The large scale structure of the Universe as seen by Planck

Aurélien Benoit-Lévy

University College London

On behalf of the Planck Collaboration

XVII. Gravitational lensing by large scale structure

XVI. Cosmological parameters

XVIII. Gravitational lensing - infrared background correlation

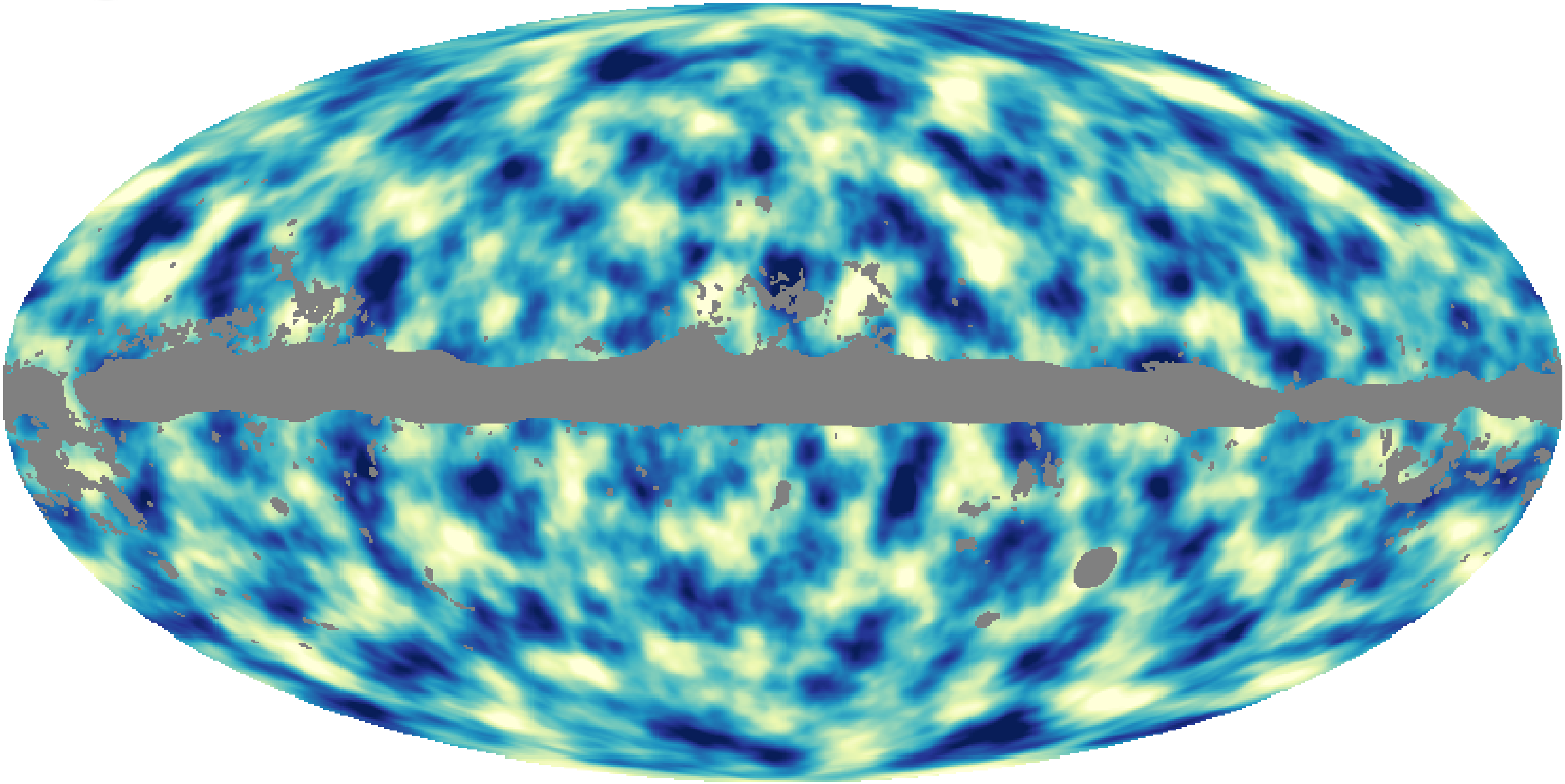
XIX. The integrated Sachs-Wolfe effect

IX^{ème} Rencontres du Vietnam - Cosmology in the Planck era - July 2013

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

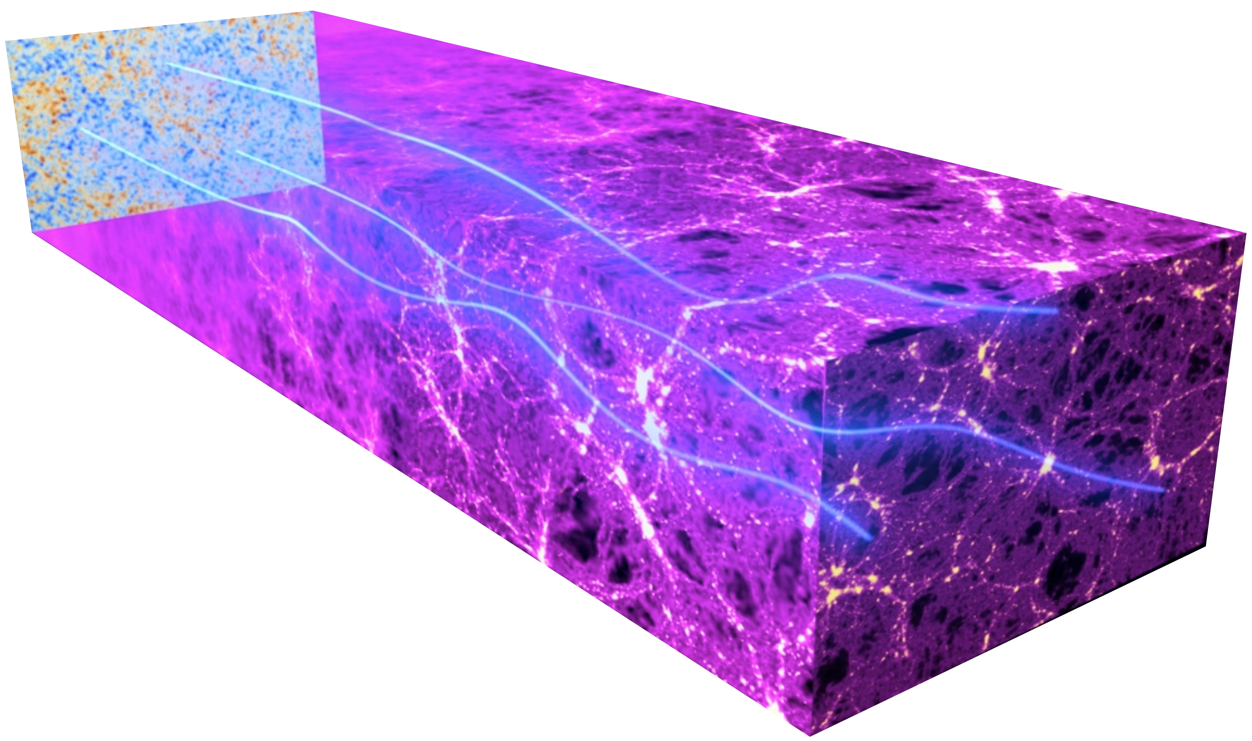
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

The matter in the Universe



Planck picture of the matter distribution at z~2

CMB lensing



Typical deflection δβ sourced by potential Ψ

$\Psi \sim 2\ 10^{-5}$ $\delta\beta \sim 10^{-4}$

Photons encounter ~ 50 potential wells

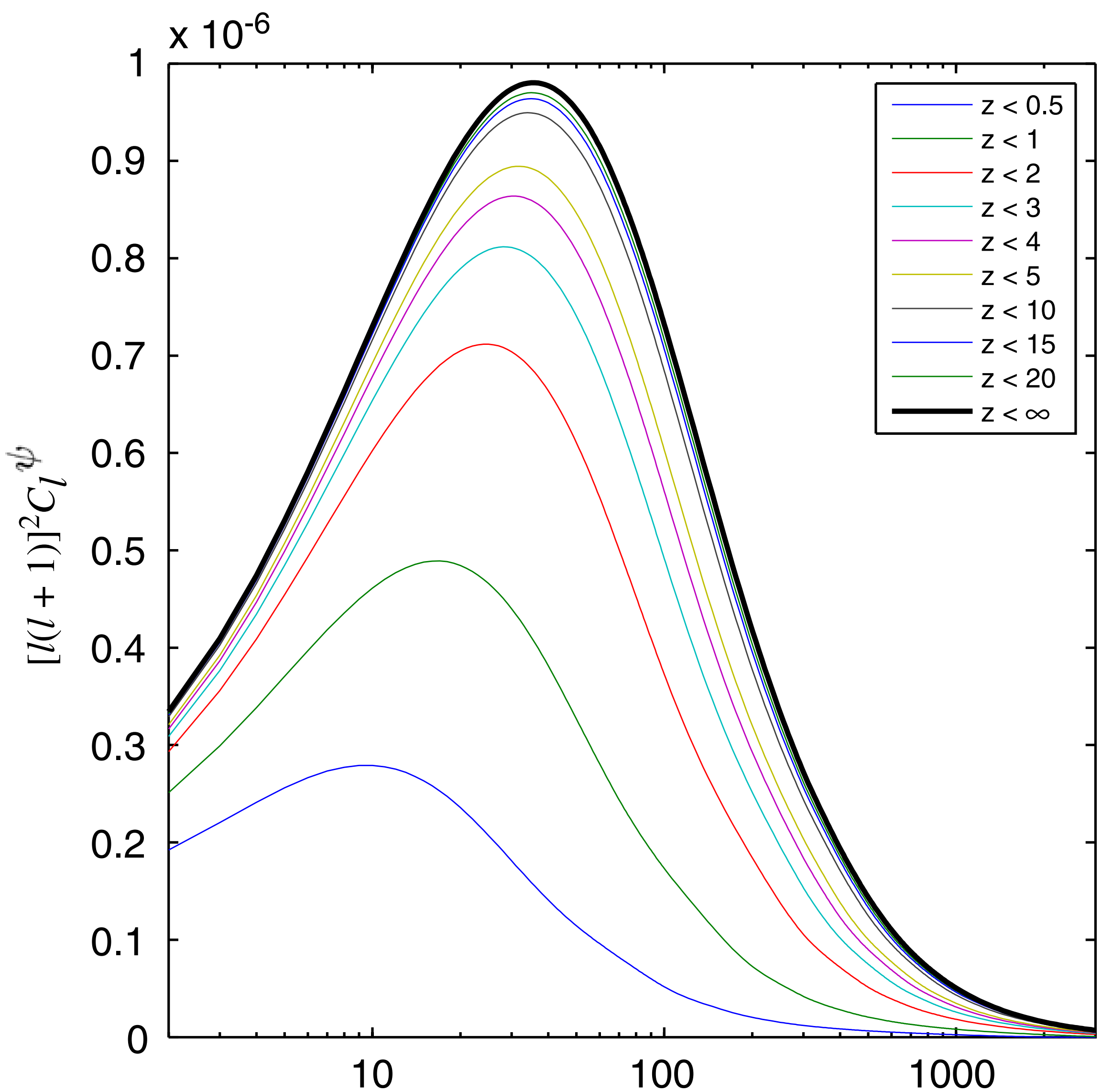
r.m.s deflection
$50^{1/2} * 10^{-4} \sim 2$ arcmin

$$\Theta[\hat{\mathbf{n}}] = \tilde{\Theta}[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})] \approx \tilde{\Theta}[\hat{\mathbf{n}}] + \nabla\phi[\hat{\mathbf{n}}]\ \nabla\tilde{\Theta}[\hat{\mathbf{n}}] + \cdots$$

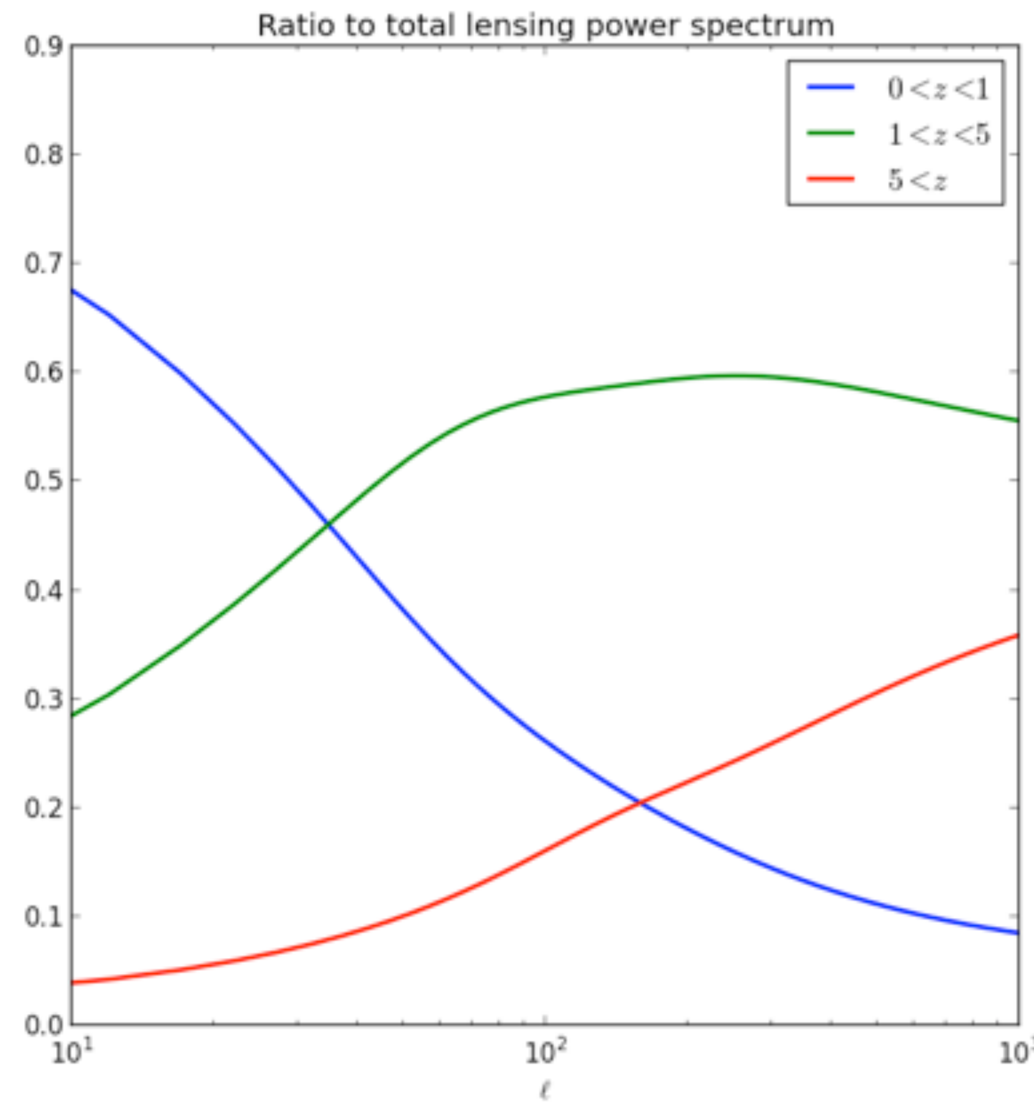
$$\phi(\hat{\boldsymbol{n}}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{\boldsymbol{n}}; \eta_0 - \chi).$$

The lensing potential

$$\phi(\hat{\boldsymbol{n}}) = -2 \int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi \hat{\boldsymbol{n}}; \eta_0 - \chi).$$

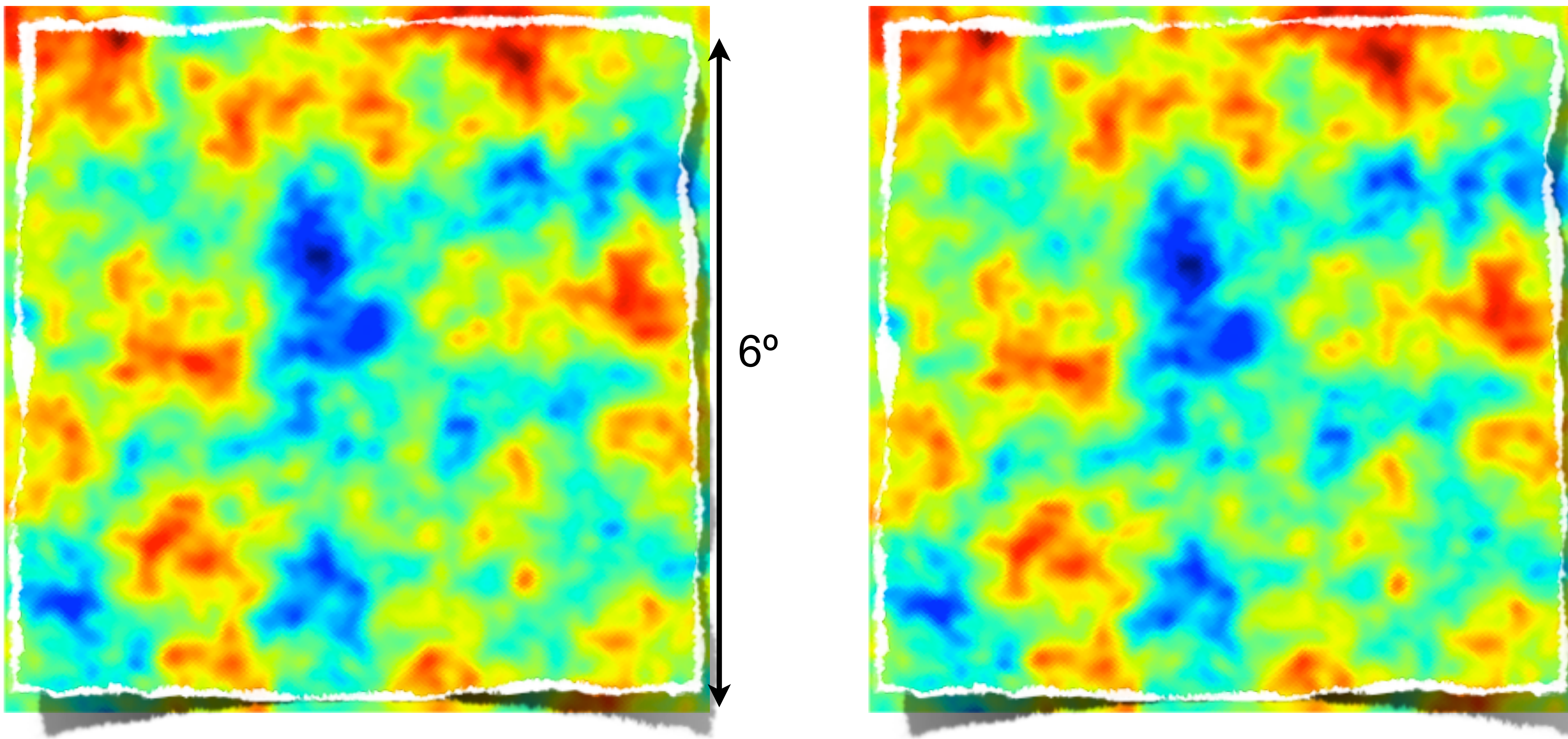


Lewis & Challinor, 2006



CMB lensing

Deflections are about 2 arcmin

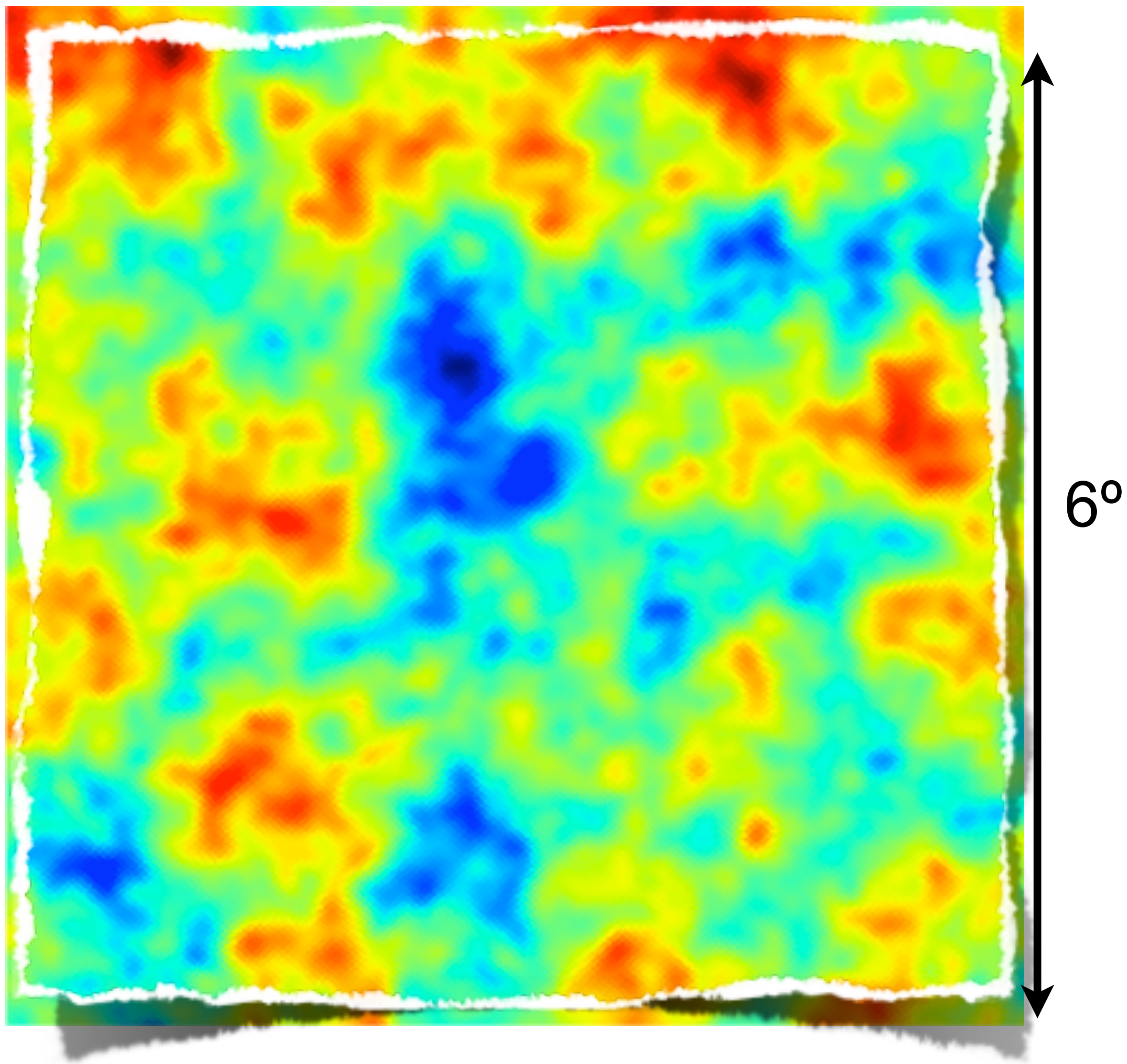


Unlensed

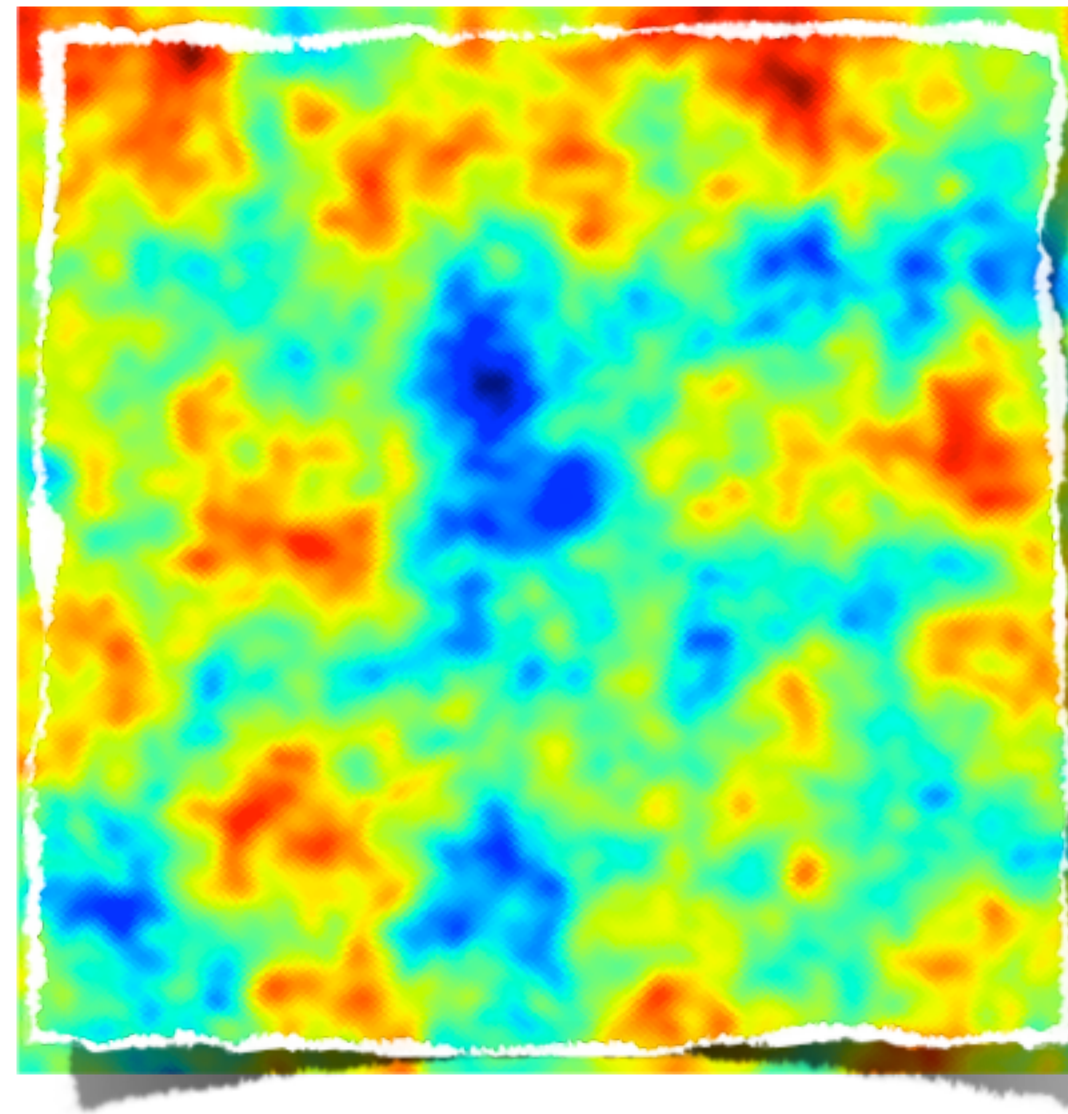
Lensed

CMB lensing

Deflections are about 2 arcmin



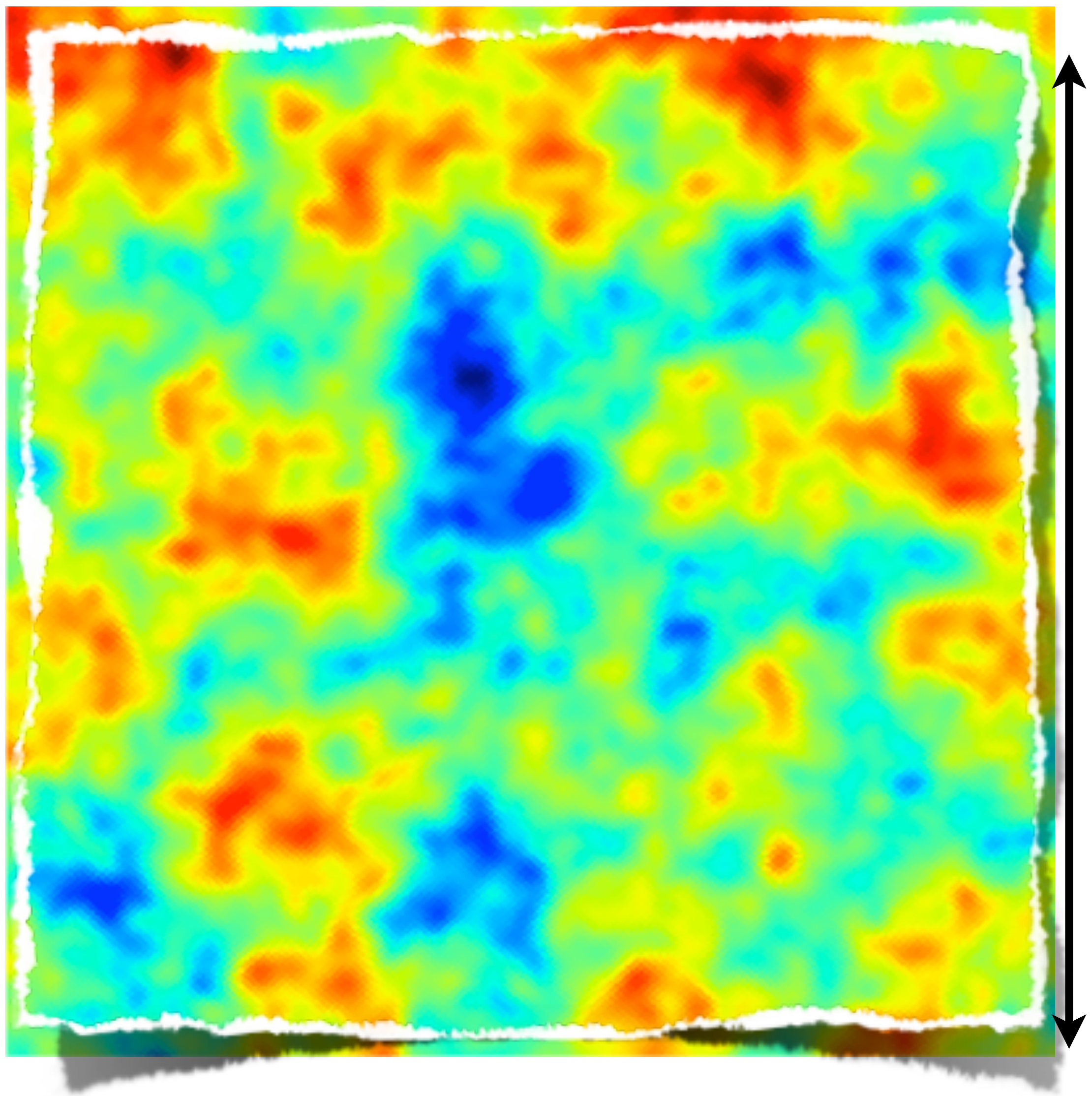
Unlensed



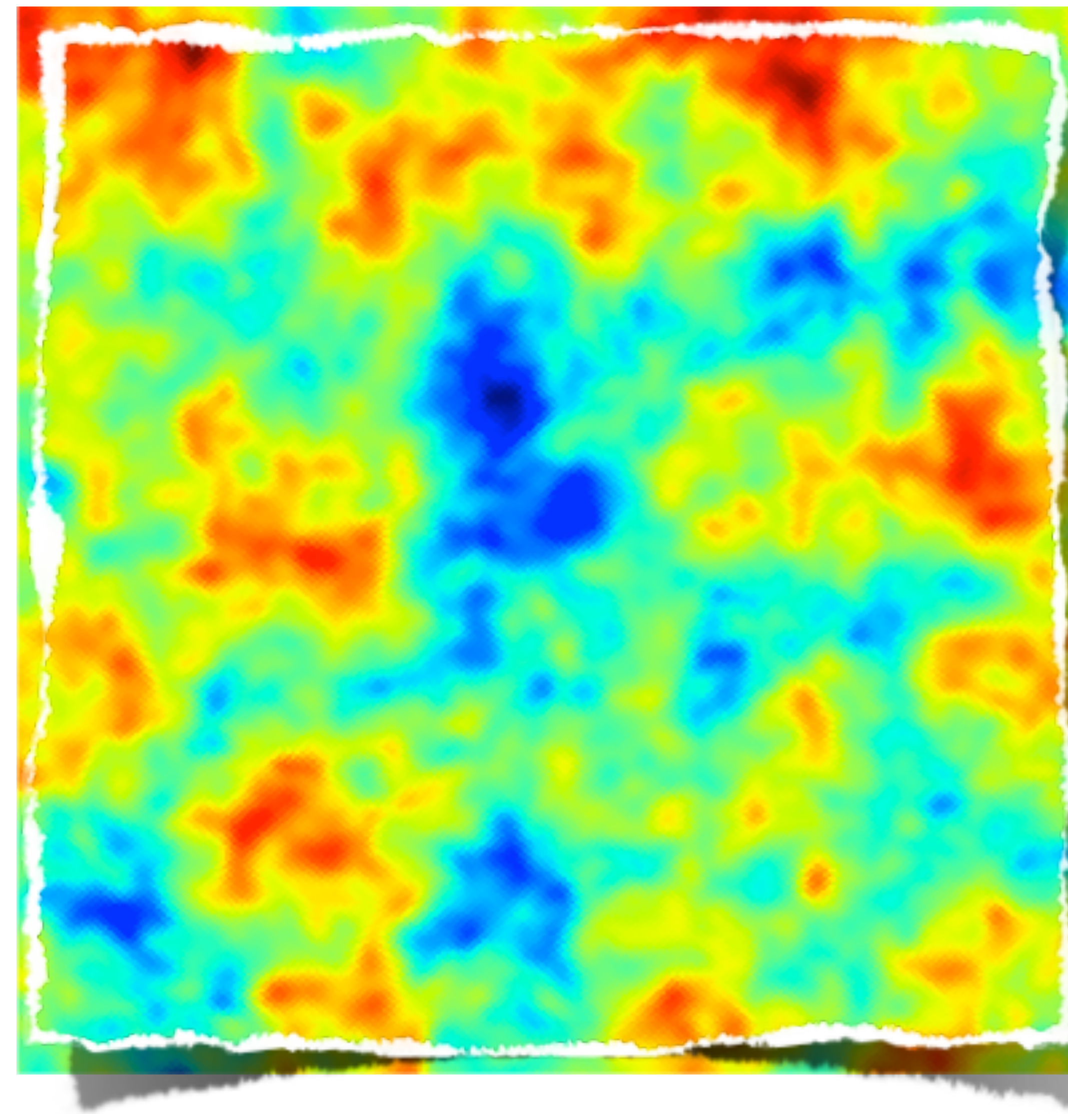
Unlensed

CMB lensing

Deflections are about 2 arcmin



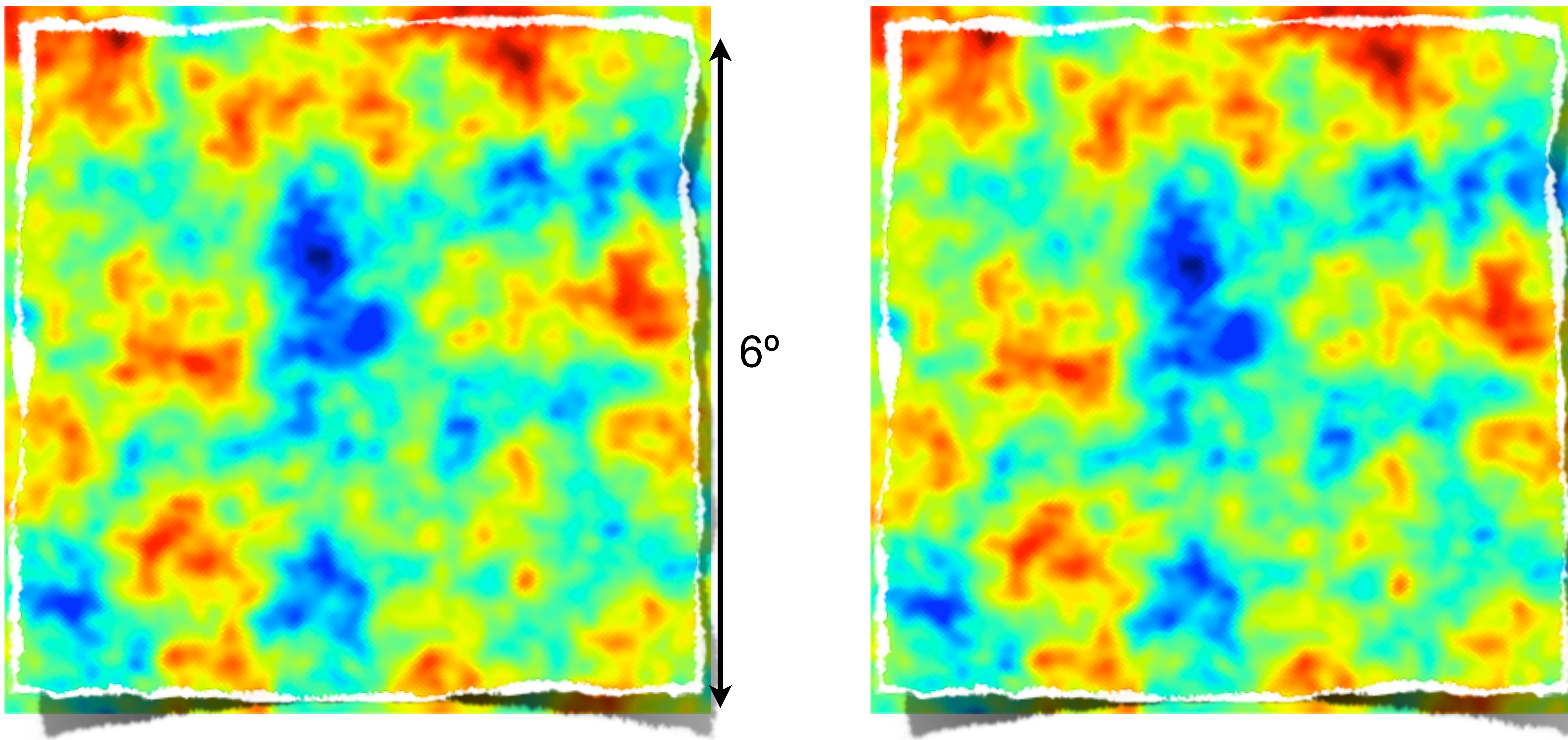
Unlensed



Lensed

CMB lensing

Deflections are about 2 arcmin



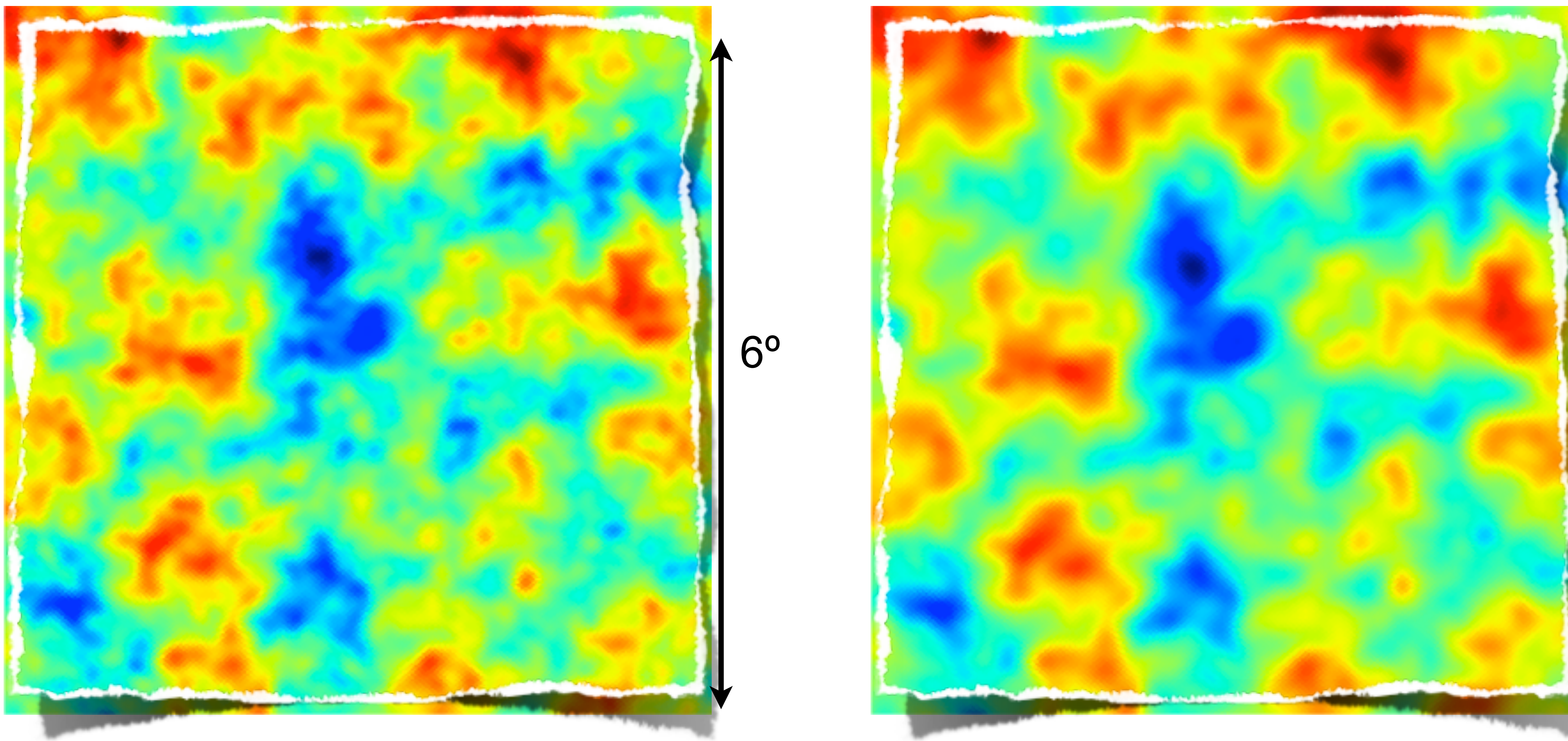
Unlensed

Lensed

Deflections are correlated on the degree scale

CMB lensing

Deflections are about 2 arcmin



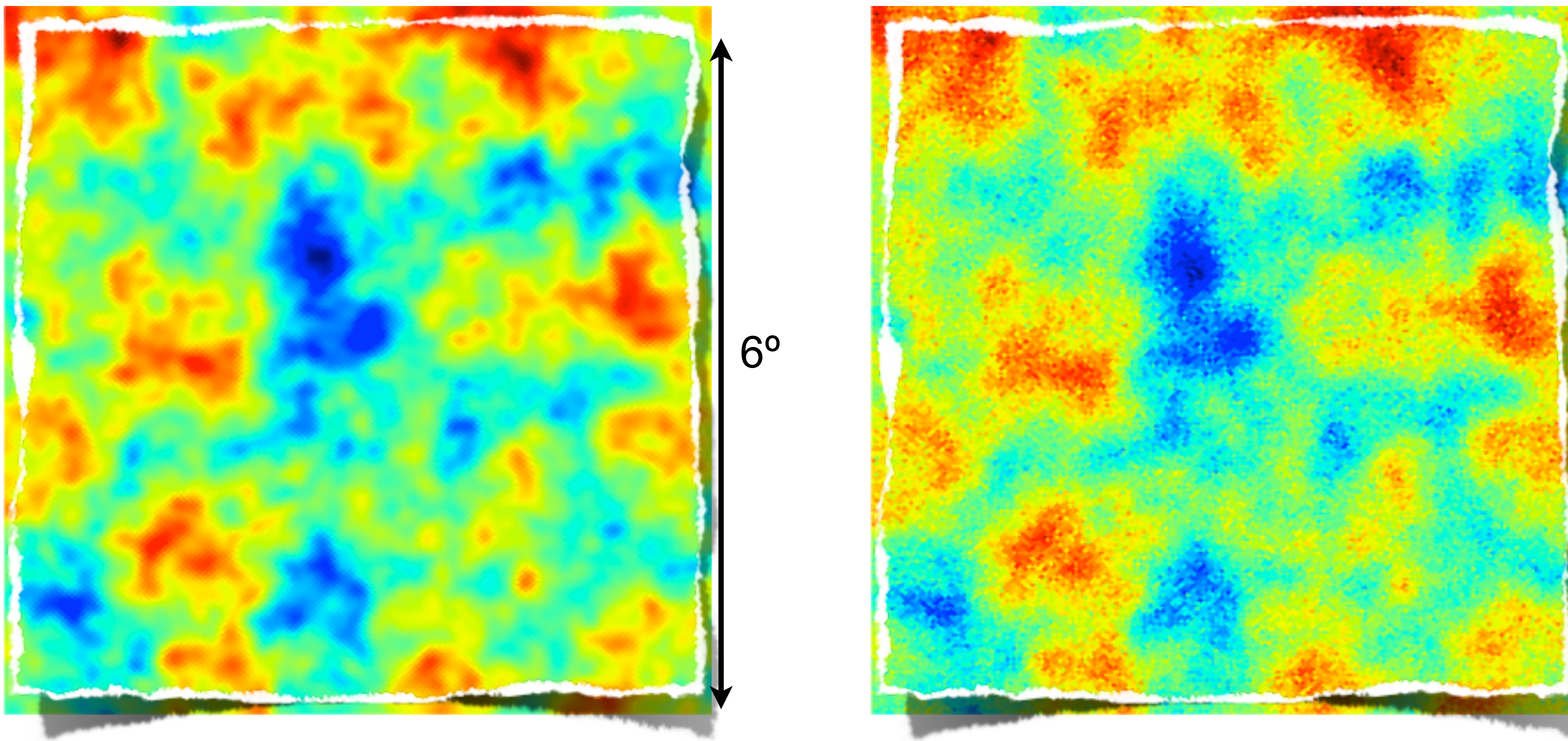
Unlensed

Lensed,
beamed

Deflections are correlated on the degree scale

CMB lensing

Deflections are about 2 arcmin



Unlensed

Lensed,
beamed, noised

Deflections are correlated on the degree scale

Impact on CMB

- CMB lensing induces statistical anisotropies

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

Lensing can also be detected in TT
~10 sigma with Planck2013

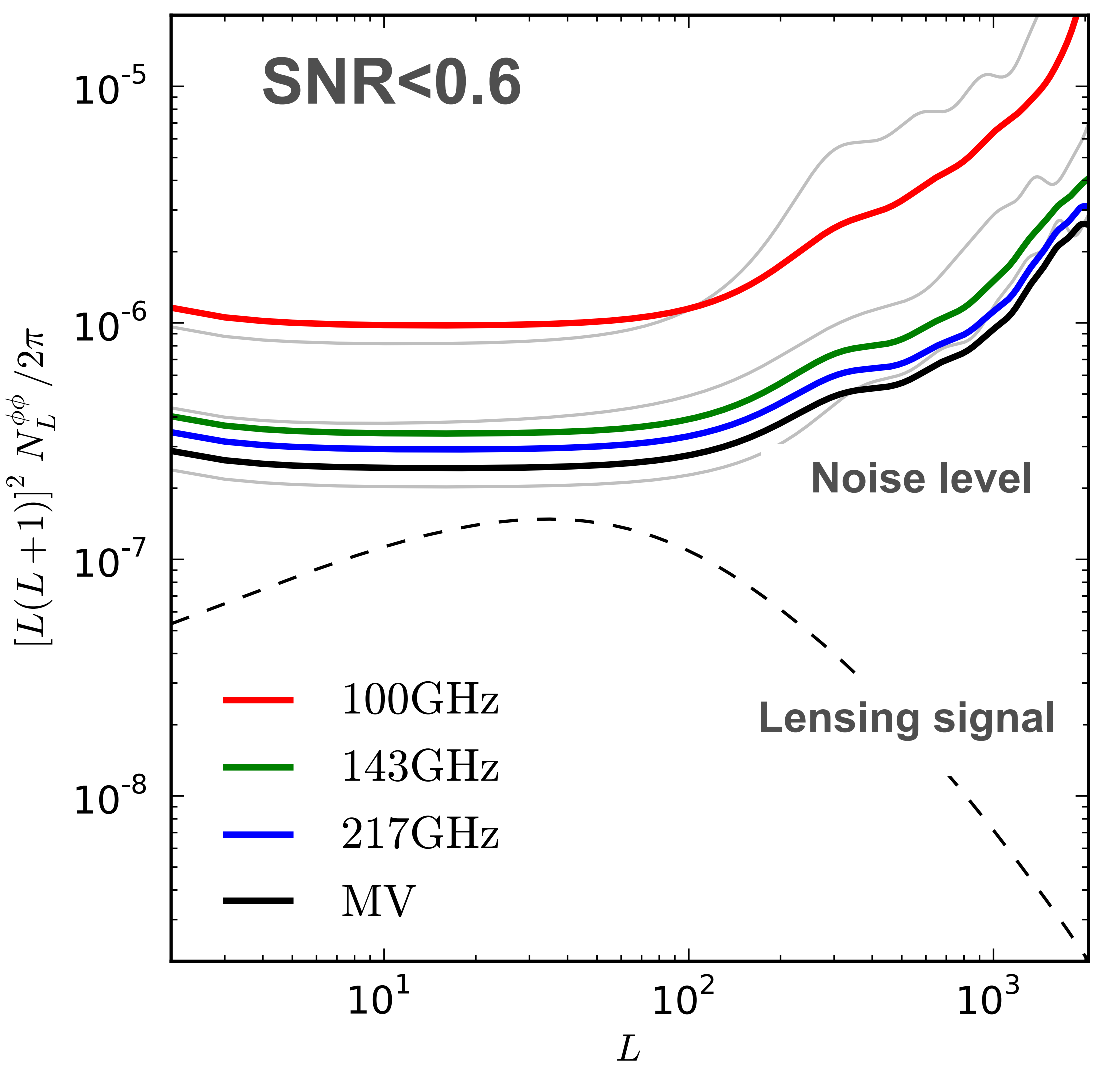
- Quadratic estimator (Hu & Okamoto)

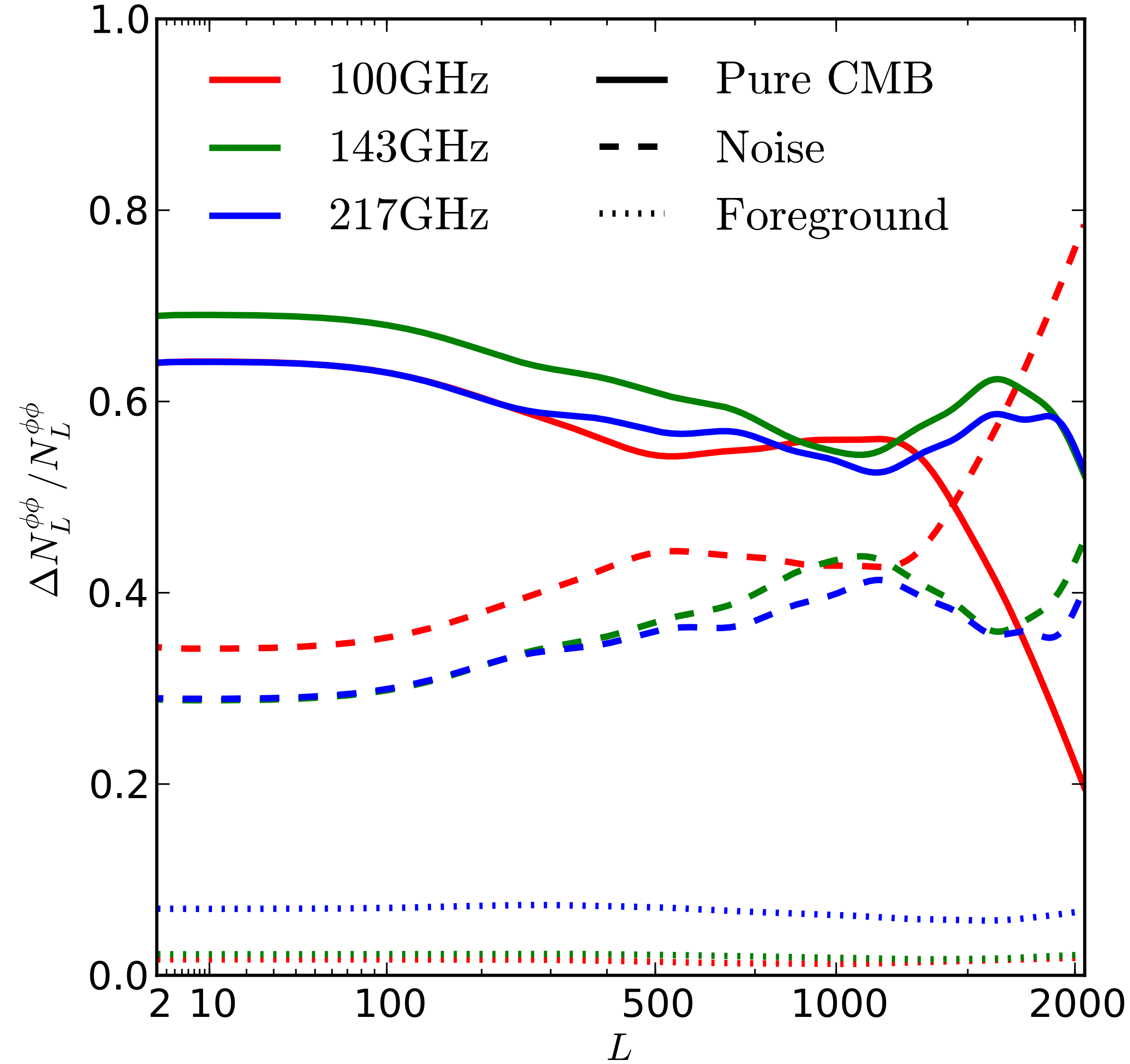
$$\bar{x}_{LM} = \frac{1}{2} \sum_{\ell_1 m_1, \ell_2 m_2} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W^{x}_{\ell_1 \ell_2 L} \bar{T}^{(1)}_{\ell_1 m_1} \bar{T}^{(2)}_{\ell_2 m_2}.$$

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

CMB lensing reconscruction

- Ideal Planck case

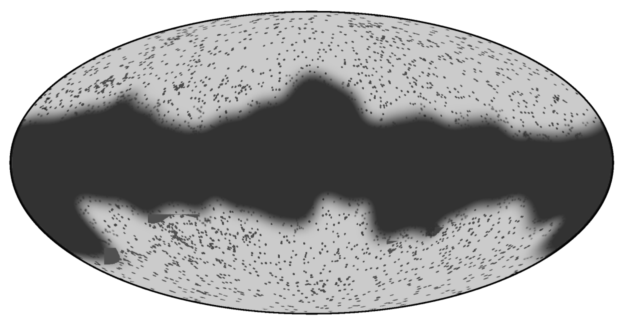




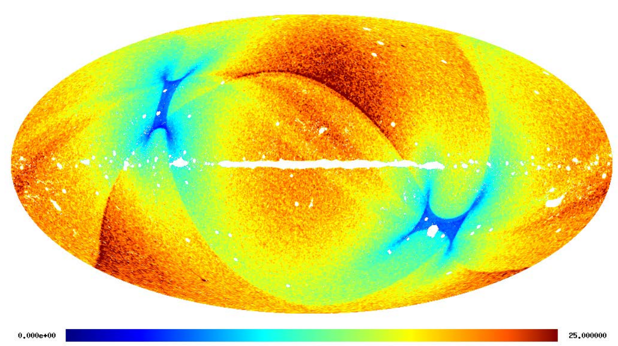
CMB lensing reconscruction

- Other souces of statistical anisotropies

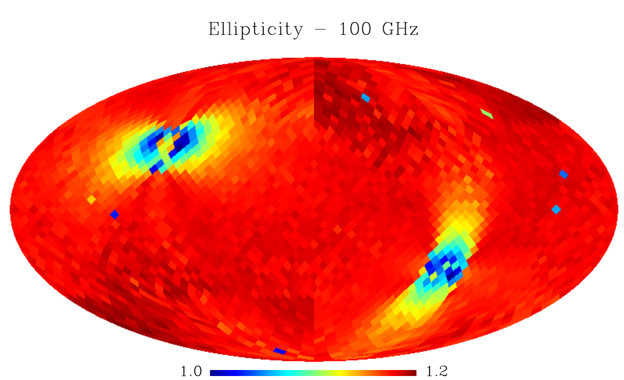
Galactic + PS mask

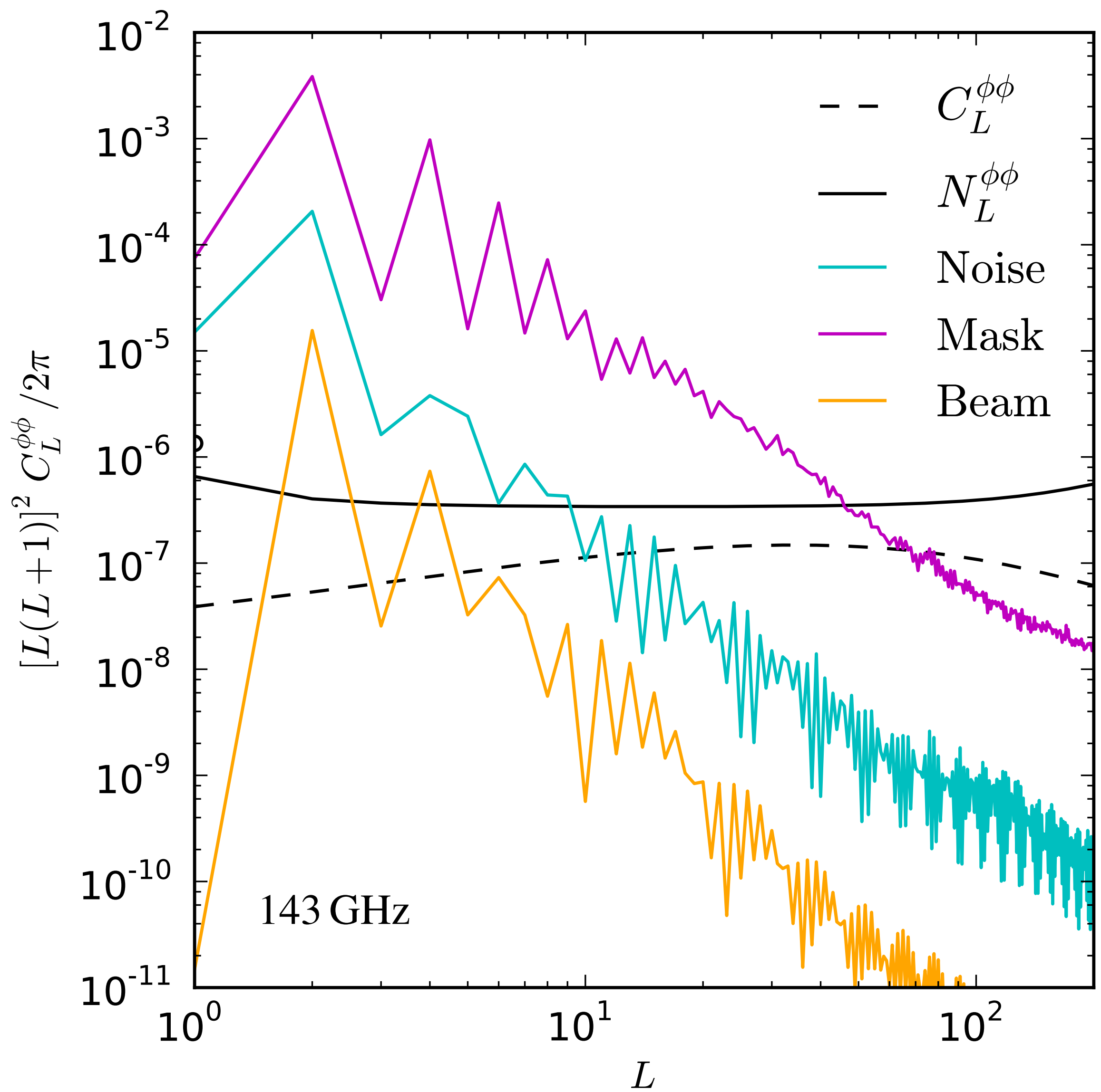


Inh. noise



Beam ellipticity





CMB lensing reconscruction

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

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

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

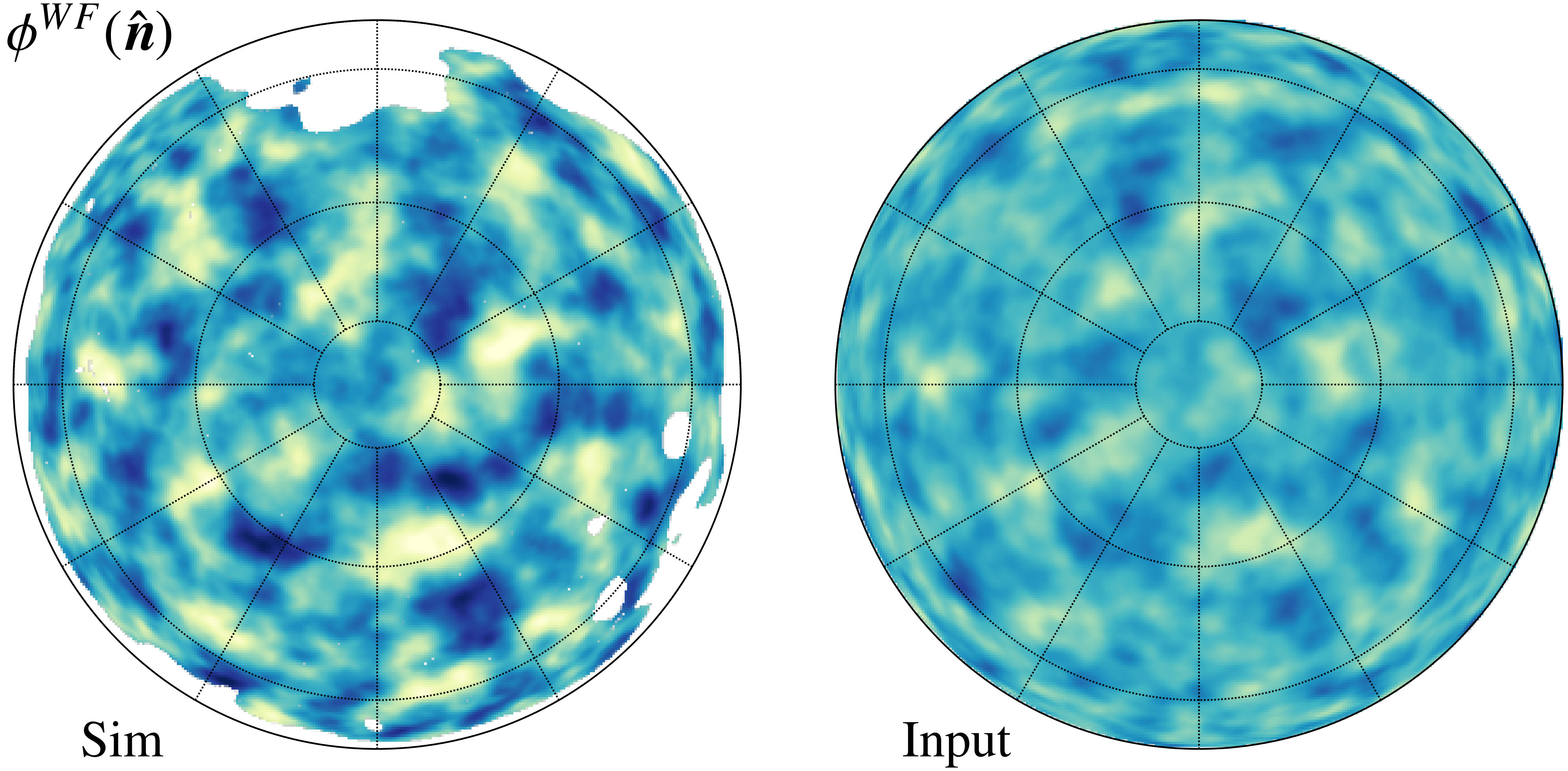
$$\bar{\phi}_{\ell m} = \left[(C^{-1}T) \nabla (S C^{-1} T) \right]_{\ell m}$$

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

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

- Take two temperature maps and inverse-variance filter them
- Multiply one by the temperature power spectrum and differentiate it
- Multiply it with the first filtered map
- Do the same on a set of realistic simulations
- Take the difference and normalize to get unbiased estimator

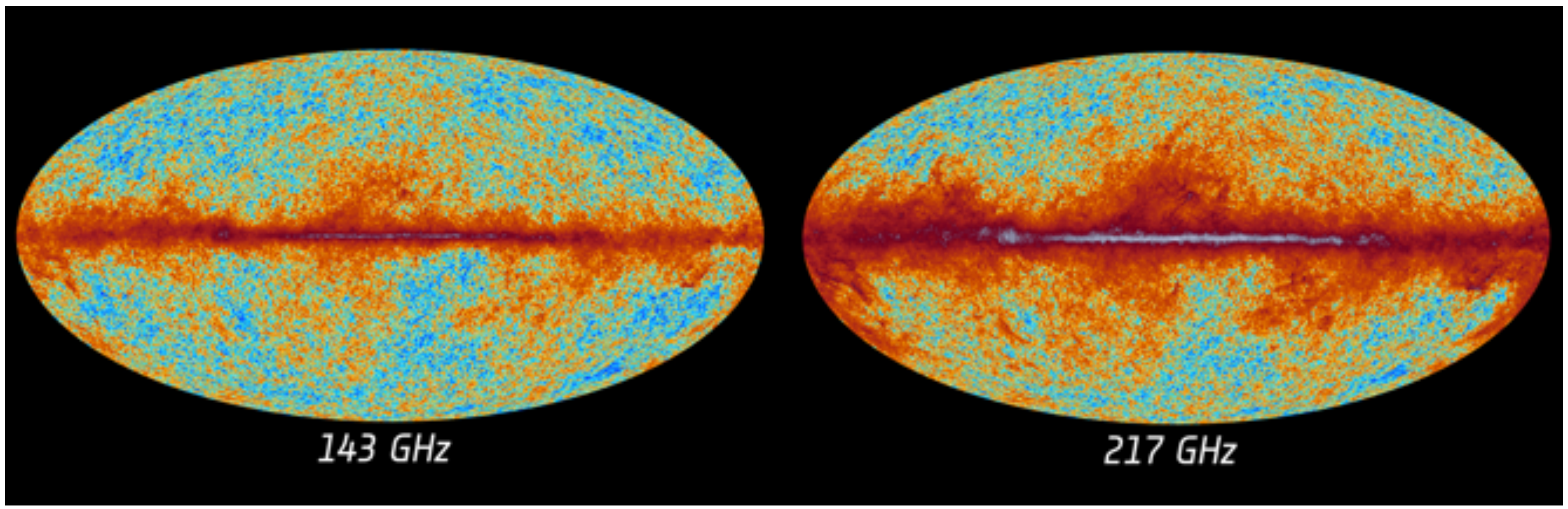
CMB lensing reconscruction

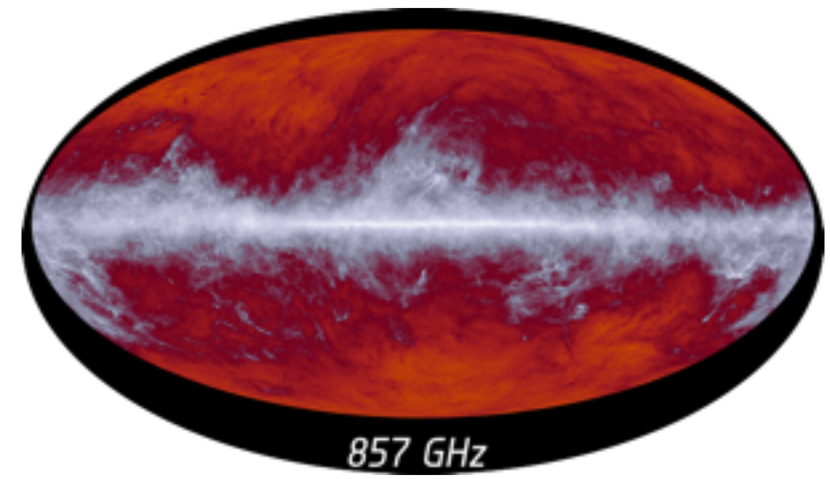


Reconstruction on a realistic Planck simulation

Best reconstruction

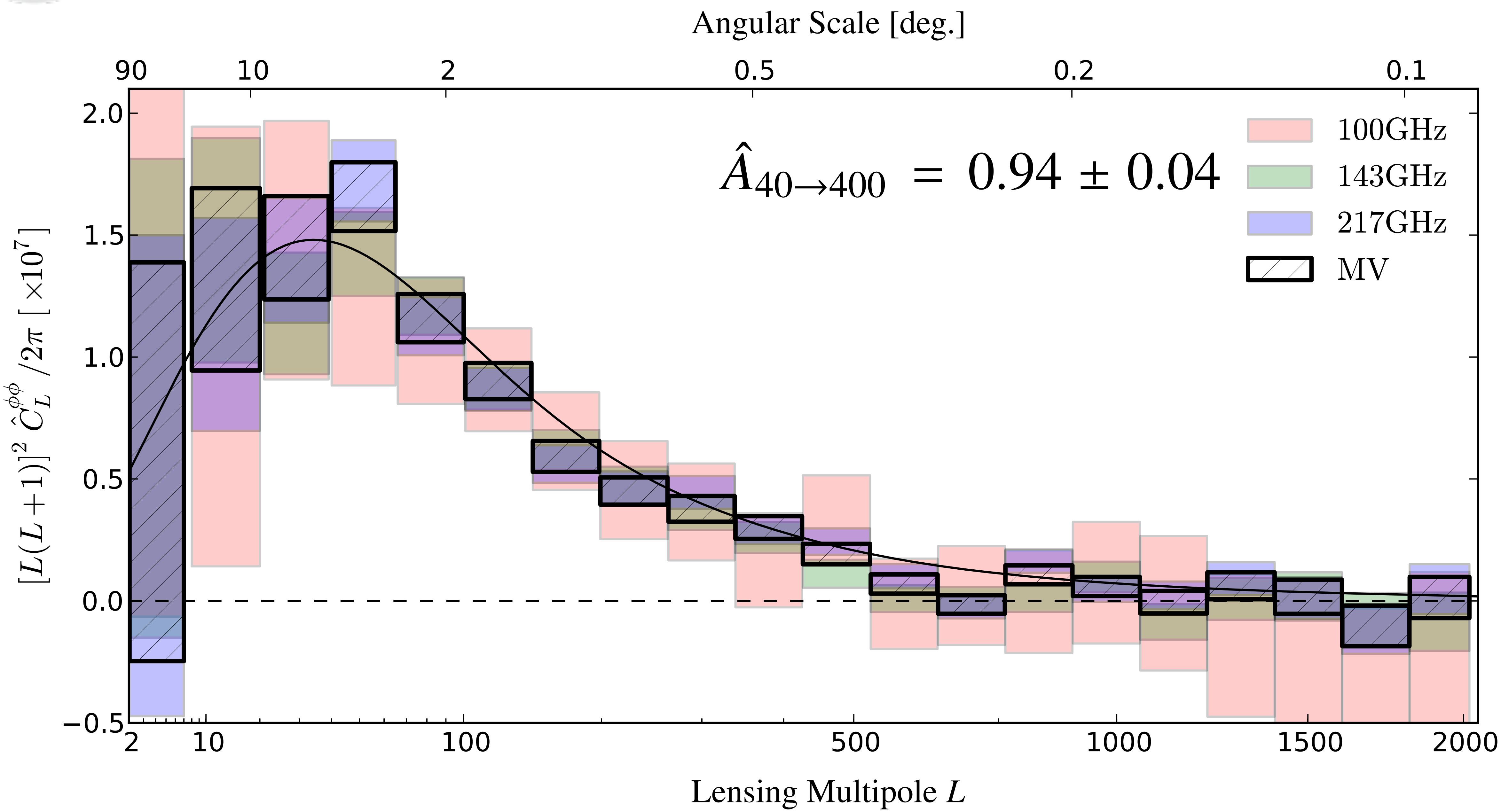
- Minimun-variance combination of 143GHz & 217 GHz





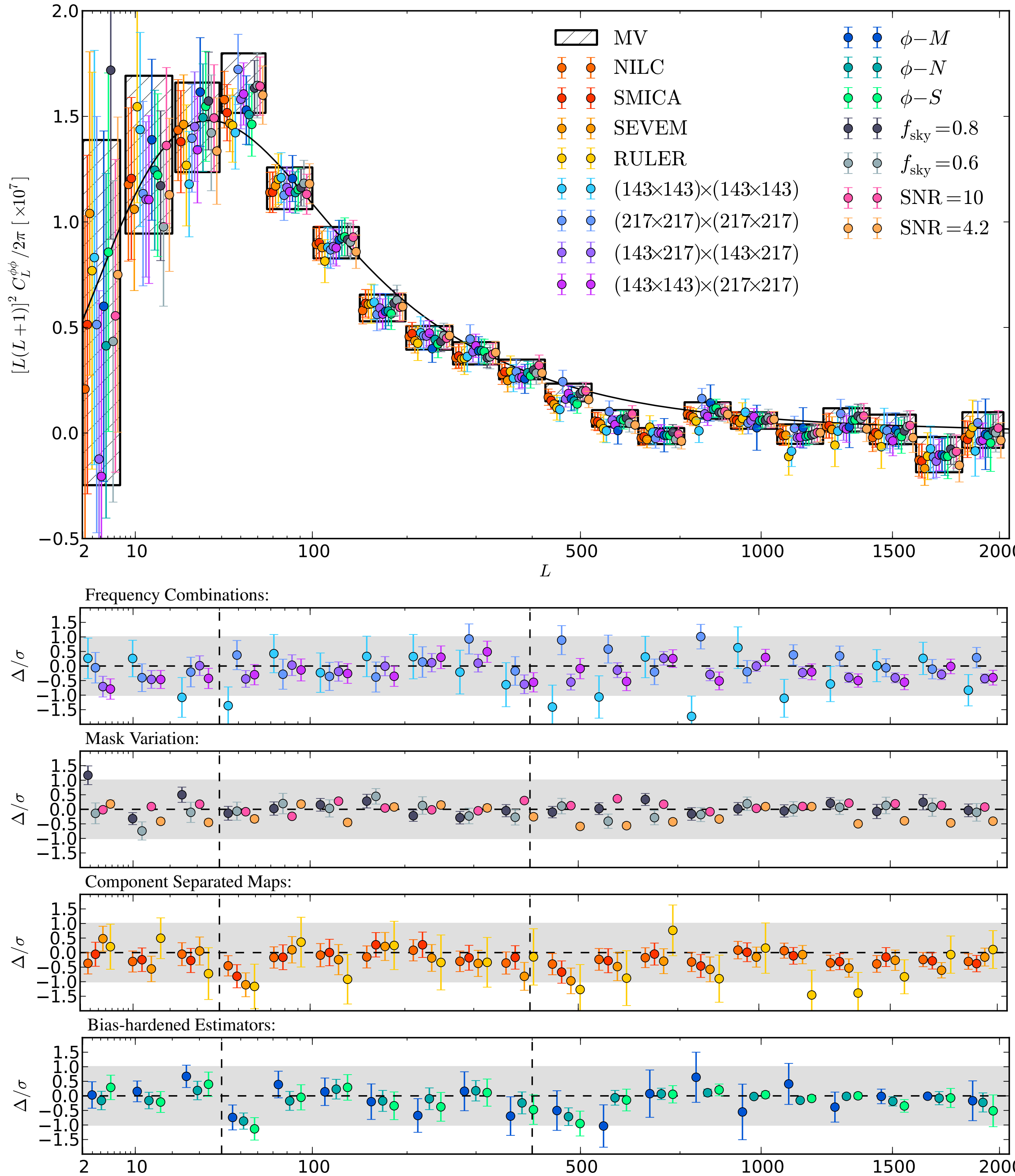
- 857 GHz map used as a template for dust cleaning
- 30 % Galactic mask +CO+ point sources
- 5º apodization (for lensing power spectrum estimation)

Best reconstruction

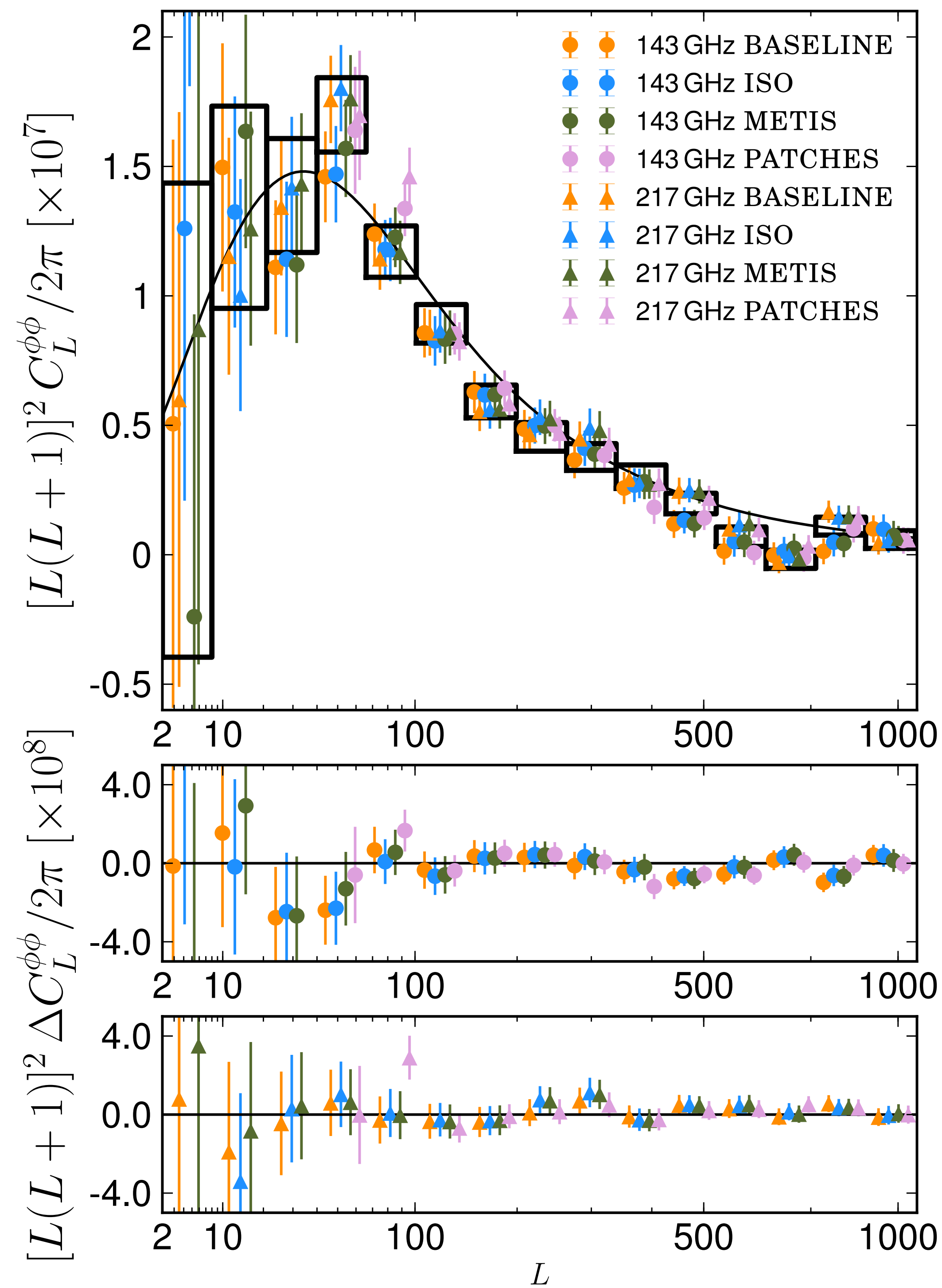


Tests

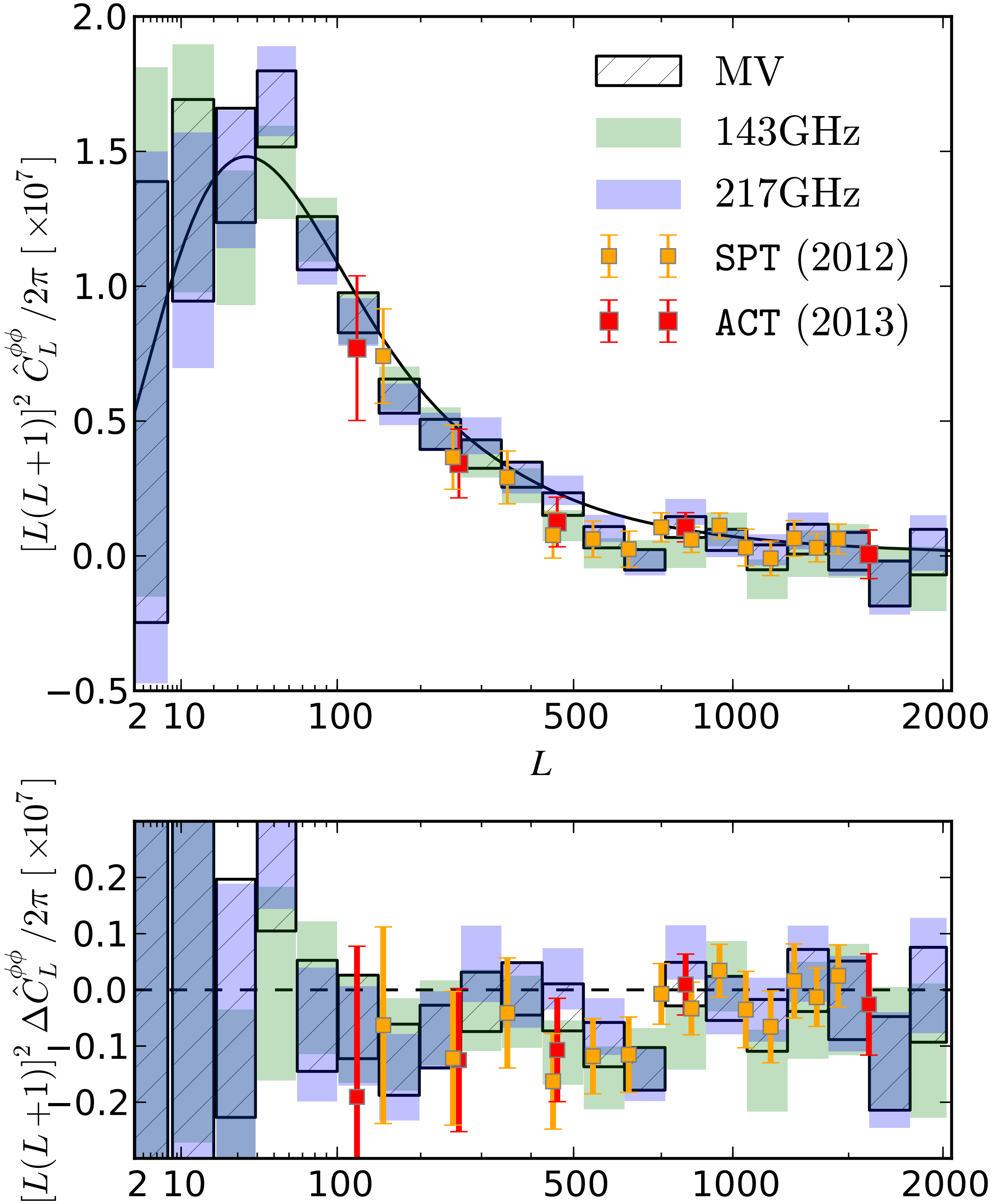
Testing foreground contamination



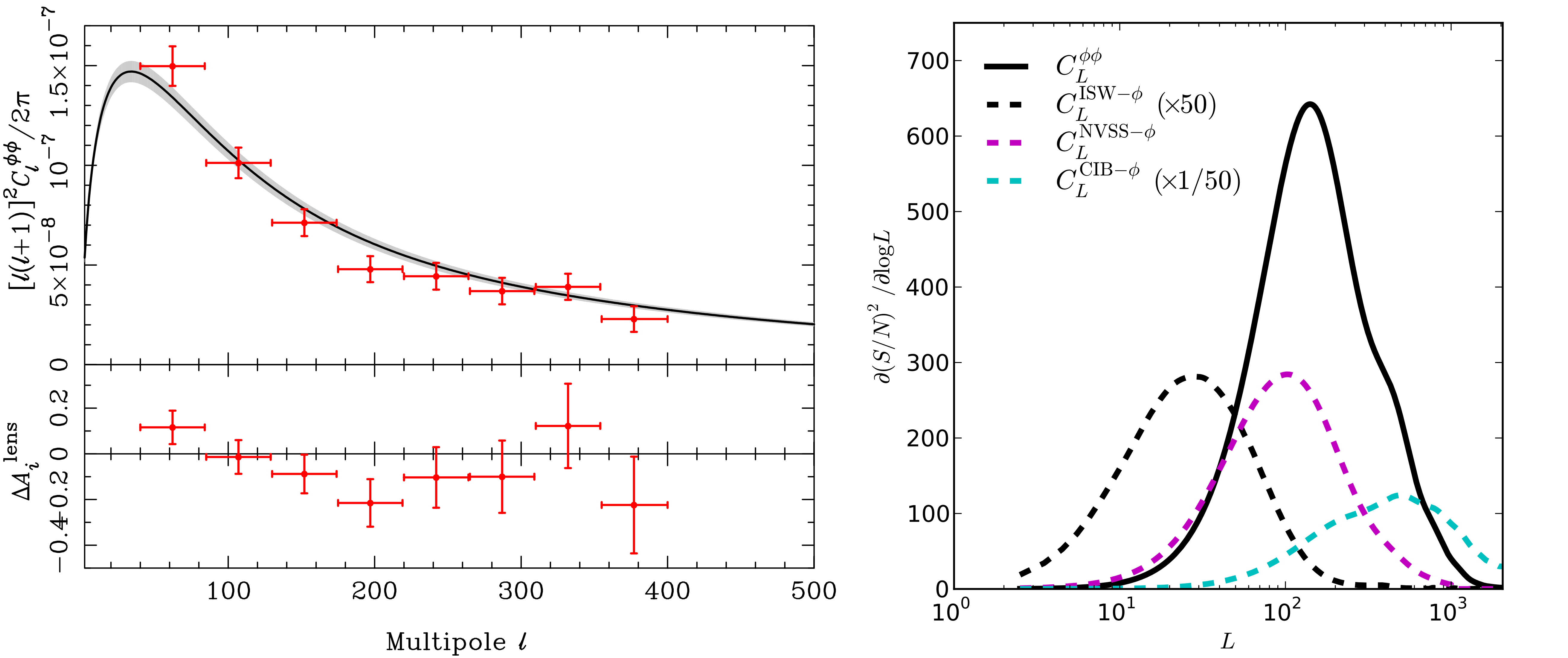
Testing the filter & implementation



Comparison to other surveys

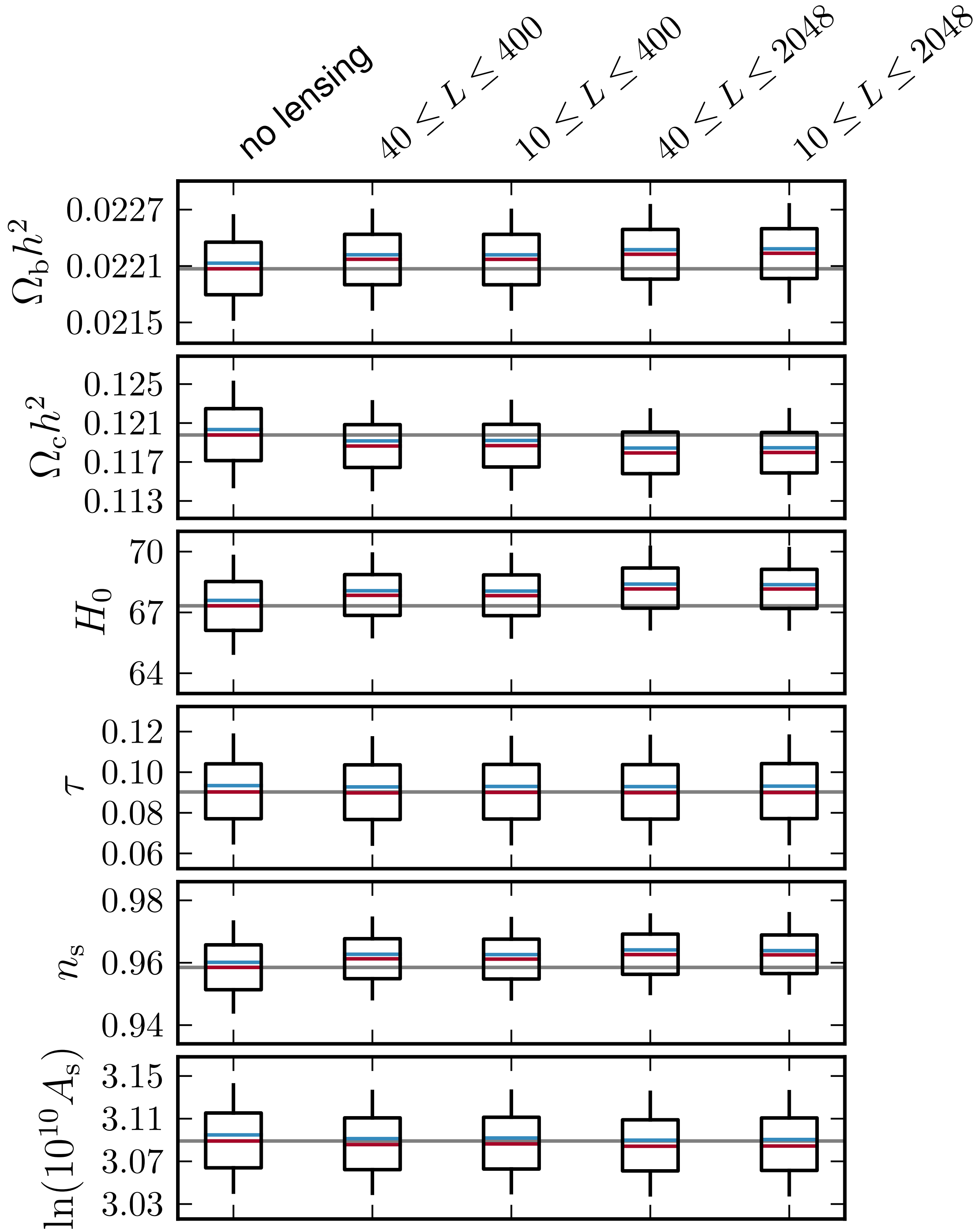


Cosmology



$[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
$\Delta A_i^{\rm lens}$
Multipole ℓ
$C_L^{\phi\phi}$
$C_L^{\rm ISW-\phi}$ (×50)
$C_L^{\rm NVSS-\phi}$
$C_L^{\rm CIB-\phi}$ (×1/50)
$\partial(S/N)^2/\partial \log L$
L

Cosmology

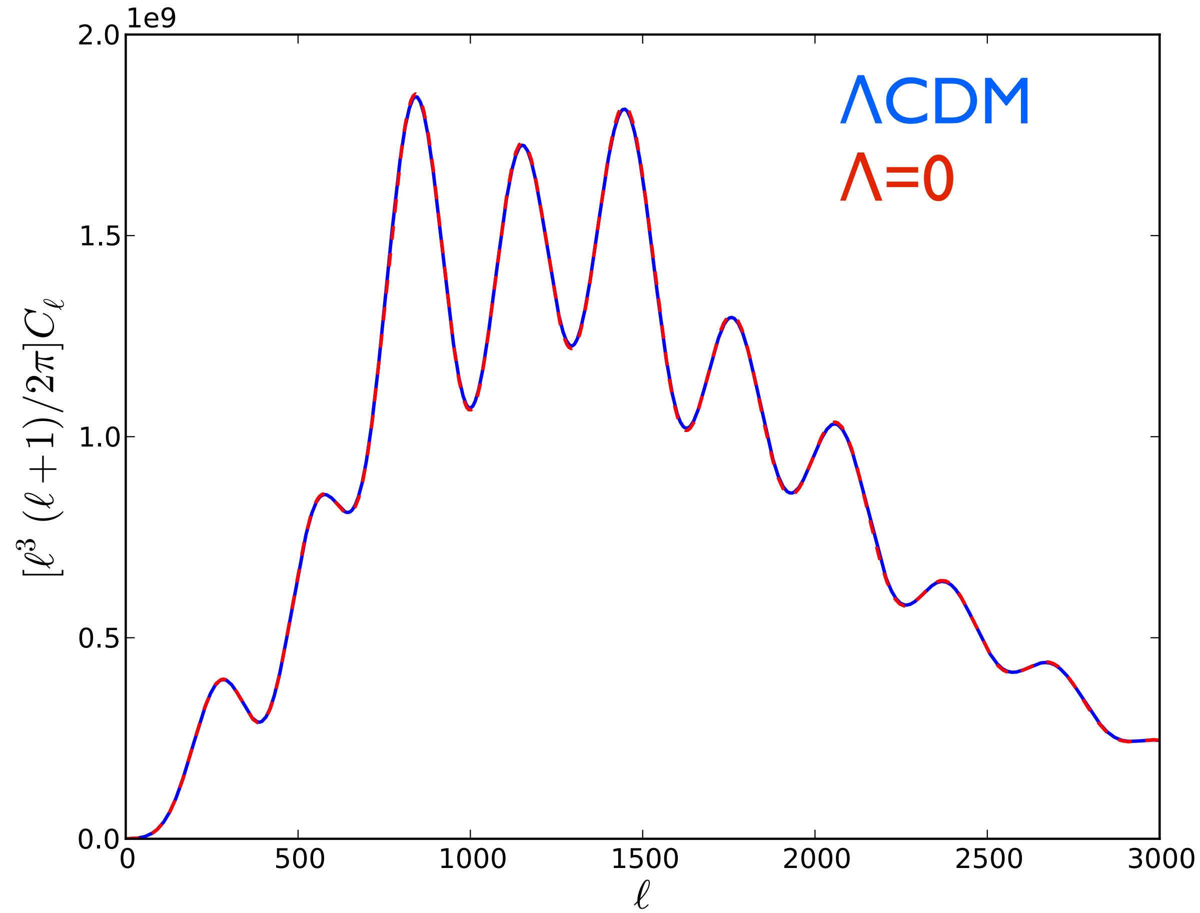


Adding lensing reconstruction brings ~20% improvement on some paramaters

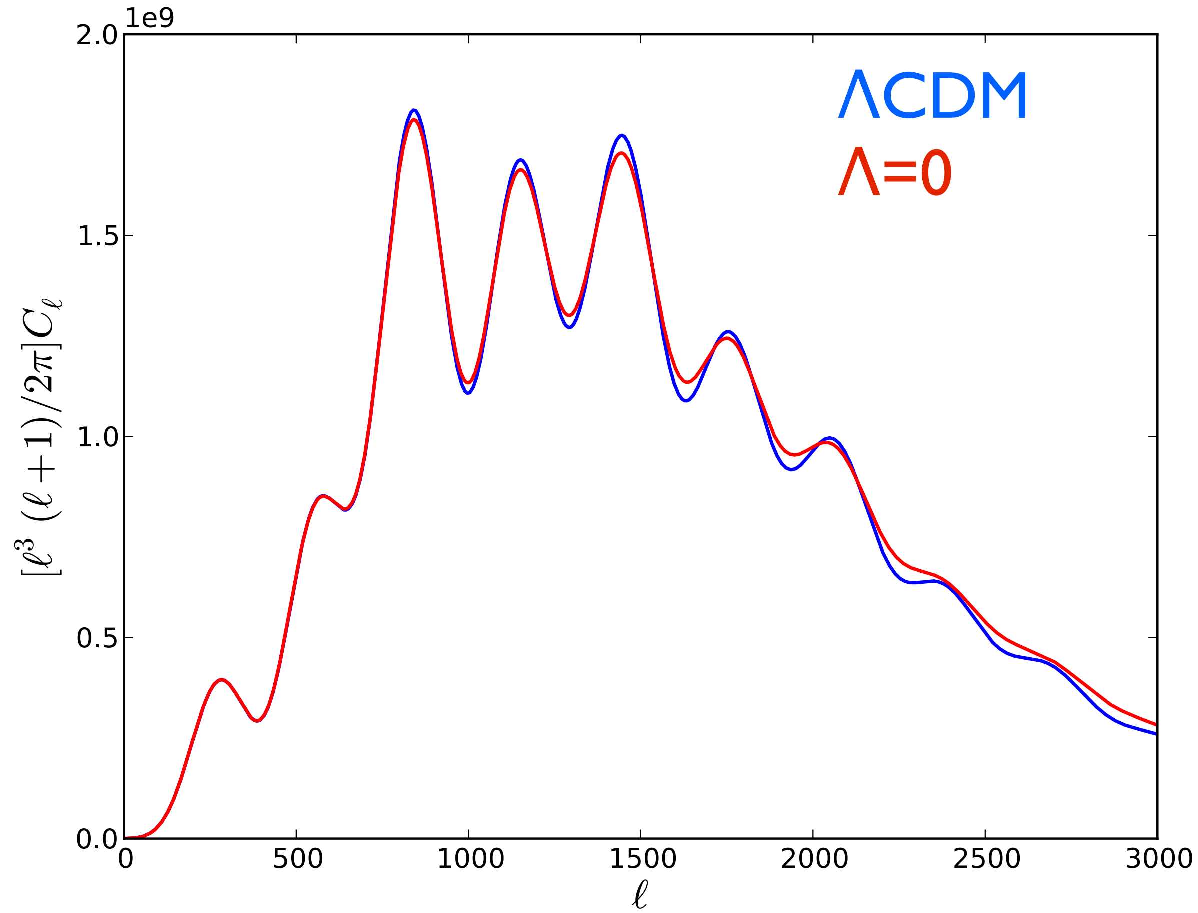
Adding low-L and high-L lensing information does not improve precision but slighly shift central values

Cosmology

- CMB lensing break the angular diameter degeneracy



Unlensed TT



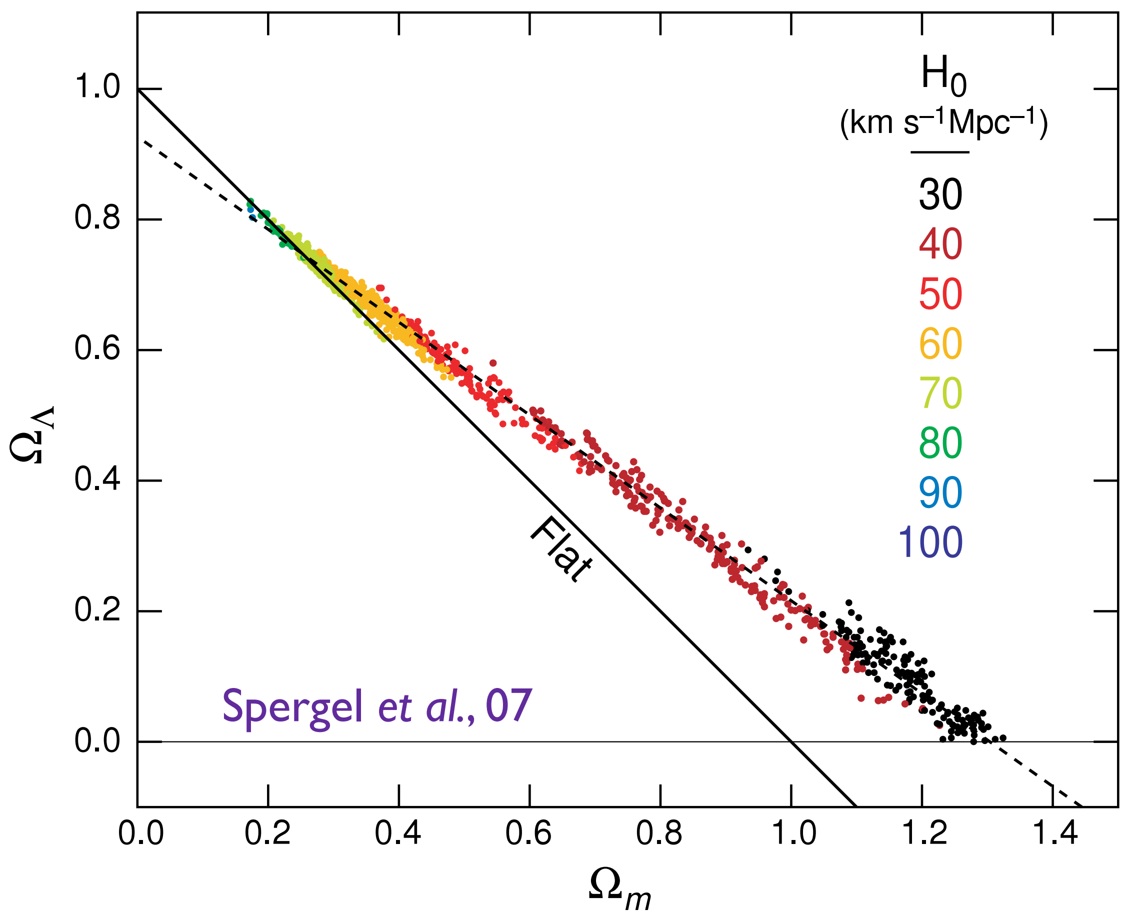
Lensed TT

See also Sherwin *et al.*, 11 (ACT)

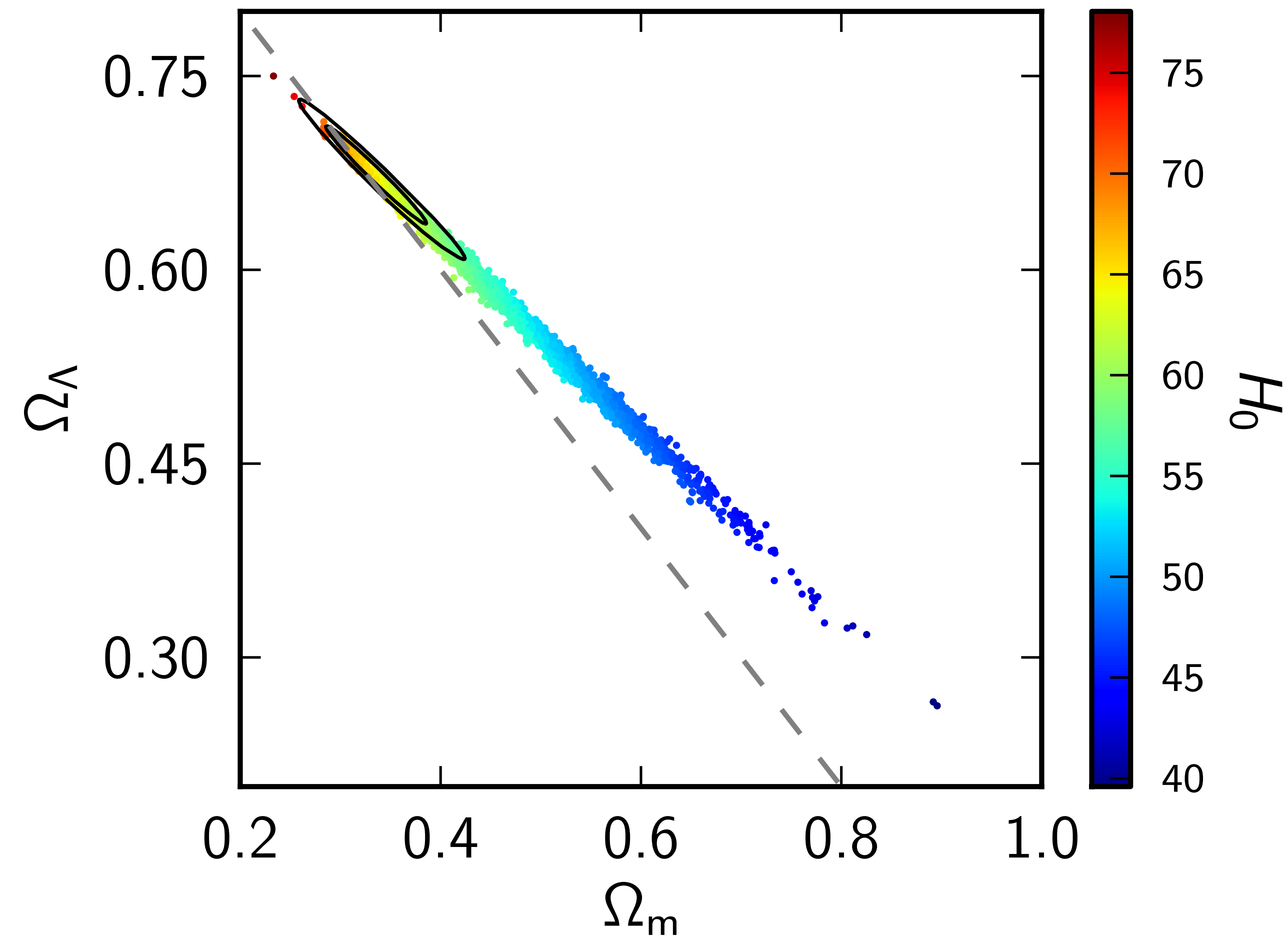
Cosmology

- CMB lensing break the angular diameter degeneracy

WMAP3

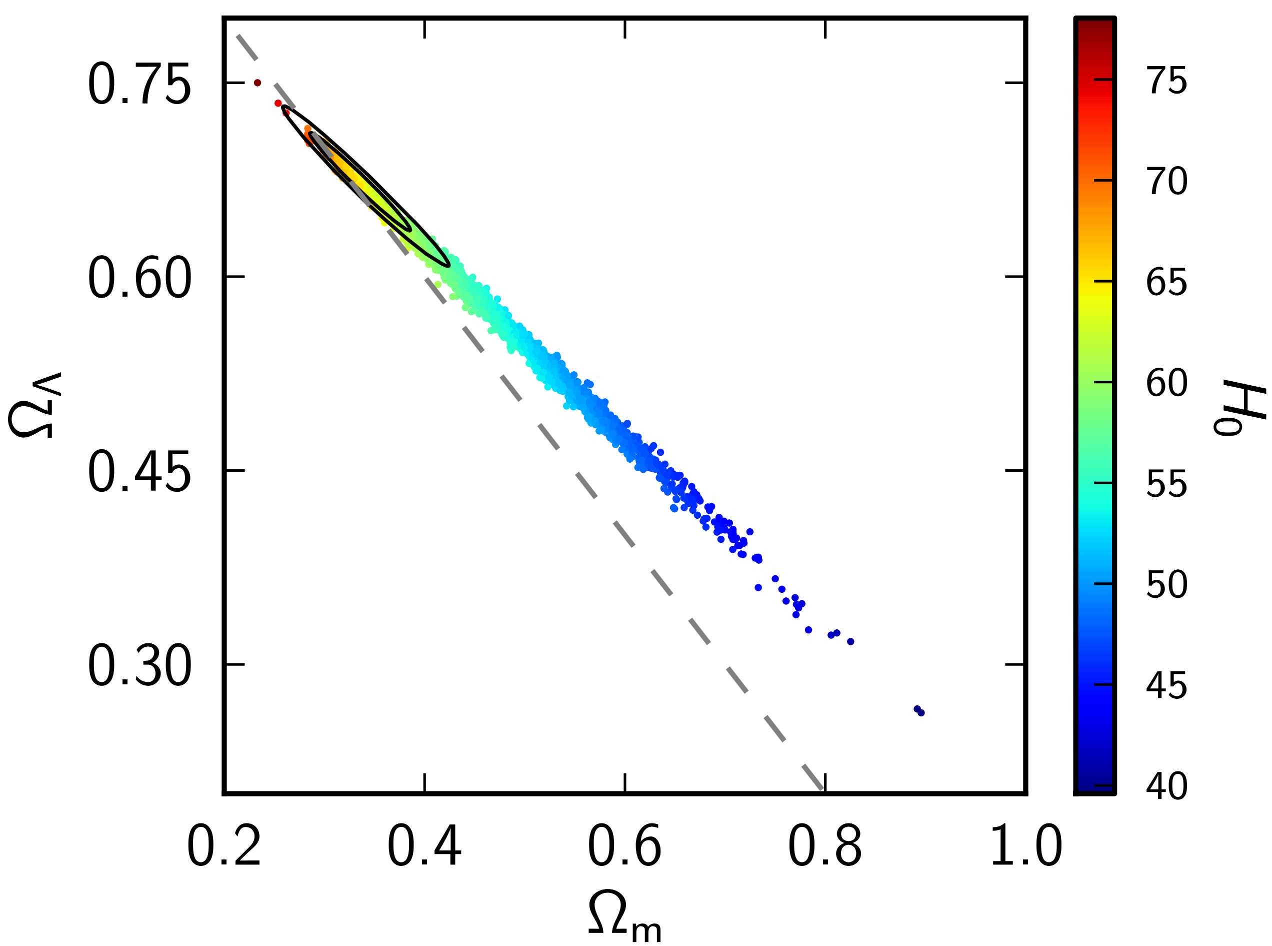


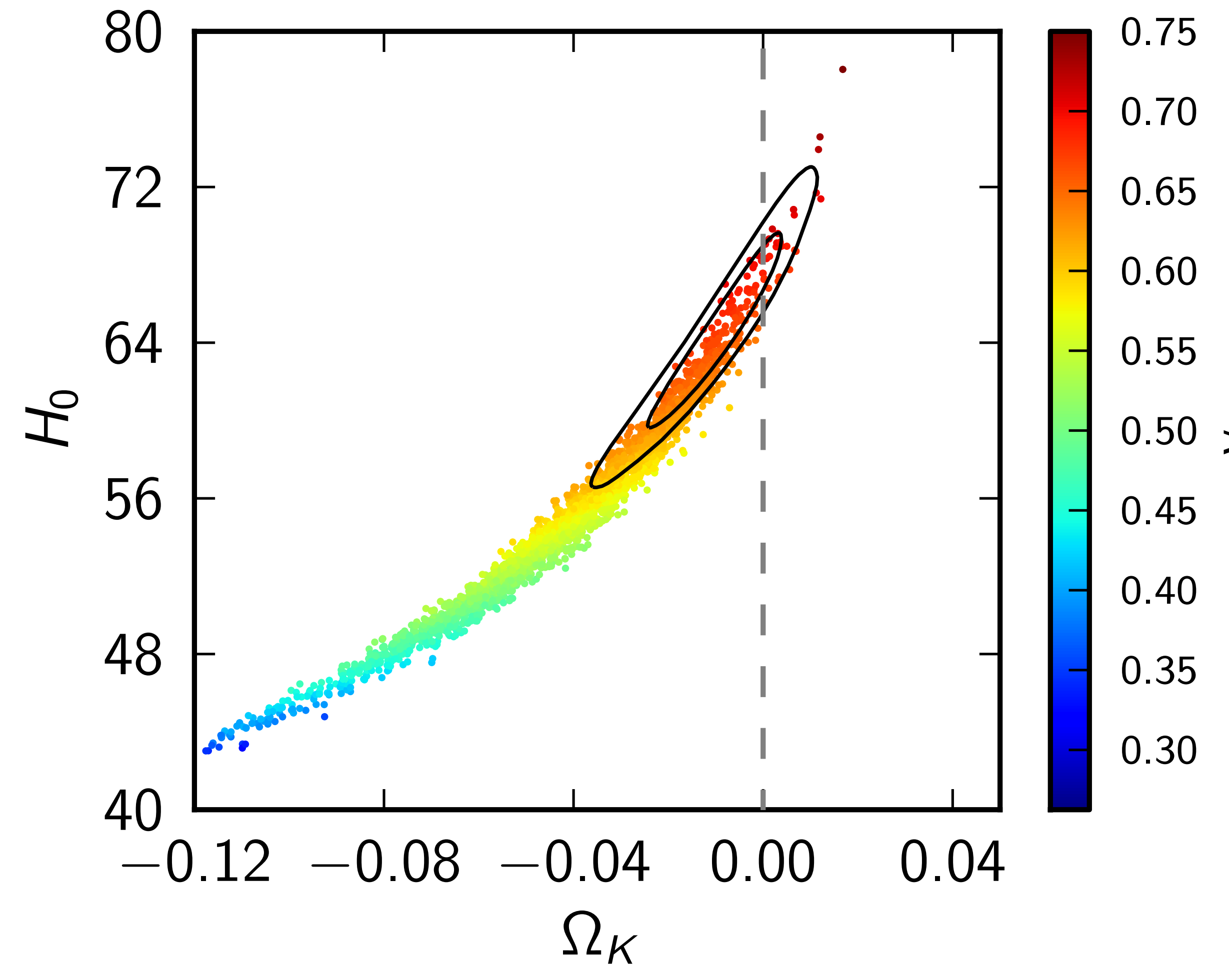
Planck 2013



Cosmology

- CMB lensing break the angular diameter degeneracy





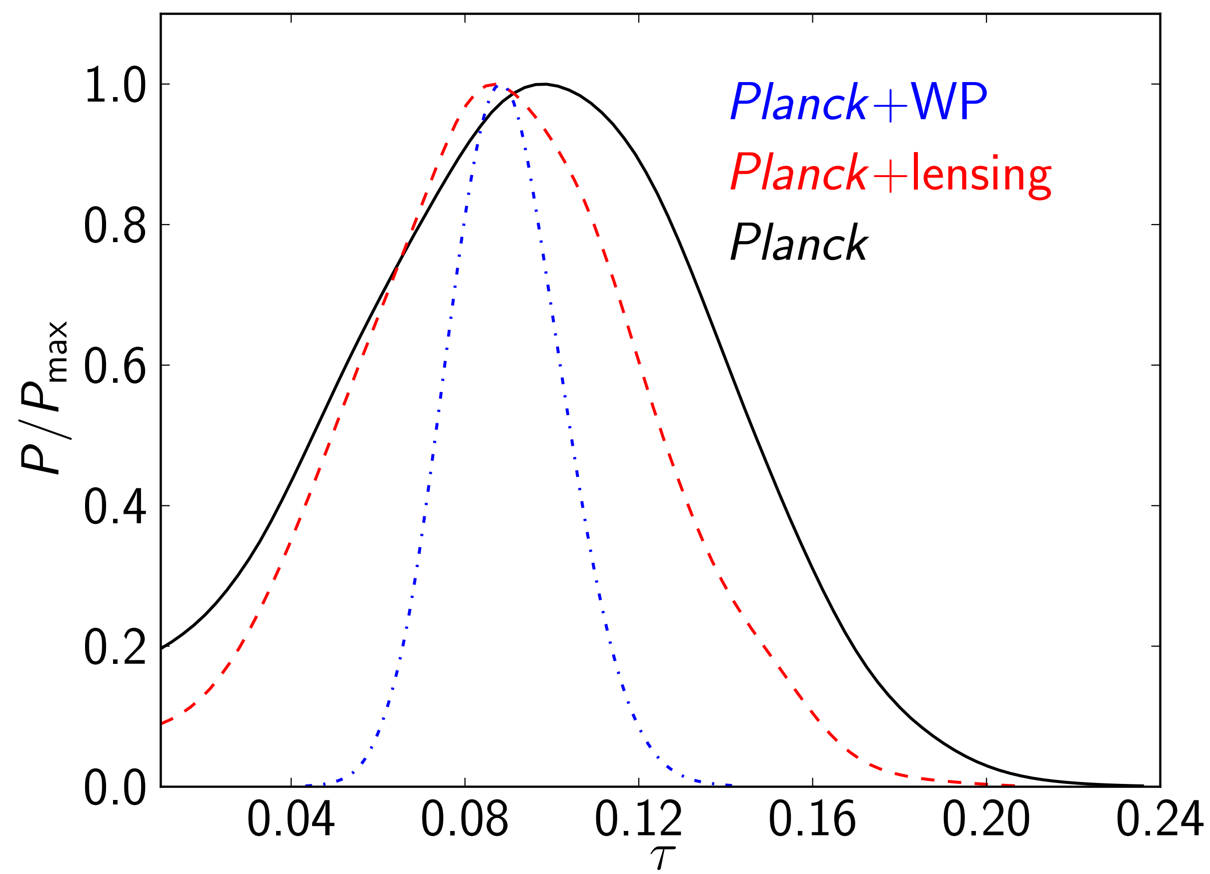
$$\Omega_\Lambda = 0.57^{+0.073}_{-0.055} \quad \text{(68\%; \textit{Planck}+WP+highL)}$$
$$\Omega_\Lambda = 0.67^{+0.027}_{-0.023} \quad \text{(68\%; \textit{Planck}+lensing+WP+highL).}$$

$$100\Omega_K = -4.2^{+4.3}_{-4.8} \quad \text{(95\%; \textit{Planck}+WP+highL);}$$
$$100\Omega_K = -1.0^{+1.8}_{-1.9} \quad \text{(95\%; \textit{Planck}+lensing + WP+highL).}$$

Cosmology

- Reionization

Optical depth - Amplitude degenerascy $A_s e^{-2\tau}$

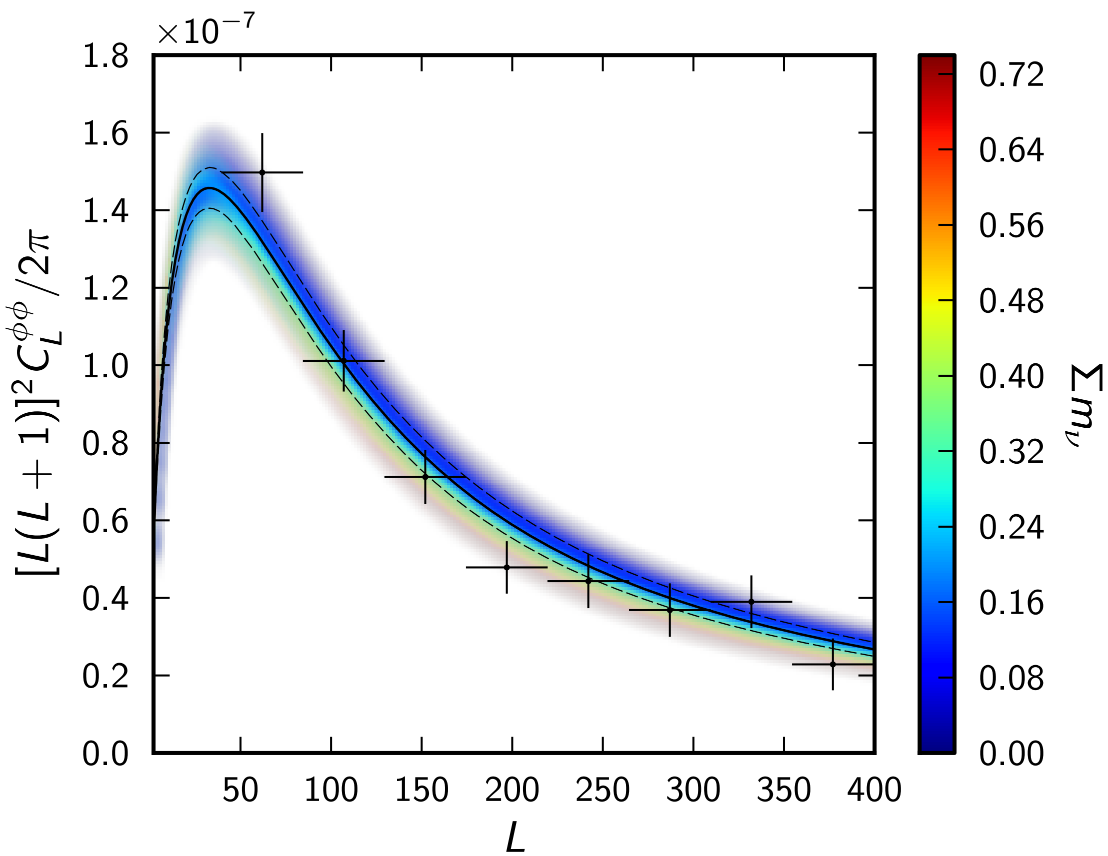


$$\tau = 0.097 \pm 0.038 \quad (68\%; \textit{Planck})$$
$$\tau = 0.089 \pm 0.032 \quad (68\%; \textit{Planck}\text{+lensing}).$$

Cosmology

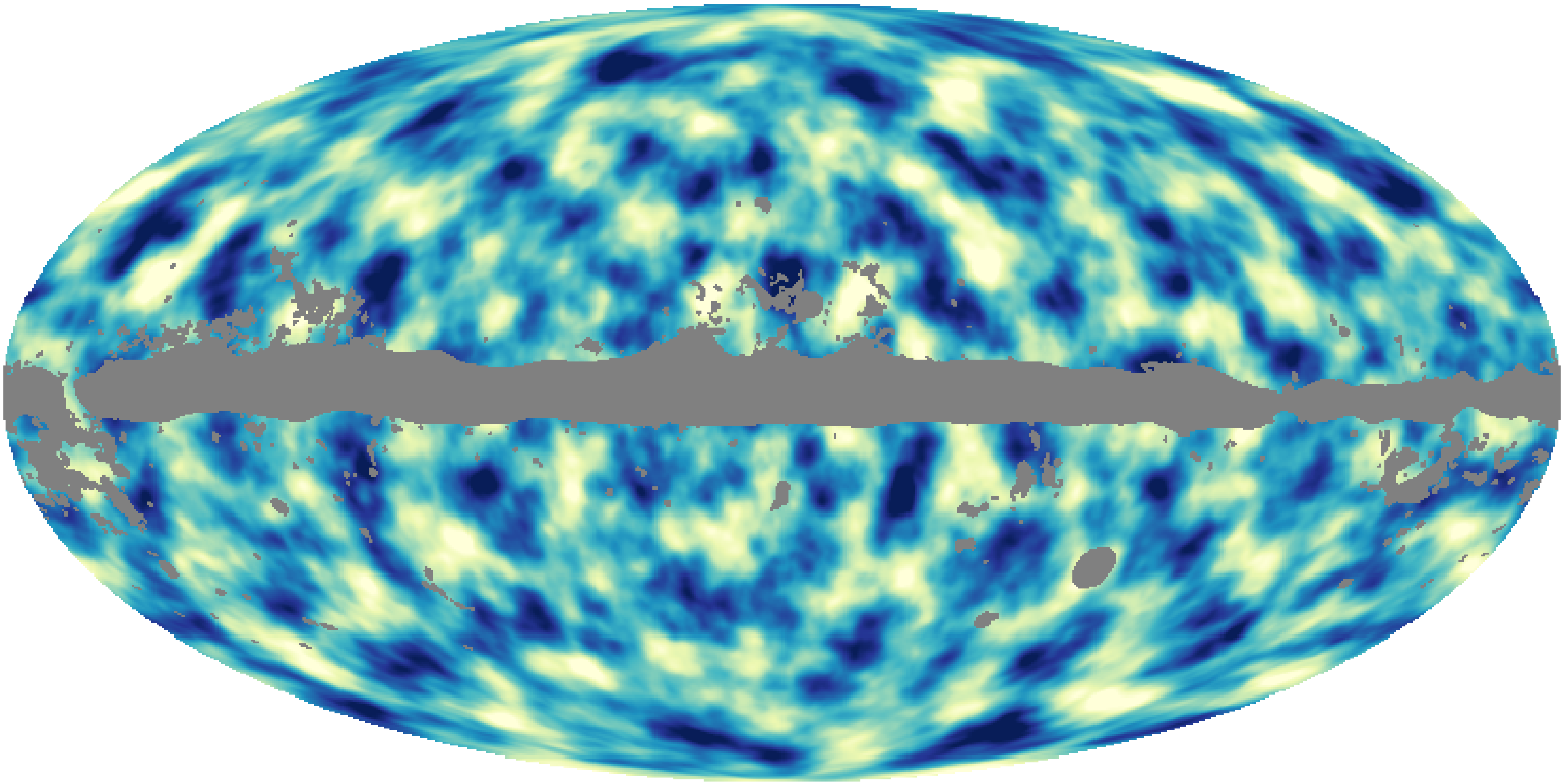
- Sum of neutrinos masses

- Mild tension : constraint weaker than expected!
- Temperature power spectra: more lensing = smaller mass
- Reconstruction: less lensing = larger mass



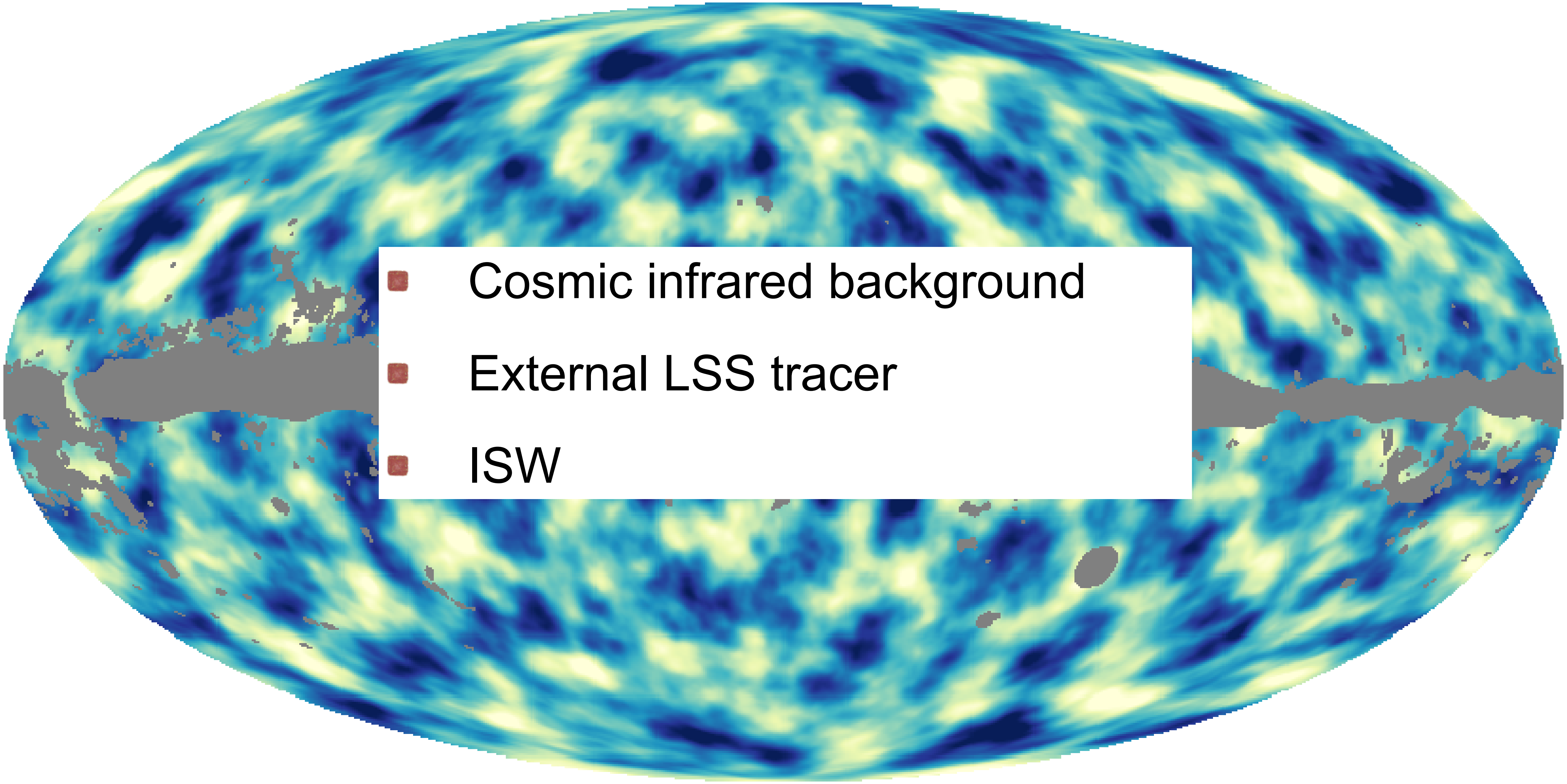
$$\sum m_\nu < 0.66\,\mathrm{eV}, \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}),$$
$$\sum m_\nu < 0.85\,\mathrm{eV}, \quad (95\%;\ \textit{Planck}+\mathrm{lensing}+\mathrm{WP}+\mathrm{highL}),$$

Cross-correlations



The lensing map traces the matter distribution up to the last scattering surface

Cross-correlations

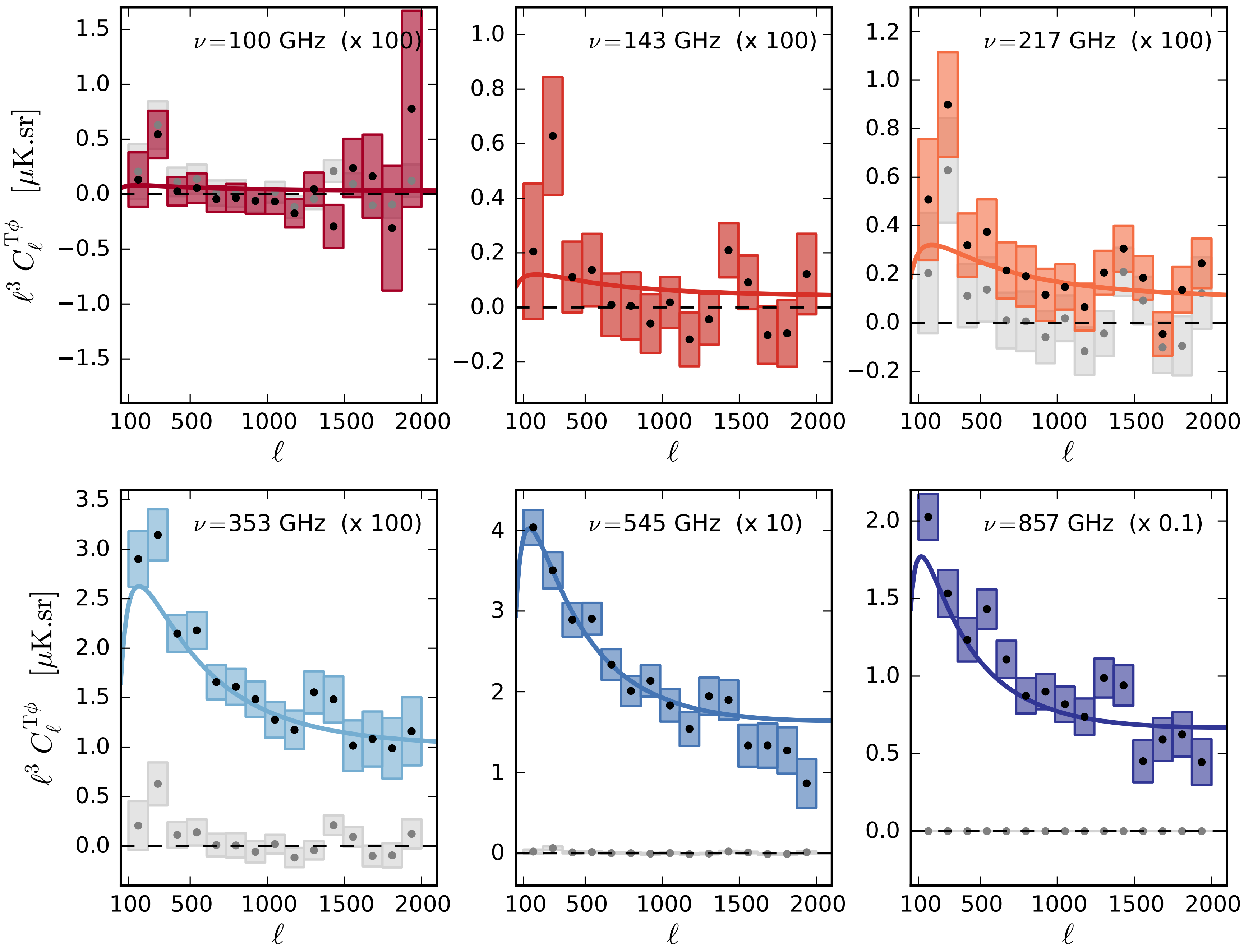


- Cosmic infrared background
- External LSS tracer
- ISW

The lensing map traces the matter distribution up to the last scattering surface

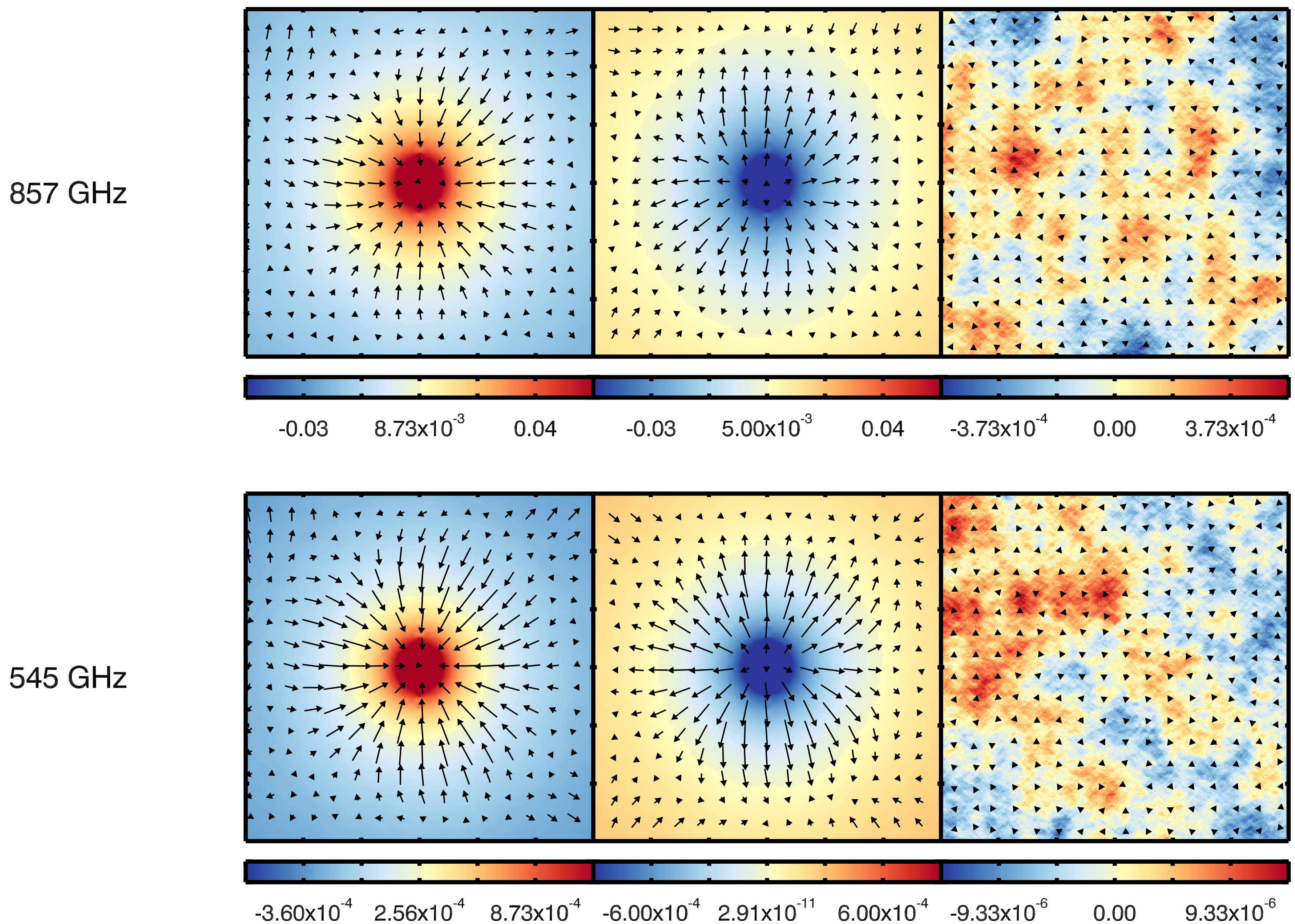
CMB lensing - CIB

- Lensing potential correlated with HFI temperature maps



CMB lensing - CIB

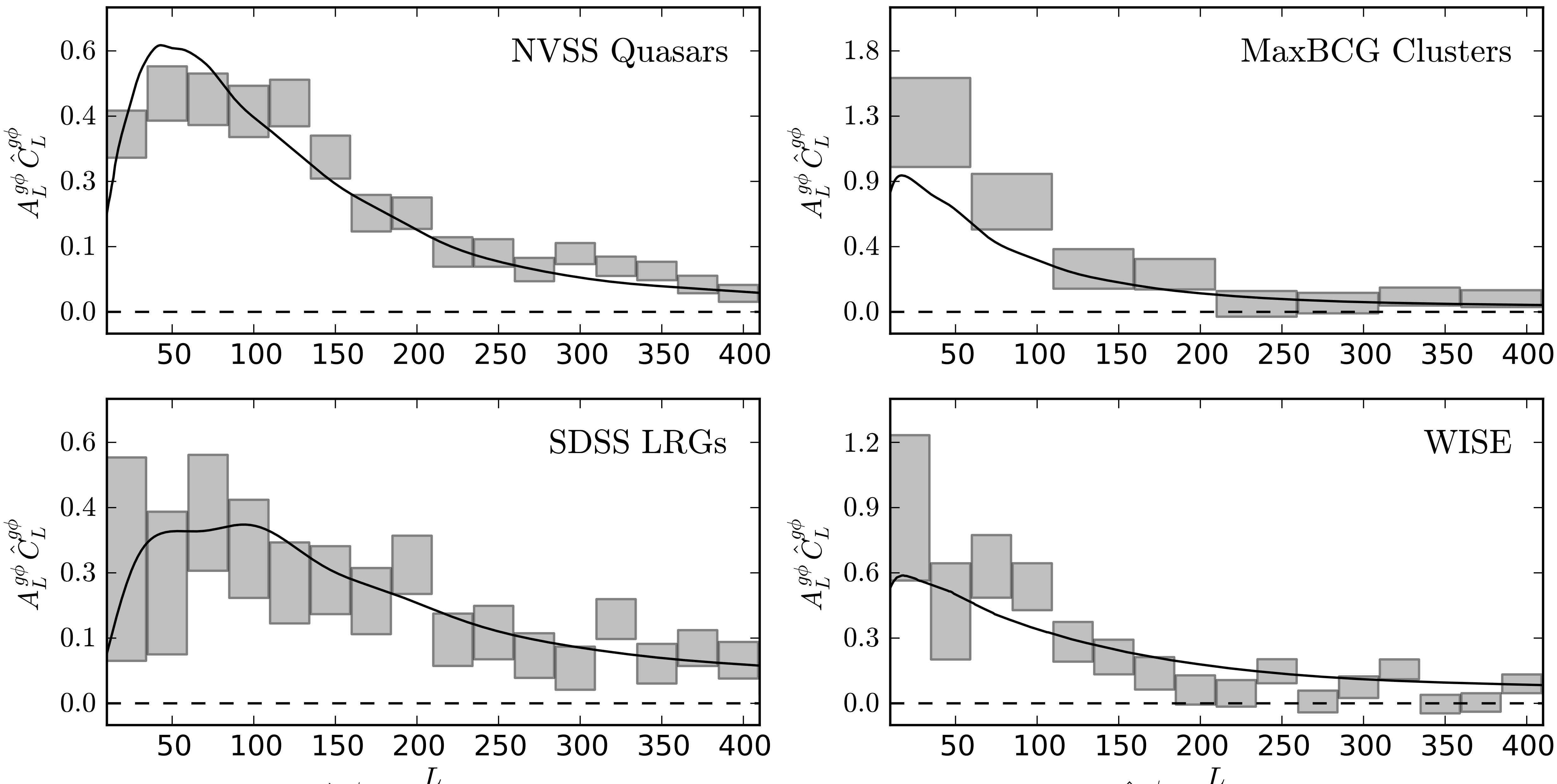
- Deflection stacked on 20.000 temperature extrema



CMB lensing - External tracers

$b(z) = 1.7 \rightarrow \hat{A}^{g\phi}_{\mathrm{NVSS}} = 1.03 \pm 0.05$ ($\approx 20\sigma$)

$b(z) = 3 \rightarrow \hat{A}^{g\phi}_{\mathrm{MaxBCG}} = 1.54 \pm 0.21$ ($\approx 7\sigma$)

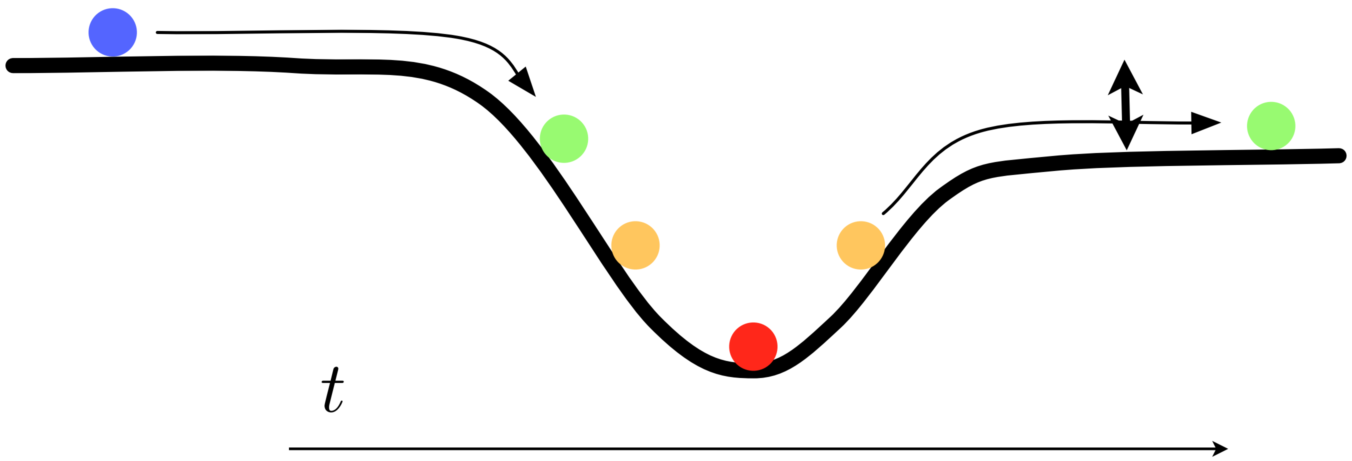


$b(z) = 2 \rightarrow \hat{A}^{g\phi}_{\mathrm{LRGs}} = 0.96 \pm 0.10$ ($\approx 10\sigma$)

$b(z) = 1 \rightarrow \hat{A}^{g\phi}_{\mathrm{WISE}} = 0.97 \pm 0.13$ ($\approx 7\sigma$)

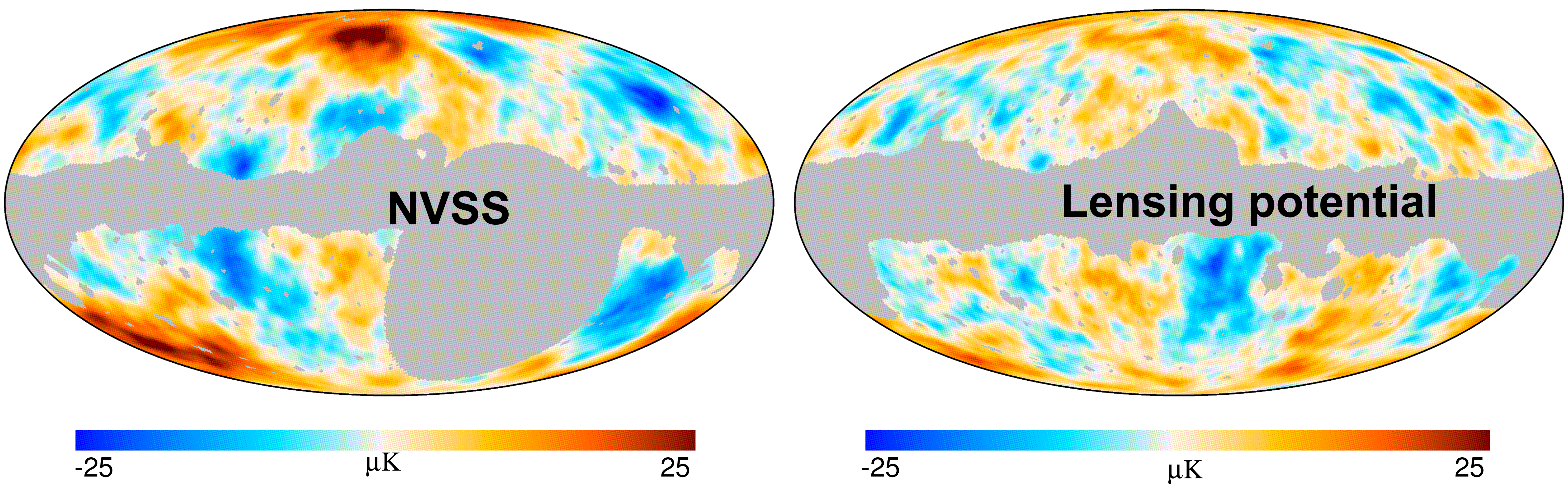
ISW

Shallowing of the potential due to expansion driven by dark energy



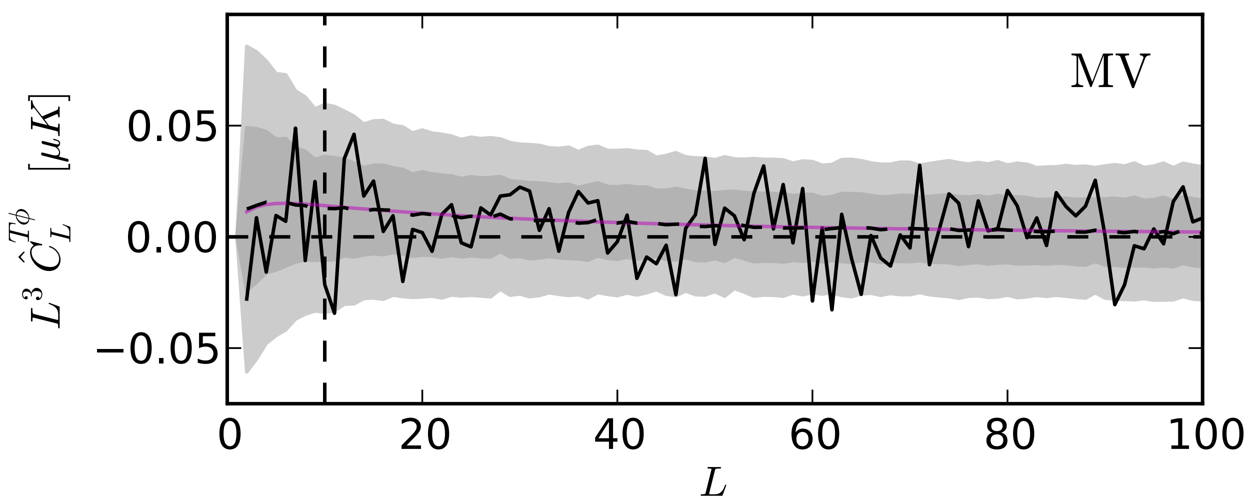
$$\frac{\Delta T}{T} = \frac{2}{c^3} \int_{\eta^*}^{\eta_0} \mathrm{d}\eta \frac{\partial \Phi}{\partial \eta}$$

Courtesy: K. Benabed



Planck ISW maps

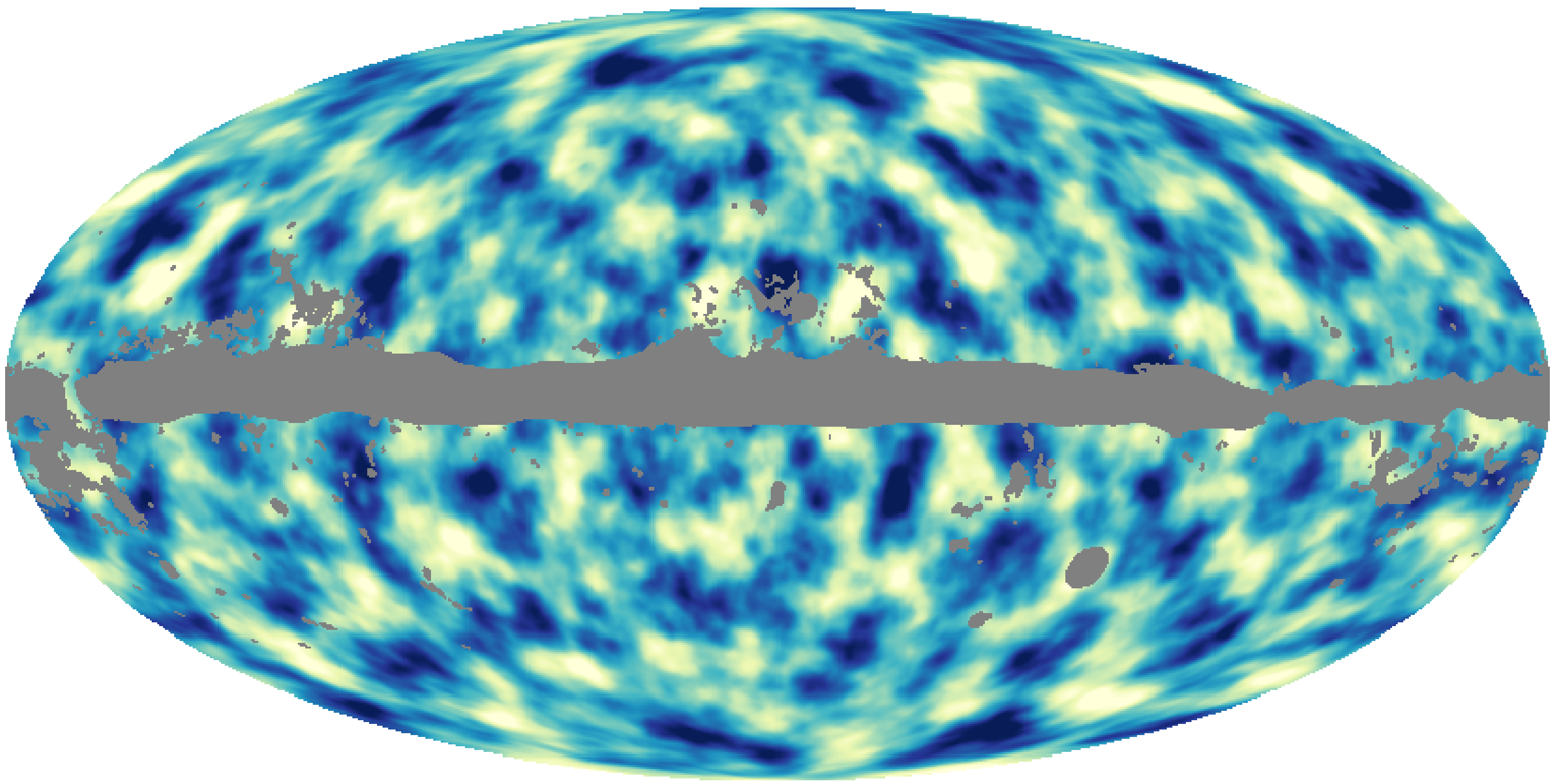
ISW - Lensing correlation



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 2.5sigma detection. Robust againt dataset and estimator**
- **Links Λ and CDM**

The Planck lensing map



- (Almost) Full-sky map of the large scale structure at z~2
- Will be used for the next 10-20 years (DES, Euclid, LSST, ...)
- Available on the PLA