The large scale structure of the Universe as seen by Planck

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University College London

On behalf of the Planck Collaboration

XVII. Gravitational lensing by large scale structure

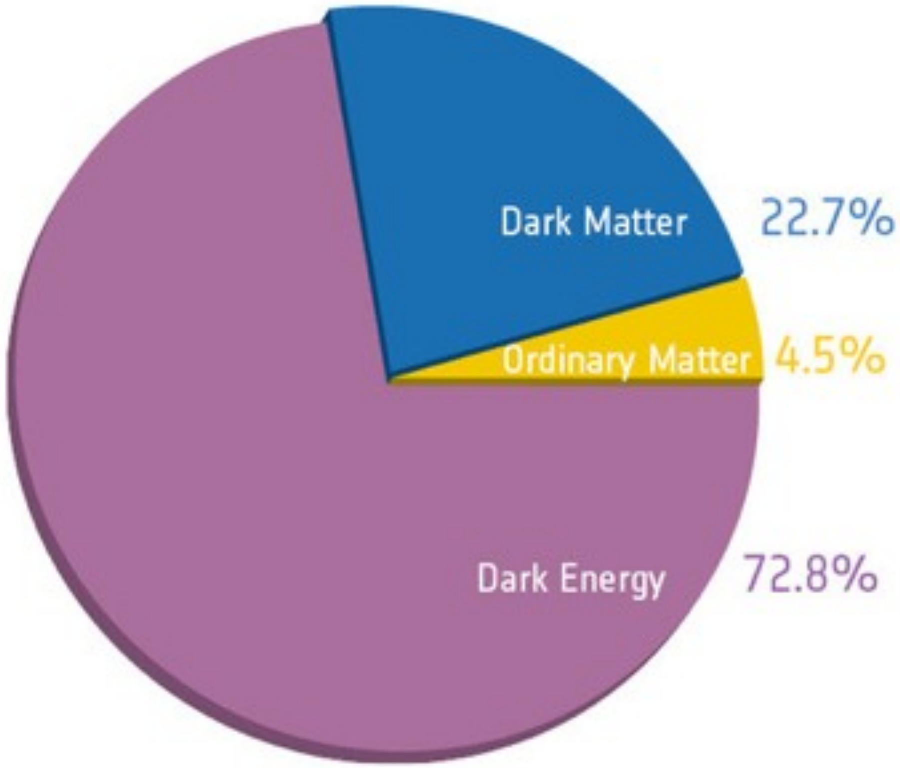
XVI. Cosmological parameters

XVIII. Gravitational lensing - infrared background correlation

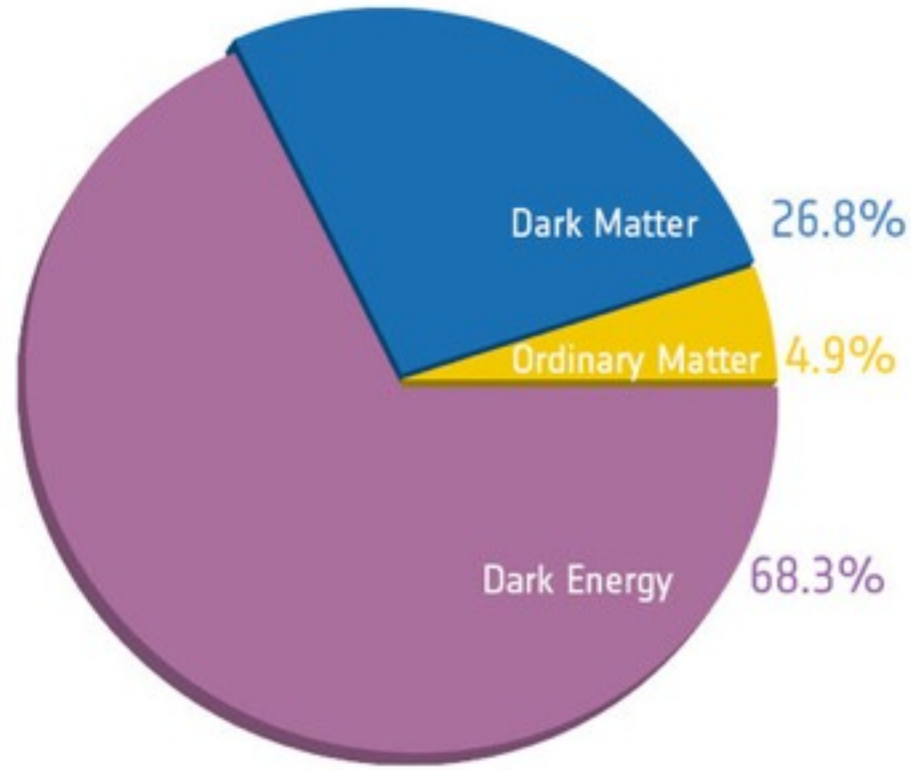
XIX. The integrated Sachs-Wolfe effect

Séminaire du SPP - 23 septembre 2013

A quick summary of the current status of cosmology

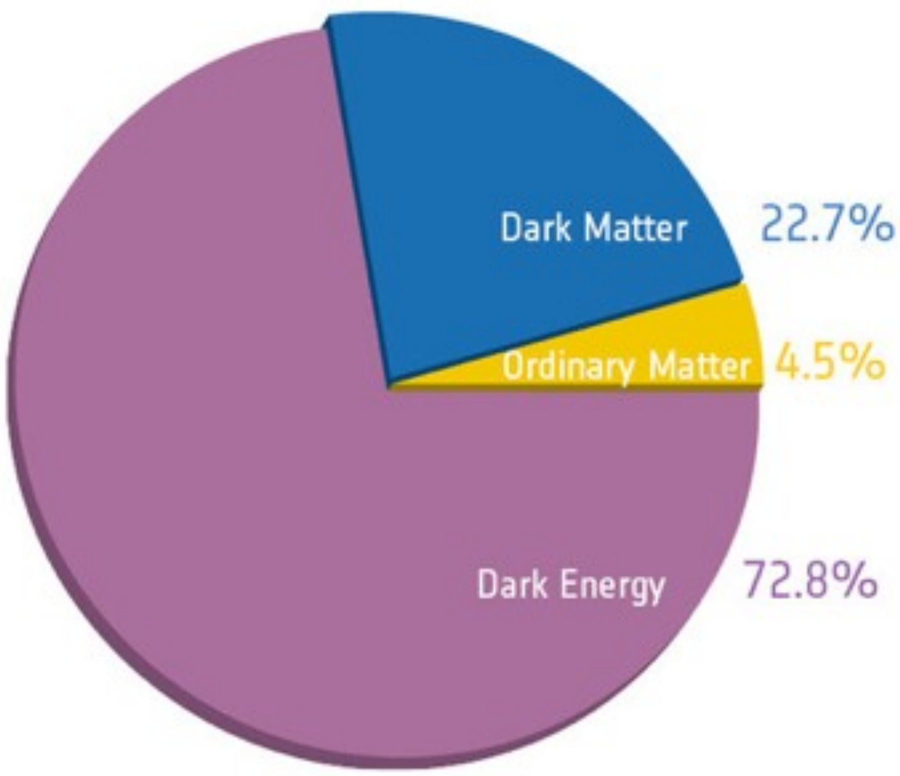


Before Planck

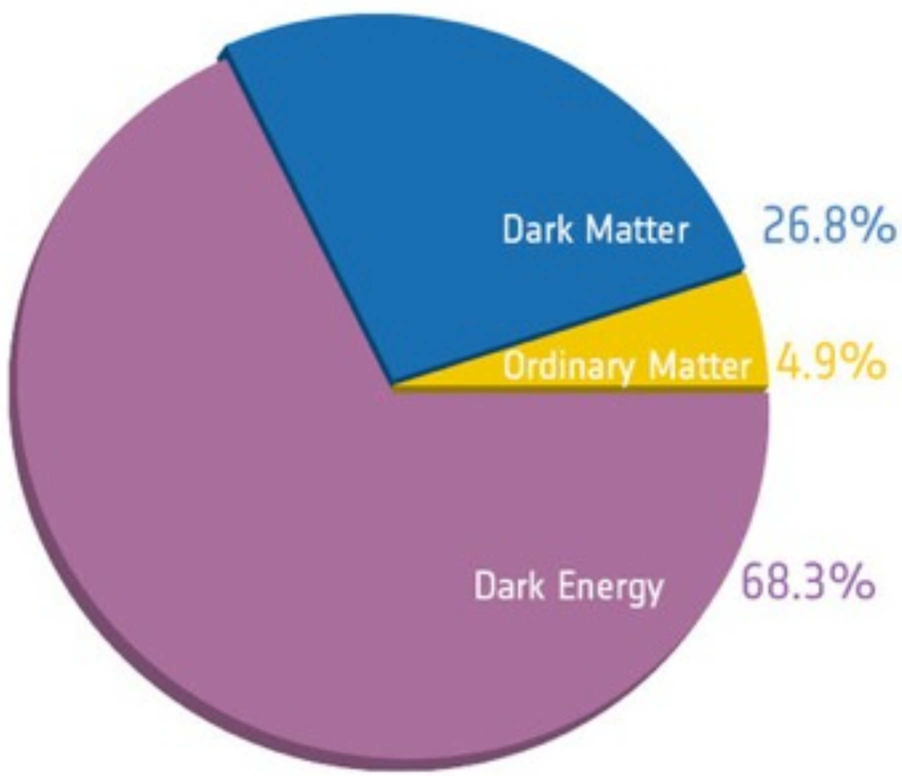


After Planck

A quick summary of the current status of cosmology



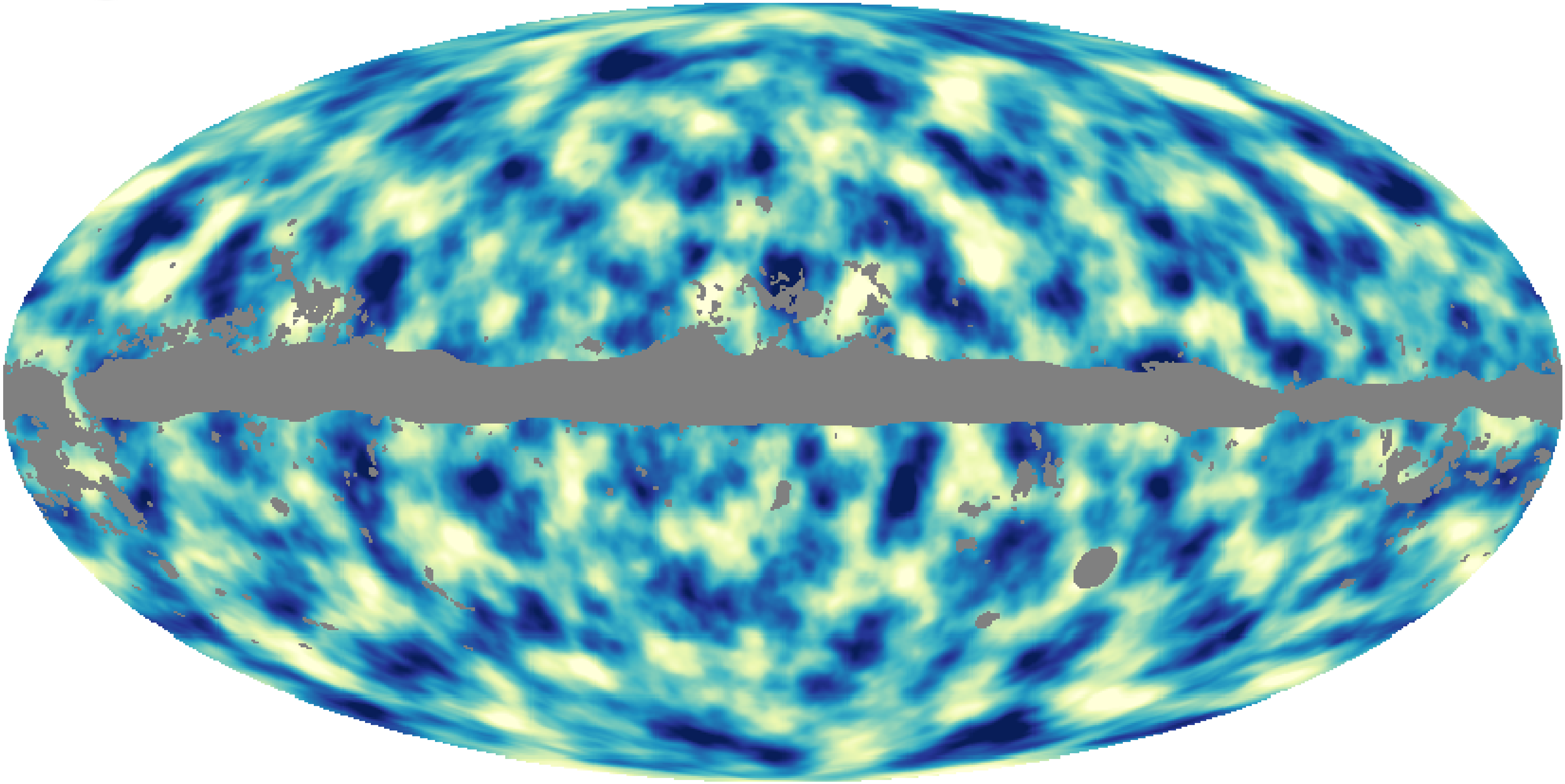
Before Planck



After Planck

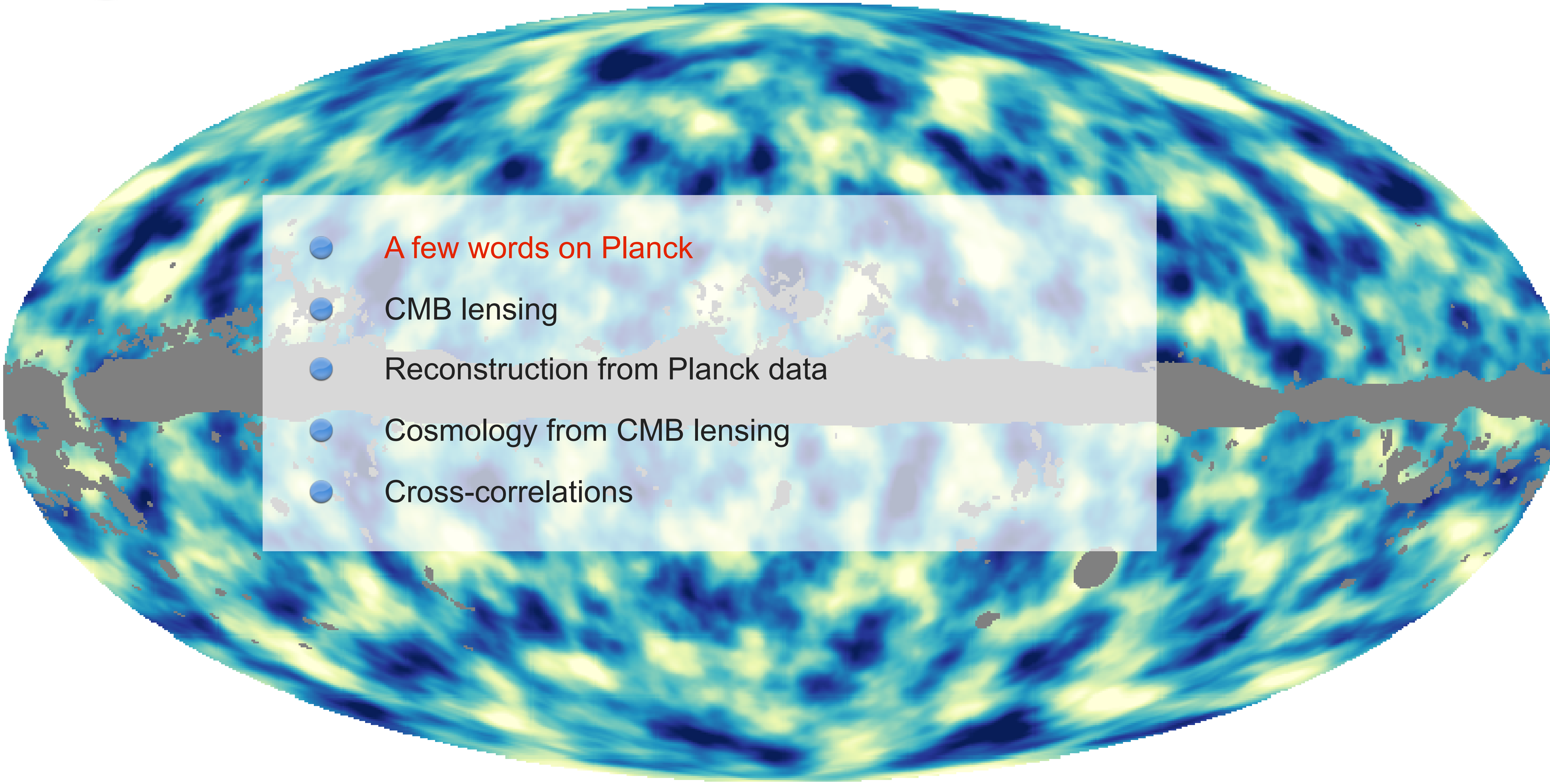
We still have no idea what Dark Energy is

The matter in the Universe



Planck picture of the matter distribution at z~2

Outline

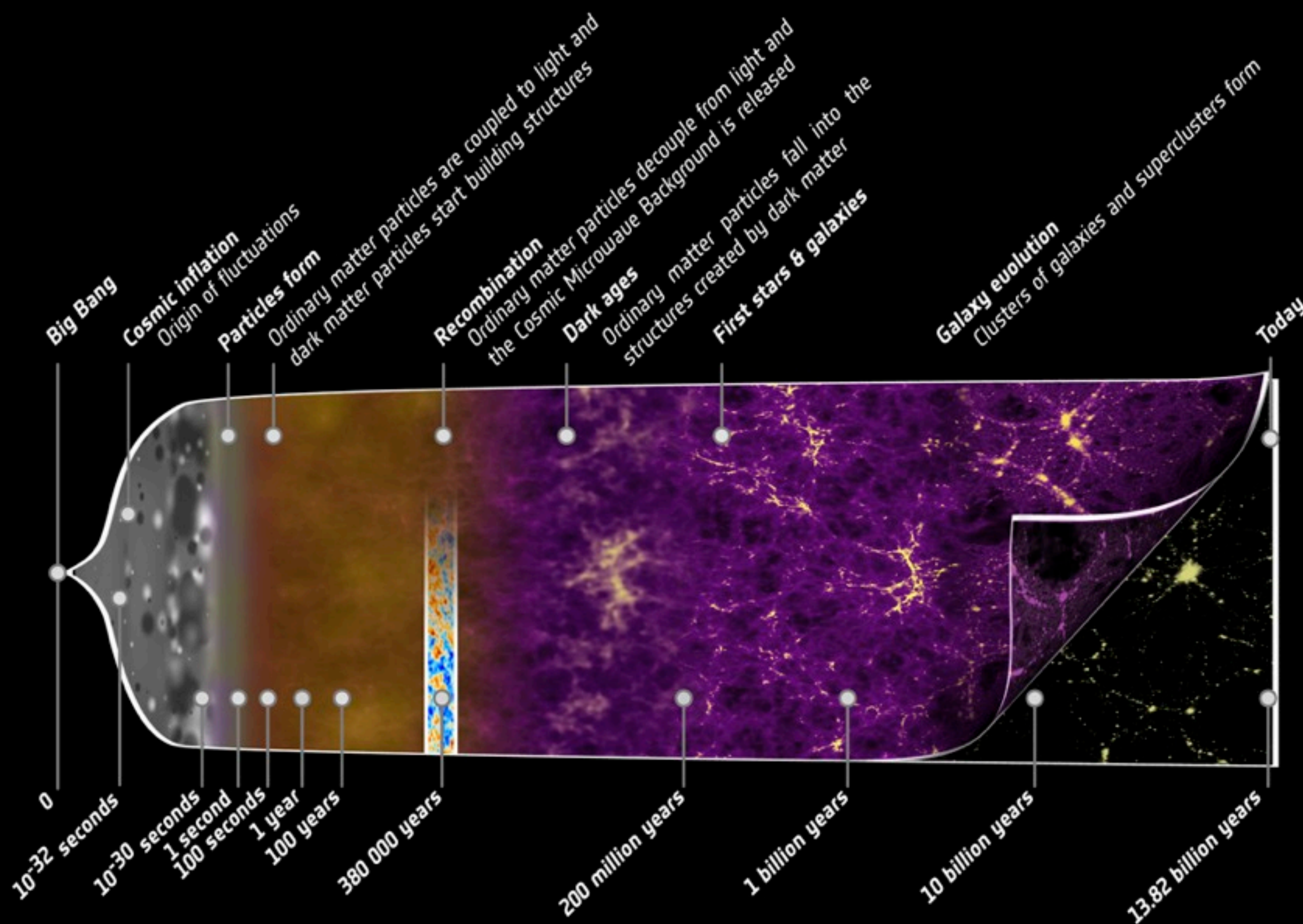


- A few words on Planck
- CMB lensing
- Reconstruction from Planck data
- Cosmology from CMB lensing
- Cross-correlations

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.

A (very) schematic history of our Universe



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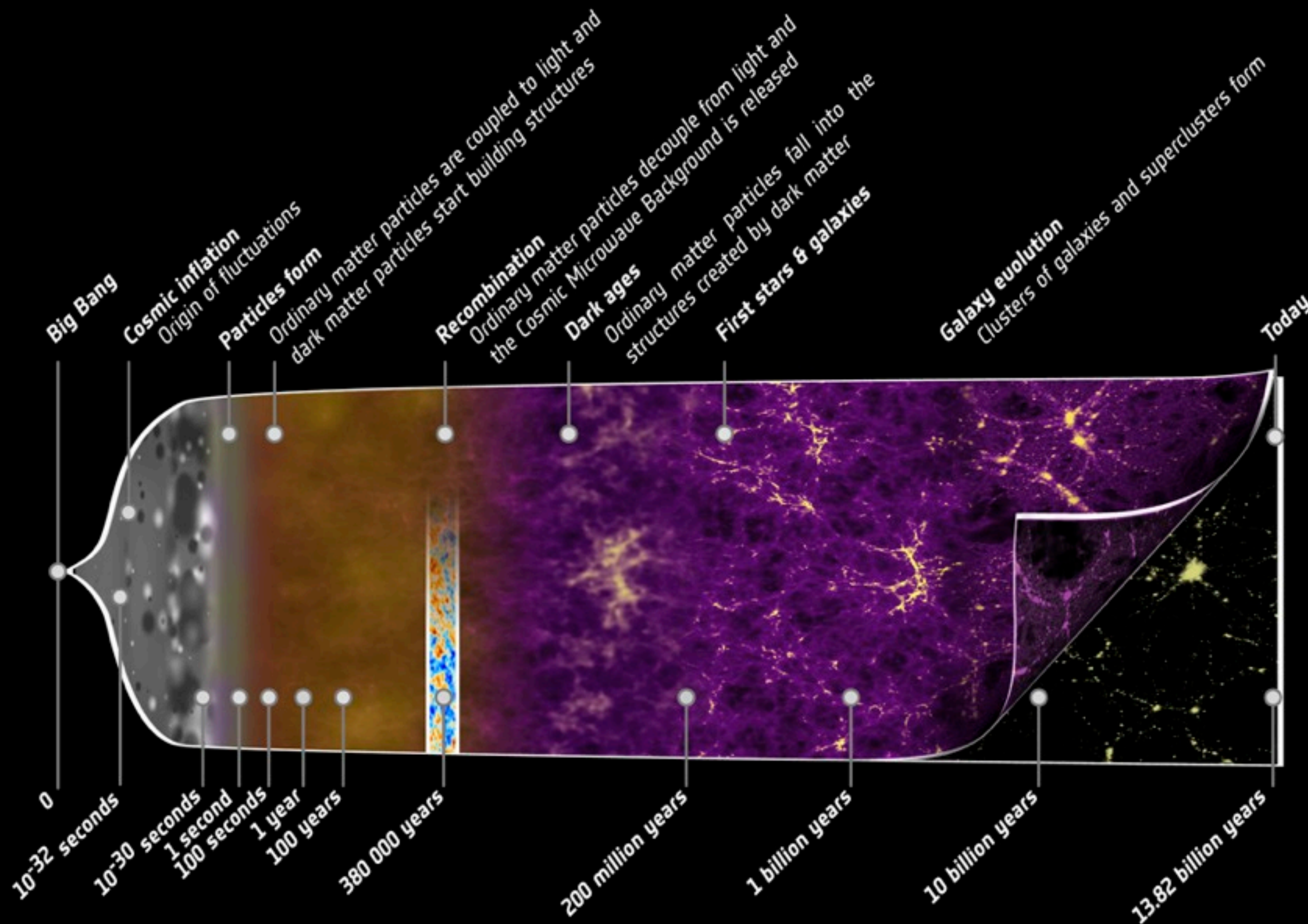
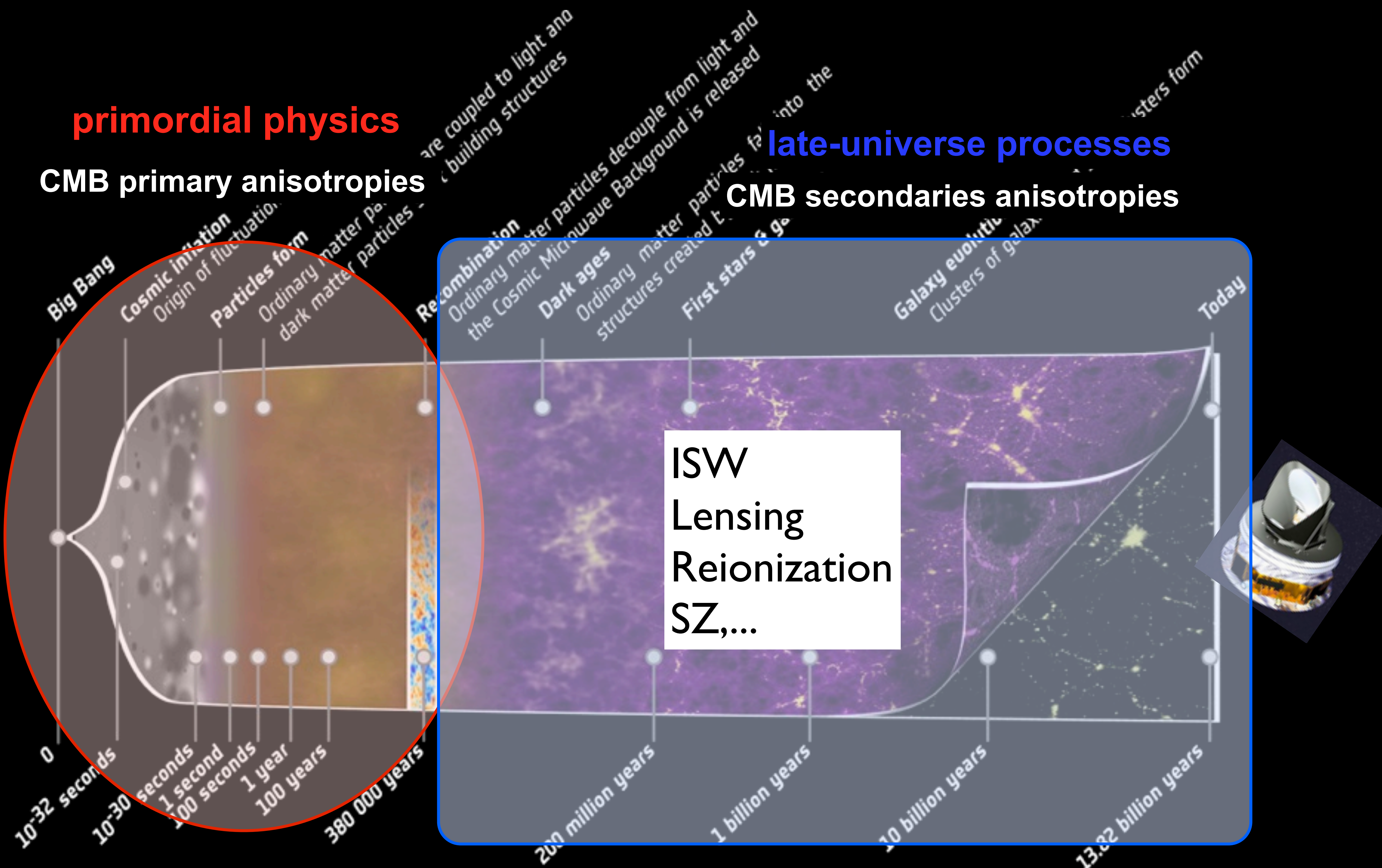
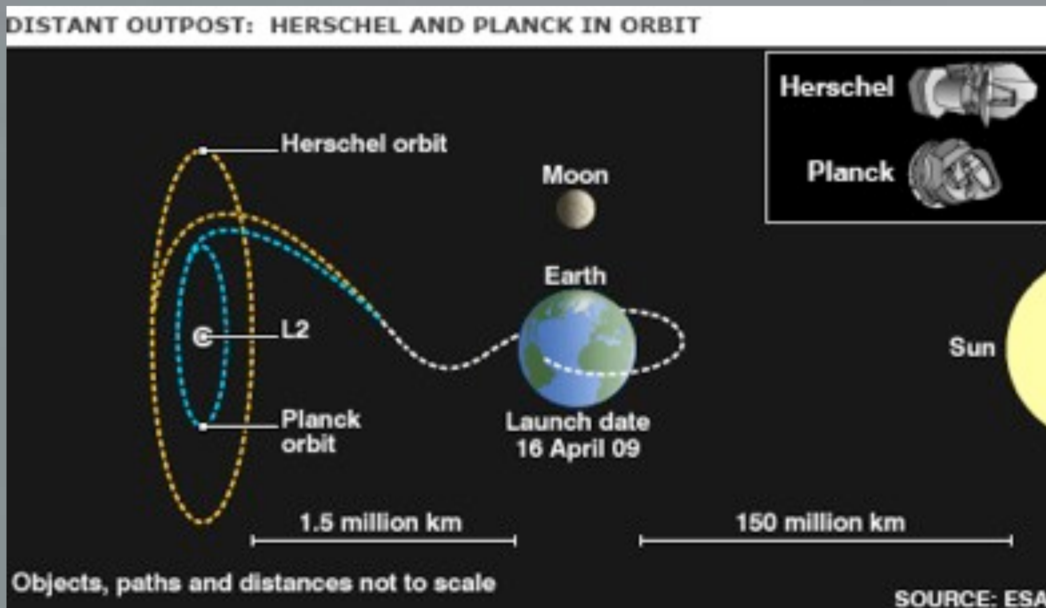
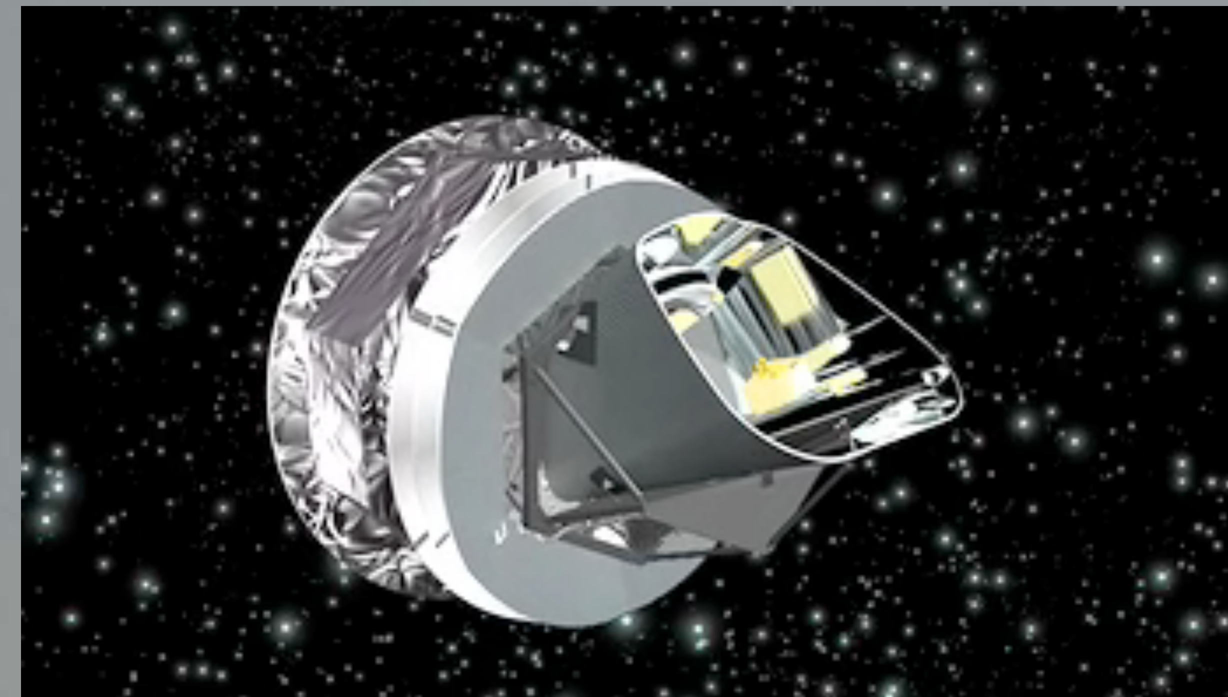


CMB: central observation in cosmology



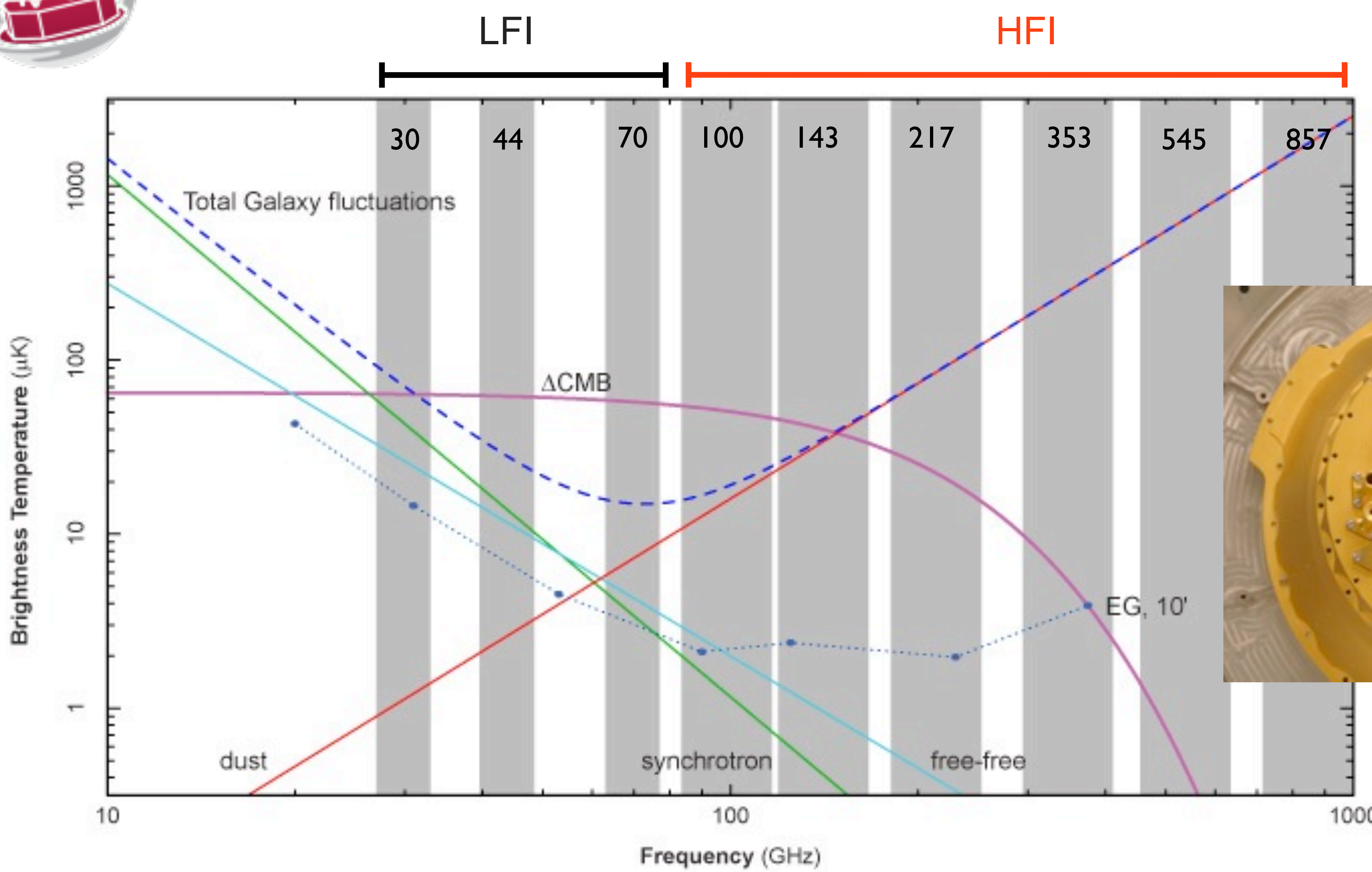


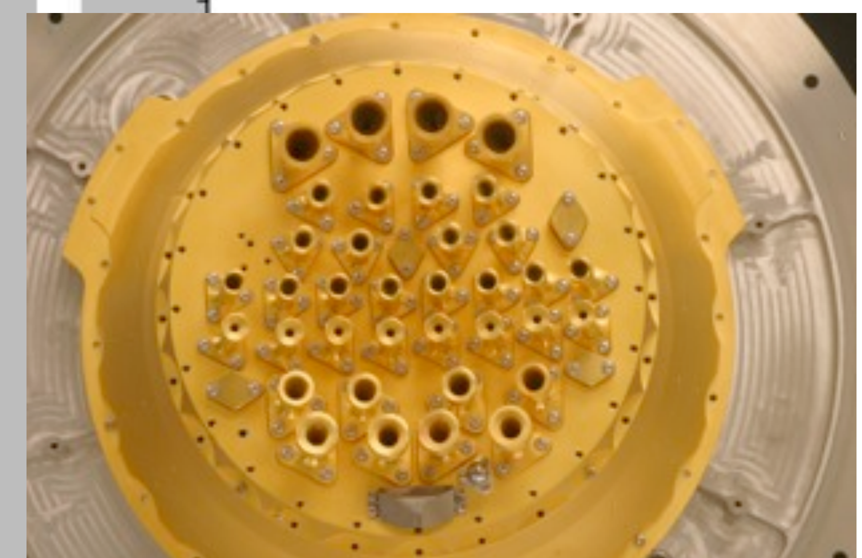


- Proposed to ESA in 1993, selected in 1996
- Launched on May 14th 2009
- First complete coverage of sky in June 2010
- Nominal mission completed in November 2010
- End of light (HFI) January 14th 2012. 32 months after launch
- March 2013: First cosmological data release
- August 2013: Departure manoeuvre from L2. 1554 days of mission. 8 LFI surveys
- Full release in 2014

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

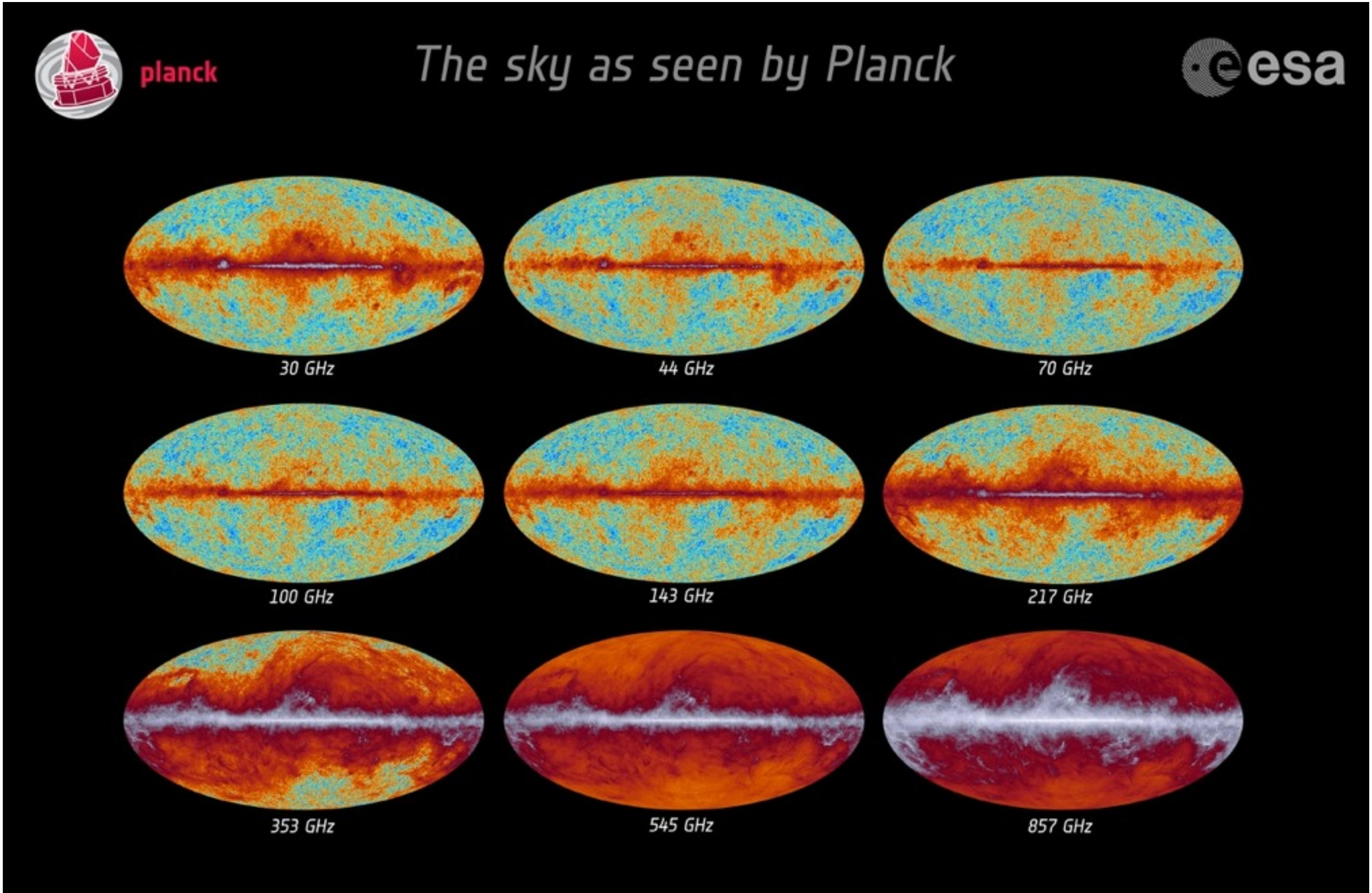
Planck frequency coverage



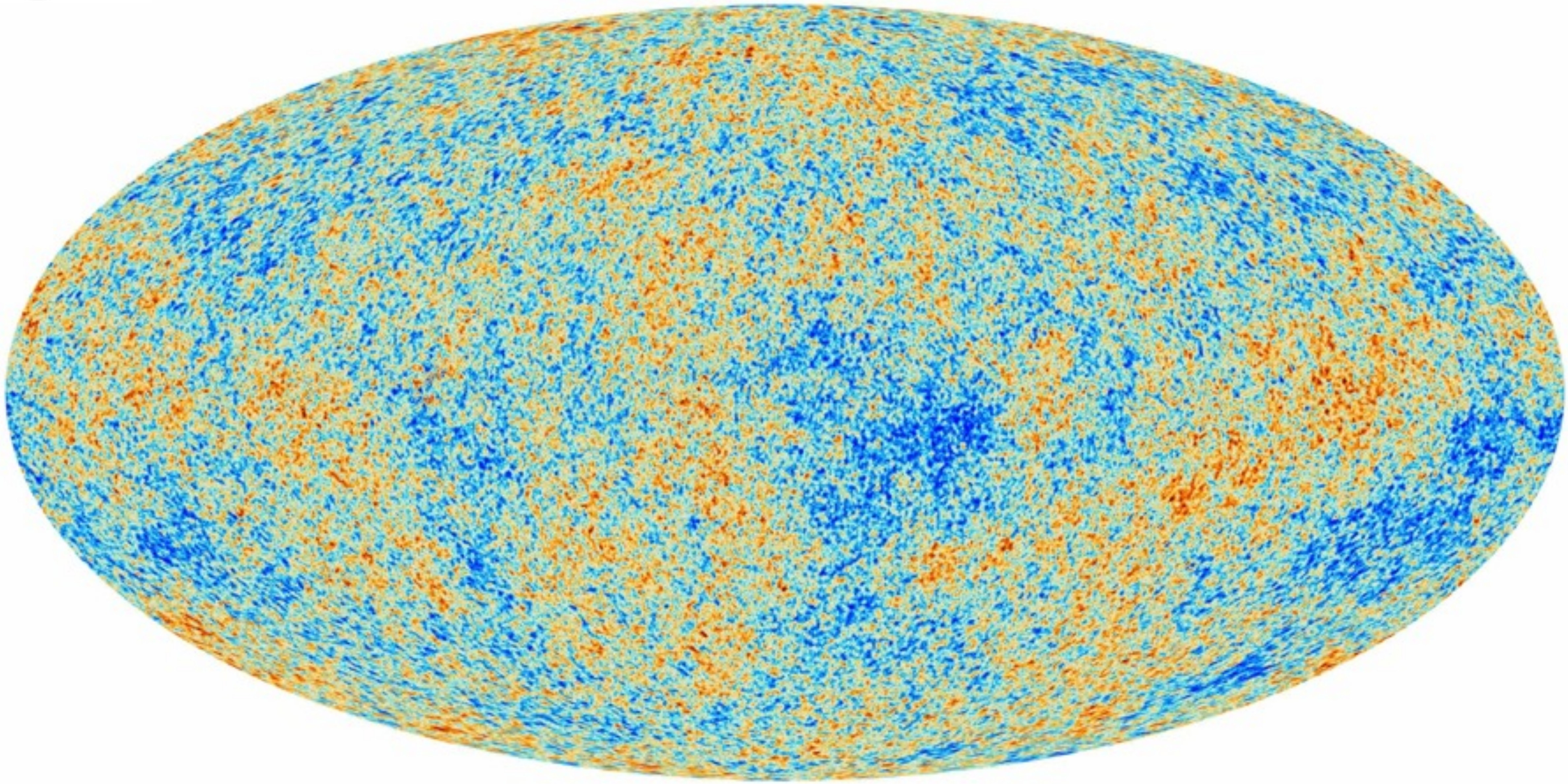


PLANCK	LFI			HFI					
Center Freq (GHz)	30	44	70	100	143	217	353	545	857
Angular resolution (FWHM arcmin)	33	24	14	10	7.1	5.0	5.0	5	5
Sensitivity in I [μK.deg] [$\sigma_{pix}\ \Omega_{pix}^{1/2}$]	3.0	3.0	3.0	1.1	0,7	1.1	3.3	33	3.0

Planck frequency coverage



Full-sky temperature map

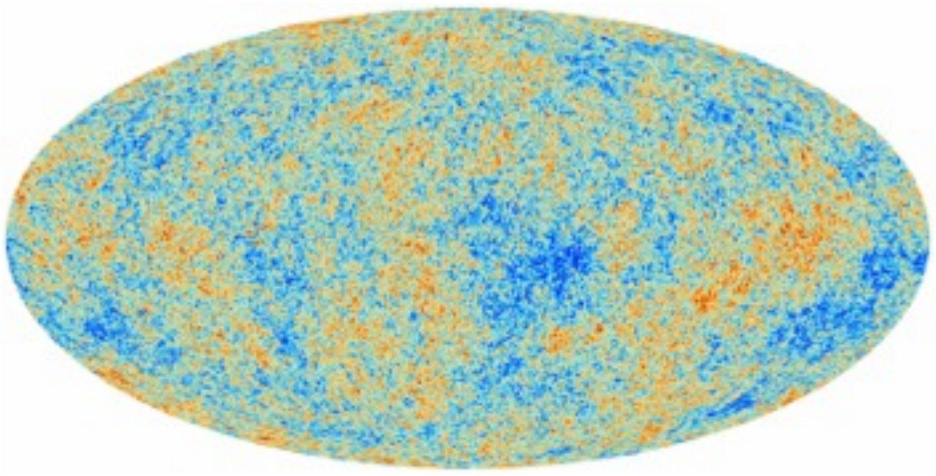


- 3% sky fraction filled with Gaussian constrained realisations

Cosmic Microwave Background

- Decompose the temperature on the sphere $T(\hat{\mathbf{n}}) \longrightarrow T_{\ell m}$

$T(\hat{\mathbf{n}})$



$T_{\ell m}$

```
-1.36393664e-06 +1.78900125e-07j,
 3.48160018e-07 +5.48607128e-07j,
 8.64414116e-07 +1.58062970e-06j,
 2.32962756e-07 +1.72990879e-07j,
 2.07366735e-07 -1.48637056e-06j,
 1.33636760e-06 +1.44430207e-06j,
-1.33047477e-06 +1.49222938e-06j,
 2.01588688e-07 +1.39367943e-08j,
 1.20185303e-06 -1.04105033e-06j,
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 3.98739296e-07 +1.19163879e-07j,
-1.24503110e-06 -1.93401840e-06j,
 5.68052758e-07 +6.49802586e-08j,
 5.05386856e-07 -2.28955226e-07j,
-2.60272490e-07 +2.21246718e-06j,
-1.11889361e-06 +1.87312956e-06j,
 9.72080476e-07 -6.89214224e-07j,
 3.26351028e-07 +1.08530943e-06j,
 2.14977119e-06 -9.44341599e-07j,
```

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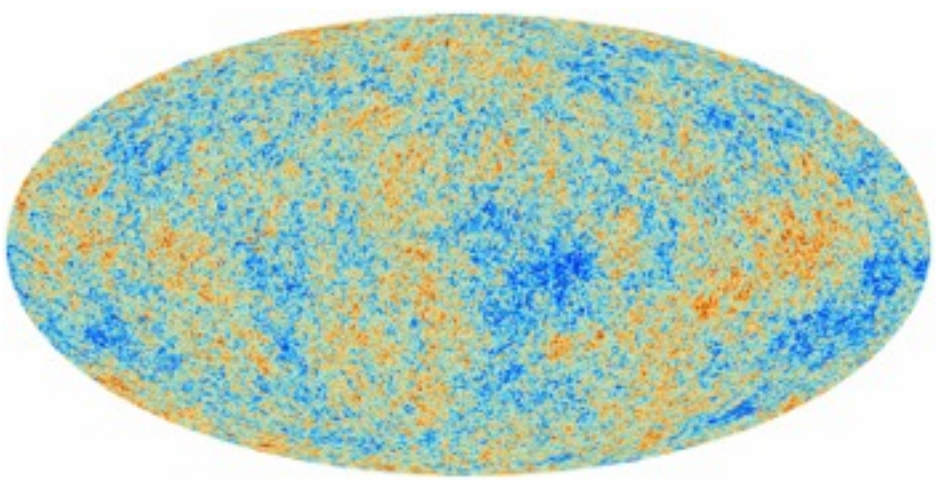

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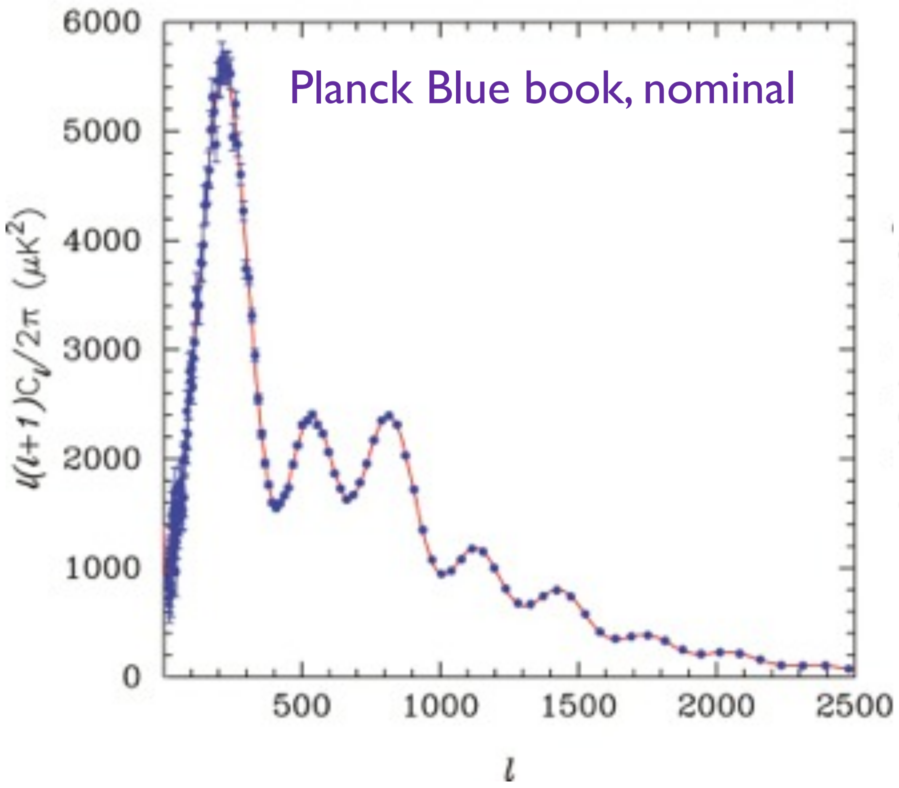
```

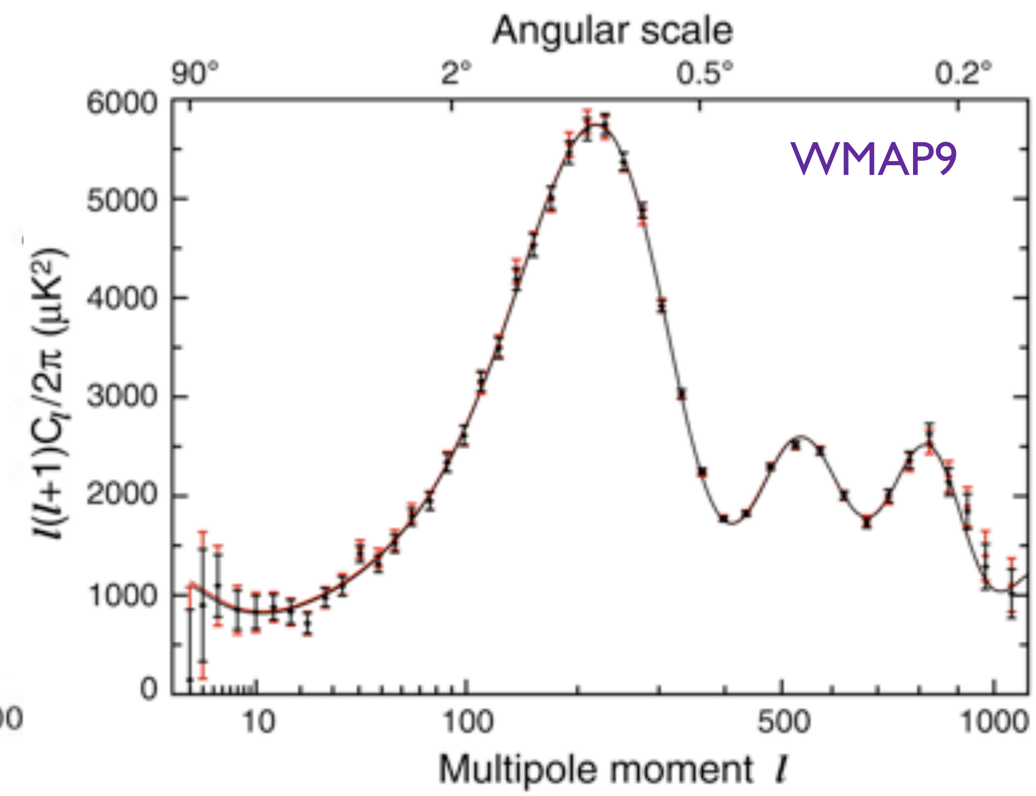
- CMB is (almost) Gaussian: all the information is in the variance $\langle t_{\ell m} t^*_{\ell' m'} \rangle = C_\ell$

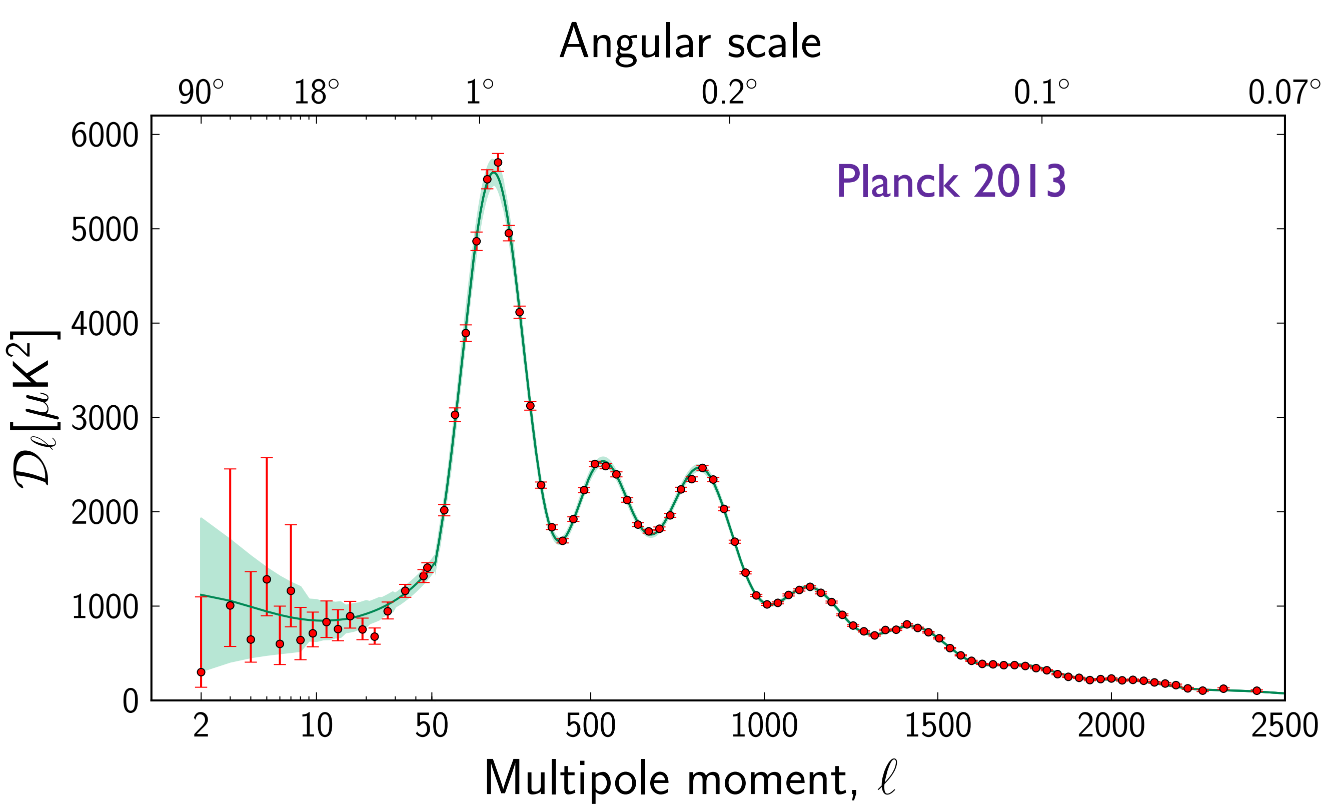
  Power spectrum can be computed: e.g. CAMB

  Can be measured from observations: e.g. pseudo-Cl's $\hat{C}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |T_{\ell m}|^2$

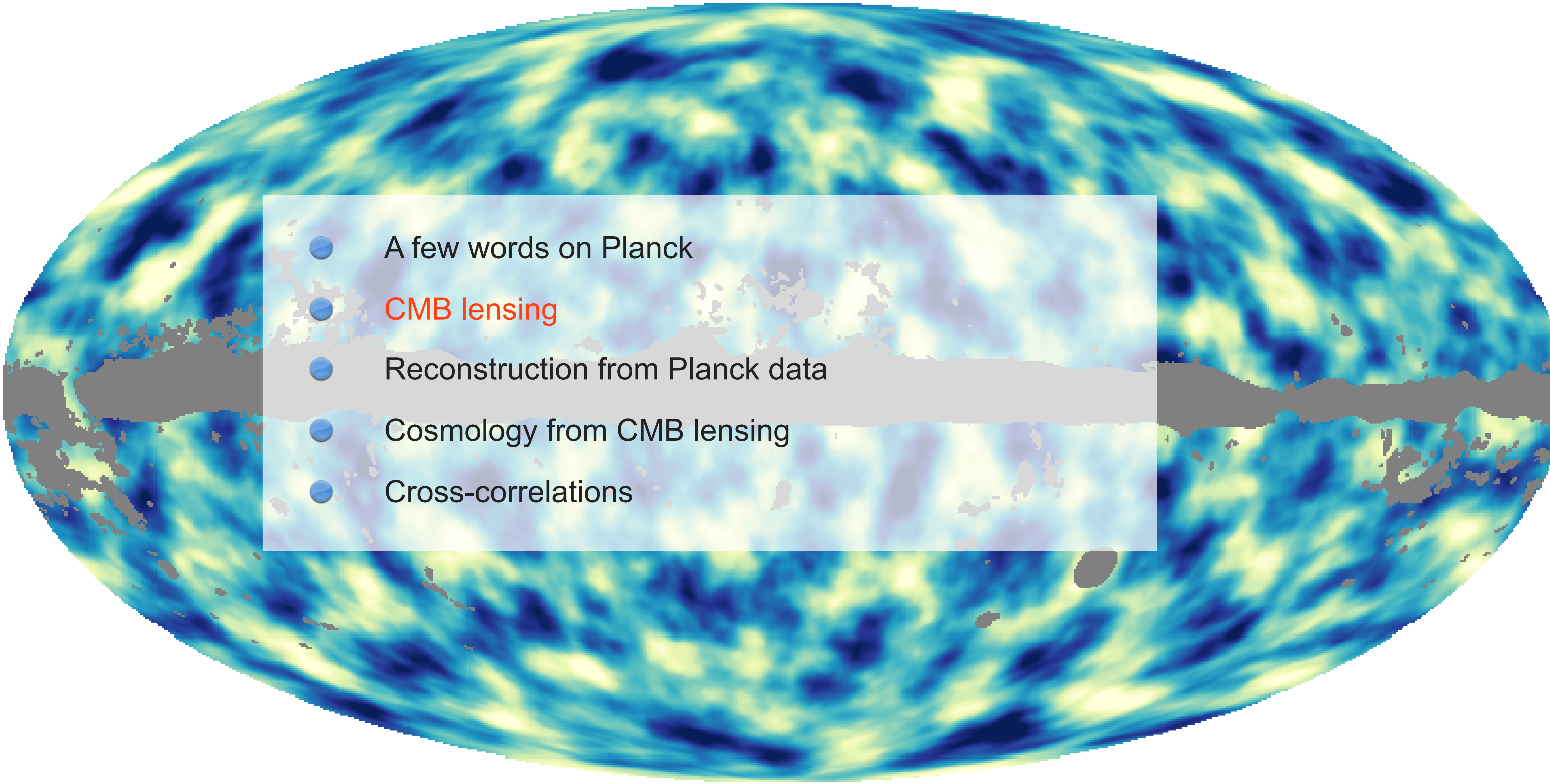
Cosmic Microwave Background







Outline



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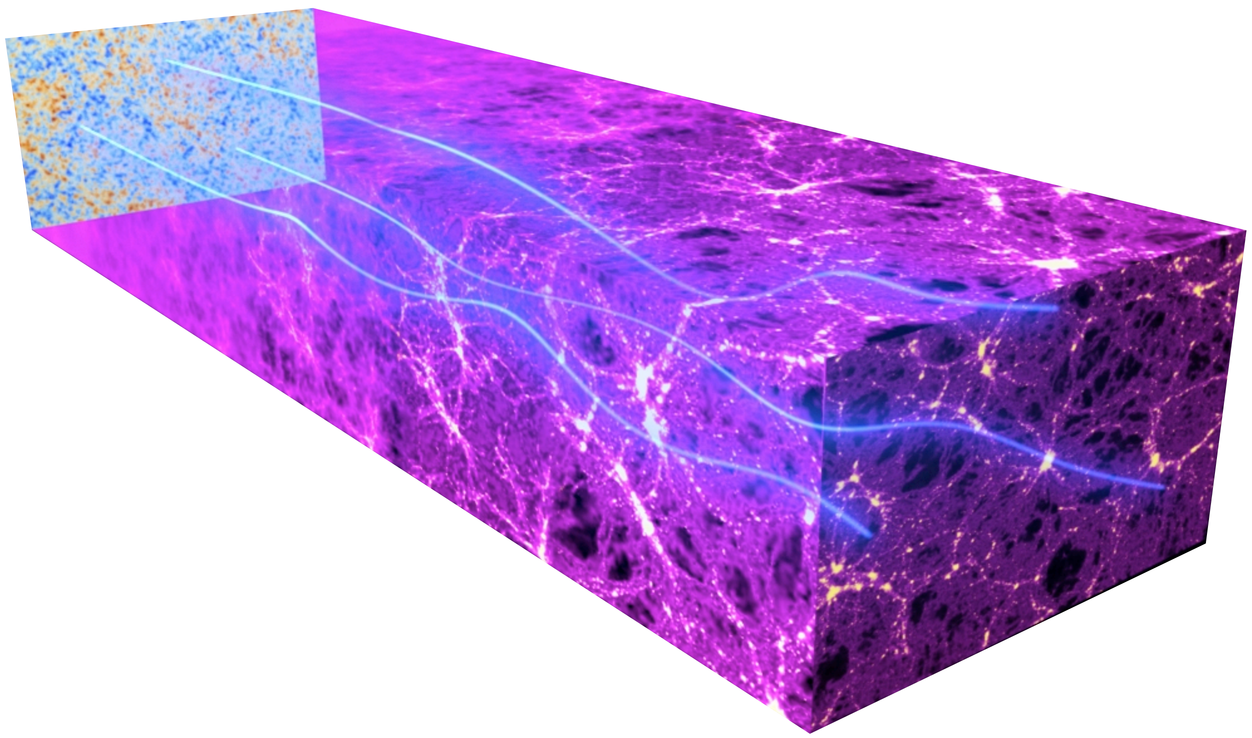
CMB lensing



Typical deflection δβ sourced by potential Ψ

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

Potential well size ~ 300 Mpc
Distance to last scattering surface ~ 14 000 Mpc

Photons encounter ~ 50 potential wells

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

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

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

The lensing potential

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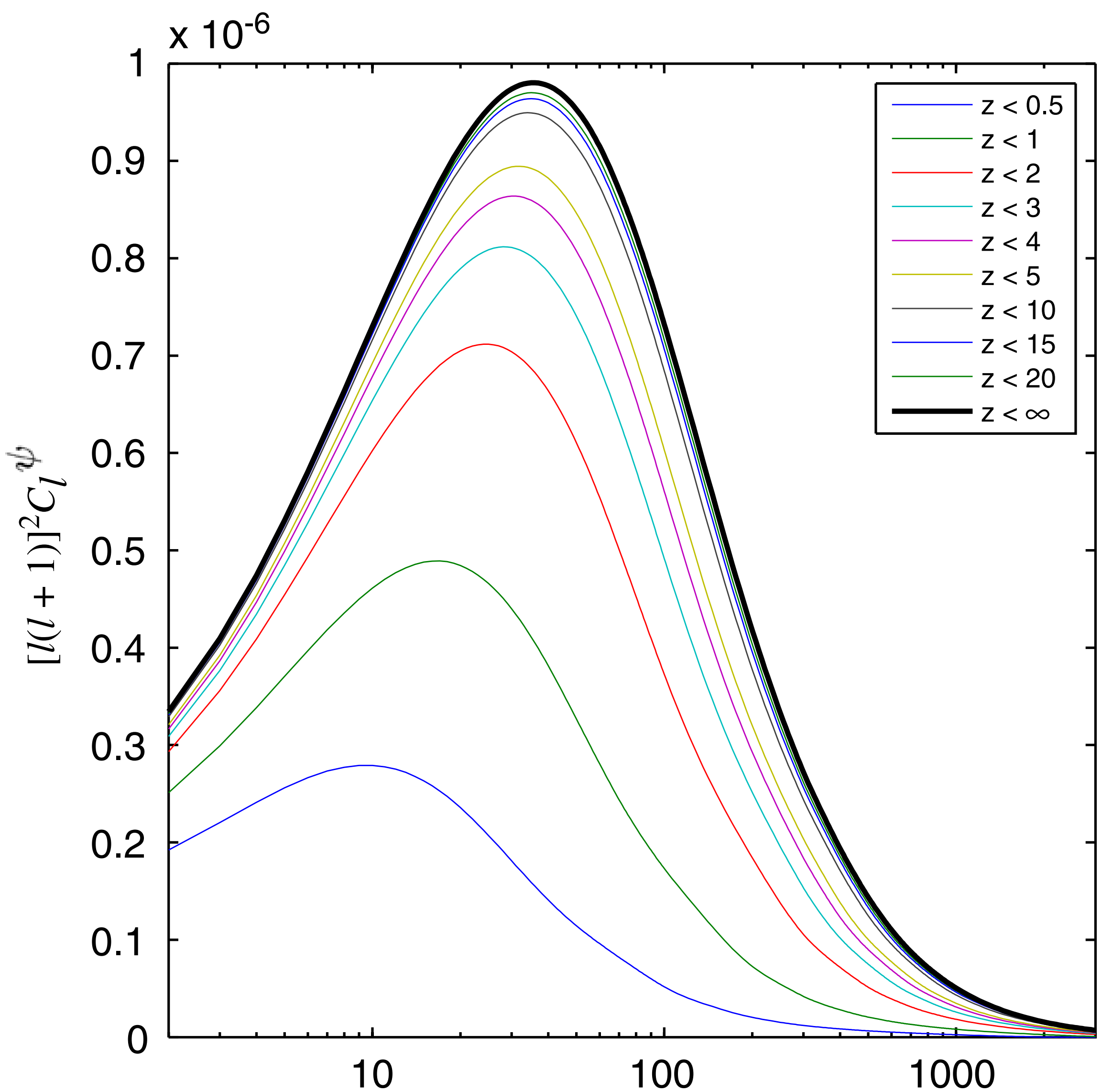
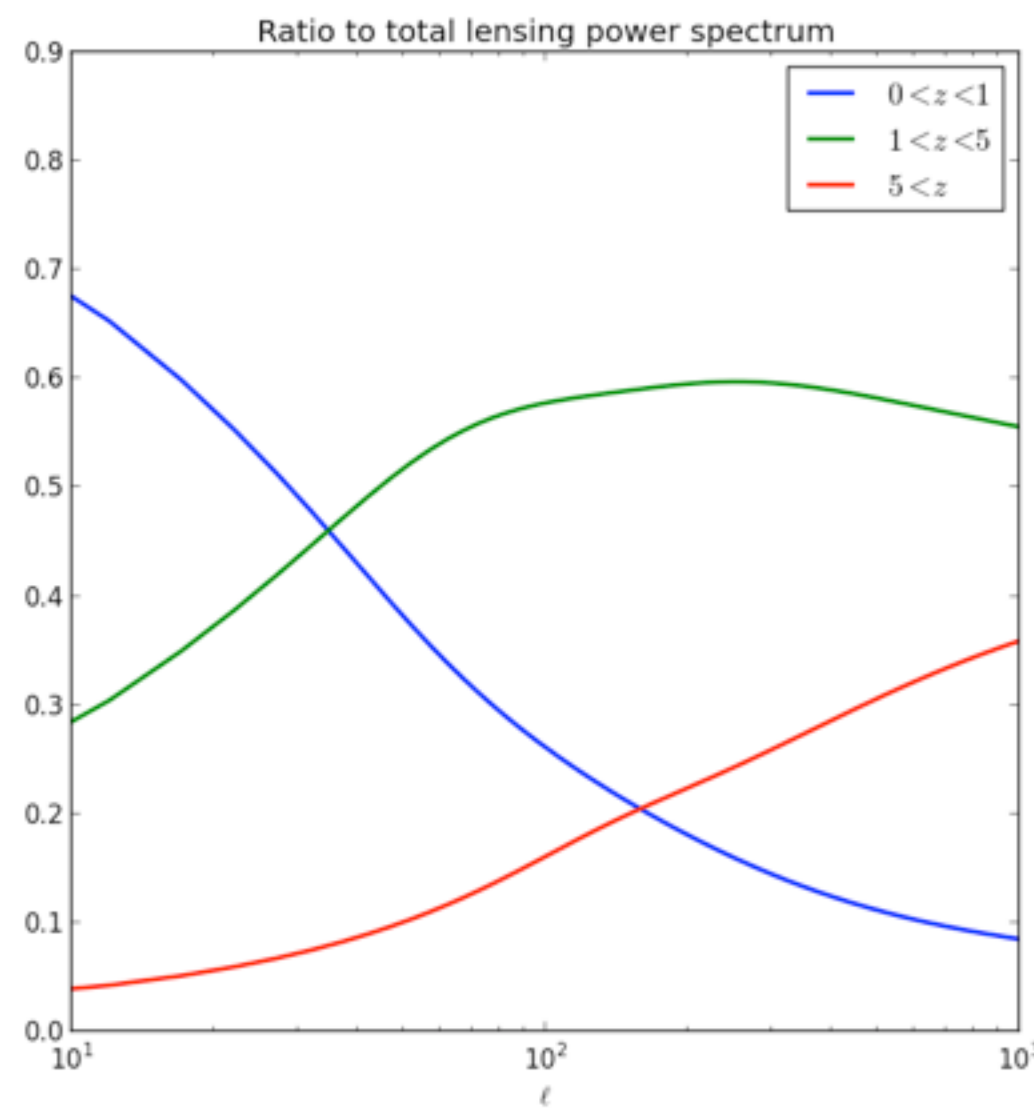
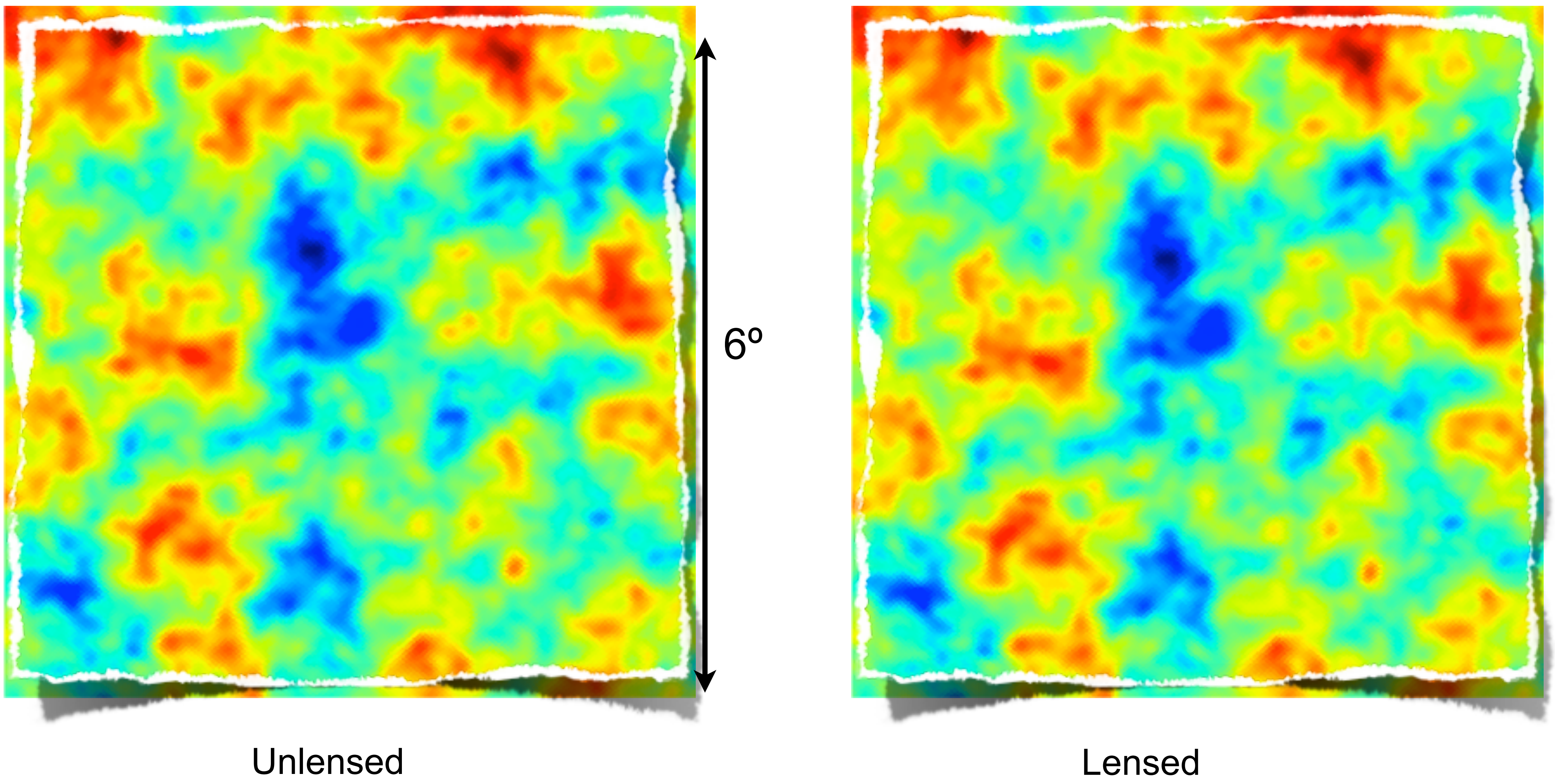


Lewis & Challinor, 2006



CMB lensing

Deflections are about 2 arcmin



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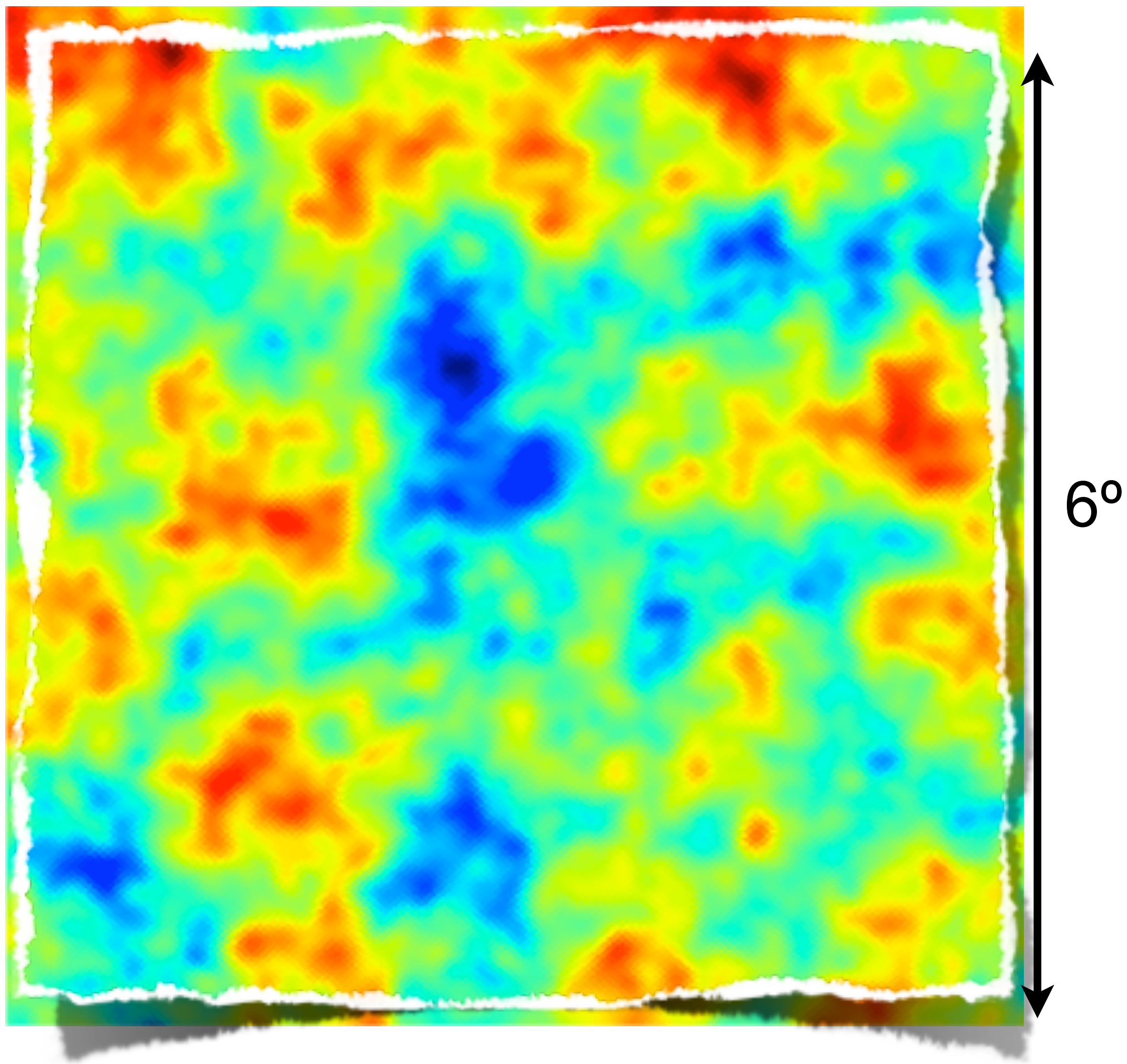
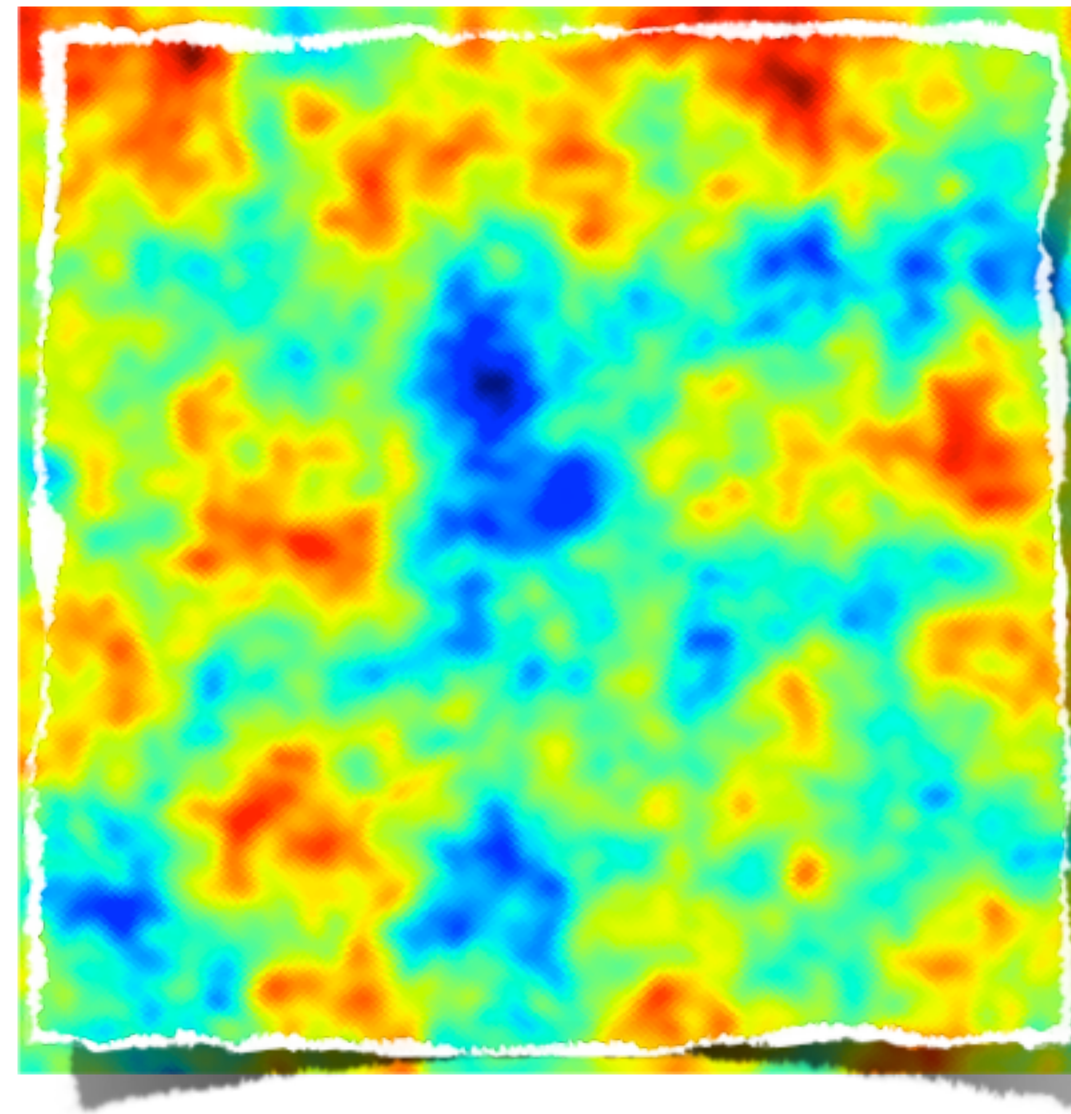


Unlensed



Unlensed

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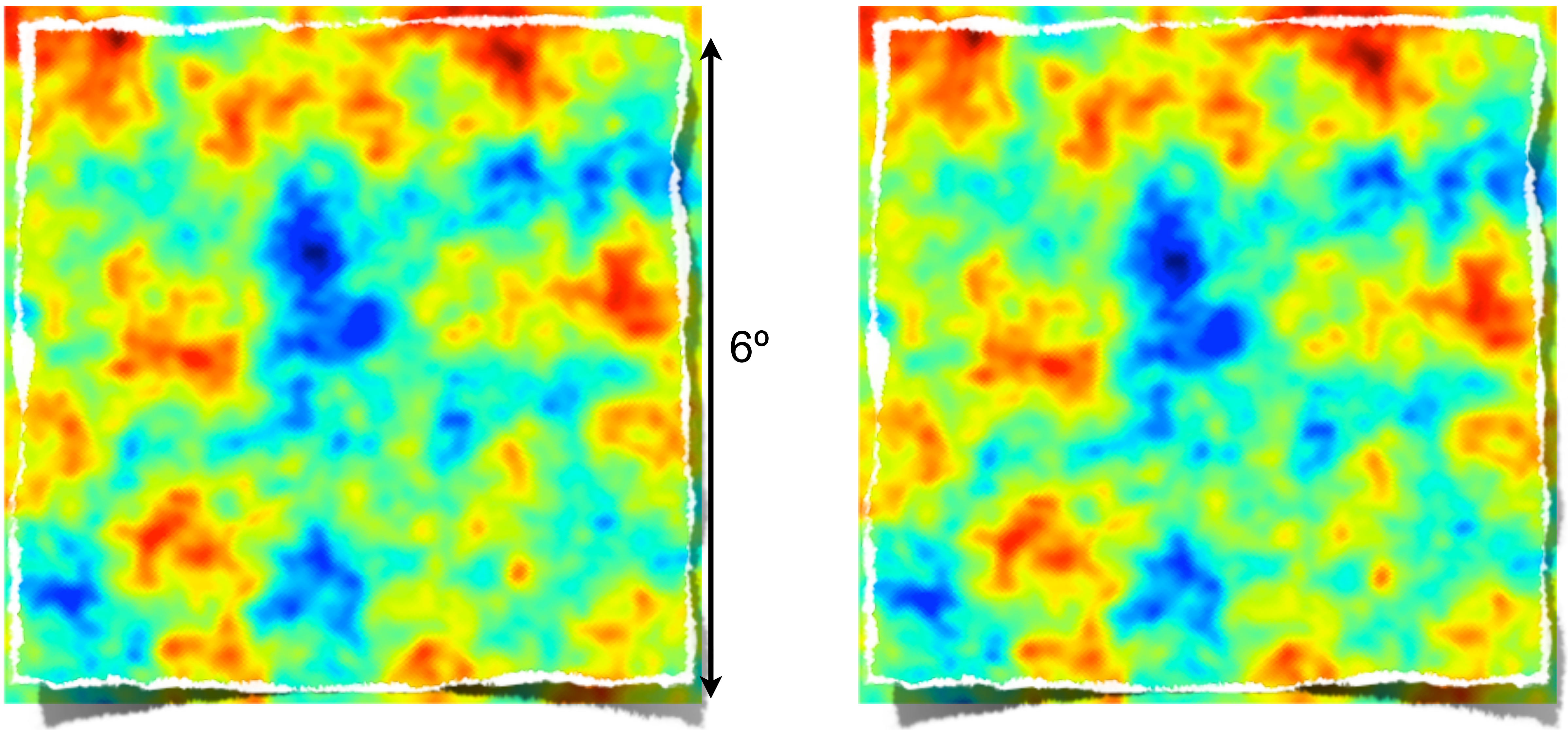

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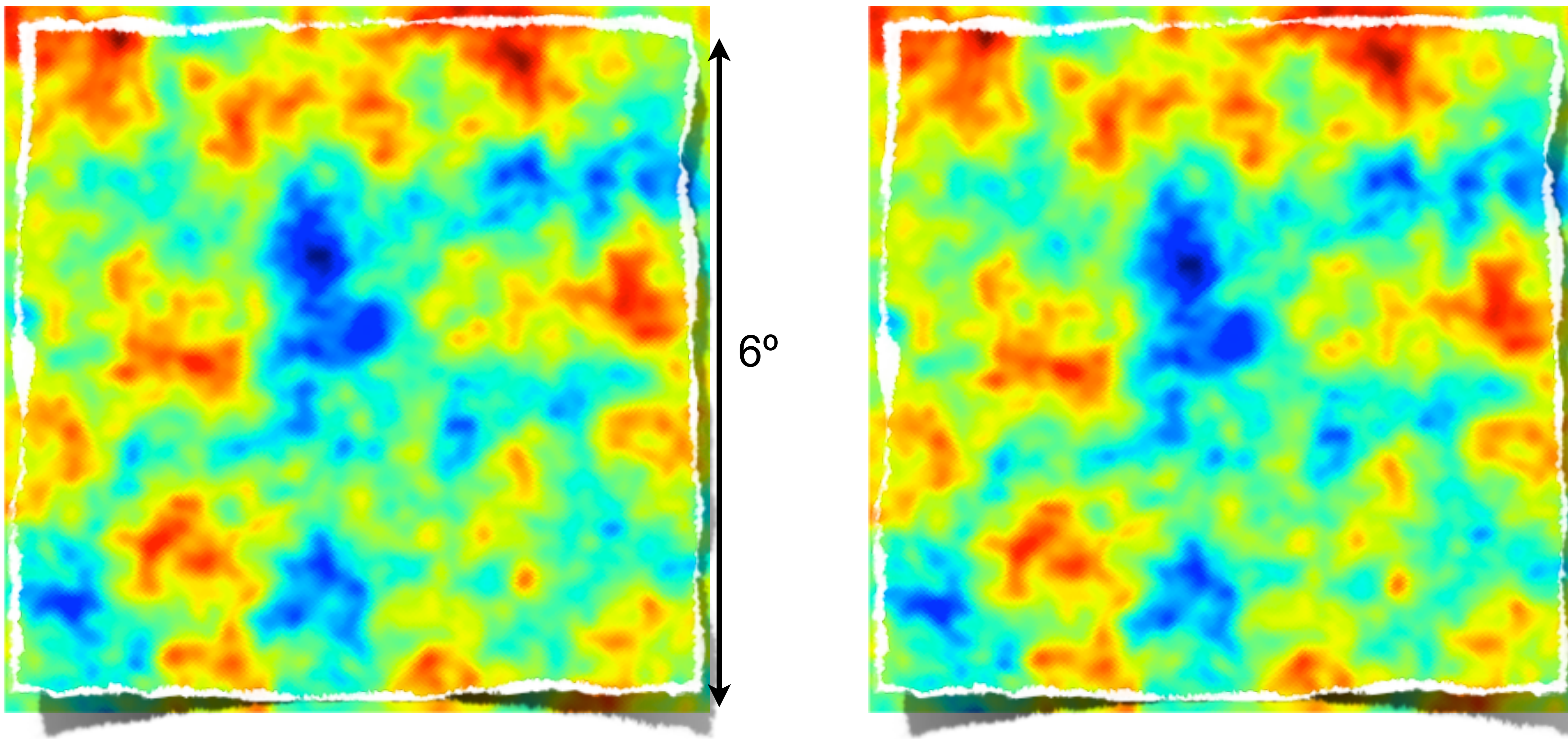


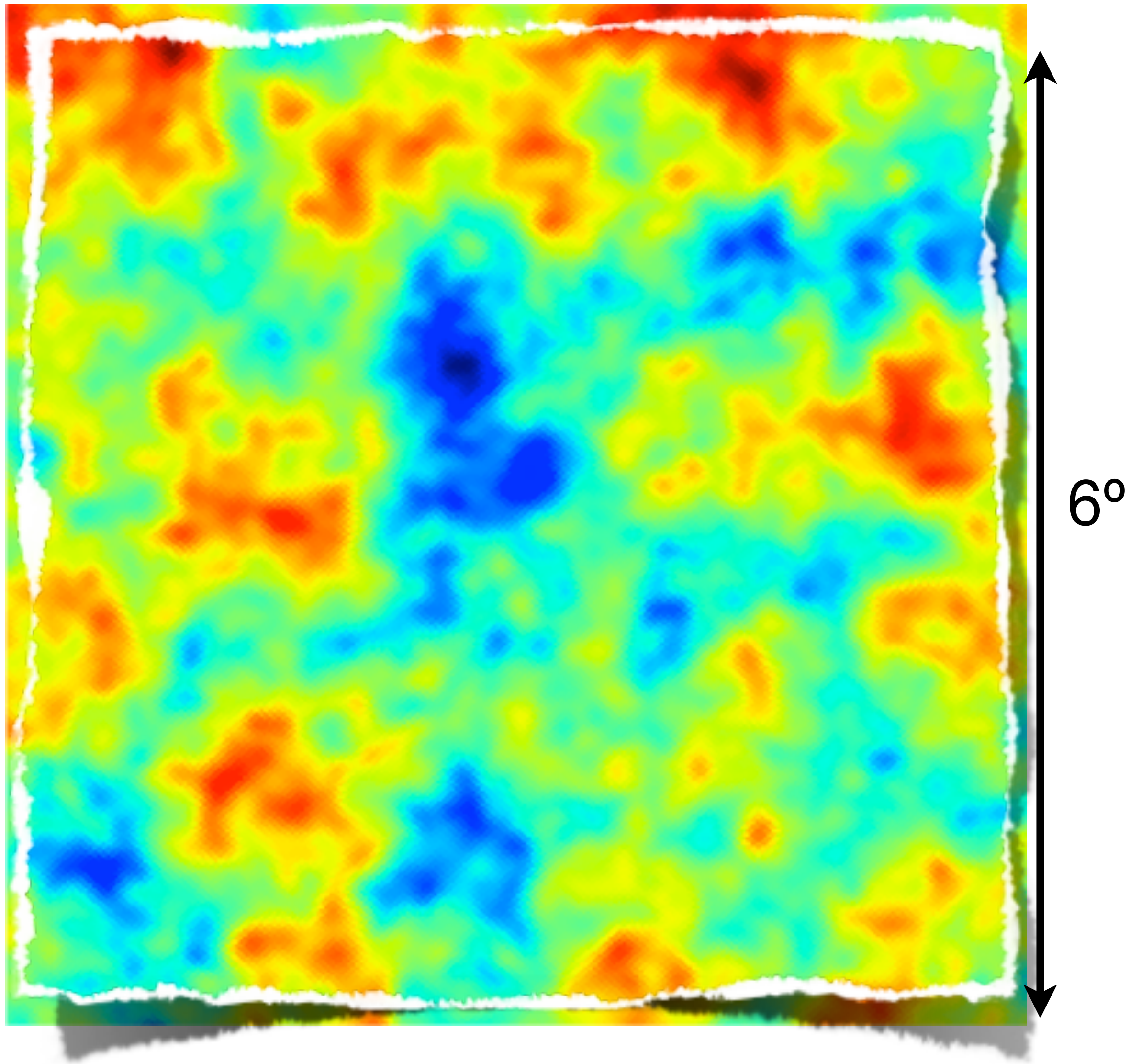
Unlensed

Lensed

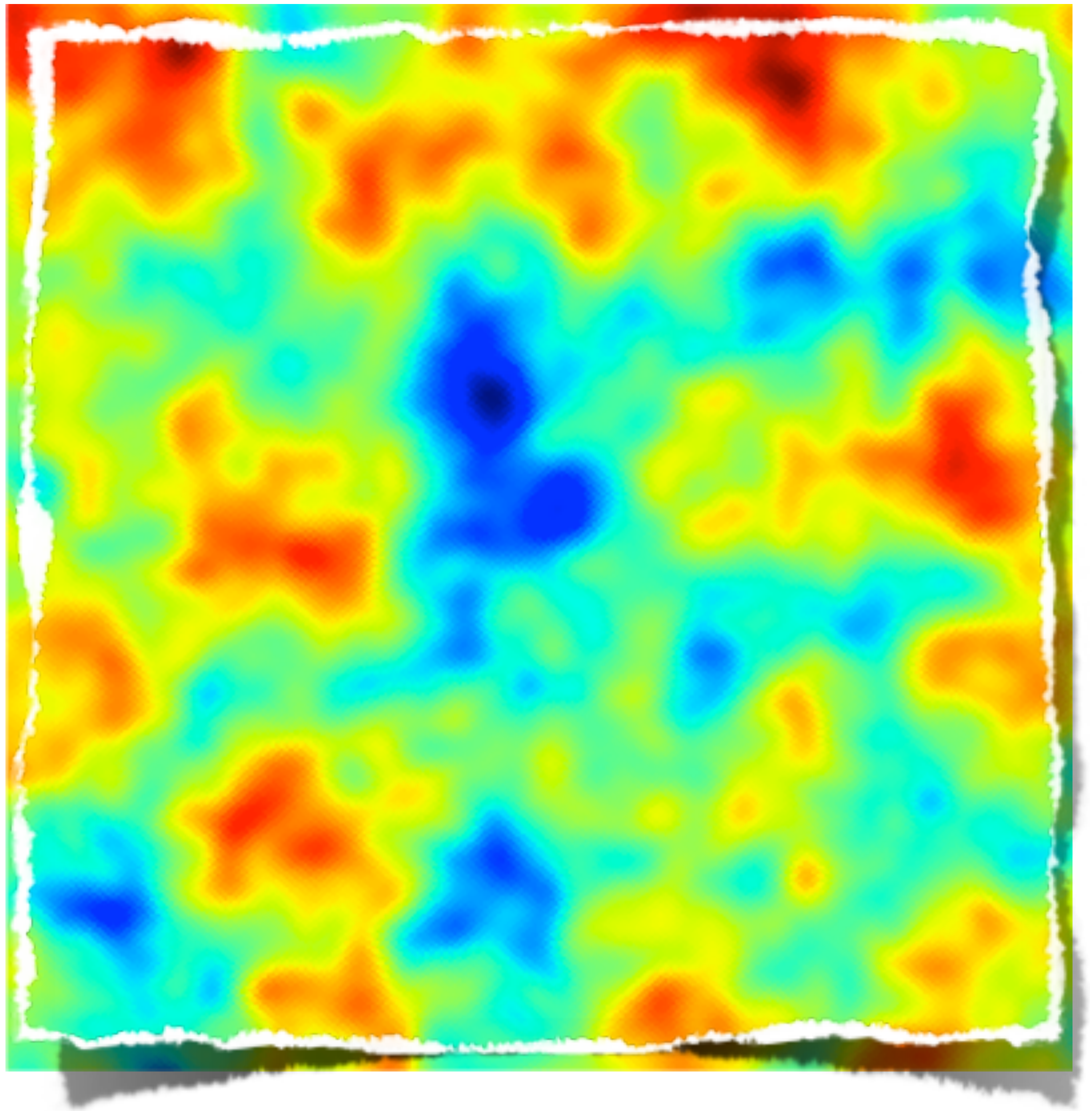
Deflections are correlated on the degree scale

CMB lensing

Deflections are about 2 arcmin



Unlensed

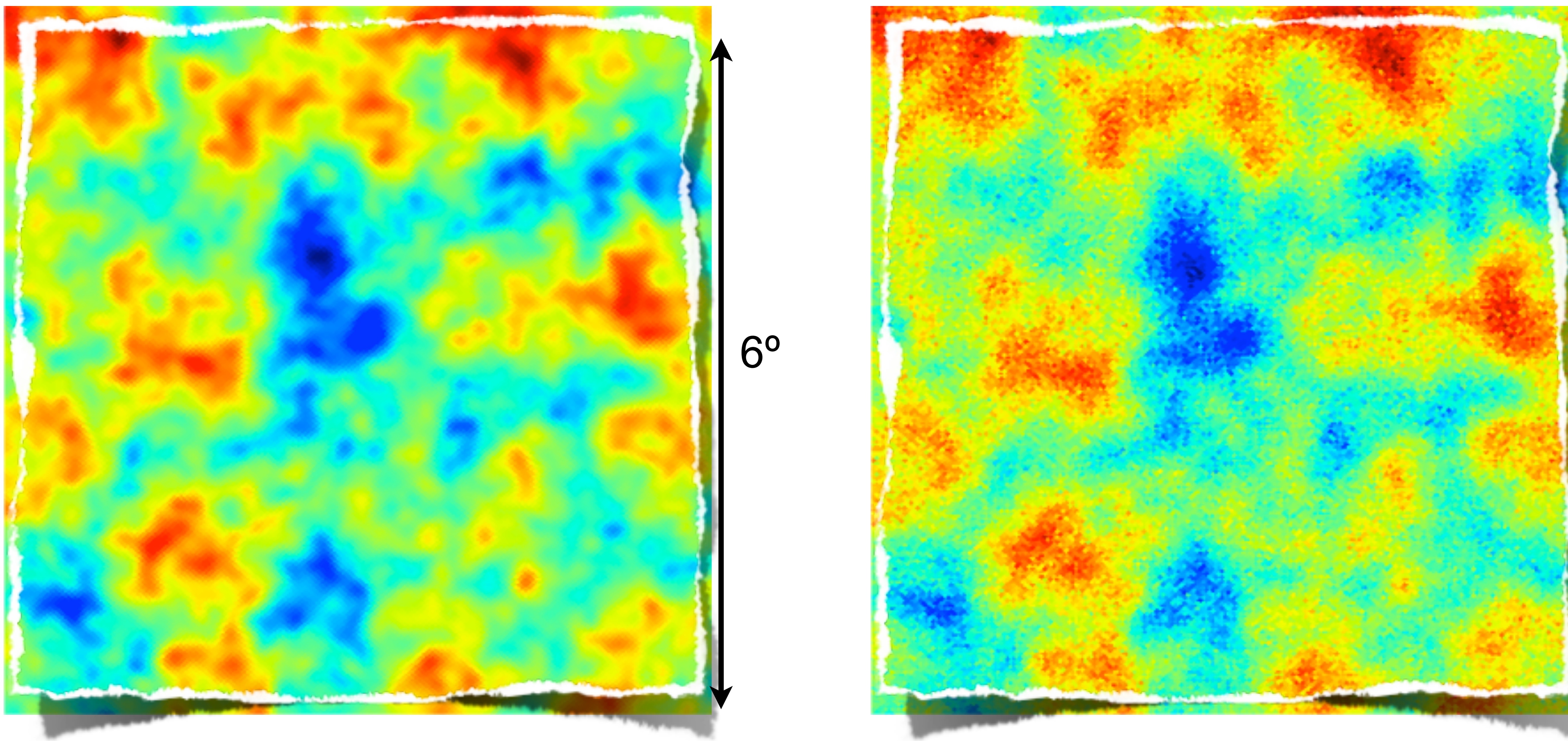


Lensed, beamed

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 temperature-gradient correlations

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

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- CMB lensing induces statistical anisotropies

$$\langle T_{\ell_1 m_1} T^*_{\ell_2 m_2} \rangle = C_{\ell_1} \delta_{\ell_1 \ell_2} \delta_{m_1 m_2}$$

Impact on CMB

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Impact on CMB

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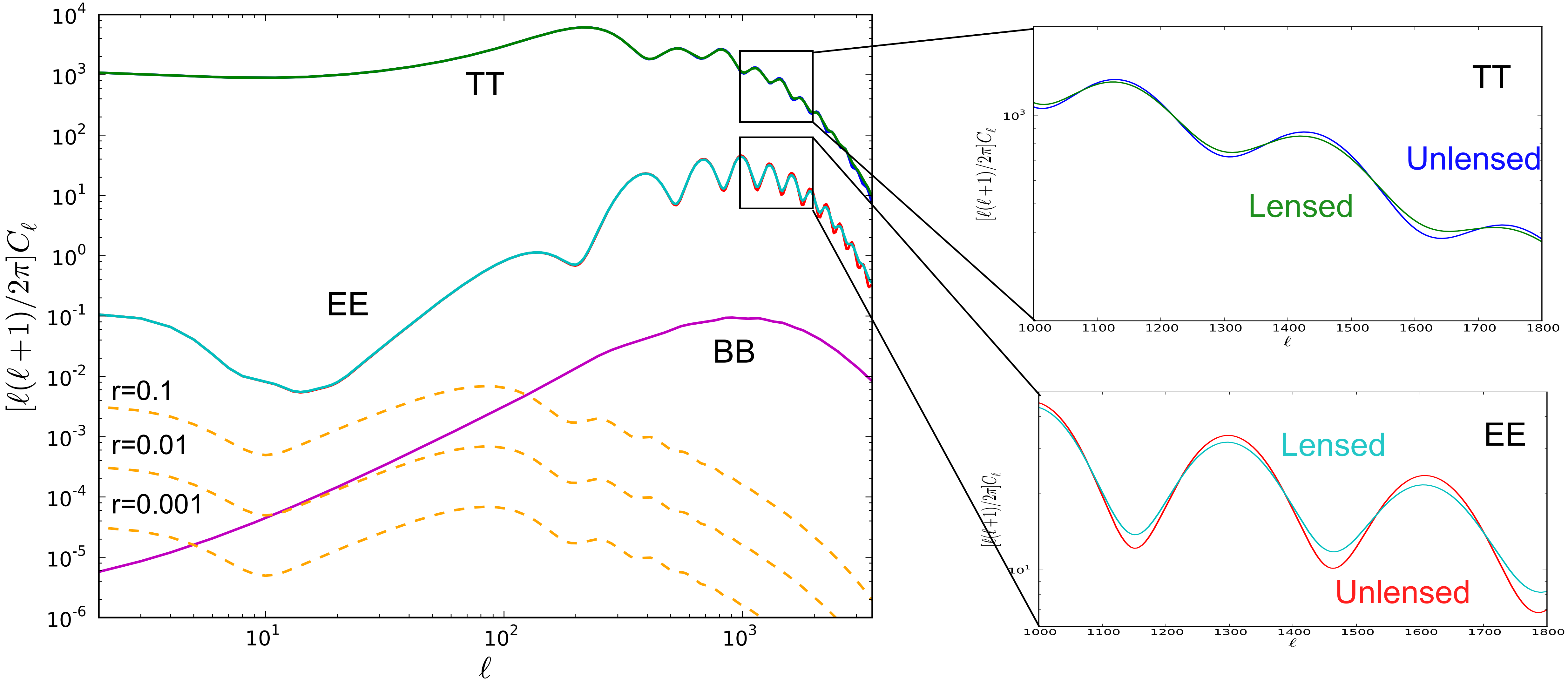
$$W^{\phi}_{\ell_1\ell_2 L} = -\sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2L+1)}{4\pi}}\sqrt{L(L+1)\ell_1(\ell_1+1)} \times C^{TT}_{\ell_1}\left(\frac{1+(-1)^{\ell_1+\ell_2+L}}{2}\right)\begin{pmatrix} \ell_1 & \ell_2 & L \\ 1 & 0 & -1 \end{pmatrix} + (\ell_1 \leftrightarrow \ell_2). \quad (6)$$

Impact on anisotropies power spectra

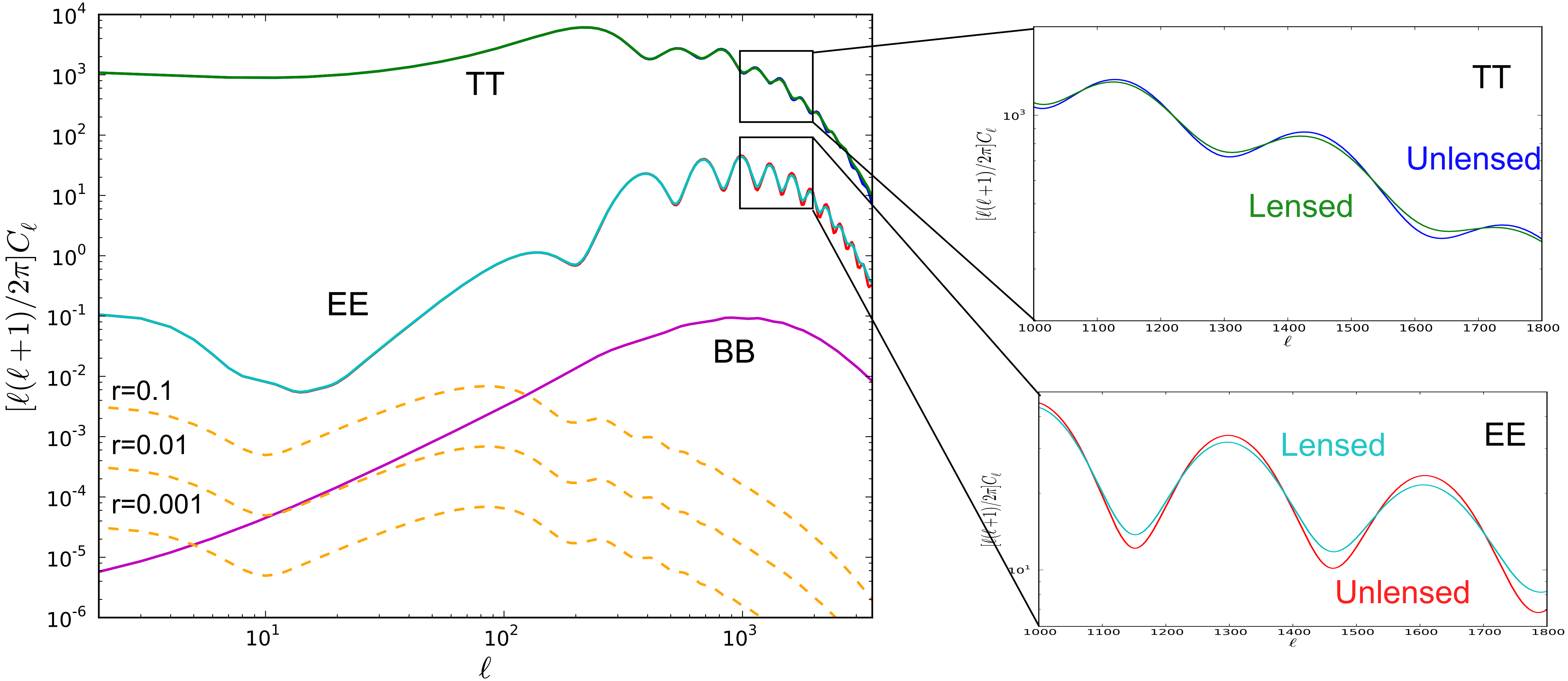
$$C_\ell \sim (1-\alpha_\ell)\tilde{C}_\ell + \sum_{\ell_1 \ell_2} C_{\ell_1}^{\phi\phi} \tilde{C}_{\ell_2} F_{\ell \ell_1 \ell_2}$$



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

Impact on anisotropies power spectra

$$C_\ell \sim (1-\alpha_\ell)\tilde{C}_\ell + \sum_{\ell_1 \ell_2} C^{\phi\phi}_{\ell_1} \tilde{C}_{\ell_2} F_{\ell \ell_1 \ell_2}$$



2) Multipoles become correlated.
Lensing induced non-Gaussian covariance

ABL, Smith, Hu 2012

Lensing reconstruction

- CMB lensing induces statistical anisotropies

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

- Quadratic estimator on the full sky

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

Okamoto & Hu, 2003

Lensing reconstruction

- CMB lensing induces statistical anisotropies

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Okamoto & Hu, 2003

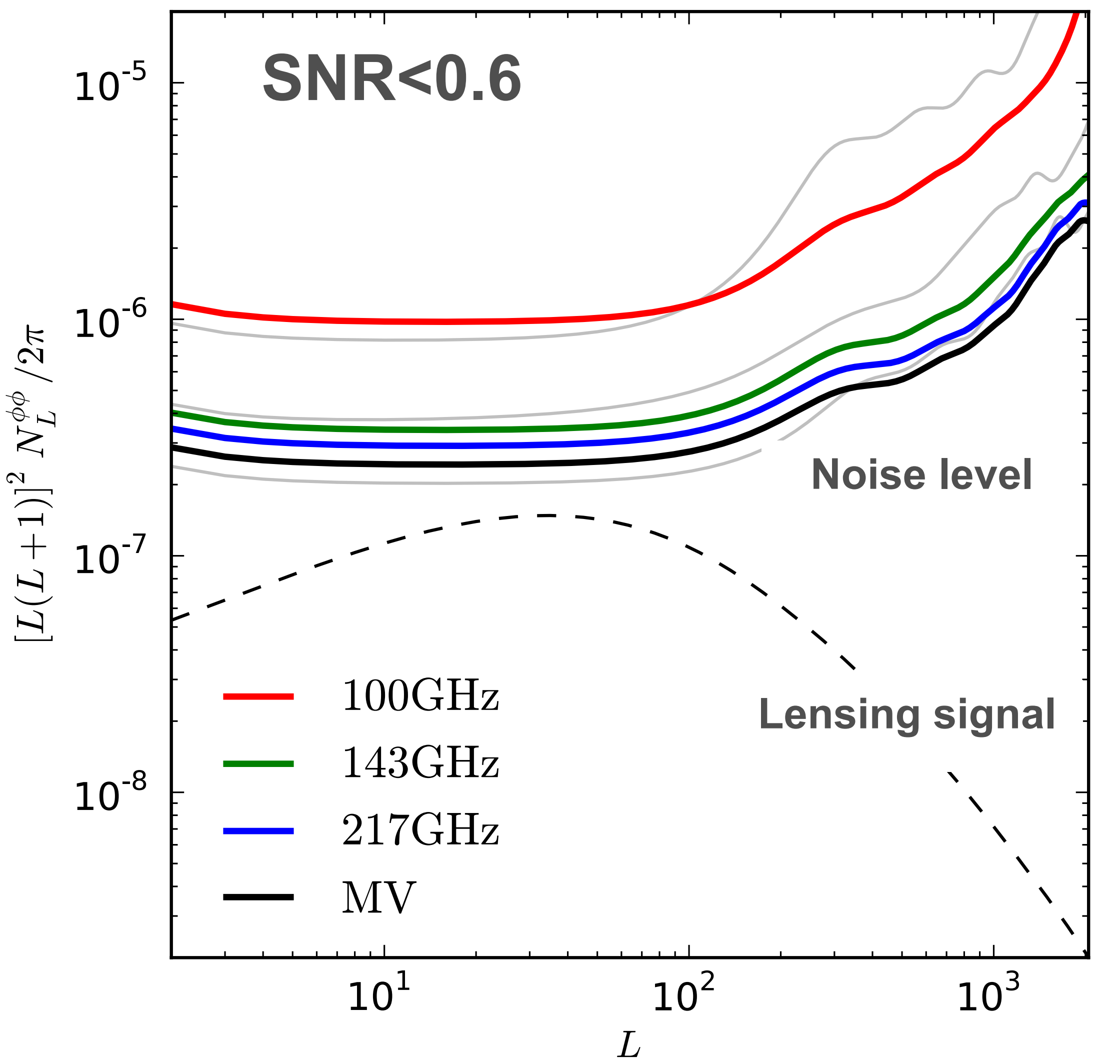
Filtered temperature. Multiple choices.

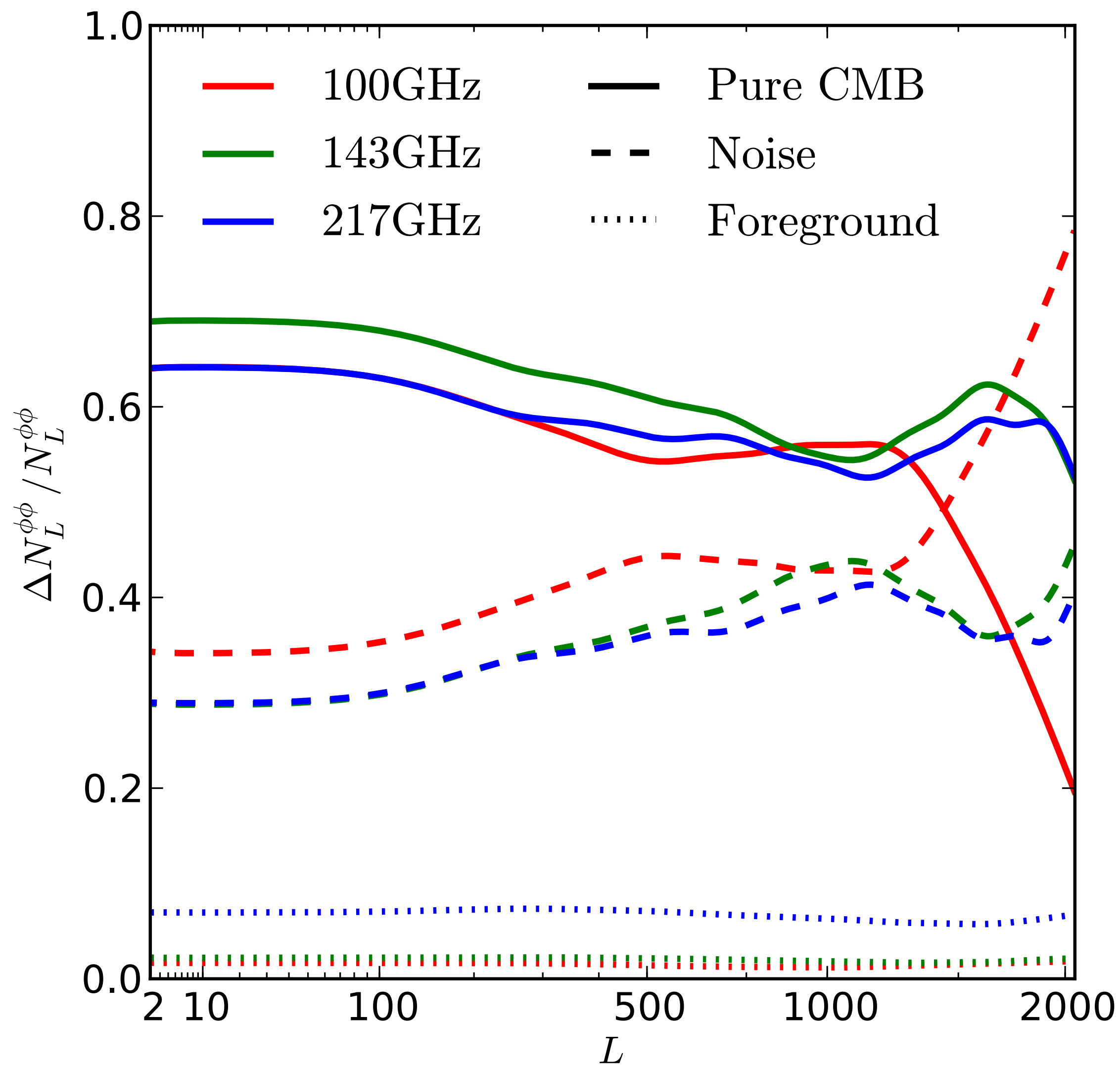
Typically: T_1 is inverse-variance filtered, and T_2 is Wiener filtered

Estimator is unbiased (in the absence of real-life issues), but noisy

CMB lensing reconstruction

$$\mathrm{var}(\hat{\phi}) \sim \langle \hat{\phi}\hat{\phi}^* \rangle \sim \langle \mathrm{TTTT} \rangle \sim \mathrm{C}_\ell^{\phi\phi} + \mathrm{N}_\ell^0$$





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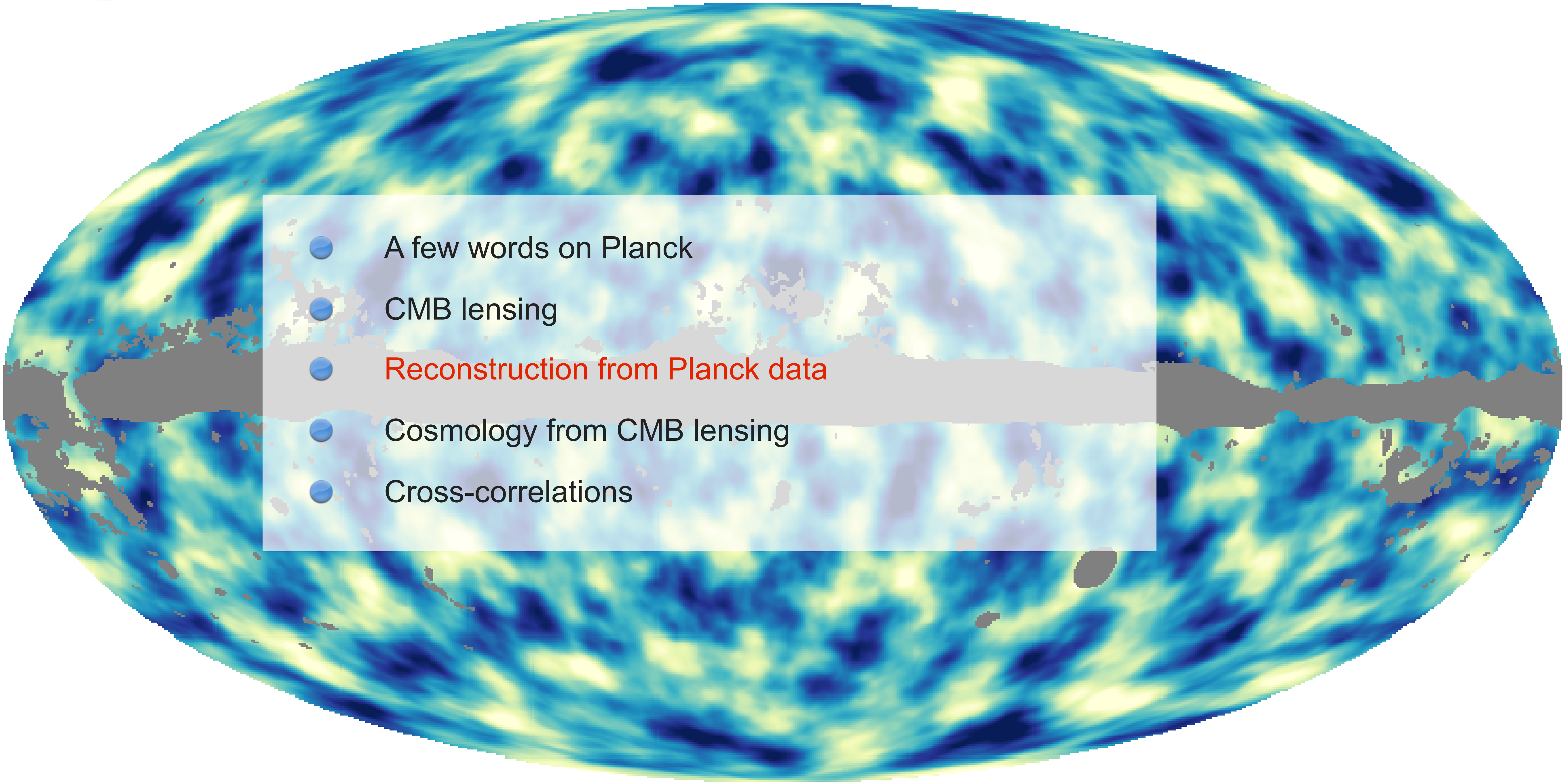

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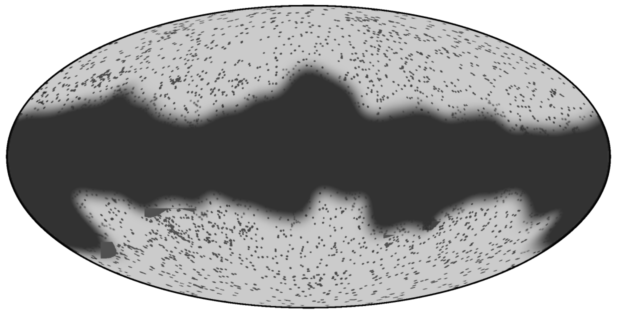
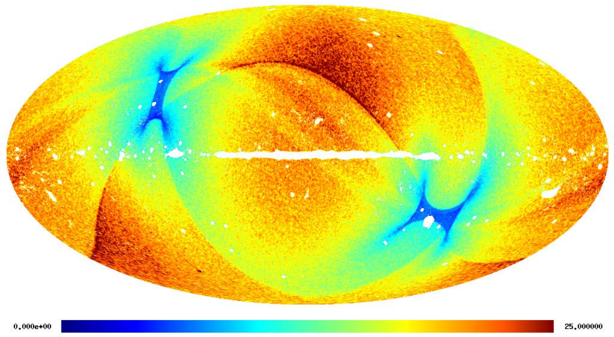
CMB lensing reconstruction

- Other sources of statistical anisotropies

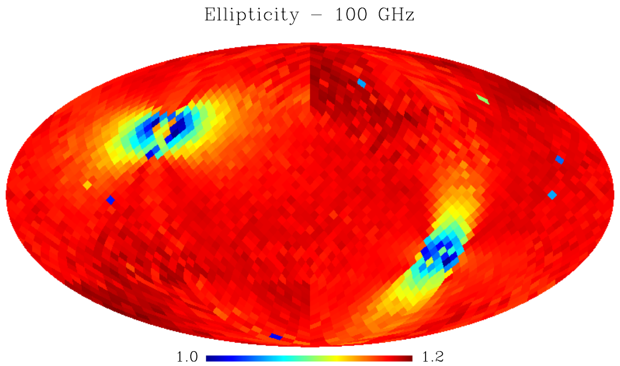
Galactic + PS mask

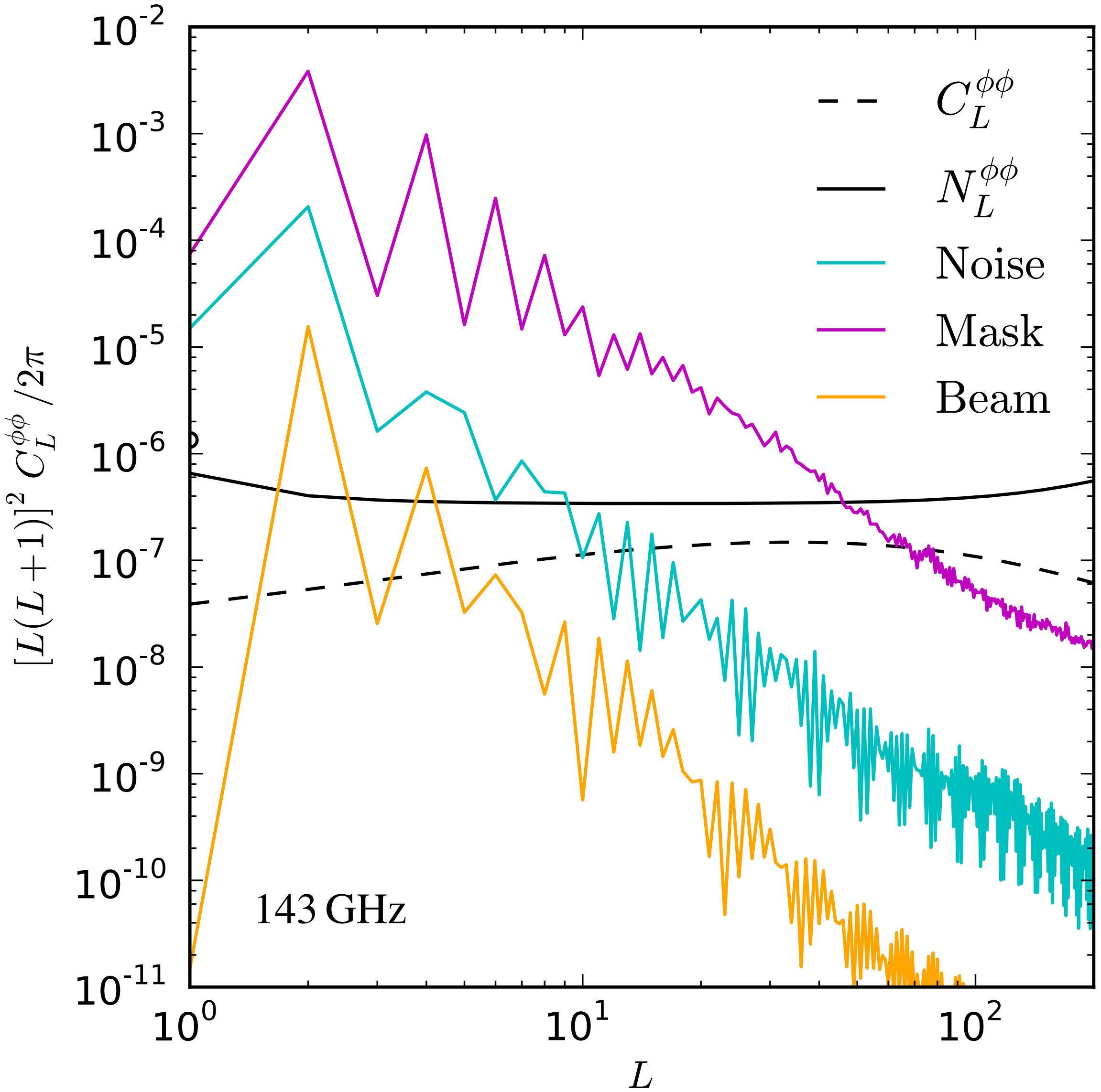


Inh. noise



Beam ellipticity





CMB lensing reconstruction

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

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

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

$$\bar{T}_{\ell m} = [S + N]^{-1} T_{\ell m} \approx [C^{TT}_{\ell} + C^{NN}_{\ell}]^{-1} T_{\ell m} = F_{\ell} T_{\ell m} \qquad \mathcal{R}_{L} = \frac{}{(2L+1)} \sum_{\ell_1 \ell_2} \frac{1}{2} W^{x}_{\ell_1 \ell_2 L} W^{\phi}_{\ell_1 \ell_2 L} F^{(1)}_{\ell_1} F^{(2)}_{\ell_2}.$$

- Take two temperature maps and inverse-variance filter them

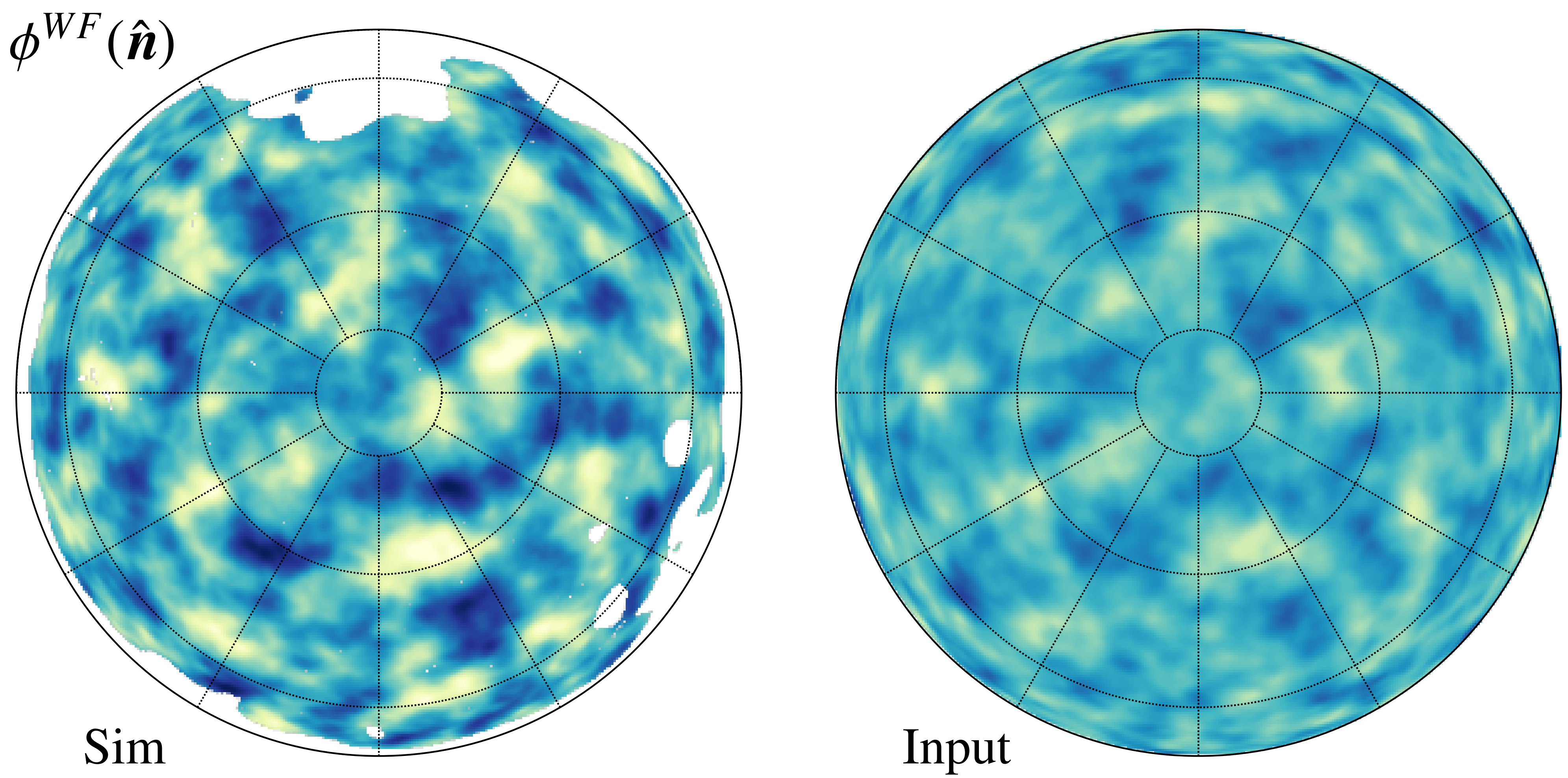
- Multiply one by the temperature power spectrum and differentiate it

- 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

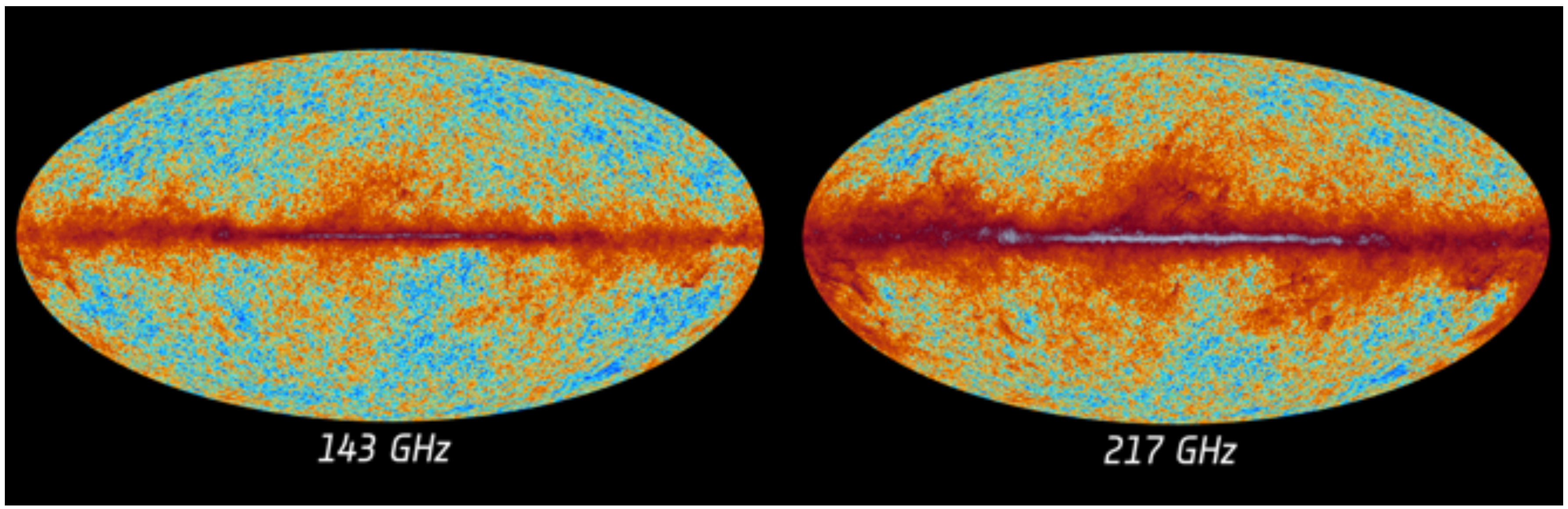
CMB lensing reconstruction

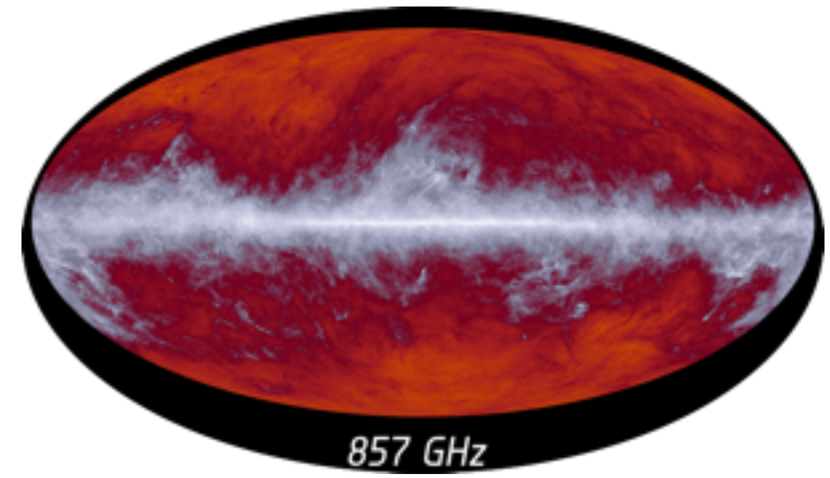


Reconstruction on a realistic Planck simulation

Best reconstruction

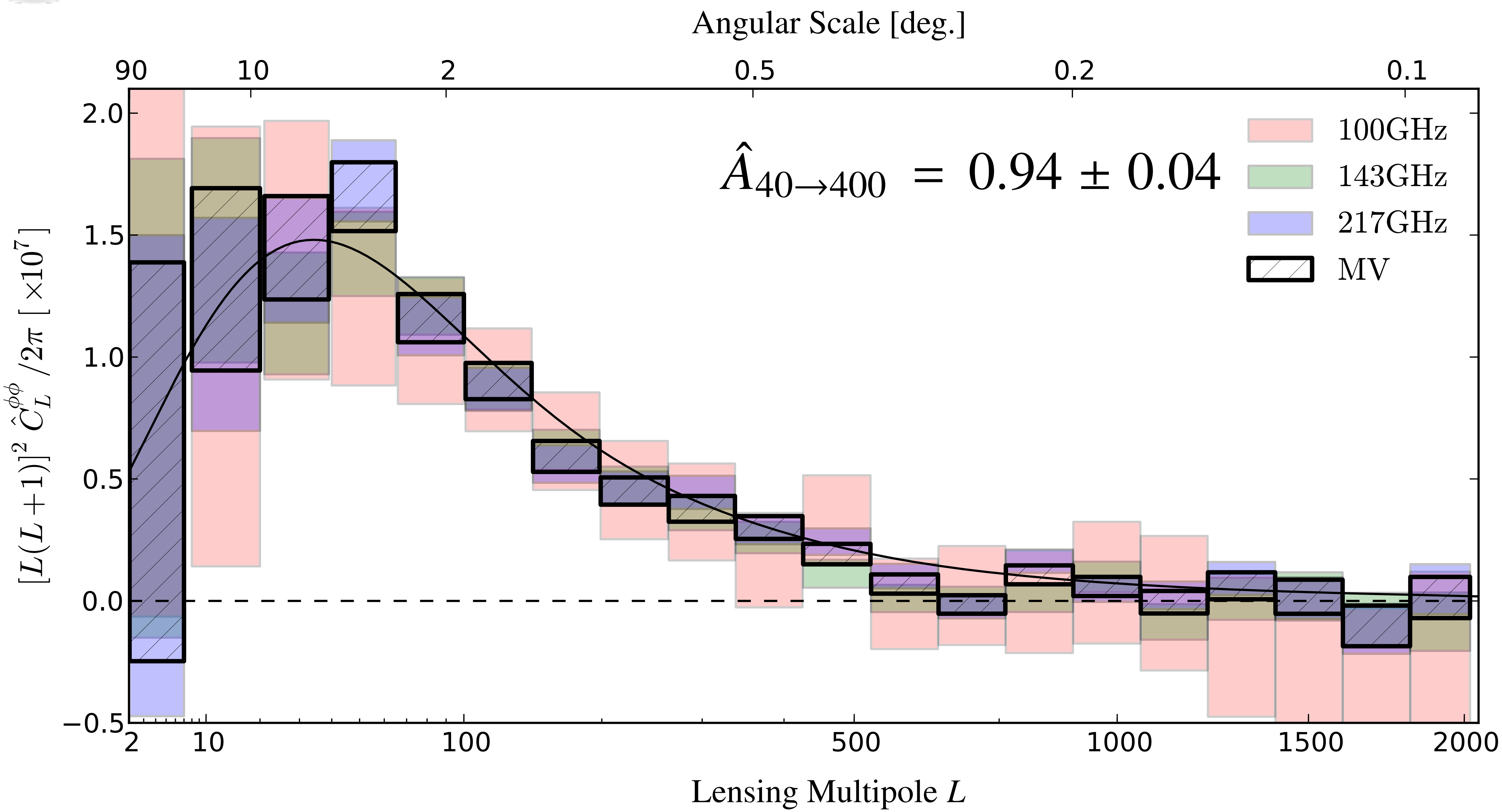
- Minimum-variance combination of 143GHz & 217 GHz



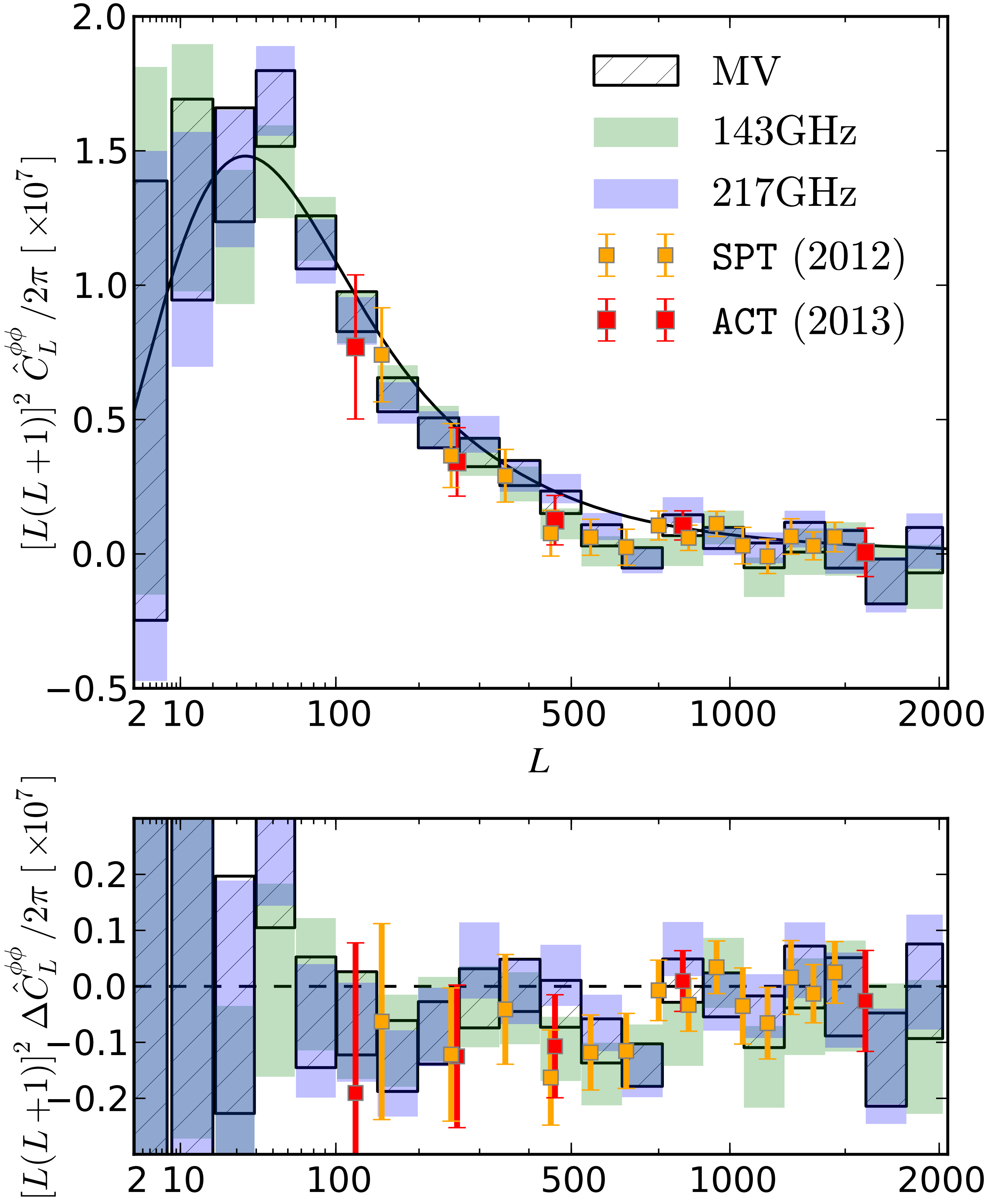


- 857 GHz map used as a template for dust cleaning
- 30 % Galactic mask +CO+ point sources
- 5º apodization (for lensing power spectrum estimation)

Best reconstruction

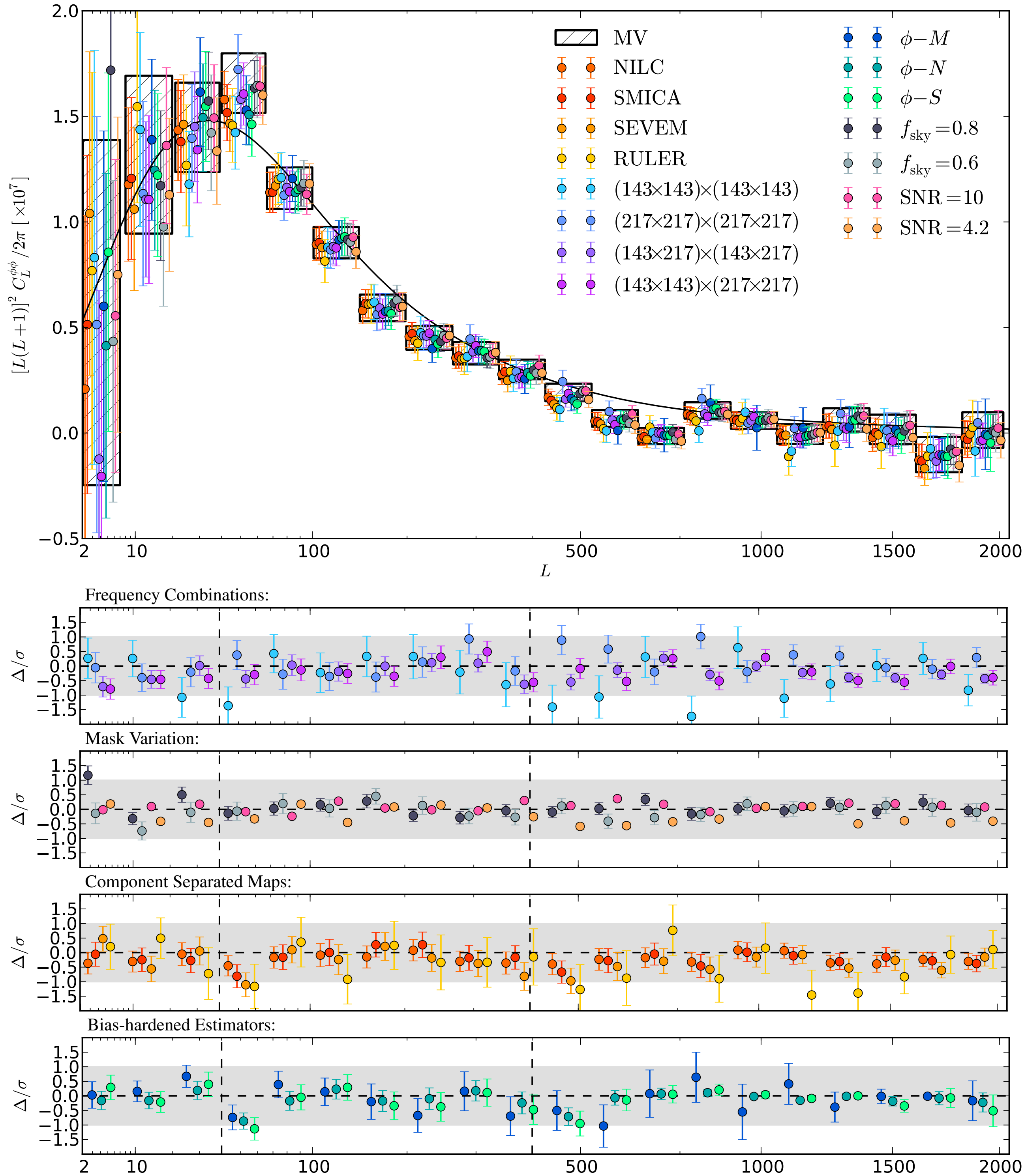


Comparison to other surveys

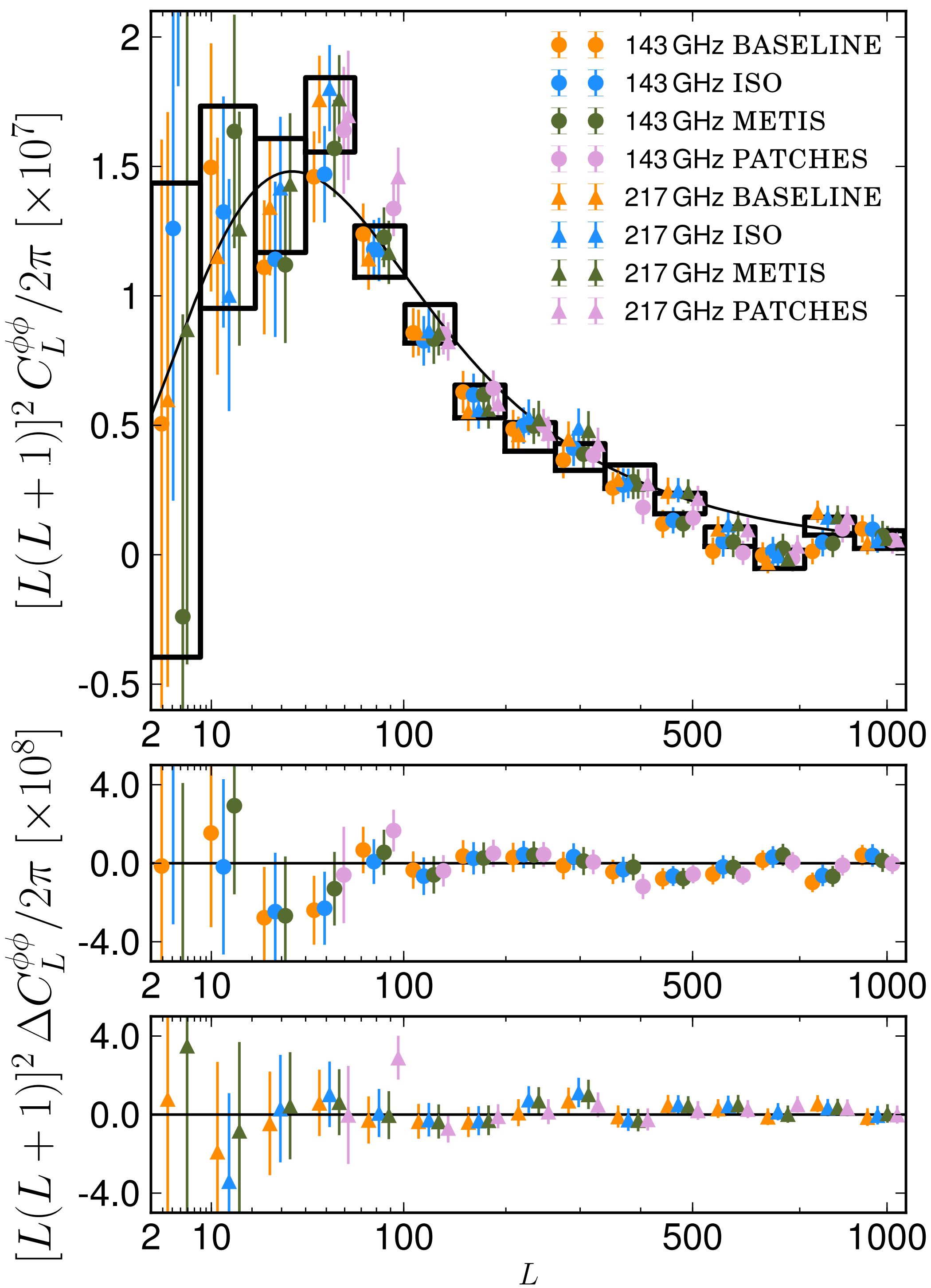


Tests

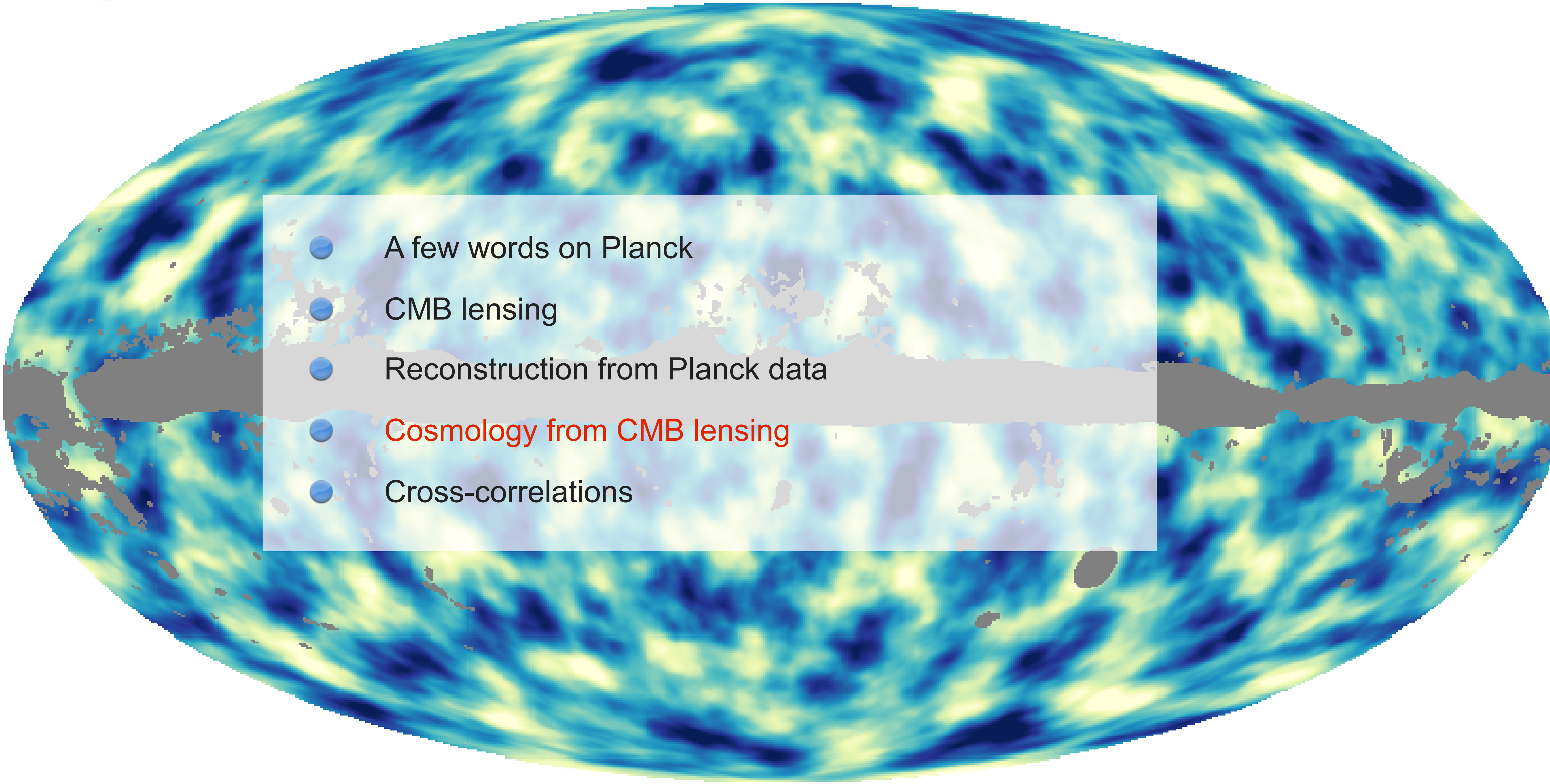
Testing foreground contamination



Testing the filter & implementation

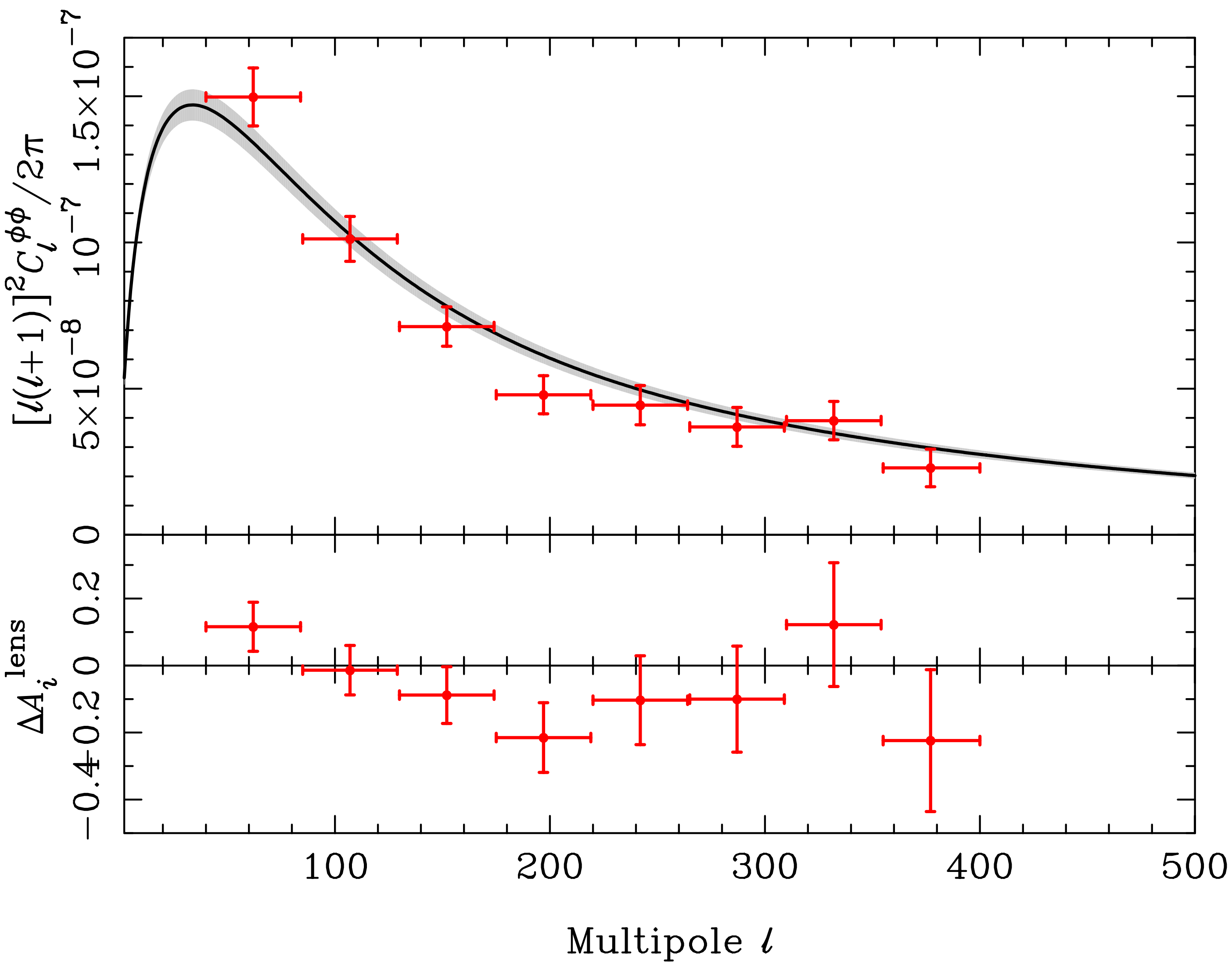


Outline

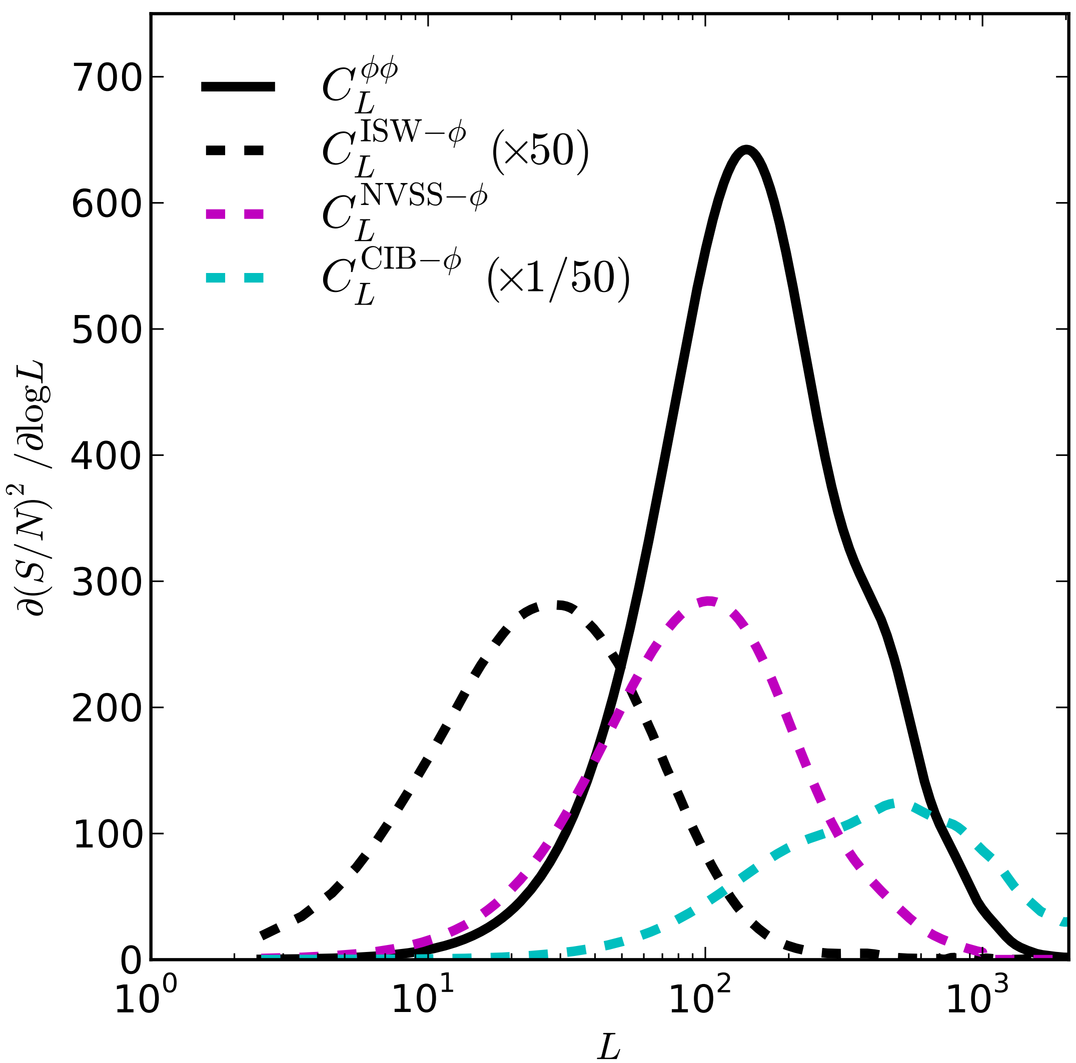


- A few words on Planck
- CMB lensing
- Reconstruction from Planck data
- Cosmology from CMB lensing
- Cross-correlations

Cosmology

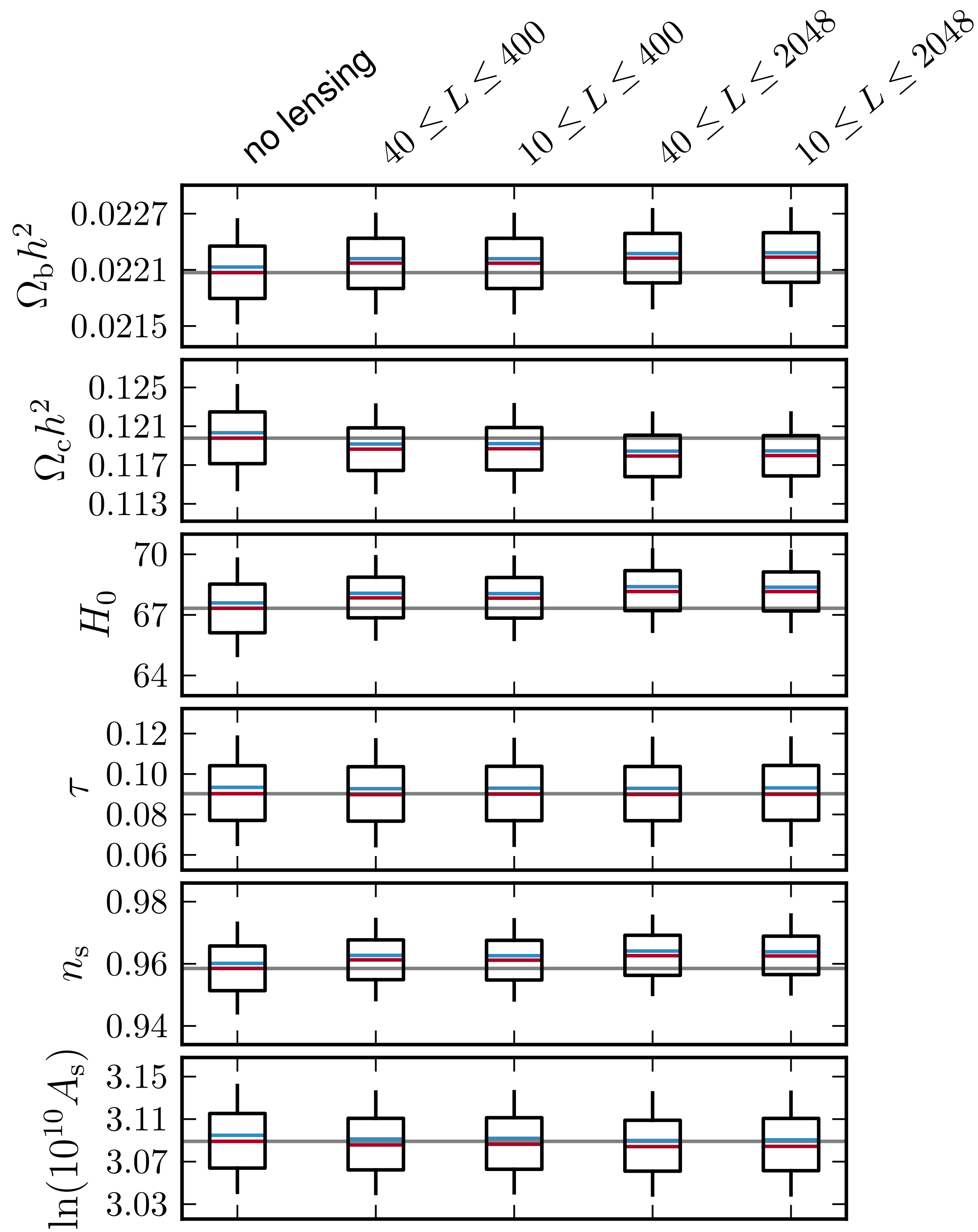


$[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
$\Delta A_i^{\rm lens}$
Multipole ℓ



$C_L^{\phi\phi}$
$C_L^{\rm ISW-\phi}$ (×50)
$C_L^{\rm NVSS-\phi}$
$C_L^{\rm CIB-\phi}$ (×1/50)
$\partial(S/N)^2/\partial \log L$
L

Cosmology

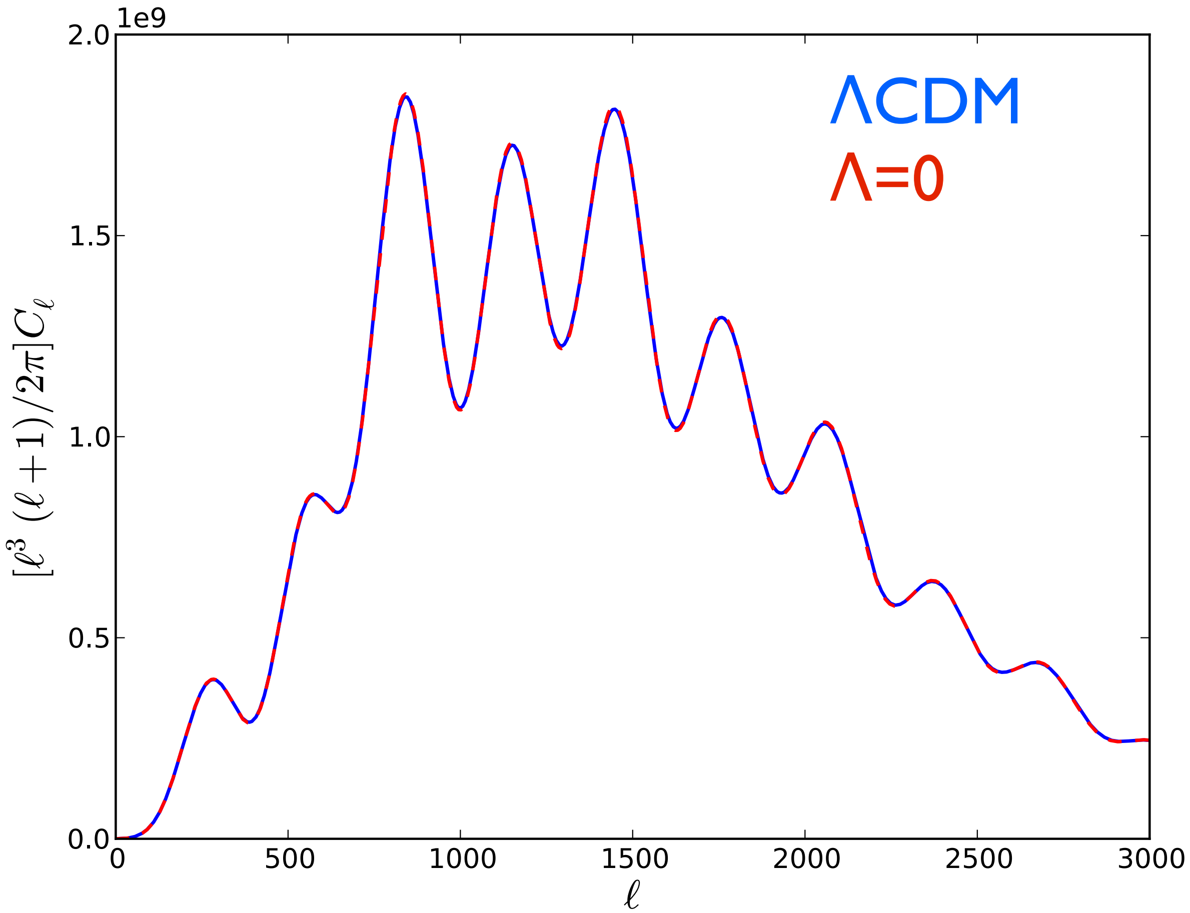


Adding lensing reconstruction brings ~20% improvement on some parameters

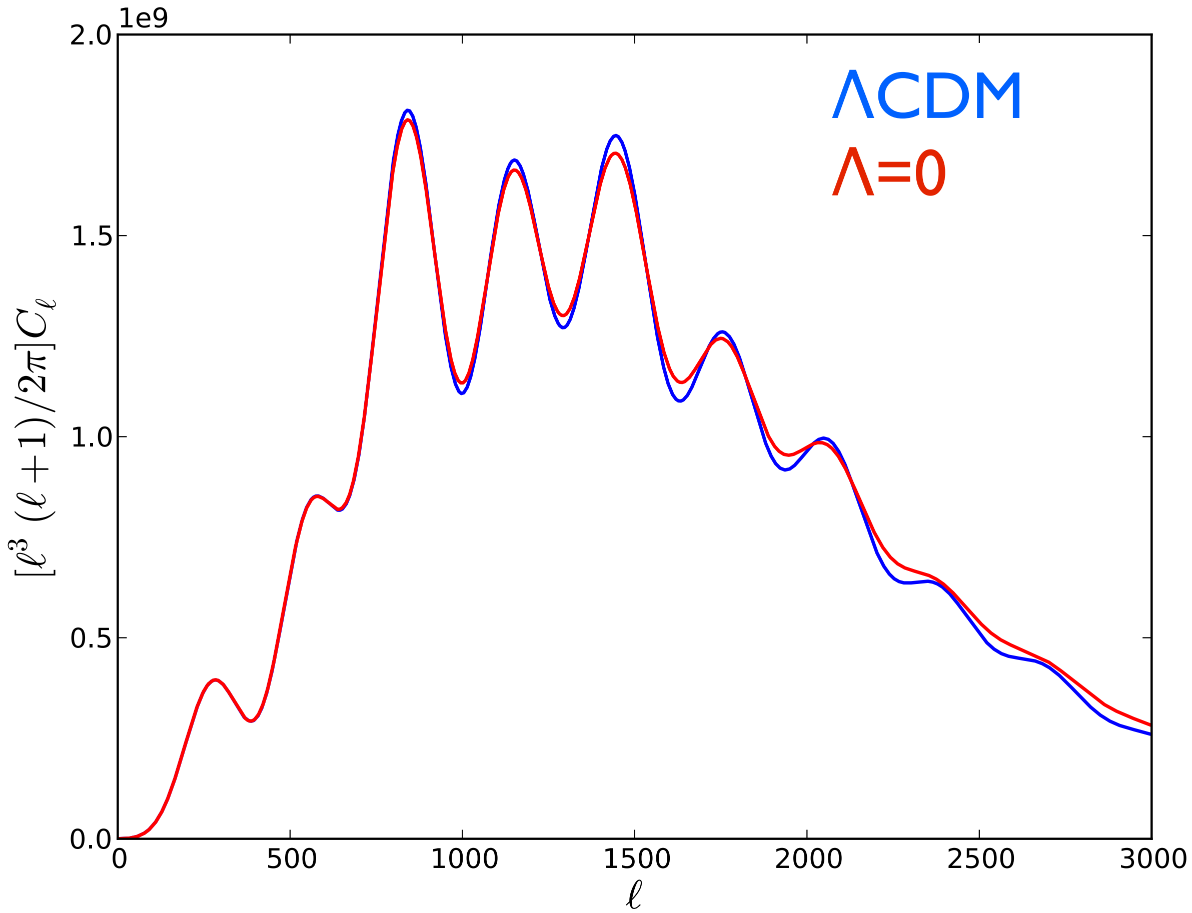
Adding low-L and high-L lensing information does not improve precision but slightly shift central values

Cosmology

- CMB lensing breaks the angular diameter degeneracy



Unlensed TT

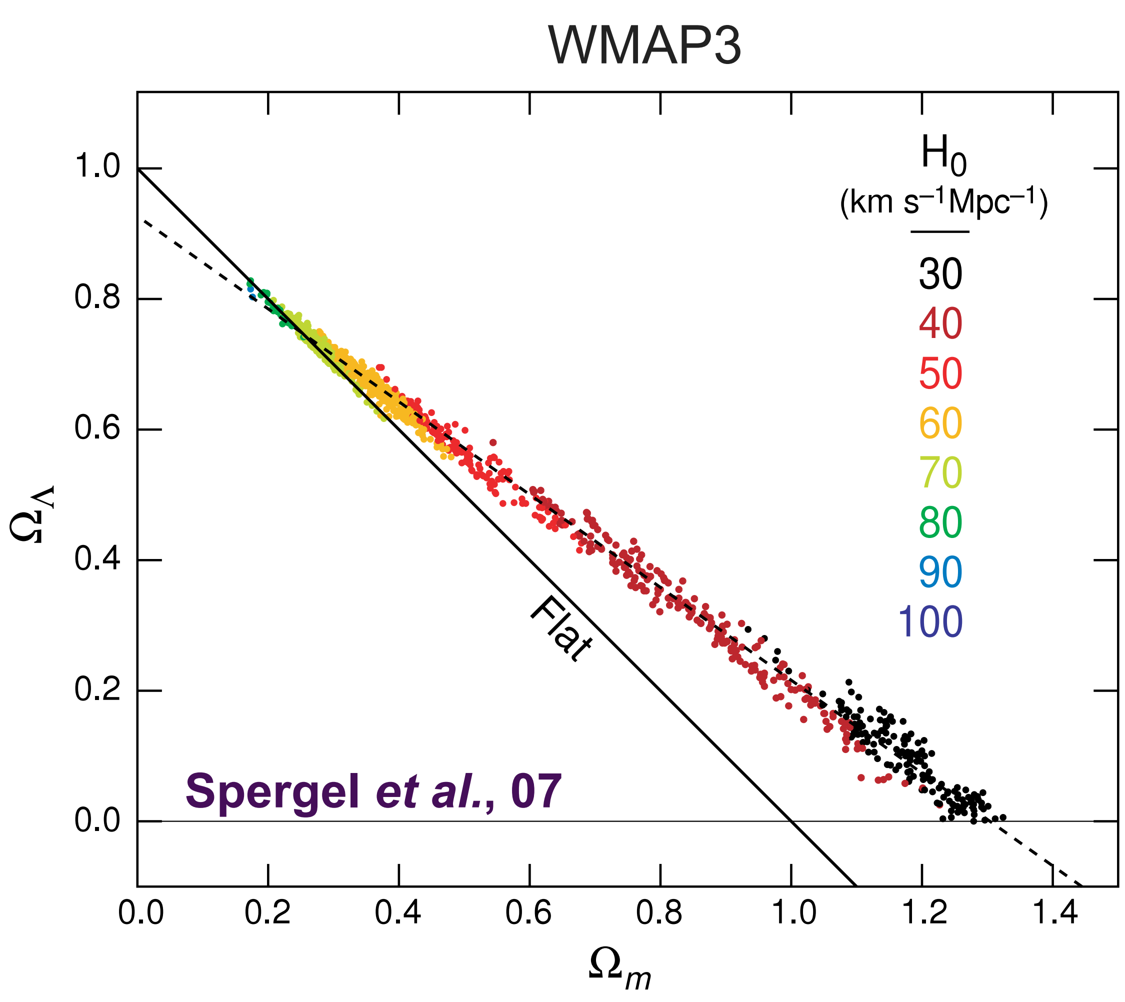


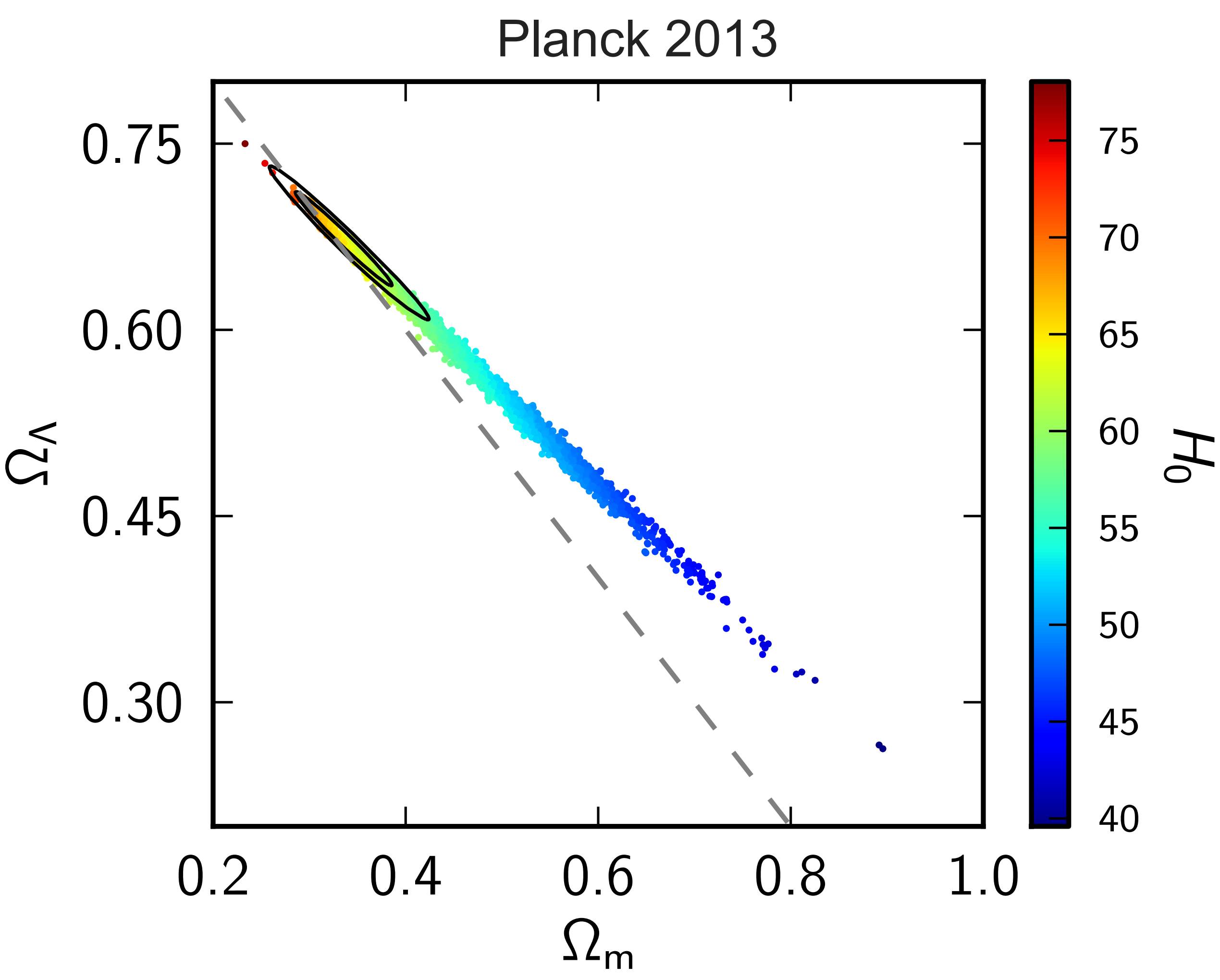
Lensed TT

see also **Sherwin *et al, 2011***,
Van Engelen *et al.,2012*

Cosmology

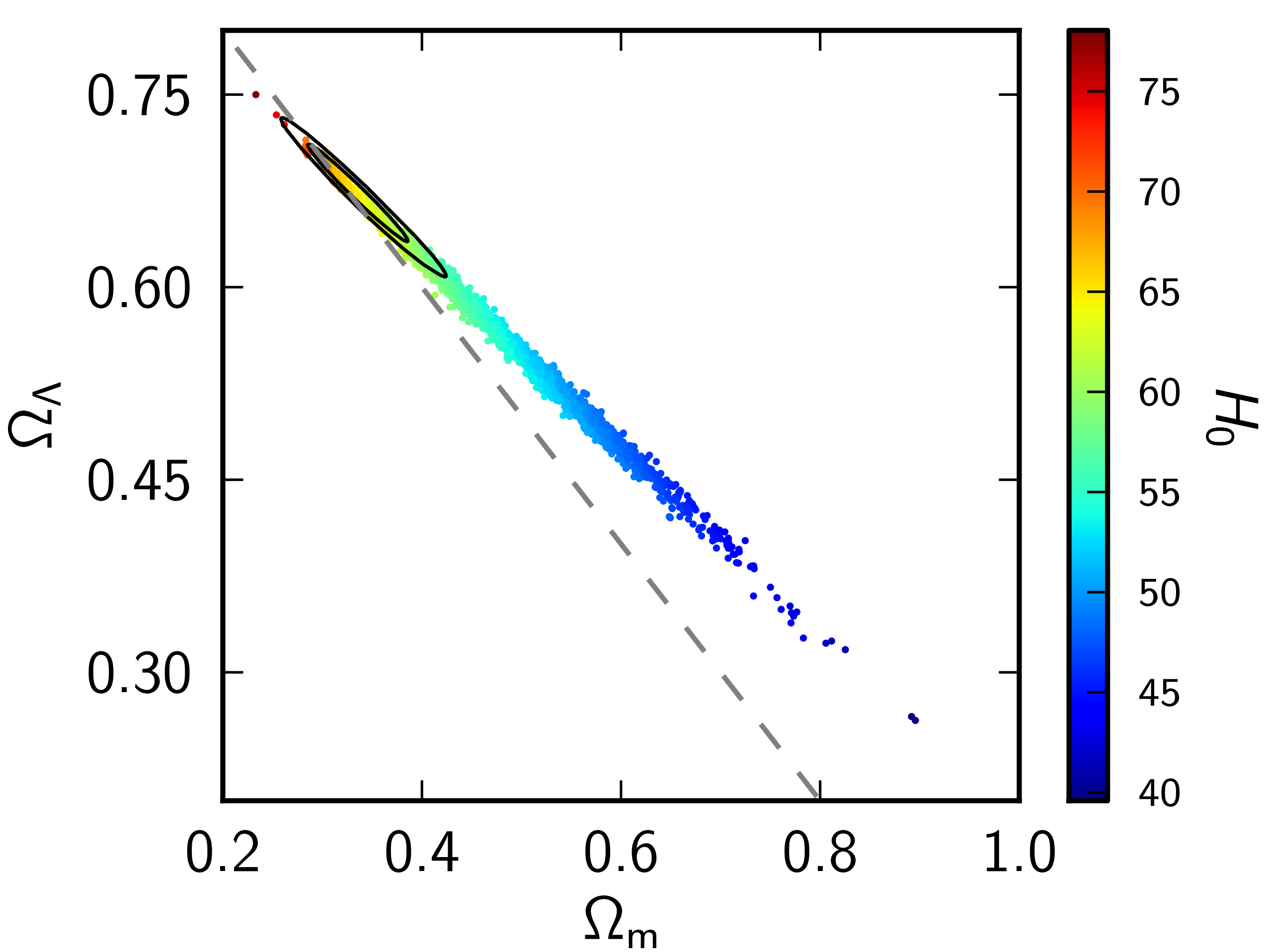
- CMB lensing breaks the angular diameter degeneracy

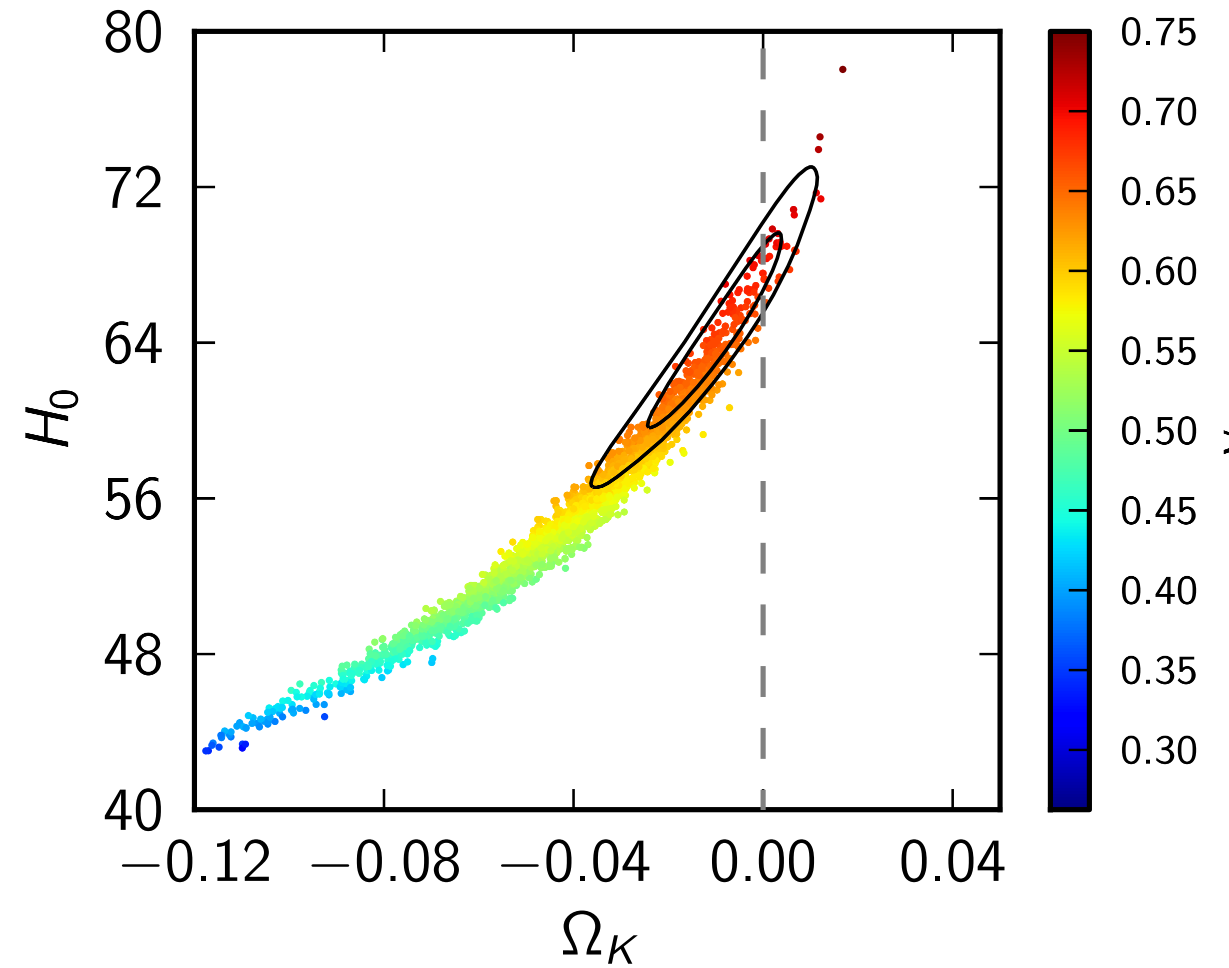




Cosmology

- CMB lensing breaks the angular diameter degeneracy





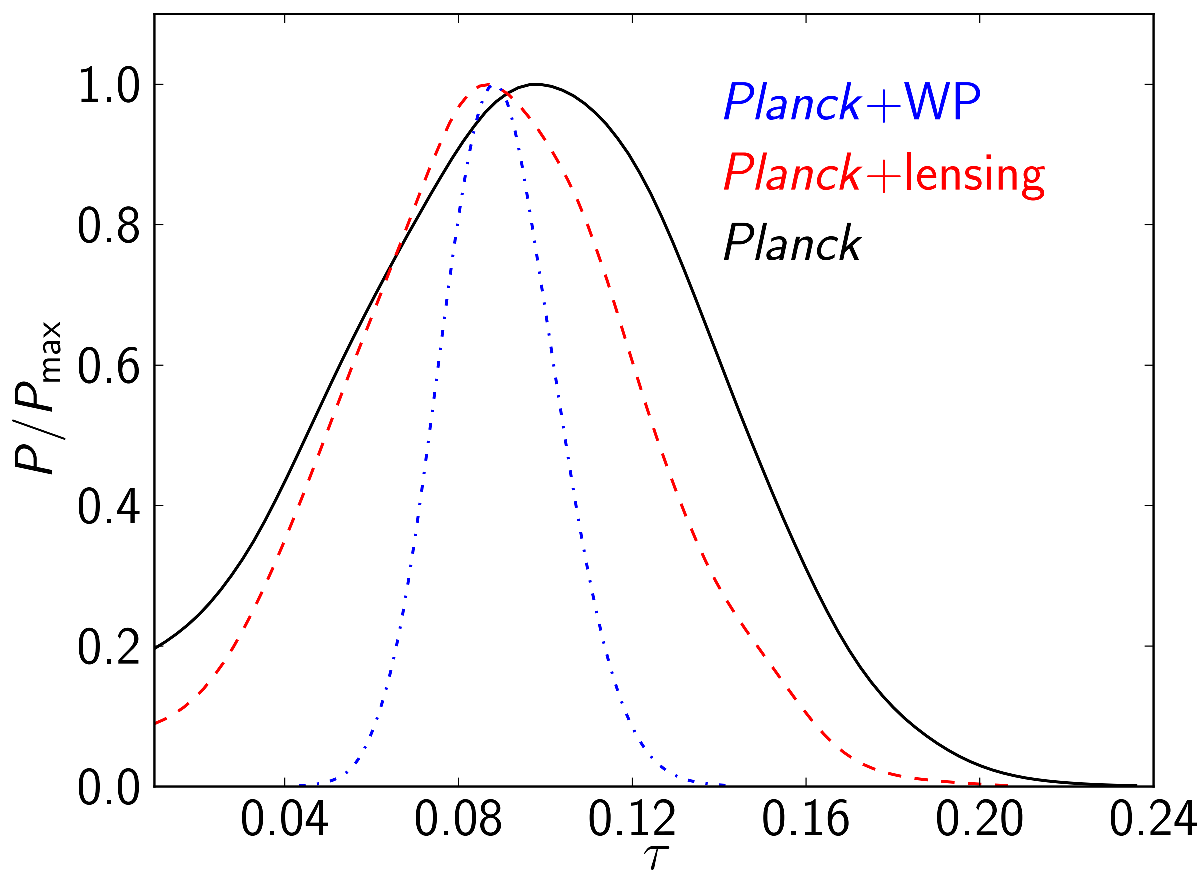
$$\Omega_\Lambda = 0.57^{+0.073}_{-0.055} \quad (68\%; \textit{Planck}\text{+WP+highL})$$
$$\Omega_\Lambda = 0.67^{+0.027}_{-0.023} \quad (68\%; \textit{Planck}\text{+lensing+WP+highL}).$$

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

Cosmology

- Reionization

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

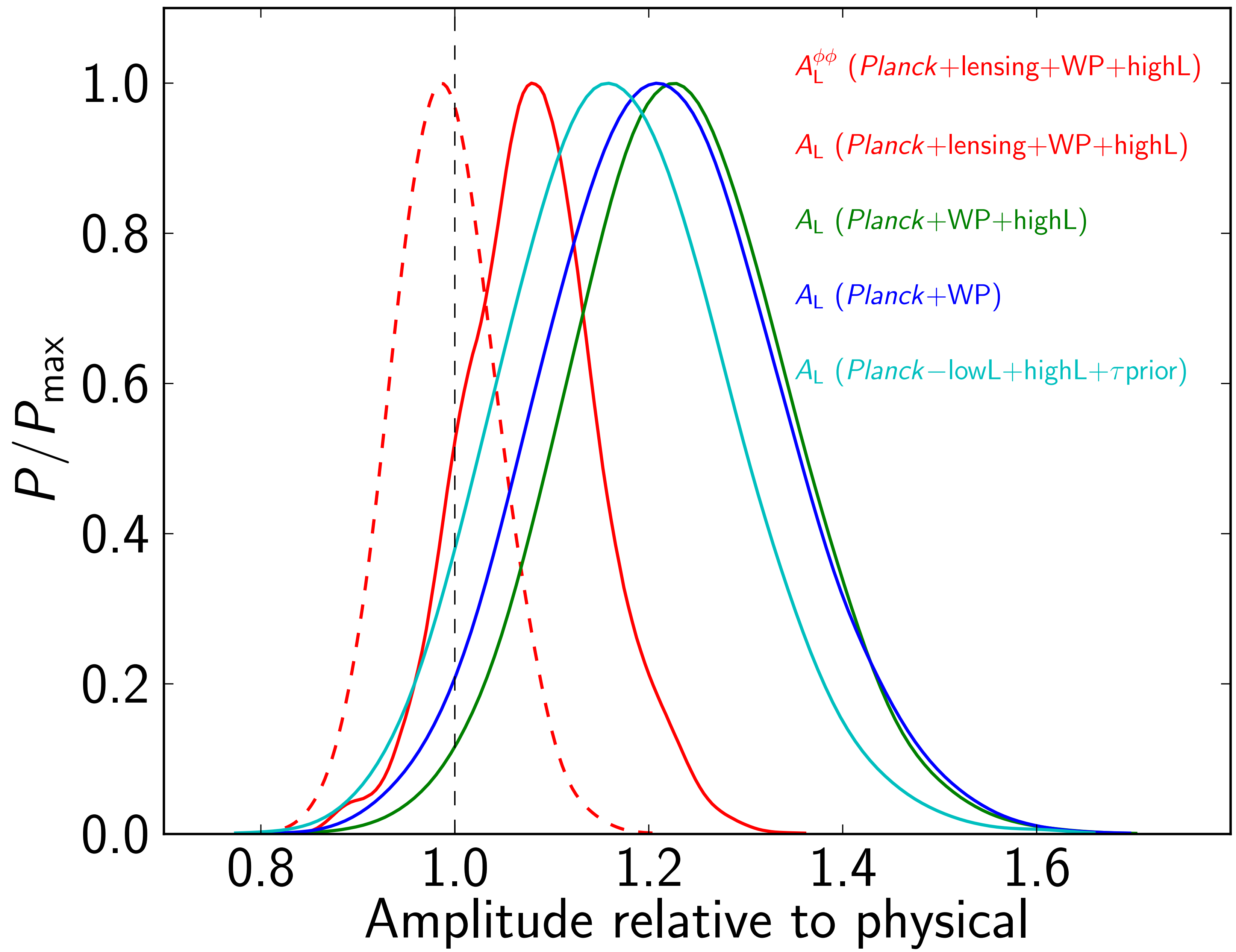


$$\tau = 0.097 \pm 0.038 \quad (68\%; \textit{Planck})$$

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

A_{lens} higher that 1?

$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$$



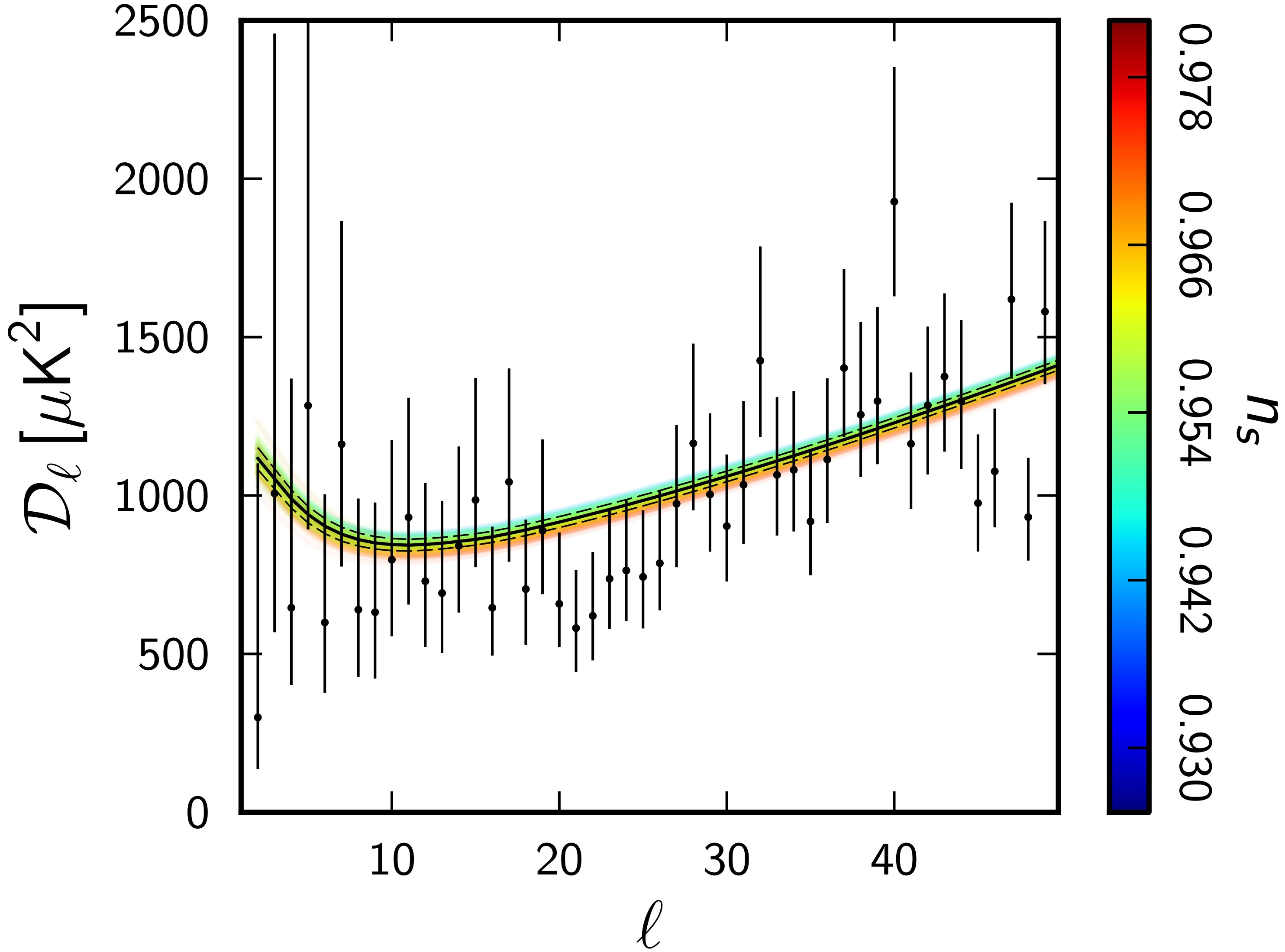
TT wants more lensing

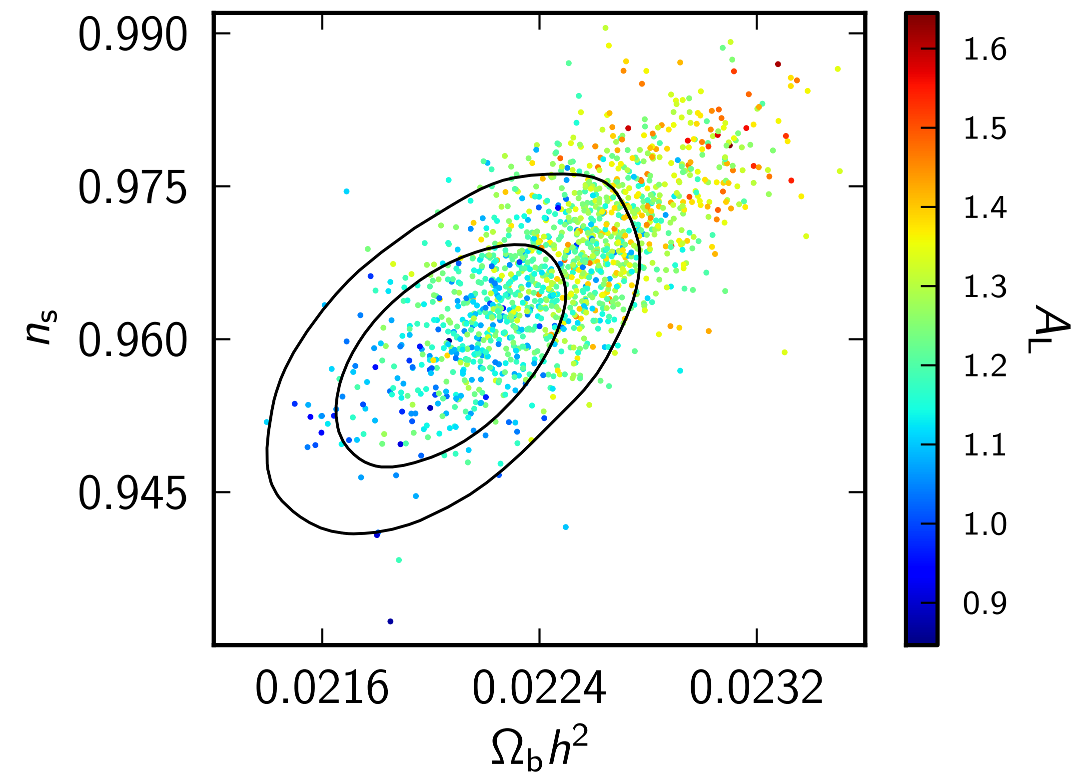
TTTT wants the right lensing (even slightly less)

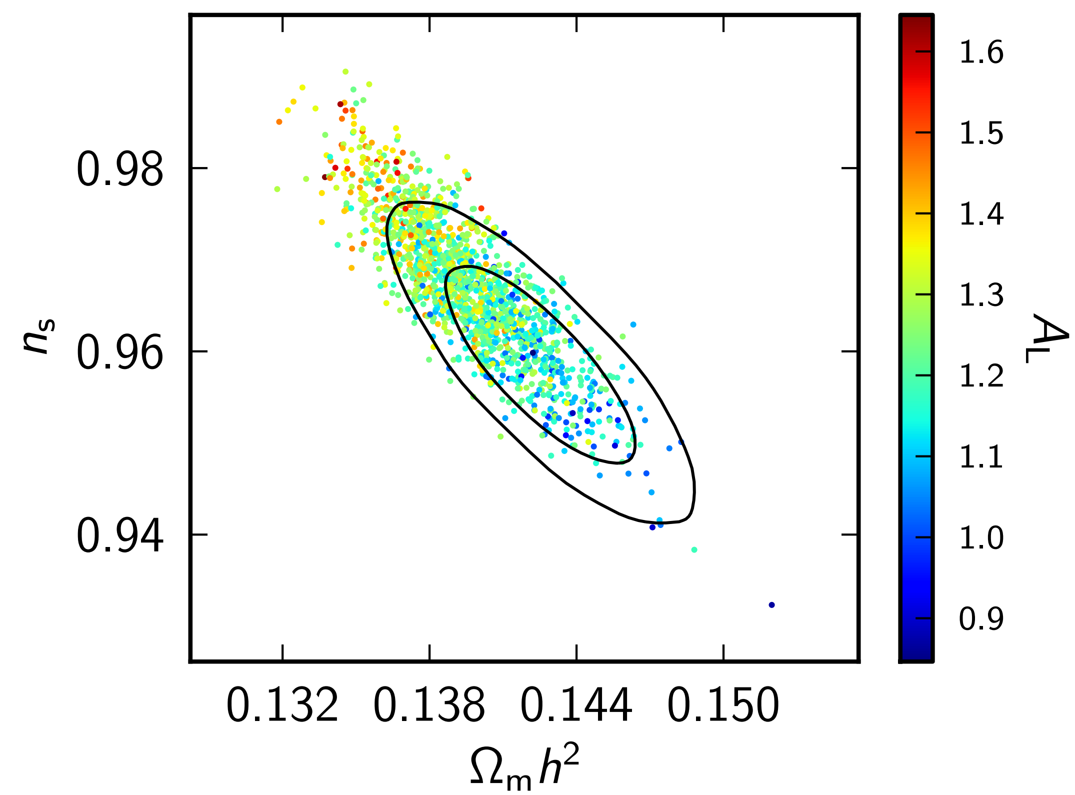
Not fully understood yet

Might have to do with low-ell lack of power

A_{lens} higher that 1?



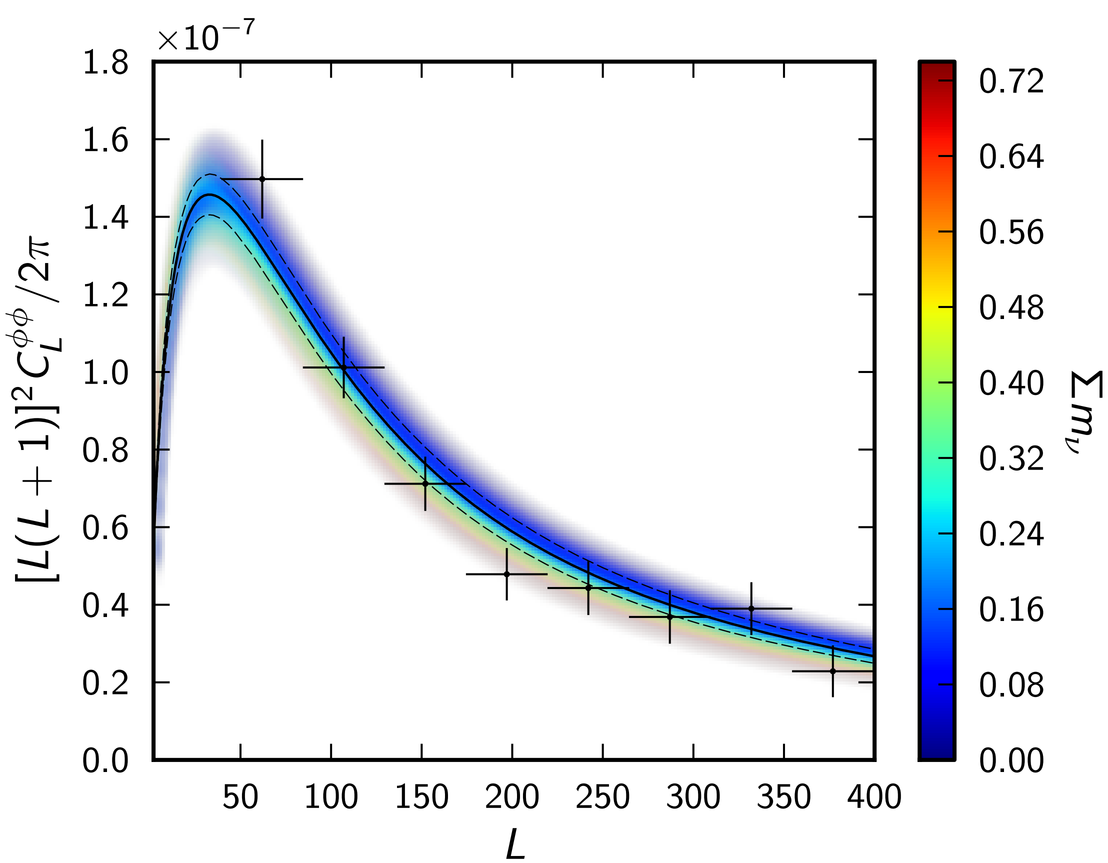




Cosmology

Sum of neutrinos masses

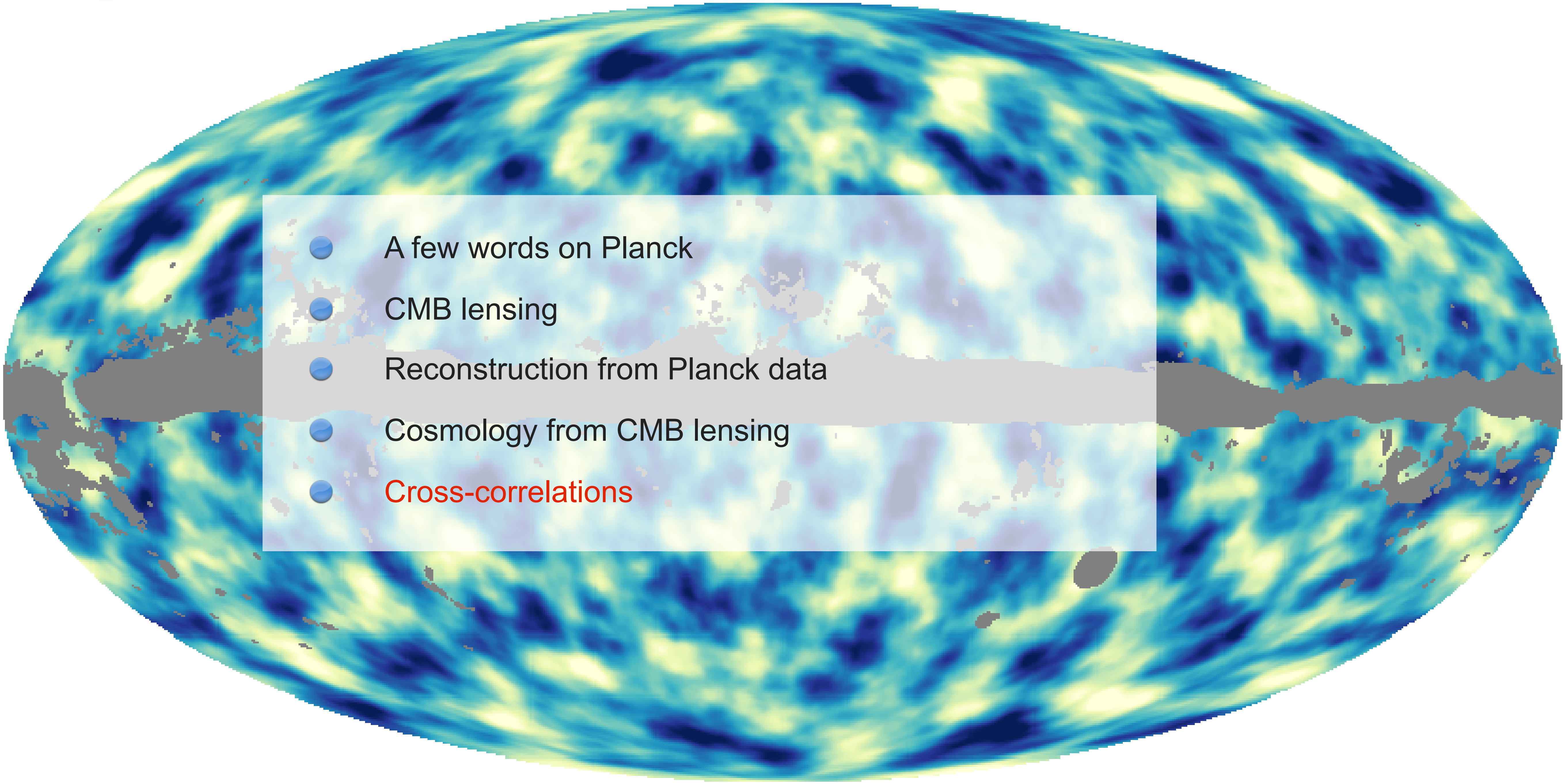
- Mild tension : constraint weaker than expected!
- Temperature power spectra: more lensing = smaller mass
- Reconstruction: less lensing = larger mass



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

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

Outline



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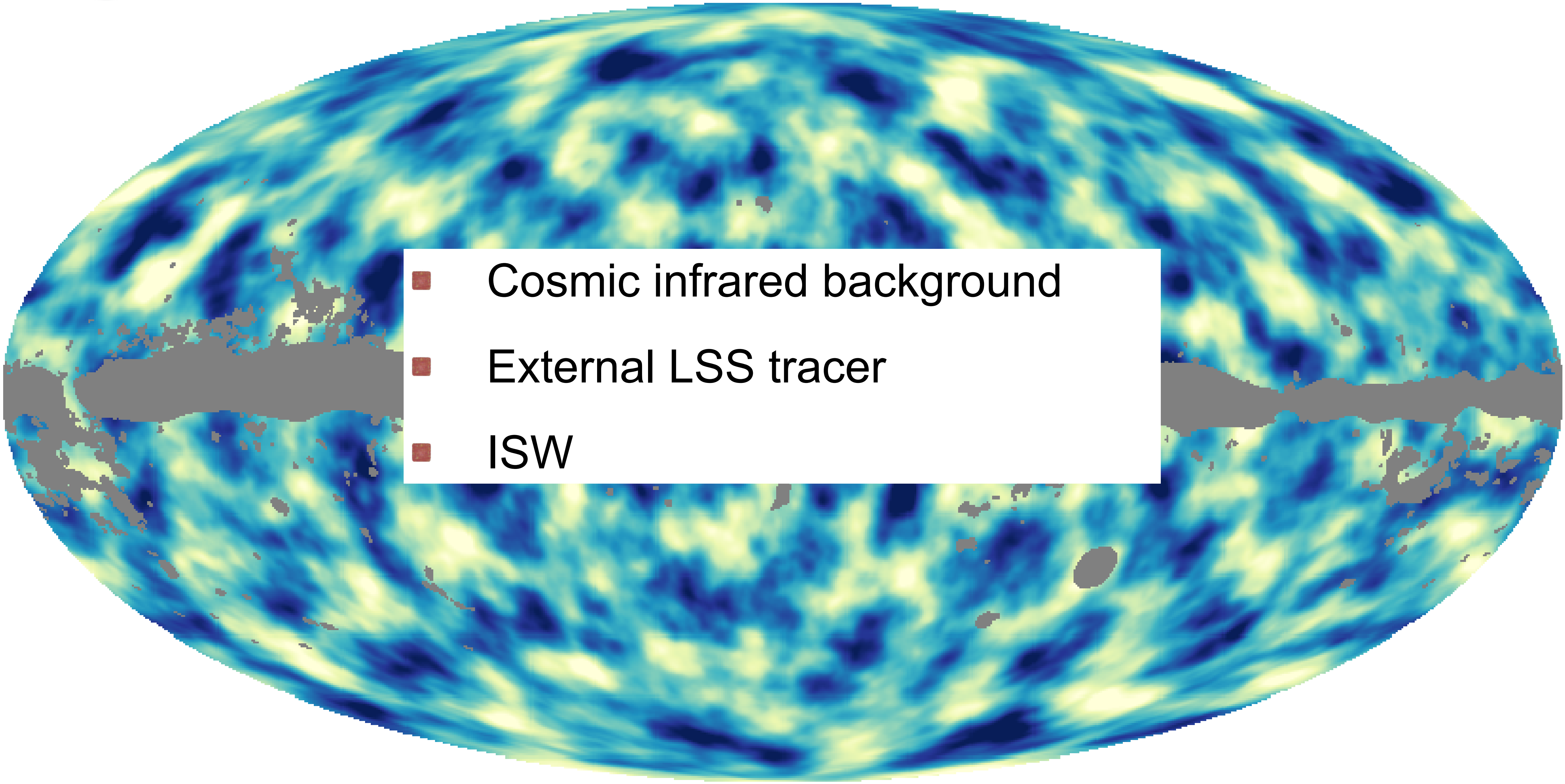
- Cosmology from CMB lensing
- Cross-correlations

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

Cross-correlations

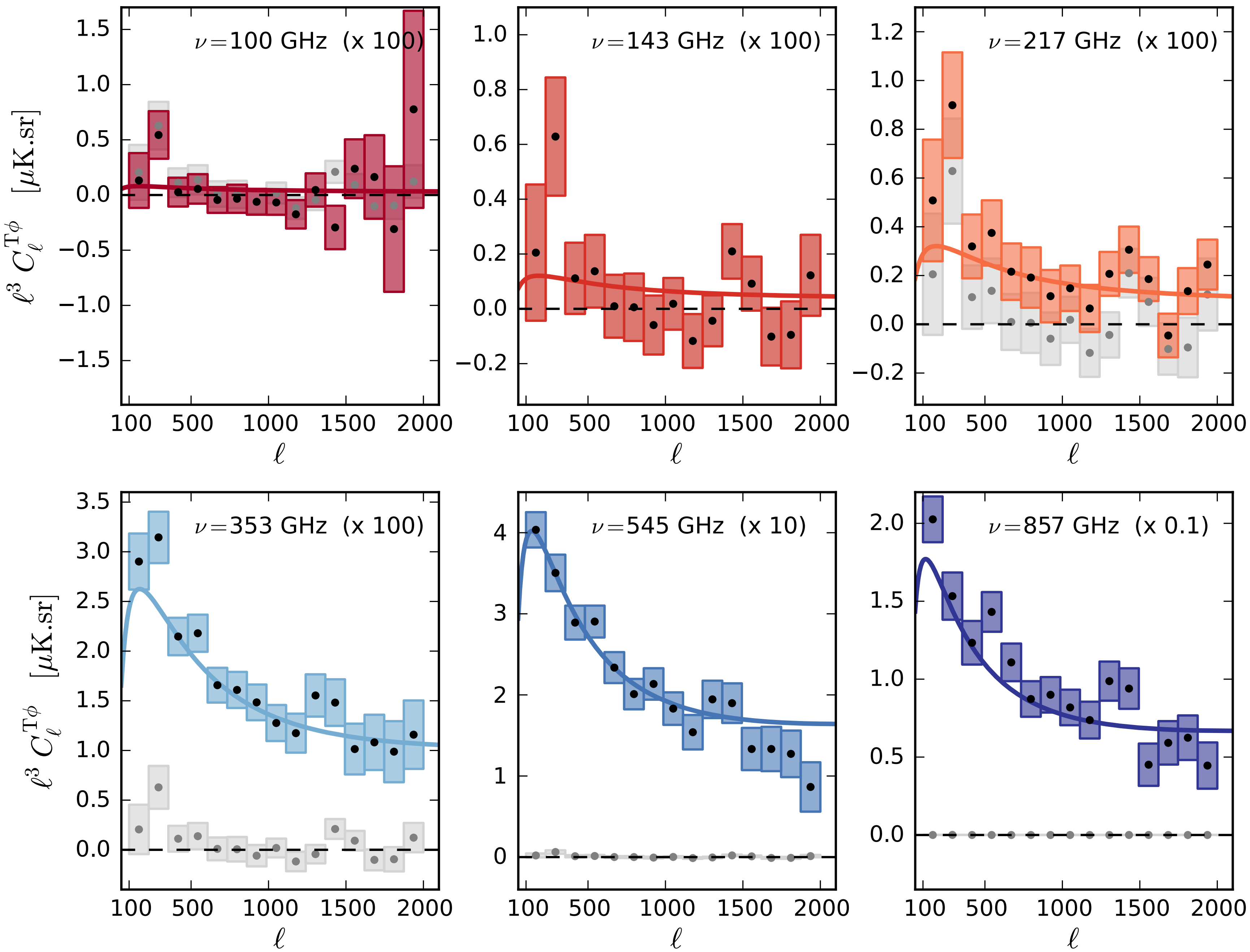


- Cosmic infrared background
- External LSS tracer
- ISW

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

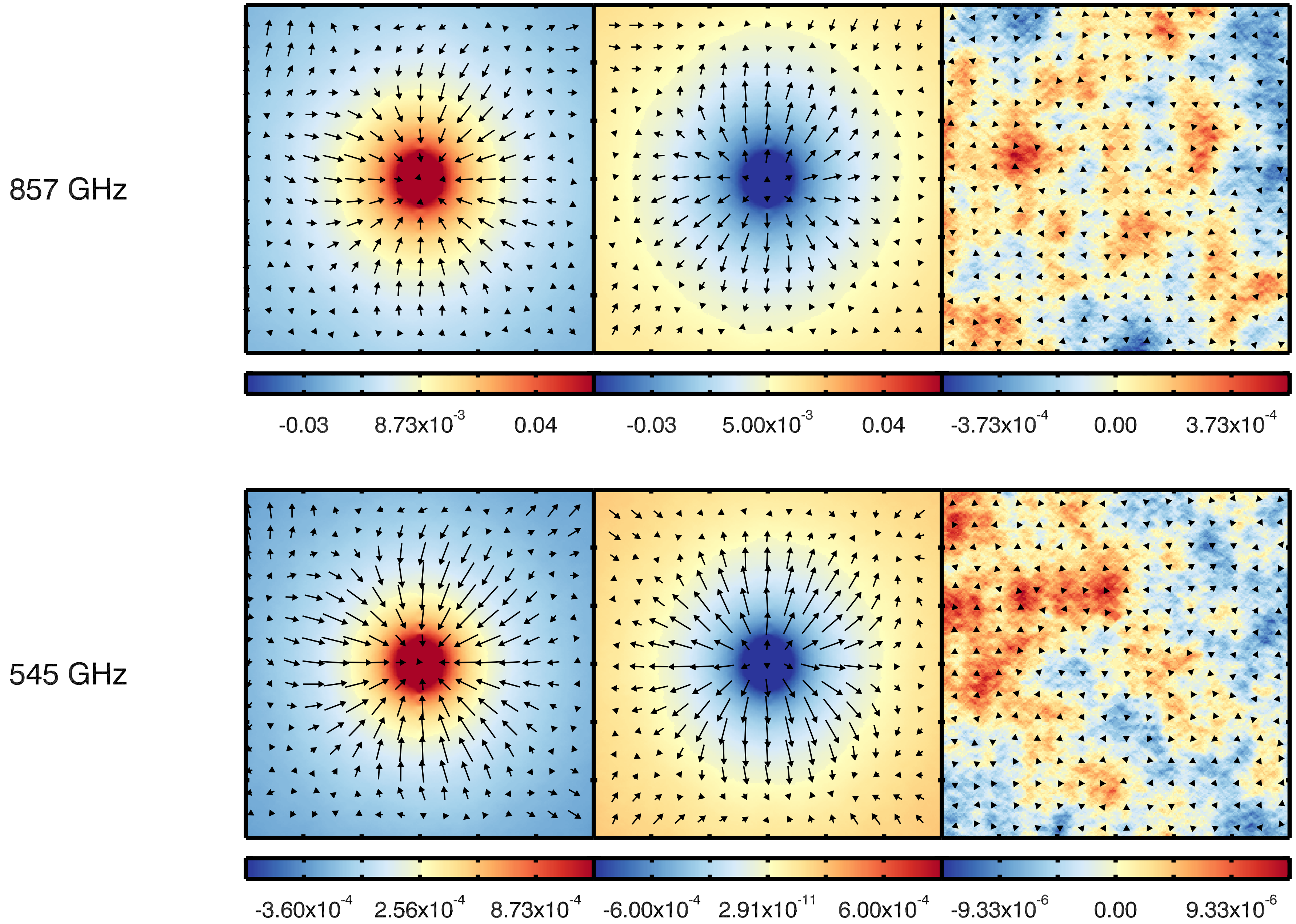
CMB lensing - CIB

- Lensing potential correlated with HFI temperature maps

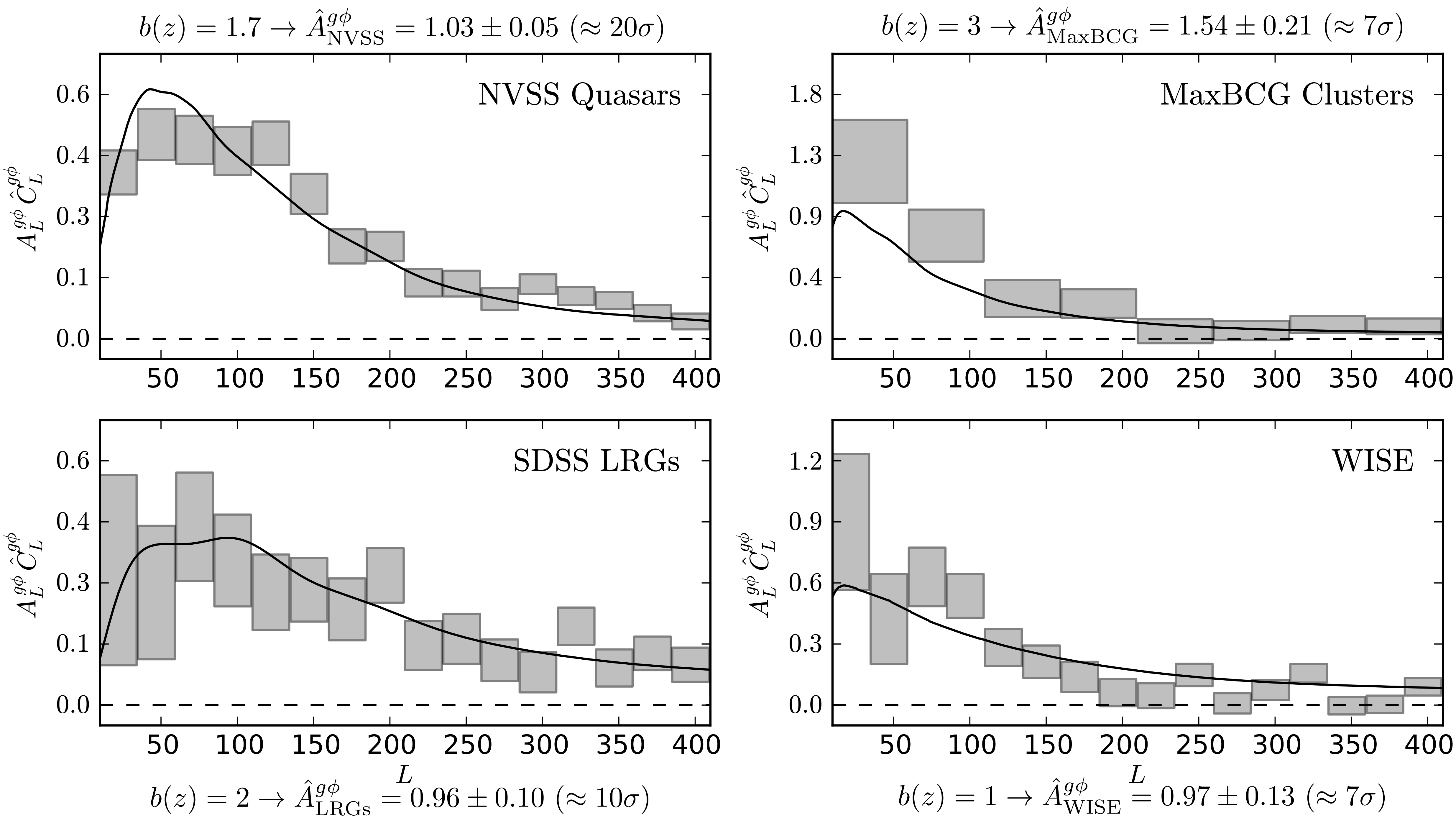


CMB lensing - CIB

- Deflection stacked on 20.000 temperature extrema

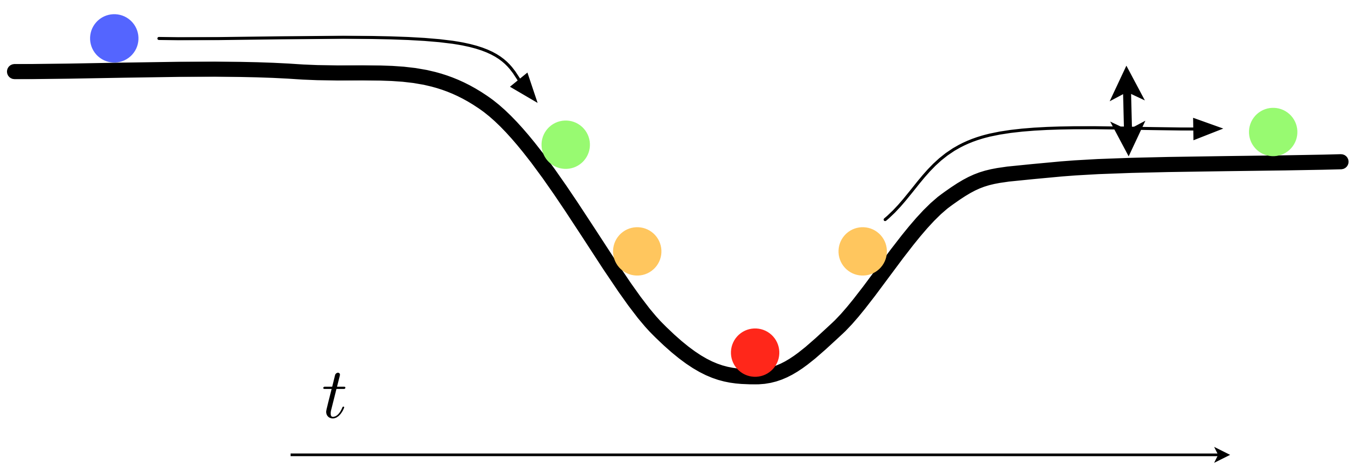


CMB lensing - External tracers



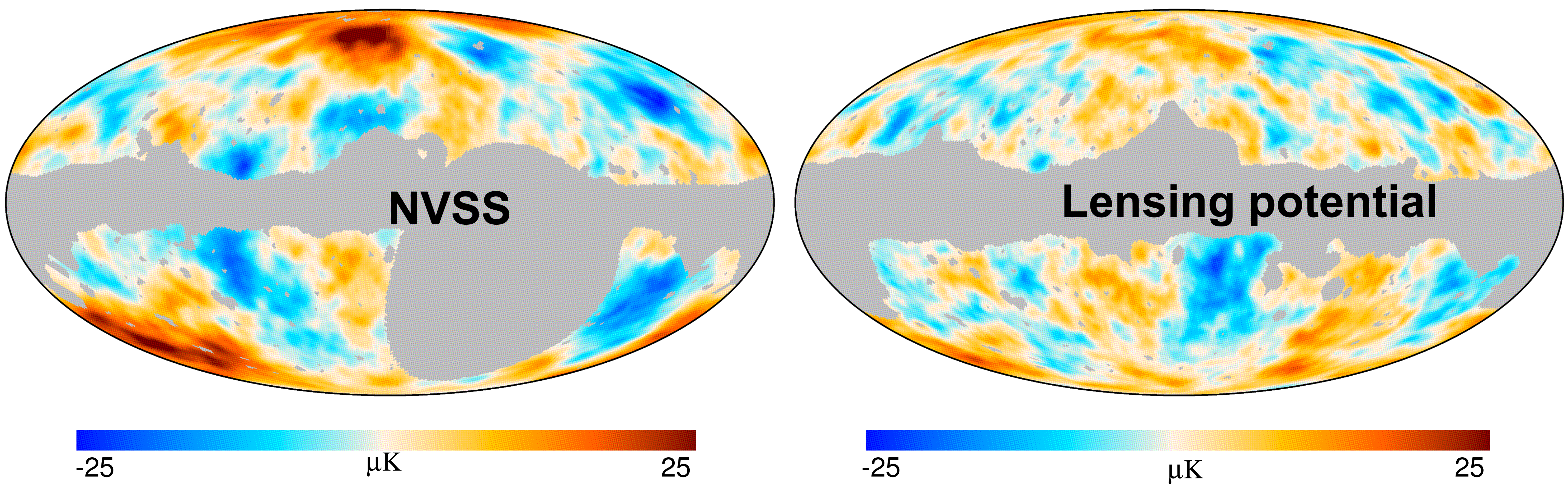
ISW

Shallowing of the potential due to expansion driven by dark energy



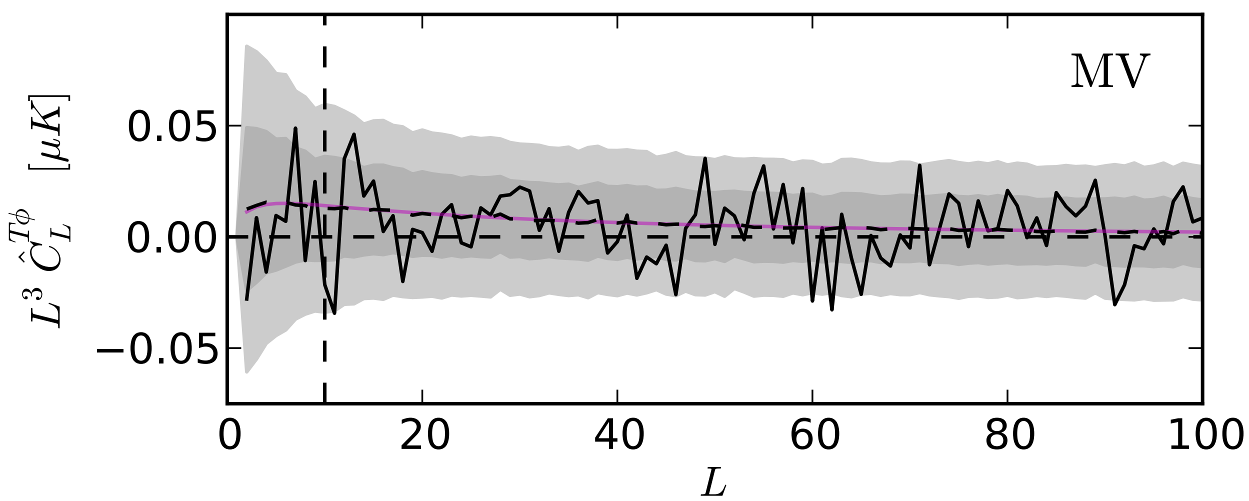
$$\frac{\Delta T}{T} = \frac{2}{c^3}\int_{\eta^*}^{\eta_0} \mathrm{d}\eta \frac{\partial \Phi}{\partial \eta}$$

Courtesy: K. Benabed



Planck ISW maps

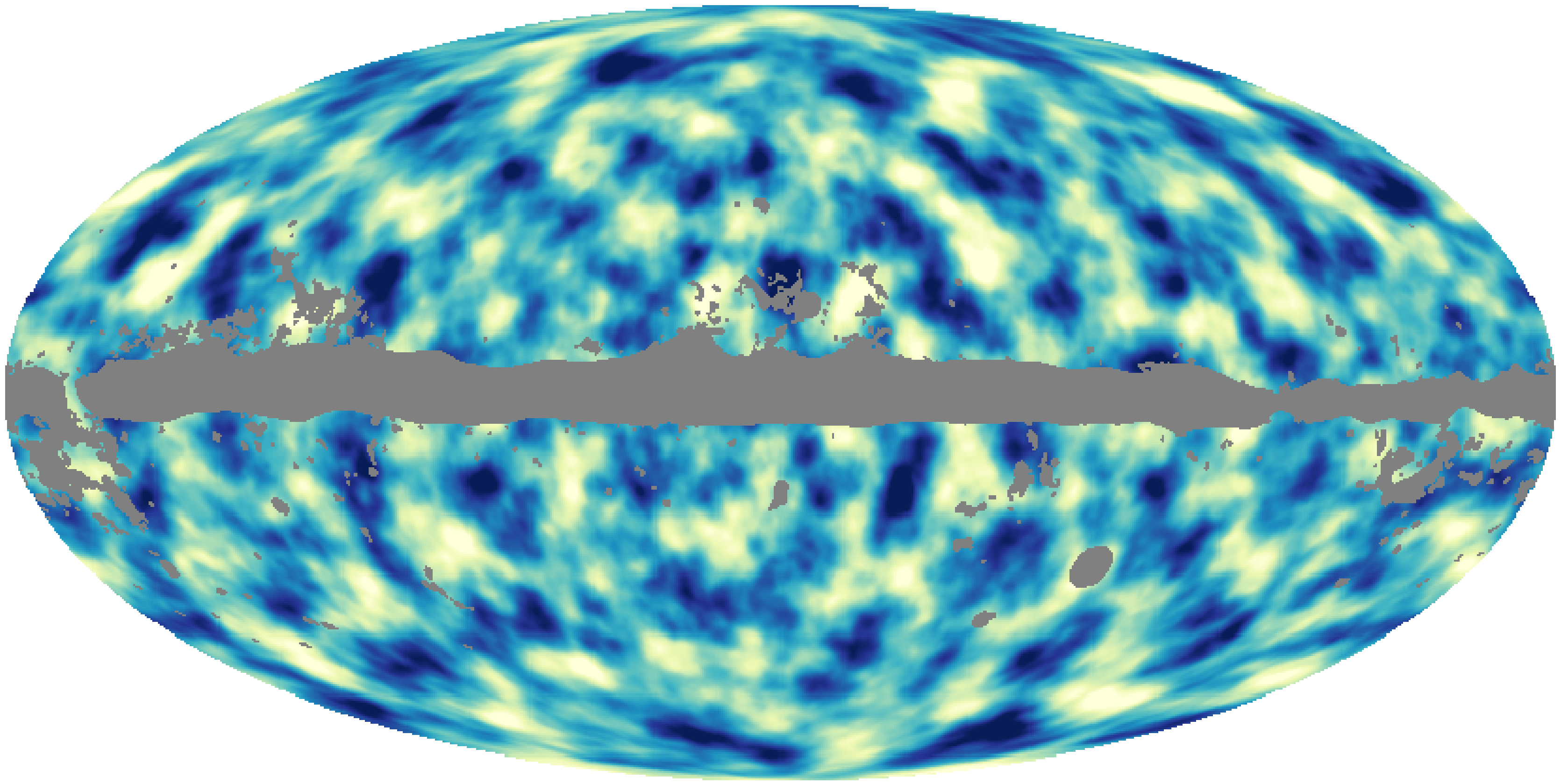
ISW - Lensing correlation



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 against 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