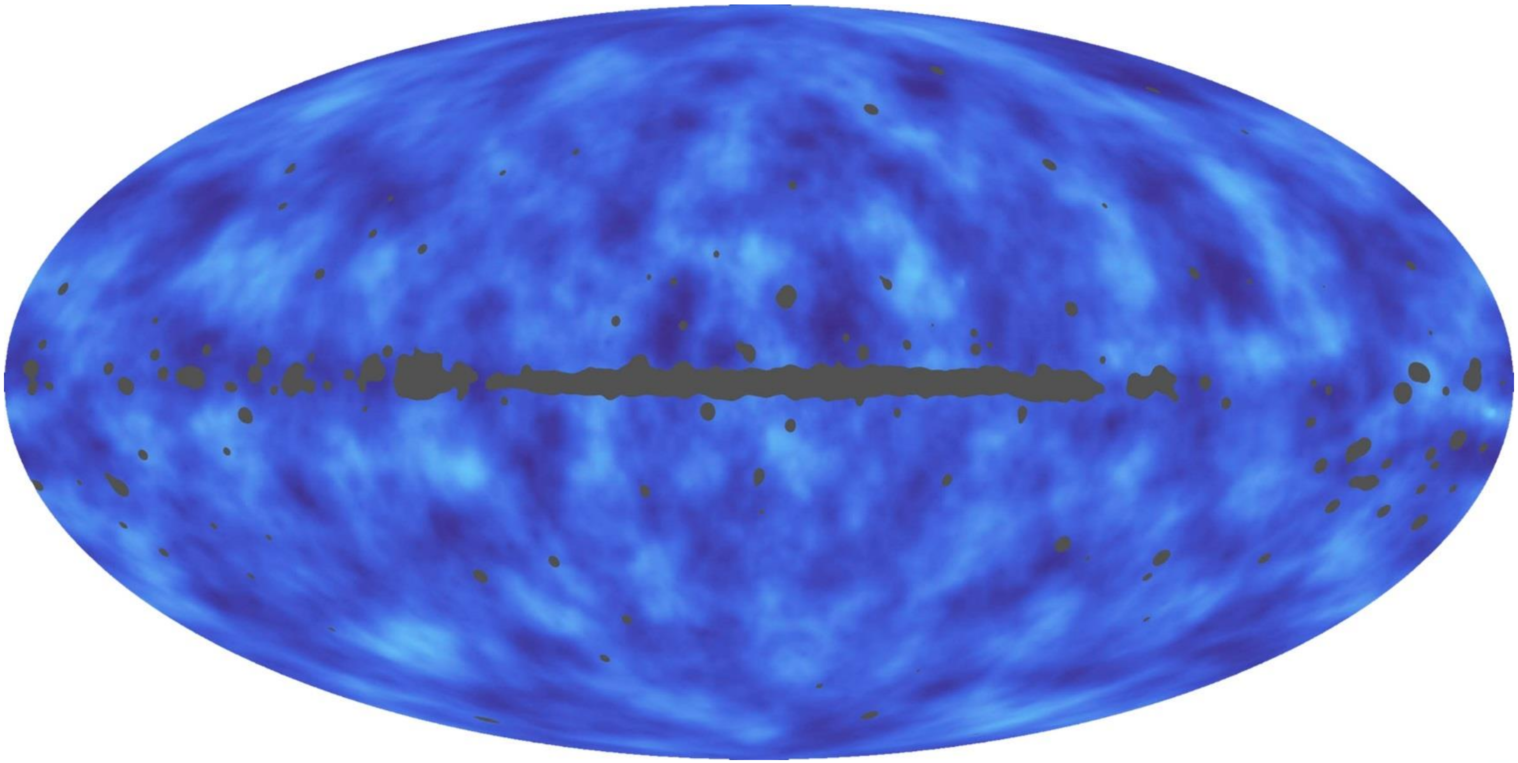
Delensing in practice and in principle

Antony Lewis

work with the Julien Carron, Anthony Challinor and Alex Hall



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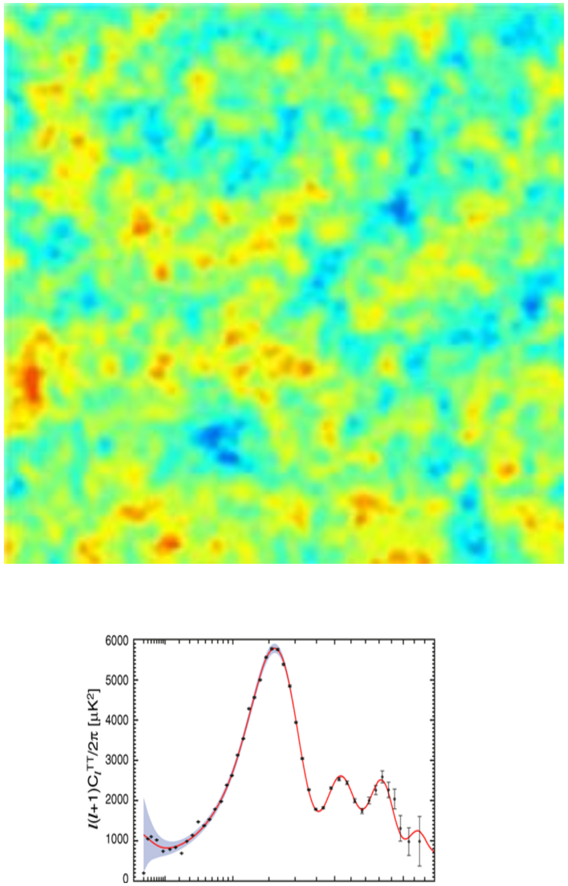
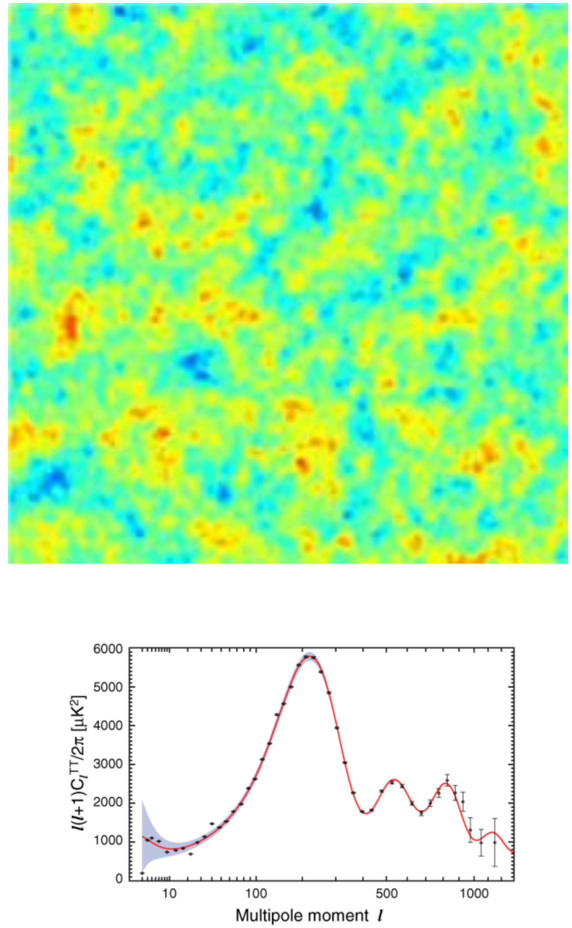
Local effect of lensing on the power spectrum

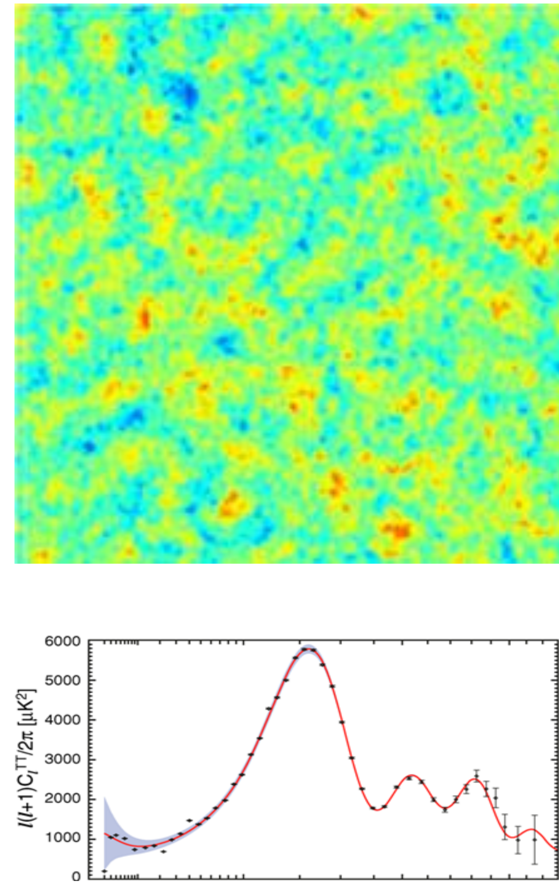
Magnified



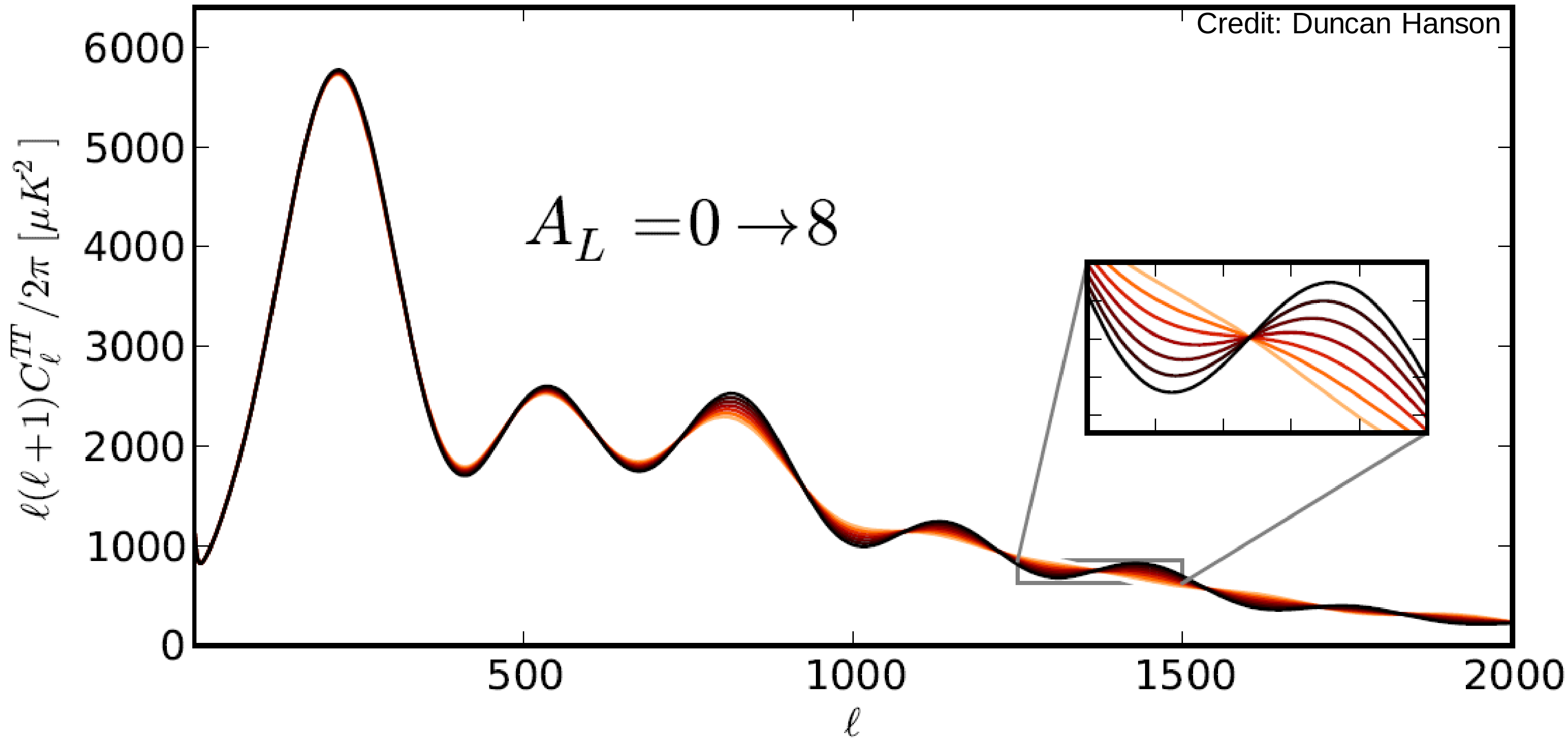
Unlensed



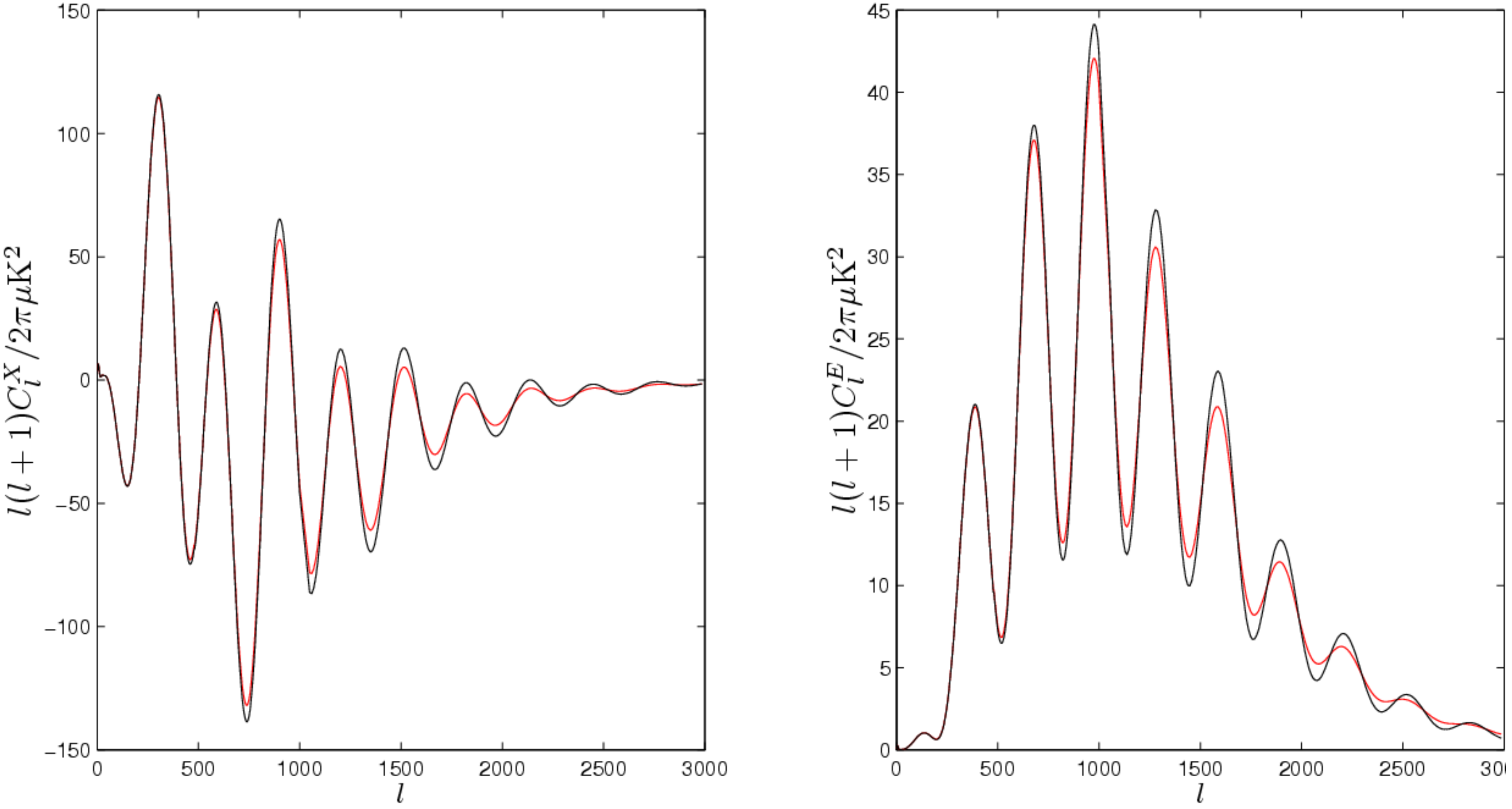
Demagnified



Averaged over the sky, lensing smooths out the power spectrum



Effect on TE and EE polarization spectra



Delensing

$$X^{\rm len}(\boldsymbol{n}) = X^{\rm unl}(\boldsymbol{n}+\boldsymbol{\alpha}(\boldsymbol{n}))$$ find β such that $$X^{\rm unl}(\boldsymbol{n}) = X^{\rm len}(\boldsymbol{n}+\boldsymbol{\beta}(\boldsymbol{n}))$$

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

2. Use the Planck 2015 lensing reconstruction

a. Use best-estimate lensing field

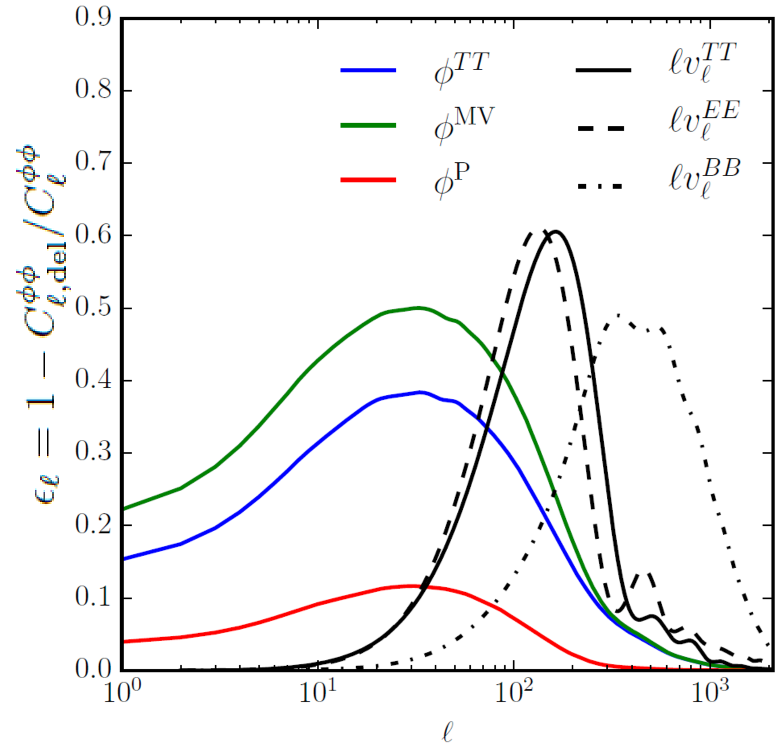
$$\hat\phi_{\mathcal{W},\ell m} = \mathcal{W}_\ell\, \hat\phi_{\ell m} \qquad \mathcal{W}_\ell = \frac{C_\ell^{\rm fid,\phi\phi}}{C_\ell^{\rm fid,\phi\phi} + N_{\ell,0}}$$

b. Approximate $\beta \approx -\alpha$ where $\alpha = \nabla\phi$

c. Remap points using estimated α to get delensed map

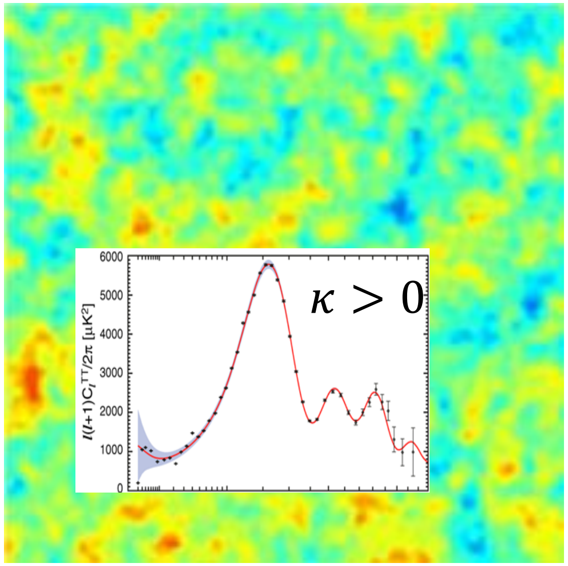
$$X^{\rm del} \equiv X^{\rm dat}(\boldsymbol{n} - \hat{\boldsymbol{\alpha}}_{\mathcal{W}}(\boldsymbol{n}))$$

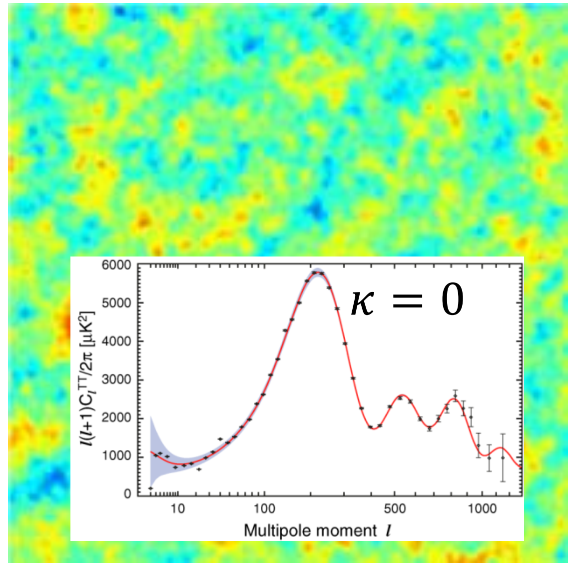
Expected Planck internal delensing efficiencies

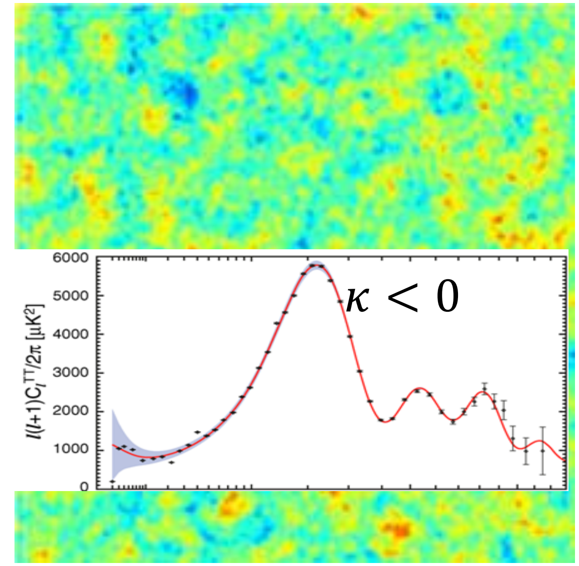


Carron, Lewis, Challinor arXiv:1701.01712

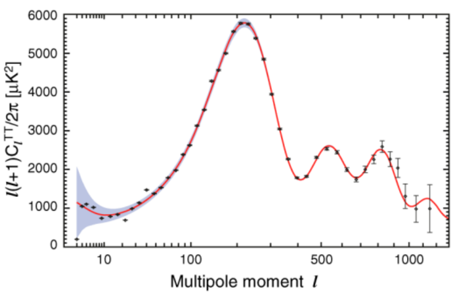
BUT: Internal delensing causes biases

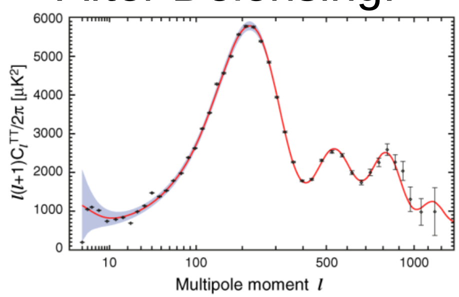


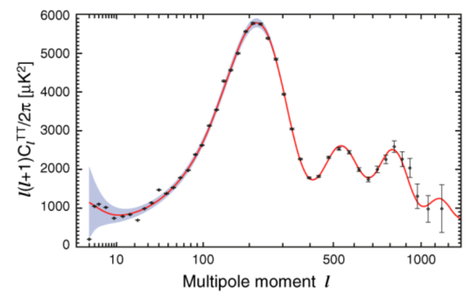




After Delensing:







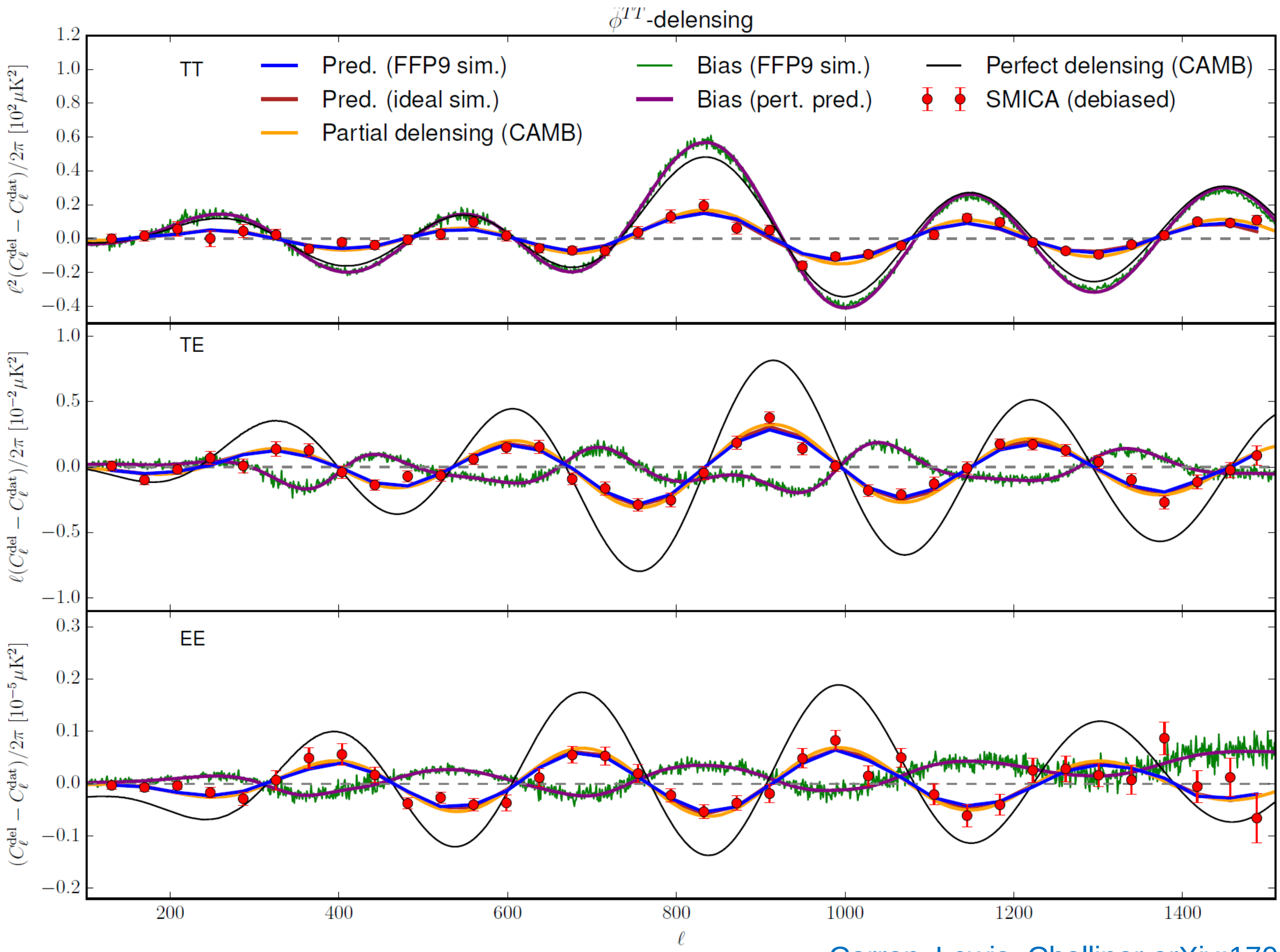
BUT: fluctuation in scale could also just be random cosmic variance

⇒ Delensing removes random fluctuations in peak location

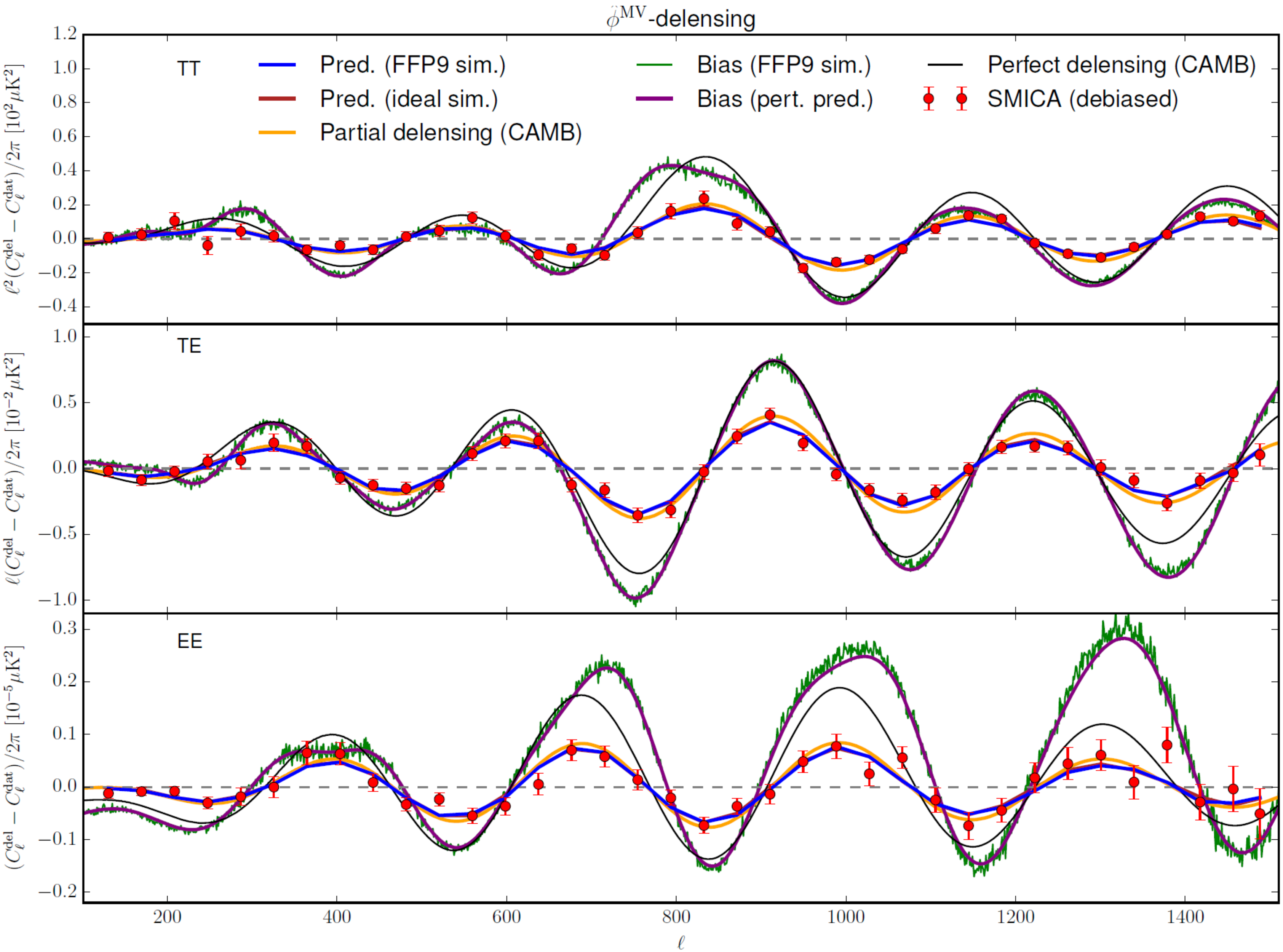
⇒ Delensing *artificially* sharpens the peaks, even with no actual lensing!

⇒ Must subtract bias expected even if no lensing

Detection of peak sharpening after delensing $C_l^{\text{delensed}} - C_l^{\text{dat}}$

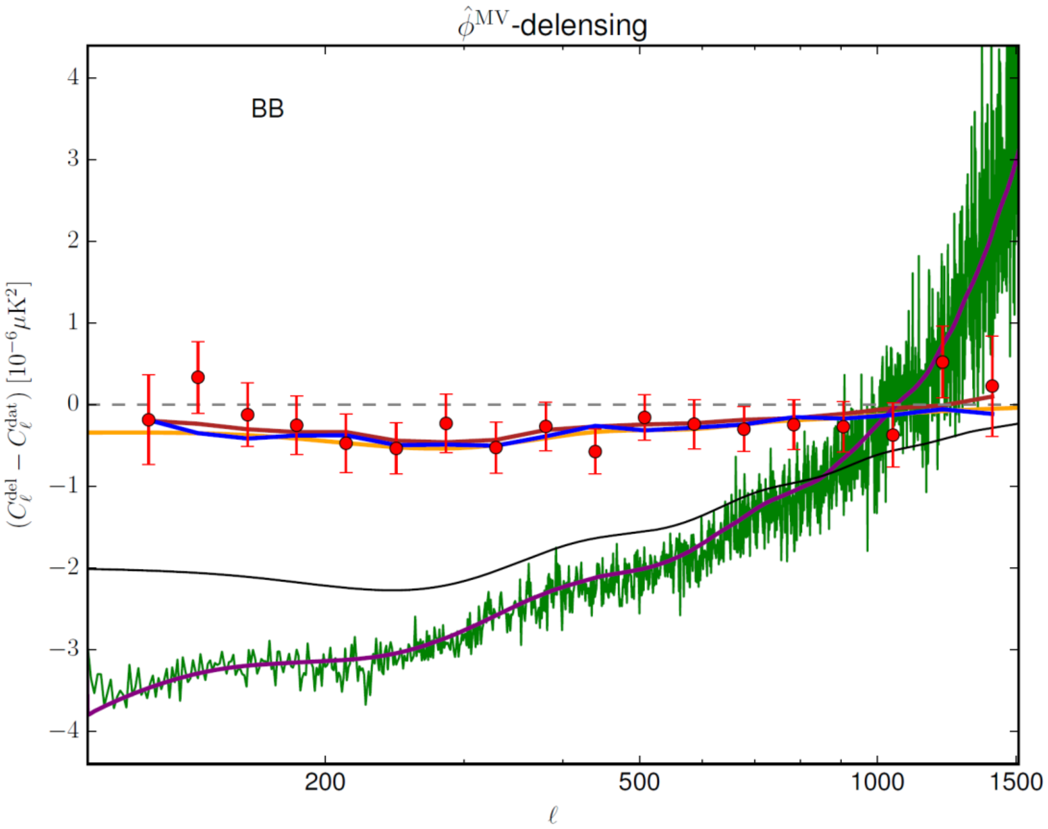


Carron, Lewis, Challinor arXiv:1701.01712



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

Planck: first detection of delensing of B-mode polarization



Detection of 7% reduction in B-mode lensing power at 4.5 σ

(but noise high, so does not yet help with tensor r constraint)

Carron, Lewis, Challinor arXiv:1701.01712

How well can we delens in principle?

Standard lensing remapping approximation:

$$\tilde{P}_{ab}(\hat{\boldsymbol{n}}) = P_{ab}(\hat{\boldsymbol{n}} + \boldsymbol{\nabla}\phi)$$

Observed		Theory	
$\tilde{E}, \tilde{B}$	lensing ← → Delensing?	E, ϕ	(almost all modes small-scale, unlensed $B = 0$)
2 d.o.f.		2 d.o.f.	

<u>Perfect lensing reconstruction, hence delensing(?), if only 2 d.o.f.</u>

Hirata & Seljak 2003

Can we construct an “optimal” lensing reconstruction algorithm?

YES, in sense of maximum a posteriori estimators:

- Hirata & Seljak 2003: iterative estimator for idealized full-sky (astro-ph/0306354)
  (with some approximations)

- Carron & Lewis 2017: public code that can be used in practice (1704.08230)
  (efficient handling of anisotropic noise, beams, sky cuts..)

  LensIt:
  https://github.com/carronj/LensIt (Julien Carron)

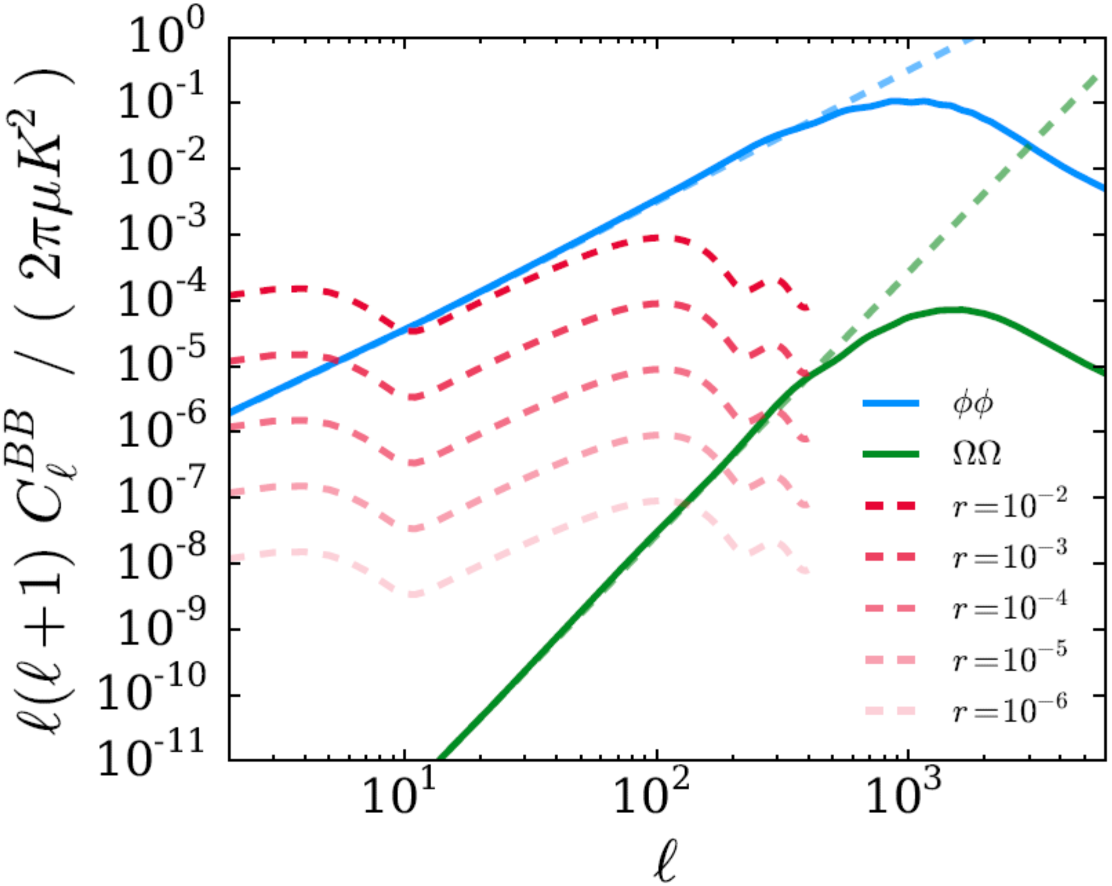
(see Marius’ talk for joint ϕ, TQU MAP estimation/sampling)

What limits delensing in principle?

(in practice: see foregrounds talk tomorrow)

1. Deflection not pure gradient: field rotation/curl shear

B-mode signal from field rotation

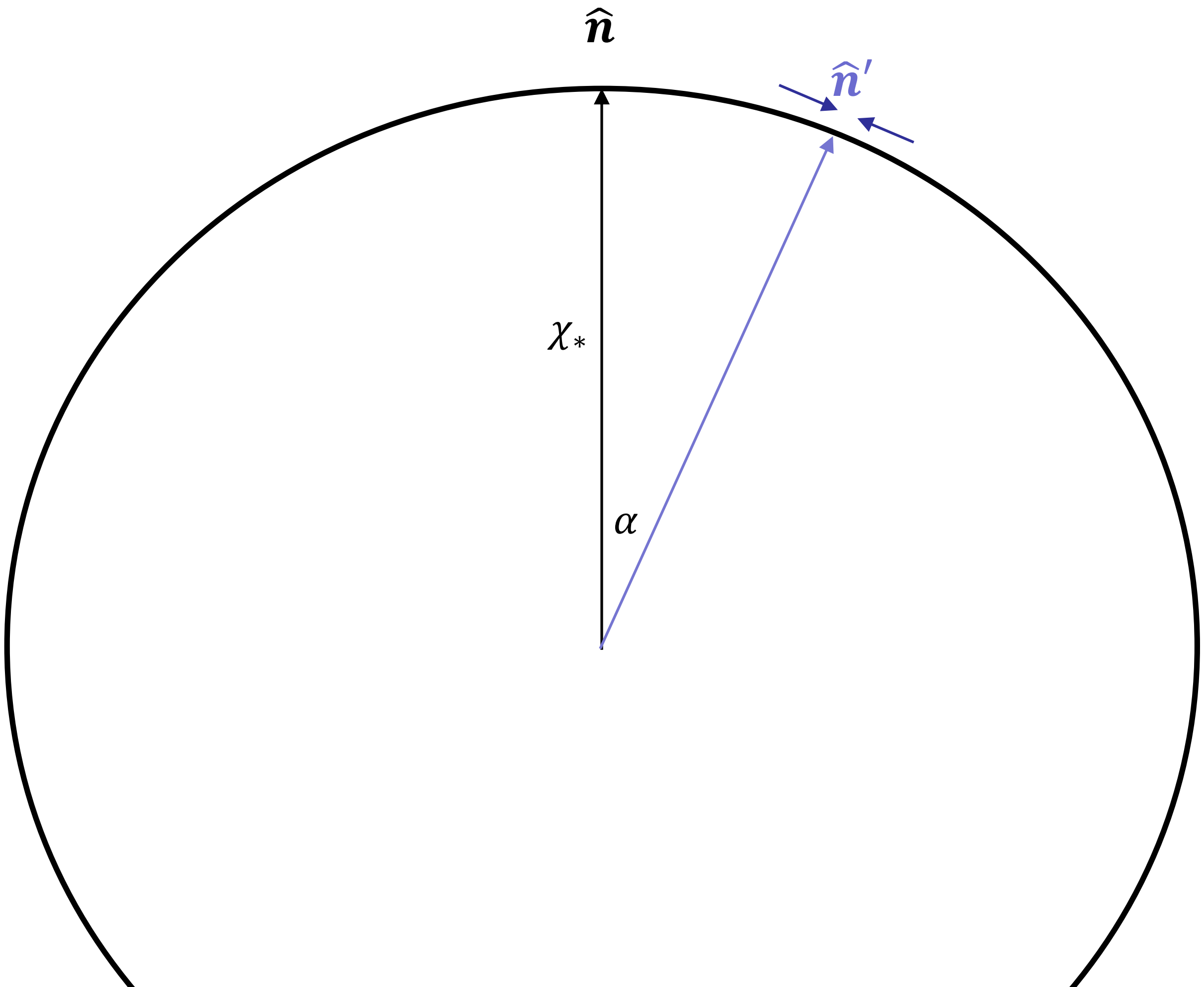


~2.5% of B mode amplitude from rotation

Pratten & Lewis: arXiv:1605.05662

2. Differences between unlensed and lensed last scattering

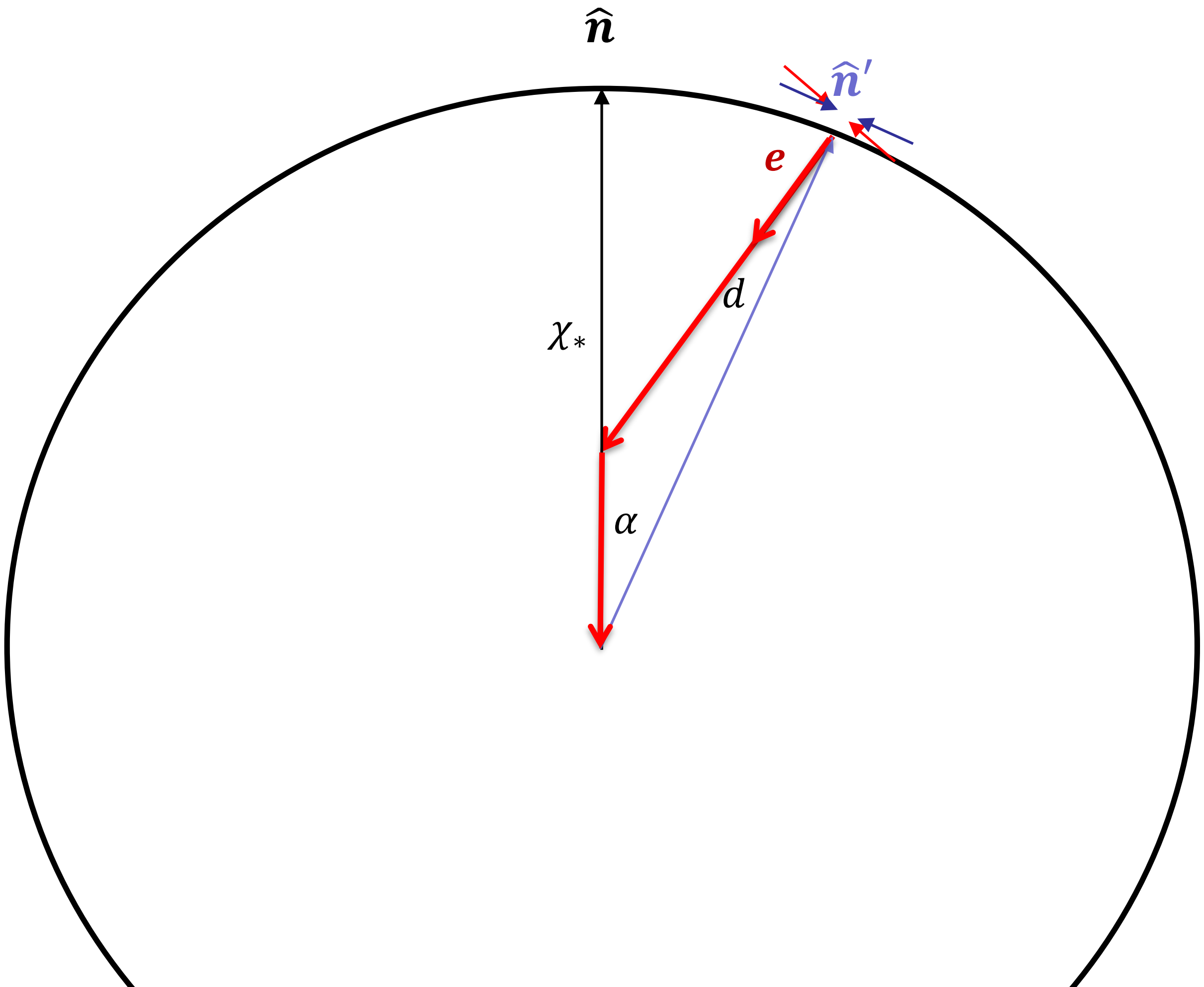
Lensed quadrupole: remapping approximation



2. Differences between unlensed and lensed last scattering

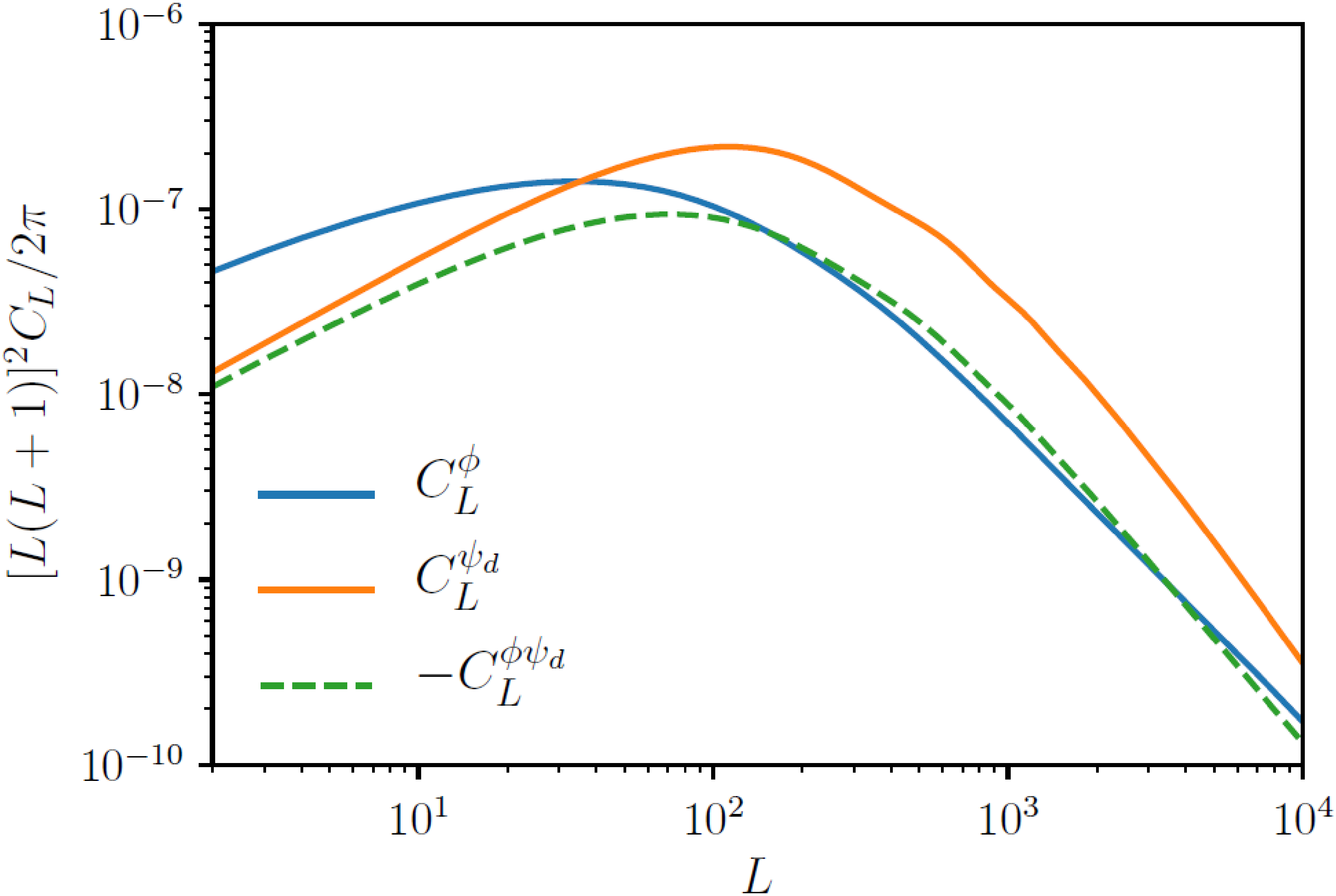
Lensed quadrupole: with emission angle d

not the same as the unlensed CMB quadrupole: observe new modes



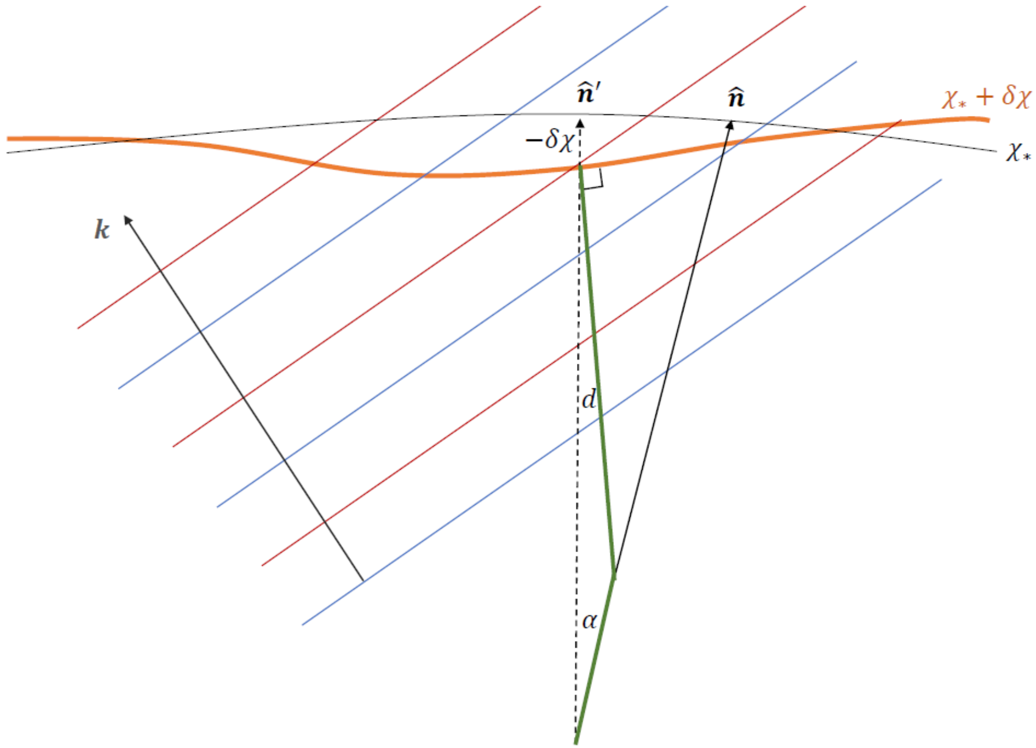
Emission angle and deflection angle power spectra

$$d = \nabla \psi_d \qquad \alpha = \nabla \phi$$

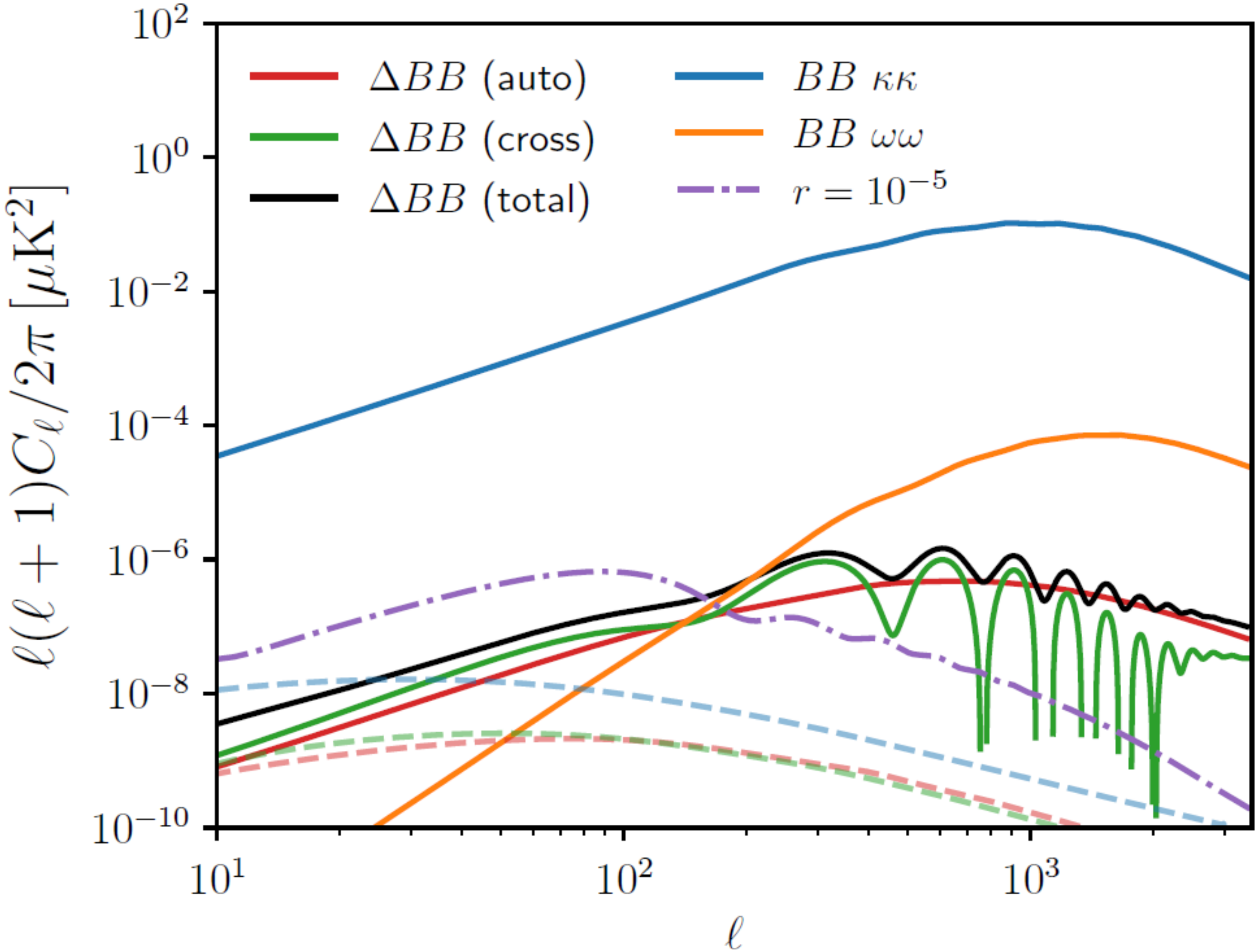


Fermat's principle: perturbed emission angle orthogonal to perturbed last scattering surface

➡ Must also account for time delay perturbing last scattering



Total emission+time delay effect dominates on large scales



Lewis, Hall, Challinor arXiv:1706.02673


Voie
44
$r = r_{min}(= 3X10^{-6}$

Conclusions

- Delensing works! Planck 2015 internal delensing:
  - High significance detection of peak sharpening (T/E)
    (but: internal delensing of T/E requires careful modelling of biases)
  - First detection of B-mode delensing
- Low noise → can delens nearly perfectly (Hirata and Seljak)
- Optimal and practical iterative method for lensing reconstruction now exists (LensIt code).
- In principle limit? Emission angle+time delay: $\Delta r \sim 2 \times 10^{-6}$
  - no problems for foreseeable future
    (potentially much larger problems in practice - foregrounds etc)

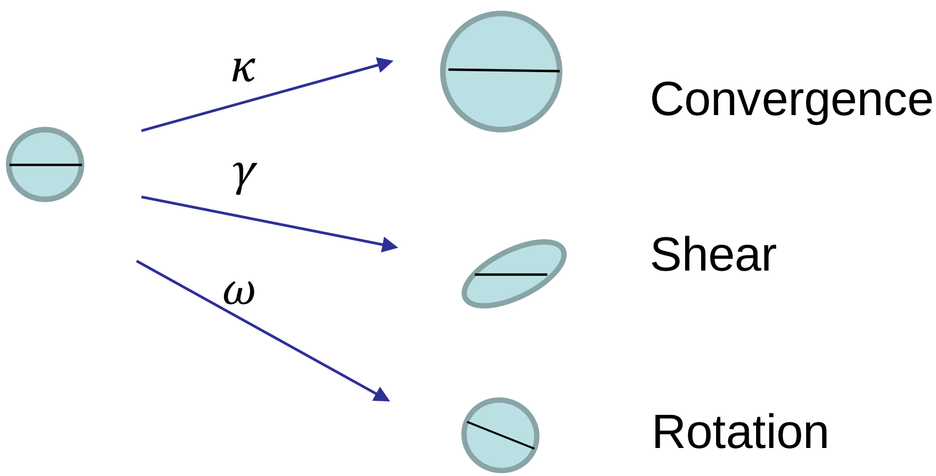
$$P_{ab}^{\mathrm{emit}}(\boldsymbol{e}) = \left[(\delta_{ac} - e_a e_c)(\delta_{bd} - e_b e_d)\mathcal{S}_{cd}(\chi_* \hat{\boldsymbol{n}}', \eta_*)\right]^{\mathrm{TT}}$$

$$e^{-\tau}\Gamma_{-\hat{\boldsymbol{n}}'}^{-\hat{\boldsymbol{n}}}\Gamma_{\boldsymbol{e}}^{-\hat{\boldsymbol{n}}'} P_{ab}^{\mathrm{emit}}(\boldsymbol{e}; \chi_* \hat{\boldsymbol{n}}') = \tilde{P}_{ab}^{\mathrm{std}}(-\hat{\boldsymbol{n}}) + 2e^{-\tau} d_{\langle a} \left[\mathcal{S}_{b\rangle}^{(1)} + \boldsymbol{\alpha} \cdot \boldsymbol{\nabla} \mathcal{S}_{b\rangle}^{(1)}\right] - d_{\langle a} P_{b\rangle c}(-\hat{\boldsymbol{n}}) d^c + \frac{3}{2} e^{-\tau} d_{\langle a} d_{b\rangle} \hat{n}^c \hat{n}^d \mathcal{S}_{cd} + \cdots , \quad (4.13)$$

Deflection angle α, shear γ_i , convergence κ , and rotation ω

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

$$A_{ij} \equiv \delta_{ij} + \frac{\partial}{\partial \theta_i}\alpha_j = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2+\omega \\ -\gamma_2-\omega & 1-\kappa+\gamma_1 \end{pmatrix}$$



$$\kappa = -\tfrac{1}{2}\nabla \cdot \boldsymbol{\alpha}$$

Rotation $\omega = 0$ from scalar perturbations in linear perturbation theory

$$\omega = 0 \Rightarrow \alpha = \nabla\psi$$