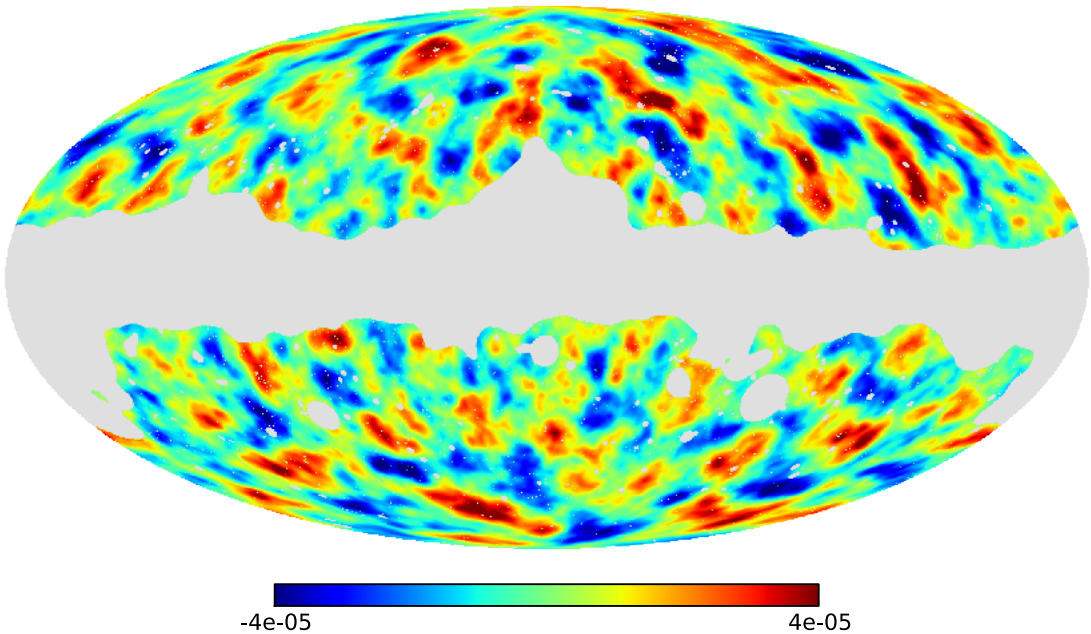
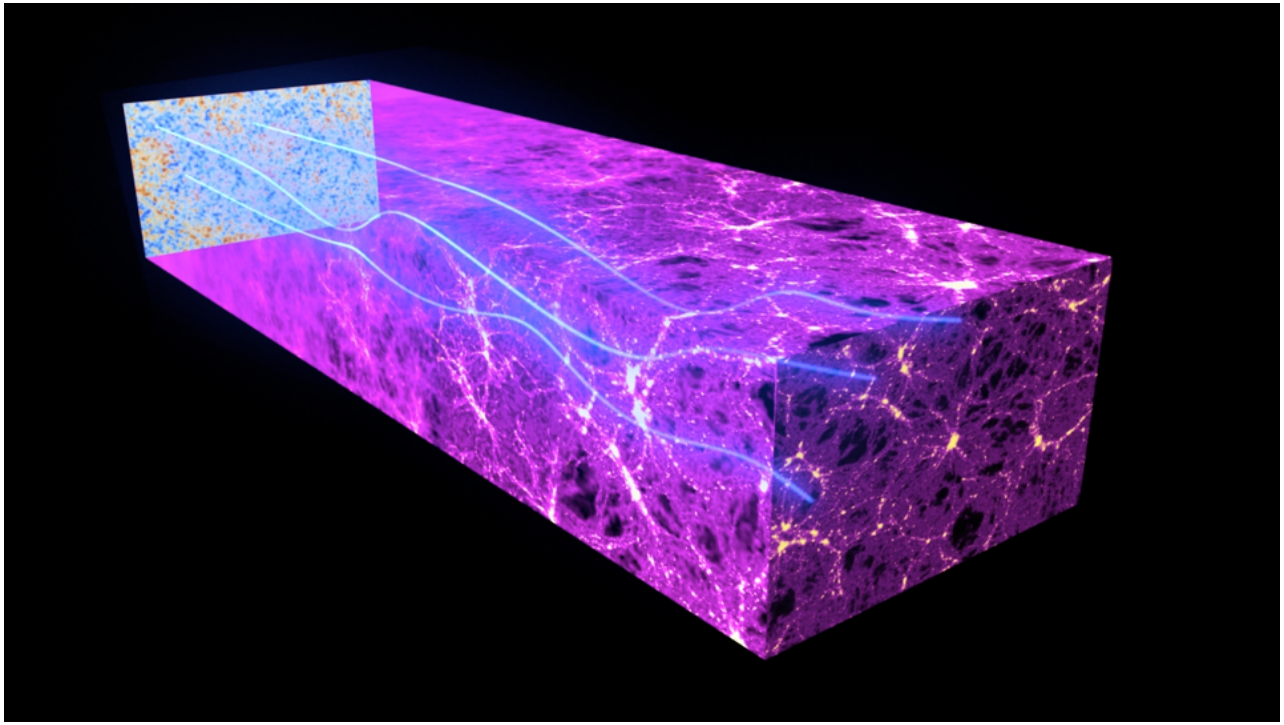
CMB lensing and delensing

Anthony Challinor



KICC/IoA/DAMTP
University of Cambridge

Lensing of the CMB

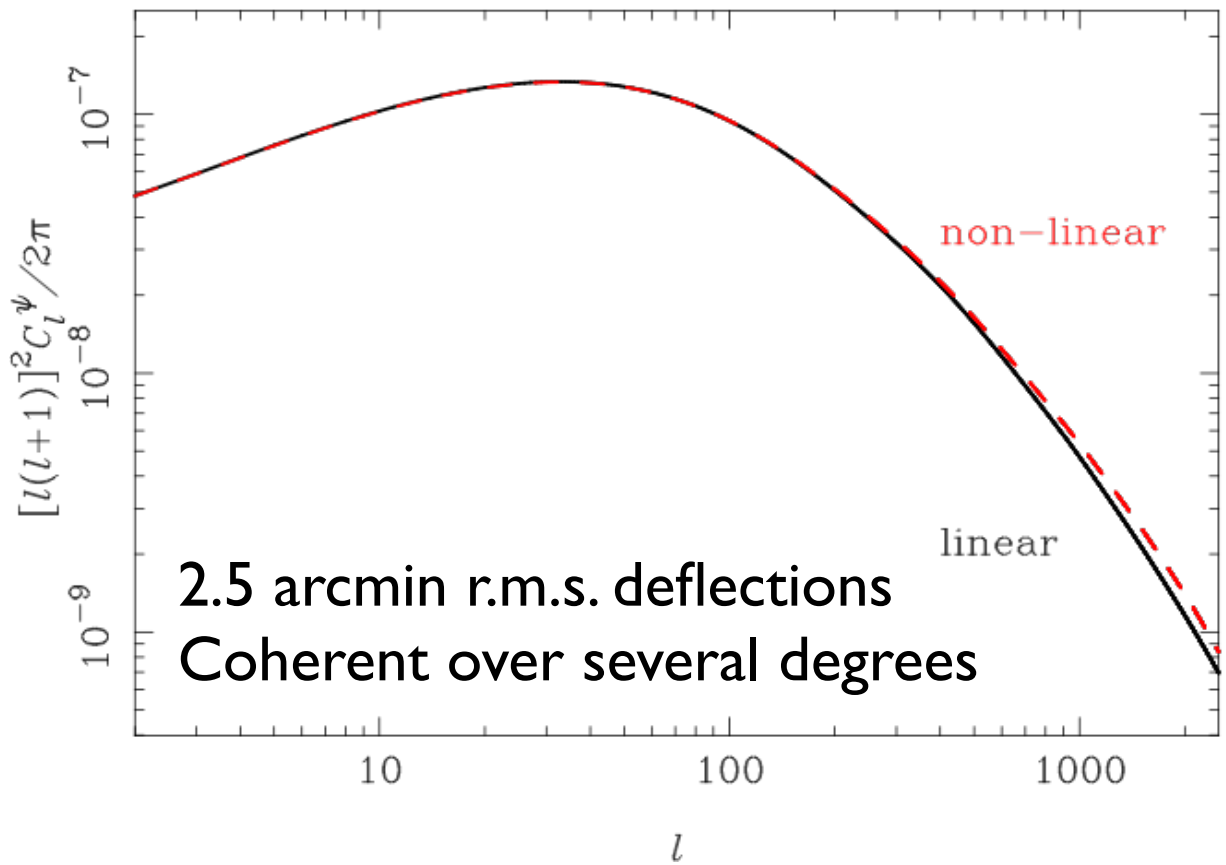


- O(50) deflections by 100 Mpc scale lenses
  - *Peak efficiency around z=2*
  - *Predicts 2.5 arcmin r.m.s. deflections coherent over several degrees*

CMB lensing power spectrum

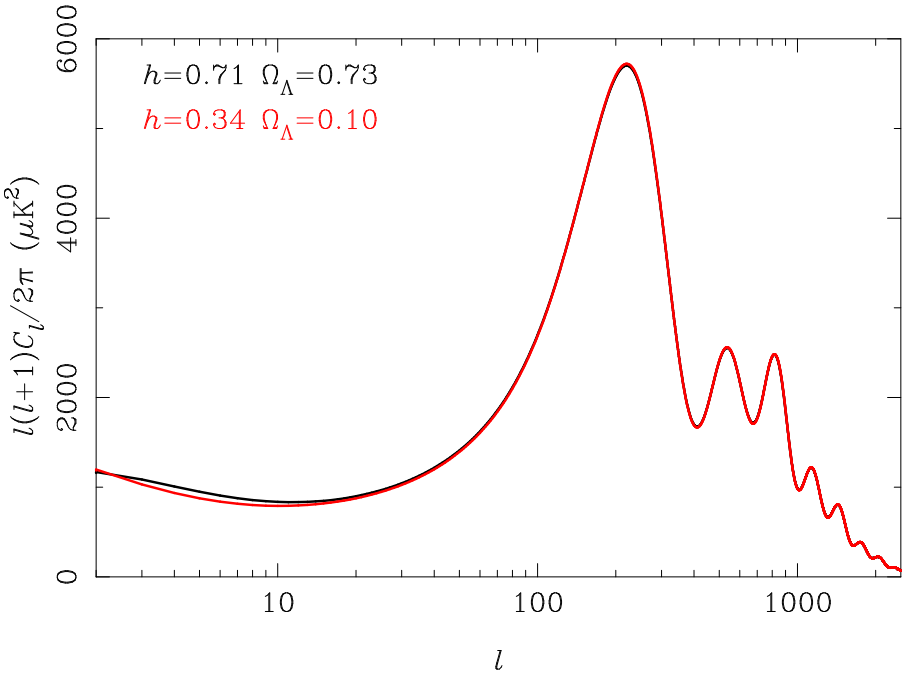
- Deflection field ***d*** = **∇**φ in linear theory

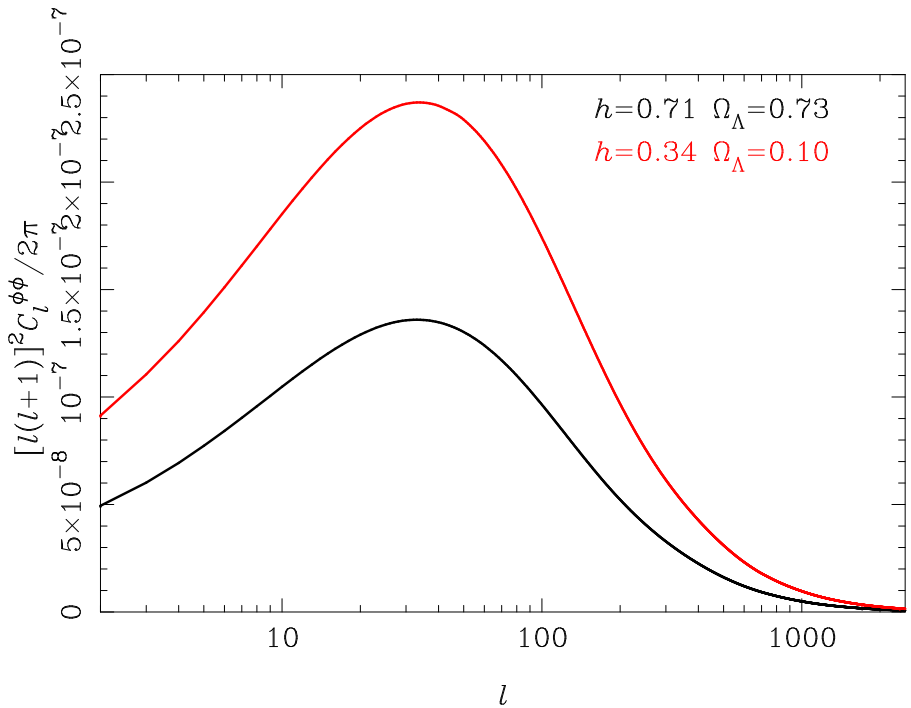
$$\phi(\hat{\boldsymbol{n}}) = -\int_0^{\chi_*} d\chi \, \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)(\chi \hat{\boldsymbol{n}}; \eta_0 - \chi)$$



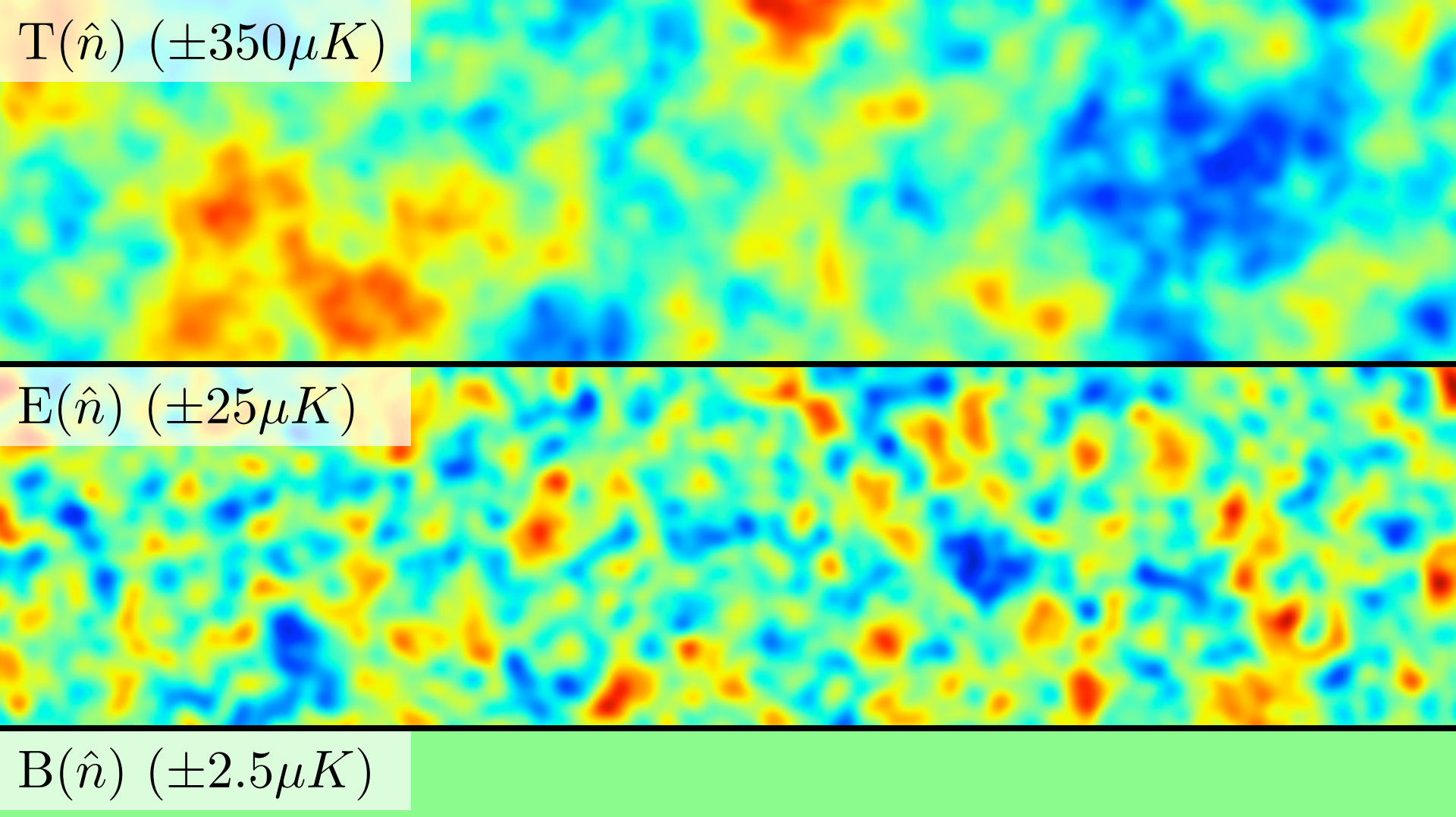
2.5 arcmin r.m.s. deflections
Coherent over several degrees

Lensing adds information

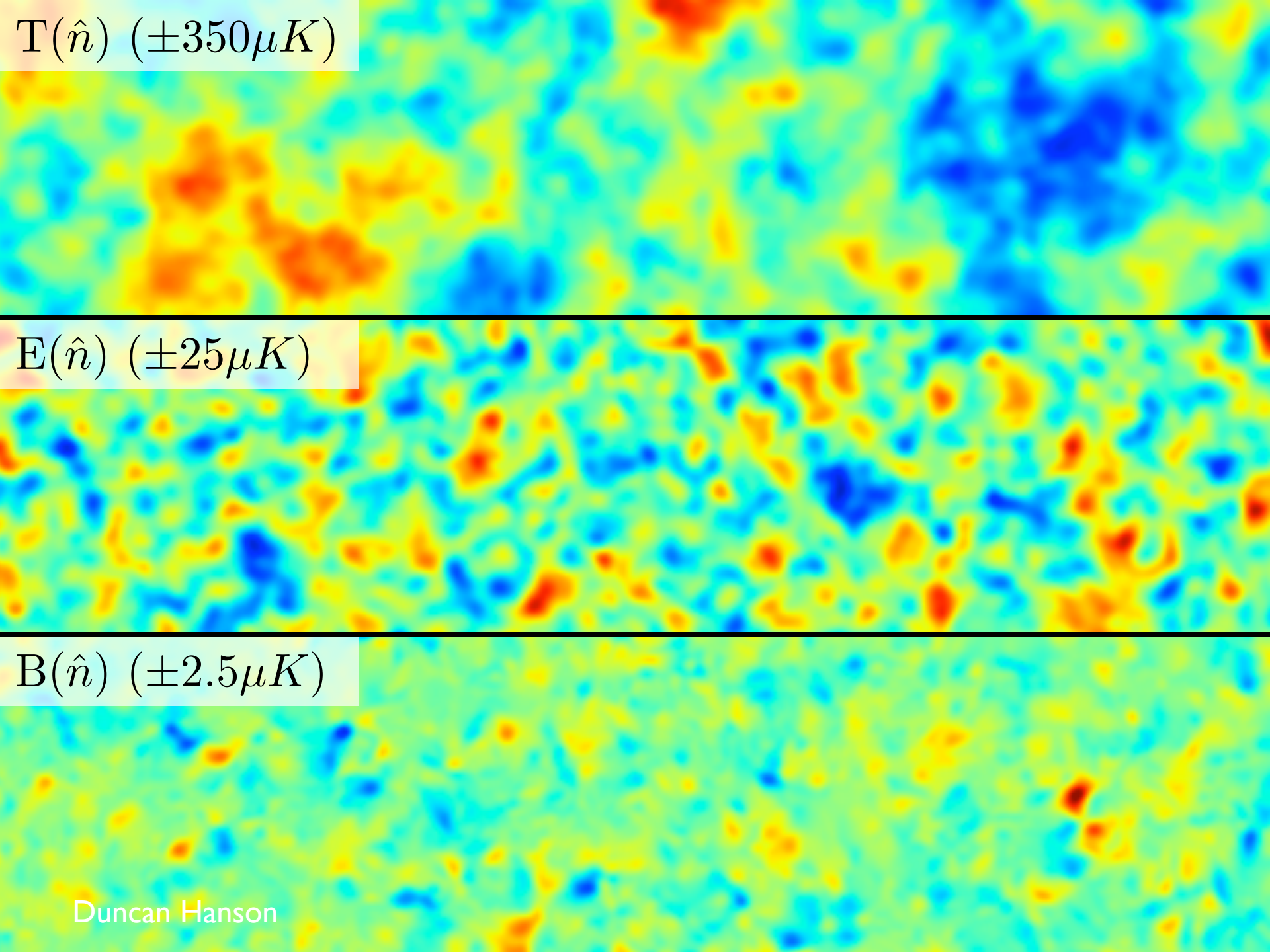




- Geometric degeneracy in CMB power spectra broken by different amounts of lensing in models with same $d_A(z_*)$
  - *Access to curvature, sub-eV neutrino masses, dark energy etc. from CMB alone*

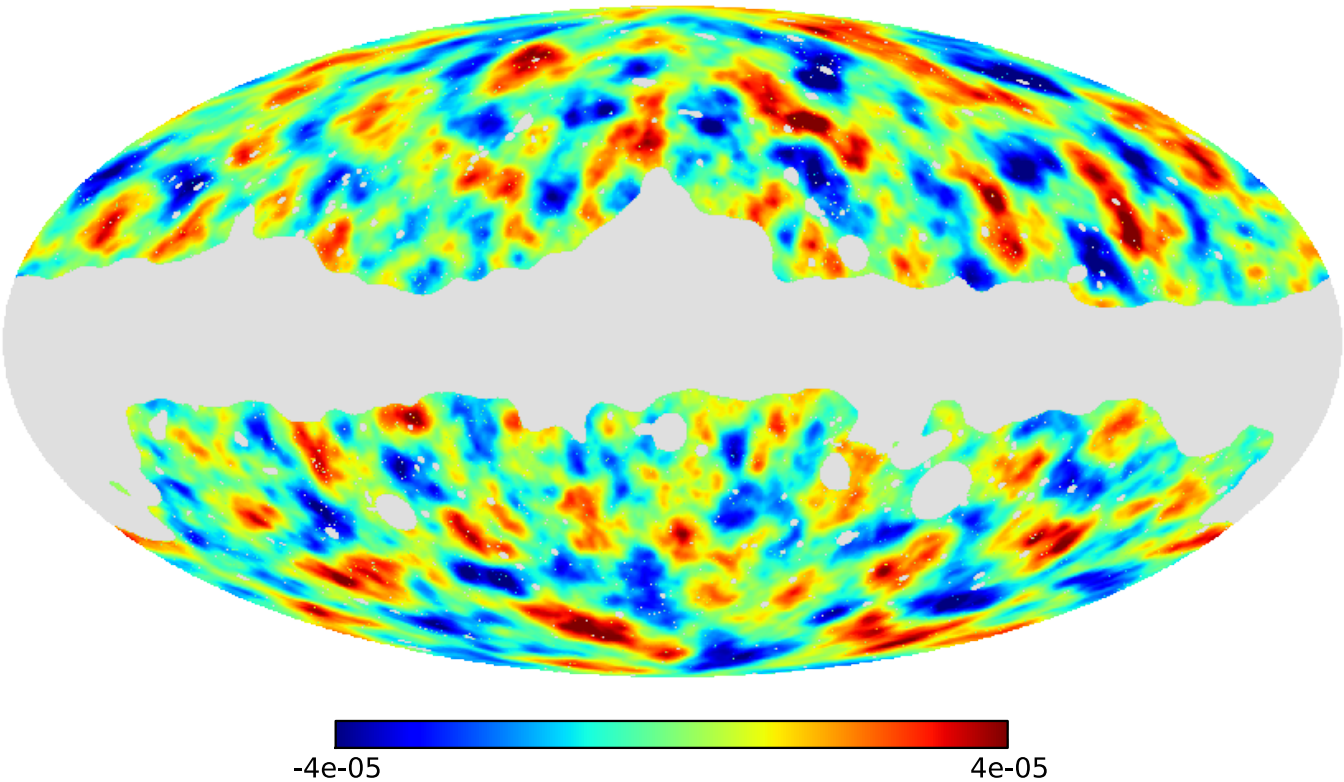


Duncan Hanson


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

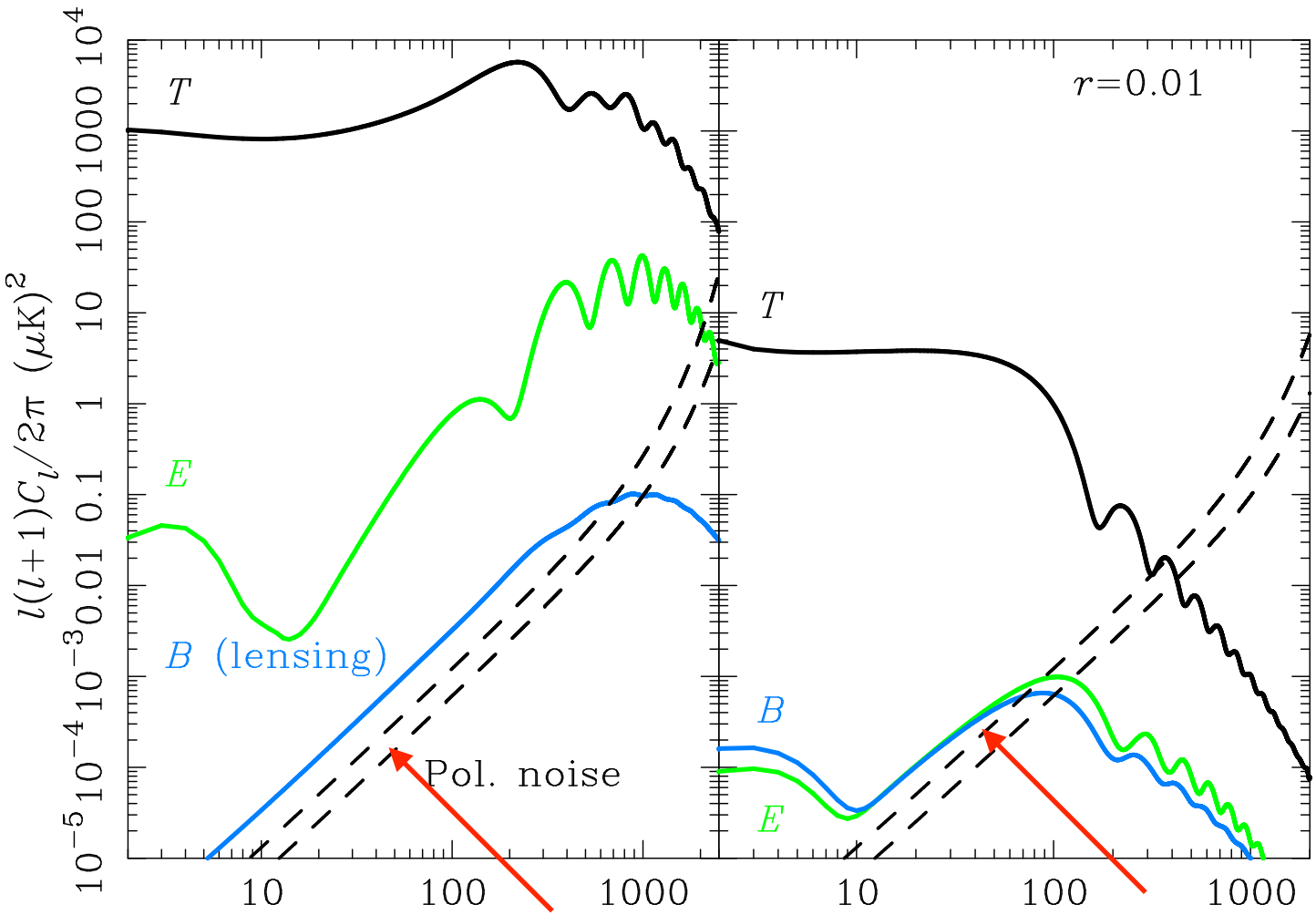
Lens reconstruction

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



Planck Collaboration 2015

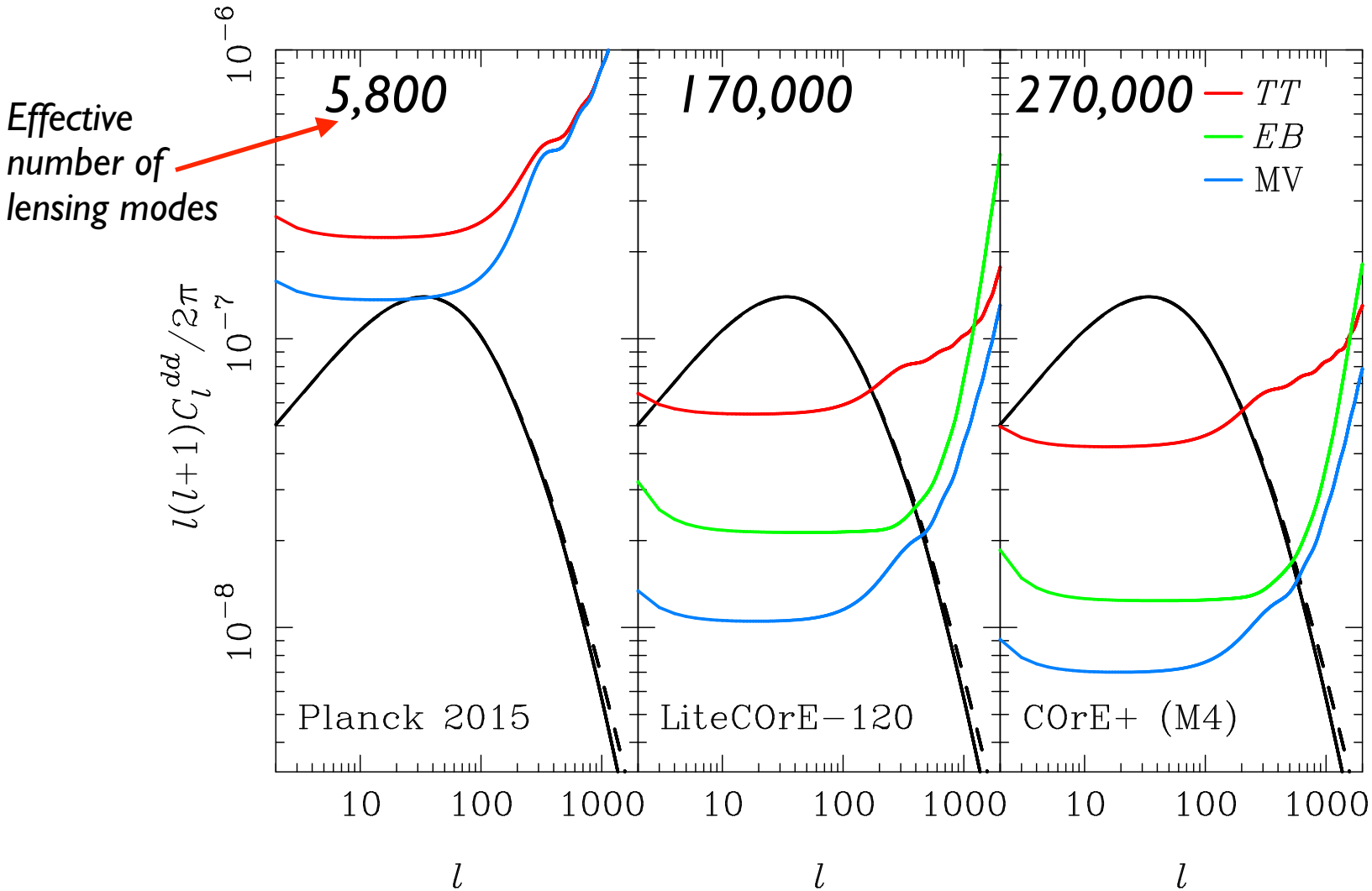
Representative T and P noise levels



COrE+ (M4)
(2.1 μKarcmin noise)

LiteCOrE-120
(3 μKarcmin noise)

Lens reconstruction noise levels



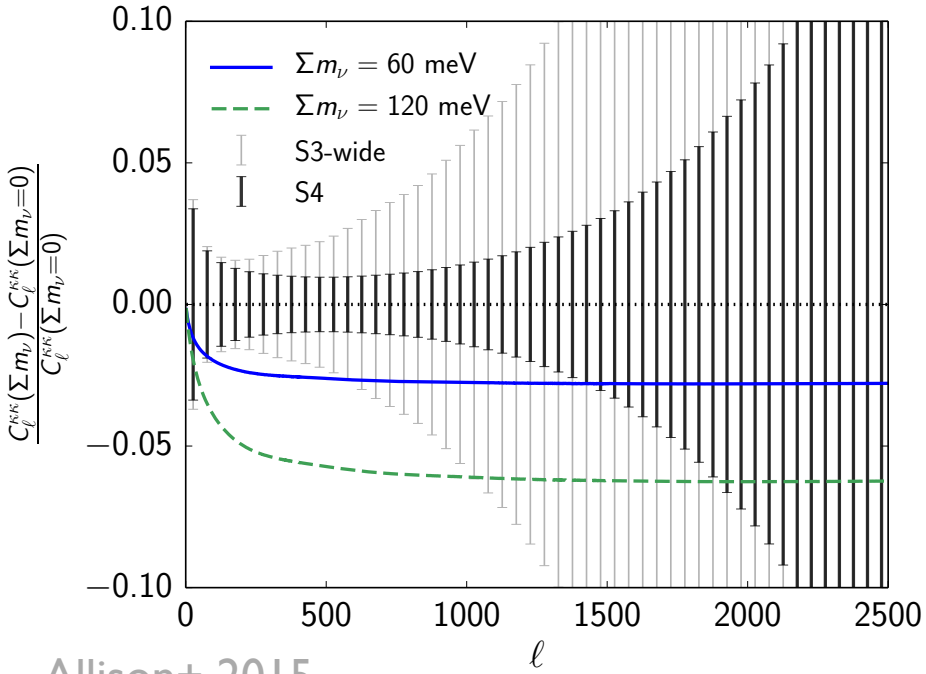
- *EB* particularly helpful for pol. noise < 5 μK arcmin

Applications of CMB lensing

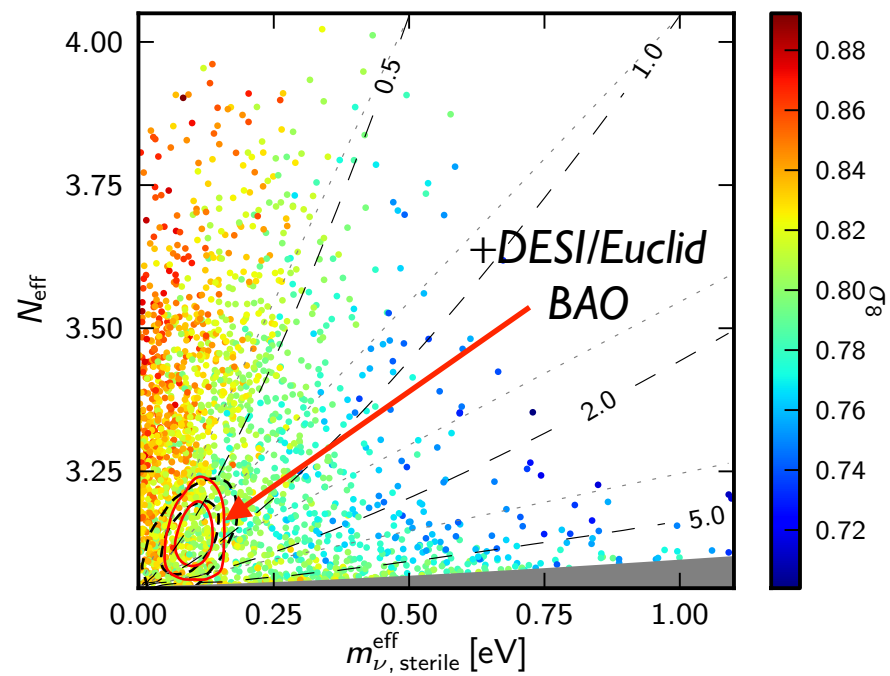
- Cosmology from auto-power spectrum
  - *Neutrino masses, curvature, (early) dark energy etc.*
- Cross-correlation with other LSS tracers
  - *Degeneracy breaking, self-calibration, high-z astrophysics*
- Delensing
  - *Improve GW constraints (r and n_t)*
  - *Delens high-l EE (sharpen peaks for N_{eff}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

(see clusters talks)

Neutrino physics



Allison+ 2015



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

$\sigma(\sum m_\nu) = 15\,\mathrm{meV}$ +DESI/*Euclid* BAO

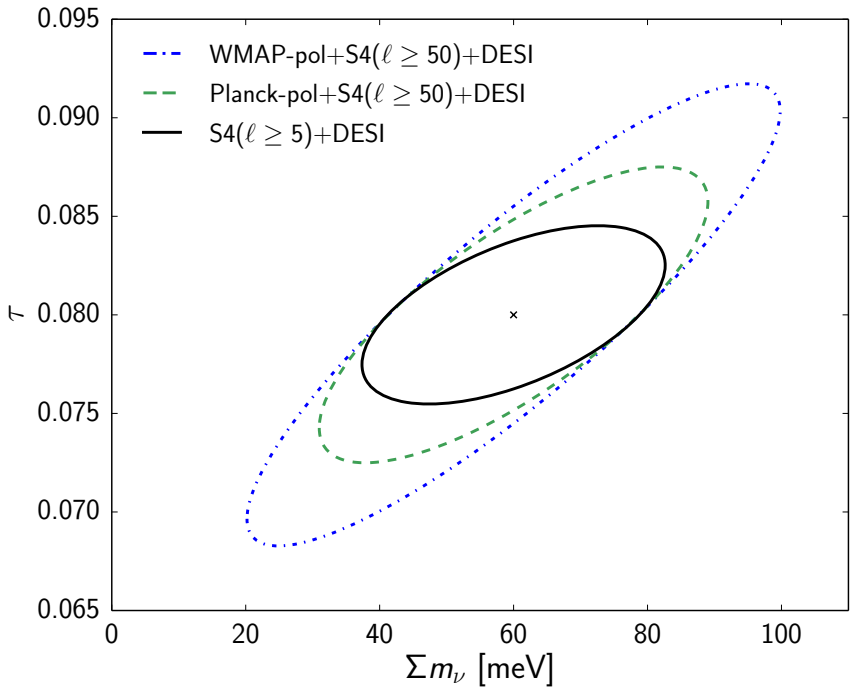
$\sigma(m^{\rm eff}_{\nu,\rm sterile}) = 20\,\mathrm{meV}$

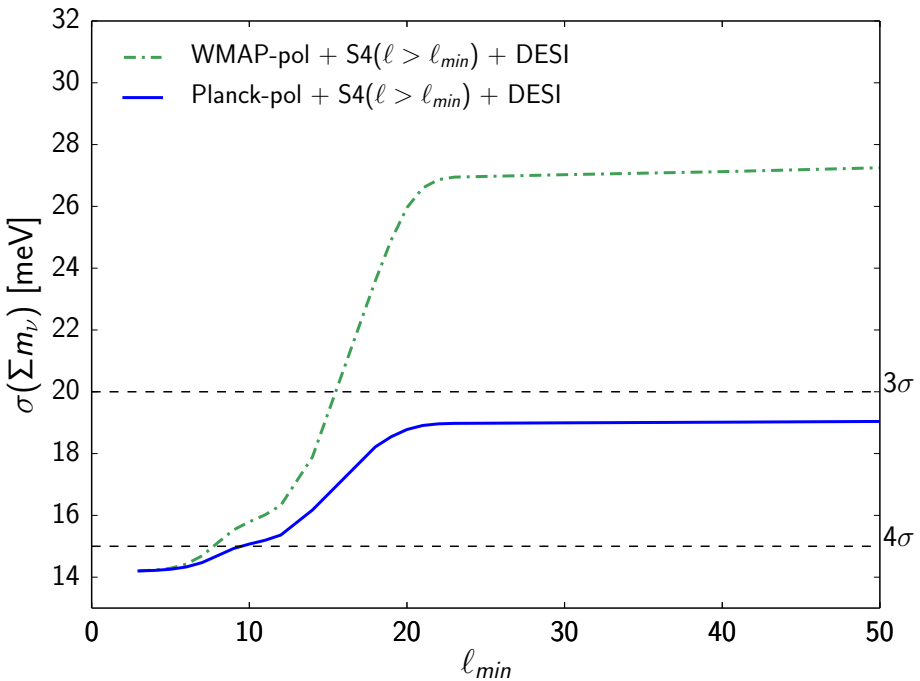
$\sigma(\sum N_{\rm eff}) = 0.04$

Similar constraints for LiteCOrE-120

Sufficient to rule out any post-QCD thermal relic

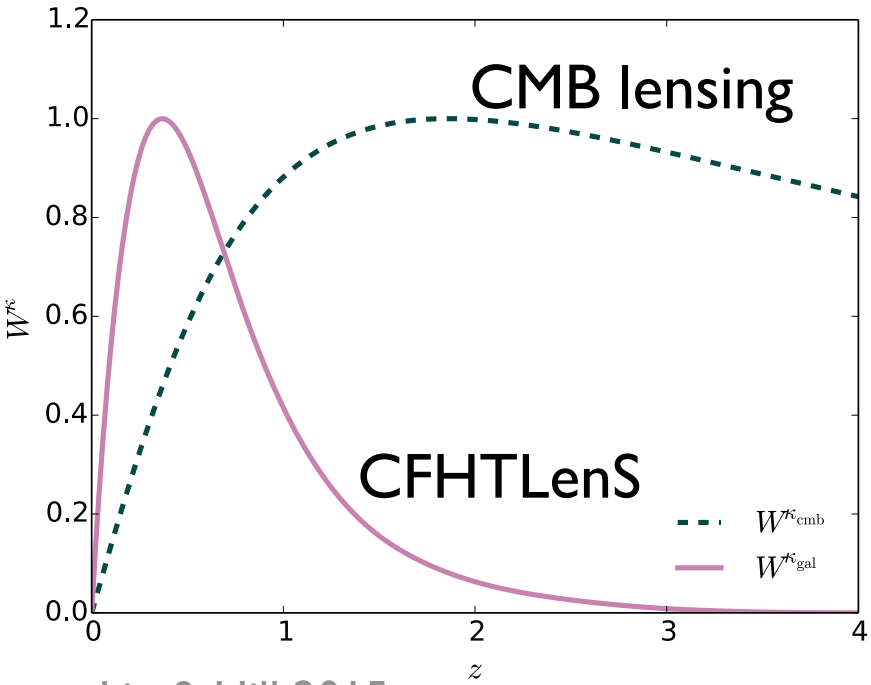
Role of reionization optical depth



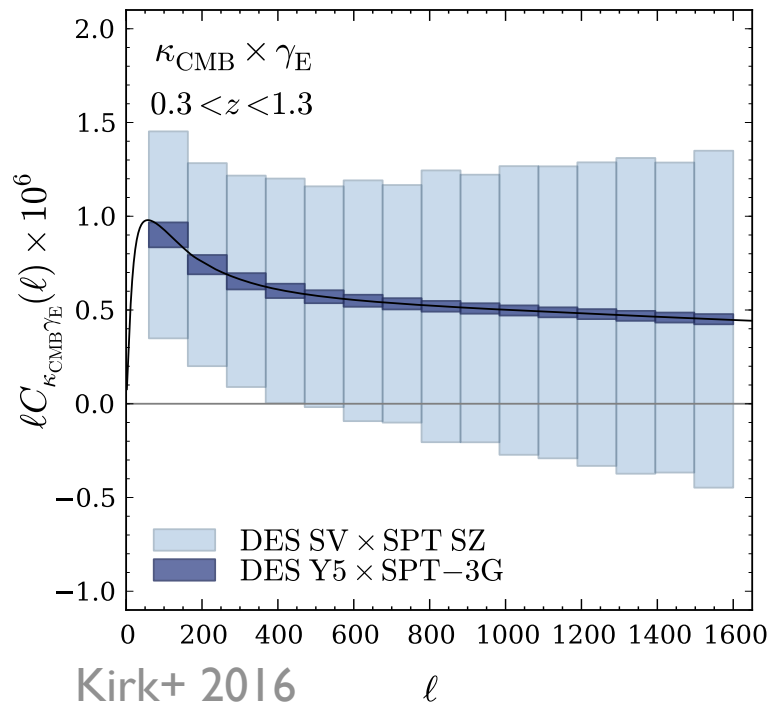


Allison+ 2015

Galaxy lensing-CMB lensing



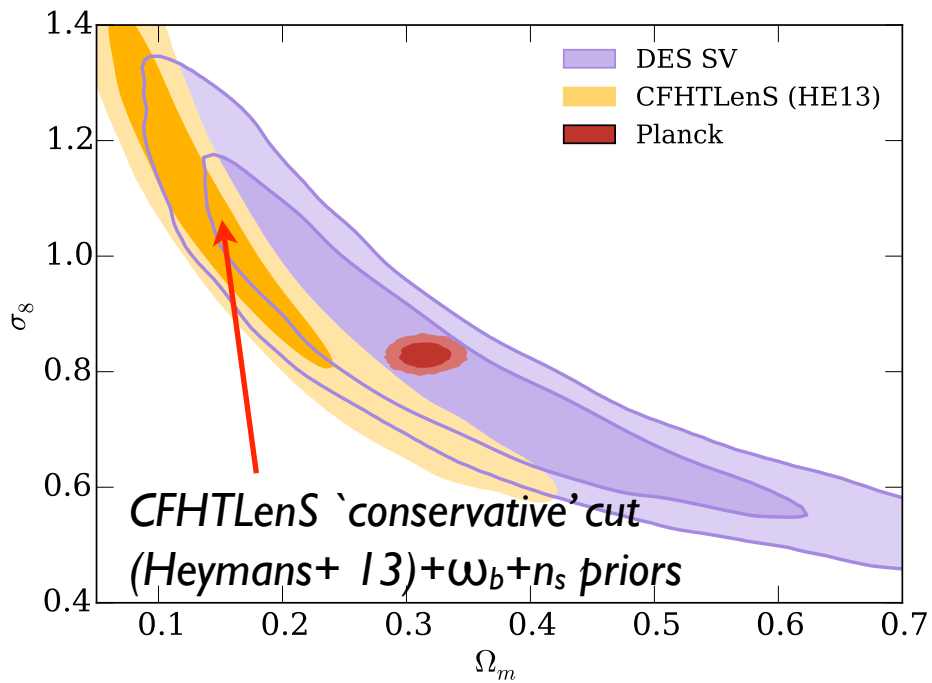
Liu & Hill 2015



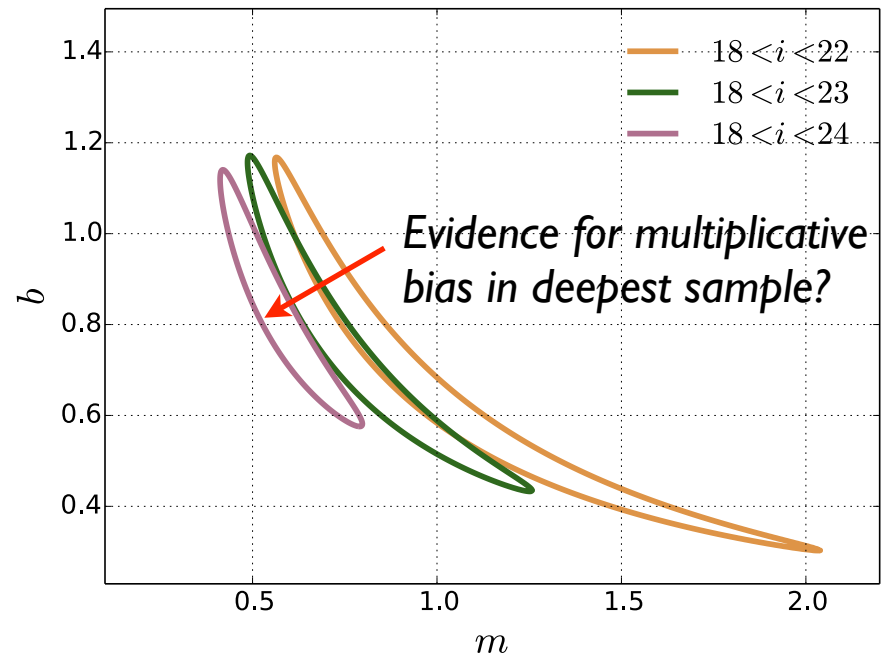
Kirk+ 2016

- Probes redshifts intermediate to CMB lensing and galaxy autos
- X-correlation more immune to additive systematic effects
- Full joint analysis can calibrate multiplicative bias effects in shape measurement and intrinsic alignments

Evidence for lensing systematics?



DES Collaboration 2015



Liu+ 2016

Multiplicative bias in measured shear

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

Galaxy bias

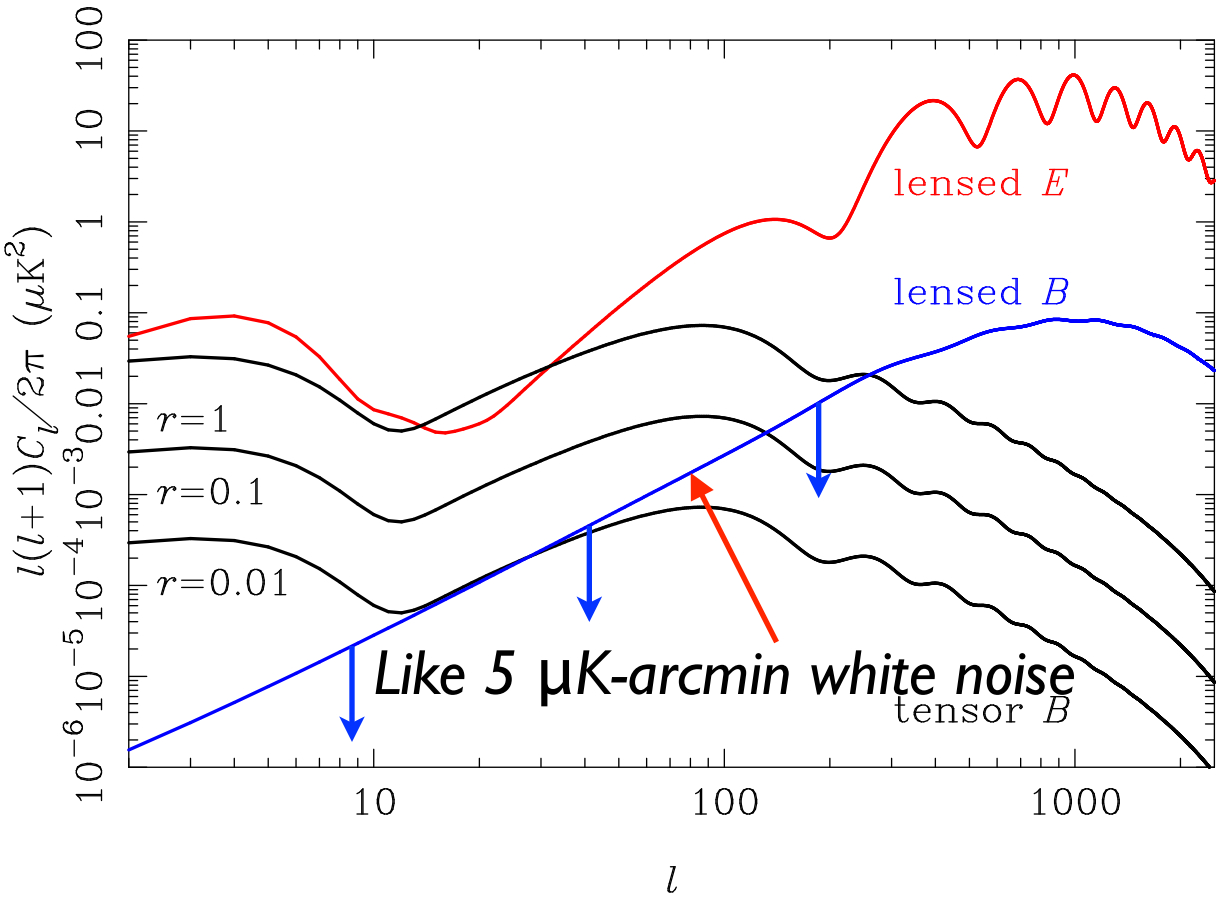
$$\langle \kappa_{\rm CMB}\Sigma\rangle \propto b$$

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

Other causes?

- *photo-z errors*
- *Intrinsic alignments*

Delensing degree-scale B-modes

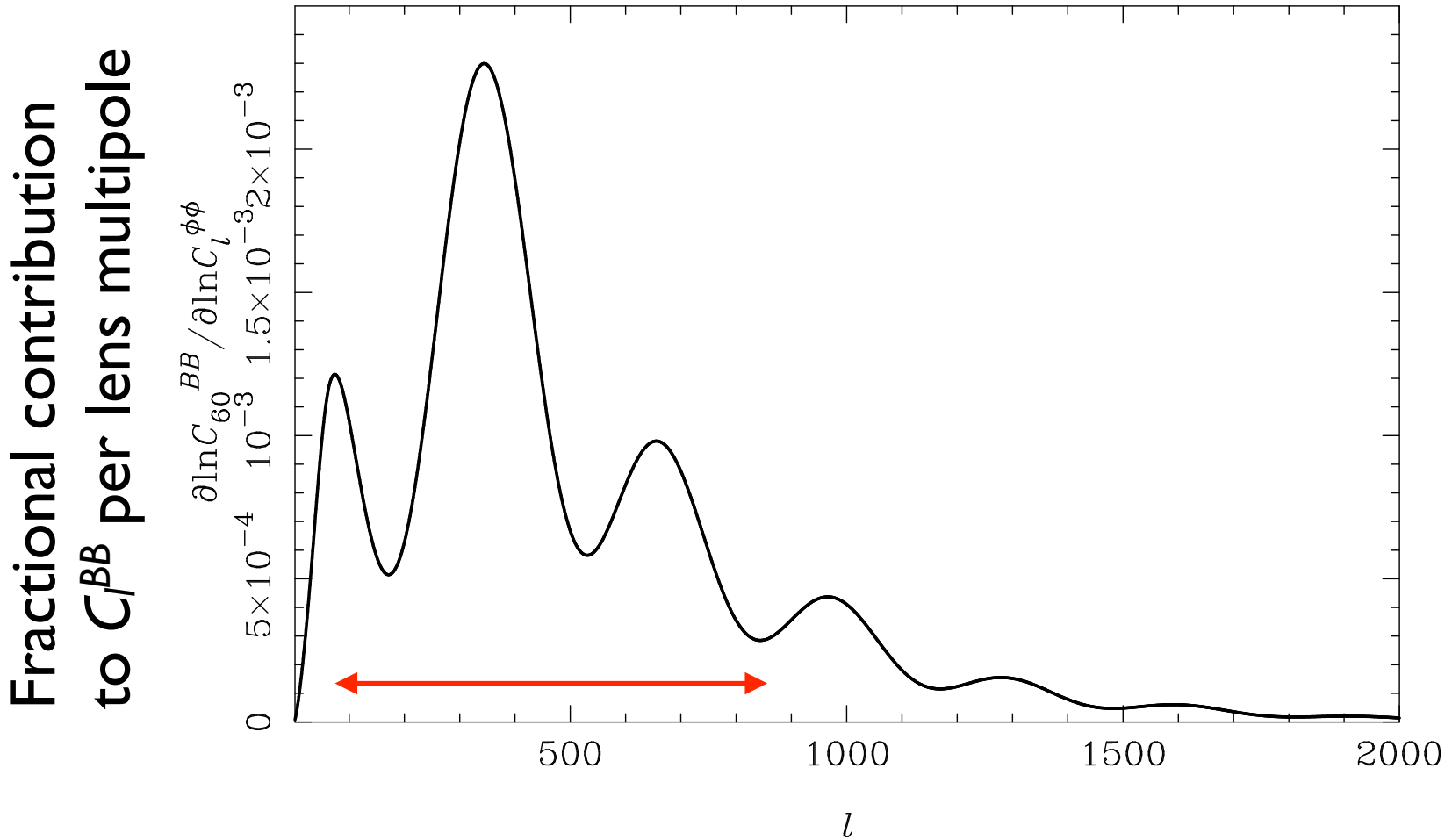


- Improve limits on amplitude of GWs
- Access primordial *B*-modes on smaller scales
  - *Tensor tilt*
  - *Oscillations?*

Some proxy for lensing potential

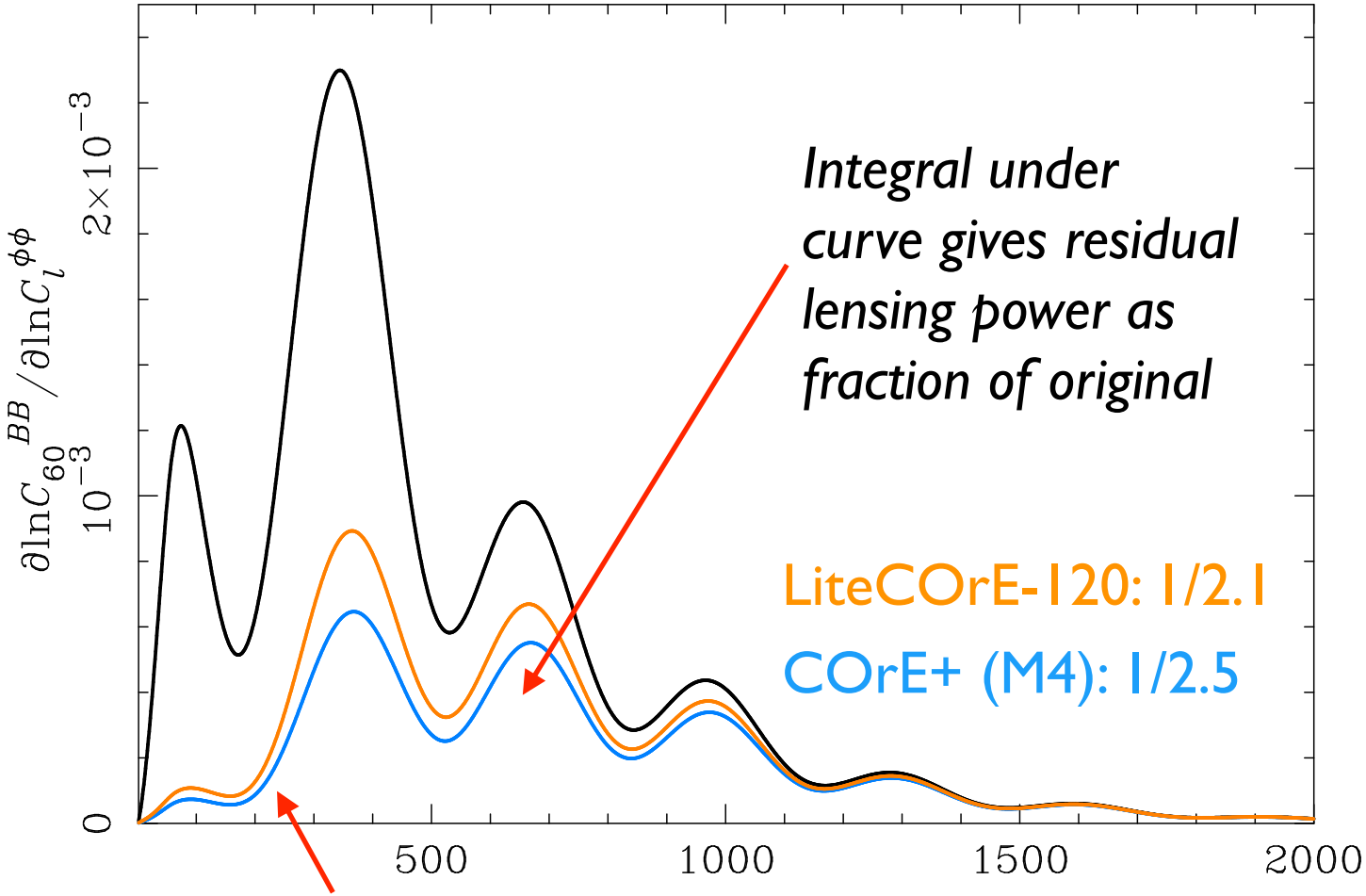
$$B_{\rm delens} \sim B - E\hat{\phi}$$

What scales are important?



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

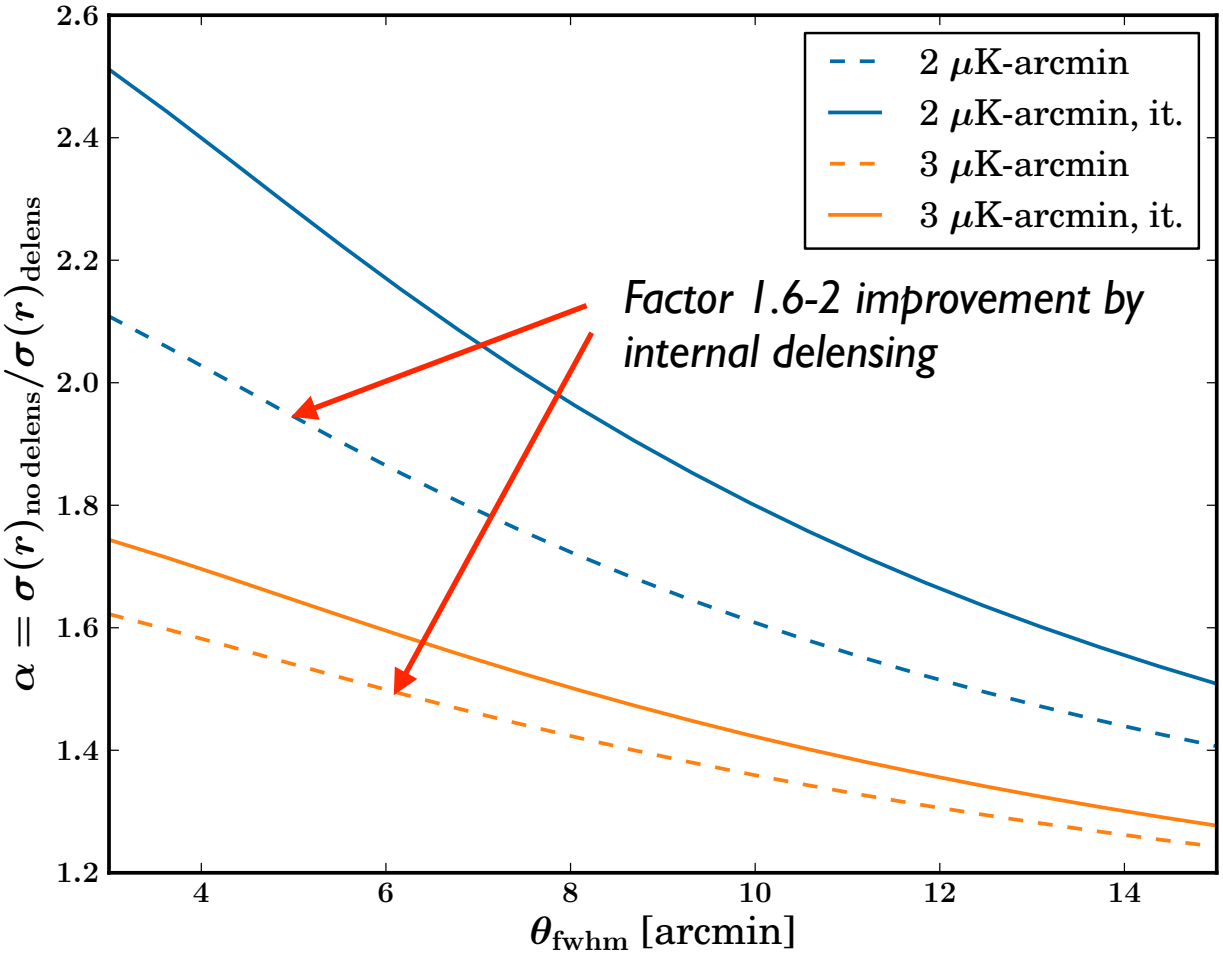
Impact of delensing



High S/N reconstruction on these scales

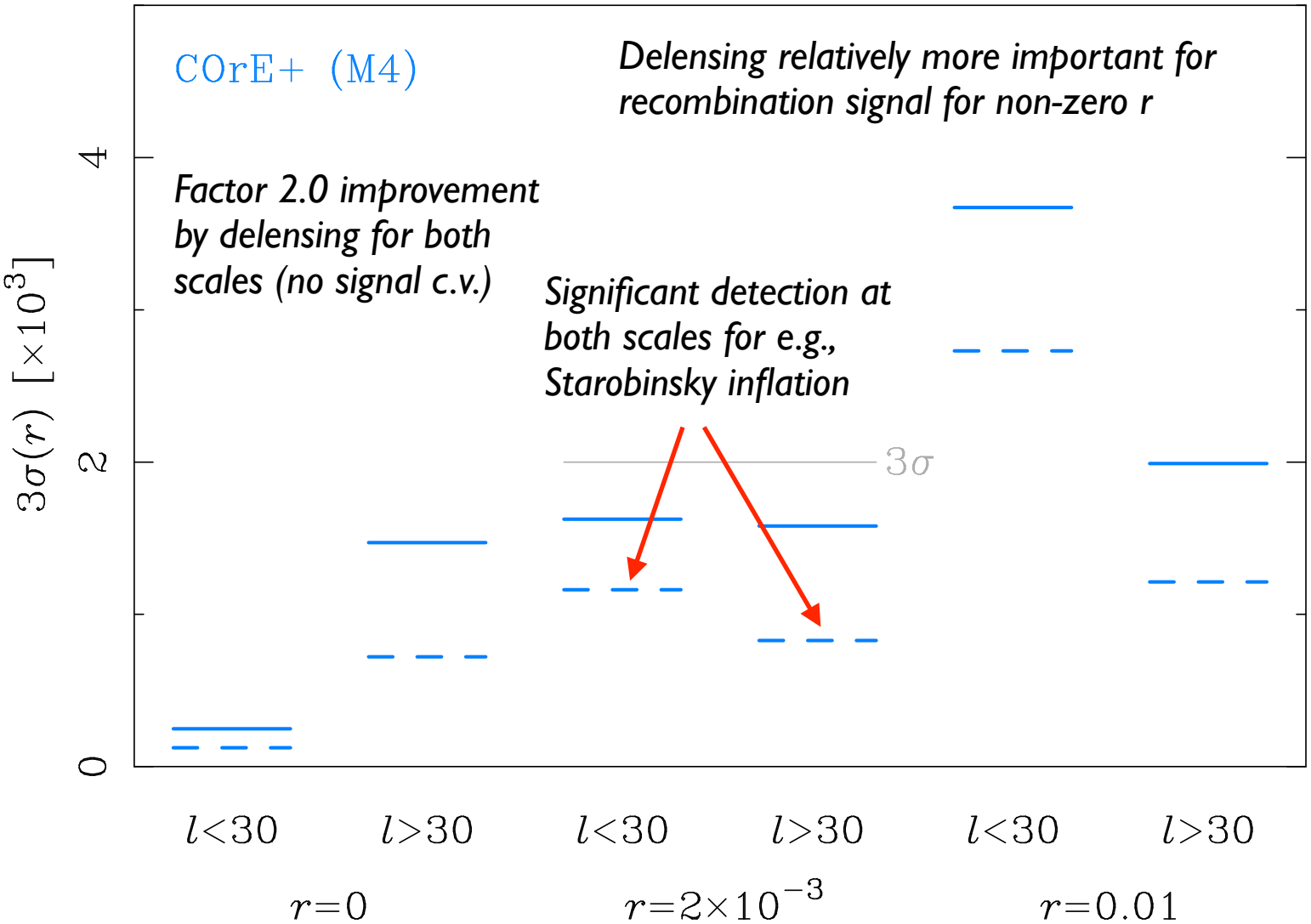
Requirements for delensing BB

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

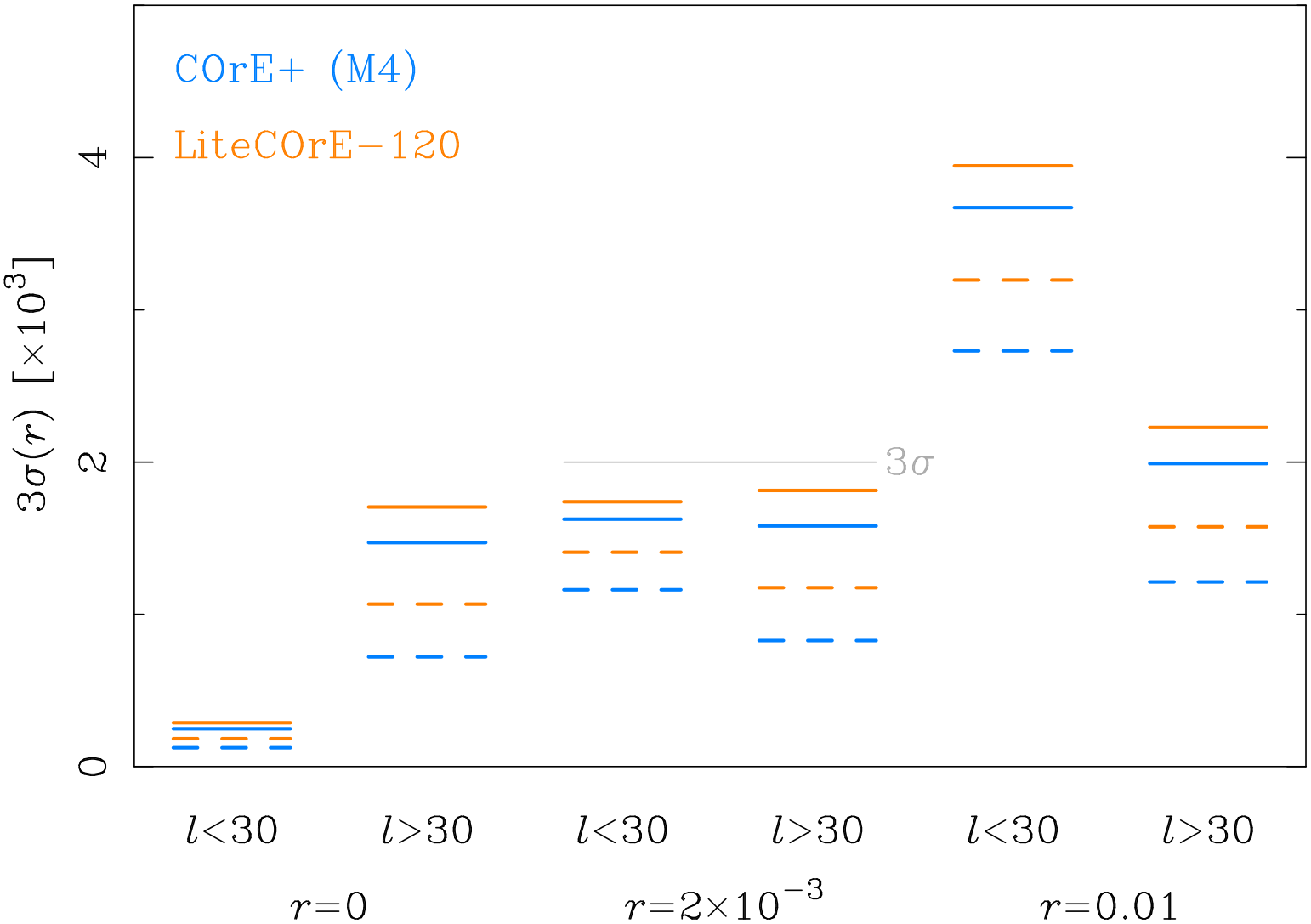


Feeney & Errard

Implications for inflation constraints

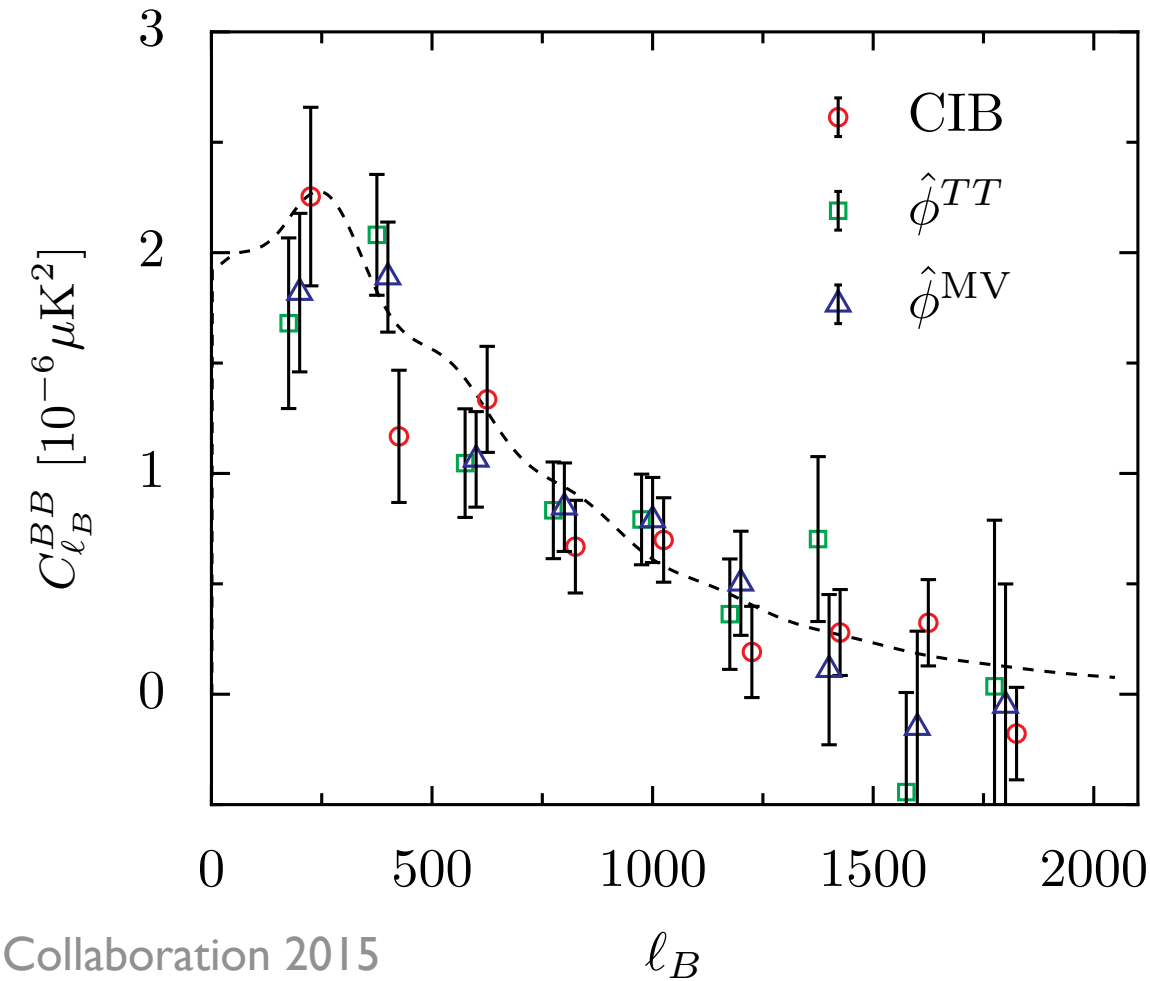


Implications for inflation constraints



Towards delensing: indirect BB

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



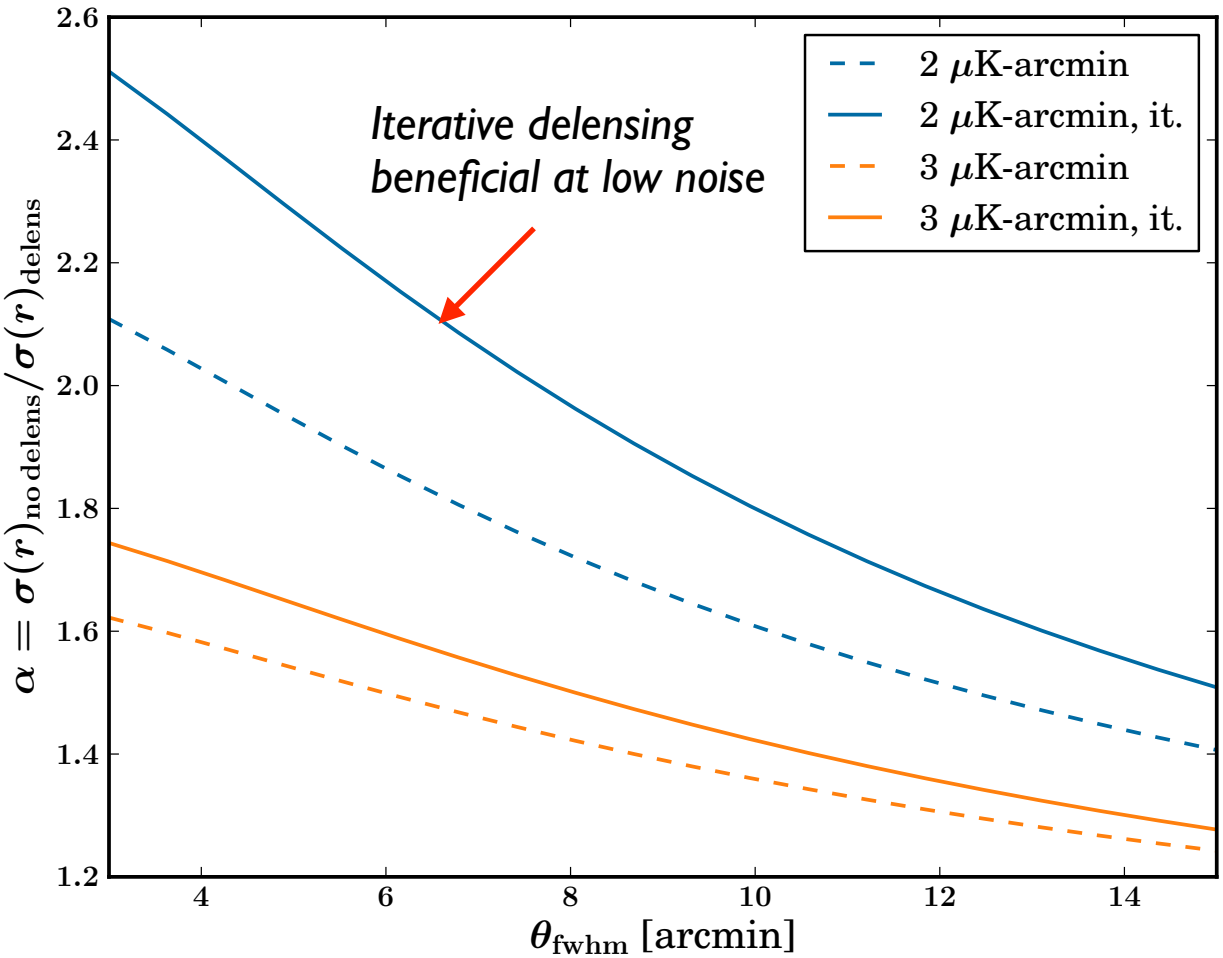
$$C^{B\hat{B}} \sim B(E\hat{\phi})$$

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

Planck Collaboration 2015

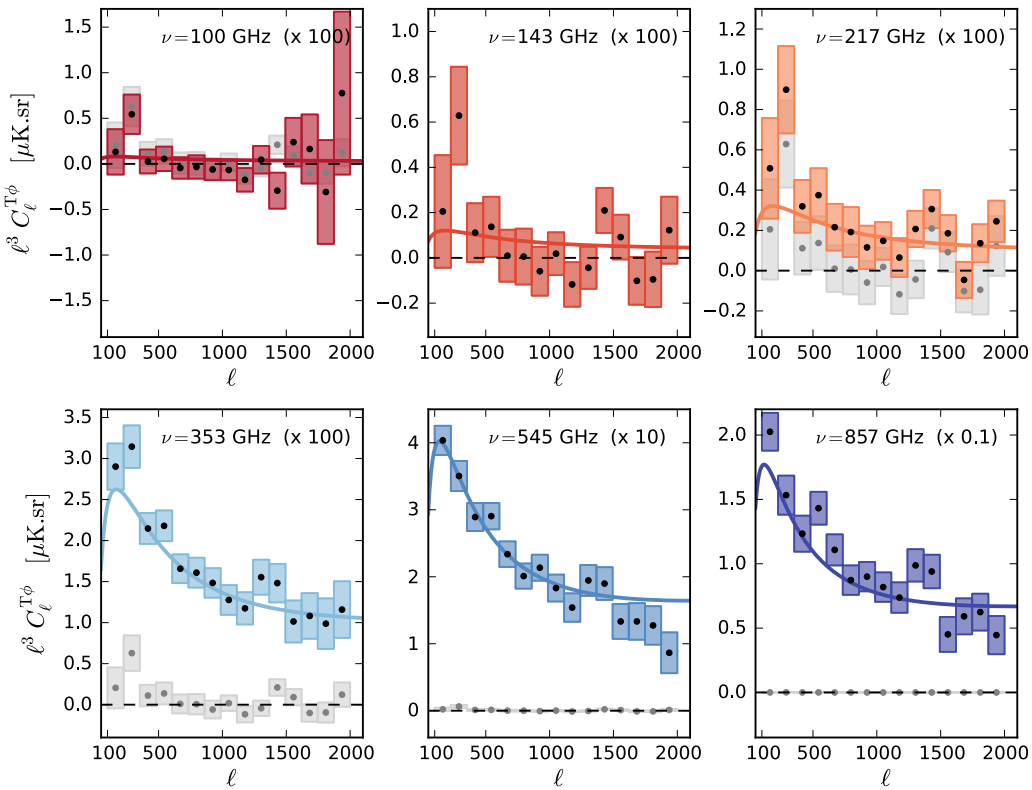
Iterative delensing?

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



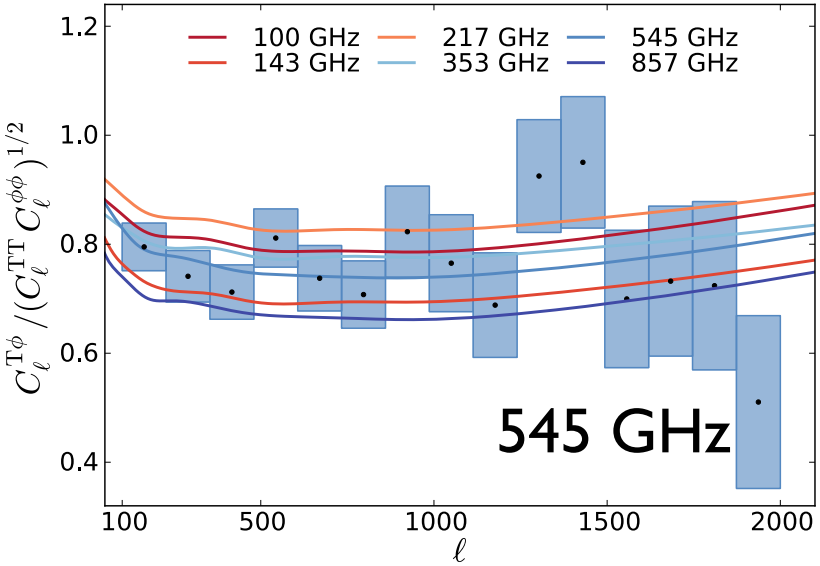
Feeney & Errard

CIB-CMB lensing



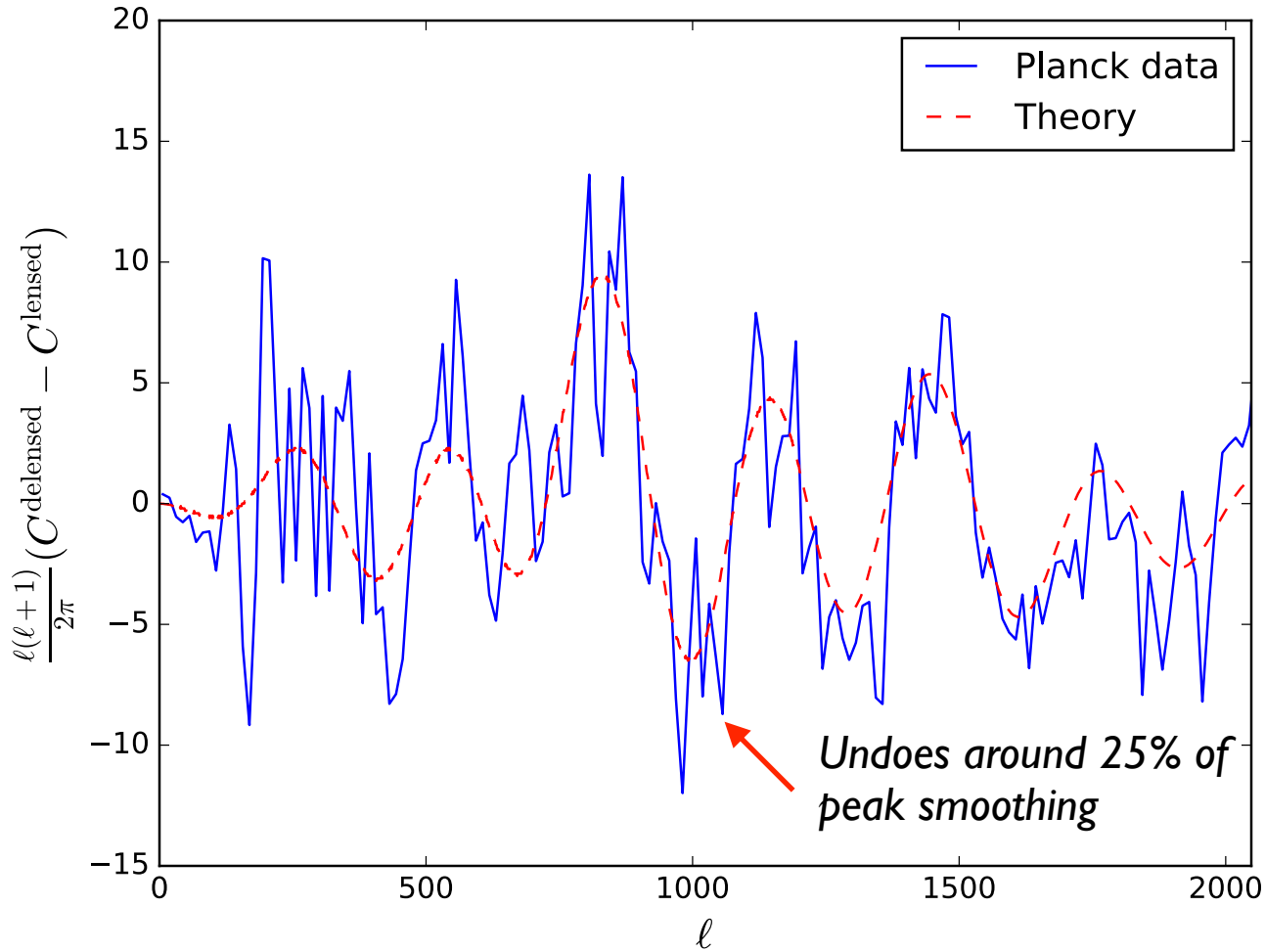
Planck Collaboration 2014

- 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}

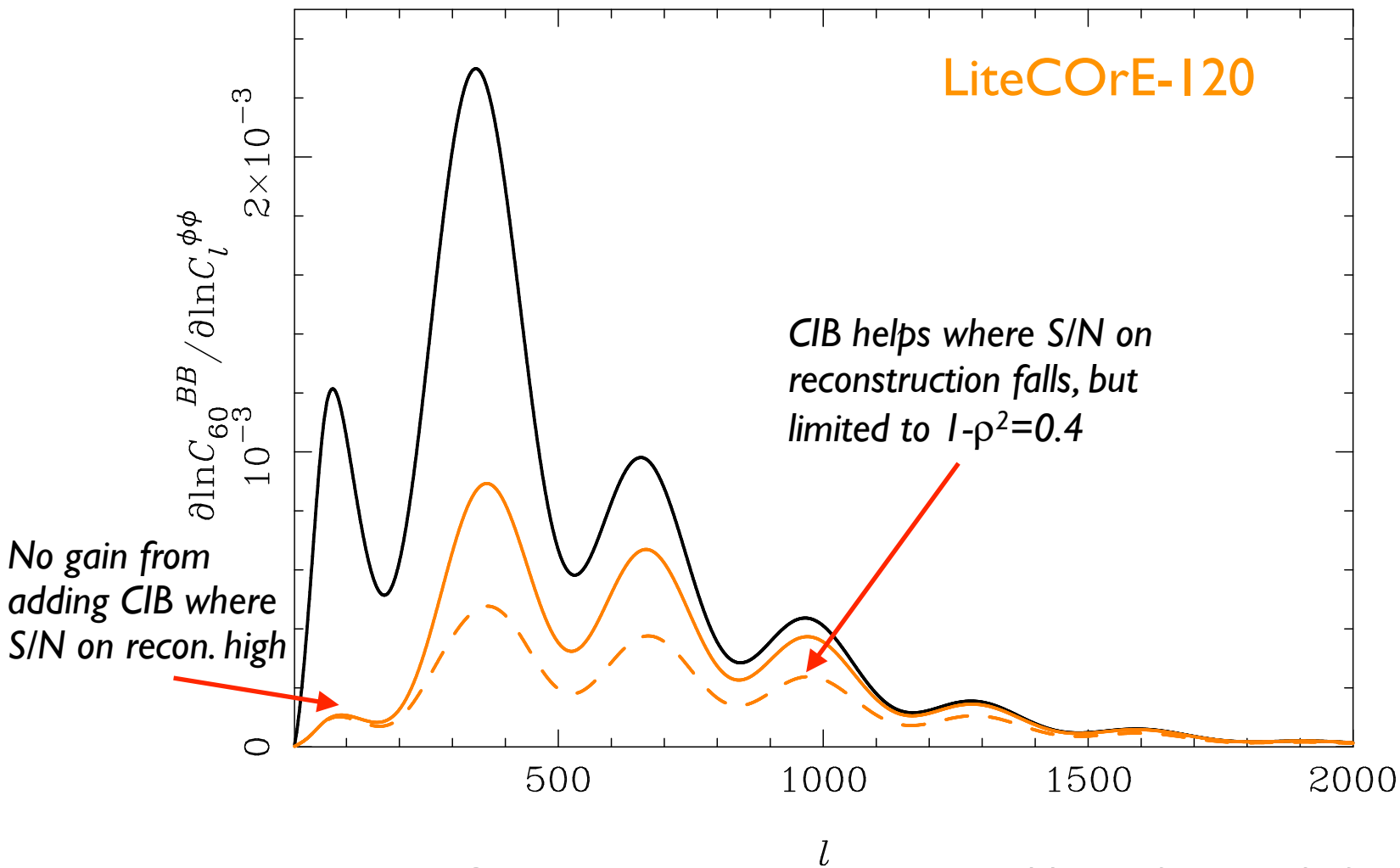
First demonstration of CIB delensing



- CIB from 857-α545 Planck channels
  - *Reduces correlation with CIB below 80%*

Larsen, AC+ in prep.

On what scales does CIB help?



- Reconstruction+CIB delensing improves σ(*r*) by factor 2 for *r=0* for LiteCOrE-120, cf. 1.6 with only reconstruction

Summary

- CMB lensing important part of science case at intermediate (space) and high-resolution (e.g., S3 and S4)
- CMB lensing power spectrum enhances cosmology
  - *E.g., at least 4σ detection of neutrino mass (with DESI/ Euclid BAO)*
- O(2×10^5) well-understood lensing modes for cross-correlation and other legacy science
- Can improve σ(*r*) by factor 1.6-2.3 with internal delensing (for low *r*) at few arcmin resolution
  - *Modest further improvements in combination with CIB*
- Cluster masses of full SZ-selected samples