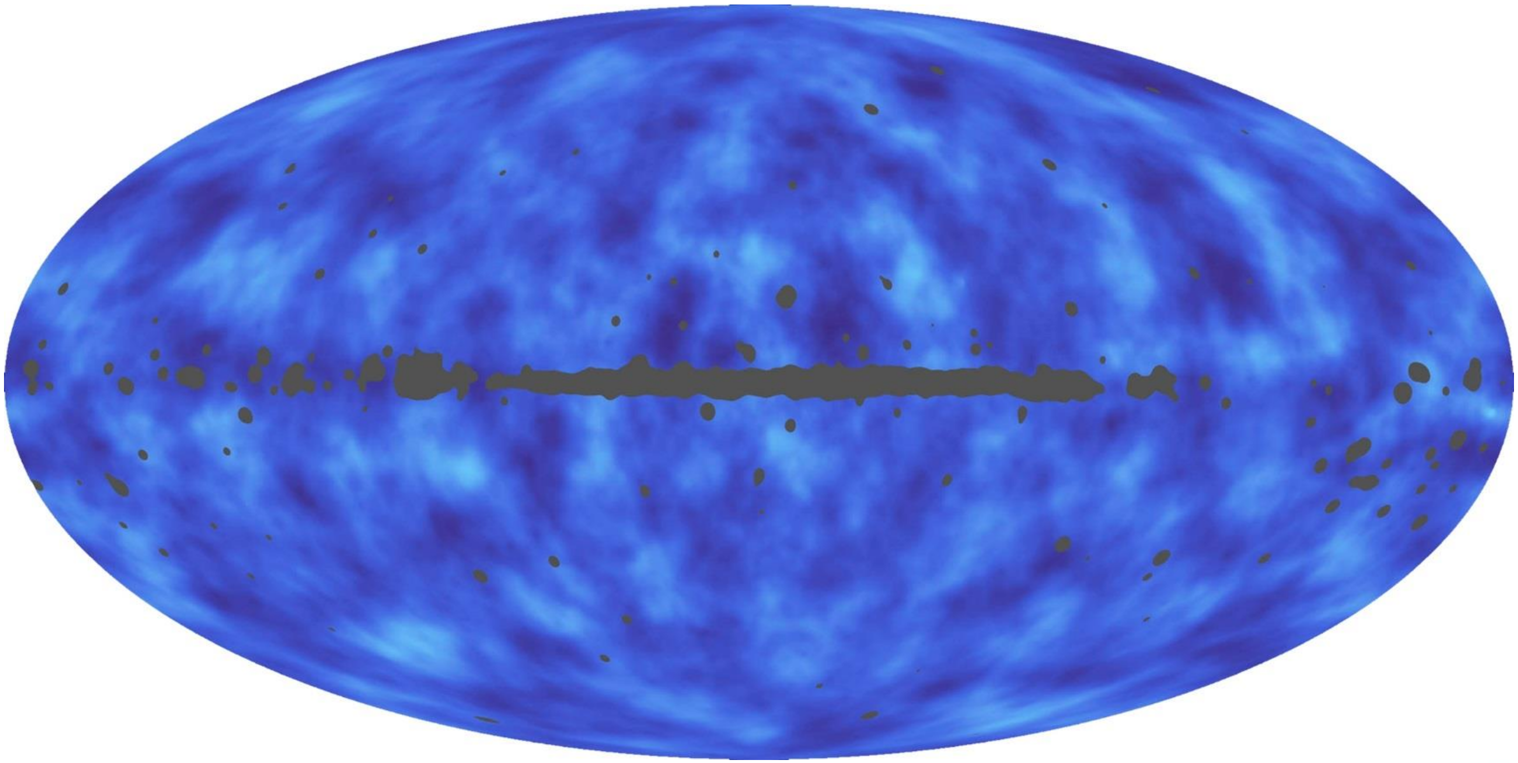
CMB Lensing and Delensing

Antony Lewis



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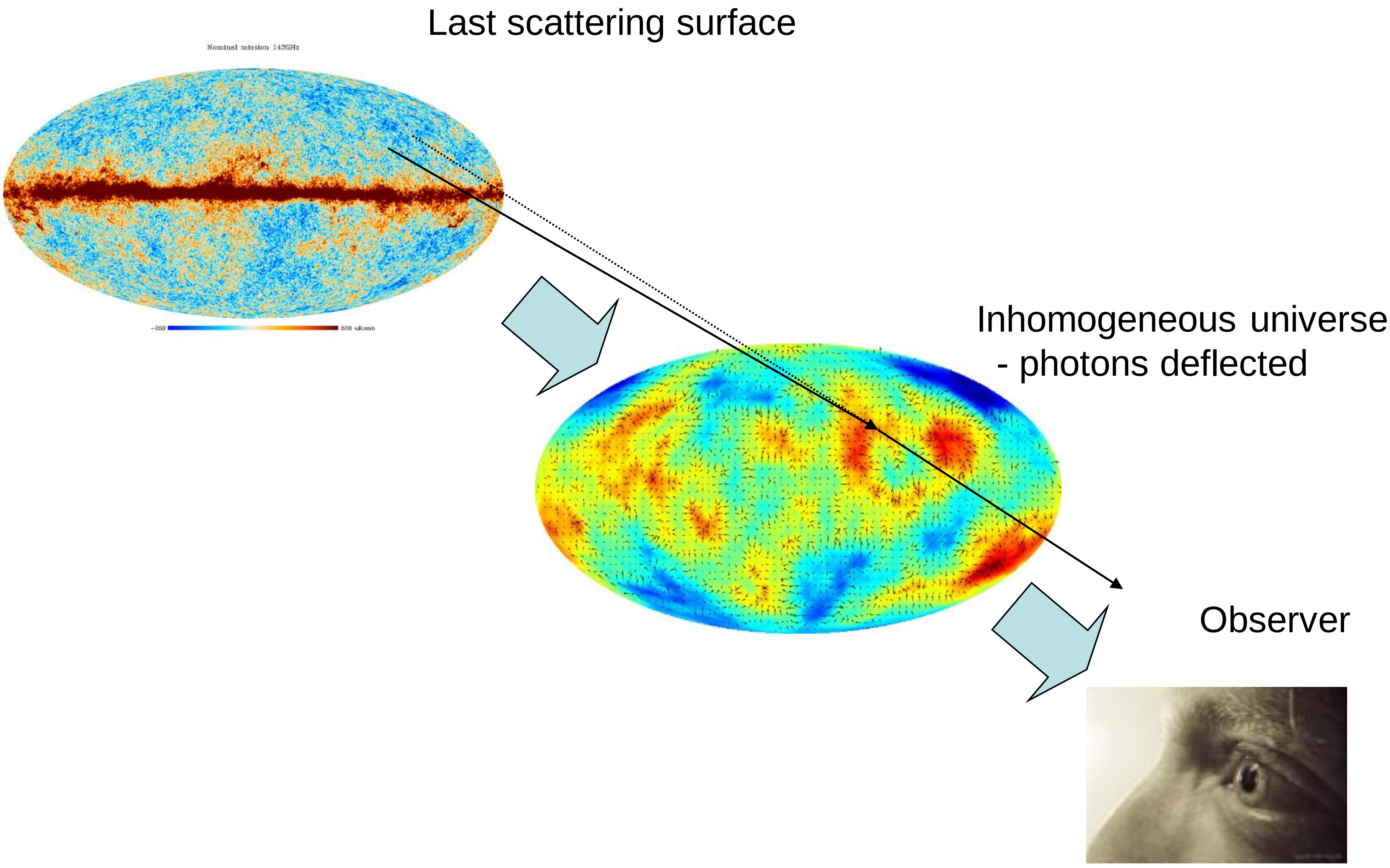
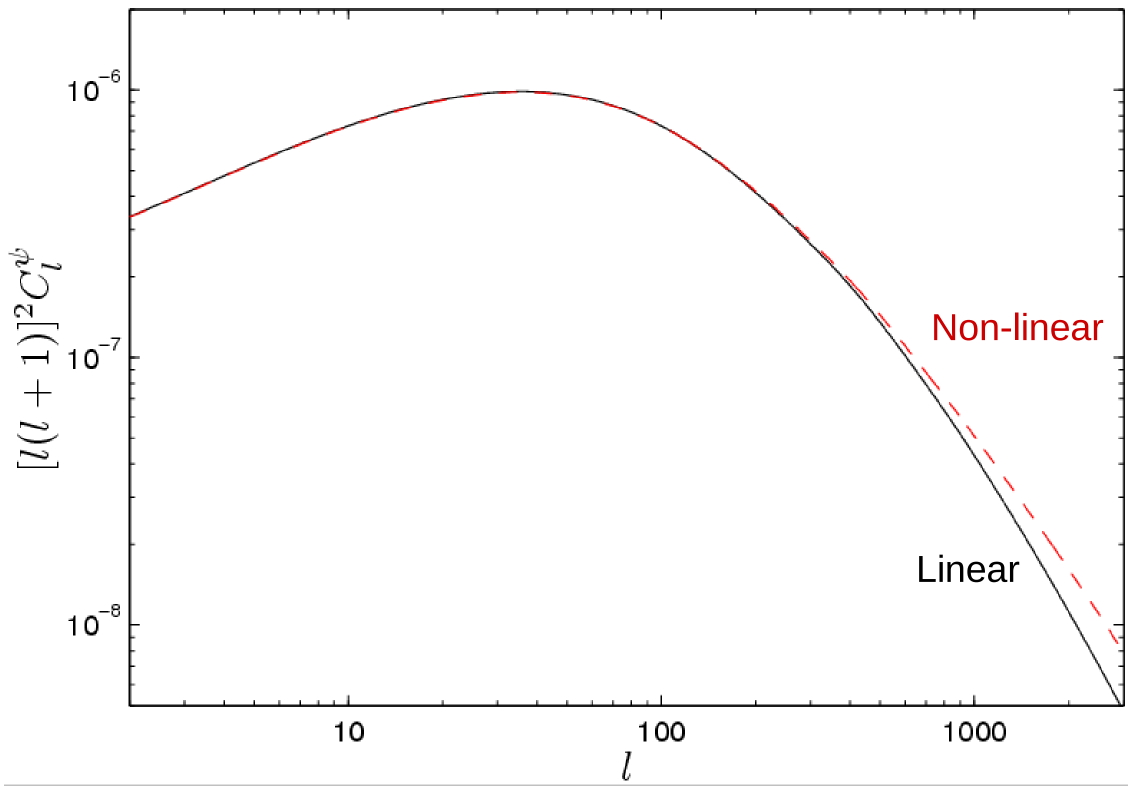
CMB Lensing


Last scattering surface
Nominal mission 143GHz
−250
500 uKcmb
Inhomogeneous universe
- photons deflected
Observer

Deflection angle power spectrum

Large-scale lenses: potentials nearly linear, clean physics

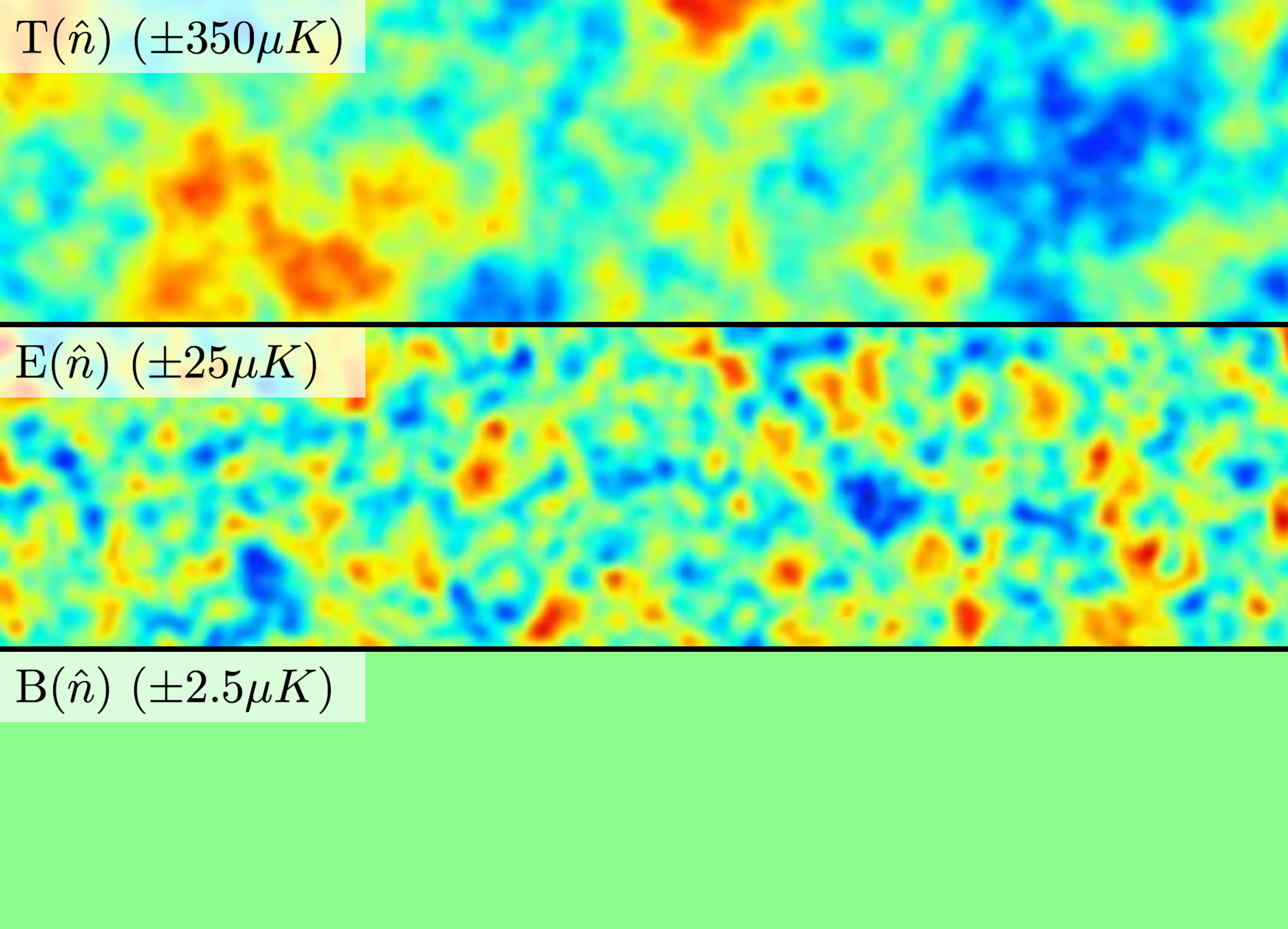
$$\boldsymbol{\alpha} = \nabla\psi$$



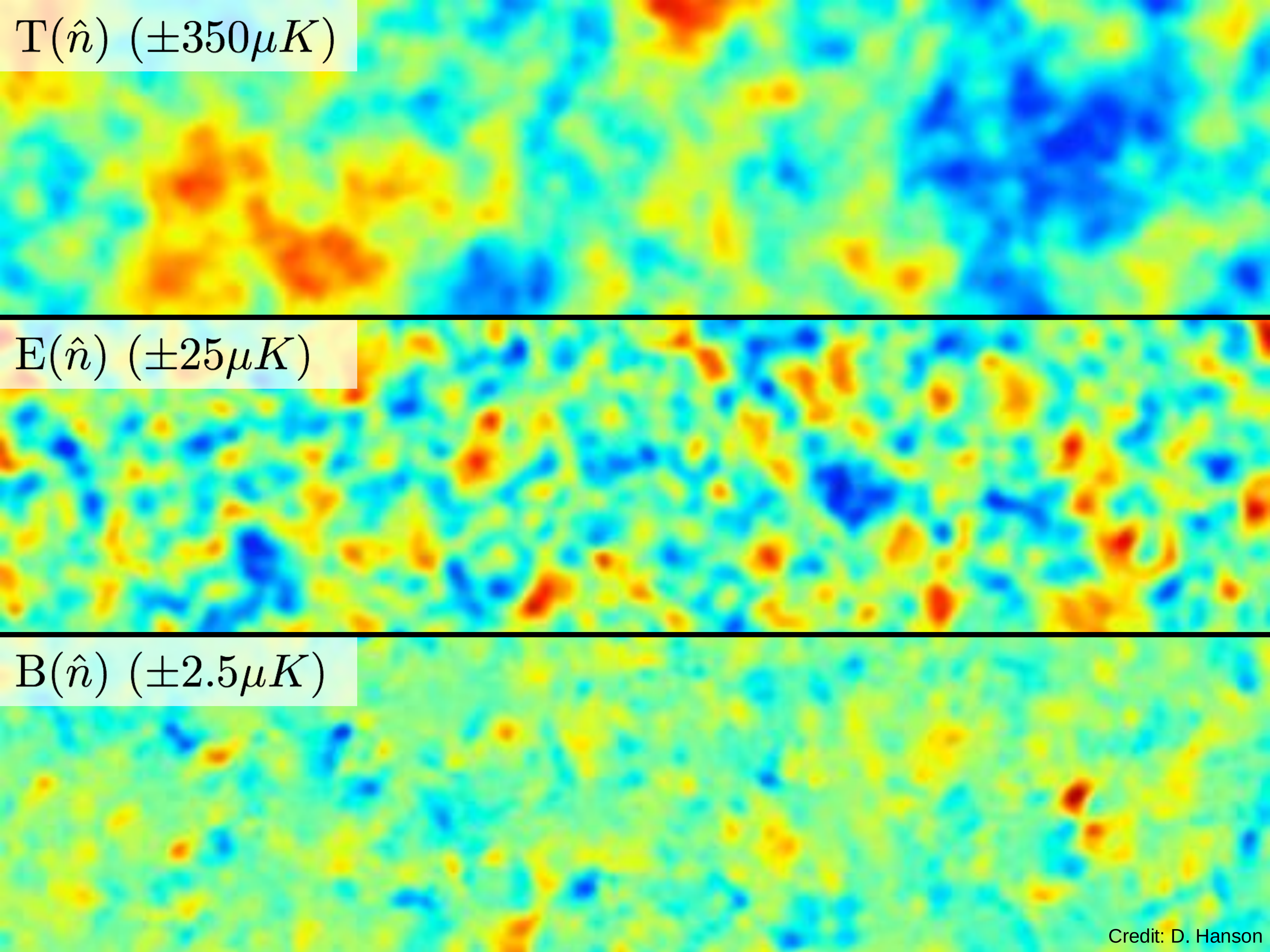
Deflections $O(10^{-3})$, but coherent on degree scales

Probes matter distribution at roughly $0.5 < z < 6$ depending on l

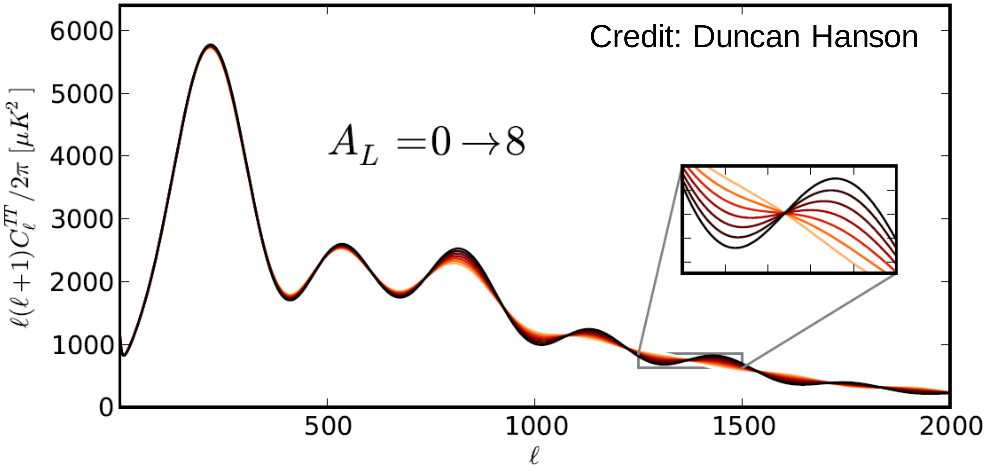
Non-linear structure growth effects not a major headache



Credit: D. Hanson

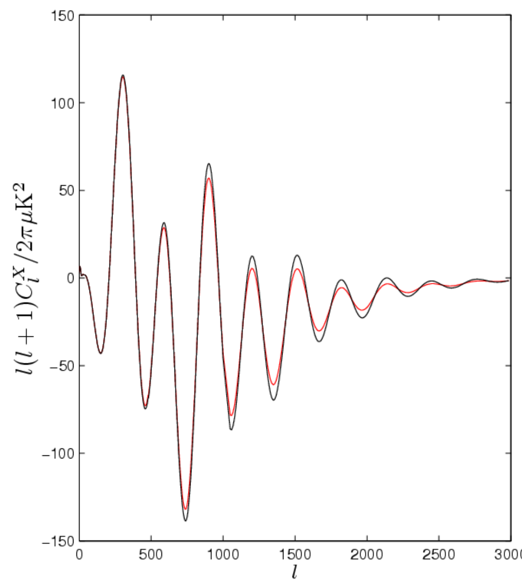

$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Credit: D. Hanson

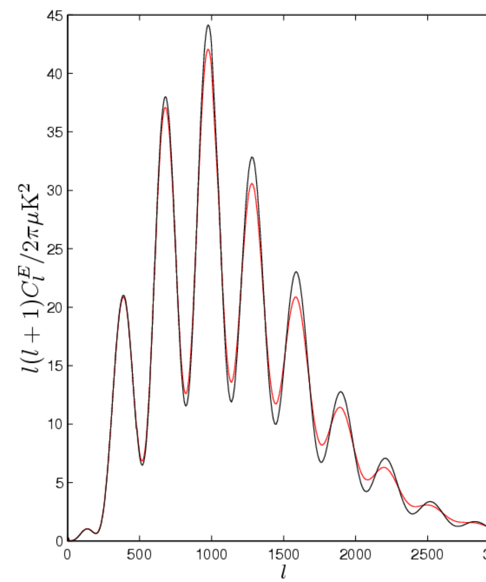
Averaged over the sky, lensing smooths out the power spectrum



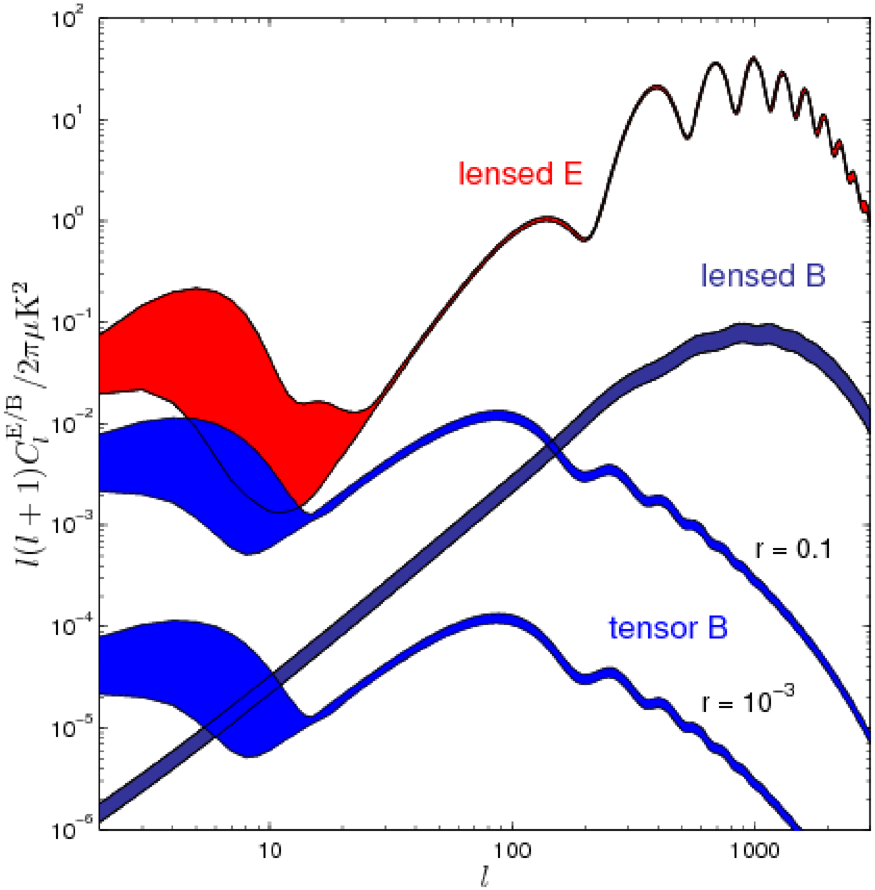
TT

TE and EE





Lensing B-mode

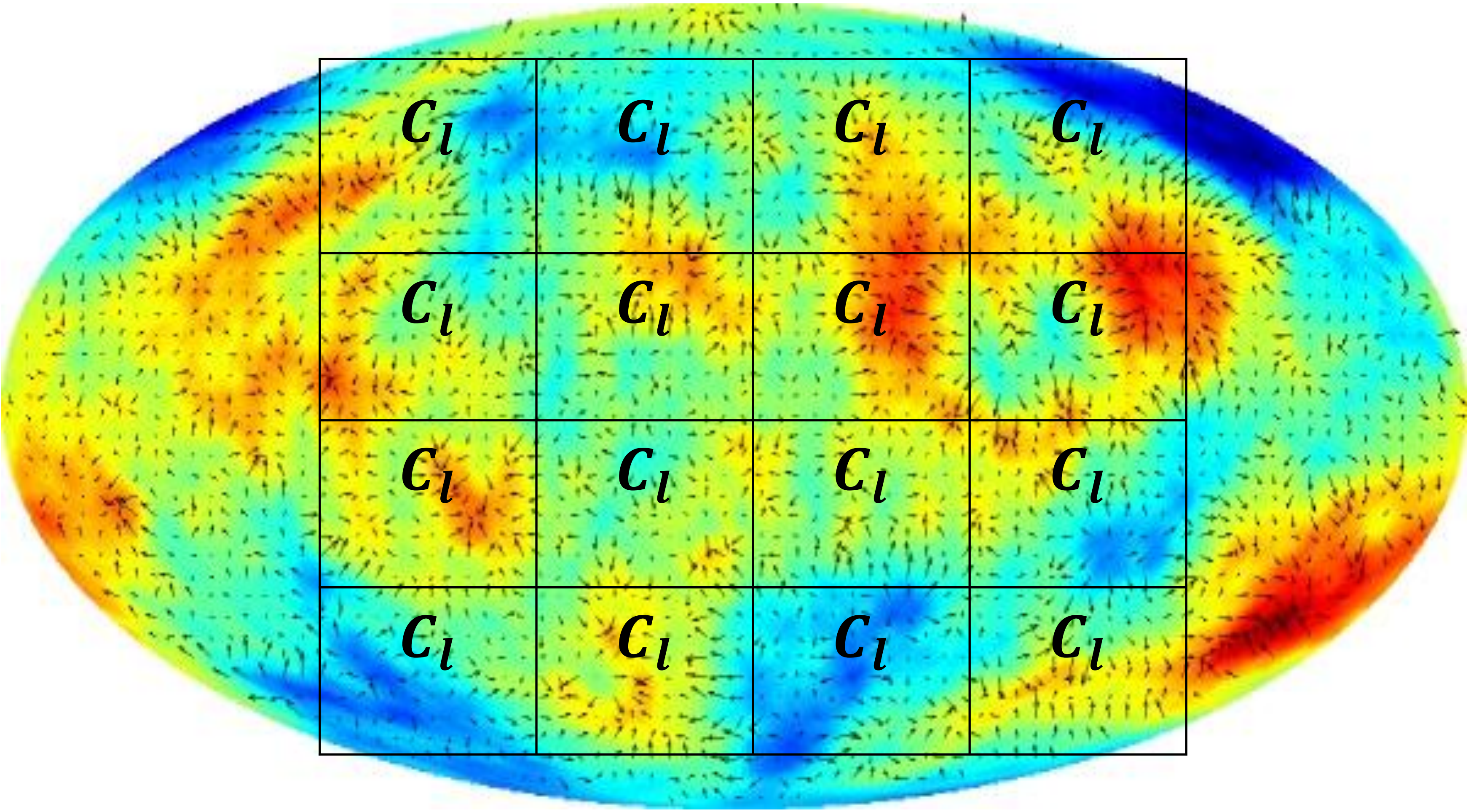


$$\tilde{C}_l^B \sim \int \frac{d^2\mathbf{l}'}{(2\pi)^2} l'^4 C_{l'}^{\psi} C_{l'}^E \sin^2 2(\phi_{\mathbf{l}'} - \phi_{\mathbf{l}}) = \frac{1}{4\pi}\int \frac{dl'}{l'} l'^4 C_{l'}^{\psi} l'^2 C_{l'}^E,$$

For measuring r lensing B like a white $\sim 5\,\mu K$ arcmin noise

- Model as noise (power spectrum subtraction – limited by cosmic variance)
- Subtract (map subtraction - *delensing*)

Lensing reconstruction (concept)



Measure spatial variations in magnification and shear

Use assumed unlensed spectrum, and unlensed statistical isotropy

Lensing Reconstruction Estimators

Quadratic estimators

Measure off-diagonal covariance induced by lensing

$$\hat{\psi}(\mathbf{L}) \equiv N(\mathbf{L}) \int \frac{\mathrm{d}^2\mathbf{l}}{2\pi} \tilde{\Theta}(\mathbf{l}) \tilde{\Theta}^*(\mathbf{l}-\mathbf{L}) g(\mathbf{l}, \mathbf{L}),$$

(Hu & Okamoto, etc.)

- Fast to implement
- Very nearly optimal for current and S2/S3 observations

Maximum likelihood

For fixed lenses, sky is Gaussian but anisotropic. Maximize likelihood:

$$-\mathscr{L}(\hat{\Theta}|\alpha) = \frac{1}{2}\hat{\Theta}^T \left(\hat{C}^{\hat{\Theta}\hat{\Theta}}\right)^{-1} \hat{\Theta} + \frac{1}{2}\ln\det(\hat{C}^{\hat{\Theta}\hat{\Theta}}),$$

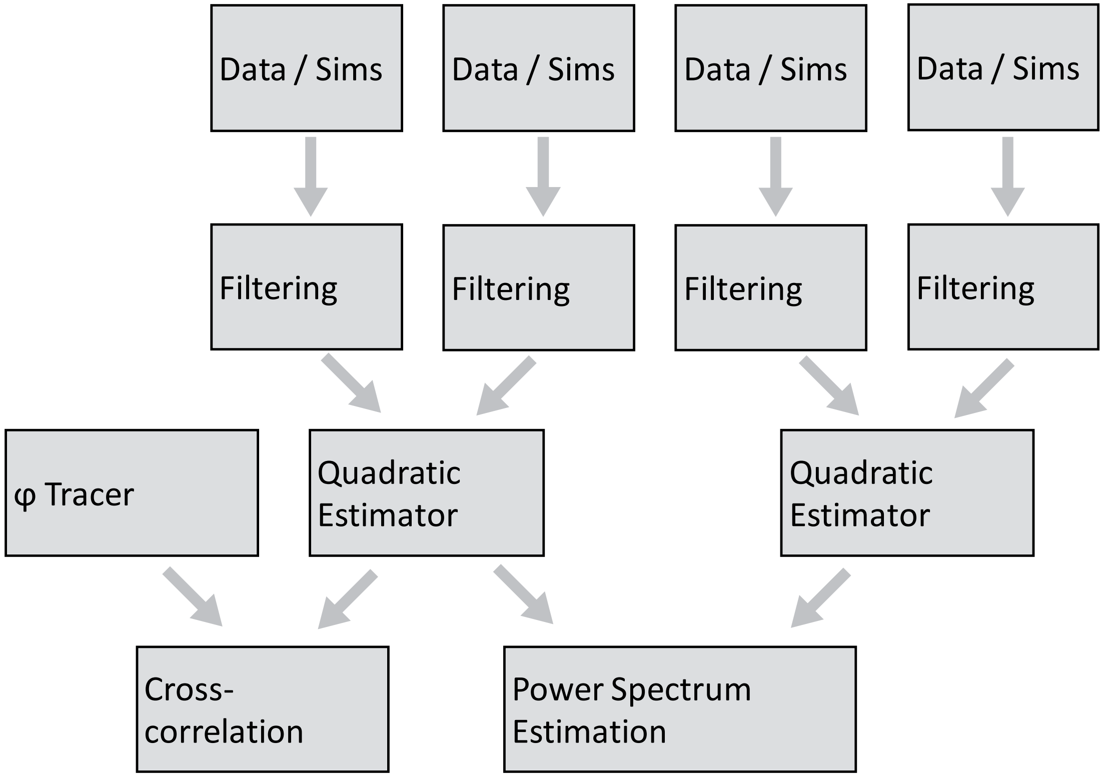
- More expensive, but tractable iteratively (Hirata & Seljak 03, Carron & Lewis 17)
- Better reconstruction at S4 noise levels

Quadratic Estimator Pipeline

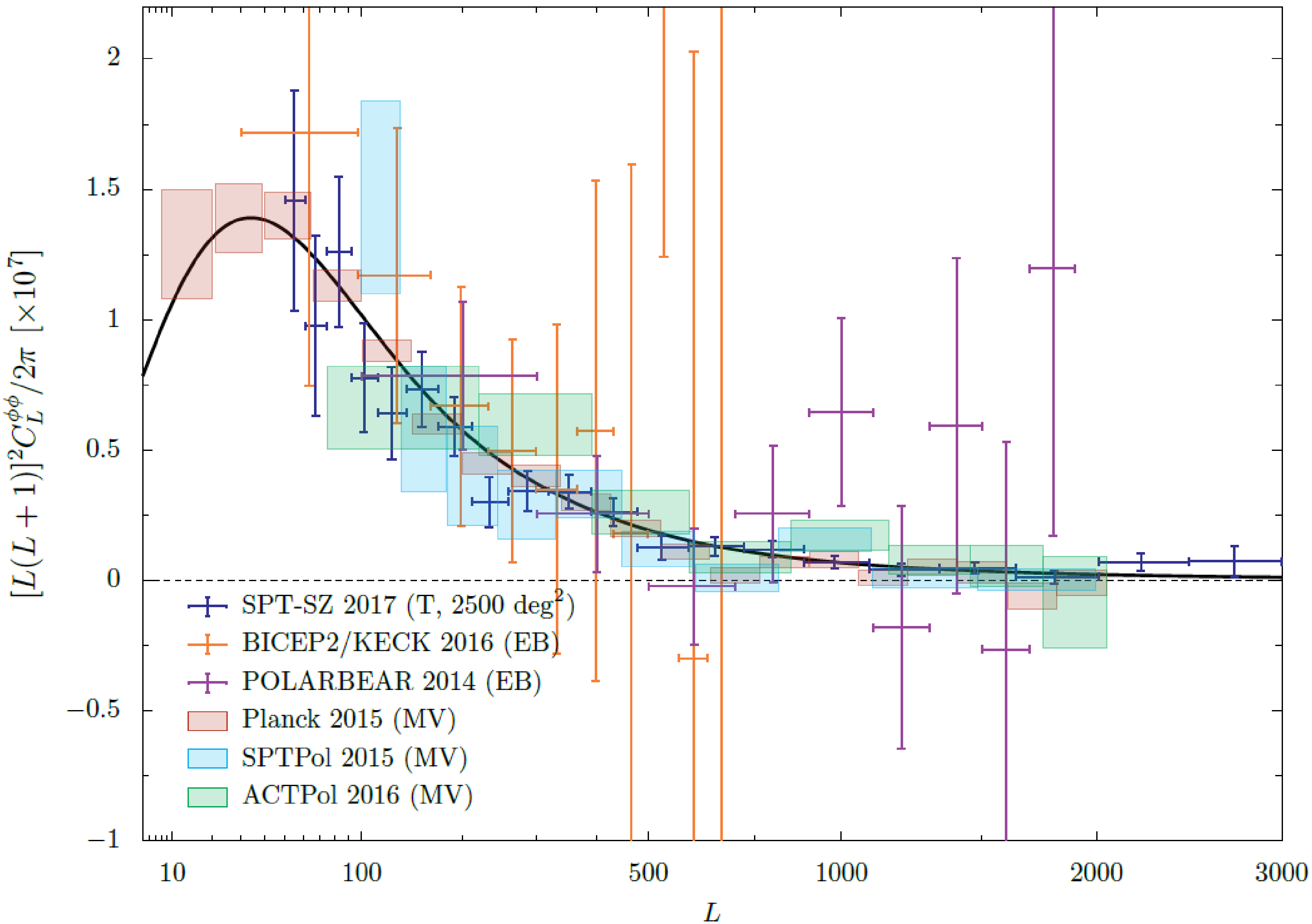
→ process input maps

→ estimate lensing potential from anisotropic 2-point

→ estimate lensing power spectrum.



Current lensing reconstruction power spectra

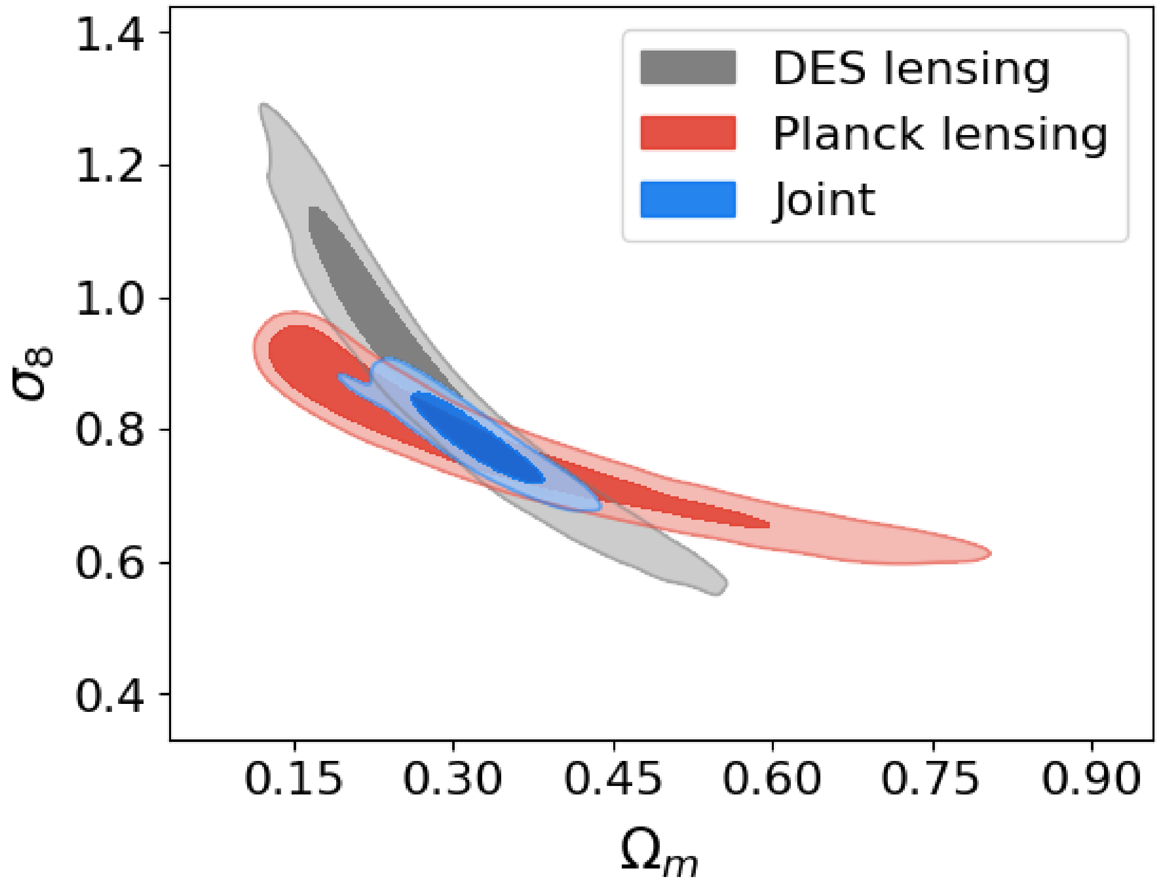


Challinor et al. arXiv:1707.02259

CMB lensing currently competitive with galaxy lensing

Probes higher redshift ⇒ constrains $\Omega_m \sigma_8^{0.25}$ vs. galaxy $\Omega_m \sigma_8^{0.5}$

DES 1YR +Planck lensing only LCDM forecast



DES 1Yr has 10 nuisance parameters, conservative cuts: limited by modelling not statistics
CMB lensing currently limited by low S/N (and only one source redshift plane)

CMB lensing to calibrate shear for galaxy lensing

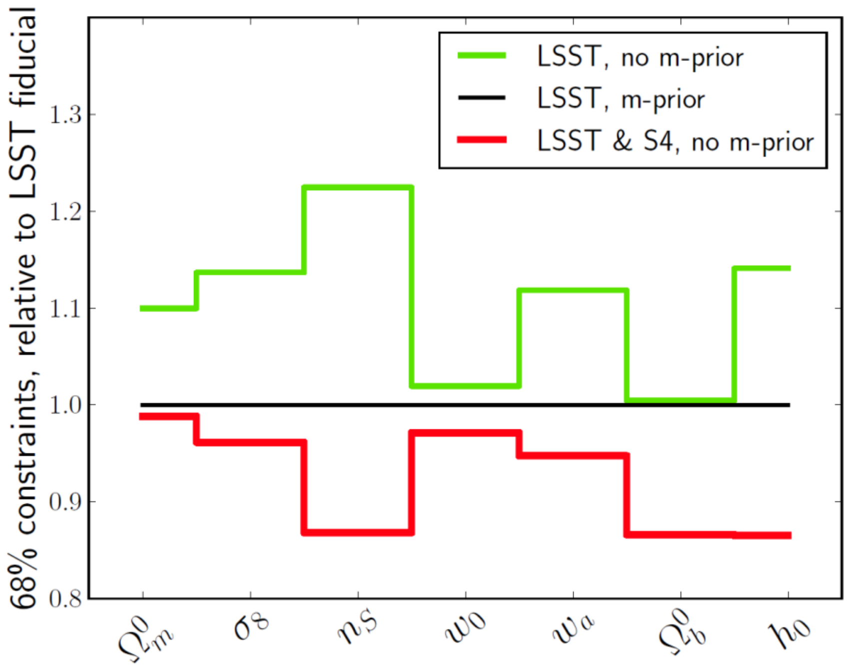
Galaxy lensing surveys measure (roughly) galaxy ellipticity e_g.
Hard to relate directly to lensing shear $\gamma_{\rm lens}$.

$$e_{\rm g} \sim (1+m)\gamma_{\rm lens}$$

m could mimic different dark energy models.

Cross-correlation with CMB lensing can measure m

e.g. S4 to calibrate LSST



Valuable for EUCLID, WFIRST, LSST, etc.
- more robust prior-independent constraints on dark energy

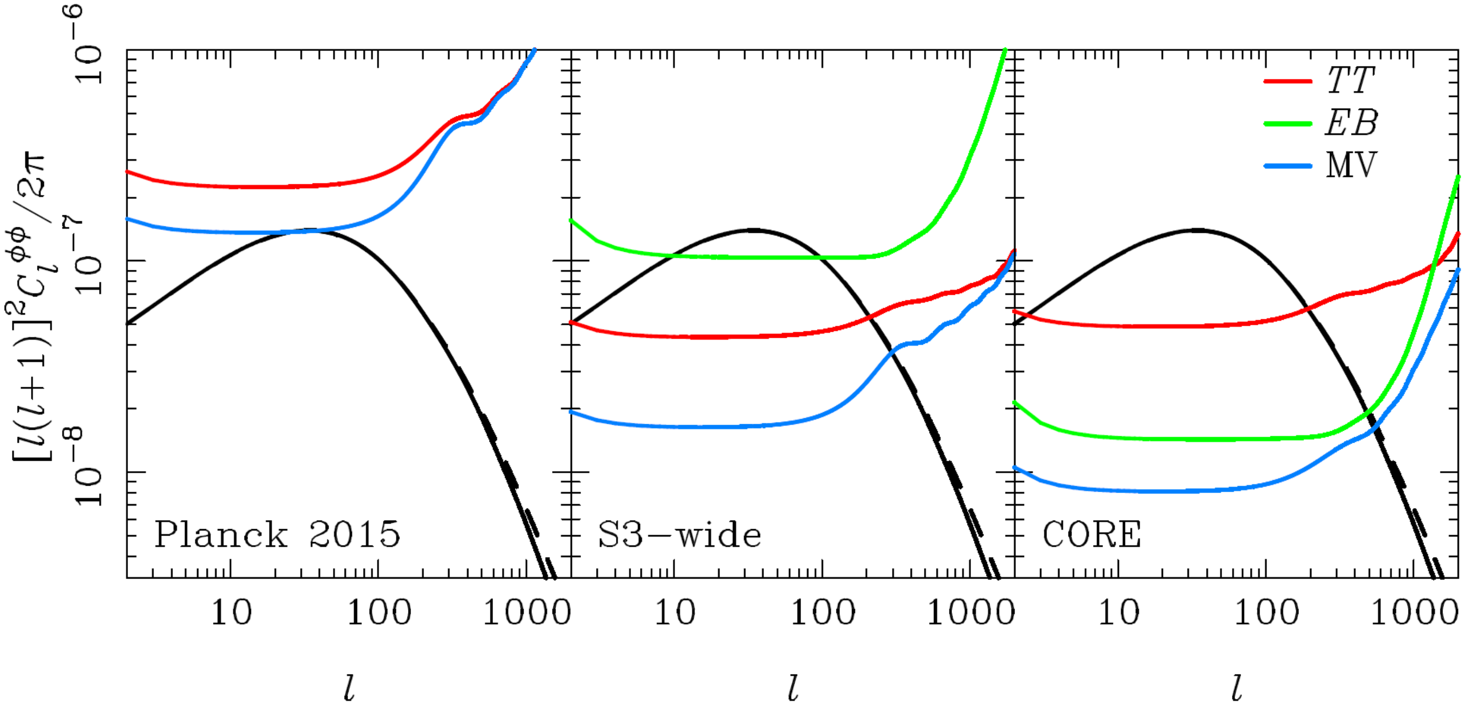
Schaan et al. arXiv: 1607.01761

Lensing reconstruction with polarization

- Expect *no* primordial small-scale B modes (r-modes only large scales $l < \sim 300$)

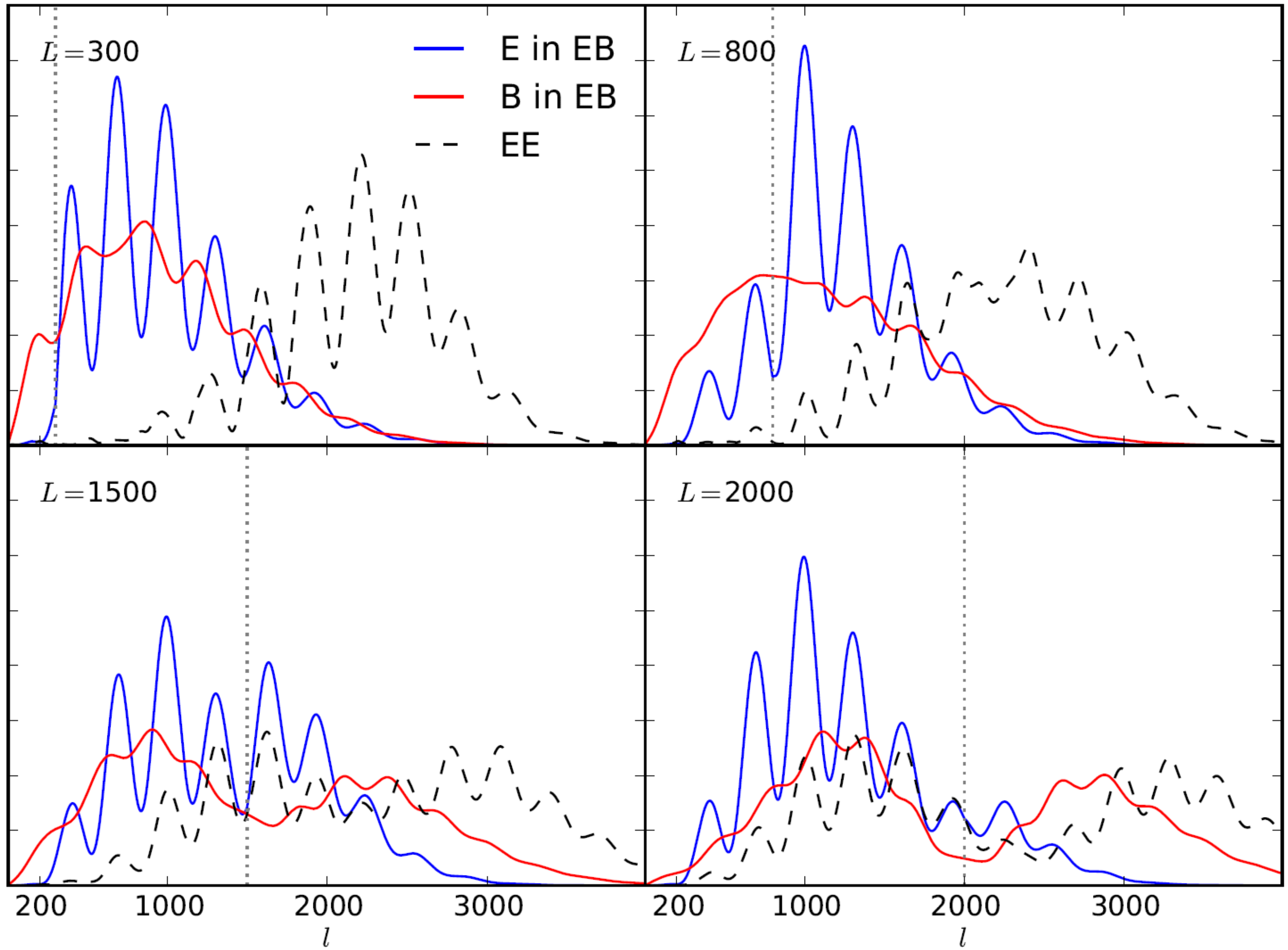
- *All* small-scale B-mode signal is lensing: *no* cosmic variance confusion with primordial signal as for E and T

- Polarization data does *much* better than temperature if sufficiently good S/N (mainly EB estimator).



Challinor et al. arXiv:1707.02259

Lensing reconstruction at L typically needs E,B at $\ell \gg L$. **Need small scales.**



(4 μK arcmin noise, 1.4 arcmin beam)

Pearson, Sherwin, Lewis arXiv: 1403.3911

Neutrino mass from high S/N lensing reconstruction

see Erminia's talk

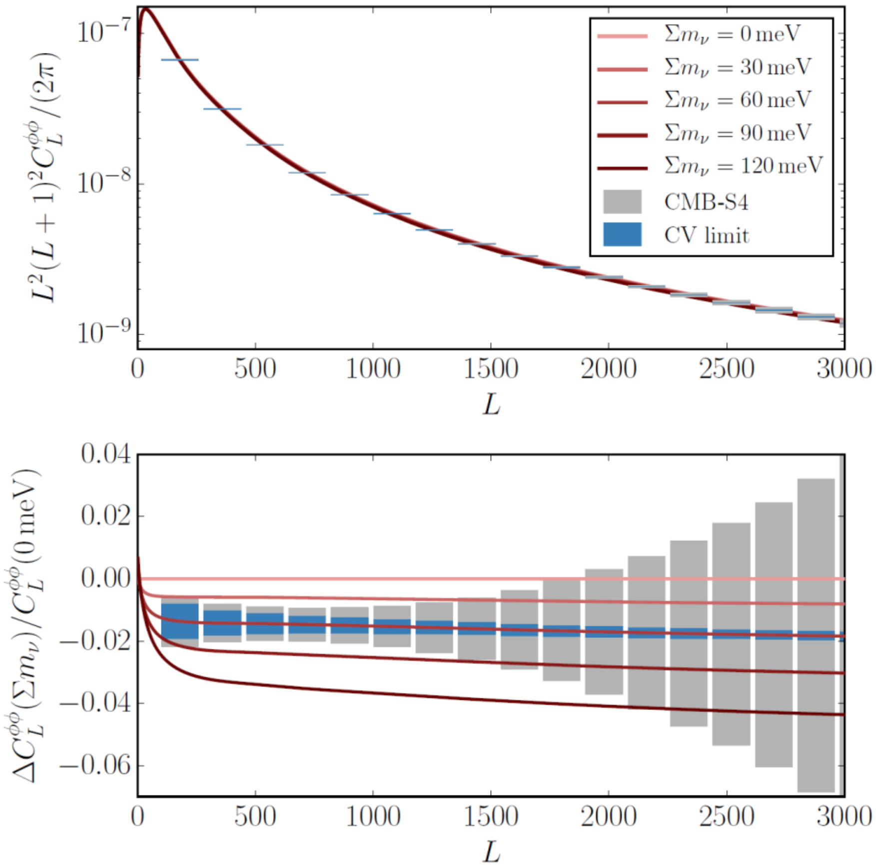


Figure 49. *Constraining neutrino mass with CMB-S4. Top: lensing power spectra for multiple neutrino masses (curves) together with forecasted errors for S4. Bottom: residual from curve at zero neutrino mass. Error boxes are shown centered at the minimal value of 60 meV. S4 will be targeted to resolve differences in neutrino mass of 20 meV.*

S4 Science Book

Delensing

$$X^{\rm len}(\boldsymbol{n}) = X^{\rm unl}(\boldsymbol{n} + \boldsymbol{\alpha}(\boldsymbol{n}))$$

Current (Planck) delensing efficiencies

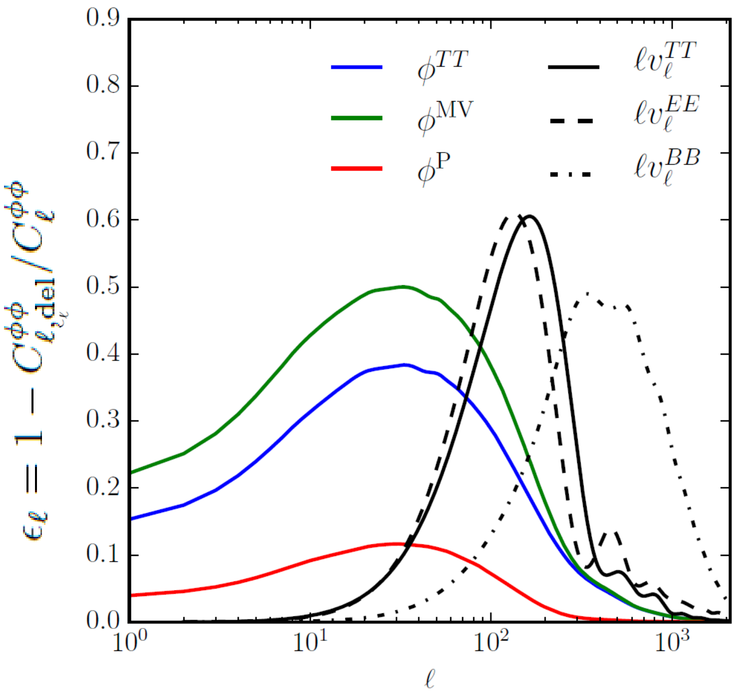
Measure ψ (hence $\alpha = \nabla\psi$)

Re-map back lensed fields
or subtract perturbative lensing signal

To measure ψ:

1. Use external tracer of matter, e.g. CIB.
   (Sherwin et al 2015, Larsen et al. 2016)

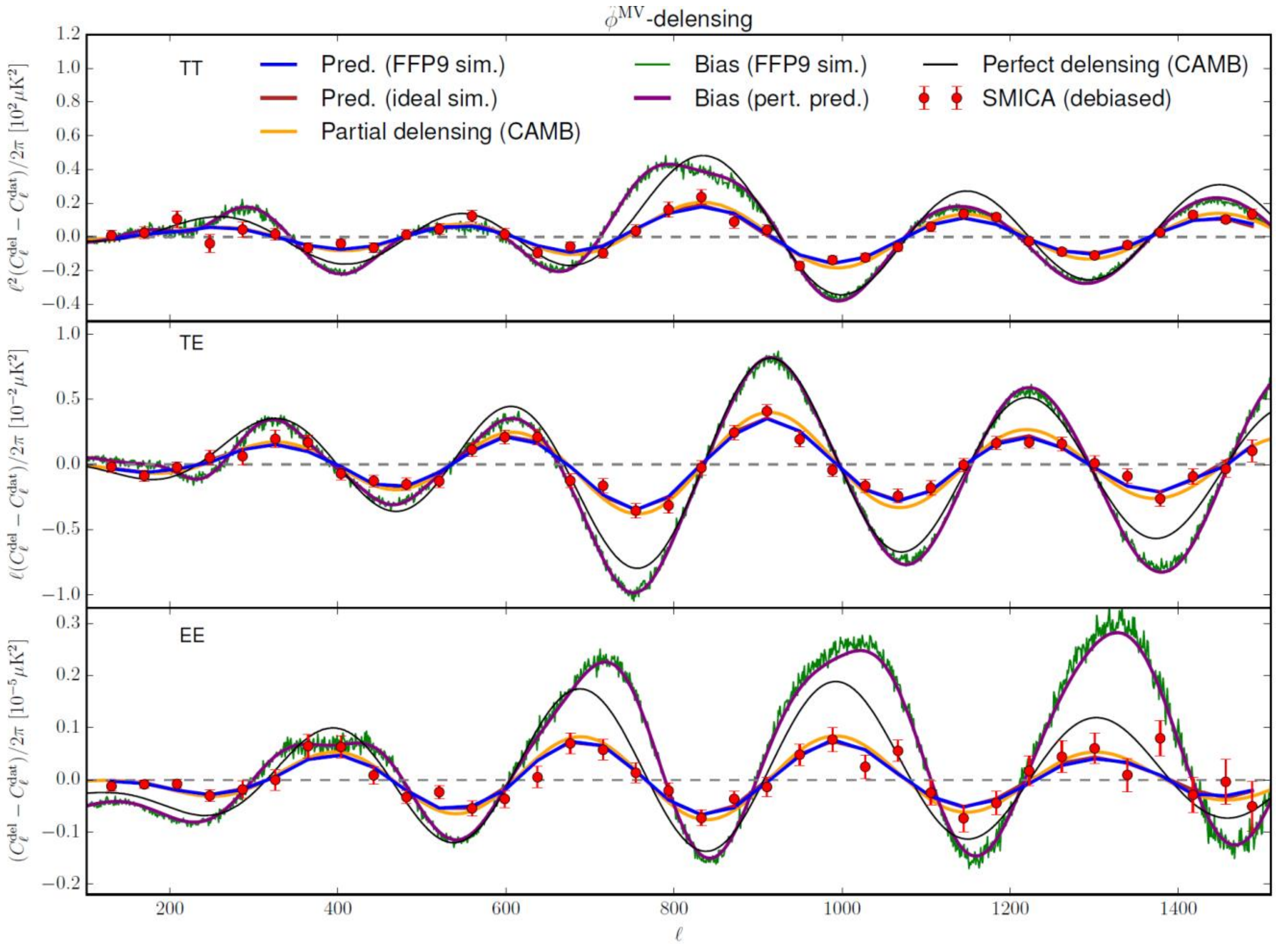
2. Use internal lensing reconstruction



Carron, Lewis, Challinor arXiv:1701.01712

Planck internal delensing of TT, TE, EE

Carron, Lewis, Challinor arXiv:1701.01712

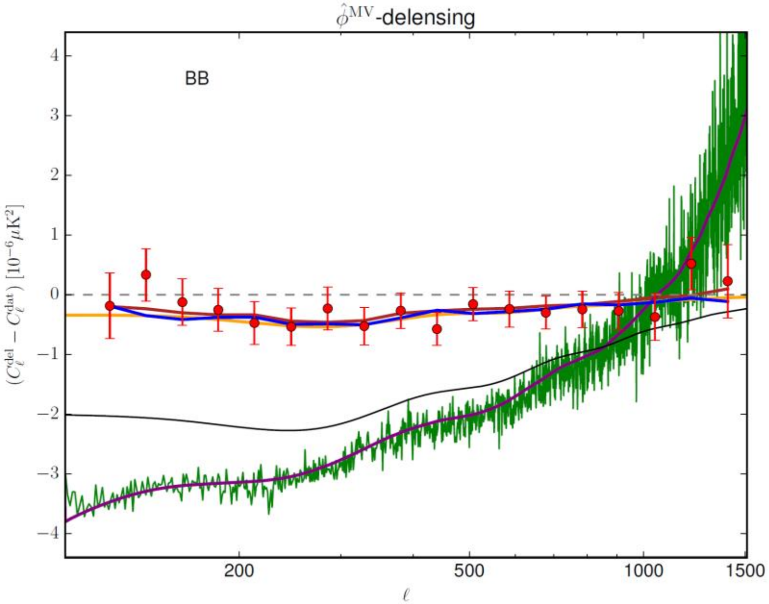


$\sim 25\sigma$ detection of TT delensing, 20σ of polarization delensing; consistent with expectations

(S4 EE/TE delensing could sharpen peaks and decrease errors by up to ~ 20%, arXiv: **1609.08143)**

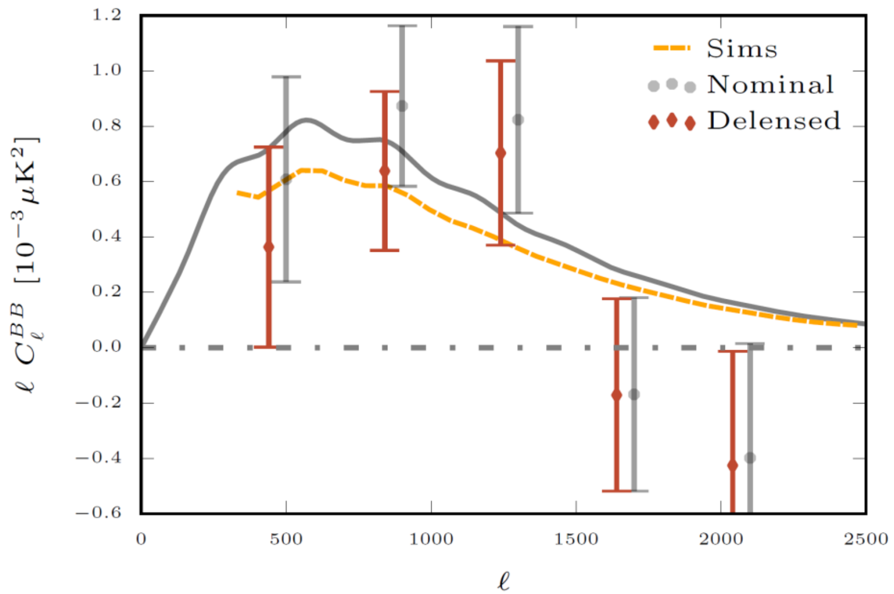
Current status of B-Mode Delensing

Planck internal
First detection of delensing of B-mode polarization at 4.5 σ



Carron, Lewis, Challinor arXiv:1701.01712

SPTpol and Herschel
28% delensing detected at 6.9σ

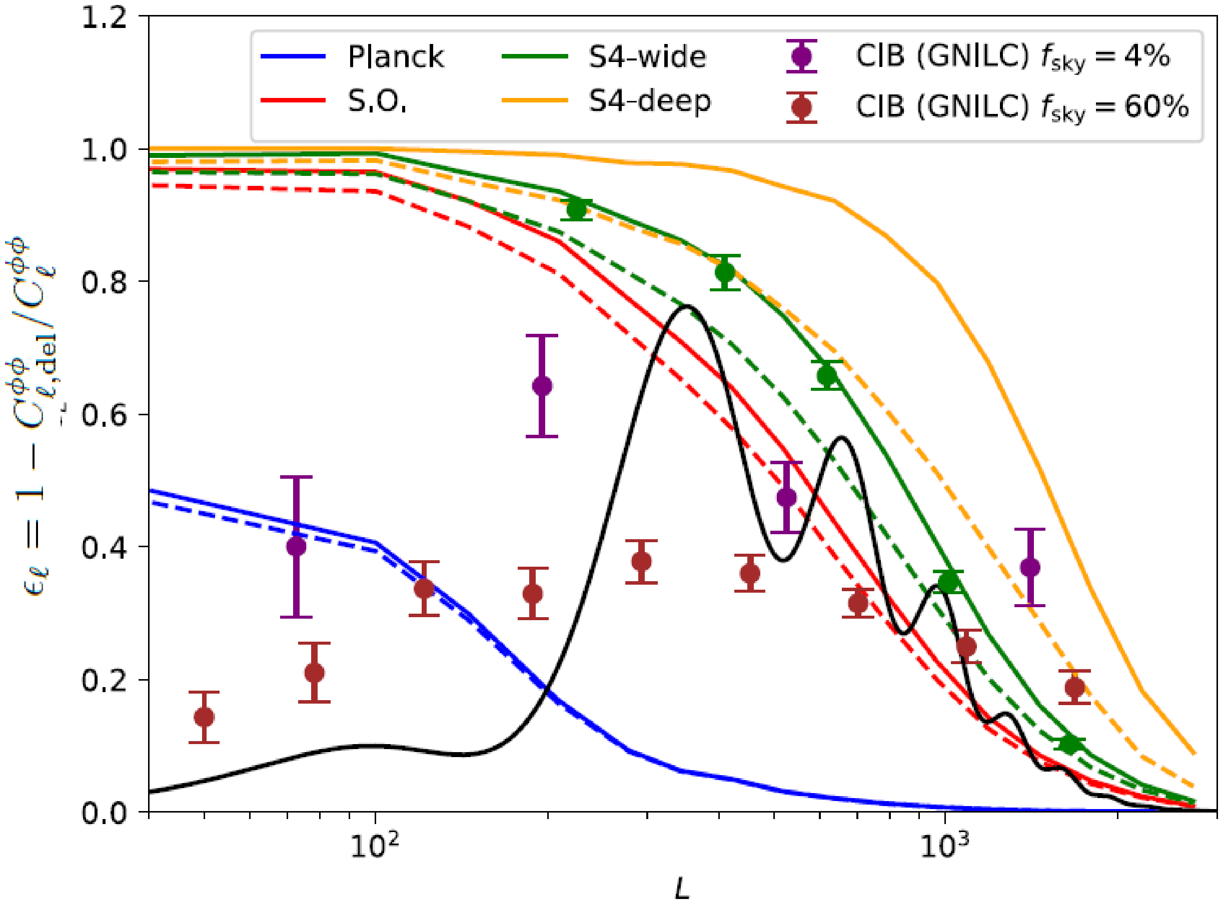


Manzotti et al. arXiv:1701.04396

(*Proof of principle only*: noise high, so does not yet help at all with tensor r constraint)

Future lensing reconstruction efficiency

quadratic estimator (dashed)
Iterative estimator (solid)
CIB not competitive for S4, though may help (reddish points)



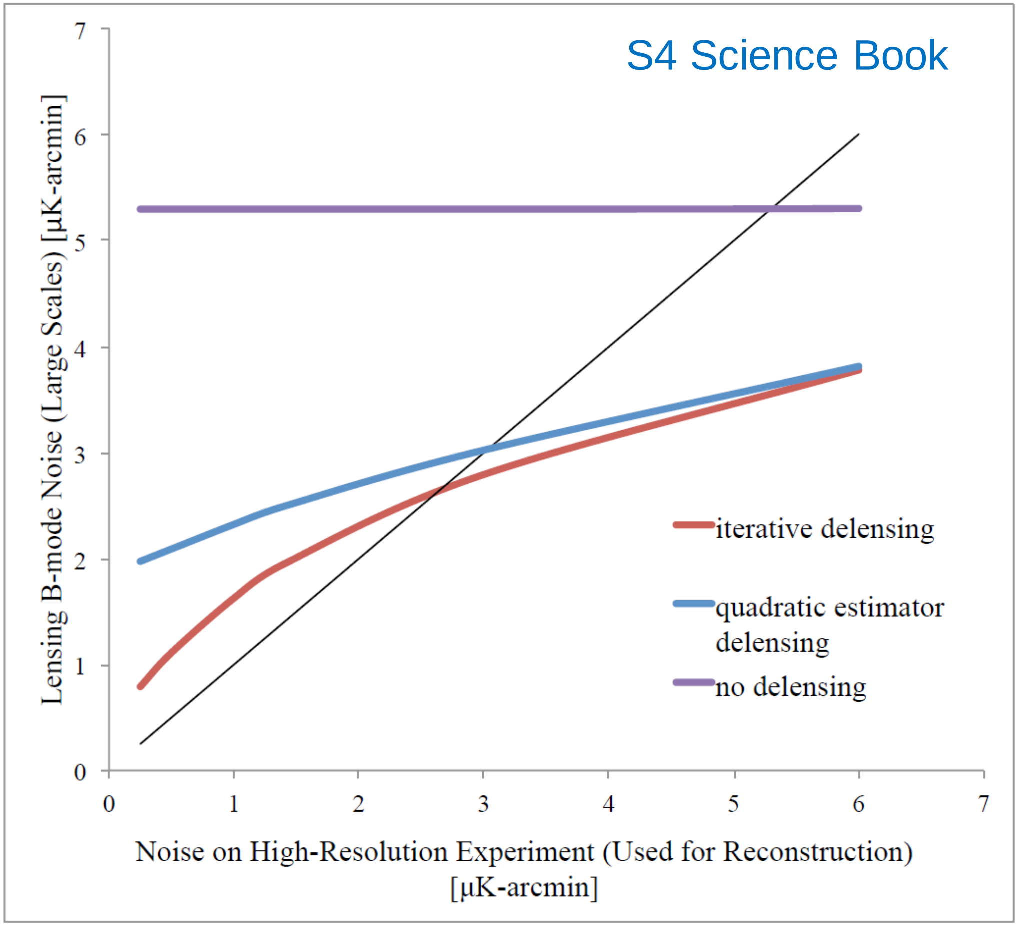
LensIt: Iterative reconstruction code for realistic data
https://github.com/carronj/LensIt (Julien Carron)

Carron & Lewis, 1704.08230

(see also Millea et al. arXiv: 1708.06753 for joint reconstruction)

Without delensing, r limited by lensing not instrumental noise smaller than $\sim 5\ \mu K$ arcmin

Future high-resolution data could remove most of large-scale B-mode “noise” on r



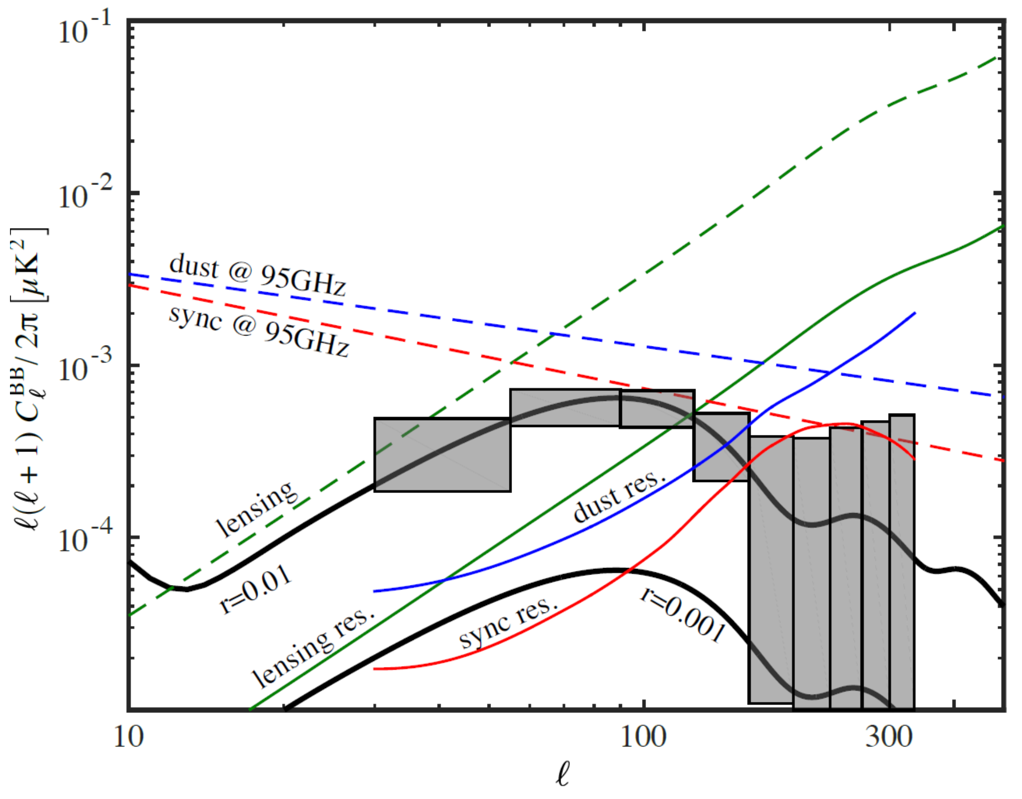
Limits on delensing

Optimal internal reconstruction in principle only limited by noise down to $r \sim 10^{-4} - 10^{-6}$

But: residual foregrounds in B may limit nearer $r \sim 10^{-3}$ - see Josquin Errard talk

Lensing B still important source of noise for $r \sim 10^{-3}$: delensing still required

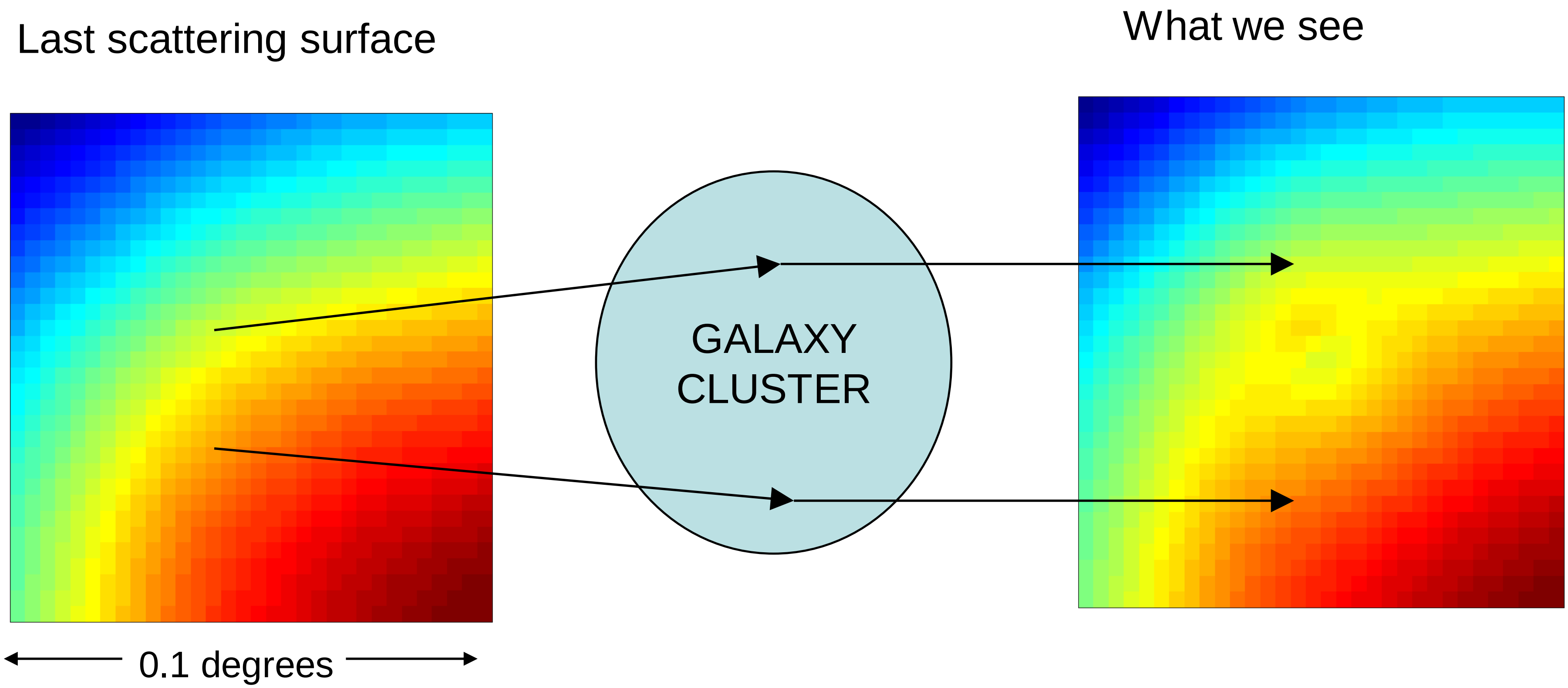
e.g. S4 Science Book



Cluster CMB lensing

e.g. for mass calibration of high-z clusters

CMB very smooth on small scales: approximately a gradient



Need sensitive ~ arcminute resolution observations e.g. high-sensitivity, high-resolution CMB can calibrate mass of 1000 stacked clusters to a few percent

S4 Science Book

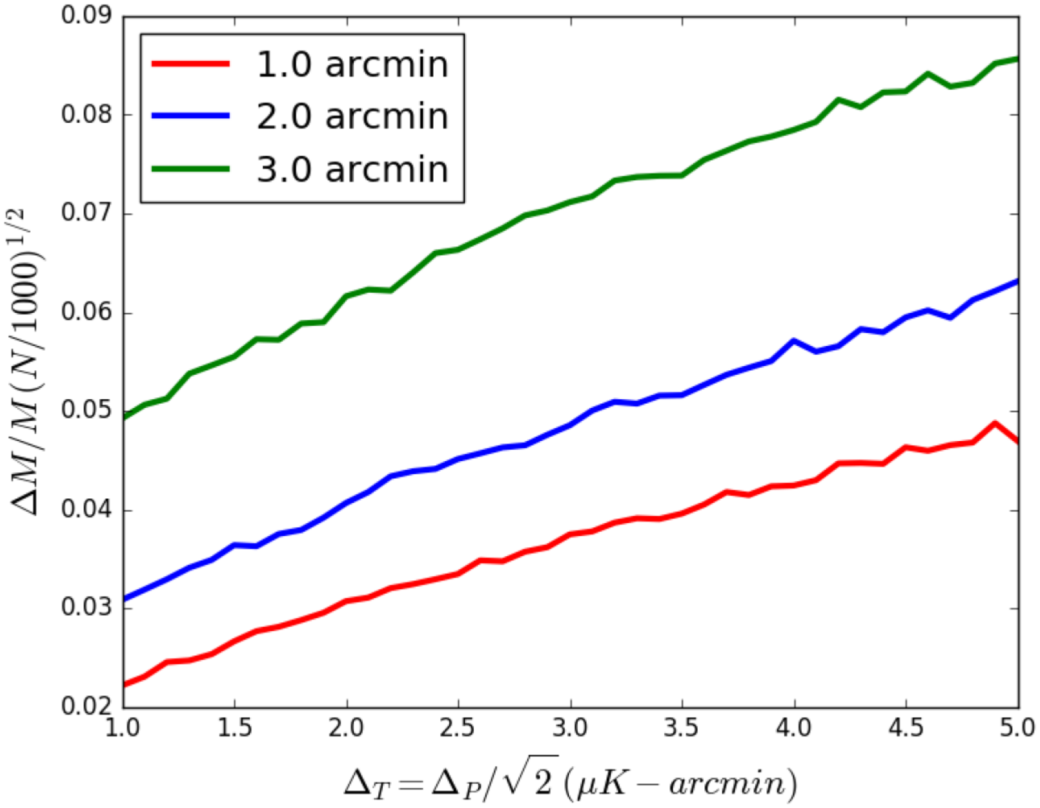


Figure 53. *Mass uncertainty from CMB halo lensing measurements stacking 10^3 halos of mass $M_{180\rho_{m0}} \approx 5 \times 10^{14} M_\odot$, as a function of instrumental noise and varying instrumental resolution.*

CMB lensing summary

- Lensing reconstruction probes mass in the universe at 0.5 <~ z <~ 7.

- Well reconstructed using small-scale CMB polarization

  needs high resolution even to reconstruct large-scale lensing modes

- C_l^{ψ}: integrated probe of total matter fluctuation and geometry

  measure absolute neutrino mass scale

- Cross-correlation can calibrate galaxy shear and cluster masses.

  synergy with galaxy lensing from EUCLID, LSST, etc. for constraining dark energy

- Generates large-scale B modes with white spectrum ($5\ \mu K$ arcmin lensing 'noise')

  major source of 'noise' for primordial gravitational waves if $r < 10^{-2}$

- Delensing required to measure $r \ll 10^{-2}$ optimally

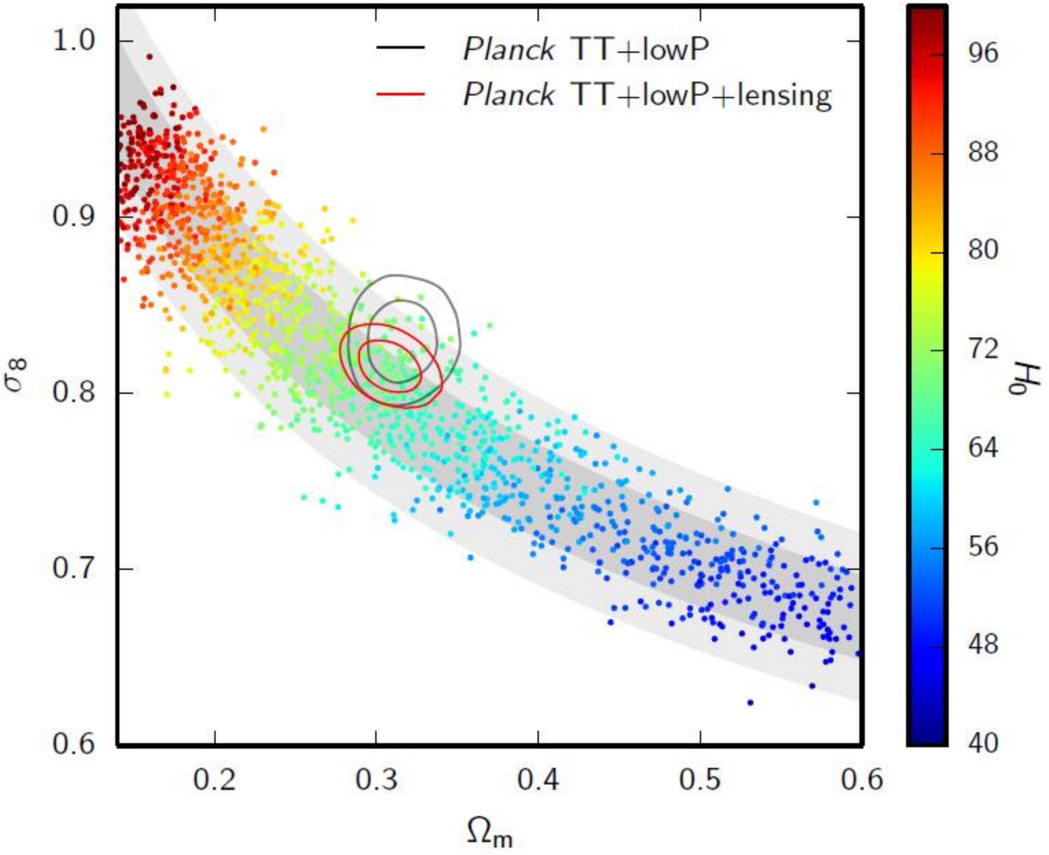
  - CIB currently competitive, but internal reconstruction required for optimal S4
  - use small-scale E and B to reconstruct ψ
  - use ψ and E to de-lens large-scale B: extract gravity wave signal
  - needs high sensitivity and resolution (few arcminutes)
  - Ultimate r limit probably determined by large-scale foregrounds not by limitations of delensing

- Delensing detected as proof of principle (TT,TE, EE and BB)

Cosmological parameters in LCDM

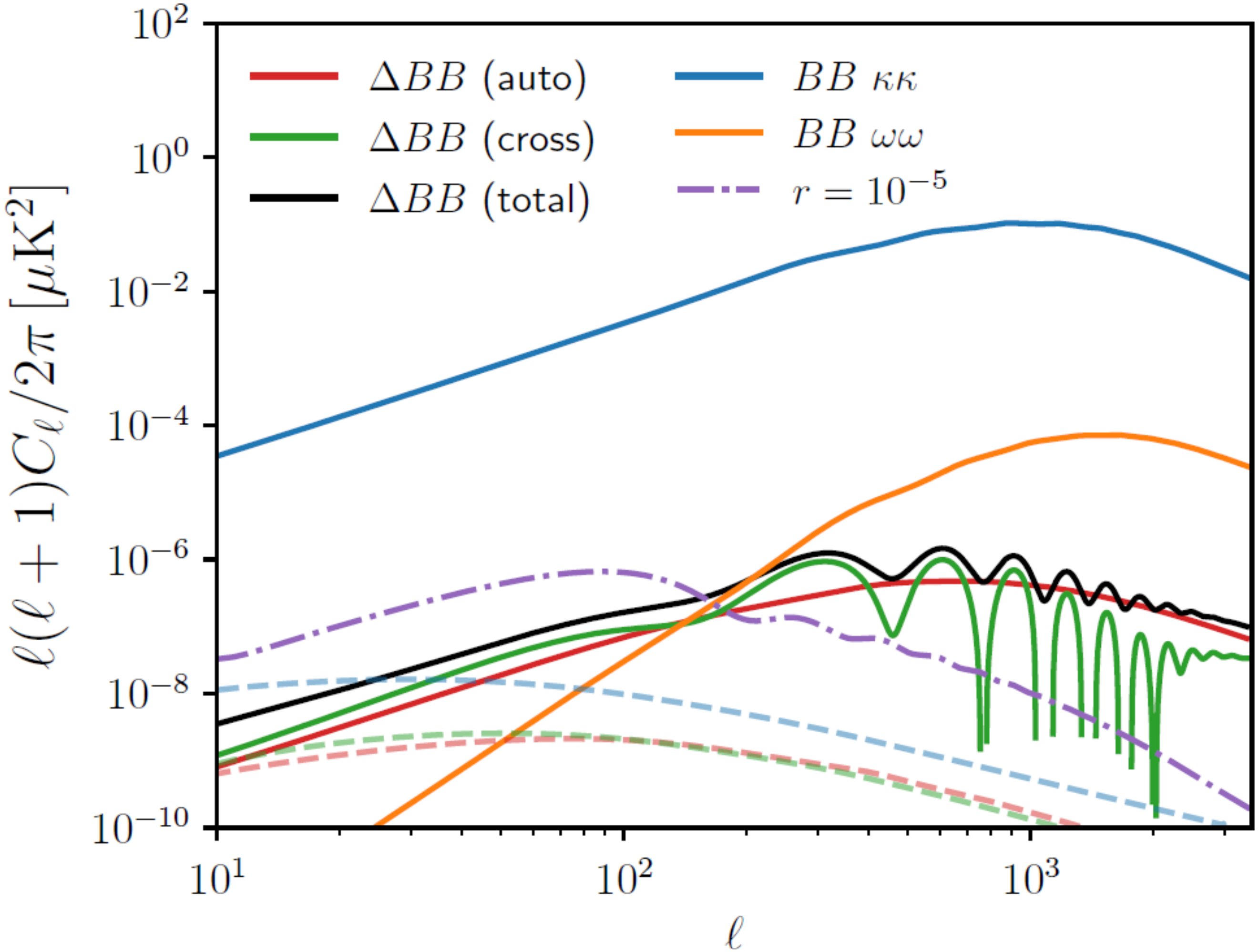
Measures late-time fluctuation amplitude independently of τ

Planck 2015 CMB Lensing



Future: measure neutrino mass in combination with CMB/BAO

Total emission+time delay effect dominates on large scales



Lewis, Hall, Challinor arXiv:1706.02673