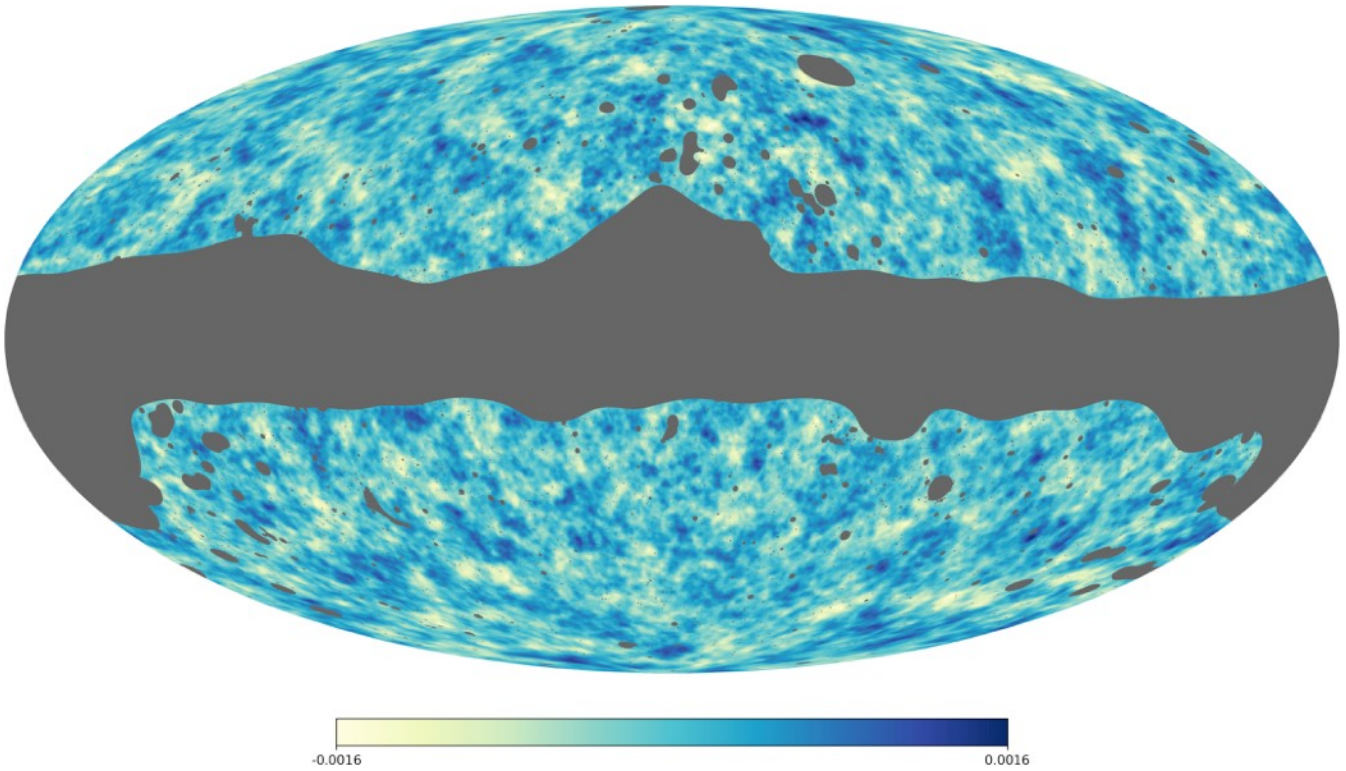
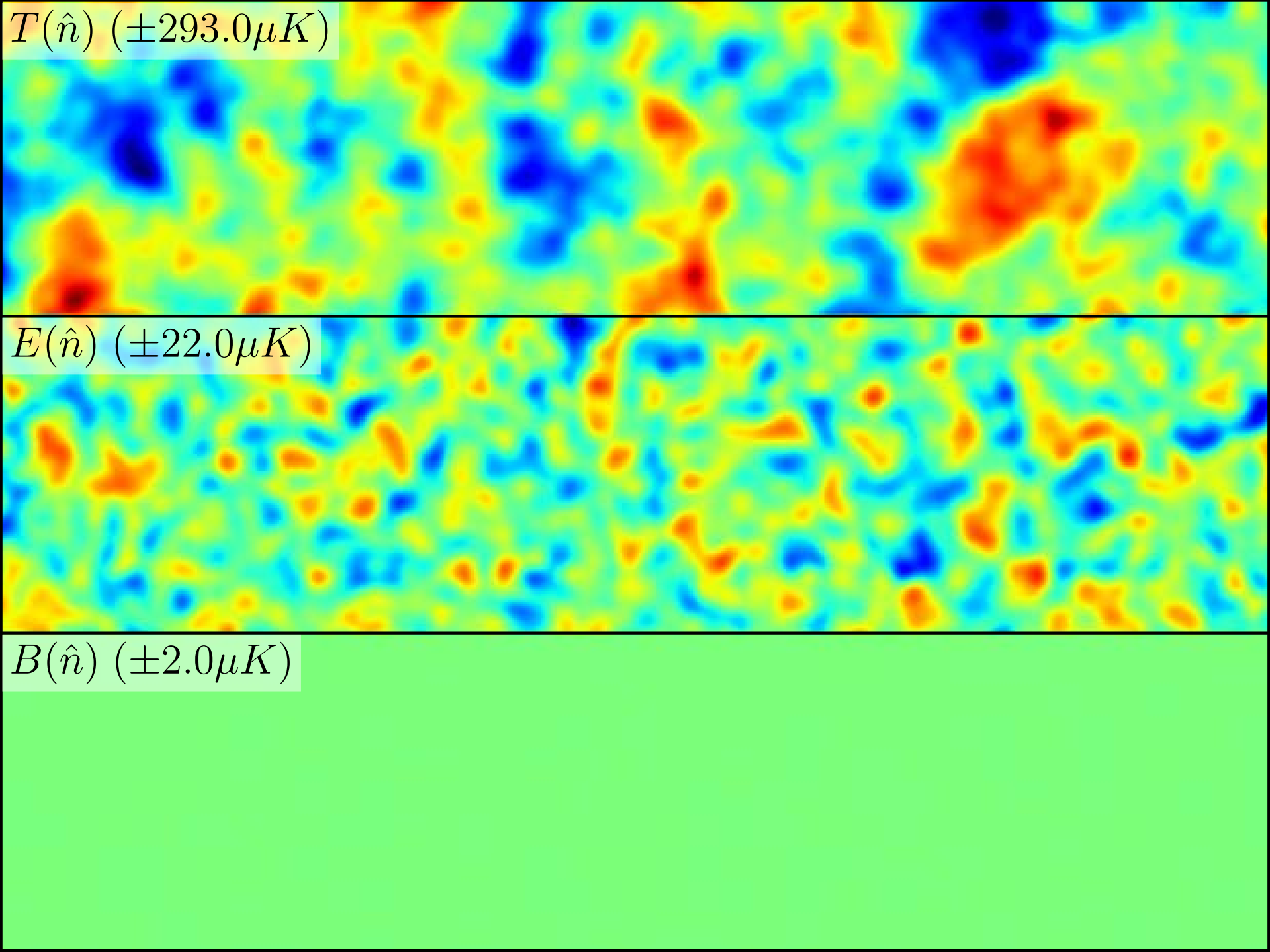
Planck 2018 CMB lensing

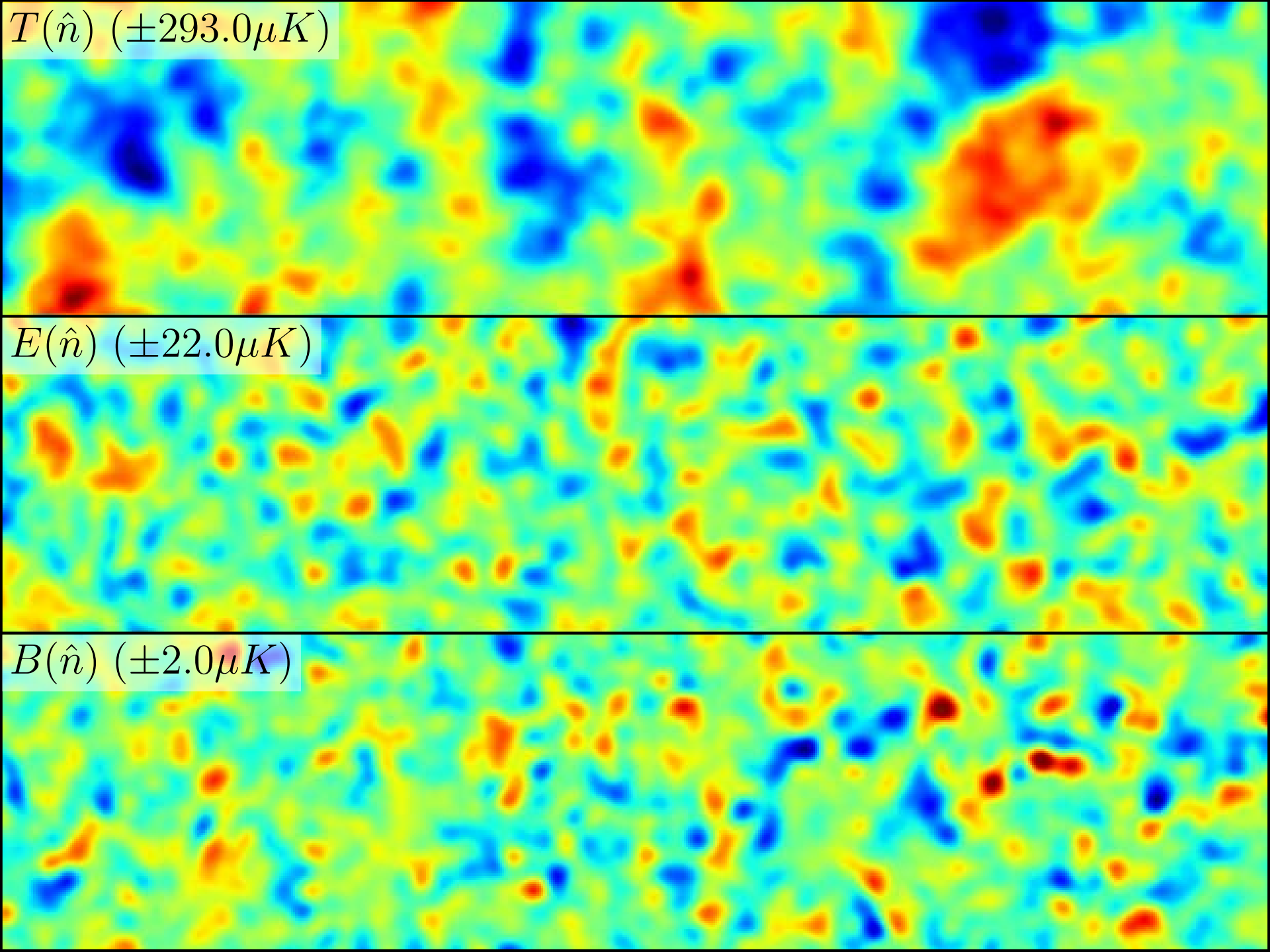
1807.06210



Julien Carron, University of Sussex

for the Planck Collaboration


$T(\hat{n})$ $(\pm 293.0 \mu K)$
$E(\hat{n})$ $(\pm 22.0 \mu K)$
$B(\hat{n})$ $(\pm 2.0 \mu K)$

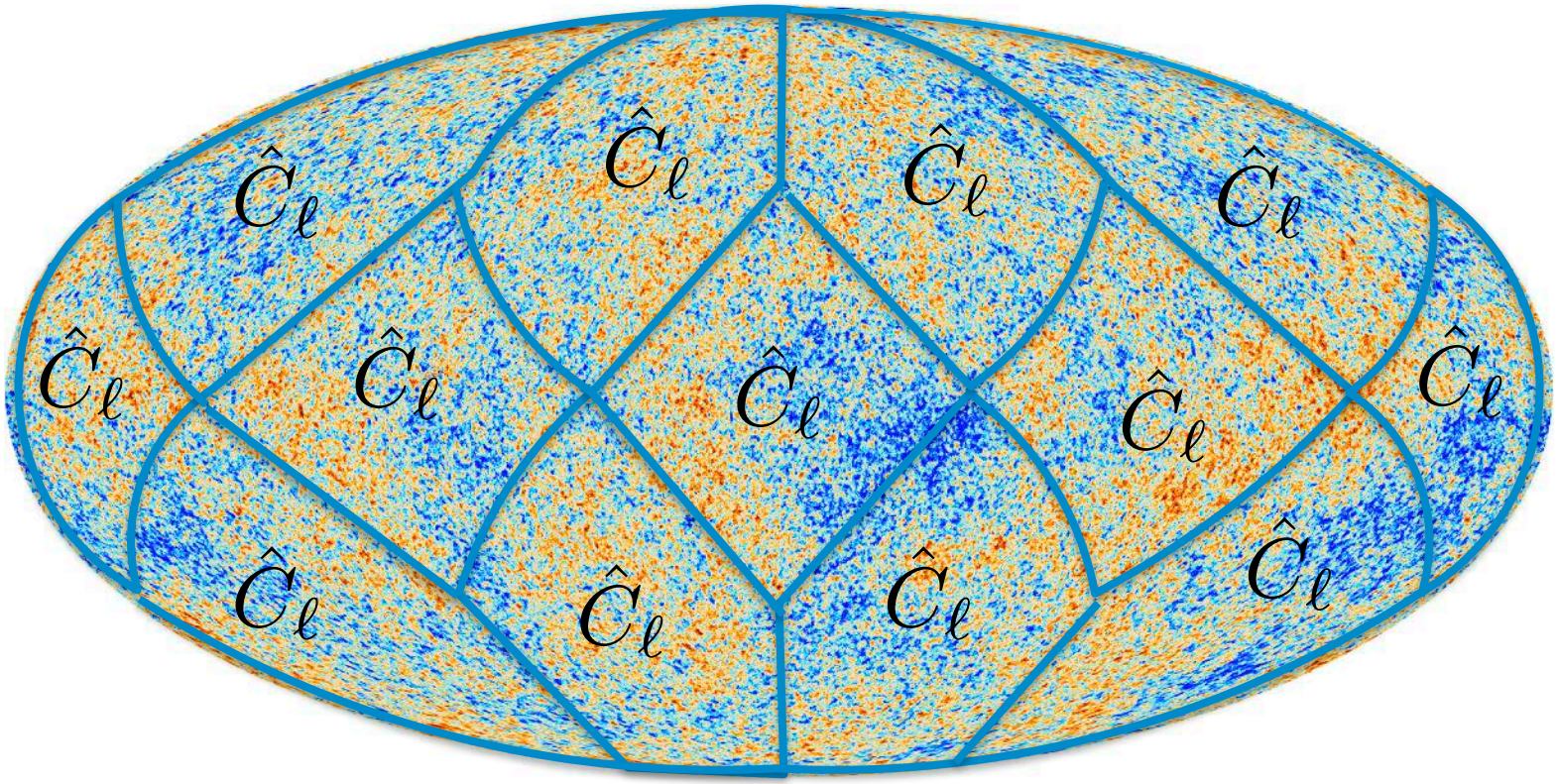

$T(\hat{n})$ $(\pm 293.0 \mu K)$
$E(\hat{n})$ $(\pm 22.0 \mu K)$
$B(\hat{n})$ $(\pm 2.0 \mu K)$

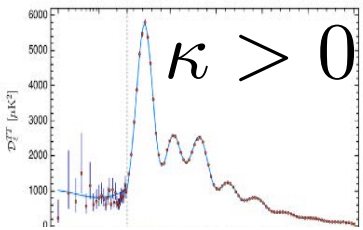
2018 lensing maps, band powers

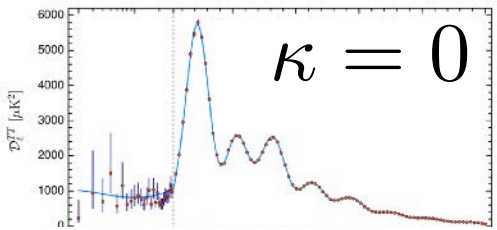
Lens quadratic estimation

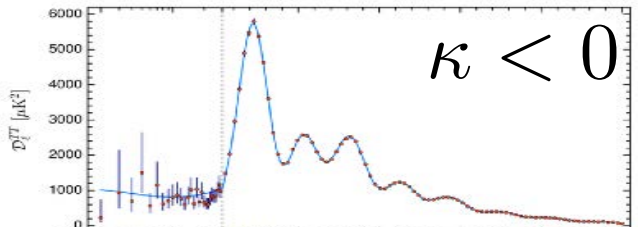
local magnification and shear:

$$C_{\boldsymbol{\ell}} = C^0_\ell \left[1 + \kappa \frac{\partial \ln \ell^2 C^0_\ell}{\partial \ln \ell} + \gamma \cos(2\theta_\ell) \frac{\partial \ln C^0_\ell}{\partial \ln \ell}\right]$$









Lens quadratic estimation

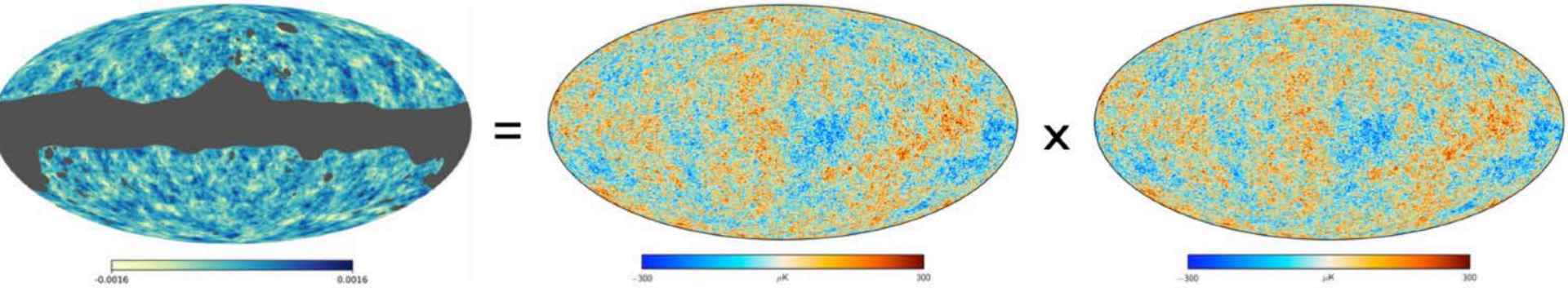
- Noisy lensing estimates from quadratic CMB combinations:

$$\hat{\phi}_{LM} = \frac{(-1)^M}{2} \frac{1}{\mathcal{R}_L^{XY}} \sum_{l_1 m_1, l_2 m_2} \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \left[\mathcal{W}_{l_1 l_2 L}^{XY}\right]^* \bar{X}_{l_1 m_1} \bar{Y}_{l_2 m_2}$$

Normalisation

Known lensing-induced correlations

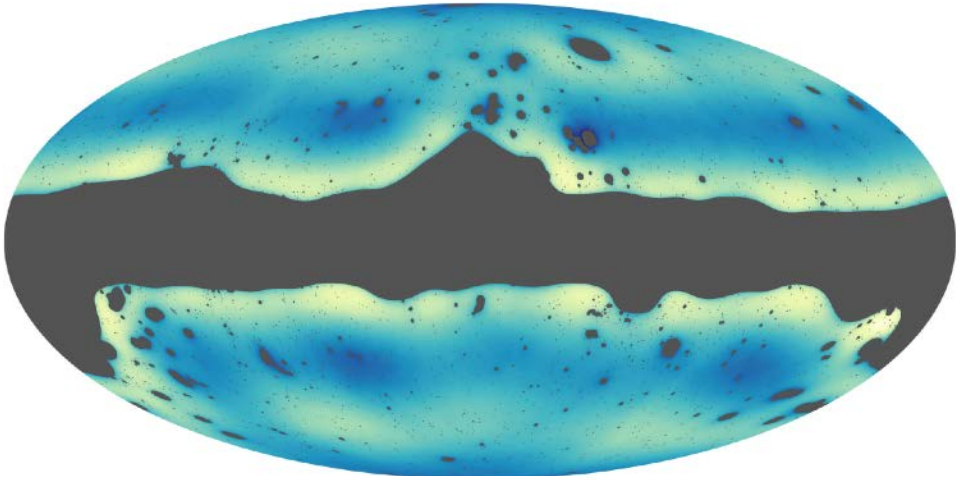
Inverse-variance-weighted CMB fields



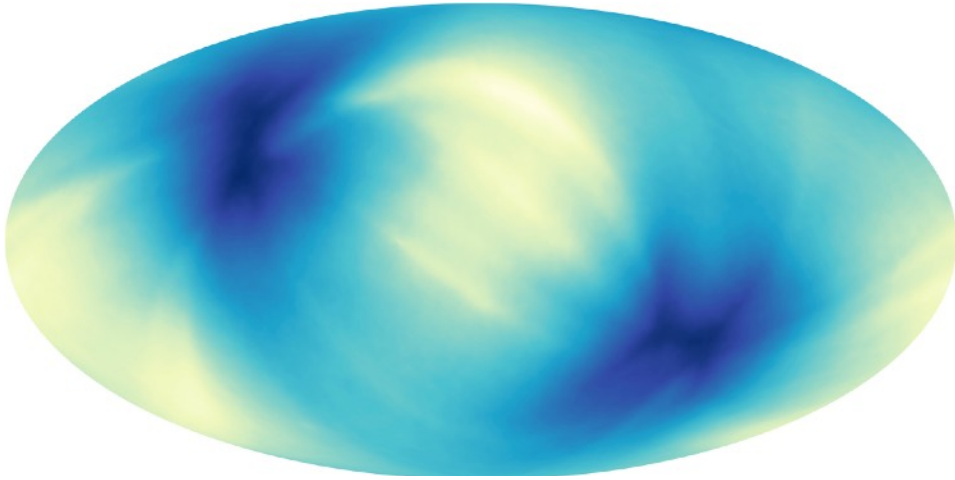
- We use foreground-cleaned (SMICA) maps

Lensing maps biases ('mean-fields')

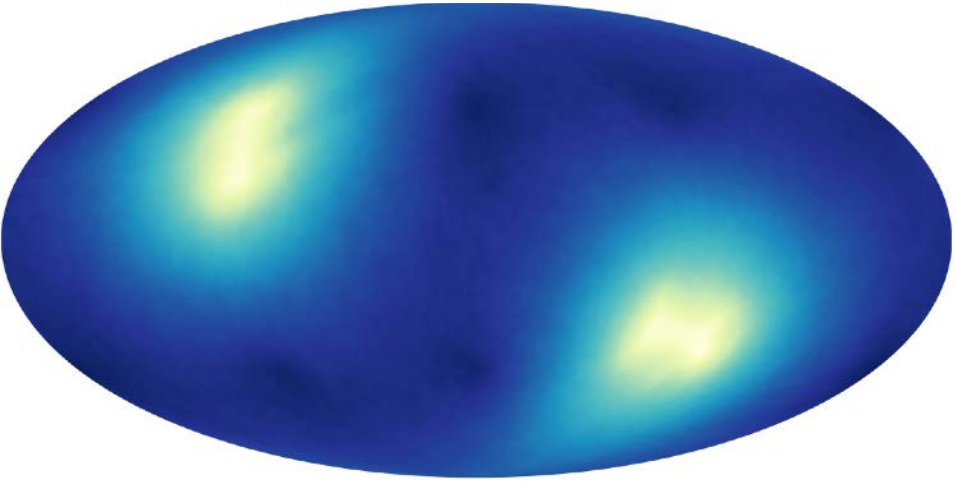
Mask



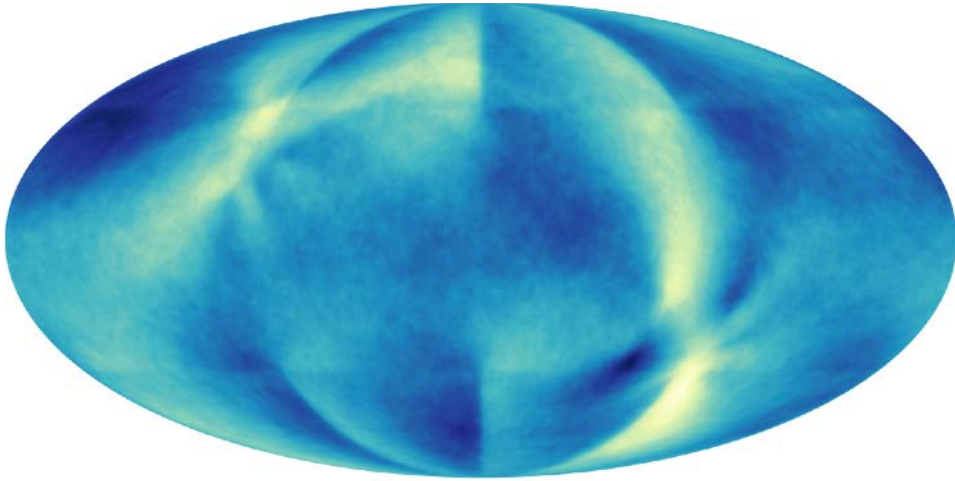
Noise



Beams

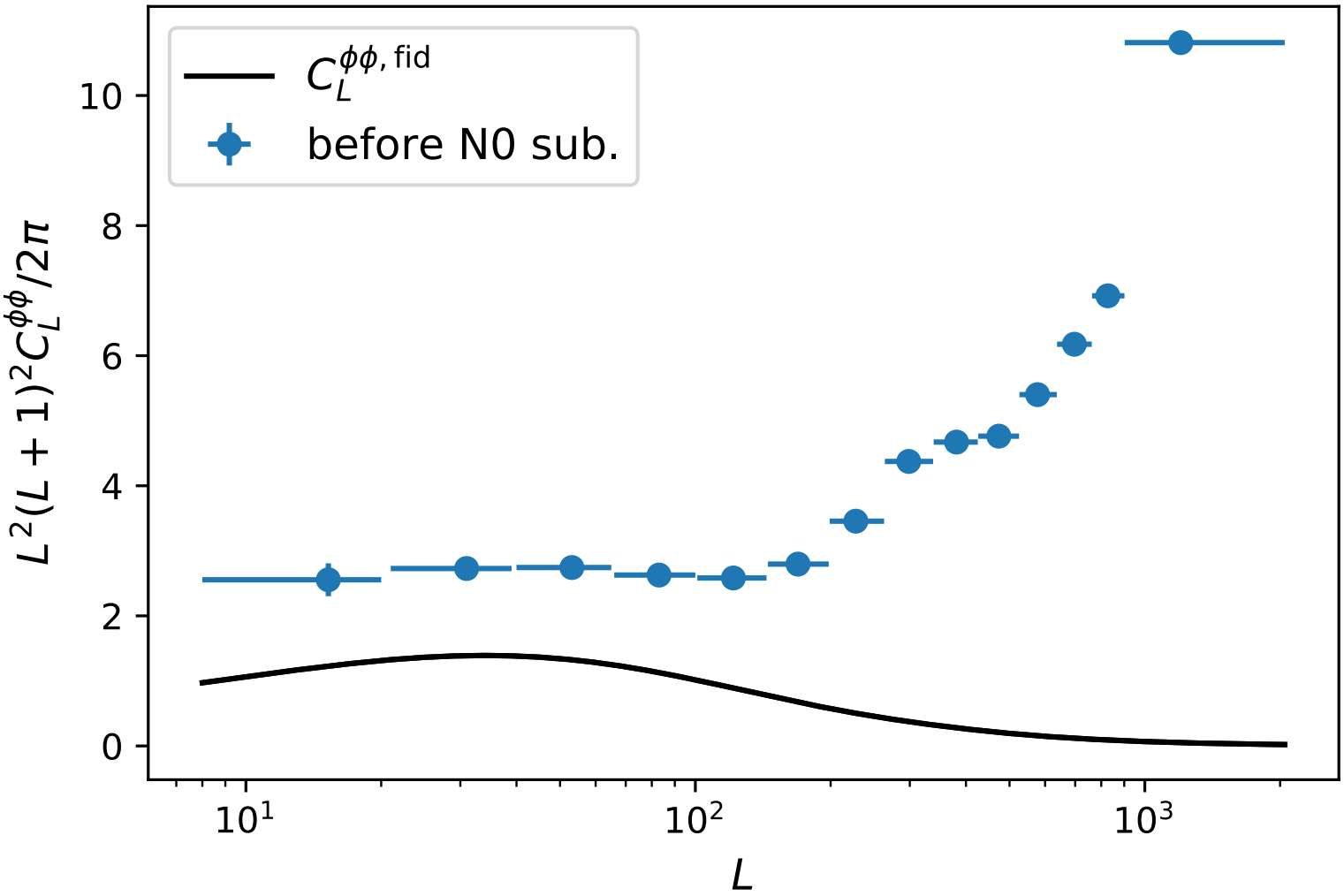


Pixelization



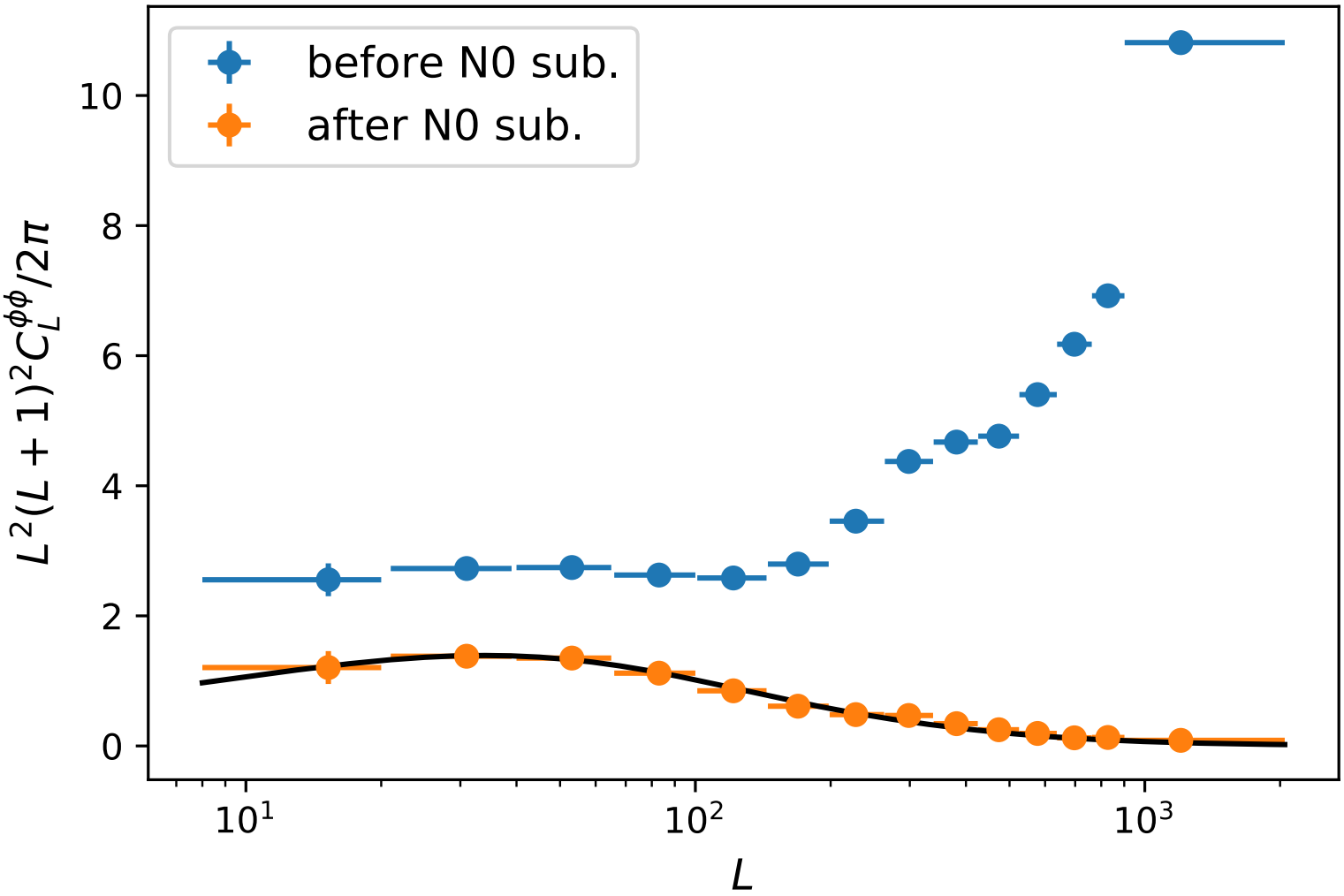
Lensing reconstruction

- *Raw spectrum*



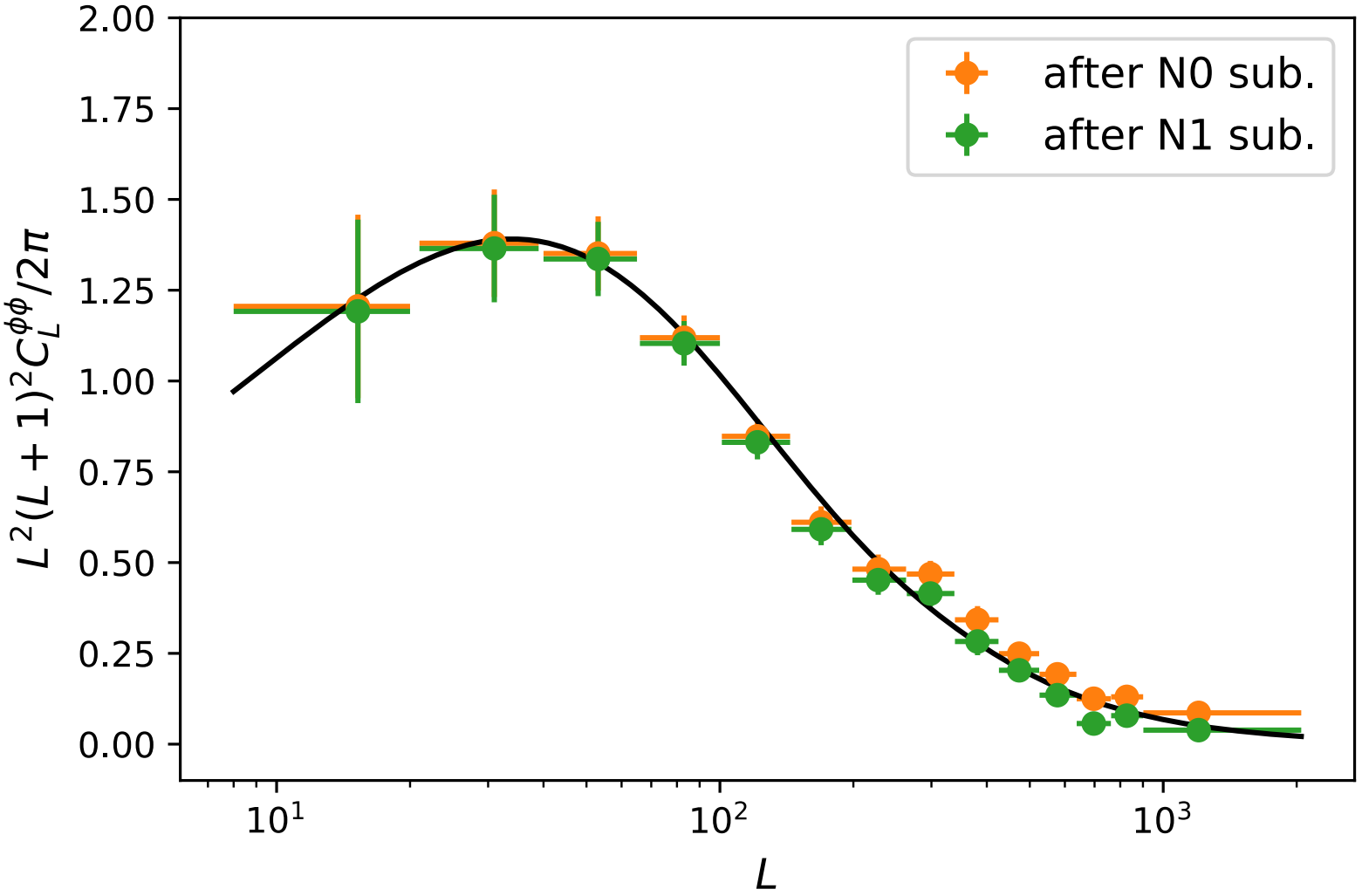
Lensing reconstruction

- *Noise debiasing (N0, Gauss. CMB and noise fluct.)*



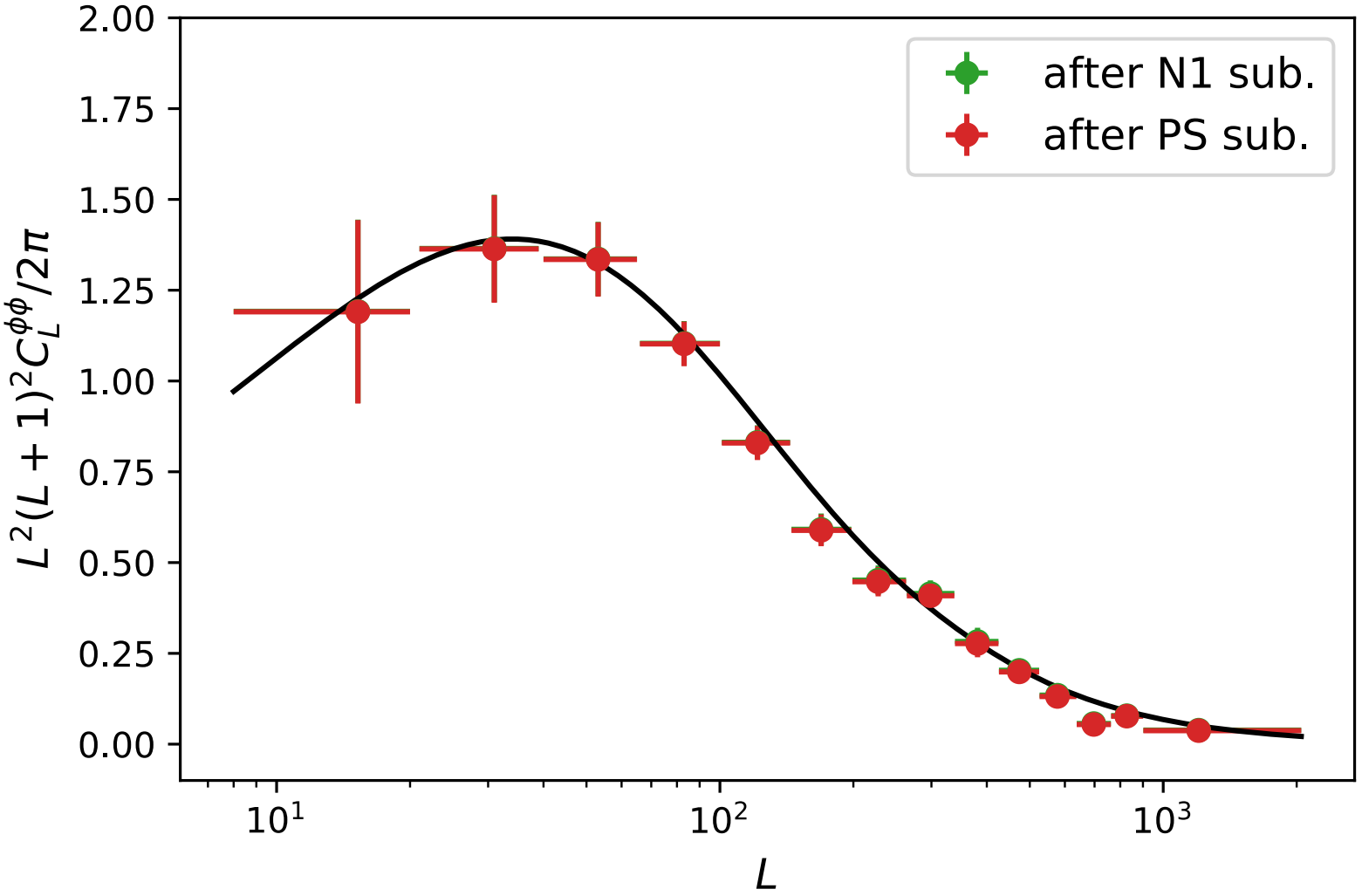
Lensing reconstruction

- *Secondary trispectrum debiasing (N1)*



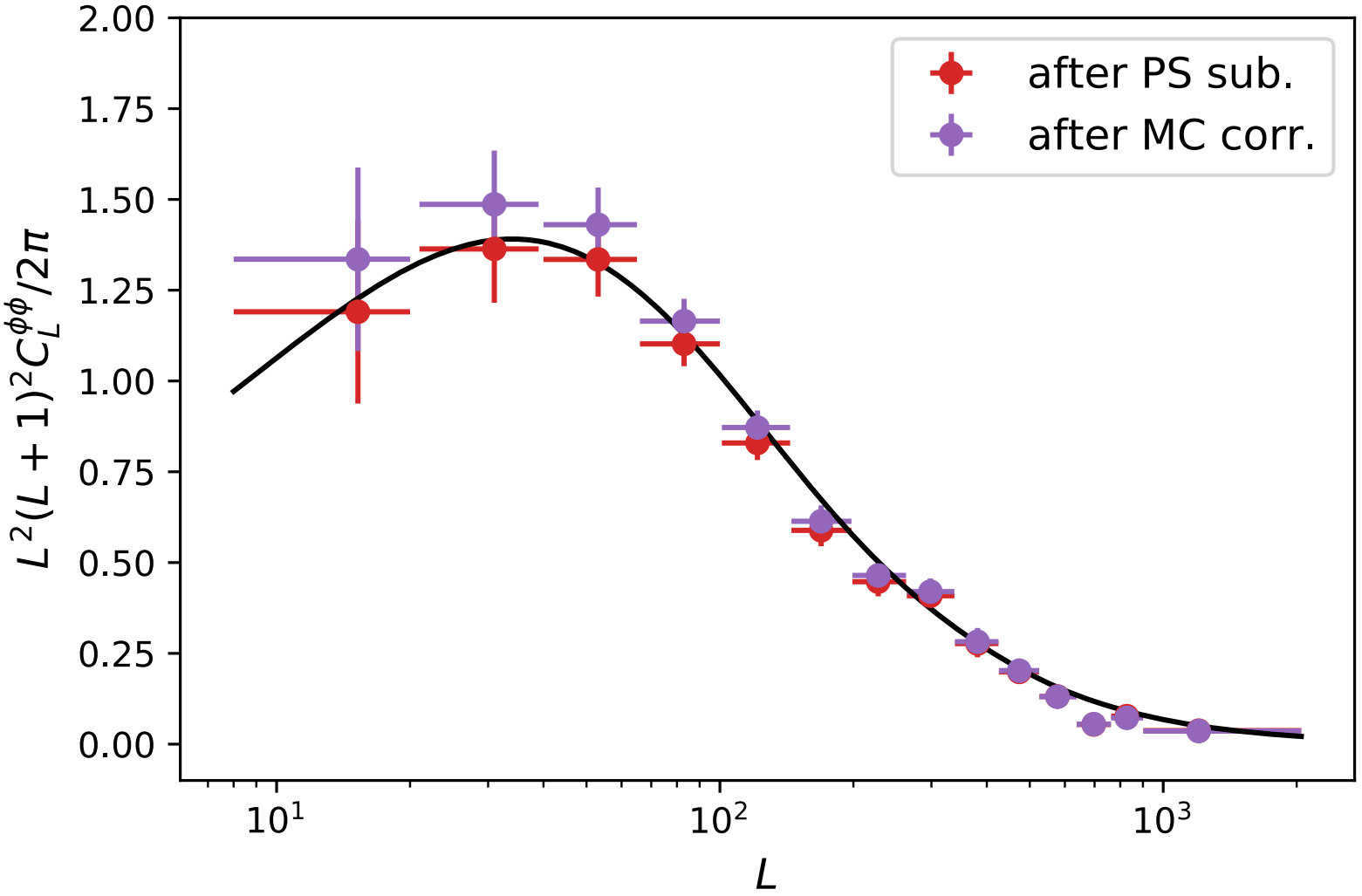
Lensing reconstruction

- *Point source debiasing (other fgds also under control)*

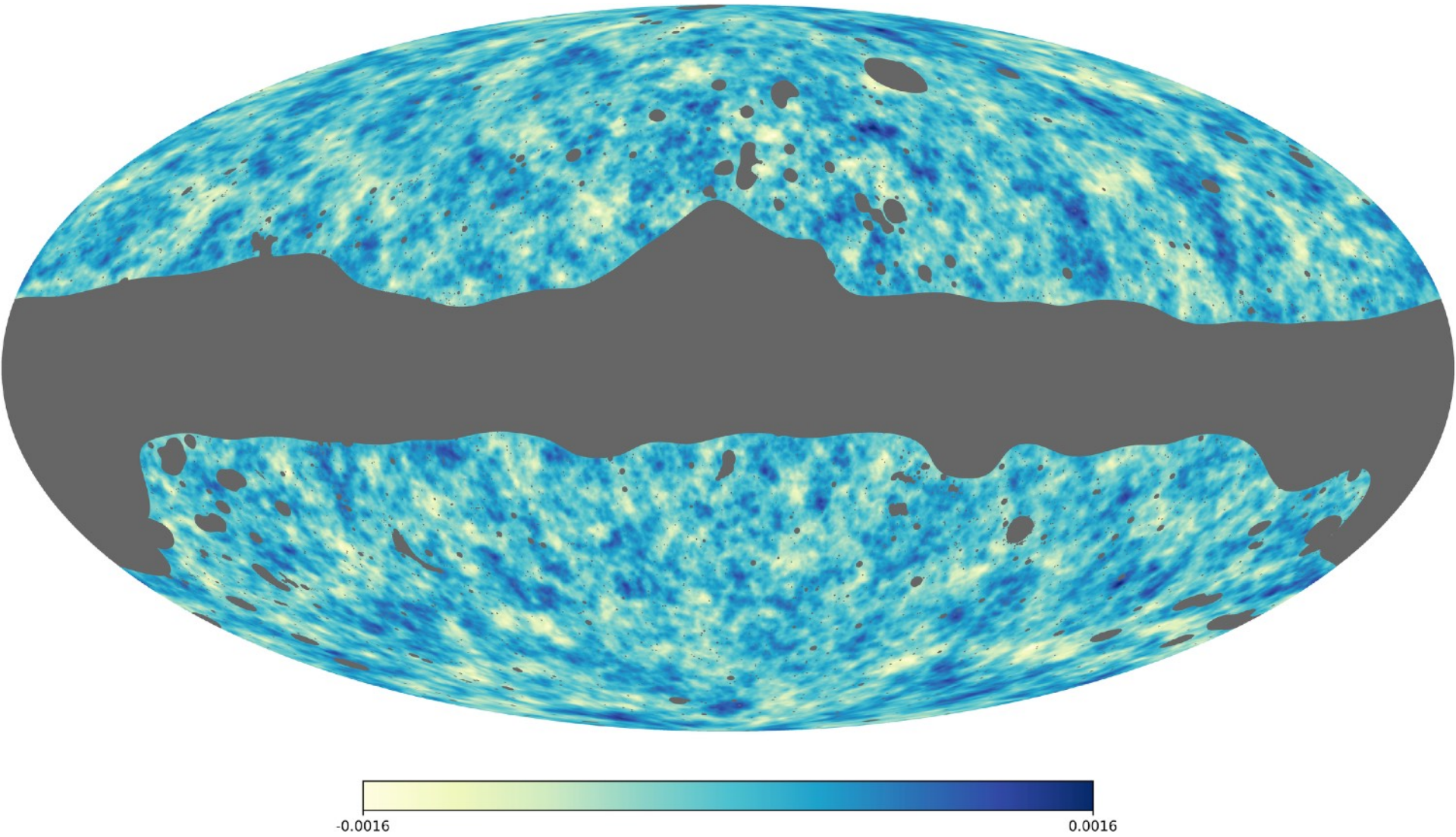


Lensing reconstruction

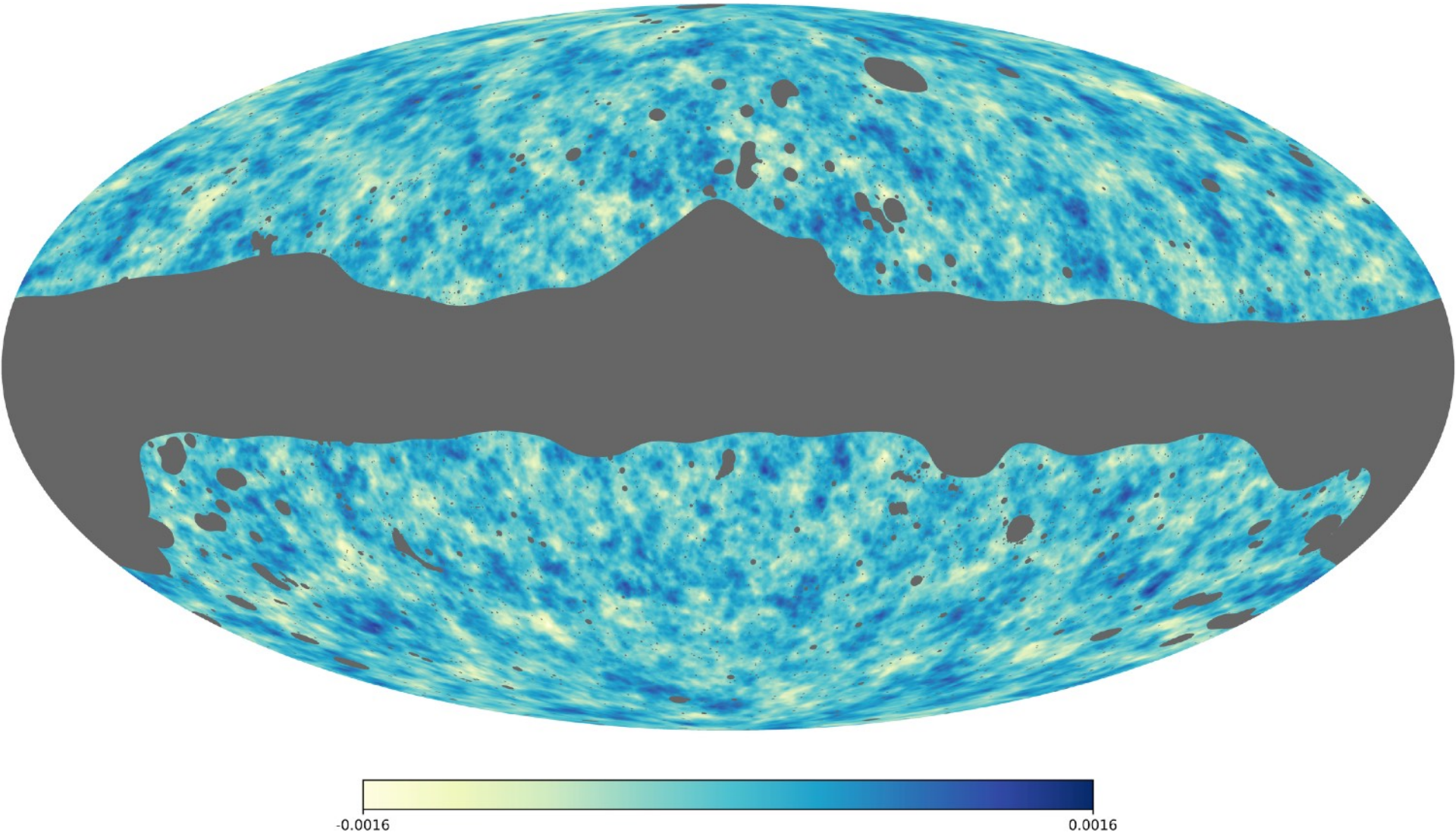
- *Monte-Carlo correction*
  (from masking and other non-idealities corrections)



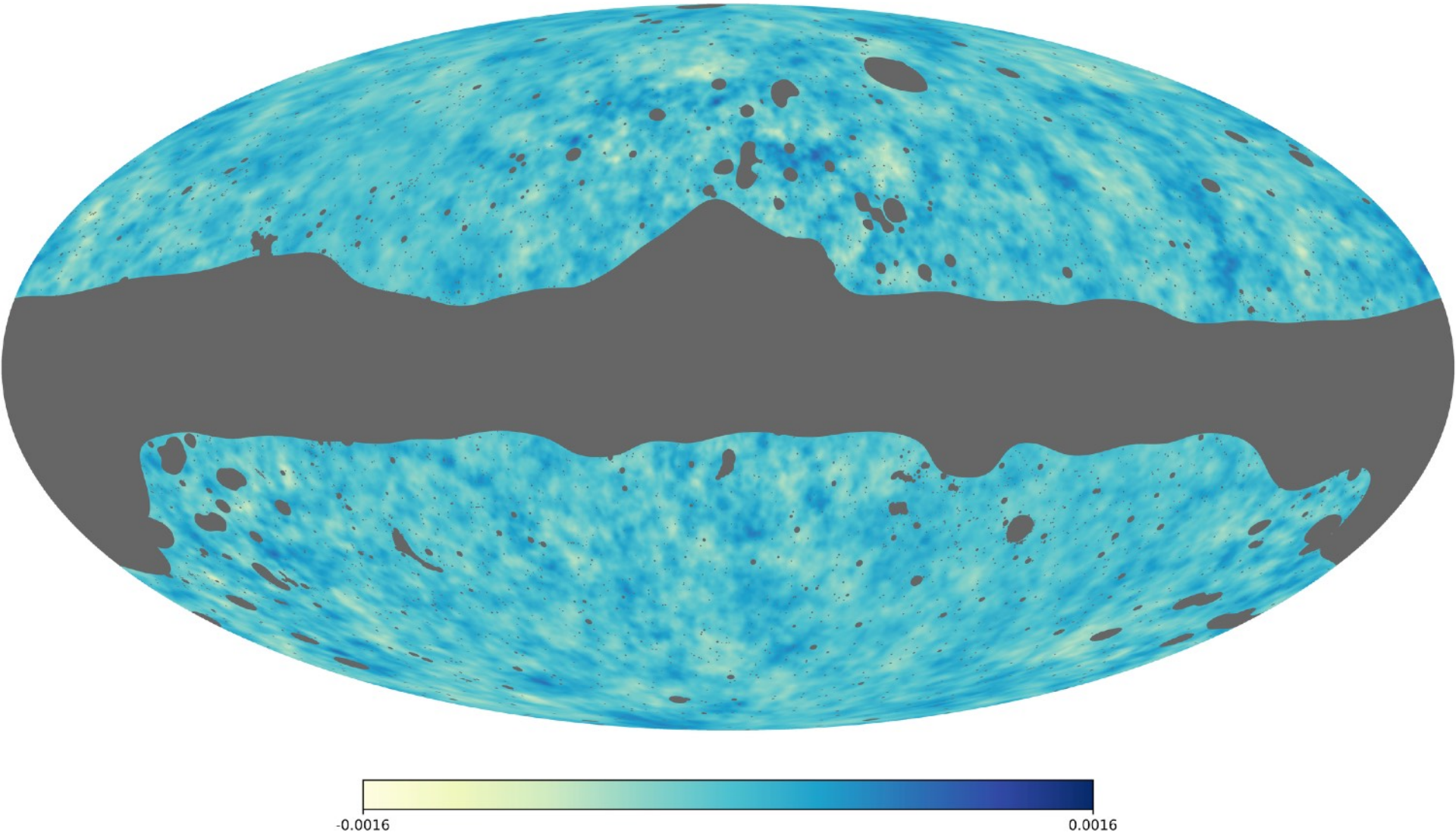
2018 lensing map. MV



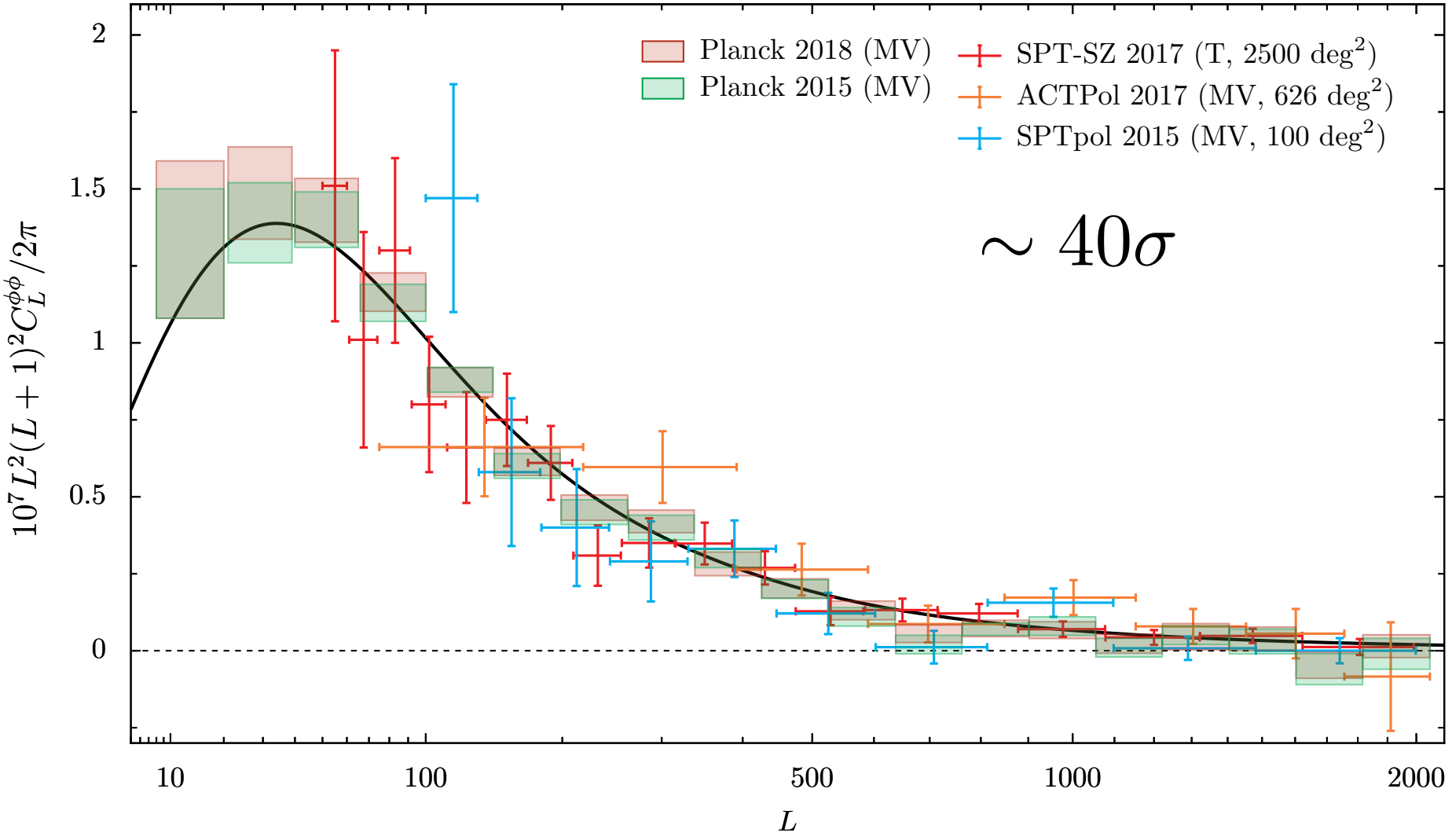
2018 lensing map. TT



2018 lensing map. Pol.

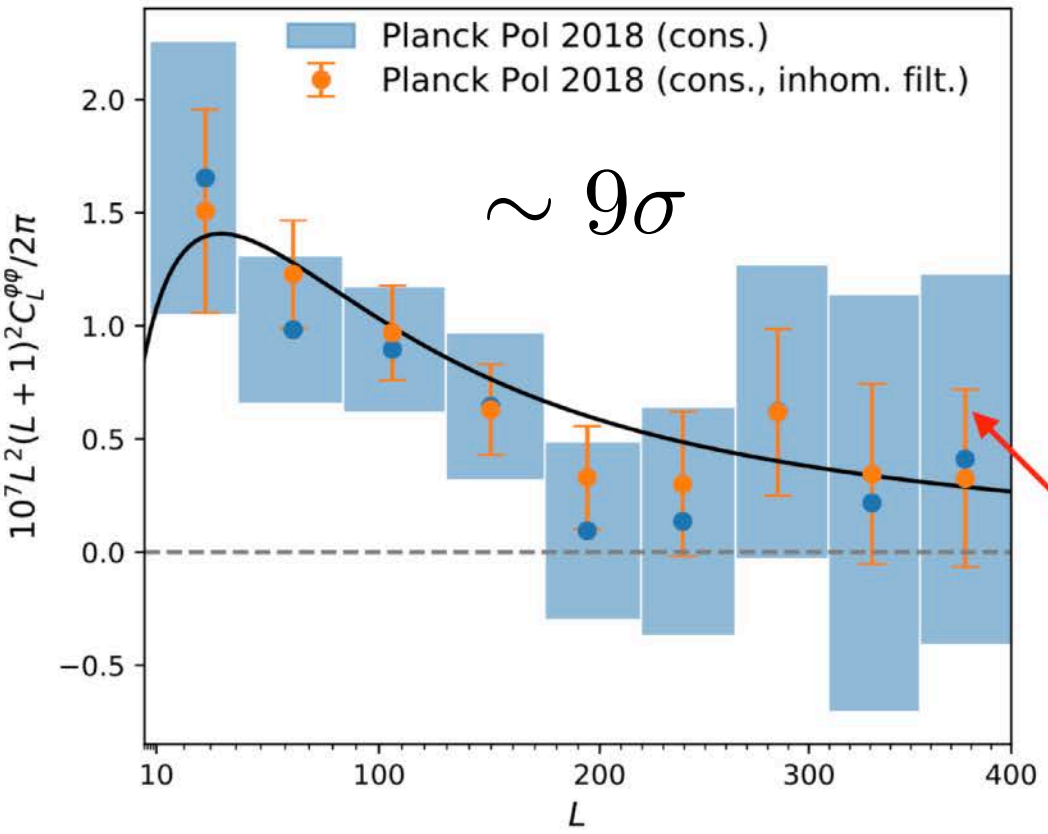


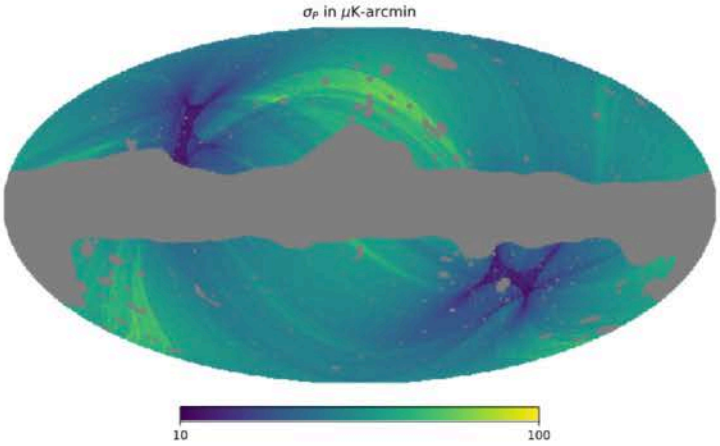
Spectrum band-powers



Polarisation band-powers

- *Improved inverse-variance filtering*

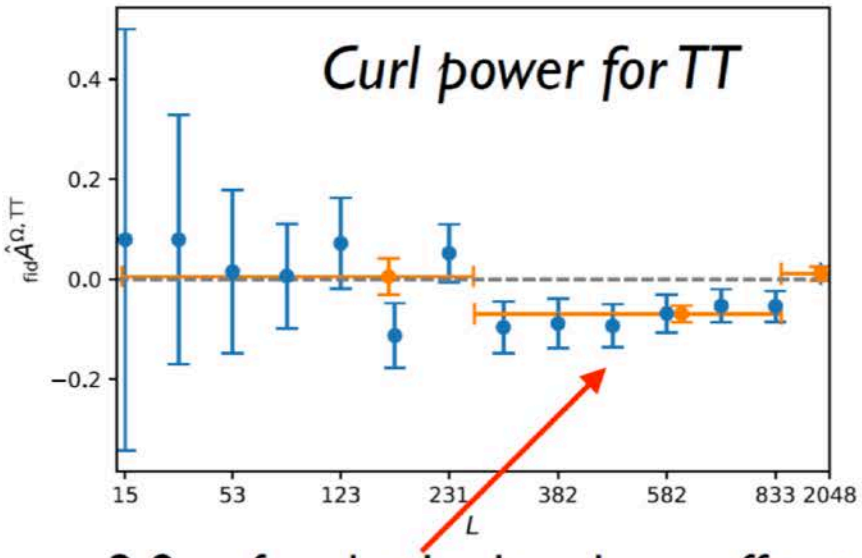




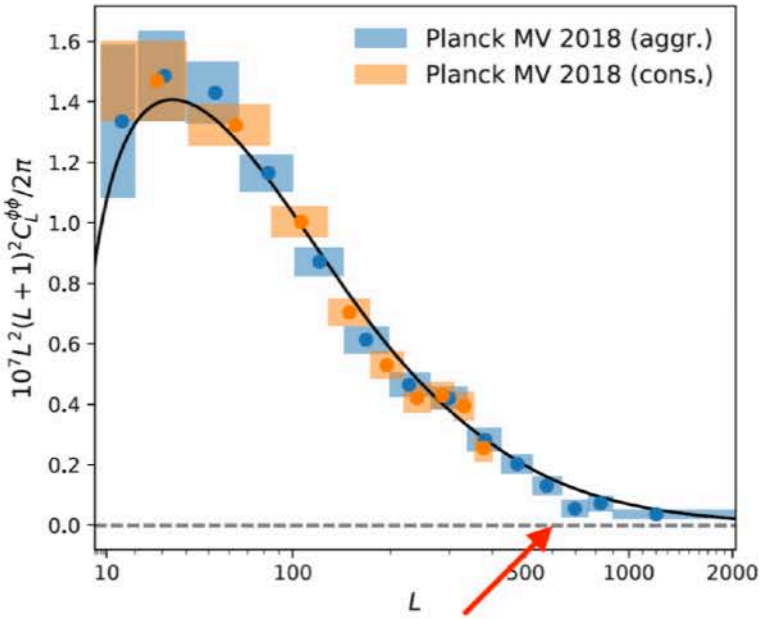
Significant improvement in polarization-only error bars by accounting for noise anisotropy in filters

- *(lensing response become position dependent)*

TT Band powers 'features'



- 2.9σ after look-elsewhere effects
- Specific to *TT* estimator
- Some sensitivity to sky region
  - *Closer to zero at ecliptic poles but not statistically significant*



- Only anomalous at 5% in *TT*
- Not seen in cross-correlation
- Lower in HM1 than HM2 (but difference ok statistically)

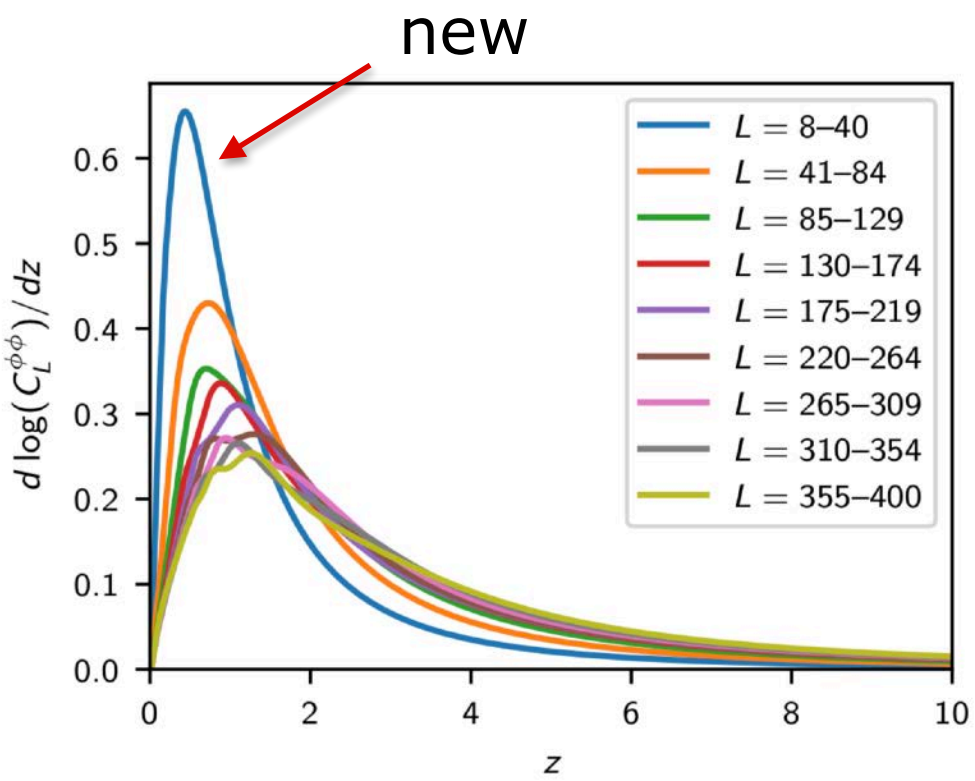
"Conservative" reconstruction L=8–400 robust to many tests

CMB-lensing parameter constraints

Main likelihood changes

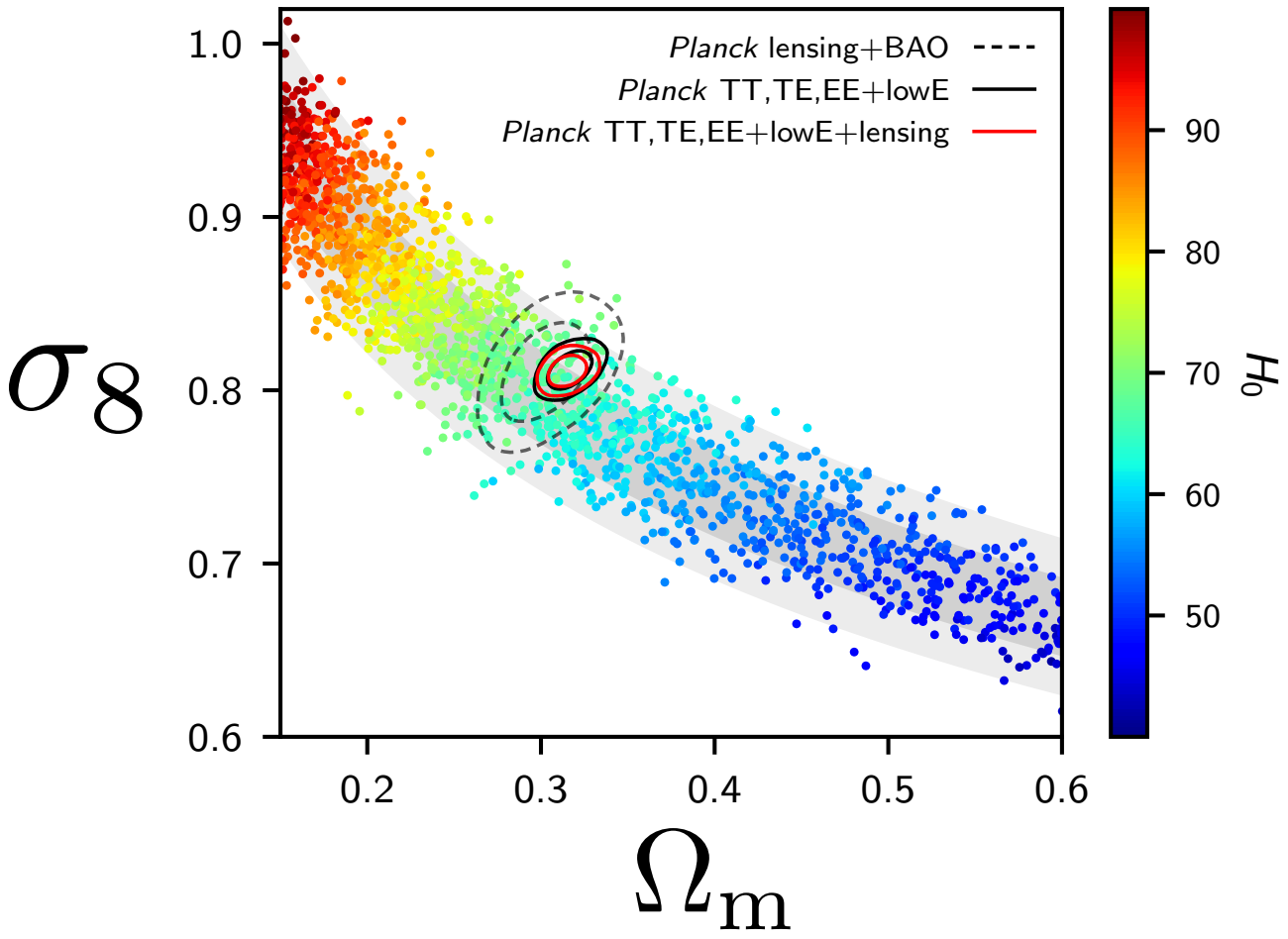
- Likelihood extended to

$$L_{\rm min} = 8 \ ({\rm was} \ L_{\rm min} = 40)$$



- Likelihood is now CMB-marginalized.
  (independent of cosmology-fit to CMB spectra)

Parameter constraints



Planck lensing+BAO:

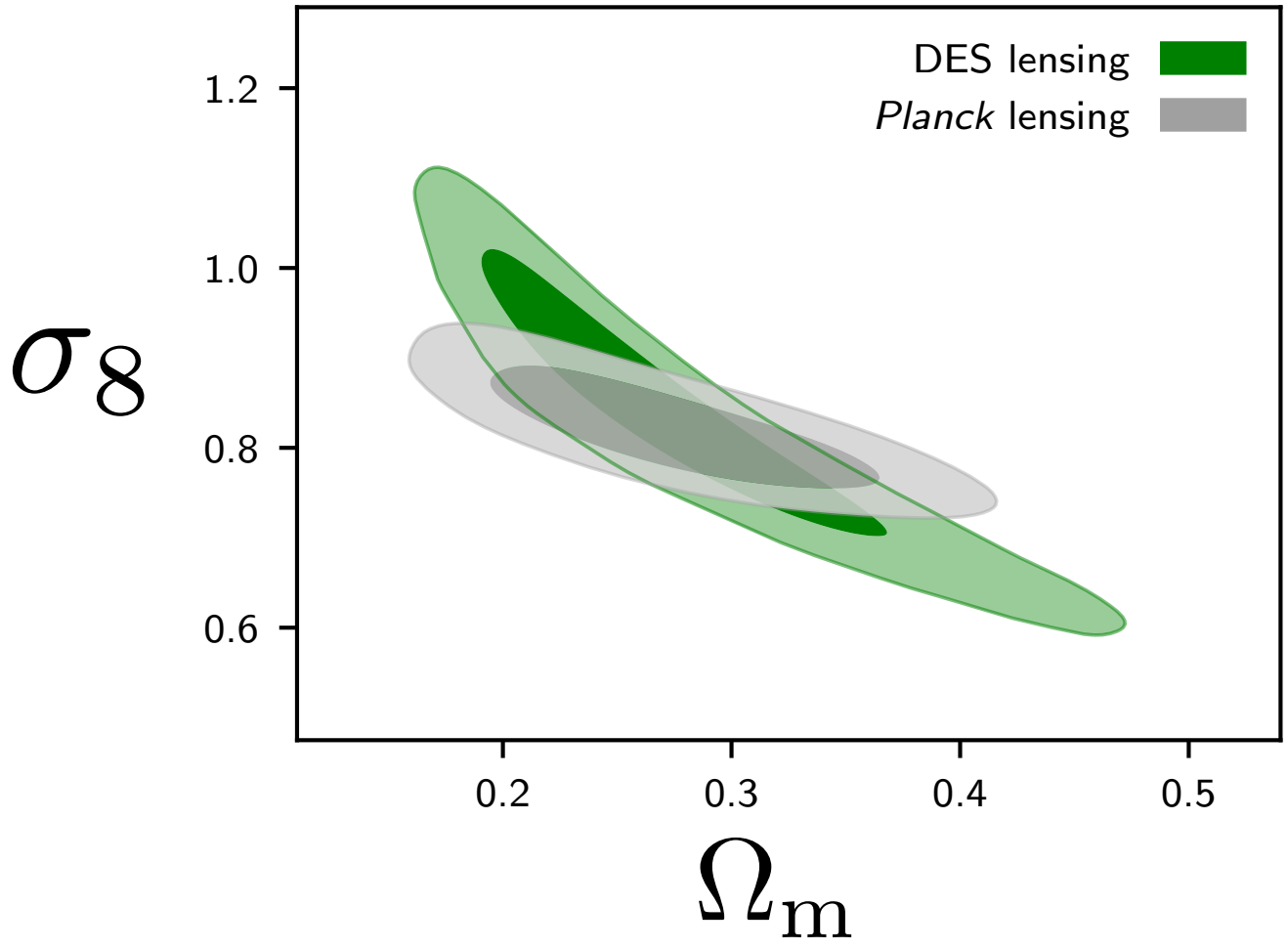
$\sigma_8 = 0.811 \pm 0.019$

$H_0 = 67.9^{+1.2}_{-1.3}\,\mathrm{km\,s^{-1}\,Mpc^{-}}$

$\Omega_{\rm m} = 0.303^{+0.016}_{-0.018}$

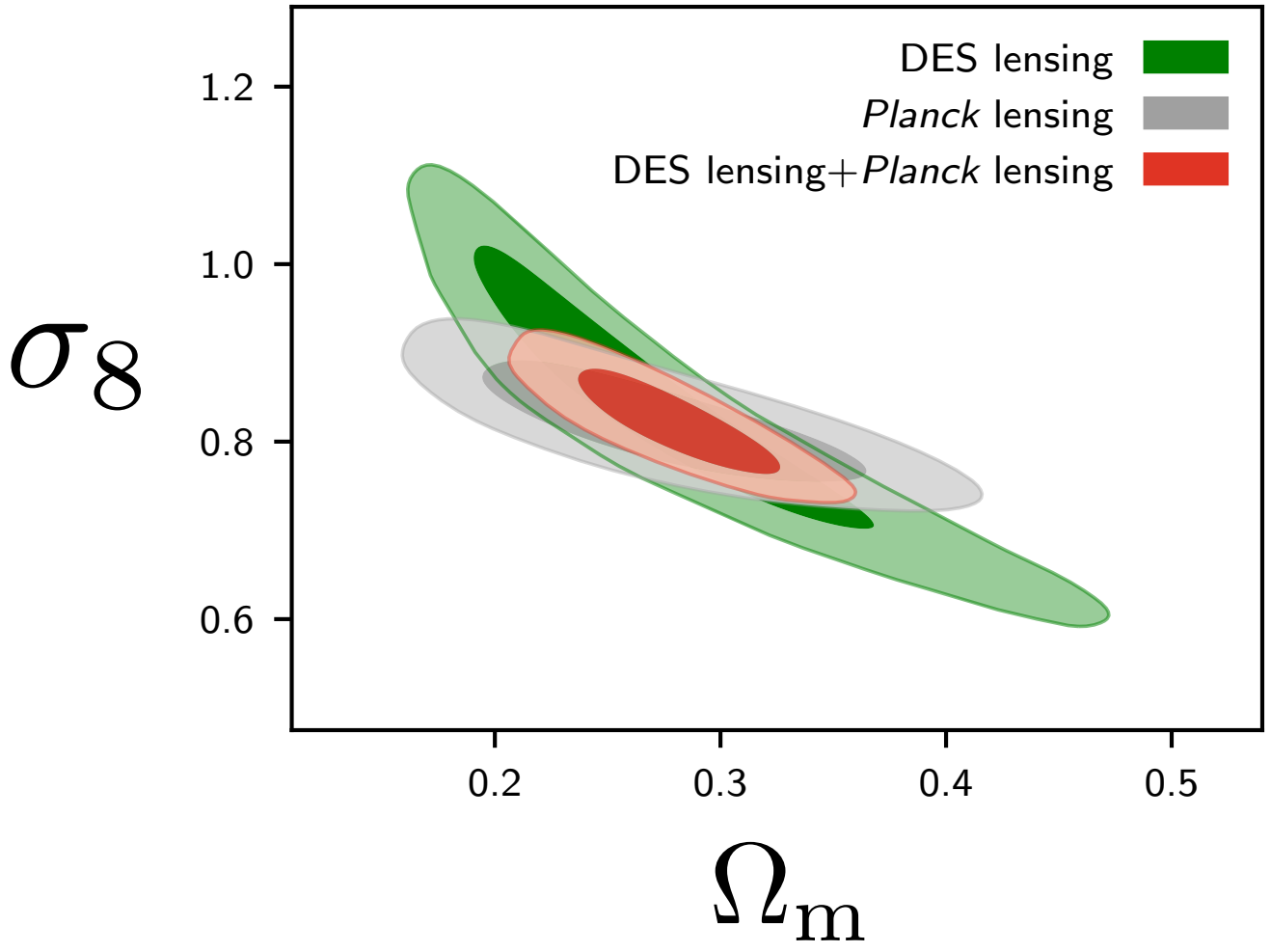
CMB lensing best measures $\sim \sigma_8 \Omega_m^{0.25} = 0.589 \pm 0.020.$
(with weak priors)

Parameter constraints

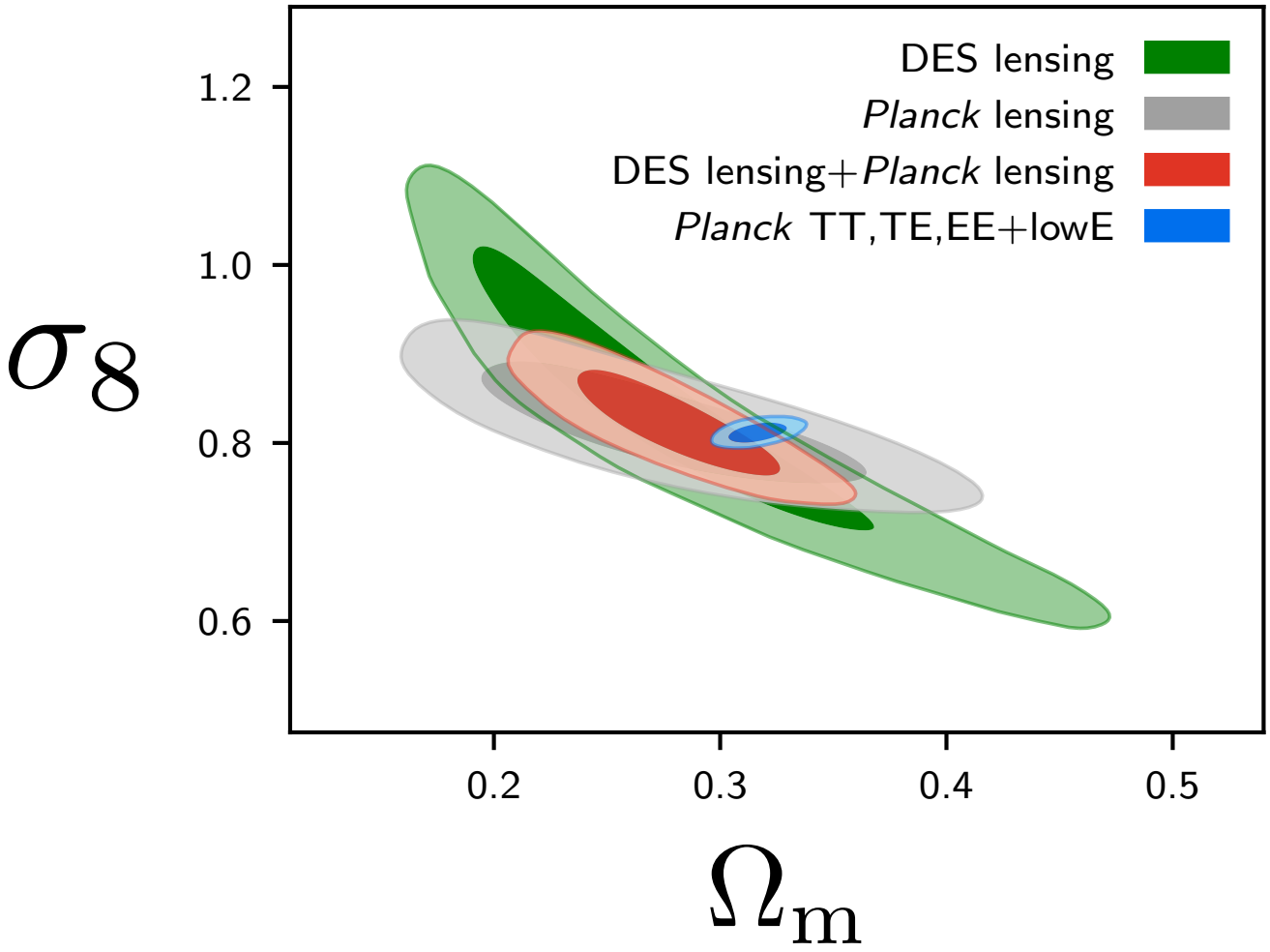


Planck lensing more powerful than DES lensing

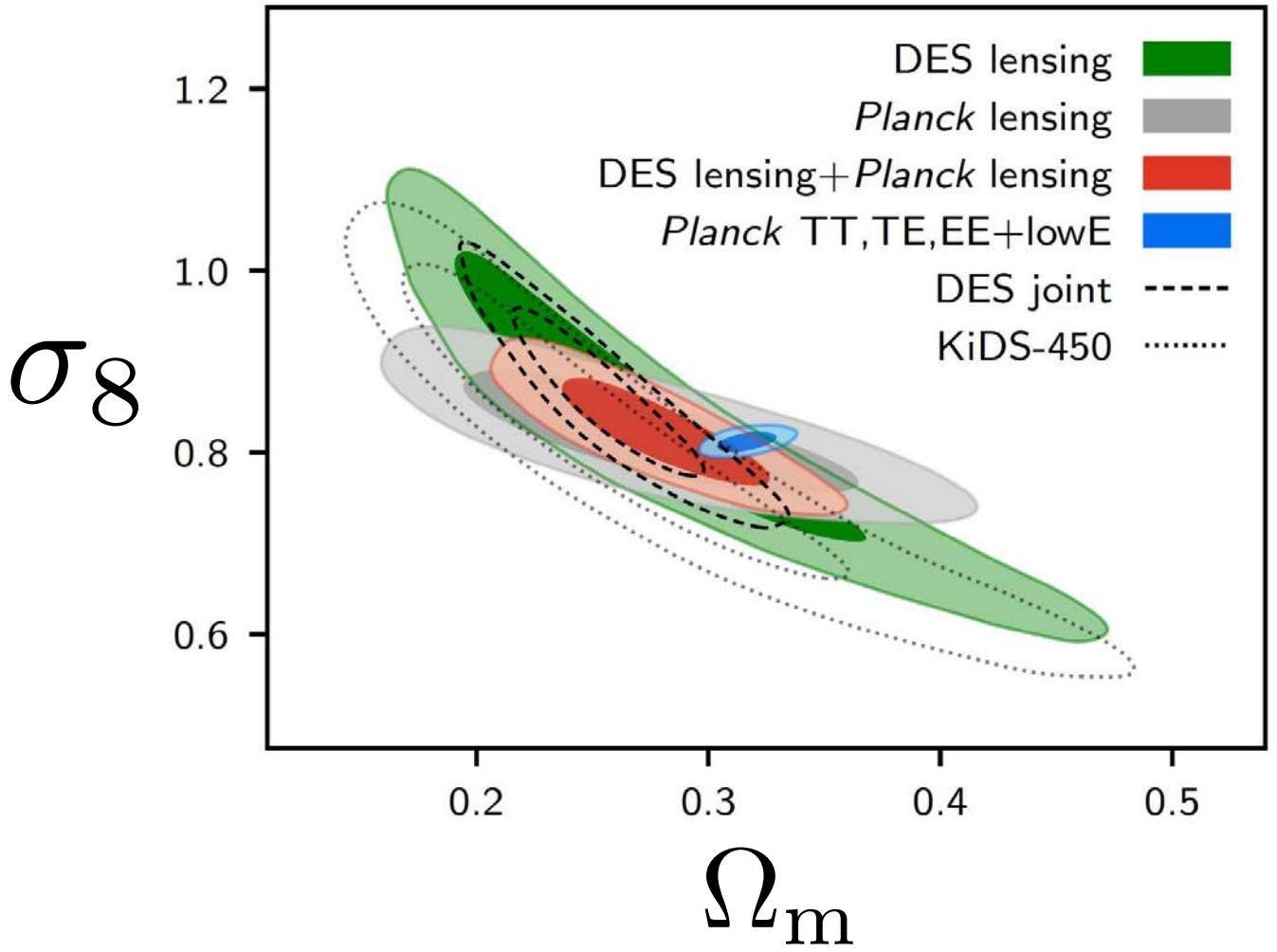
Parameter constraints



Parameter constraints



Parameter constraints

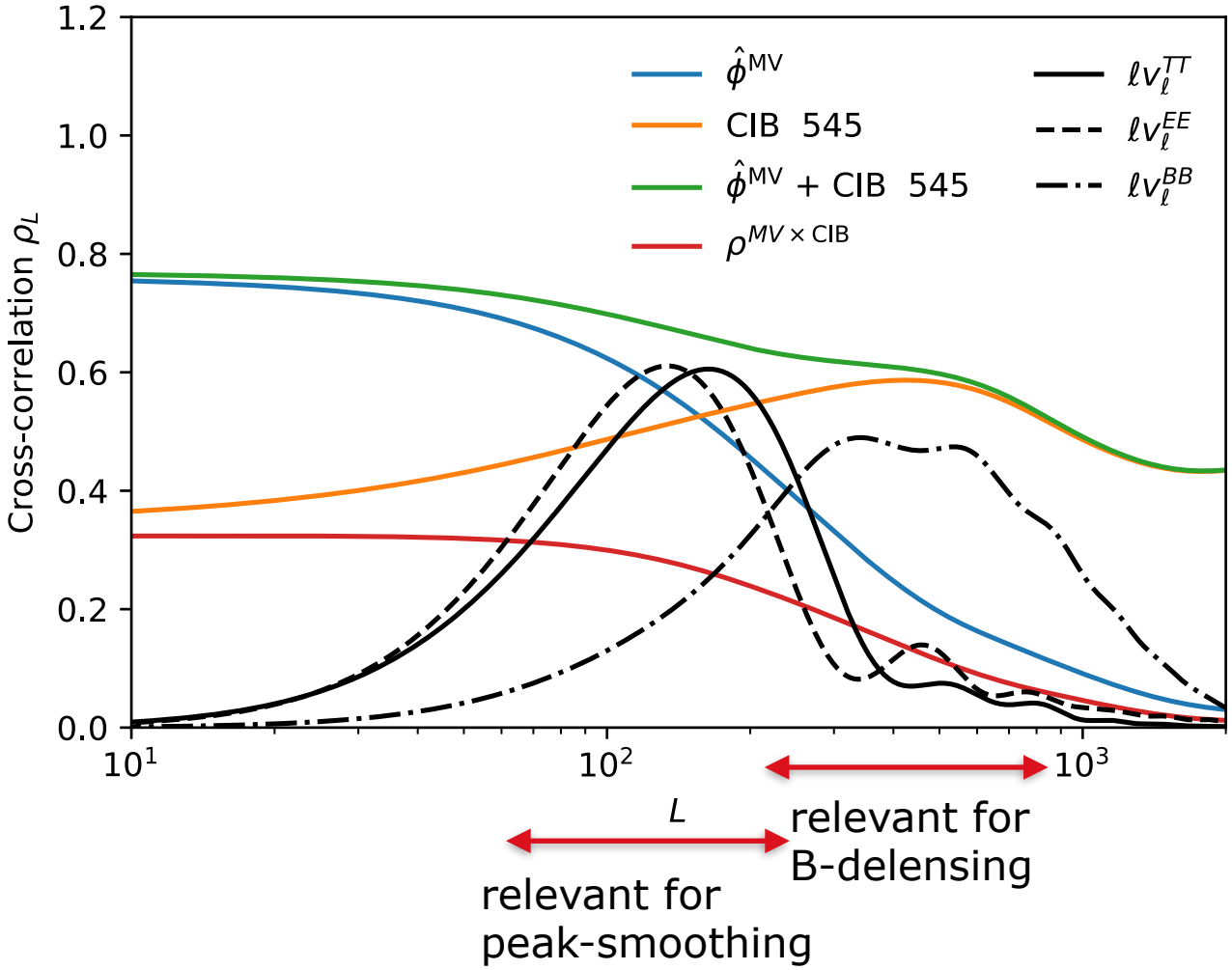


Slight tension with DES clustering

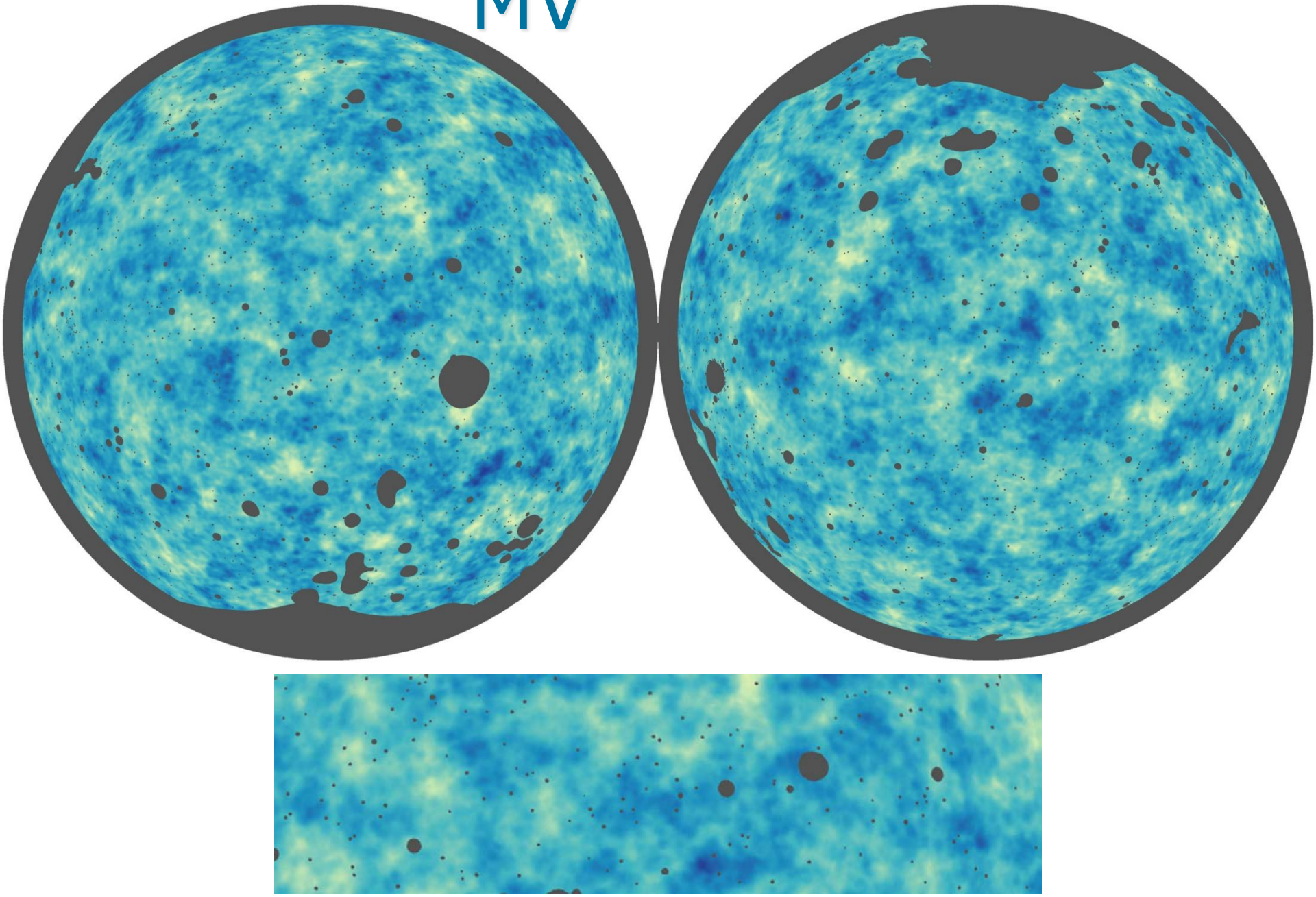
Combination with CIB, delensing

Combination with CIB

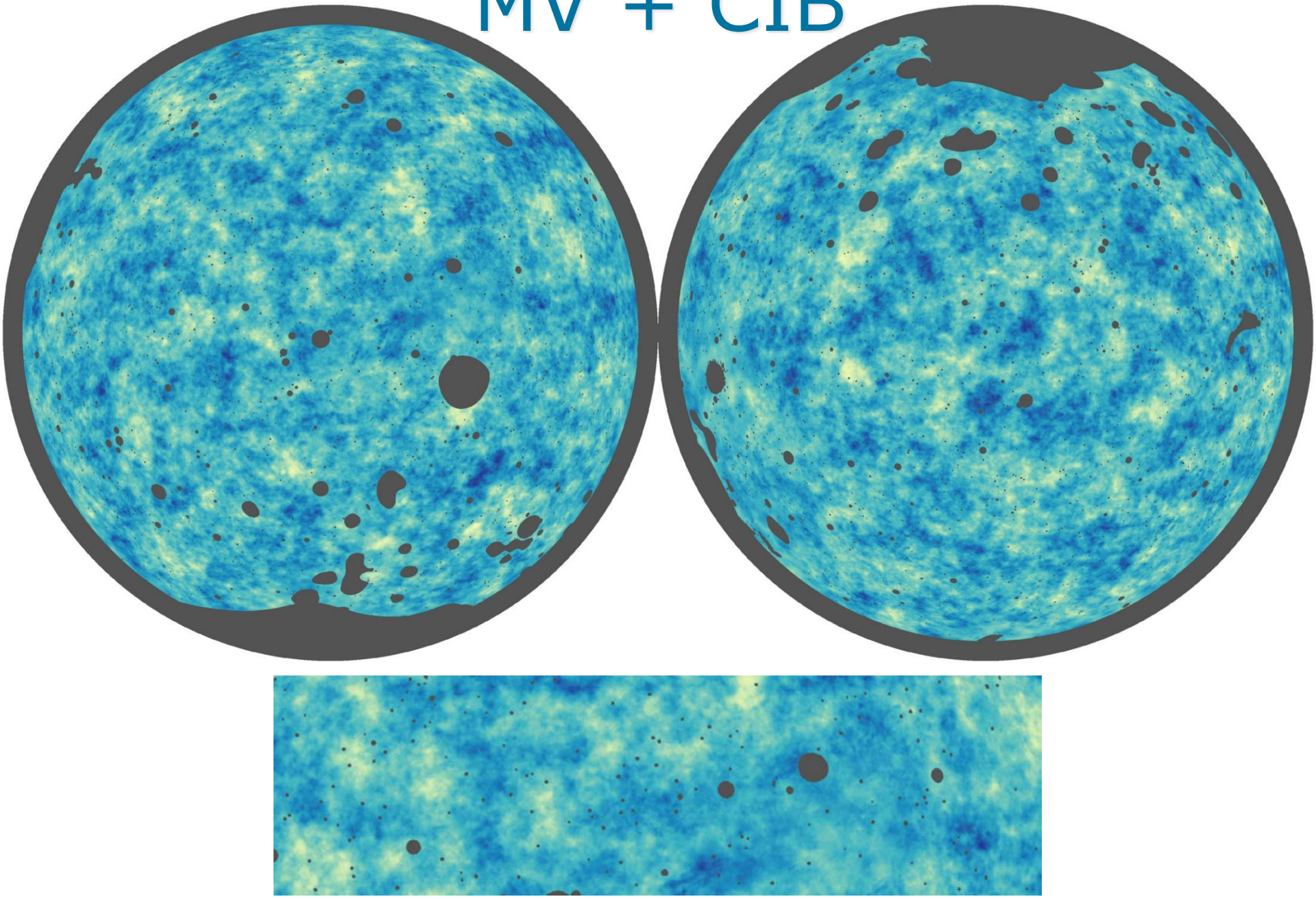
We use GNILC CIB maps



MV

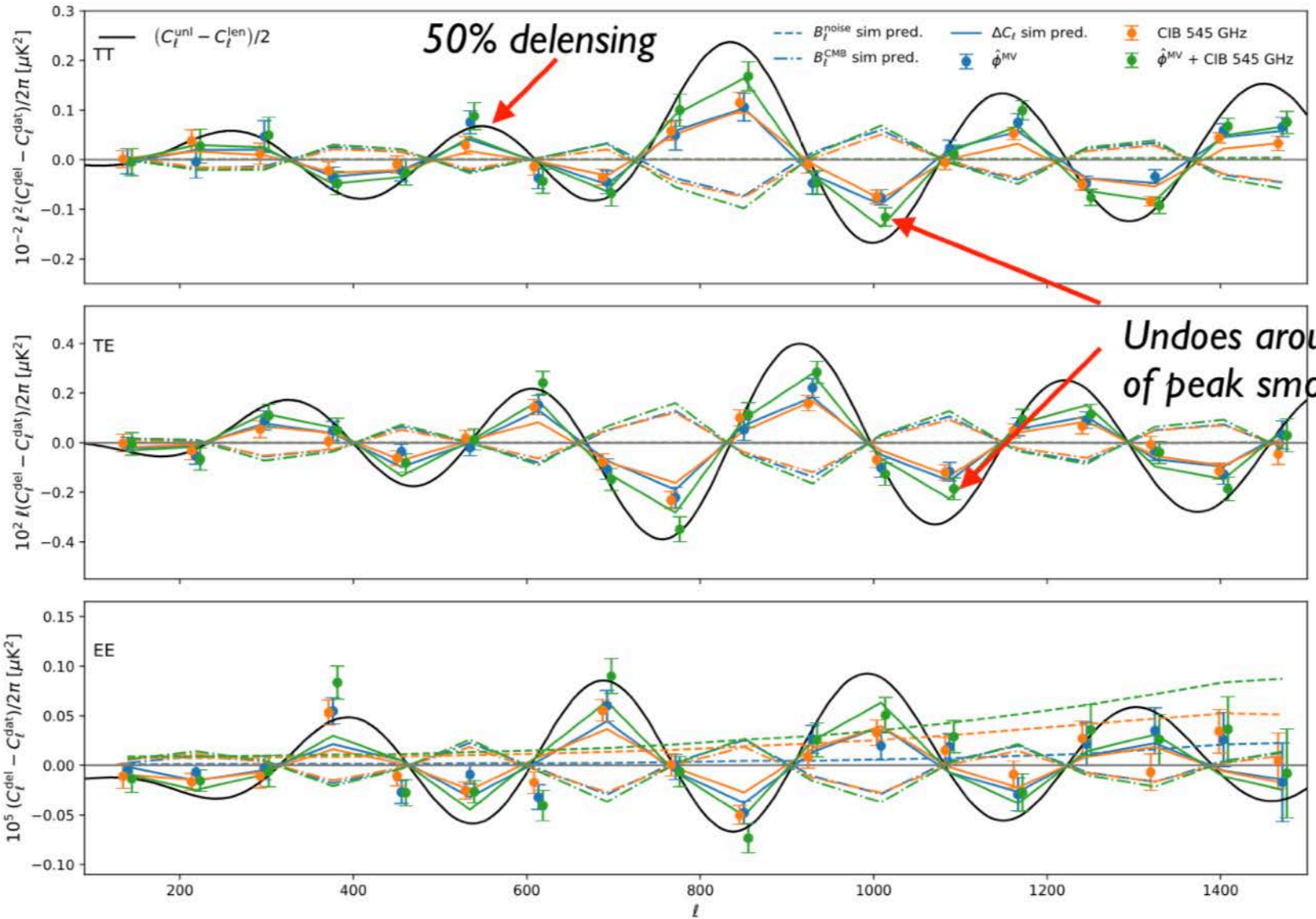


MV + CIB

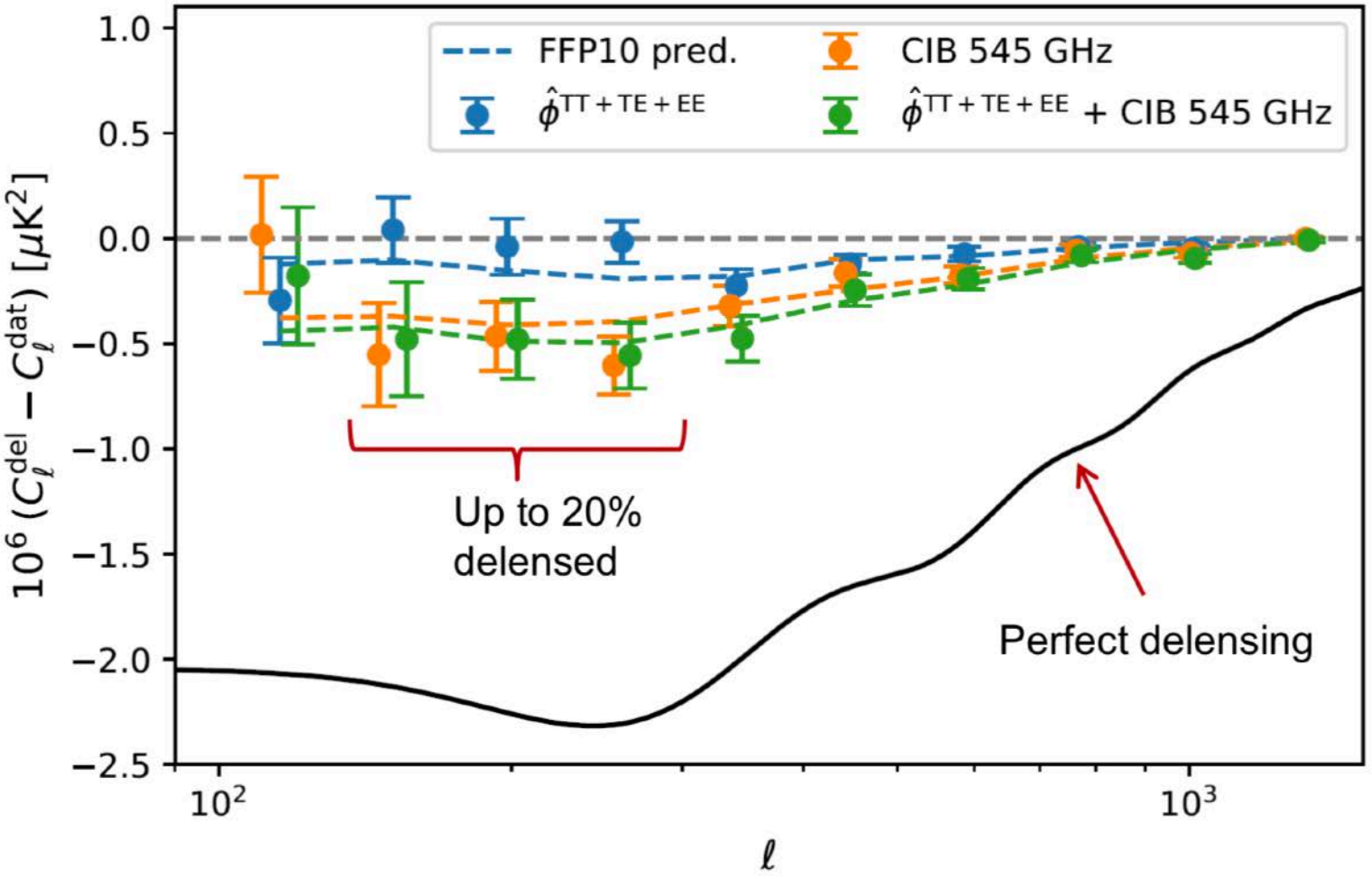


Acoustic peak delensing

Remapping



B-mode delensing *(proof of concept)*



Template delensing (limited by E-noise).

Lensing data products

https://pla.esac.esa.int

https://wiki.cosmos.esa.int/planck-legacy-archive/index.php/Lensing

1. *Lensing maps (TT, PP, MV, tSZ-deprojected) and entire simulation suite.*

2. *Joint internal + CIB lensing tracer maps combination and simulations.*

3. *B-mode templates on 60% of the sky and simulations*

4. *Likelihood files and MCMC chains*

esa

planck

cnes

agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

INAF ISTITUTO NAZIONALE DI ASTROFISICA

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

PLANCK LFI

HFI PLANCK
a look back to the birth of Universe

IAS orsay

IAP

INAF - IASF BO
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ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

Aalto University

ioa

KICC

Cavendish Astrophysics

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astrophysique & planétologie

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cnrs INSU
Observer & comprendre

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Les deux infinis

ipac

HELSINKI INSTITUTE OF PHYSICS

IFCA

Imperial College London

UNIVERSITÀ DEGLI STUDI DI MILANO

NÉEL institut

IPAG

ISDC
DATA CENTRE FOR ASTROPHYSICS

JPL

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

LERMA

LPSC
Grenoble

NERSC

MANCHESTER 1824
The University of Manchester

MilliLab

Rutherford Appleton Laboratory

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF
OSSERVATORIO ASTRONOMICO DI PADOVA

SAPIENZA
UNIVERSITÀ DI ROMA

UBC

UC
UNIVERSIDAD DE CANTABRIA

UCSB

SISSA

ALMA

ESO

US
University of Sussex

HAVERFORD

esa

UNIVERSITY OF HELSINKI

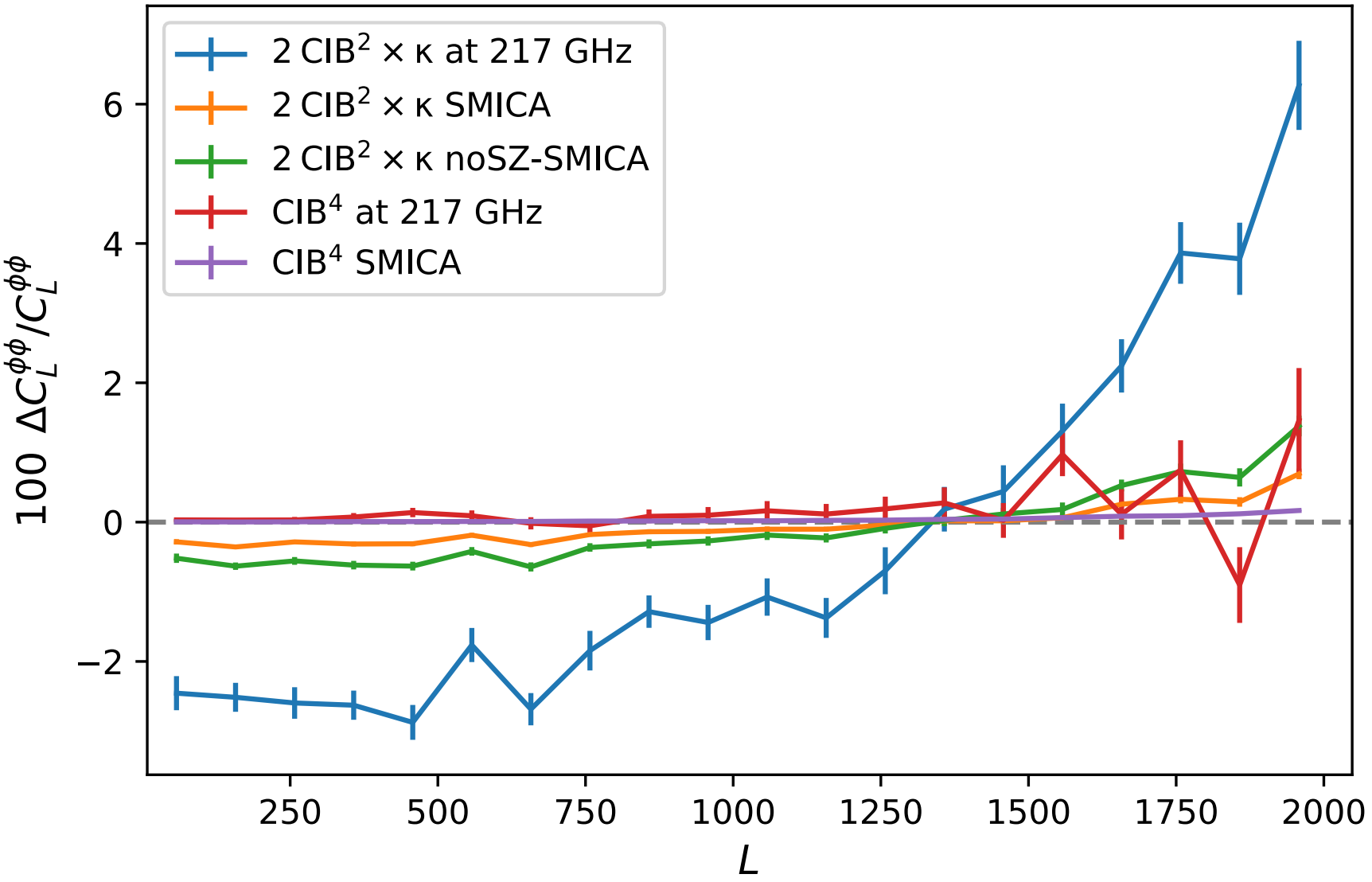
UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

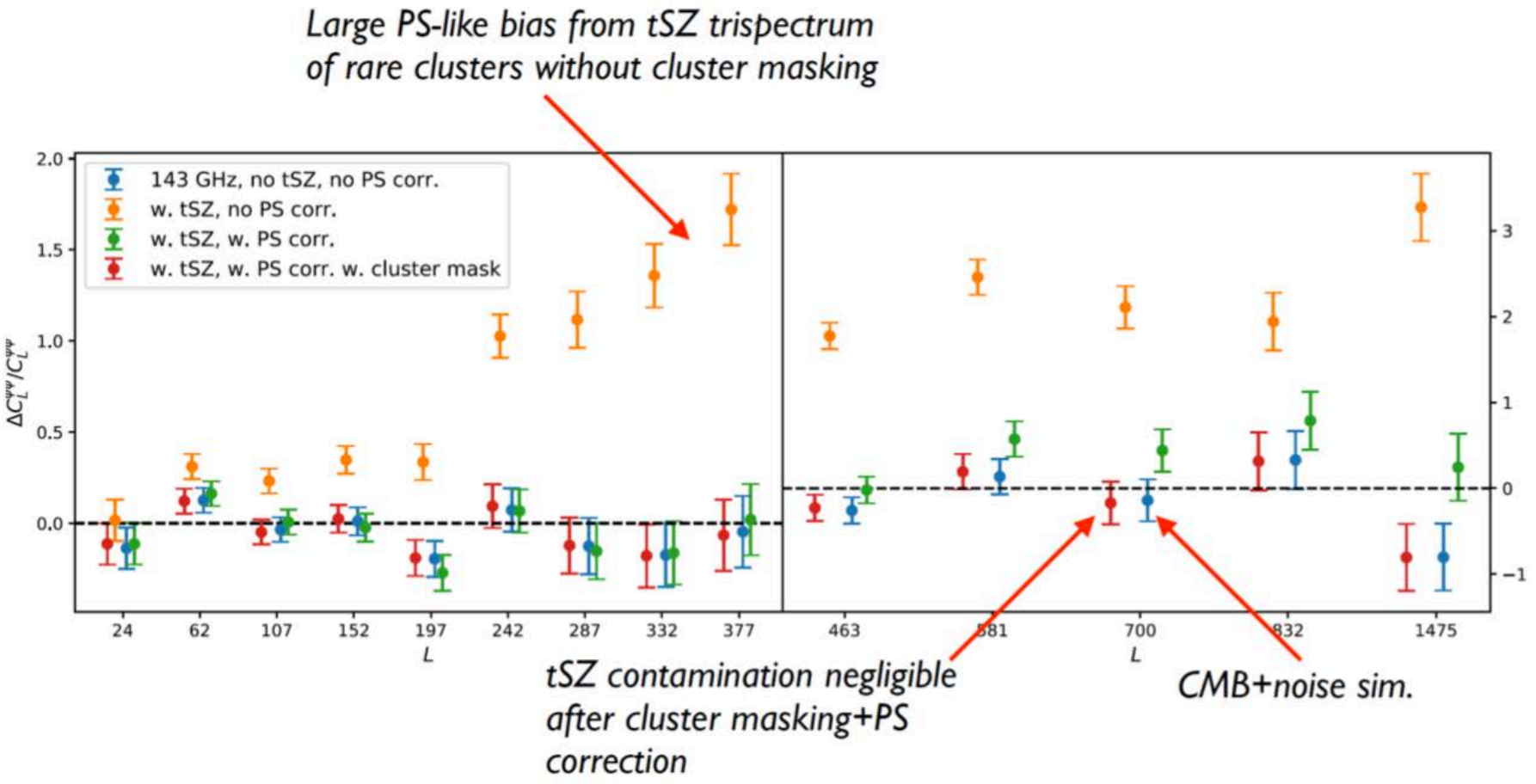
UNIVERSITÉ DE PARIS-SUD XI

asdc
ASI Science Data Center

CIB

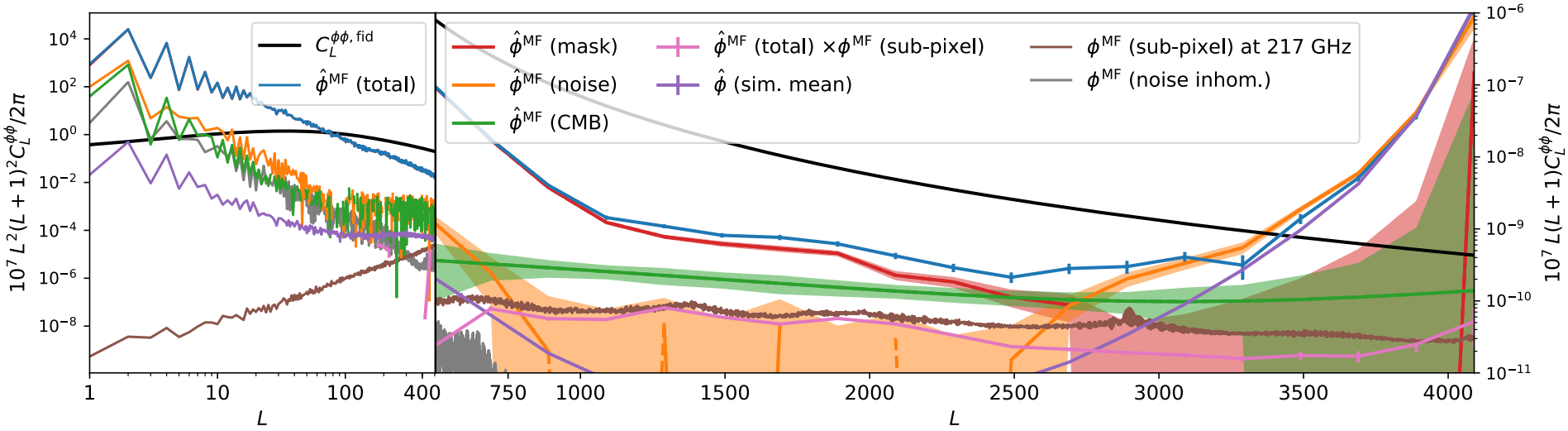

2 CIB^2 × κ at 217 GHz
2 CIB^2 × κ SMICA
2 CIB^2 × κ noSZ-SMICA
CIB^4 at 217 GHz
CIB^4 SMICA
$100\ \Delta C_L^{\phi\phi}/C_L^{\phi\phi}$
6
4
2
0
−2
250
500
750
1000
1250
1500
1750
2000
L

tSZ

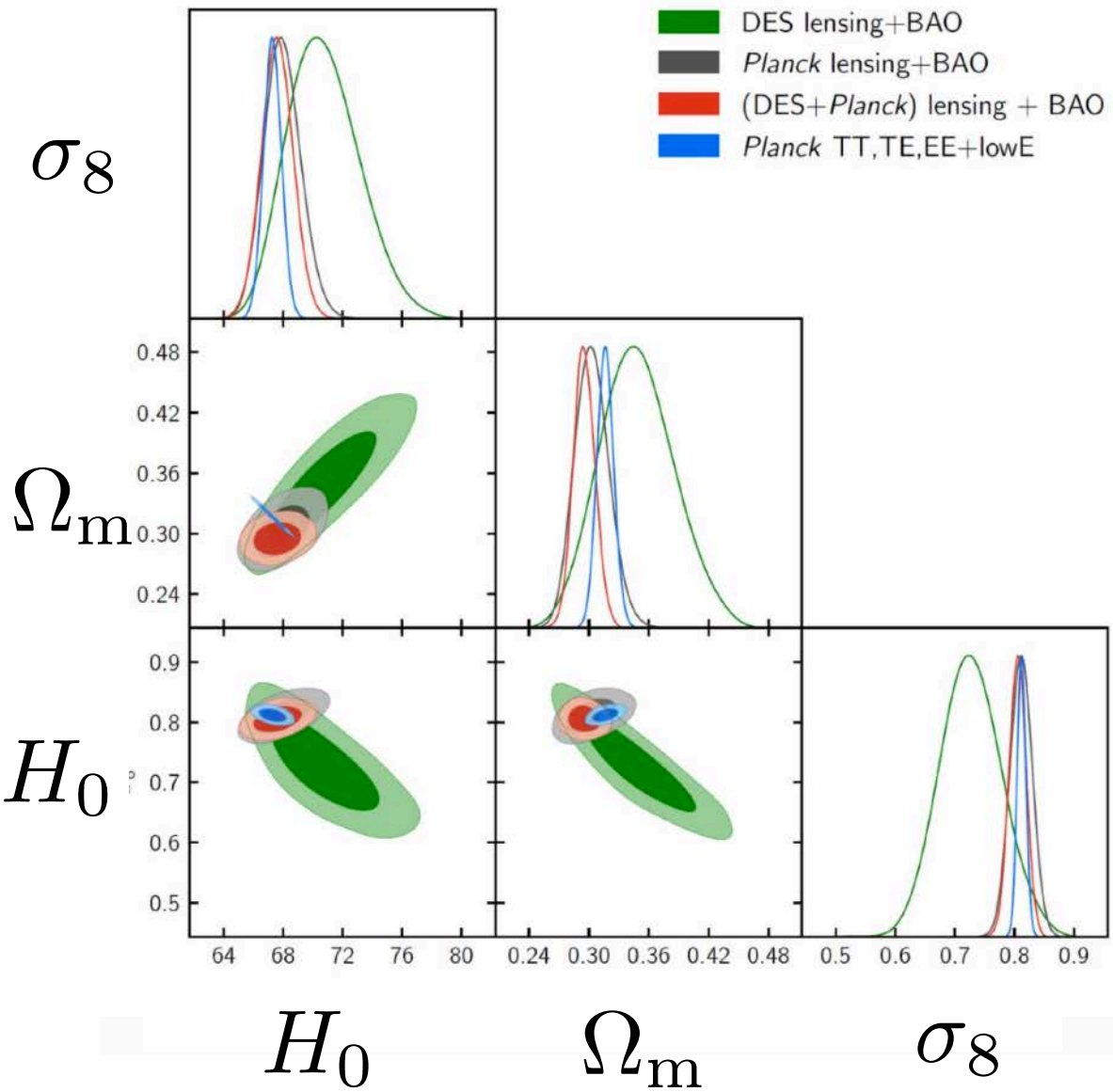


- Negligible impact on lensing power itself by masking clusters

Mean-fields


$C_L^{\phi\phi,\mathrm{fid}}$
$\hat{\phi}^{\mathrm{MF}}$ (total)
$\hat{\phi}^{\mathrm{MF}}$ (mask)
$\hat{\phi}^{\mathrm{MF}}$ (noise)
$\hat{\phi}^{\mathrm{MF}}$ (CMB)
$\hat{\phi}^{\mathrm{MF}}$ (total) $\times\phi^{\mathrm{MF}}$ (sub-pixel)
$\hat{\phi}$ (sim. mean)
ϕ^{MF} (sub-pixel) at 217 GHz
ϕ^{MF} (noise inhom.)
$10^7\,L^2(L+1)^2C_L^{\phi\phi}/2\pi$
$10^7\,L(L+1)C_L^{\phi\phi}/2\pi$
L
L

Parameter constraints



$H_0 = 67.9^{+1.2}_{-1.3}$ km s^{-1}Mpc^{-1},
$\sigma_8 = 0.811 \pm 0.019$,
$\Omega_m = 0.303^{+0.016}_{-0.018}$,
} 68 %, lensing+BAO

$H_0 = 70.7^{+2.1}_{-2.7}$ km s^{-1}Mpc^{-1}
$\sigma_8 = 0.727 \pm 0.052$
$\Omega_m = 0.348^{+0.033}_{-0.040}$
} 68%, DES lensing+BAO.

$H_0 = (67.6 \pm 1.1)$ km s^{-1}Mpc^{-1}
$\sigma_8 = 0.805 \pm 0.014$
$\Omega_m = 0.295 \pm 0.011$
} 68%, DES lensing +*Planck* lensing+BAO

Changes since 2015

- Maps largely unchanged at high-ℓ
  - *but* component-separation (SMICA) frequency weights changed
- Better masks: lower point-source contamination
- Extensive data consistency tests + correlated foreground simulations to assess foreground biases
- Likelihood extended to $L_{\rm min} = 8$ (was $L_{\rm min} = 40$)
- Lensing-only likelihood is CMB marginalized (independent of cosmology fit to CMB spectra)
- Results to higher $L_{\rm max}$
- Multiplicative MC correction (good for optimal filtering)
- Monte Carlo errors included in covariance

New Results

- New optimally-filtered polarization reconstruction
- Combined reconstruction+CIB lensing map
- Template BB delensing
- TT,TE,EE peak sharpening

} Using MV, TT+TE+EE and with CIB