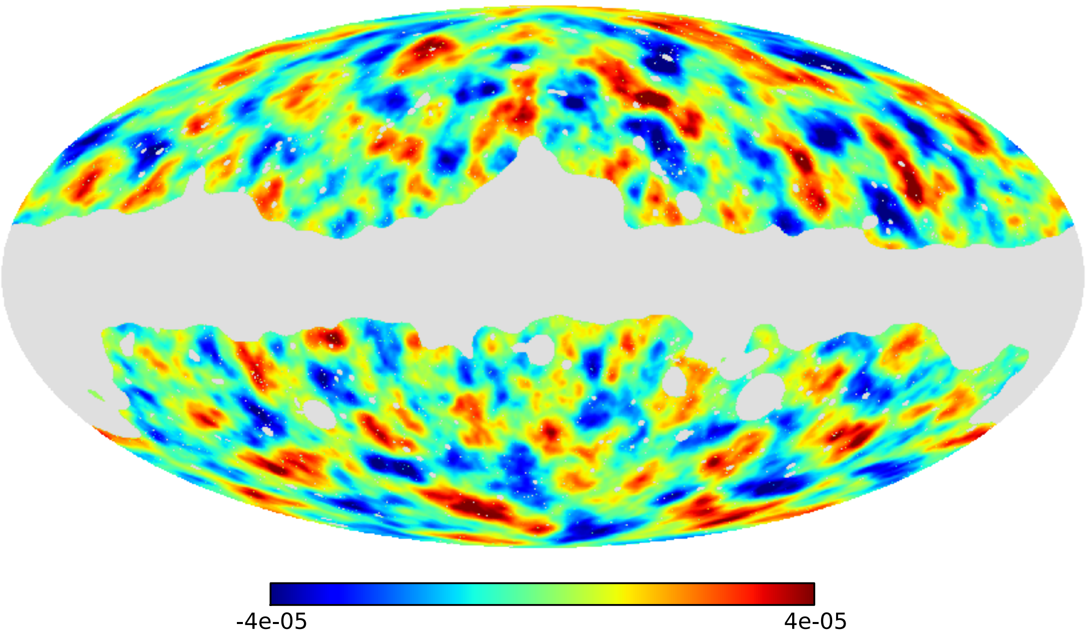
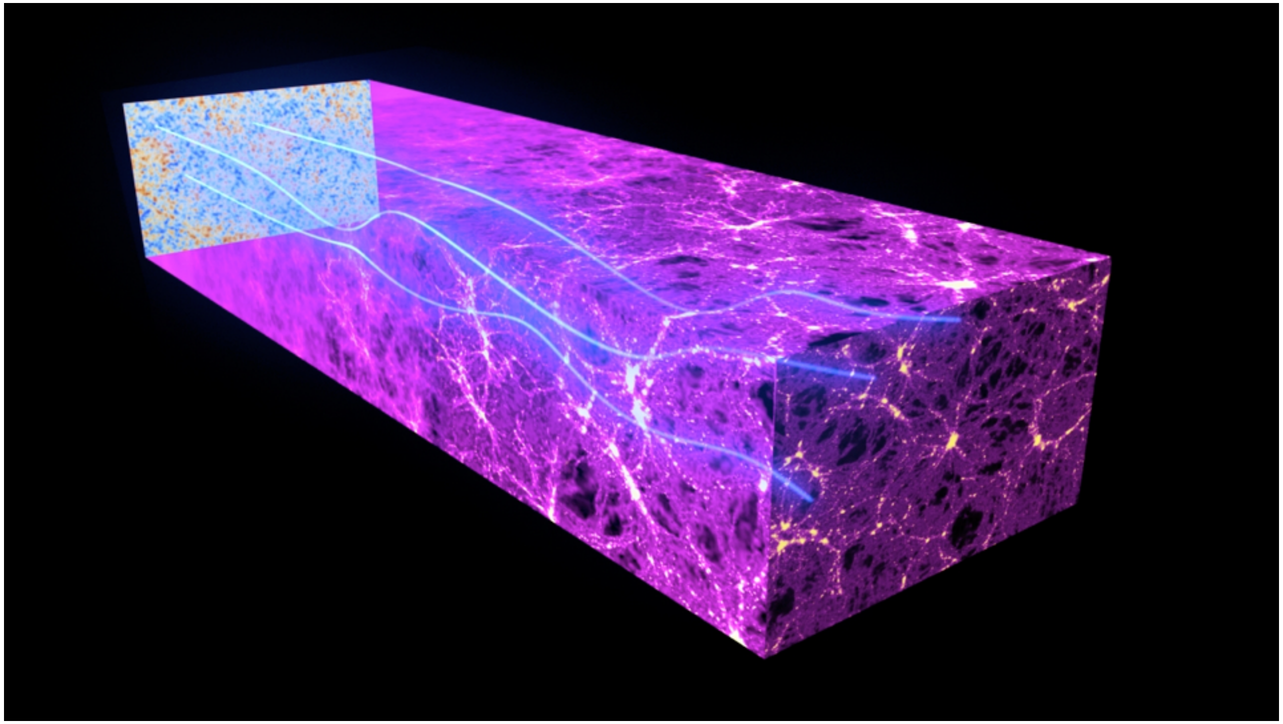
CMB lensing and delensing

Anthony Challinor



KICC/IoA/DAMTP
University of Cambridge

Lensing of the CMB

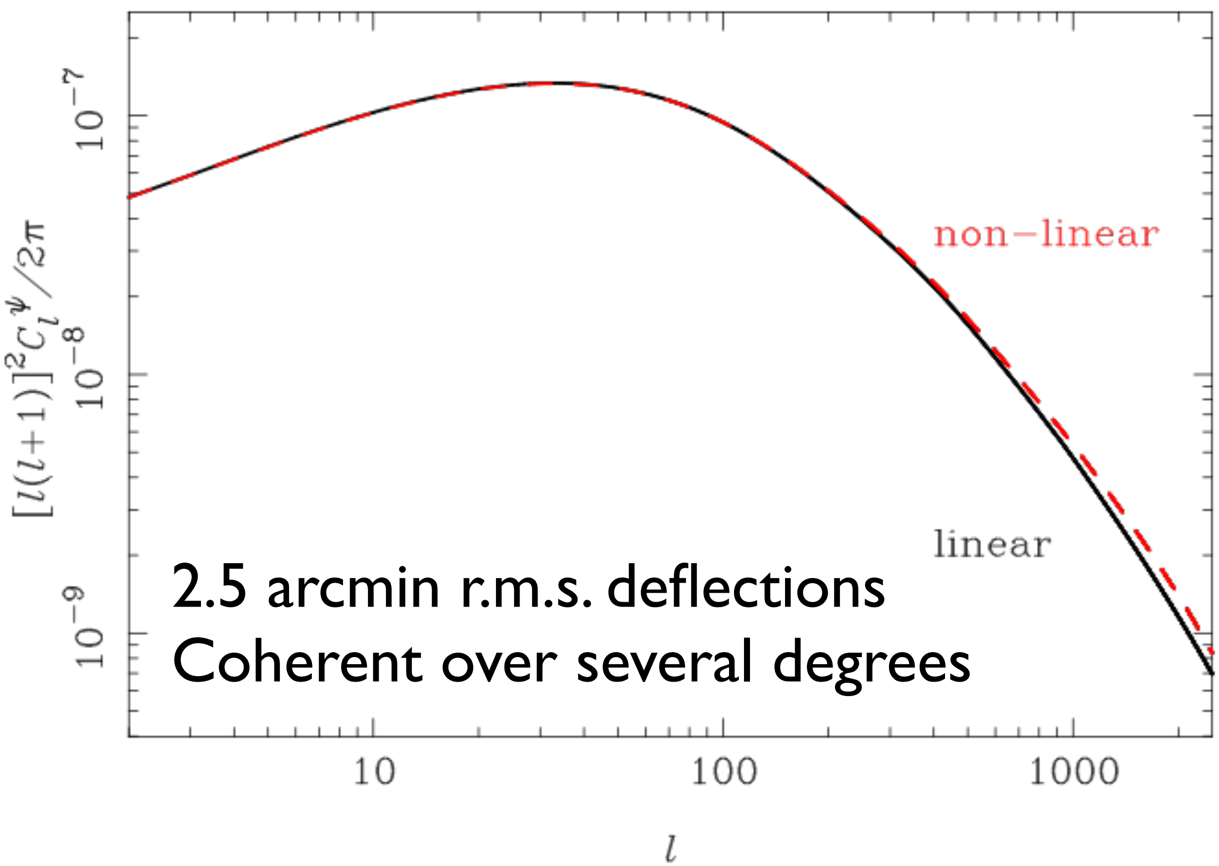


- O(50) deflections by 100 Mpc scale lenses
  - *Peak efficiency around z=2*
  - *Predicts 2.5 arcmin r.m.s. deflections coherent over several degrees*

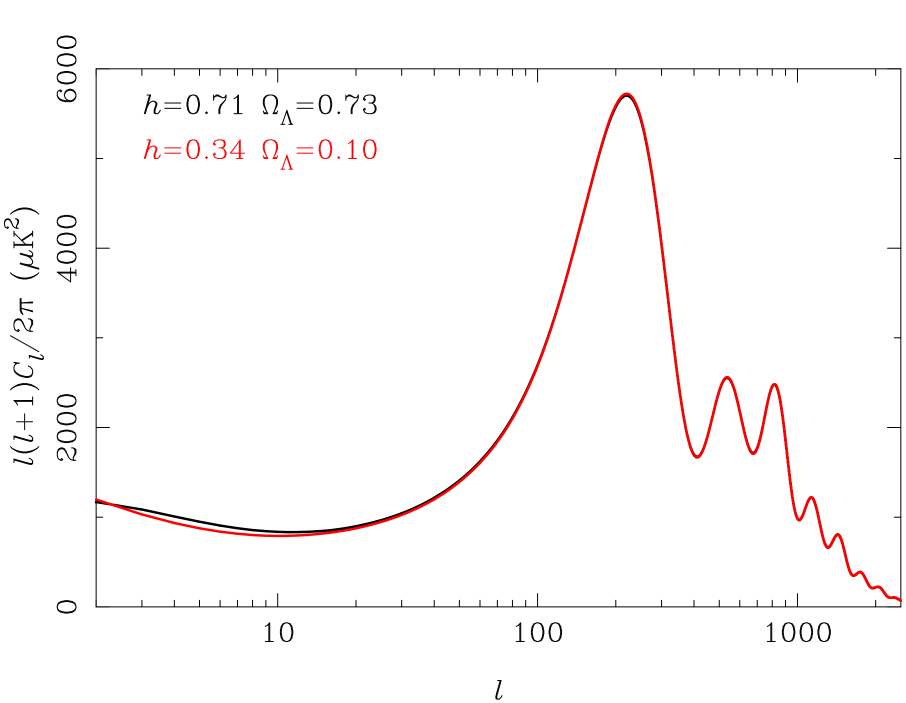
CMB lensing power spectrum

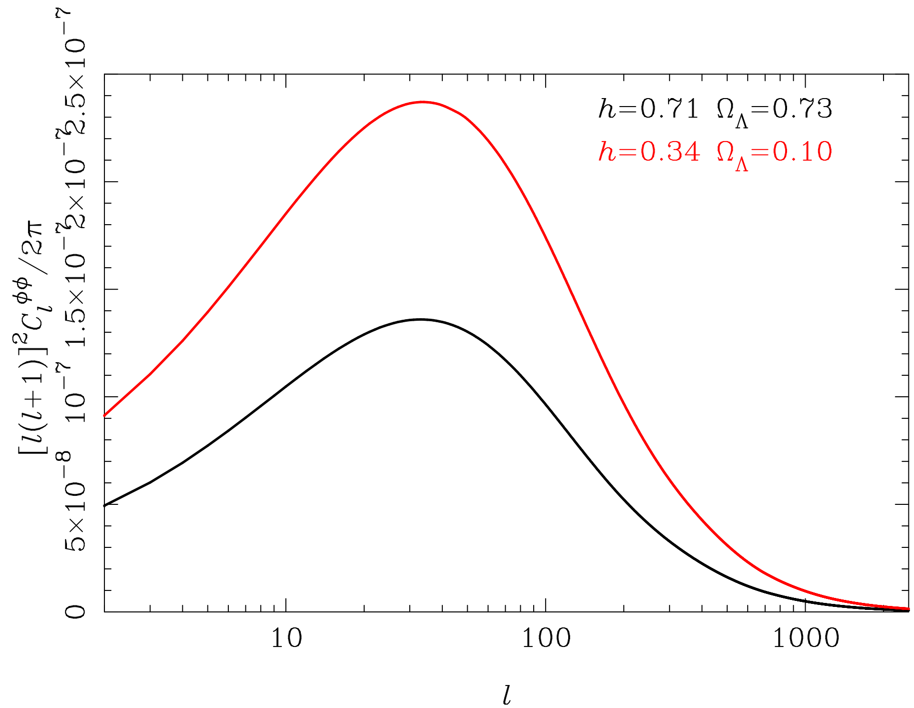
- Deflection field ***d*** = **∇**φ in linear theory

$$\phi(\hat{\boldsymbol{n}}) = -\int_0^{\chi_*} d\chi \, \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)(\chi \hat{\boldsymbol{n}}; \eta_0 - \chi)$$



Lensing adds information





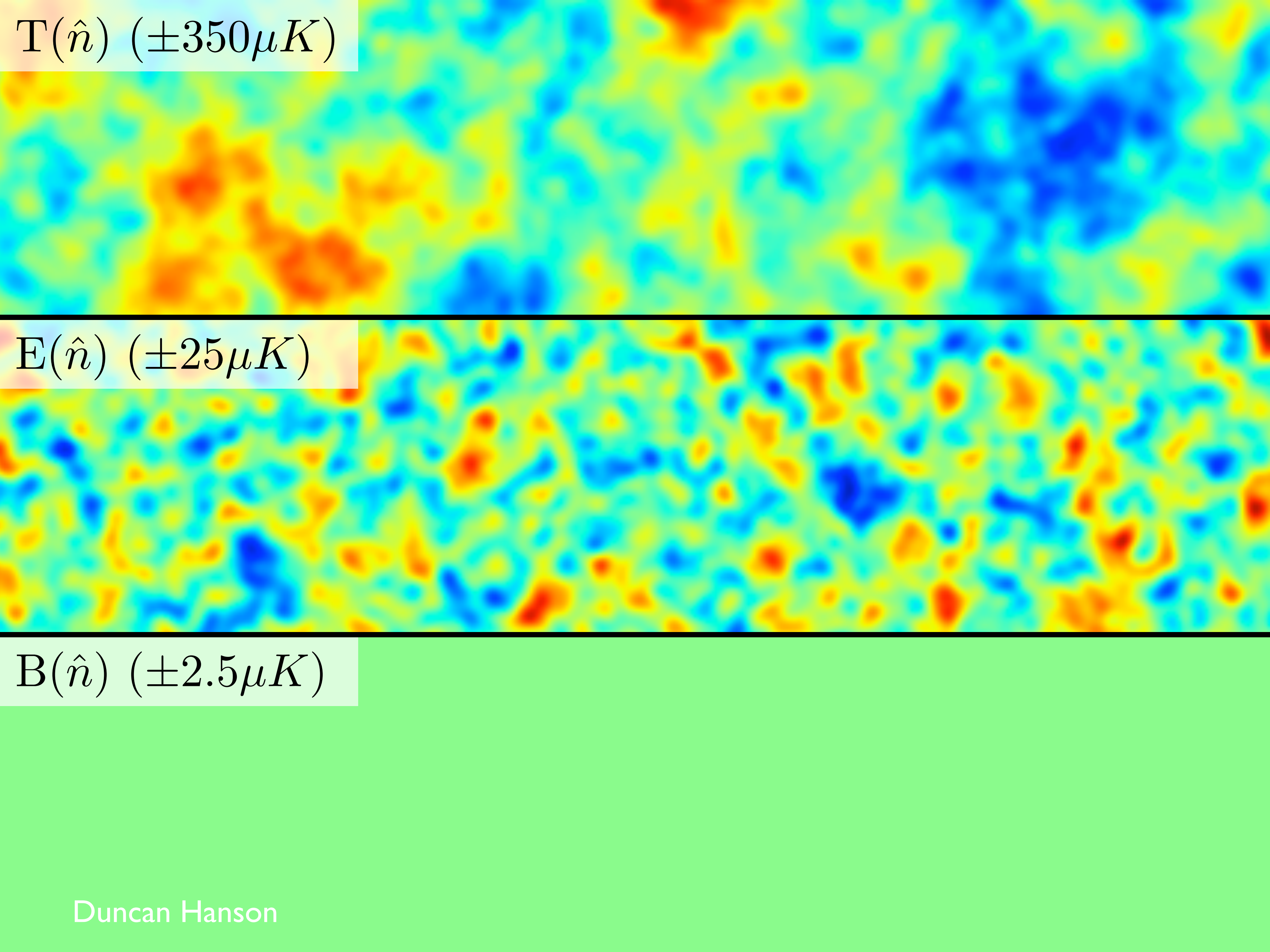
- Geometric degeneracy in CMB power spectra broken by different amounts of lensing in models with same $d_A(z_*)$
  - *Access to curvature, sub-eV neutrino masses, dark energy etc. from CMB alone*

Effects of lensing on the CMB

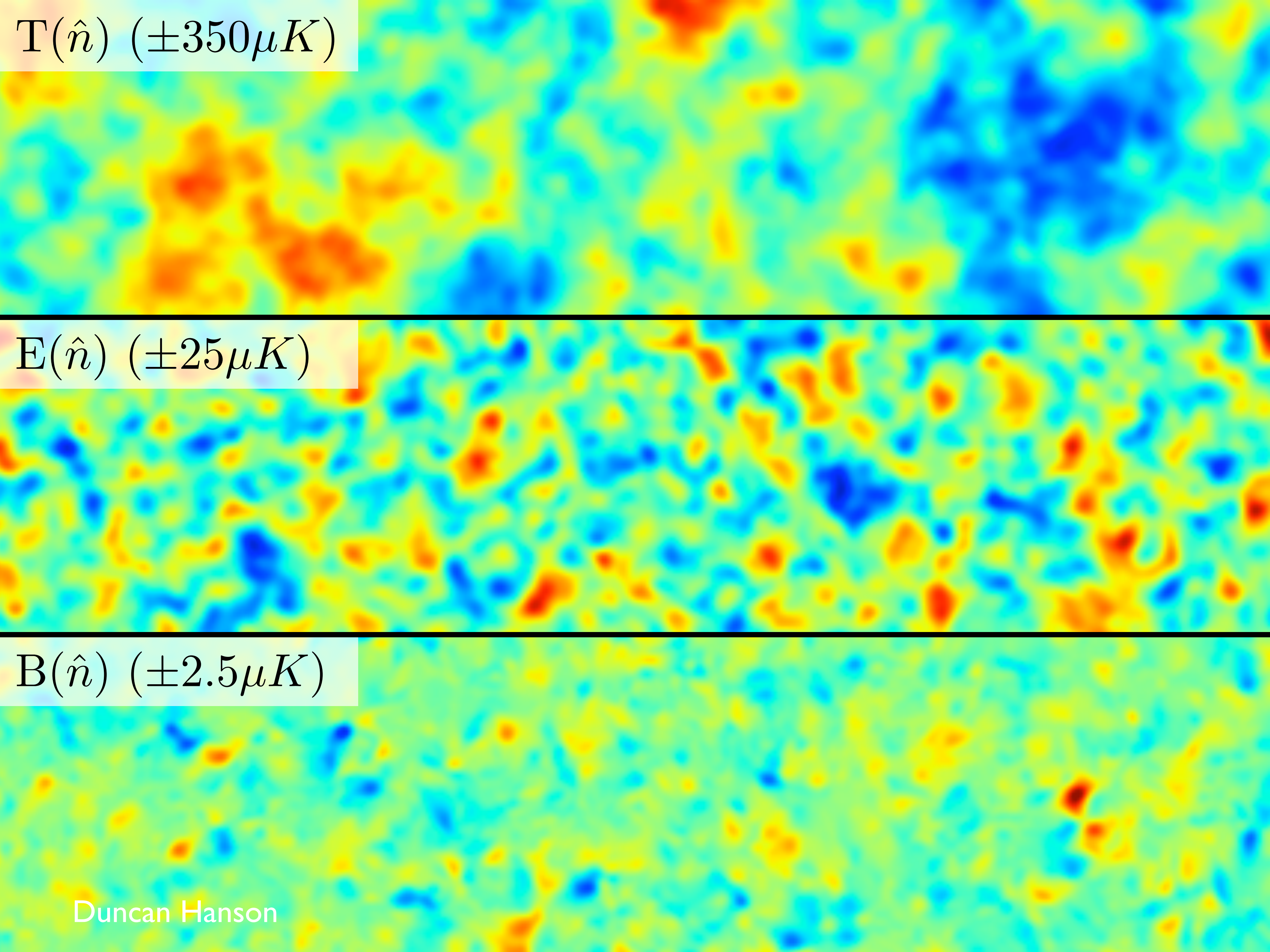
$$\tilde{T}(\boldsymbol{x}) = T(\boldsymbol{x} + \boldsymbol{\nabla}\phi)$$

$$(\tilde{Q} \pm i\tilde{U})(\boldsymbol{x}) = (Q \pm iU)(\boldsymbol{x} + \boldsymbol{\nabla}\phi)$$

- Smooths out acoustic peaks in *TT*, *TE*, and *EE* power
- Generates power at arcmin scales in *TT*, *TE*, and *EE*
- Generates *B*-modes from *E-modes* with almost white noise power
- Introduces non-Gaussianity
  - *4-point function proportional to* $C_l^{\varphi\varphi}$
  - *3-point function with LSS tracers correlated with* φ

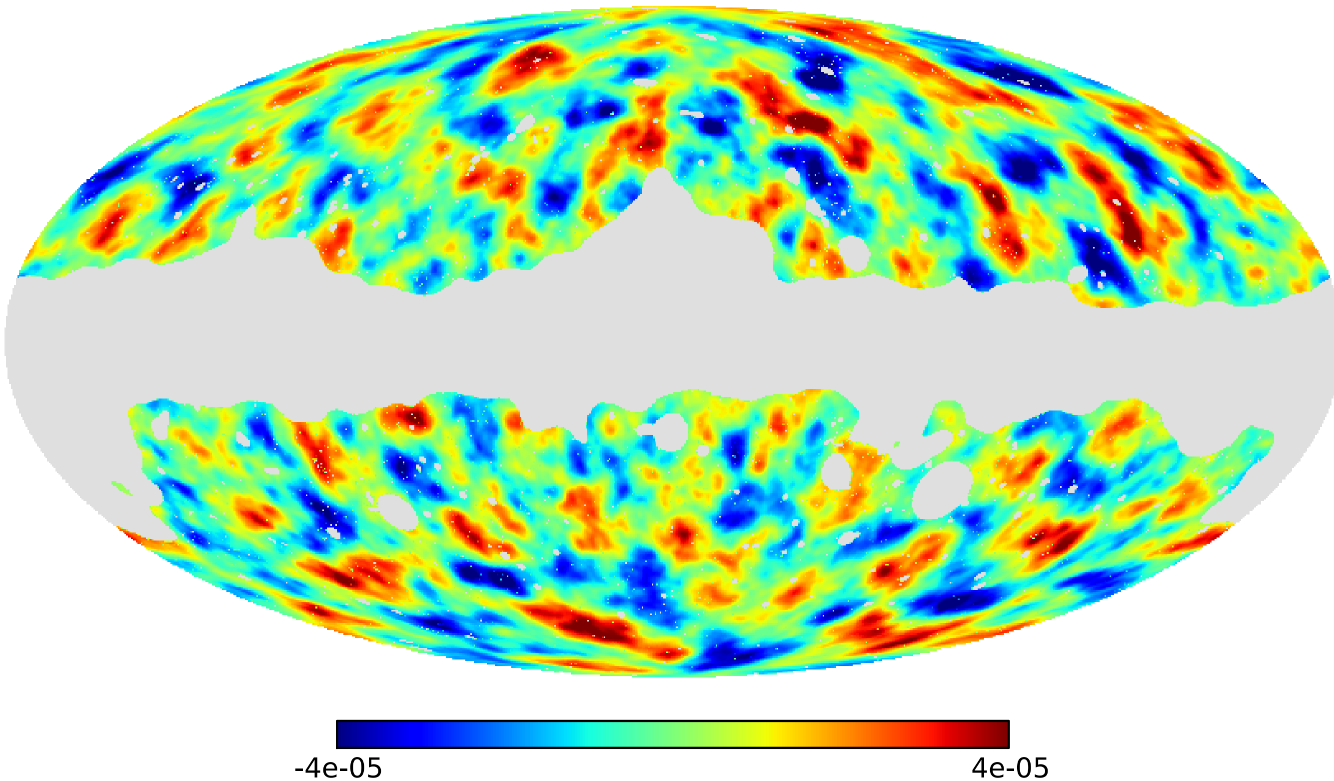


Duncan Hanson


$T(\hat{n})$ ($\pm 350 \mu K$)
$E(\hat{n})$ ($\pm 25 \mu K$)
$B(\hat{n})$ ($\pm 2.5 \mu K$)
Duncan Hanson

Lens reconstruction

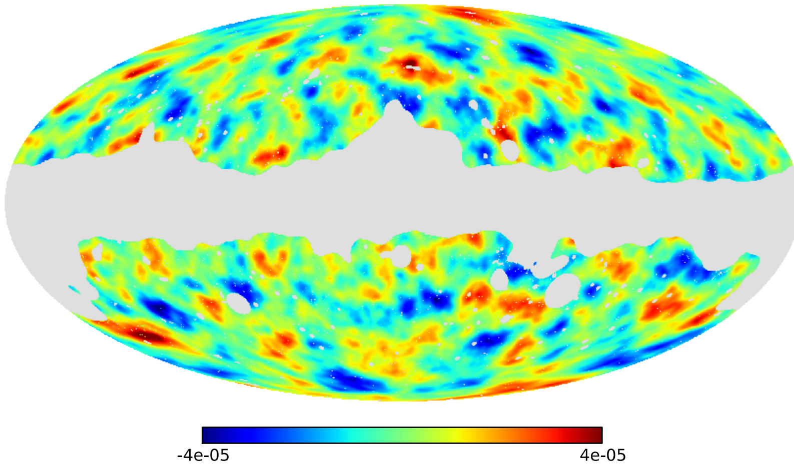
$$\Delta\langle X_{l_1 m_1} Y_{l_2 m_2}\rangle_{\rm CMB} = \sum_{LM} (-1)^M \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \mathcal{W}^{XY}_{l_1 l_2 L} \phi_{LM}$$



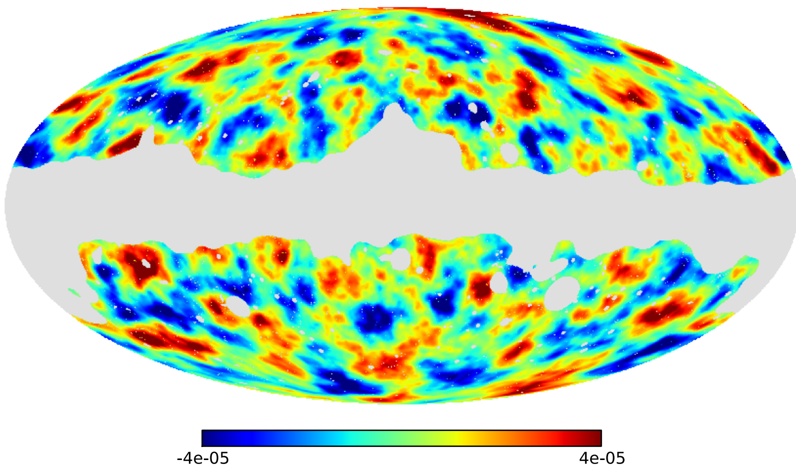
Planck Collaboration 2015

Reconstruction is noisy

- Chance correlations in noisy CMB introduce statistical noise in reconstruction (like shape noise in galaxy lensing)

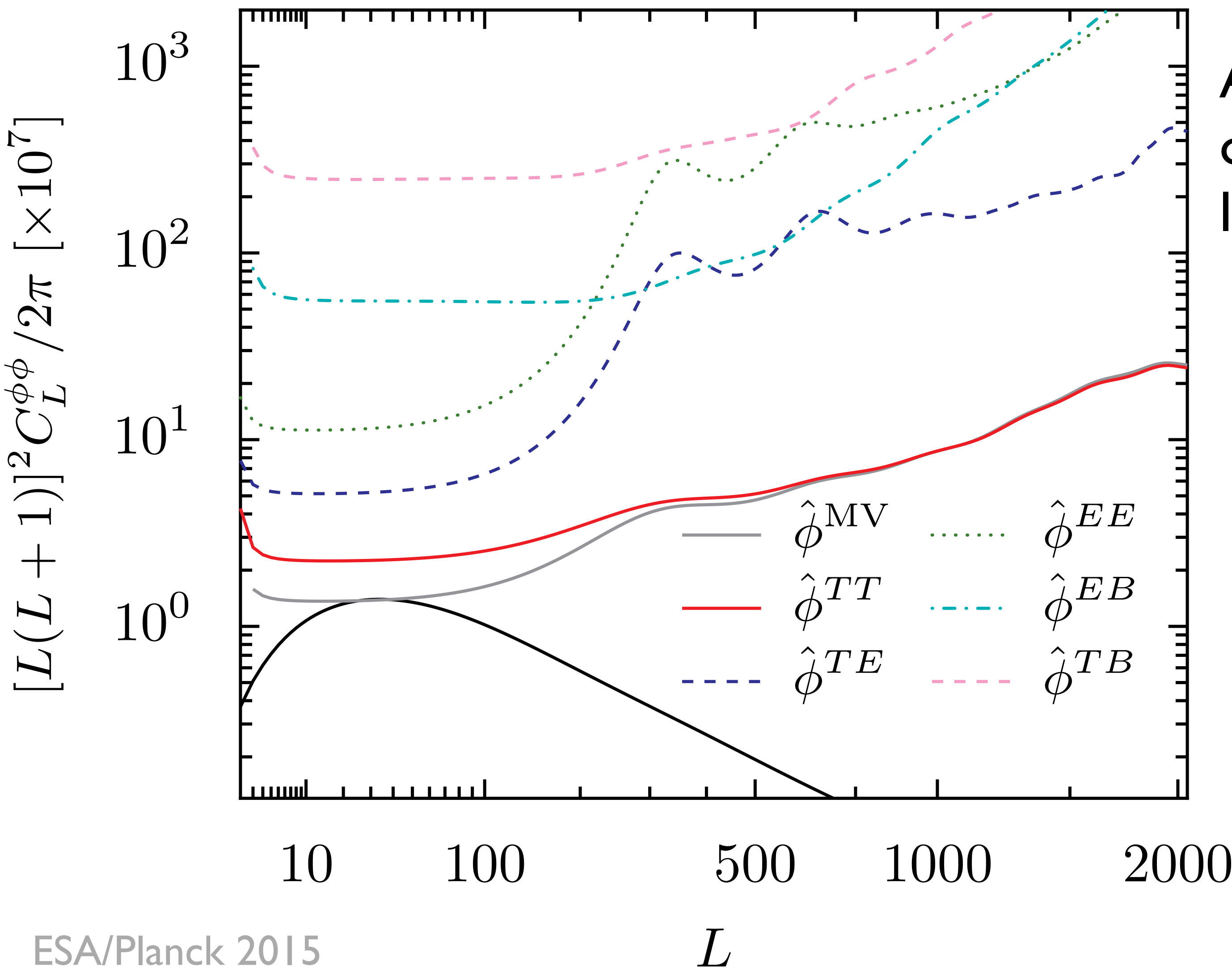


Input



Recovered at Planck noise levels

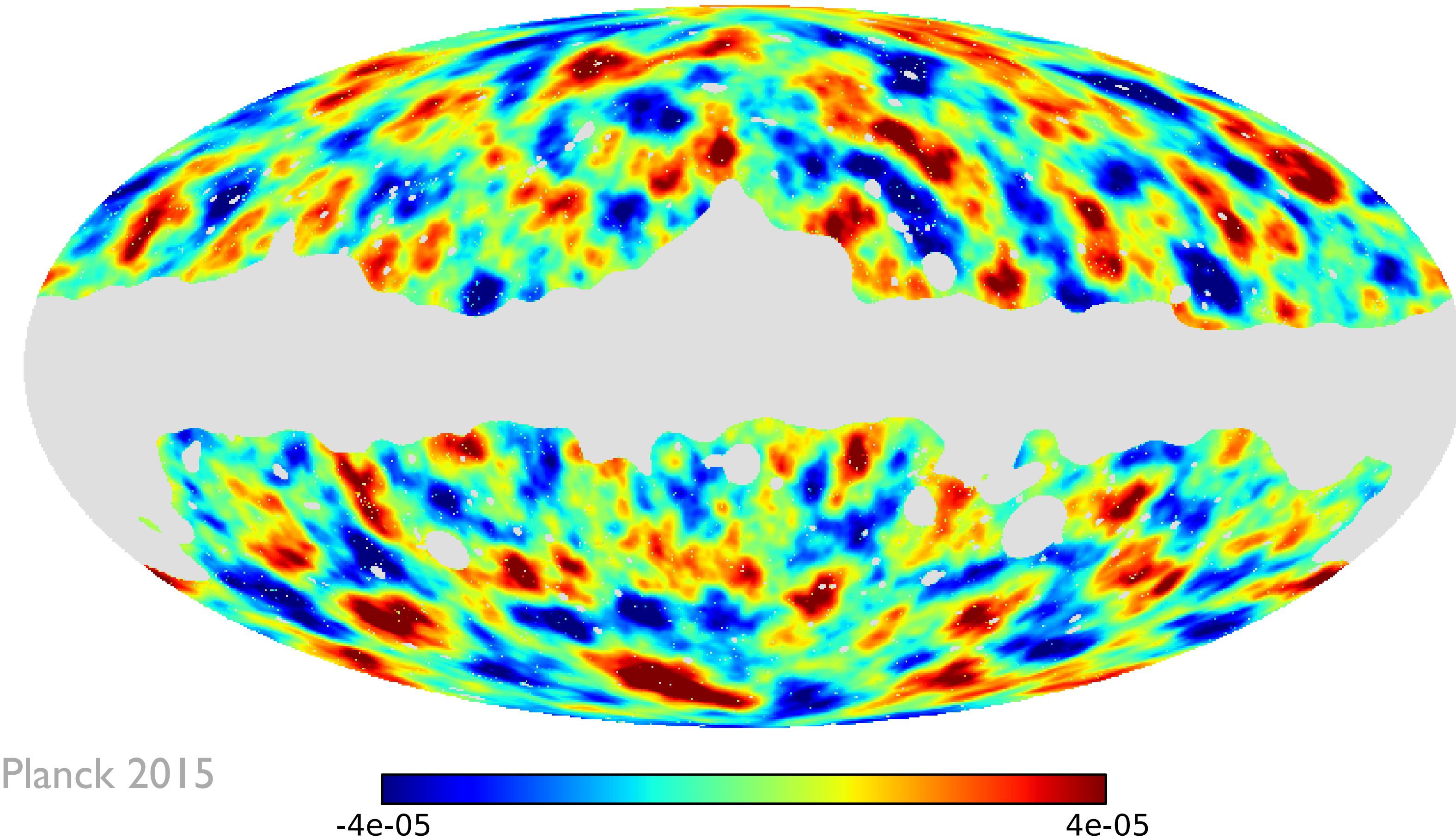
Planck reconstruction noise levels



Almost white noise on $L(L+1)\varphi_{LM}$ on large scales

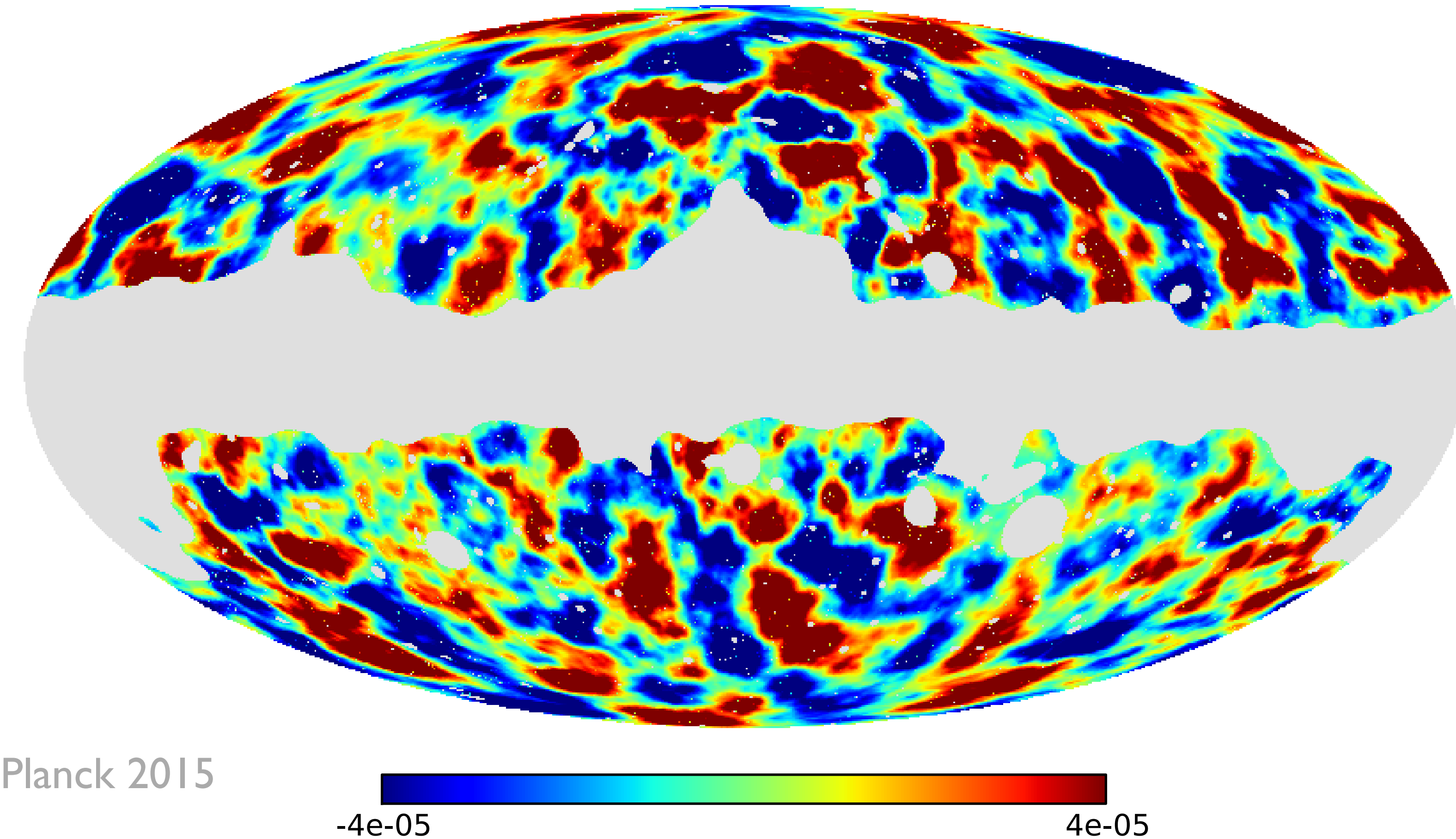
ESA/Planck 2015

Planck 2015 TT



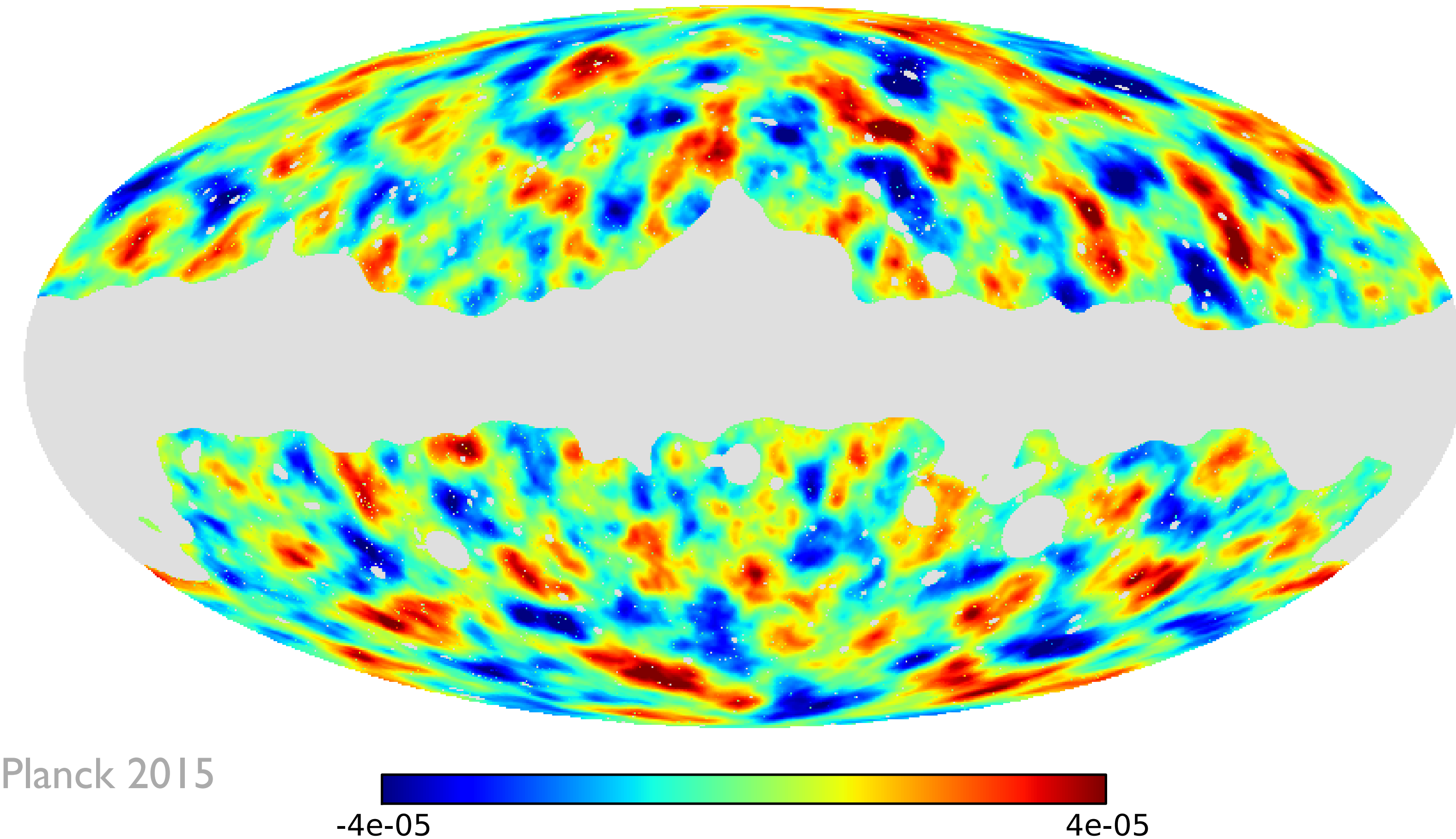
ESA/Planck 2015

Planck 2015 pol. only



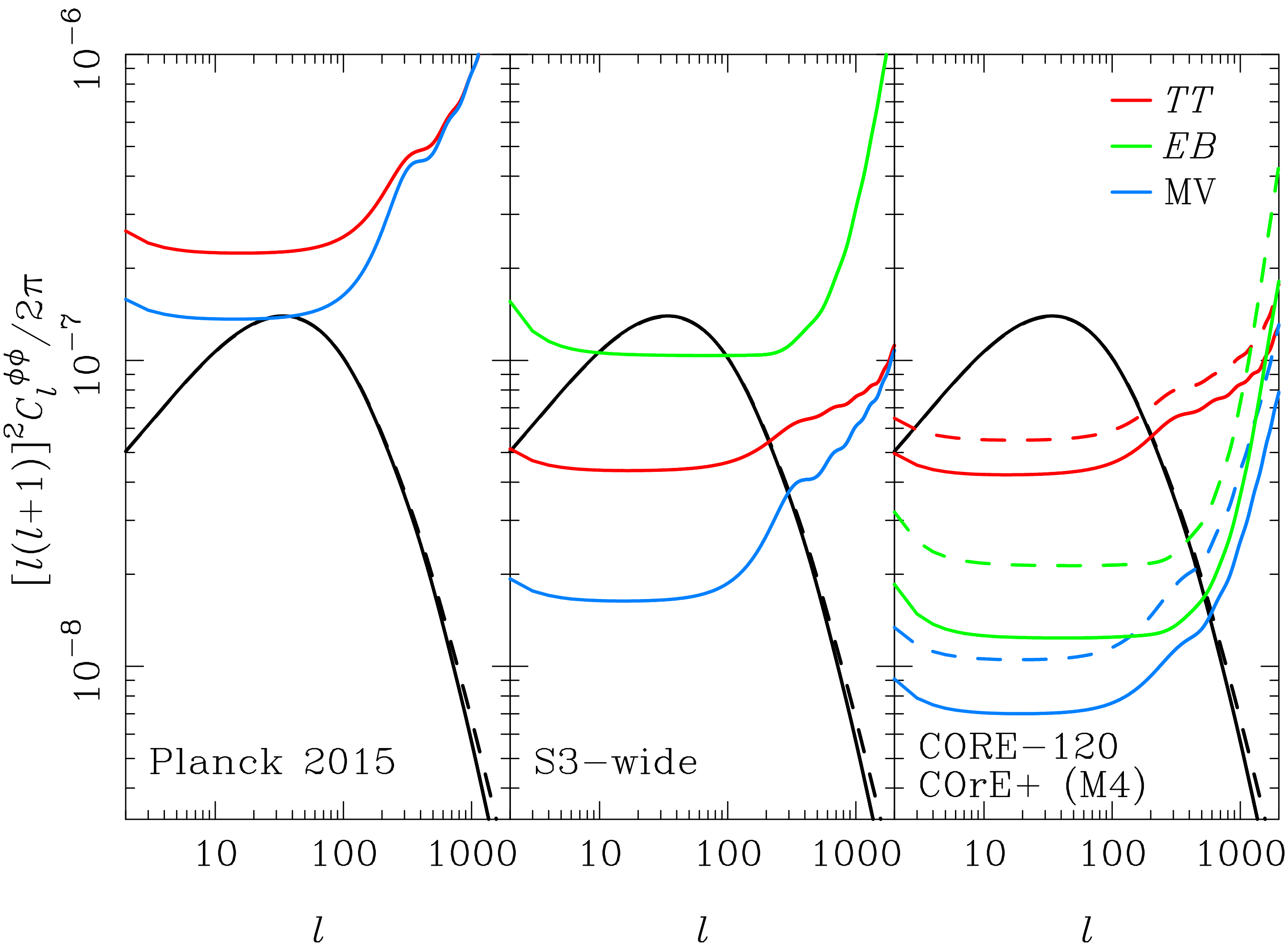
ESA/Planck 2015

Planck 2015 minimum-variance



ESA/Planck 2015

Lens reconstruction noise levels

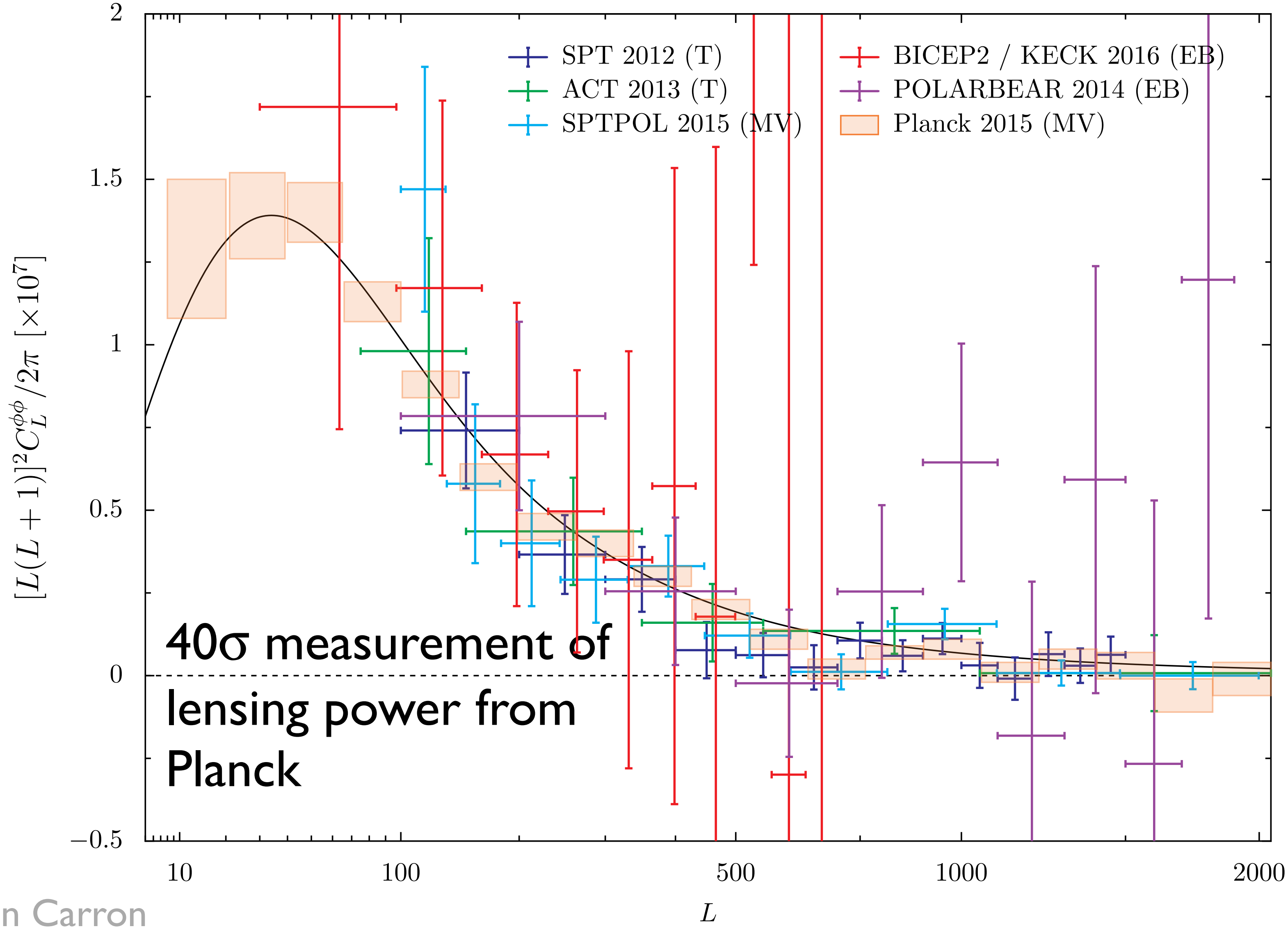


- *EB* particularly helpful for pol. noise < 5 μK arcmin

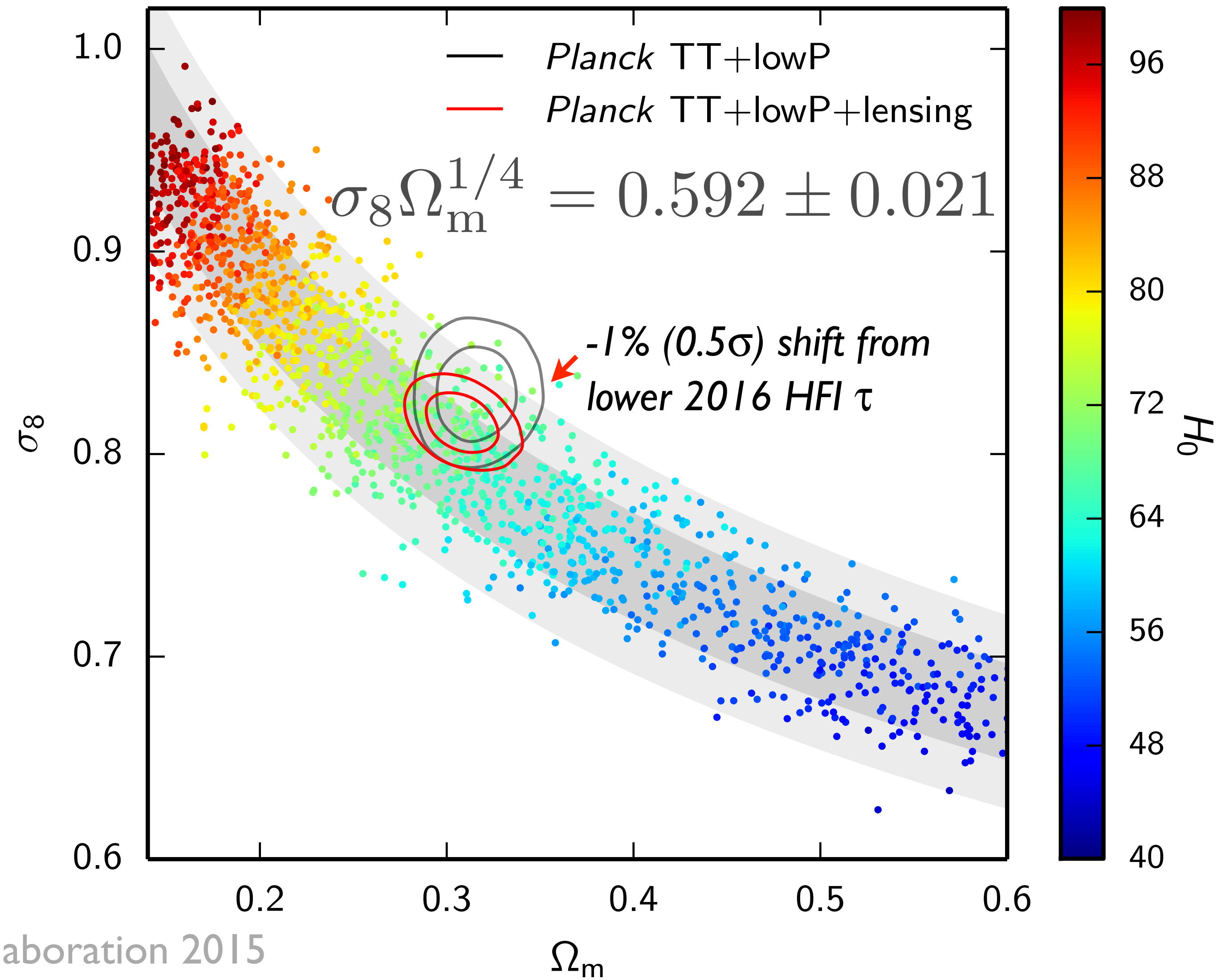
Applications of CMB lensing

- Cosmology from auto-power spectrum (and higher moments)
  - *Neutrino masses, curvature, (early) dark energy etc.*
- Cross-correlation with other LSS tracers
  - *Degeneracy breaking, self-calibration, high-z astrophysics*
- Delensing
  - *Improve GW constraints*
  - *Delens high-l EE (sharpen peaks for N_{eff} etc.)*
- (Measure cluster masses of large SZ-selected samples)

Current measurements

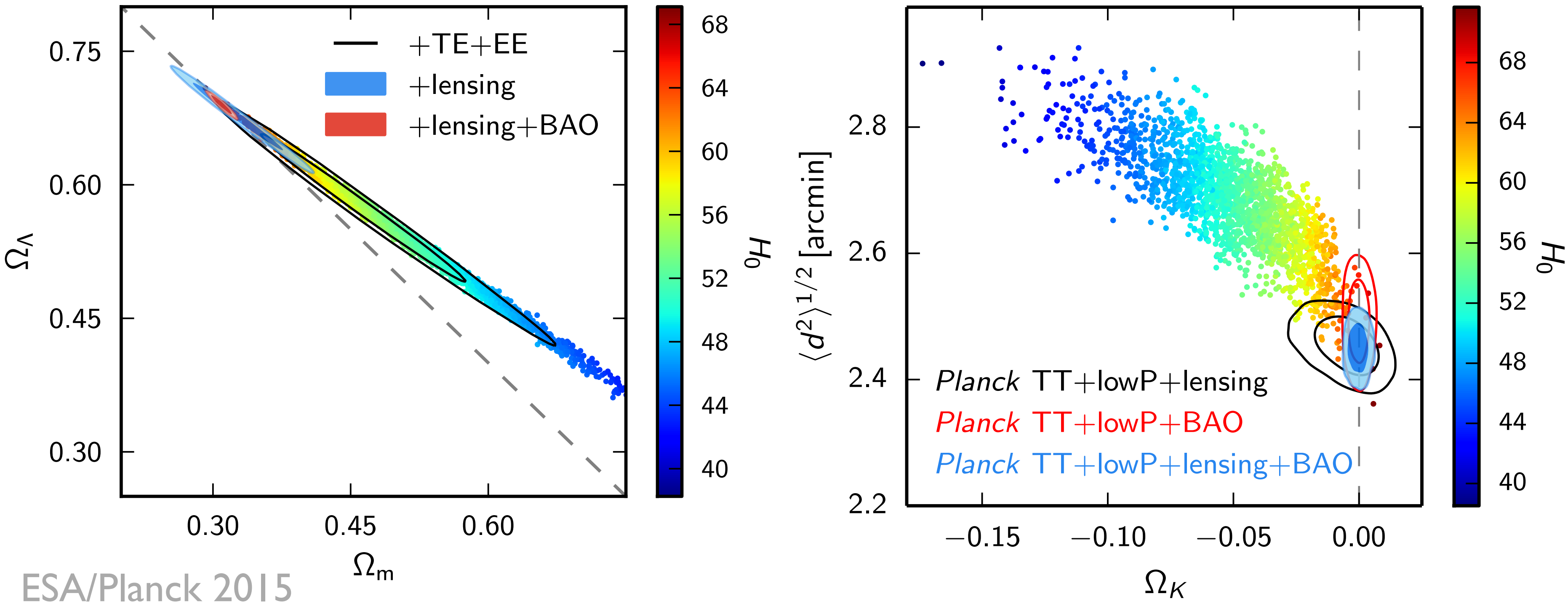


LCDM joint constraints



Planck Collaboration 2015

Curvature



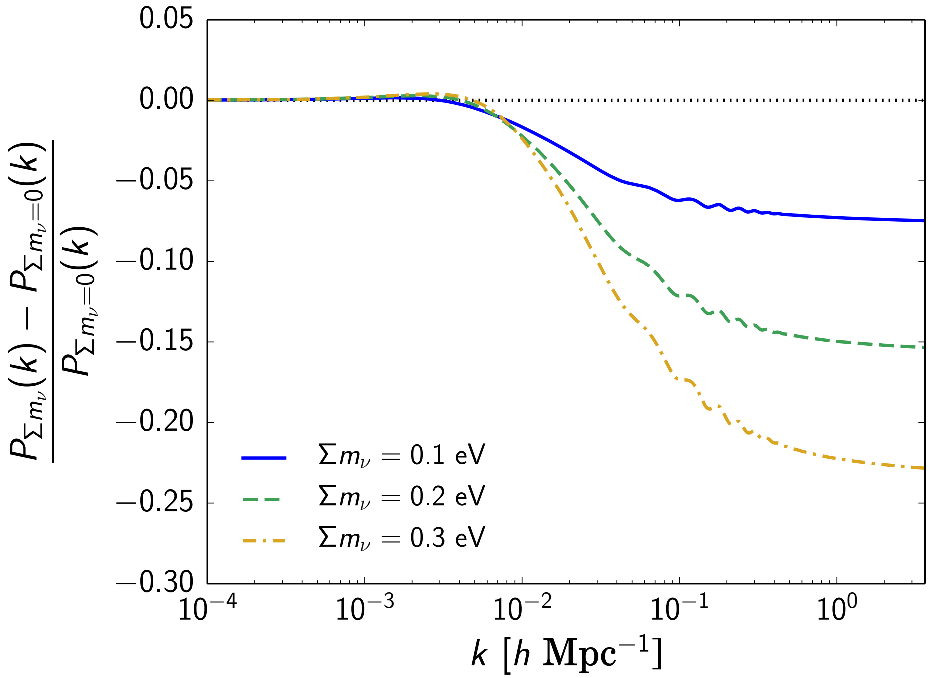
ESA/Planck 2015

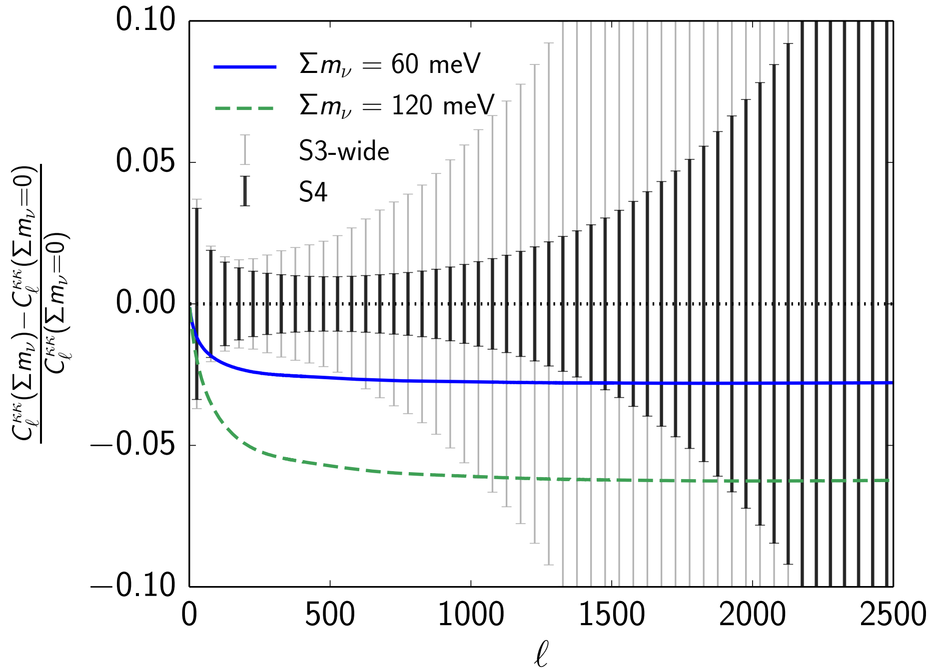
$$\Omega_K = -0.052^{+0.032}_{-0.018} \quad (68\%;\ Planck\ \mathrm{TT+lowP})$$

$$\Omega_K = -0.0053^{+0.0089}_{-0.0075} \quad (68\%;\ Planck\ \mathrm{TT+lowP+lensing})$$

$$\Omega_K = -0.0002 \pm 0.0026 \quad (68\%;\ Planck\ \mathrm{TT+lowP+lensing+BAO})$$

Future: neutrino masses





Allison+ 2015

$$\sigma(\sum m_\nu) = 40\,\text{meV} \qquad COrE+$$

$$\sigma(\sum m_\nu) = 15\,\text{meV} \qquad +\text{DESI}/\textit{Euclid}\ \text{BAO}$$

Applications of CMB lensing

- Cosmology from auto-power spectrum
  - *Neutrino masses, curvature, (early) dark energy etc.*
- Cross-correlation/joint analysis with other LSS tracers
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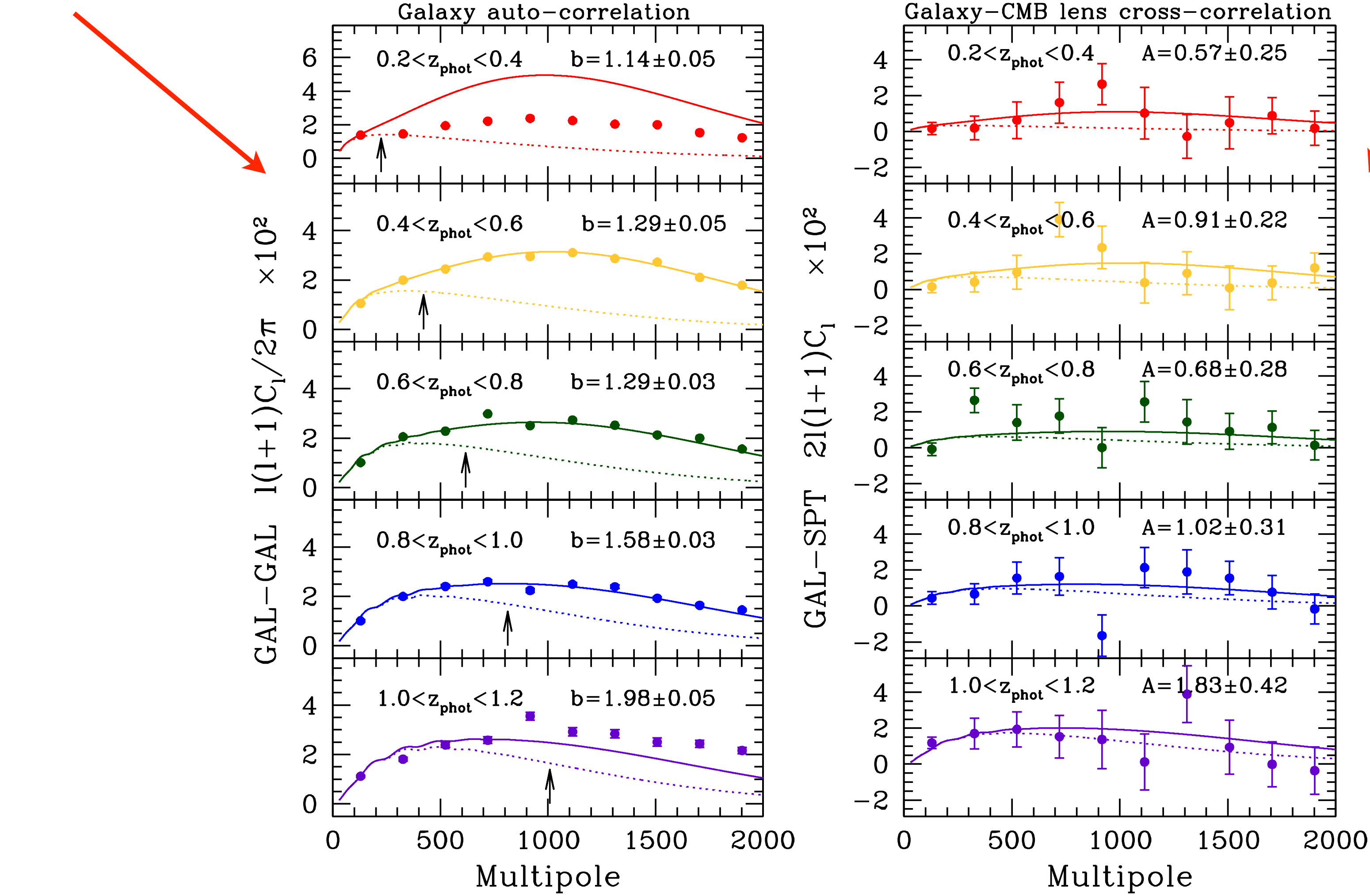
Tomography with galaxy x-corr.

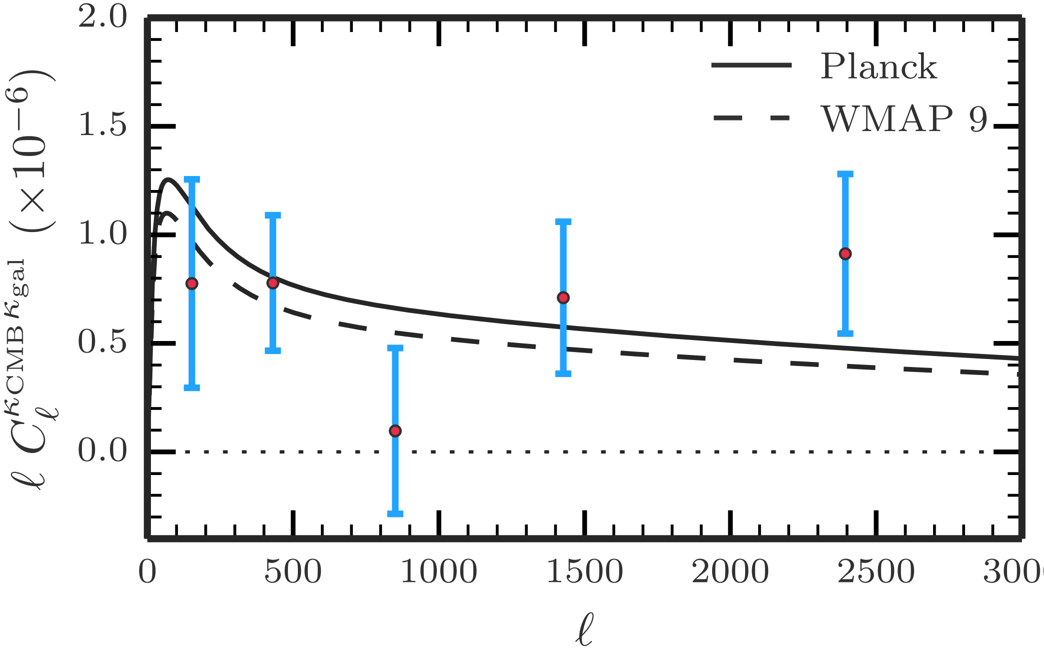
$\langle \Sigma\Sigma \rangle \propto b^2(z) D^2(z)$

$\langle \kappa_{\rm CMB} \Sigma \rangle \propto b(z) D^2(z)$

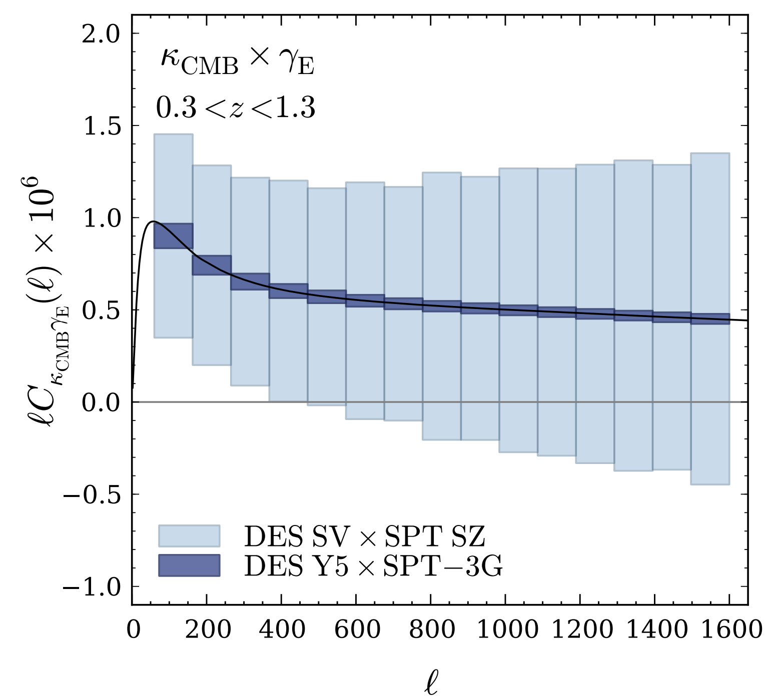


Giannantonio+ 2016

Galaxy lensing-CMB lensing



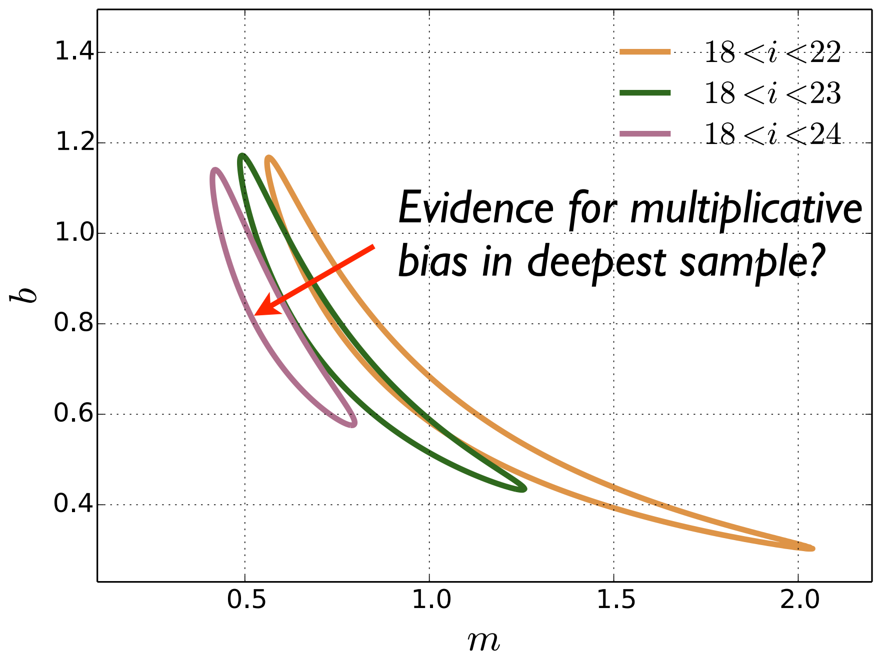
Hand+2013; see also Liu & Hill 2015



Kirk+ 2016

- Current detections around 3σ
- Will improve to >50σ with e.g., DES 5-yr x SPT-3G
- X-correlation more immune to additive systematic effects
- Full joint analysis can calibrate multiplicative bias effects in shape measurement and intrinsic alignments

Self-calibration of galaxy shapes



Liu+ 2016 (following Vallinotto 2012)

$$\gamma_{\rm measured} = m\gamma_{\rm true}$$

Multiplicative bias in measured shear

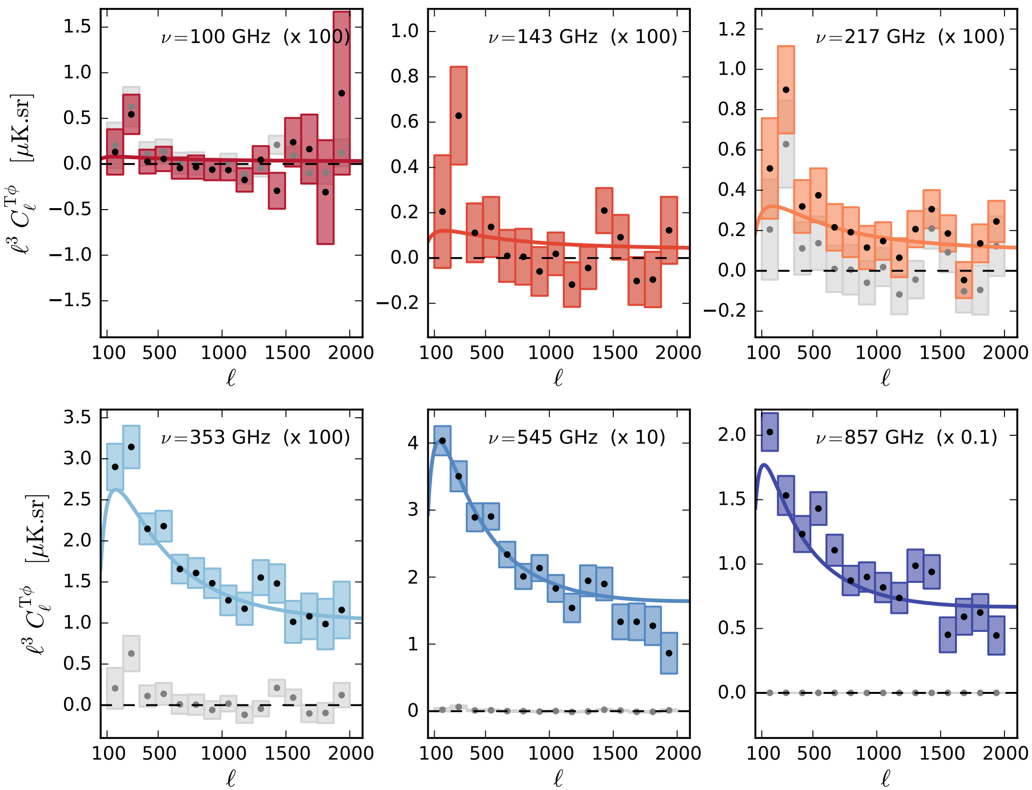
Galaxy bias

$$\langle \kappa_{\rm CMB}\Sigma\rangle \propto b$$

$$\langle \kappa_{\rm gal}\Sigma\rangle \propto mb$$

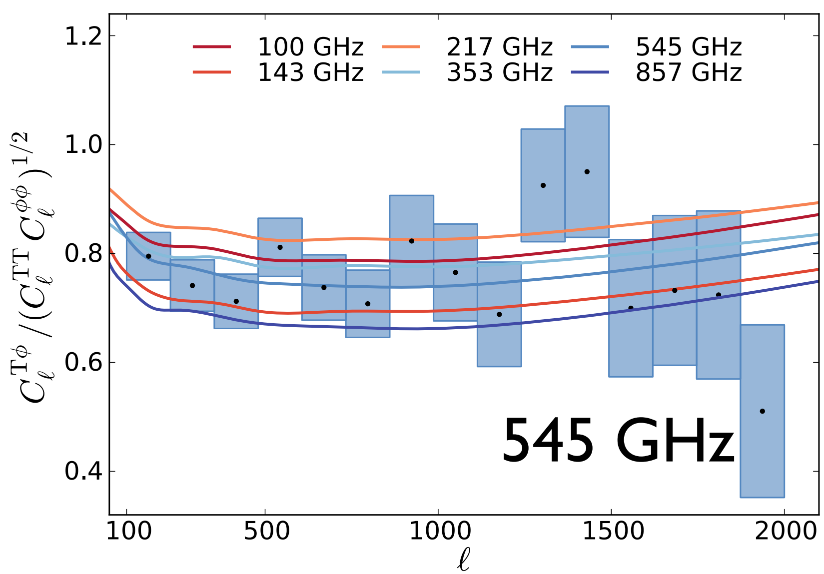
- Other causes?
  - *Photo-z, IAs, wrong b(z) assumptions etc.*
- Joint analysis of (Stage-4 expts.) clustering, galaxy lensing and CMB lensing to self-calibrate *m*(z) to <0.5% (e.g., Schaan+ 2016)

CIB-CMB lensing



Planck Collaboration 2014

- CIB well-matched in z and halo mass with CMB lensing
  - *80% correlated*



- High-z clustering and emissivity of star-forming galaxies
- Scale-dependent bias and f_{NL}^{loc}

Applications of CMB lensing

- Cosmology from auto-power spectrum
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  - *Improve GW constraints*
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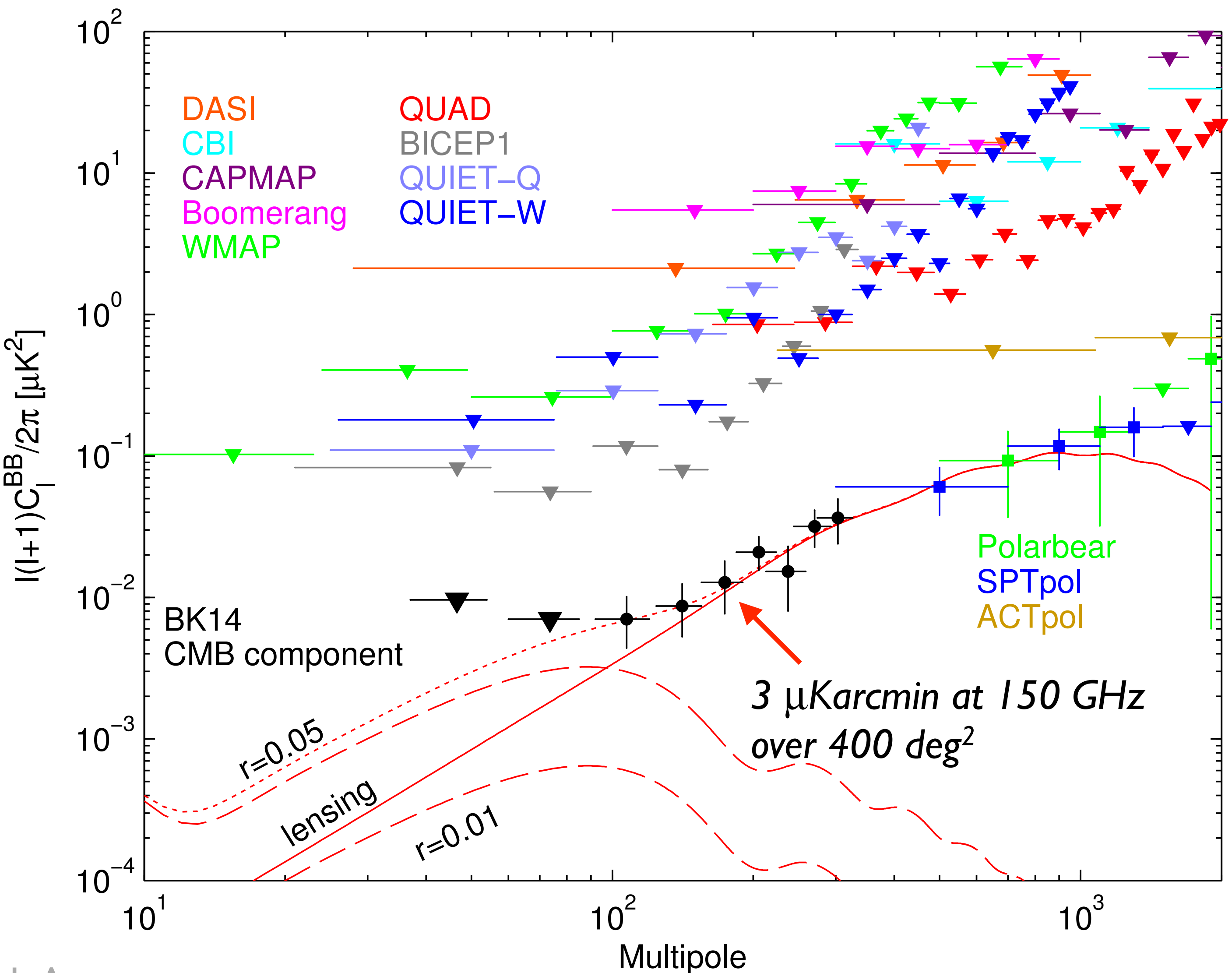
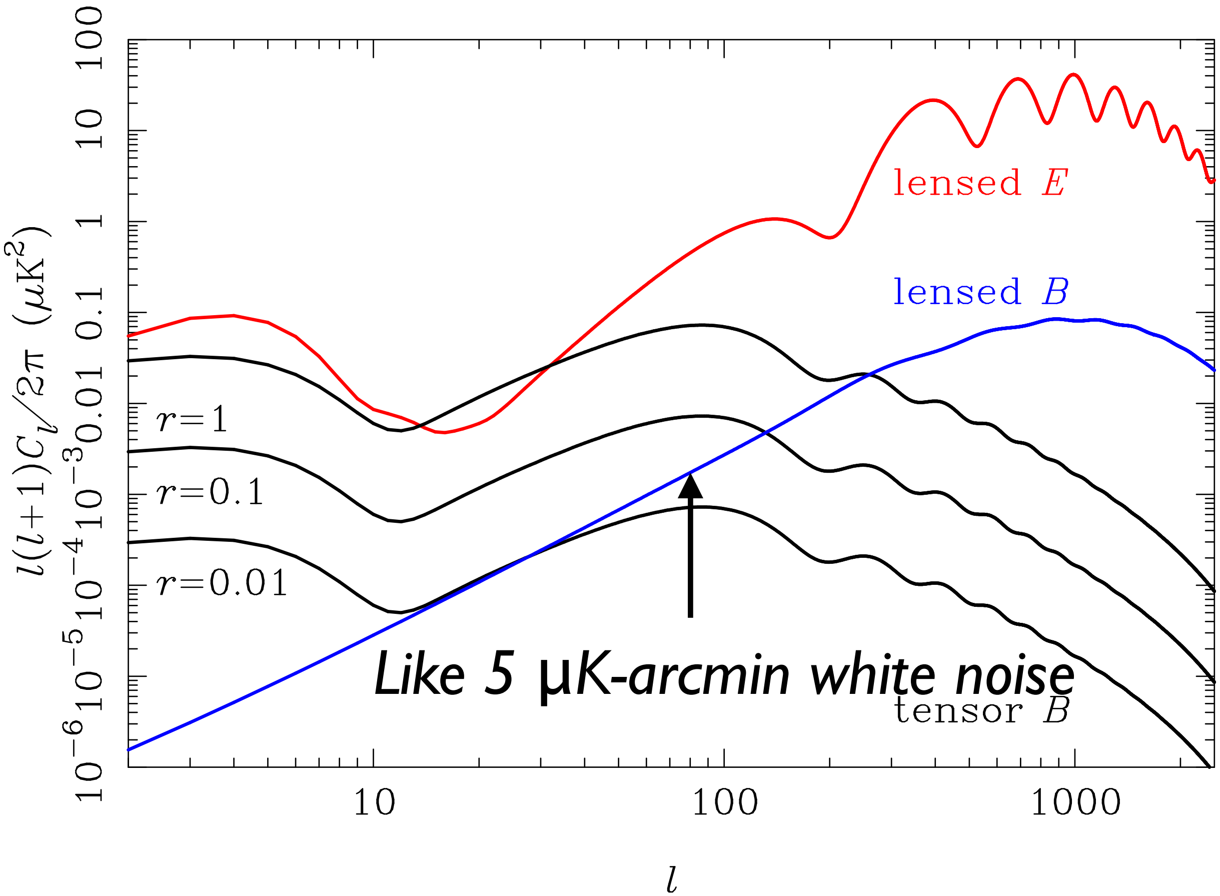
B-mode power measurements



BICEP/Keck Array

Delensing degree-scale B-modes

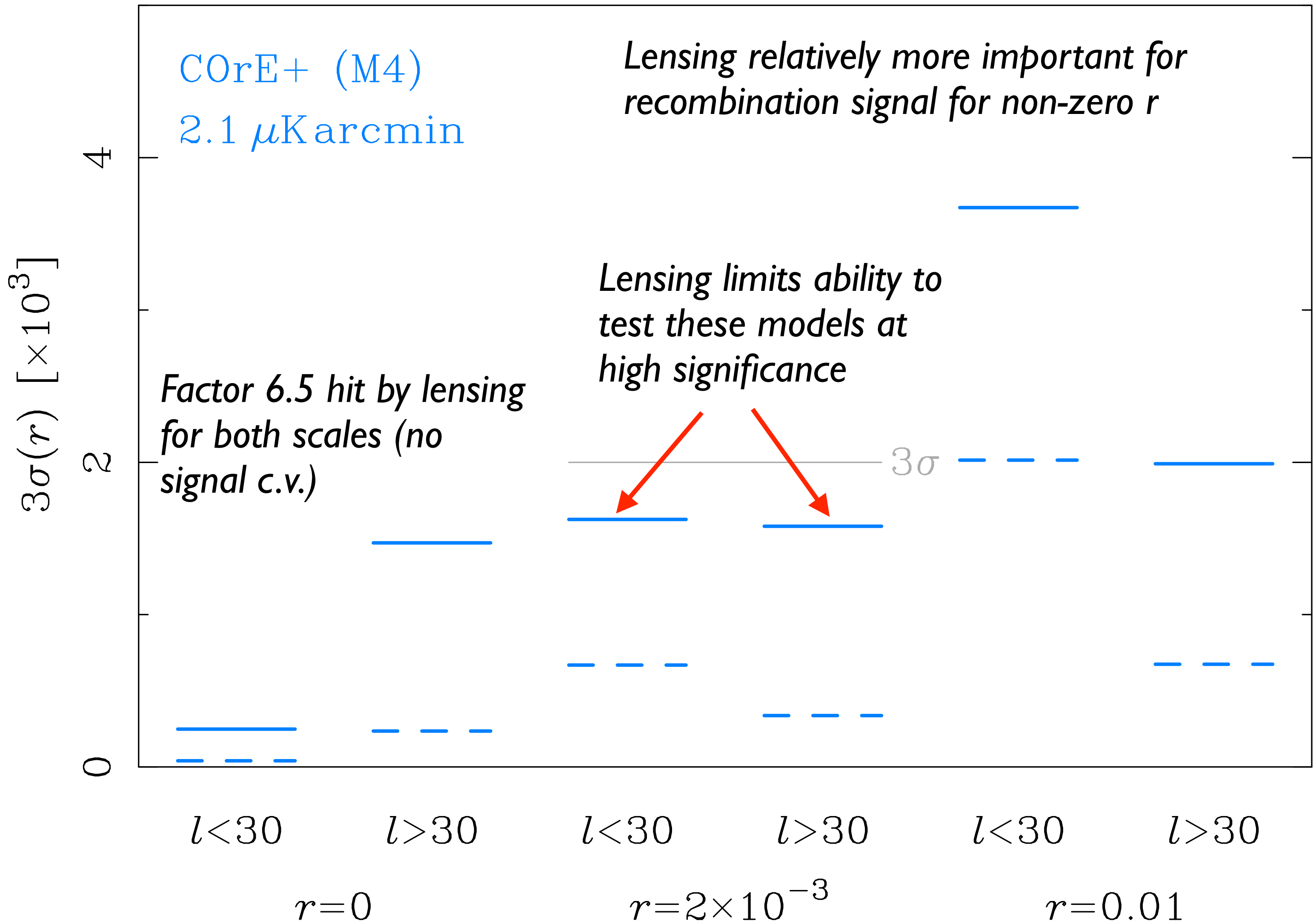


- Improve limits on amplitude of GWs
- Access primordial *B*-modes on smaller scales
  - *Tensor tilt*
  - *Oscillations?*

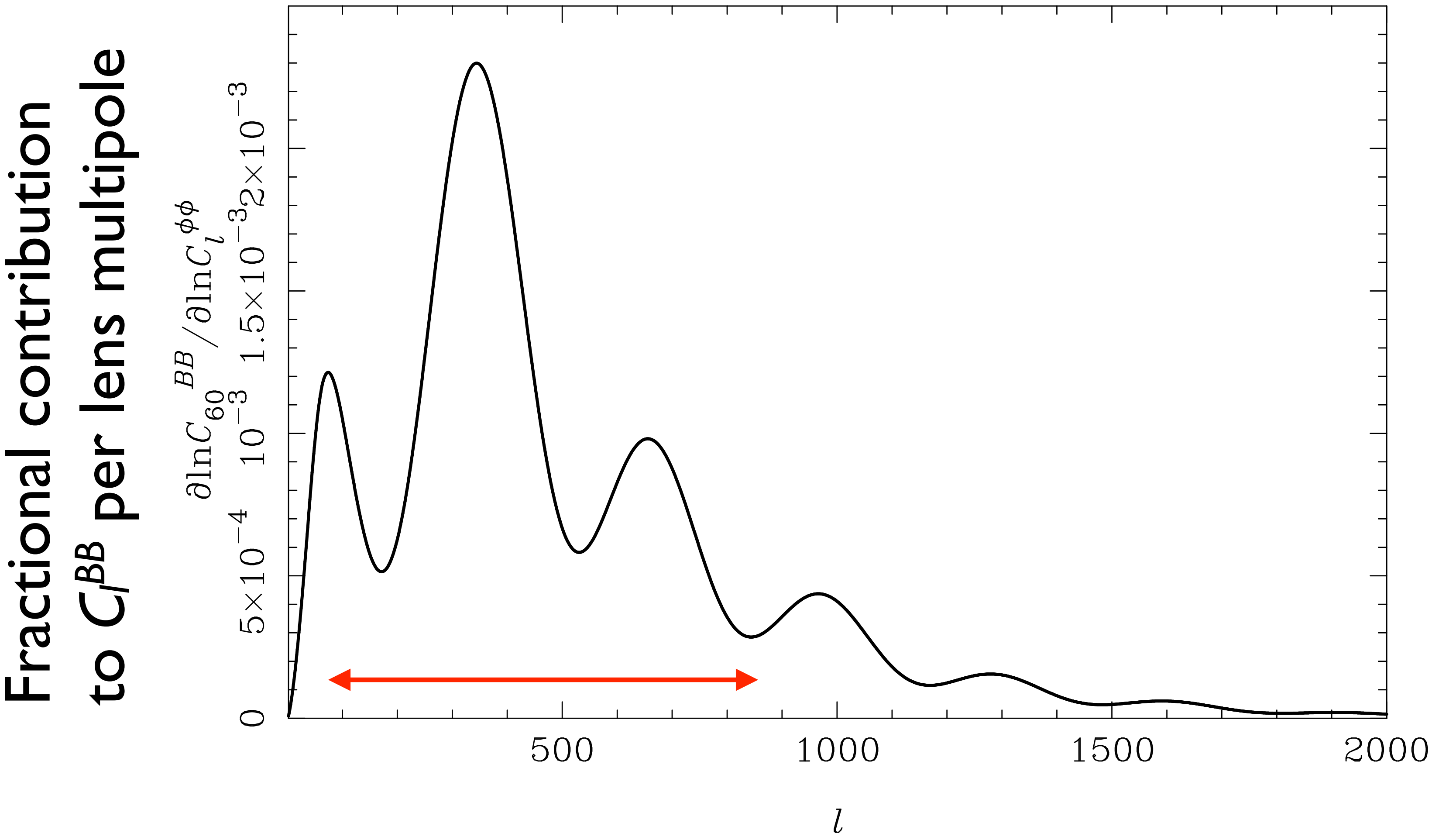
Some proxy for lensing potential

$$B_{\rm delens} \sim B - E\hat{\phi}$$

Implications for inflation constraints



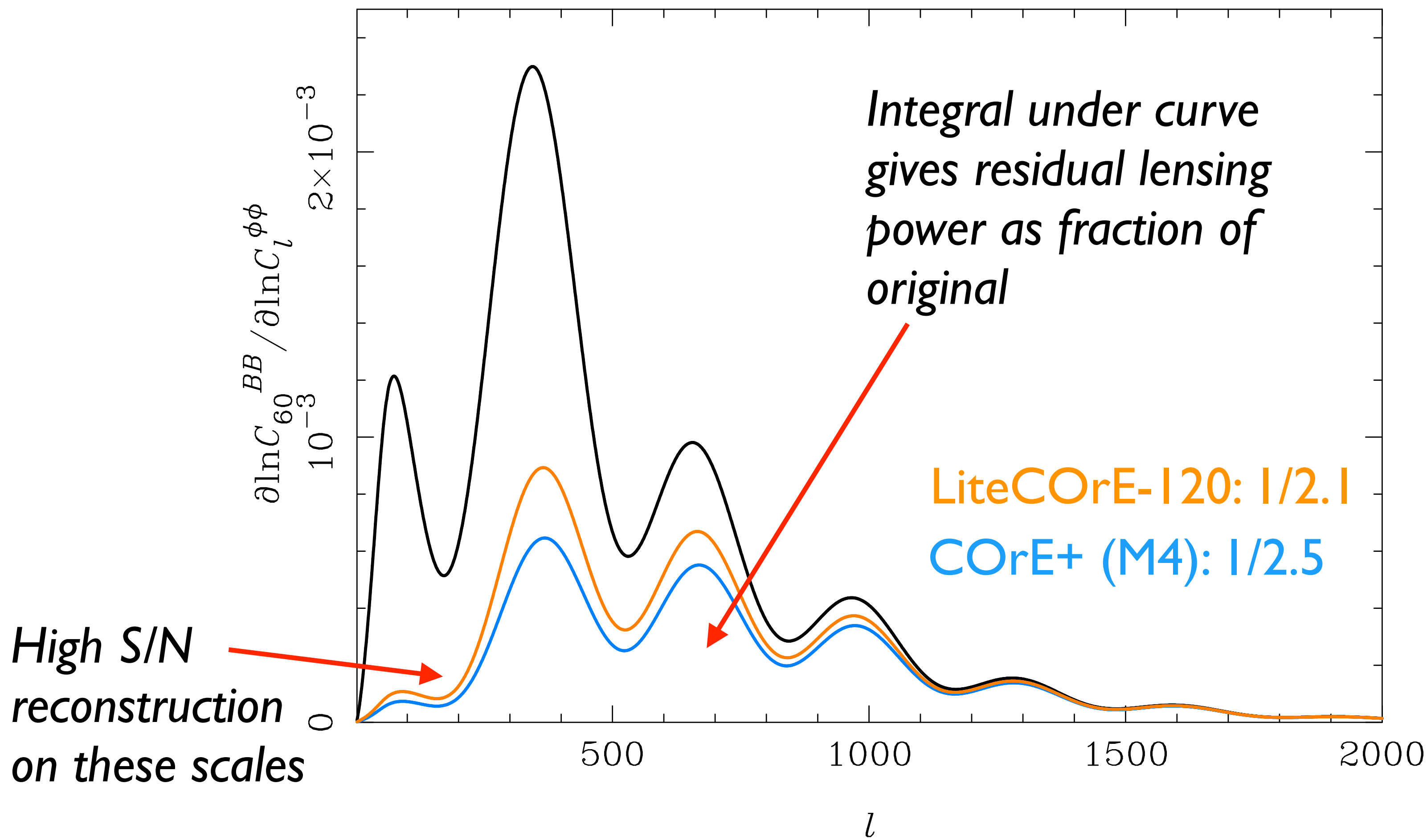
Which scales are important?



- Intermediate-scale lenses important for large-scale *BB*

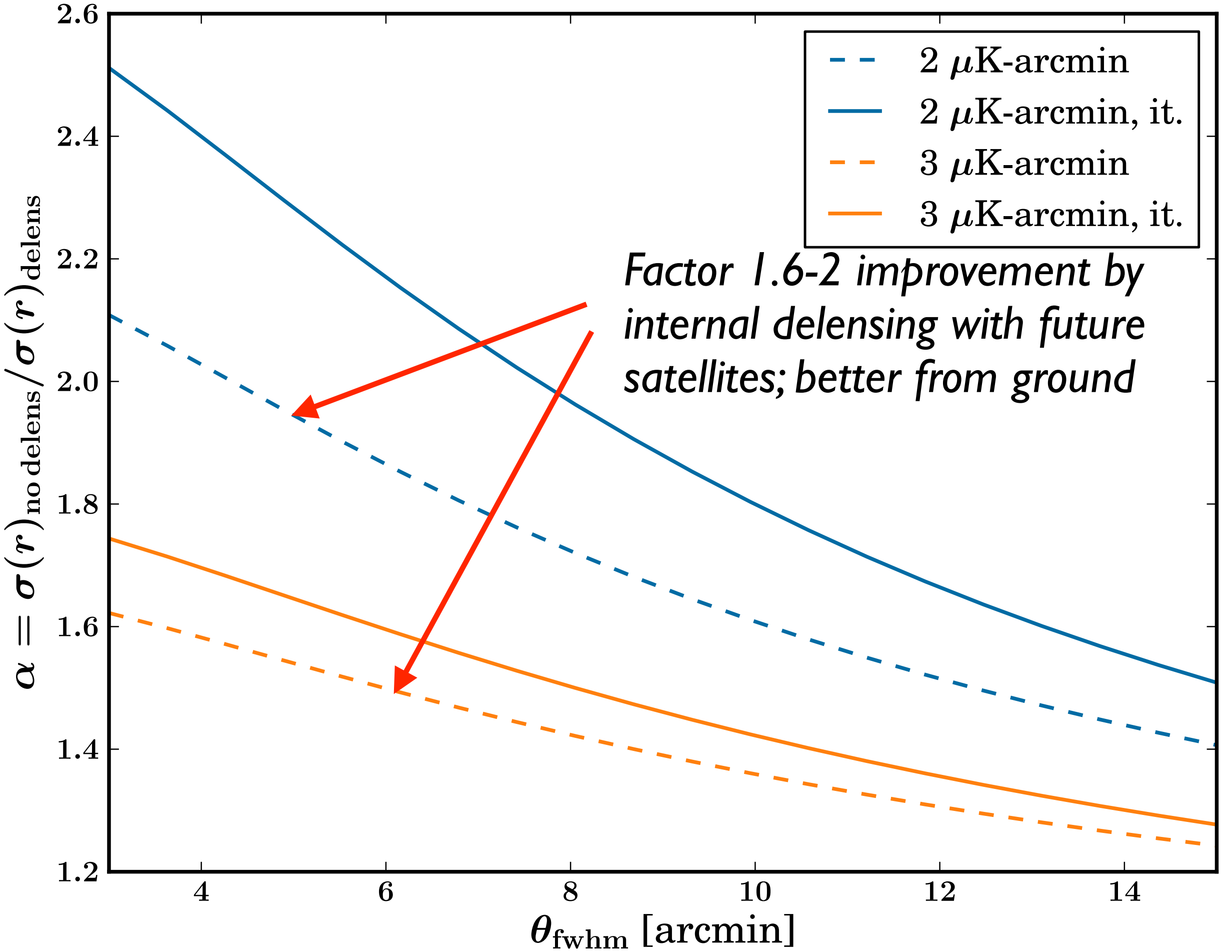
Impact of delensing

$$\frac{C_l^{BB,\mathrm{delens}}}{C_l^{BB,\mathrm{lens}}} \approx \sum_L \frac{\partial \ln C_l^{BB,\mathrm{lens}}}{\partial \ln C_L^{\phi\phi}} \left(1-\rho_L^2\right)$$



Requirements for internal delensing

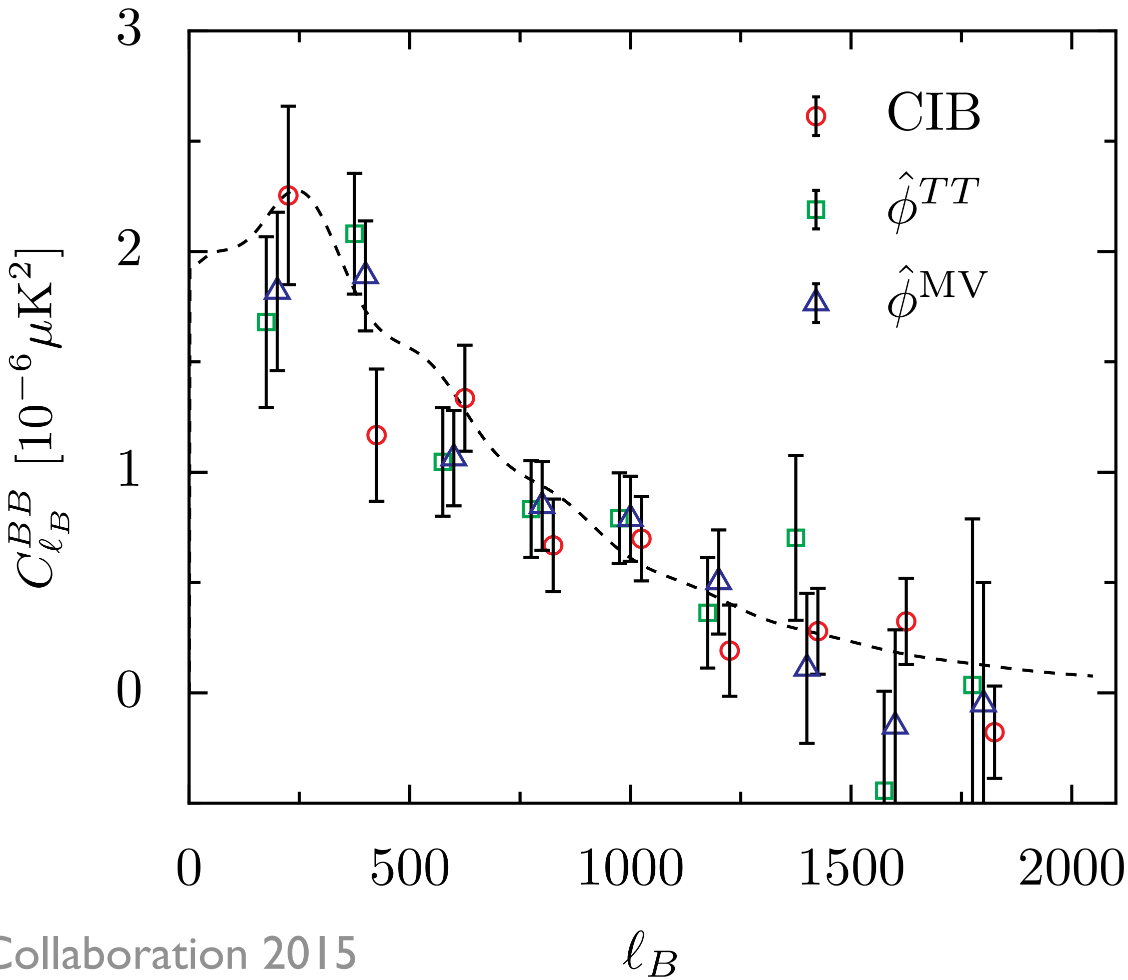
Factor by which delensing improves σ(r) for *r=0*



Feeney & Errard

Towards delensing: indirect BB

- "Correction" in $B_{\text{delens}} \sim B - E\varphi$ correlated with B at expected level

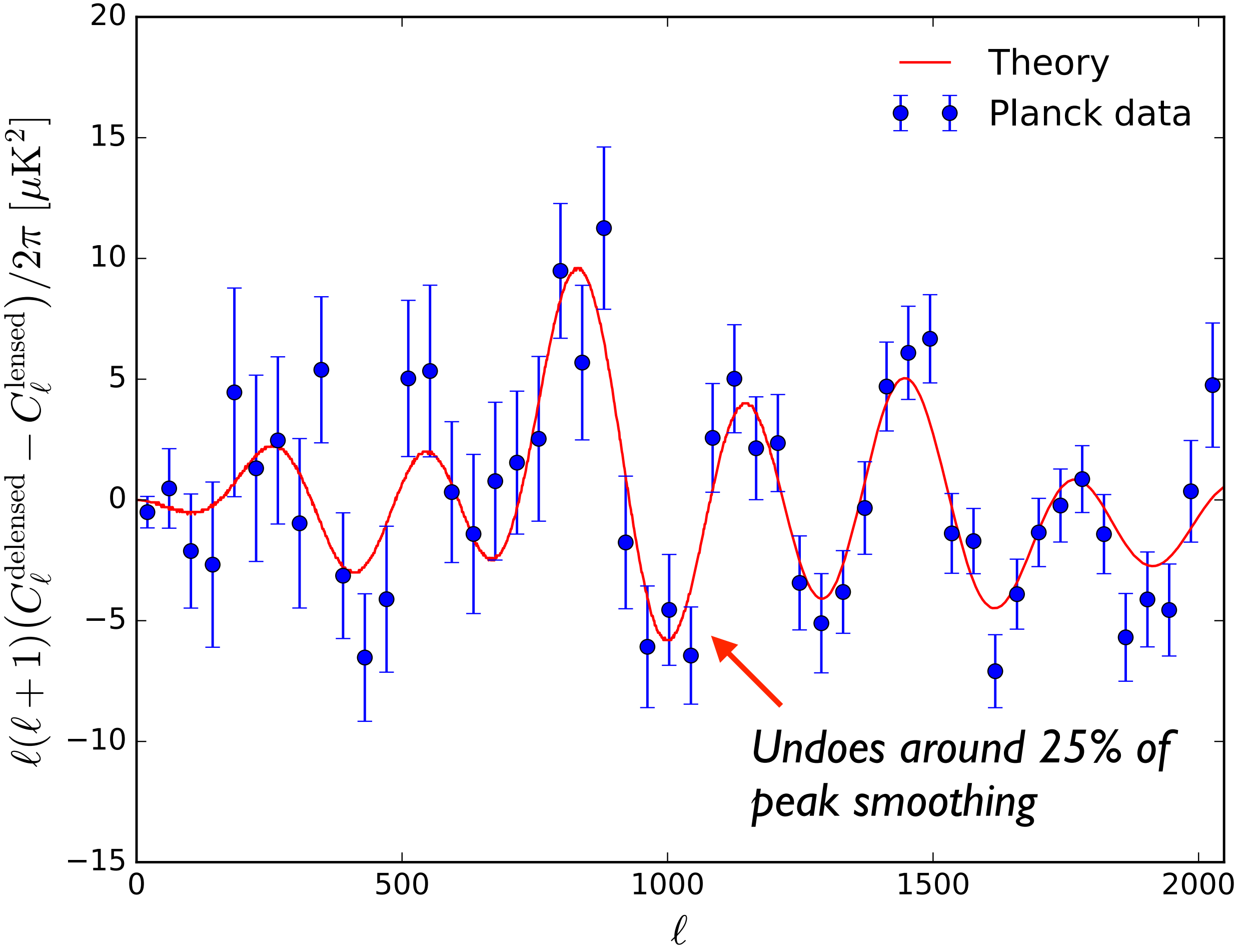


$$C^{B\hat{B}} \sim B(E\hat{\phi})$$

See also Hanson+2013, Ade+2014, and van Engelen+2014

Planck Collaboration 2015

First demonstration of CIB delensing



- CIB from α545-857 Planck channels
  - *Residual dust and shot noise reduces correlation with CIB below 80%*

Larsen, AC+ 2016