The large scale structure of the Universe as seen by Planck

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On behalf of the Planck Collaboration

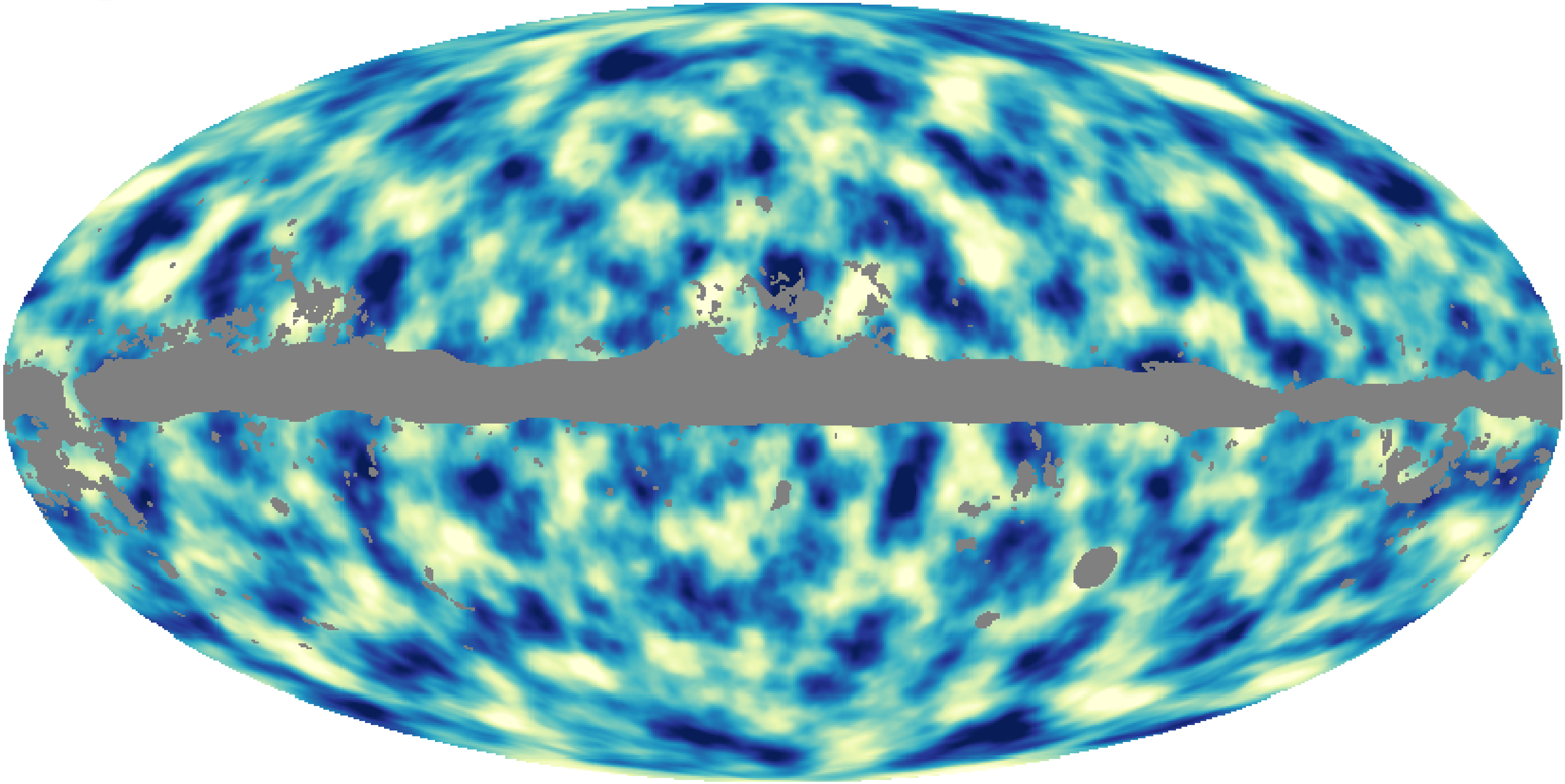
XVII. Gravitational lensing by large scale structure

XVI. Cosmological parameters

XVIII. Gravitational lensing - infrared background correlation

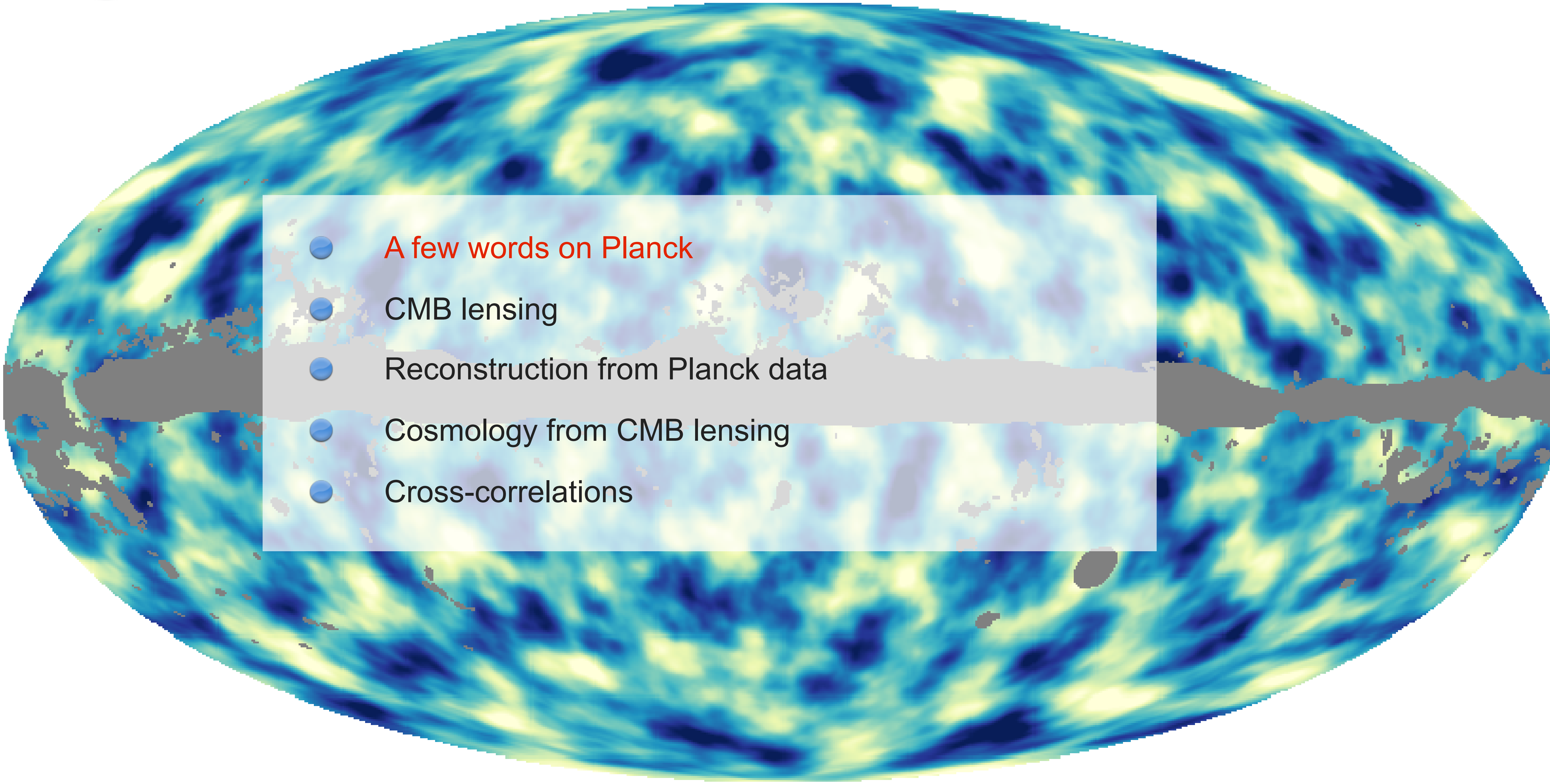
XIX. The integrated Sachs-Wolfe effect

The matter in the Universe



Planck picture of the matter distribution at z~2

Outline

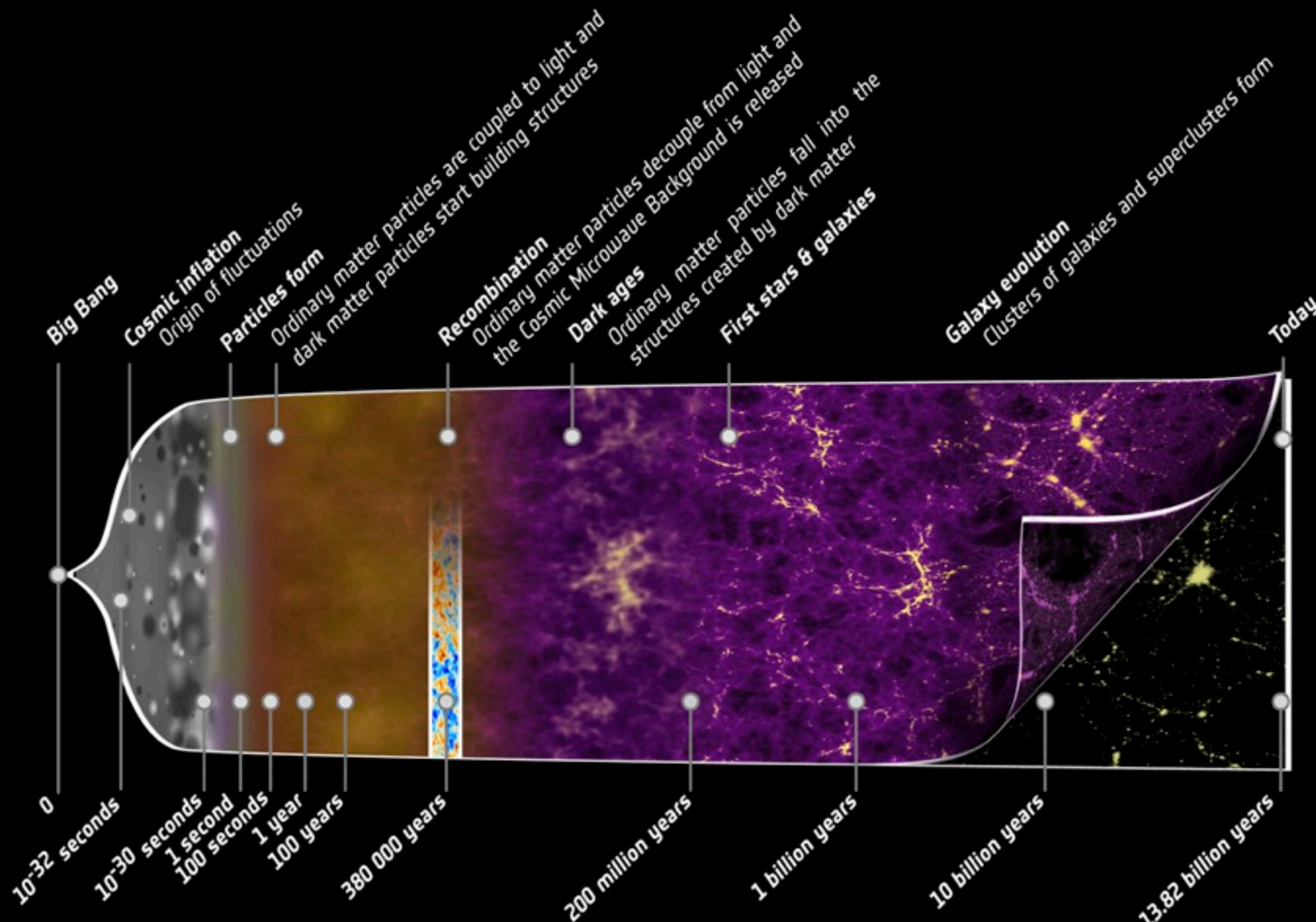


- A few words on Planck
- CMB lensing
- Reconstruction from Planck data
- Cosmology from CMB lensing
- Cross-correlations

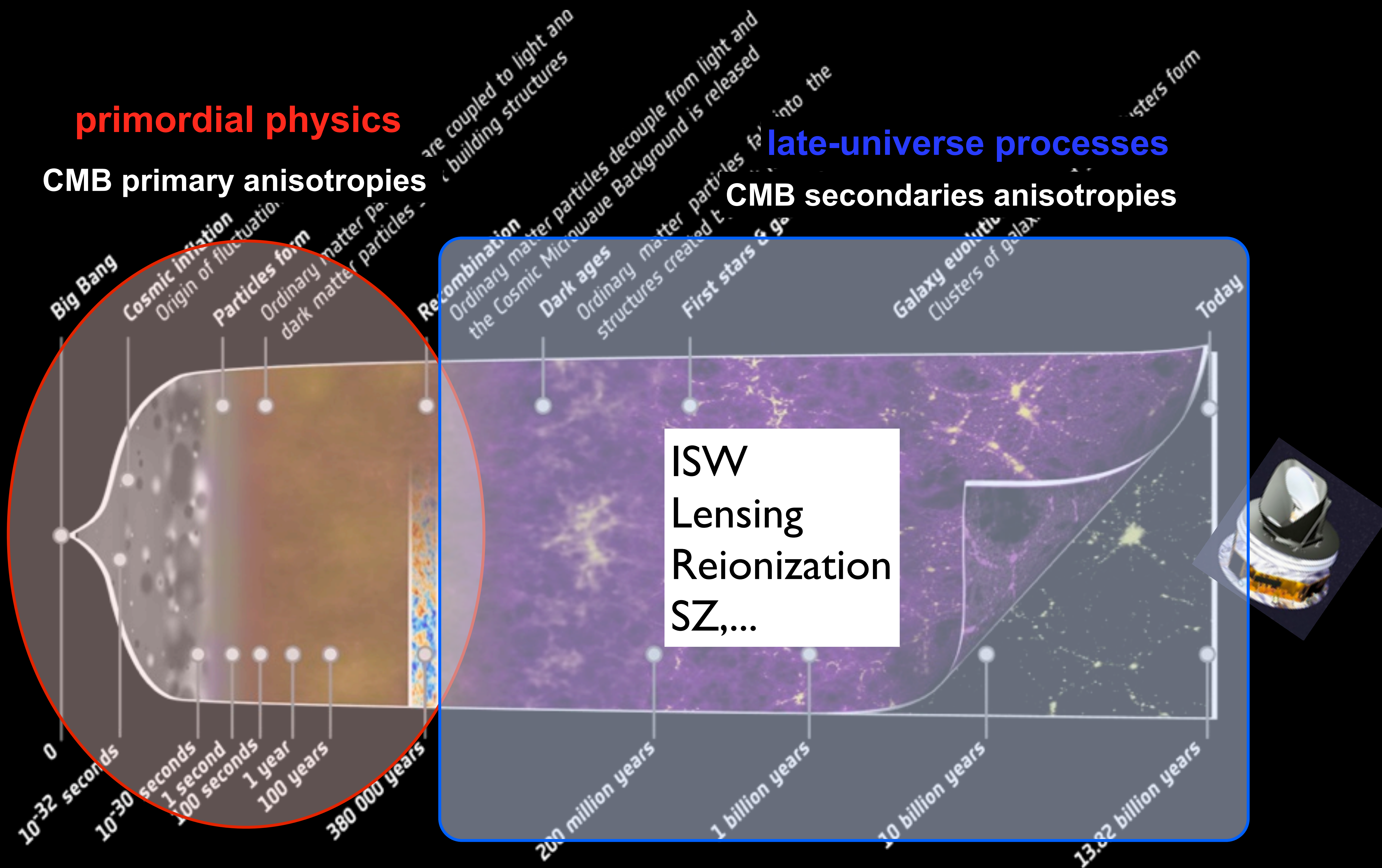
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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



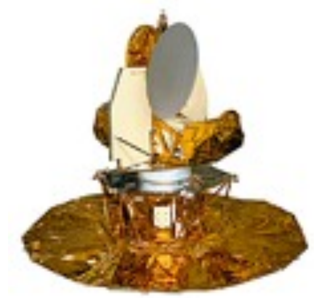
CMB: central observation in cosmology



Historical slide

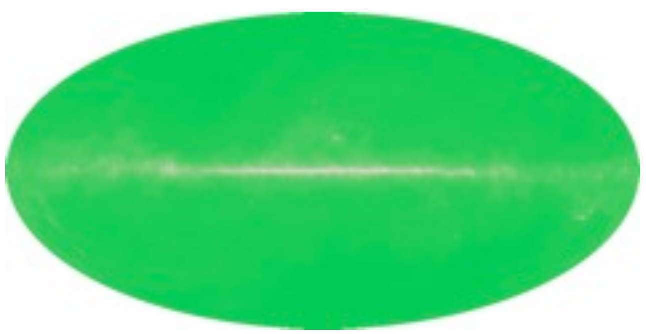
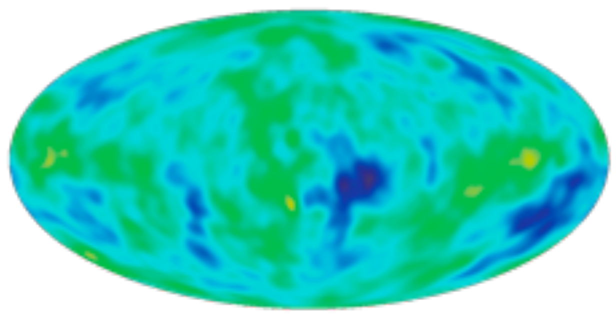
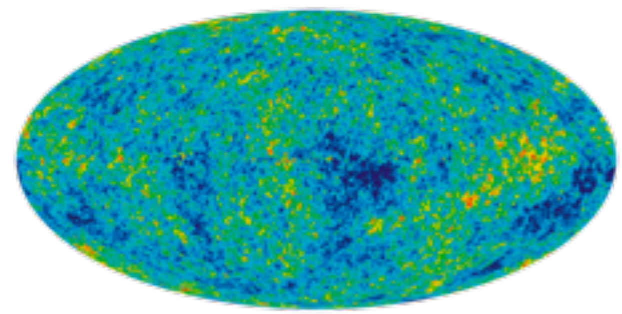
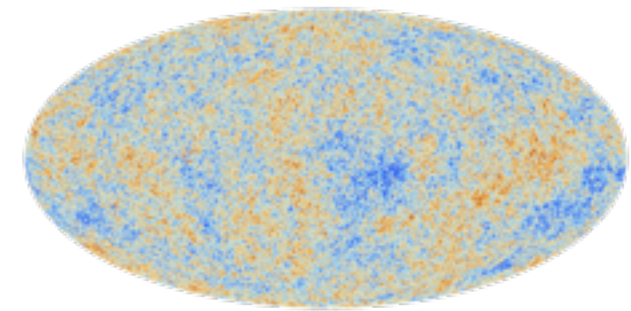
Penzias & Wilson

COBE



WMAP

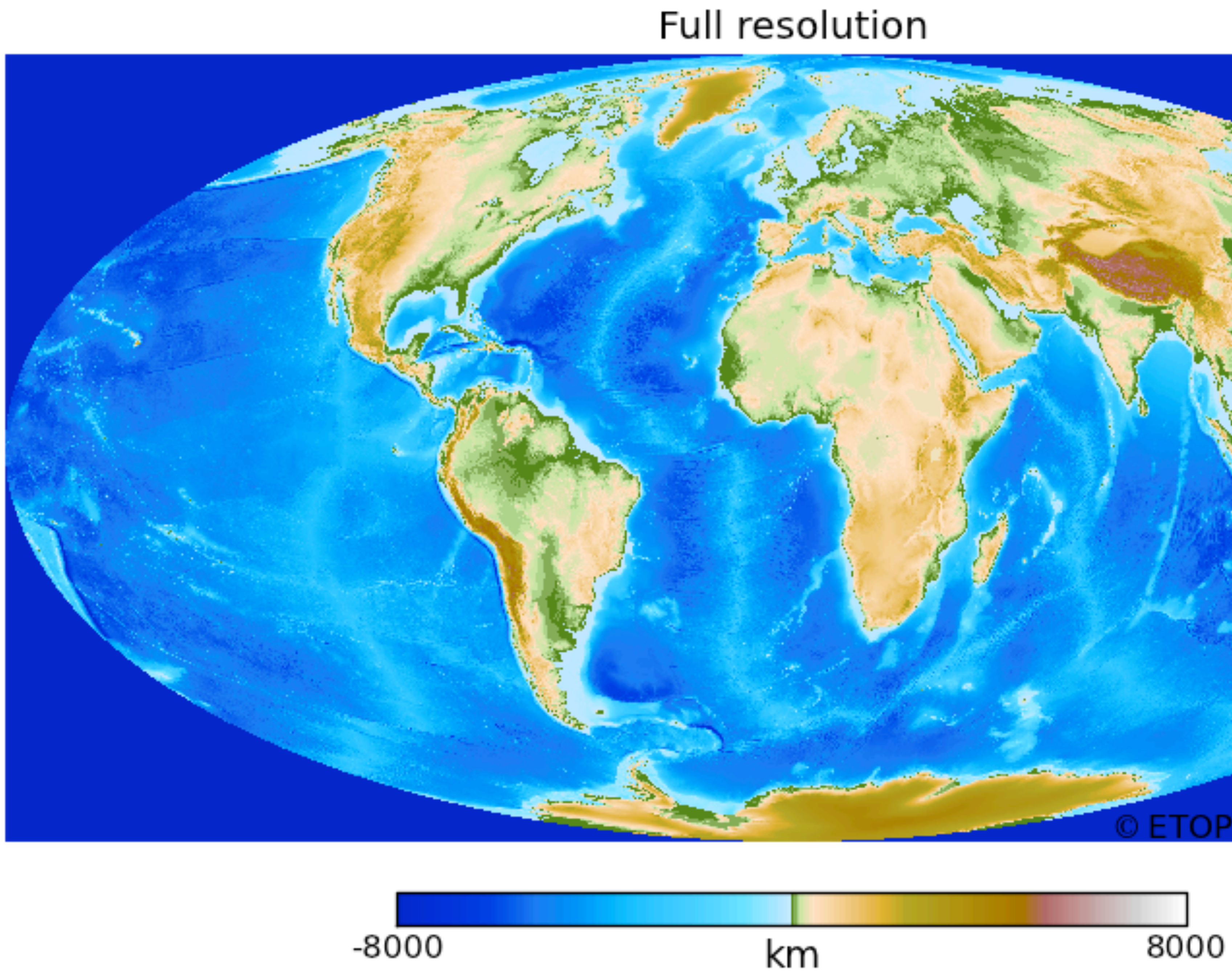
Planck

Better angular resolution →

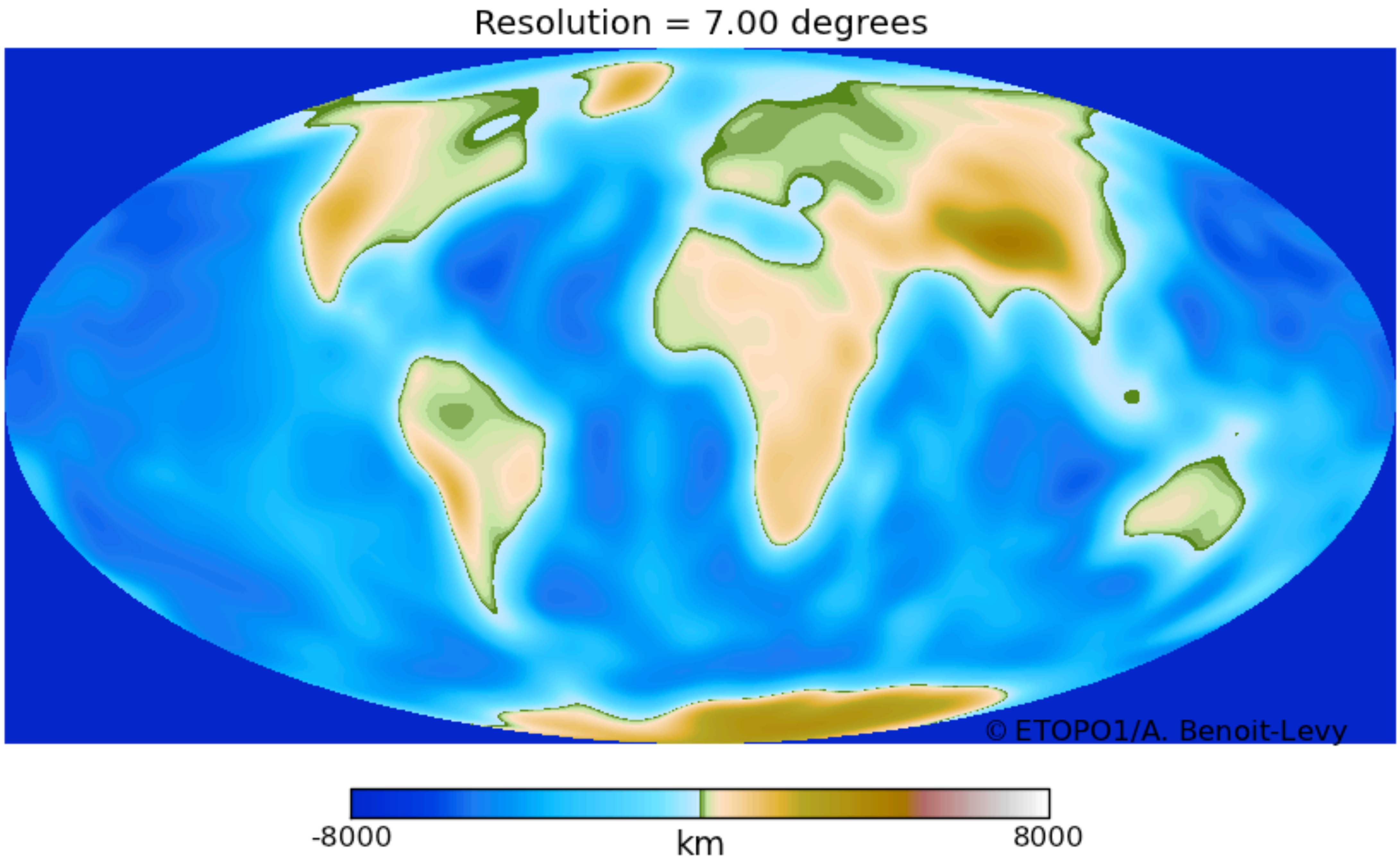
CMB has become the cornerstone of modern cosmology

The Earth as seen by CMB satellites



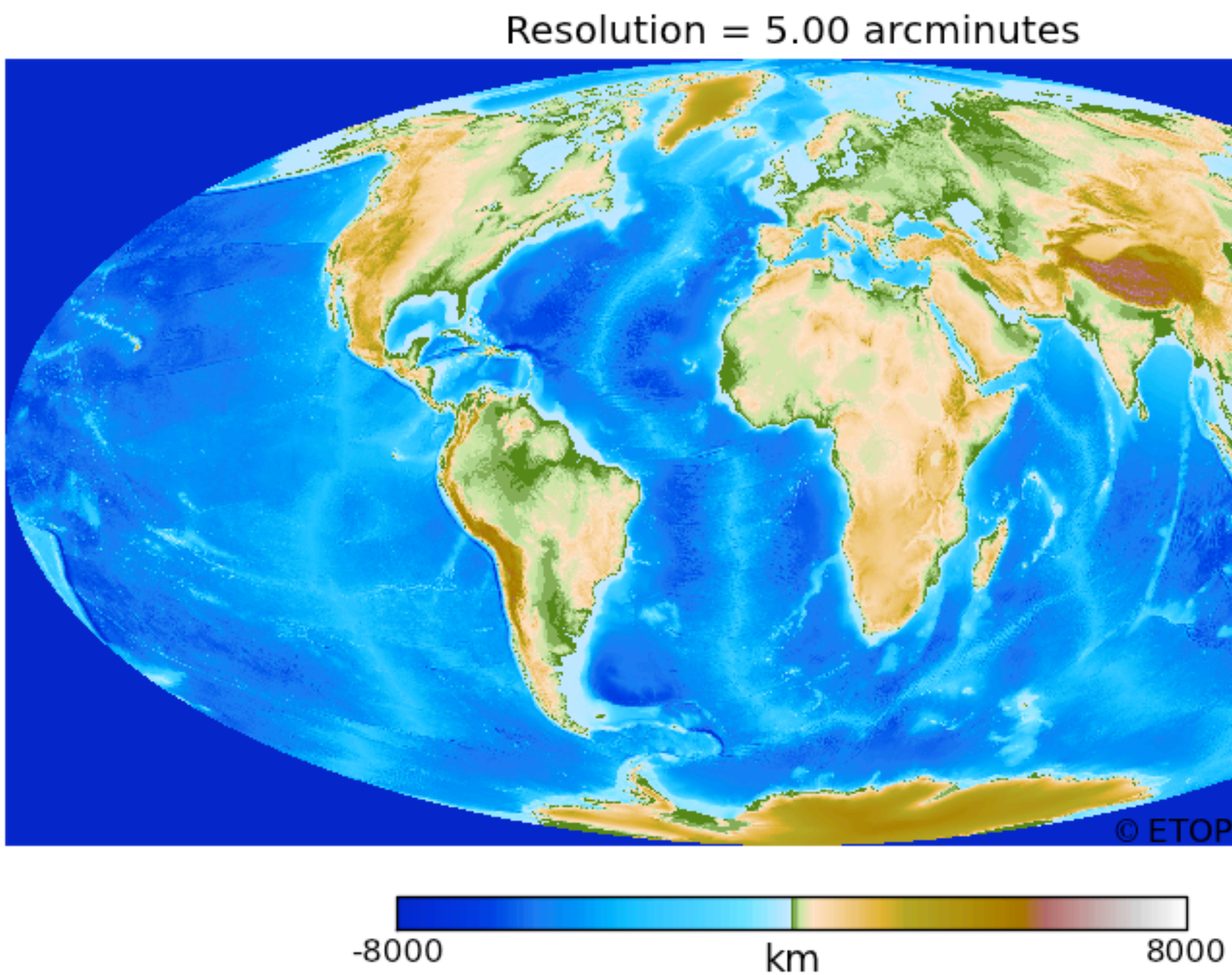
The Earth as seen by CMB satellites

COBE

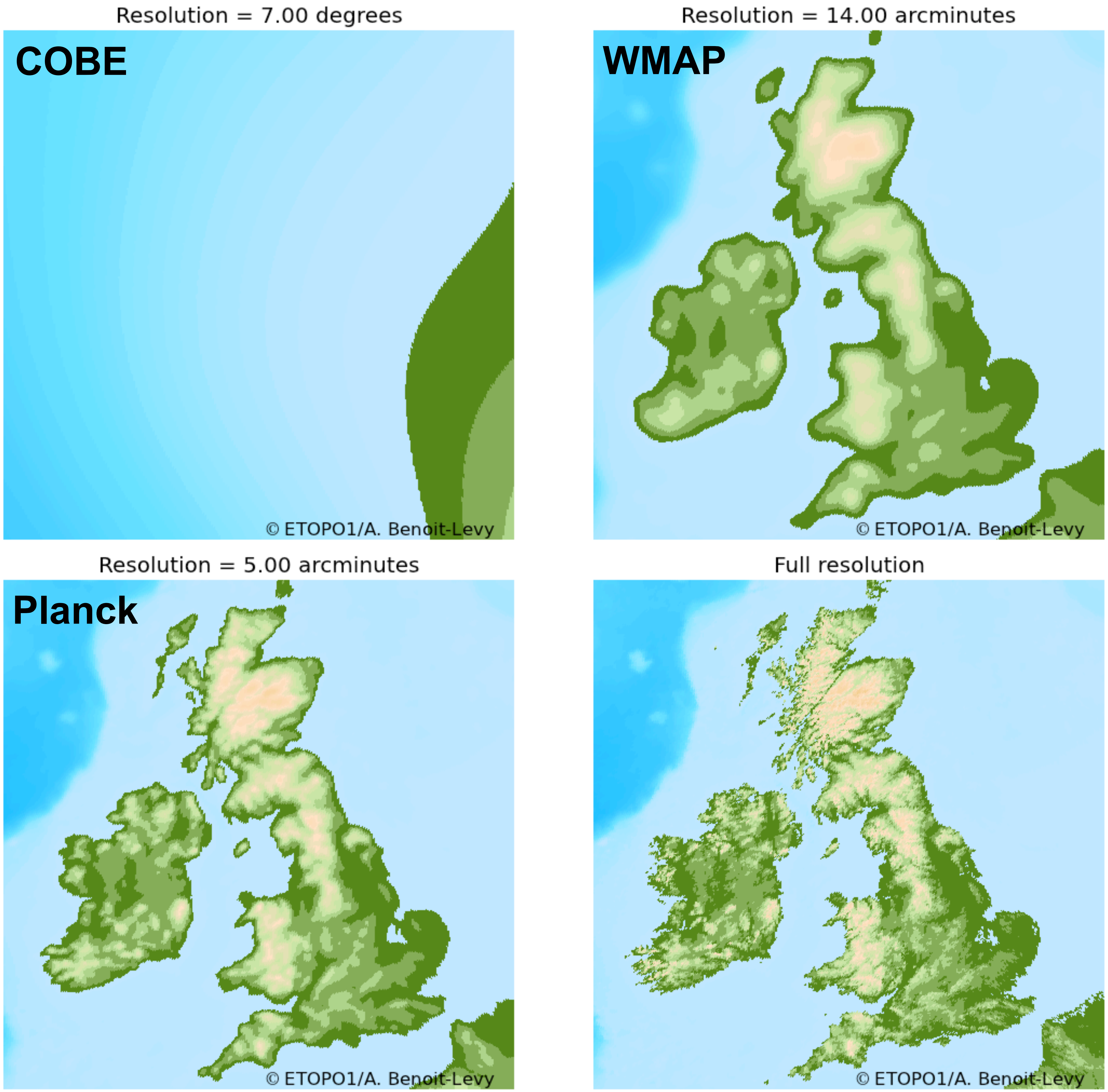


The Earth as seen by CMB satellites

Planck



Focus on the British Isles



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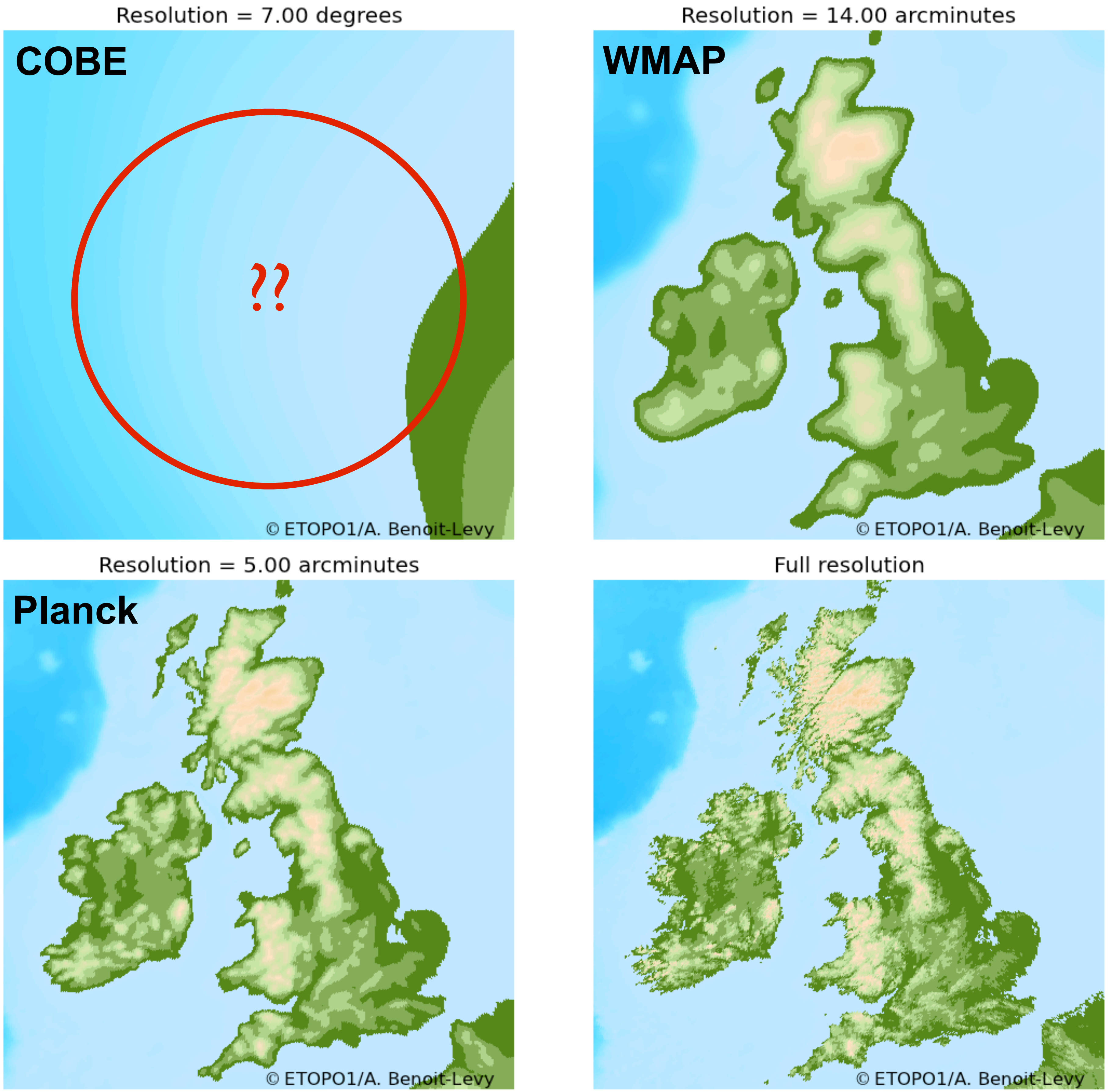

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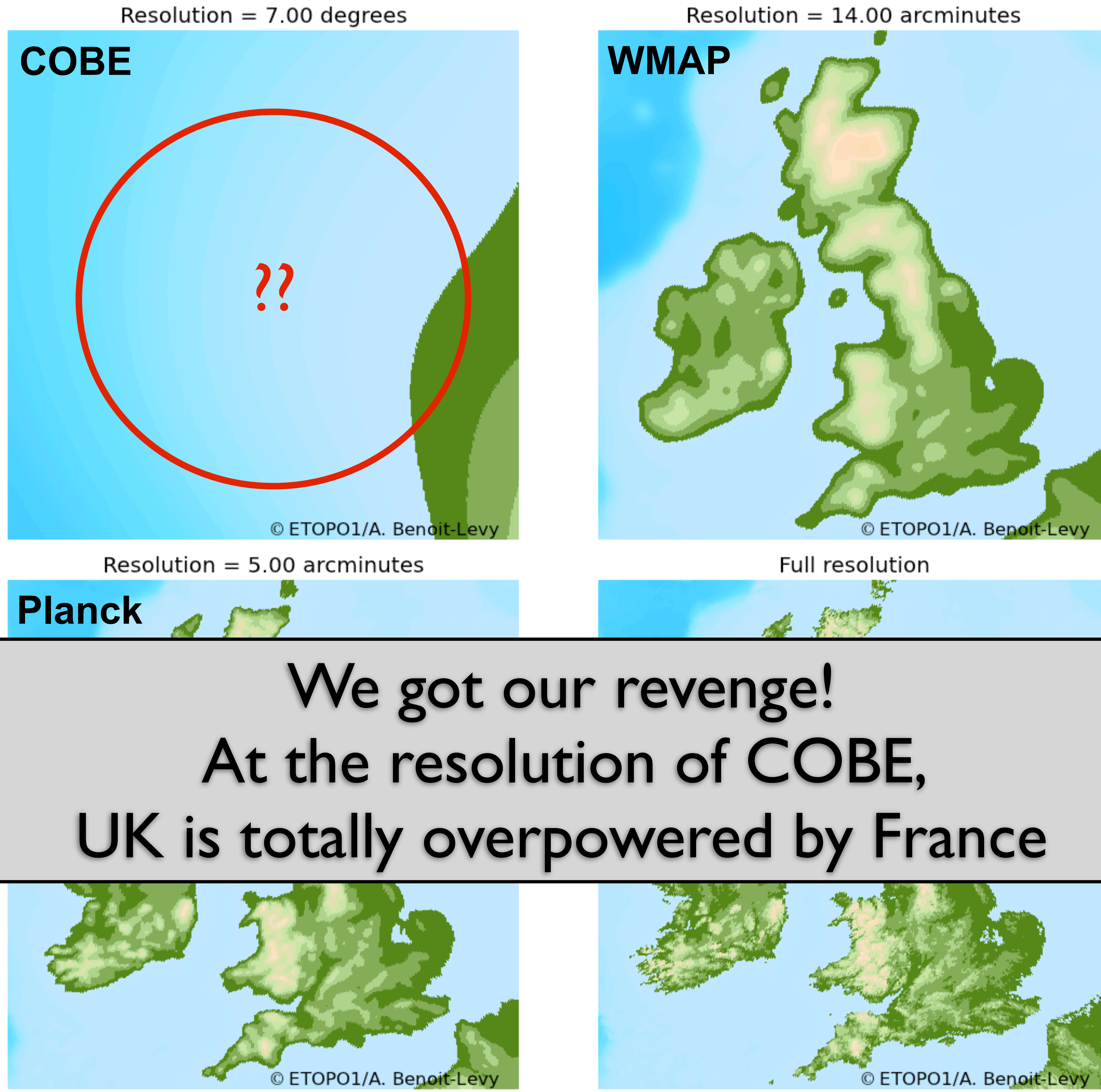
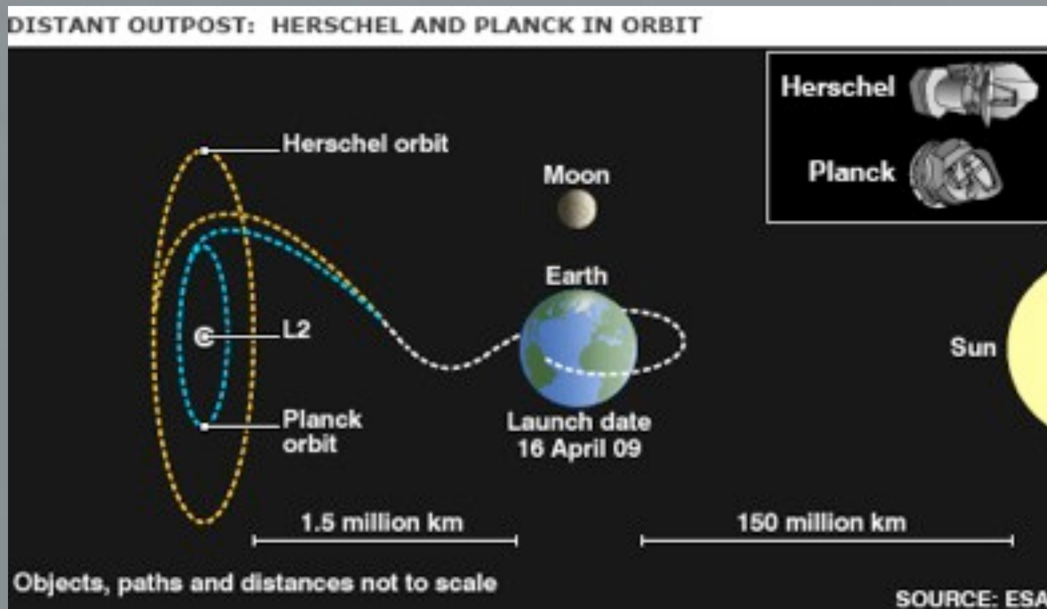
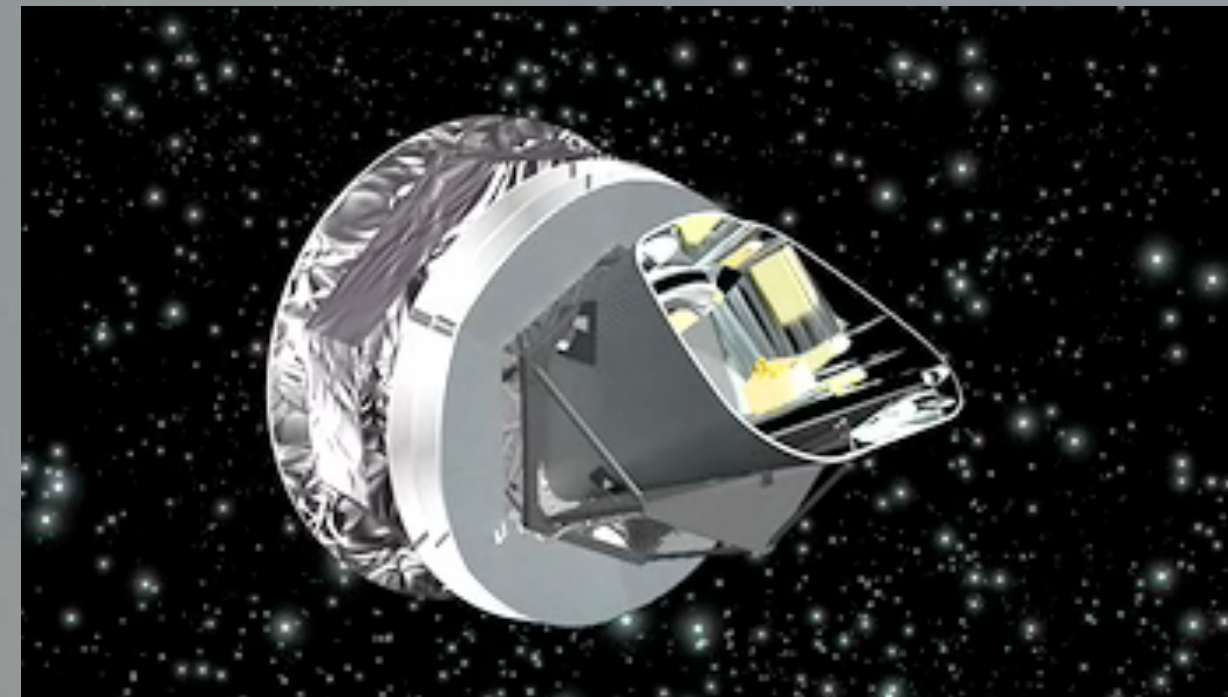


We got our revenge!
At the resolution of COBE,
UK is totally overpowered by France

The Planck concept

- Perform the *ultimate* measurement of CMB temperature anisotropies
  - Extract all the information contained in primary anisotropies
  - Full sky coverage
  - Sensitivity/resolution limited by ability to disentangle astrophysical foregrounds

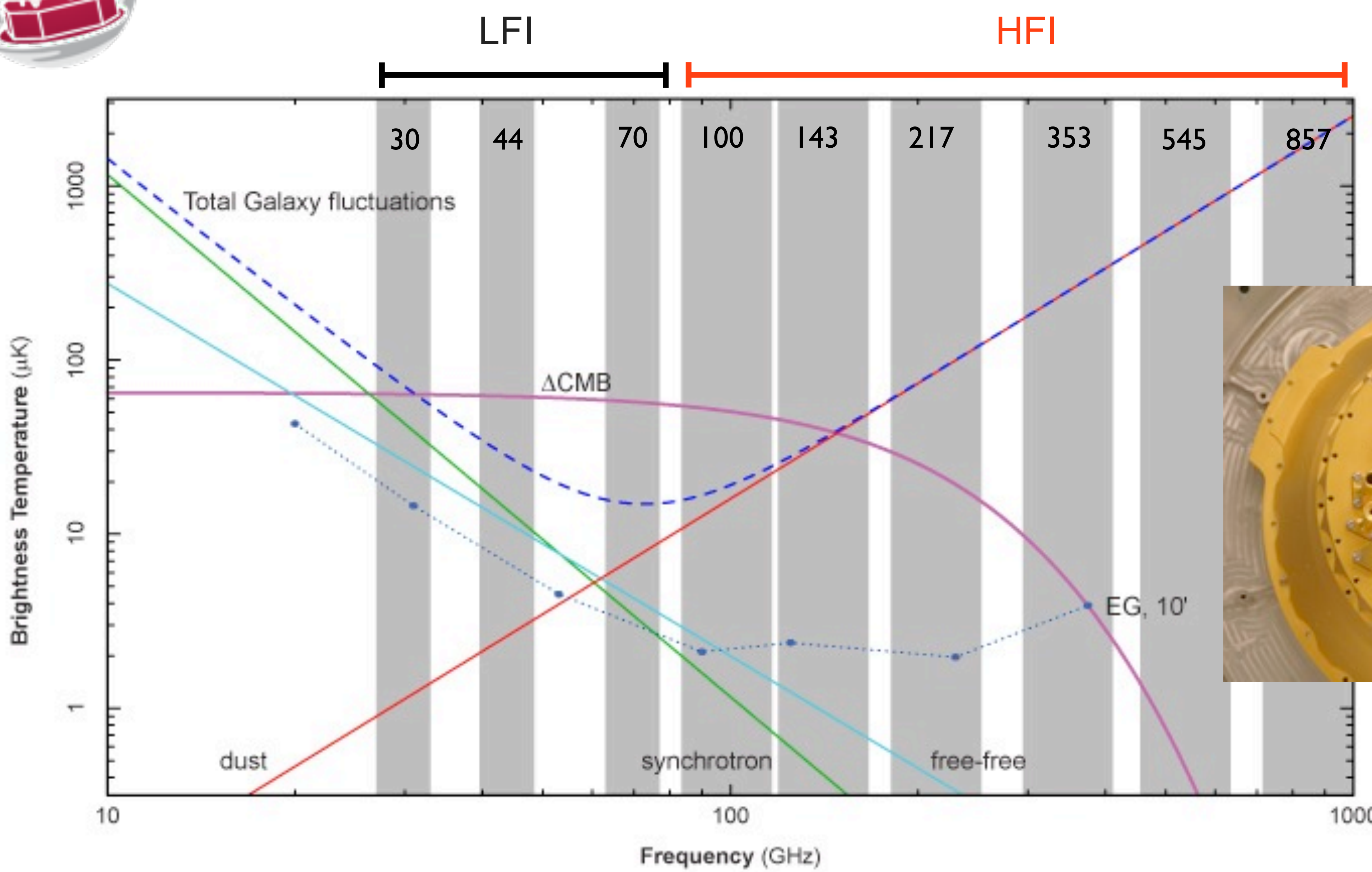




- Proposed to ESA in 1993, selected in 1996
- Launched on May 14th 2009
- First complete coverage of sky in June 2010
- Nominal mission completed in November 2010
- End of light (HFI) January 14th 2012. 32 months after launch
- March 2013: First cosmological data release
- August 2013: Departure manoeuvre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

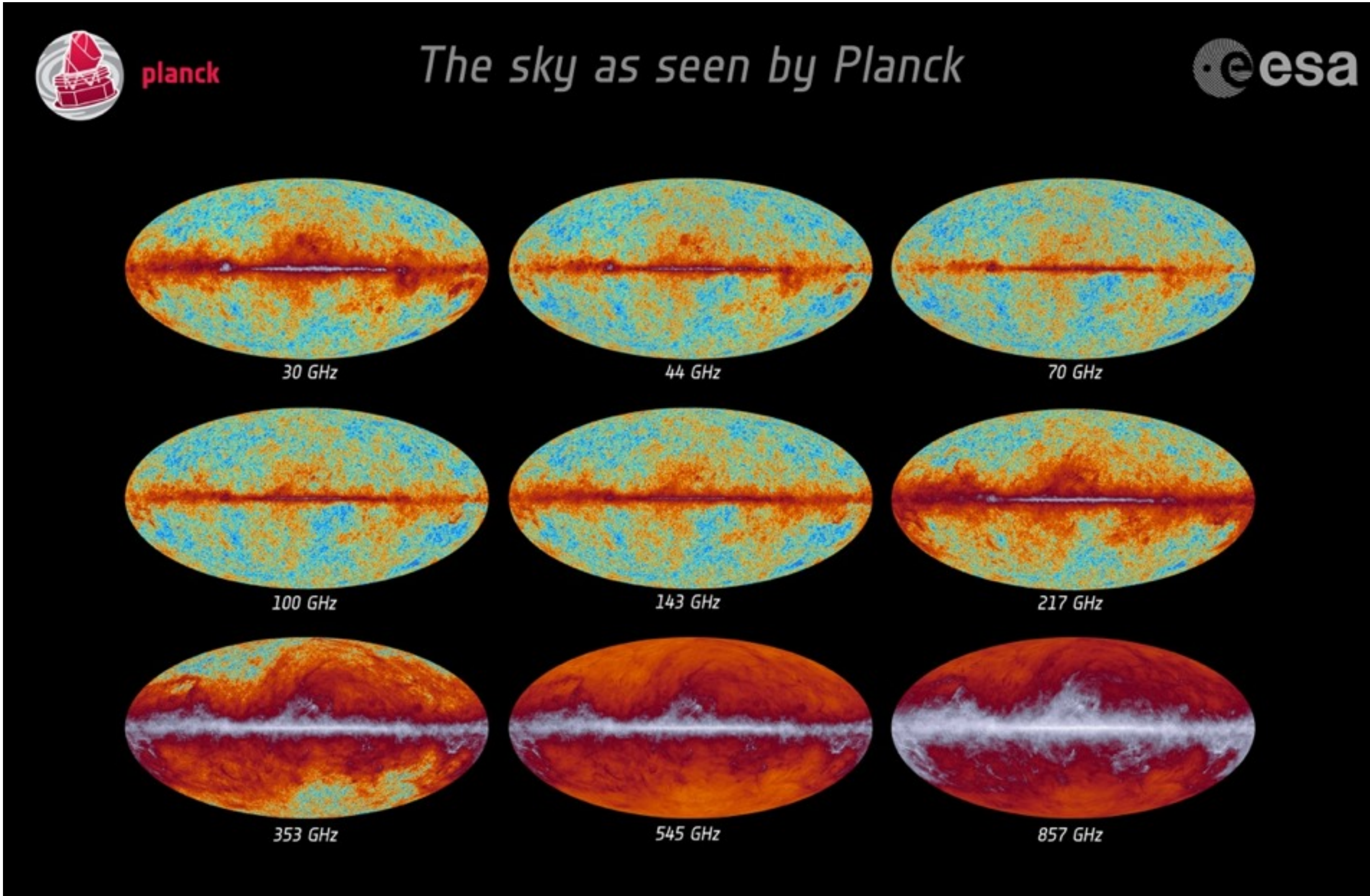
Ariane 5 ECA Launch • HERSCHEL – PLANCK - *May 14, 2009*

Planck frequency coverage

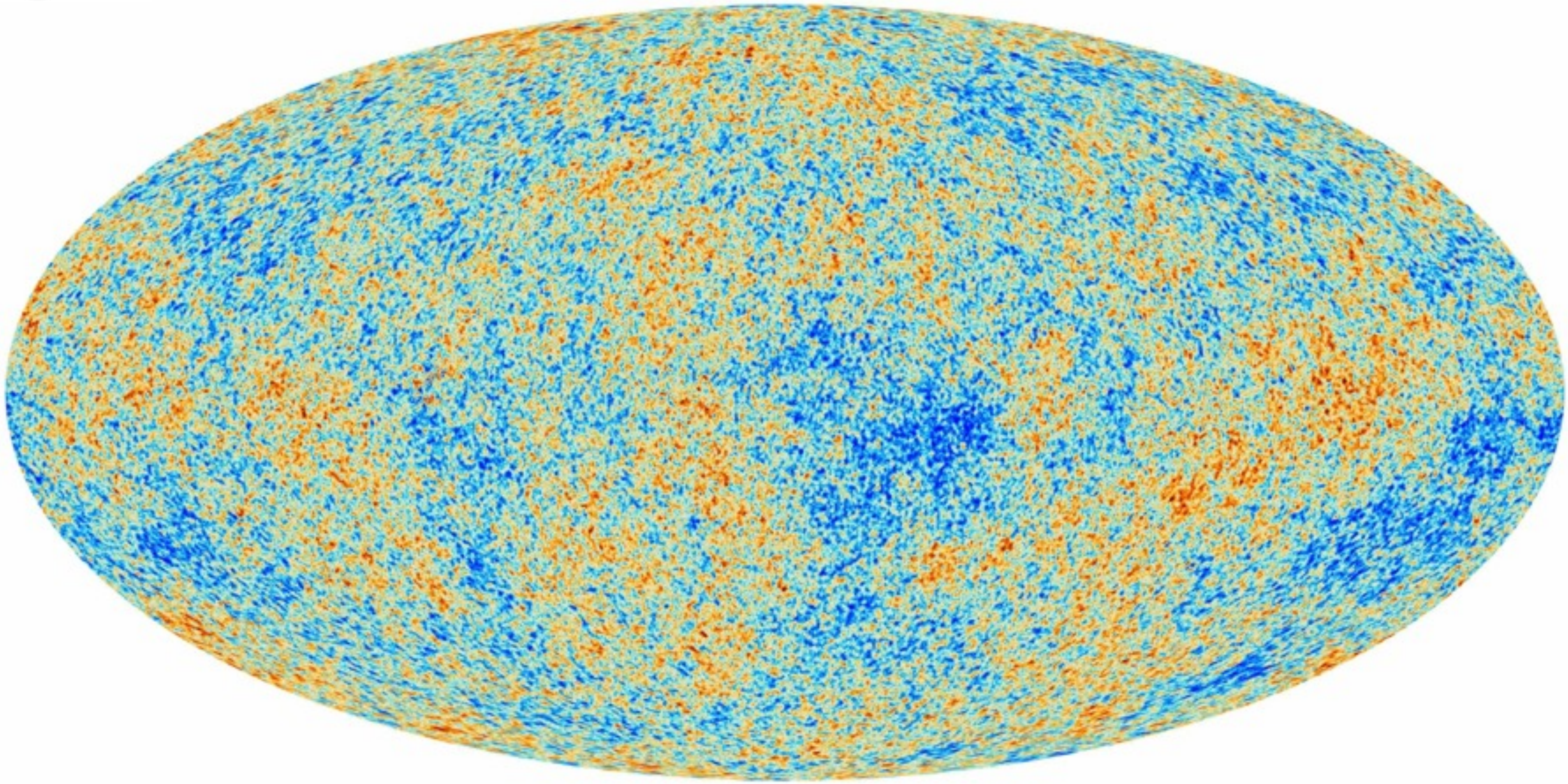


PLANCK	LFI			HFI					
Center Freq (GHz)	30	44	70	100	143	217	353	545	857
Angular resolution (FWHM arcmin)	33	24	14	10	7.1	5.0	5.0	5	5
Sensitivity in I [μK.deg] [$\sigma_{pix}\ \Omega_{pix}^{1/2}$]	3.0	3.0	3.0	1.1	0,7	1.1	3.3	33	3.0

Planck sky maps



Full-sky temperature map

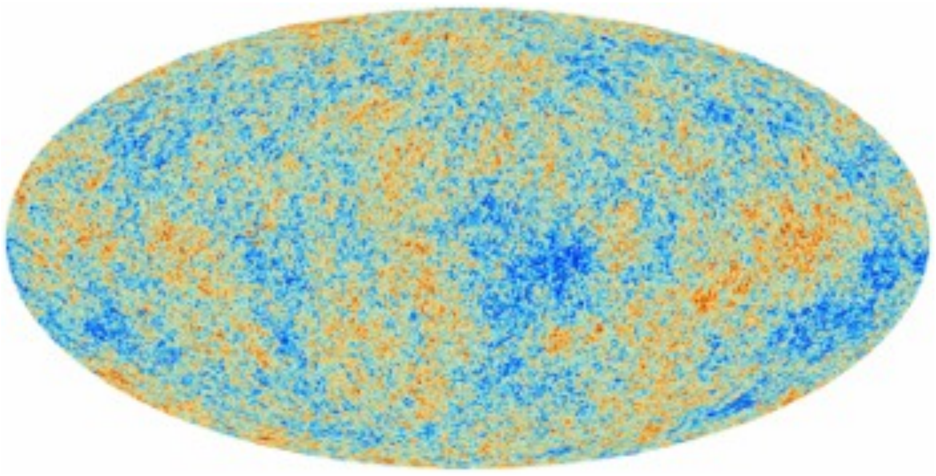


- 3% sky fraction filled with Gaussian constrained realisations

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,
-1.88960308e-06 -2.69868746e-07j,
 1.06239463e-06 +4.31127048e-07j,
 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,
```

Cosmic Microwave Background

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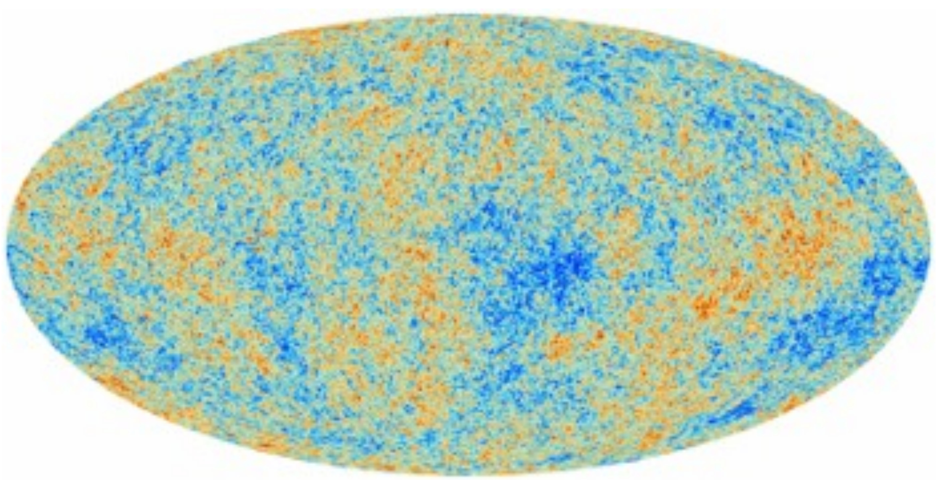
$T(\hat{\mathbf{n}})$



$T_{\ell m}$

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 3.48160018e-07 +5.48607128e-07j,
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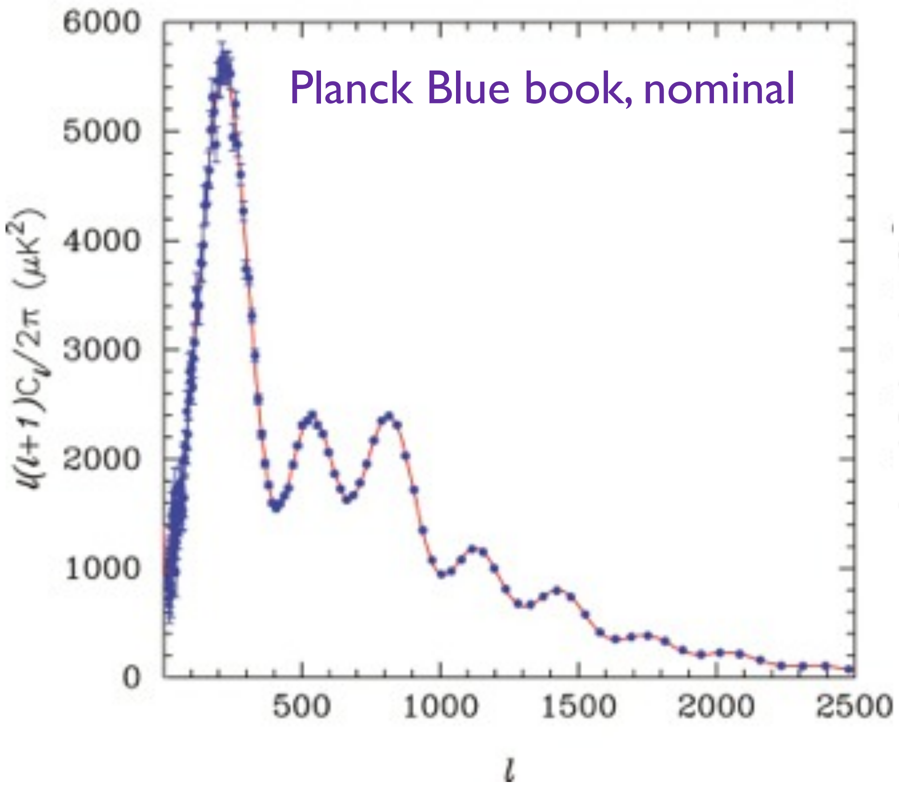
-1.24503110e-06 -1.93401840e-06j,
 5.68052758e-07 +6.49802586e-08j,
 5.05386856e-07 -2.28955226e-07j,
-2.60272490e-07 +2.21246718e-06j,
-1.11889361e-06 +1.87312956e-06j,
 9.72080476e-07 -6.89214224e-07j,
 3.26351028e-07 +1.08530943e-06j,
 2.14977119e-06 -9.44341599e-07j,
```

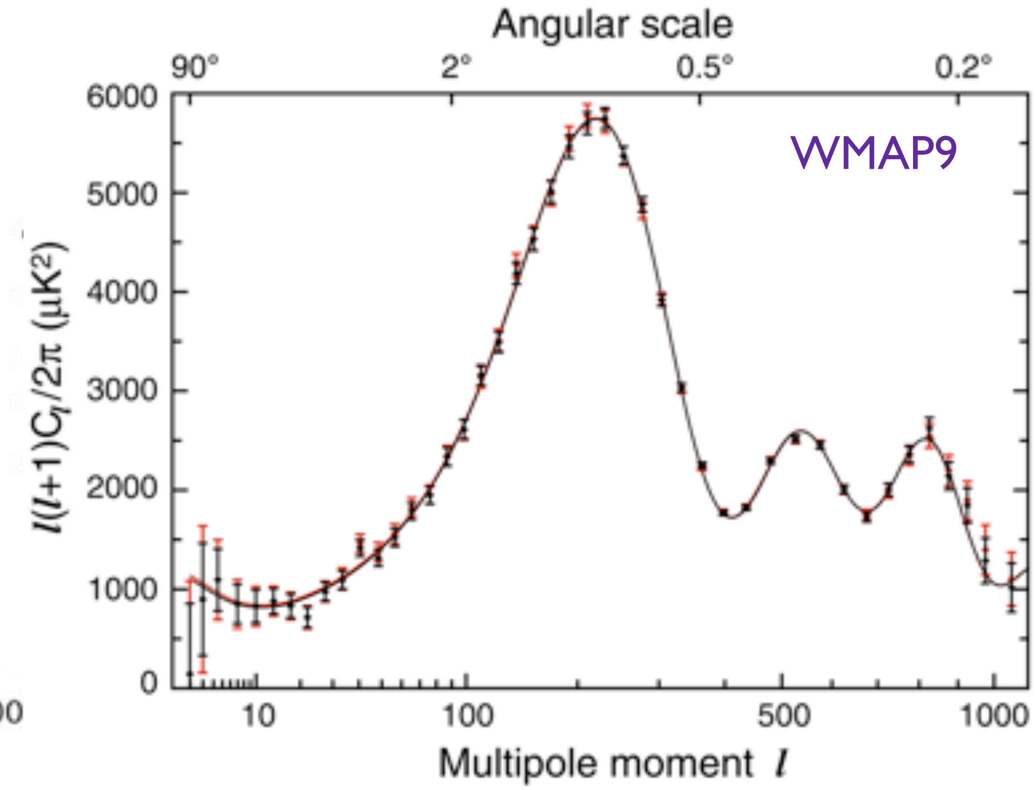
- CMB is (almost) Gaussian: all the information is in the variance $\langle t_{\ell m} t^*_{\ell' m'} \rangle = C_\ell$

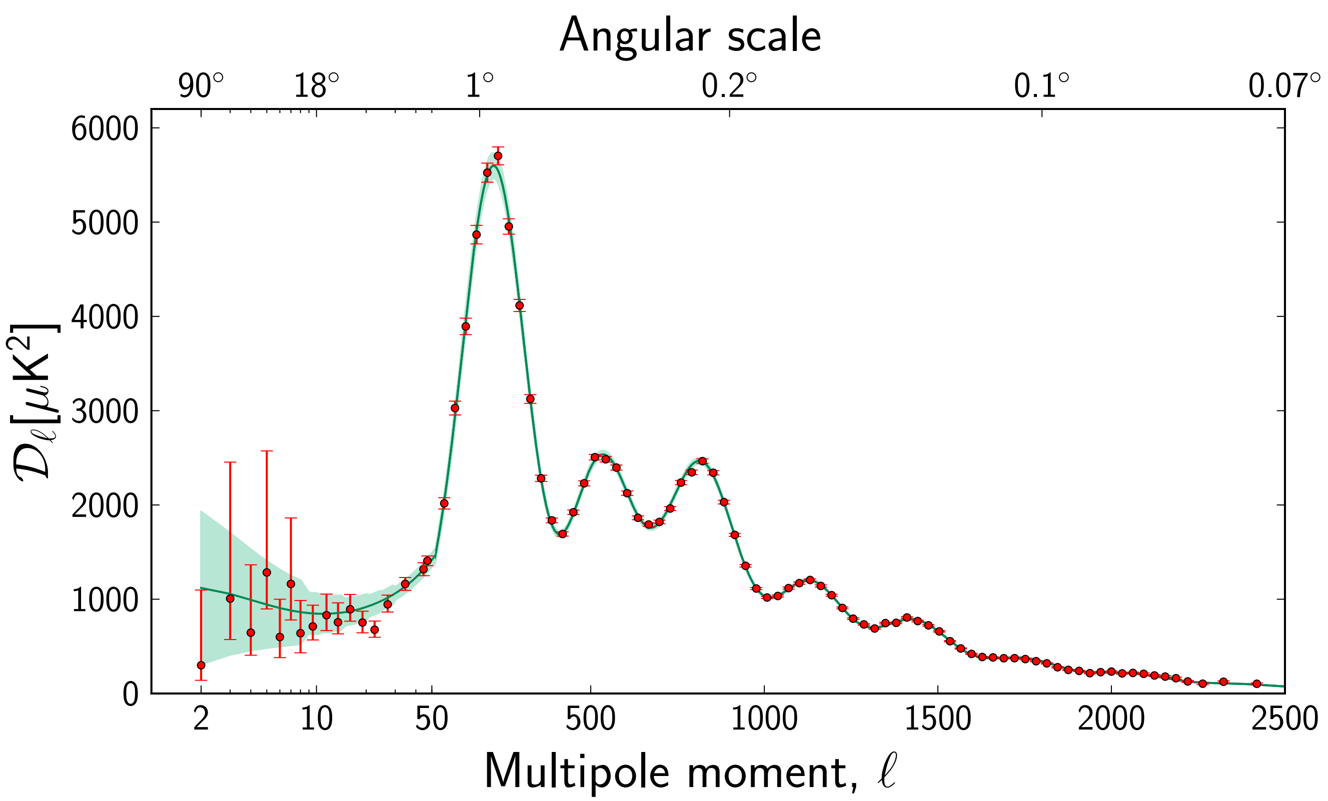
  Power spectrum can be computed: e.g. CAMB

  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

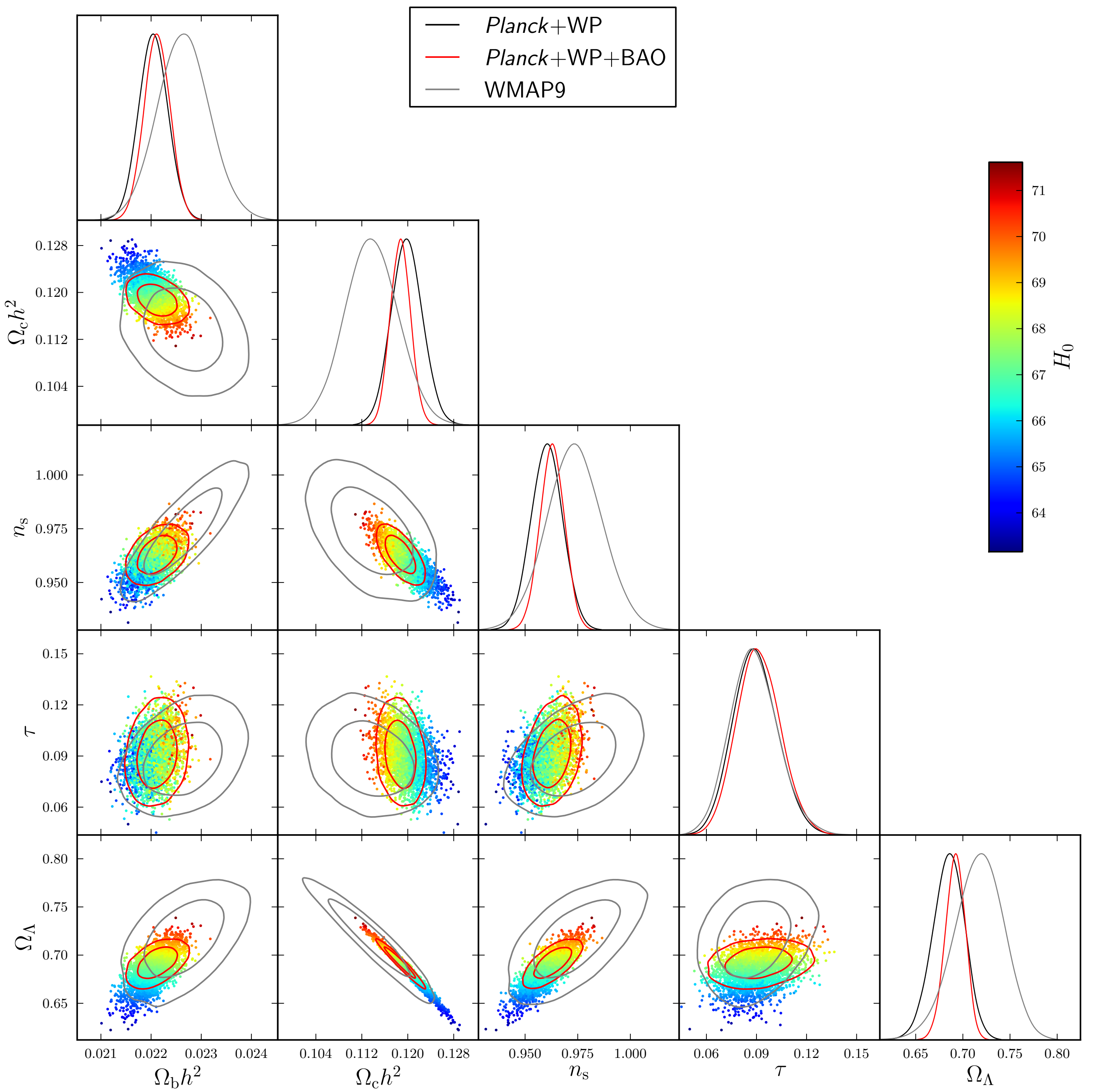






The Planck parameters

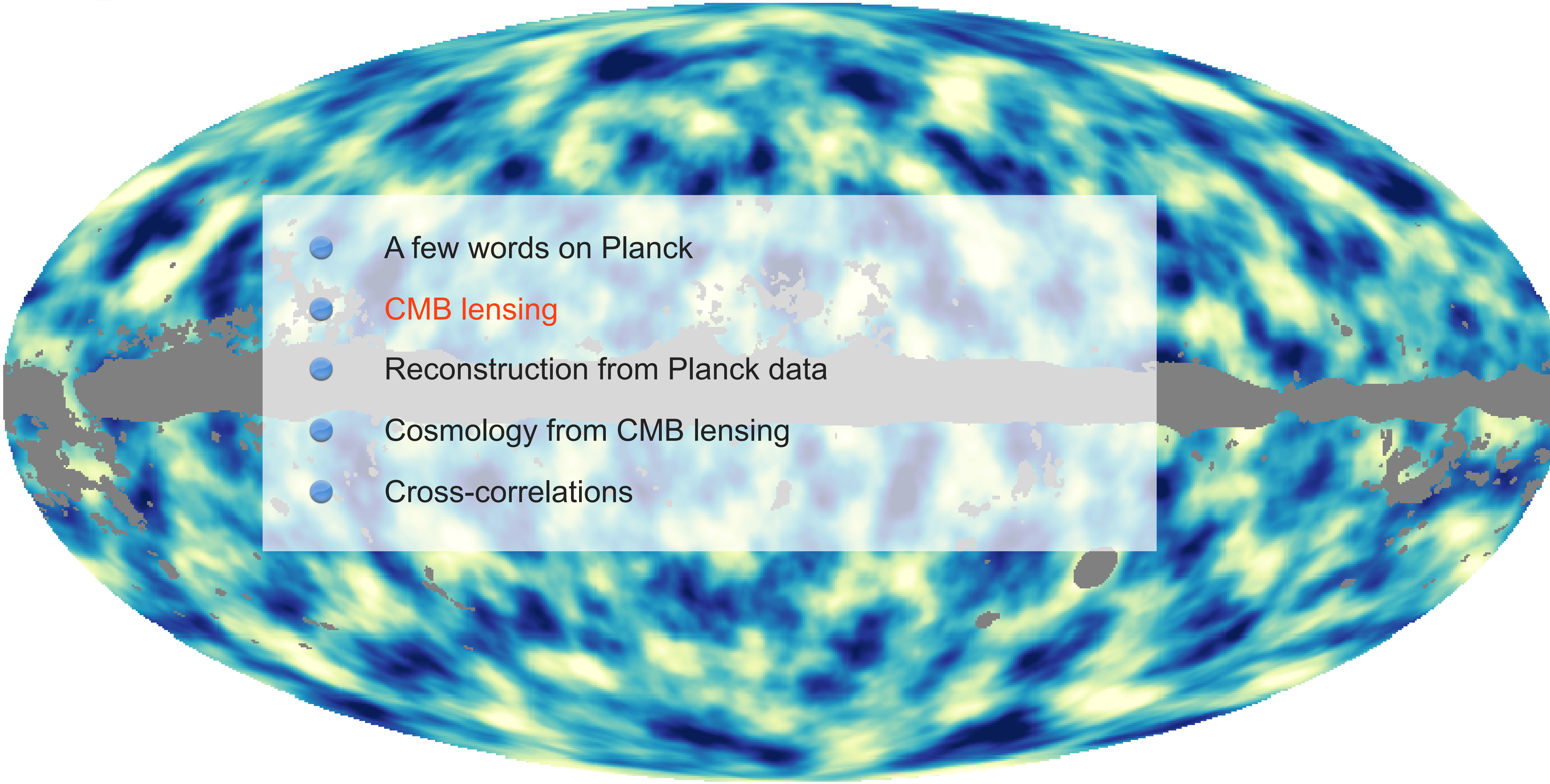
- **A model described by only 6 parameters**



Planck + WP

- Peak scale 0.060%
- Baryon density 1.3%
- CDM density 2.3%
- Primordial amplitude 2.5%
- Primordial spectral index 0.76%
- Reionization optical depth 0.13%

Outline



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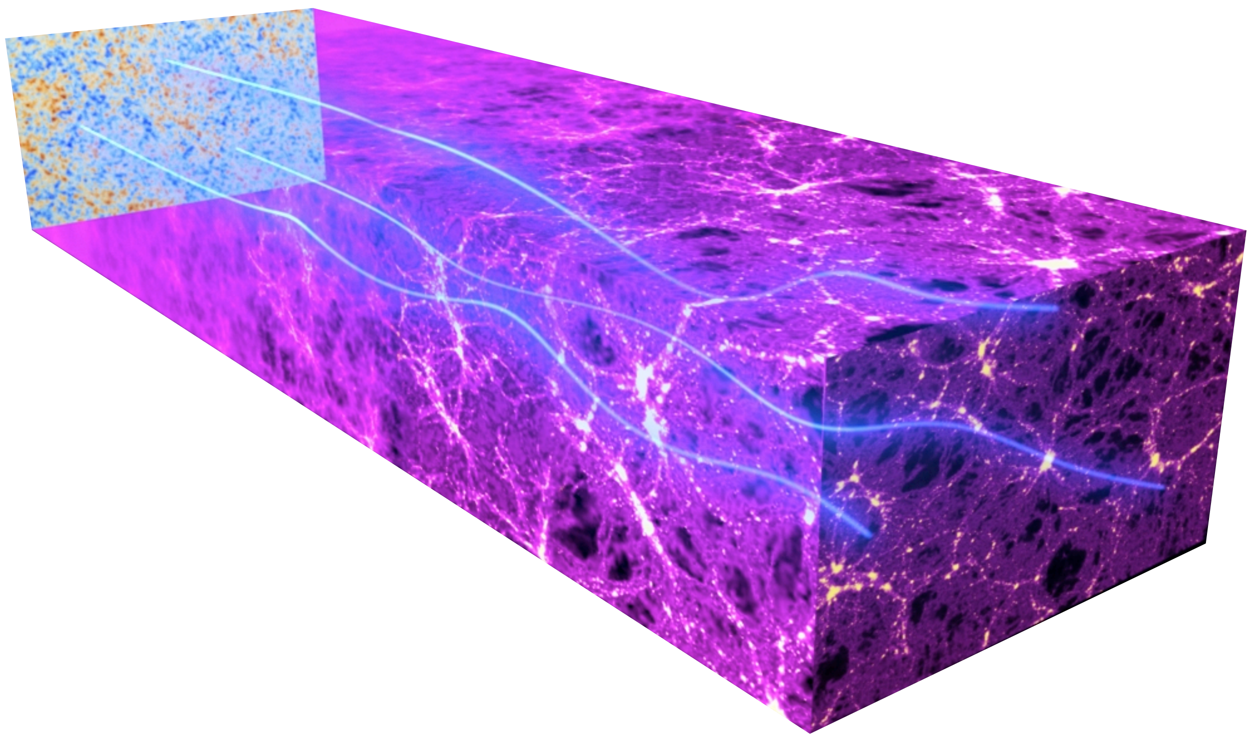
CMB lensing



Typical deflection δβ sourced by potential Ψ

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

Photons encounter ~ 50 potential wells

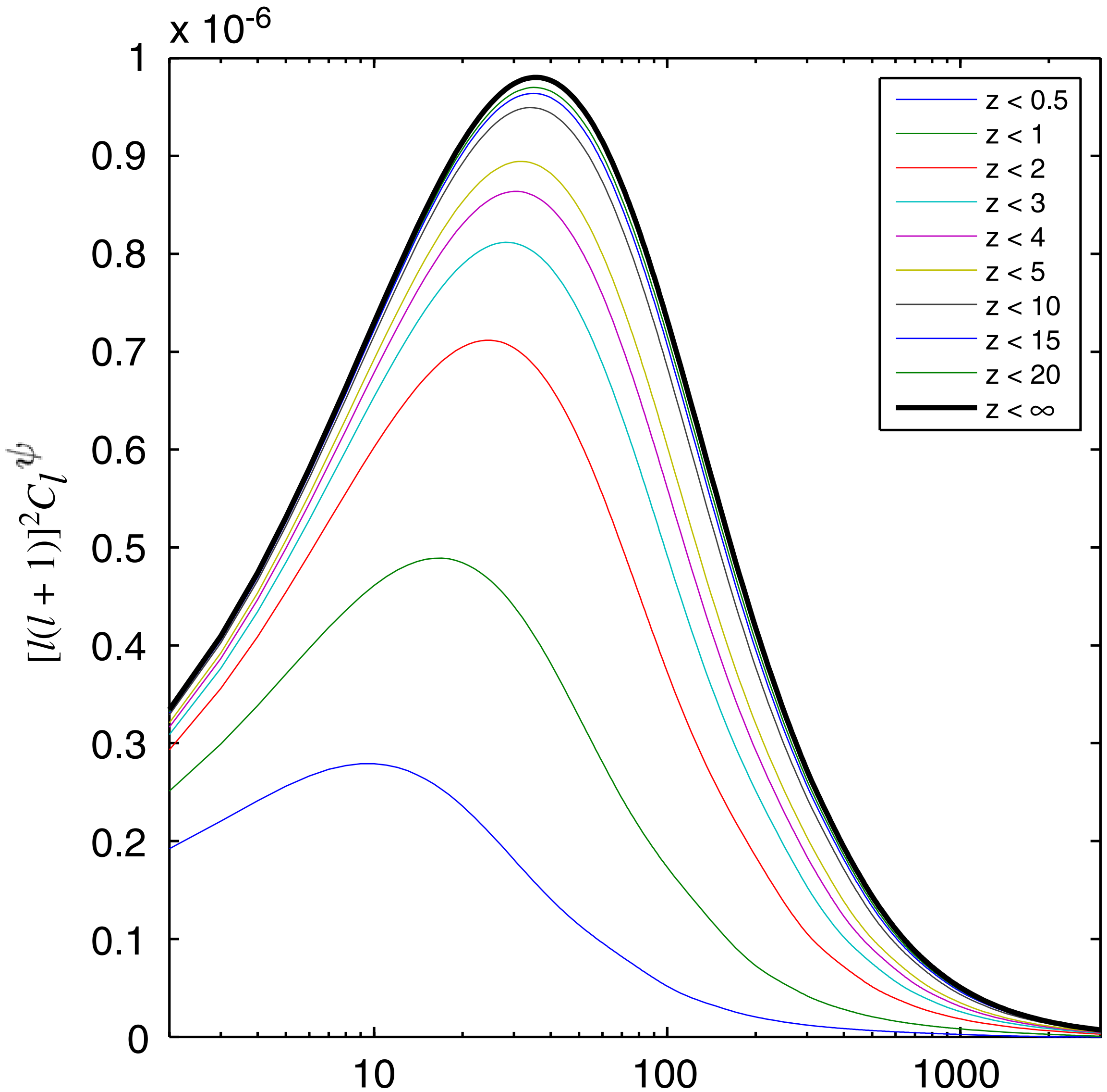
r.m.s deflection
$50^{1/2} * 10^{-4} \sim 2$ arcmin

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

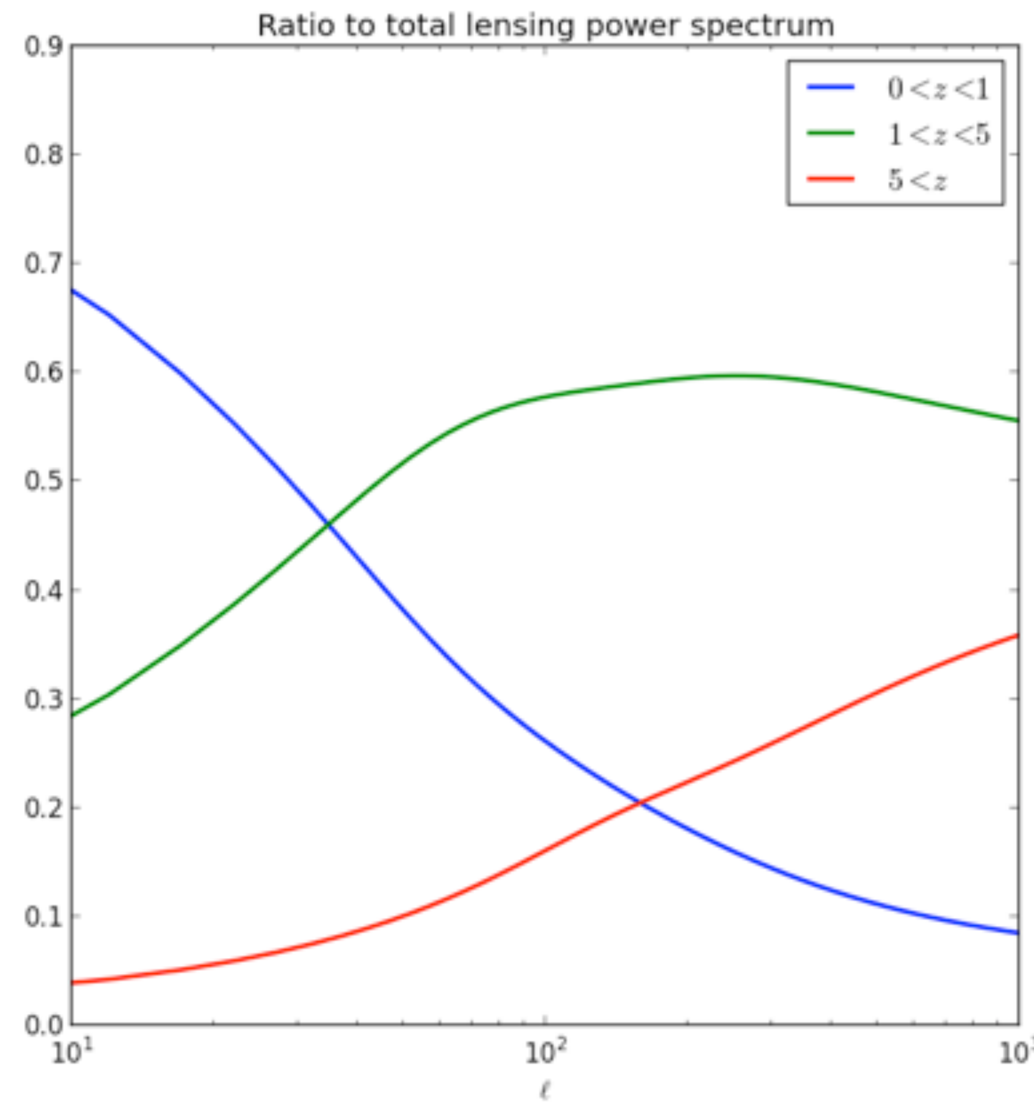
$$\phi(\hat{\boldsymbol{n}}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{\boldsymbol{n}}; \eta_0 - \chi).$$

The lensing potential

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

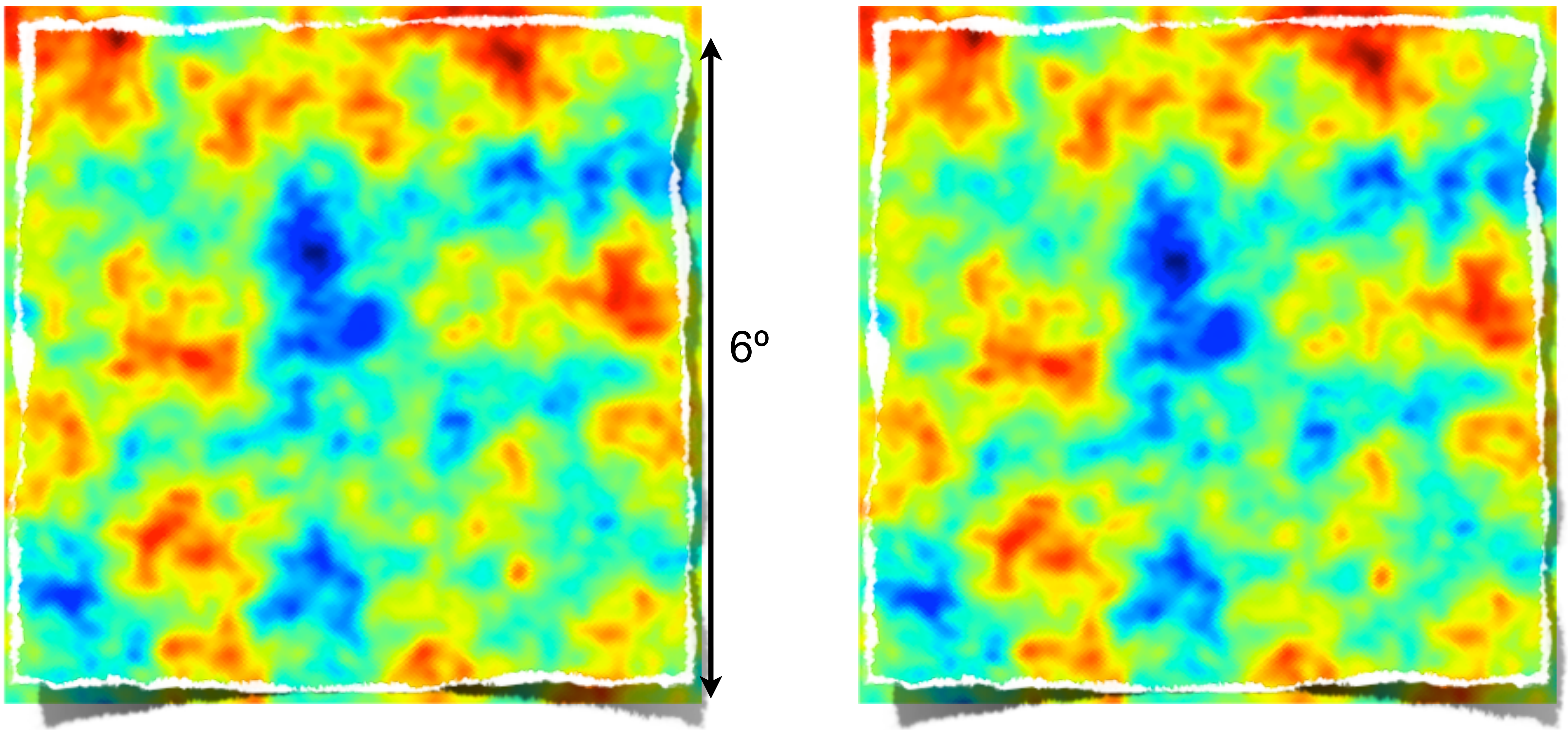


Lewis & Challinor, 2006



CMB lensing

Deflections are about 2 arcmin

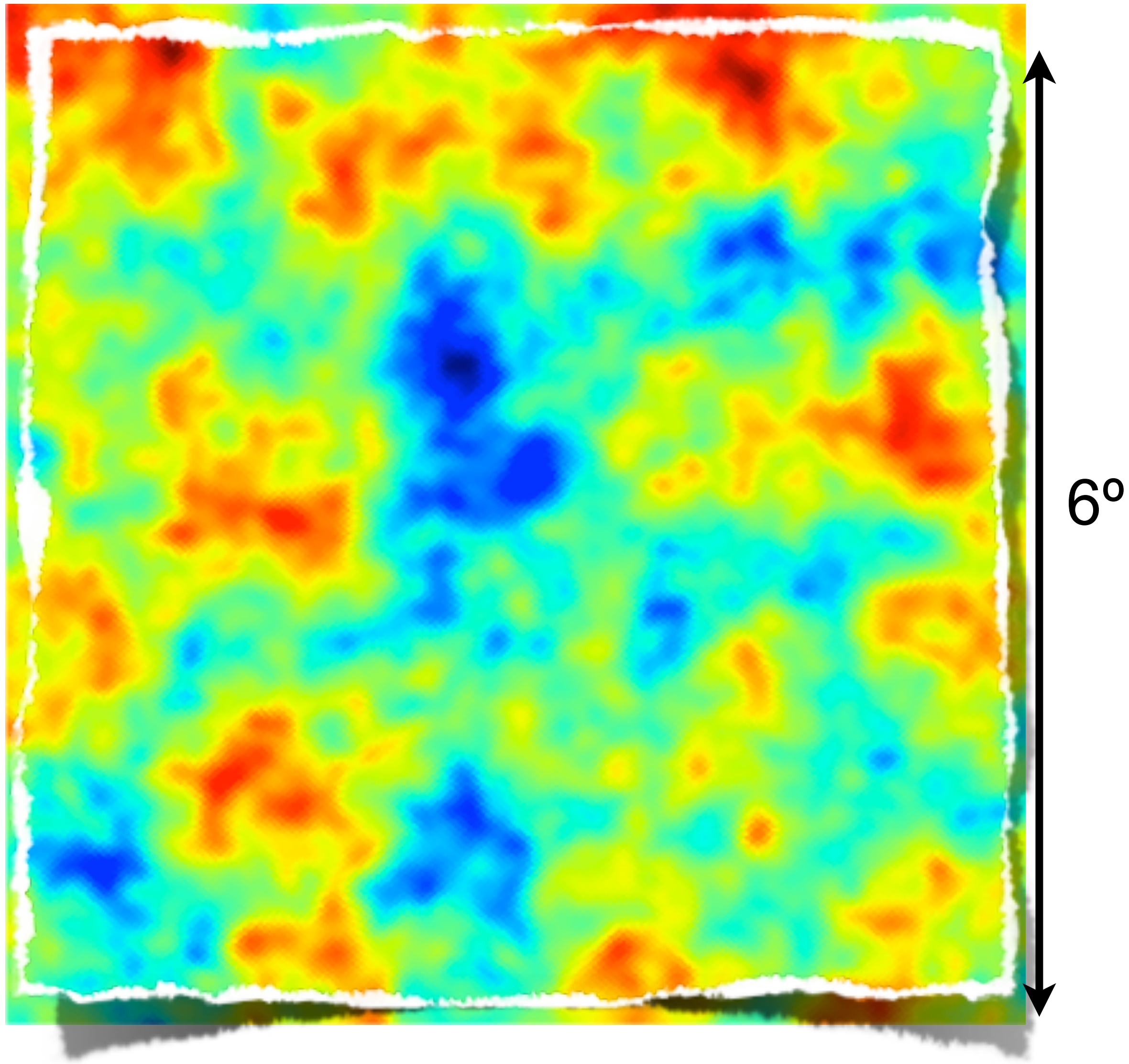


Unlensed

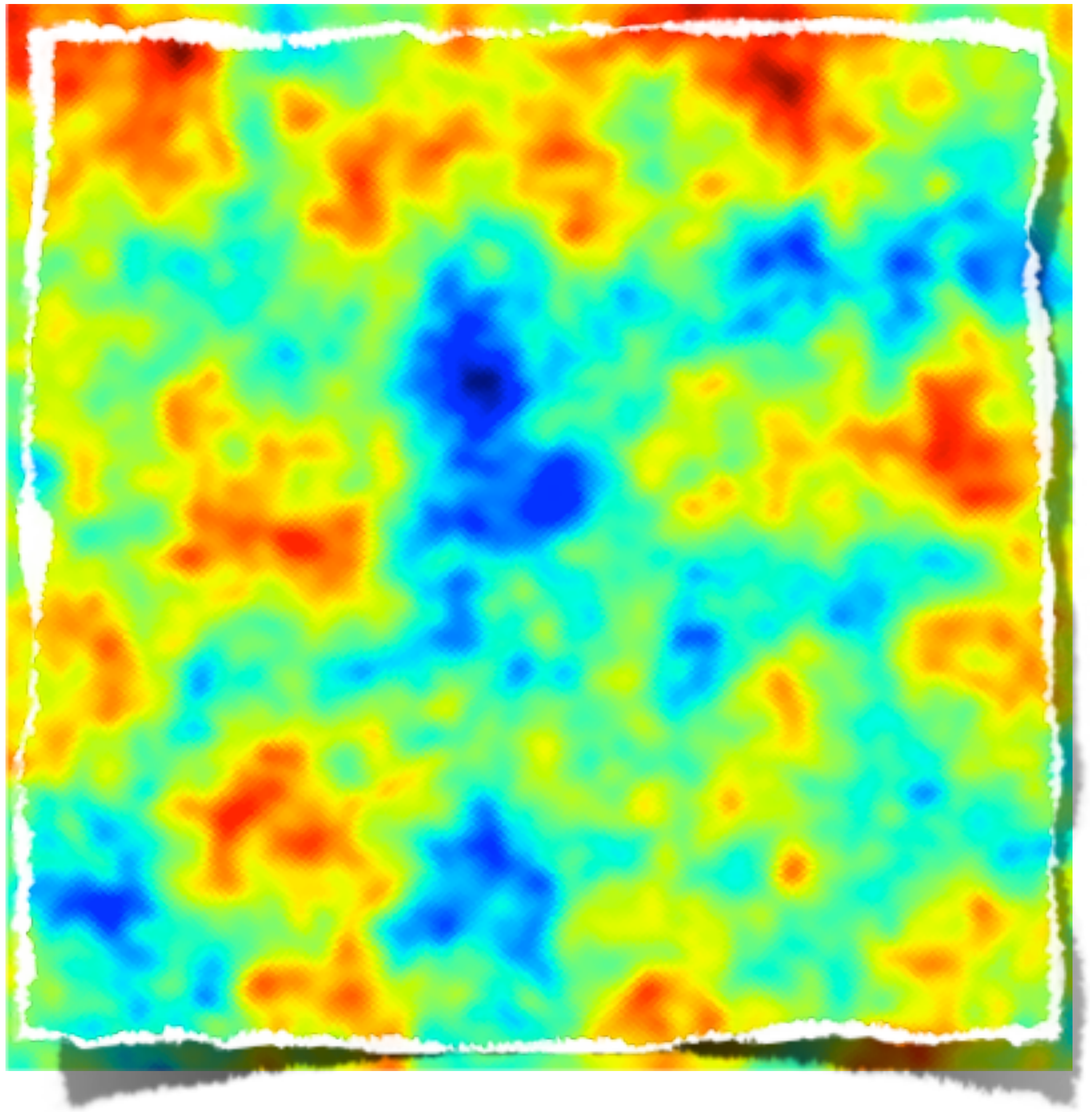
Lensed

CMB lensing

Deflections are about 2 arcmin



Unlensed



Unlensed

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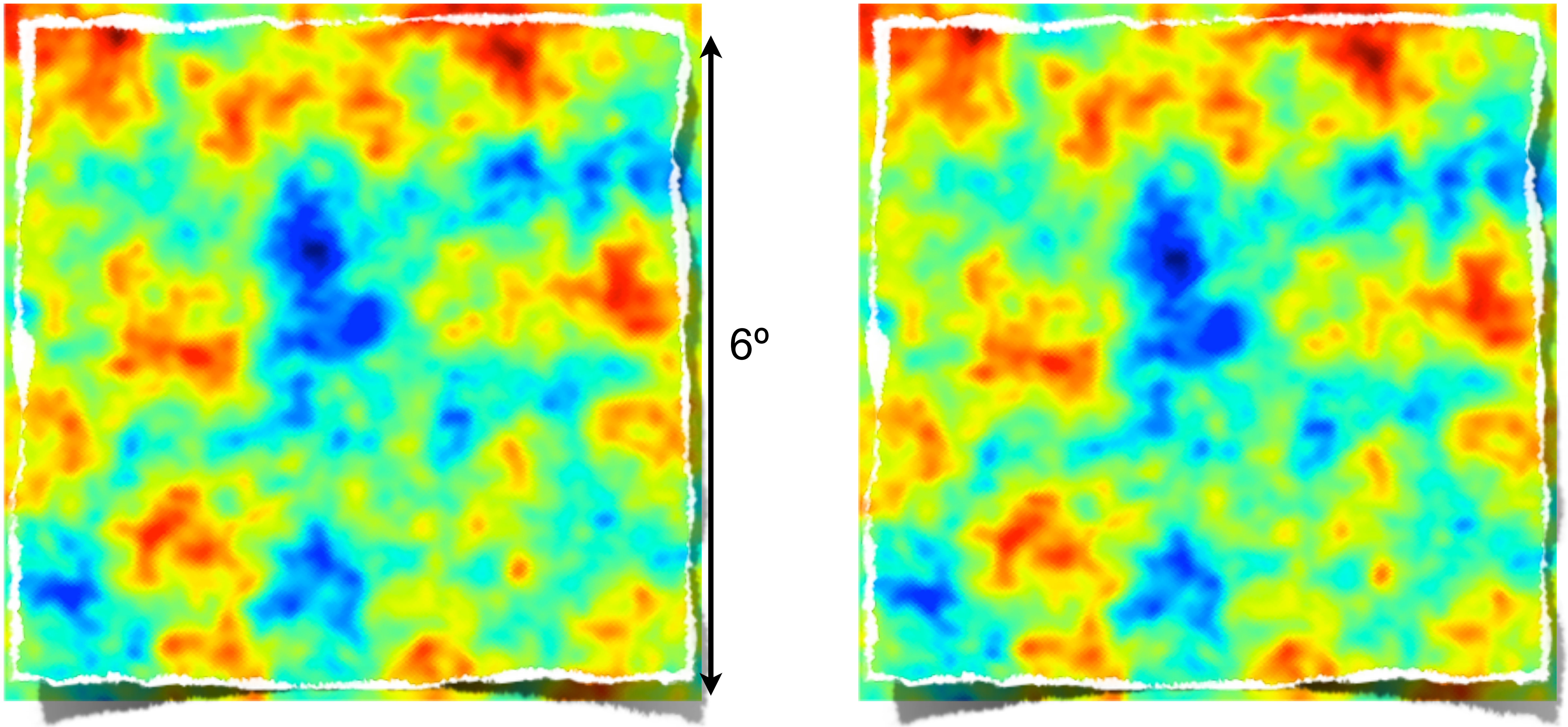

Unlensed

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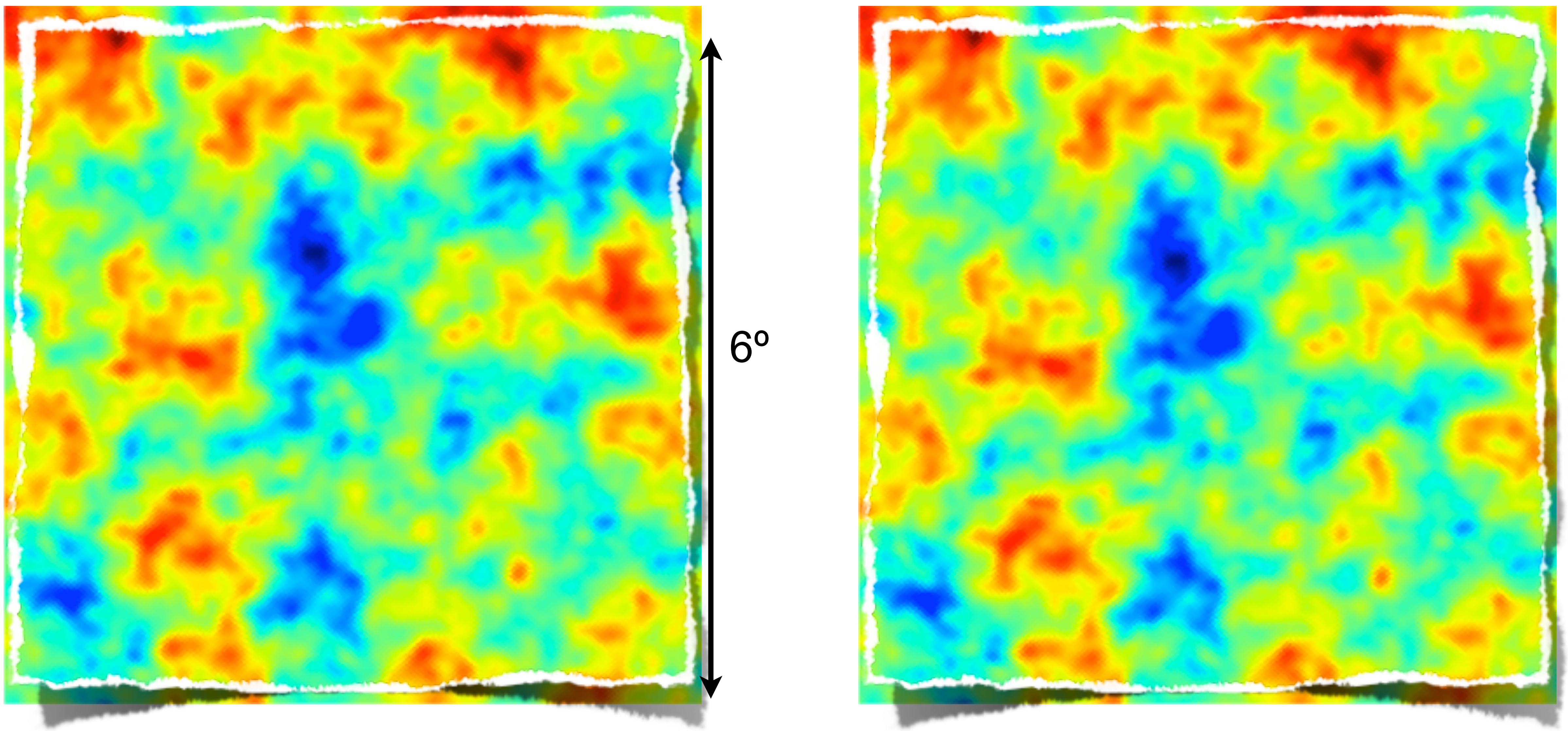


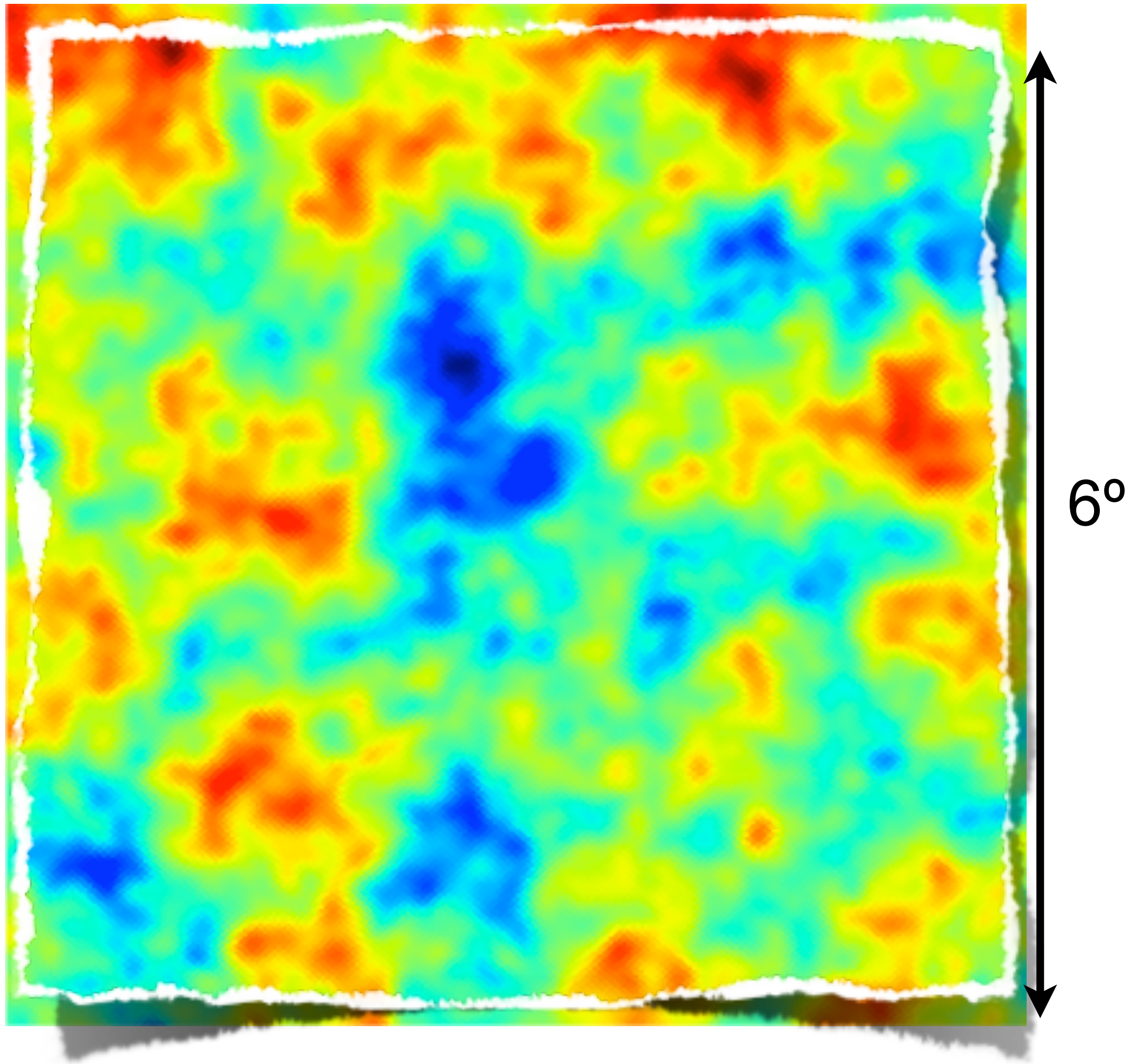
Unlensed

Lensed

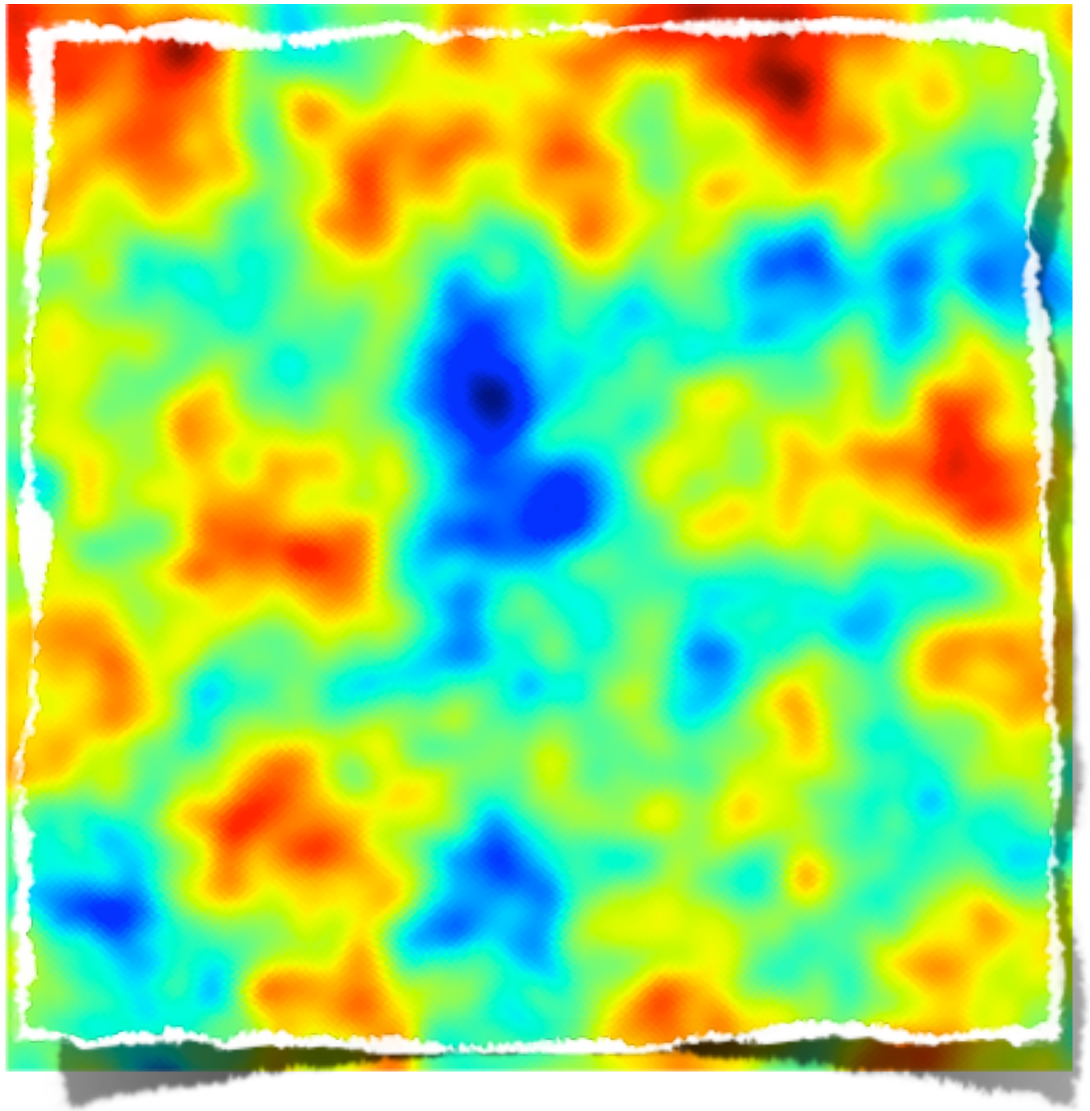
Deflections are correlated on the degree scale

CMB lensing

Deflections are about 2 arcmin



Unlensed

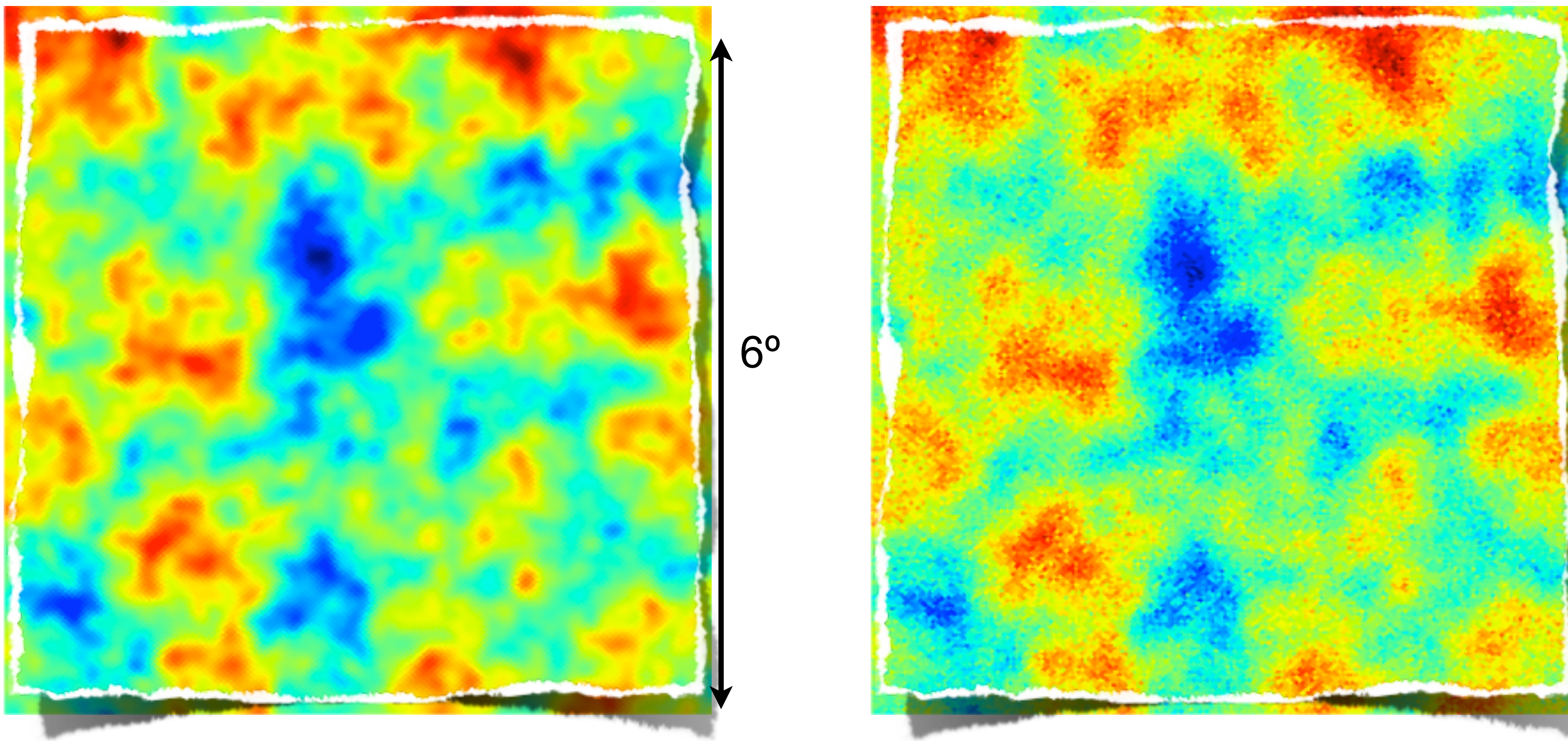


Lensed,
beamed

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

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

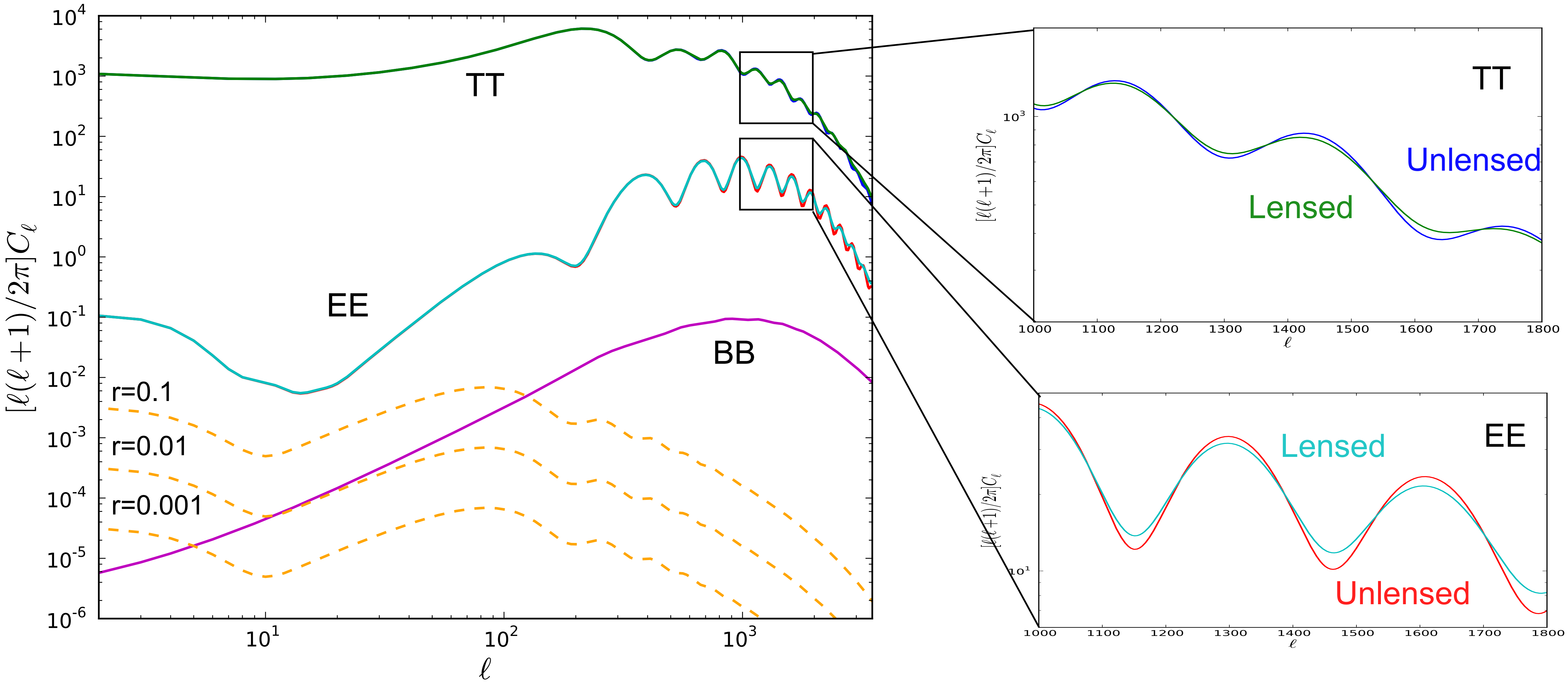
- CMB lensing induces statistical anisotropies

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

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

Impact on anisotropies power spectra

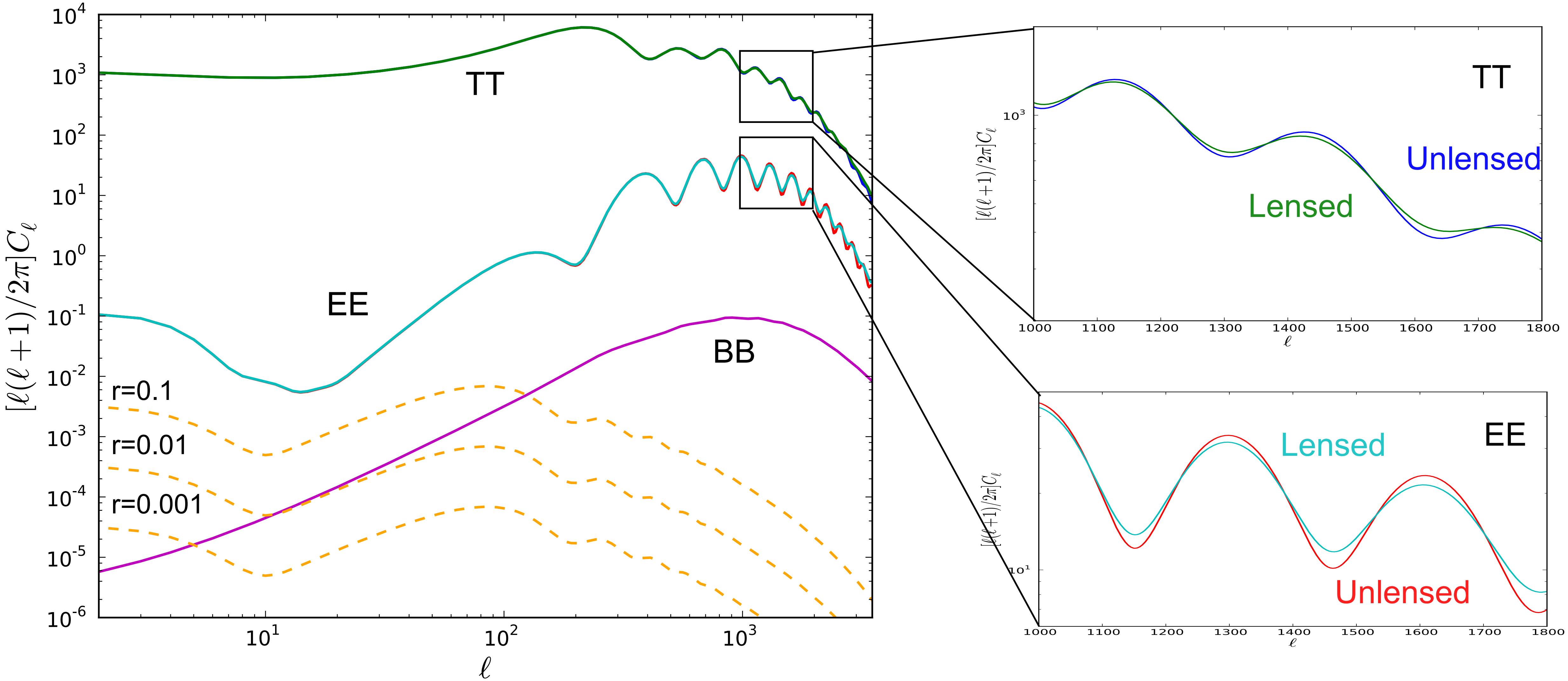
$$C_\ell \sim (1-\alpha_\ell)\tilde{C}_\ell + \sum_{\ell_1 \ell_2} C_{\ell_1}^{\phi\phi} \tilde{C}_{\ell_2} F_{\ell \ell_1 \ell_2}$$



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

Impact on anisotropies power spectra

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



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

ABL, Smith, Hu 2012

Lensing reconstruction

- 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

- Quadratic estimator on the full sky

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

Okamoto & Hu, 2003

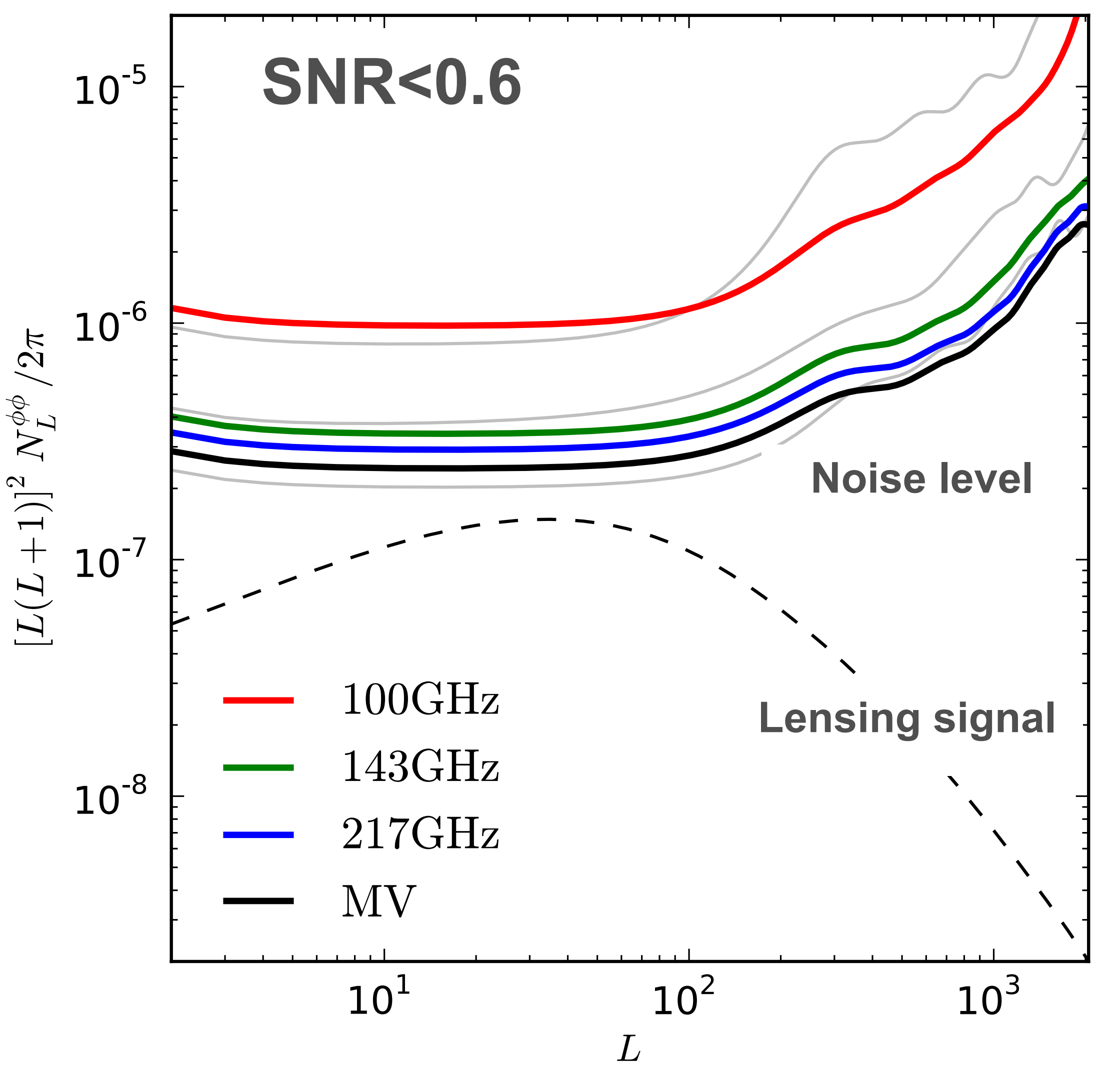
Filtered temperature. Multiple choices.

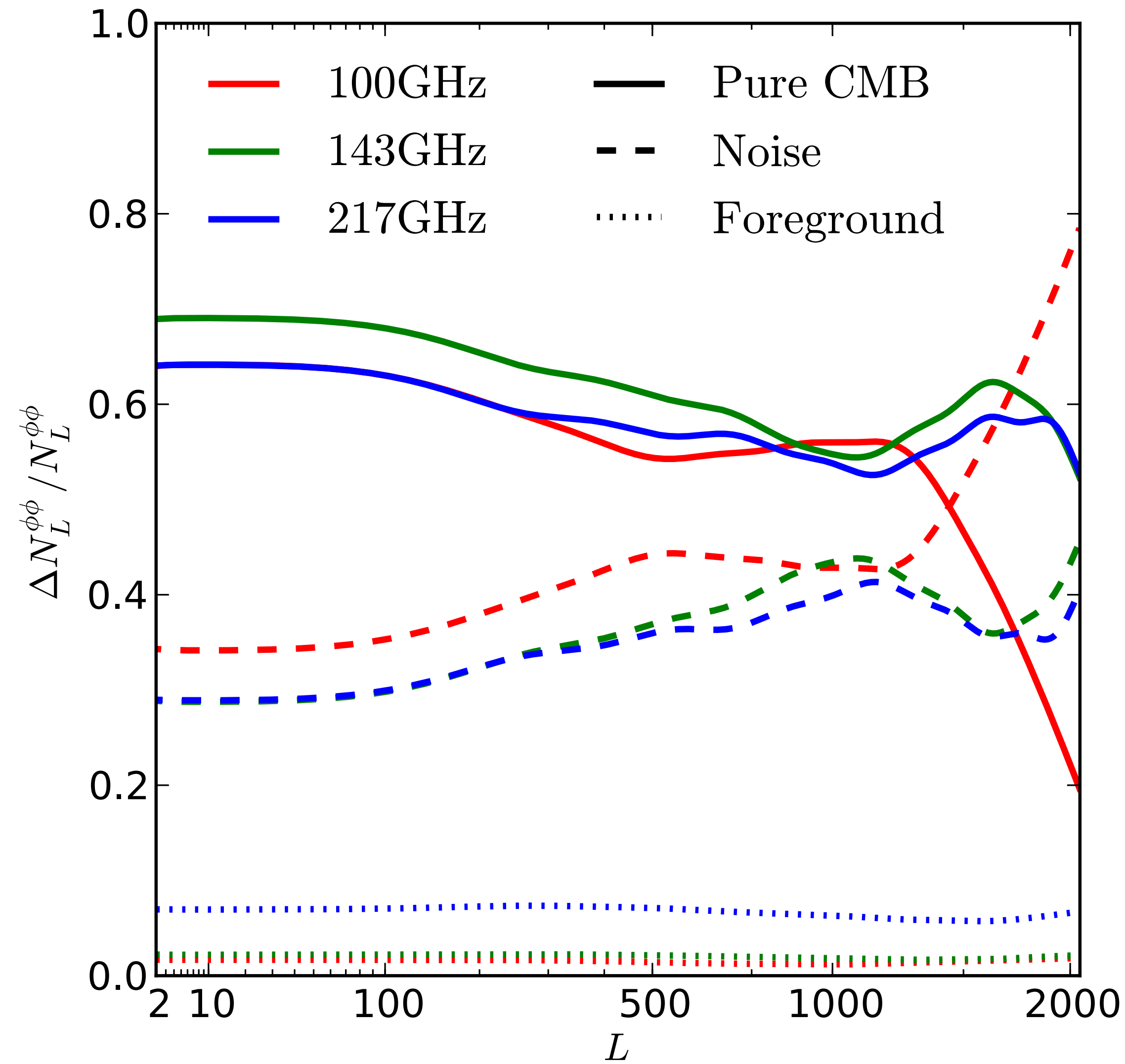
Typically: T_1 is inverse-variance filtered, and T_2 is Wiener filtered

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

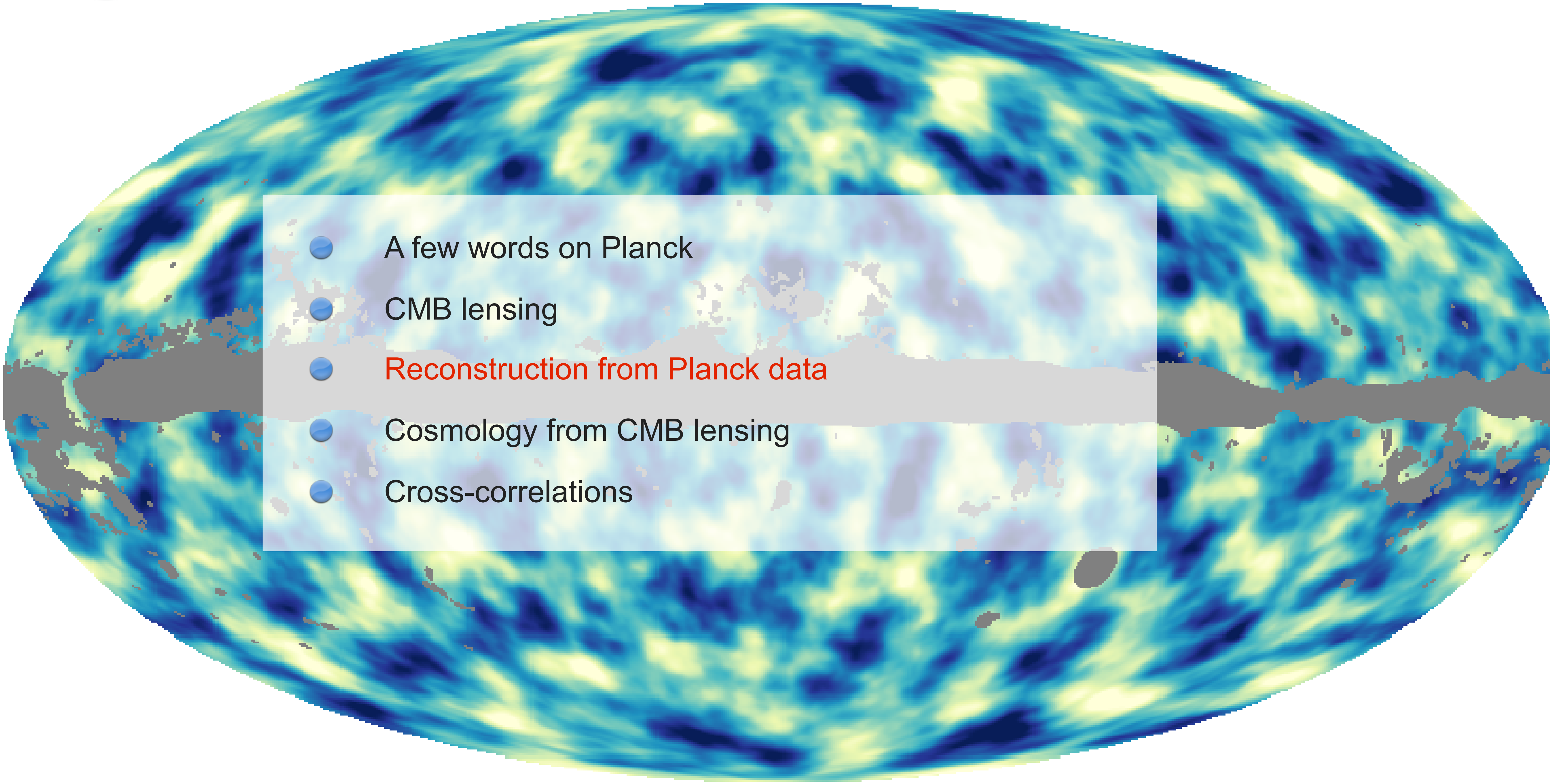
CMB lensing reconstruction

- Ideal Planck case





Outline



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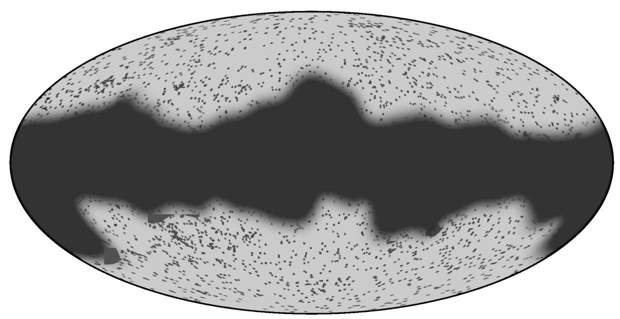
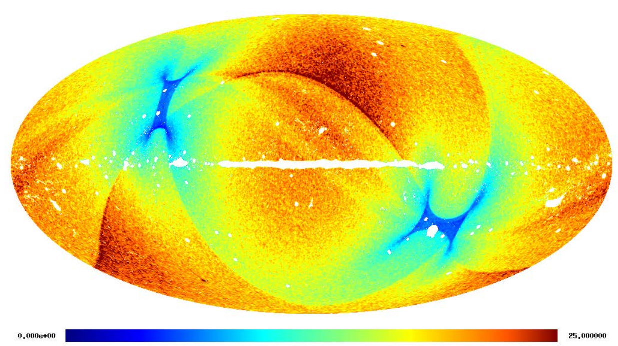
CMB lensing reconstruction

- Other sources of statistical anisotropies

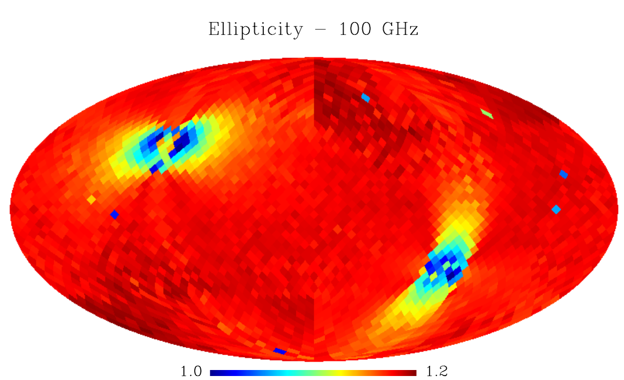
Galactic + PS mask

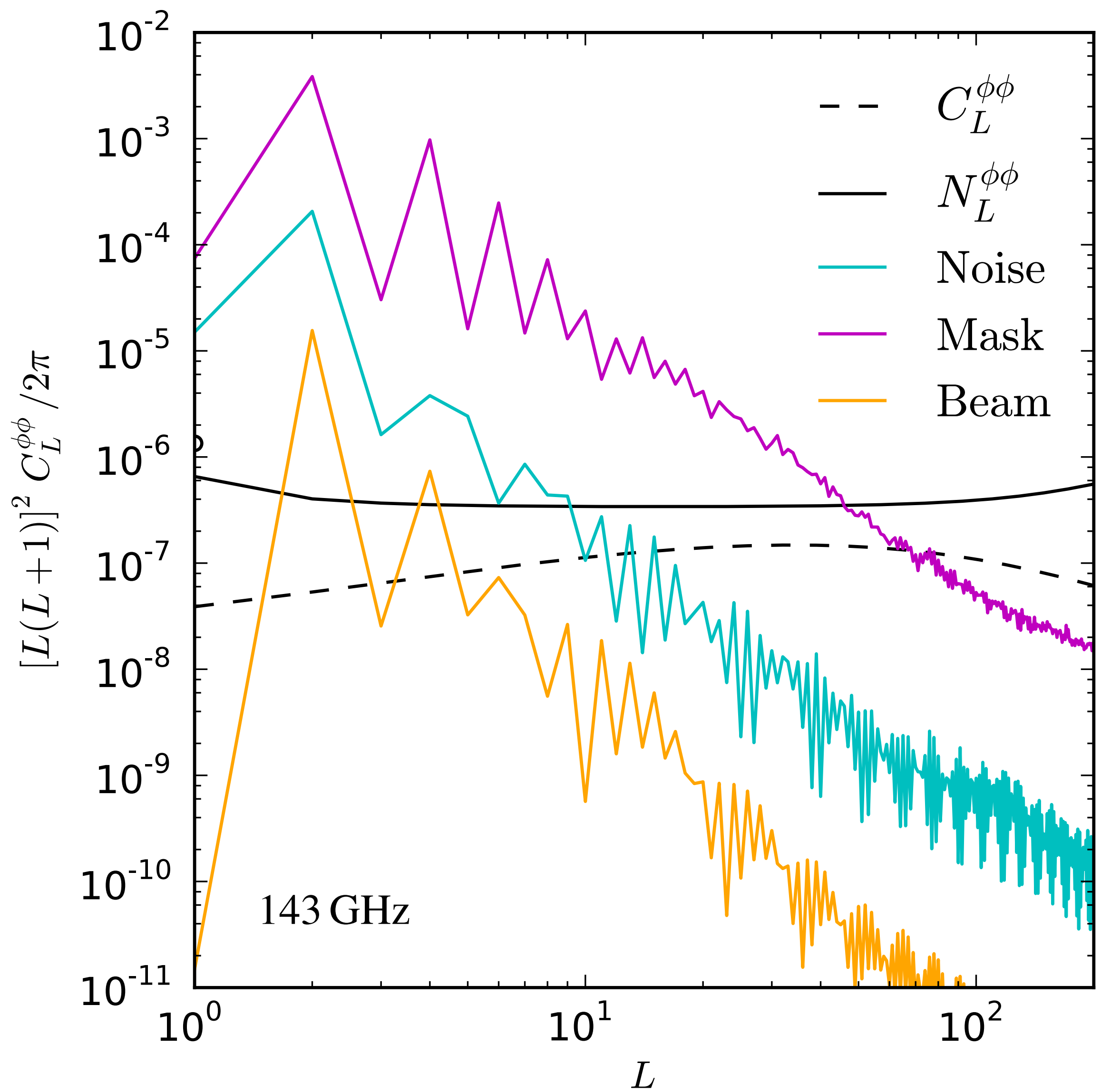


Inh. noise



Beam ellipticity





CMB lensing reconstruction

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

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

- Take two temperature maps and inverse-variance filter them

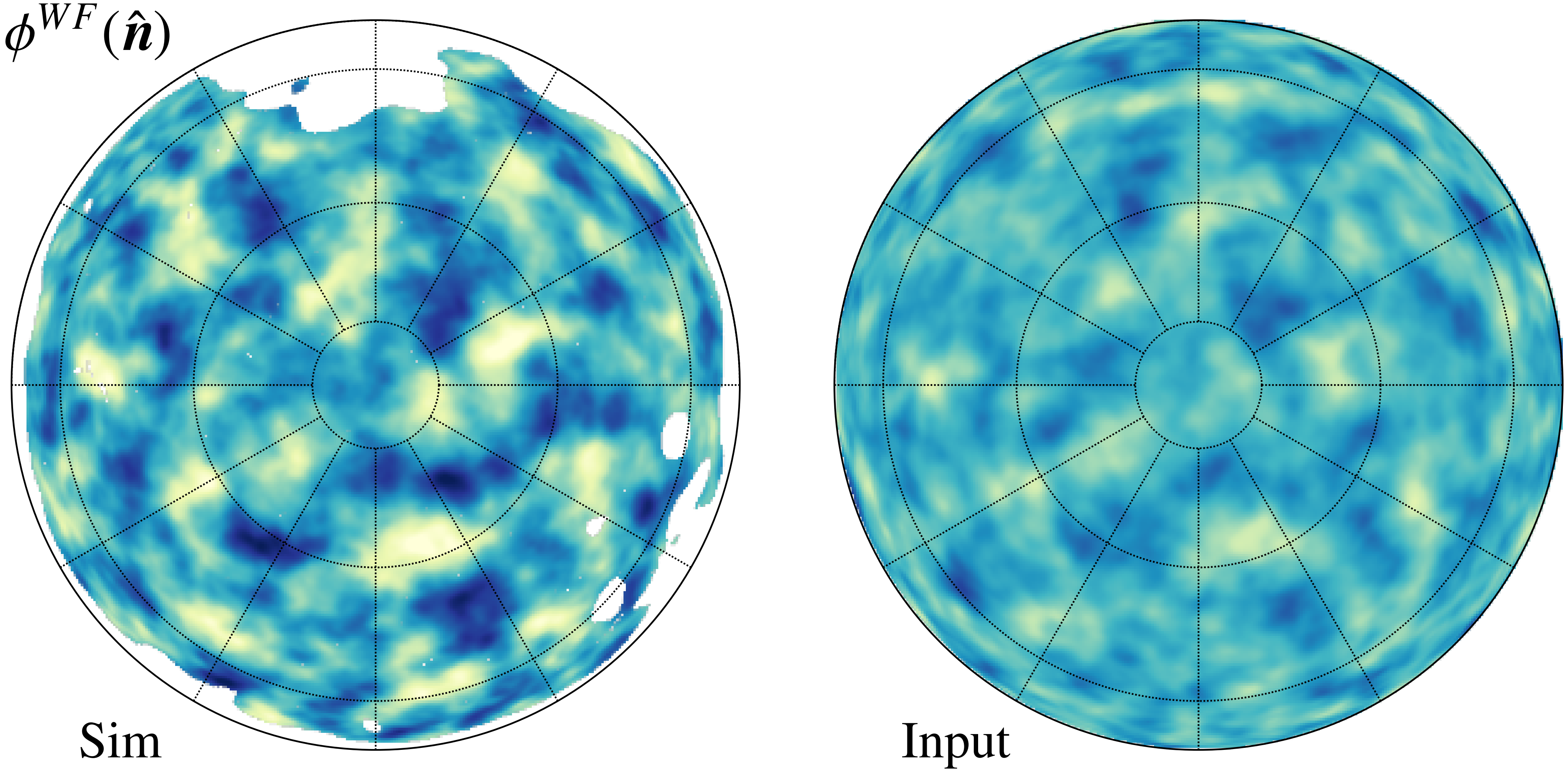
- Multiply one by the temperature power spectrum and differentiate it

- 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

Power spectrum estimator

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

Pseudo-Cl of an apodized version of the reconstructed lensing potential

Power spectrum estimator

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

Pseudo-Cl of an apodized version of the reconstructed lensing potential

Gaussian noise. Disconnected part of the CMB trispectrum. Computed by simulations

Power spectrum estimator

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

Pseudo-Cl of an apodized version of the reconstructed lensing potential

Gaussian noise. Disconnected part of the CMB trispectrum. Computed by simulations

High-order term. Depends on the lensing spectrum. Computed with fiducial spectrum.

Power spectrum estimator

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

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Contribution from unresolved point sources. Measured on data

Power spectrum estimator

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Pseudo-Cl of an apodized version of the reconstructed lensing potential

Gaussian noise. Disconnected part of the CMB trispectrum. Computed by simulations

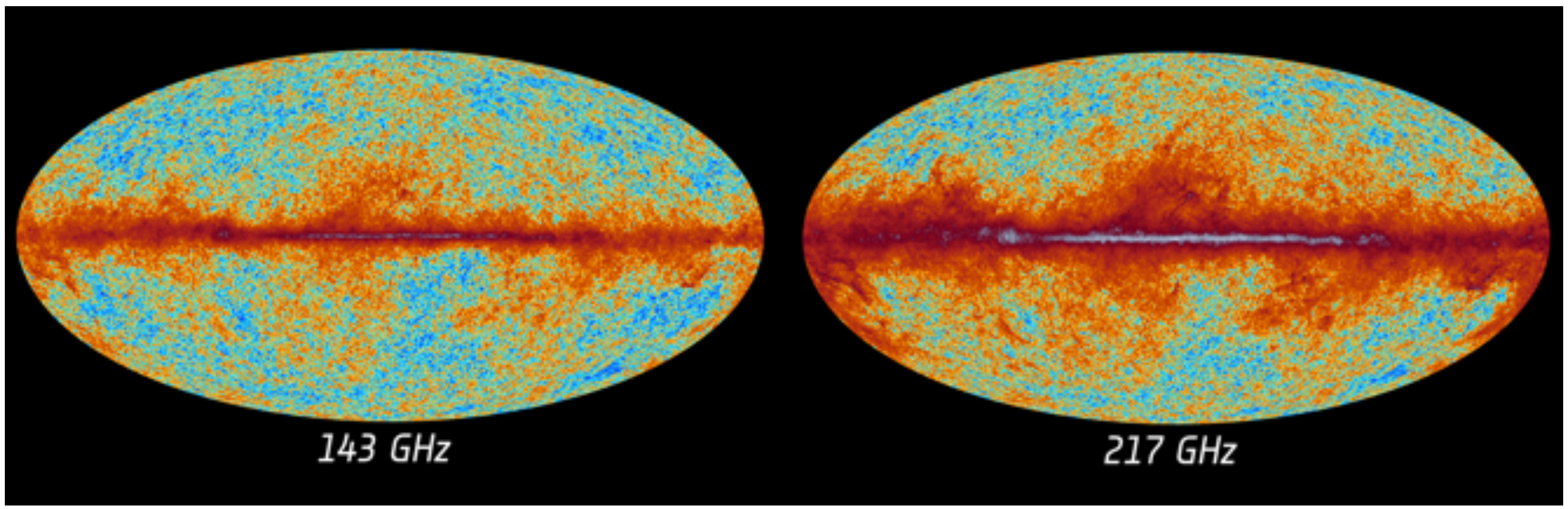
High-order term. Depends on the lensing spectrum. Computed with fiducial spectrum.

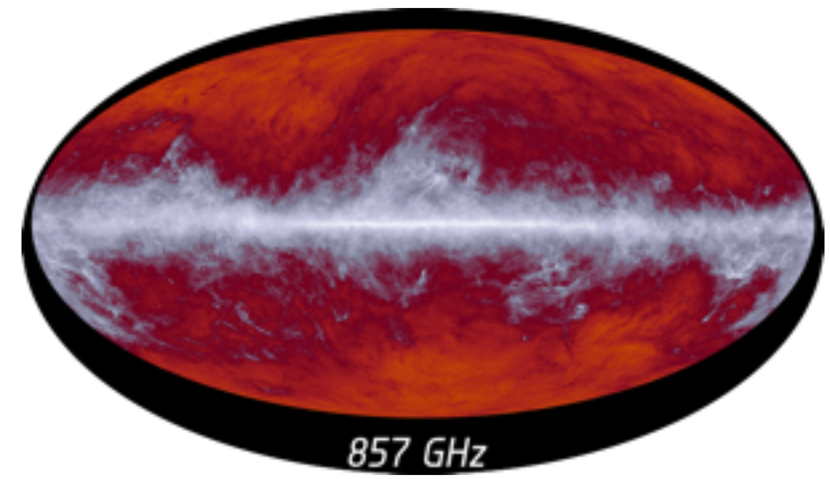
Contribution from unresolved point sources. Measured on data

Additional uncertainties dealt with by Monte-Carlo.

Best reconstruction

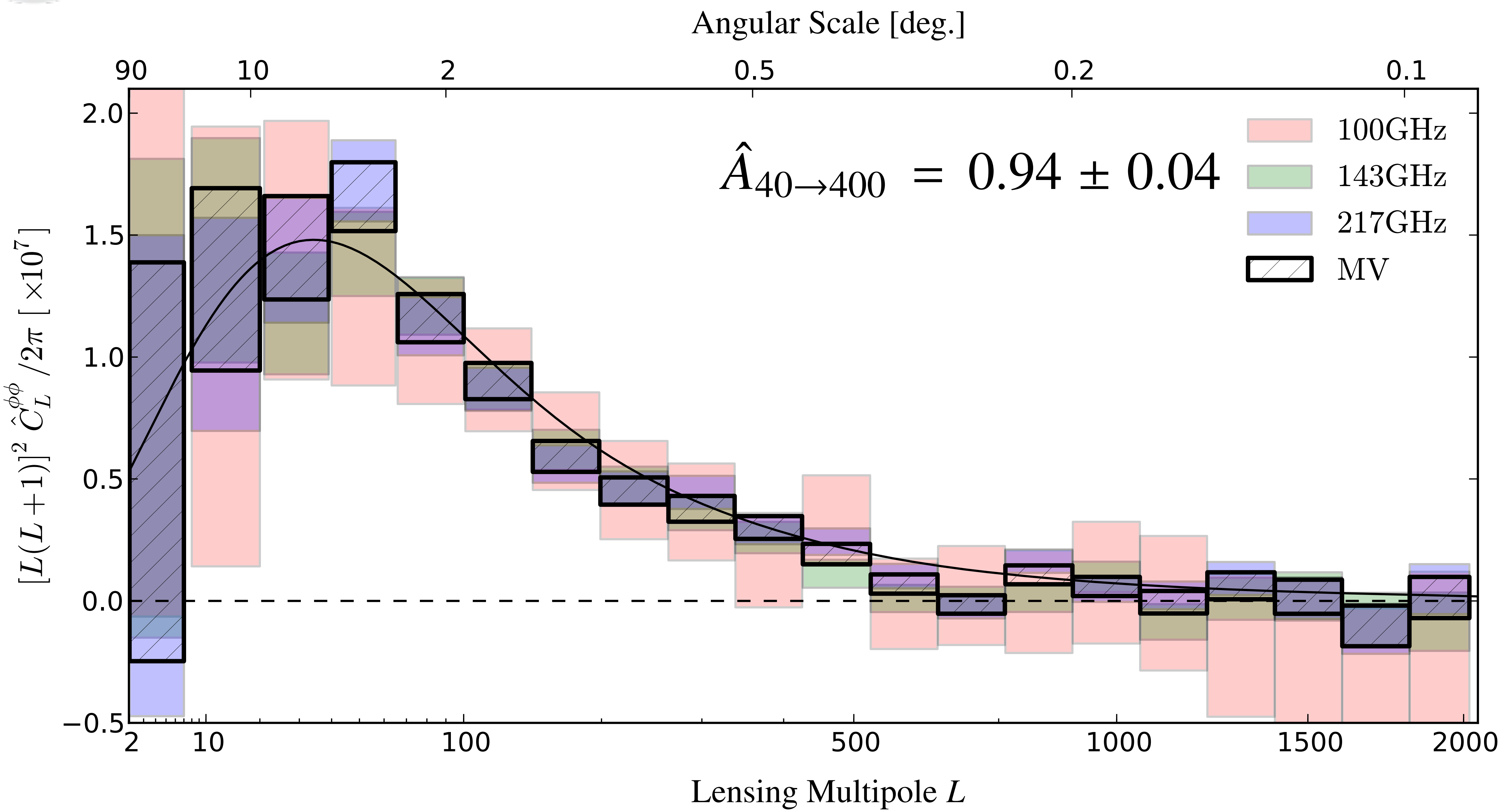
- Minimun-variance combination of 143GHz & 217 GHz



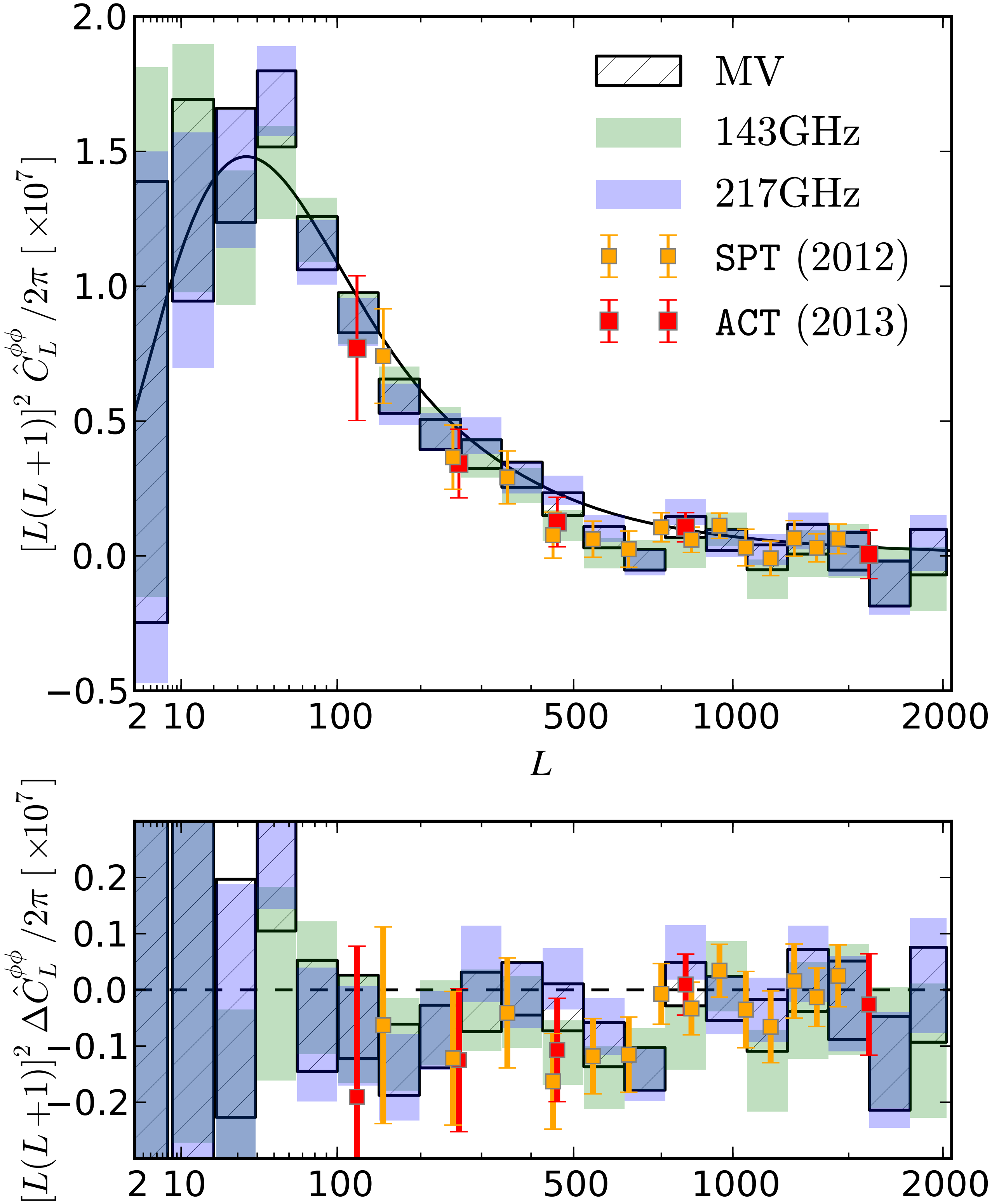


- 857 GHz map used as a template for dust cleaning
- 30 % Galactic mask +CO+ point sources
- 5º apodization (for lensing power spectrum estimation)

Best reconstruction

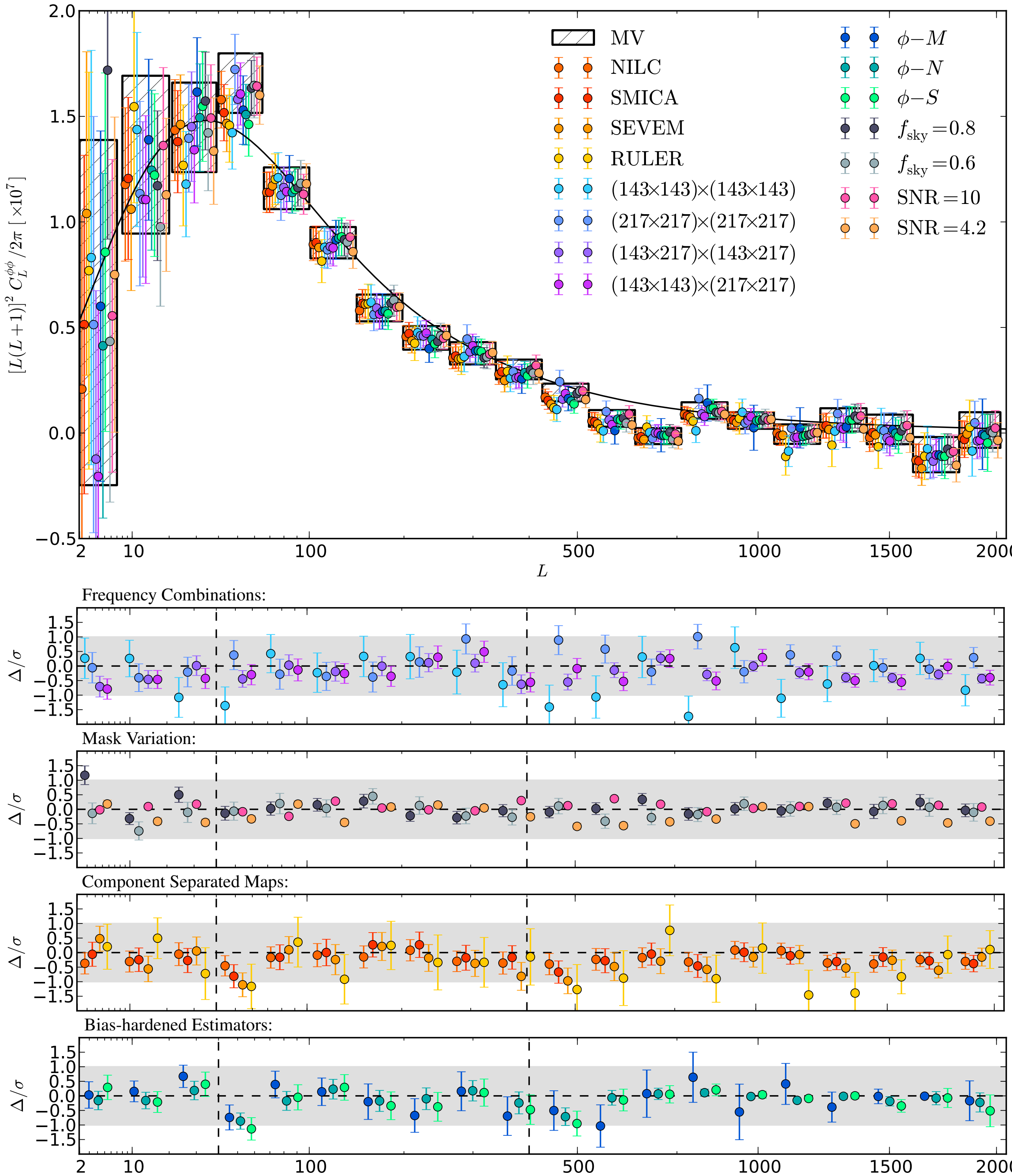


Comparison to other surveys

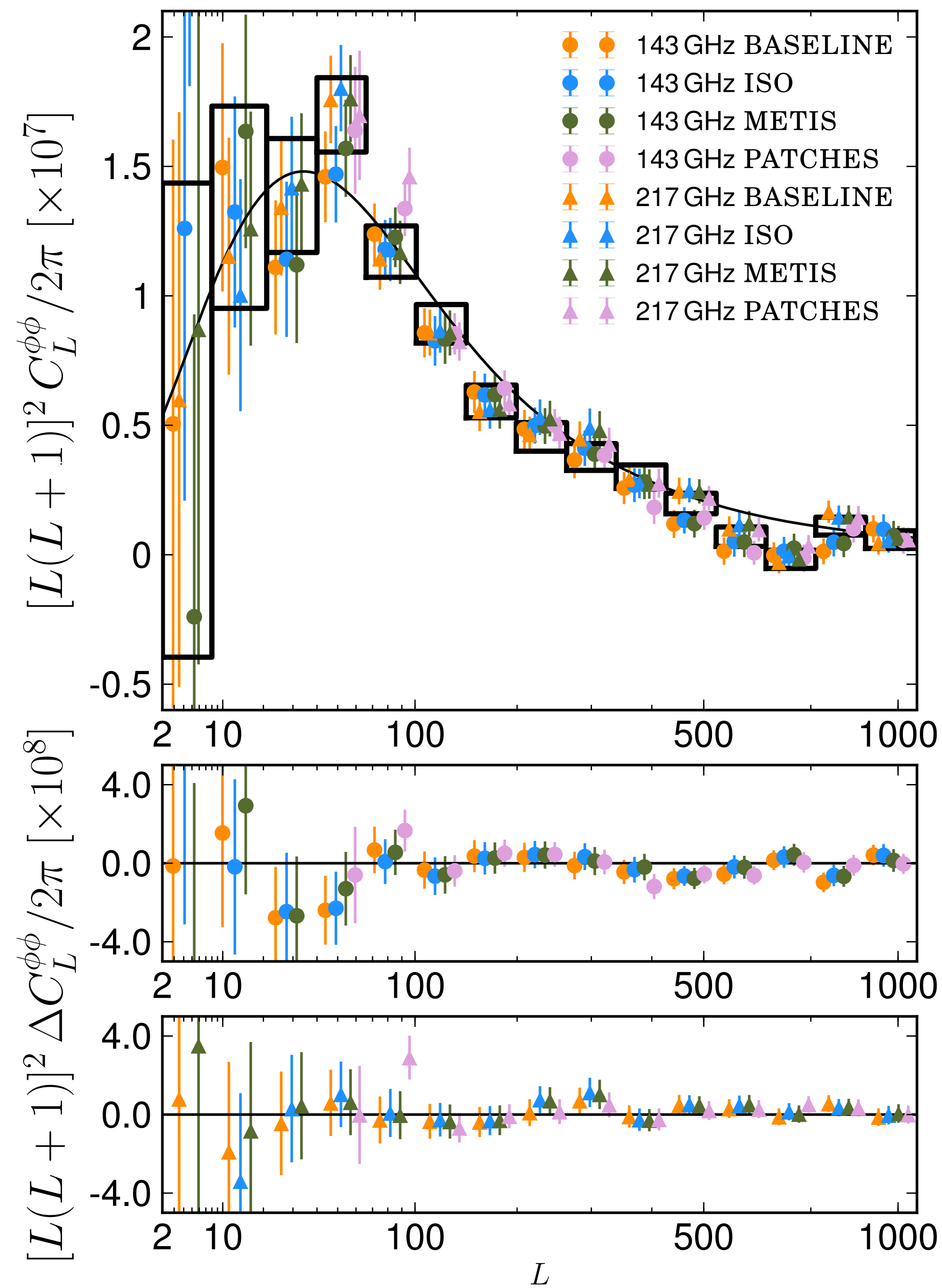


Tests

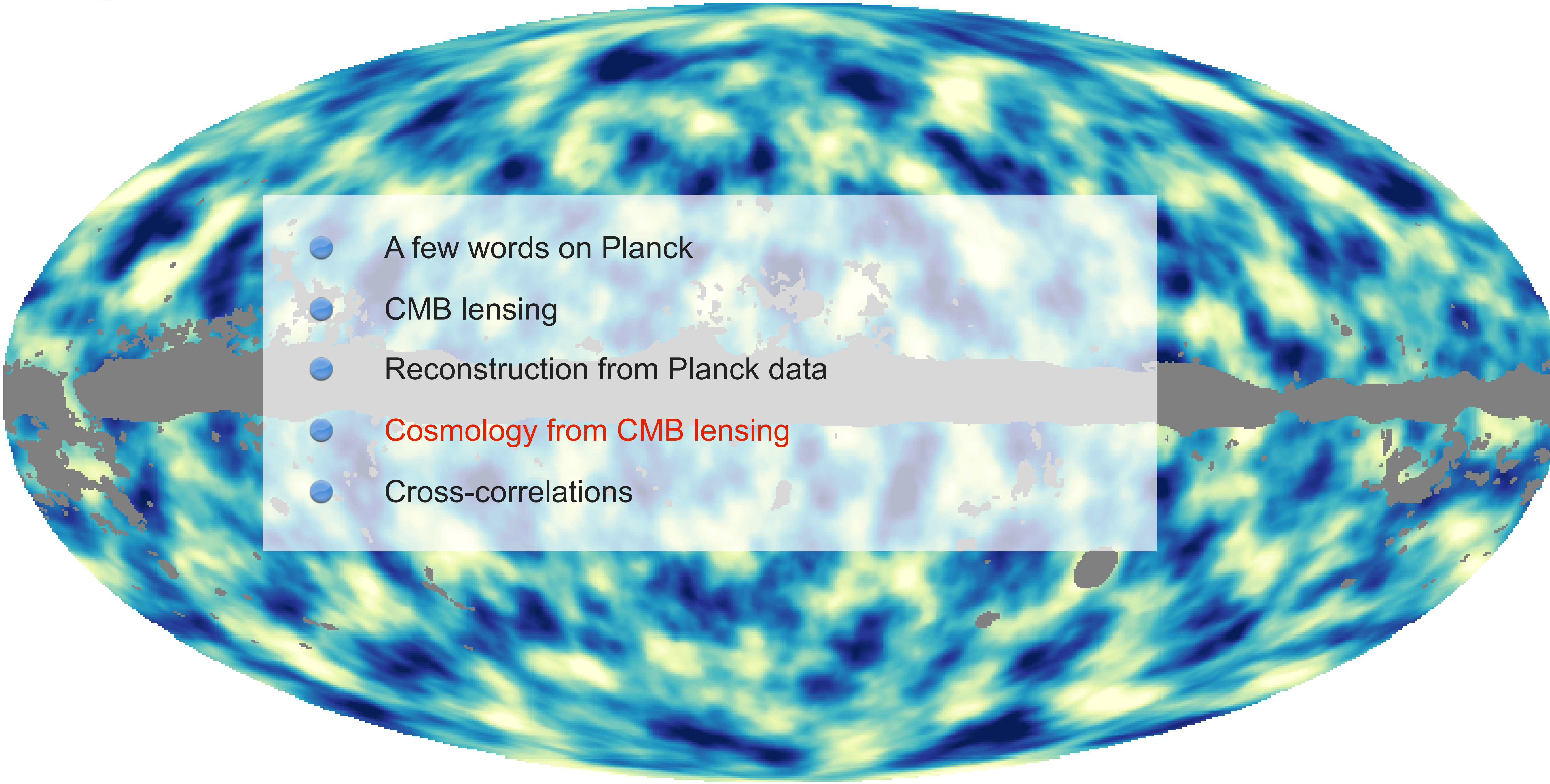
Testing foreground contamination



Testing the filter & implementation

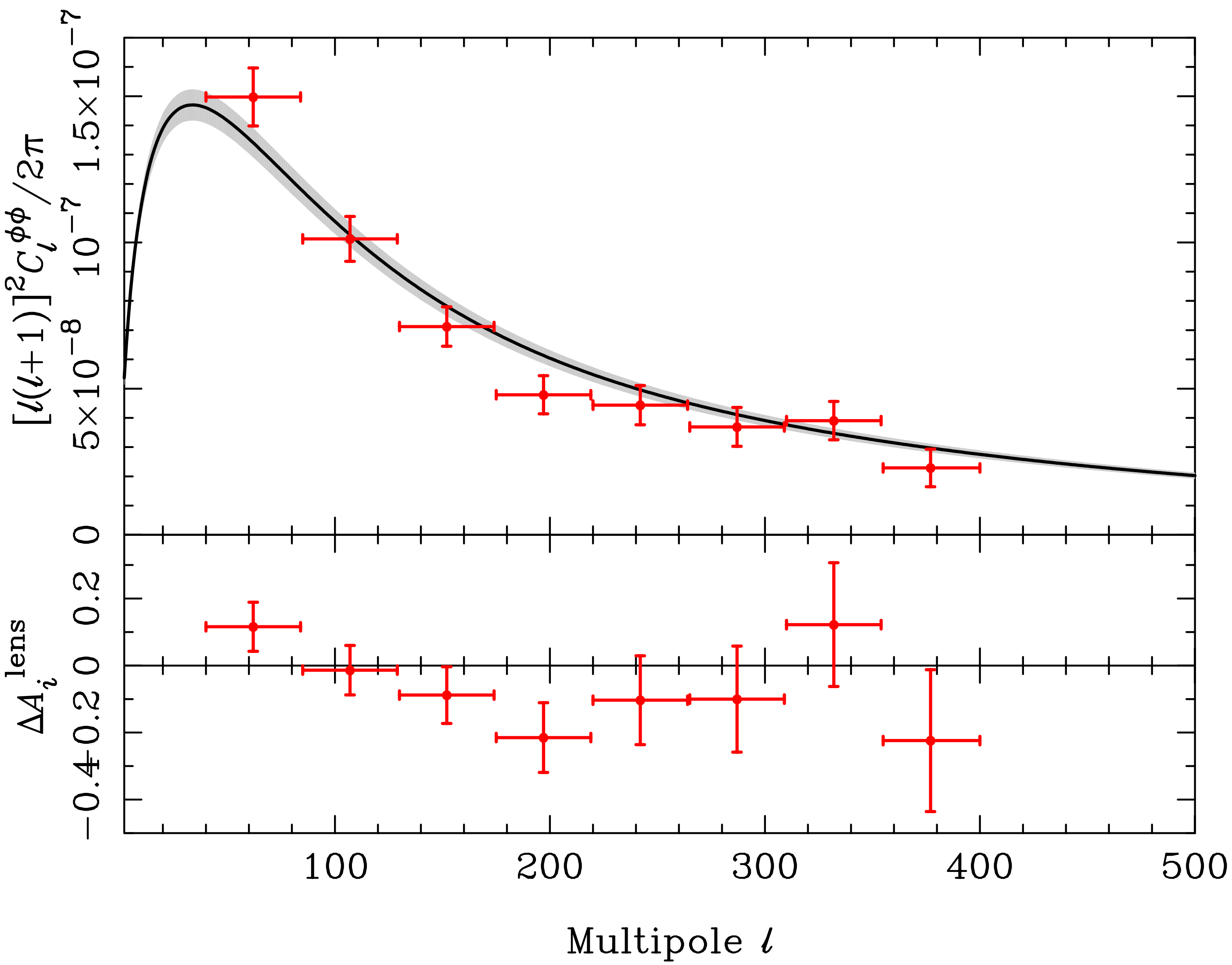


Outline

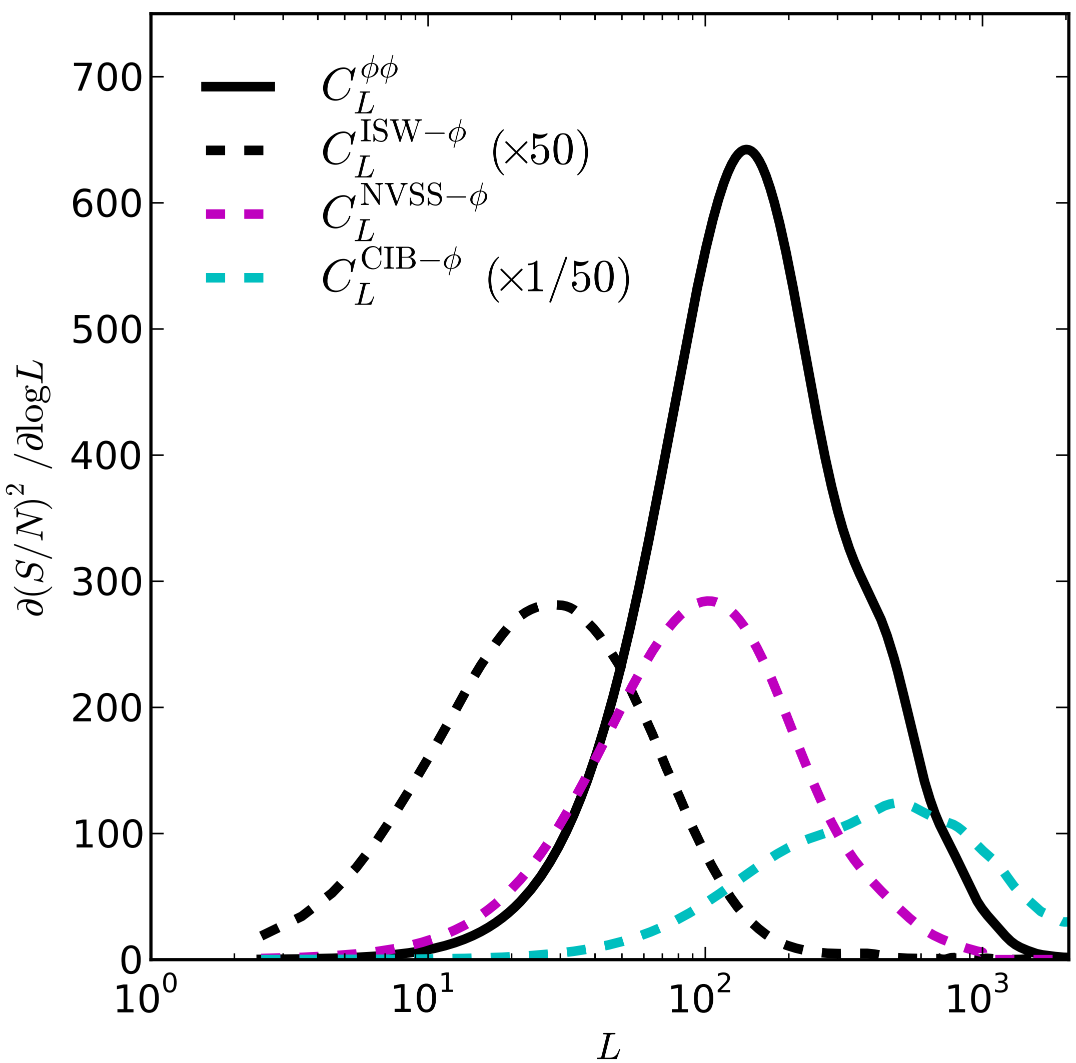


- A few words on Planck
- CMB lensing
- Reconstruction from Planck data
- Cosmology from CMB lensing
- Cross-correlations

Cosmology

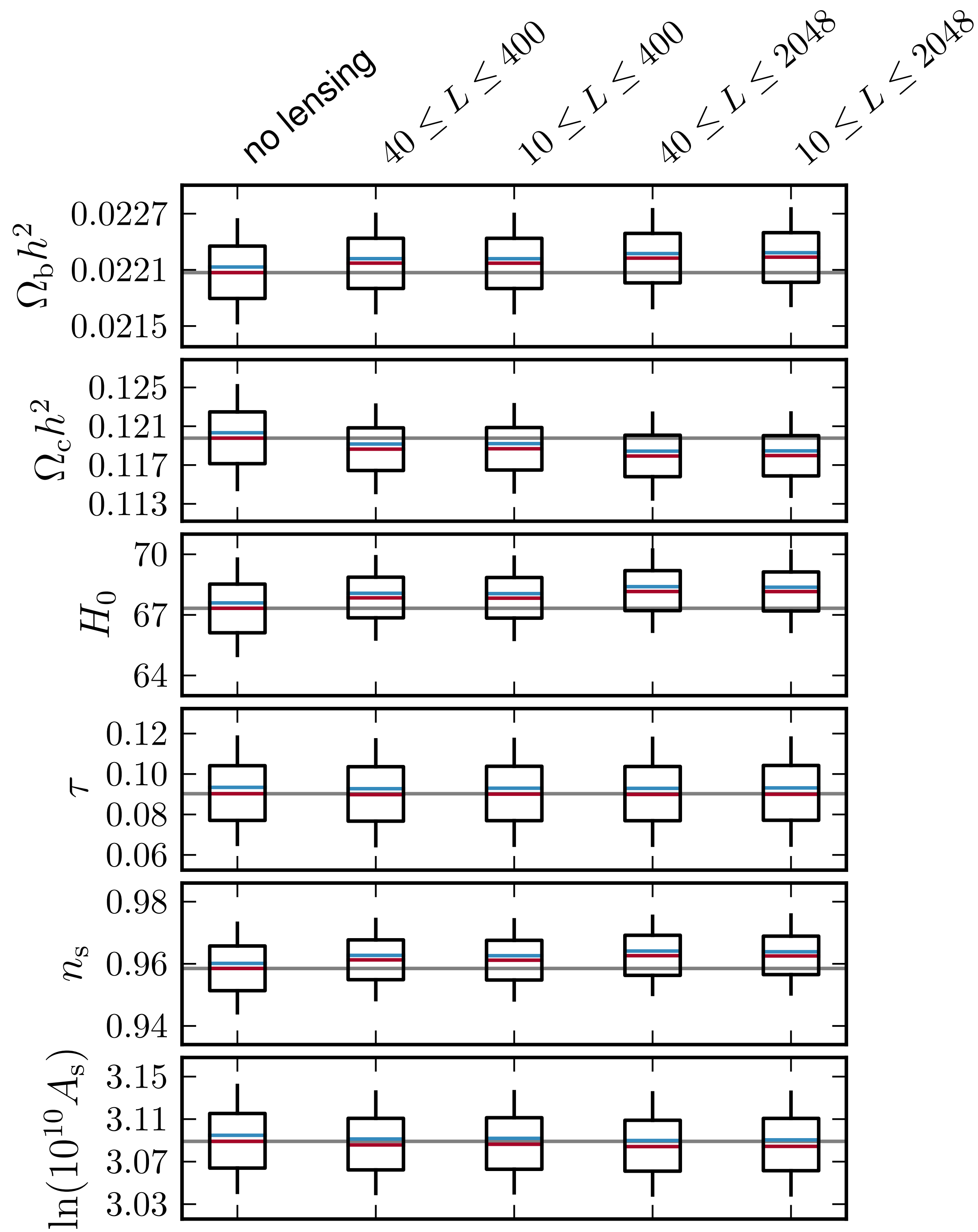


$[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
1.5×10^{-7}
10^{-7}
5×10^{-8}
0
0.2
0
-0.2
-0.4
$\Delta A_i^{\mathrm{lens}}$
100
200
300
400
500
Multipole ℓ



$C_L^{\phi\phi}$
$C_L^{\mathrm{ISW}-\phi}$ (×50)
$C_L^{\mathrm{NVSS}-\phi}$
$C_L^{\mathrm{CIB}-\phi}$ (×1/50)
$\partial(S/N)^2/\partial\log L$
700
600
500
400
300
200
100
0
10^0
10^1
10^2
10^3
L

Cosmology

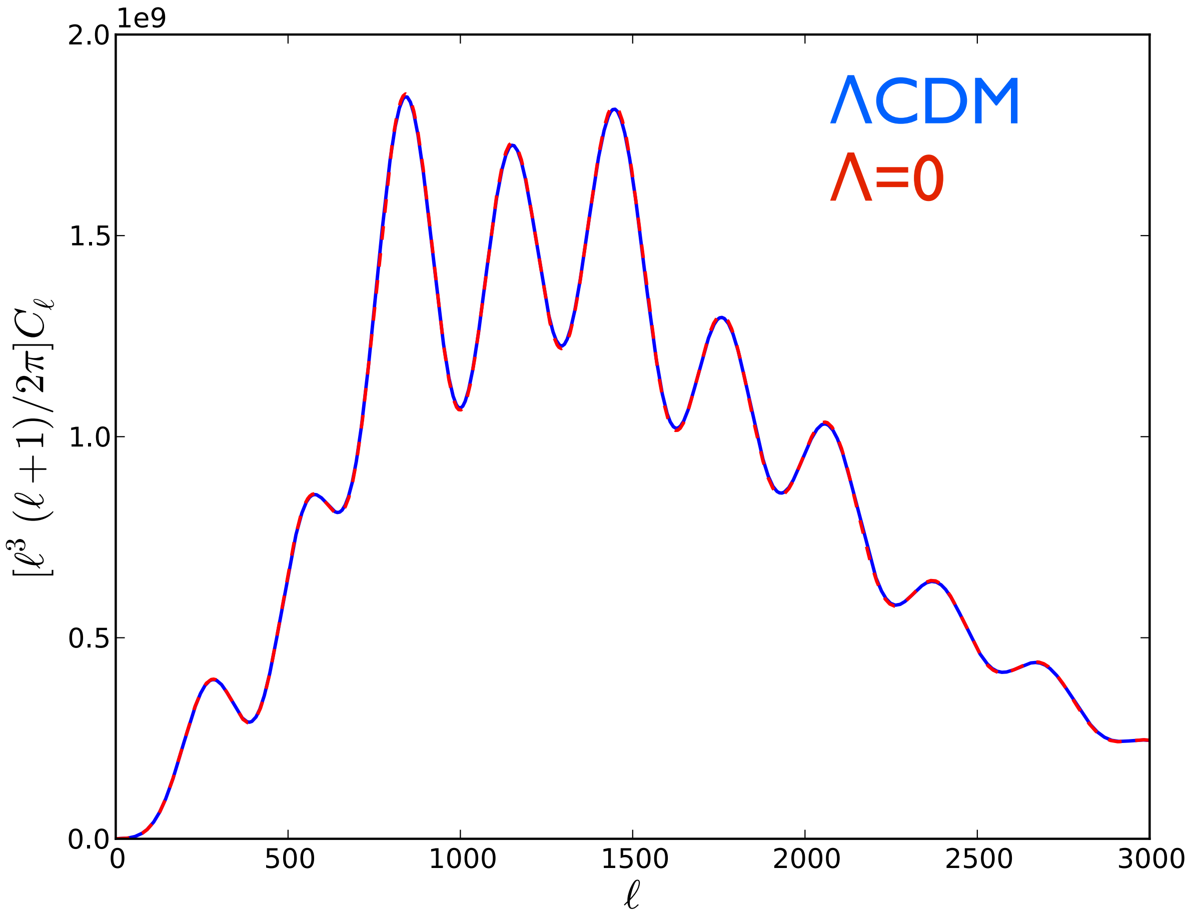


Adding lensing reconstruction brings ~20% improvement on some paramaters

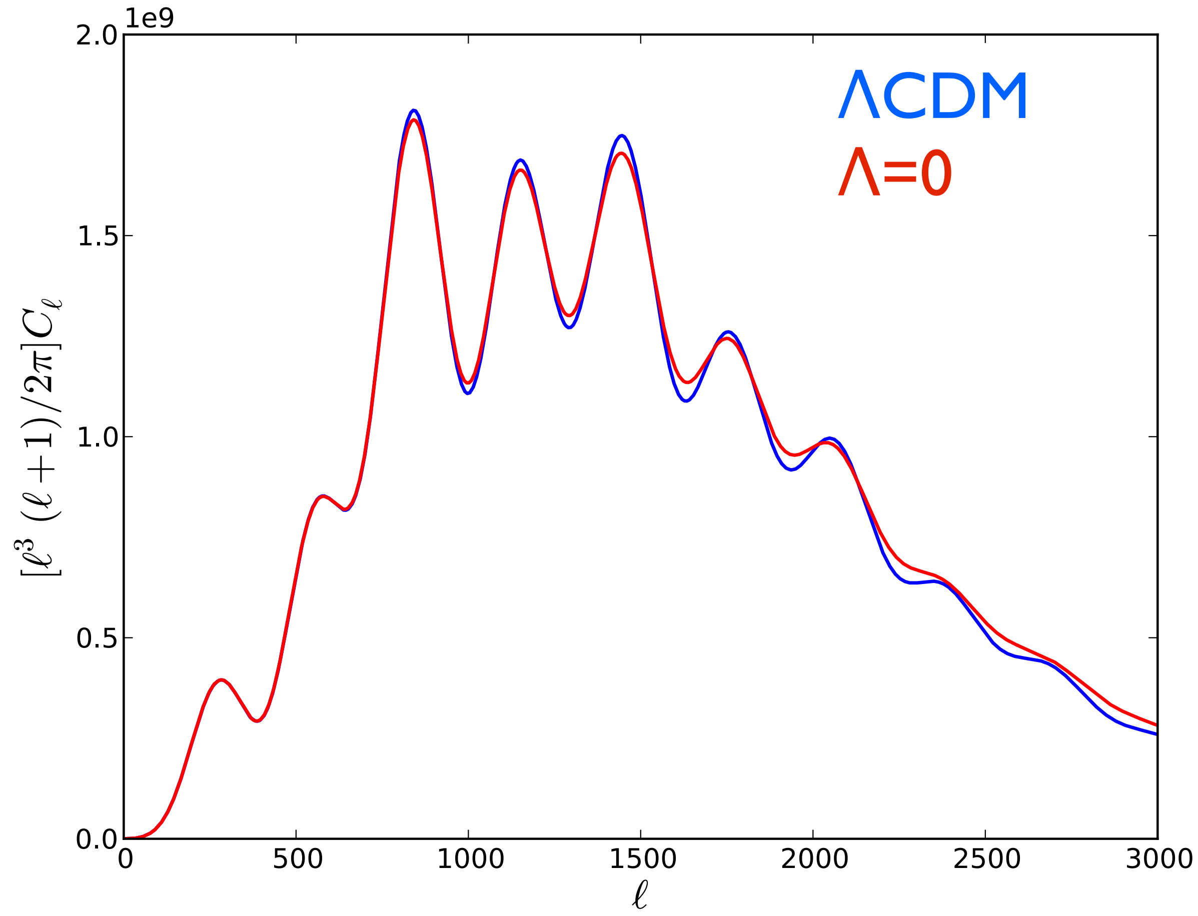
Adding low-L and high-L lensing information does not improve precision but slighly shift central values

Cosmology

- CMB lensing breaks the angular diameter degeneracy



Unlensed TT

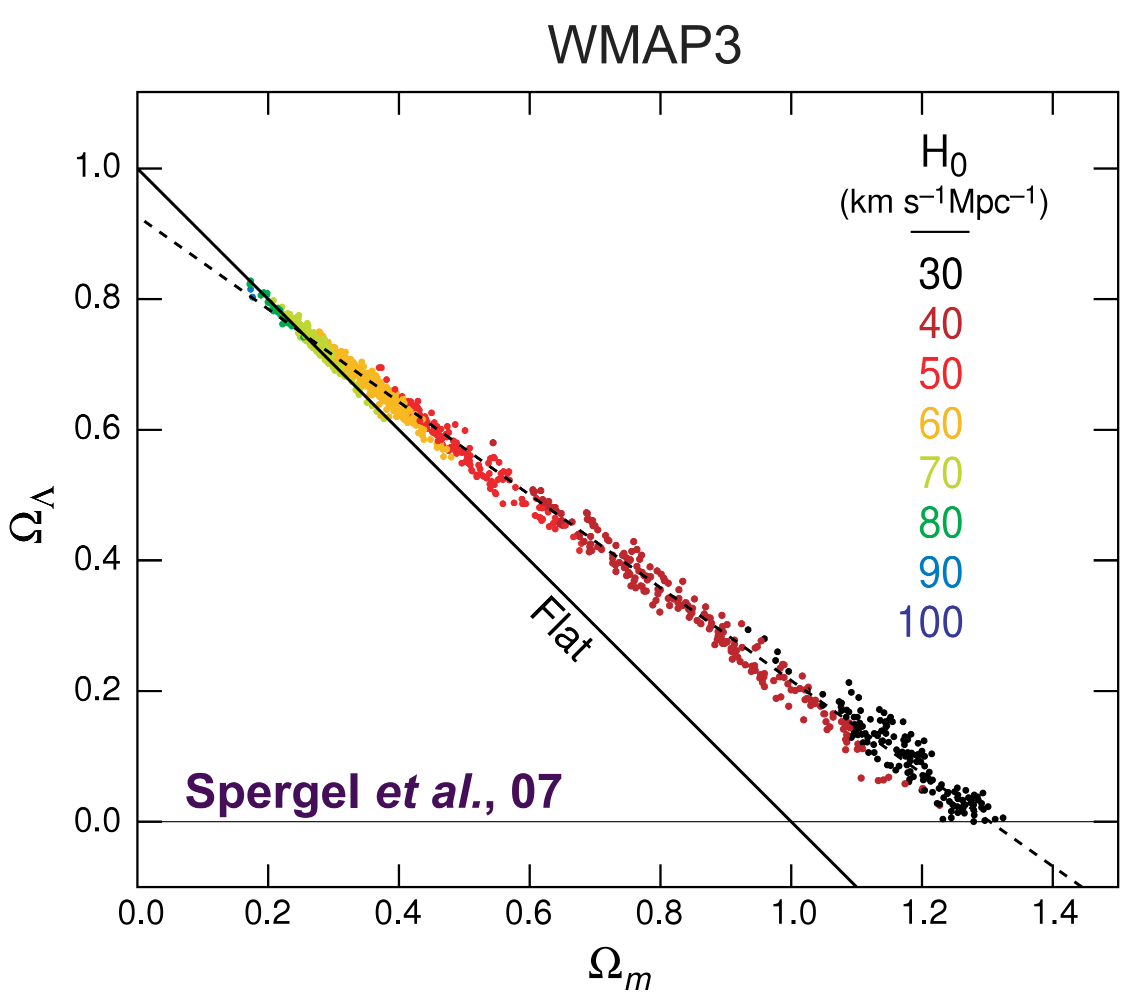


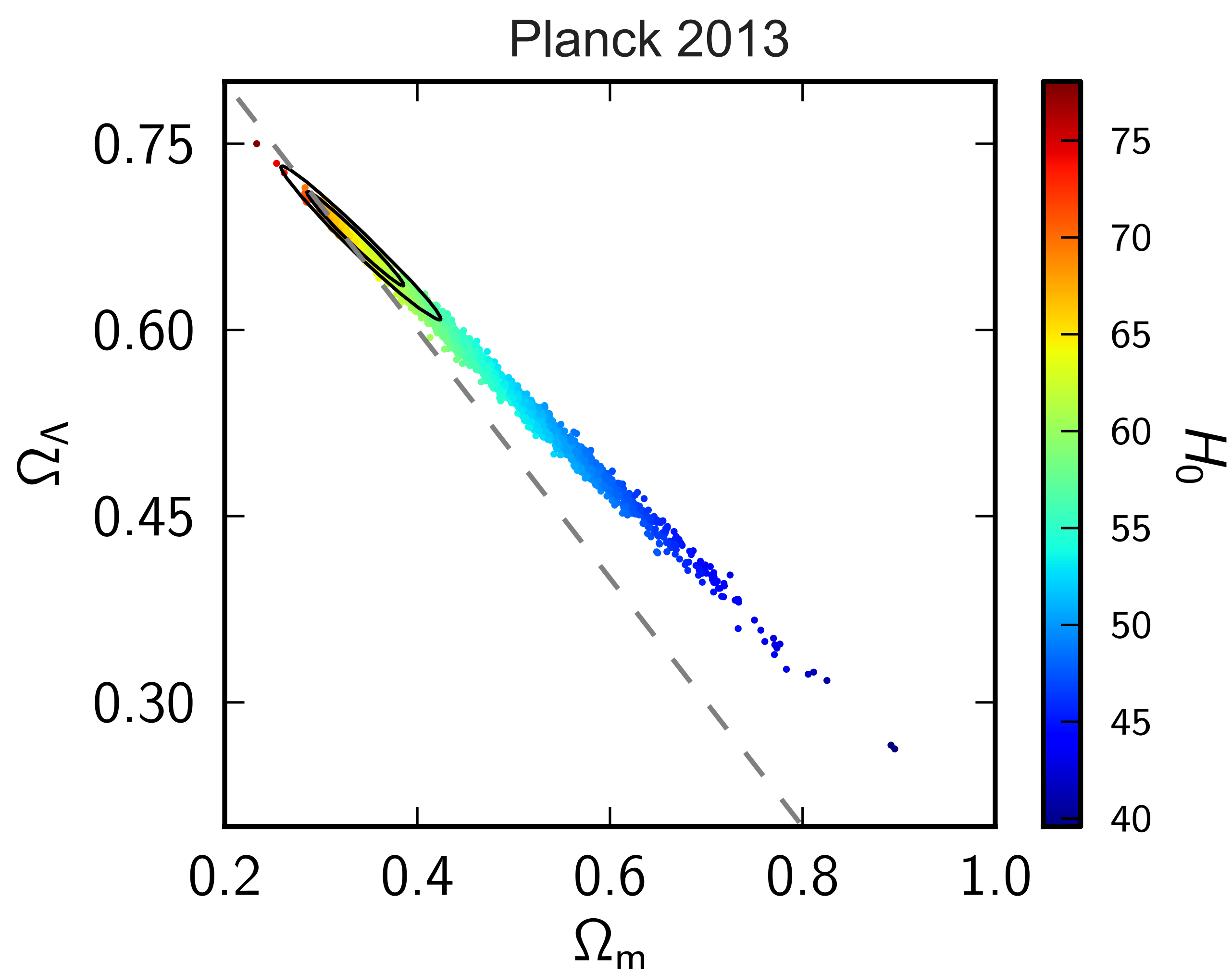
Lensed TT

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

Cosmology

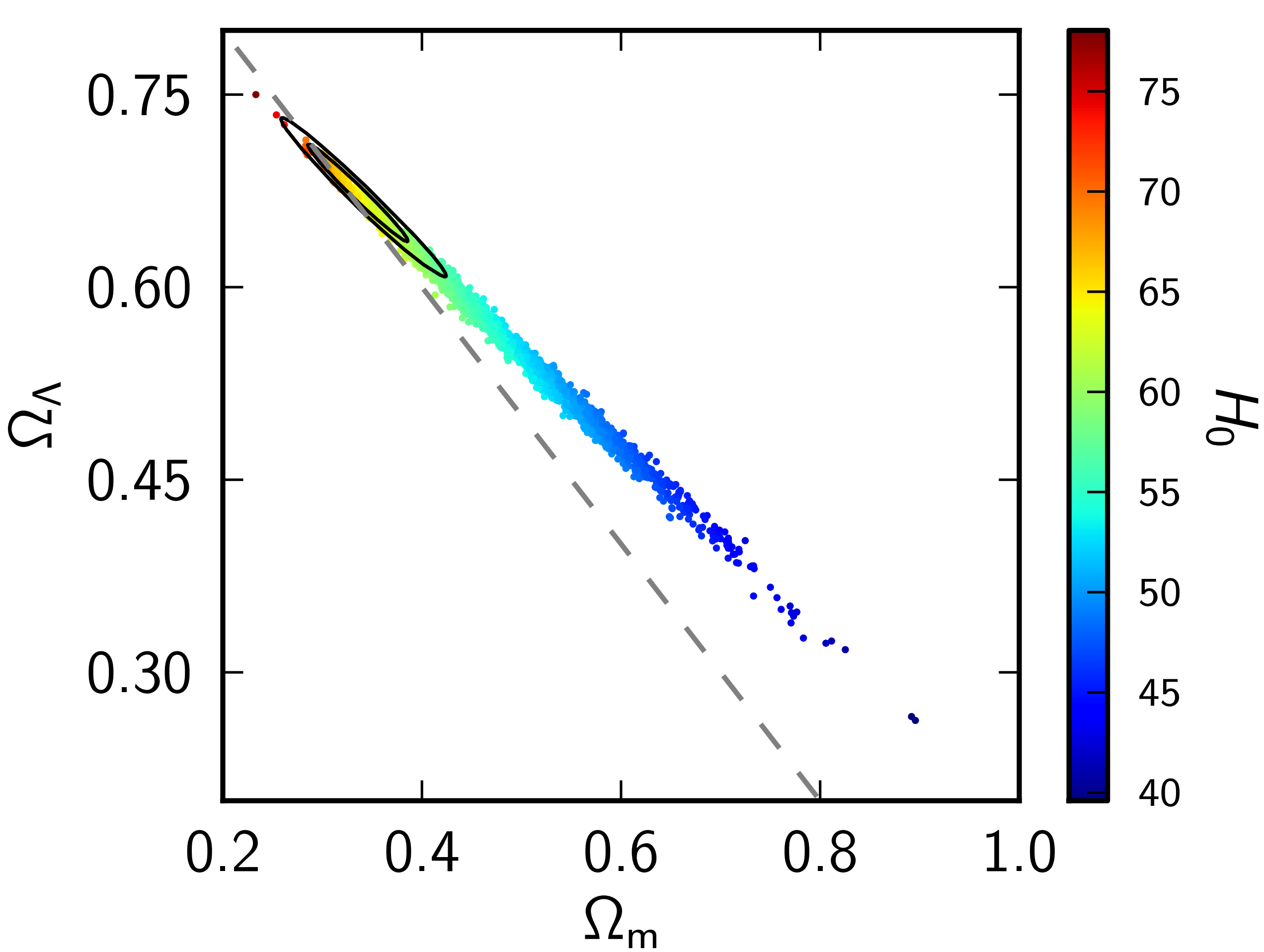
- CMB lensing breaks the angular diameter degeneracy

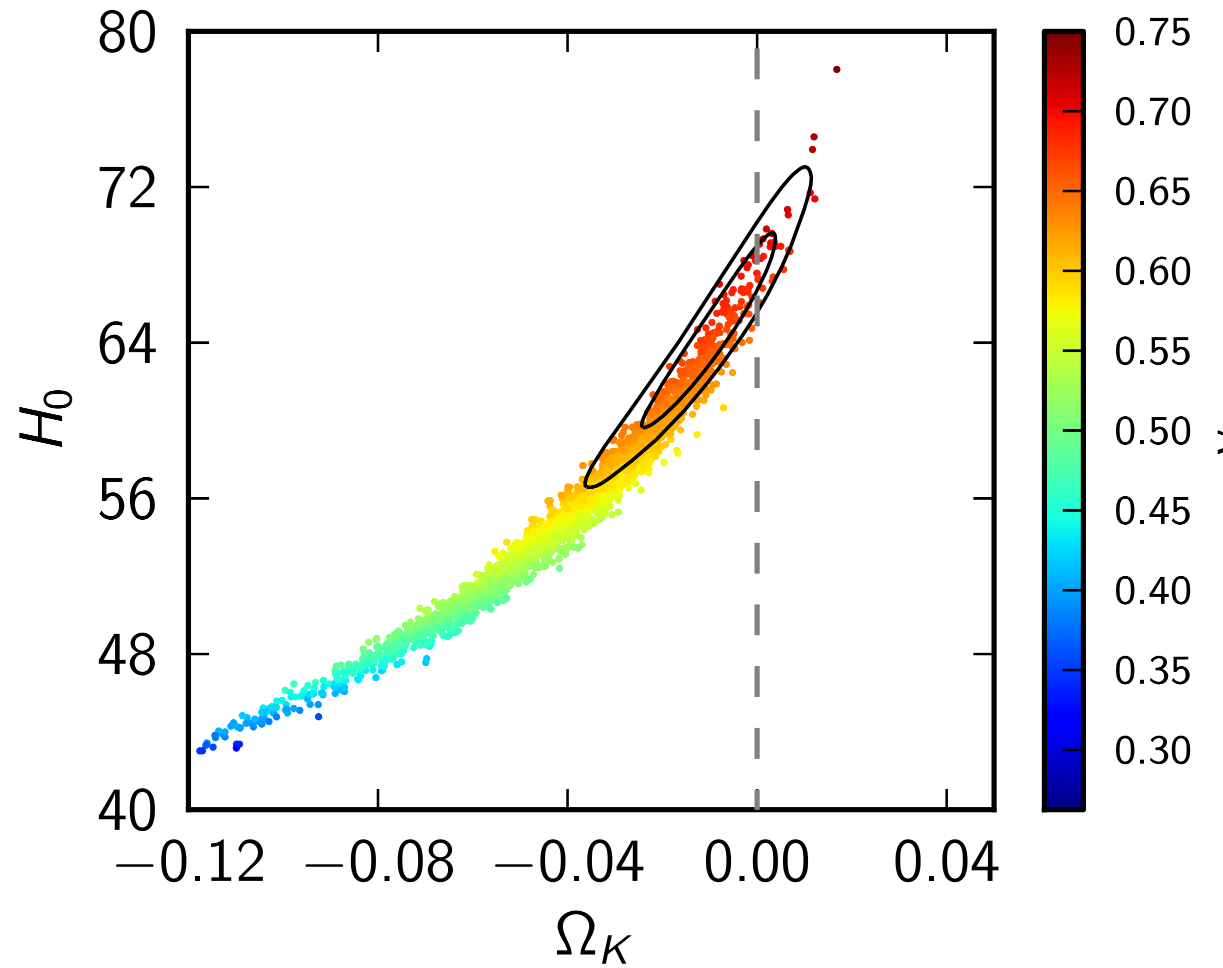




Cosmology

- CMB lensing breaks the angular diameter degeneracy





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

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

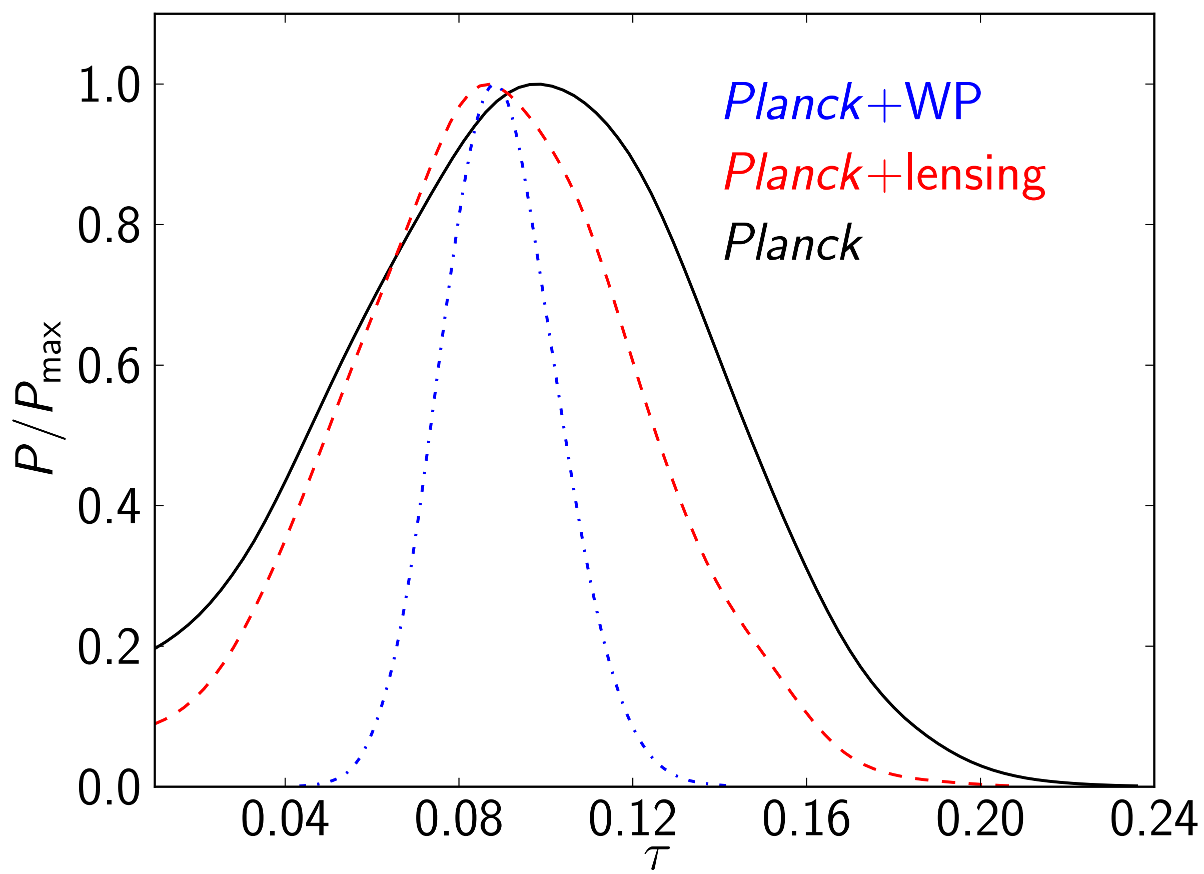
$100\Omega_K = -4.2^{+4.3}_{-4.8}$ (95%; *Planck*+WP+highL);

$100\Omega_K = -1.0^{+1.8}_{-1.9}$ (95%; *Planck*+lensing + WP+highL).

Cosmology

- Reionization

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



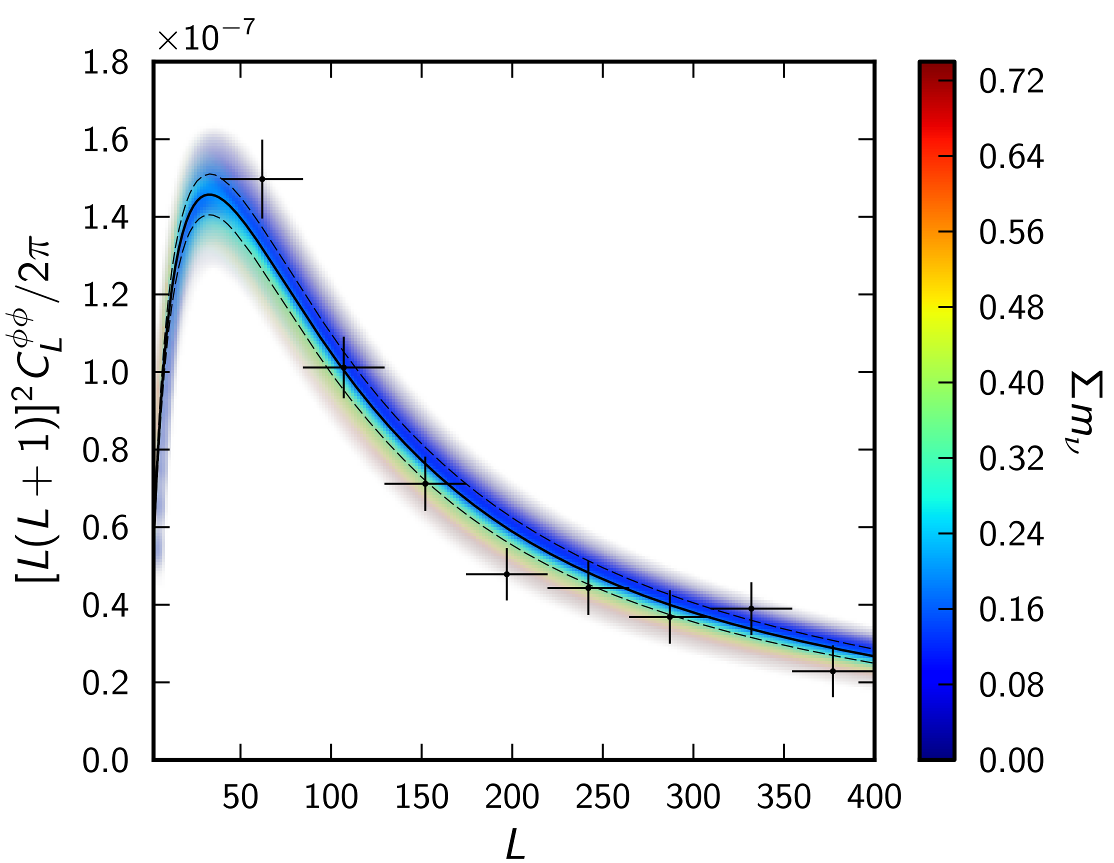
$$\tau = 0.097 \pm 0.038 \quad (68\%; \textit{Planck})$$

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

Cosmology

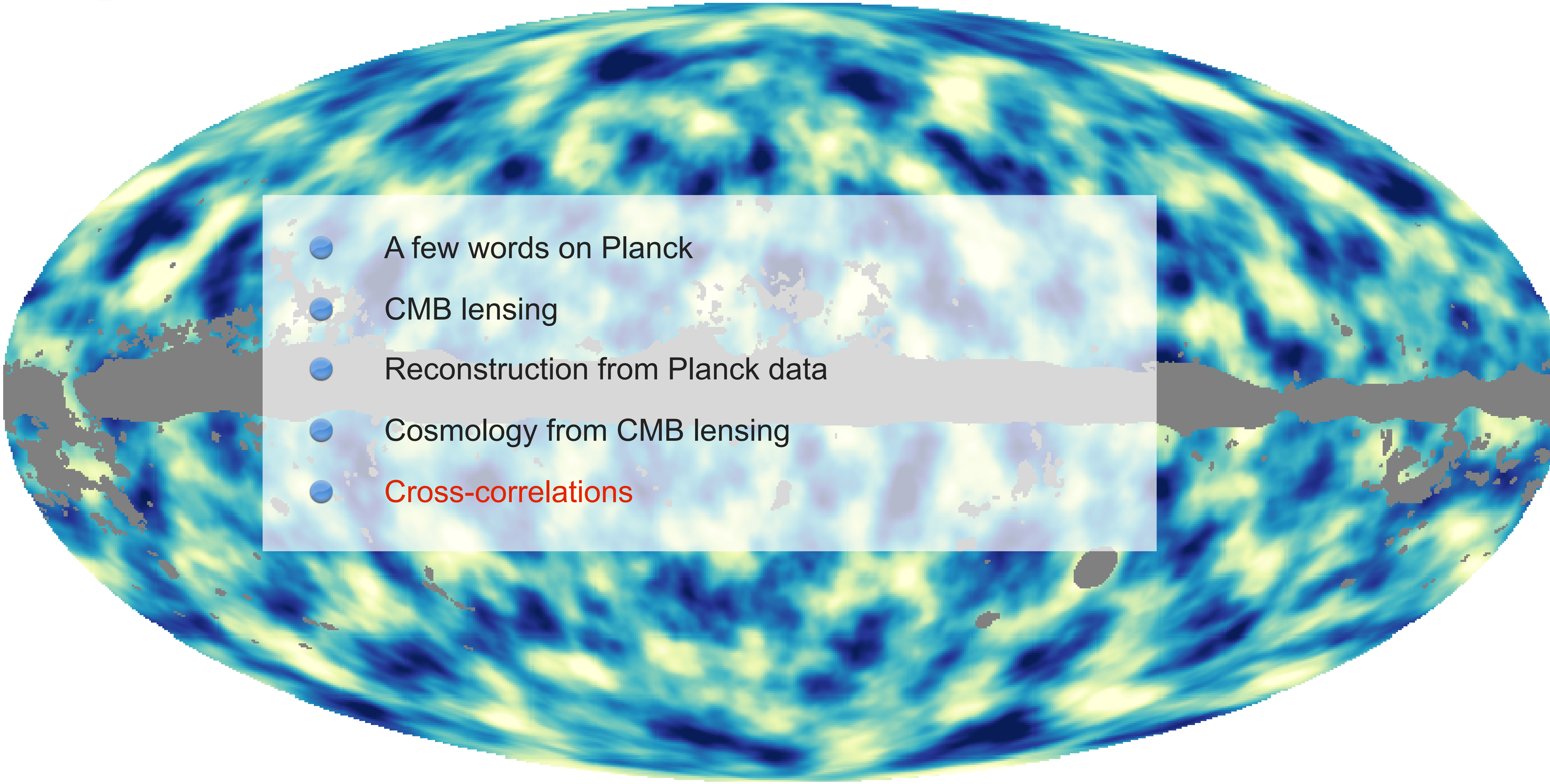
Sum of neutrinos masses

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



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

Outline



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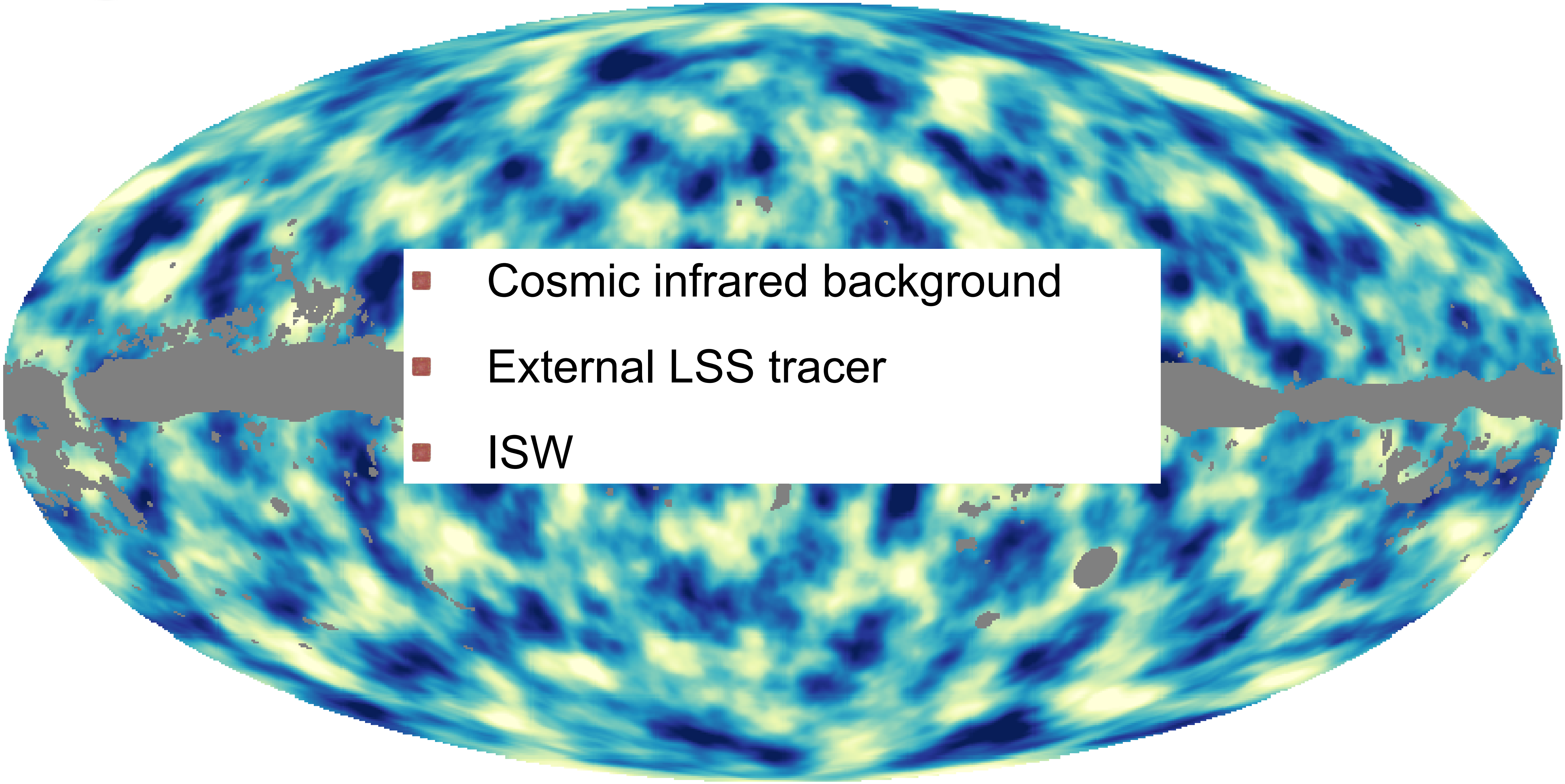
The lensing map traces the matter distribution up to the last scattering surface

Cross-correlations

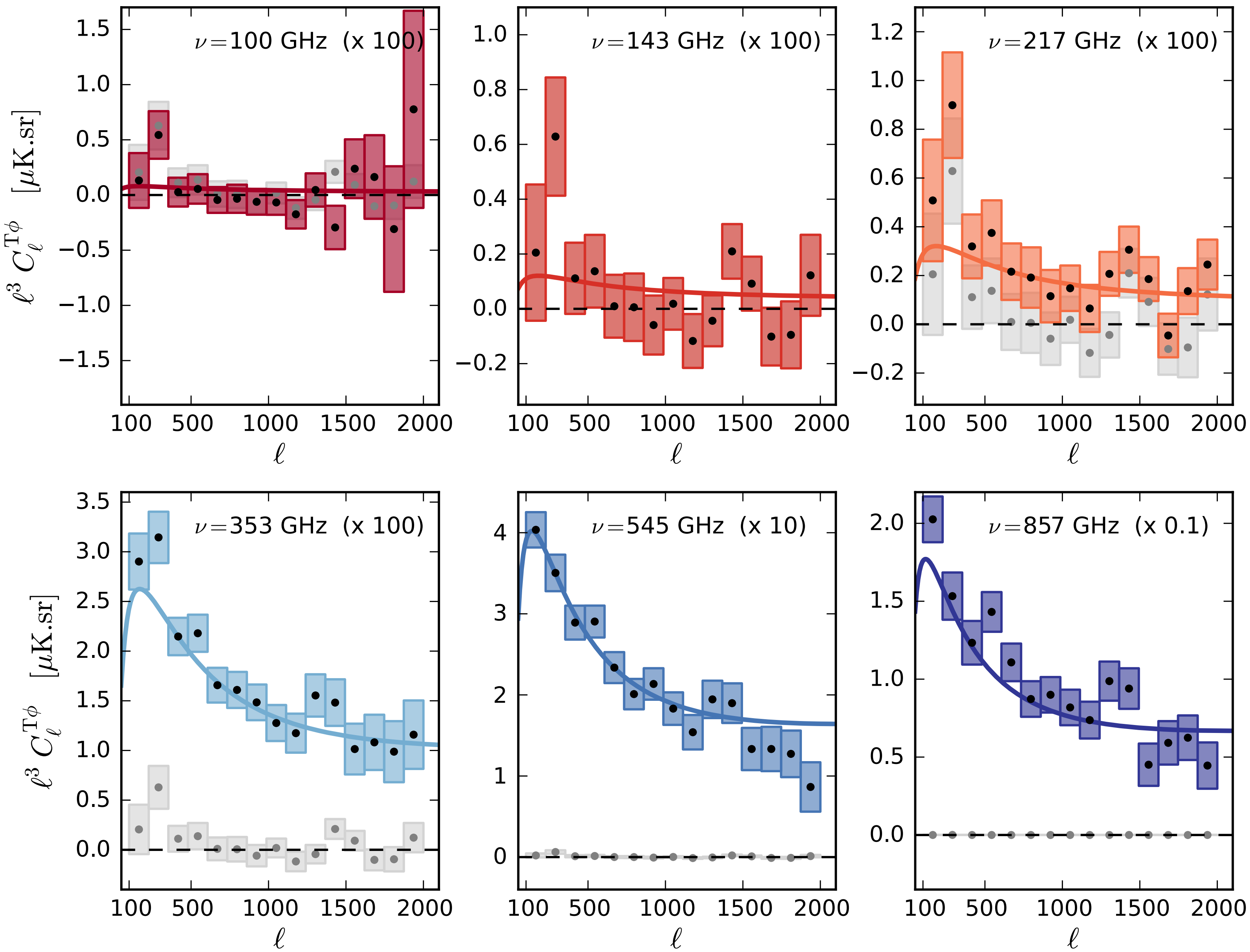


- Cosmic infrared background
- External LSS tracer
- ISW

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

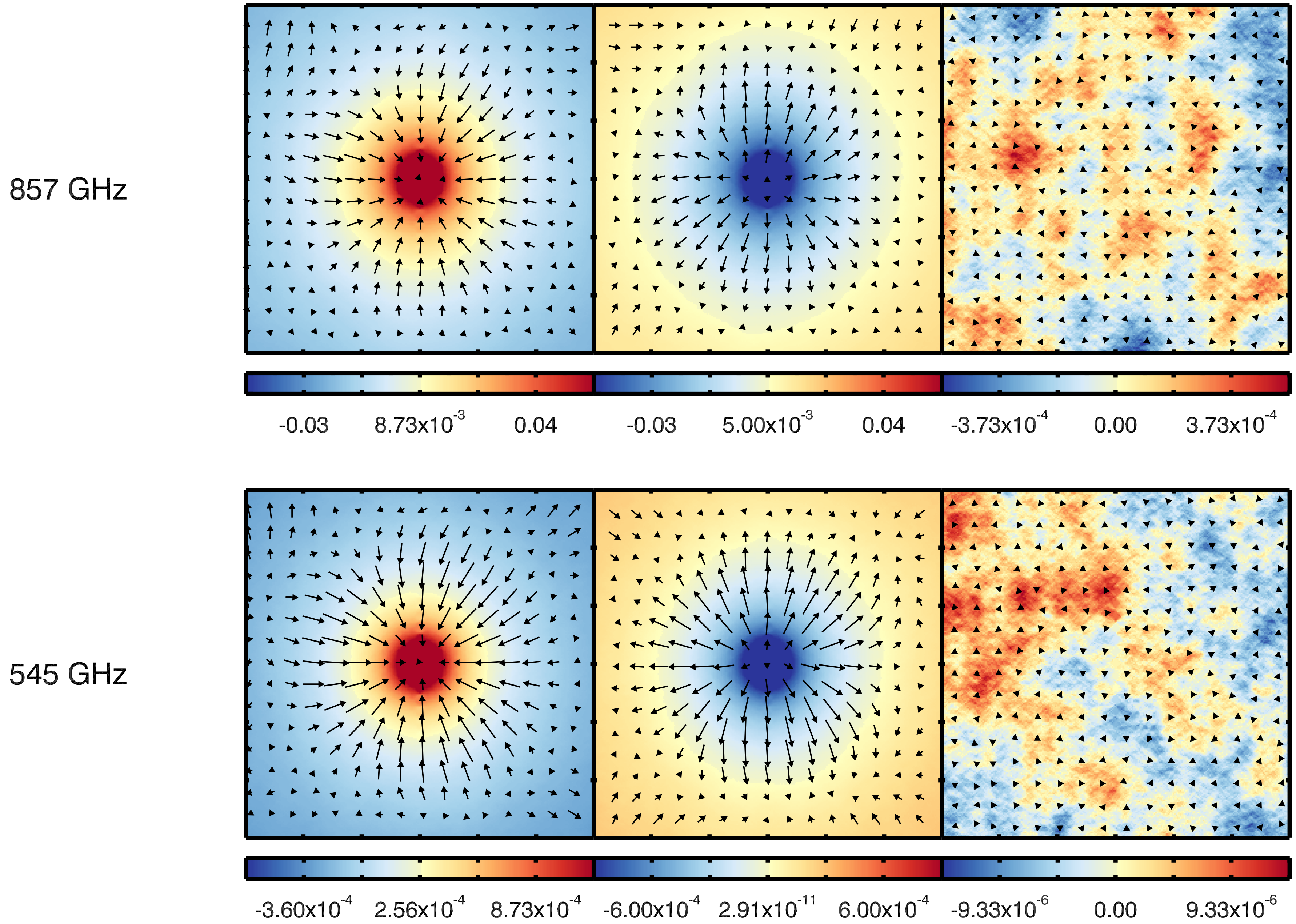
CMB lensing - CIB

- Lensing potential correlated with HFI temperature maps



CMB lensing - CIB

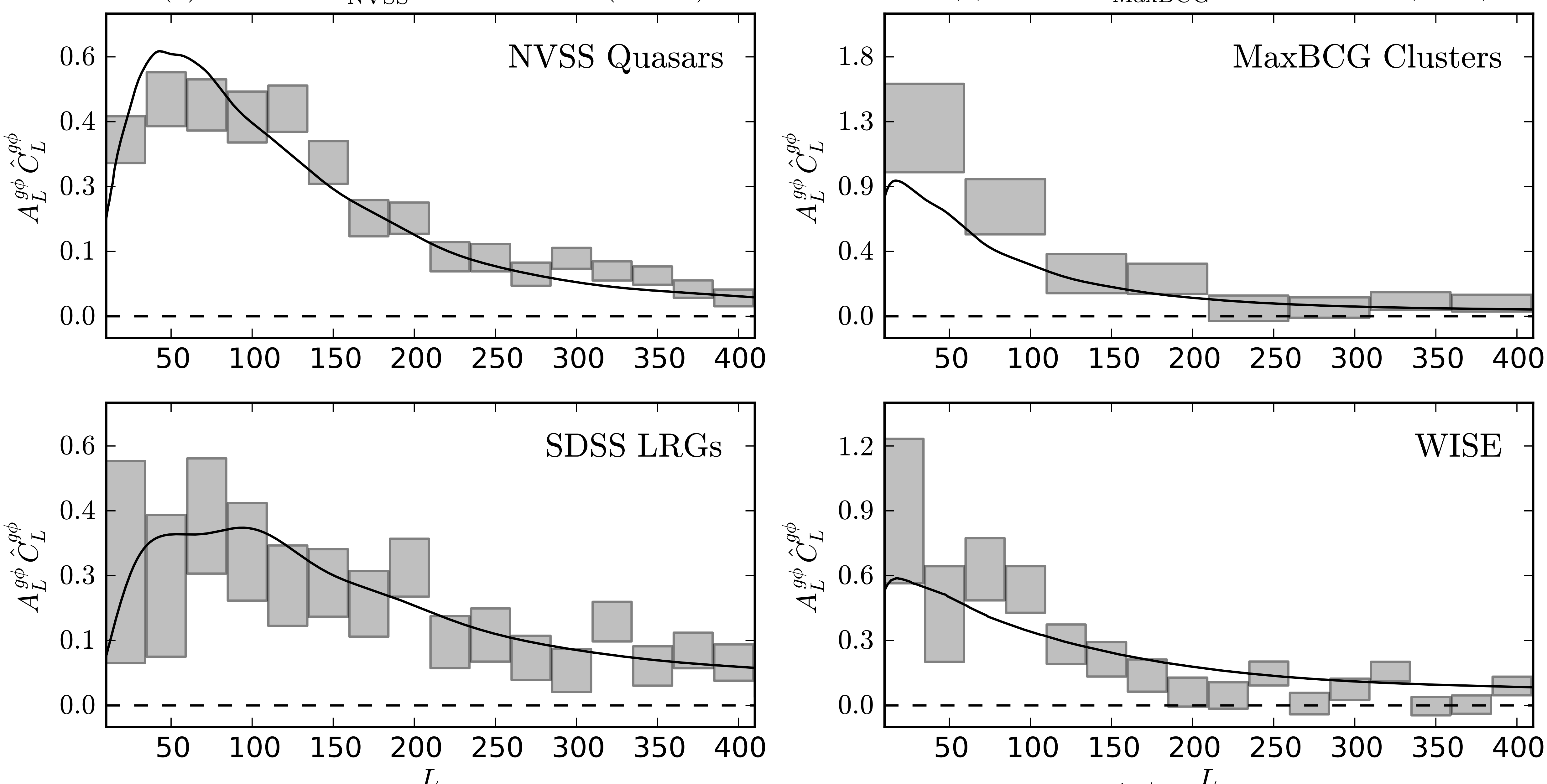
- Deflection stacked on 20.000 temperature extrema



CMB lensing - External tracers

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

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

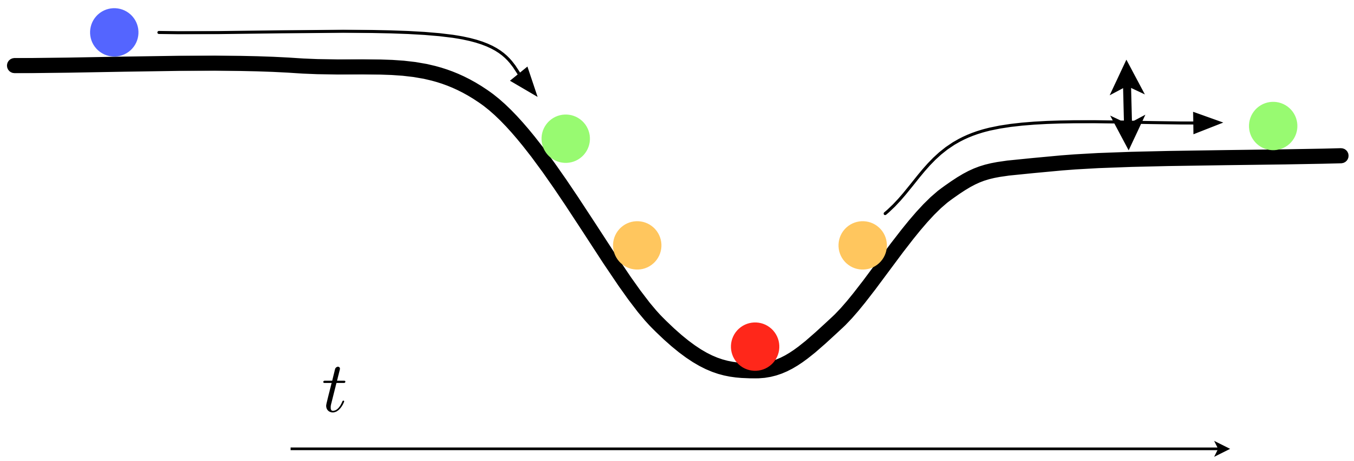


$b(z) = 2 \rightarrow \hat{A}^{g\phi}_{\mathrm{LRGs}} = 0.96 \pm 0.10 \ (\approx 10\sigma)$

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

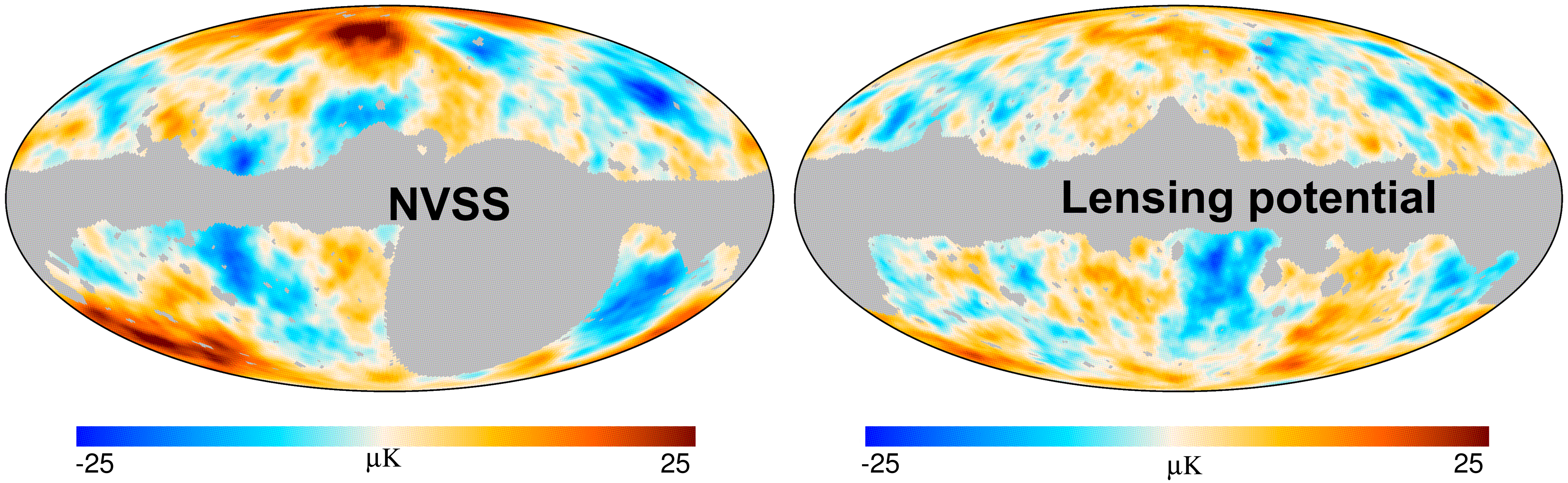
ISW

Shallowing of the potential due to expansion driven by dark energy



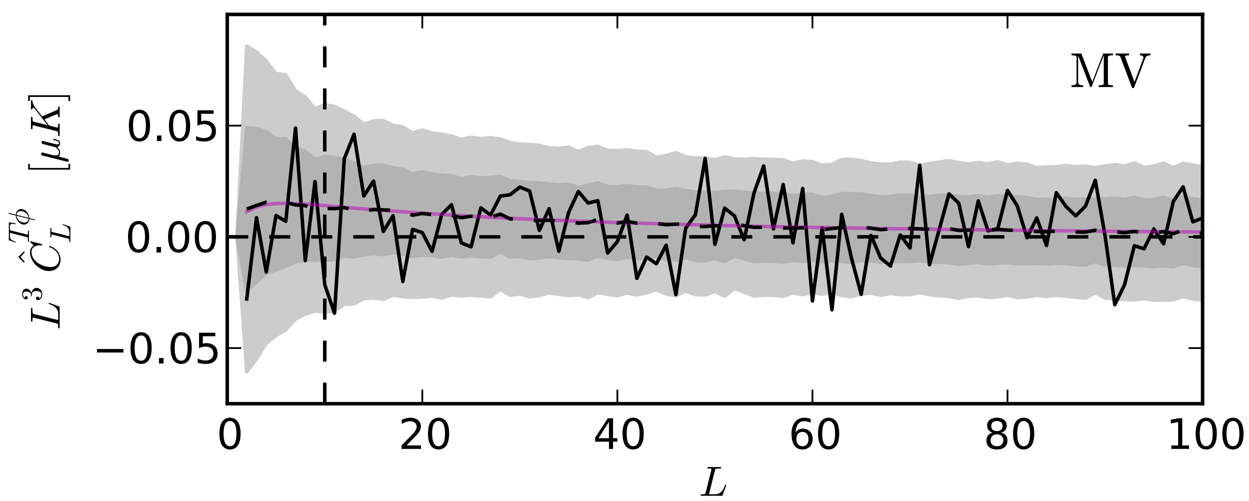
$$\frac{\Delta T}{T} = \frac{2}{c^3}\int_{\eta^*}^{\eta_0} \mathrm{d}\eta \frac{\partial \Phi}{\partial \eta}$$

Courtesy: K. Benabed



Planck ISW maps

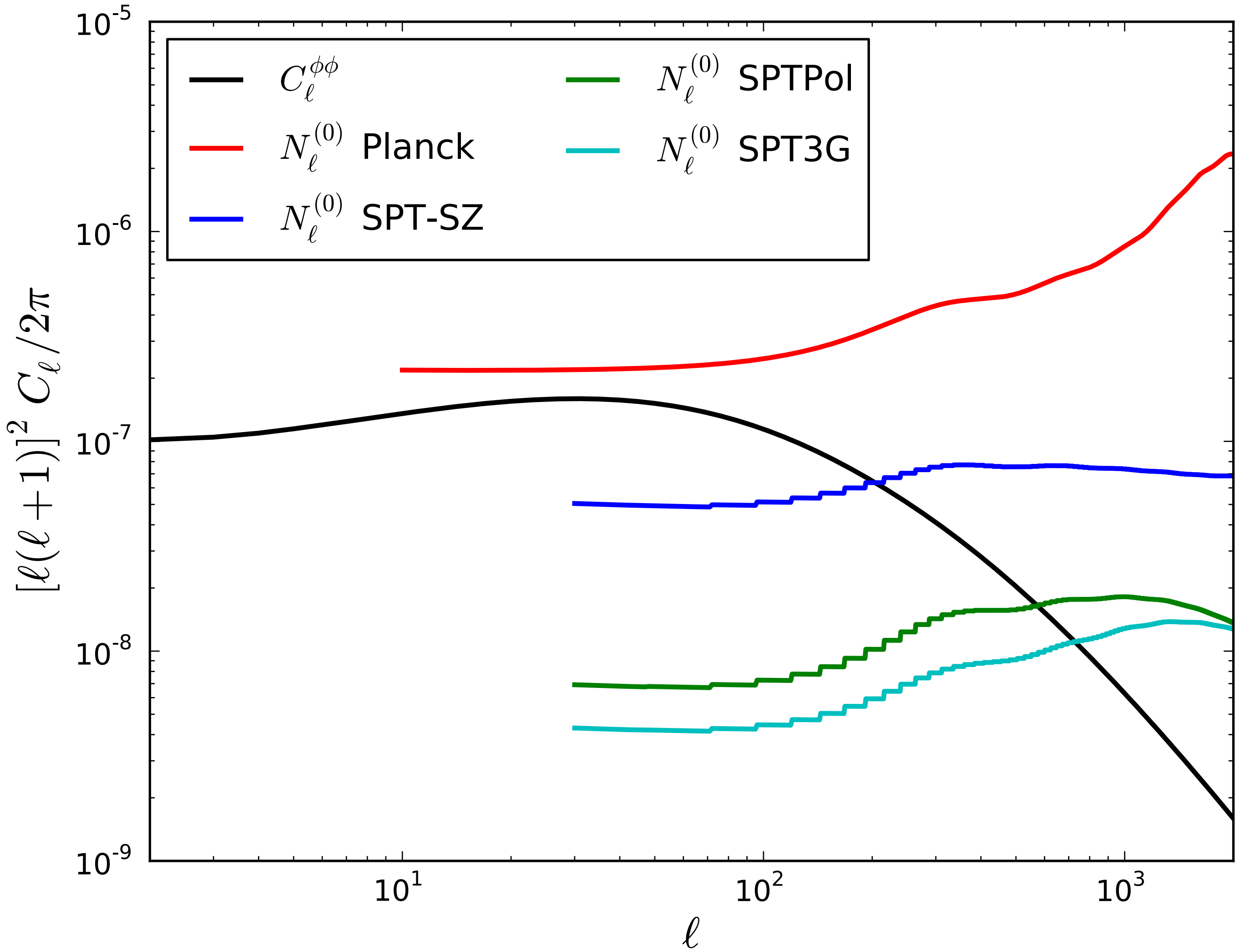
ISW - Lensing correlation



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

Perspectives: cross-correlations with DES and Euclid



2500 sq. deg.

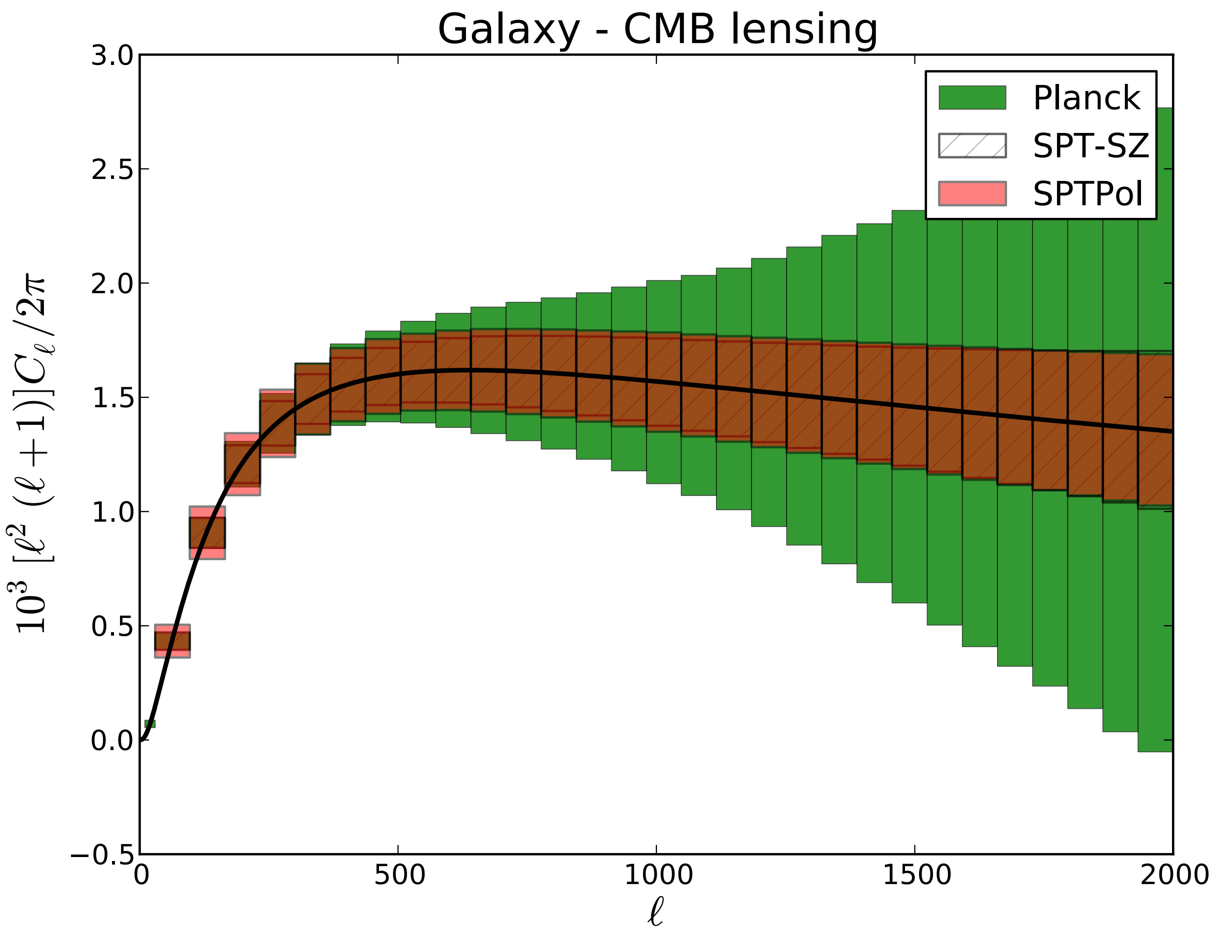
600 sq. deg.

2500 sq. deg.

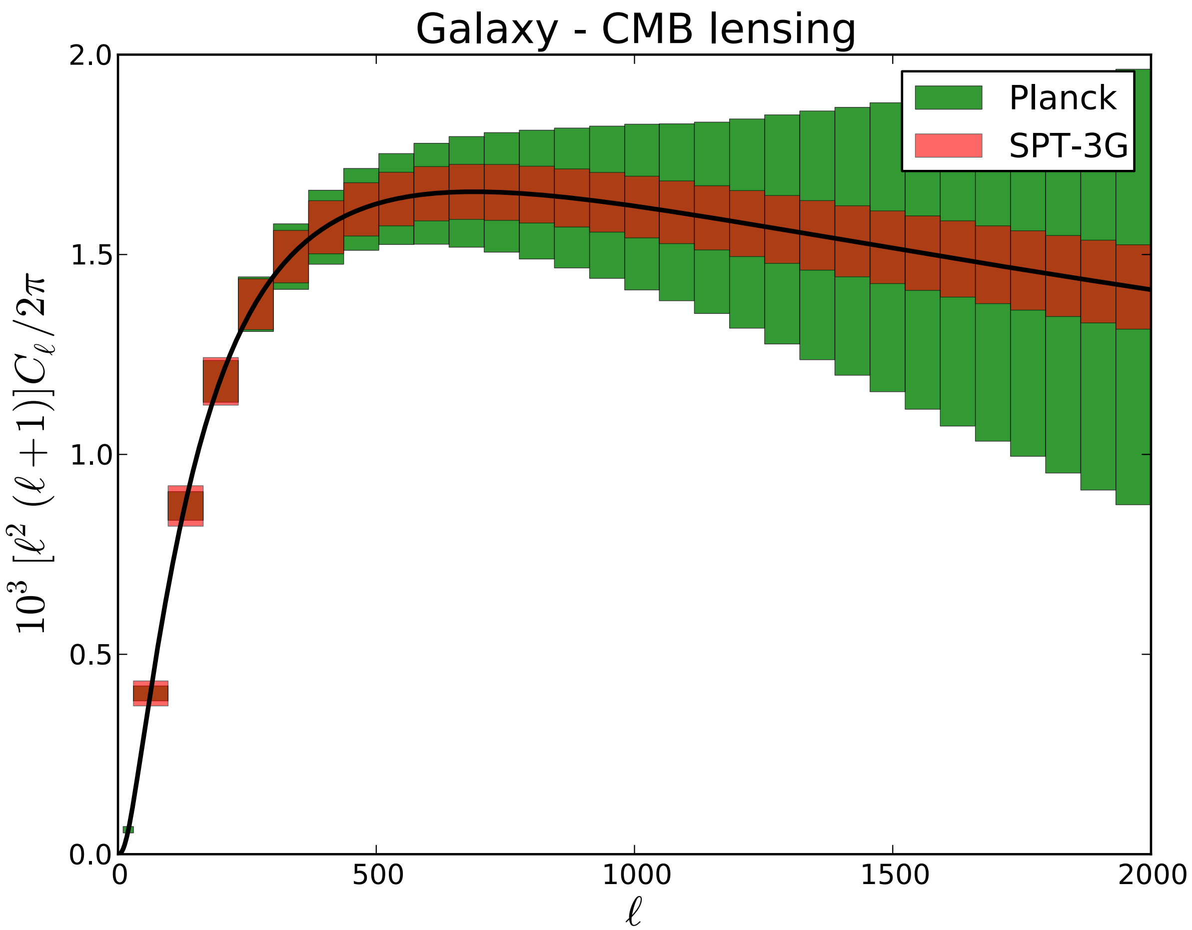
SPT lensing noises provided by **Gabrielle Simard**

Perspectives: cross-correlations with DES and Euclid

DES



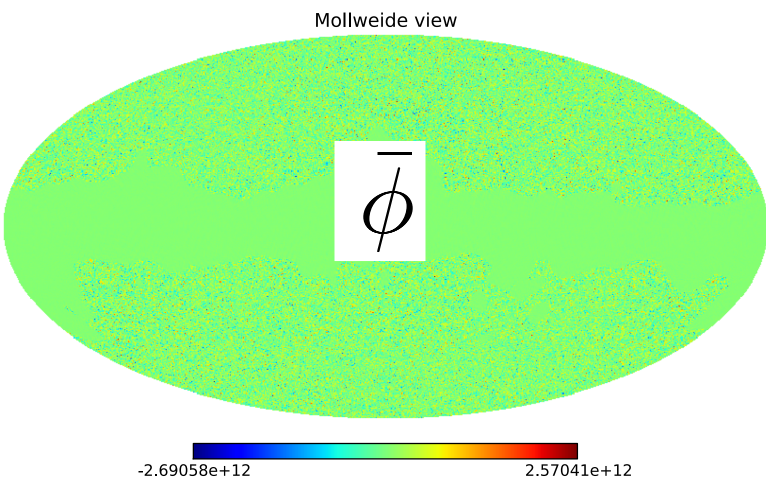
Euclid

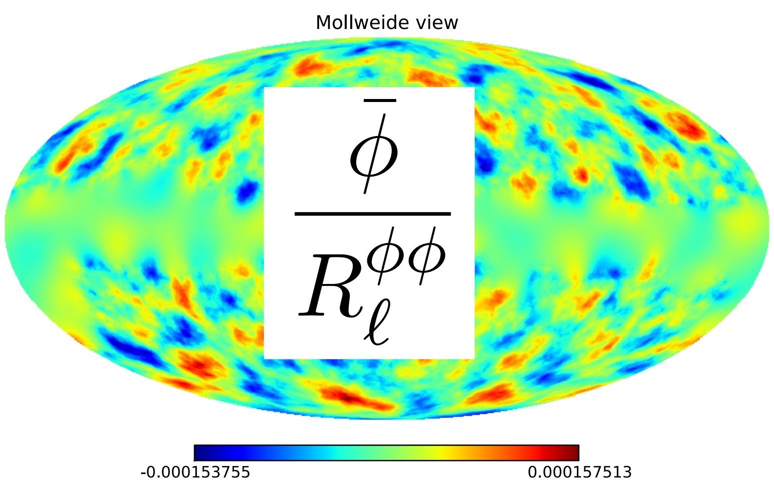


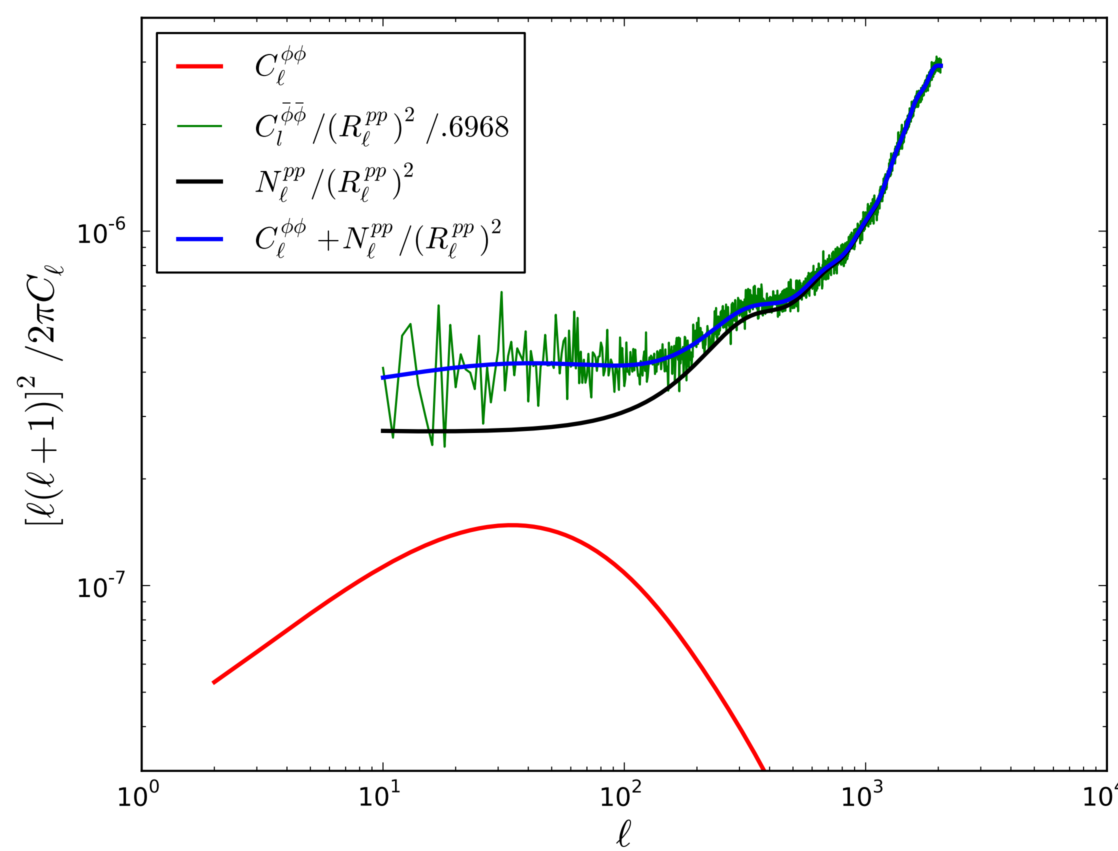
- Planck larger area should provide large-scale information
- SPT-x will dominate at small scales

How to use the Planck lensing map

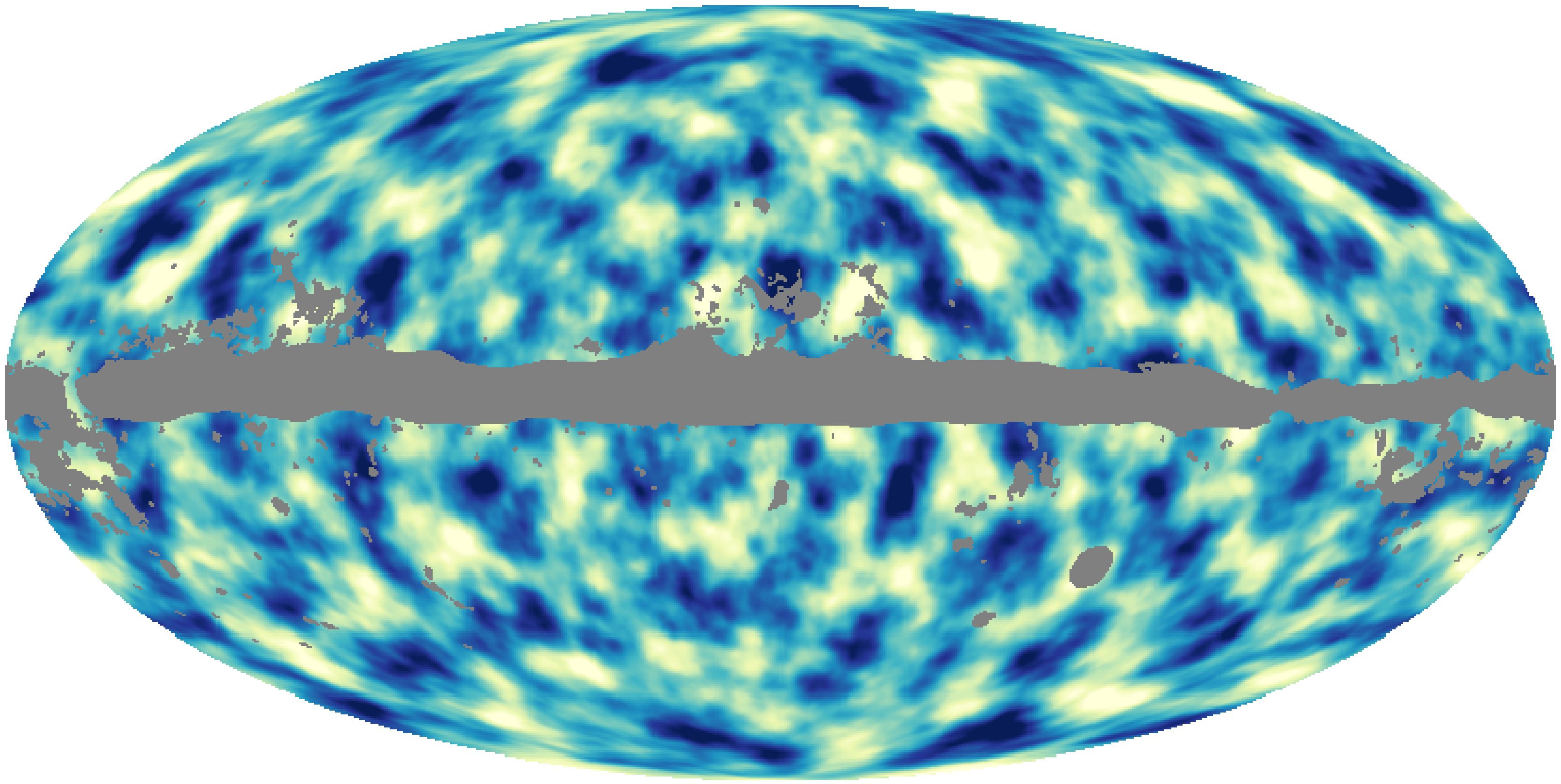
- **On the PLA: COM_CompMap_Lensing_2048_R1.10.fits**
  - Un-normalized lensing potential $\bar{\phi}$, mask
  - «Normalisation window» $R_\ell^{\phi\phi}$, lensing noise $N_\ell^{\phi\phi}$







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