The large-scale structure of the Universe as seen by Planck

Results from Planck 2013 Results. XVII

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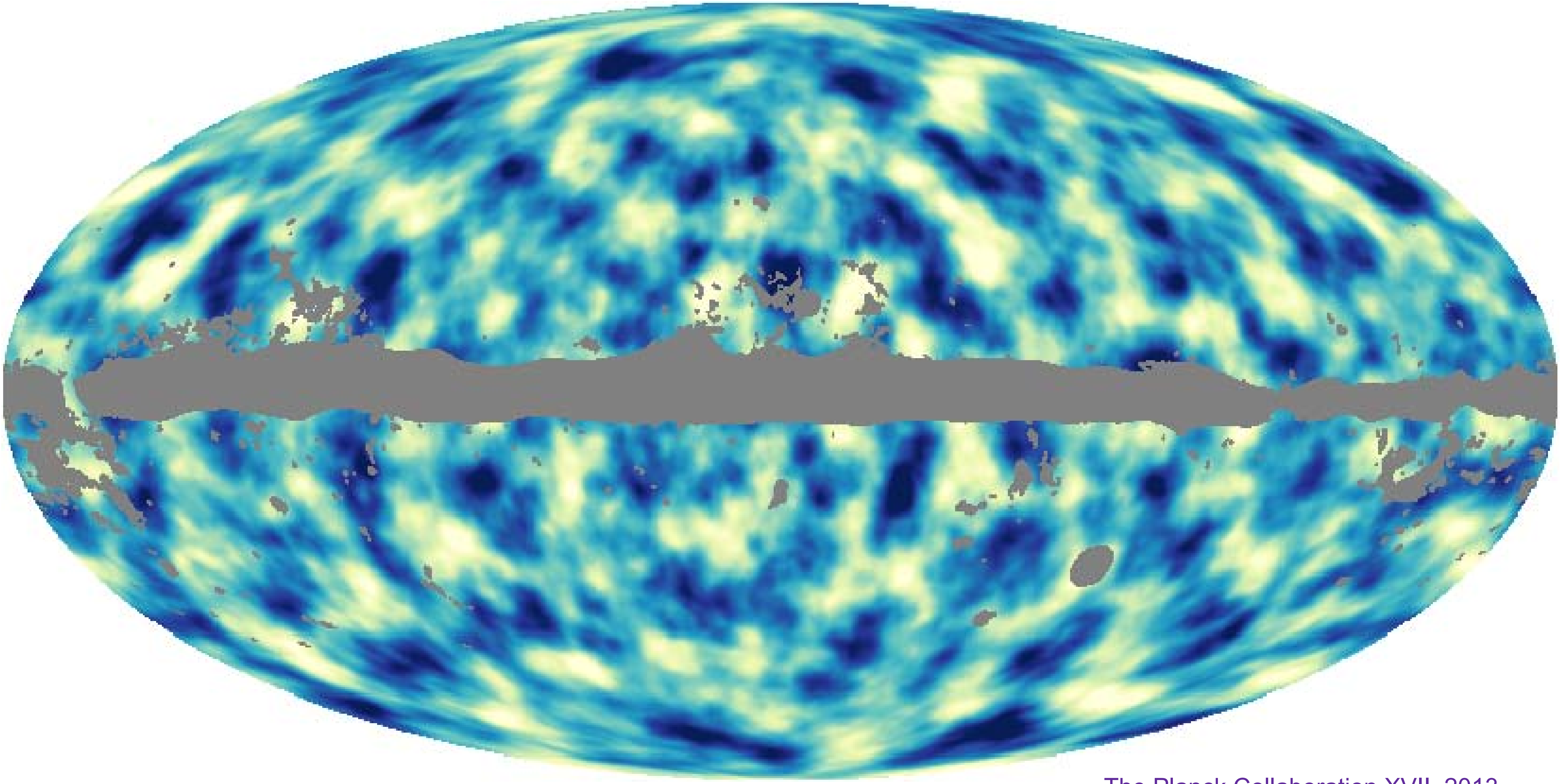
University College London

LPHNE - 8 avril 2013

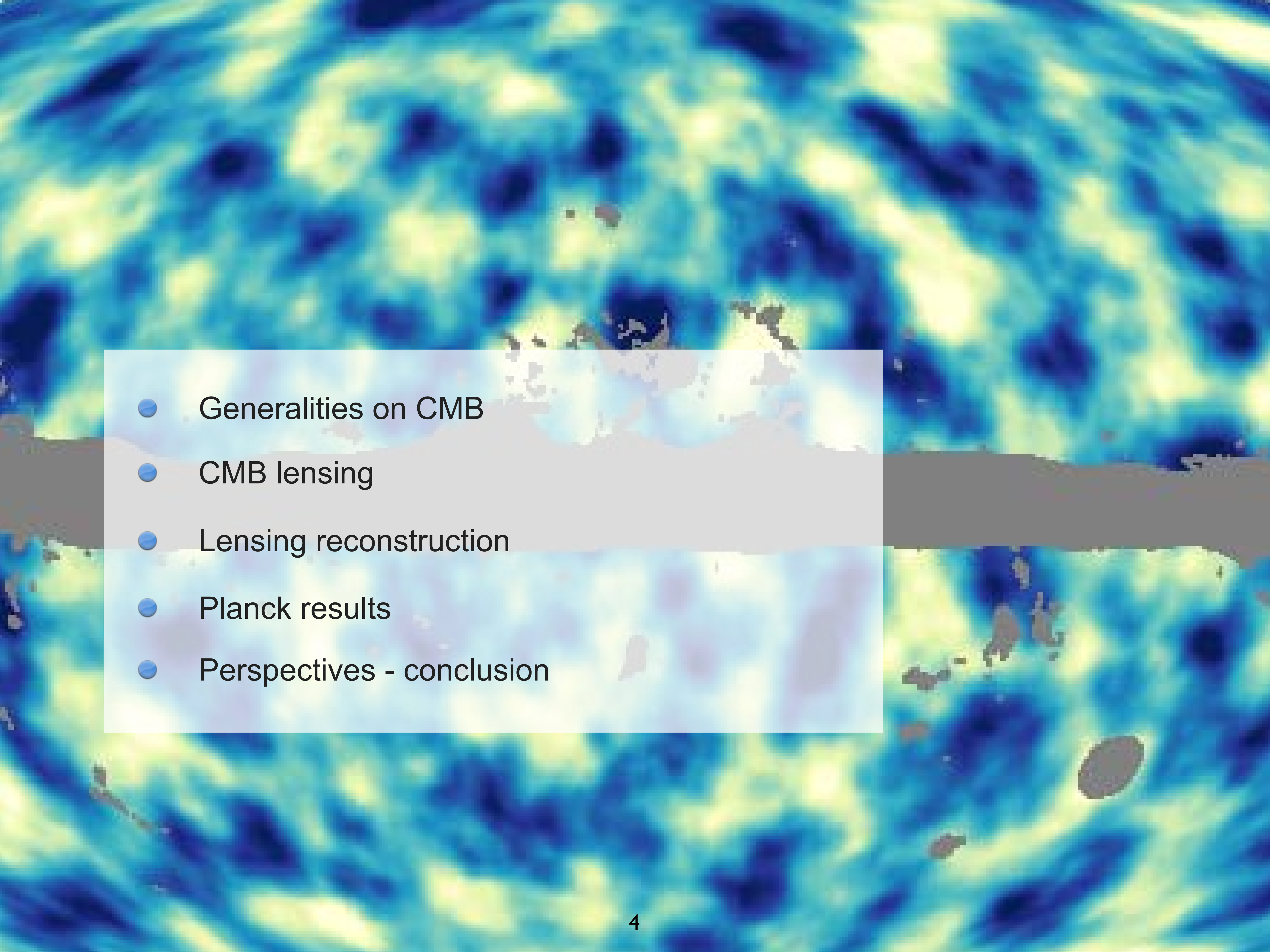
The matter in the Universe as seen by Planck



The Planck Collaboration XVII, 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.



- Generalities on CMB
- CMB lensing
- Lensing reconstruction
- Planck results
- Perspectives - conclusion

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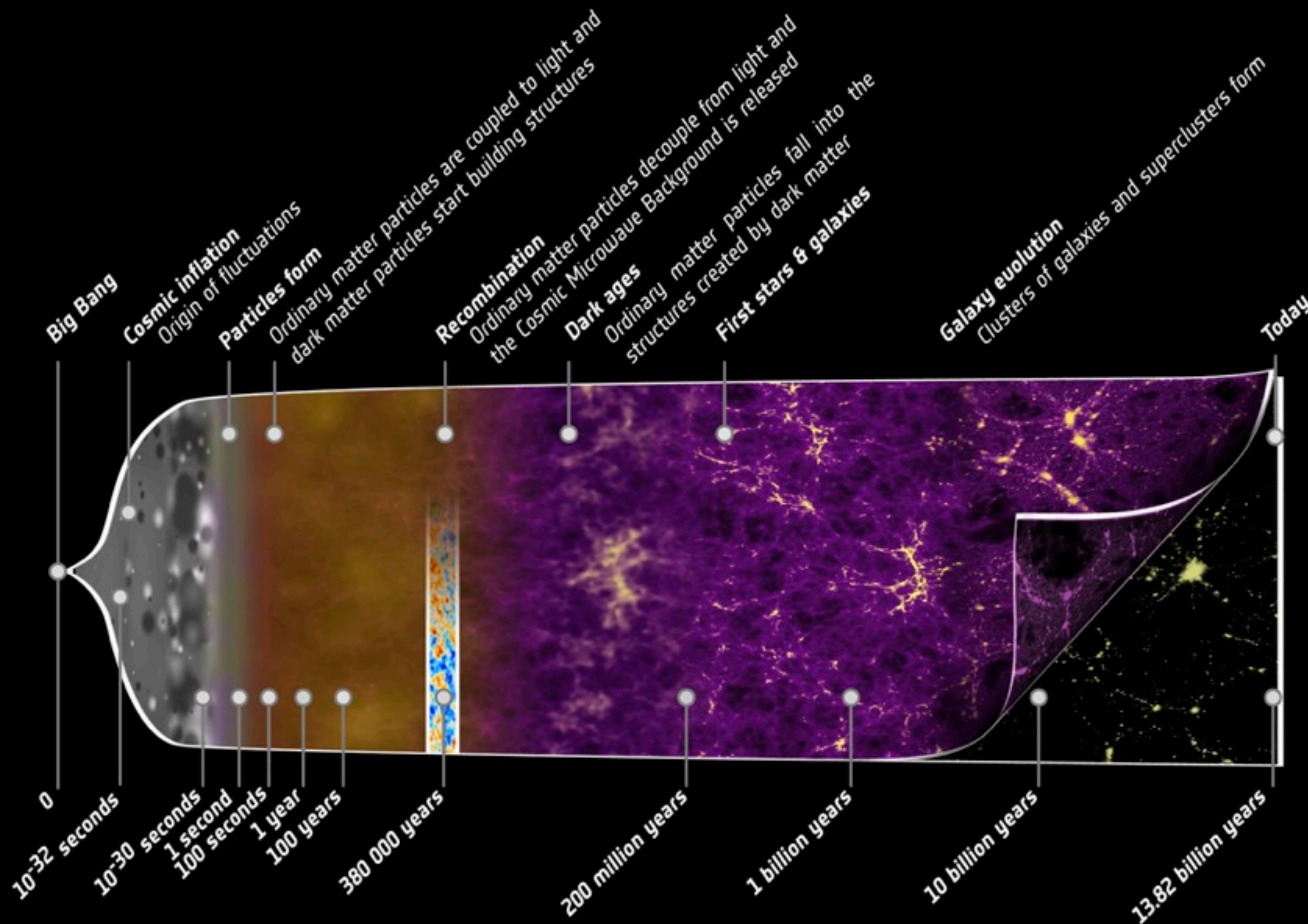
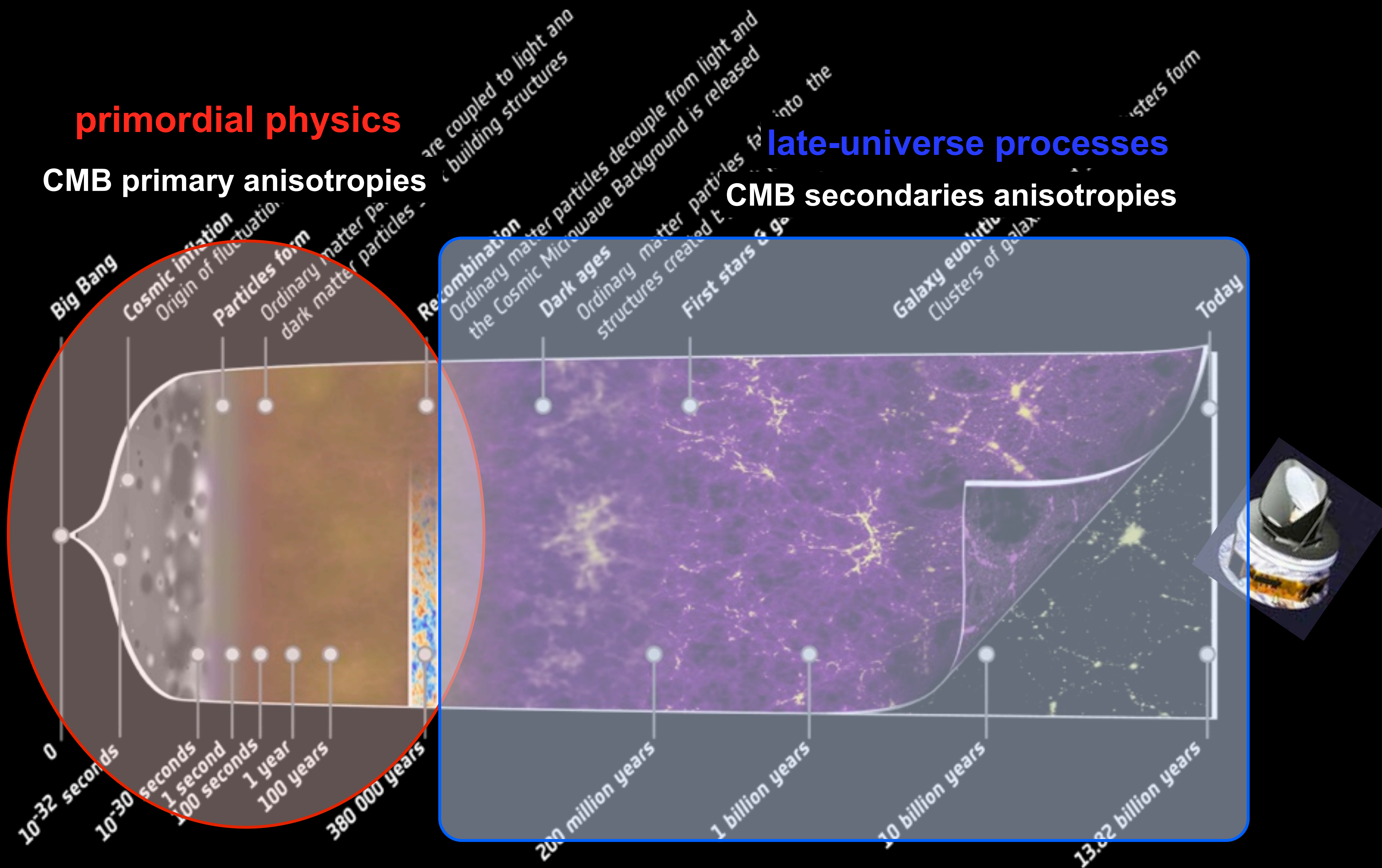
A (very) schematic history of our Universe

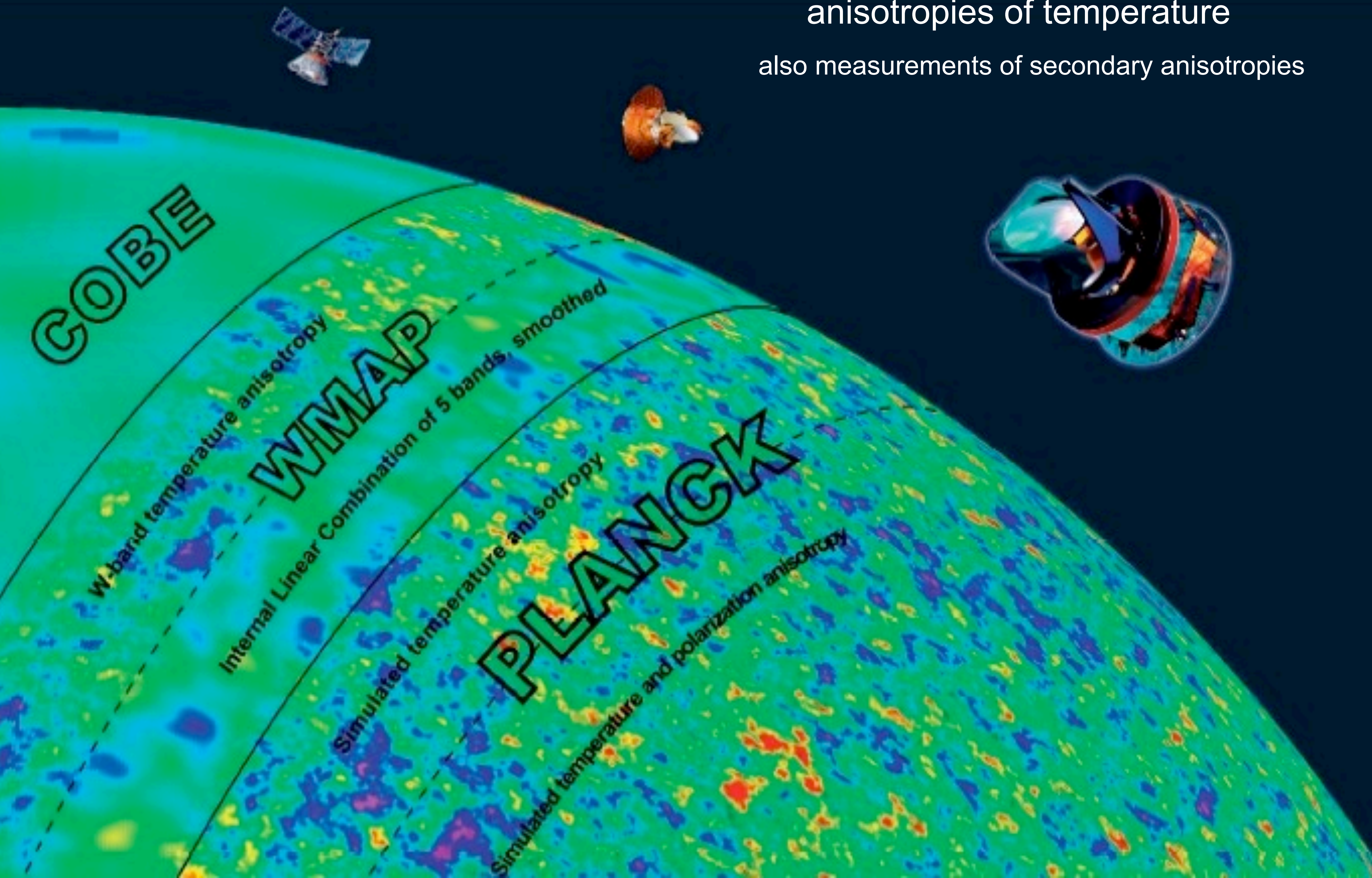


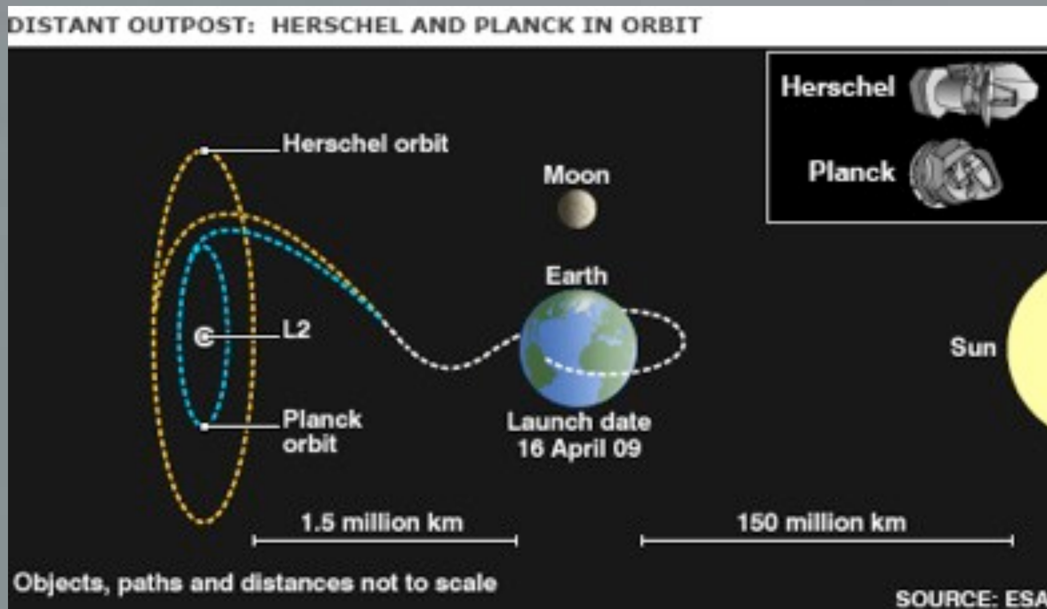
CMB: central observation in cosmology

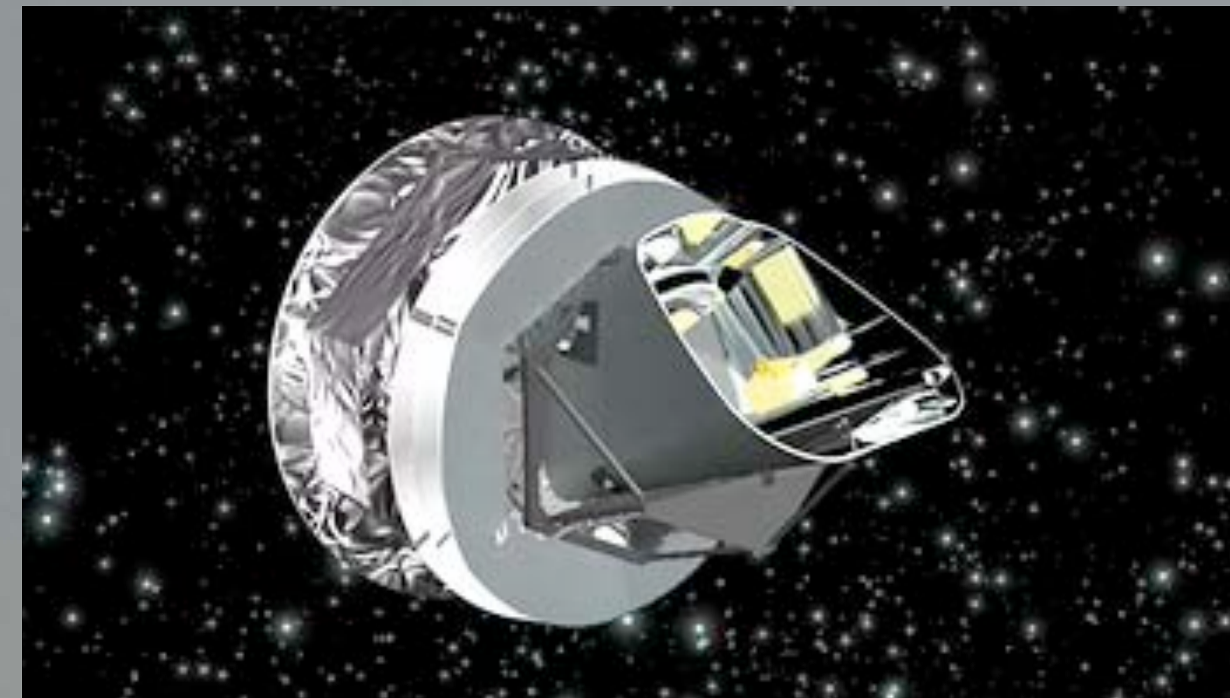


ultimate measurements of primary anisotropies of temperature

also measurements of secondary anisotropies







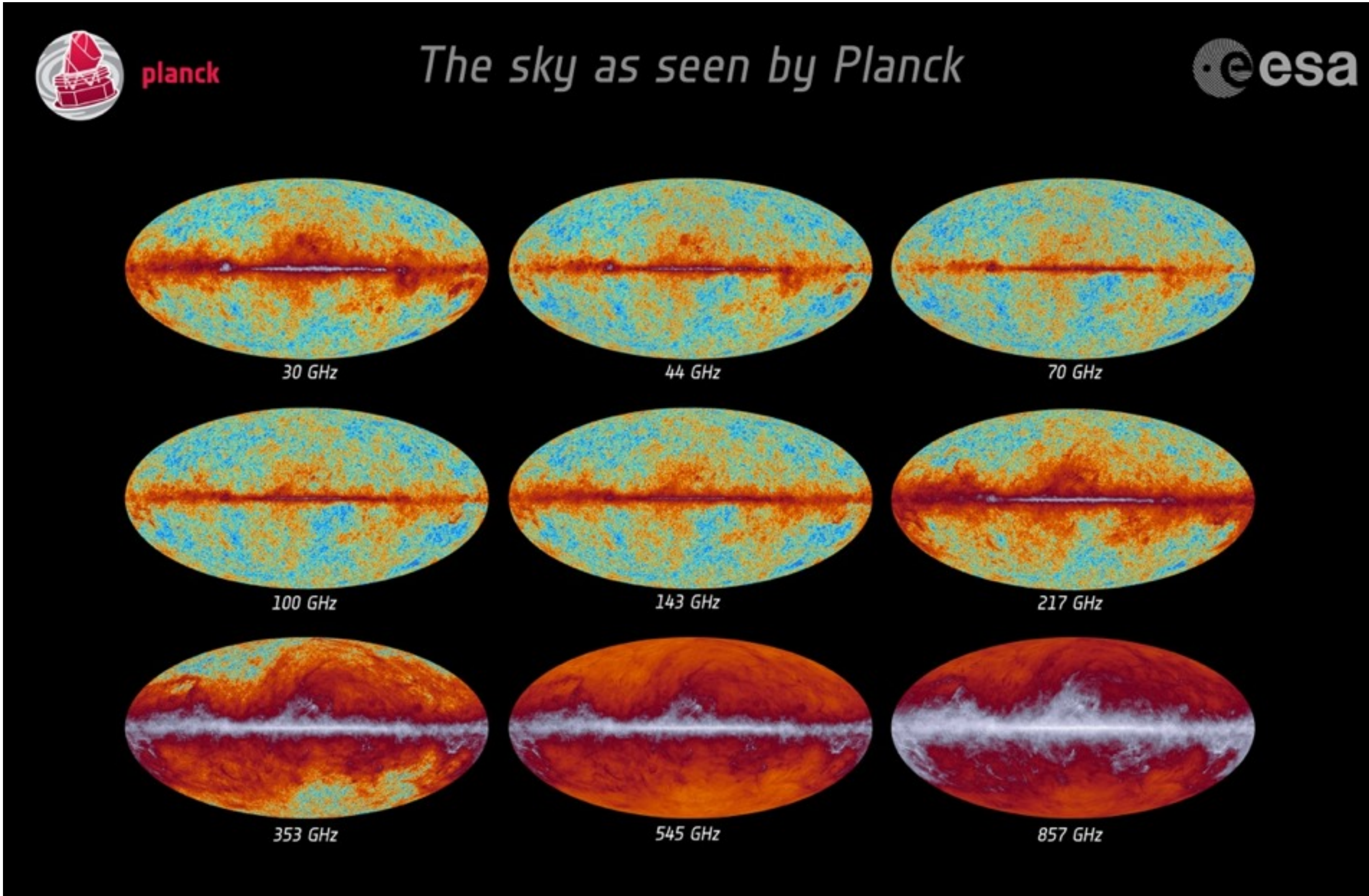
- Launched in May 14th 2009
- First complete coverage of sky in June 2010
- Nominal mission completed in November 2010
- End of light January 14th 2012. 32 months after launch

First cosmology release 21st March 2013

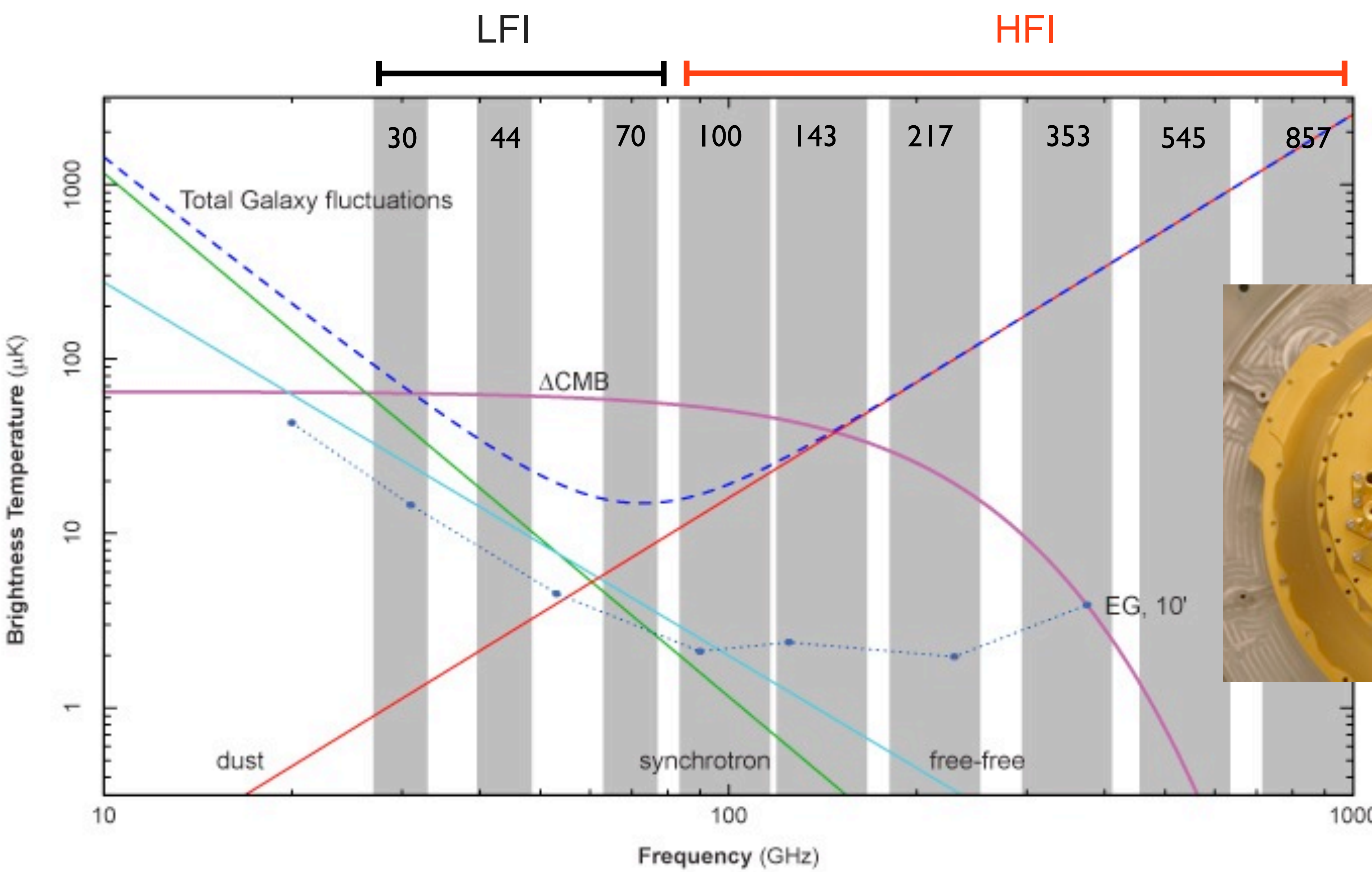
- Full release in 2014

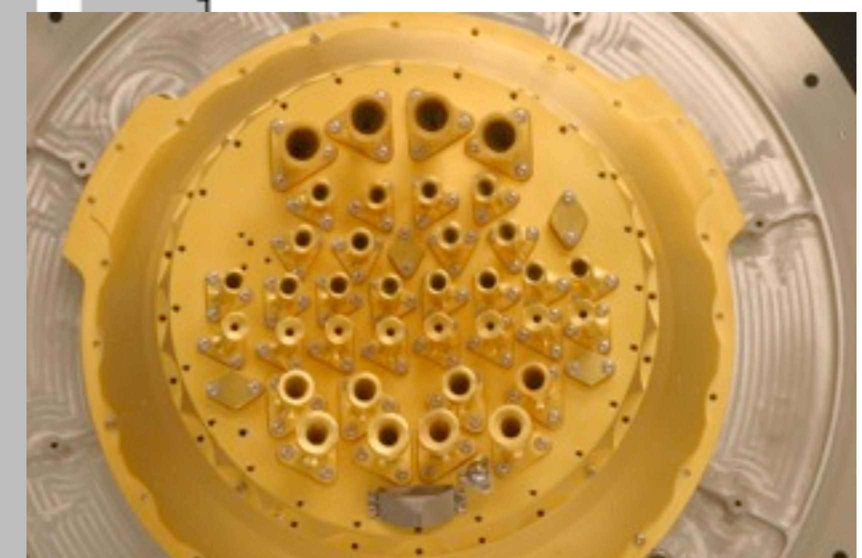
Ariane 5 ECA Launch • HERSCHEL – PLANCK - May 14, 2009

Planck sky maps



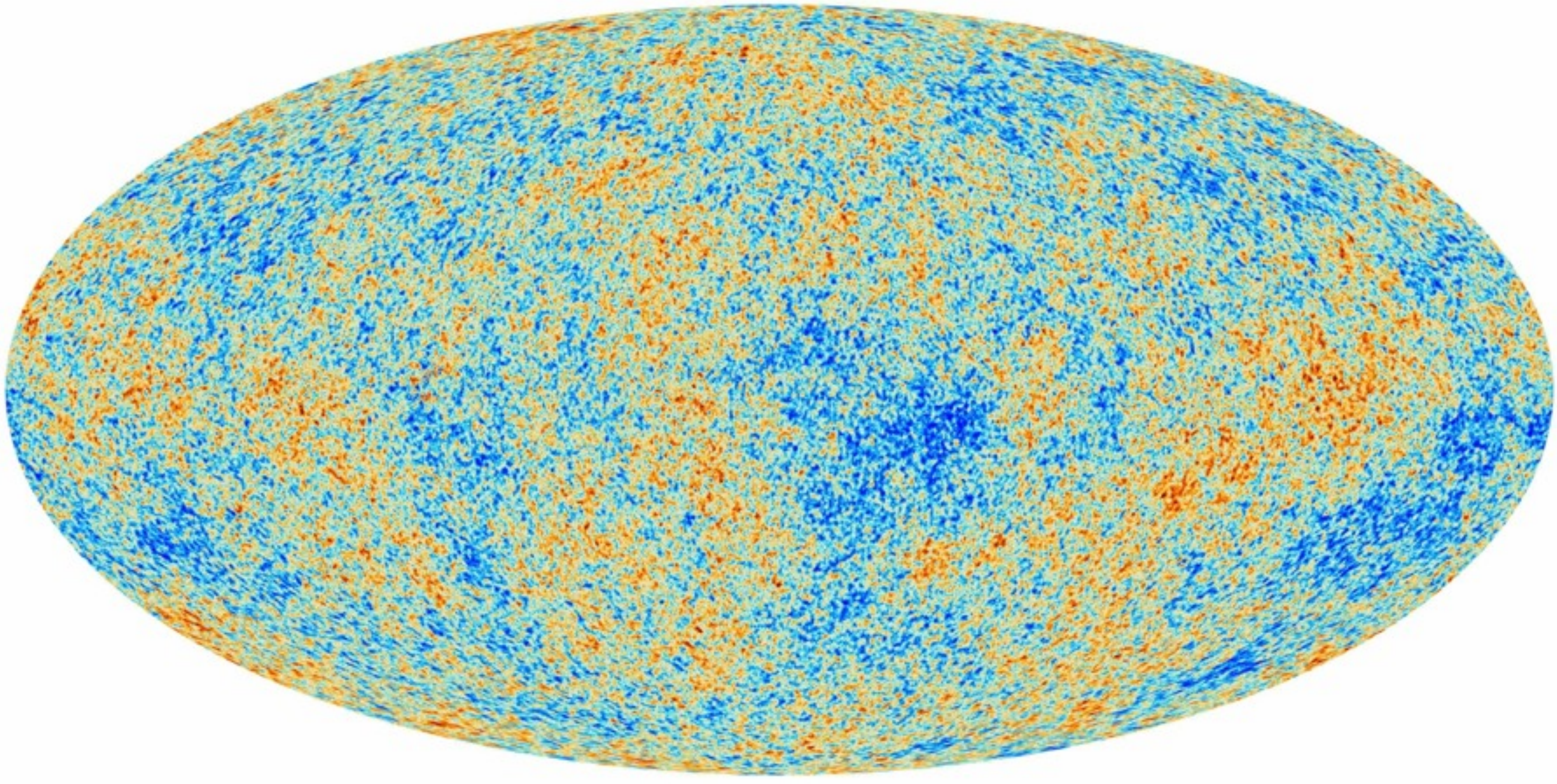
Planck concept





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 full-sky CMB map



- 3% sky fraction filled with Gaussian constrained realisations

Cosmic Microwave background

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

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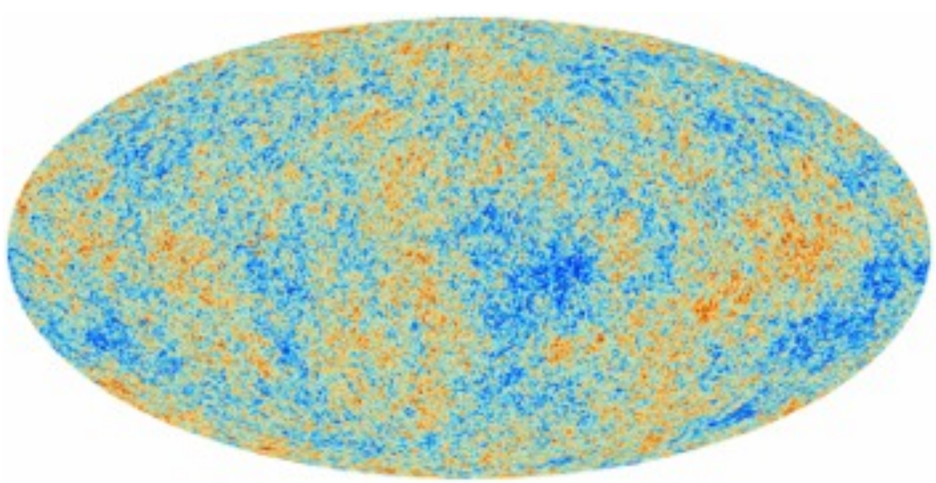
$T(\hat{\mathbf{n}})$



$T_{\ell m}$

```
-1.36393664e-06 +1.78900125e-07j,
 3.48160018e-07 +5.48607128e-07j,
 8.64414116e-07 +1.58062970e-06j,
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 5.05386856e-07 -2.28955226e-07j,
-2.60272490e-07 +2.21246718e-06j,
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 9.72080476e-07 -6.89214224e-07j,
 3.26351028e-07 +1.08530943e-06j,
 2.14977119e-06 -9.44341599e-07j,
```

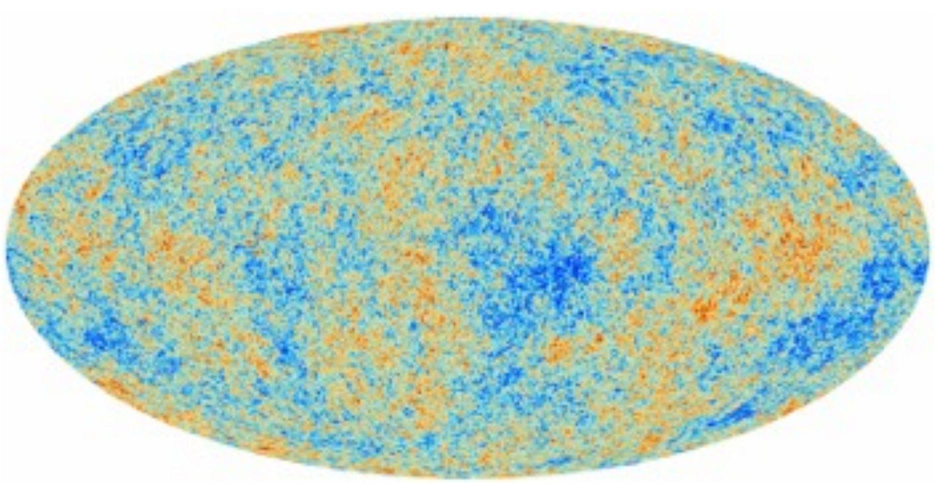
Cosmic Microwave background

- Decompose the temperature on the sphere $T(\hat{\mathbf{n}}) \longrightarrow T_{\ell m}$
- 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 $$\hat{C}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |T_{\ell m}|^2$$

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



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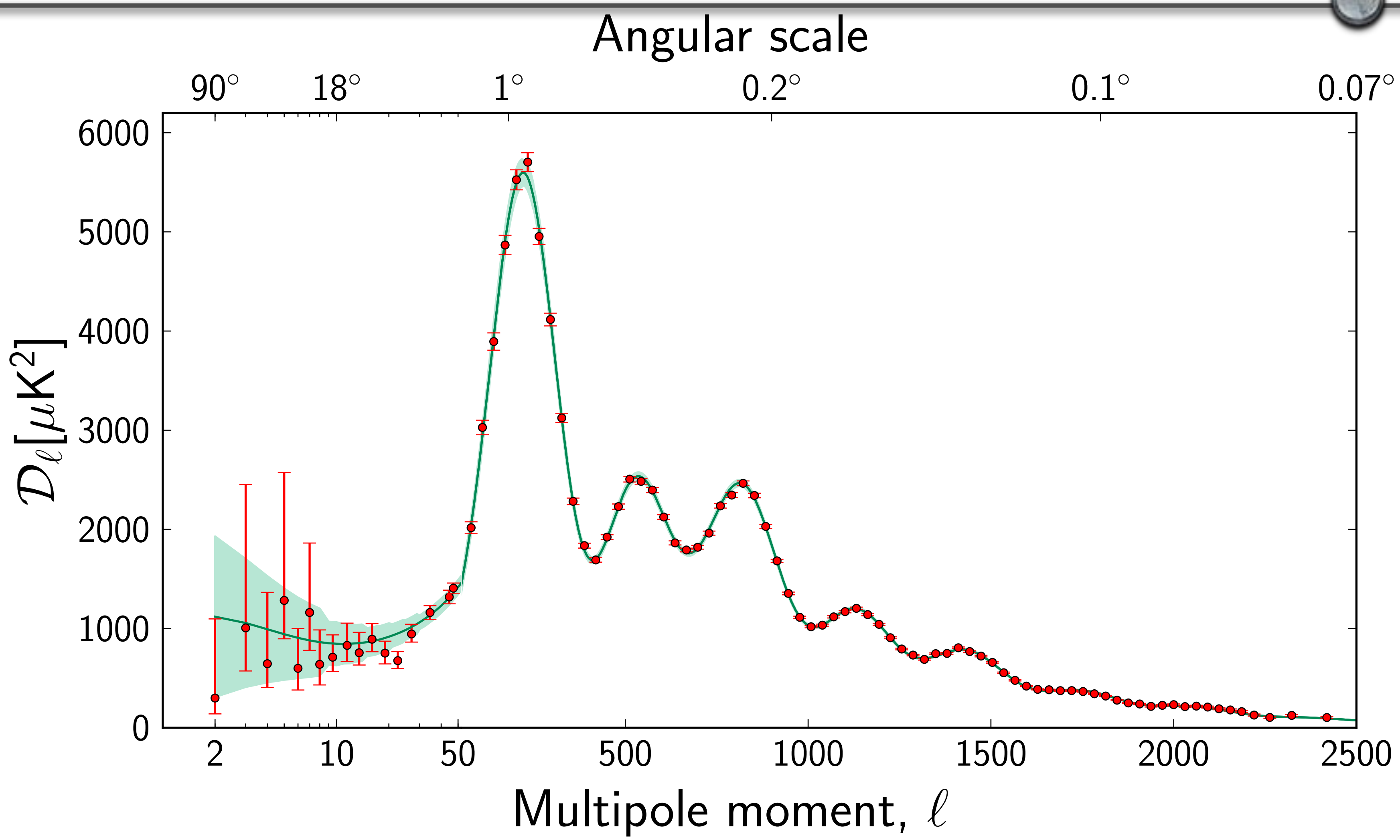

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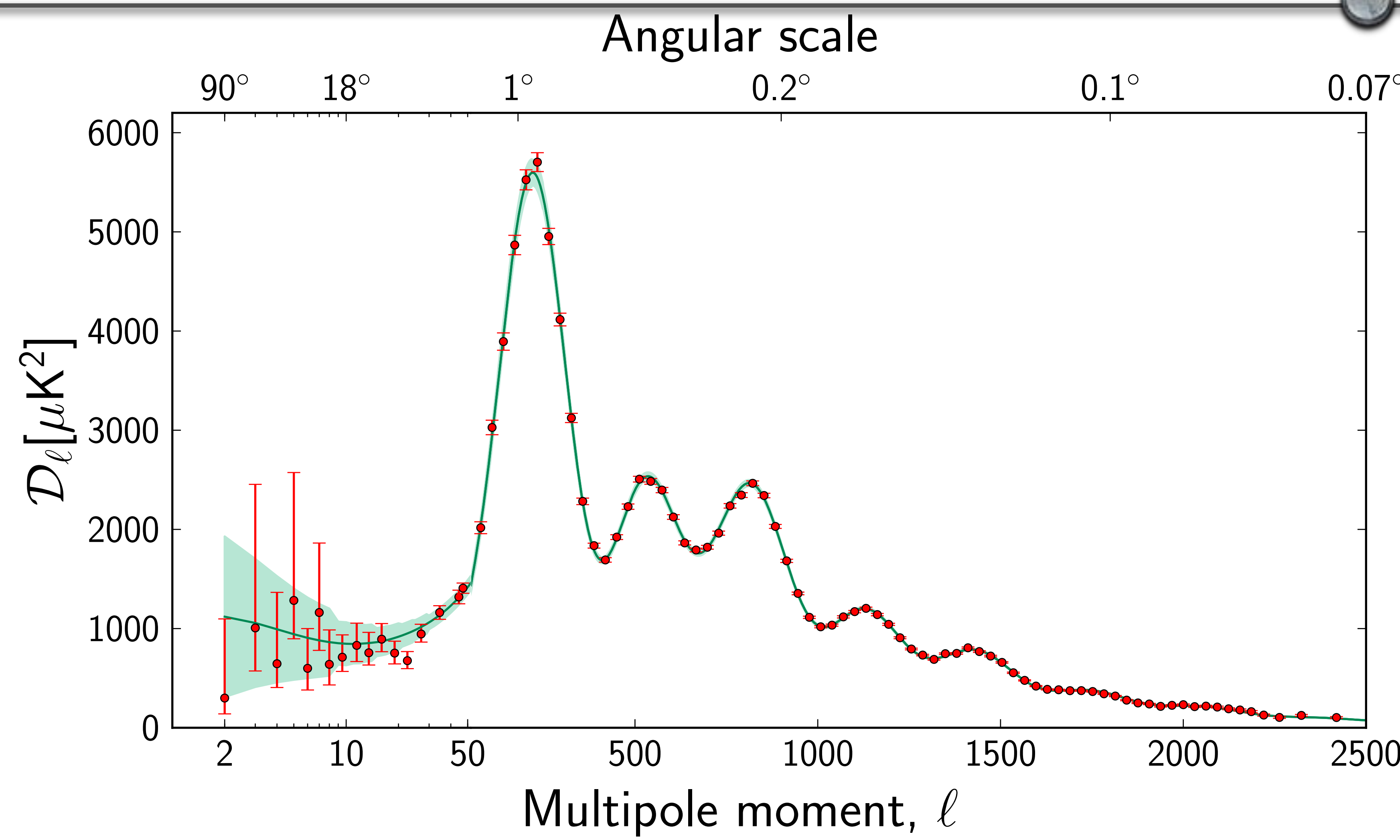
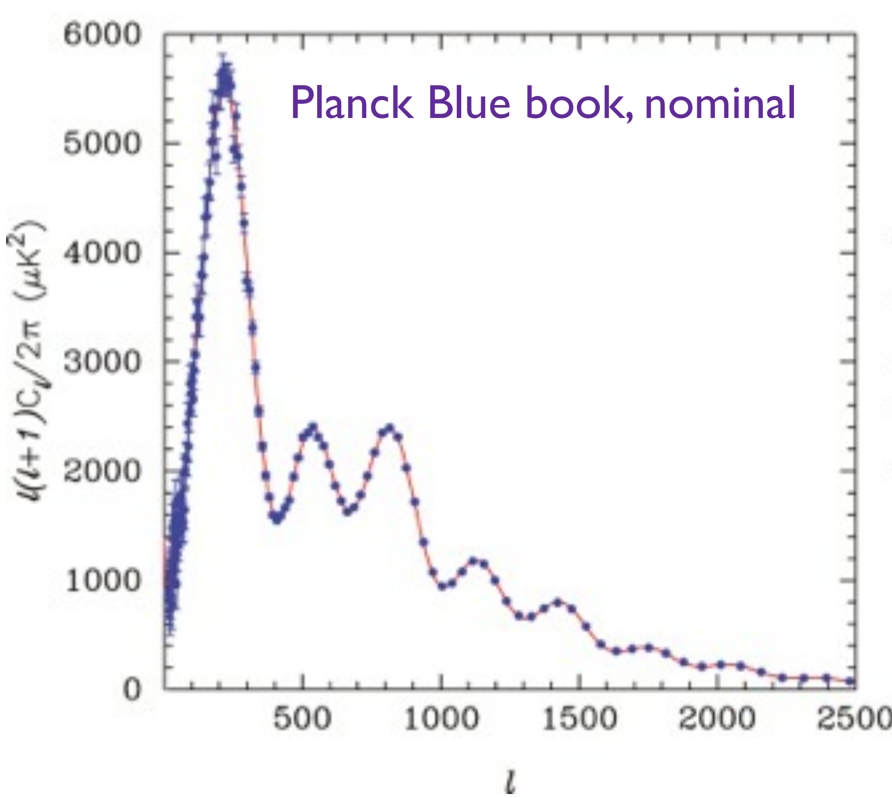
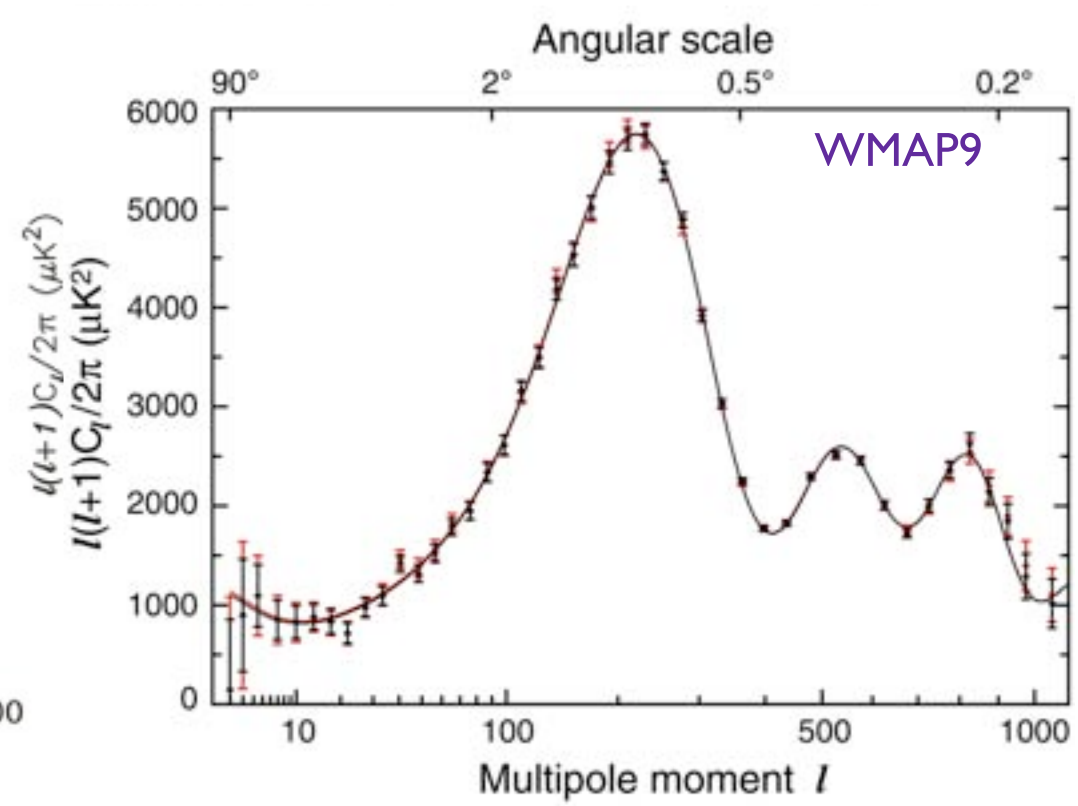
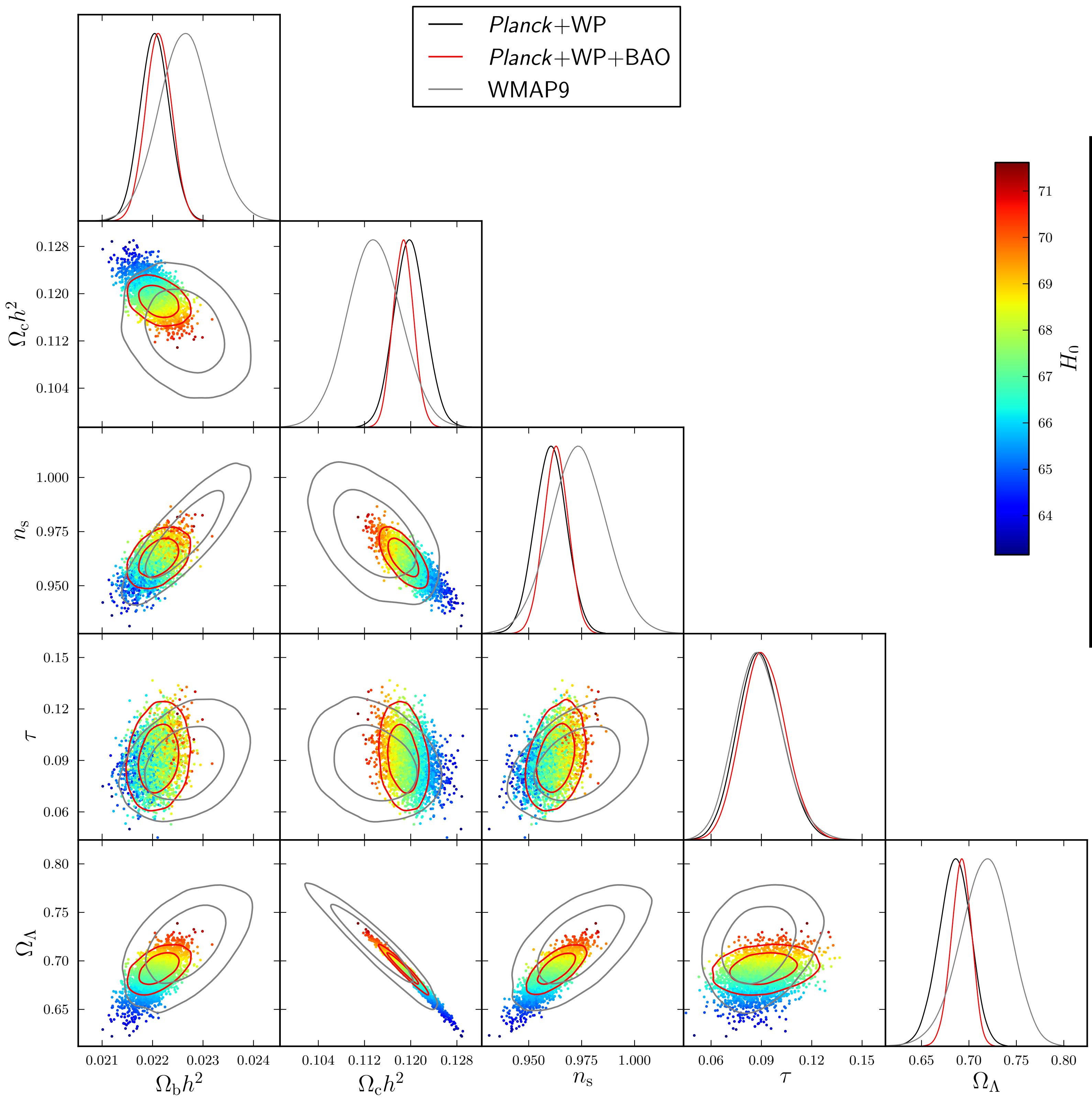






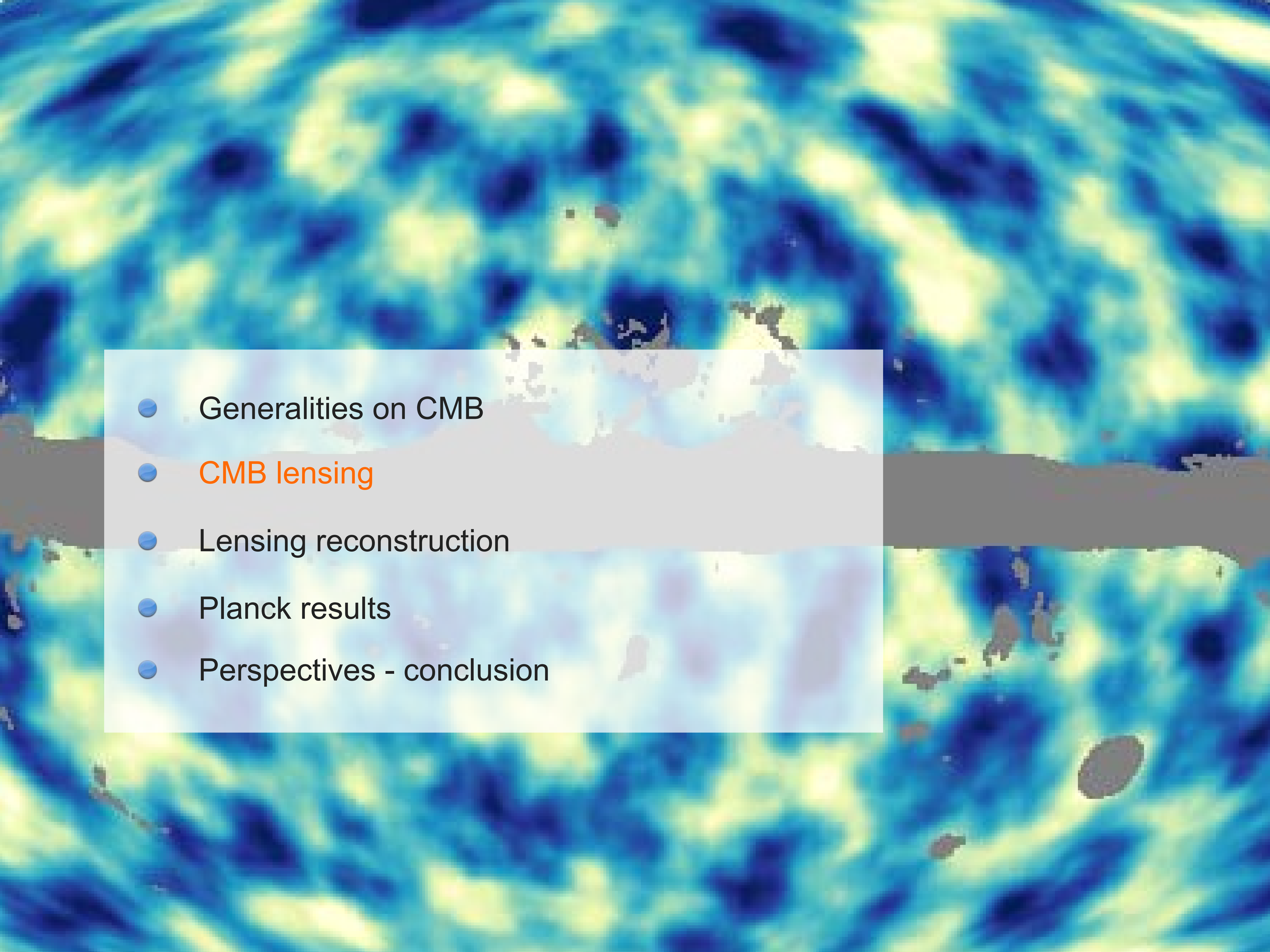
Planck cosmological parameters

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%



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Cosmic Microwave background

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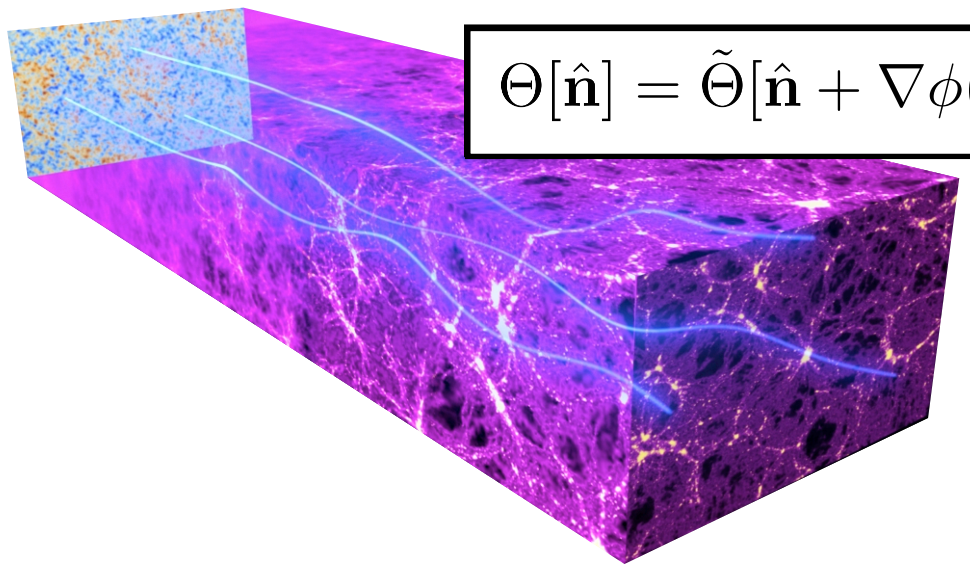
- CMB is (almost) Gaussian: all the information is in the variance $\langle t_{\ell m} t^*_{\ell' m'} \rangle = C_\ell$
  - Primordial non-Gaussianities, e.g f_{nl}
  - Gravitational lensing of the CMB
  - ...

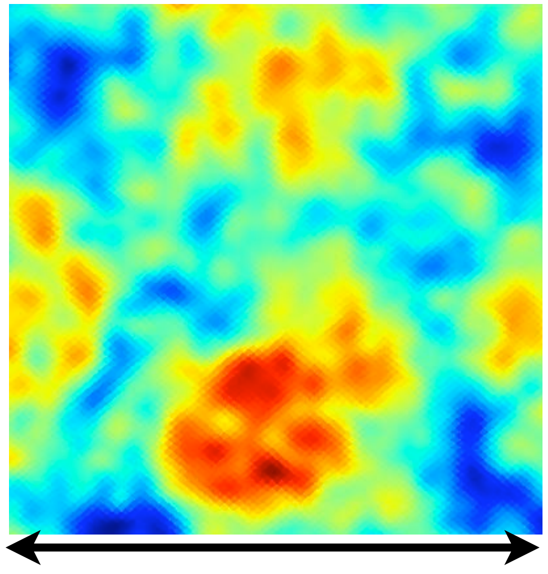
CMB lensing

- **Photons from last scattering surface deflected by gravitational potential of large-scale structure**



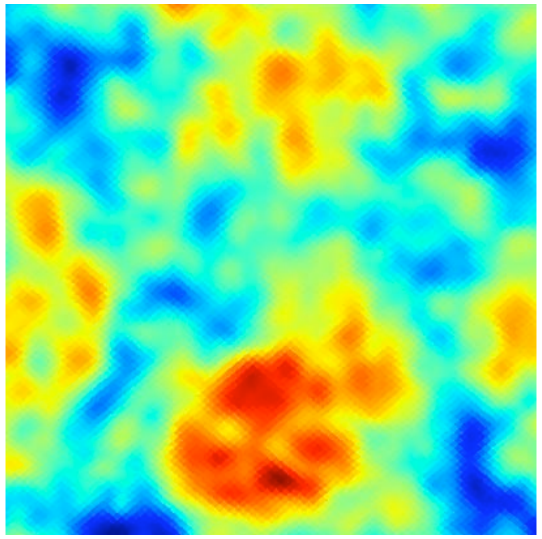
$$\Theta[\hat{\mathbf{n}}] = \tilde{\Theta}[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})]$$

Unlensed



2.5º

Lensed



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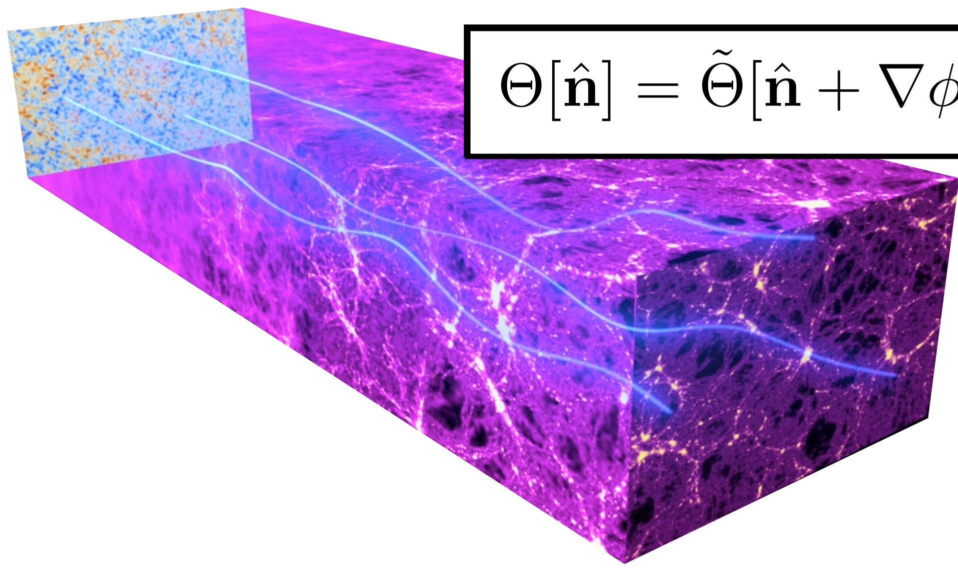

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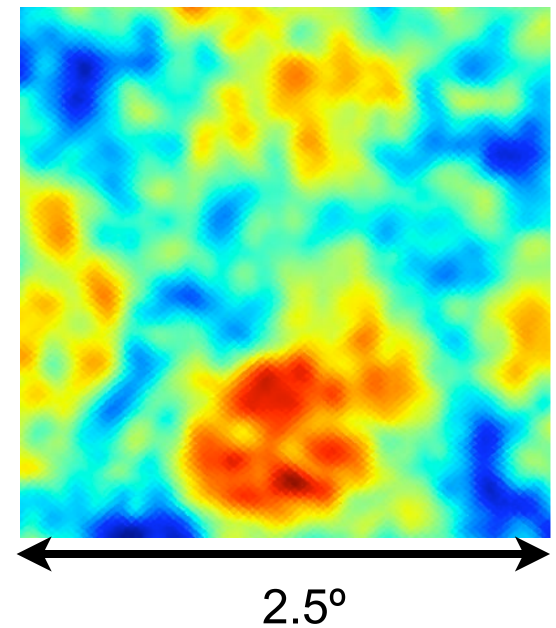
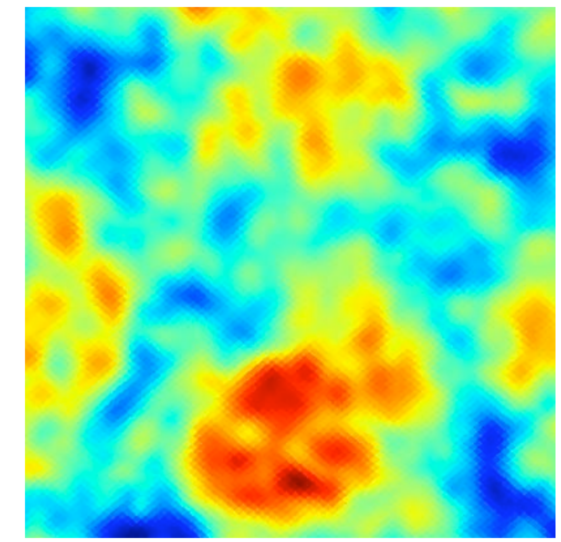


Lensed



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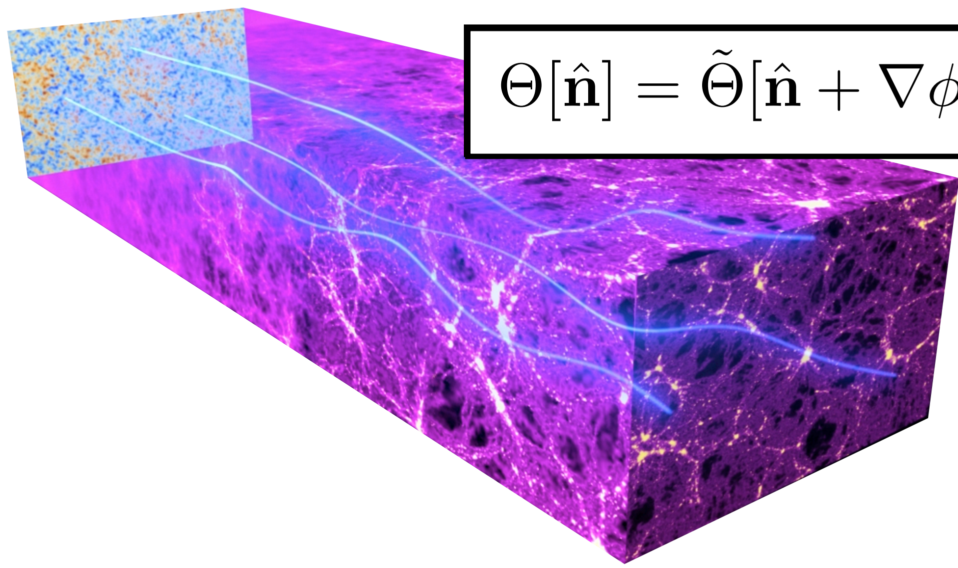

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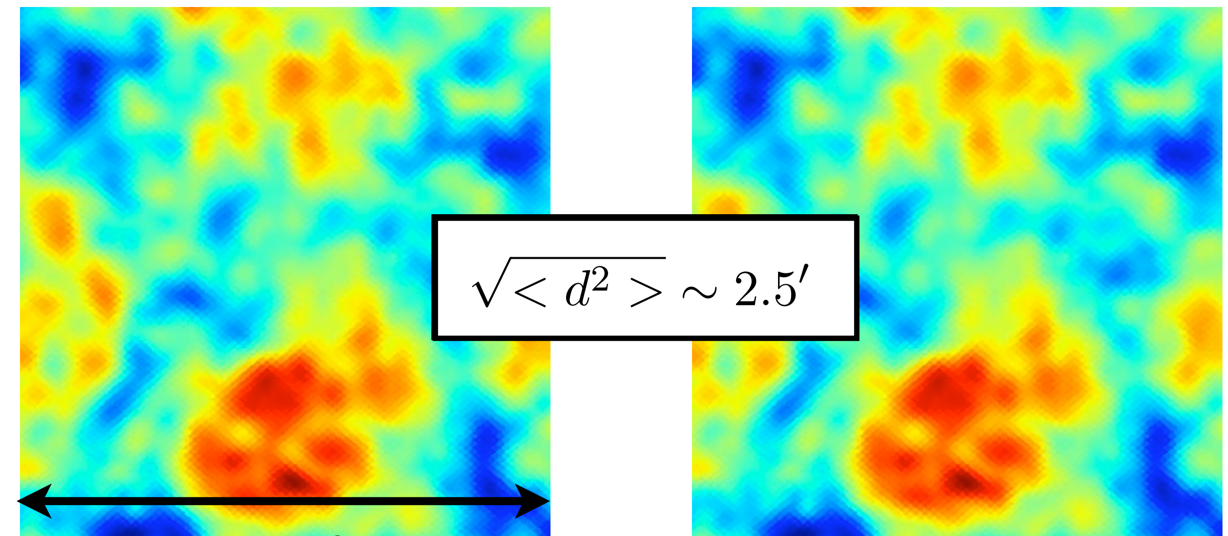

$$\sqrt{< d^2 >} \sim 2.5'$$

$$\phi(\widehat{\mathbf{n}}) = -2\int d\eta \frac{\chi(\eta - \eta_{\rm rec})}{\chi(\eta_{\rm rec})\chi(\eta)}\Psi(\chi\widehat{\mathbf{n}}, \eta)$$

- Typical deflections: ~2.5 arcmin
- Coherent on the degree scale
- Sources temperature-gradient correlation

Lensing potential reconstruction

Impact of CMB lensing

$$\Theta[\hat{\mathbf{n}}] = \tilde{\Theta}[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})] \longrightarrow \Theta(\hat{\mathbf{n}}) = \tilde{\Theta}(\hat{\mathbf{n}}) + \nabla_i\phi(\hat{\mathbf{n}})\nabla^i\tilde{\Theta}(\hat{\mathbf{n}}) + \cdots$$

Temperature and gradient become correlated

$$\langle t_{\ell m} t^*_{\ell' m'} \rangle_{|\mathrm{CMB}} = C_\ell + \sum_{\lambda\mu} F^{\ell\ell'\lambda}_{mm'\mu}\phi_{\lambda\mu}$$

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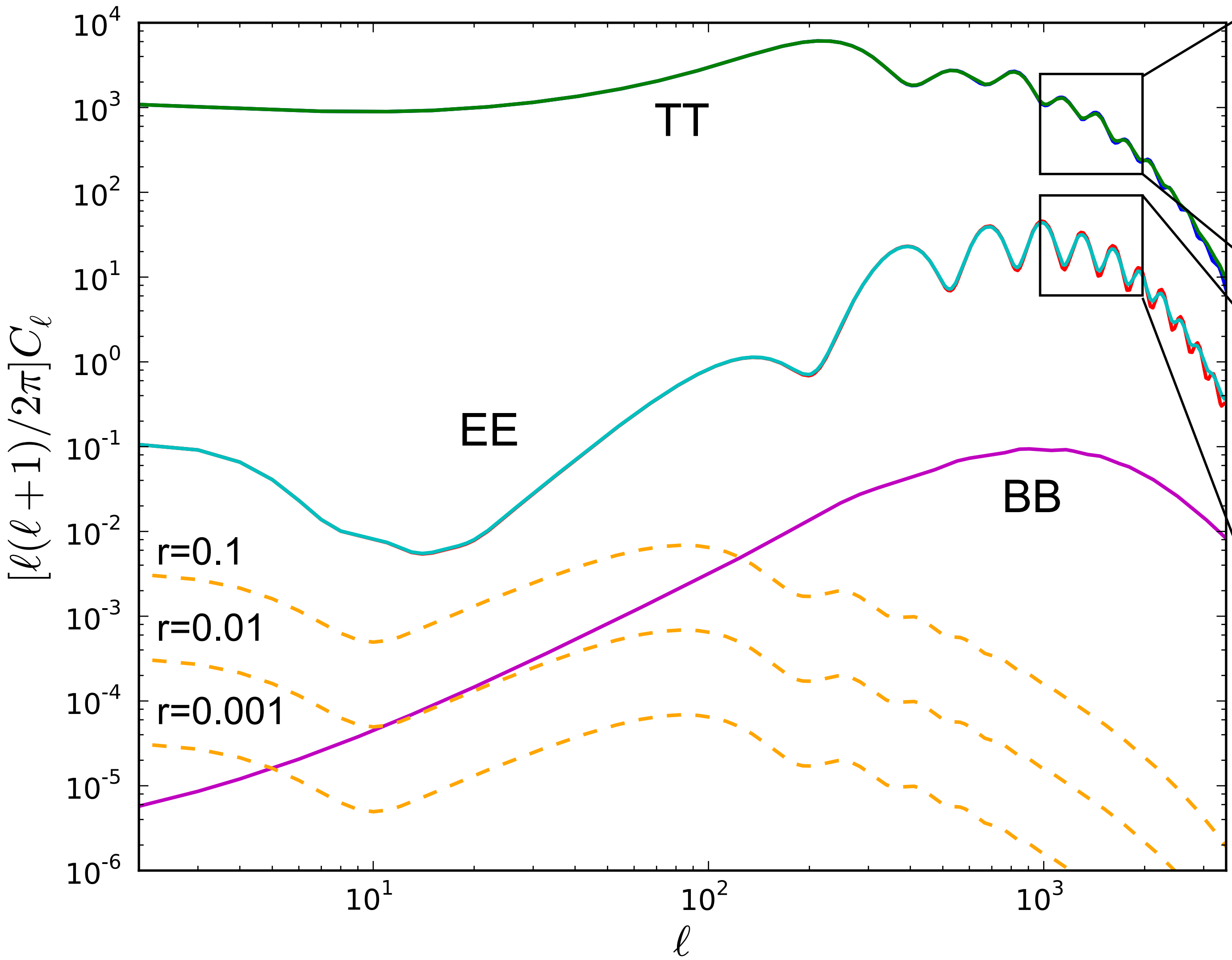
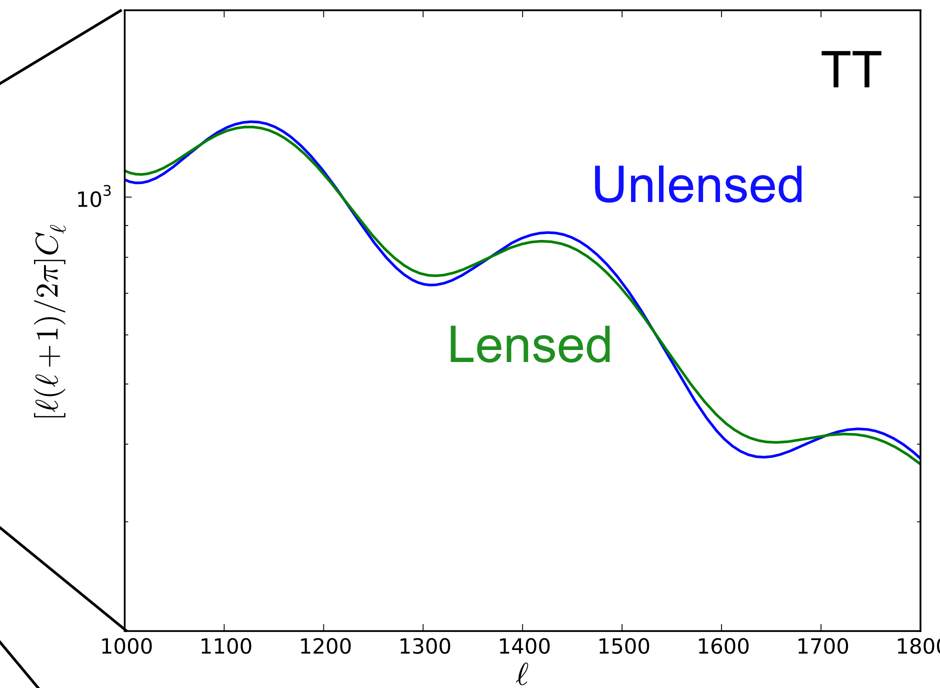
CMB lensing induces mode coupling

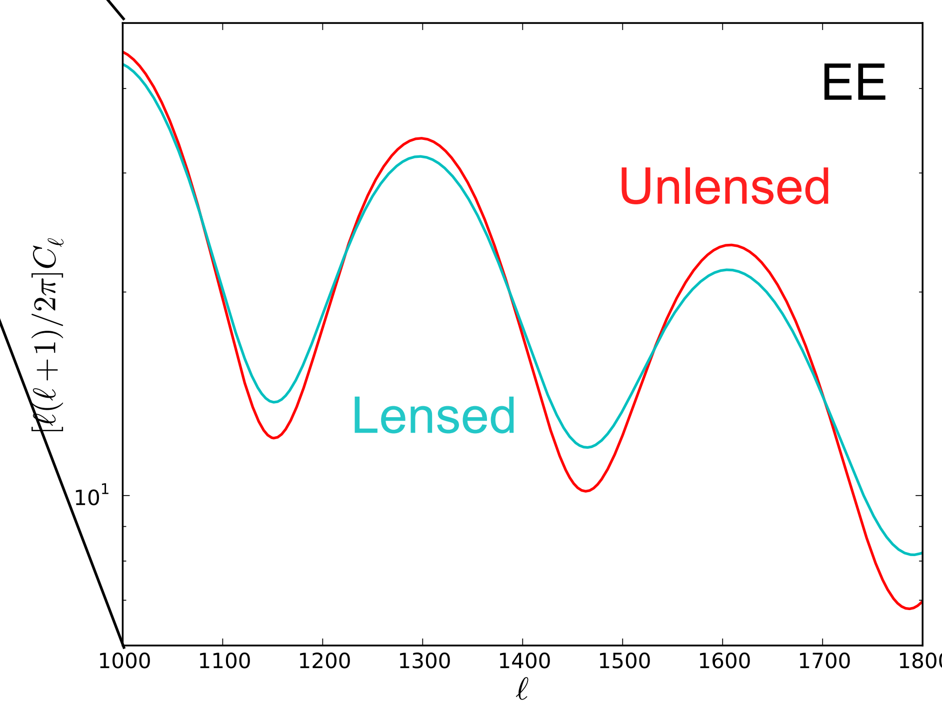
$$C_\ell \sim (1-\alpha_\ell)\tilde{C}_\ell + \sum_{\ell_1\ell_2} C^{\phi\phi}_{\ell_1}\tilde{C}_{\ell_2}F_{\ell\ell_1\ell_2}$$

- Modifies the shape of observed power spectra

Effect on power spectra







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- Modifies the shape of observed power spectra
- Creates non-Gaussian terms in the spectra covariance

ABL, Smith & Hu (*PRD, 2012*)

Lensing information is encoded in anisotropies spectra

Effect on power spectra covariance

- Unlensed CMB is Gaussian: modes are independant

$$\mathrm{cov}(\mathrm{C}_{\ell_1}^{\mathrm{XY}}, \mathrm{C}_{\ell_2}^{\mathrm{WZ}}) = \mathrm{cov}^{\mathrm{G}}(\mathrm{C}_{\ell_1}^{\mathrm{XY}}, \mathrm{C}_{\ell_2}^{\mathrm{WZ}})$$

$$\mathrm{Cov}_{\ell_1 \ell_2}^{XY,WZ} = \frac{1}{2\ell_1 + 1}[C_{\ell_1}^{XW} C_{\ell_1}^{YZ} + C_{\ell_1}^{XZ} C_{\ell_1}^{YW}]\delta_{\ell_1,\ell_2}$$

$$\mathrm{Cov}_{\ell_1 \ell_2}^{BB,BB} = \frac{2}{2\ell_1 + 1}\left(C_{\ell_1}^{BB}\right)^2 \delta_{\ell_1,\ell_2}$$

Effect on power spectra covariance

- Covariance induced by CMB lensing

$$\mathrm{cov}(\mathrm{C}_{\ell_1}^{\mathrm{XY}}, \mathrm{C}_{\ell_2}^{\mathrm{WZ}}) = \mathrm{cov}^{\mathrm{G}}(\mathrm{C}_{\ell_1}^{\mathrm{XY}}, \mathrm{C}_{\ell_2}^{\mathrm{WZ}}) + \mathrm{cov}^{\mathrm{NG}}(\mathrm{C}_{\ell_1}^{\mathrm{XY}}, \mathrm{C}_{\ell_2}^{\mathrm{WZ}})$$

$$\begin{aligned}\mathrm{Cov}_{\ell_1\ell_2}^{XY,WZ} &= \frac{1}{2\ell_1+1}[C_{\ell_1}^{XW}C_{\ell_1}^{YZ} + C_{\ell_1}^{XZ}C_{\ell_1}^{YW}]\delta_{\ell_1,\ell_2} \\ &+ \sum_\ell \left[\frac{\partial C_{\ell_1}^{XY}}{\partial C_\ell^{\phi\phi}} \mathrm{Cov}_{\ell\ell}^{\phi\phi,\phi\phi} \frac{\partial C_{\ell_2}^{WZ}}{\partial C_\ell^{\phi\phi}}\right]\end{aligned}$$

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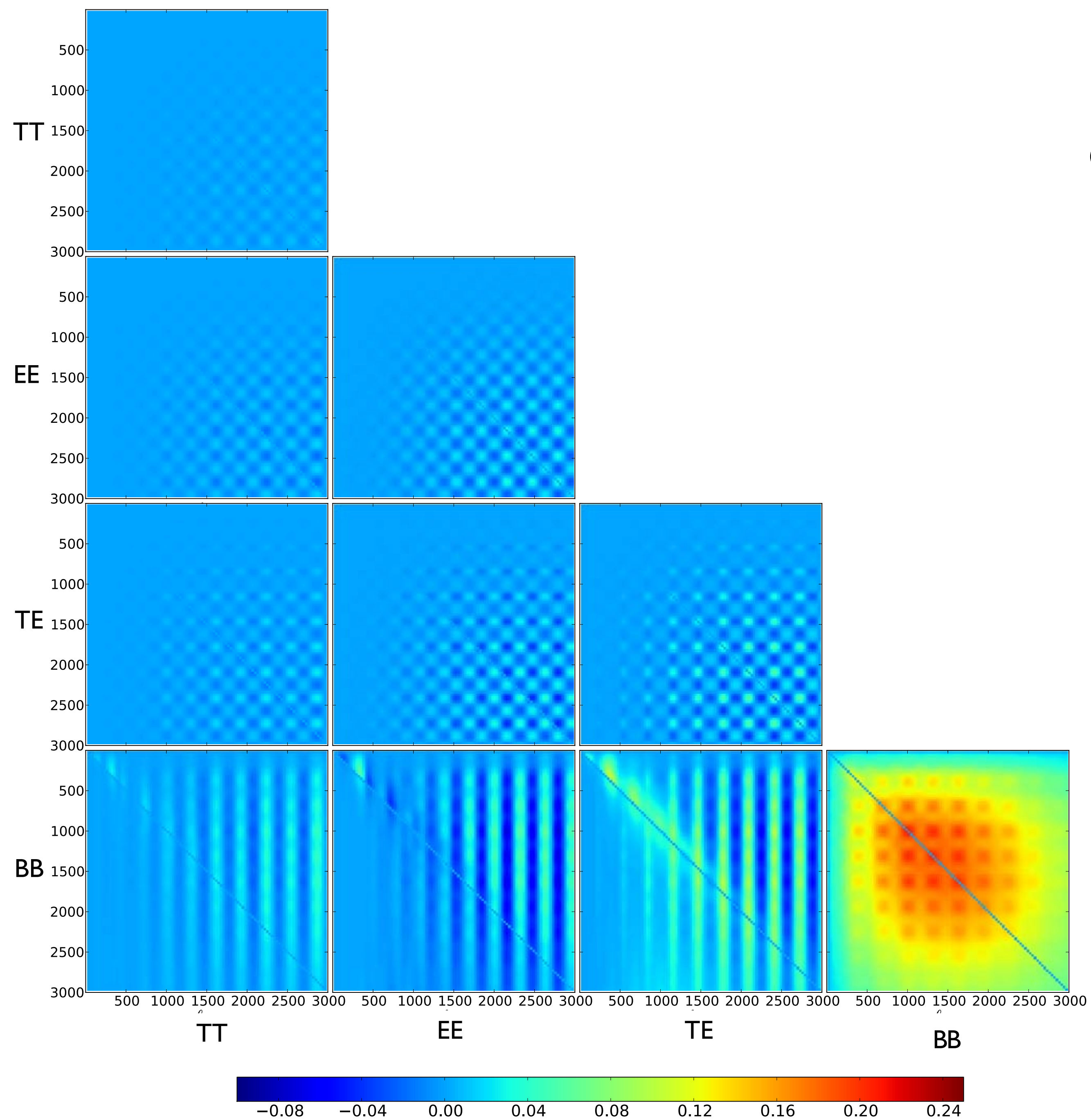


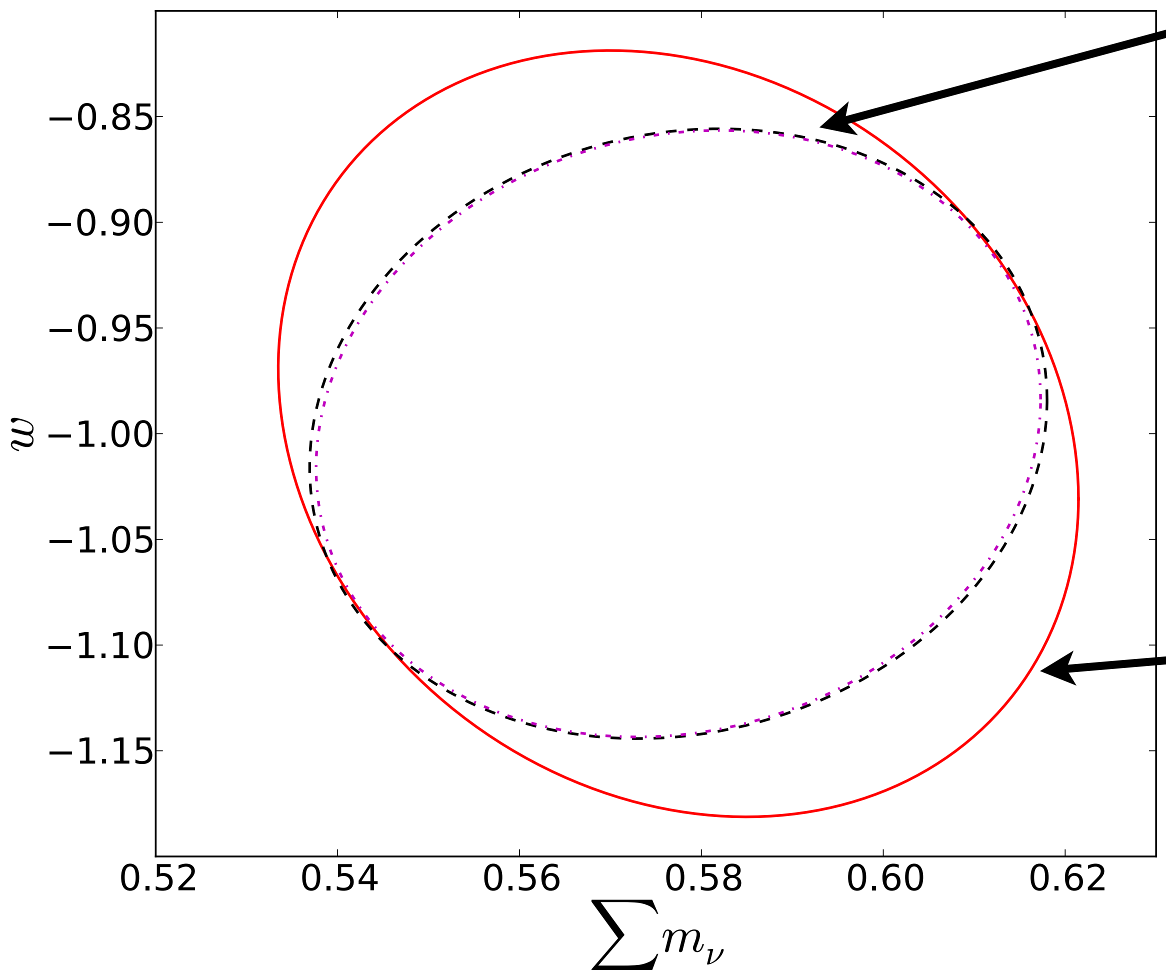
$$\mathrm{Cov}^{XY,WZ}_{\ell_1\ell_2} = \frac{1}{2\ell_1+1}[C^{XW}_{\ell_1}C^{YZ}_{\ell_1} + C^{XZ}_{\ell_1}C^{YW}_{\ell_1}]\delta_{\ell_1,\ell_2} + \sum_{\ell}\left[\frac{\partial C^{XY}_{\ell_1}}{\partial C^{\phi\phi}_{\ell}}\mathrm{Cov}^{\phi\phi,\phi\phi}_{\ell\ell}\frac{\partial C^{WZ}_{\ell_2}}{\partial C^{\phi\phi}_{\ell}}\right]$$

$$\mathrm{Cov}^{BB,BB}_{\ell_1\ell_2} = \frac{2}{2\ell_1+1}\left(C^{BB}_{\ell_1}\right)^2\delta_{\ell_1,\ell_2} + \sum_{\ell}\left(\frac{\partial C^{BB}_{\ell_1}}{\partial C^{\tilde{E}\tilde{E}}_{\ell}}\mathrm{Cov}^{\tilde{E}\tilde{E},\tilde{E}\tilde{E}}_{\ell\ell}\frac{\partial C^{BB}_{\ell_2}}{\partial C^{\tilde{E}\tilde{E}}_{\ell}}\right) + \sum_{\ell}\left(\frac{\partial C^{BB}_{\ell_1}}{\partial C^{\phi\phi}_{\ell}}\mathrm{Cov}^{\phi\phi,\phi\phi}_{\ell\ell}\frac{\partial C^{BB}_{\ell_2}}{\partial C^{\phi\phi}_{\ell}}\right)$$

ABL, Smith & Hu (*PRD, 2012*)

Effect on power spectra covariance

CMBPol noise levels



Gaussian power spectrum covariance

Full non-Gaussian power spectrum covariance

ABL, Smith & Hu (*PRD, 2012*)

Significant effect for a post-Planck experiment

Impact of CMB lensing

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«Statistical inversion»

$$\langle \Theta \nabla \Theta \rangle \Rightarrow \phi$$

- Allows the reconstruction of the lensing potential and its power spectrum

Reconstruction provides direct measurement of the lensing potential

- Generalities on CMB
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Lensing reconstruction

- **Optimal quadratic estimator** Okamoto & Hu (2003)

$$\hat{\phi}_L^M \propto A_L \sum_{l_1 m_1} \sum_{l_2 m_2} (-1)^M \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \frac{(\tilde{C}_{\ell_2} F_{\ell_1 L \ell 2} + \tilde{C}_{\ell_1} F_{\ell_2 L \ell_1})^2}{2 C^{\rm tot}_{\ell_1} C^{\rm tot}_{\ell_2}} \Theta^{l_1}_{m_1} \Theta^{l_2}_{m_2}$$

Harmonic space

$$\hat{\phi}_L^M \propto A_L \int d\hat{\mathbf{n}} Y_L^{M*} \left(\sum_{\ell_1 m_1} \frac{1}{C^{\rm tot}_{\ell_1}} \Theta^{m_1}_{\ell_1} Y^{m_1}_{\ell_1} \right) \nabla \left(\sum_{\ell_2 m_2} \frac{\tilde{C}_{\ell_2}}{C^{\rm tot}_{\ell_2}} \Theta^{m_2}_{\ell_2} Y^{m_2}_{\ell_2} \right)$$

Real space

Lensing reconstruction

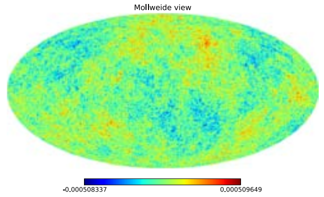
- **Optimal quadratic estimator** Okamoto & Hu (2003)

$$\hat{\phi}_L^M \propto A_L \sum_{l_1 m_1} \sum_{l_2 m_2} (-1)^M \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \frac{(\tilde{C}_{\ell_2} F_{\ell_1 L \ell 2} + \tilde{C}_{\ell_1} F_{\ell_2 L \ell_1})^2}{2 C_{\ell_1}^{\rm tot} C_{\ell_2}^{\rm tot}} \Theta_{m_1}^{l_1} \Theta_{m_2}^{l_2}$$

Harmonic space

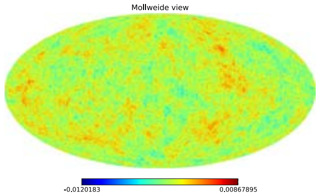
$$\hat{\phi}_L^M \propto A_L \int d\hat{\mathbf{n}} Y_L^{M*} \left(\sum_{\ell_1 m_1} \frac{1}{C_{\ell_1}^{\rm tot}} \Theta_{\ell_1}^{m_1} Y_{\ell_1}^{m_1} \right) \nabla \left(\sum_{\ell_2 m_2} \frac{\tilde{C}_{\ell_2}}{C_{\ell_2}^{\rm tot}} \Theta_{\ell_2}^{m_2} Y_{\ell_2}^{m_2} \right)$$

Real space



- Consider the observed map
- Two different filters
- Take the gradient of the second filtered map
- Multiply the two
- Extract the gradient component

Here is the lensing field !



Lensing reconstruction

$$\mathbf{d} = \nabla\phi + \nabla\times\psi$$

Gradient of the lensing potential

Curl component ***null*** for lensing

- **Mean of the estimator**

$$\langle\hat{\phi}^g_{lm}\rangle|_{\rm lens} = A_l\,\phi_{lm} + \delta_{l0}X \qquad \langle\hat{\phi}^c_{lm}\rangle|_{\rm lens} = 0$$

- **Covariance of the estimator**

$$\langle\hat{\phi}_{lm}\hat{\phi}^*_{lm}\rangle = A_l^2\sum_{\ell_i m_i}\begin{pmatrix}\ell_1 & \ell_2 & l\\ m_1 & m_2 & -m\end{pmatrix}\begin{pmatrix}\ell_3 & \ell_4 & l\\ m_3 & m_4 & -m\end{pmatrix} g_{\ell_1\ell_2}(l)g_{\ell_3\ell_4}(l)\langle\Theta^{m_1}_{\ell_1}\Theta^{m_2}_{\ell_2}\Theta^{m_3}_{\ell_3}\Theta^{m_4}_{\ell_4}\rangle$$

Summation of the trispectrum (4-points correlation function)

$$\langle\hat{\phi}^M_L\hat{\phi}^{M*}_L\rangle^G = C^{\phi\phi}_L + N^{(0,G)}_L + N^{(1,G)}_L + N^{(2,G)}_L + \cdots$$

Gaussian noise

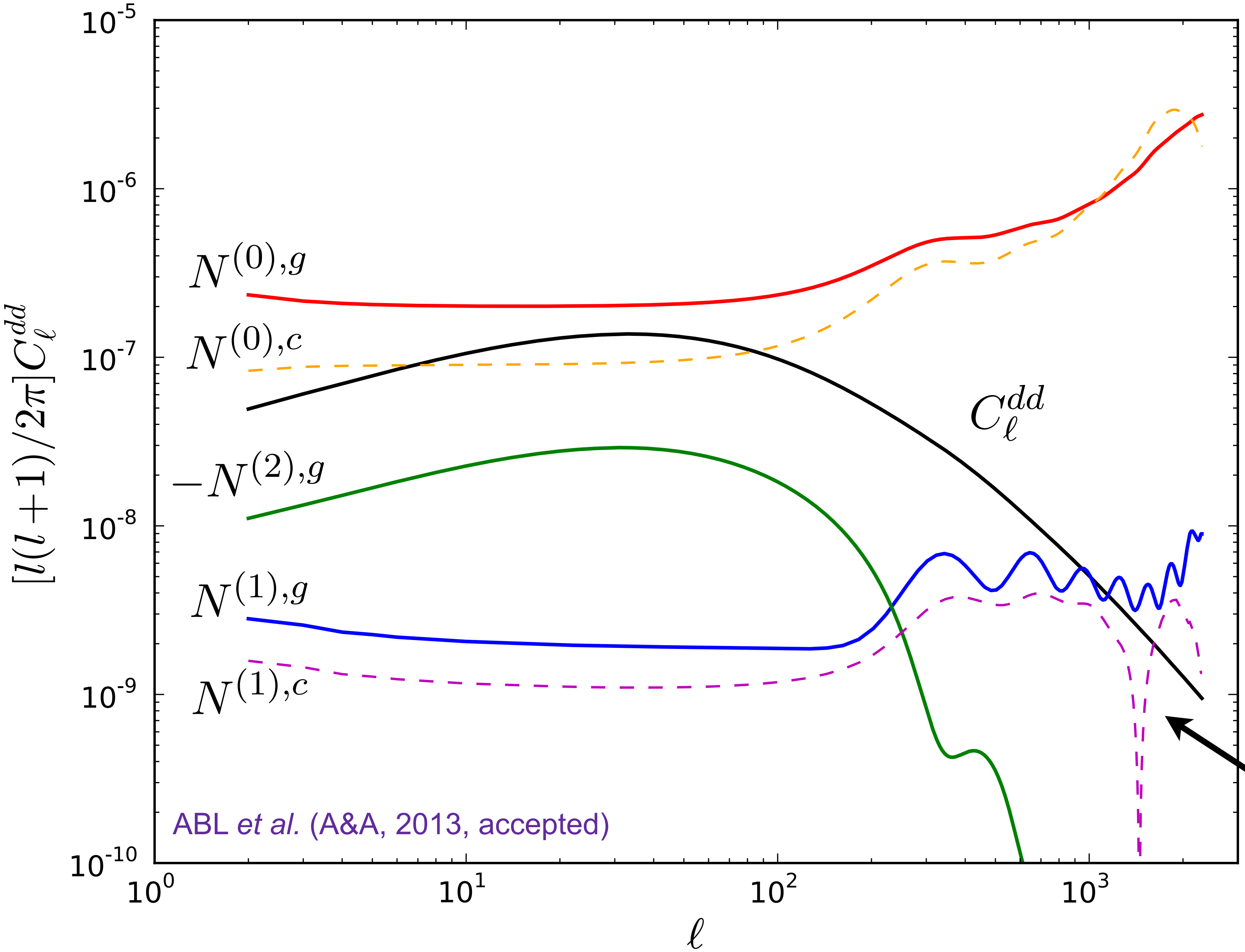
high order biases

$$\langle\hat{\phi}^M_L\hat{\phi}^{M*}_L\rangle^C = N^{(0,C)}_L + N^{(1,C)}_L + \cdots$$

Kesden *et al.* (2003), Hanson *et al.* (2011), ABL *et al.* (A&A, 2013, accepted)

Lensing potential and biases

$$\langle \hat{\phi}_L^M \hat{\phi}_L^{M*} \rangle^G = C_L^{\phi\phi} + N_L^{(0,G)} + N_L^{(1,G)} + N_L^{(2,G)} + \cdots$$



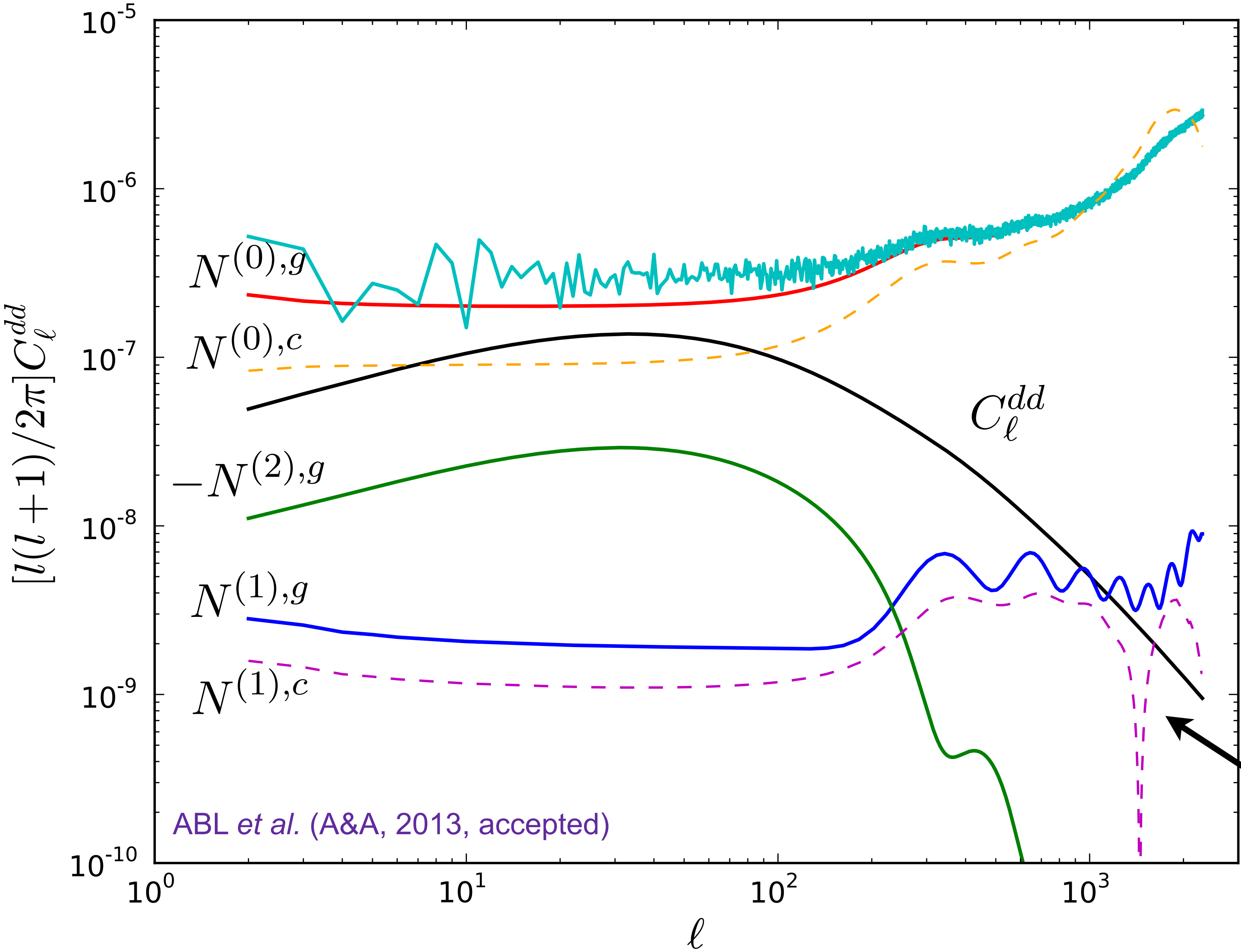
Planck-like specifications

- noise: 50 μK. arcmin
- beam: 5 arcmin
- l_{max} = 2300

$N^{(1)}$ term of the curl component

Lensing potential and biases

$$\langle \hat{\phi}_L^M \hat{\phi}_L^{M*} \rangle^G = C_L^{\phi\phi} + N_L^{(0,G)} + N_L^{(1,G)} + N_L^{(2,G)} + \cdots$$

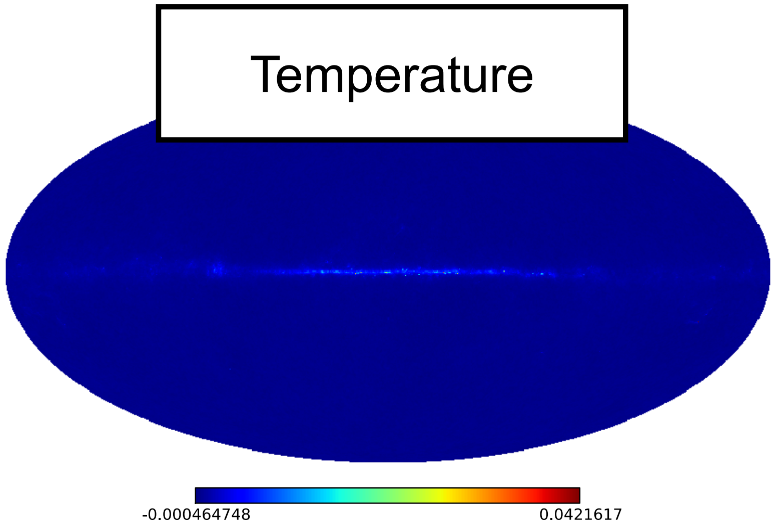


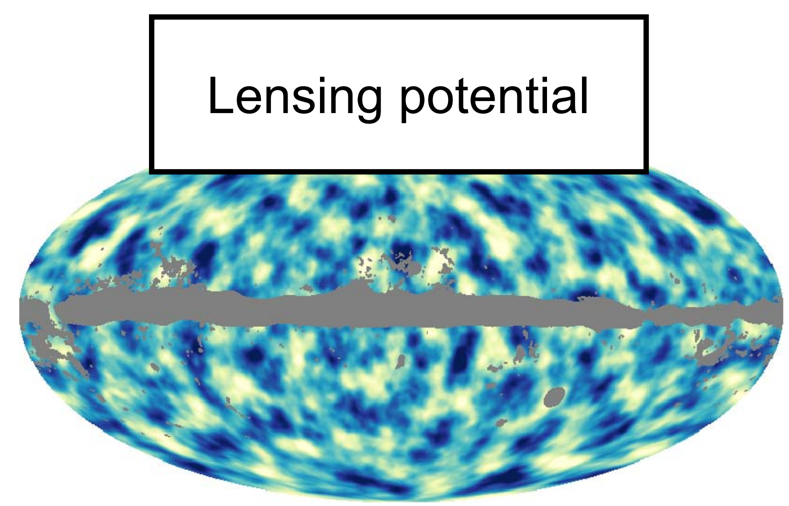
Planck-like specifications

- noise: 50 μK. arcmin
- beam: 5 arcmin
- l_{max} = 2300

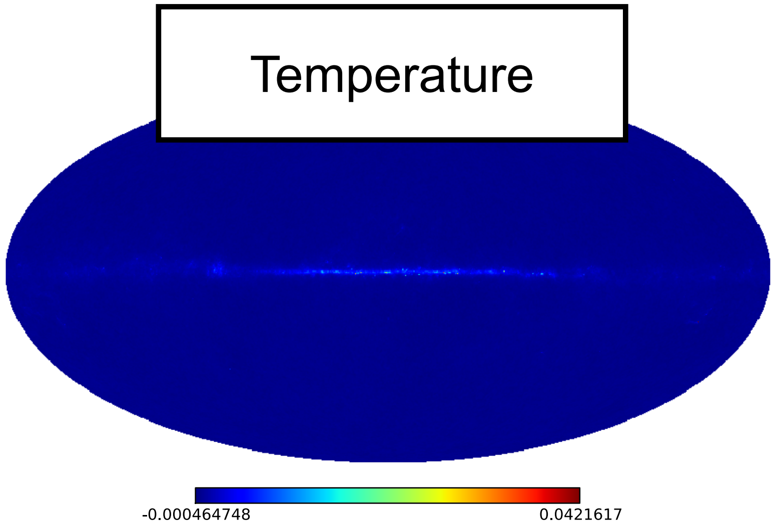
$N^{(1)}$ term of the curl component

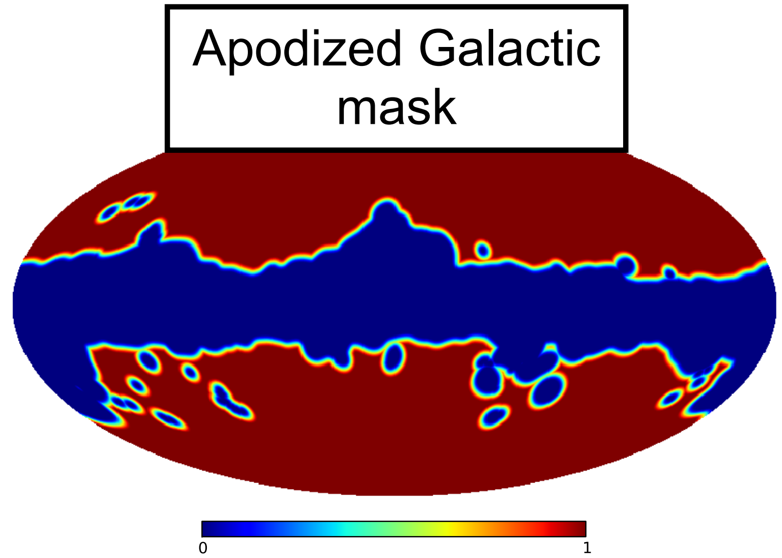
CMB lensing reconstruction with masks

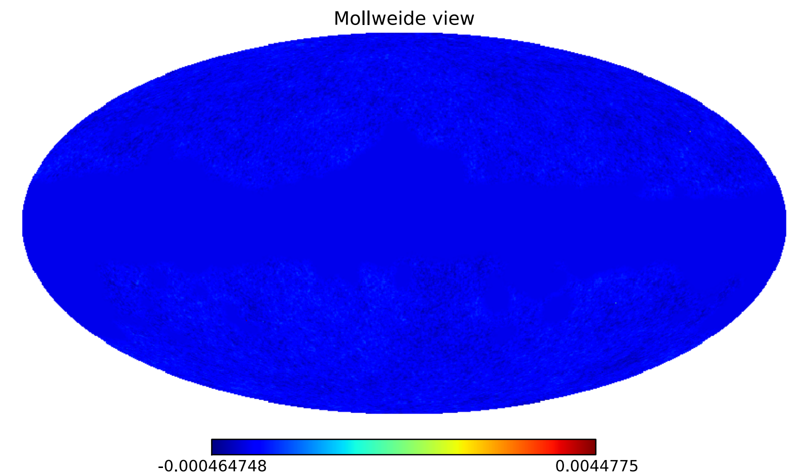




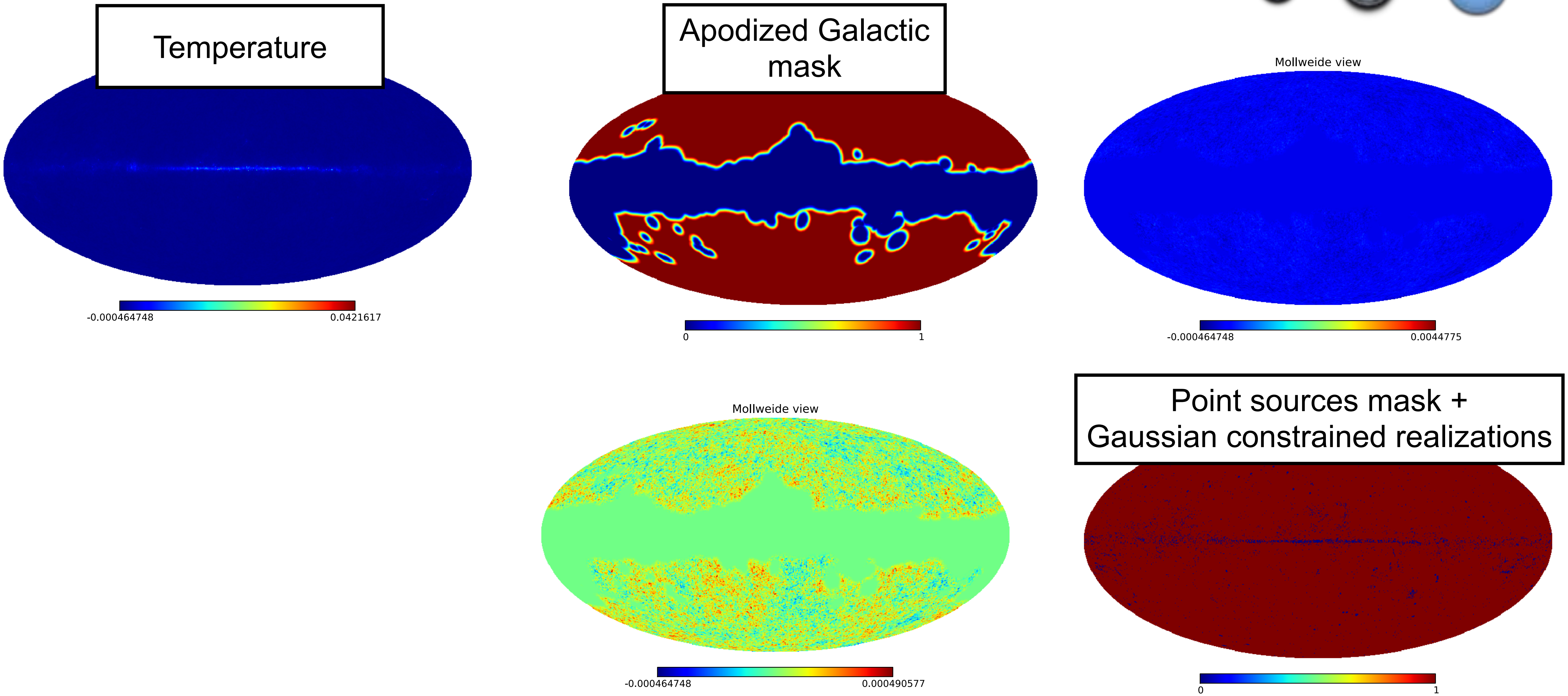
CMB lensing reconstruction



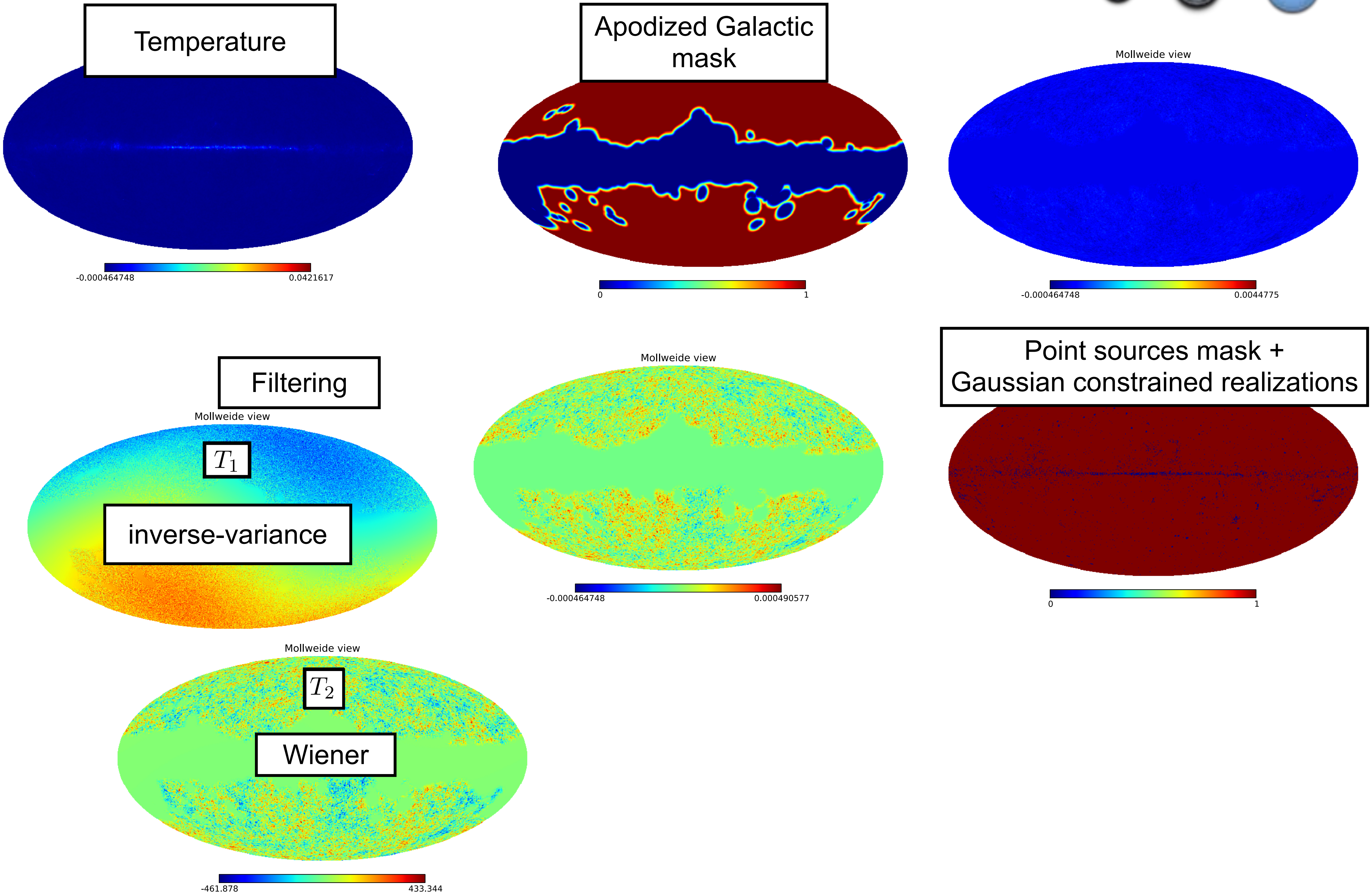




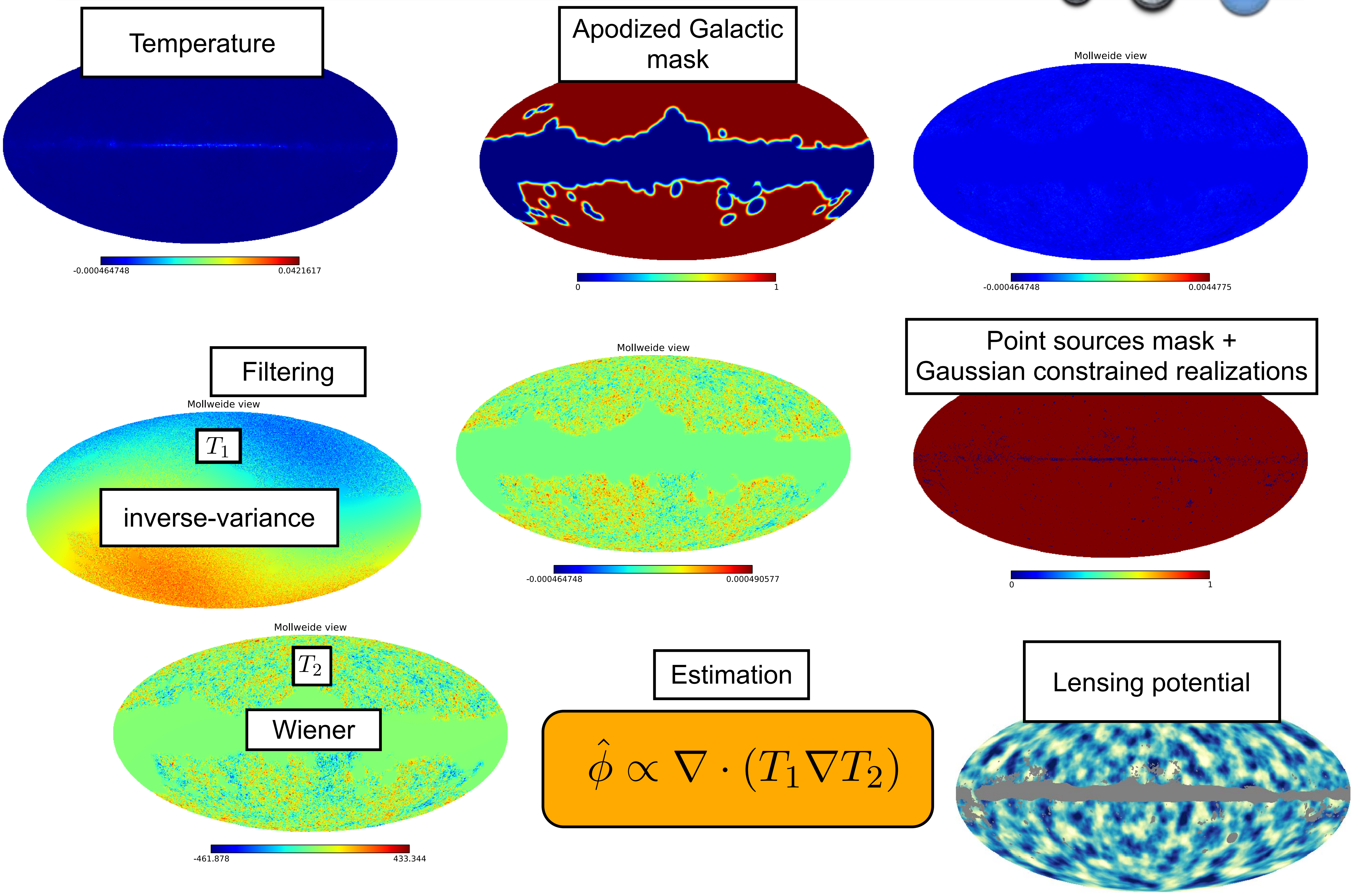
CMB lensing reconstruction



CMB lensing reconstruction

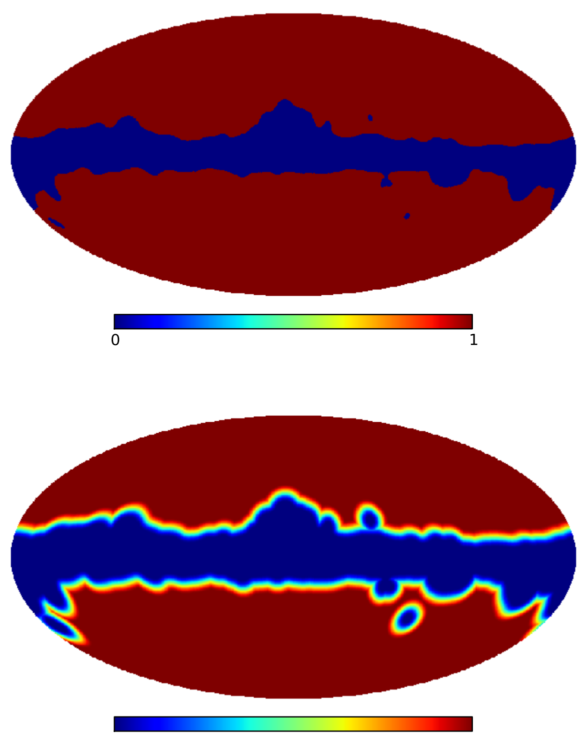


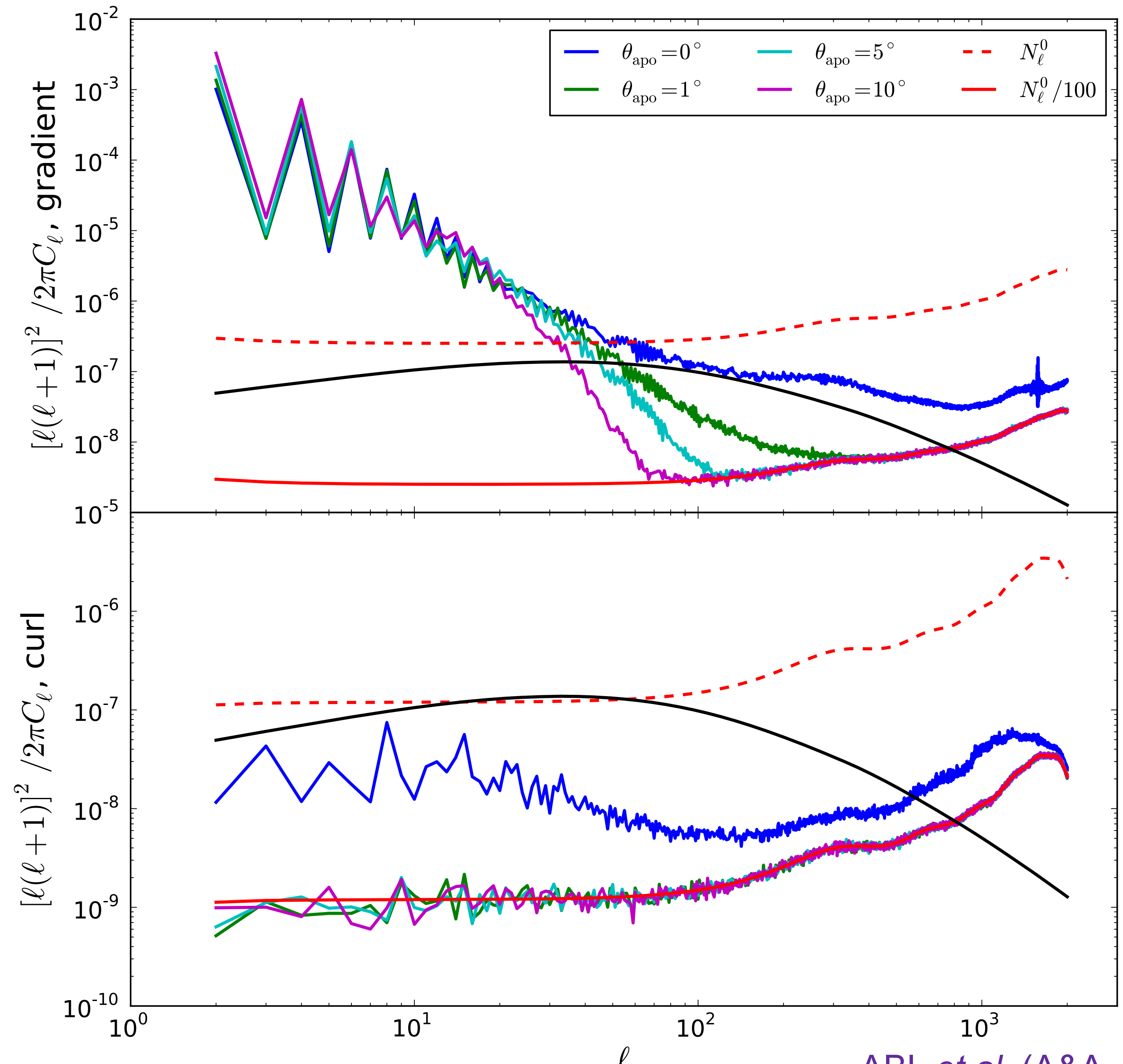
CMB lensing reconstruction



Treatment of masks

- **Galaxy**
  - Mask creates a bias in the estimator: mask mean field
  - Apodized mask
  - Apodization reduces mode couplings
  - Mean-field can be efficiently substracted

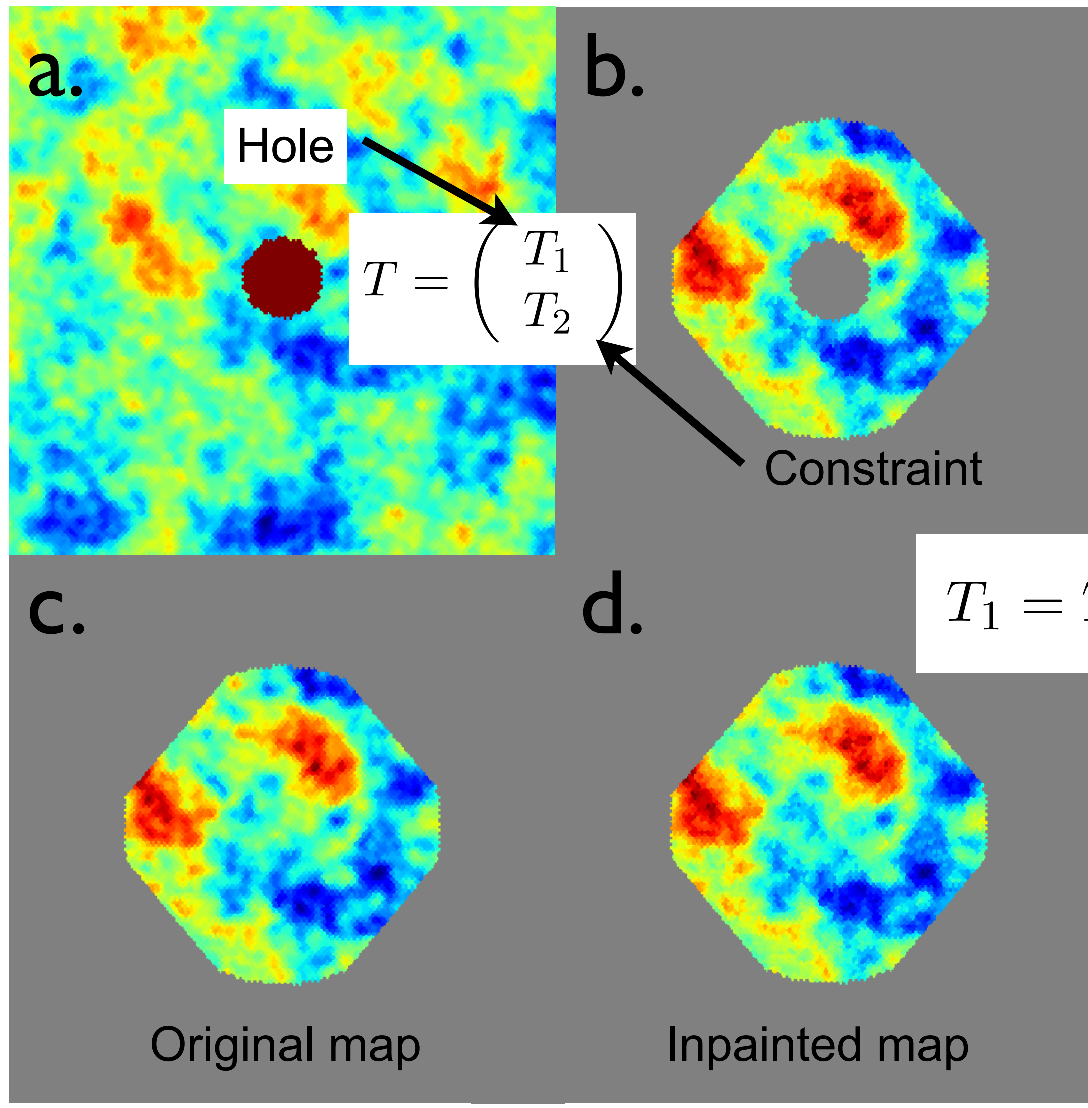




ABL *et al.* (A&A, 2013, accepted)

Treatment of masks

Point source inpainting



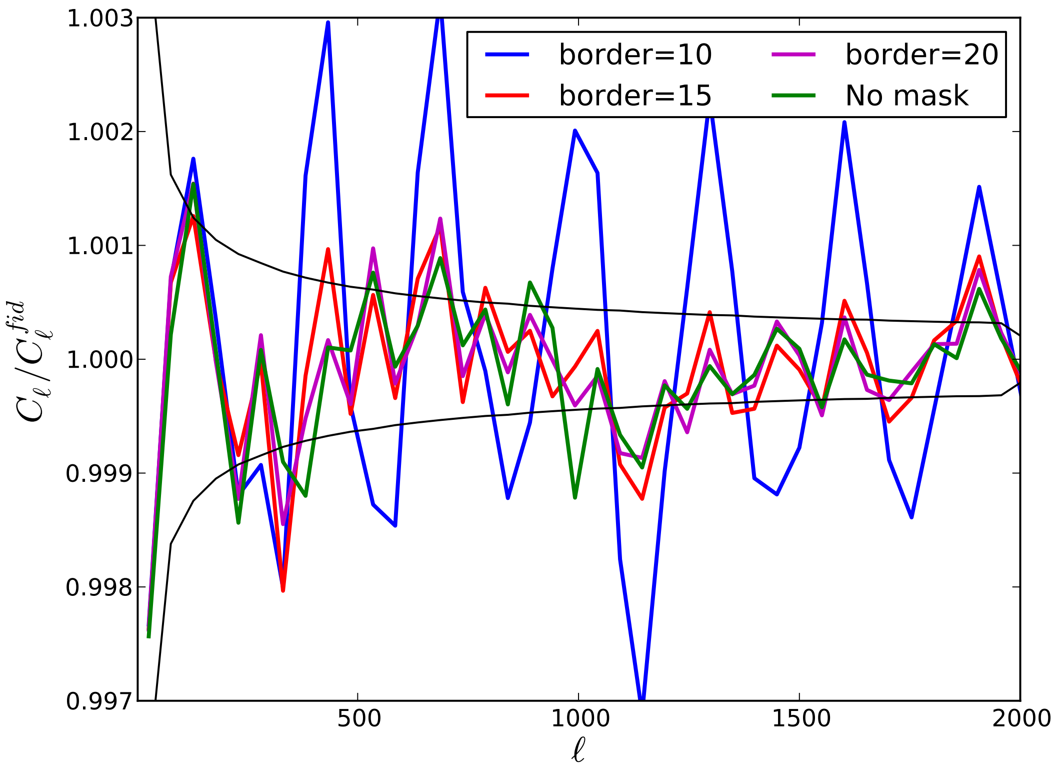
$$T_1 = \tilde{T}_1 + C_{12} C_{22}^{-1} (T_2 - \tilde{T}_2)$$

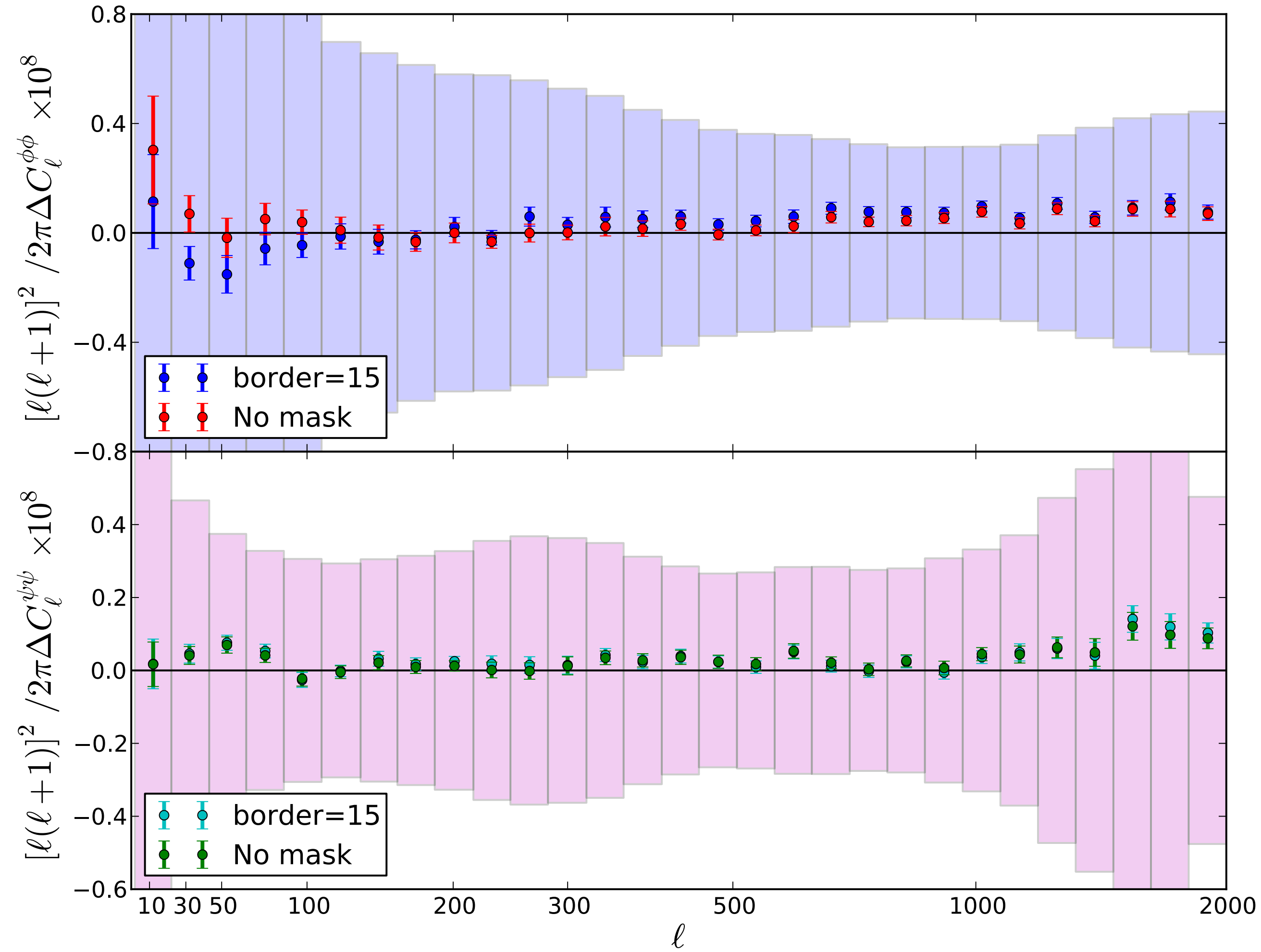
ABL *et al.* (A&A, 2013, accepted)

Treatment of masks

Point sources

- Fill in missing data with realistic simulated data
- Neighboring pixels used to generate constrained Gaussian realizations
- Two-point statistic is restored (i.e. power spectrum)
- Creates no bias in lensing estimator

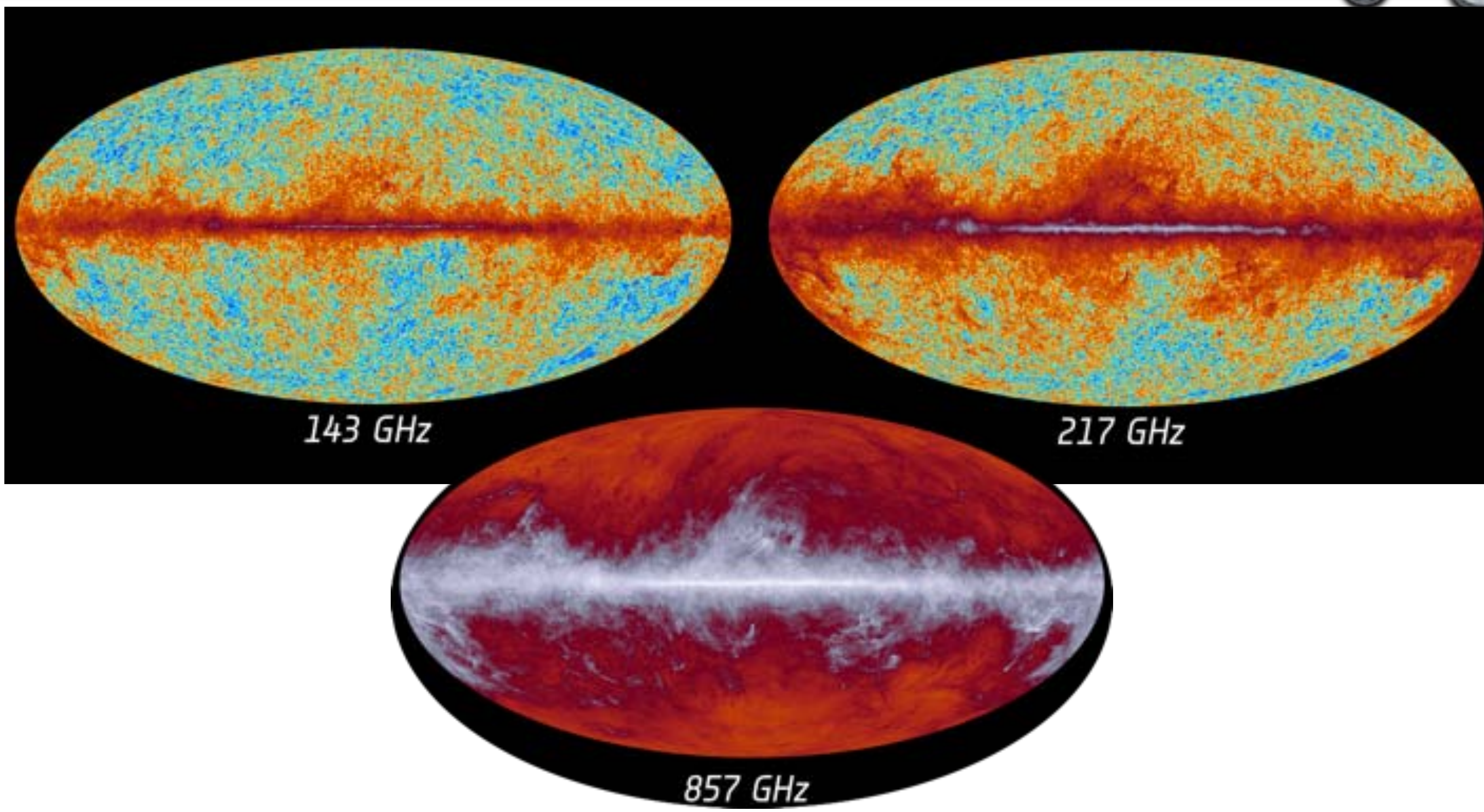




ABL *et al.* (A&A, 2013, accepted)

- Generalities on CMB
- CMB lensing
- Lensing reconstruction
- Planck results
- Perspectives - conclusion

Fiducial data map



- Minimum-variance combination of 143GHZ & 217GHz
- 857 GHz map used a template for dust cleaning
- 30% Galactic mask + CO + point sources
- 5º apodization (for lensing power spectrum estimation)

Some technical details

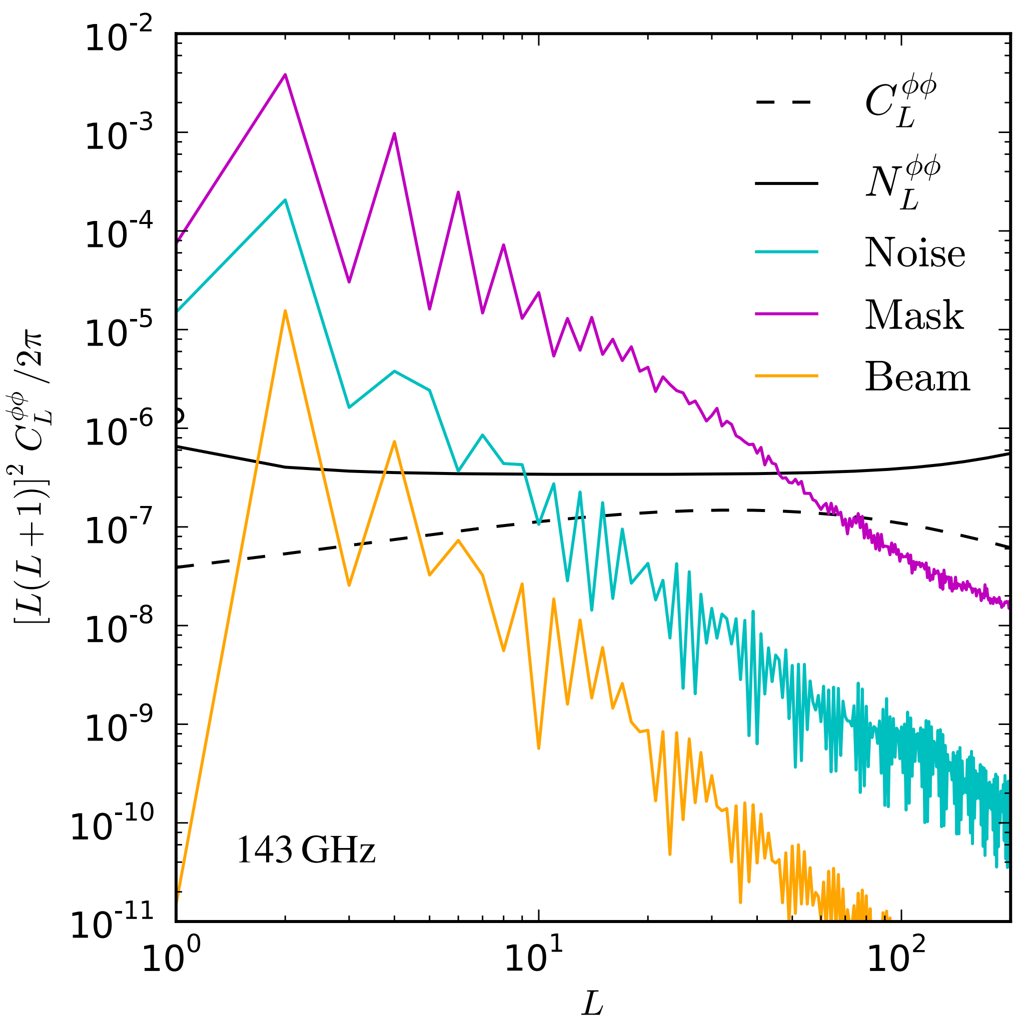
$$\hat{\phi}^{x}_{LM} = \frac{1}{\mathcal{R}^{x\phi}_{L}}\left(\bar{x}_{LM} - \bar{x}^{MF}_{LM}\right).$$

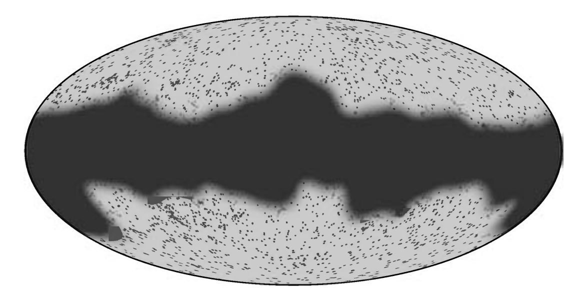
$$\mathcal{R}^{x\phi,(1)(2)}_{L} = \frac{1}{(2L+1)}\sum_{\ell_1\ell_2}\frac{1}{2}W^{x}_{\ell_1\ell_2L}W^{\phi}_{\ell_1\ell_2L}F^{(1)}_{\ell_1}F^{(2)}_{\ell_2}.$$

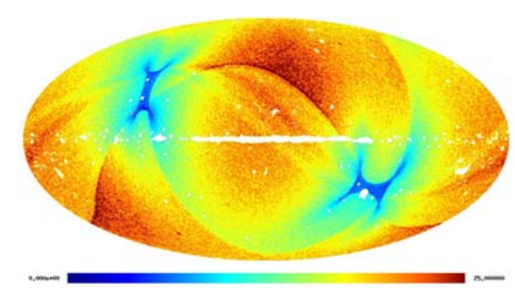
$$\bar{x}_{LM} = \frac{1}{2}\sum_{\ell_1m_1,\ell_2m_2}(-1)^M\begin{pmatrix}\ell_1 & \ell_2 & L\\ m_1 & m_2 & -M\end{pmatrix}W^{x}_{\ell_1\ell_2L}\bar{T}^{(1)}_{\ell_1m_1}\bar{T}^{(2)}_{\ell_2m_2}.$$

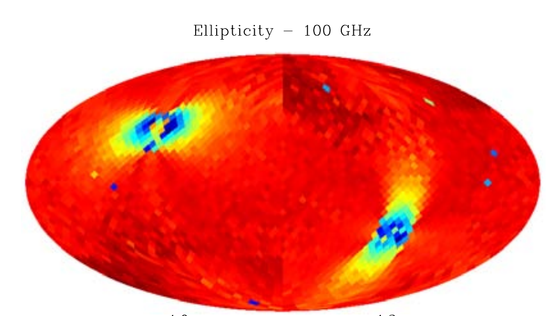
$$\bar{x}^{MF}_{LM} = \frac{1}{2}\sum_{\ell_1m_1,\ell_2m_2}(-1)^M\begin{pmatrix}\ell_1 & \ell_2 & L\\ m_1 & m_2 & -M\end{pmatrix}W^{x}_{\ell_1\ell_2L}\langle\bar{T}^{(1)}_{\ell_1m_1}\bar{T}^{(2)}_{\ell_2m_2}\rangle$$

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









The Planck Collaboration XVII, 2013

Some technical details

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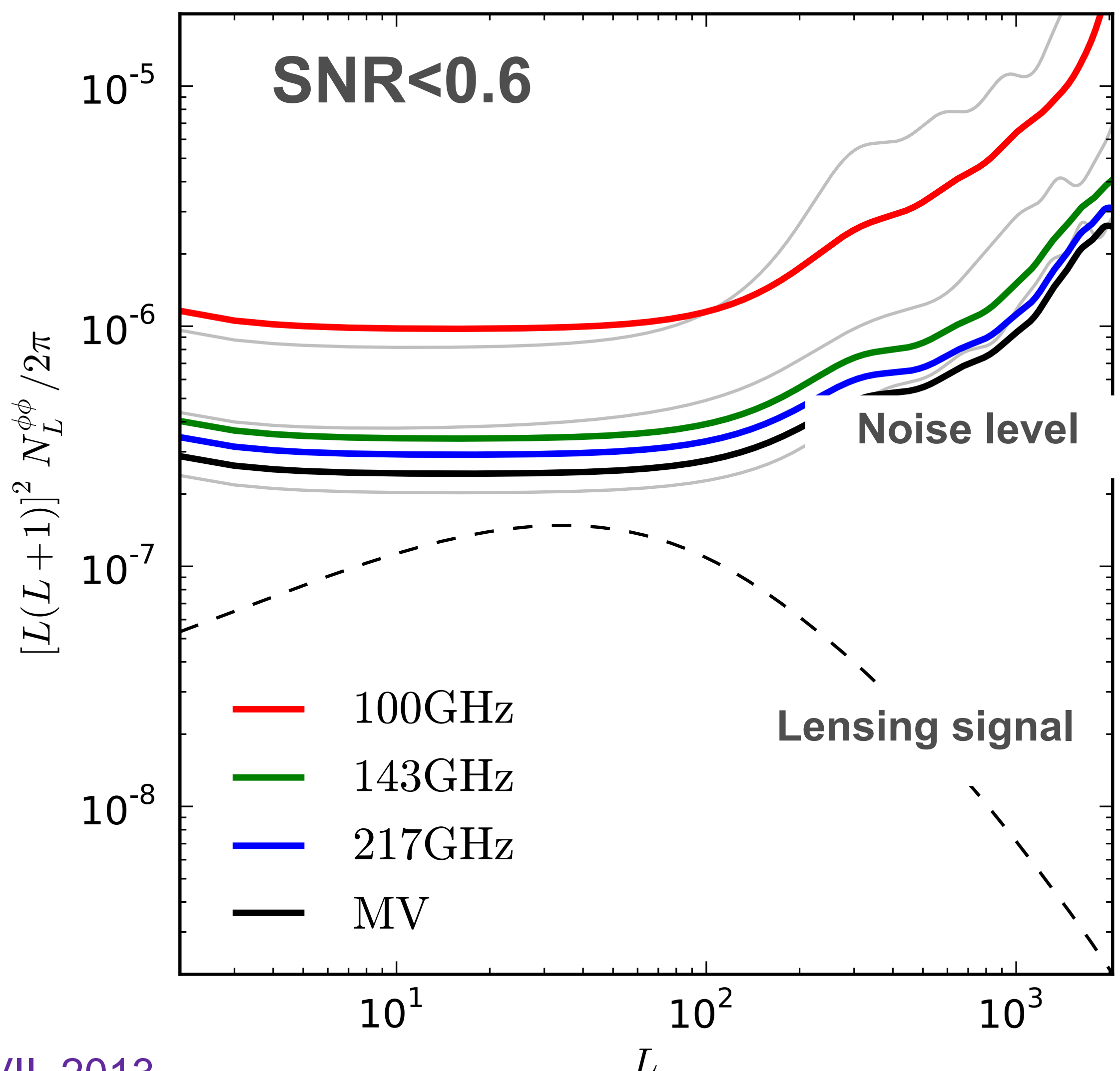
$$\bar{x}^{MF}_{LM} = \frac{1}{2}\sum_{\ell_1 m_1,\ell_2 m_2}(-1)^M\begin{pmatrix}\ell_1 & \ell_2 & L\\ m_1 & m_2 & -M\end{pmatrix}W^x_{\ell_1\ell_2 L}\langle\bar{T}^{(1)}_{\ell_1 m_1}\bar{T}^{(2)}_{\ell_2 m_2}\rangle$$

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



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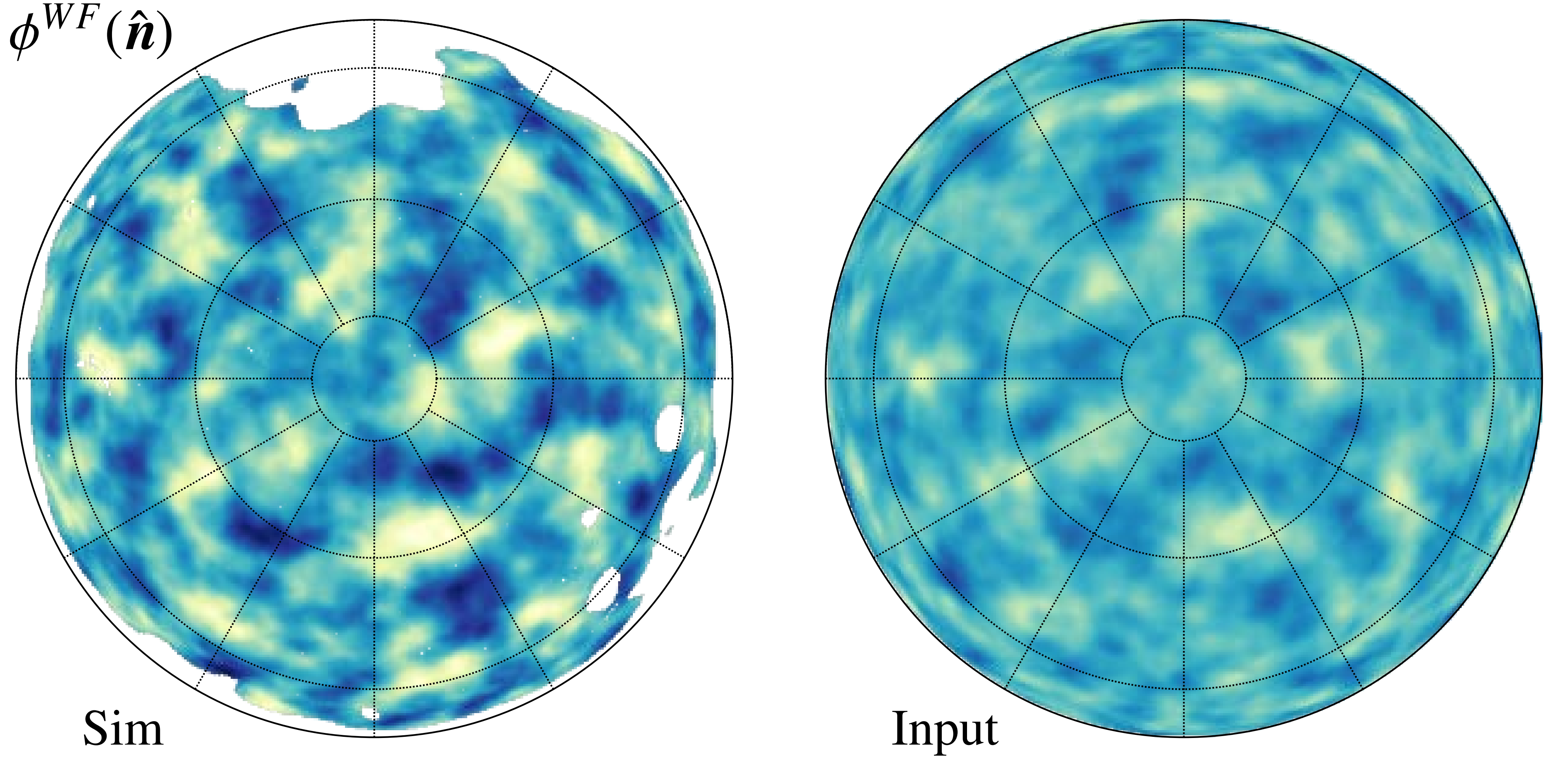
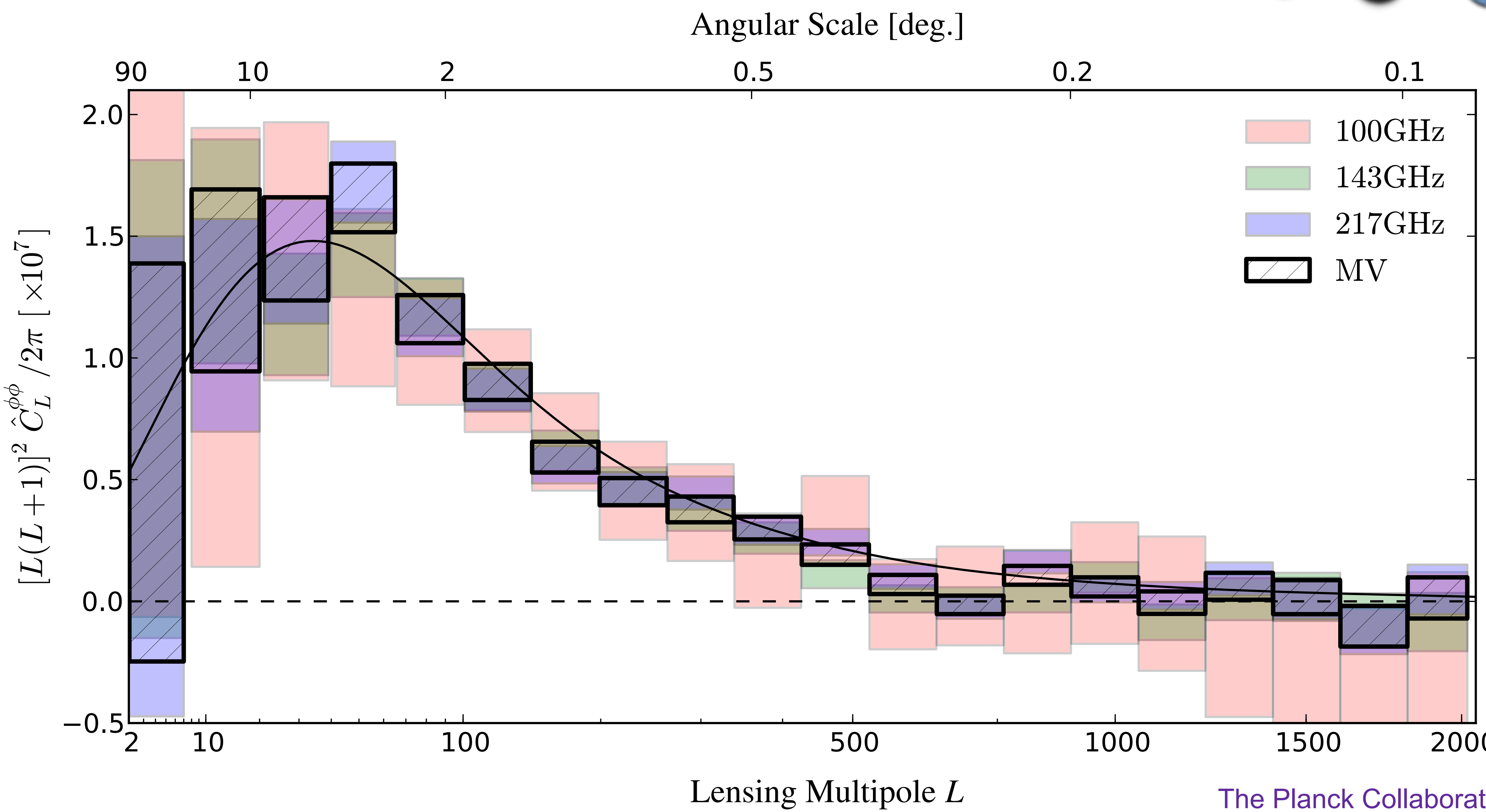
Reconstruction on simulation



Reconstruction on a realistic Planck simulation

Cosmological constraints



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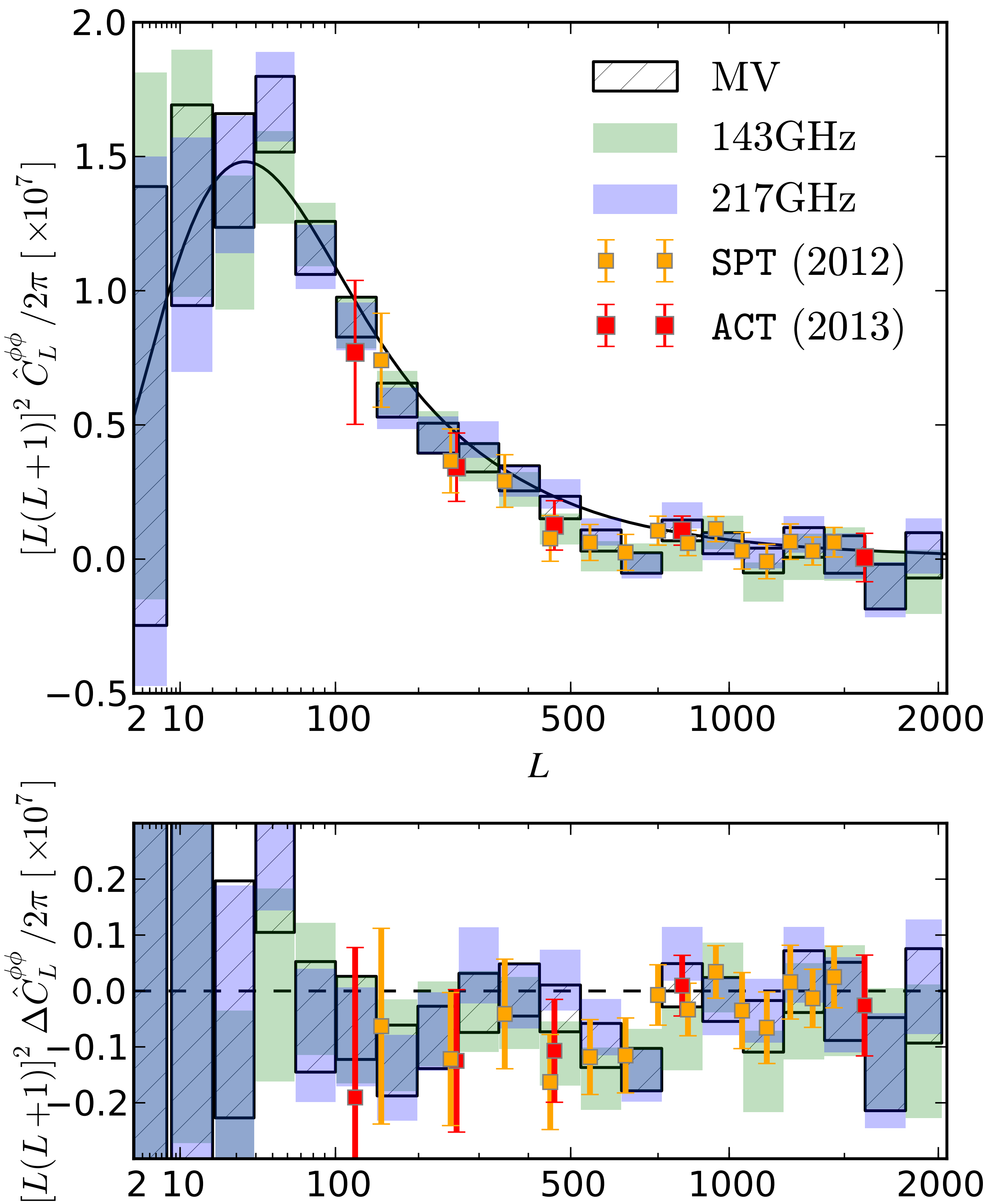
- Agreement between 3 frequencies
- Agreement with the prediction
- New cosmological constraints

$$\hat{A}_{40\rightarrow 400} = 0.94 \pm 0.04$$

Comparison to ACT and SPT



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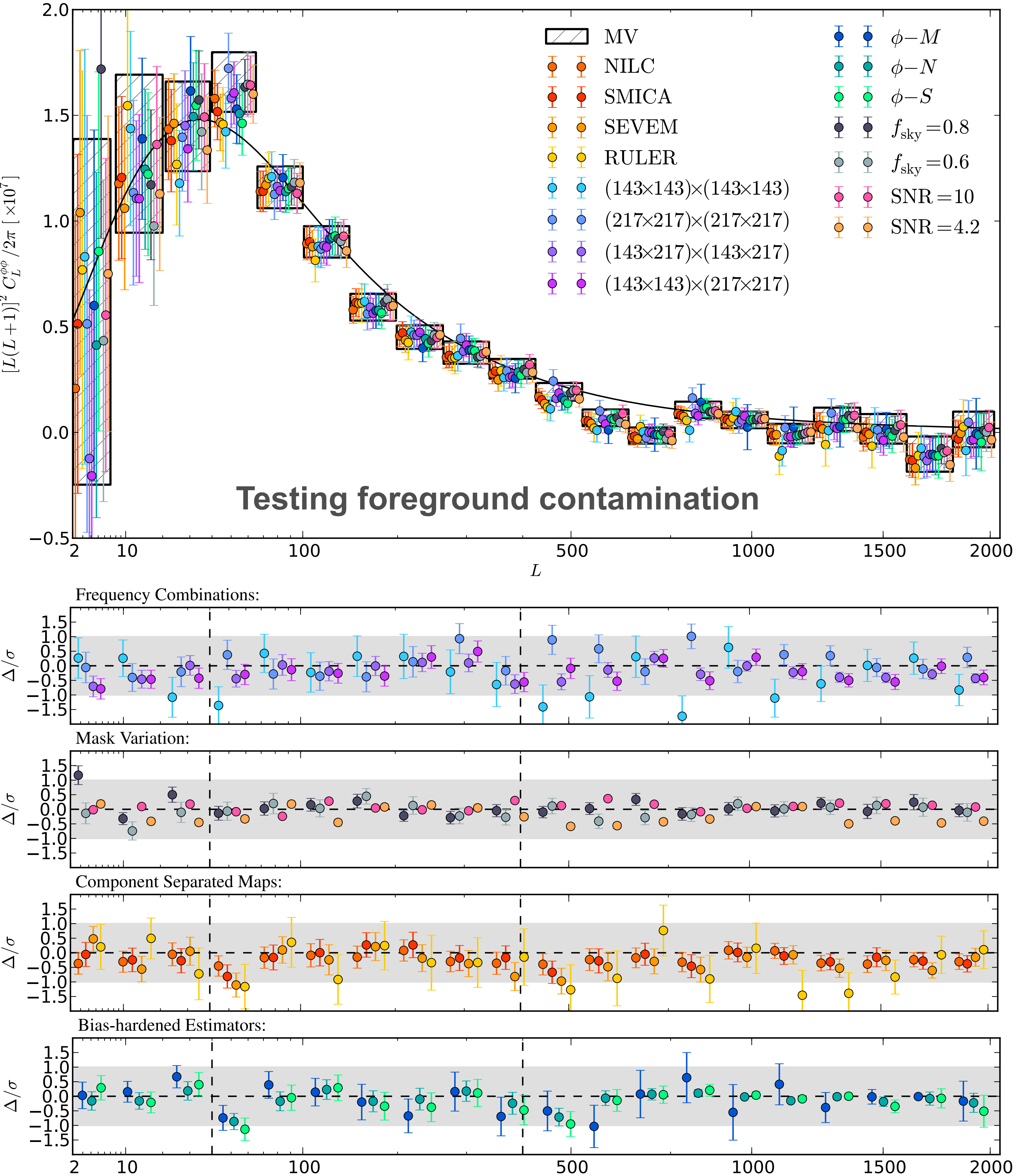
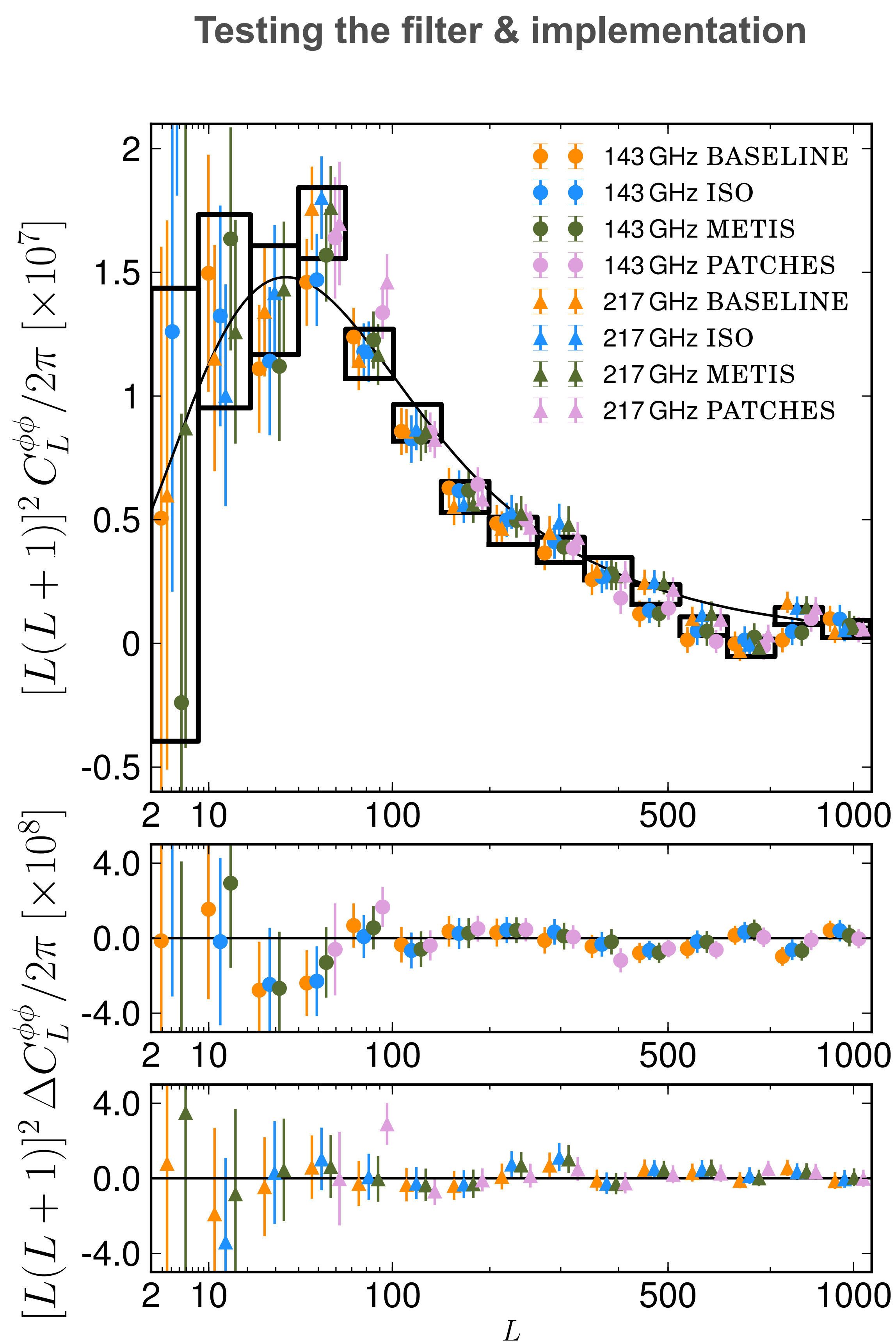
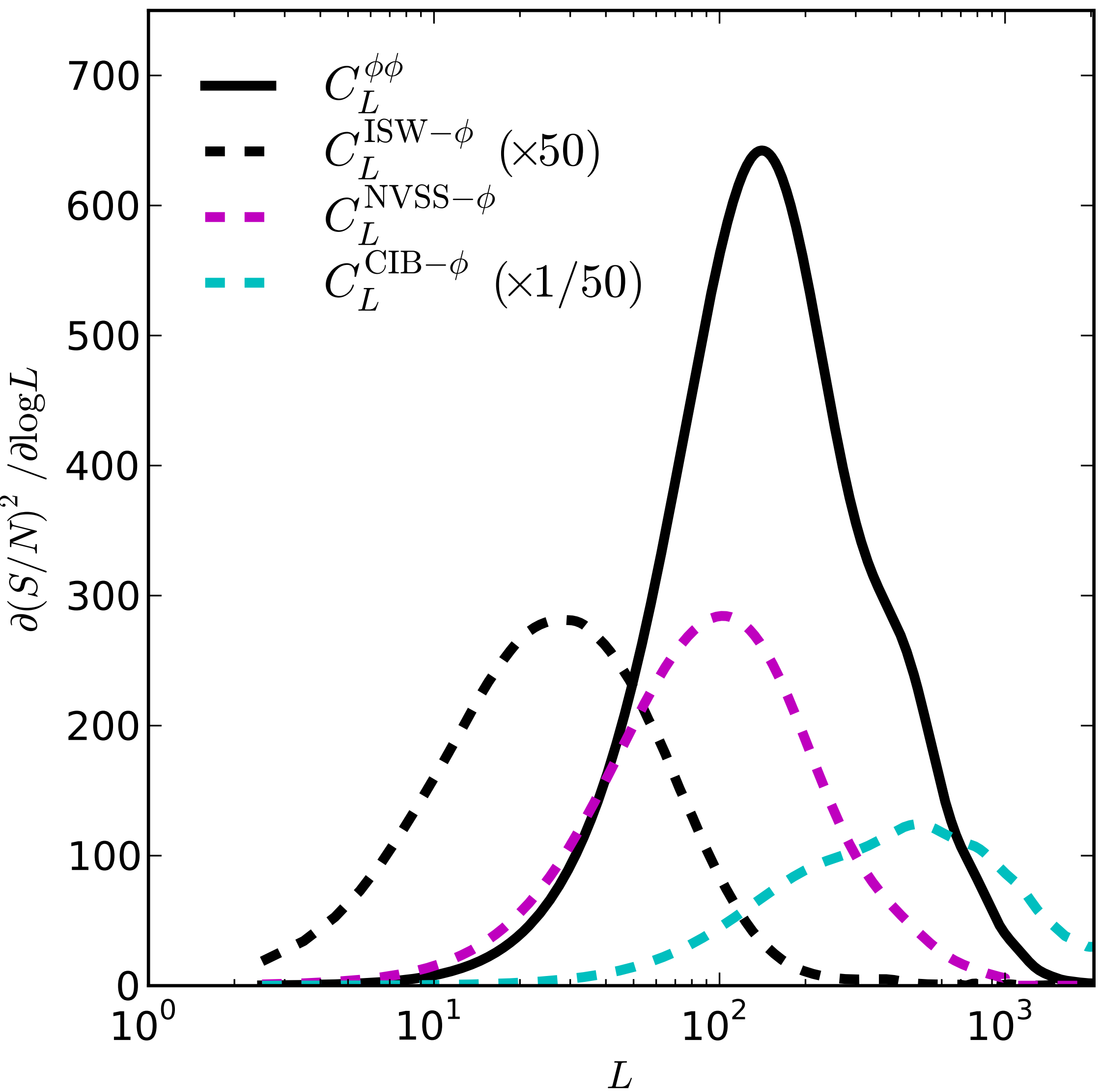
Robustness

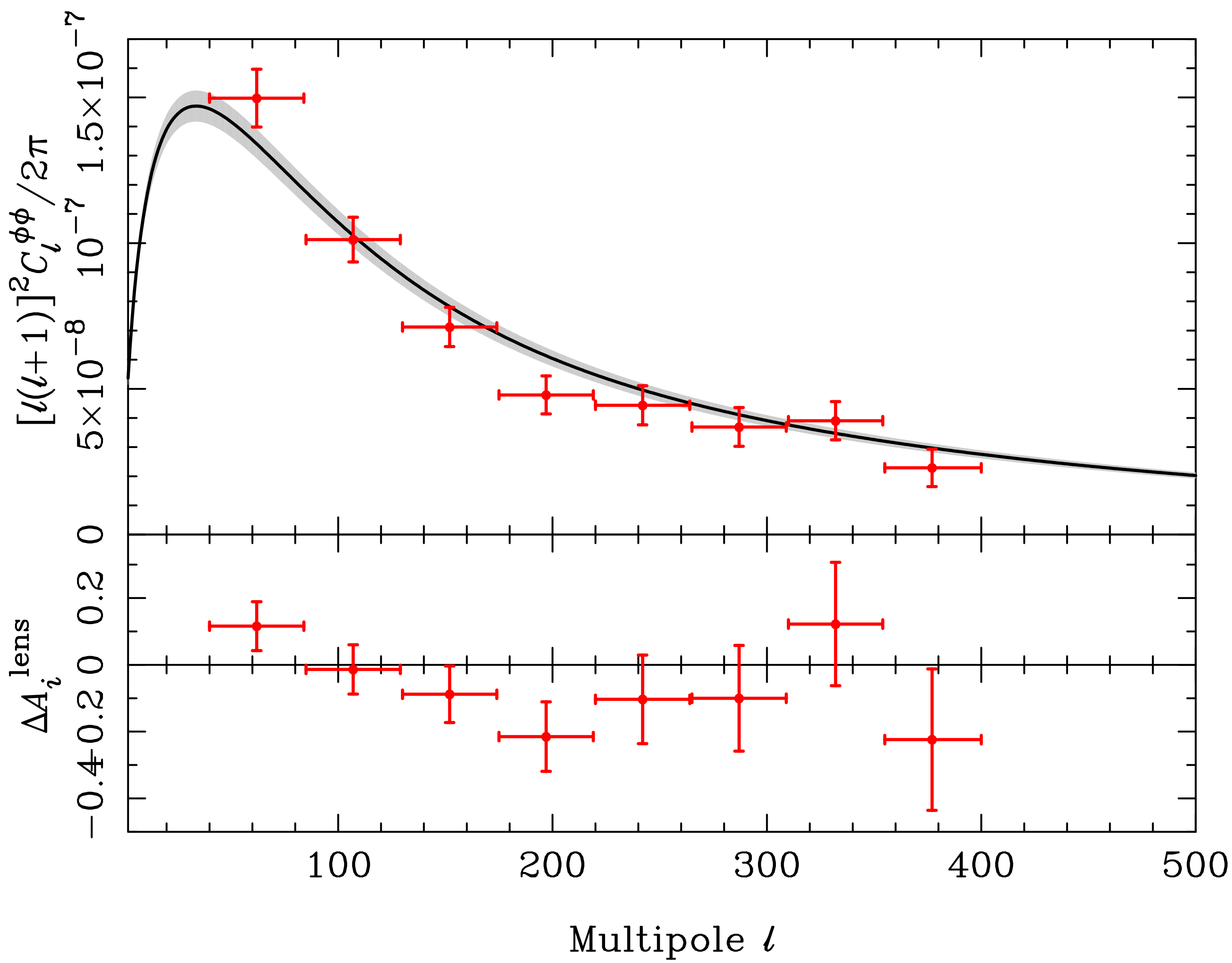

Testing foreground contamination
MV
NILC
SMICA
SEVEM
RULER
(143×143)×(143×143)
(217×217)×(217×217)
(143×217)×(143×217)
(143×143)×(217×217)
$\phi-M$
$\phi-N$
$\phi-S$
$f_{\rm sky}=0.8$
$f_{\rm sky}=0.6$
SNR =10
SNR =4.2
Frequency Combinations:
Mask Variation:
Component Separated Maps:
Bias-hardened Estimators:
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
Δ/σ
L


Testing the filter & implementation
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

Lensing likelihood



The Planck Collaboration XVII, 2013



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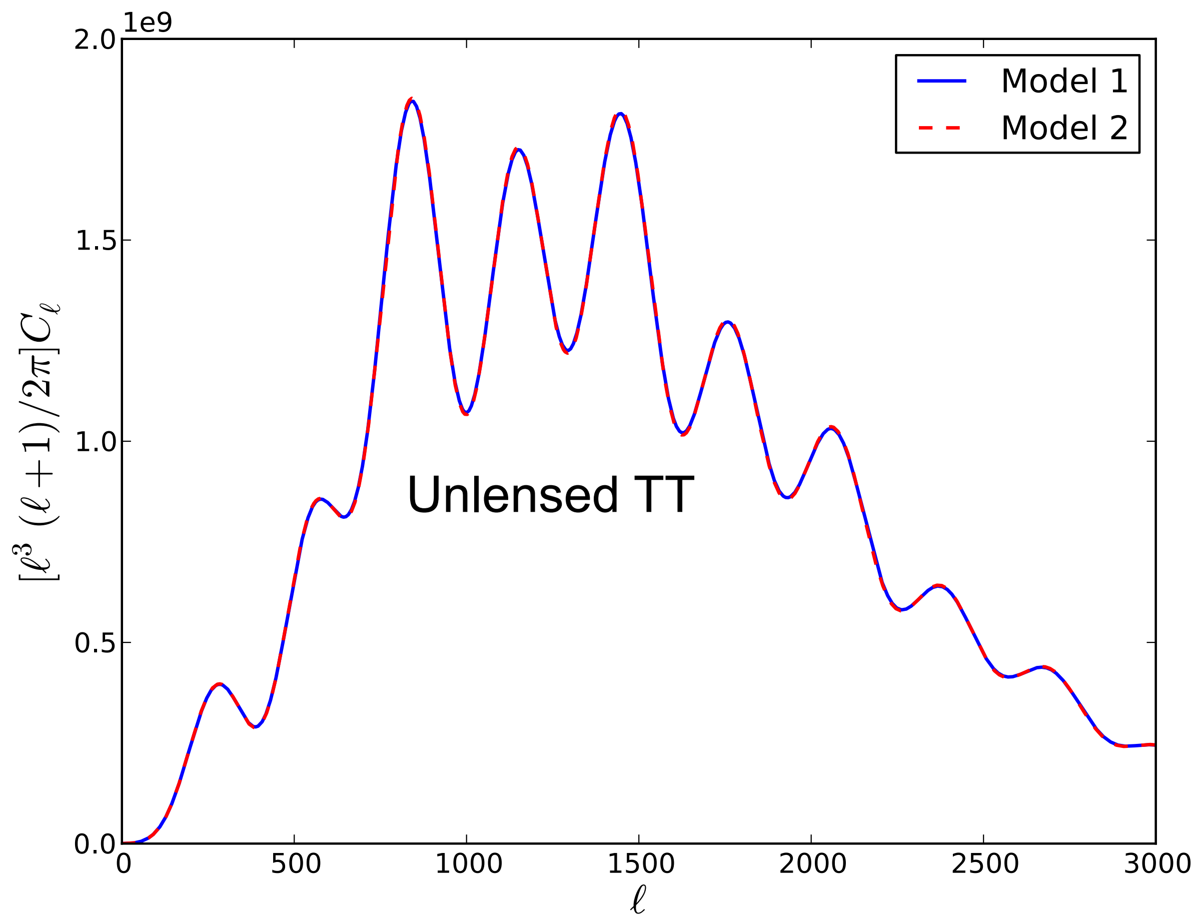
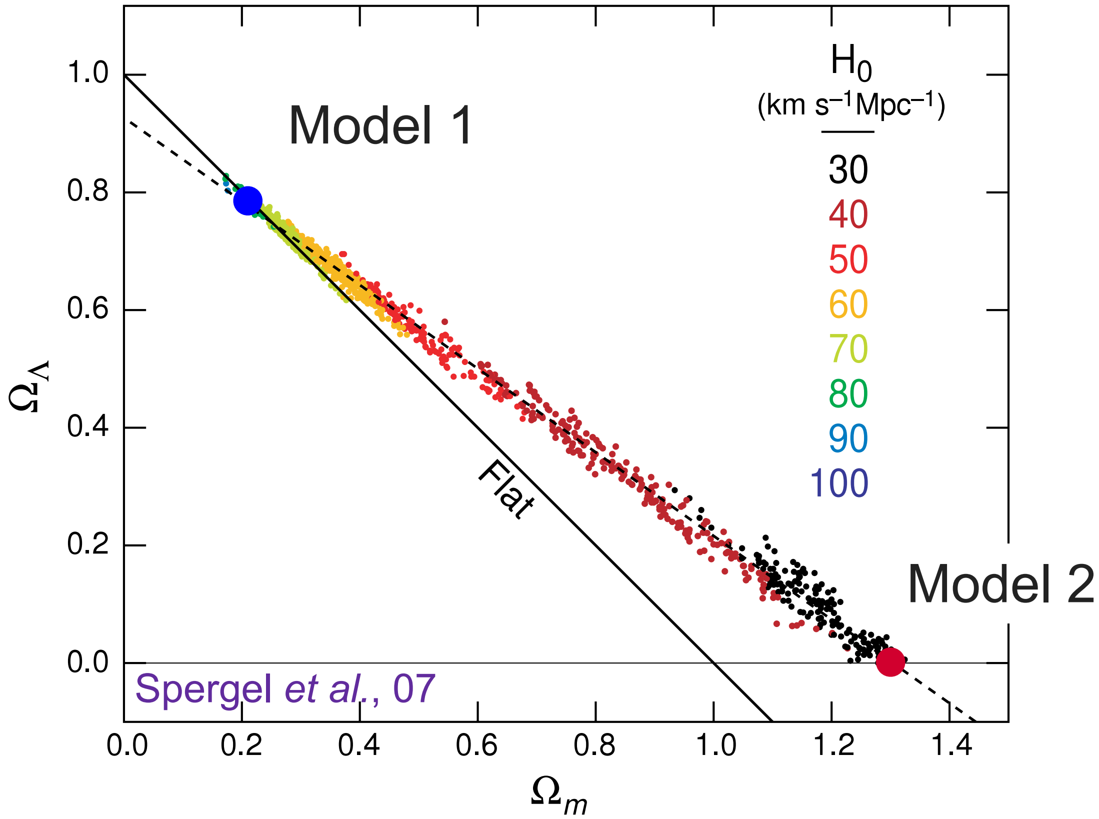
Cosmological information from CMB lensing

- **«Lensing breaks diameter degeneracy»**





Cosmological information from CMB lensing

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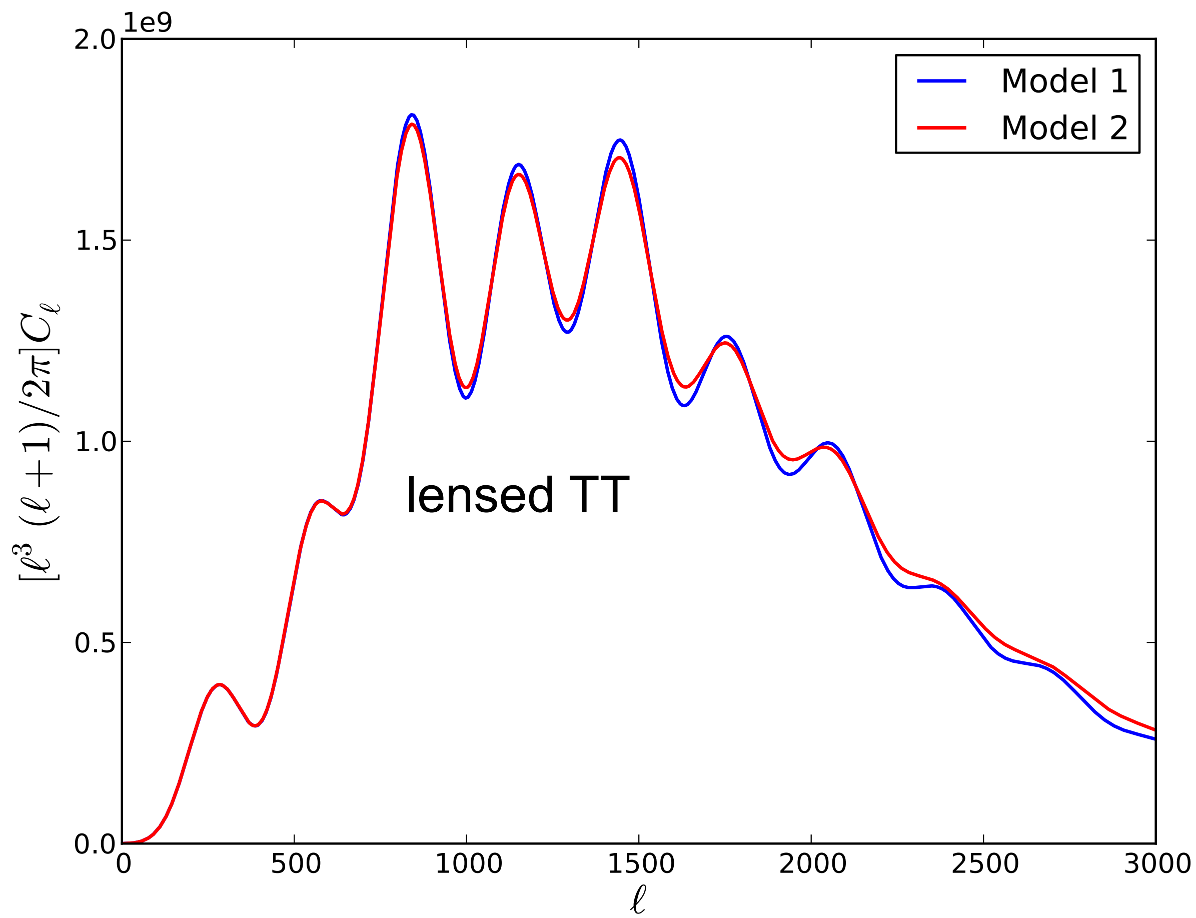
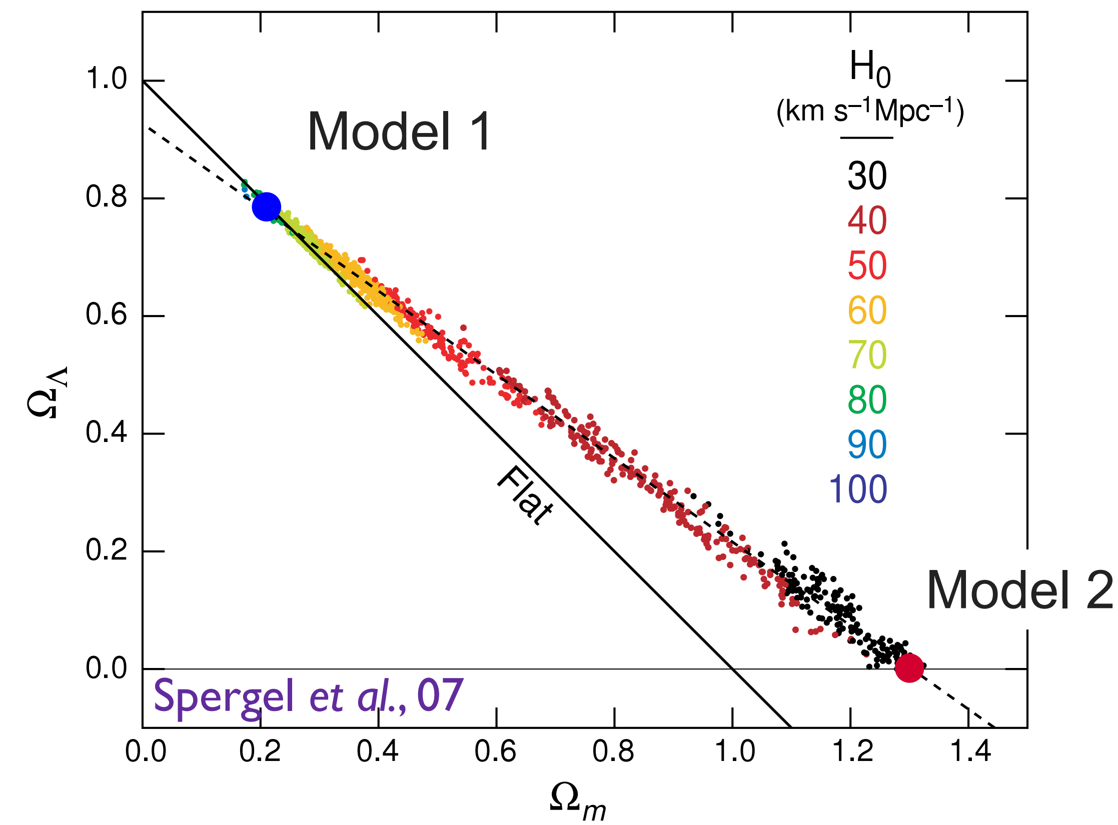
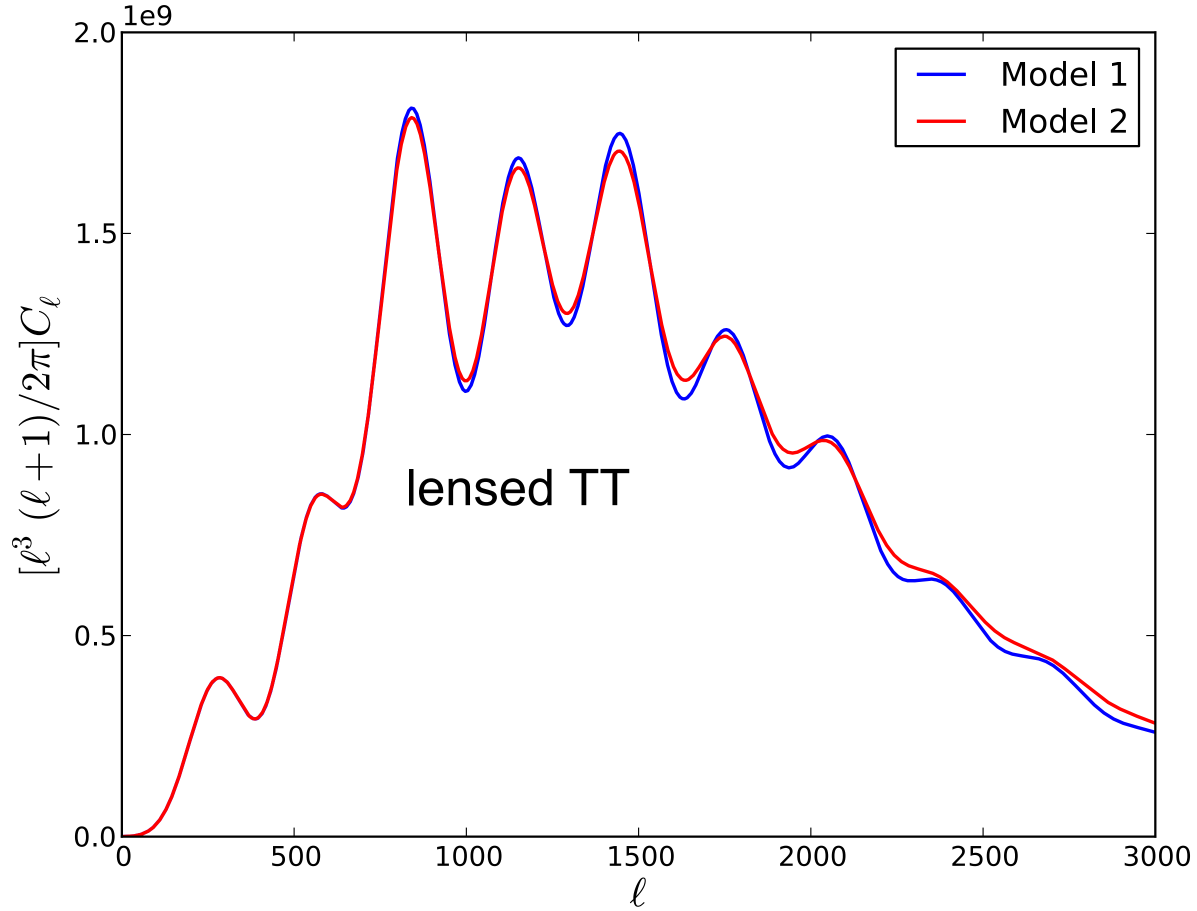


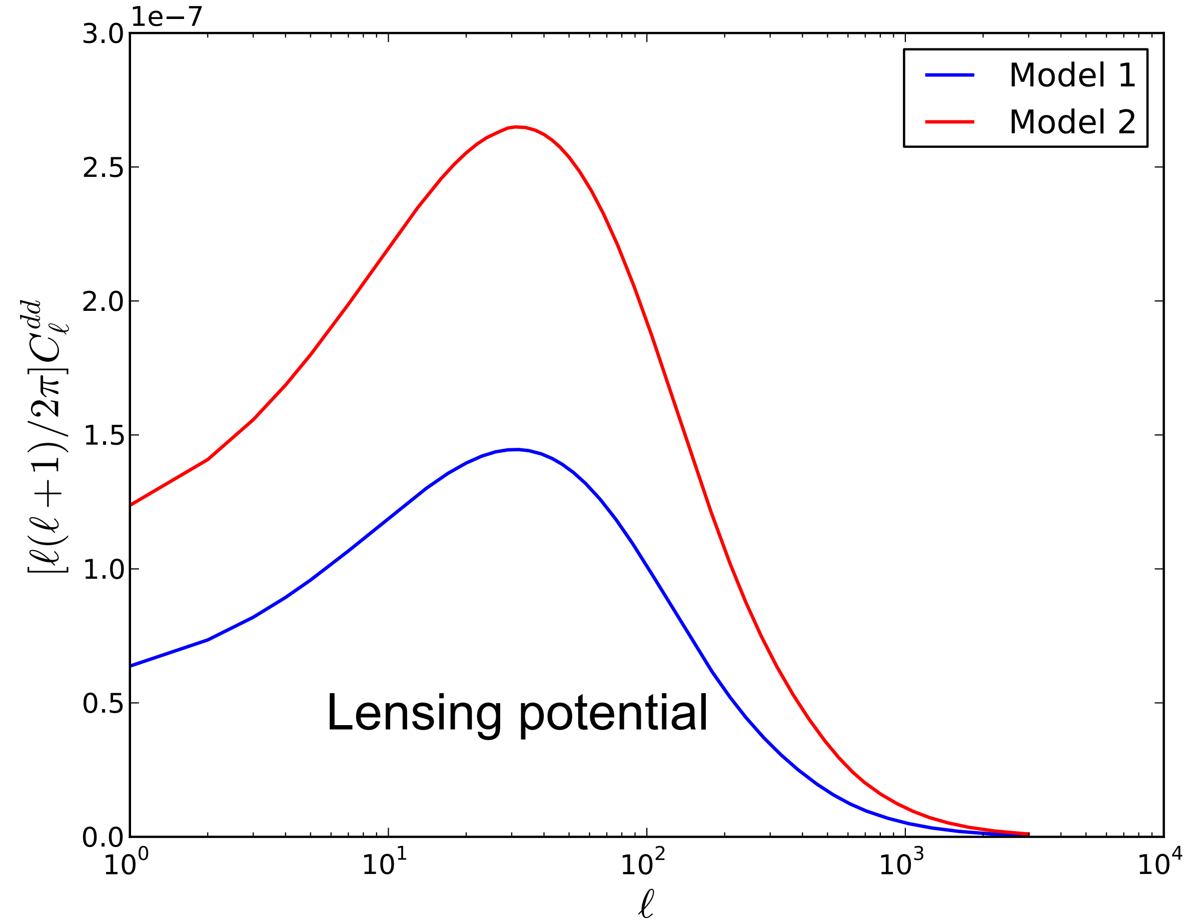


- If lensed power spectra are different, that's because of lensing potential

Cosmological information from CMB lensing

- **«Lensing breaks diameter degeneracies»**





Cosmological information from CMB lensing

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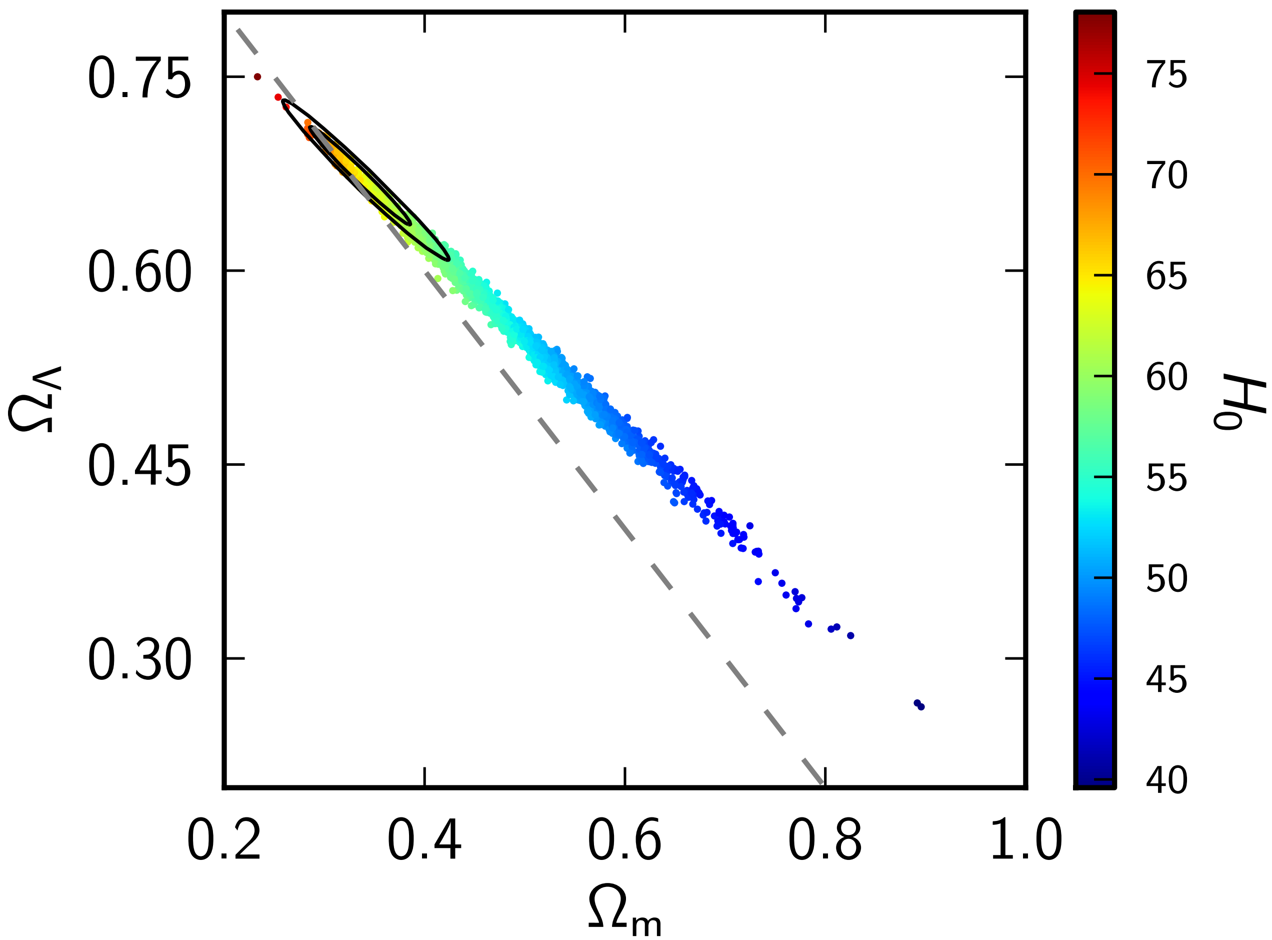

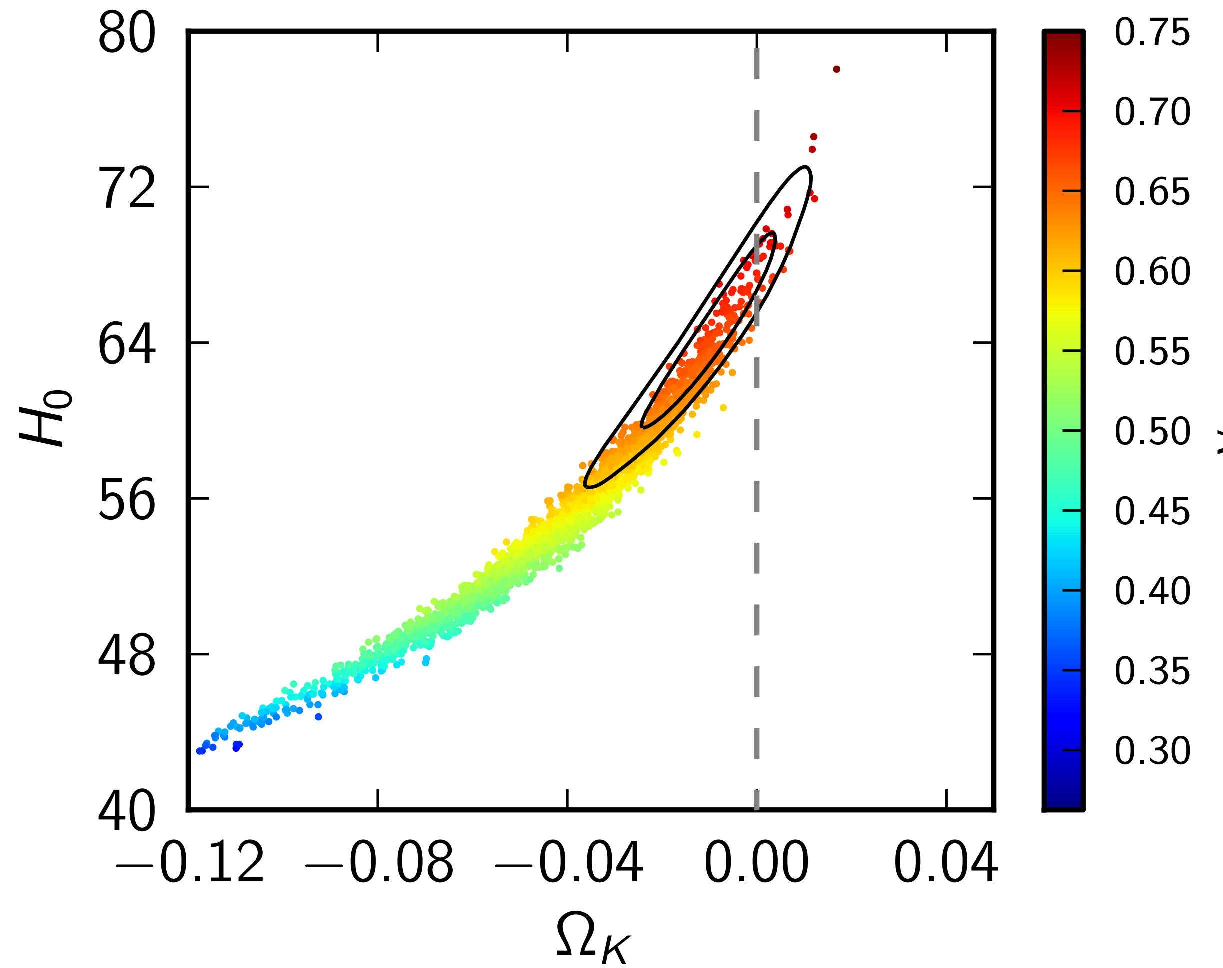

$$\Omega_\Lambda = 0.57^{+0.073}_{-0.055} \quad (68\%; \textit{Planck}+\text{WP}+\text{highL})$$

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

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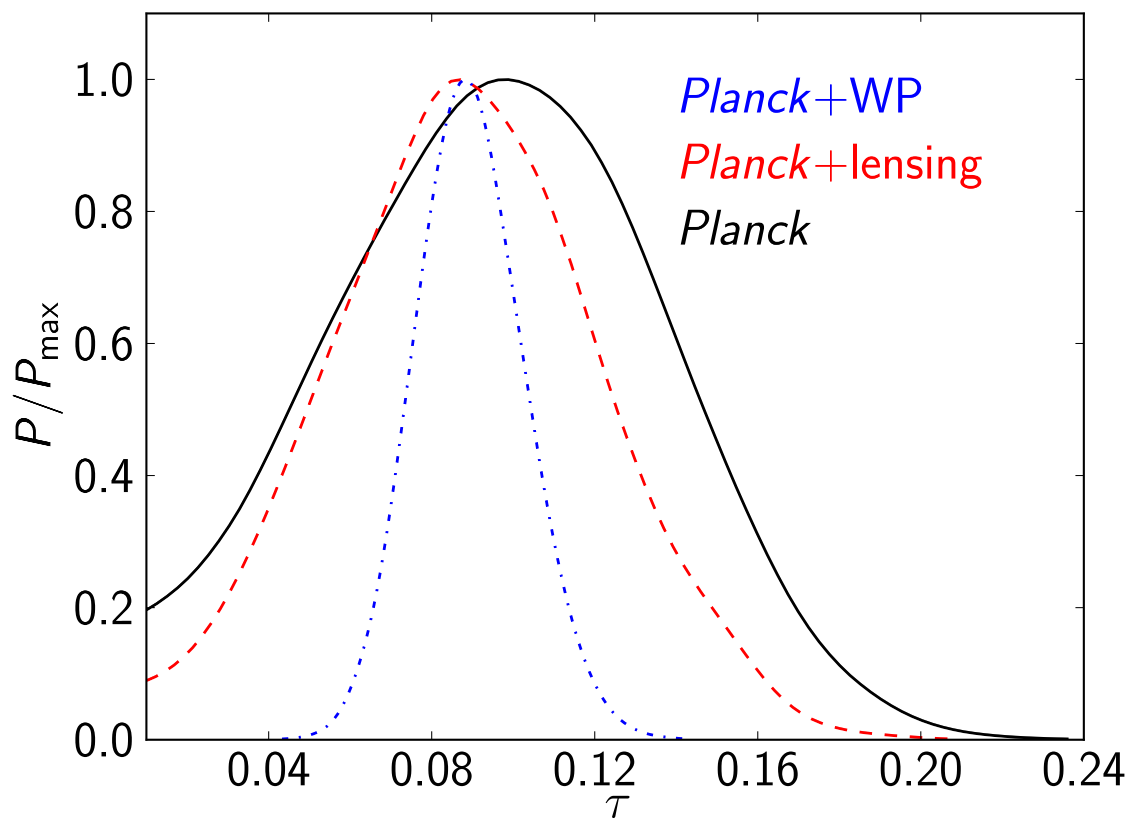
$$100\Omega_K = -4.2^{+4.3}_{-4.8} \quad (95\%; \textit{Planck}+\text{WP}+\text{highL});$$

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

Cosmological information from CMB lensing

Reionization

- Lensing provides «Planck only» constraint
- Cross-check of polarization

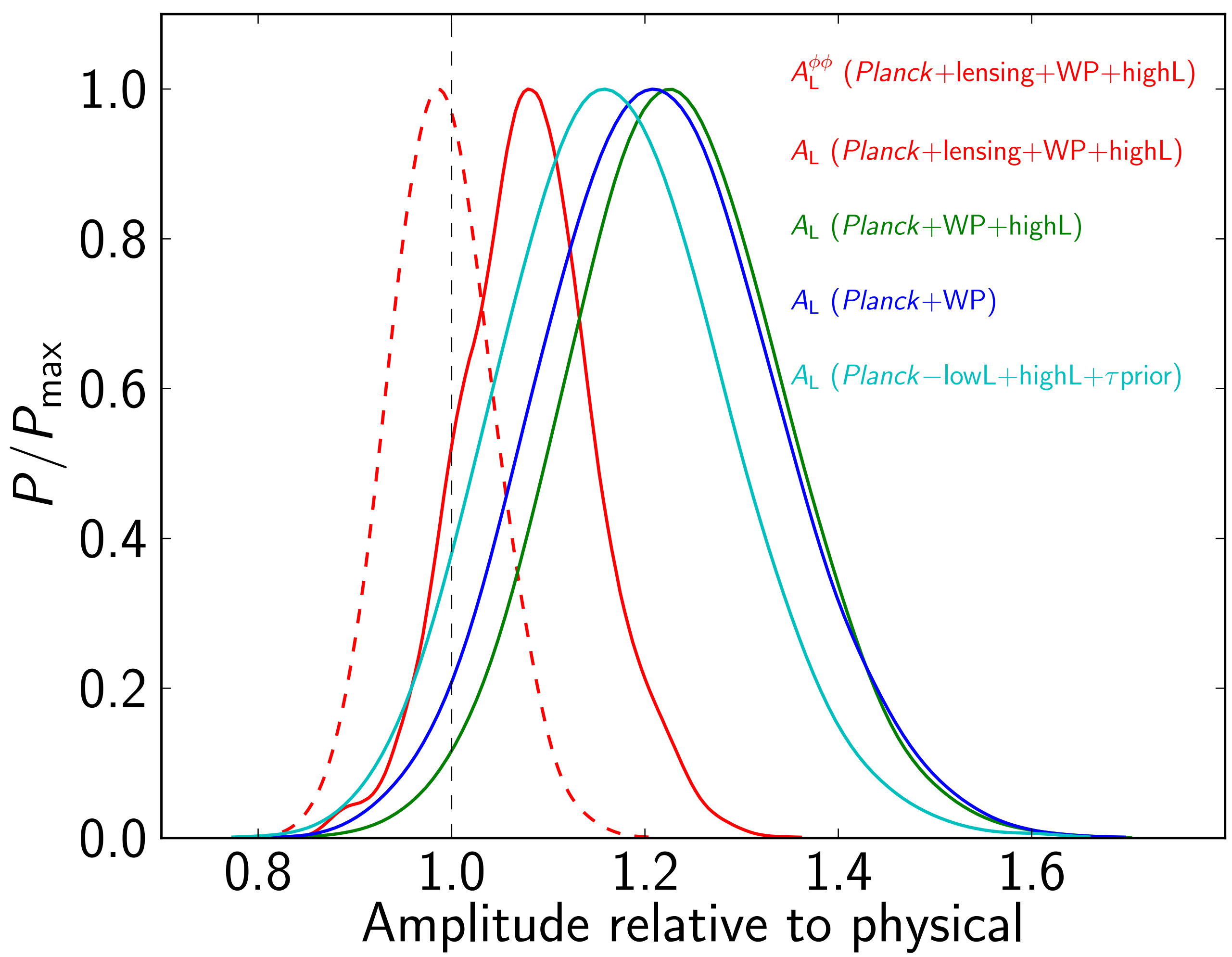


$$\tau = 0.097 \pm 0.038 \quad (68\%;\ \textit{Planck})$$
$$\tau = 0.089 \pm 0.032 \quad (68\%;\ \textit{Planck}+\text{lensing}).$$

Cosmological information from CMB lensing

Sum of neutrino masses

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



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

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

- Generalities on CMB
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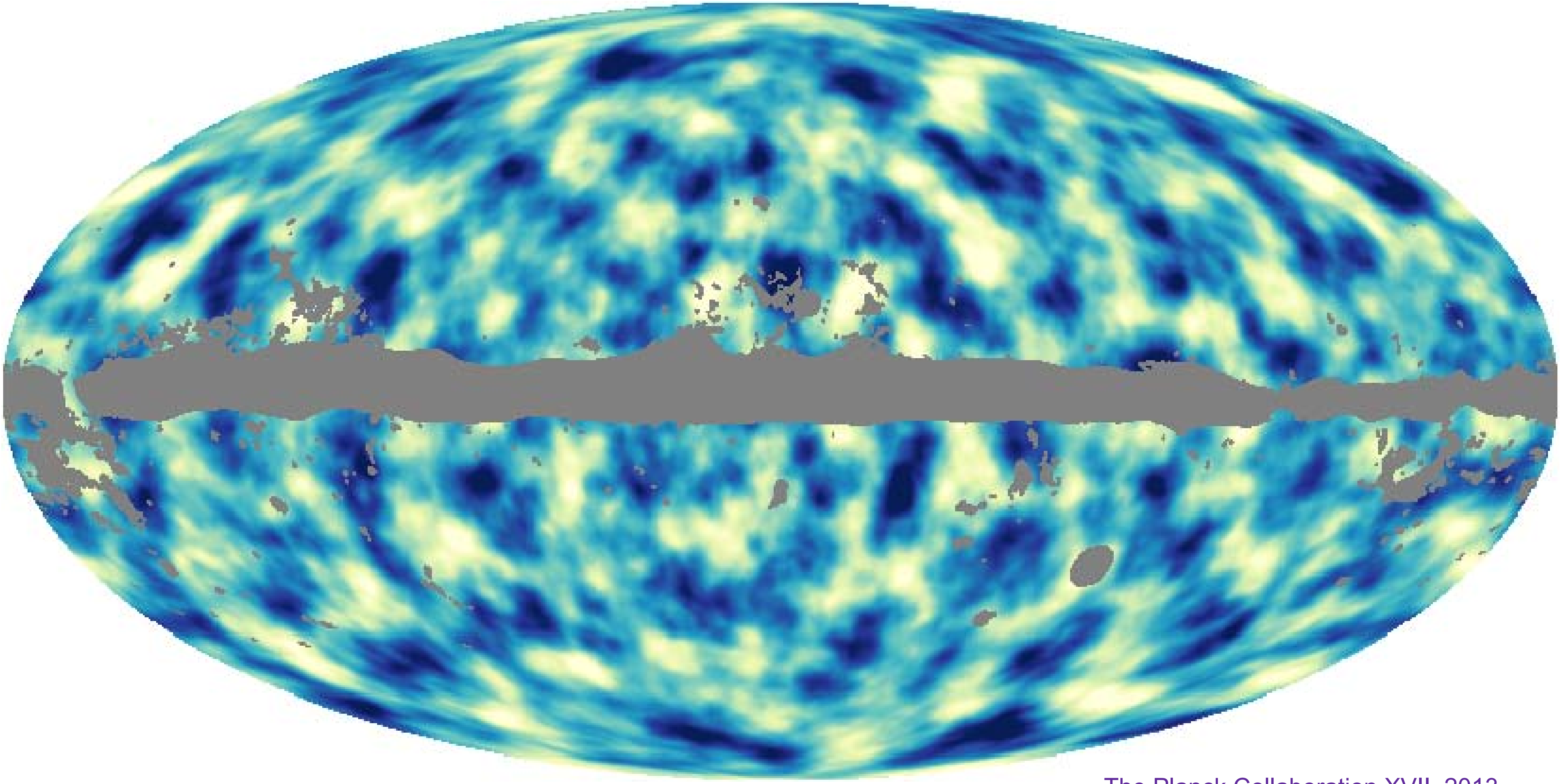
The matter in the Universe as seen by Planck



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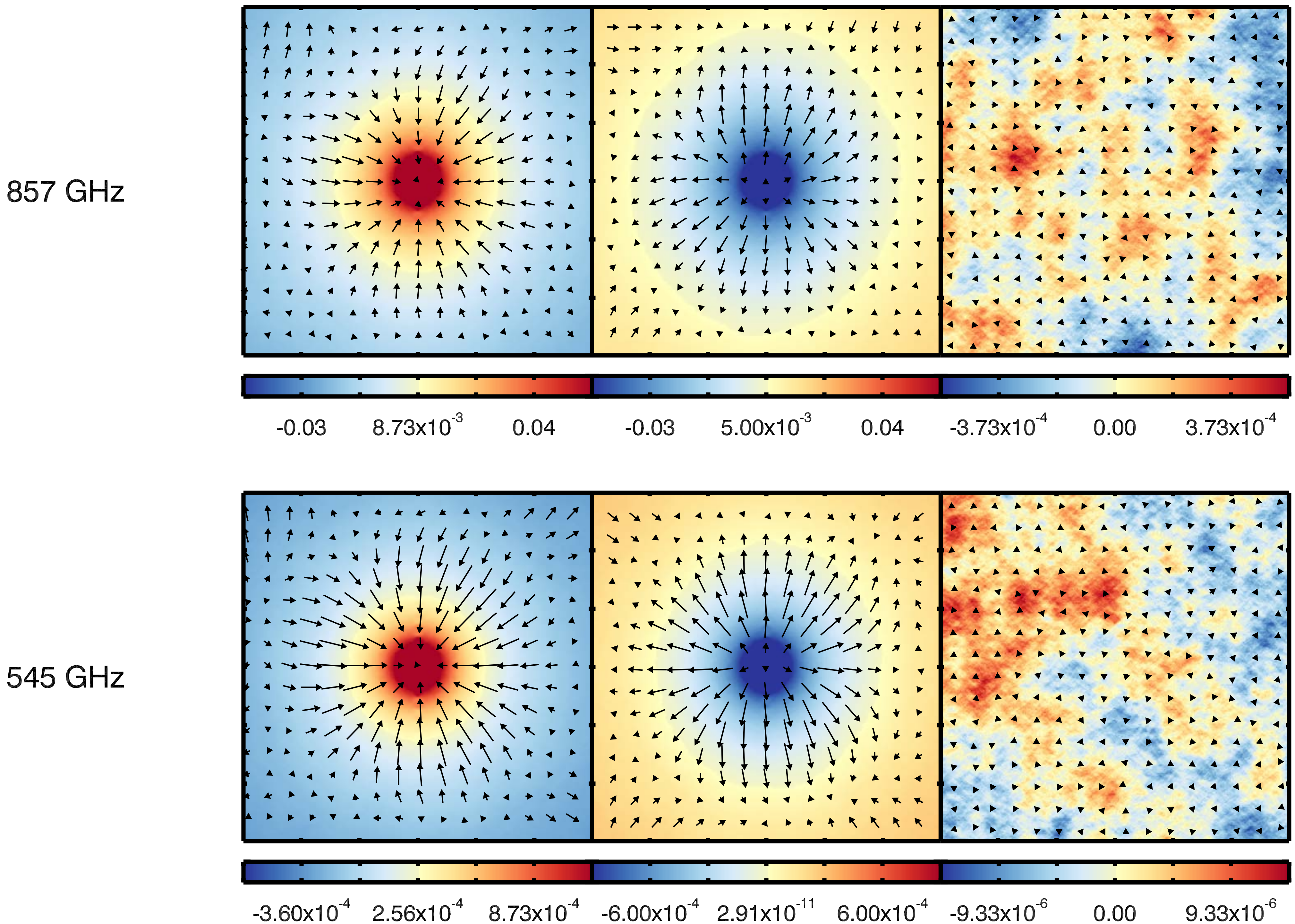
The lensing map traces the matter distribution up to the last scattering surface

CMB Lensing x CIB



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Cross-correlations

$$C_\ell^{XY} \sim \int_0^{\chi_*} d\chi w^X(\chi) w^Y(\chi) P(\ell/\chi, \chi)$$

$$w^l(\chi) \propto \Omega_m H_0^2 \frac{\chi_* - \chi}{\chi_*}\frac{\chi}{a}$$

CMB lensing

Planck

$$w^g(\chi) \propto b\frac{dN}{d\chi}$$

Galaxy distribution

SDSS, NVSS

Cross-correlations

$$C_\ell^{XY} \sim \int_0^{\chi_*} d\chi w^X(\chi) w^Y(\chi) P(\ell/\chi, \chi)$$

$$w^l(\chi) \propto \Omega_m H_0^2 \frac{\chi_* - \chi}{\chi_*} \frac{\chi}{a}$$

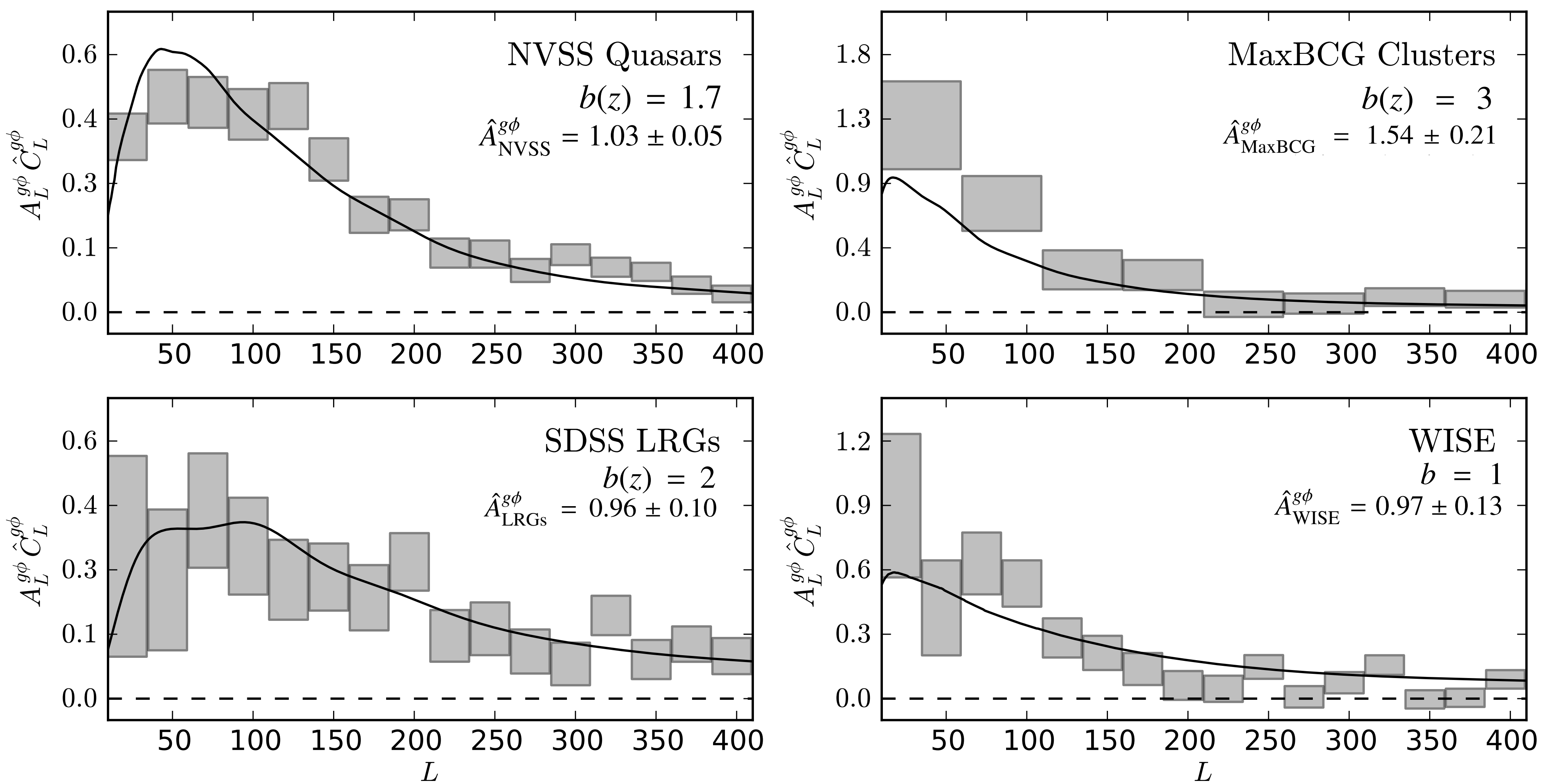
CMB lensing

$$w^g(\chi) \propto b \frac{dN}{d\chi}$$

Galaxy distribution

Planck

SDSS, NVSS



Planck mass will stay the reference on the full-sky for many years!

Corrélations croisées

$$C_\ell^{XY} \sim \int_0^{\chi_*} d\chi w^X(\chi) w^Y(\chi) P(\ell/\chi, \chi)$$

$$w^l(\chi) \propto \Omega_m H_0^2 \frac{\chi_* - \chi}{\chi_*} \frac{\chi}{a}$$

CMB lensing

Planck

$$w^g(\chi) \propto b \frac{dN}{d\chi}$$

Galaxy distribution

SDSS, DES, Euclid, LSST

$$w^s(\chi) \propto H_0^2 \Omega_m \frac{\chi}{a} \int_\chi^{\chi_*} d\chi' \frac{dN}{d\chi'} \frac{\chi' - \chi}{\chi'}$$

Weak lensing on galaxies

DES, Euclid, LSST

- CMB lensing: non biased, purely geometric, source plane well-known

Corrélations croisées

$$C_\ell^{XY} \sim \int_0^{\chi_*} d\chi w^X(\chi) w^Y(\chi) P(\ell/\chi, \chi)$$

$w^l(\chi) \propto \Omega_m H_0^2 \frac{\chi_* - \chi}{\chi_*} \frac{\chi}{a}$	$w^g(\chi) \propto b \frac{dN}{d\chi}$	$w^s(\chi) \propto H_0^2 \Omega_m \frac{\chi}{a} \int_\chi^{\chi_*} d\chi' \frac{dN}{d\chi'} \frac{\chi' - \chi}{\chi'}$
CMB lensing	Galaxy distribution	Weak lensing on galaxies
Planck	SDSS, DES, Euclid, LSST	DES, Euclid, LSST

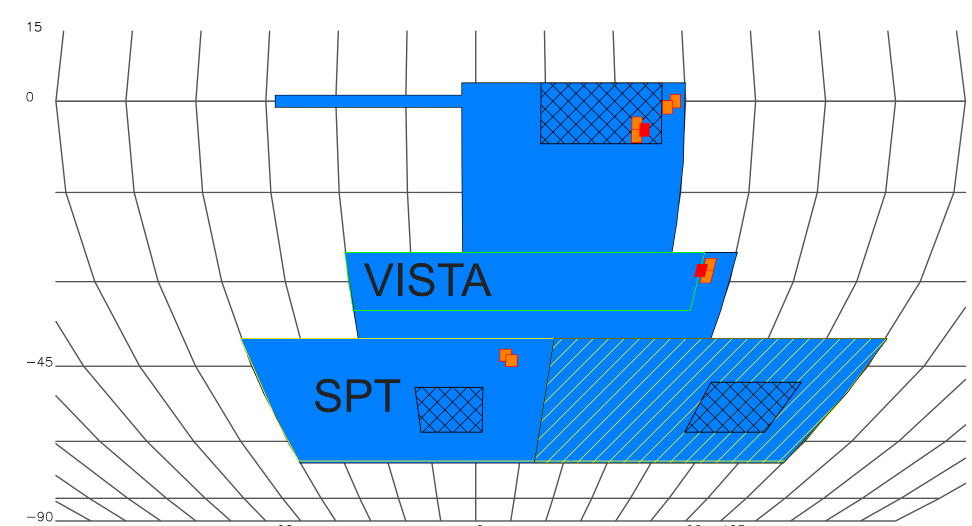
- CMB lensing: non biased, purely geometric, source plane well-known

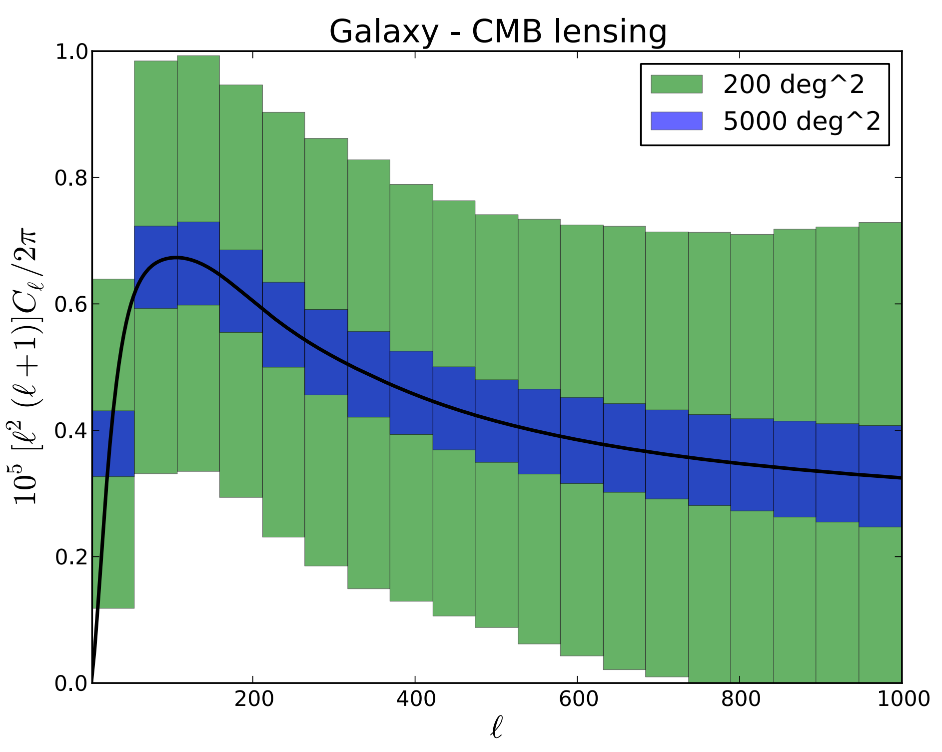
The Dark Energy Survey

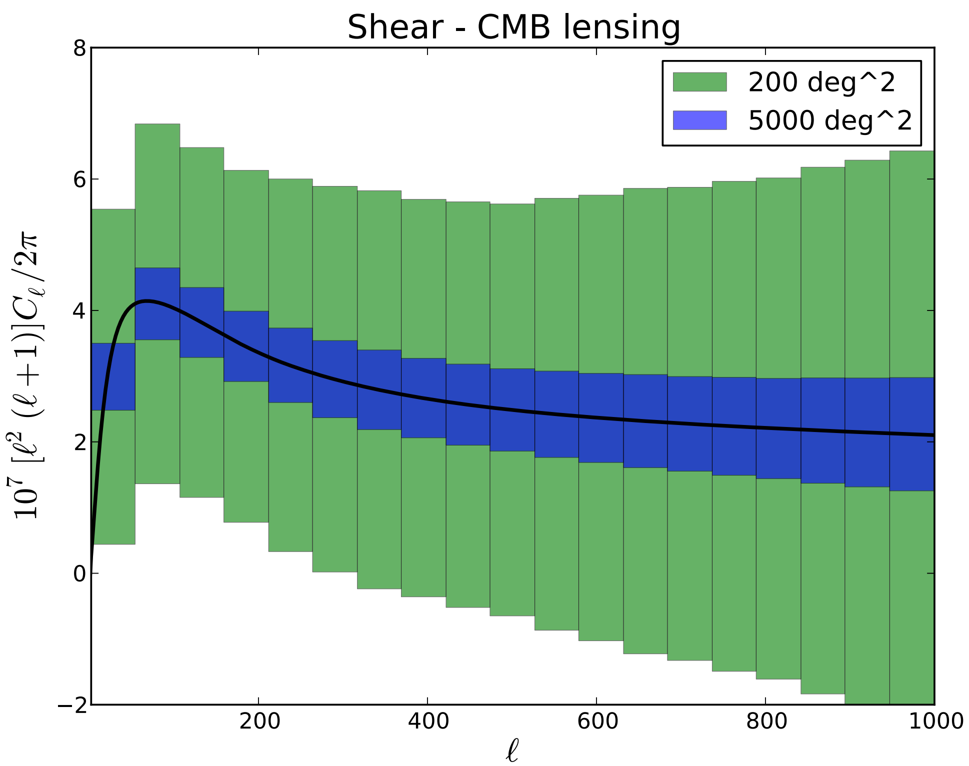
- 5000 deg^2 grizY to 24th mag
- 15 deg^2 for type Ia supernovae
- 5 years
- 300 millions photometric redshifts

- Cluster count
- Weak lensing
- Large Scale structure
- Type Ia supernovae

DES footprint







Benoit-Lévy & Kirk, DES internal note

- **Open questions**
  - Simply new observable?
  - Better control on systematic errors?
  - Better contraints on bias?
  - Would a post-Planck CMB lensing measurement help?

CMB lensing: central in observational cosmology

large-scale structure

Additional weak lensing observable
Complete information on matter distribution
Will be used in joint analysis with all the galaxy surveys

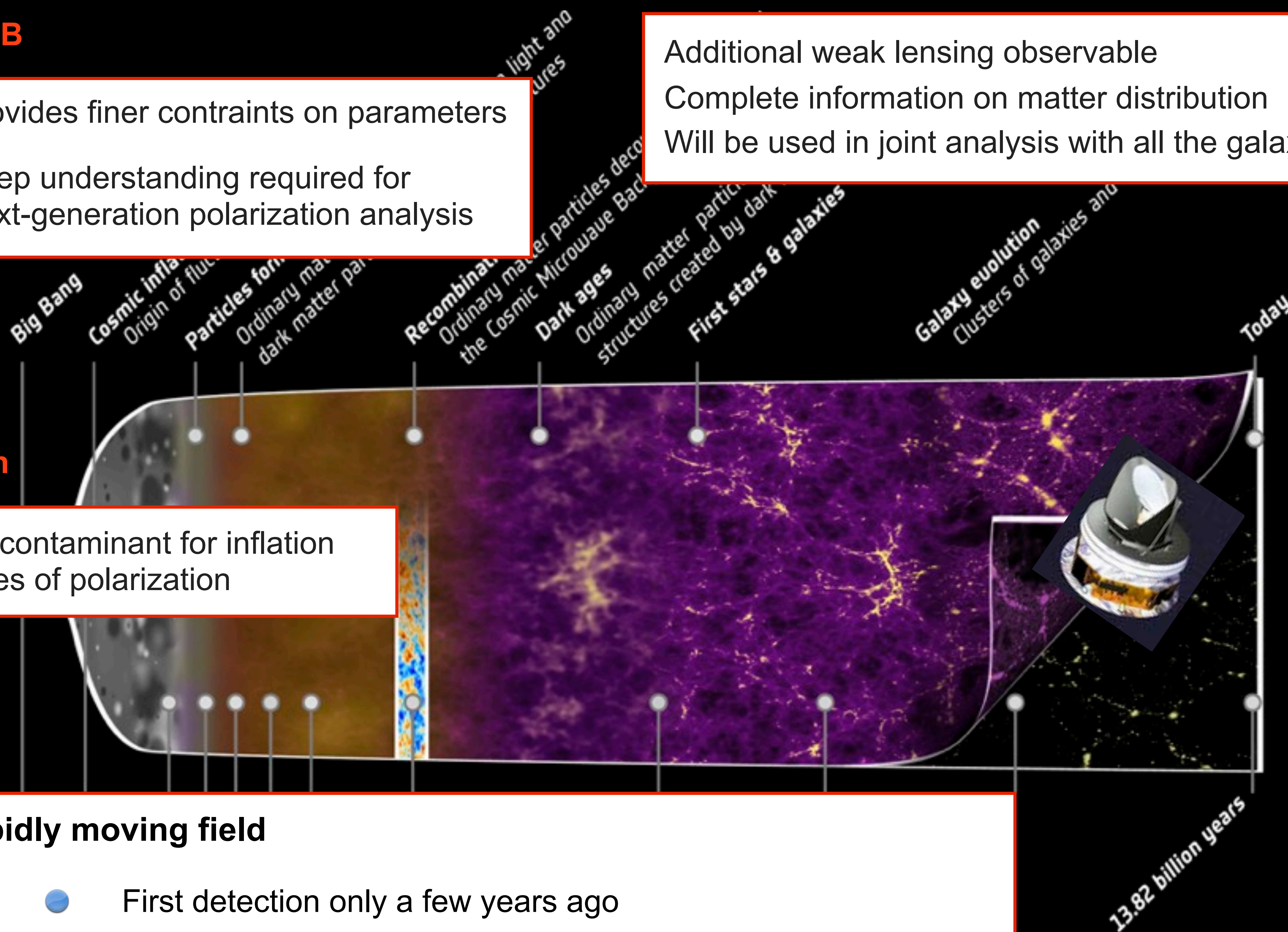
CMB

provides finer contraints on parameters

deep understanding required for
next-generation polarization analysis

Inflation

known contaminant for inflation
B-modes of polarization



Rapidly moving field

- First detection only a few years ago
- Planck full-sky lensing map available!

Large-scale structure needed