to the response of the quadratic estimator to sources of statistical anisotropies in the data.

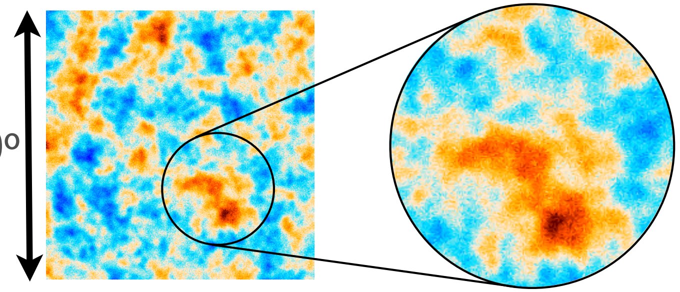
Dominates the largest scales.

Can be removed on average by estimating a «mean-field» contribution from Monte Carlo.

CMB lensing reconstruction

$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$



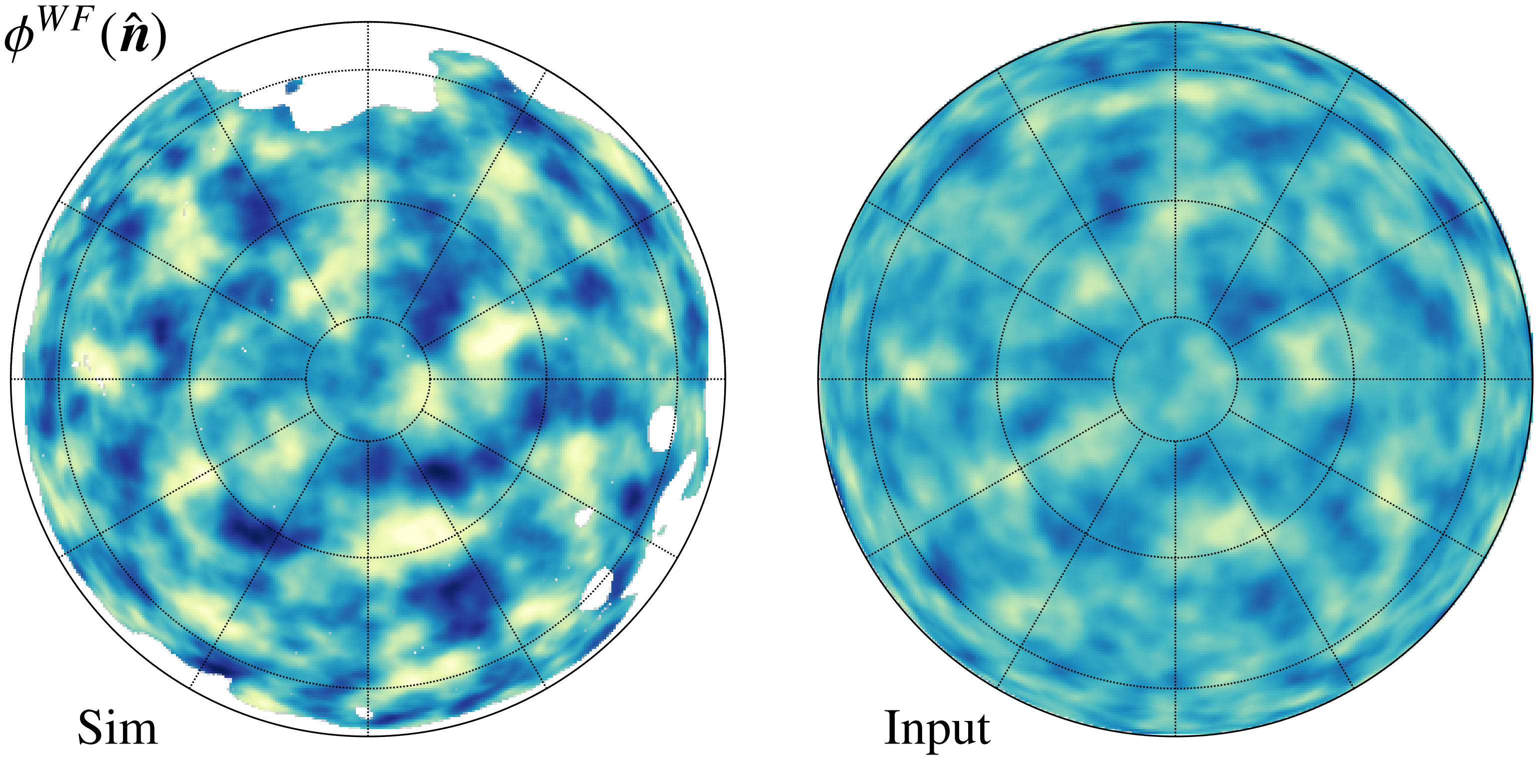


A quadratic estimator to measure the specific NG signature.

$$\bar{\phi} = \Delta^{-1}\vec{\nabla}\cdot[C^{-1}T\,\vec{\nabla}(C^{-1}T)]$$

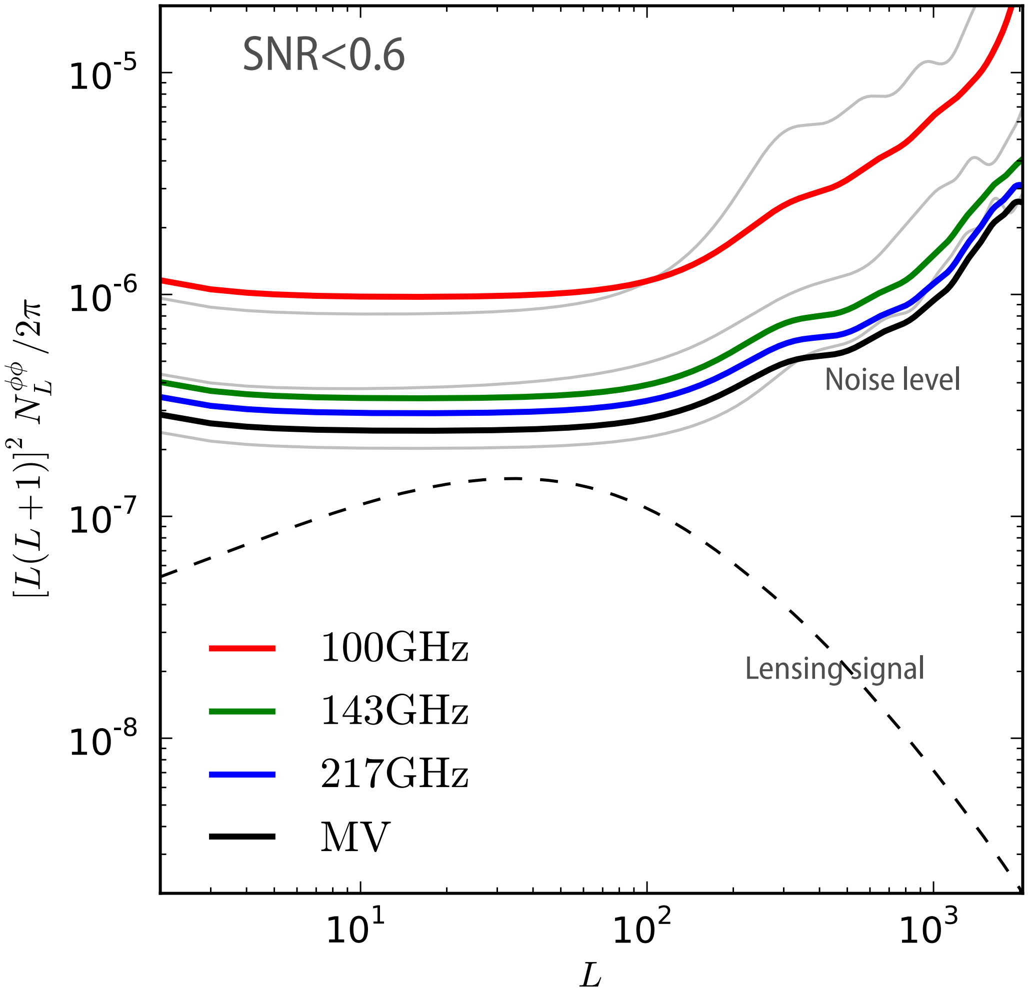
- Take two temperature maps and inverse variance filter them.
- Differentiate one and filter it by the temperature power spectrum
- Multiply with the other inverse variance filtered map
- Do the same with a set of CMB simulations containing your source of statistical anisotropies (mask, noise, beams)
- Take the difference and normalize

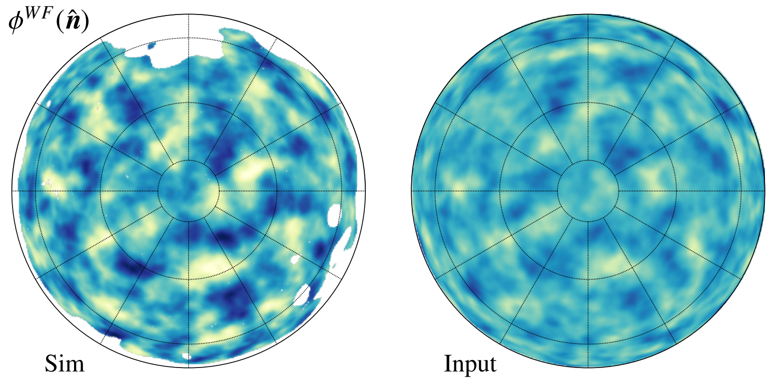
On simulation



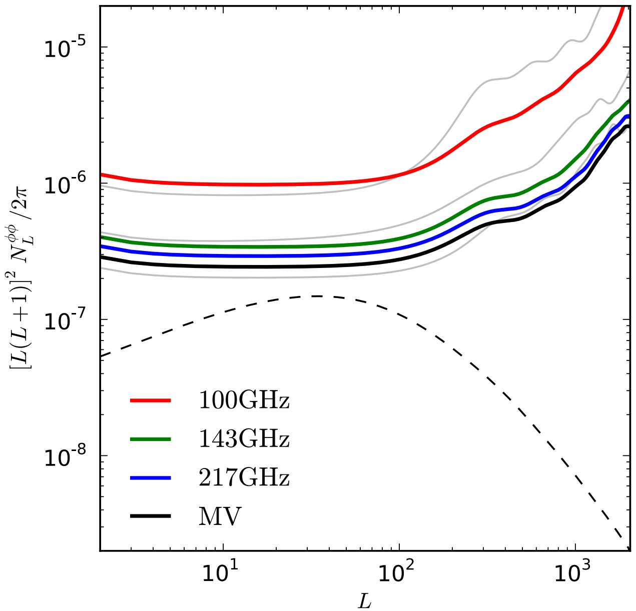
Reconstruction on a realistic Planck simulation.

Map noise - spectrum biases



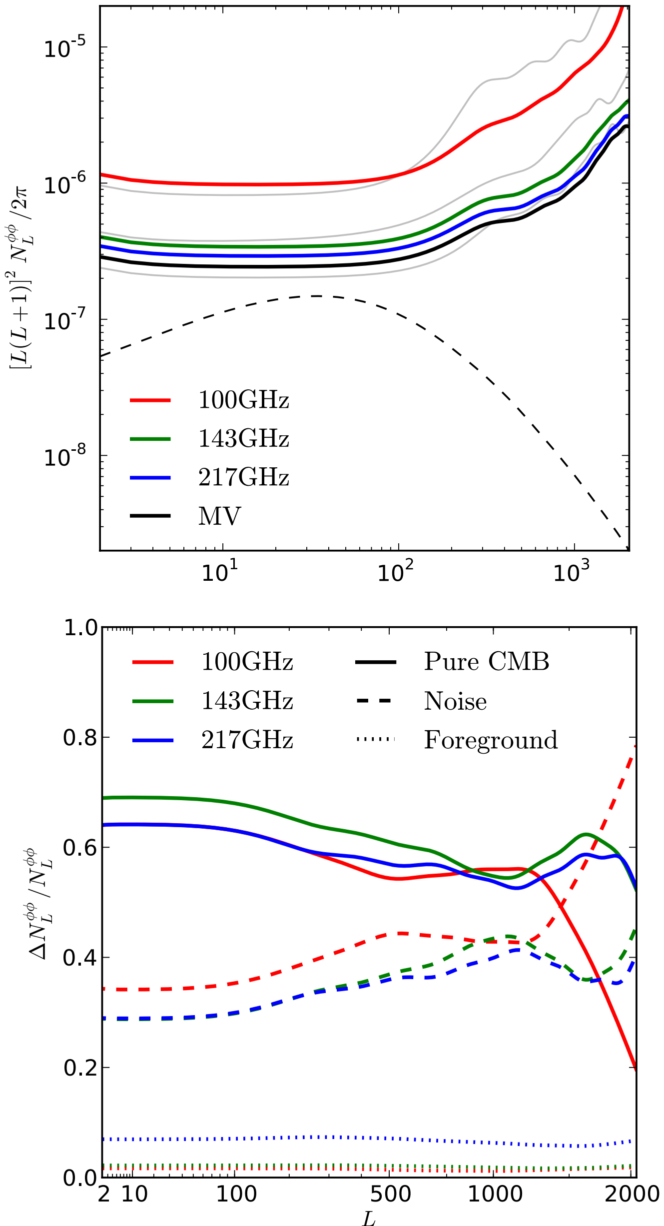


Power spectrum biases



$$\hat{C}^{\phi\phi}_{L,x} = \frac{f^{-1}_{\mathrm{sky},2}}{2L+1} \sum_M |\widetilde{\phi}^x_{LM}|^2 - \Delta C^{\phi\phi}_L\Big|_{\mathrm{N0}} - \Delta C^{\phi\phi}_L\Big|_{\mathrm{N1}} - \Delta C^{\phi\phi}_L\Big|_{\mathrm{PS}} - \Delta C^{\phi\phi}_L\Big|_{\mathrm{MC}},$$

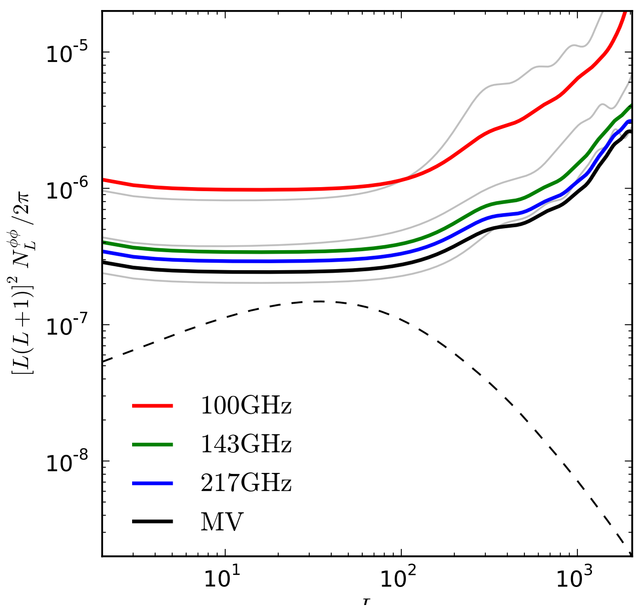
Power spectrum biases

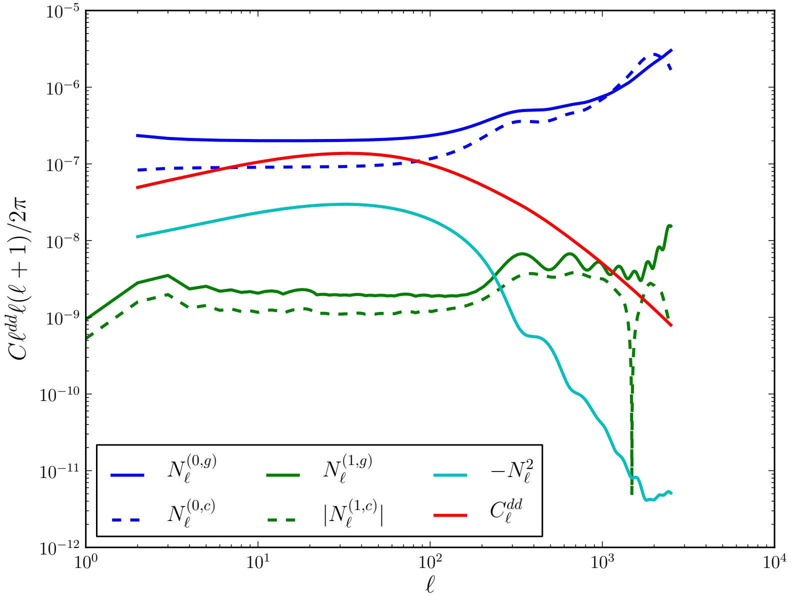


$$\hat{C}^{\phi\phi}_{L,x} = \frac{f^{-1}_{\mathrm{sky},2}}{2L+1} \sum_M |\widetilde{\phi}^x_{LM}|^2 - \Delta C^{\phi\phi}_L\big|_{\mathrm{N0}} - \Delta C^{\phi\phi}_L\big|_{\mathrm{N1}} - \Delta C^{\phi\phi}_L\big|_{\mathrm{PS}} - \Delta C^{\phi\phi}_L\big|_{\mathrm{MC}},$$

Gaussian bias. Dealt with by MC. Close to the analytical value.
Dominates the final error budget.

Power spectrum biases





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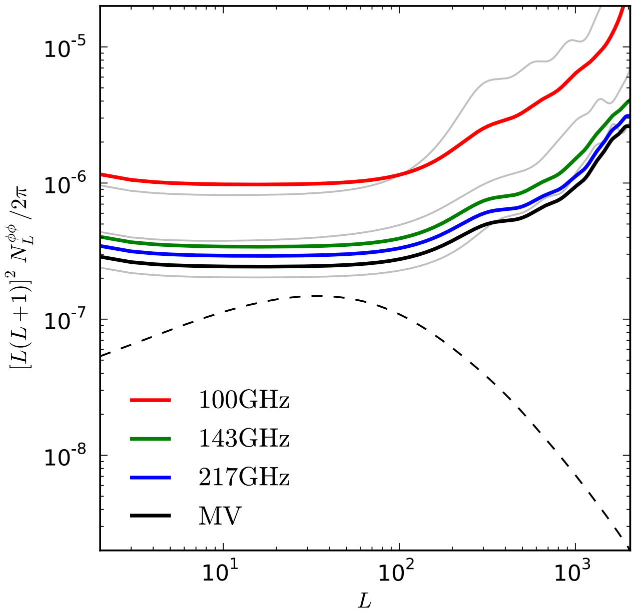
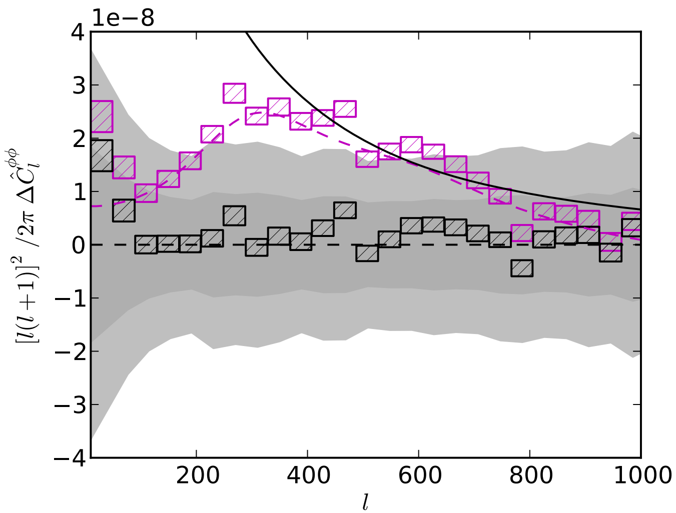
Gaussian bias. Dealt with by MC. Close to the analytical value.
Dominates the final error budget.

Higher order bias. We further include cosmological uncertainty.

Power spectrum biases





$$\hat{C}^{\phi\phi}_{L,x} = \frac{f^{-1}_{\mathrm{sky},2}}{2L+1}\sum_M |\widetilde{\phi}^x_{LM}|^2 - \Delta C^{\phi\phi}_L\Big|_{\mathrm{N0}} - \Delta C^{\phi\phi}_L\Big|_{\mathrm{N1}} - \boxed{\Delta C^{\phi\phi}_L\Big|_{\mathrm{PS}}} - \Delta C^{\phi\phi}_L\Big|_{\mathrm{MC}},$$

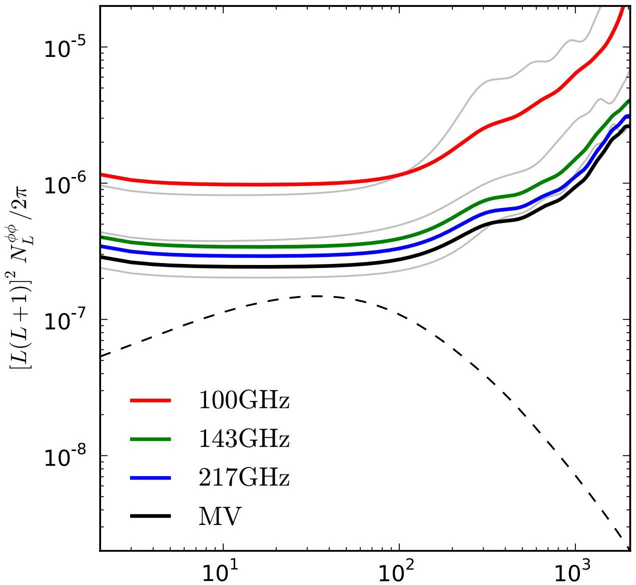
Gaussian bias. Dealt with by MC. Close to the analytical value.
Dominates the final error budget.

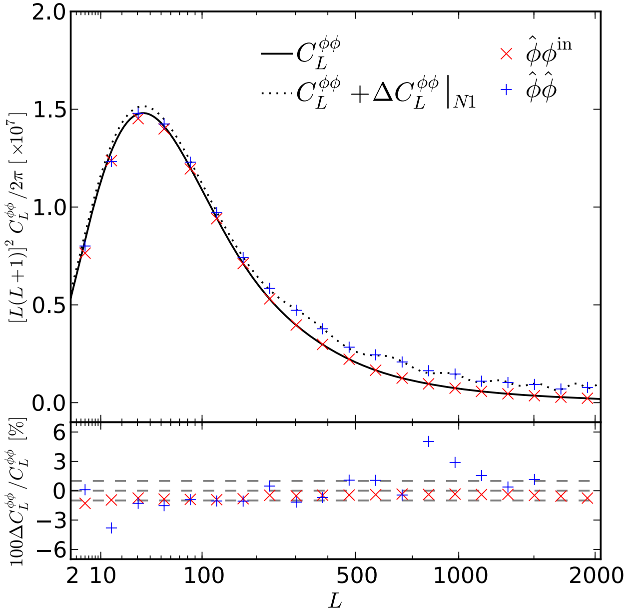
Higher order bias. We further include cosmological uncertainty.

Point source trispectrum contribution. Measured on data

Power spectrum biases

HFI PLANCK





$$\hat{C}^{\phi\phi}_{L,x} = \frac{f^{-1}_{\mathrm{sky},2}}{2L+1}\sum_M |\widetilde{\phi}^x_{LM}|^2 - \Delta C^{\phi\phi}_L\big|_{\mathrm{N0}} - \Delta C^{\phi\phi}_L\big|_{\mathrm{N1}} - \Delta C^{\phi\phi}_L\big|_{\mathrm{PS}} - \Delta C^{\phi\phi}_L\big|_{\mathrm{MC}},$$

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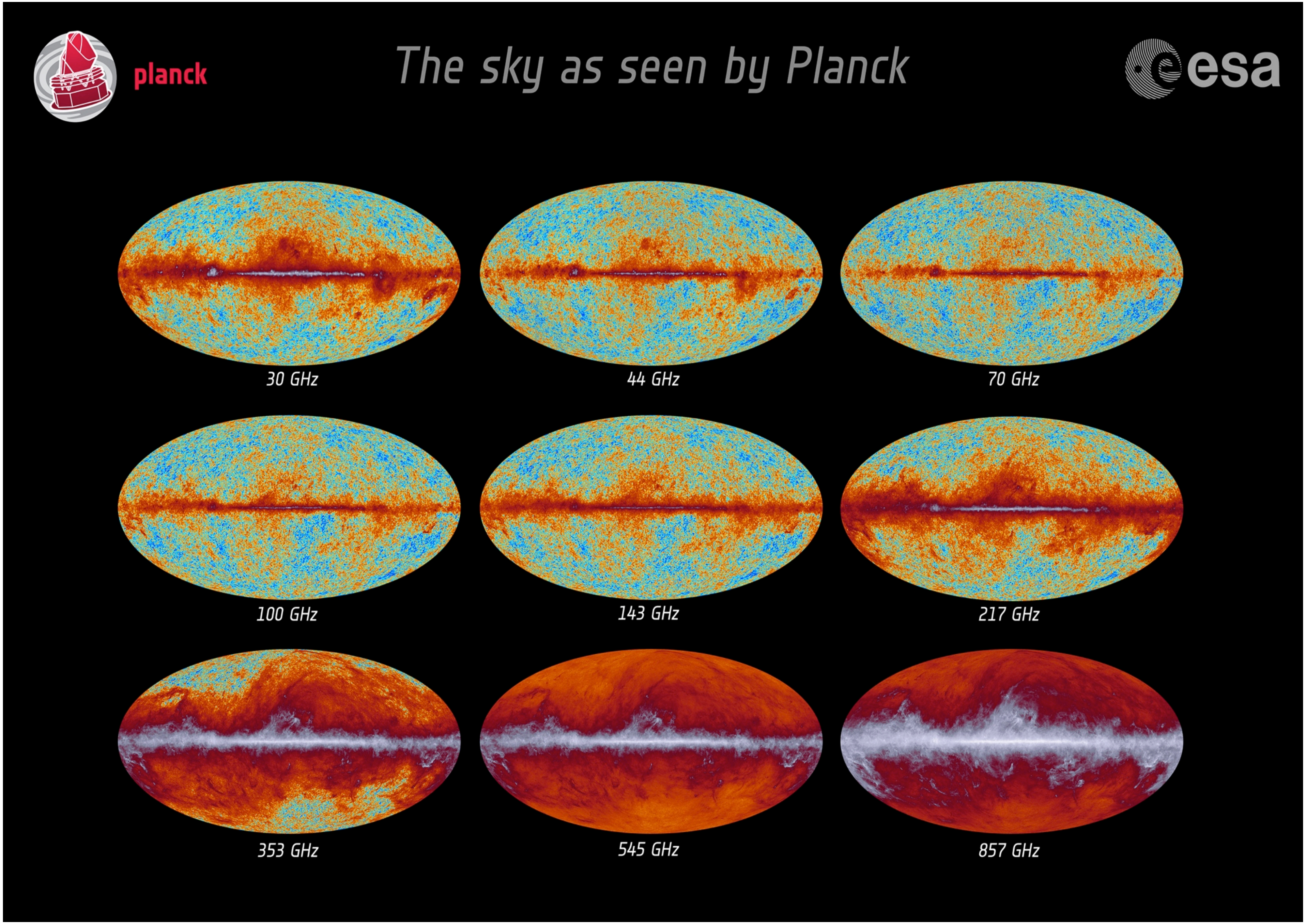
Dominates the final error budget.

Higher order bias. We further include cosmological uncertainty.

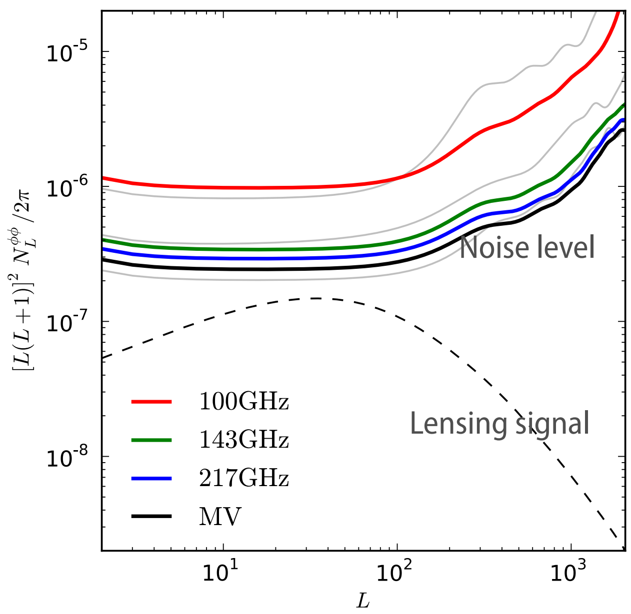
Point source trispectrum contribution. Measured on data

Residual bias. Also account for small multiplicative bias. Dealt with lensed MC.


planck
The sky as seen by Planck
esa
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

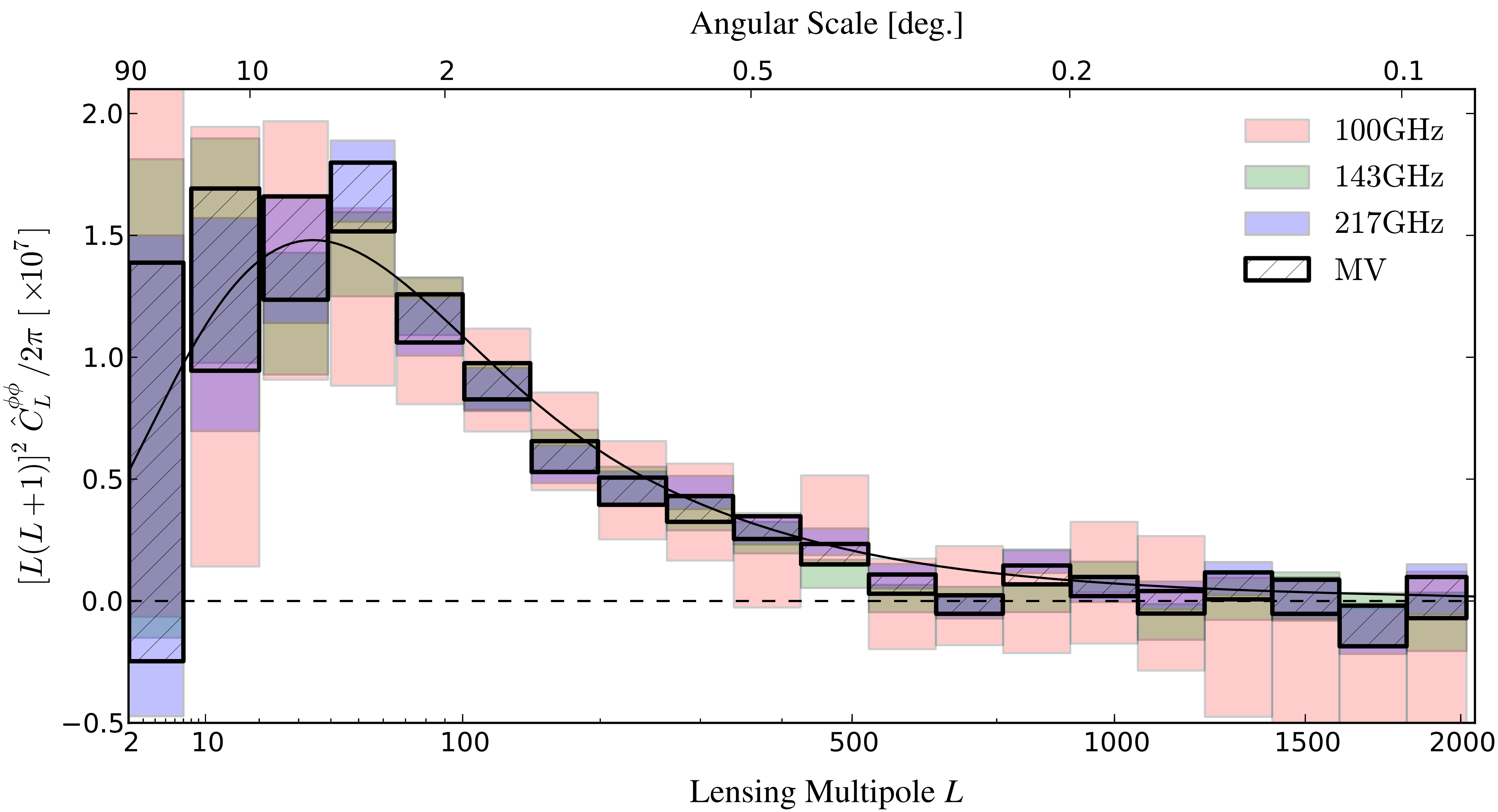
Best reconstruction

- MV combination between the 143GHz & 217GHz
- 857GHz used as a template for dust cleaning
- 30% Galactic mask + CO mask + point sources SNR5
- 5º apodization (for power spectrum estimation)
- fsky = 0.67

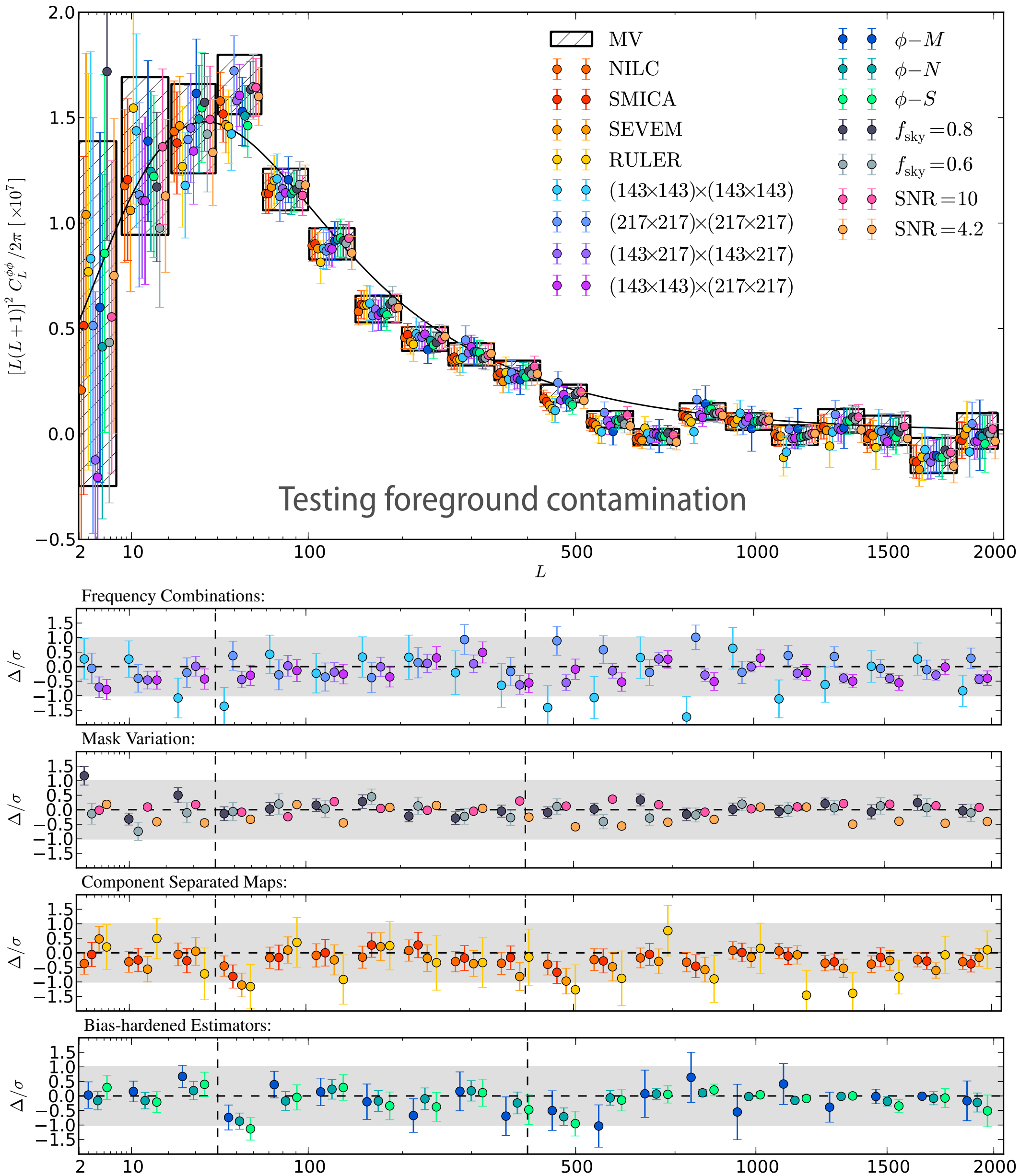


CMB lensing reconstruction

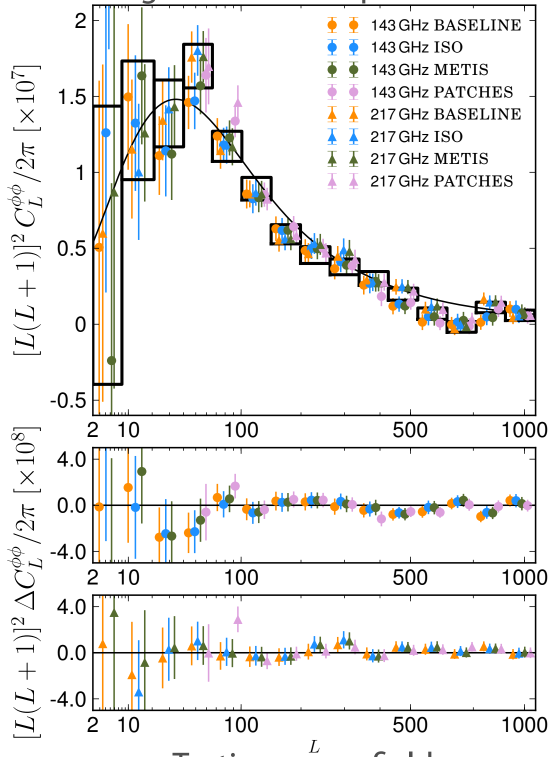
HFi PLANCK



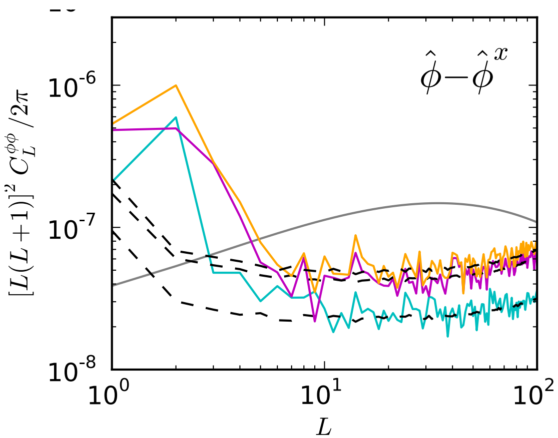
Robustness



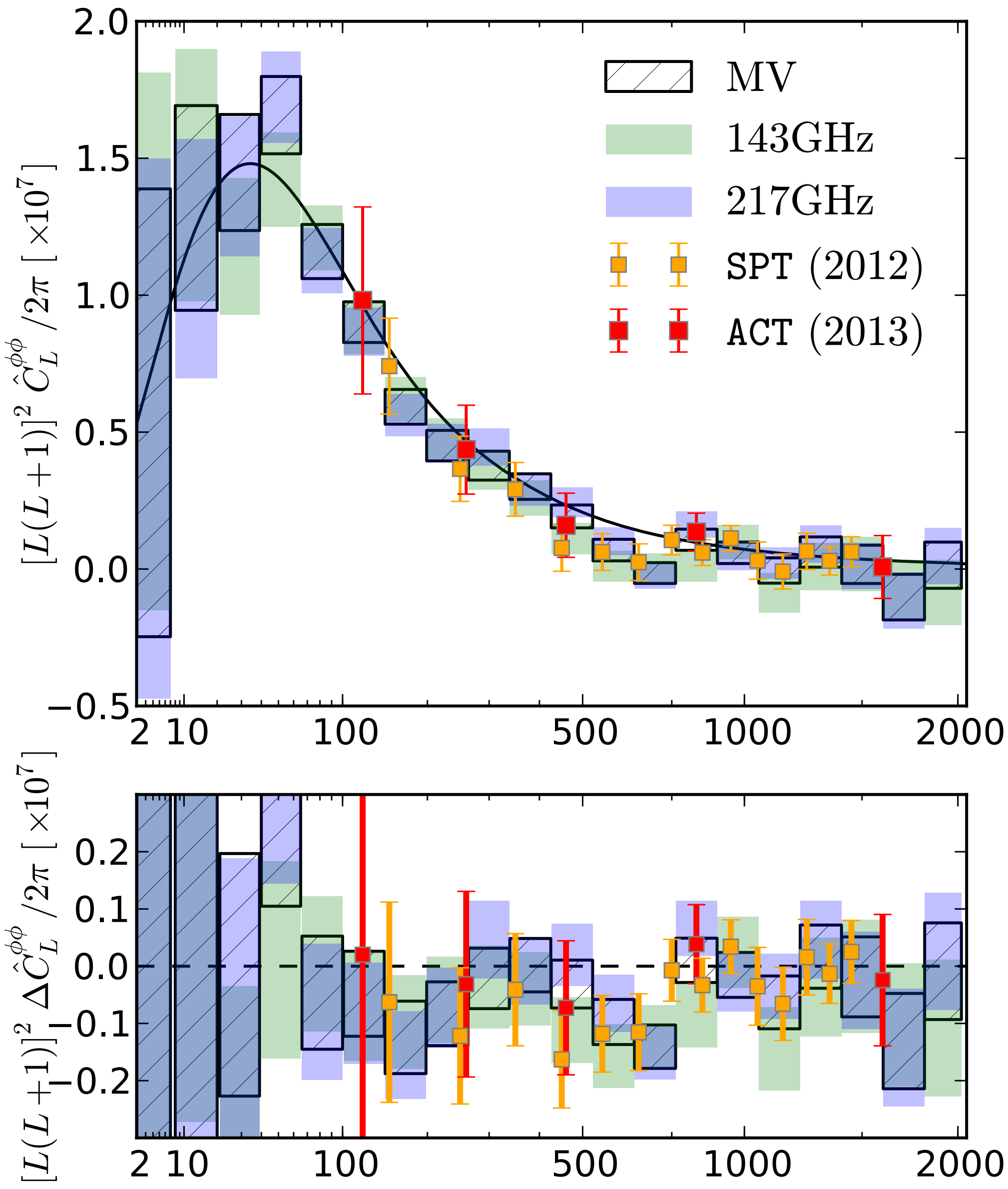
Testing the filter & implementation



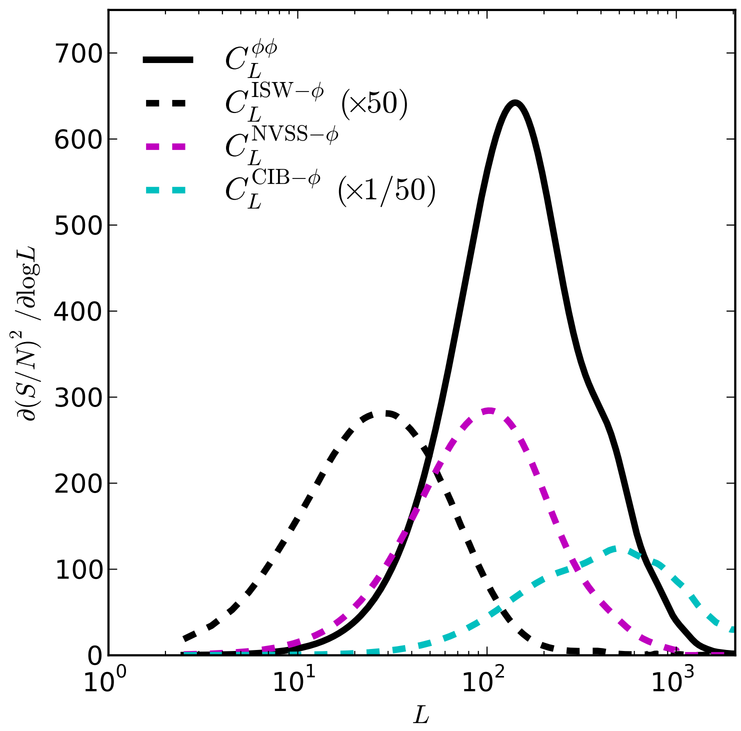
Testing mean field

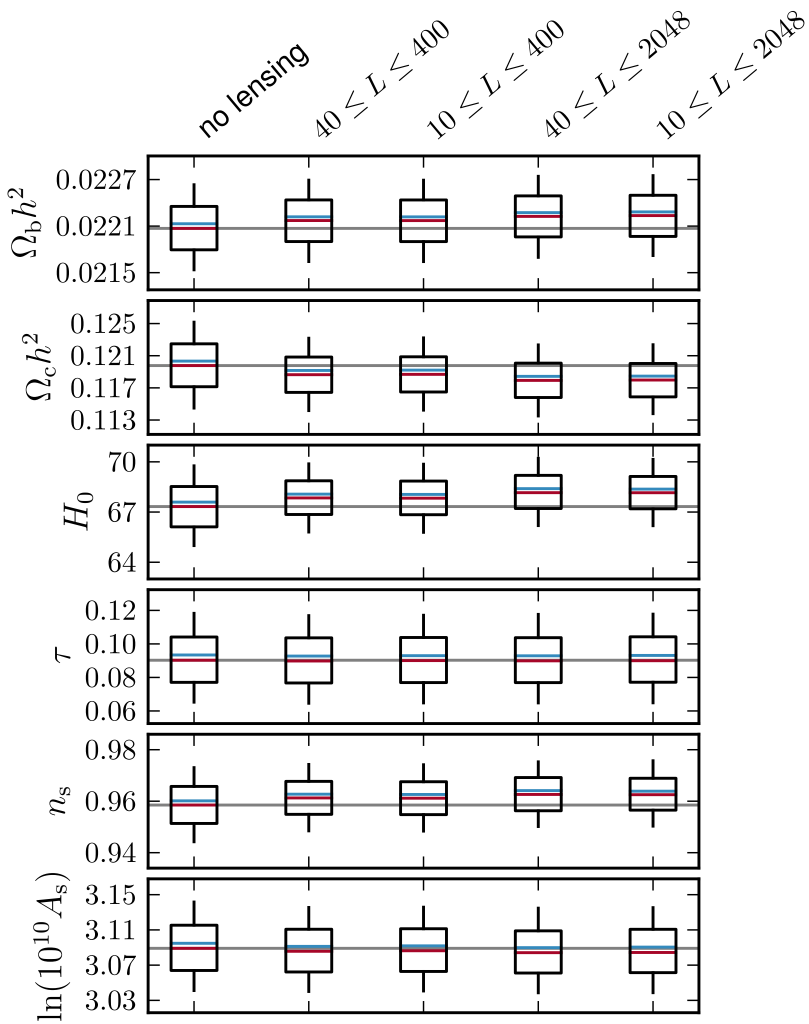


Comparison to other surveys



Cosmology

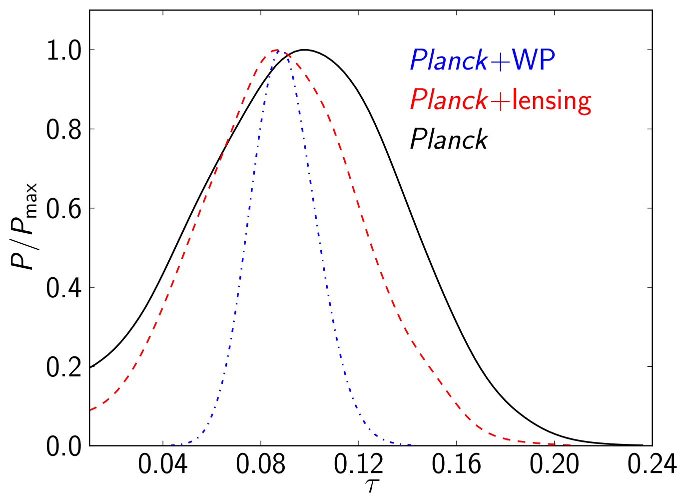


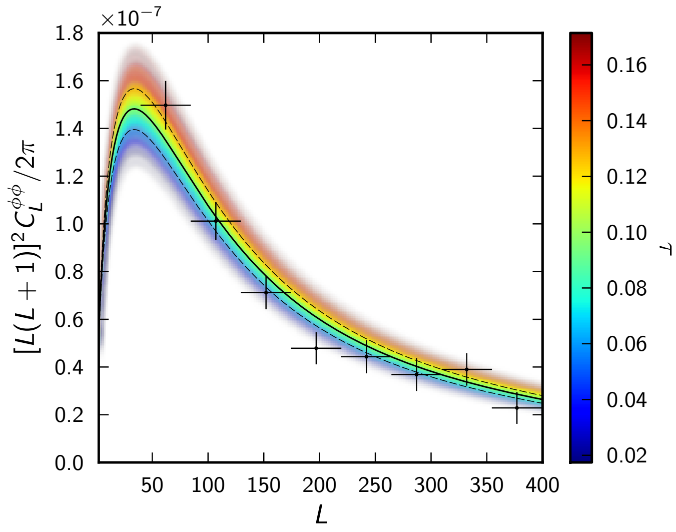


We are using the most significant (and cleanest) part of the data L=40-400.
Lensing brings a 20%ish improvement on some of the vanilla LCDM parameters.

Cosmology - I

Constraining the reionization from Planck alone strengthen the Polarization result



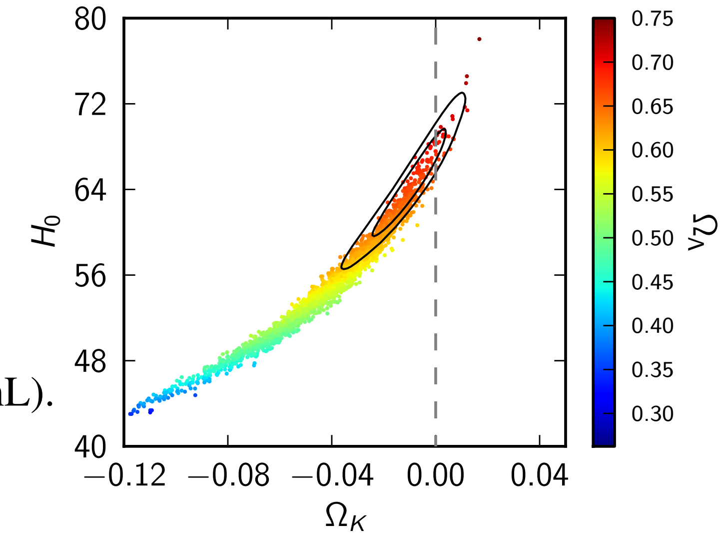


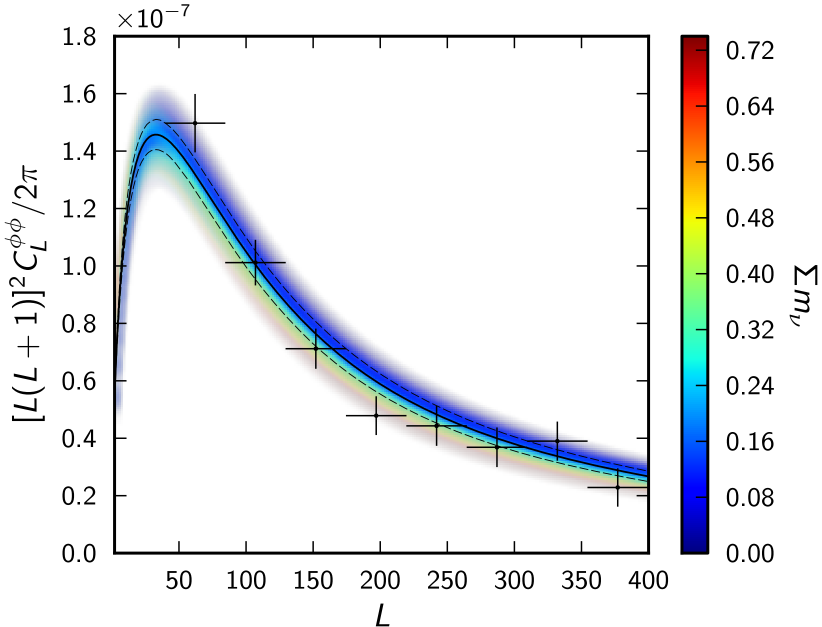
$$\tau = 0.097 \pm 0.038 \quad (68\%; \textit{Planck})$$
$$\tau = 0.089 \pm 0.032 \quad (68\%; \textit{Planck}\text{+lensing}).$$

Cosmology - II

Breaking the geometrical degeneracy
2+fold improvement on the errorbar
3% precision determination of Dark Energy from CMB alone

$$\Omega_\Lambda = 0.57^{+0.073}_{-0.055} \quad (68\%;\ \textit{Planck}+\text{WP}+\text{highL})$$
$$\Omega_\Lambda = 0.67^{+0.027}_{-0.023} \quad (68\%;\ \textit{Planck}+\text{lensing}+\text{WP}+\text{highL}).$$

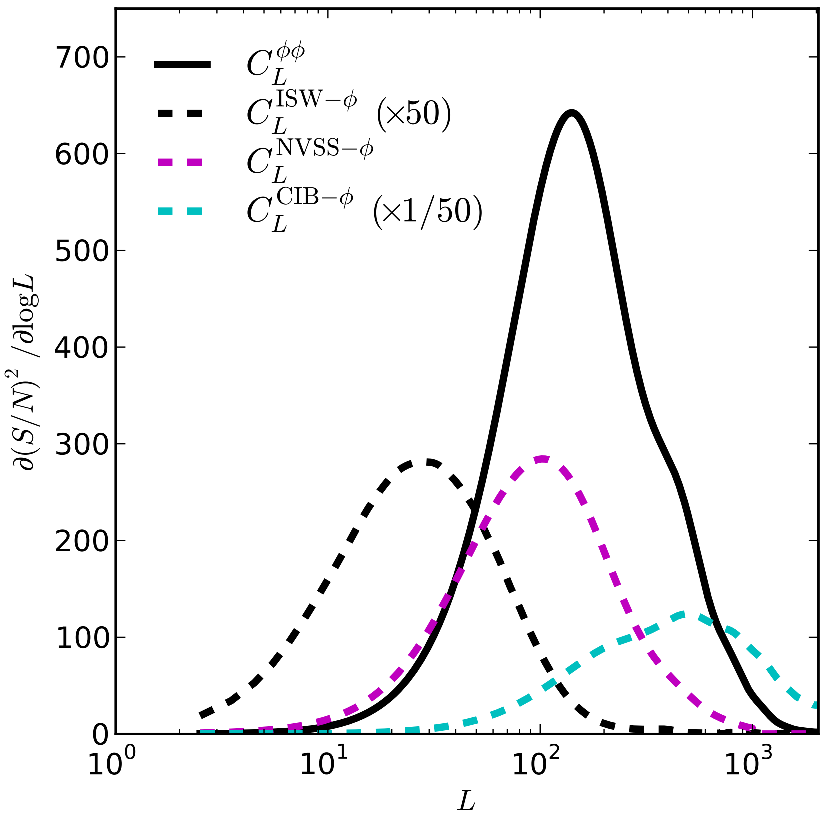


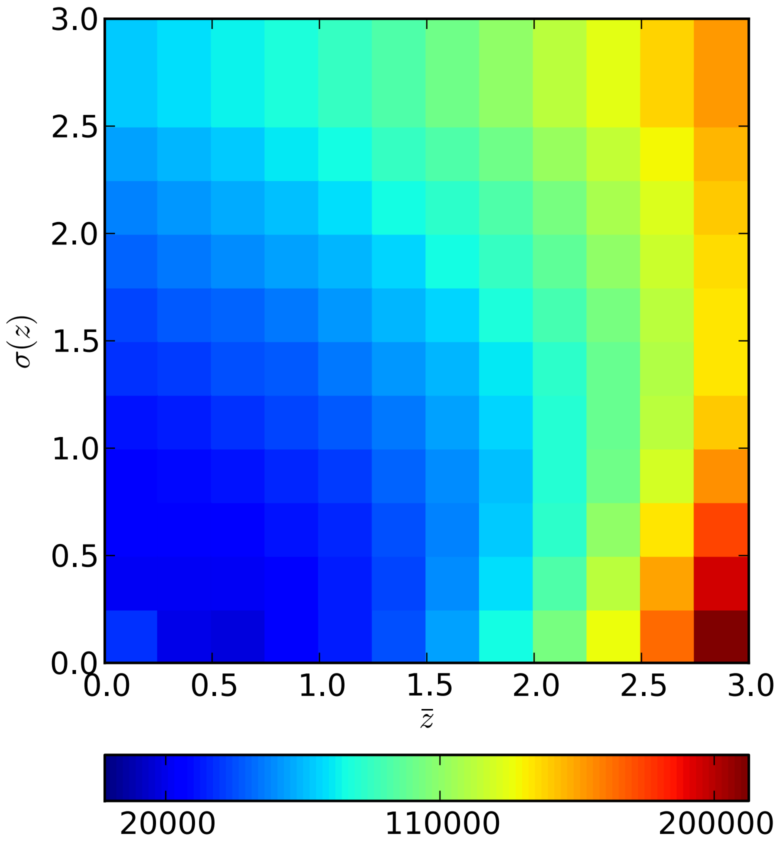


Mild tension with neutrino masses
TT wants more lensing
TTTT wants less lensing

$$\sum m_\nu < 0.66\,\text{eV}, \quad (95\%;\ \textit{Planck}+\text{WP}+\text{highL}),$$
$$\sum m_\nu < 0.85\,\text{eV}, \quad (95\%;\ \textit{Planck}+\text{lensing}+\text{WP}+\text{highL}),$$

Cross correlation

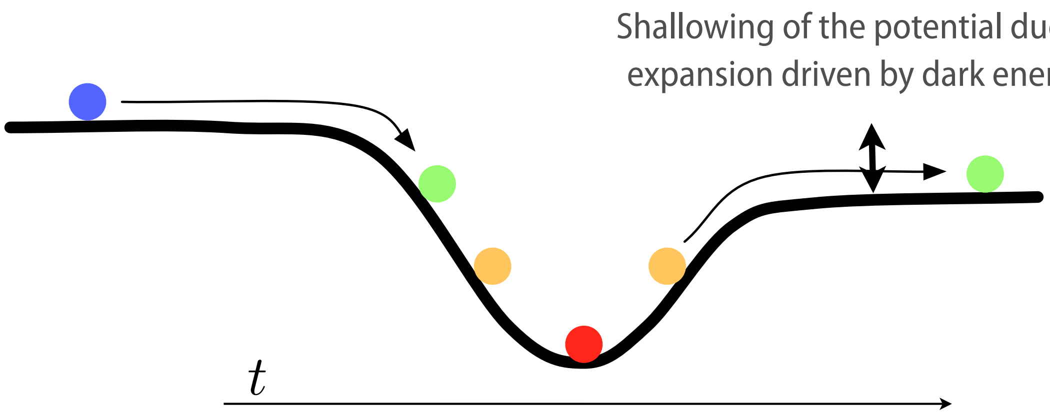




Number of object needed for a 5sigma cross correlation with CMB lensing on 20% of the sky as a function of redshift and redshift dispersion

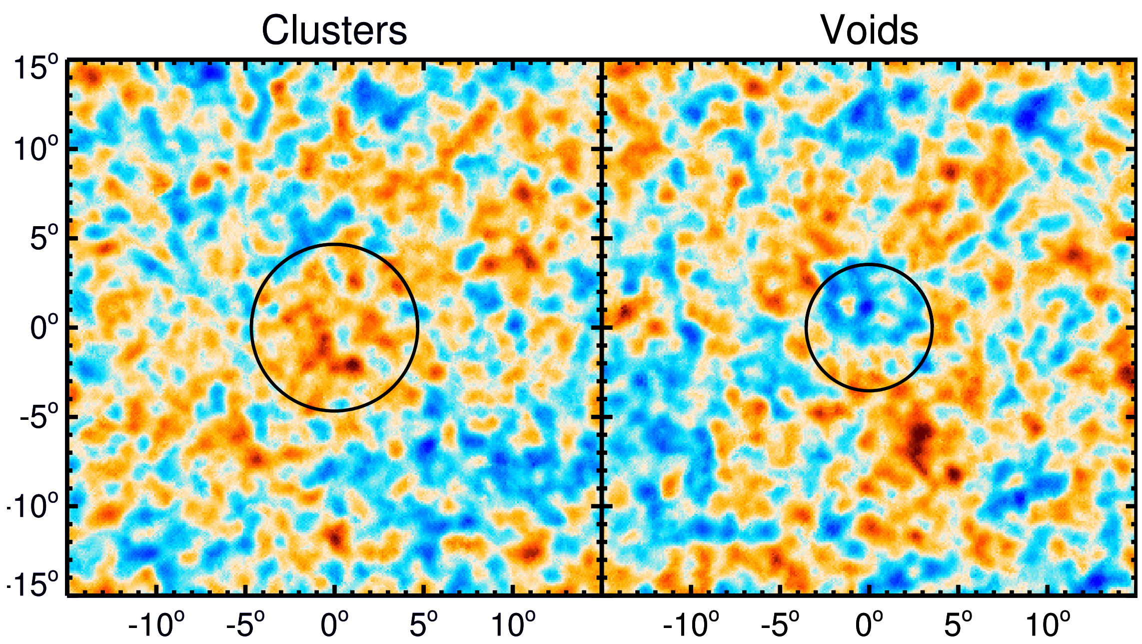
D. Hanson

ISW



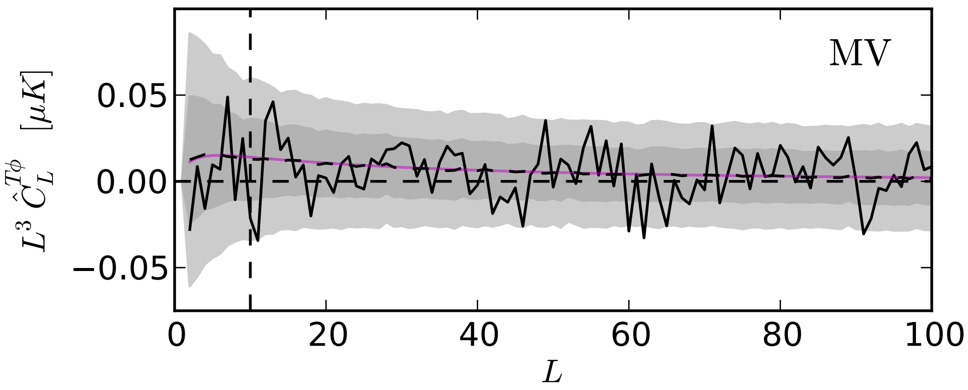
$$\frac{\Delta T}{T} = \frac{2}{c^3}\int_{\eta^*}^{\eta_0} \mathrm{d}\eta \frac{\partial \Phi}{\partial \eta}$$

Stacking the *Planck* CMB at the location of clusters and voids



ISW - Lensing correlation

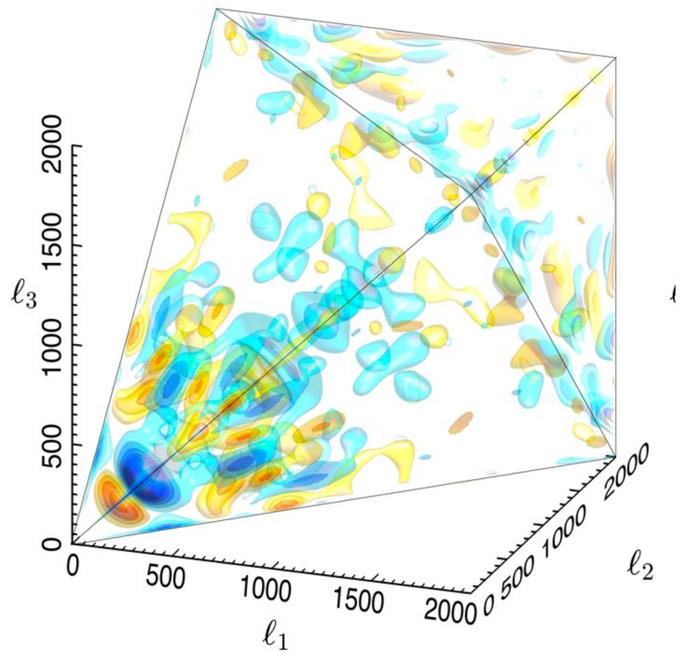
Estimator		C-R	σ	NILC	σ	SEVEM	σ	SMICA	σ	MV	
$T\phi$	$\ell \geq 10$	0.52 ± 0.33	1.5	0.72 ± 0.30	2.4	0.58 ± 0.31	1.9	0.68 ± 0.30	2.3	0.78 ± 0.32	2.4
	$\ell \geq 2$	0.52 ± 0.32	1.6	0.75 ± 0.28	2.7	0.62 ± 0.29	2.1	0.70 ± 0.28	2.5		
KSW		0.75 ± 0.32	2.3	0.85 ± 0.32	2.7	0.68 ± 0.32	2.1	0.81 ± 0.31	2.6		
binned		0.80 ± 0.40	2.0	1.03 ± 0.37	2.8	0.83 ± 0.39	2.1	0.91 ± 0.37	2.5		
modal		0.68 ± 0.39	1.7	0.93 ± 0.37	2.5	0.60 ± 0.37	1.6	0.77 ± 0.37	2.1		



First detection
2.5sigma
robust against foreground contamination and detection algorithm

Non-Gaussianity

Planck bispectrum

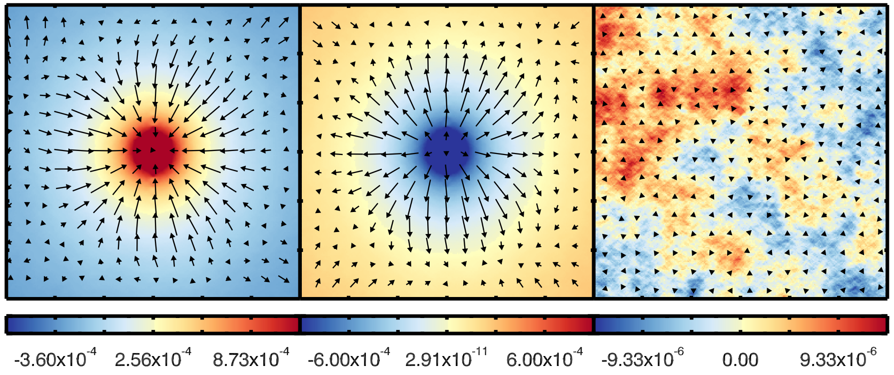


	Independent				ISW-lensing subtracted		
	KSW	Binned	Modal		KSW	Binned	Modal
SMICA							
Local	9.8 ± 5.8	9.2 ± 5.9	8.3 ± 5.9	. . . . .	**2.7** ± **5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	−37 ± 75	−20 ± 73	−20 ± 77	. . . . .	**−42** ± **75**	−25 ± 73	−20 ± 77
Orthogonal	−46 ± 39	−39 ± 41	−36 ± 41	. . . . .	**−25** ± **39**	−17 ± 41	−14 ± 42

No NG !

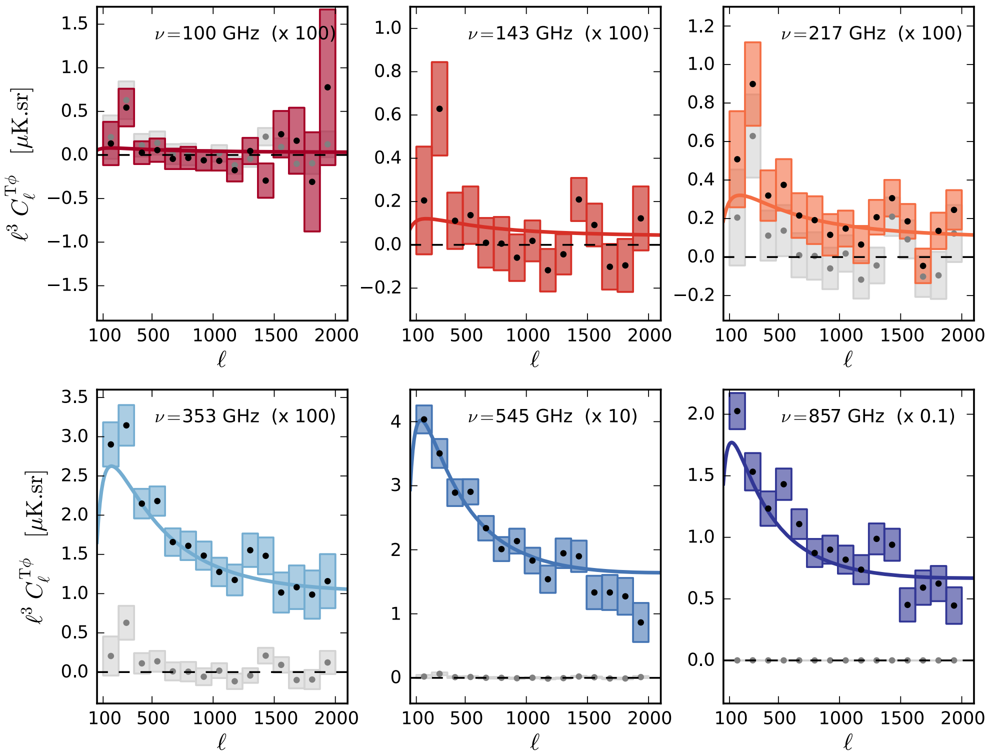
(WMAP9 constraint : local fNL=37 ± 20)

Planck lensing X planck CIB



Stacking of the extrema of the CIB field (and at random locations)

Impressive visual correlation on degree scale



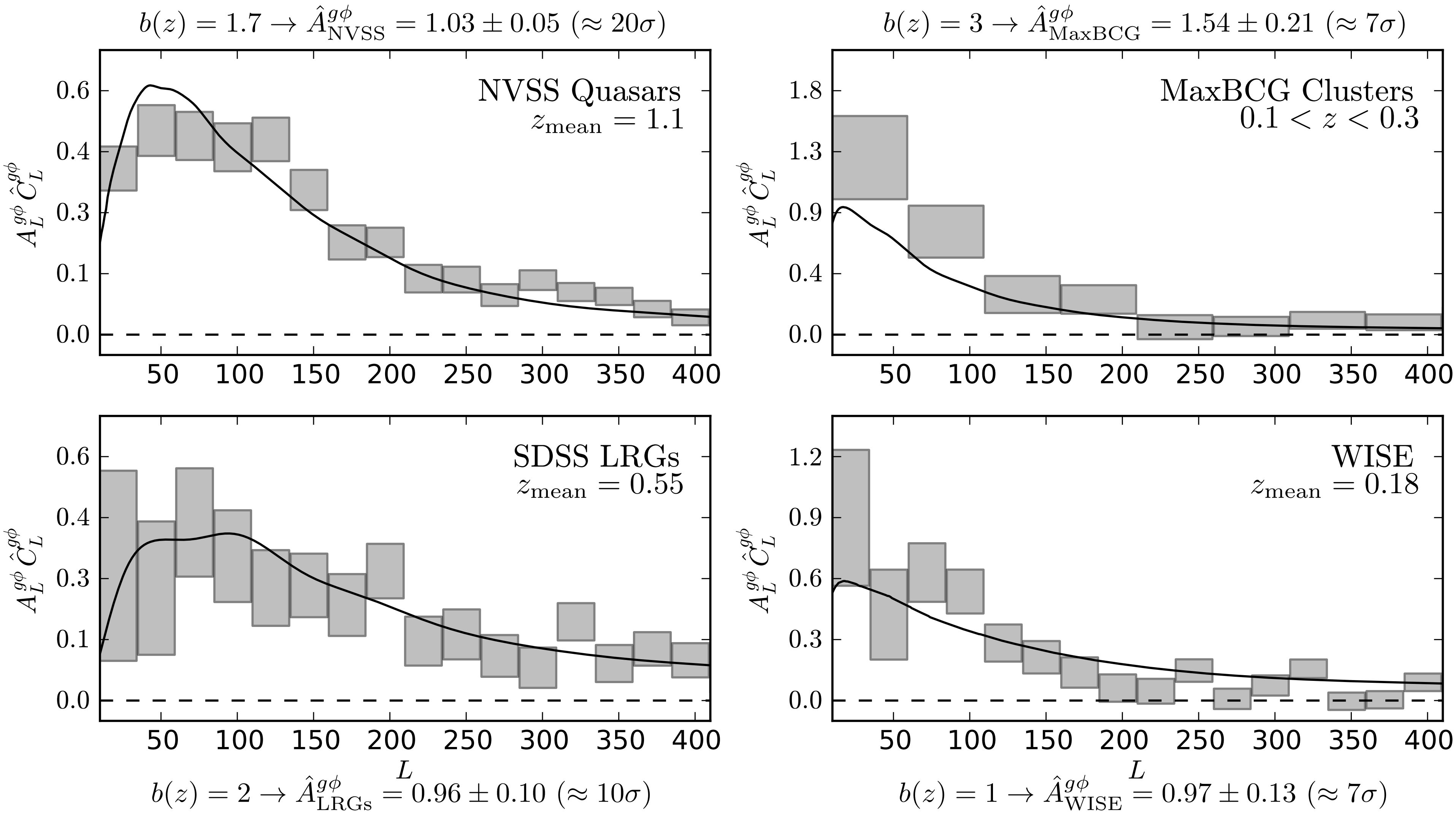
Cross correlation of the maps

Using the best 40% of the CIB & lensing from Planck

Boxes give statistical errors. Grey boxes are the 143-lensing X 143-cib correlation

Lines are the predictions from the Planck Early papers !

Lensing external tracers



No particular effort here to optimize the model for the external survey

There is an untapped astrophysical treasure in the Planck Lensing Map

Conclusion

- Planck trace late dark matter distribution
  - Lensing reconstruction on the whole sky
  - **Reconstruction of the full sky dark matter distribution**
  - First determination of the ISW-lensing correlation
  - Improvement of the cosmological parameters constraint
  - Tension for neutrino masses
  - **Great potential for cross-correlation with other surveys**
- Where do we go from here
  - SPT/ACT/others will greatly improve the small scales
  - PRISM ?