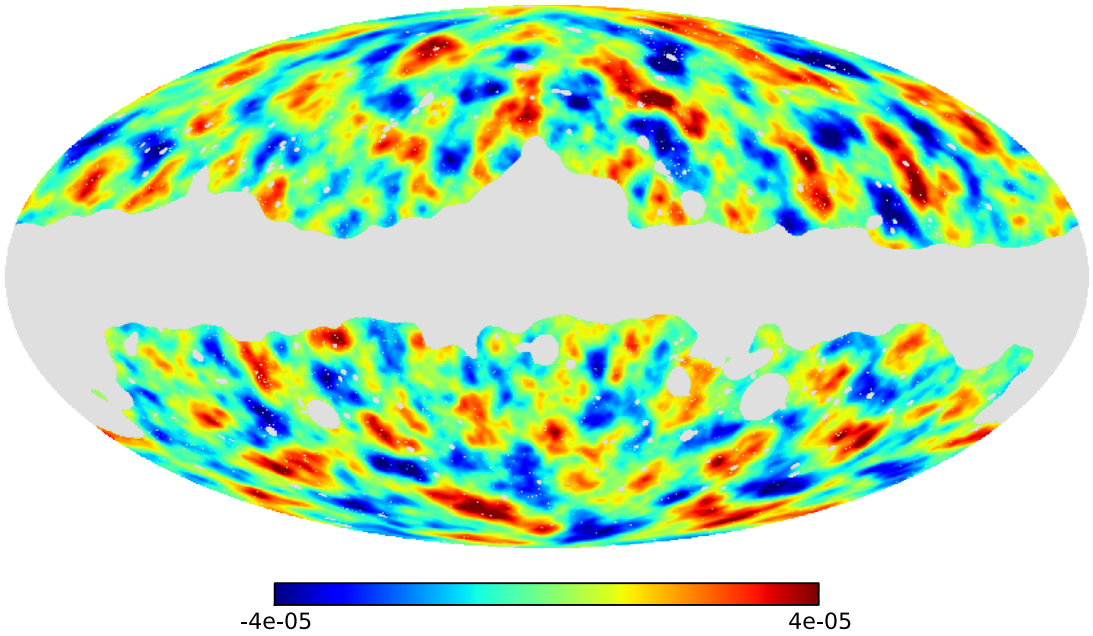
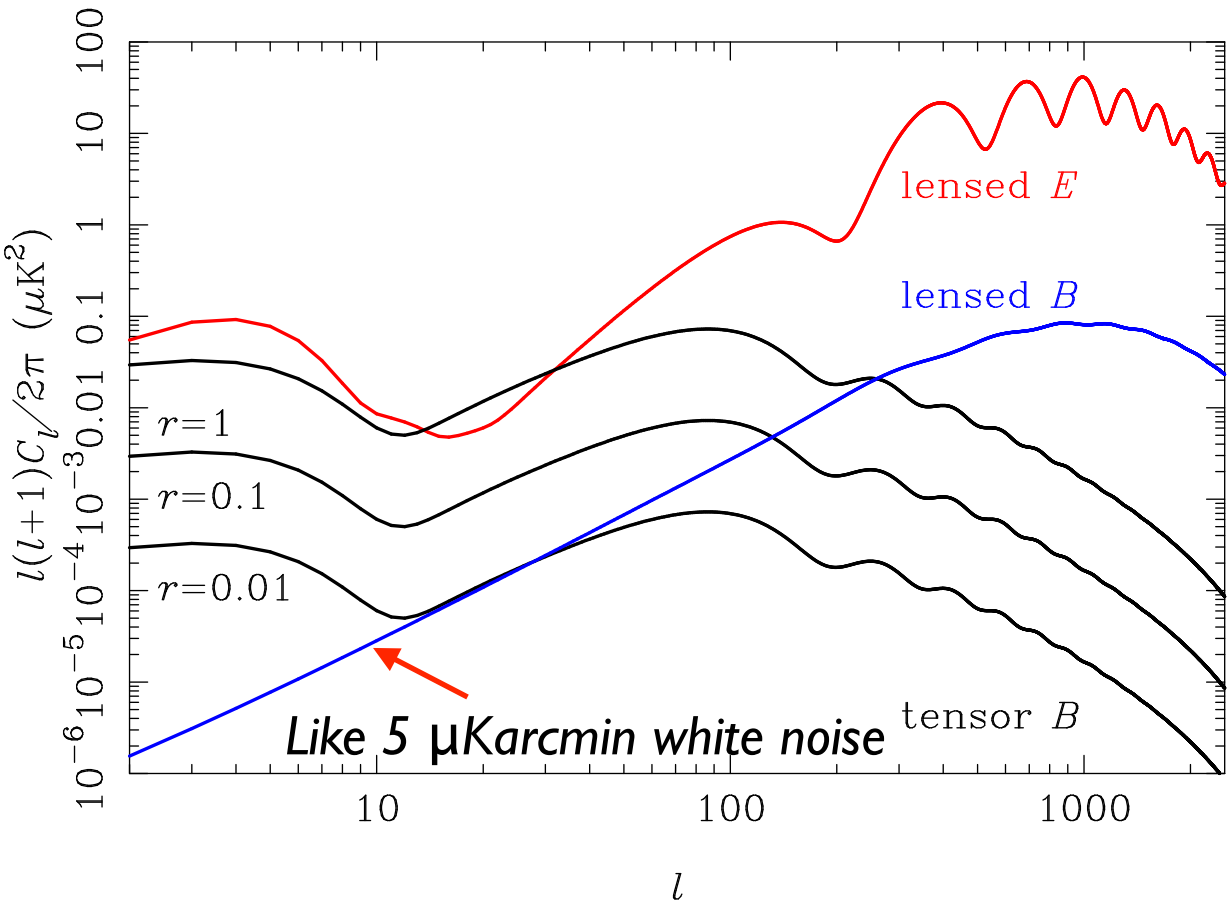
Delensing the cosmic microwave background

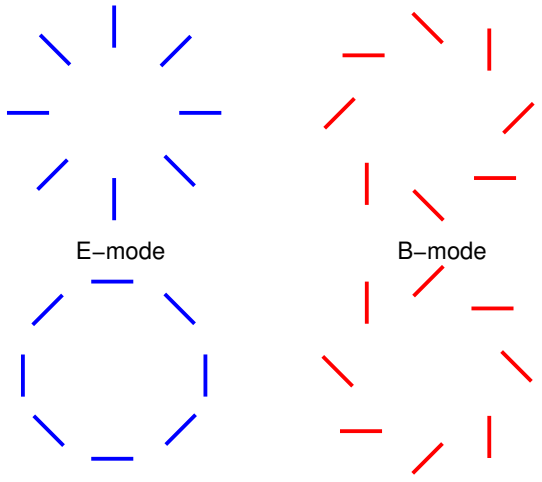
Anthony Challinor



KICC/IoA/DAMTP
University of Cambridge

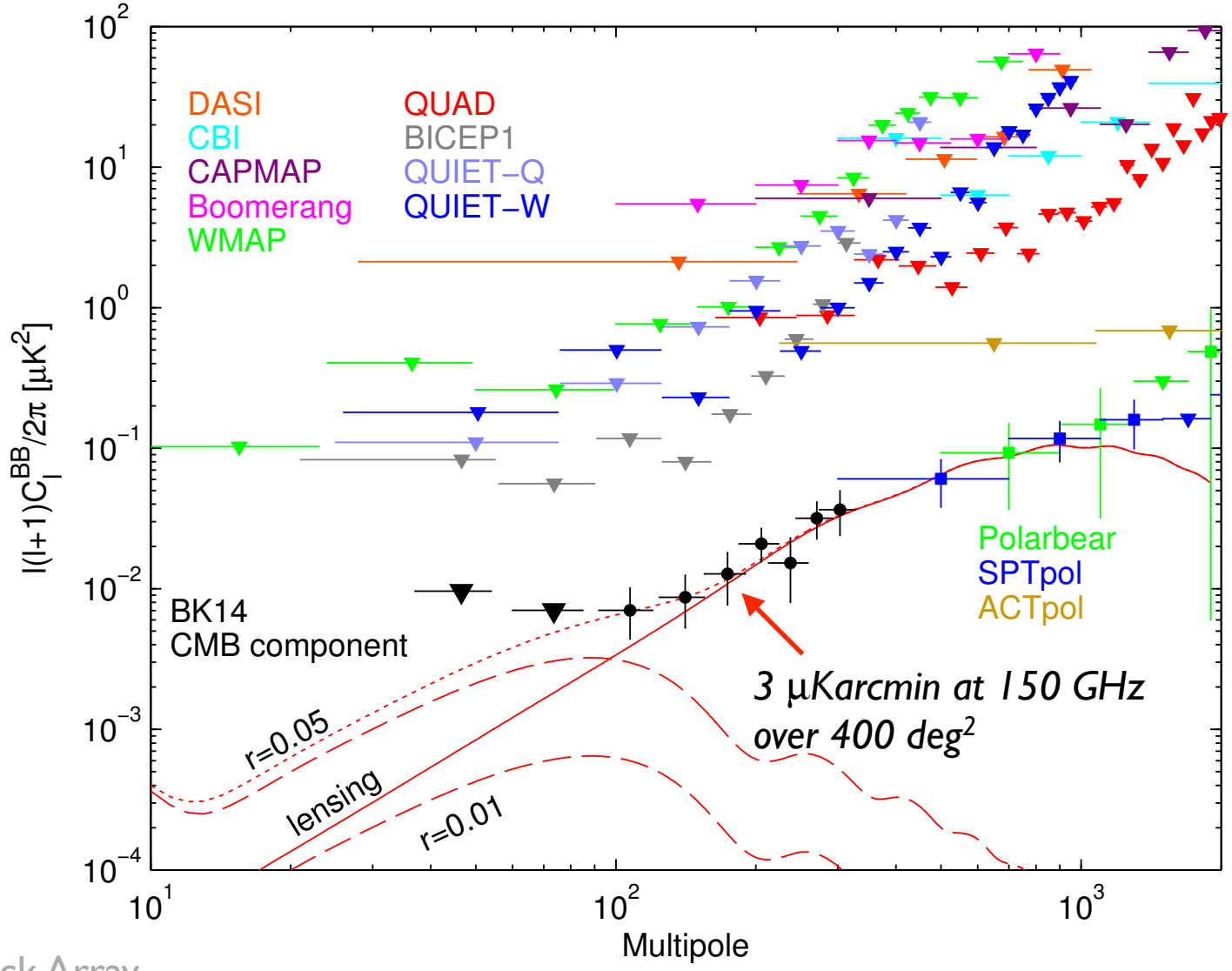
B-modes from lensing





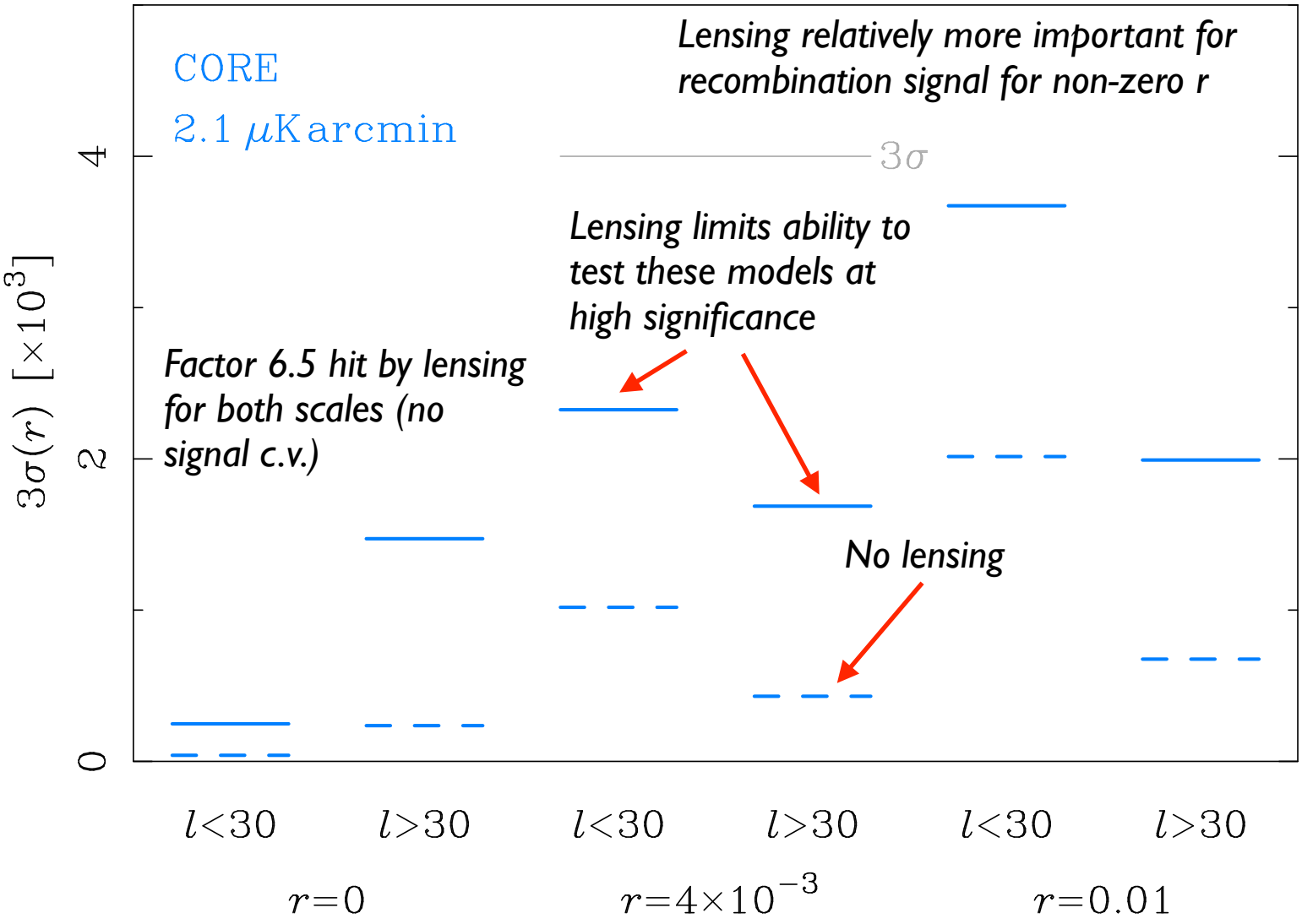
- Lensing *B*-mode power can be accurately modelled (currently around 1% uncertainty due to parameter errors)
  - *Additional cosmic variance is main obstacle for primordial B-modes*

B-mode power measurements



BICEP/Keck Array

Implications for inflation constraints



AC+CORE Collaboration 2017

Delensing the CMB

- Remap CMB with Wiener-filtered tracer *I* of CMB lensing

$$\hat{\phi}_{\mathcal{W}} = \mathcal{W} * I$$

$$X^{\rm delens}(\hat{\mathbf{n}}) = X^{\rm obs}(\hat{\mathbf{n}} - \nabla\hat{\phi}_{\mathcal{W}})$$

$$\approx X^{\rm unlens}(\hat{\mathbf{n}} + \nabla(\underbrace{\phi - \hat{\phi}_{\mathcal{W}}}_{\text{Residual lensing}})) + \text{noise}$$

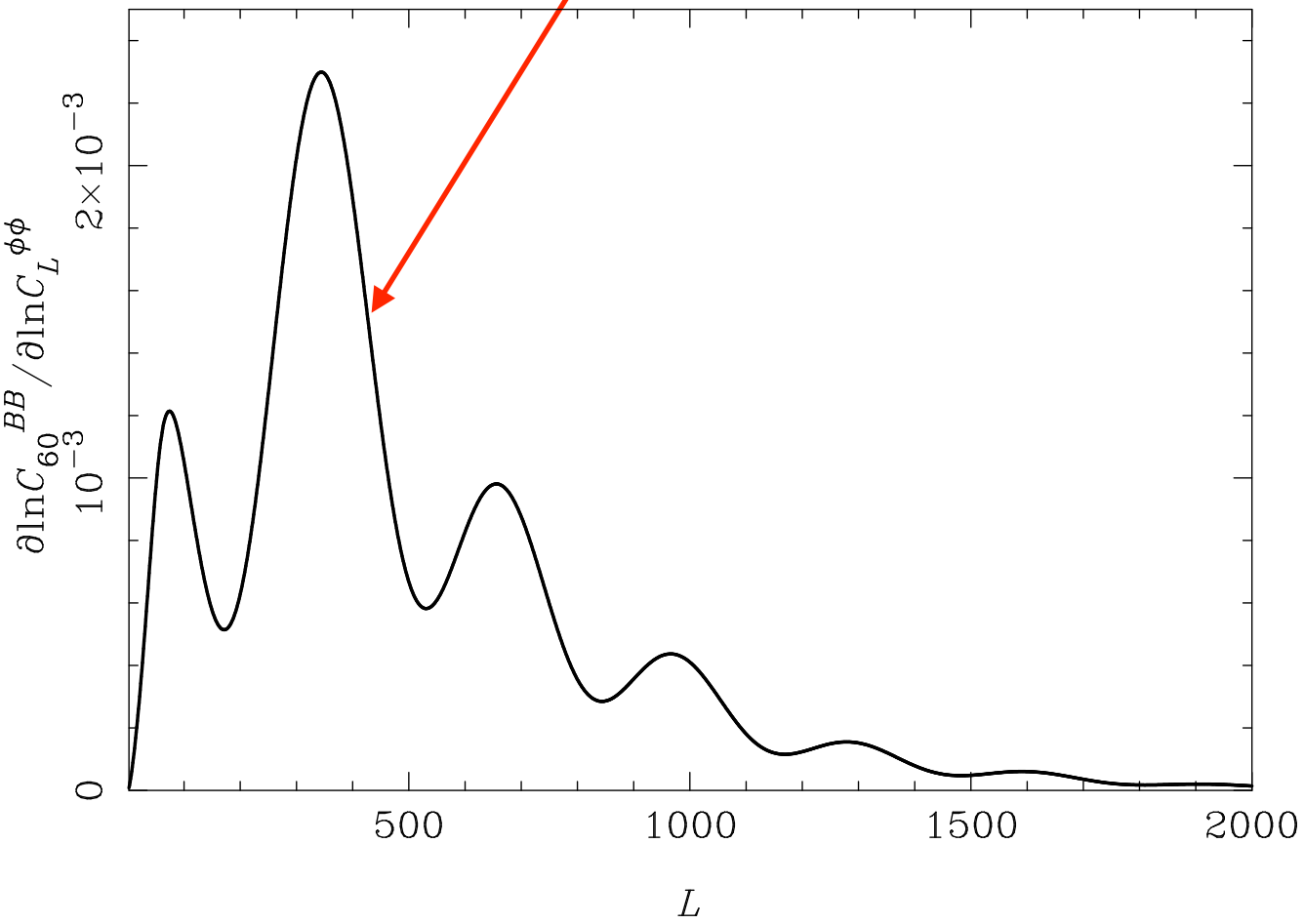
- Gradient approximation accurate for large-angle *B*-modes
- Residual lensing has power spectrum

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

$$\rho_l^2 = \frac{\left(C_l^{I\phi}\right)^2}{C_l^{II,\,\rm tot}C_l^{\phi\phi}}$$

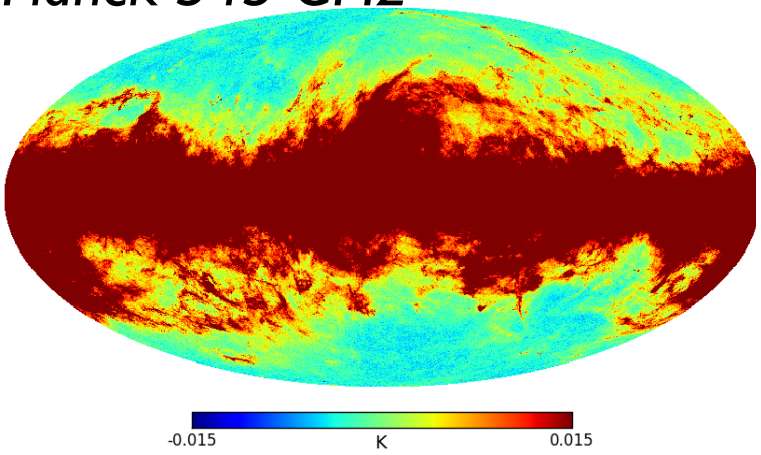
Which scales matter for BB?

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

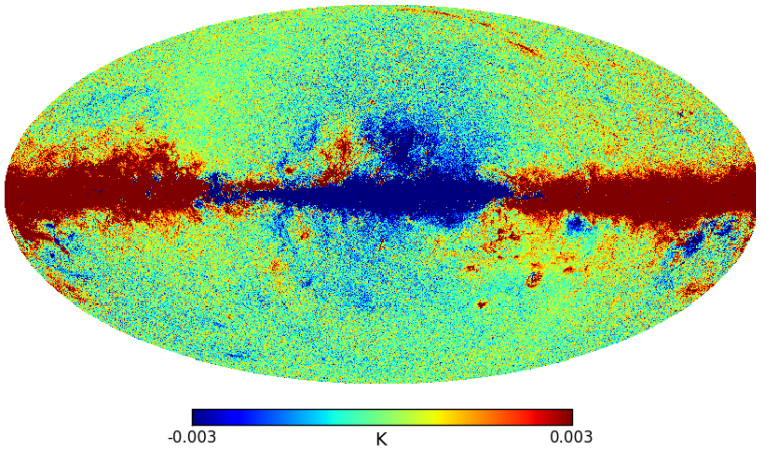


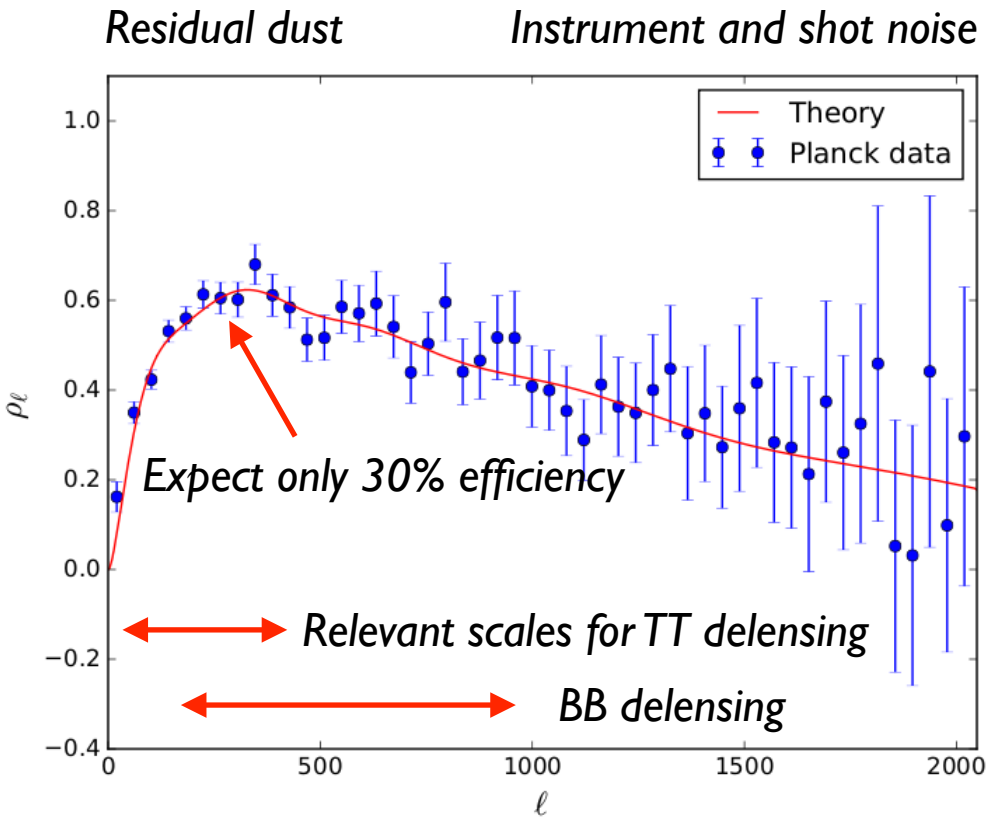
Delensing with CIB

Planck 545 GHz



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

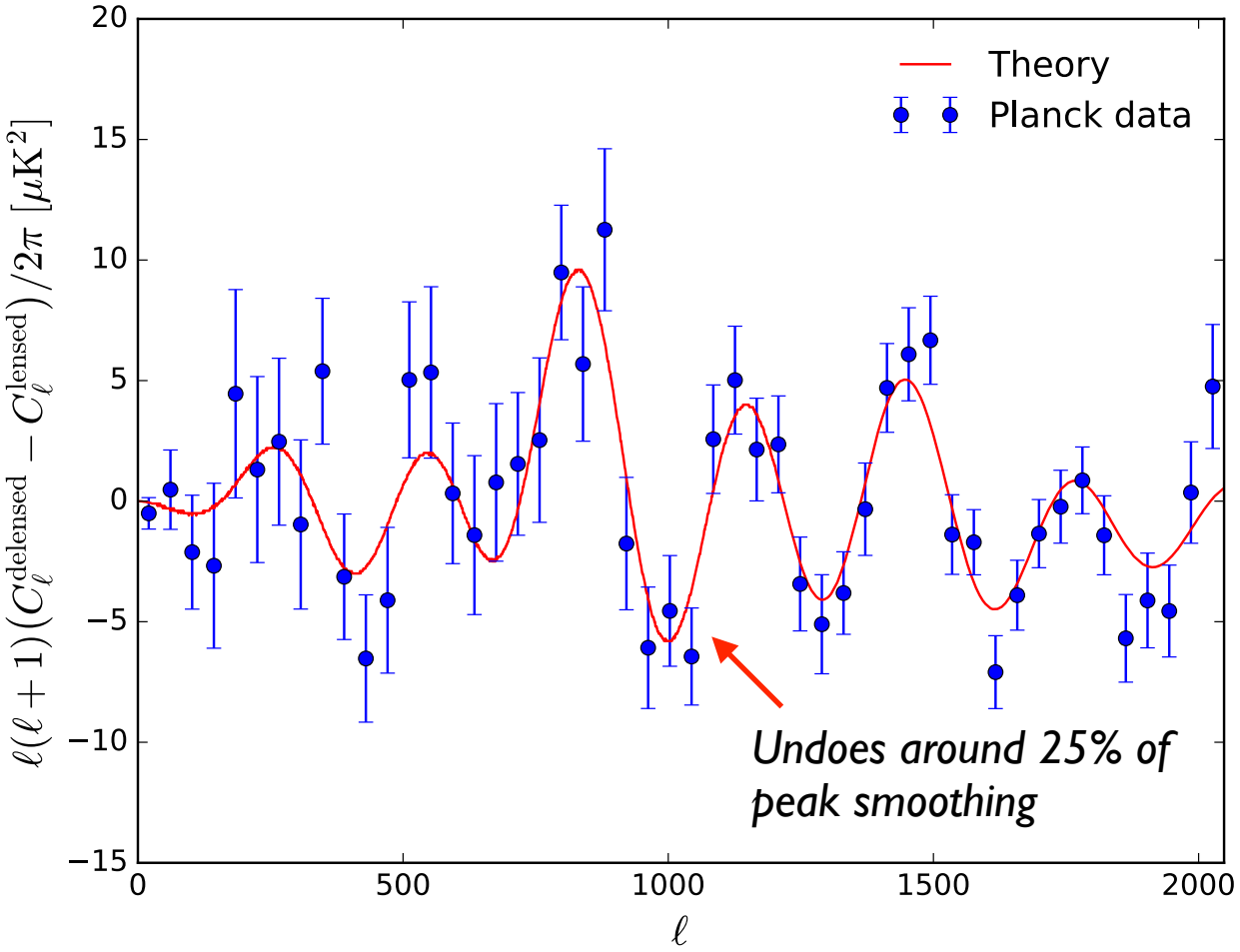




Mak, AC+ 2016; see also Planck XLVII 2016

Larsen, AC, Sherwin & Mak 2016

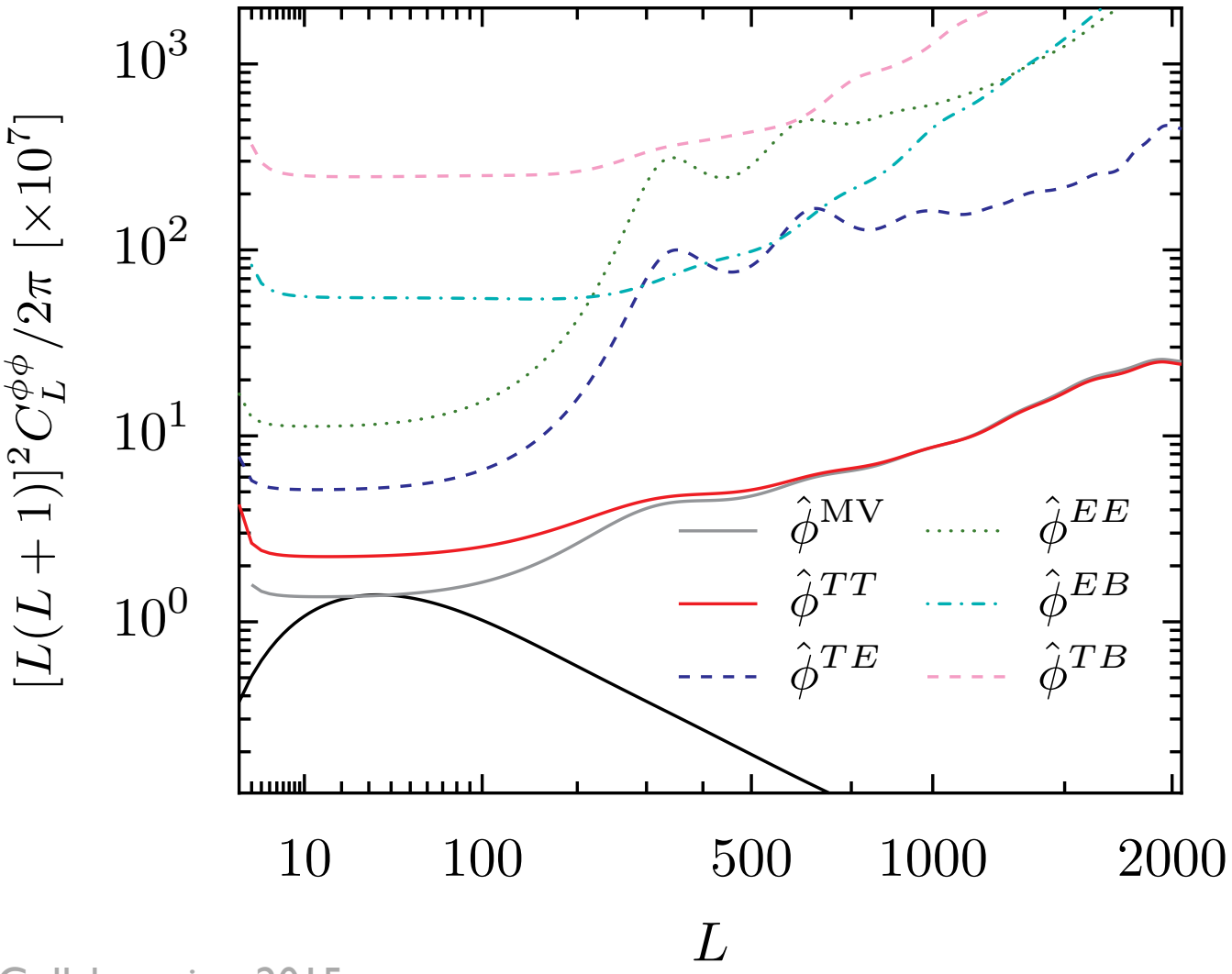
CIB delensing in practice: TT



Larsen, AC, Sherwin & Mak 2016

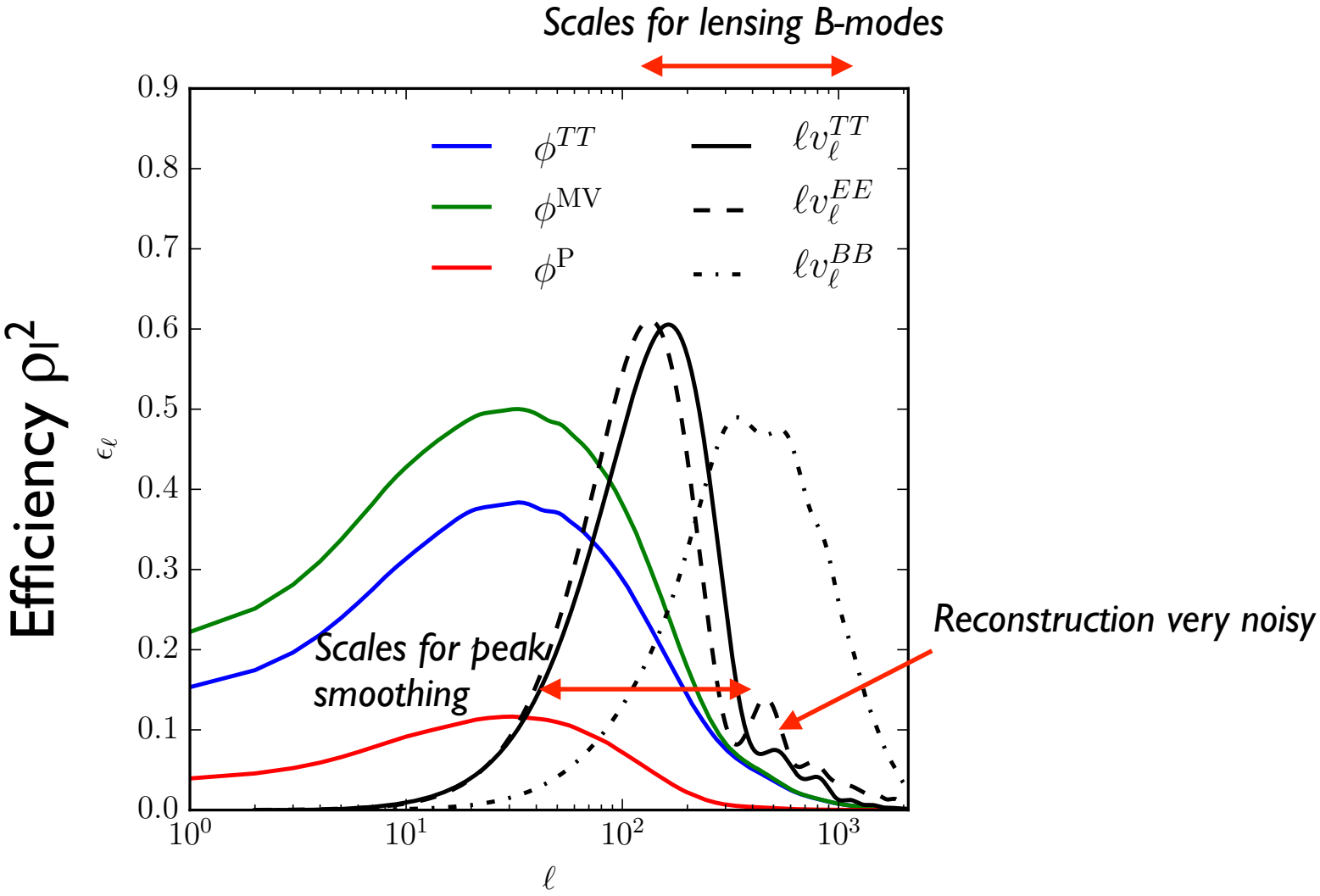
- See Manzotti+ 2017 for application to *BB* from SPTPol

Internal delensing: Planck noise



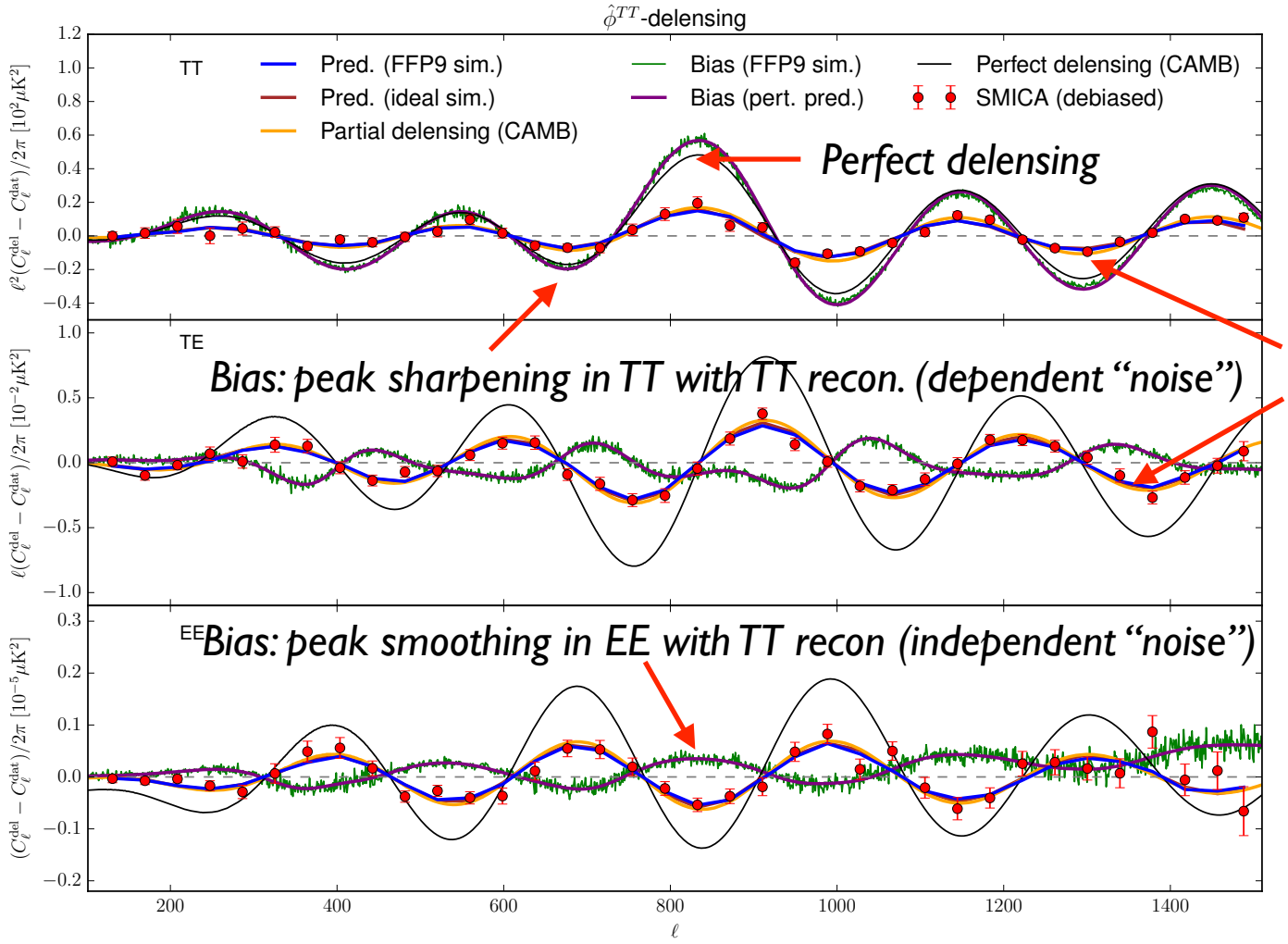
Planck Collaboration 2015

Internal delensing with Planck



Carron, Lewis & AC 2017

Planck internal delensing (TT recon.)

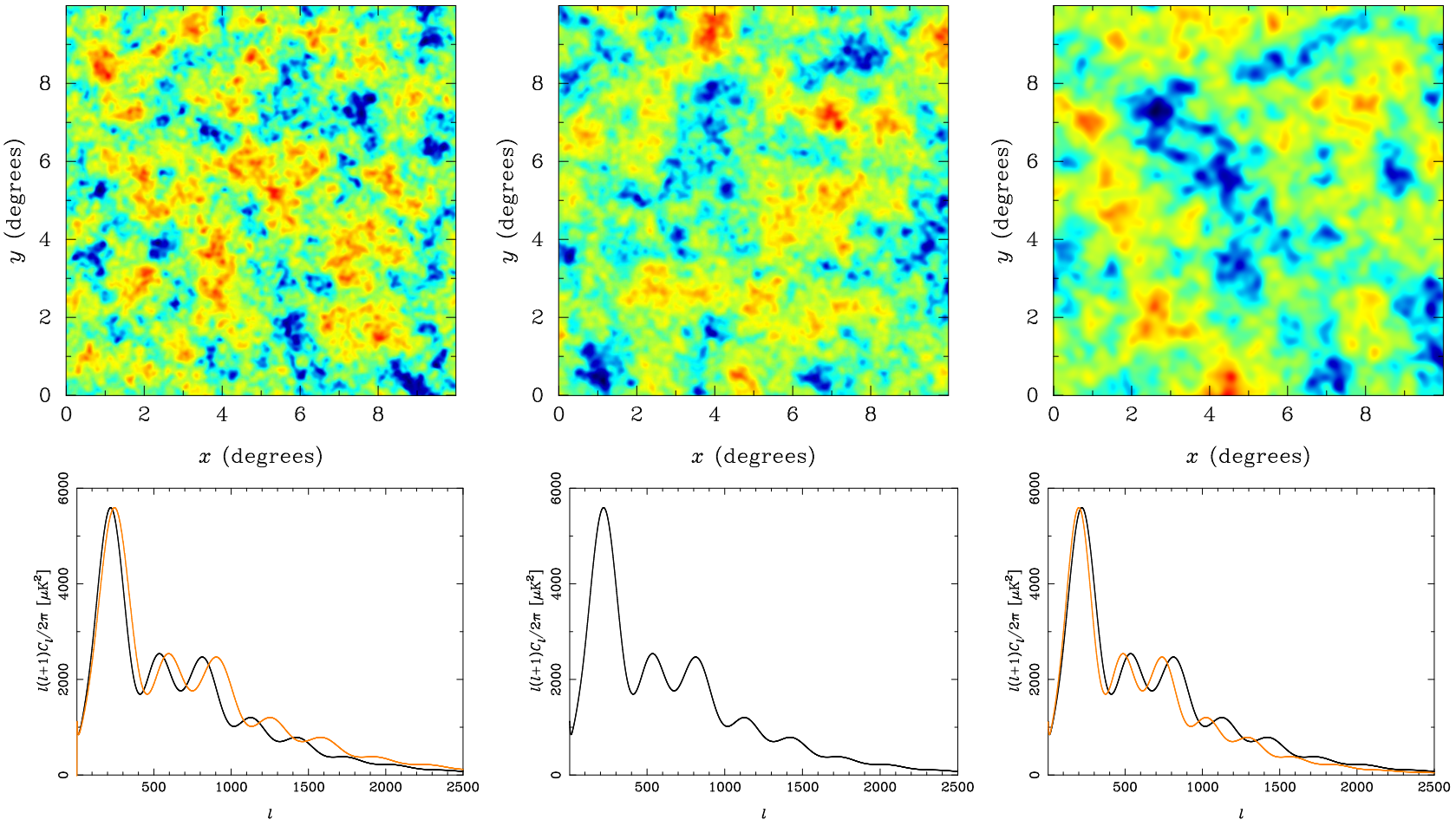


Undoes around 20% of peak smoothing

Carron, Lewis & AC 2017

Origin of "peak-sharpening" bias

- Reconstruction noise not independent of CMB fields



Carron, Lewis & AC 2017; see also Sehgal+ 2017

Bias from dependent recon. noise

- Consider *B*-mode template delensing with *XY* estimator:

$$B_{\rm delens} \sim B - \hat{E}_W \hat{\phi}_W(X,Y)$$

- Power spectrum after delensing:

$$C^{BB}_{\rm delens} \sim \langle BB \rangle - 2\langle B\hat{E}_W\hat{\phi}_W(X,Y)\rangle + \langle \hat{E}_W\hat{\phi}_W(X,Y)\hat{E}_W\hat{\phi}_W(X,Y)\rangle$$

If reconstruction noise were independent of CMB, just gives usual

$$2\langle B\hat{E}_W\phi_W\rangle$$

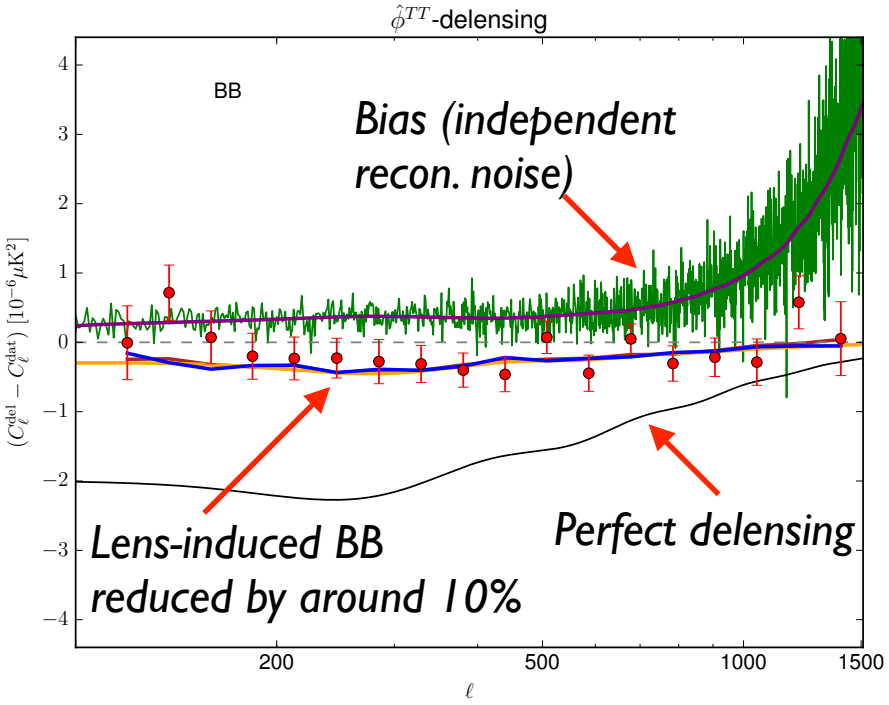
In practice, reconstruction dependent on CMB giving dominant bias

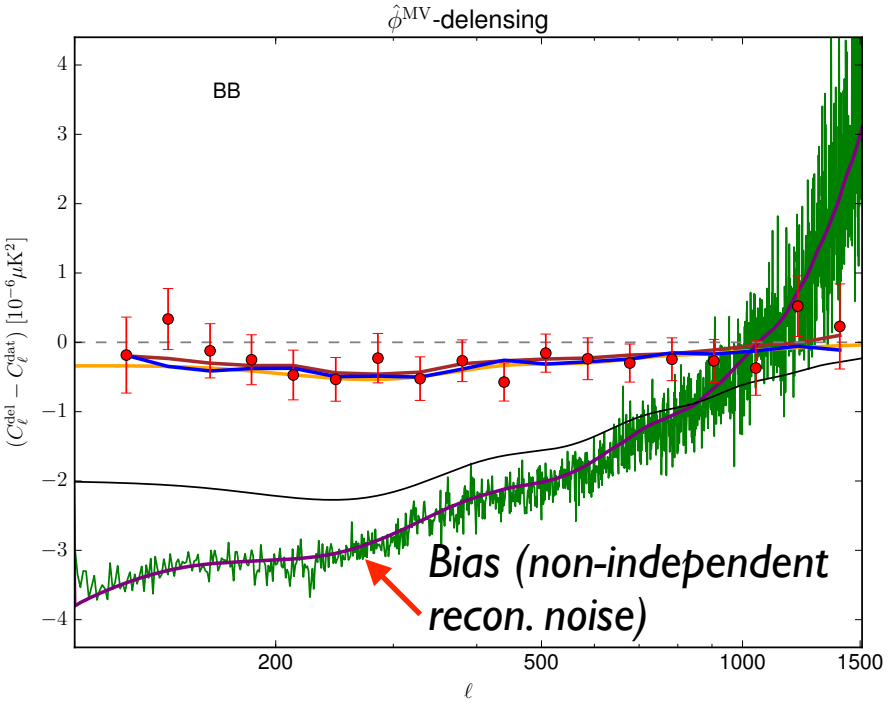
$$2B\hat{E}_W\hat{\phi}_W(X,Y) + 2B\hat{E}_W\hat{\phi}_W(X,Y)$$

- *r*-dependent bias if *X,Y=B* and overlapping scales

Carron, Lewis & AC 2017; see also Sehgal+ 2017 and Teng+ 2011

BB delensing (TT and MV recon.)

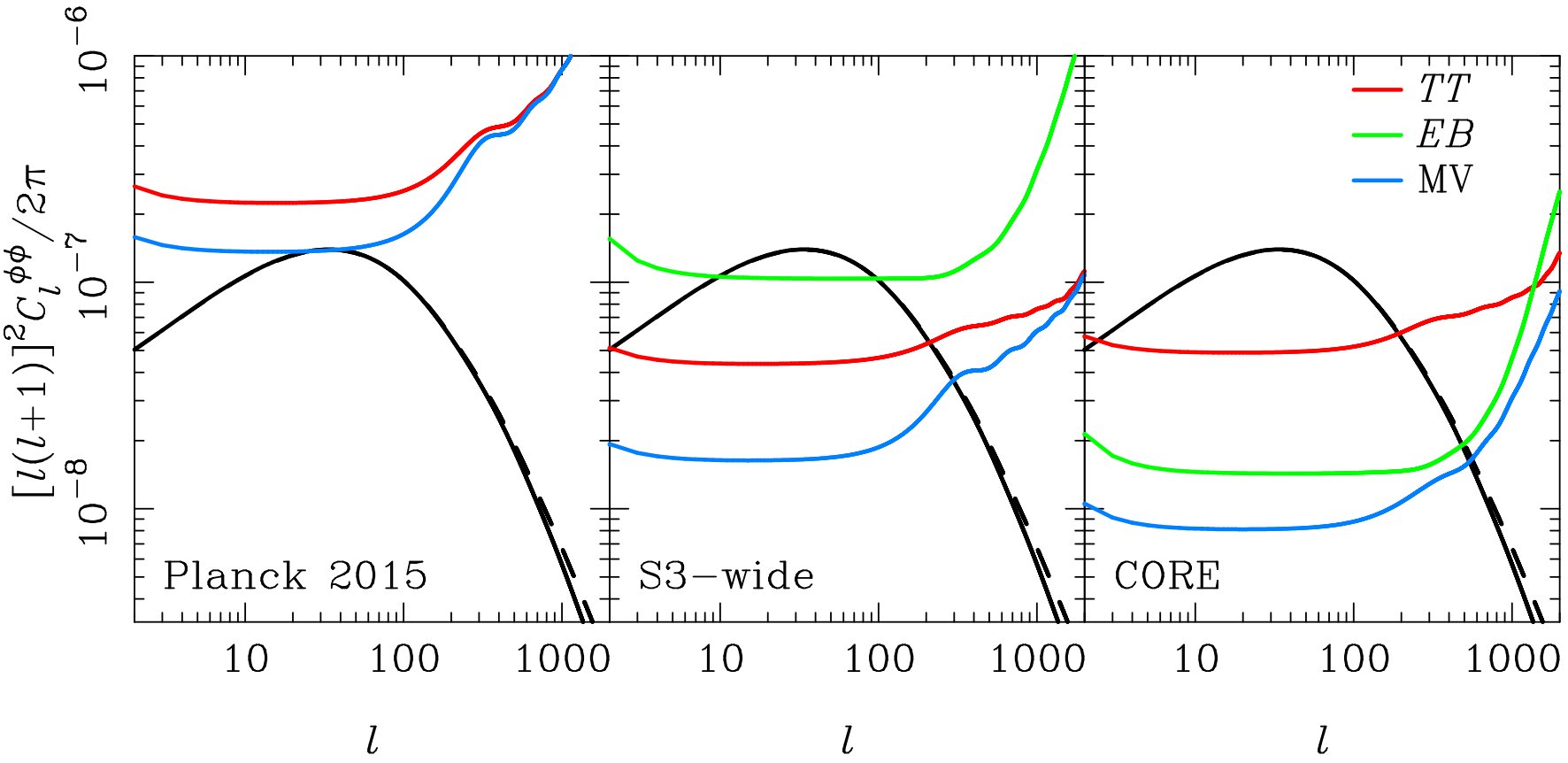




- Detect expected *change* in *BB* at 5σ (MV recon.)
- Planck too noisy to detect *BB* directly at high significance

Carron, Lewis & AC 2017

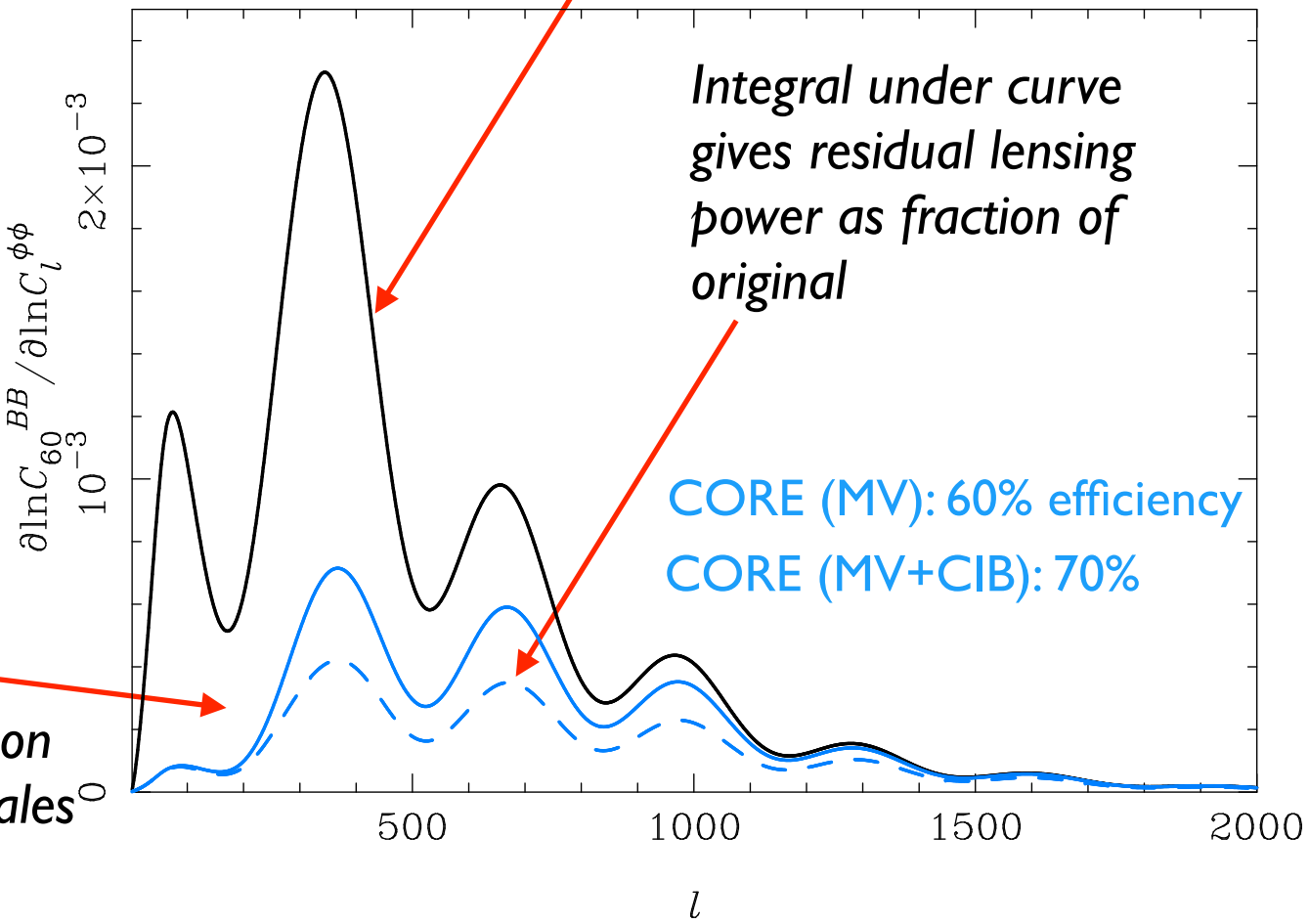
Future reconstruction noise



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

BB delensing with future CMB

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



Integral under curve gives residual lensing power as fraction of original

CORE (MV): 60% efficiency

CORE (MV+CIB): 70%

High S/N reconstruction on these scales

Corrections to lens remapping

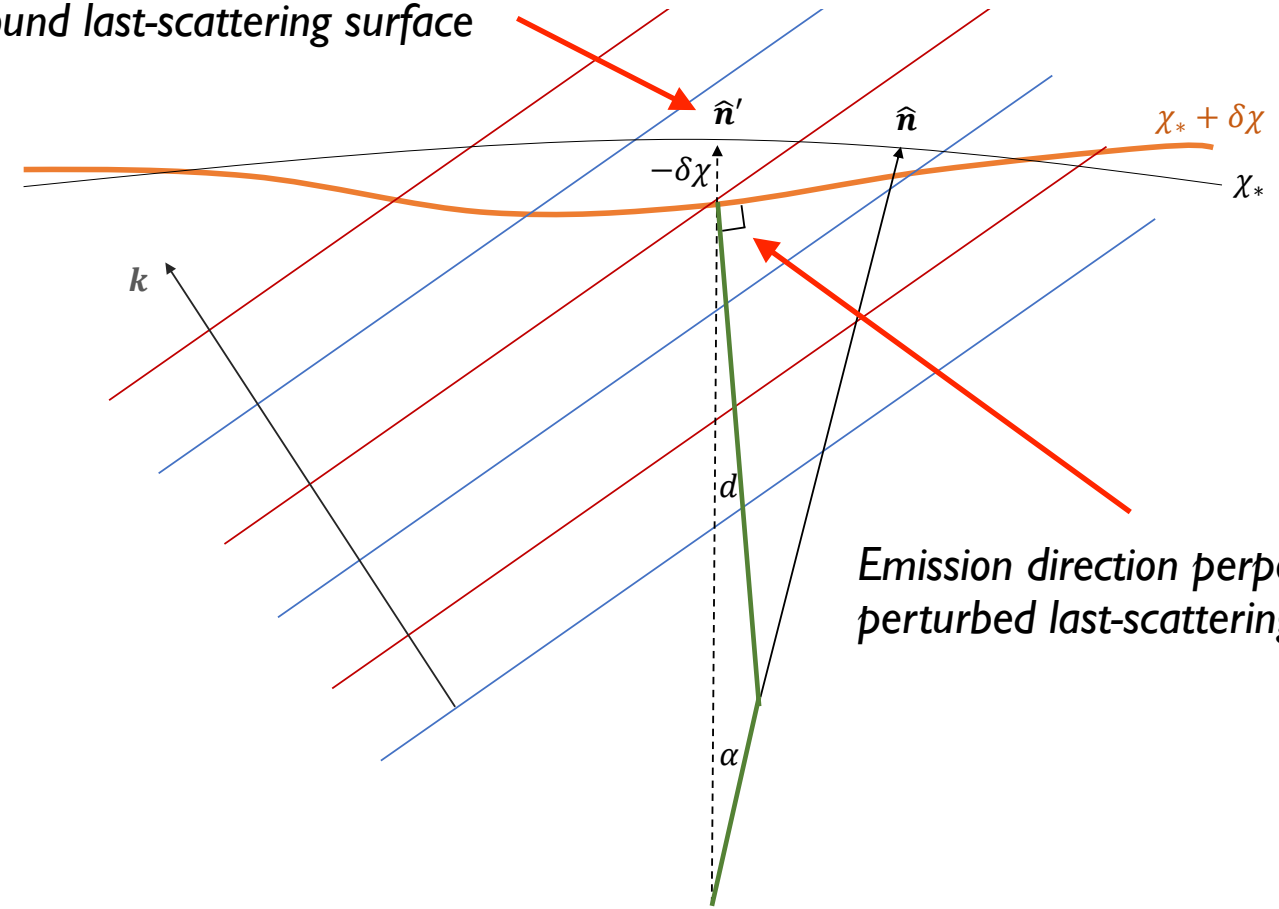
- Polarization rotation
  - *Negligible (Lewis, Hall & AC 2017) as deflection^2, i.e., less than 1 arcsec (but cf. Marozzi+ 2017, where shear^2)*
- Time delay
  - *Hu & Cooray* 2001
- Emission-angle effects
  - *Lewis, Hall & AC 2017*

} partly cancel!

- (Curl-mode lensing from e.g., post-Born effects)
  - *Hirata & Seljak 2003; Pratten & Lewis 2016 etc.*

Emission angle and time delay

Emission direction not perpendicular to background last-scattering surface



Emission direction perpendicular to perturbed last-scattering surface

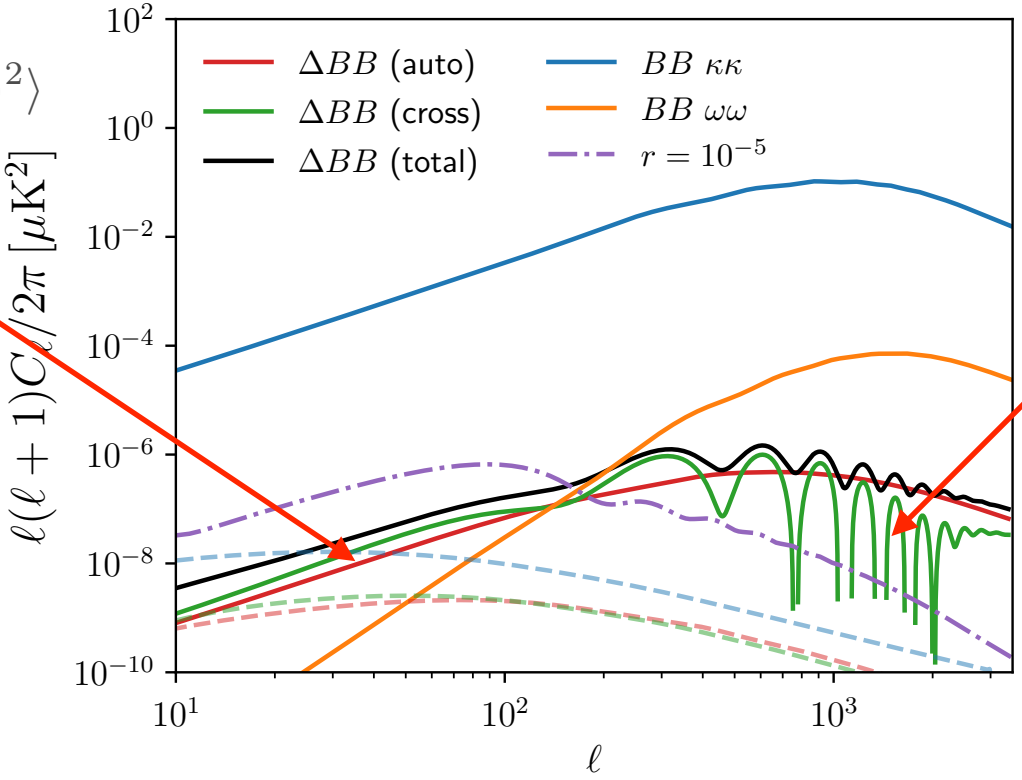
$$\Delta B \sim B_\kappa + \underbrace{B_{\rm angle} + B_{\rm delay}}_{\text{partly cancel}}$$

Lewis, Hall & AC 2017

Angle and time-delay B-modes

$\langle (B_{\rm angle} + B_{\rm delay})^2 \rangle$

Not removed by delensing



$2\langle B_\kappa (B_{\rm angle} + B_{\rm delay}) \rangle$

Partially removed by delensing

- Large-scale angle+delay *B*-modes like 0.02 μKarcmin white noise
  - *Not removable by standard delensing*
  - *Larger than B-modes from post-Born curl lensing*

Lewis, Hall & AC 2017

Summary

- CMB lensing generates *B*-modes with almost white-noise spectrum equivalent to 5 μKarcmin noise
  - *Now detected by several ground-based experiments*
- With no coherent cleaning ("delensing"), will dominate error budget for *r*
  - *E.g., limits* $\sigma(r)>5\times10^{-4}$ *from l>30 on 70% of sky*
- Can improve $\sigma(r)$ by factor few with internal delensing
  - *CIB is useful external lensing proxy*
- Internal and external delensing demonstrated on data in past year – beware of biases for internal delensing!
- Emission-angle and time-delay effects not removed by standard delensing – small but may be ultimate limit

Implications for inflation constraints