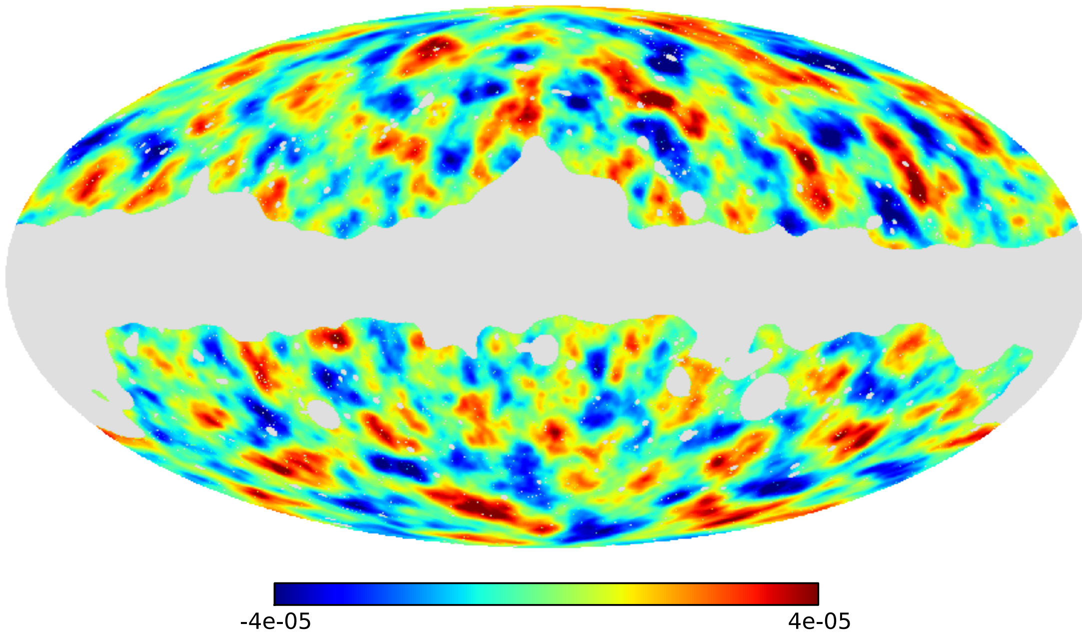
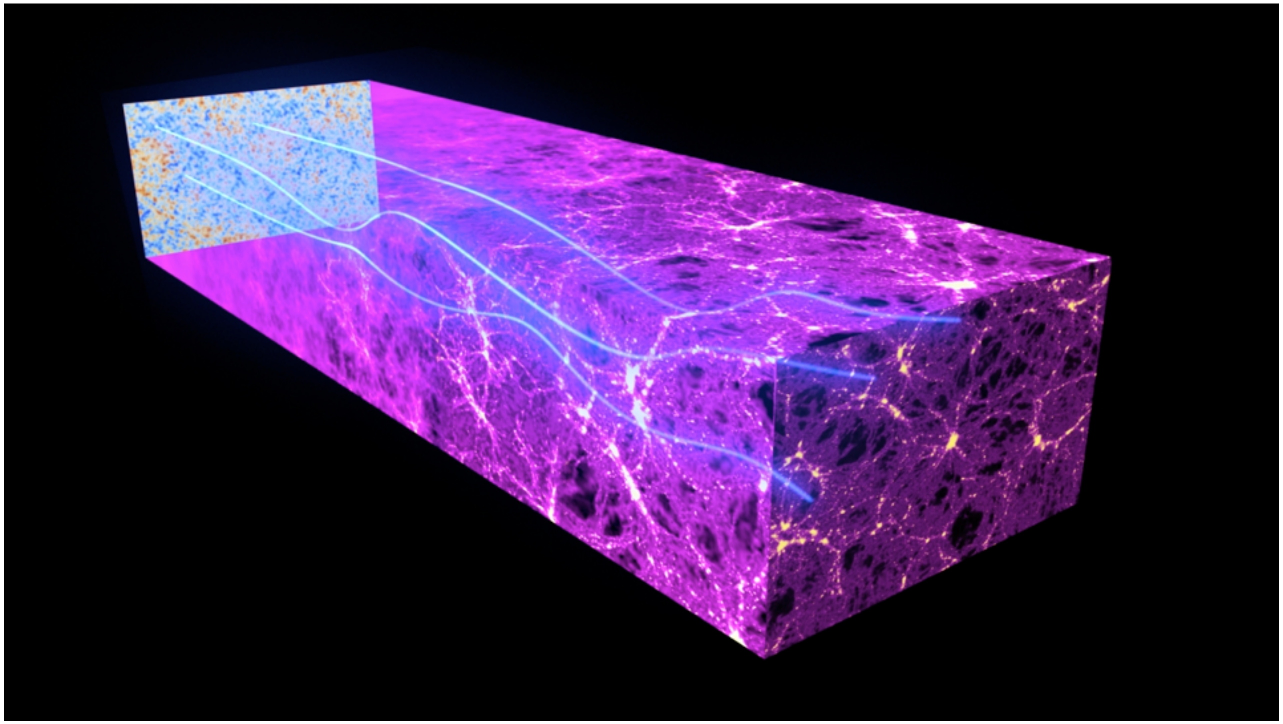
A distorted view of the CMB?

Anthony Challinor



KICC/IoA/DAMTP
University of Cambridge

Lensing of the CMB

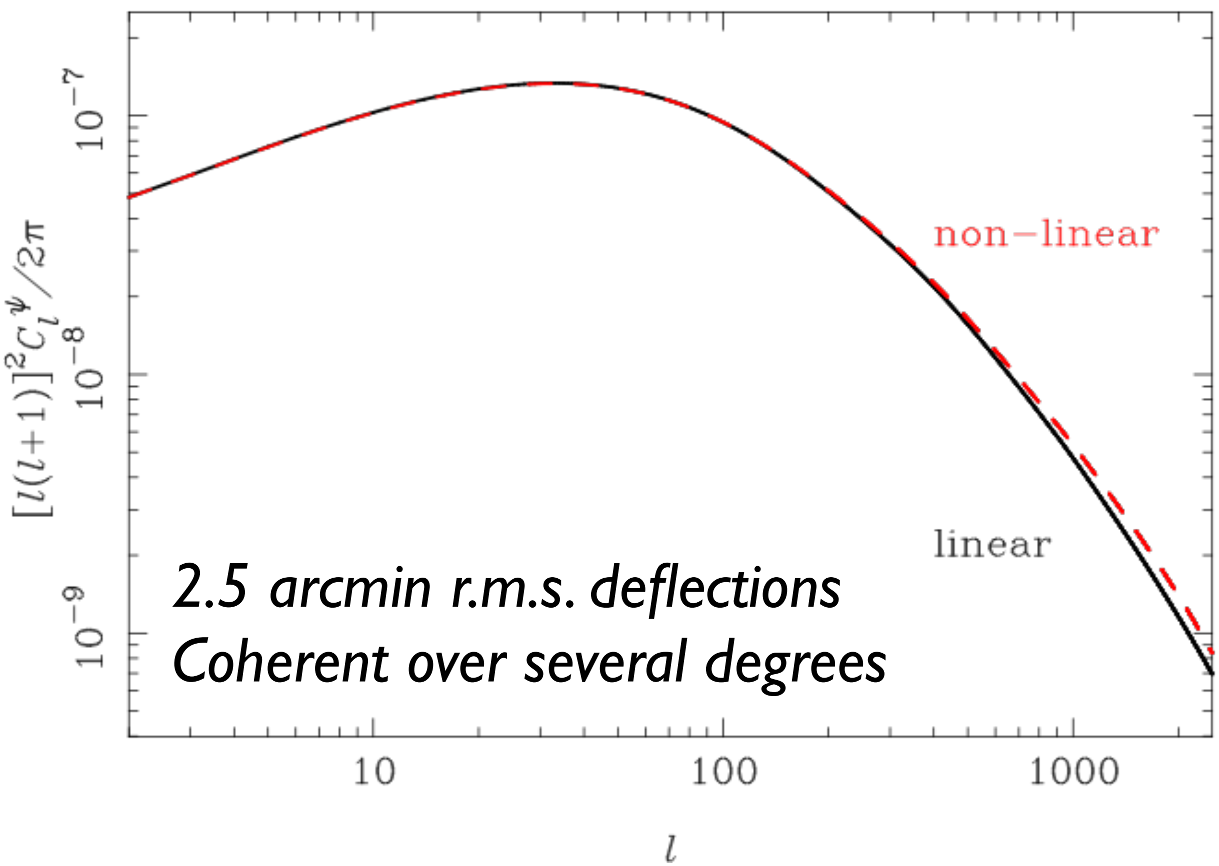


- O(50) deflections by O(100) Mpc scale lenses
  - *Peak efficiency around z=2*
  - *Predicts 2.5 arcmin r.m.s. deflections coherent over several degrees*

CMB lensing power spectrum

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

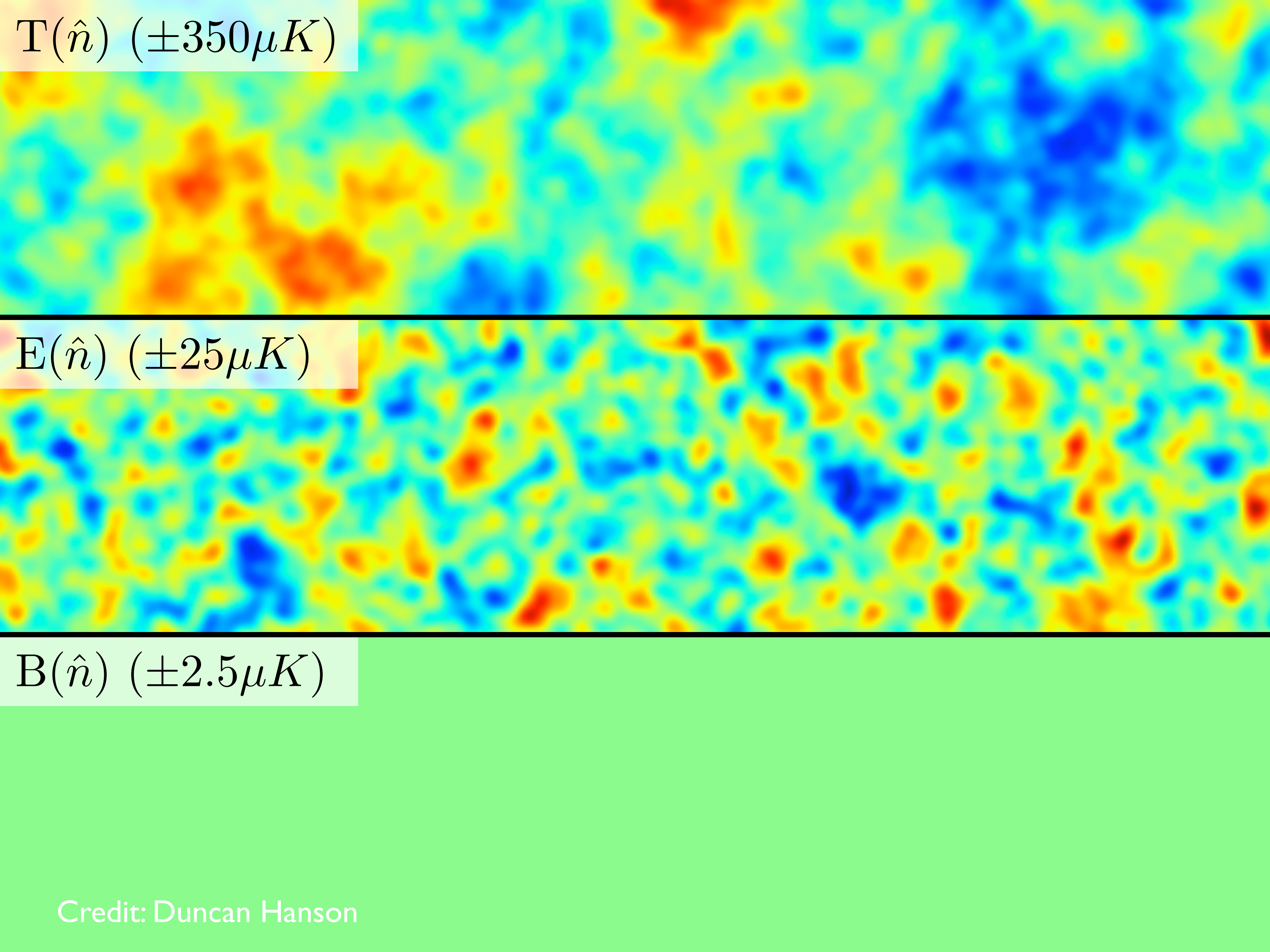
$$\phi(\hat{\boldsymbol{n}}) = -\int_0^{\chi_*} d\chi \, \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)(\chi \hat{\boldsymbol{n}}; \eta_0 - \chi)$$

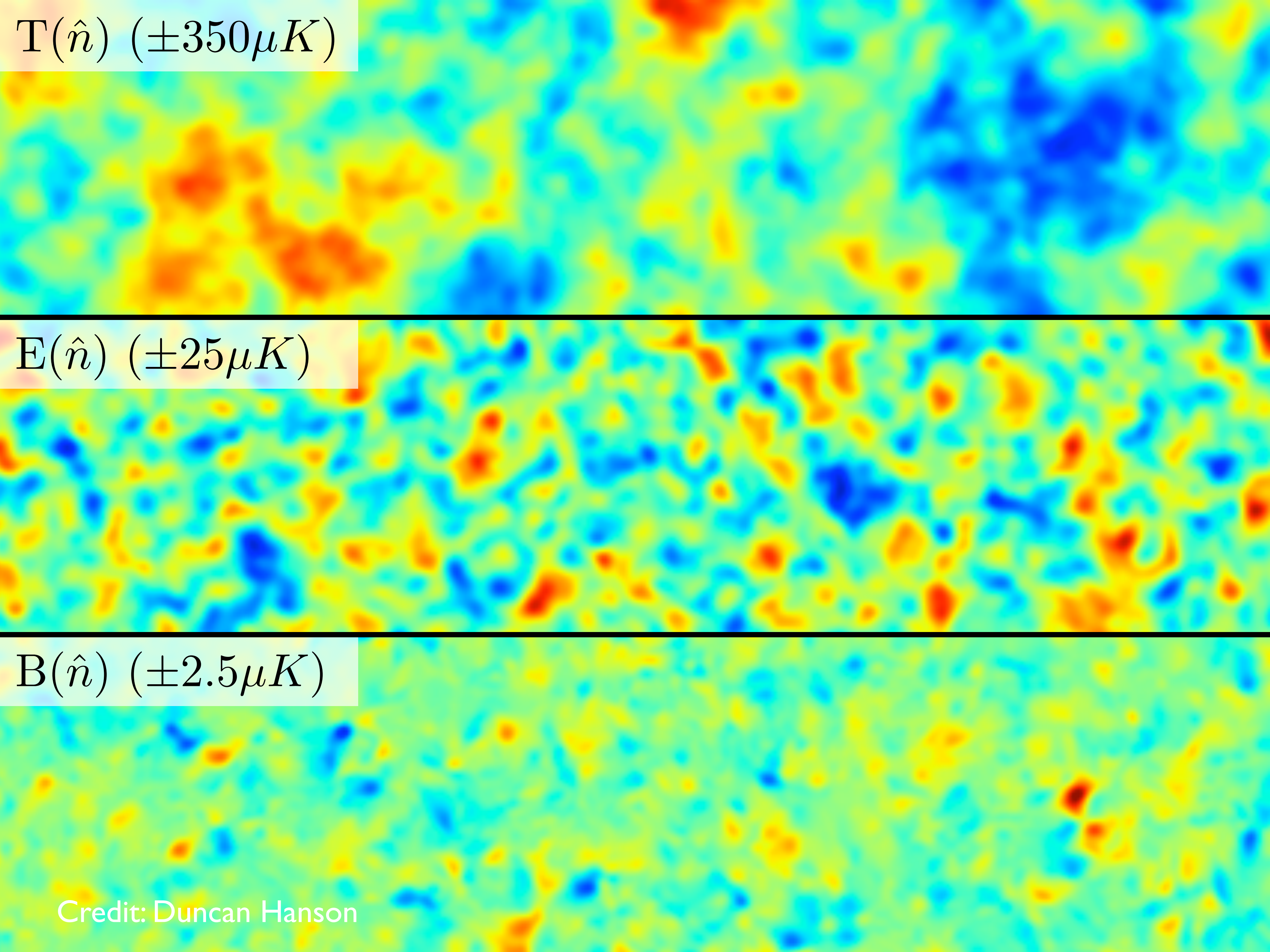


Effects of lensing on the CMB

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

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


$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Credit: Duncan Hanson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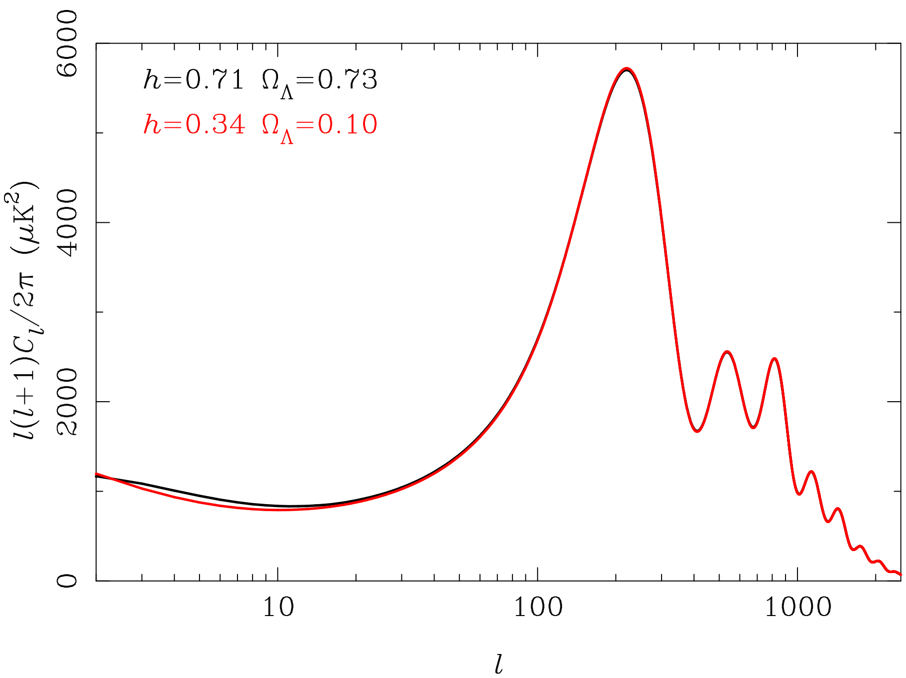
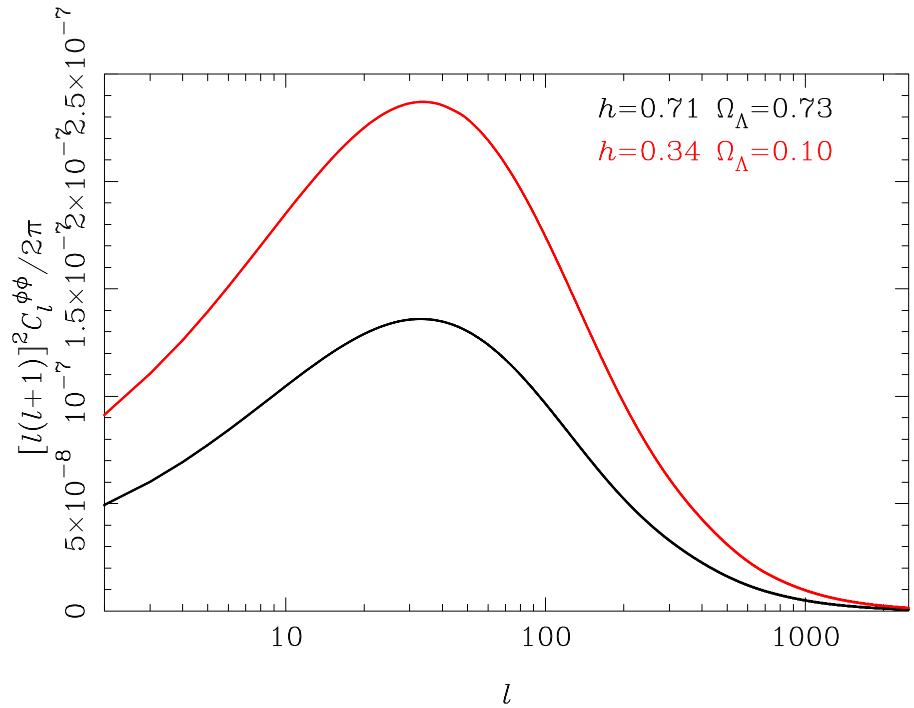
- Smooths out acoustic peaks in *TT*, *TE*, and *EE* power
- Generates power at arcmin scales in *TT*, *TE*, and *EE*
- Generates *B*-modes from *E-modes* with almost white noise power
- Introduces non-Gaussianity
  - *4-point function proportional to* $C_L^{\varphi\varphi}$
  - *3-point function with LSS tracers correlated with* φ

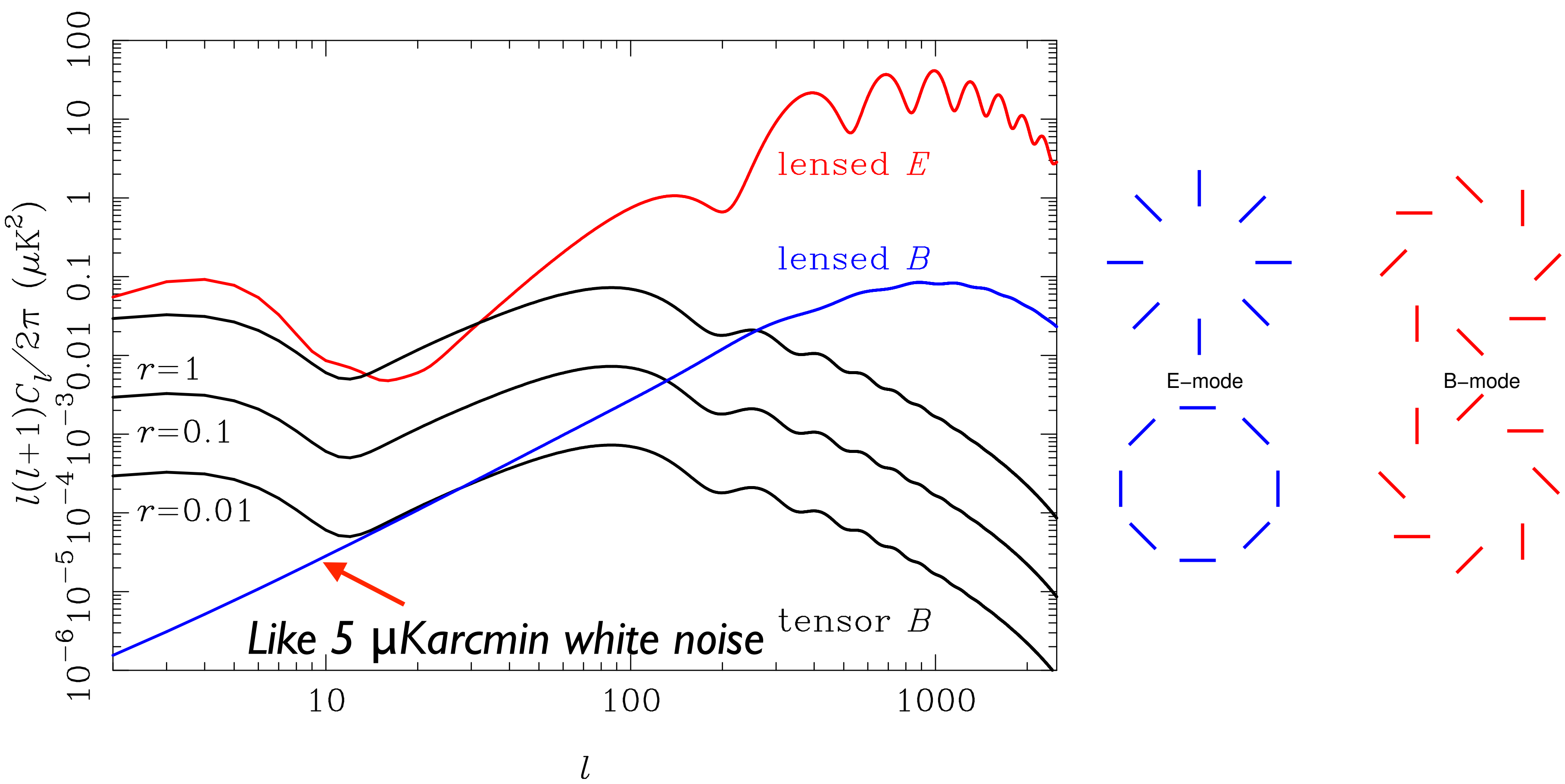
Lensing adds information…





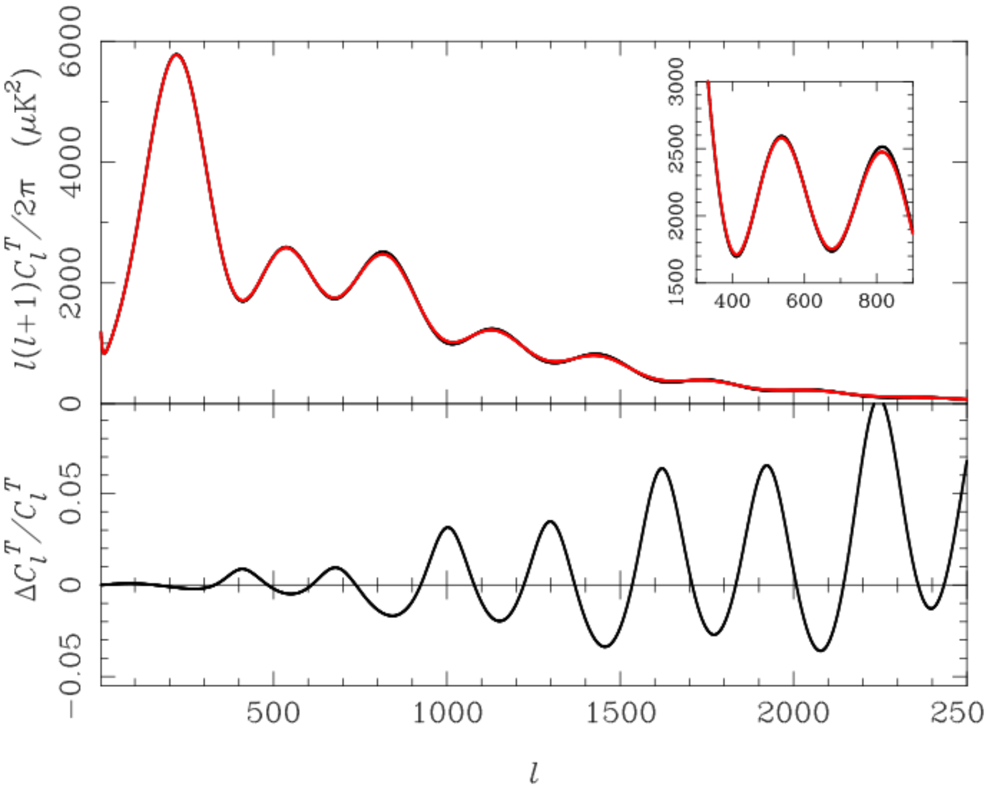
- Geometric degeneracy in CMB power spectra broken by different amounts of lensing in models with same $d_A(z_*)$
  - *Access to curvature, sub-eV neutrino masses, dark energy etc. from CMB alone*

… but also hides it

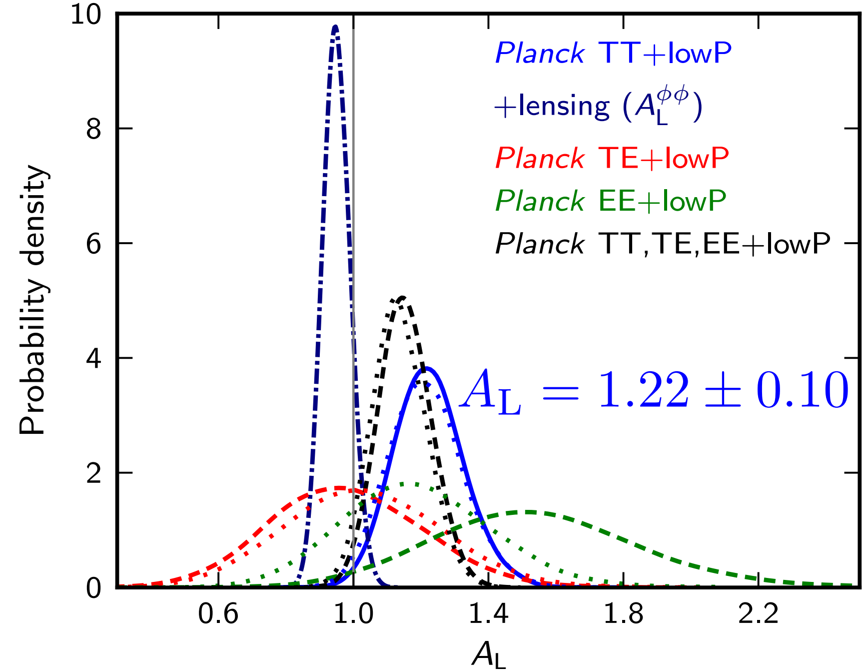


- Additional cosmic variance from lensing B-modes obstacle for instrument noise better than 5 μKarcmin

Lensing peak smoothing



$$C_l^{\phi\phi} \rightarrow A_{\rm L} C_l^{\phi\phi}$$



Planck Collaboration 2016

- Smoothing effect in *TT* detected at 10σ with Planck
- Contains information on a single (eigen)mode of $C_l^{\varphi\varphi}$

Lens reconstruction

- Fixed lenses introduce statistically-anisotropic correlations:

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

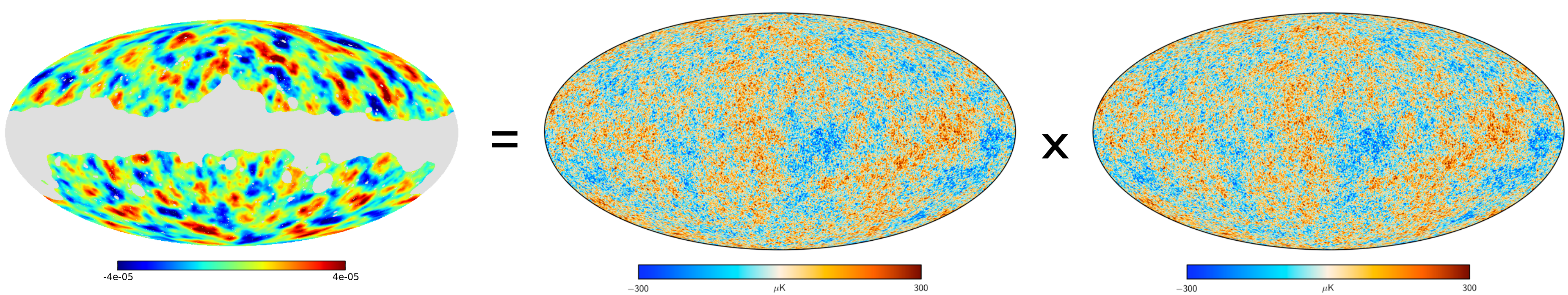
- Noisy lensing estimates from quadratic CMB combinations:

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

Normalisation

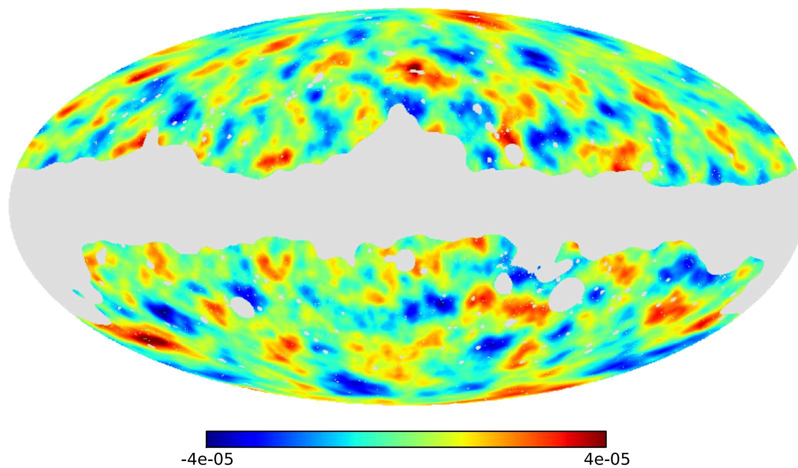
Known lensing-induced correlations

Inverse-variance-weighted CMB fields

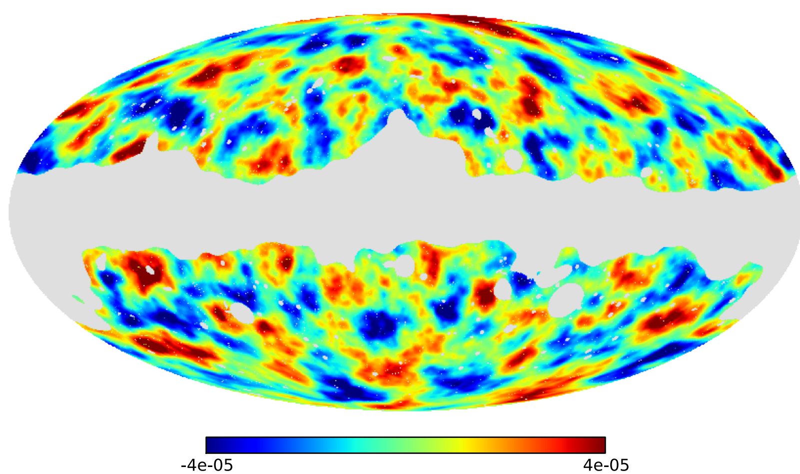


Reconstruction is noisy

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

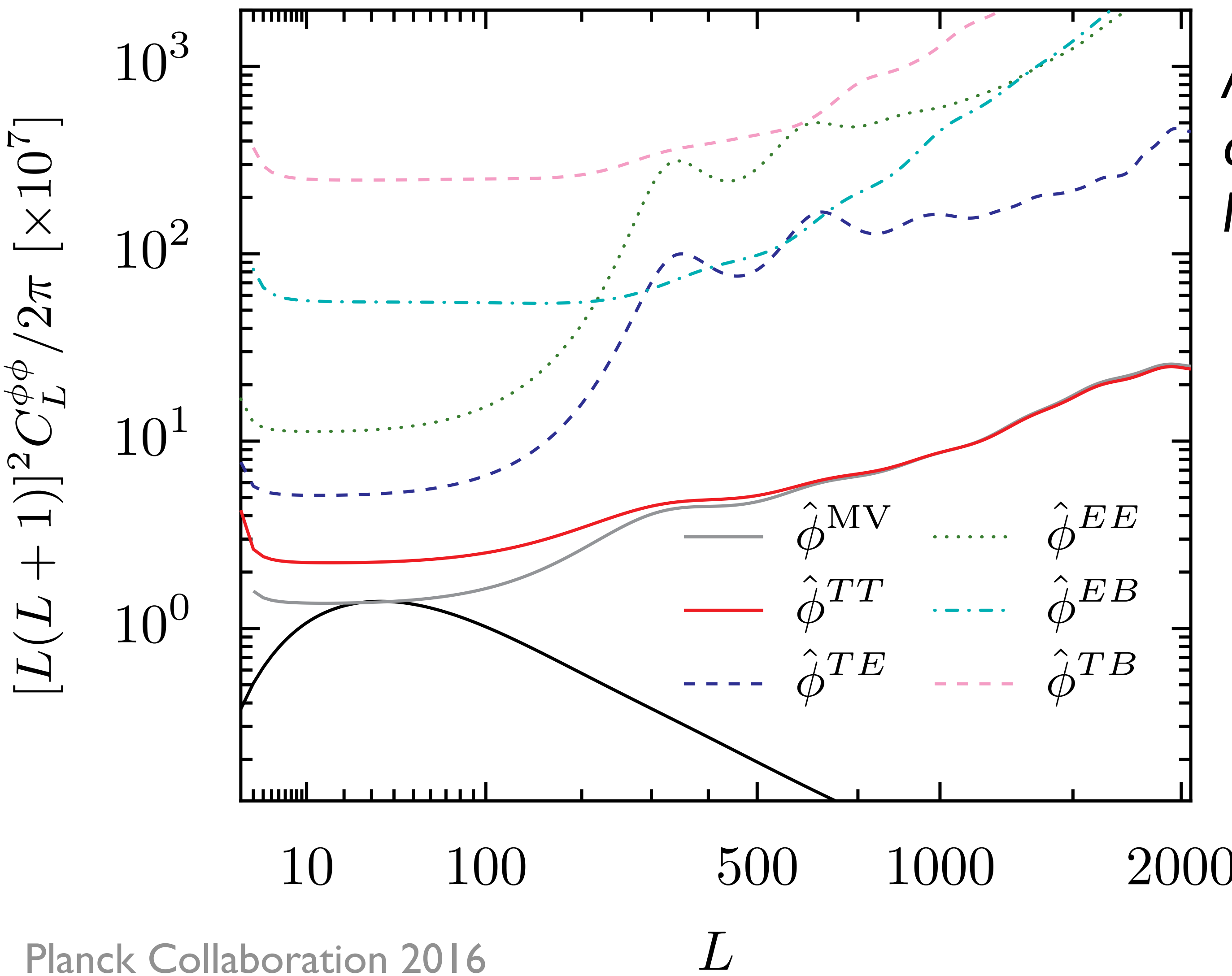


Input



Recovered at Planck noise levels

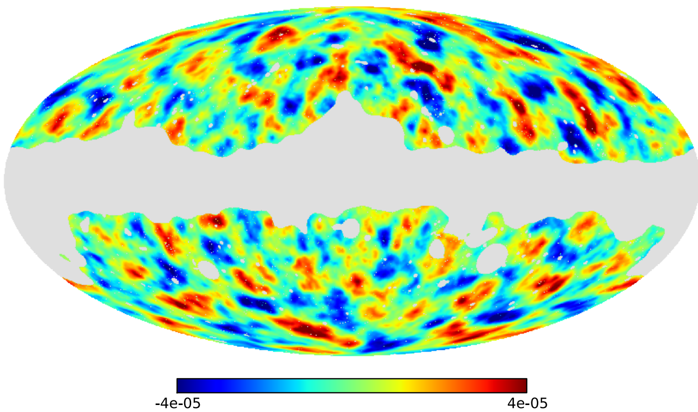
Planck reconstruction noise levels



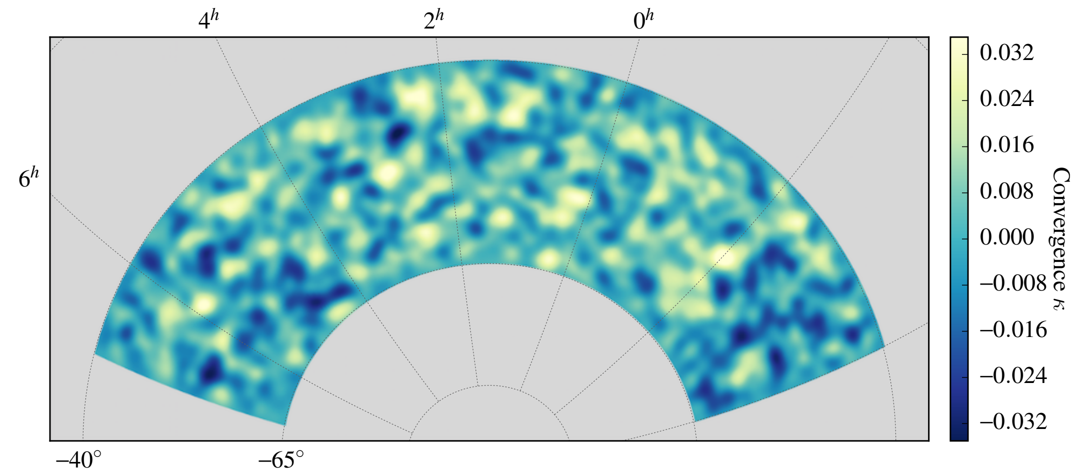
Almost white noise on $L(L+1)\varphi_{LM}$ on large scales

Planck Collaboration 2016

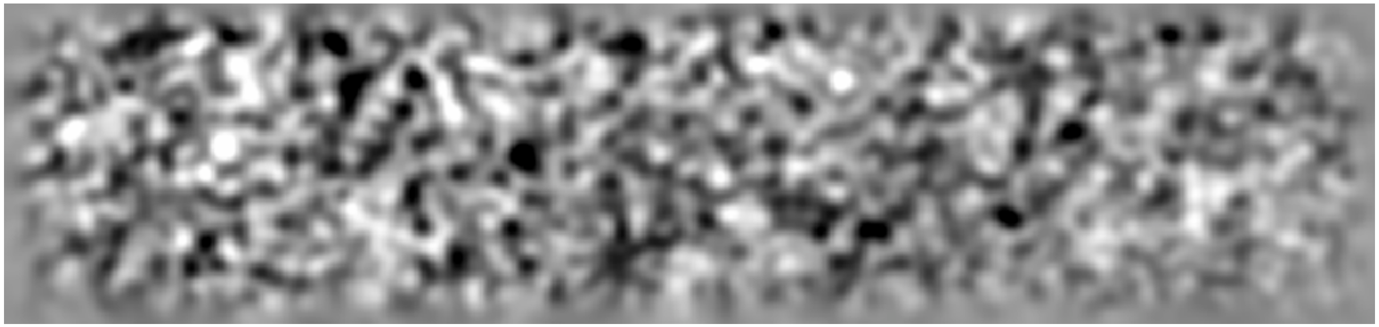
Recent lens reconstructions



Planck Collaboration 2016

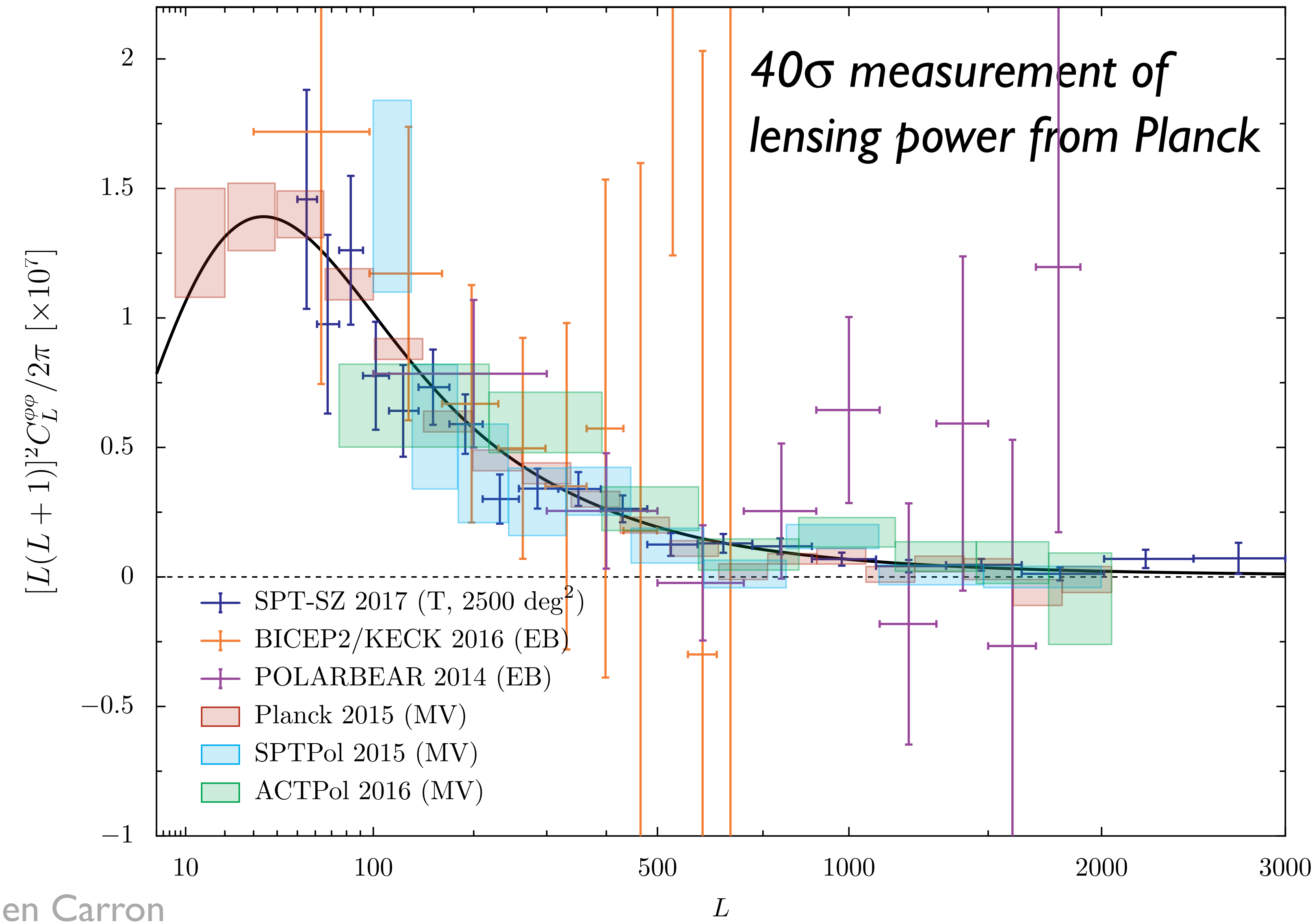


Omori+ 2017: 2500 deg^2 SPT+Planck



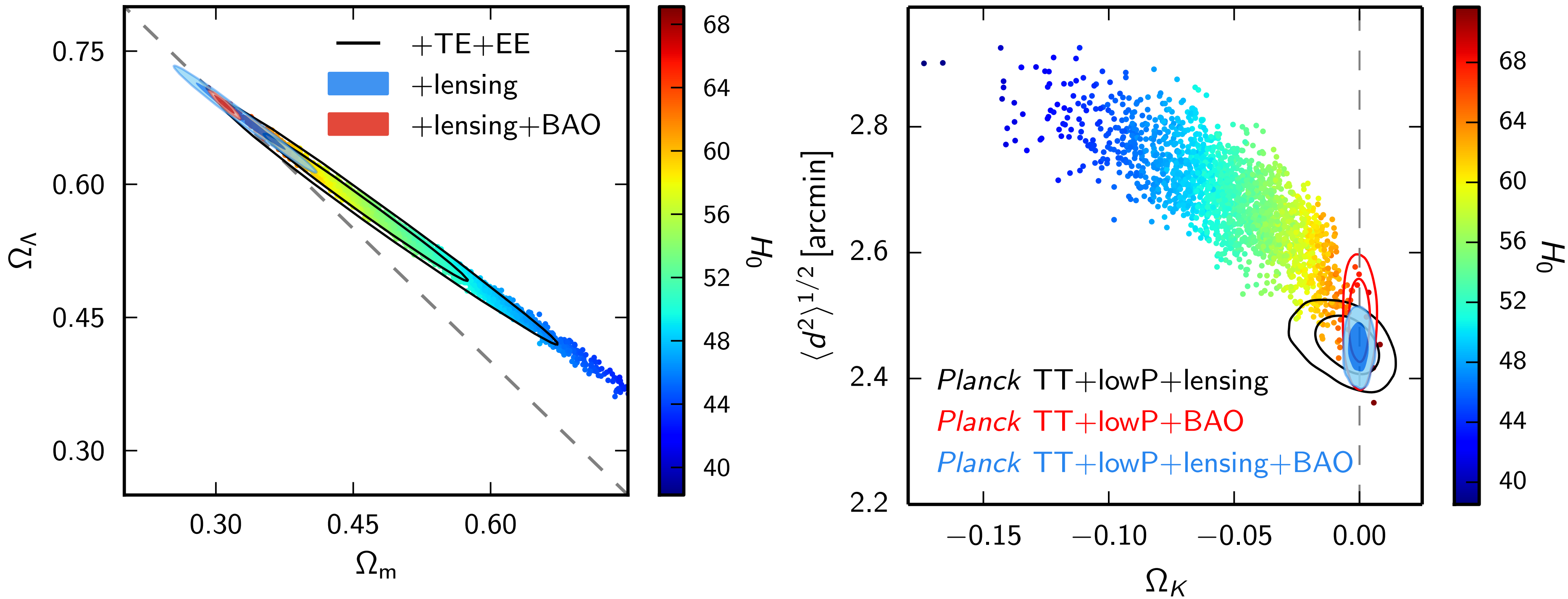
Sherwin+ 2016: 500 deg^2 two-season ACTPol

Lensing power measurements



Julien Carron

Constraining curvature



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

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

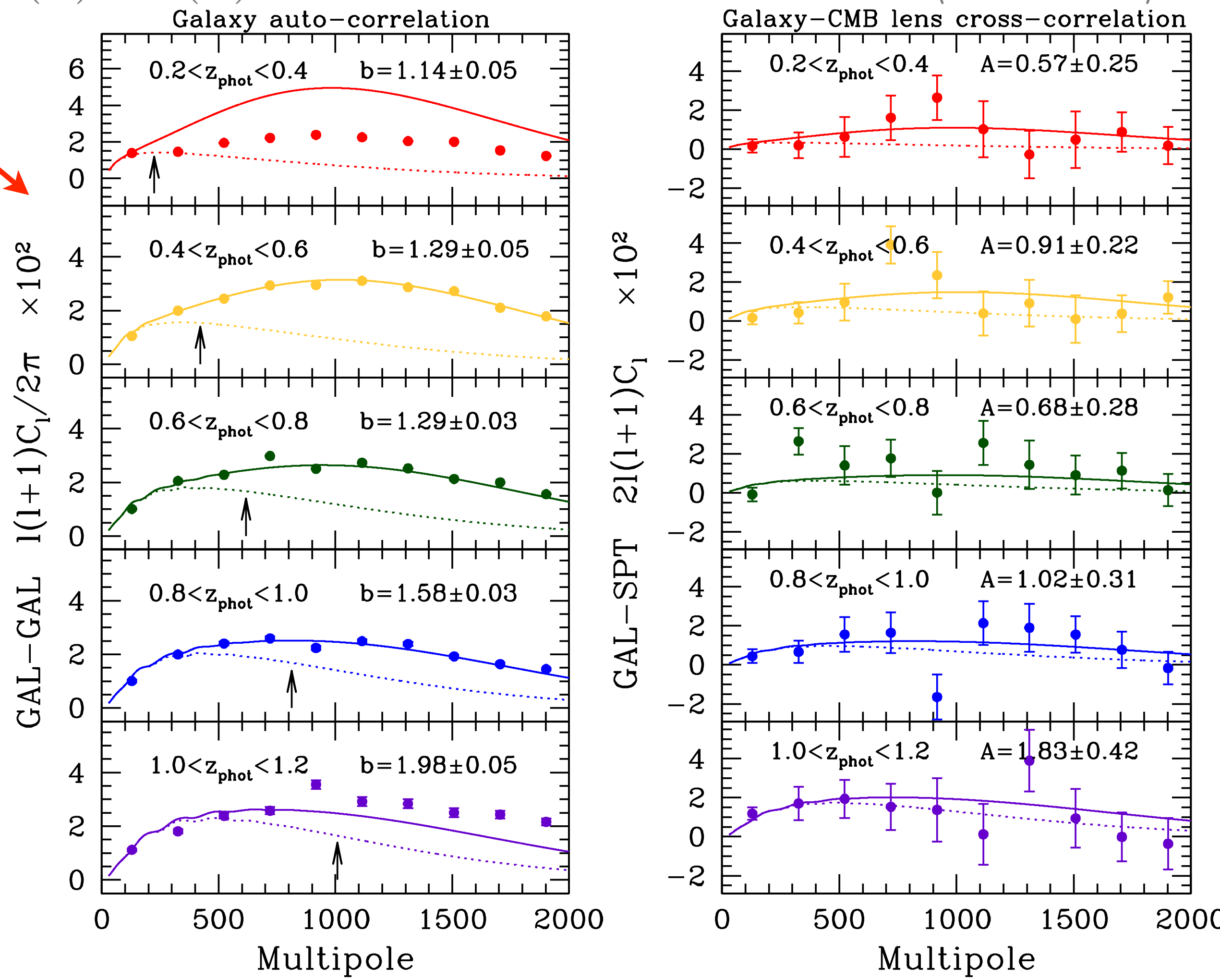
$$\Omega_K = -0.0002 \pm 0.0026 \qquad (68\%;\ \textit{Planck}\ \text{TT+lowP+lensing+BAO})$$

Planck Collaboration 2016

Growth of structure

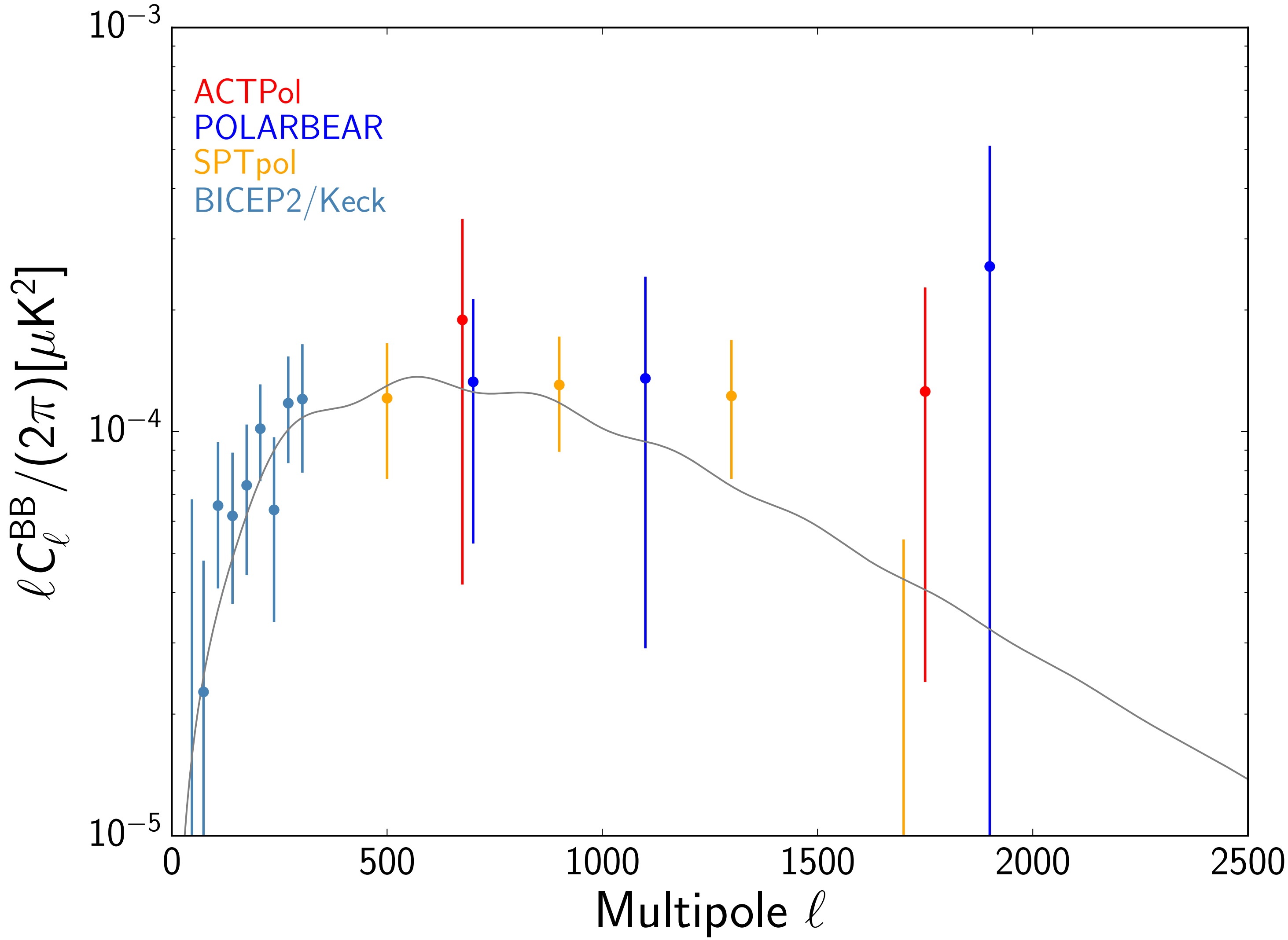
$\langle \Sigma\Sigma \rangle \propto b^2(z) D^2(z)$

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



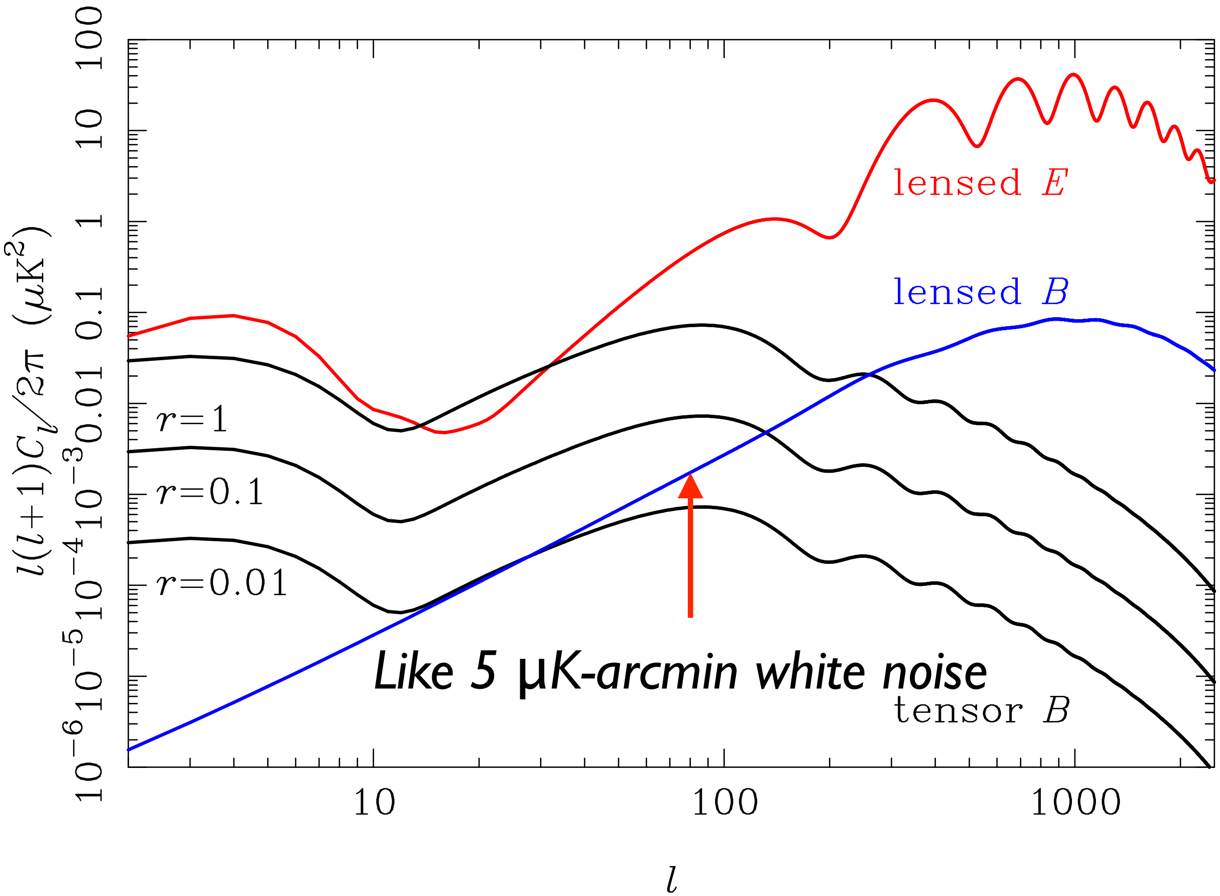
Giannantonio+ 2016

Direct BB measurements



Louis+ 2017

Delensing B-modes



- Improve limits on amplitude of GWs
  - *Soon be critical*
  - *Limits $\sigma(r)=10^{-3}$ from l>30 over 10^4 deg^2*

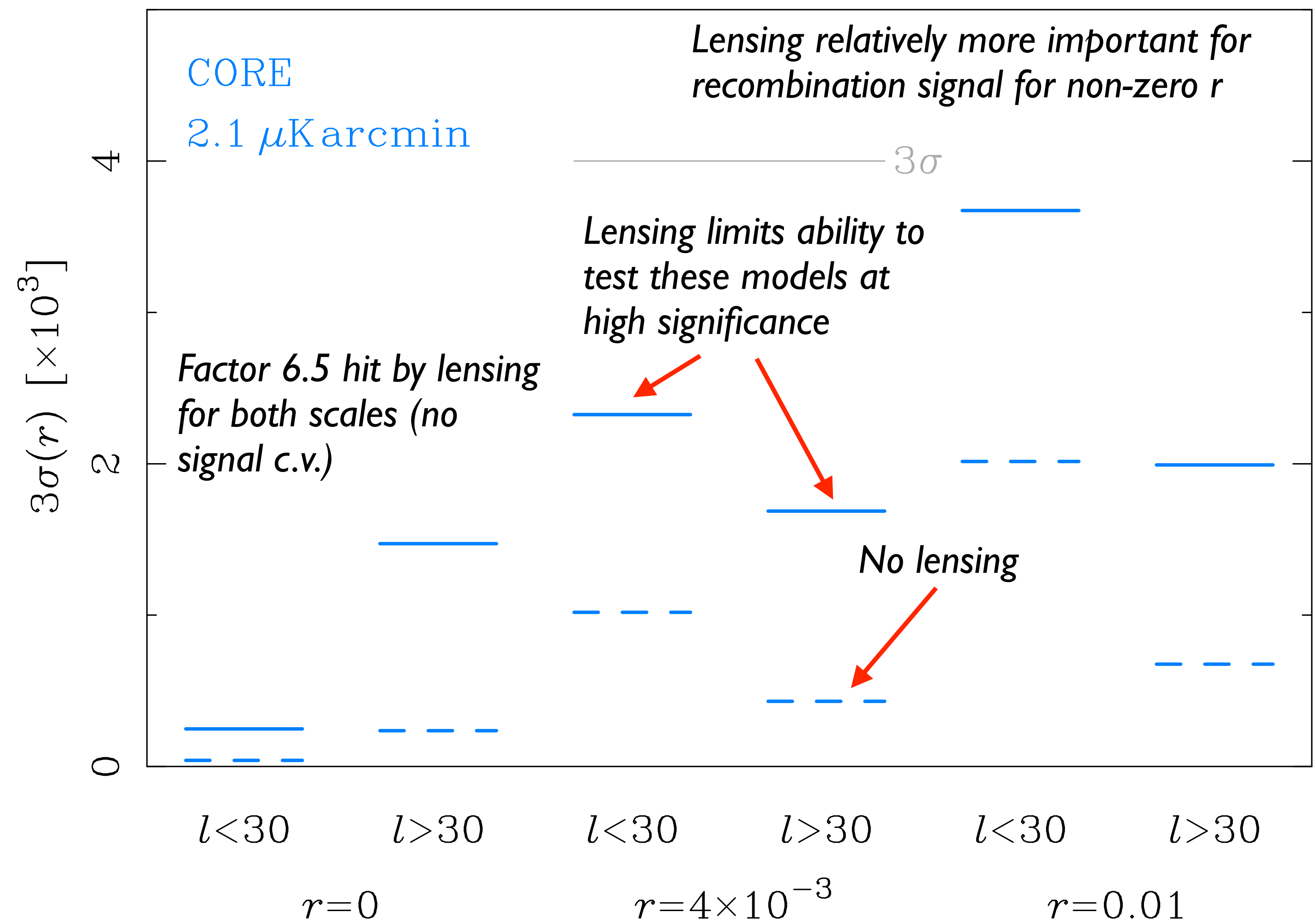
Some proxy for lensing potential

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

Residual lensing power:

$$C_l^{\phi\phi,\,\mathrm{delens}} = C_l^{\phi\phi}(1-\rho_l^2)$$

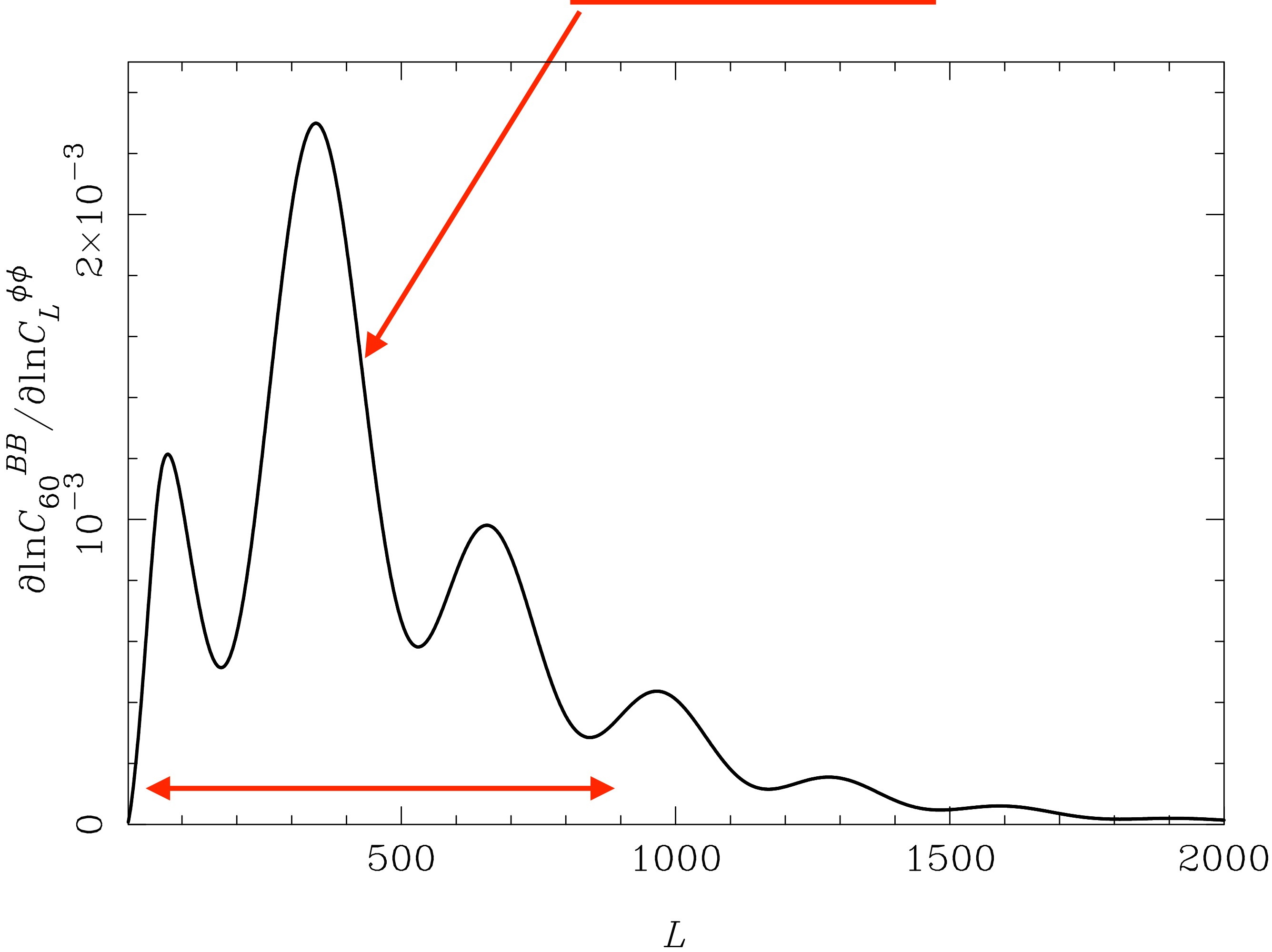
Implications for inflation constraints



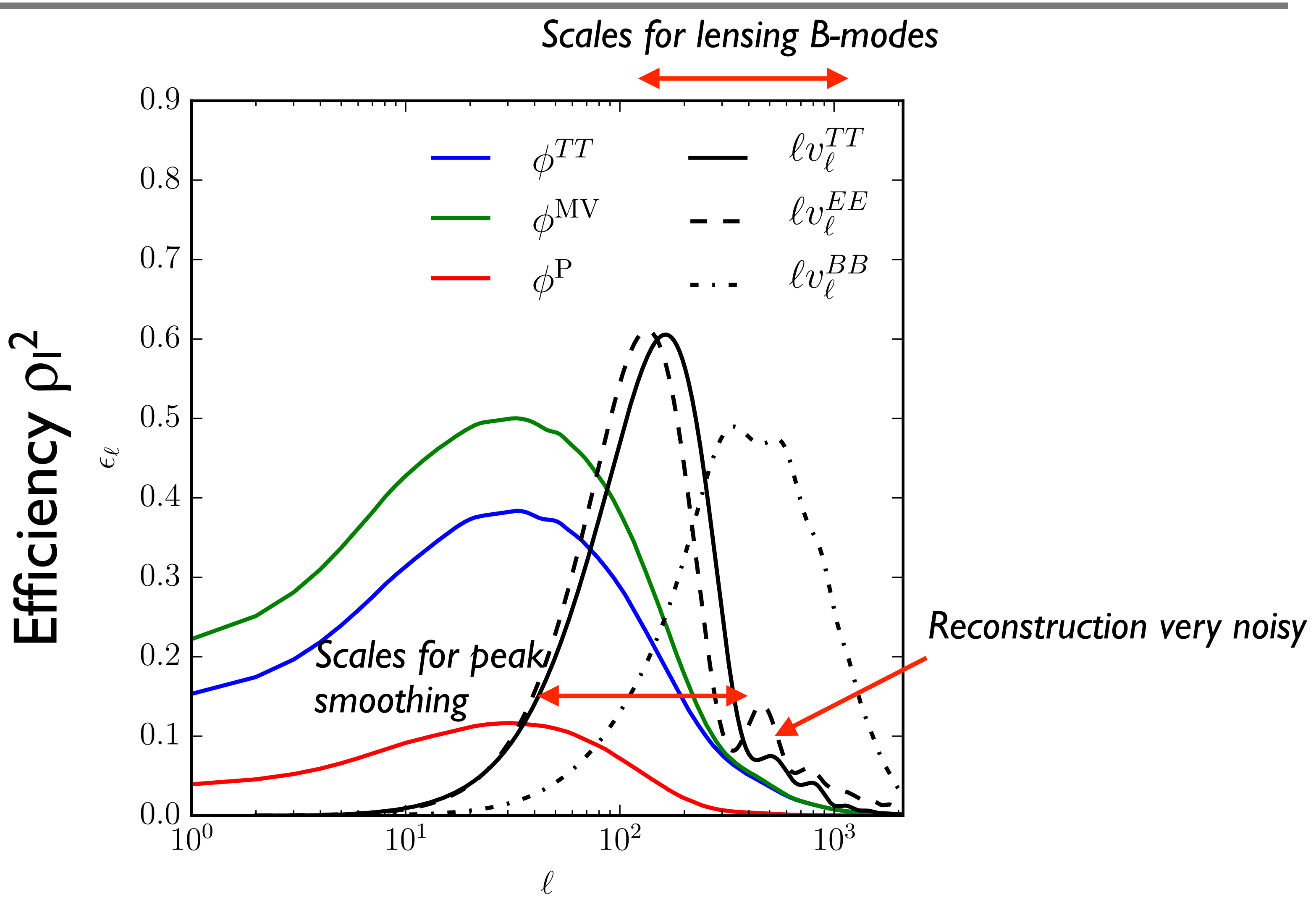
AC+CORE Collaboration 2017

Which scales matter for BB?

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



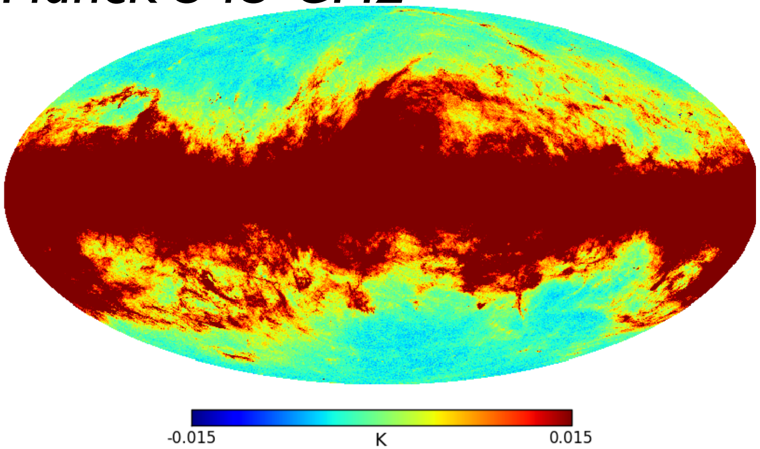
Internal delensing currently inefficient



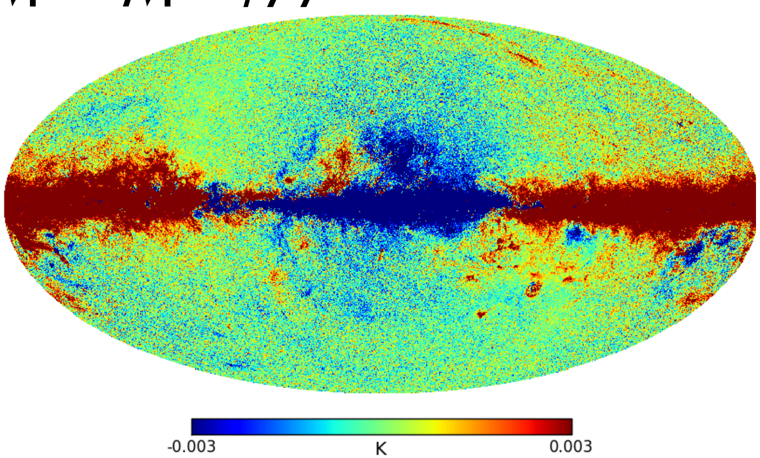
Carron, Lewis & AC 2017

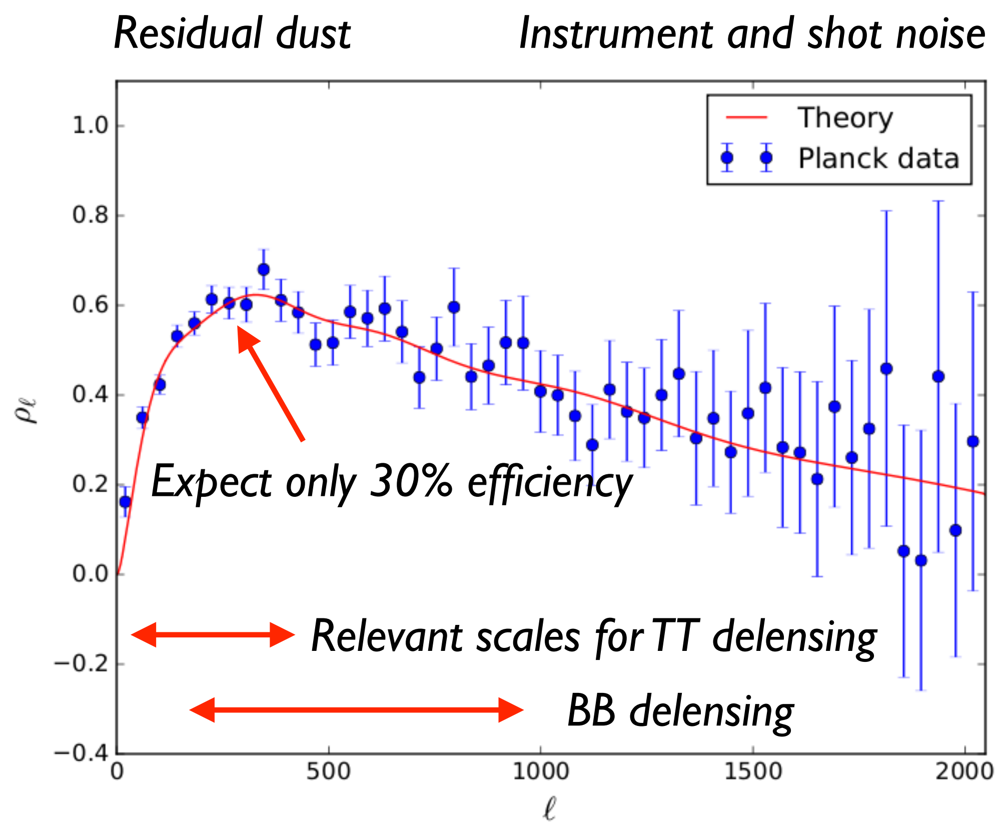
Delensing with CIB

Planck 545 GHz



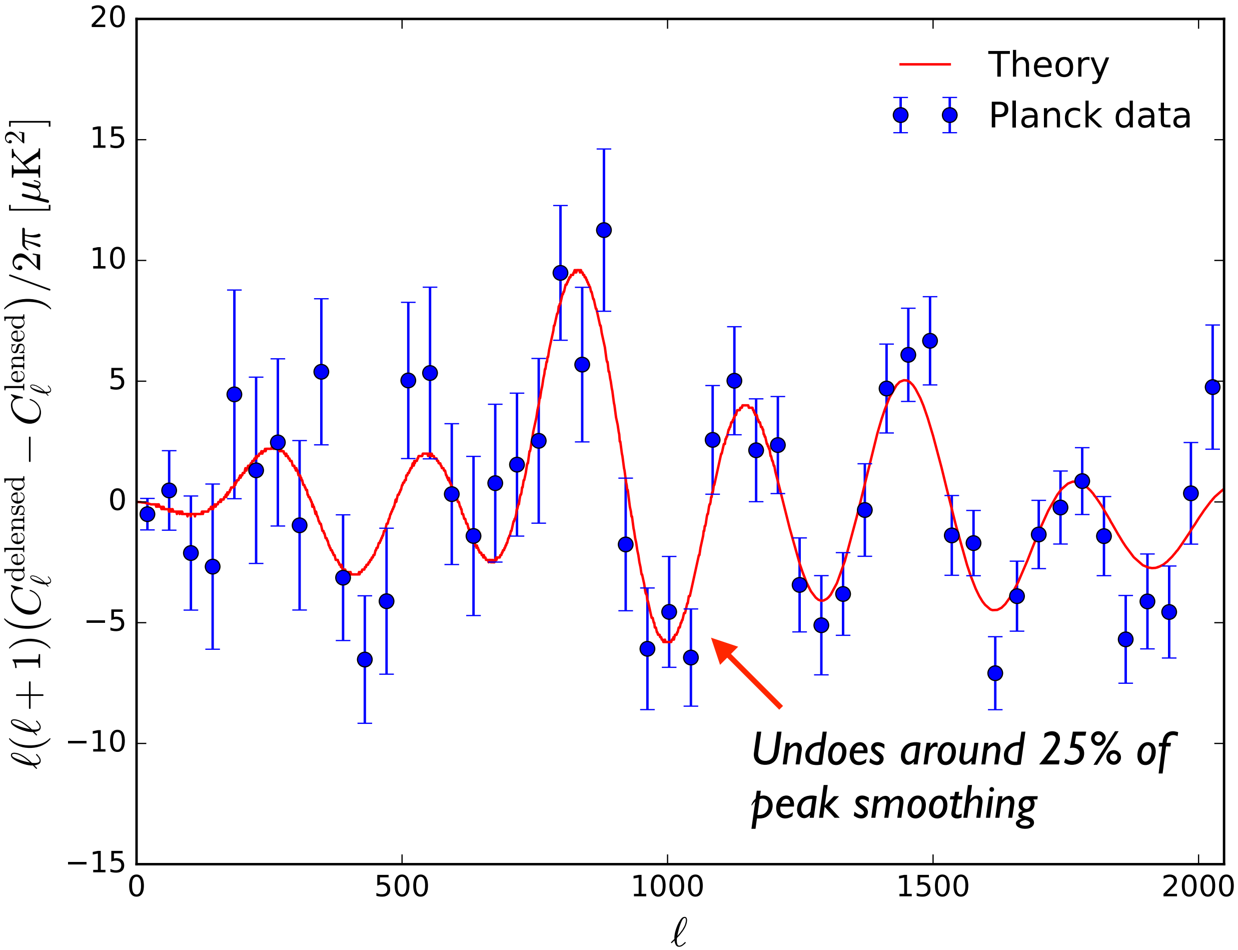
M^{545}-M^{857}/77





Mak, AC+ 2016; see also Planck XLVII 2016 Larsen, AC, Sherwin & Mak 2016

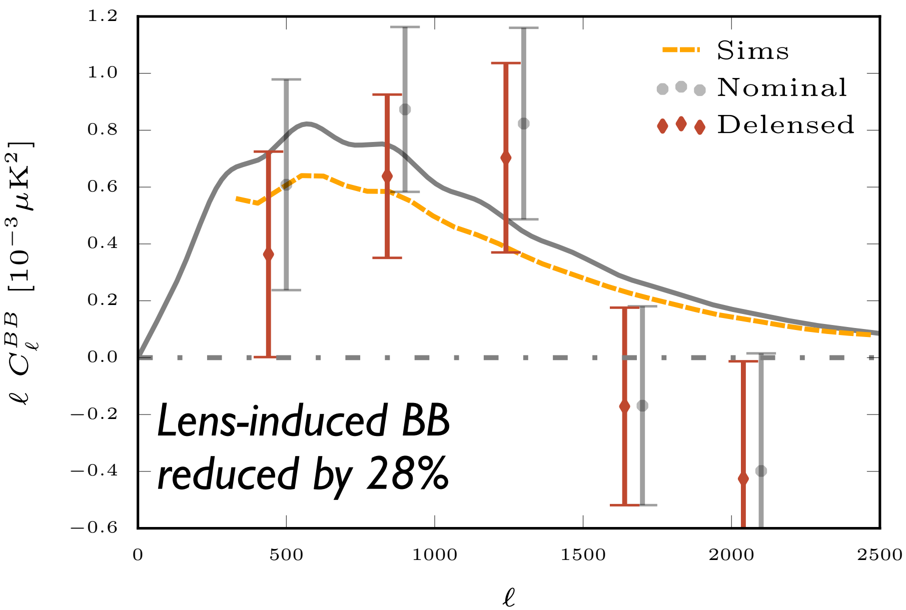
Undoing peak smoothing: TT



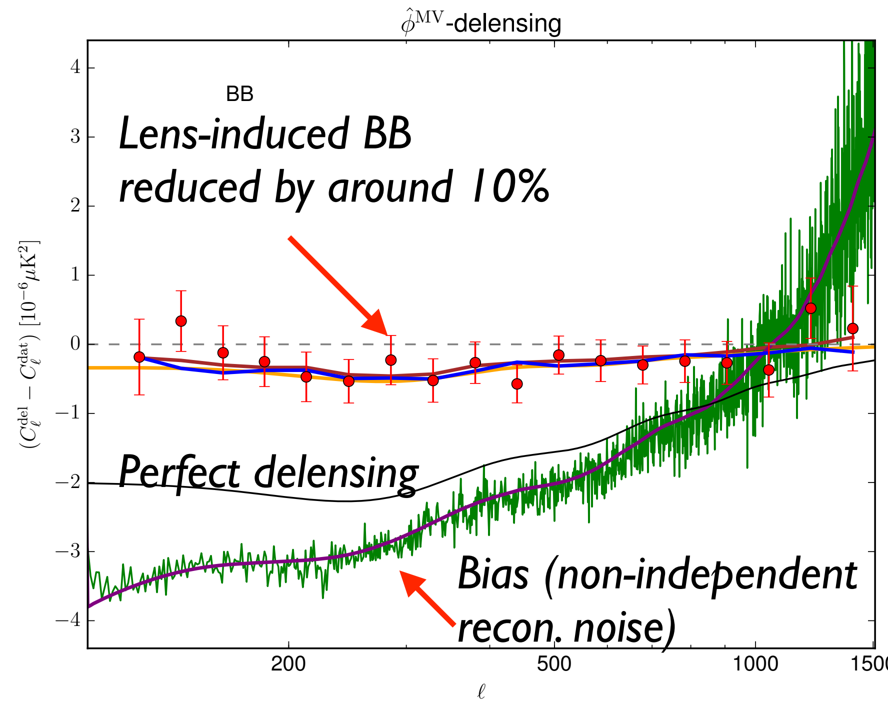
Larsen, AC, Sherwin & Mak 2016

- See Carron, Lewis & AC 2017 for internal recon. and pol.

Proof-of-concept B-mode delensing



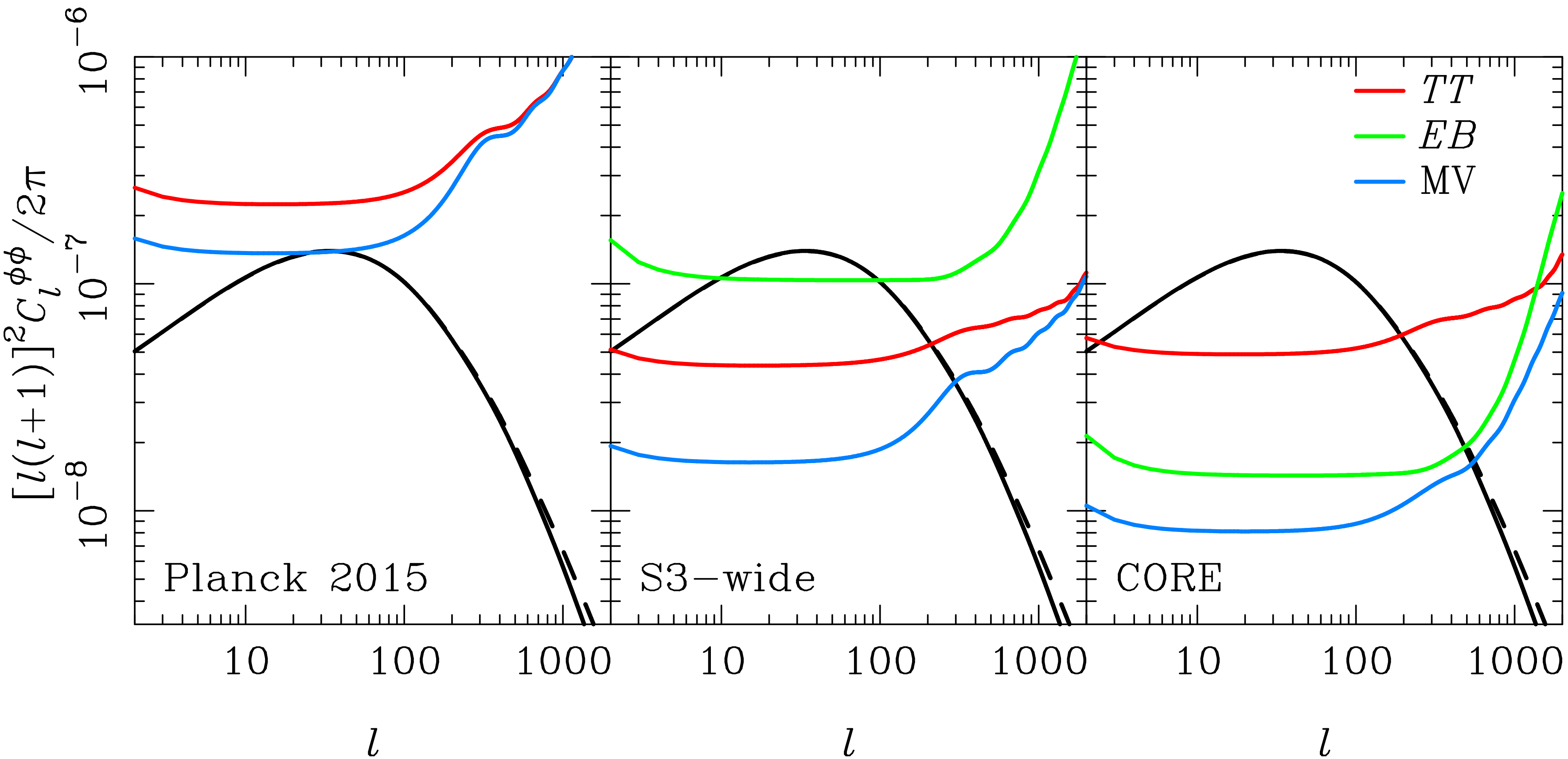
Manzotti+ 2017



Carron, Lewis & AC 2017

- 7σ detection of change in *BB* from delensing SPT with CIB
- Planck too noisy to detect *BB* directly at high significance but 10% change from internal delensing detected at 4σ

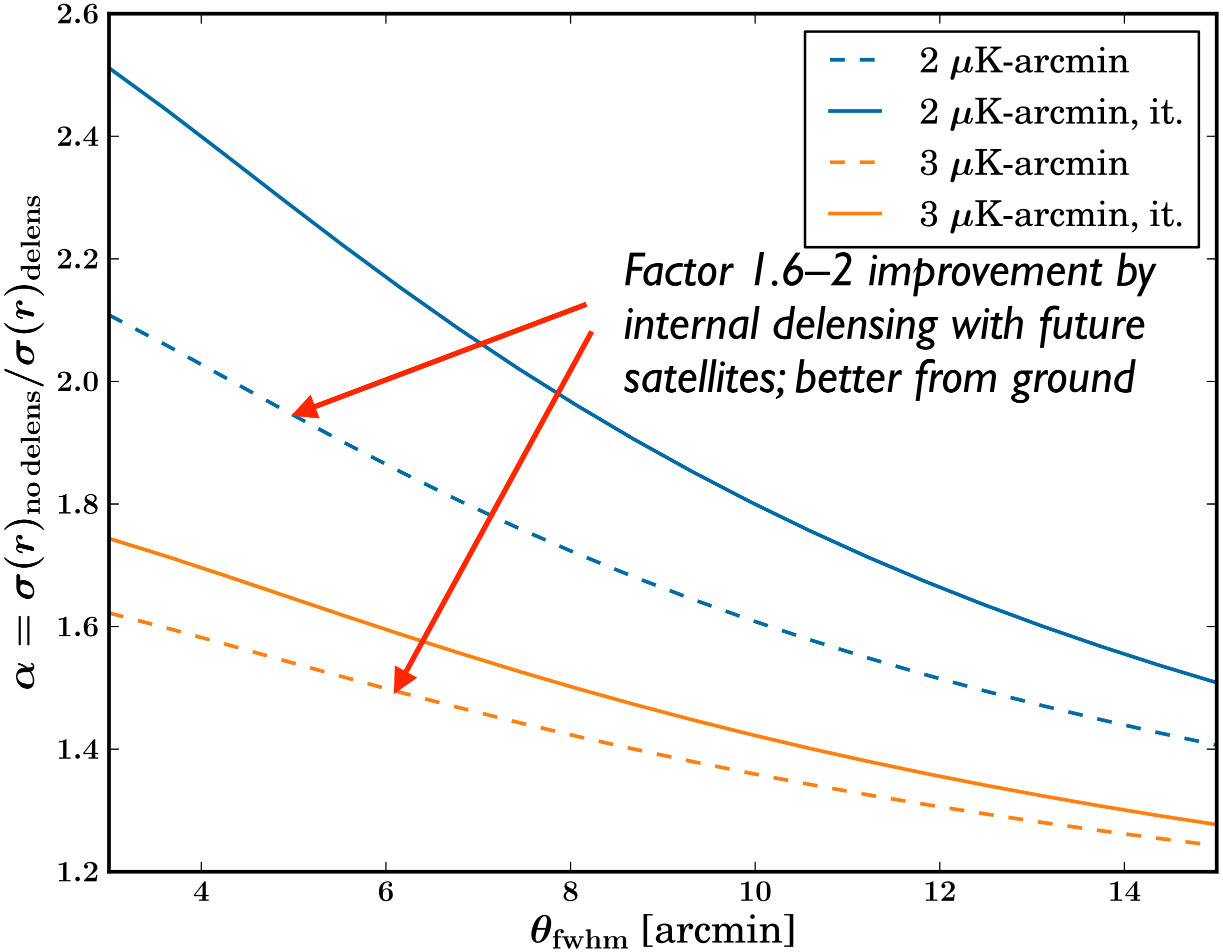
The future: towards EB dominance



- *EB* particularly helpful for pol. noise < 5 μK arcmin
  - *Polarization reconstructions less susceptible to extragalactic contamintion (e.g., tSZ)*

Prospects for internal delensing

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



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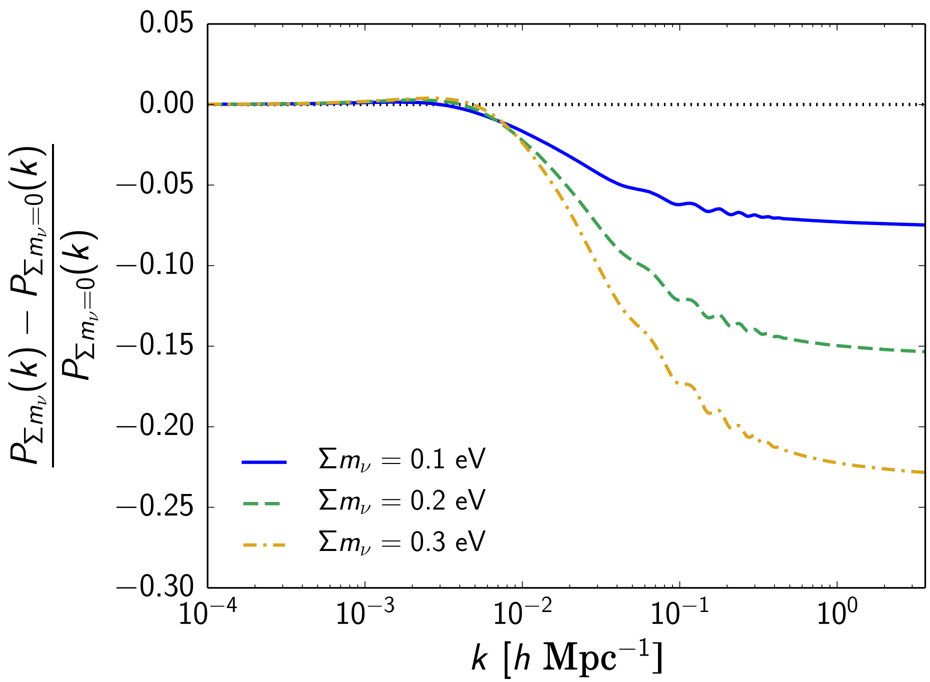
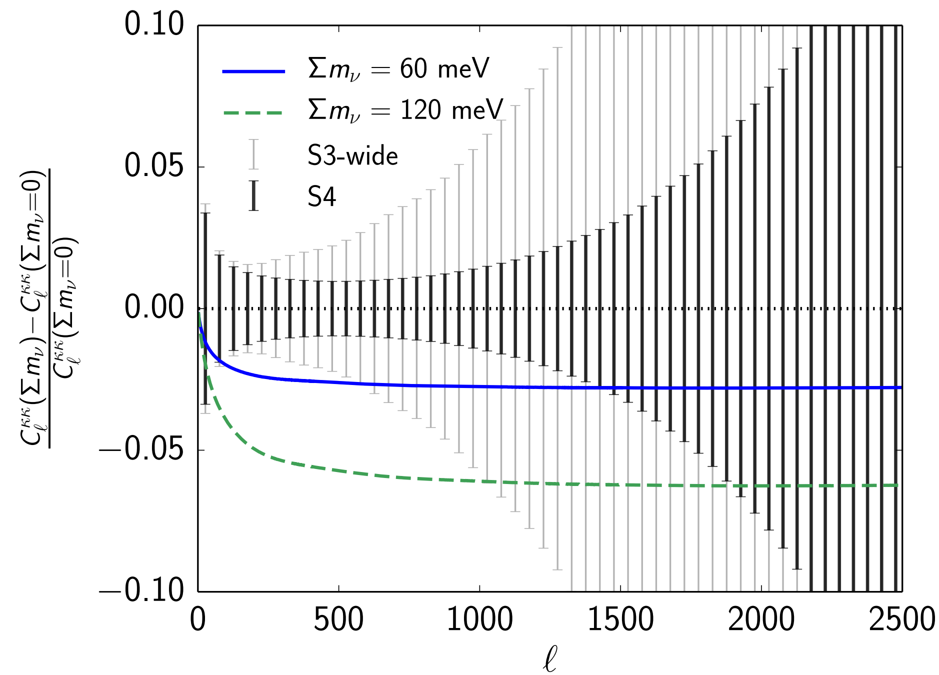
Opportunities





Allison+ 2015

- Large-area reconstructions with S/N>1 to *L*~1000
  - *Excellent prospects for cross-correlation science with Euclid/DESI/LSST etc. (few x10^5 resolved CMB lensing modes)*
  - *Summed neutrino mass to 15 meV with future BAO (contingent on τ)*