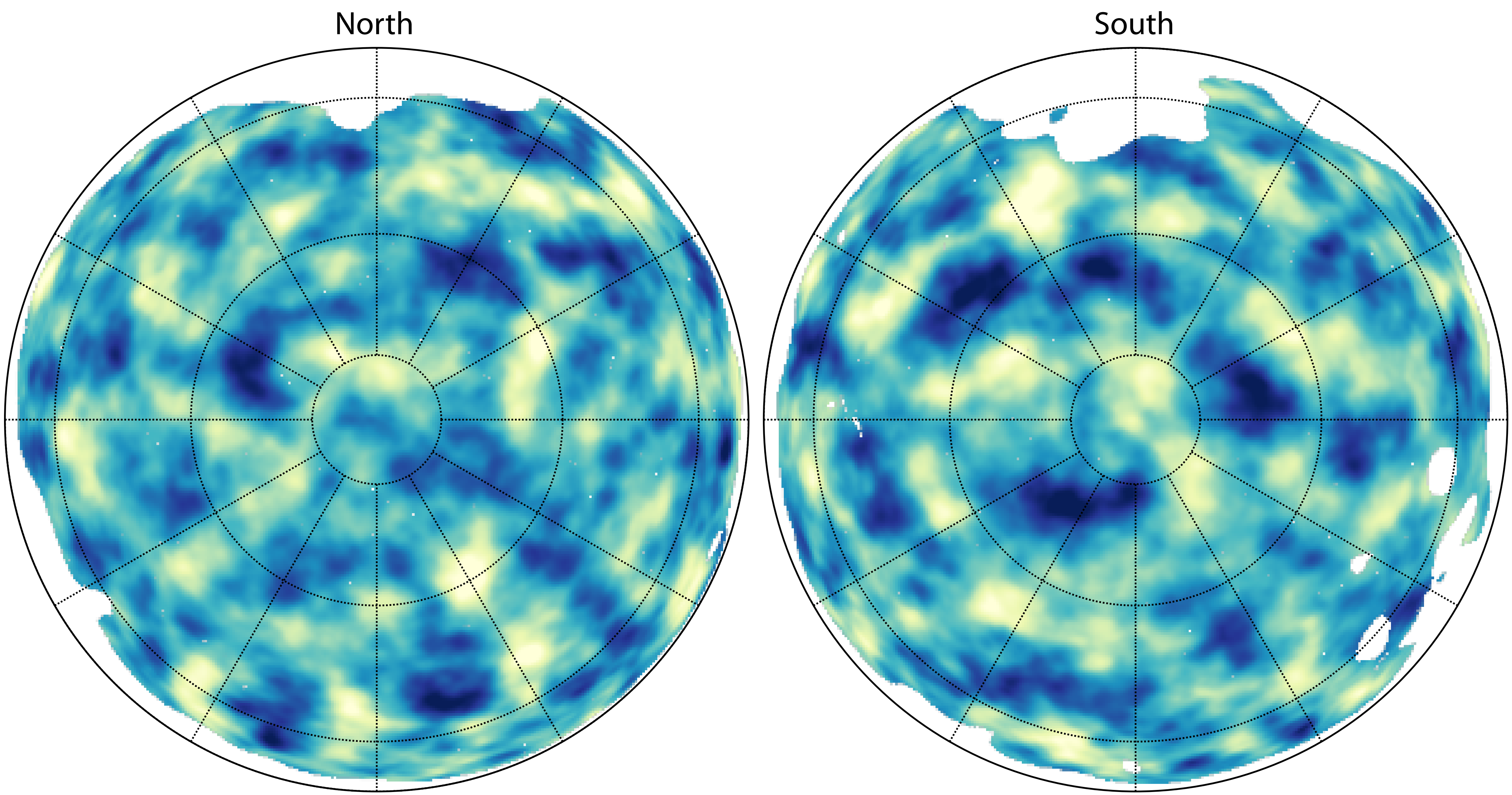
CMB Lensing & ISW

K. Benabed
Institut d'Astrophysique de Paris - UPMC
On behalf of the Planck Collaboration

XVII. Gravitational lensing by large scale structures
XIX. The integrated Sachs-Wolfe effect

Planck map of the large scale structures



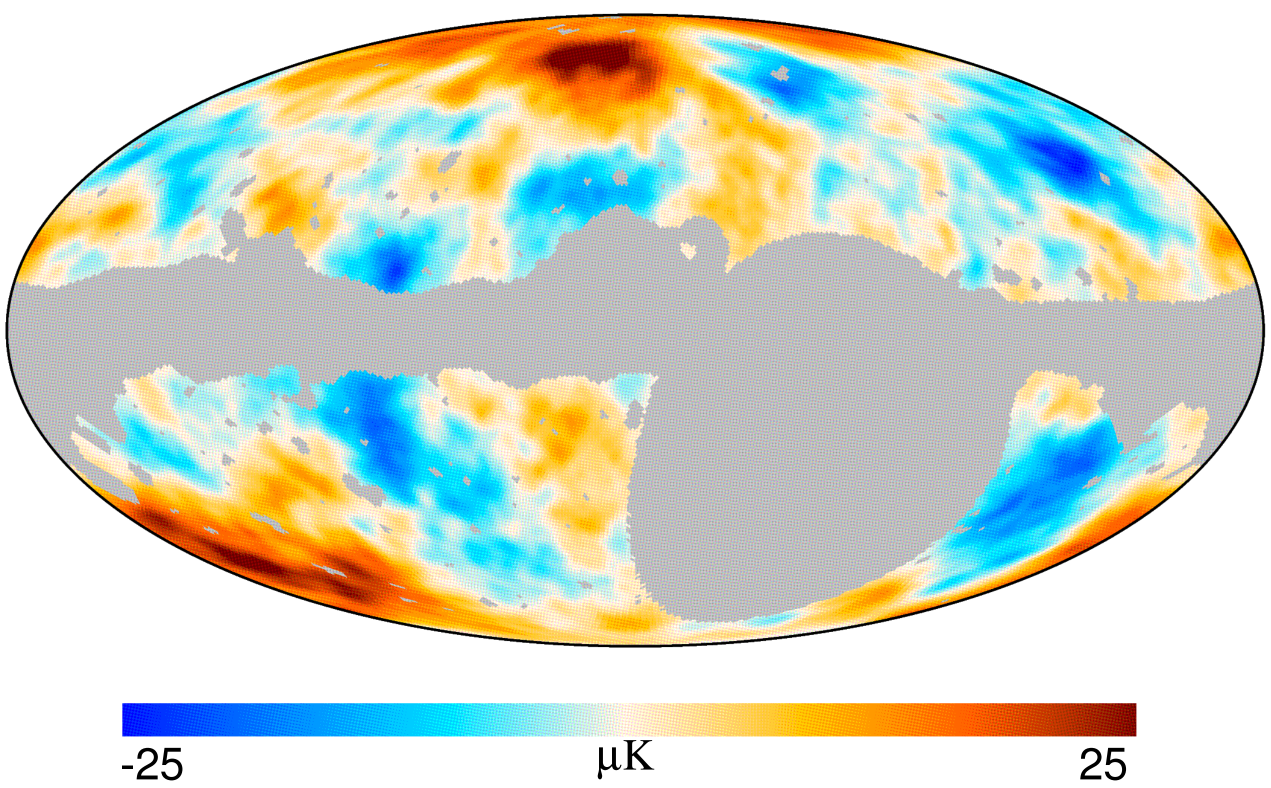
According to our reconstruction of the lensing effect

25sigma detection

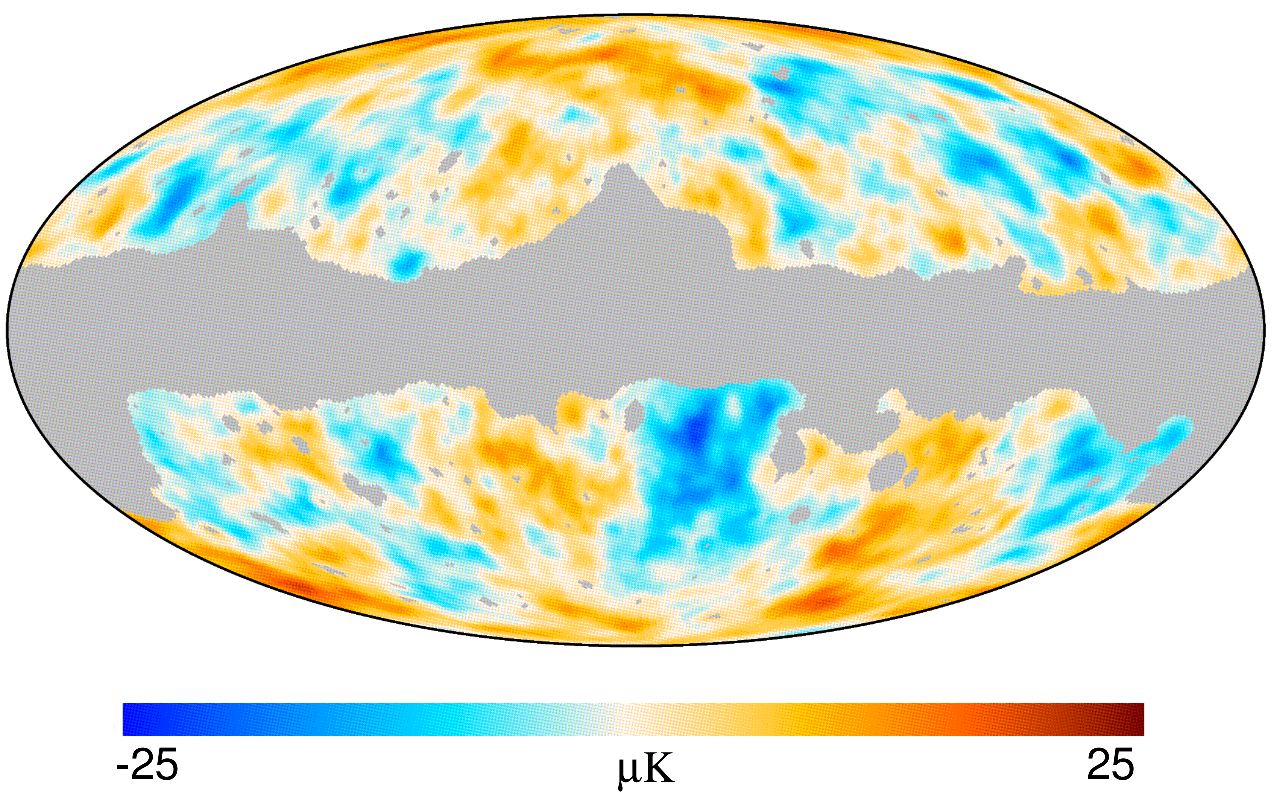
Almost full sky map of LSS at z~2

Planck map of the large scale structures

Using cross-correlation with the NVSS survey



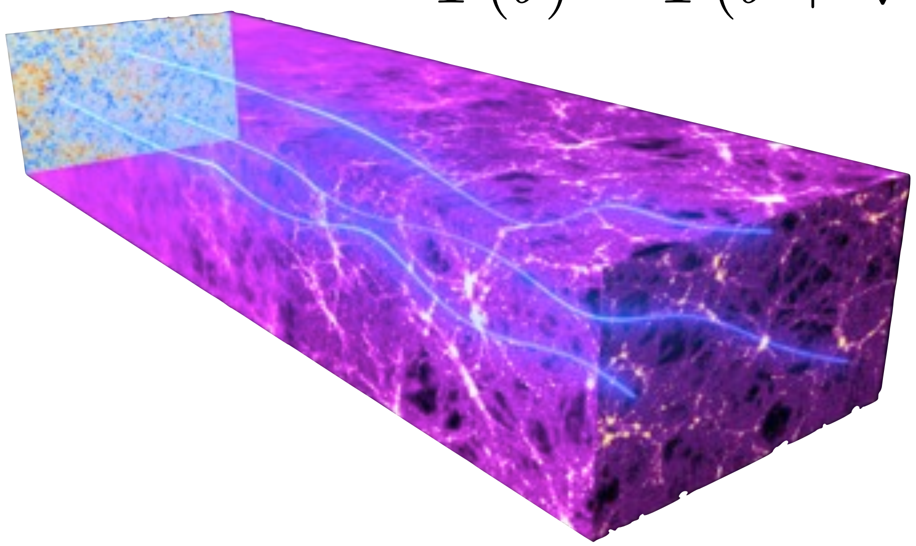
Using cross-correlation with CMB lensing

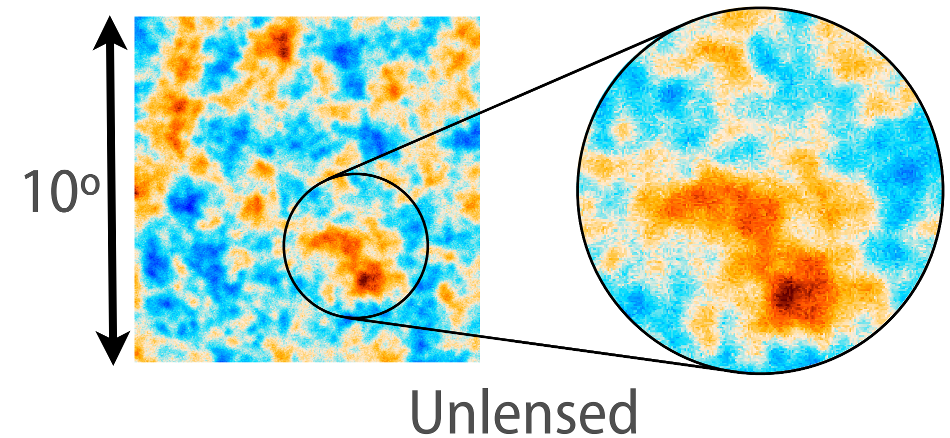


According to our reconstruction of the ISW effect
2.5sigma detection

CMB lensing reconstruction

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





CMB lensing reconstruction

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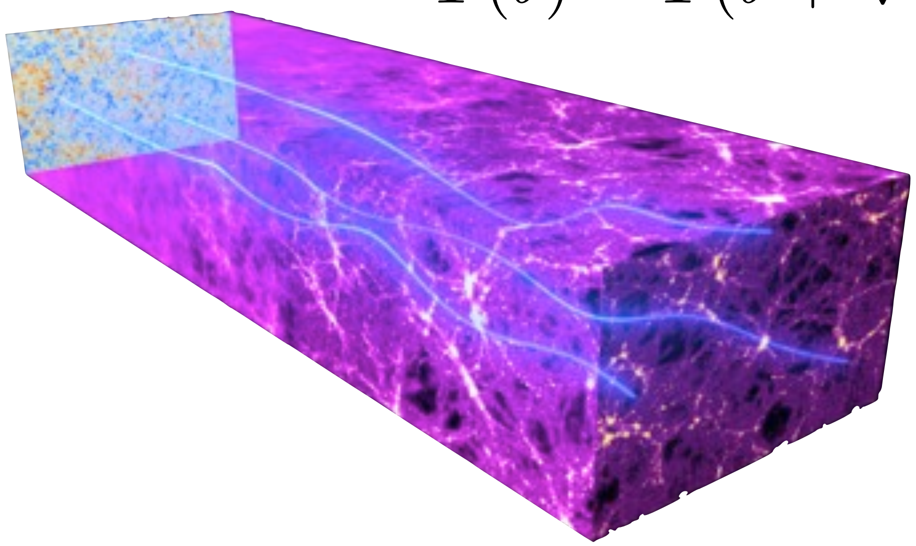

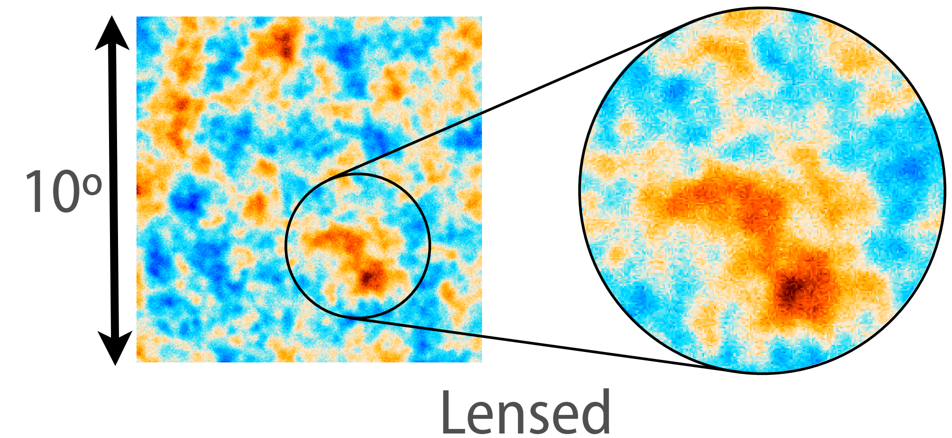

CMB lensing reconstruction

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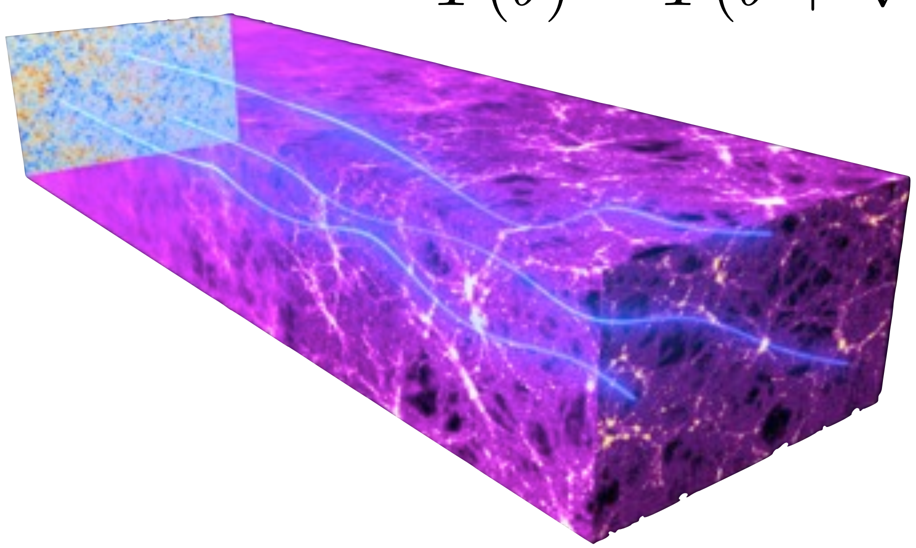
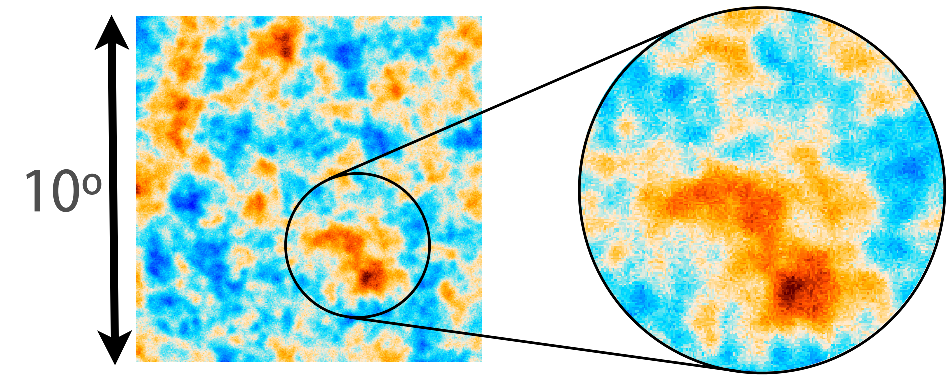




A quadratic estimator to measure the specific NG signature.

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

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

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

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

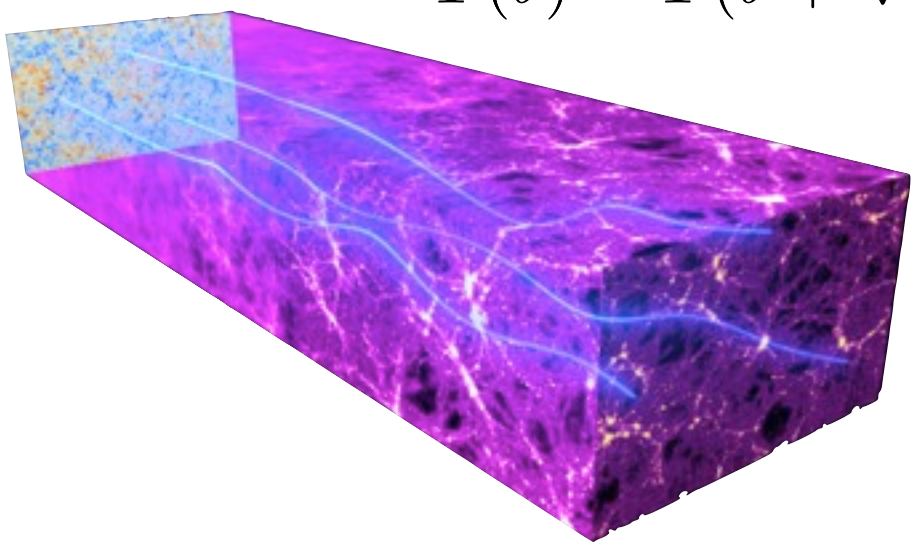
$$\bar{x}_{LM} = \frac{1}{2} \sum_{\ell_1 m_1, \ell_2 m_2} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W^{x}_{\ell_1 \ell_2 L} \bar{T}^{(1)}_{\ell_1 m_1} \bar{T}^{(2)}_{\ell_2 m_2}.$$

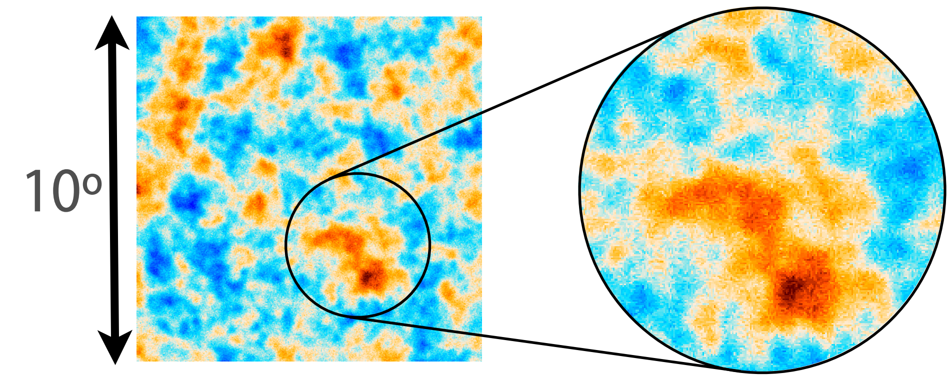
$$\bar{x}^{MF}_{LM} = \frac{1}{2} \sum_{\ell_1 m_1, \ell_2 m_2} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W^{x}_{\ell_1 \ell_2 L} \langle \bar{T}^{(1)}_{\ell_1 m_1} \bar{T}^{(2)}_{\ell_2 m_2} \rangle.$$

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

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.

$$W^{\phi}_{\ell_1\ell_2 L} = -\sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2L+1)}{4\pi}}\sqrt{L(L+1)\ell_1(\ell_1+1)}$$

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

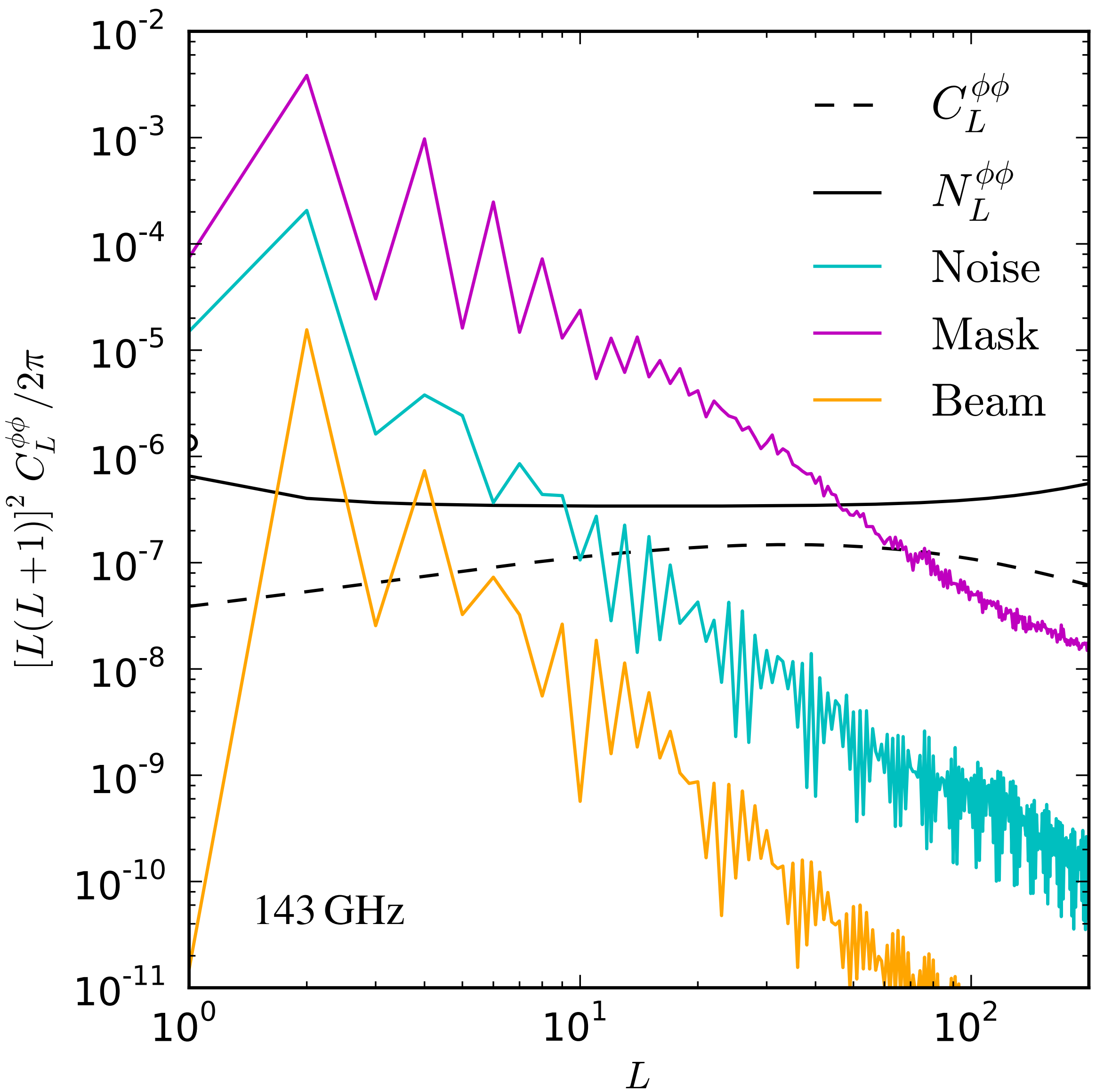
$$W^{\phi}(\boldsymbol{l}_1, \boldsymbol{l}_2) = C^{TT}_{|l_1|}\boldsymbol{l}_1 \cdot \boldsymbol{L} + C^{TT}_{|l_2|}\boldsymbol{l}_2 \cdot \boldsymbol{L}.$$

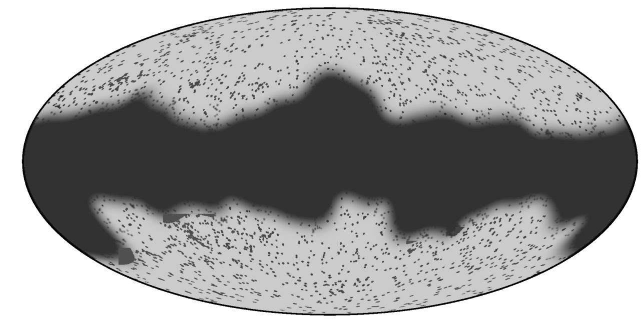
- Take two temperature maps and inverse variance filter them.
- Differentiate one and filter it by the temperature power spectrum
- Multiply with the other inverse variance filtered map
- Normalize to get unbiased estimator

$$\mathcal{R}^{x\phi,(1)(2)}_L = \frac{1}{(2L+1)}\sum_{\ell_1\ell_2}\frac{1}{2}W^x_{\ell_1\ell_2L}W^{\phi}_{\ell_1\ell_2L}F^{(1)}_{\ell_1}F^{(2)}_{\ell_2}.$$

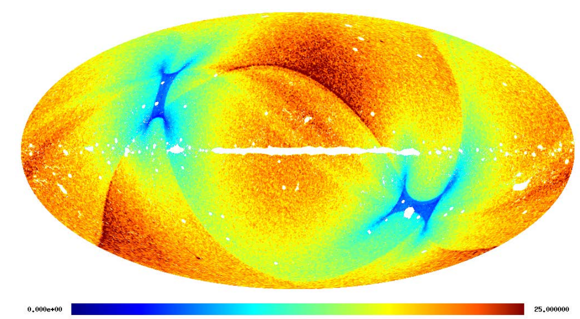
$$\bar{T}_{\ell m} = [S+N]^{-1}T_{\ell m} \approx [C^{TT}_{\ell} + C^{NN}_{\ell}]^{-1}T_{\ell m} = F_{\ell}T_{\ell m}$$

Biases at the map level

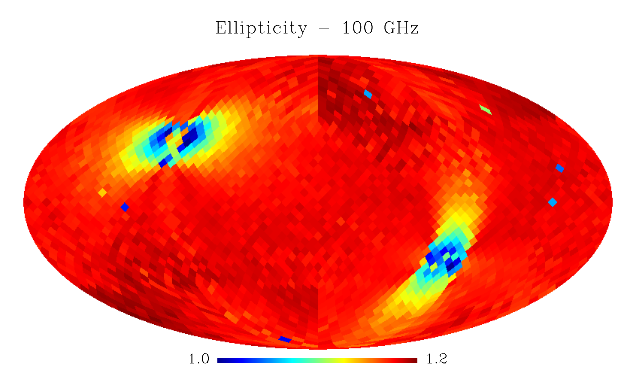




Mask



noise RMS

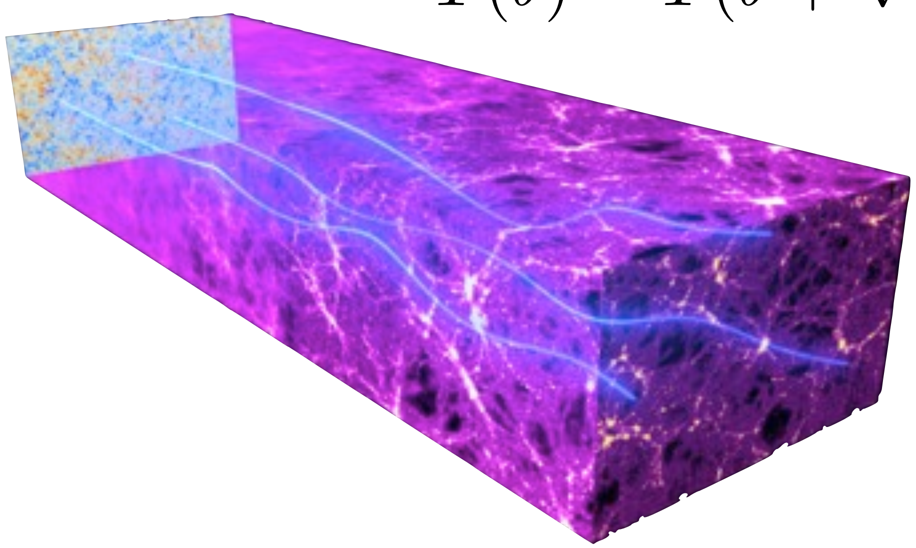


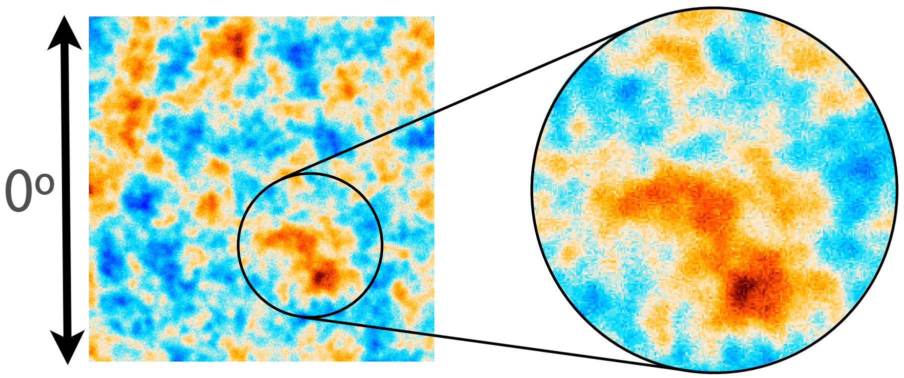
Beam ellipticity

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

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



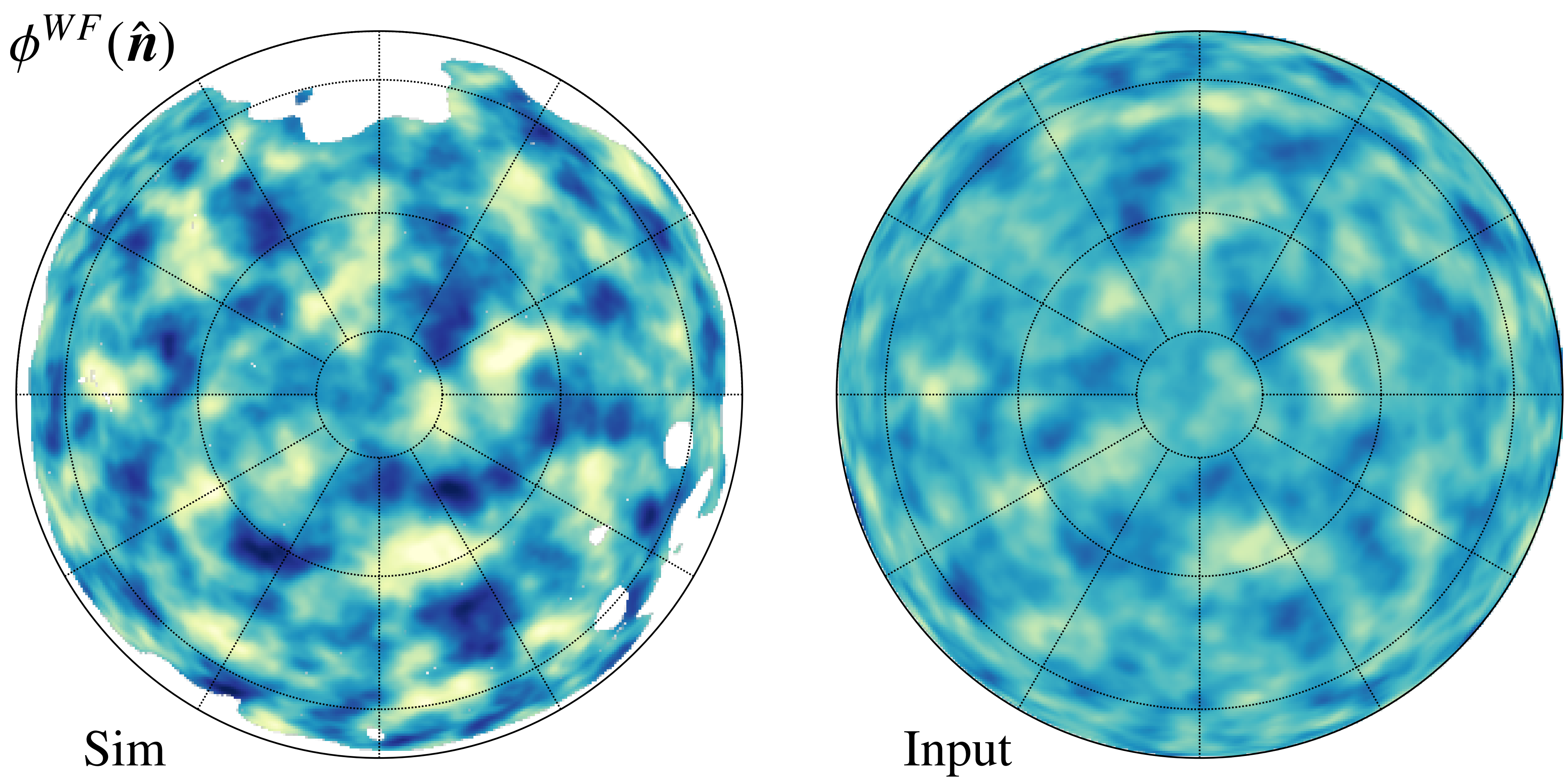


A quadratic estimator to measure the specific NG signature.

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

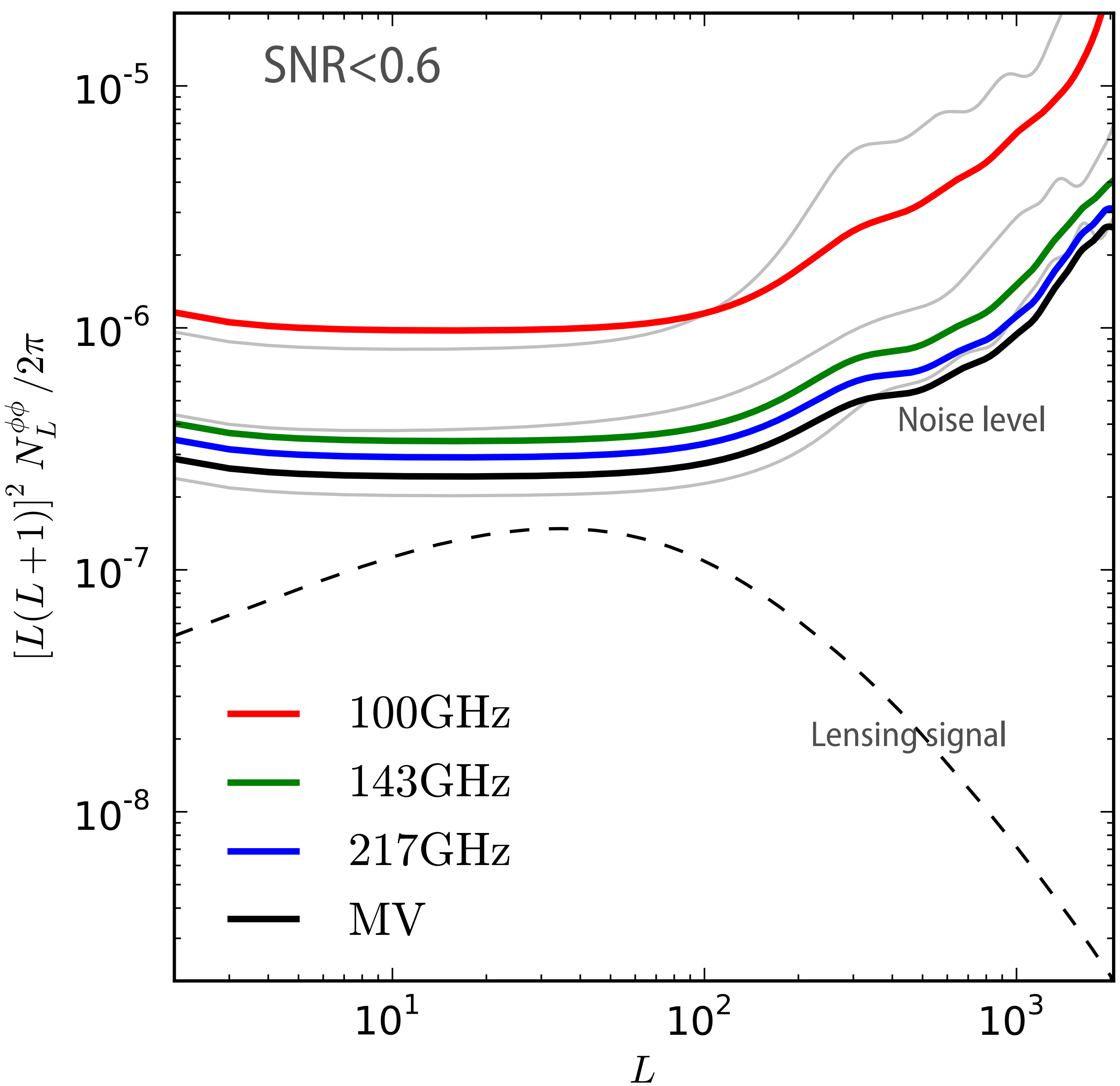
- Take two temperature maps and inverse variance filter them.
- Differentiate one and filter it by the temperature power spectrum
- Multiply with the other inverse variance filtered map
- Do the same with a set of CMB simulations containing your source of statistical anisotropies (mask, noise, beams)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

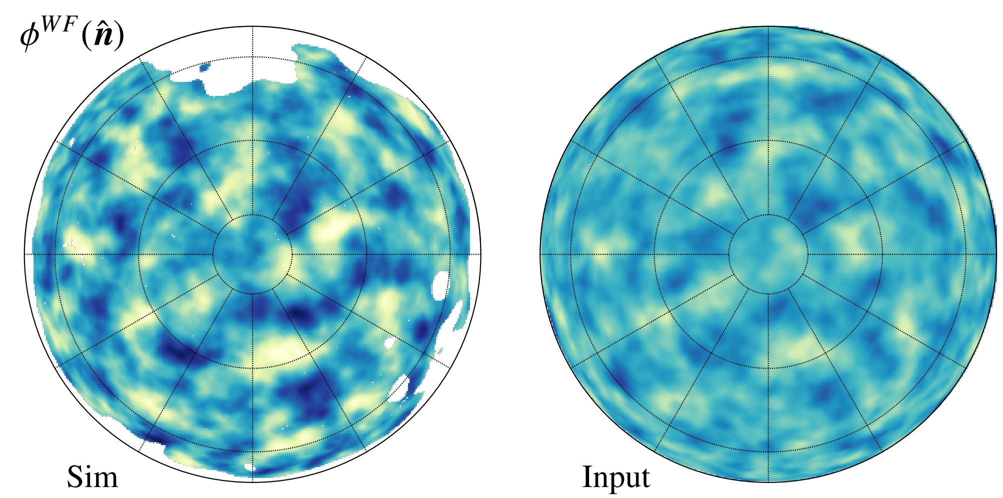
On simulation



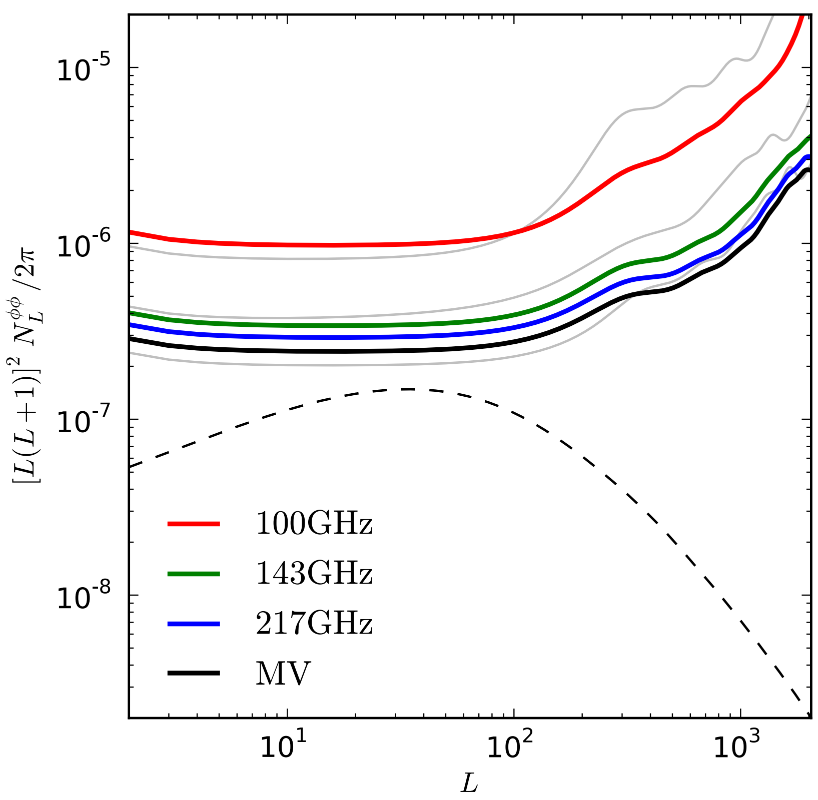
Reconstruction on a realistic Planck simulation.

Map noise - spectrum biases



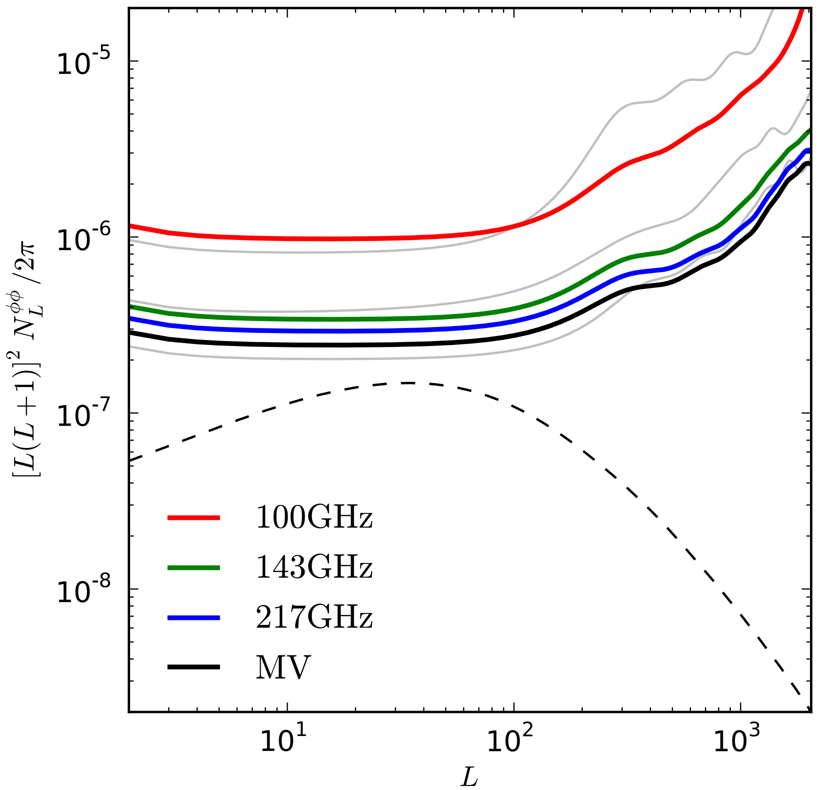


Power spectrum biases



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

Power spectrum biases



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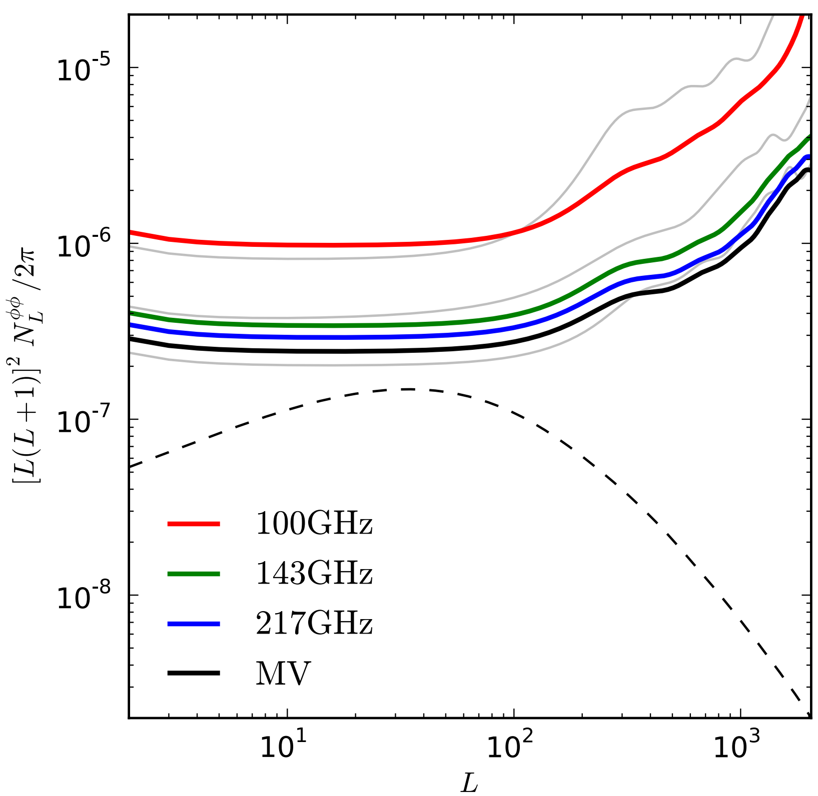
Gaussian bias. Dealt with by MC. Close to the analytical value.
Dominates the final error budget.

Power spectrum biases



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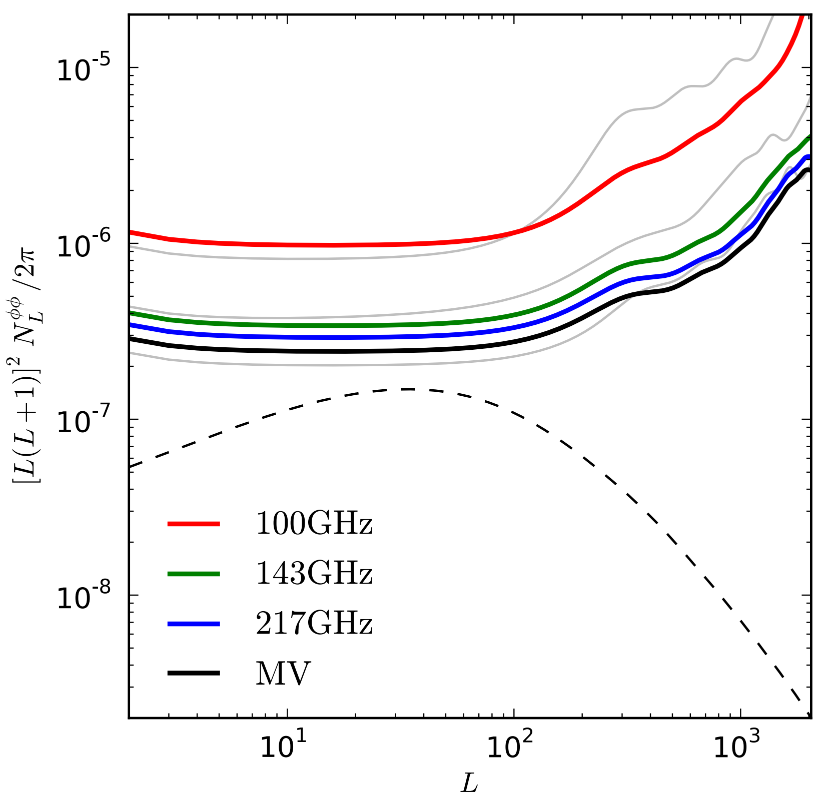
Gaussian bias. Dealt with by MC. Close to the analytical value.
Dominates the final error budget.

Higher order bias. We further include cosmological uncertainty.

Power spectrum biases



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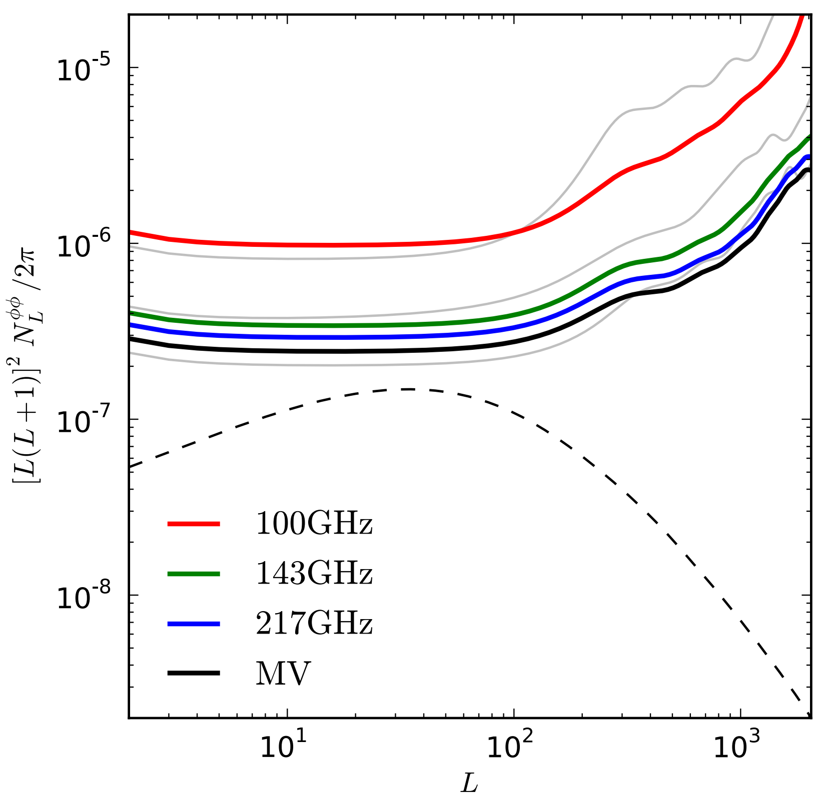
Gaussian bias. Dealt with by MC. Close to the analytical value.
Dominates the final error budget.

Higher order bias. We further include cosmological uncertainty.

Point source trispectrum contribution. Measured on data

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.

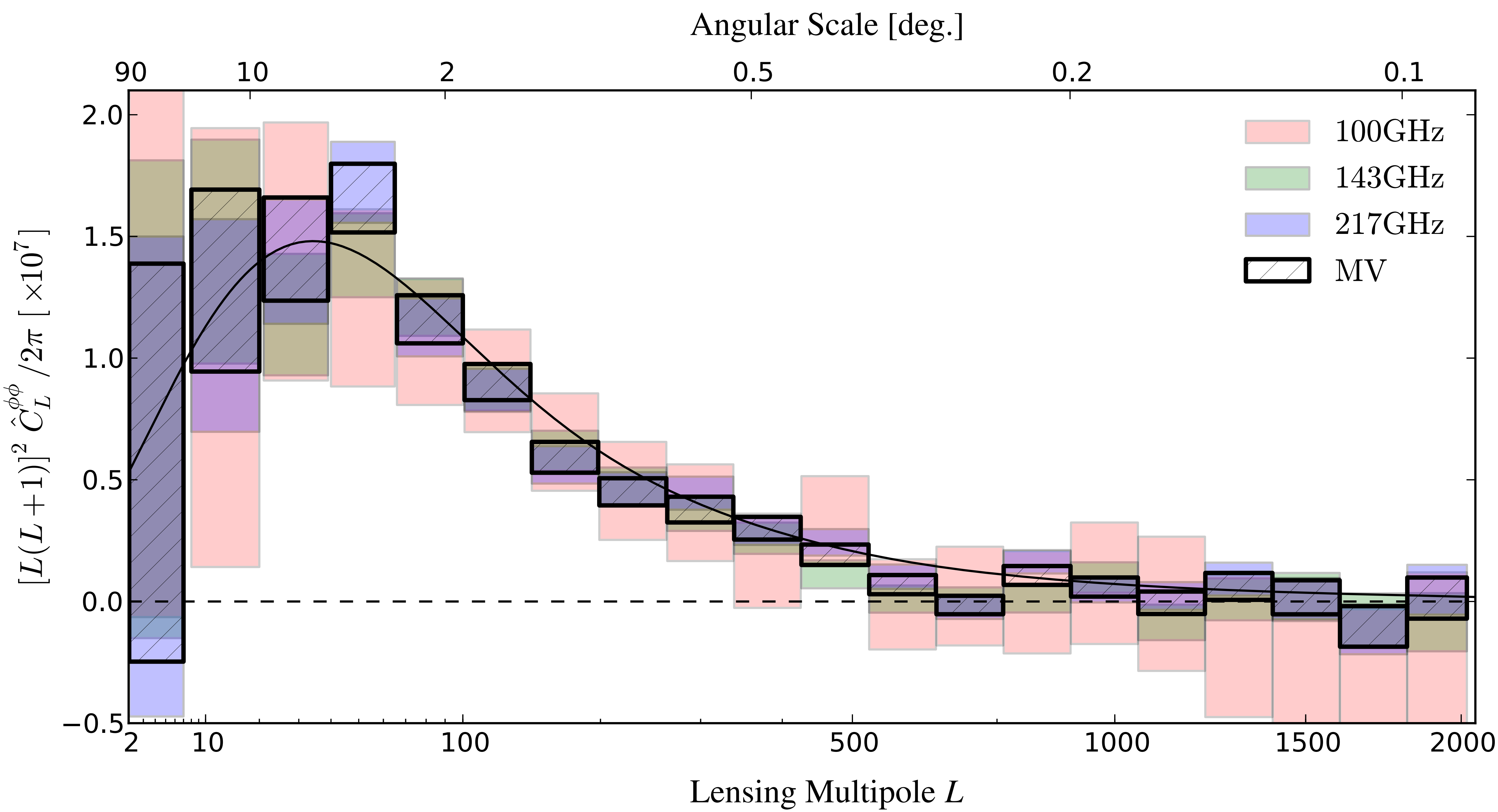
Point source trispectrum contribution. Measured on data

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

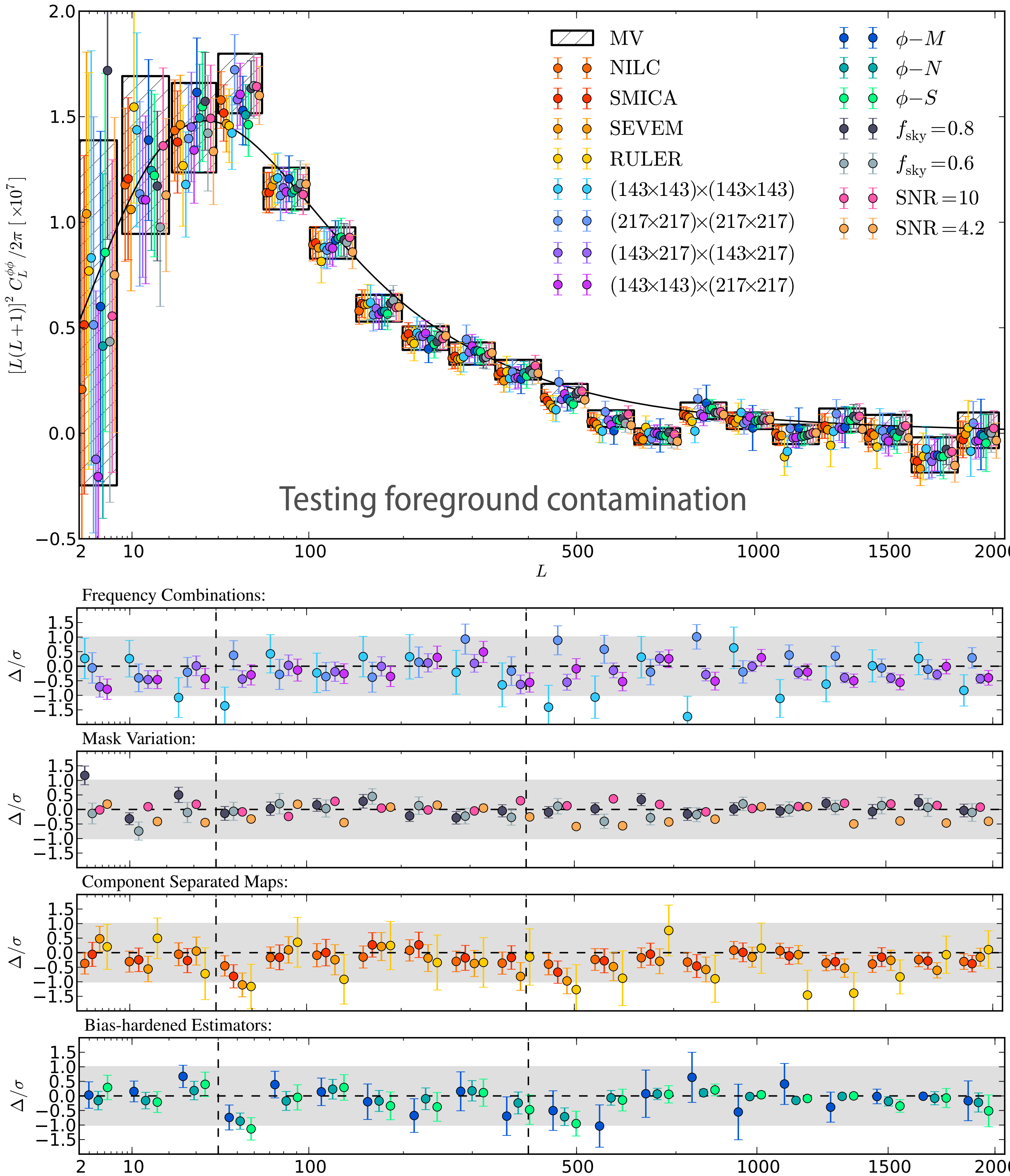
Best reconstruction

- 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

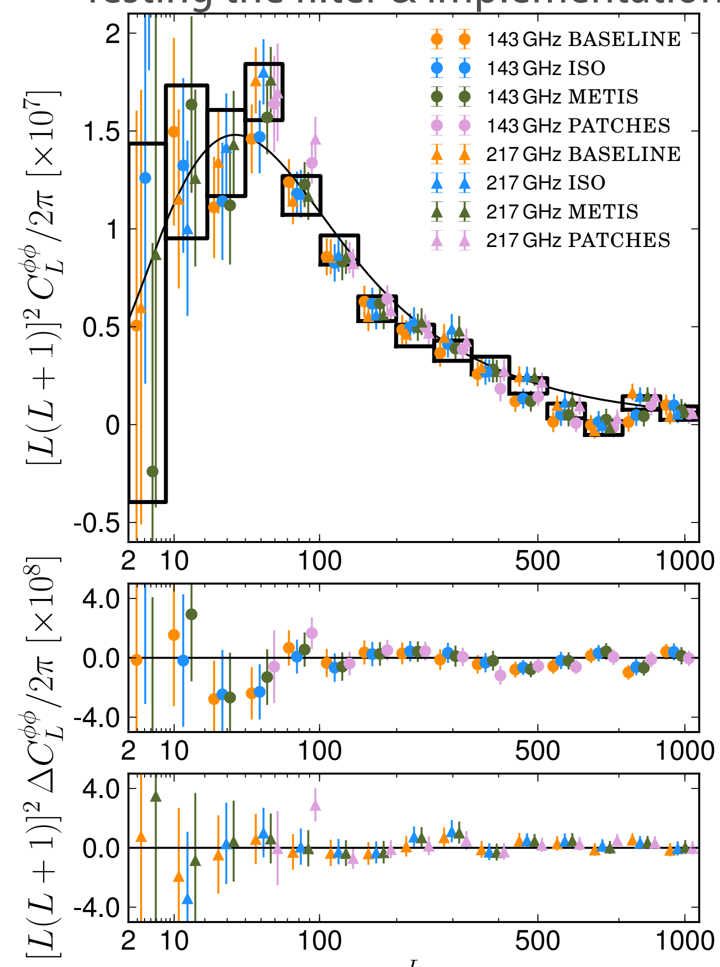
CMB lensing reconstruction



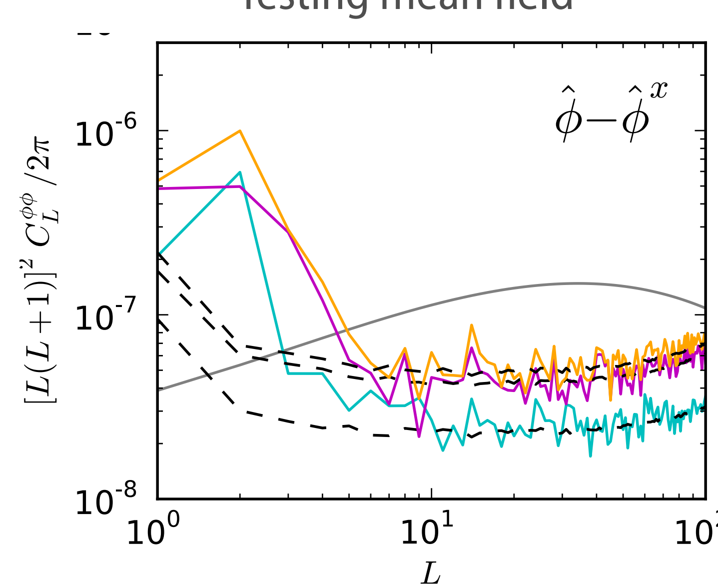
Robustness



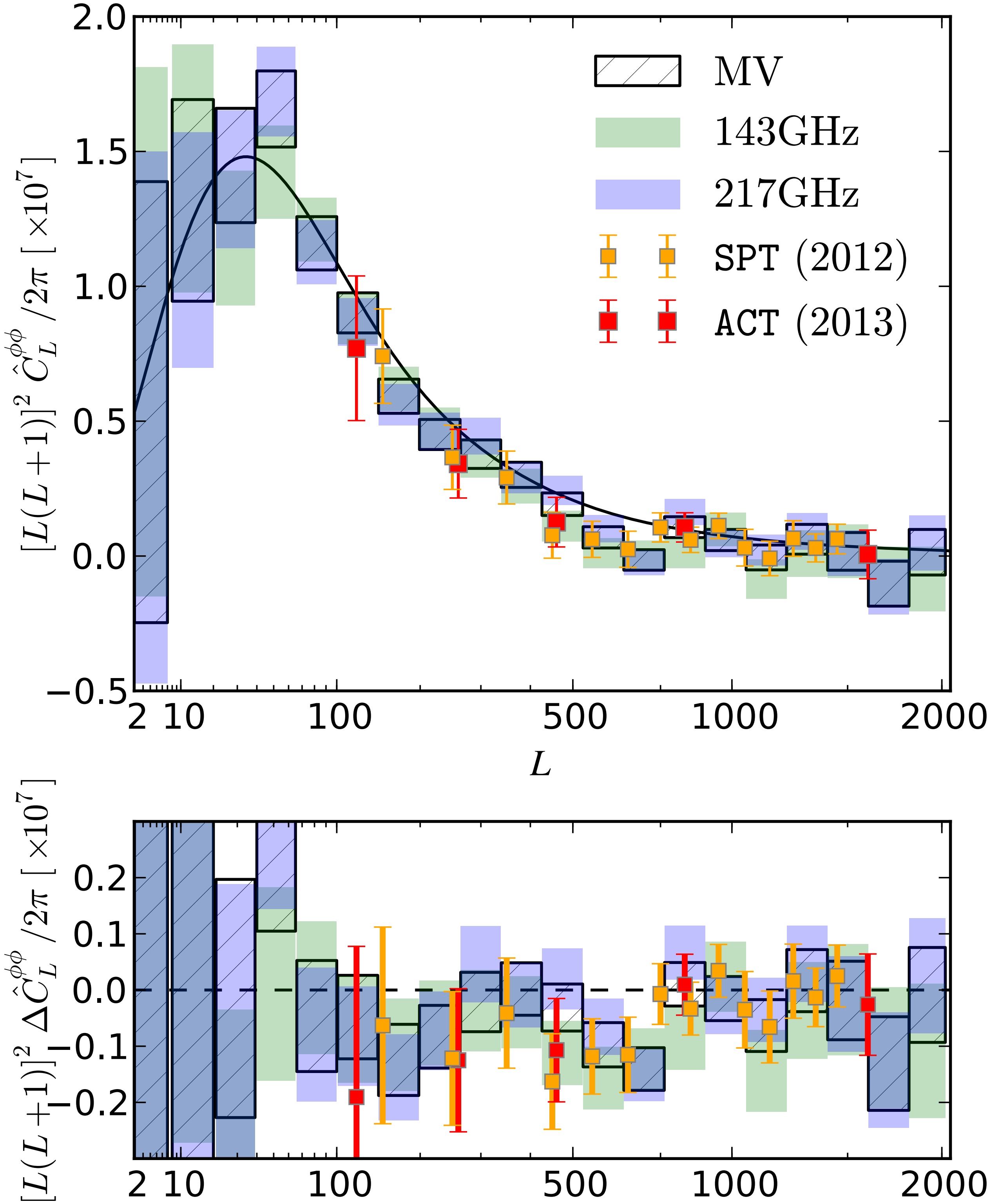
Testing the filter & implementation



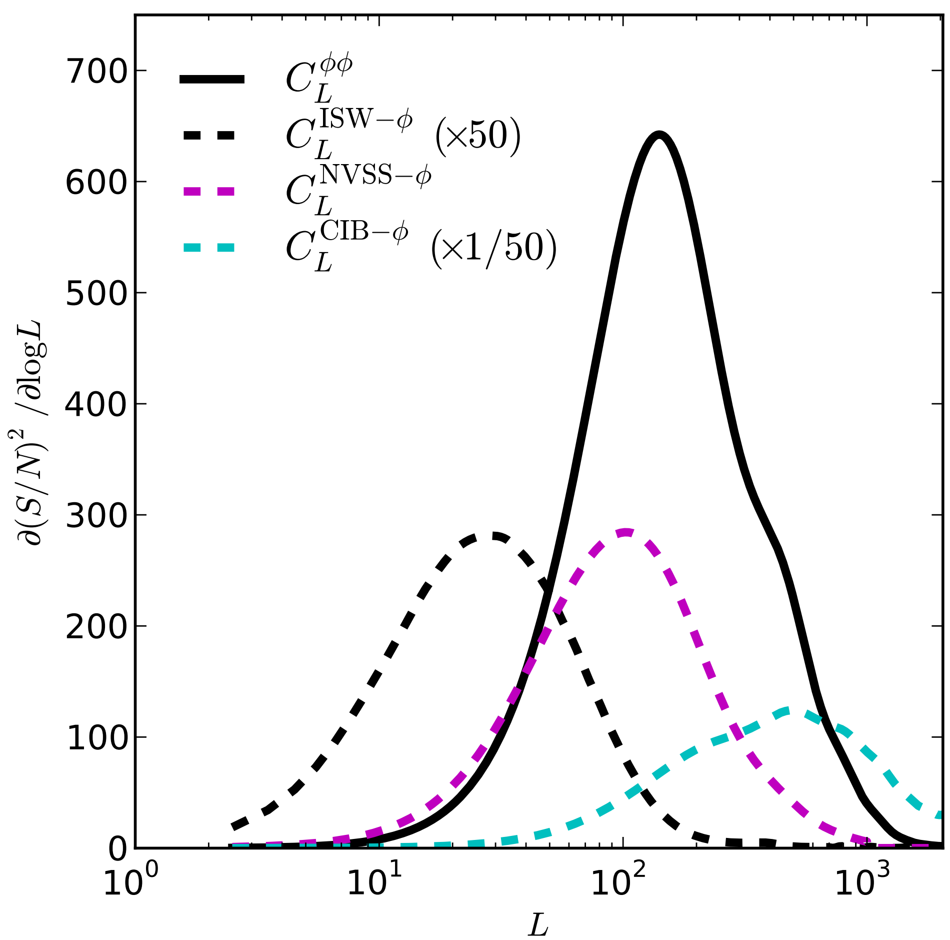
Testing mean field

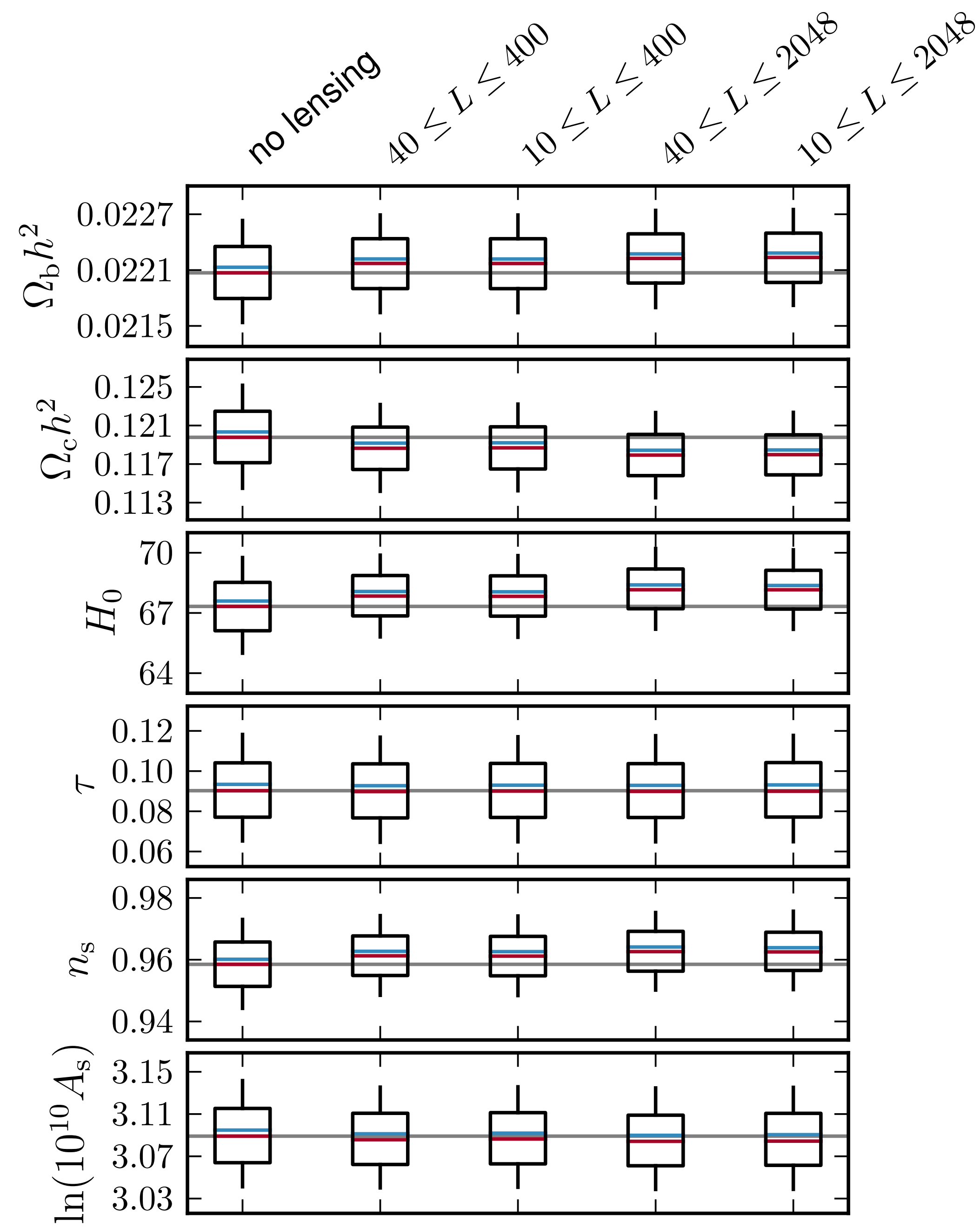


Comparison to other surveys



Cosmology

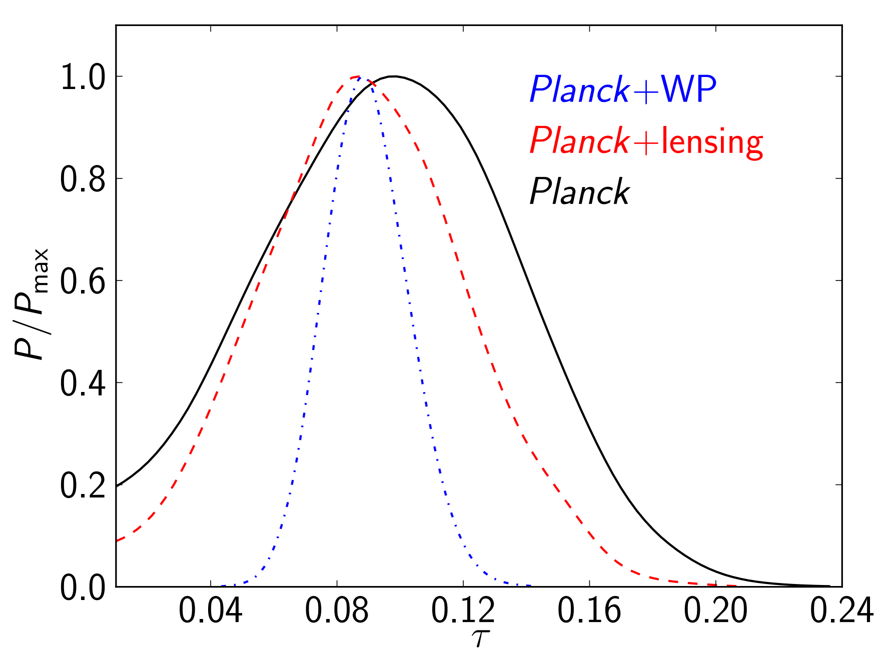


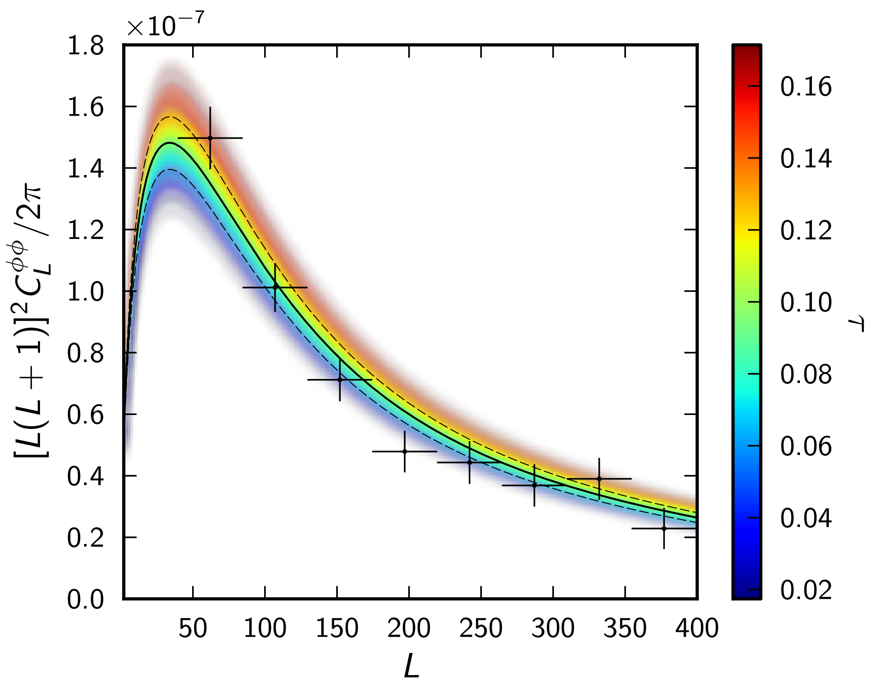


We are using the most significant (and cleanest) part of the data L=40-400.
Lensing brings a 20%ish improvement on some of the vanilla LCDM parameters.

Cosmology - I

Constraining the reionization from Planck alone strengthen the Polarization result



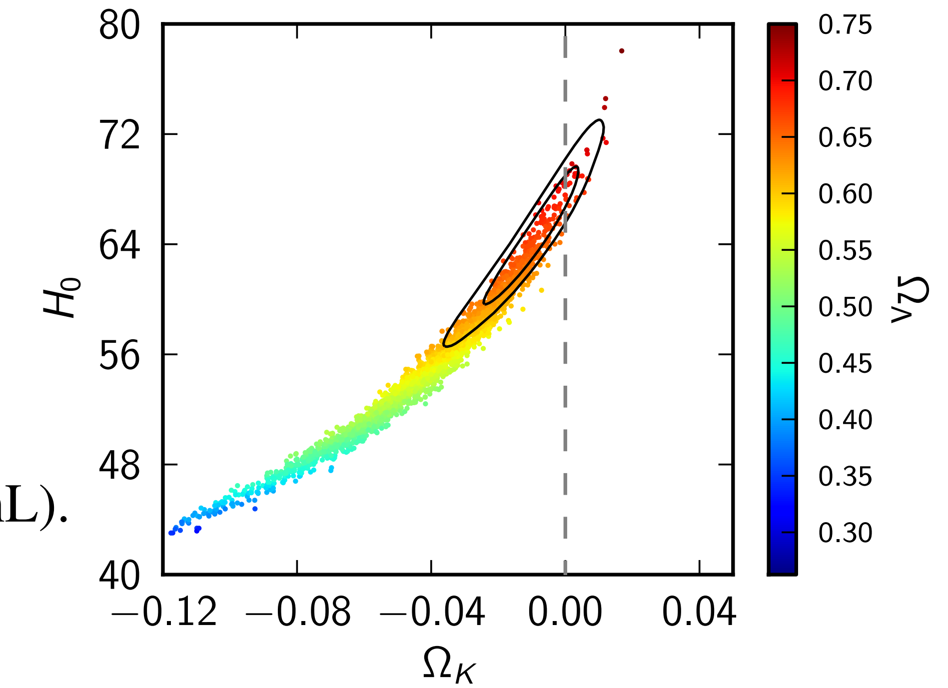


$$\tau = 0.097 \pm 0.038 \quad (68\%; \textit{Planck})$$

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

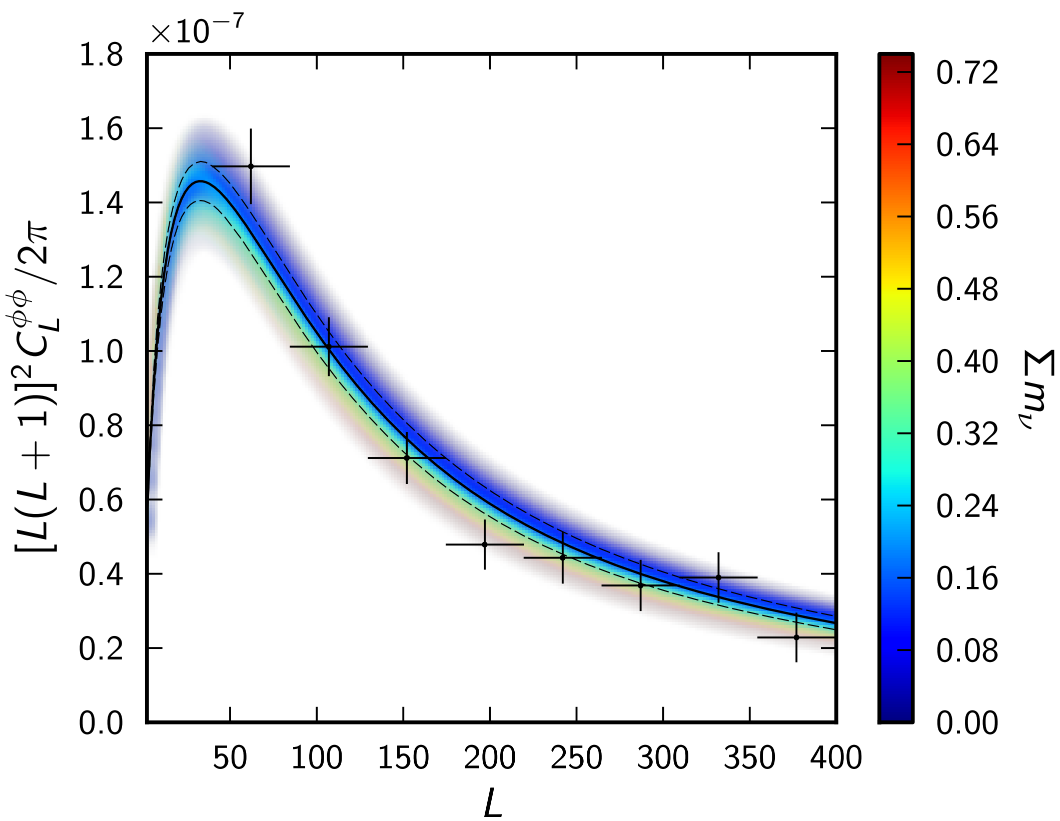
Cosmology - II

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



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

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

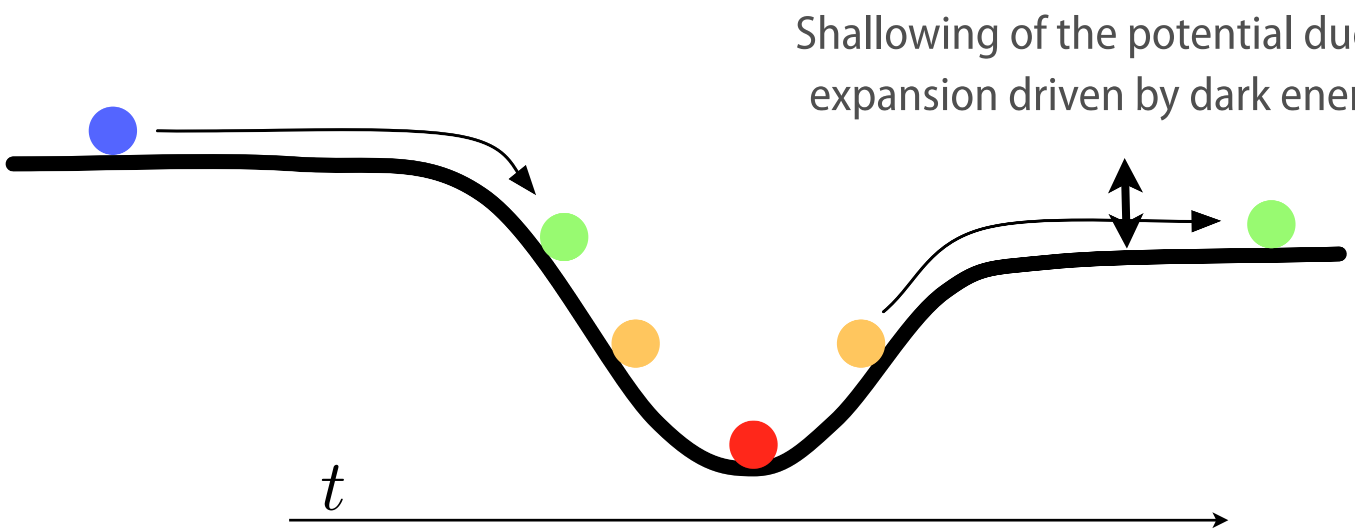


Mild tension with neutrino masses
TT wants more lensing
TTTT wants less lensing

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

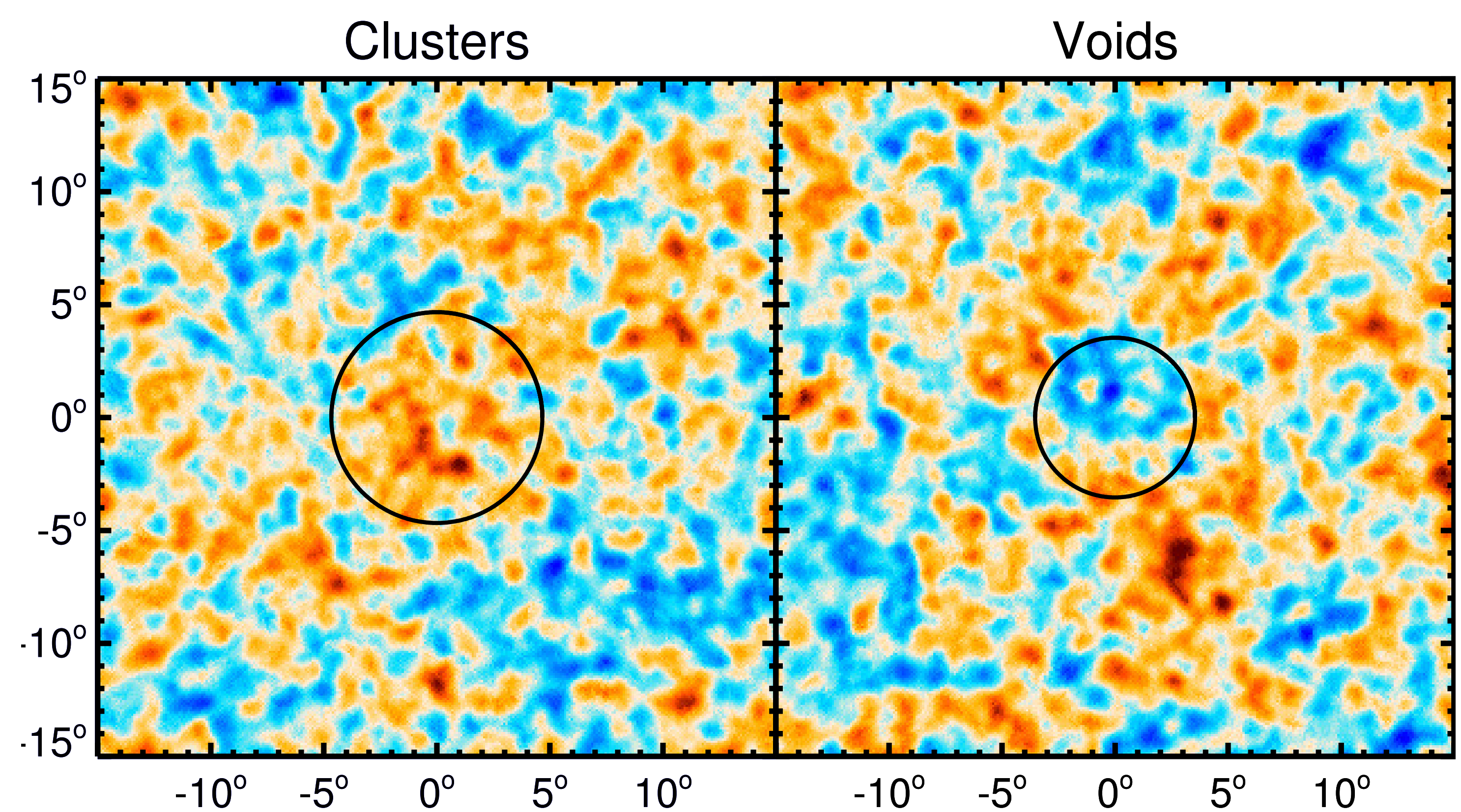
$$\sum m_\nu < 0.85\,\text{eV}, \quad (95\%;\ Planck\text{+lensing+WP+highL}),$$

ISW



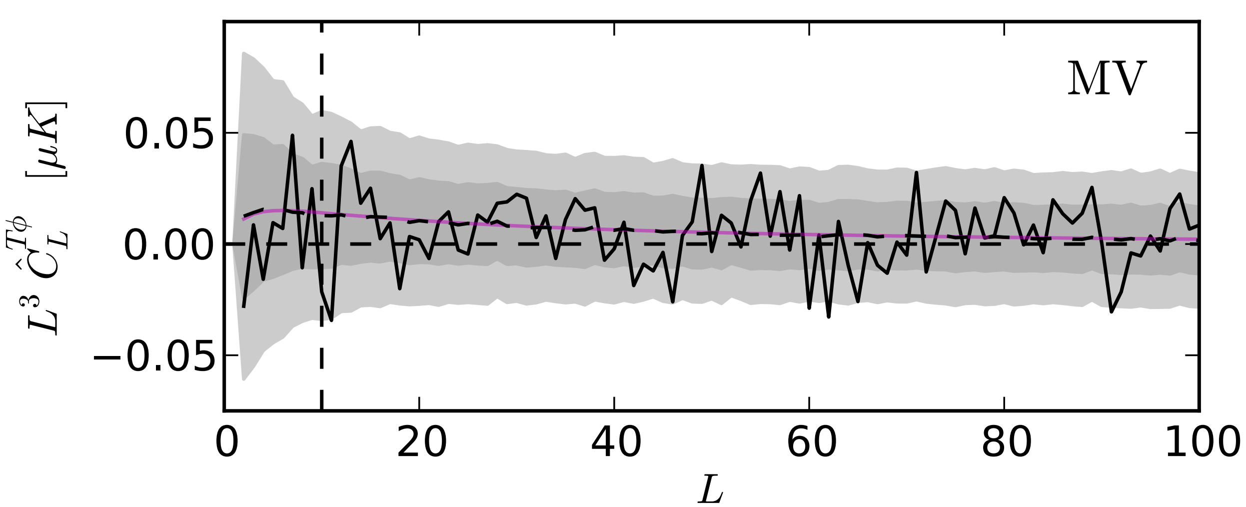
$$\frac{\Delta T}{T} = \frac{2}{c^3} \int_{\eta^*}^{\eta_0} \mathrm{d}\eta \frac{\partial \Phi}{\partial \eta}$$

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



ISW - Lensing correlation

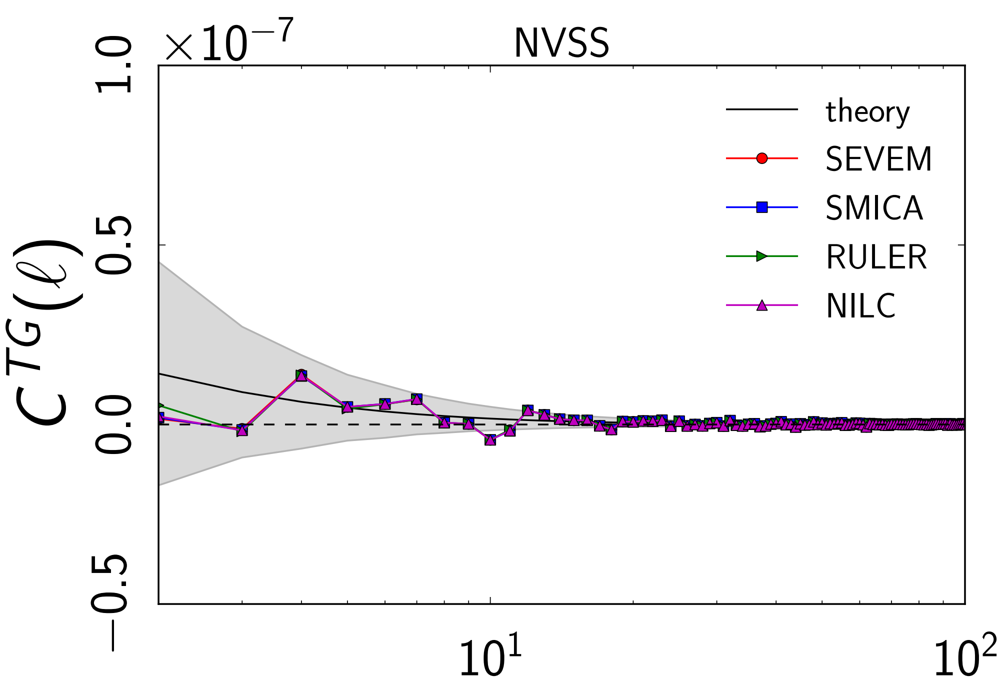
Estimator		C-R	σ	NILC	σ	SEVEM	σ	SMICA	σ	MV	
$T\phi$	$\ell \geq 10$	0.52 ± 0.33	1.5	0.72 ± 0.30	2.4	0.58 ± 0.31	1.9	0.68 ± 0.30	2.3	0.78 ± 0.32	2.4
	$\ell \geq 2$	0.52 ± 0.32	1.6	0.75 ± 0.28	2.7	0.62 ± 0.29	2.1	0.70 ± 0.28	2.5		
KSW		0.75 ± 0.32	2.3	0.85 ± 0.32	2.7	0.68 ± 0.32	2.1	0.81 ± 0.31	2.6		
binned		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

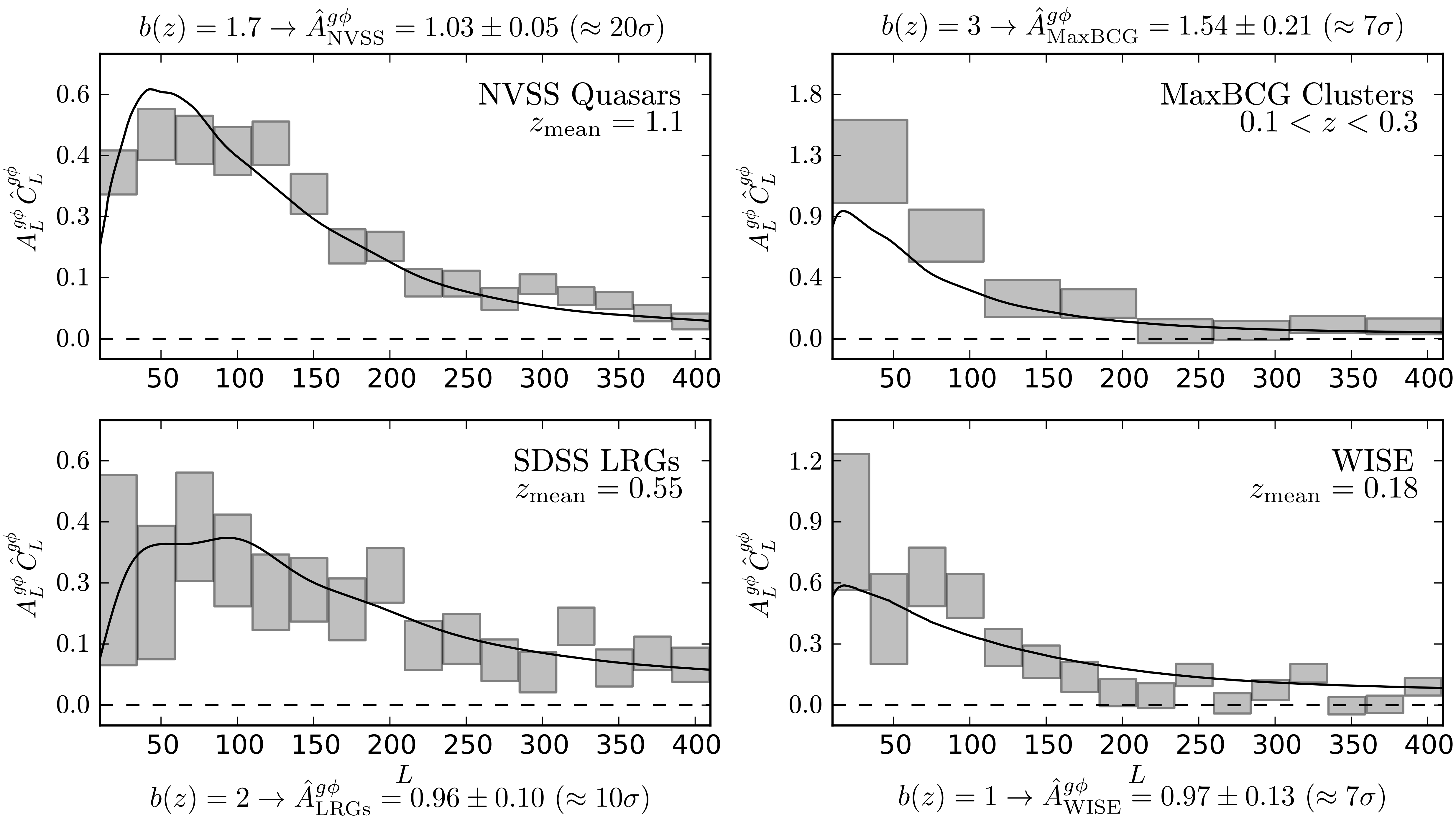
ISW - external tracers

LSS data	$\hat{\xi}_a^{xy}$	C-R	σ	NILC	σ	SEVEM	σ	SMICA	
NVSS	CAPS	0.86 ± 0.33	2.6	0.91 ± 0.33	2.8	0.90 ± 0.33	2.7	0.91 ± 0.33	2.7
	CCF	0.80 ± 0.33	2.4	0.84 ± 0.33	2.5	0.83 ± 0.33	2.5	0.84 ± 0.33	2.5
	SMHWcov	0.89 ± 0.34	2.6	0.93 ± 0.34	2.8	0.89 ± 0.34	2.6	0.92 ± 0.34	2.7
SDSS-CMASS/LOWZ	CAPS	0.98 ± 0.52	1.9	1.09 ± 0.52	2.1	1.06 ± 0.52	2.0	1.09 ± 0.52	2.1
	CCF	0.81 ± 0.52	1.6	0.91 ± 0.52	1.8	0.89 ± 0.52	1.7	0.90 ± 0.52	1.7
	SMHWcov	0.80 ± 0.53	1.5	0.89 ± 0.53	1.9	0.87 ± 0.53	1.6	0.88 ± 0.53	1.7
SDSS-MG	CAPS	1.31 ± 0.57	2.3	1.43 ± 0.57	2.5	1.35 ± 0.57	2.4	1.42 ± 0.57	2.5
	CCF	1.00 ± 0.57	1.8	1.11 ± 0.57	2.0	1.10 ± 0.57	1.9	1.10 ± 0.57	1.9
	SMHWcov	1.03 ± 0.59	1.8	1.18 ± 0.59	2.0	1.15 ± 0.59	2.0	1.17 ± 0.59	2.0
all	CAPS	0.84 ± 0.31	2.7	0.91 ± 0.31	2.9	0.88 ± 0.31	2.0	0.90 ± 0.31	2.9
	CCF	0.77 ± 0.31	2.5	0.83 ± 0.31	2.7	0.82 ± 0.31	2.6	0.82 ± 0.31	2.7
	SMHWcov	0.86 ± 0.32	2.7	0.92 ± 0.32	2.9	0.89 ± 0.32	2.8	0.91 ± 0.32	2.9



about 2 to 2.5sigma for each our external catalogs robust against foreground contamination and algorithm

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

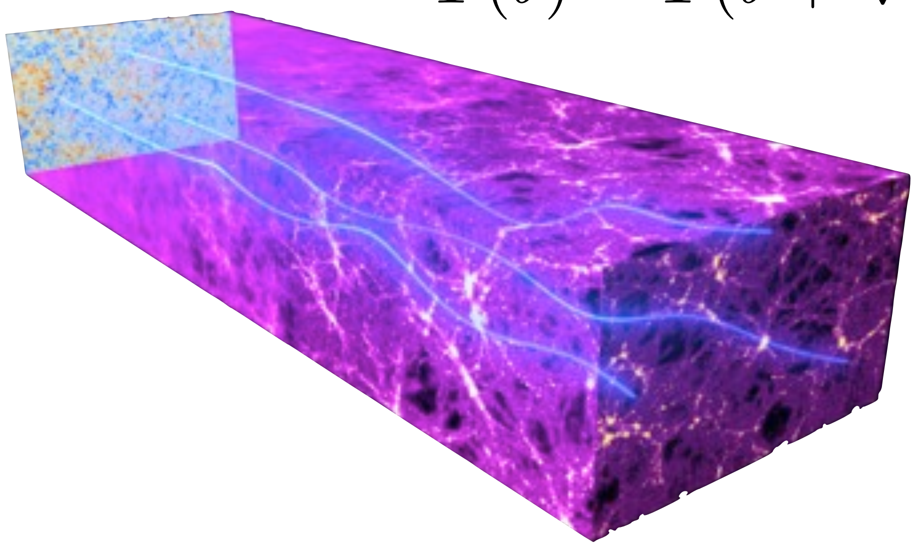
- Planck trace late dark matter distribution
  - Lensing reconstruction on the whole sky
  - First determination of the ISW-lensing correlation
  - Improvement of the cosmological parameters constraint
  - **Great potential for cross-correlation with other surveys**
- Where do we go from here
  - We will improve our lensing reconstruction
    - Full mission
    - Polarization (possibly 15sigma TTxTE)
  - Potential for improving the ISW-lensing cross correlation significance.
  - Small scales lensing will be improved by SPT & other surface experiments

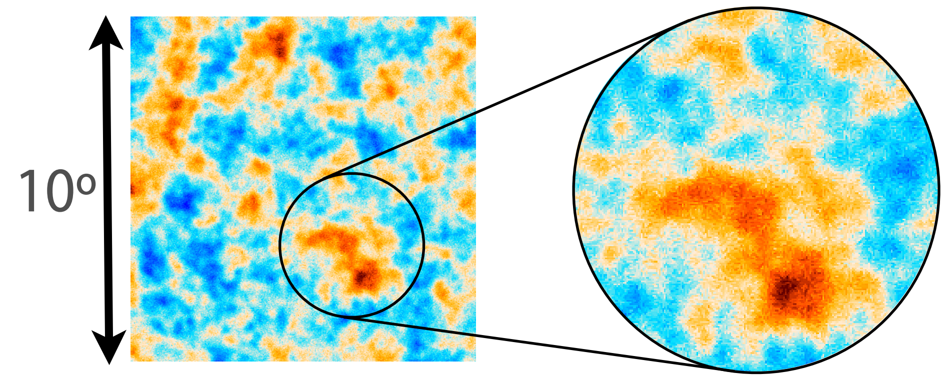
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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.

CMB lensing reconstruction

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





$$W^{\phi}_{\ell_1\ell_2 L} = -\sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2L+1)}{4\pi}}\sqrt{L(L+1)\ell_1(\ell_1+1)}$$

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

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

$$W^{\phi}(\mathbf{l}_1, \mathbf{l}_2) = C^{TT}_{|l_1|}\mathbf{l}_1 \cdot \mathbf{L} + C^{TT}_{|l_2|}\mathbf{l}_2 \cdot \mathbf{L}.$$

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

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

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

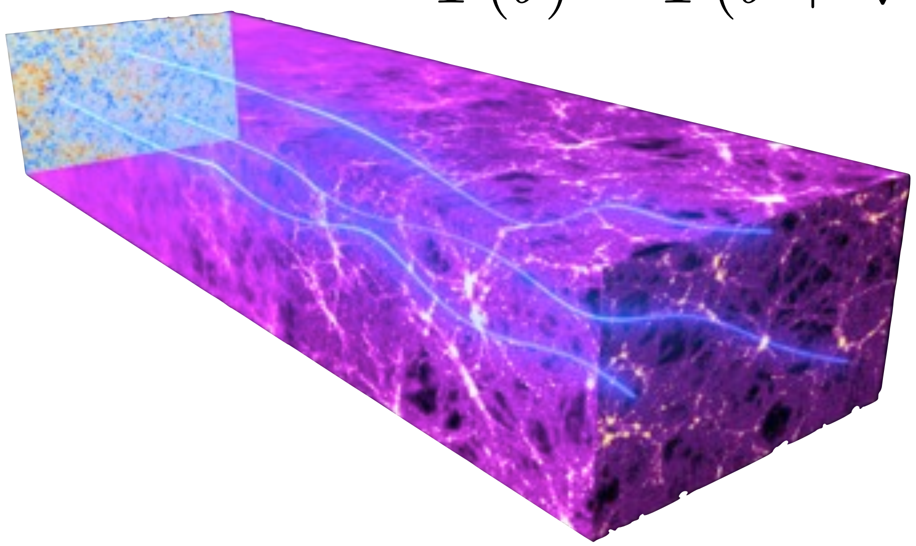
$$\bar{x}^{MF}_{LM} = \frac{1}{2}\sum_{\ell_1 m_1, \ell_2 m_2}(-1)^M \begin{pmatrix}\ell_1 & \ell_2 & L\\ m_1 & m_2 & -M\end{pmatrix} W^x_{\ell_1\ell_2 L}\langle\bar{T}^{(1)}_{\ell_1 m_1}\bar{T}^{(2)}_{\ell_2 m_2}\rangle.$$

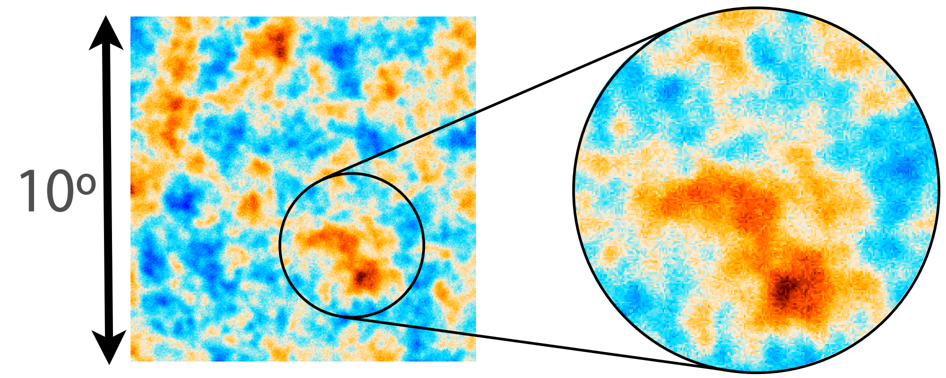
$$\mathcal{R}^{x\phi,(1)(2)}_L = \frac{1}{(2L+1)}\sum_{\ell_1\ell_2}\frac{1}{2}W^x_{\ell_1\ell_2 L}W^{\phi}_{\ell_1\ell_2 L}F^{(1)}_{\ell_1}F^{(2)}_{\ell_2}.$$

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

CMB lensing reconstruction

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



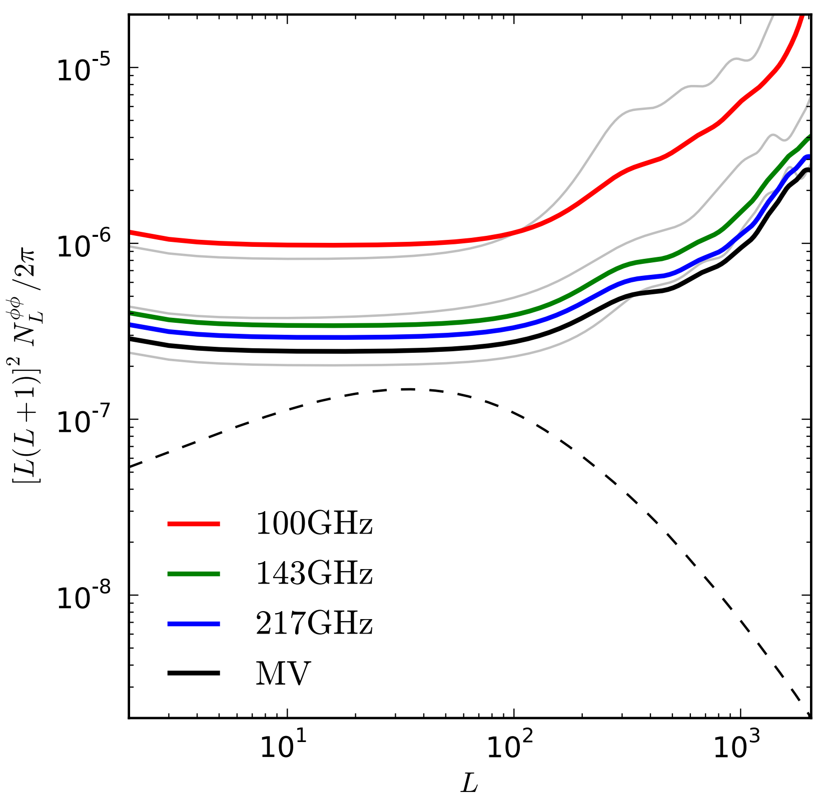


$$\Delta\langle T_{\ell_1 m_1} T_{\ell_2 m_2}\rangle = \sum_{LM} \sum_{\ell_1 m_1, \ell_2 m_2} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W^{\phi}_{\ell_1 \ell_2 L} \phi_{LM},$$

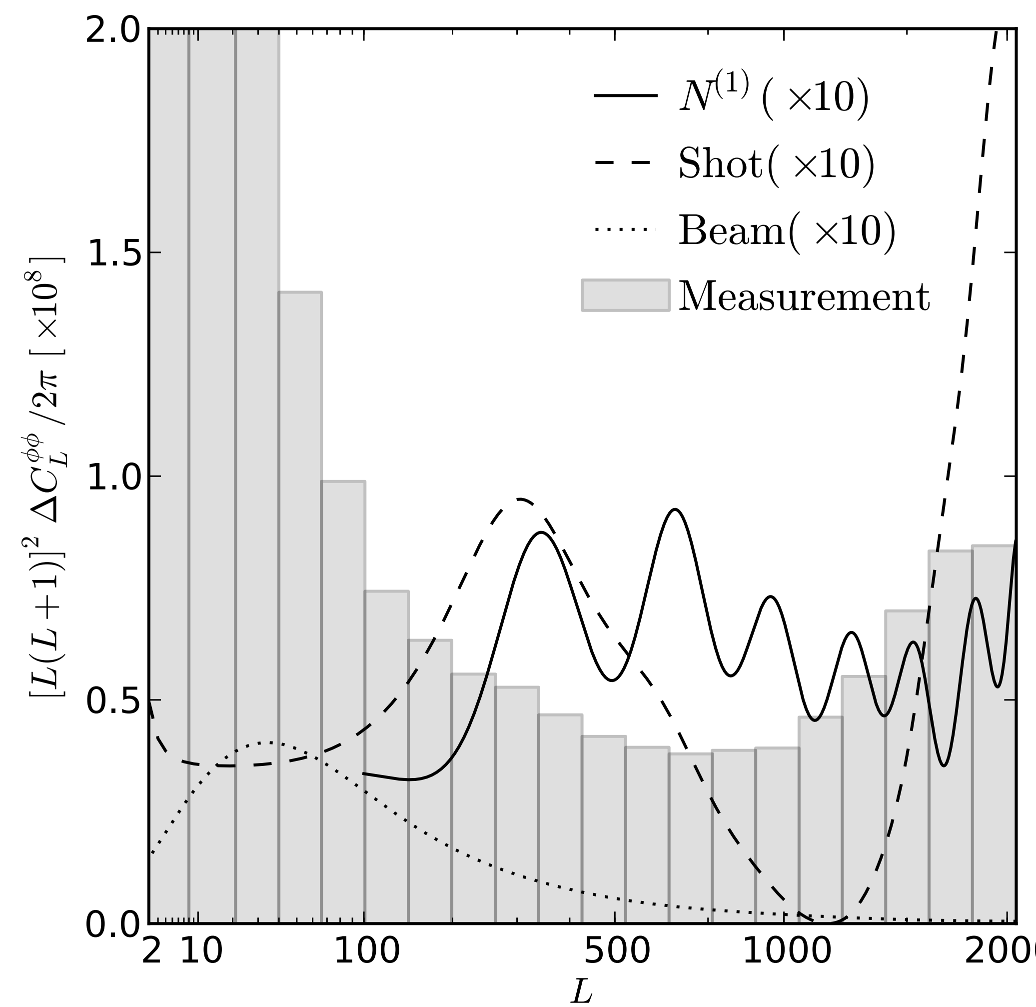
$$W^{\phi}_{\ell_1 \ell_2 L} = -\sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2L+1)}{4\pi}} \sqrt{L(L+1)\ell_1(\ell_1+1)} \times C^{TT}_{\ell_1} \left(\frac{1+(-1)^{\ell_1+\ell_2+L}}{2}\right) \begin{pmatrix} \ell_1 & \ell_2 & L \\ 1 & 0 & -1 \end{pmatrix} + (\ell_1 \leftrightarrow \ell_2). \quad (6)$$

$$W^{\phi}(\boldsymbol{l}_1, \boldsymbol{l}_2) = C^{TT}_{|\boldsymbol{l}_1|} \boldsymbol{l}_1 \cdot \boldsymbol{L} + C^{TT}_{|\boldsymbol{l}_2|} \boldsymbol{l}_2 \cdot \boldsymbol{L}.$$

Biases and errors



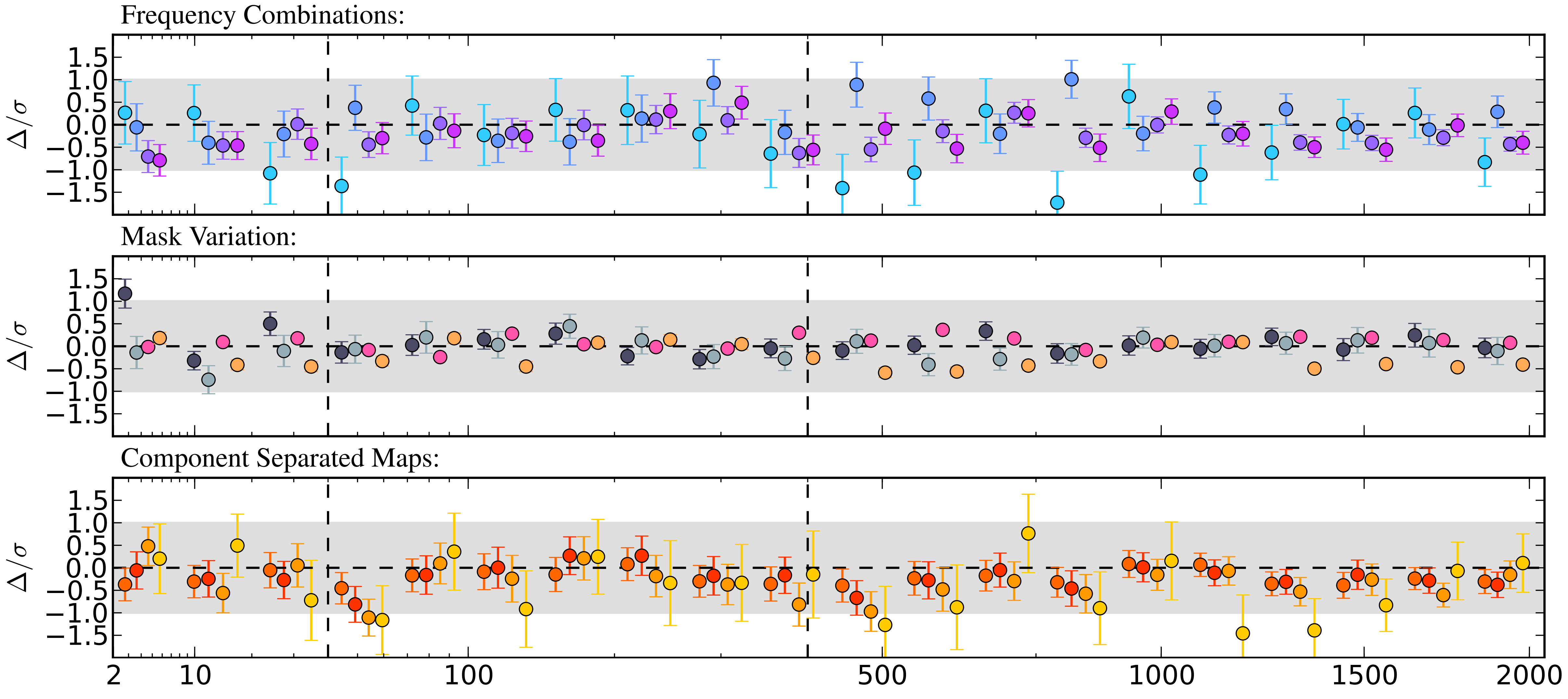
$$\hat{C}^{\phi\phi}_{L,x} = \frac{f_{\text{sky},2}^{-1}}{2L+1} \sum_M |\widetilde{\phi}^x_{LM}|^2 - \Delta C^{\phi\phi}_L\big|_{\text{N0}} - \Delta C^{\phi\phi}_L\big|_{\text{N1}} - \Delta C^{\phi\phi}_L\big|_{\text{PS}} - \Delta C^{\phi\phi}_L\big|_{\text{MC}},$$



Variance of the power spectrum dominated by the N0 bias.

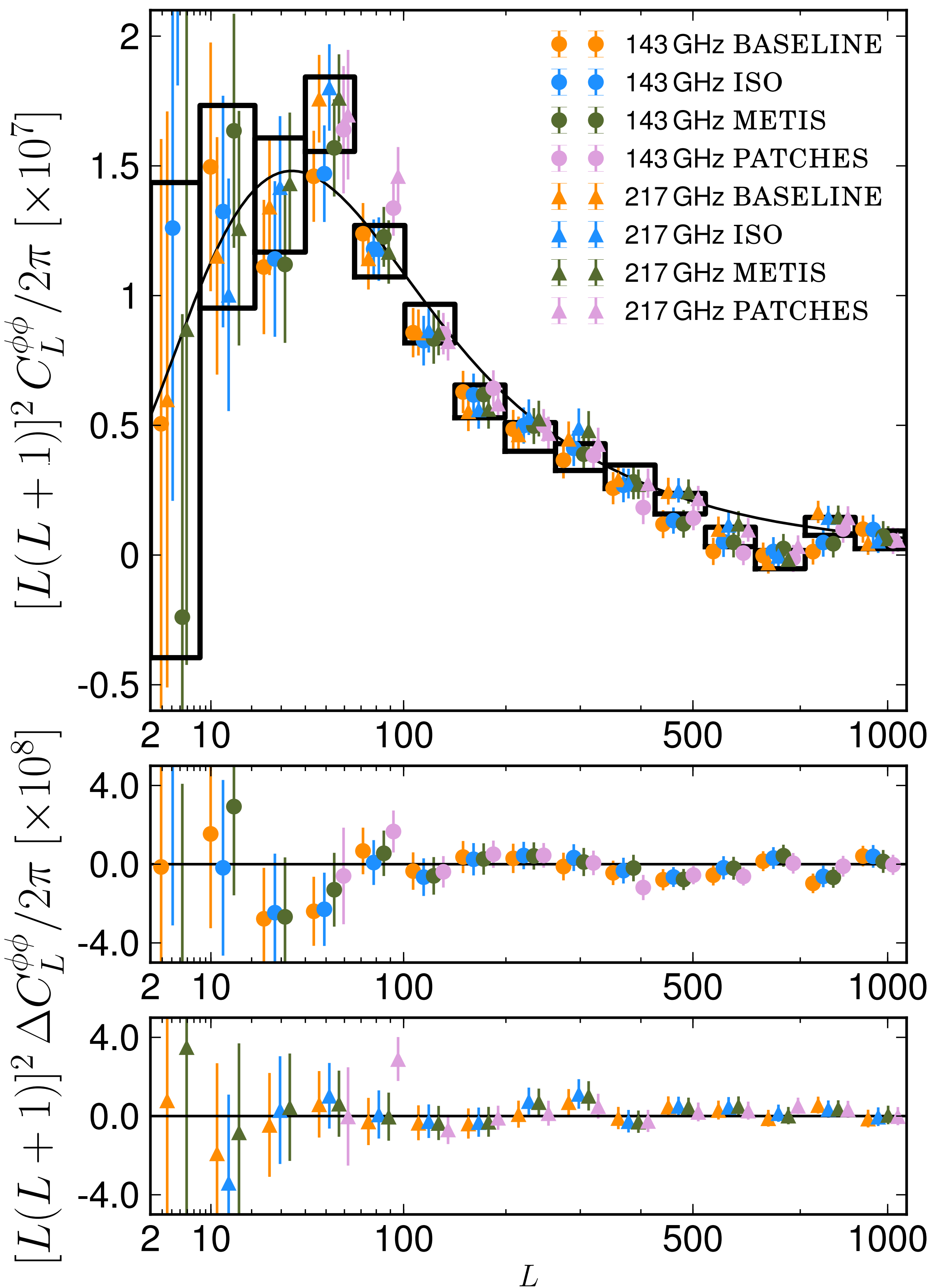
We also account for
- Beam errors
- PS correction uncertainties
- Cosmological uncertainties (N1)

Robustness



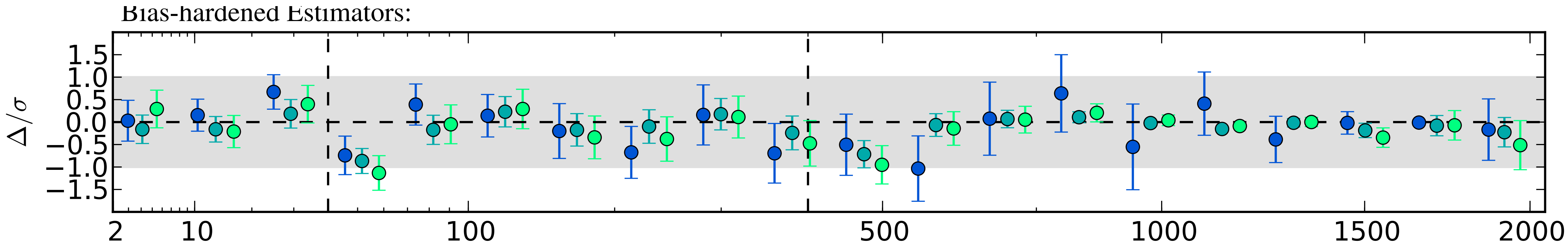
Frequency Combinations:
Mask Variation:
Component Separated Maps:
Δ/σ
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
2
10
100
500
1000
1500
2000

Robustness



143 GHz BASELINE
143 GHz ISO
143 GHz METIS
143 GHz PATCHES
217 GHz BASELINE
217 GHz ISO
217 GHz METIS
217 GHz PATCHES
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
$[L(L+1)]^2 \Delta C_L^{\phi\phi}/2\pi\ [\times 10^8]$
L
2
1.5
1
0.5
0
-0.5
4.0
0.0
-4.0
2
10
100
500
1000

Robustness



Testing mean field