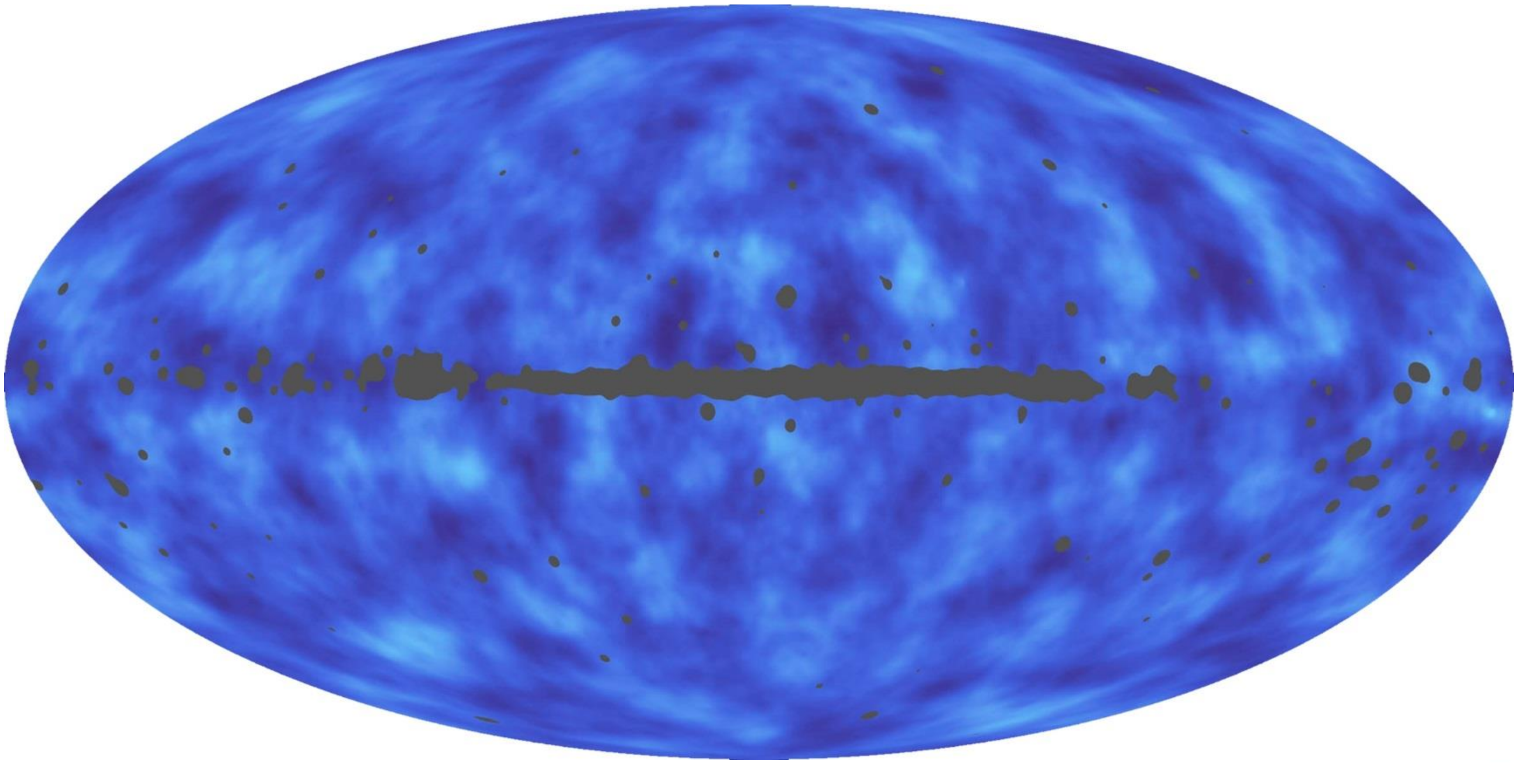
CMB Lensing and Delensing

Antony Lewis

work with the Planck Collaboration, Geraint Pratten, Julien Carron and Julien Peloton



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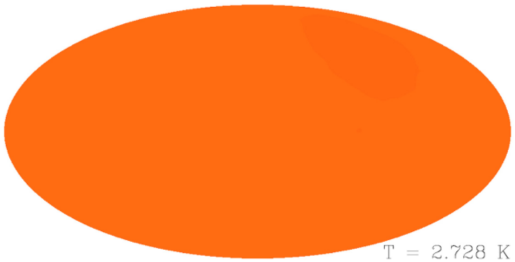
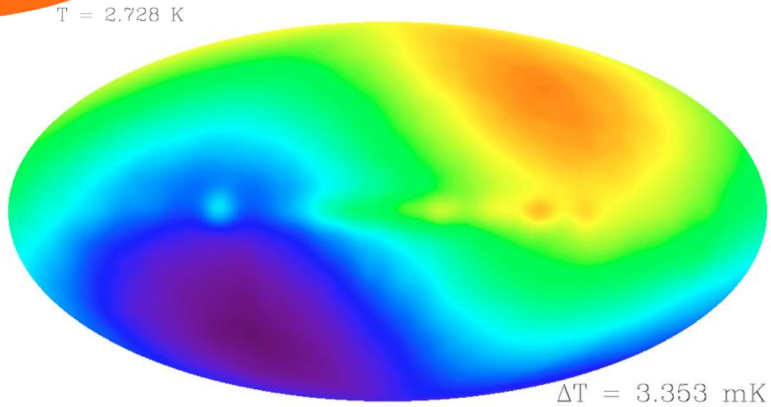
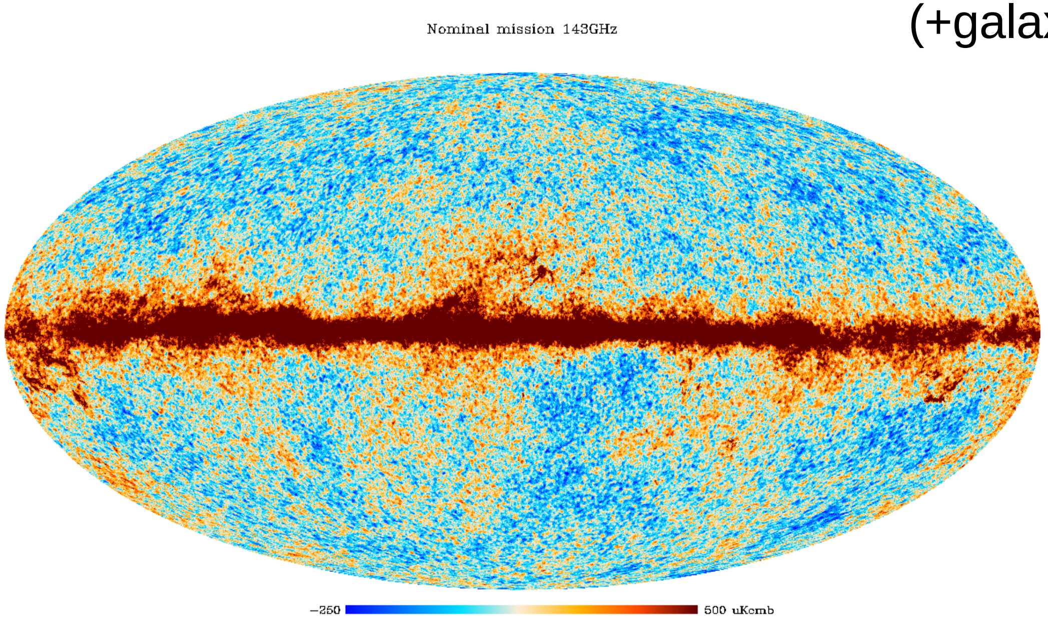


(almost) uniform 2.726K blackbody



Dipole (local motion)

O(10^{-5}) perturbations
(+galaxy)



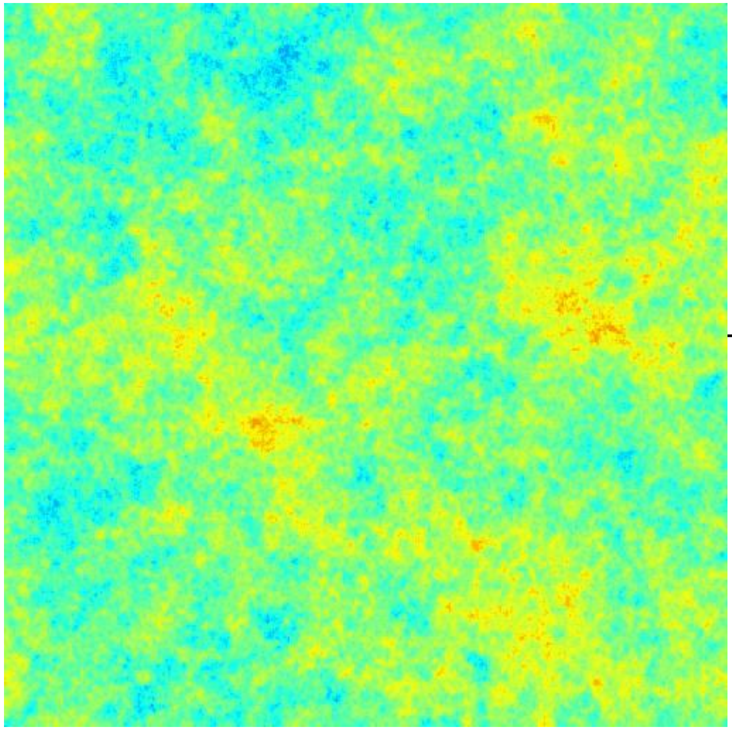
Observations: the microwave sky today

0^{th} order (uniform 2.726K) + 1^{st} order perturbations (anisotropies)

CMB temperature

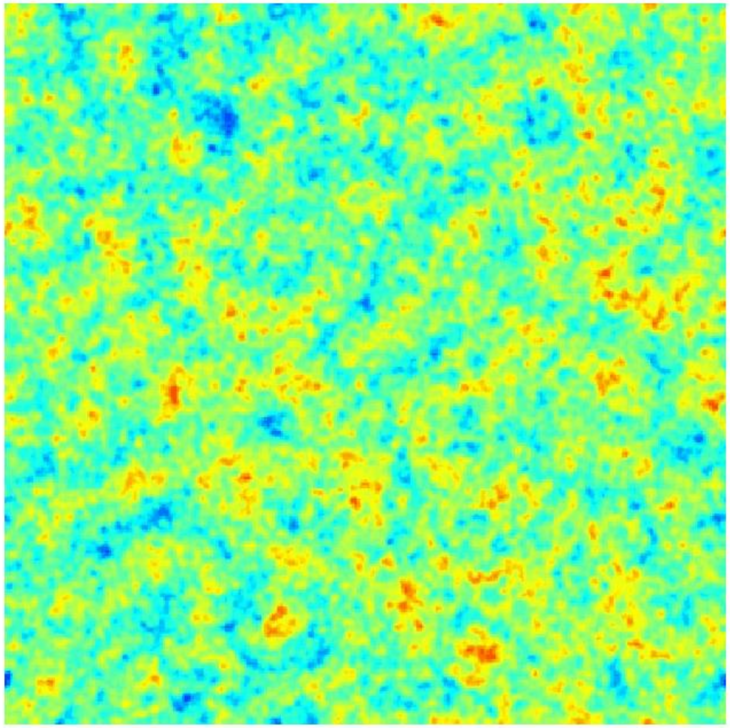
0^{th} order uniform temperature + 1^{st} order perturbations:

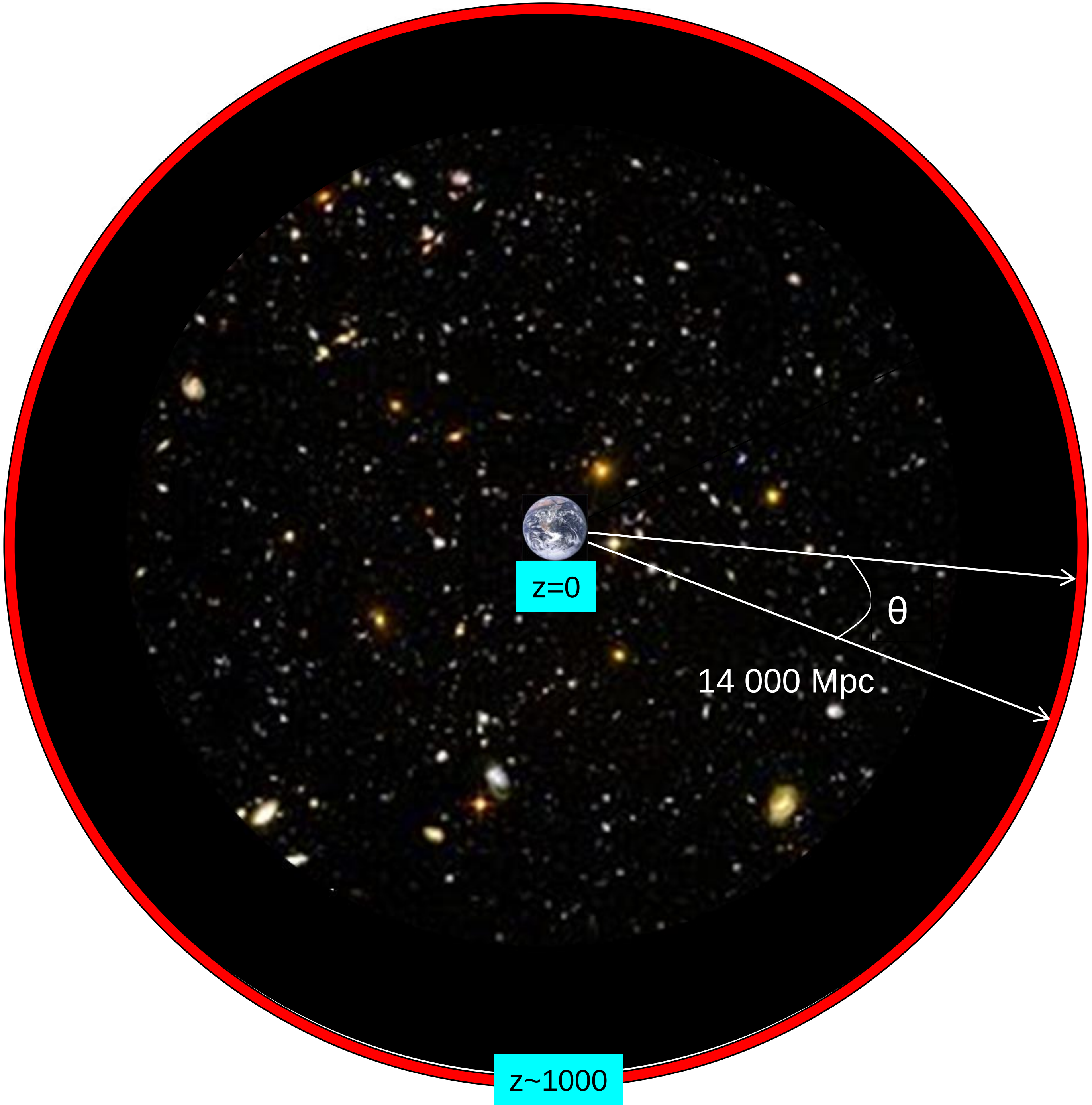
Perturbations: End of inflation

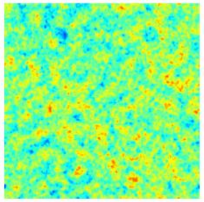


gravity+
pressure+
diffusion

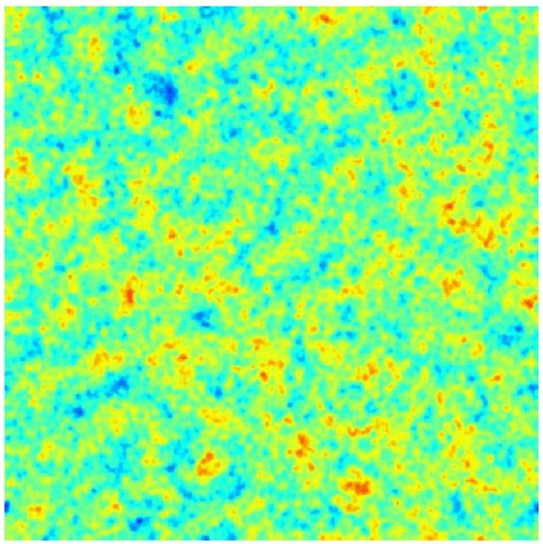
Perturbations: Last scattering surface

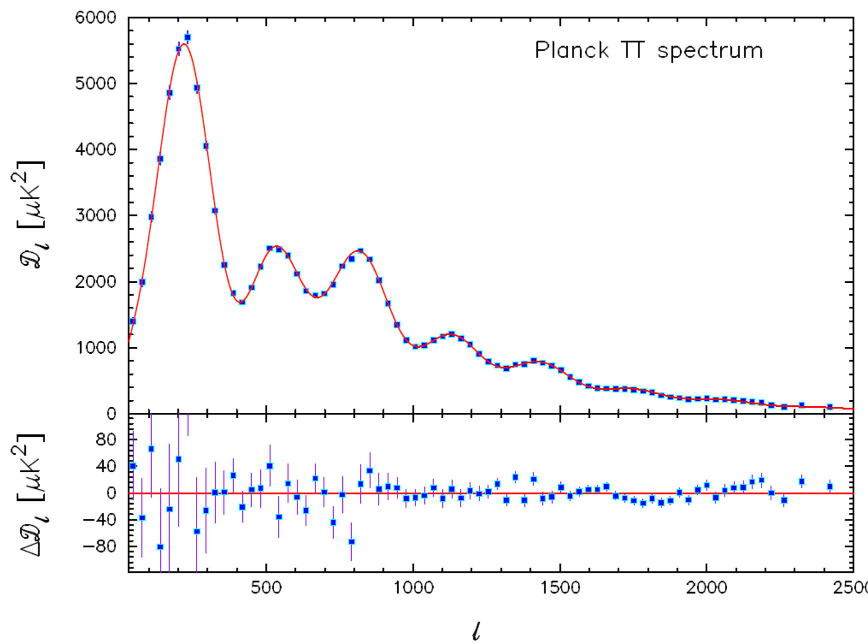



z=0
θ
14 000 Mpc
z~1000



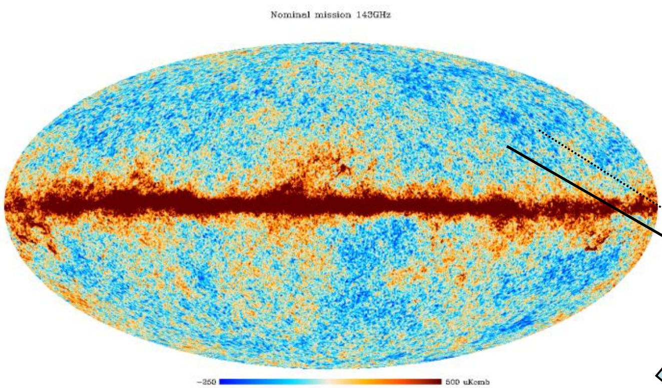
Gaussian ⇒ information in power spectrum



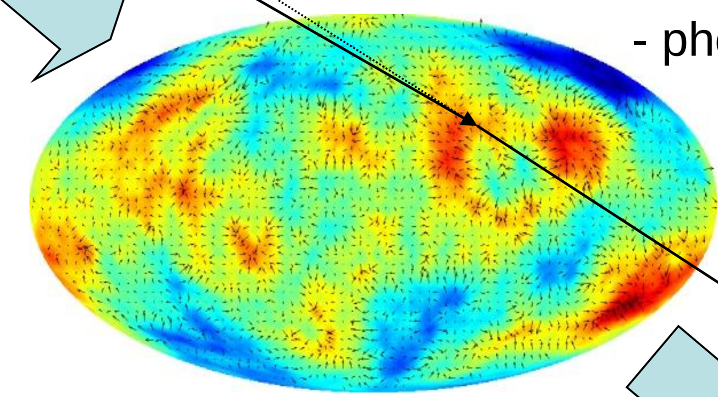


CMB Lensing

Last scattering surface



Inhomogeneous universe
- photons deflected

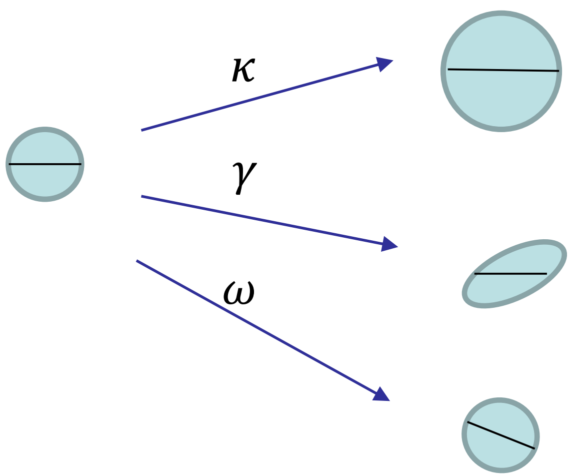


Observer

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

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

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



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

Shear

Rotation

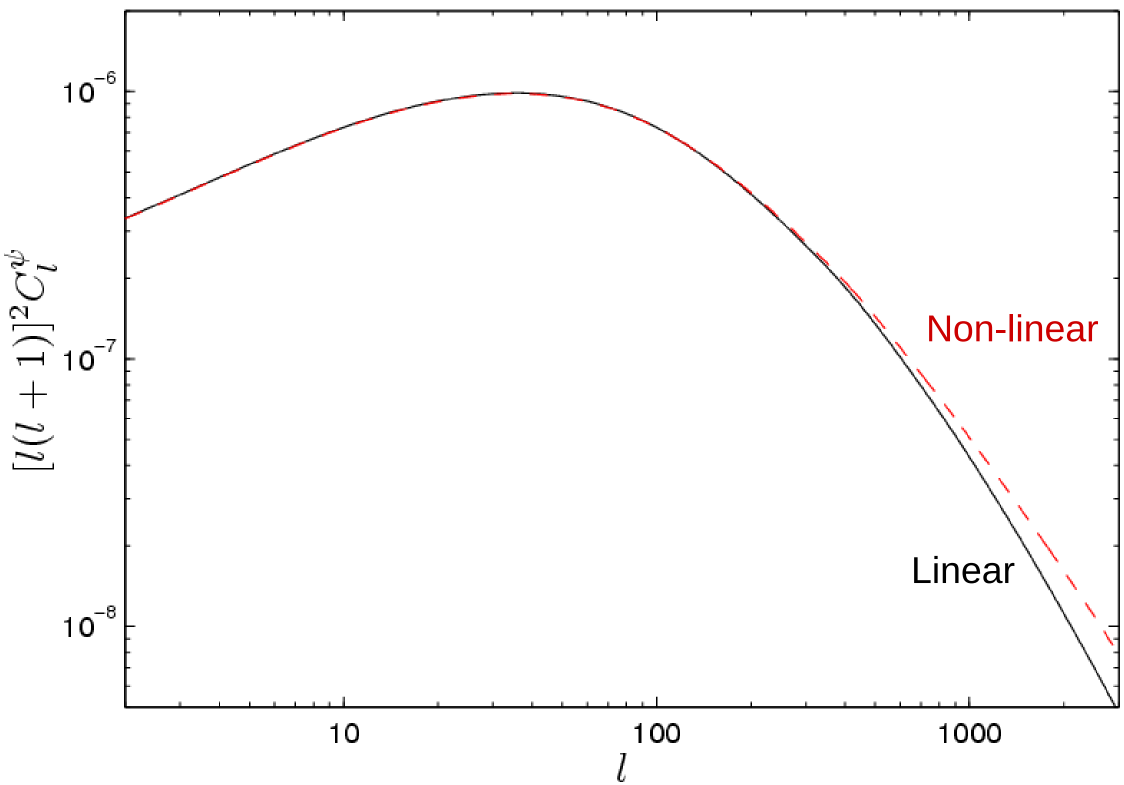
Rotation $\omega = 0$ from scalar perturbations in linear perturbation theory

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

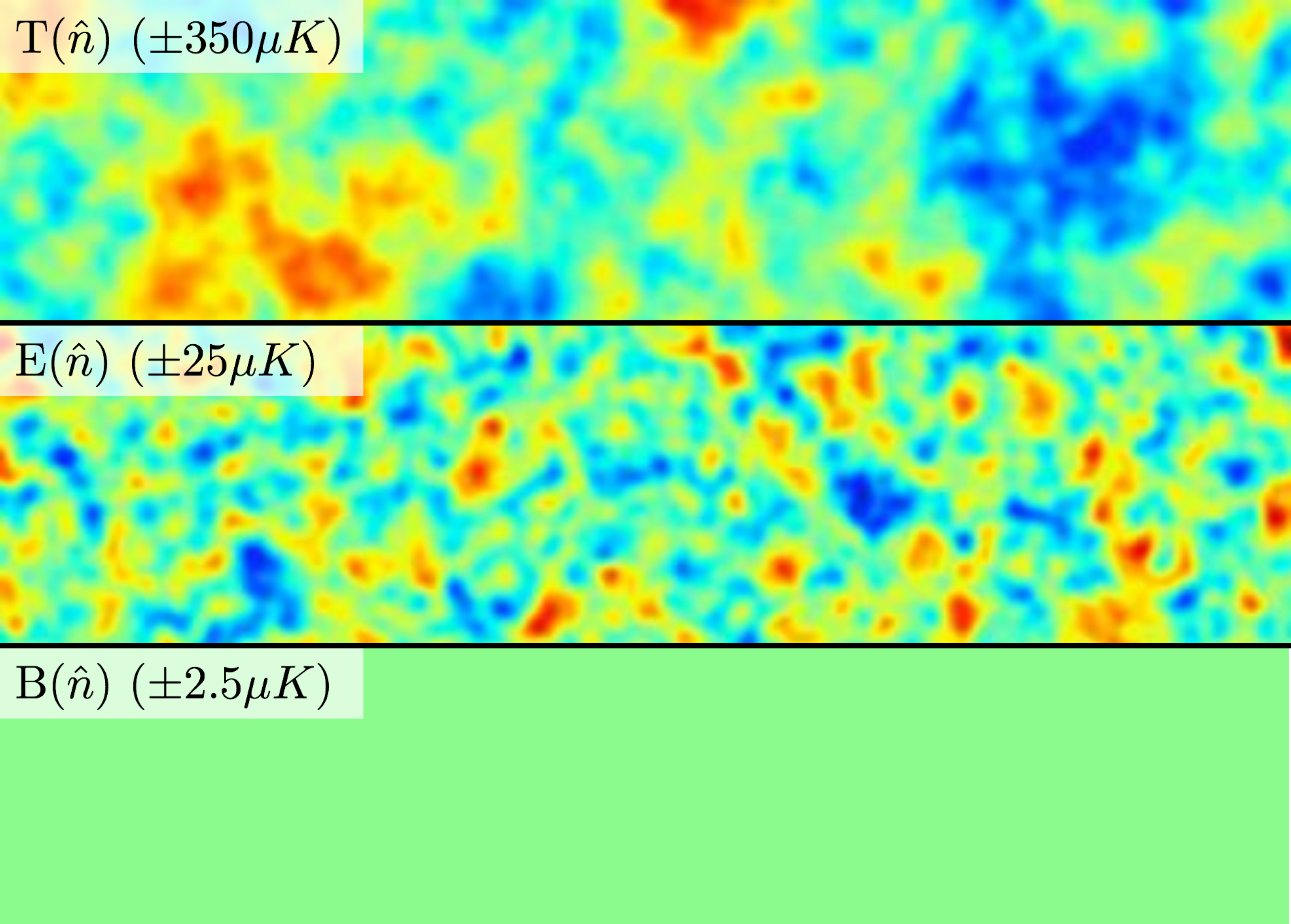
Deflection angle power spectrum

On small scales
(Limber approx. $k\chi \sim l$)

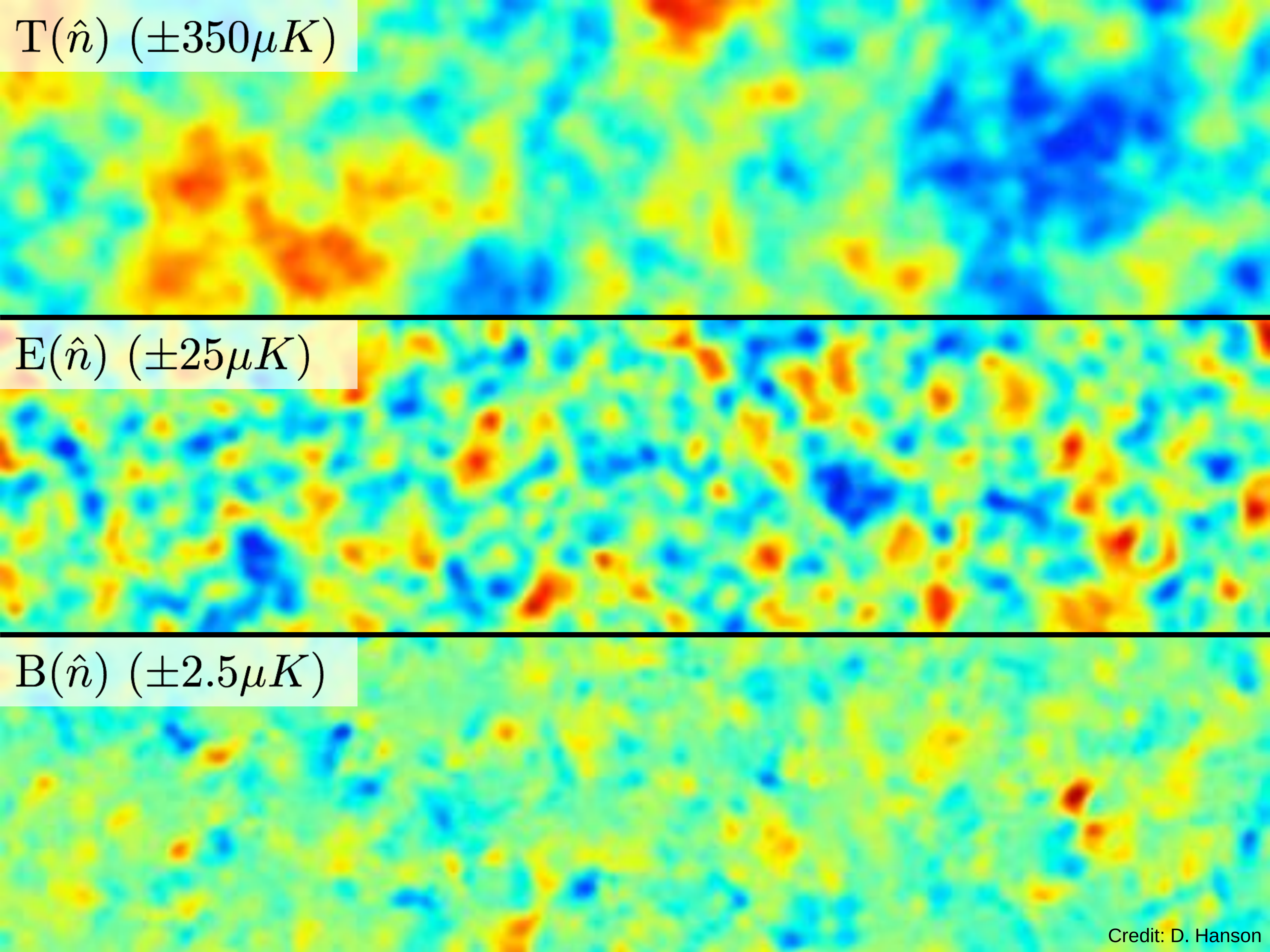
$$C_l^{\psi} \approx \frac{8\pi^2}{l^3}\int_0^{\chi_*} \chi \mathrm{d}\chi\, \mathcal{P}_\Psi(l/\chi;\eta_0-\chi)\left(\frac{\chi_*-\chi}{\chi_*\chi}\right)^2$$



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

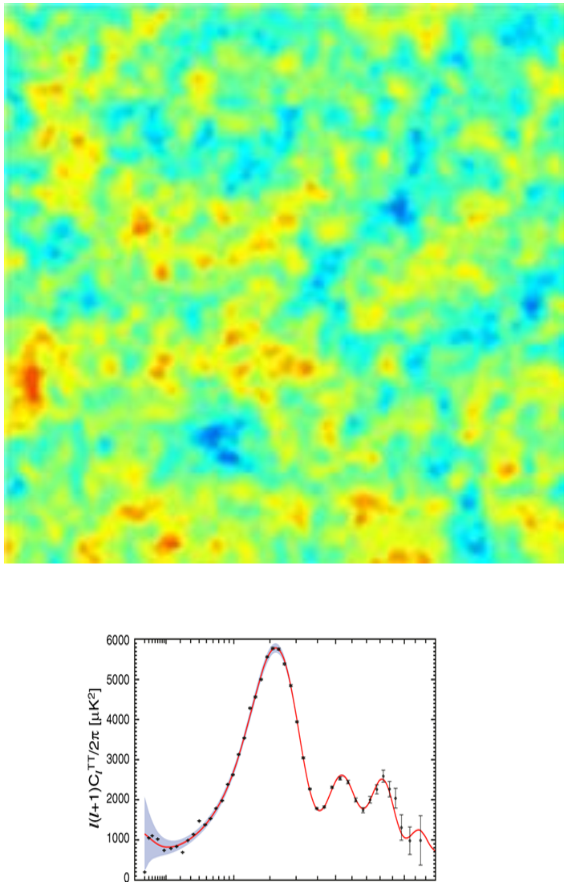


Credit: D. Hanson

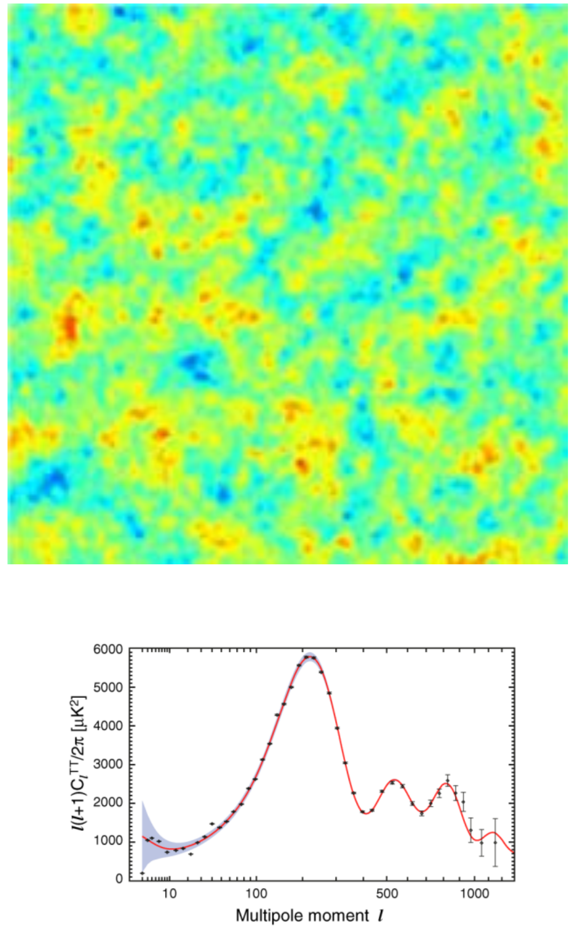

$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Credit: D. Hanson

Local effect of lensing on the power spectrum

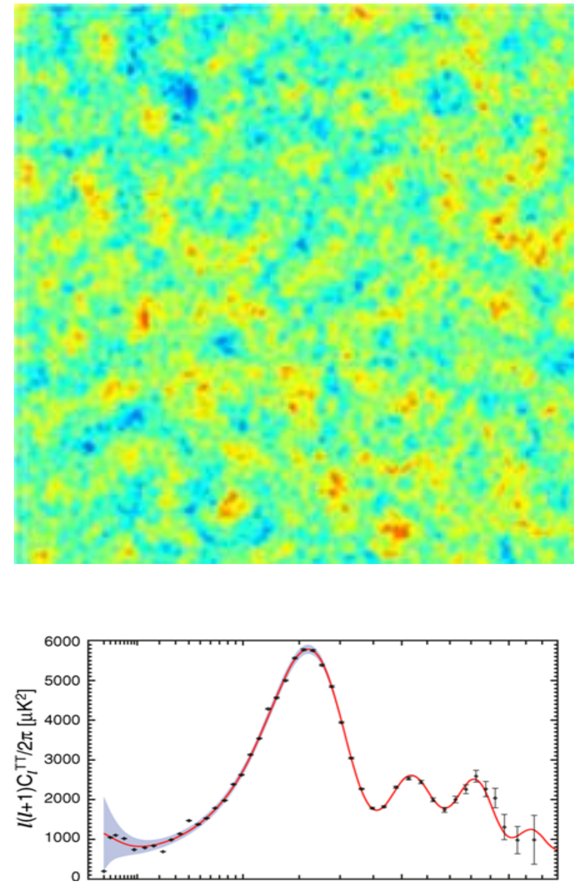
Magnified



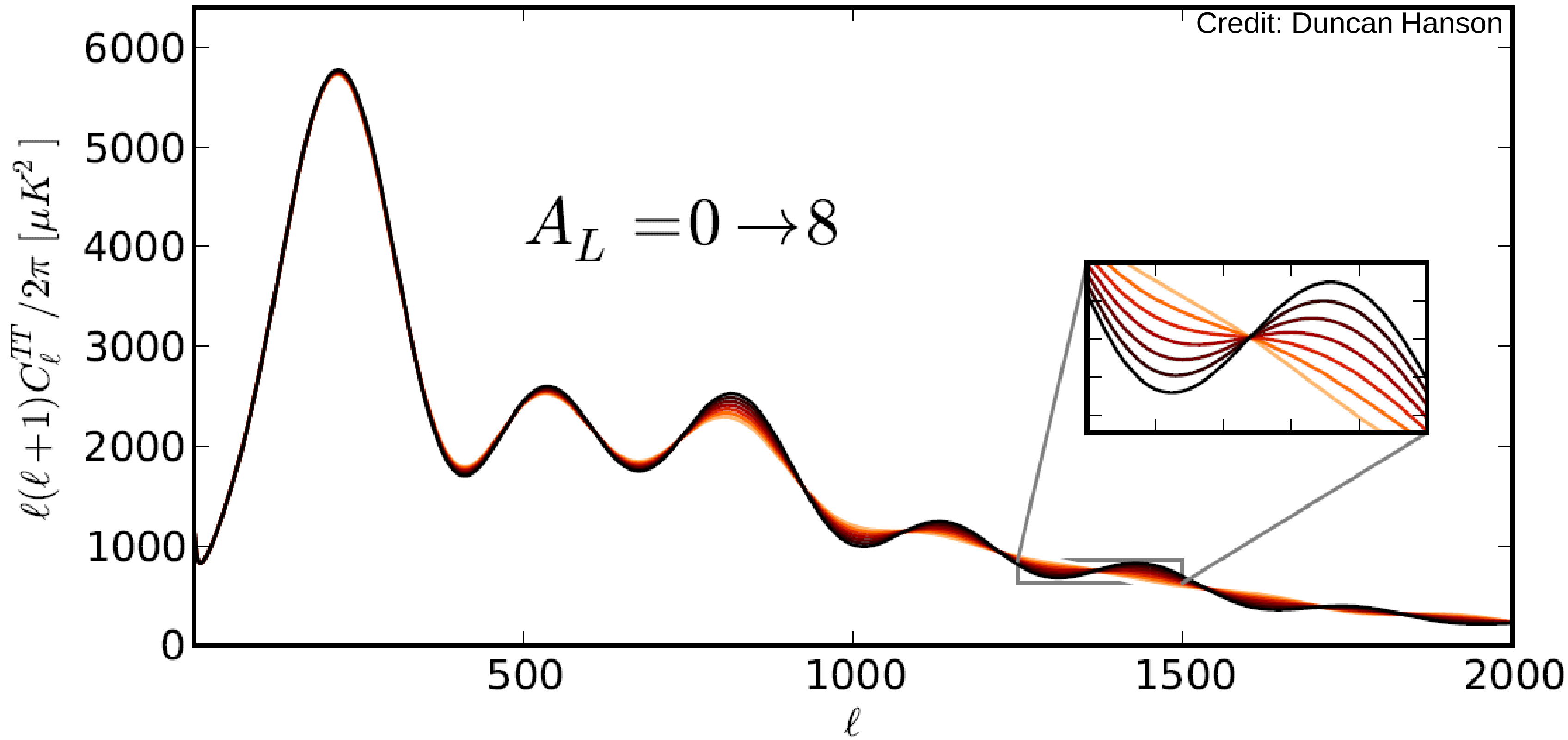
Unlensed



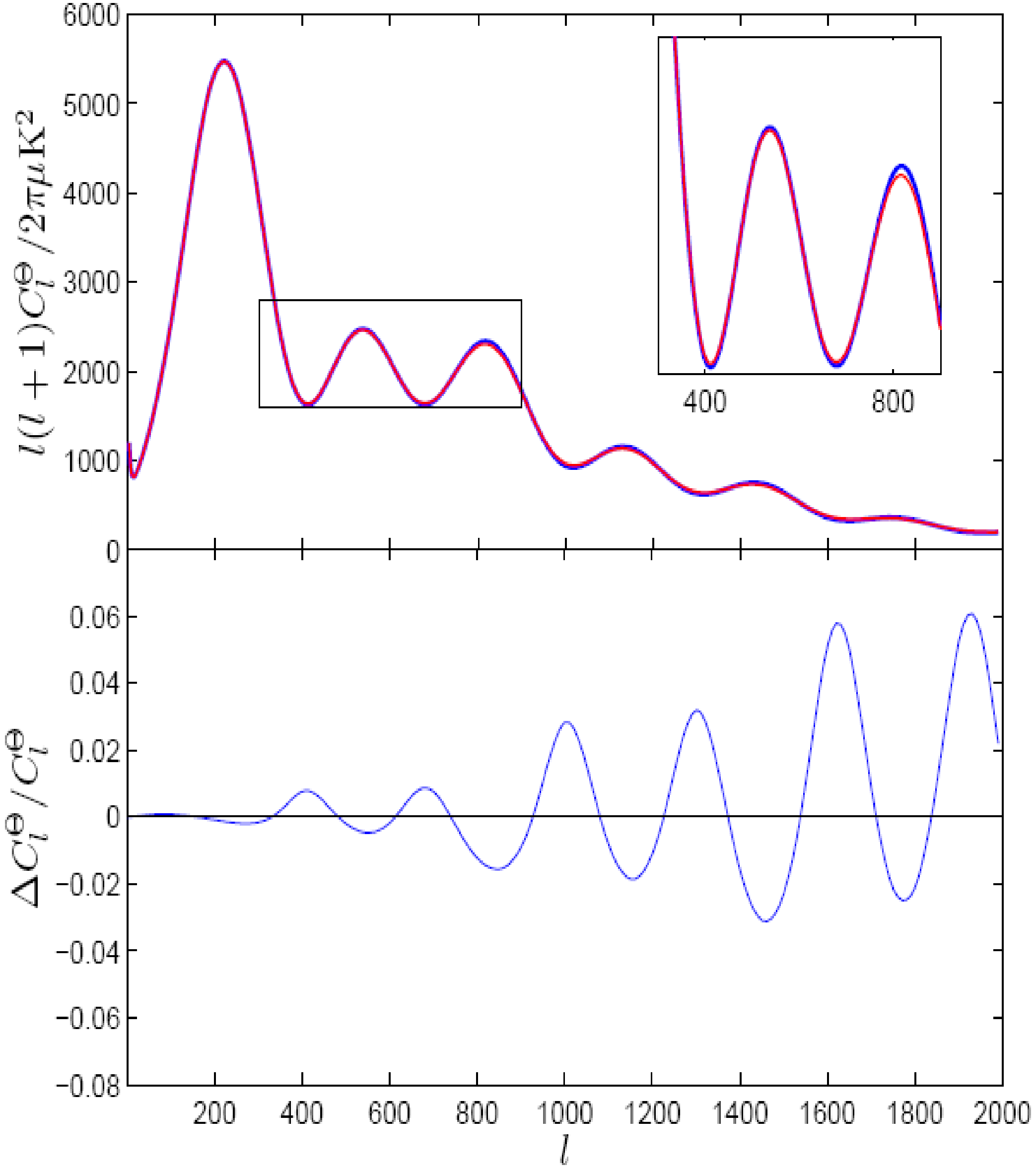
Demagnified



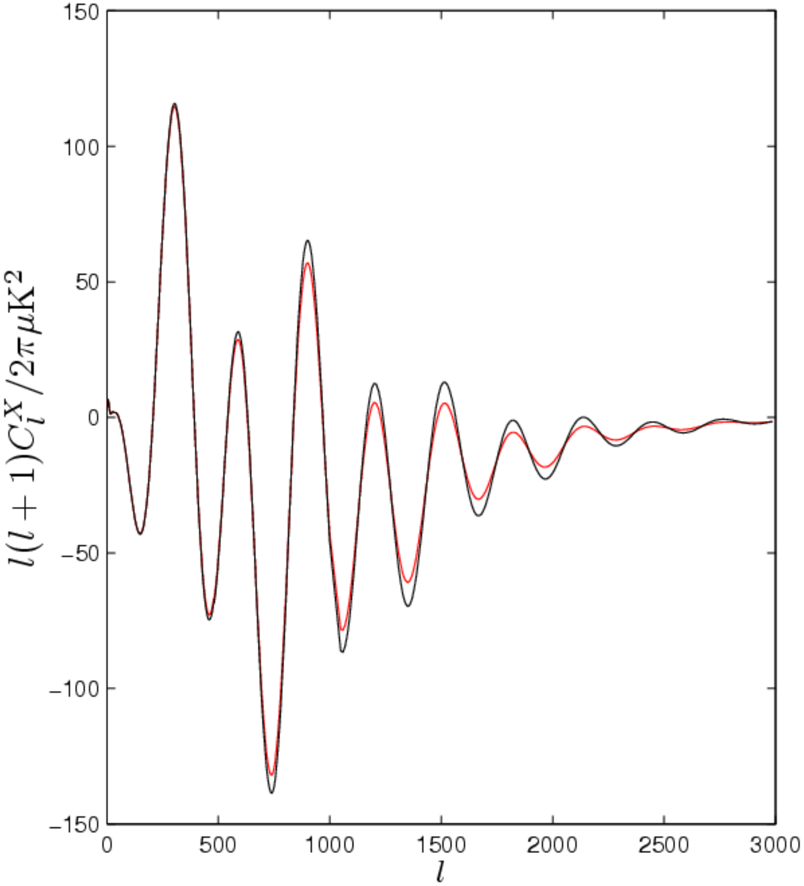
Averaged over the sky, lensing smooths out the power spectrum

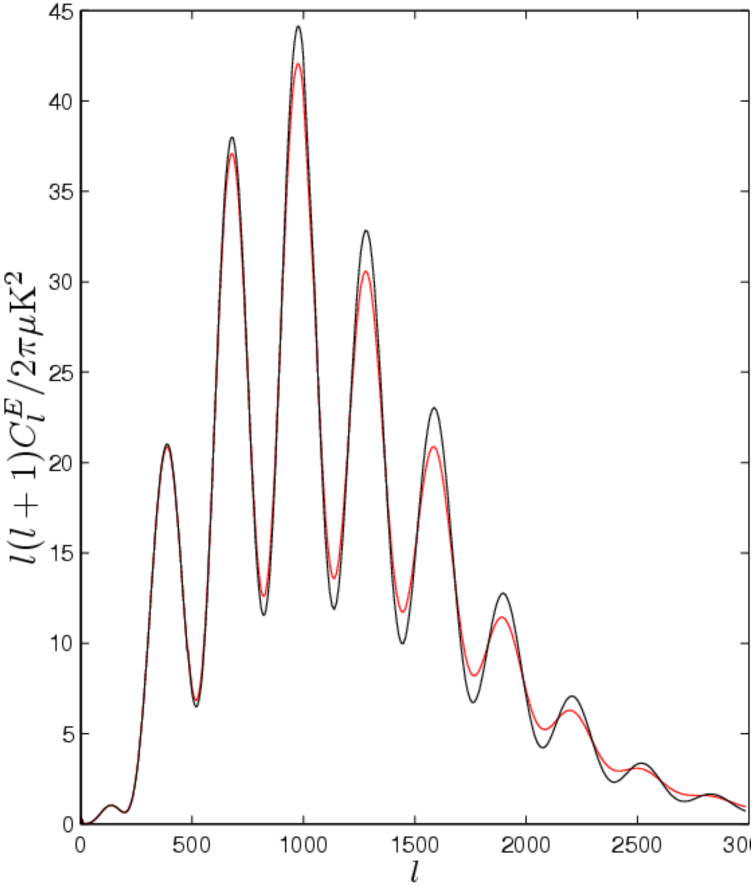


Lensing effect on CMB temperature power spectrum



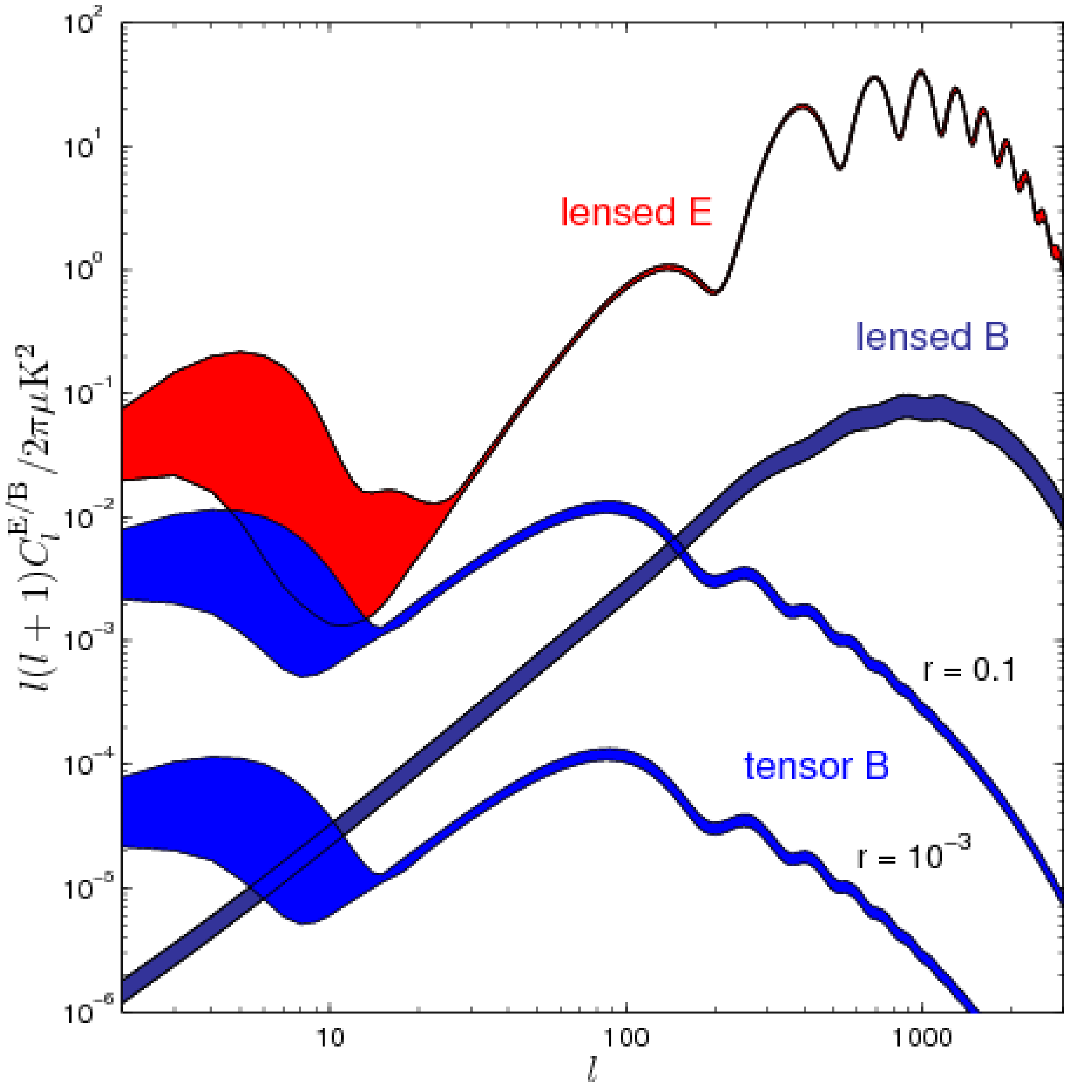
Effect on TE and EE polarization spectra





B-mode polarization power spectrum

Current 95% indirect limits for LCDM given WMAP+2dF+HST (bit old!)



<u>Lensing an important contaminant of searches for primordial gravitational waves</u>

Outline

1. Can we reconstruct the lensing?

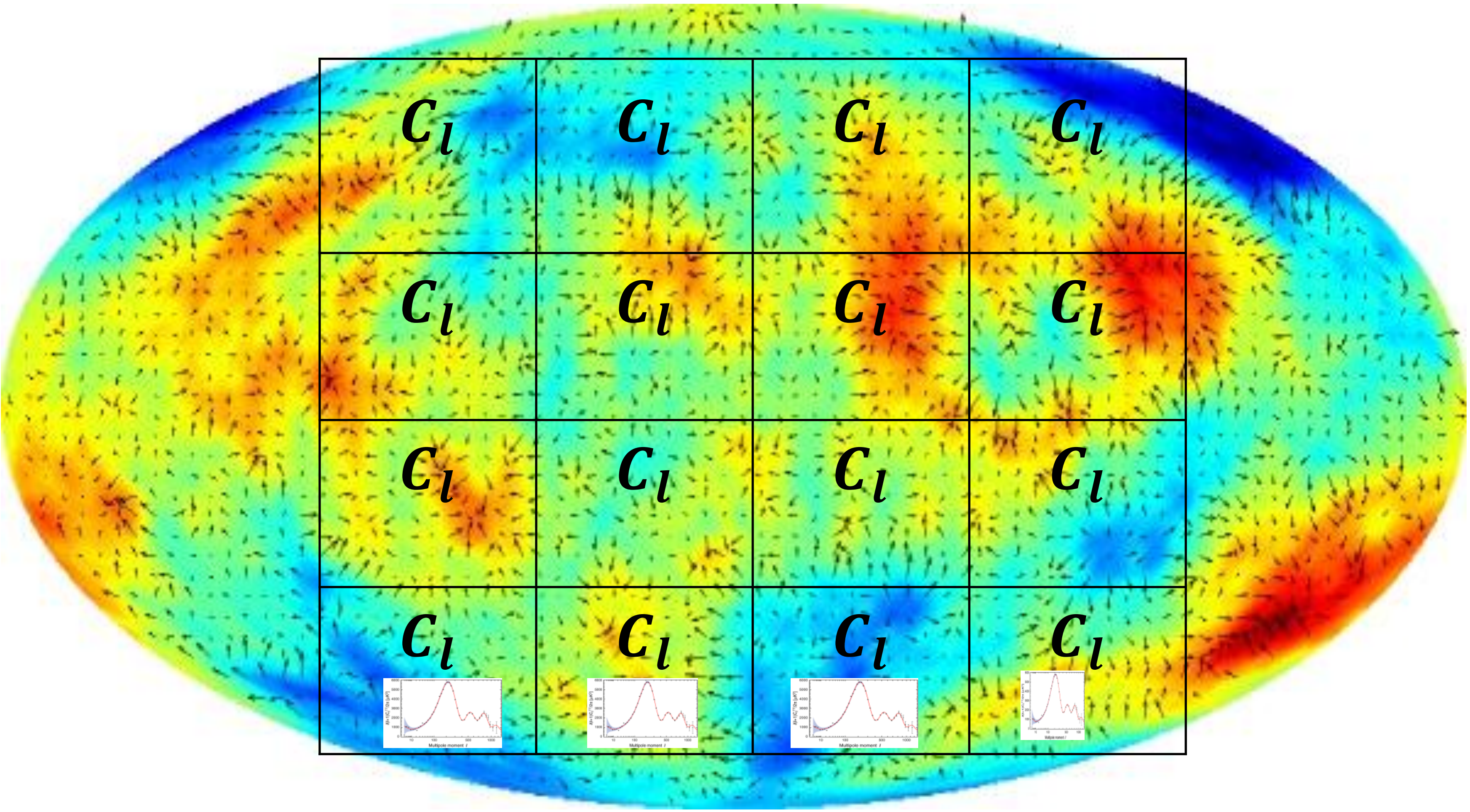
   - gives a powerful cosmological probe
     (z~2 peak; constraints on LCDM, massive neutrinos, etc.)

2. Can we then delens?

   - unsmooth the power spectra, clean the lensing B modes

3. Can we model the lensing signal accurately?

Lensing reconstruction (concept)



Measure spatial variations in magnification and shear

Use assumed unlensed spectrum, and unlensed statistical isotropy

Lensing reconstruction

- Maths and algorithm sketch

X here is lensing potential, deflection angle, or κ

For a *given* (fixed) lensing field, $T \sim P(T|X)$:

Flat sky approximation: modes correlated for $\mathbf{k}_2 \neq \mathbf{k}_3$

First-order series expansion in the lensing field:

$$\langle \tilde{T}(\mathbf{k}_2)\tilde{T}(\mathbf{k}_3)\rangle_{P(\tilde{T}|X)} \approx \int \mathrm{d}\mathbf{K} X(\mathbf{K})^* \underbrace{\left\langle \frac{\delta}{\delta X(\mathbf{K})^*} \left(\tilde{T}(\mathbf{k}_2)\tilde{T}(\mathbf{k}_3)\right) \right\rangle}_{\mathcal{A}(K,k_2,k_3)\delta(K+k_2+k_3)} \approx \mathcal{A}(K,k_2,k_3)\, X(\mathbf{K})^*|_{\mathbf{K}=-\mathbf{k}_2-\mathbf{k}_3}$$

function easy to calculate for $X(\mathbf{K}) = 0$

Can reconstruct the modulation field X

$$A(L, l_1, l_2) \sim \left(\mathbf{l}_1 \cdot \mathbf{L}\tilde{C}_{l_1} + \mathbf{l}_2 \cdot \mathbf{L}\tilde{C}_{l_2}\right)$$

Full sky analysis similar, summing modes with optimal weights gives

$$\hat{\psi}^*_{l_1 m_1} = N^{(0)}_{l_1} \sum_{l_2 l_3}^{l_1 \le l_2 \le l_3} \Delta^{-1}_{l_1 l_2 l_3} A^{TT}_{l_1 l_2 l_3} \sum_{m_2 m_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \frac{\tilde{T}_{l_2 m_2}\tilde{T}_{l_3 m_3}}{\tilde{C}^{TT}_{\mathrm{tot}\ l_2}\tilde{C}^{TT}_{\mathrm{tot}\ l_3}}$$

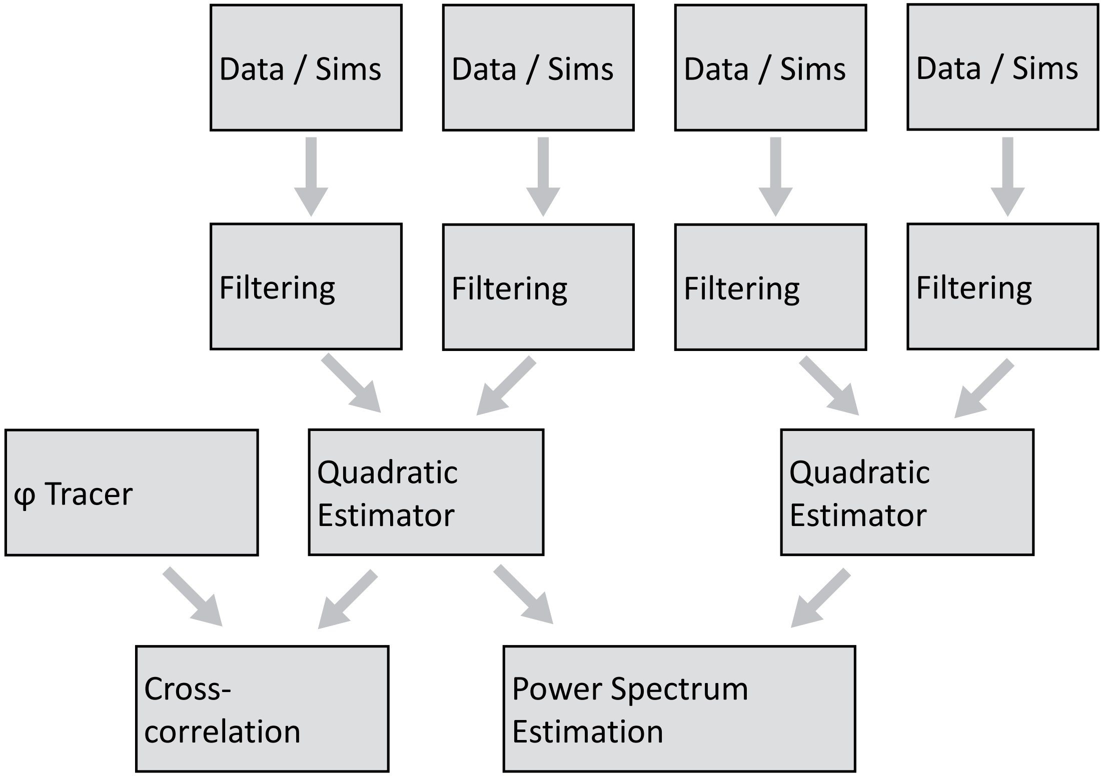
Zaldarriaga, Hu, Hanson, and others.

Lens Reconstruction Pipeline

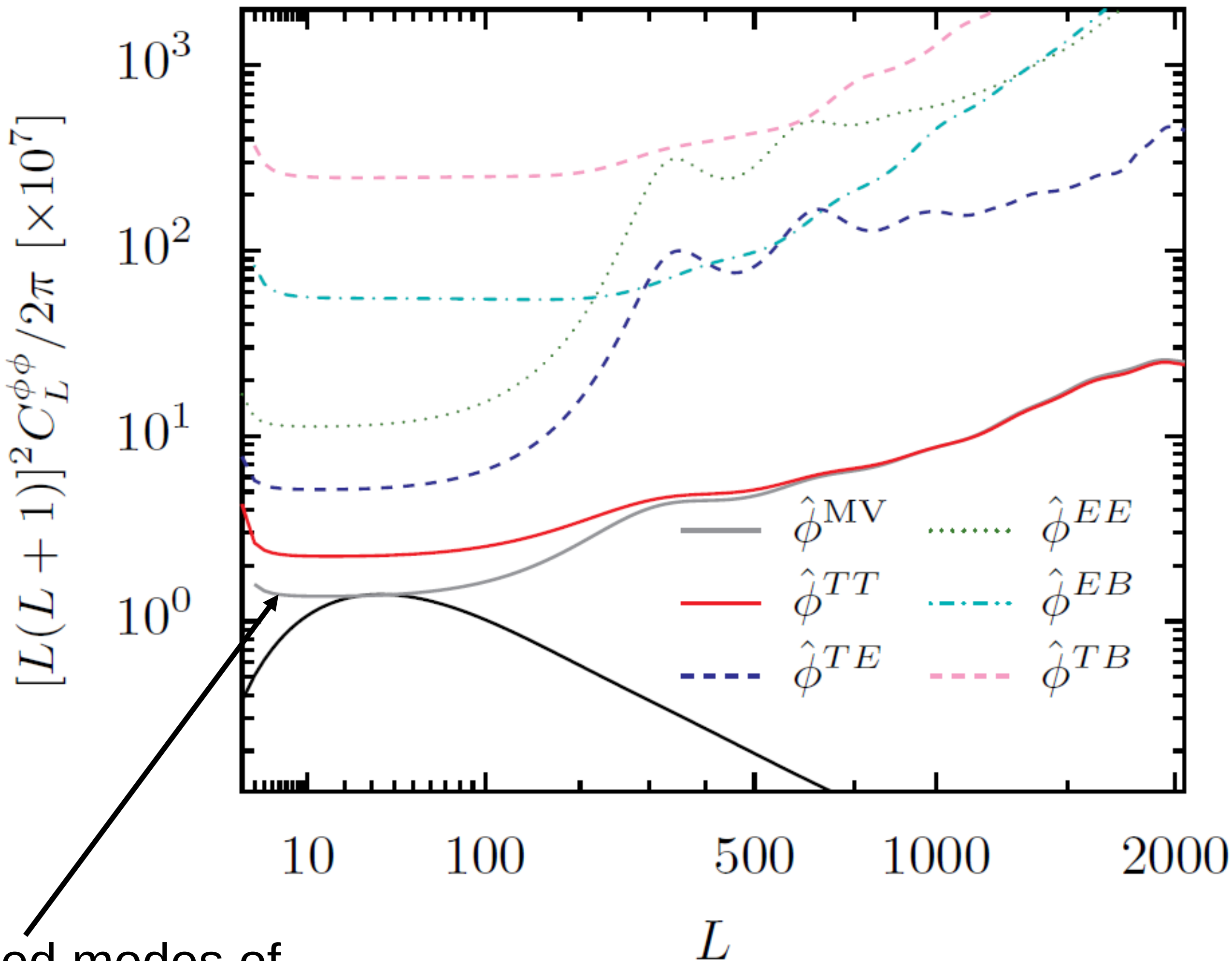
→ process input maps

→ estimate lensing potential from anisotropic 2-point

→ estimate lensing power spectrum.

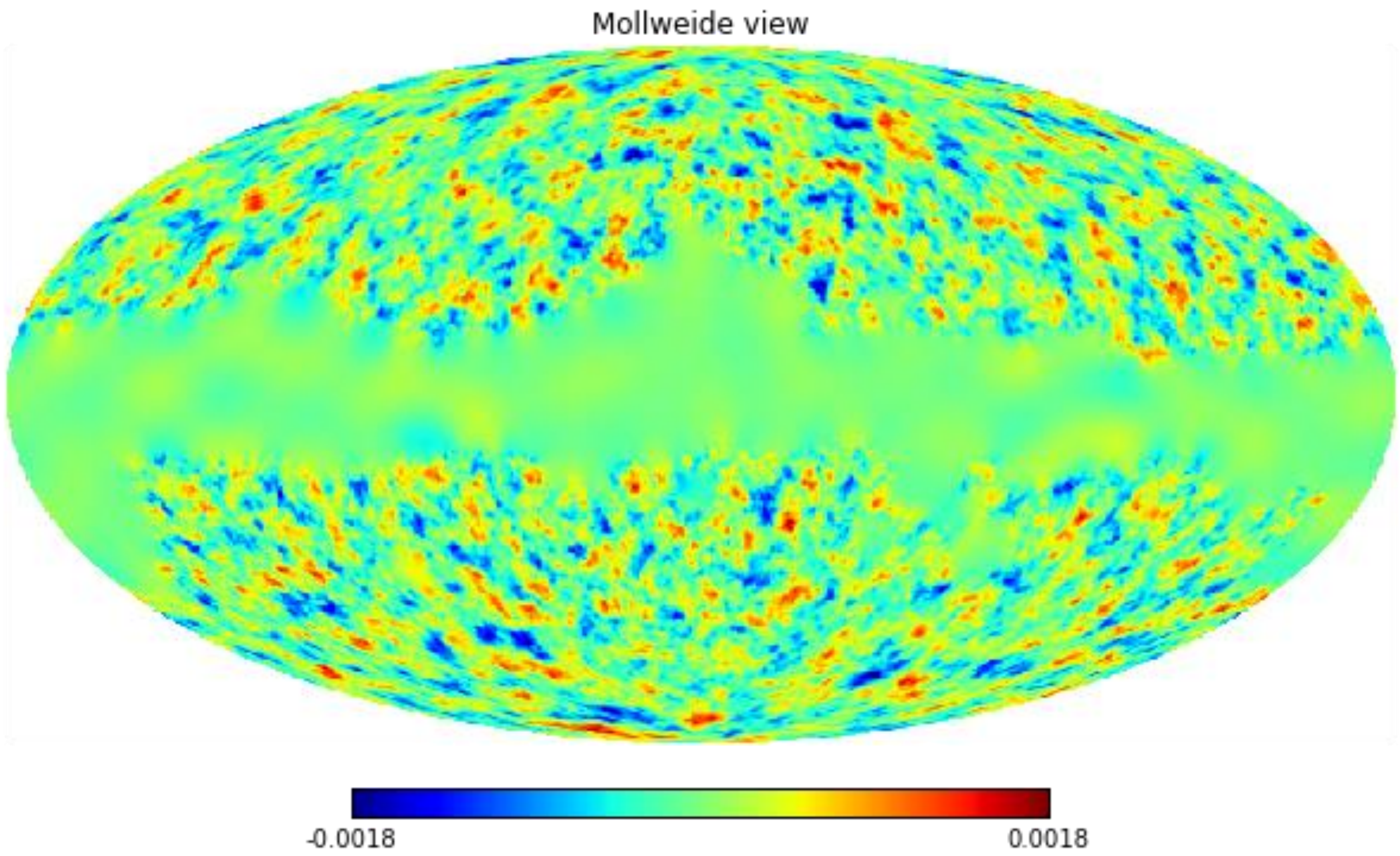


Planck noise power spectra for lensing estimators.

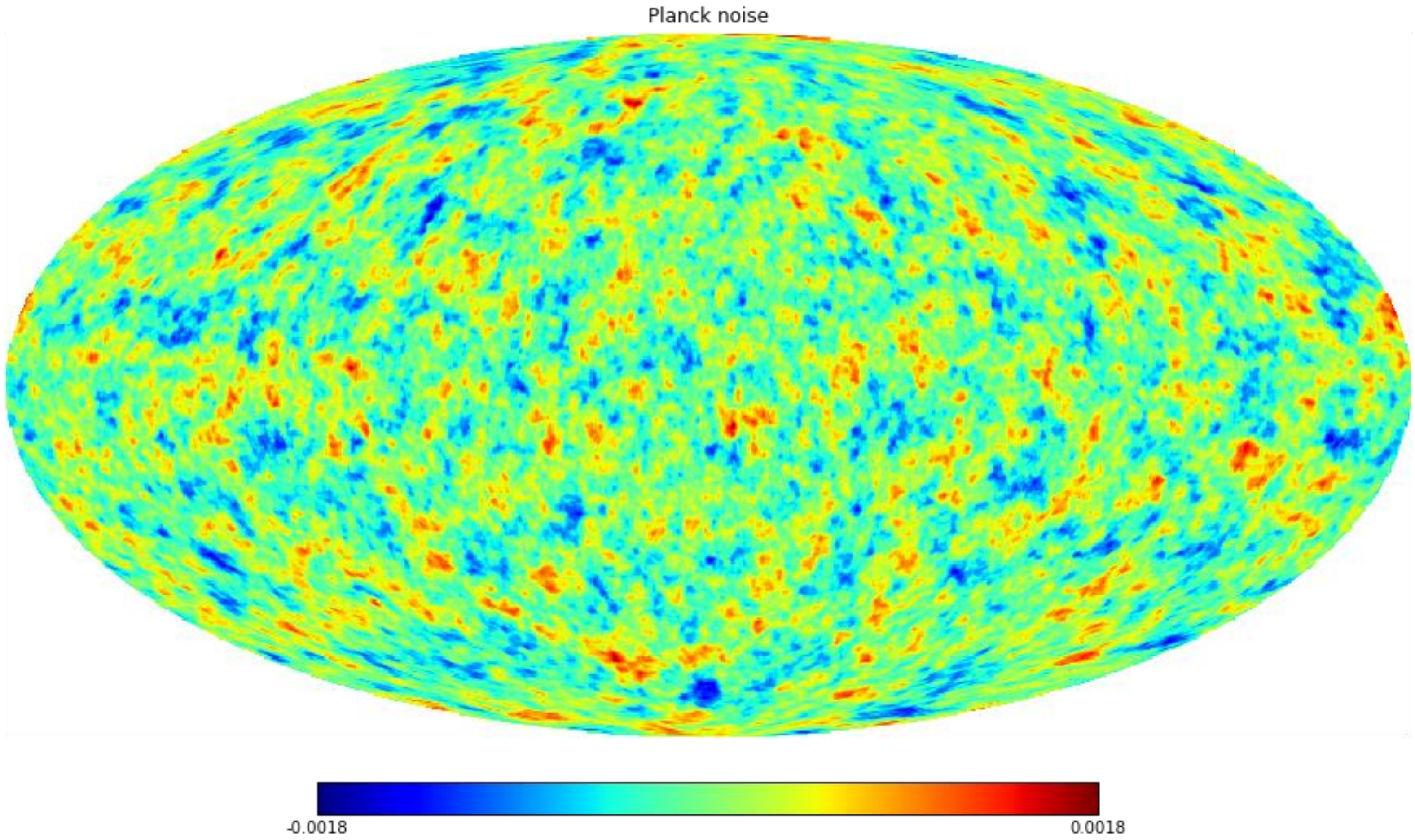


Best measured modes of
MV estimator have S/N=1.

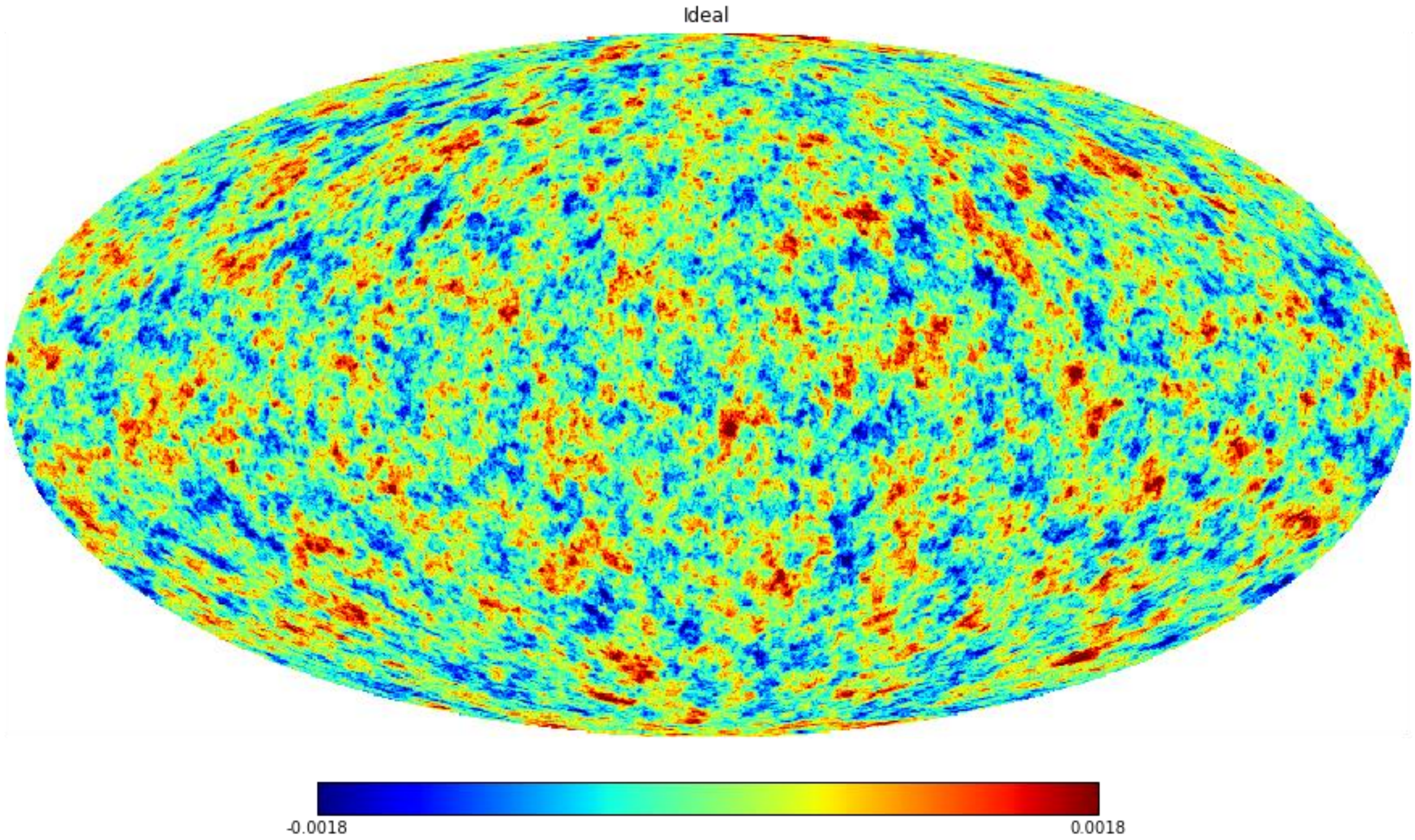
Planck 2015 lensing reconstruction ($E_{\nabla\Phi}$)



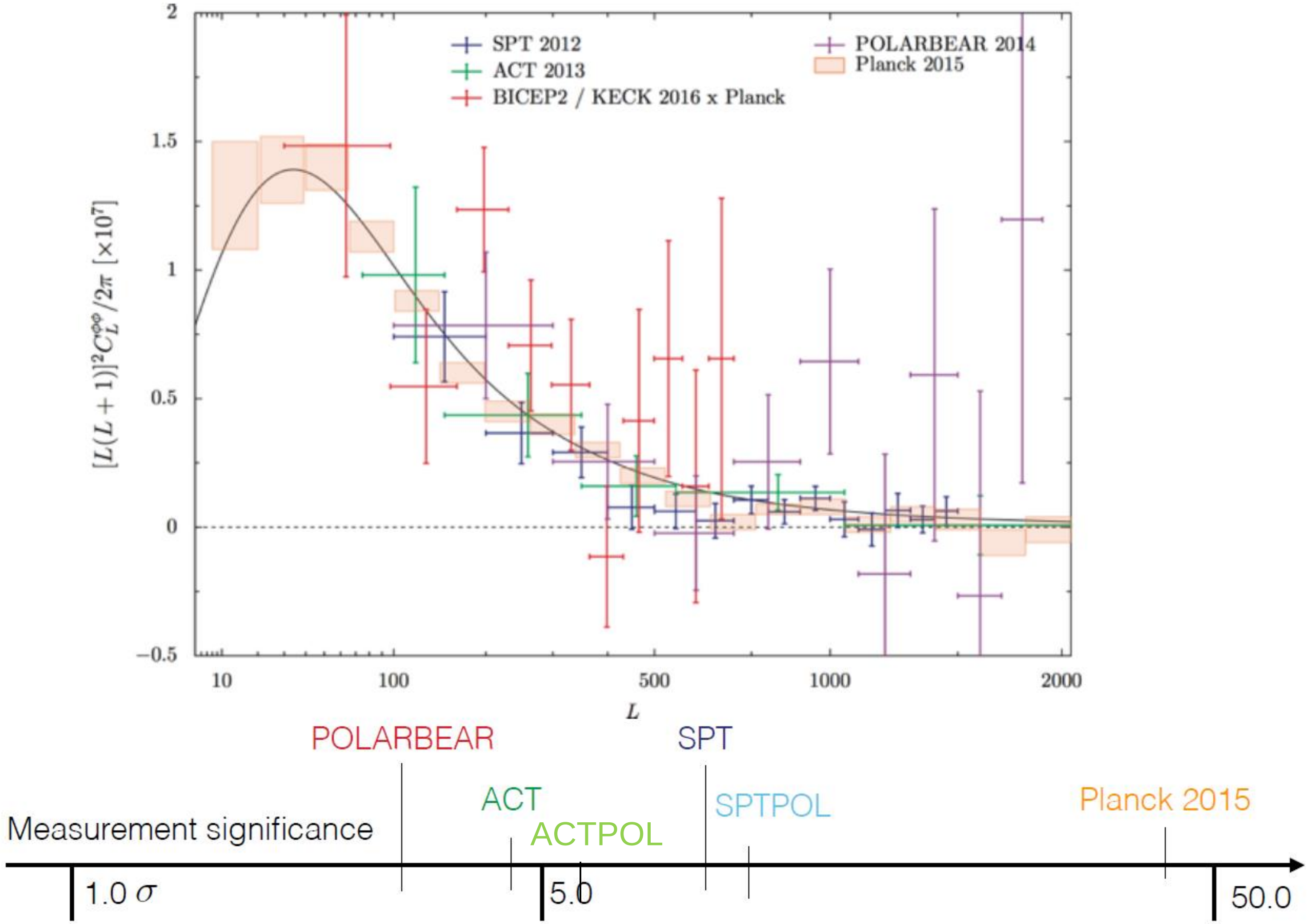
Simulated Planck lensing reconstruction



True simulation input



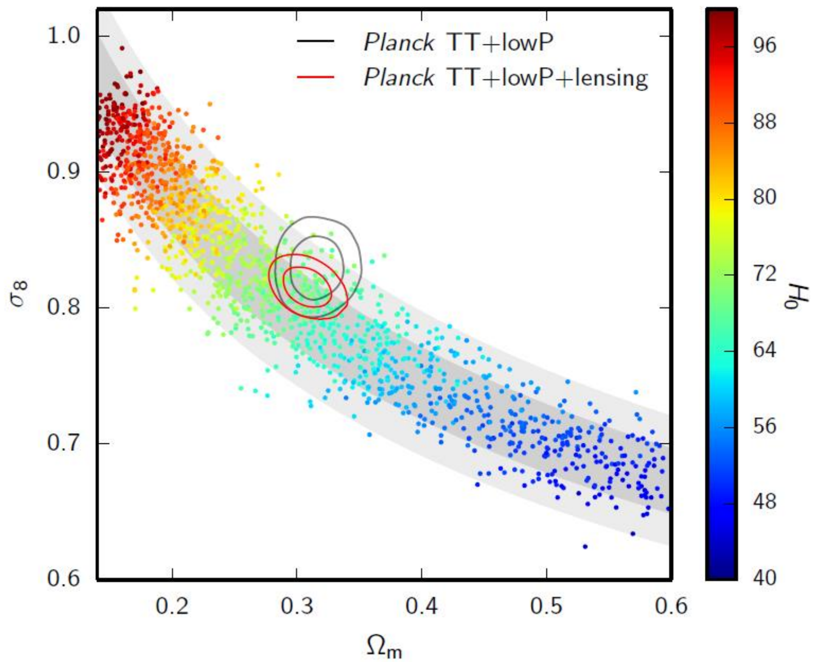
Lensing Power Spectrum Results



Credit: Julien Carron

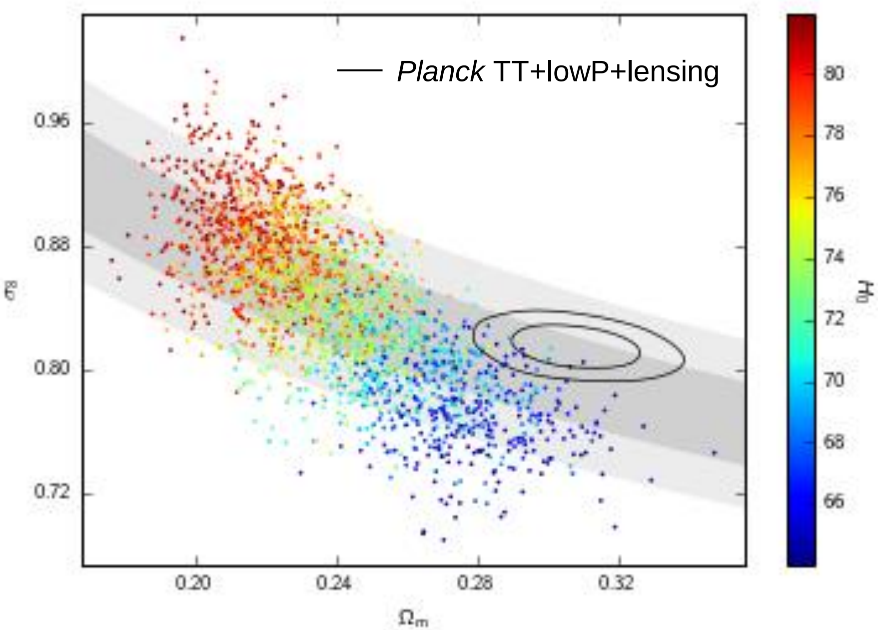
Cosmological parameters in LCDM

Planck CMB Lensing



Galaxy lensing (cosmic shear)
Kids-450 2016 (1606.05338)

+ weak Planck A_s prior



Are we heading for a clear breakdown of $LCDM$?

.. or statistical fluctuation, better understanding of galaxy shear systematics…?

In future joint analysis of CMB and lensing power spectra
should be able to detect down to $\sum m_\nu \sim 0.06\mathrm{eV}$ (with external data)

Experiment	Timeline	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$ (eV)
Planck	Present	0.18	0.23
AdvACT/SPT3G	2016-2019	0.06	0.06
CMB-S4	2020-?	0.02	0.016 (with DESI)

arXiv: 1303.5379

Full likelihood model in hand, accounting for non-independence of the signals

Full covariance of CMB and lensing reconstruction power spectra

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[2] *Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*
[3] *Berkeley Center for Cosmological Physics, University of California, Berkeley, CA 94720, USA*

(Dated: November 7, 2016)

CMB and lensing reconstruction power spectra are powerful probes of cosmology. However they are correlated, since the CMB power spectra are lensed and the lensing reconstruction is constructed using CMB multipoles. We perform a full analysis of the auto- and cross-covariances, including polarization power spectra and minimum variance lensing estimators, and compare with simulations of idealized future CMB-S4 observations. Covariances sourced by fluctuations in the unlensed CMB and instrumental noise can largely be removed by using a realization-dependent subtraction of lensing reconstruction noise, leaving a relatively simple covariance model that is dominated by lensing-induced terms and well described by a small number of principal components. The correlations between the CMB and lensing power spectra will be detectable at the level of $\sim 5\sigma$ for a CMB-S4 mission, and neglecting those could underestimate some parameter error bars by several tens of percent. However we found that the inclusion of external priors or data sets to estimate parameter error bars can make the impact of the correlations almost negligible.

arXiv:1611.01446
Code available on request to JP

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 lensing reconstruction**

a. Use best-estimate lensing field

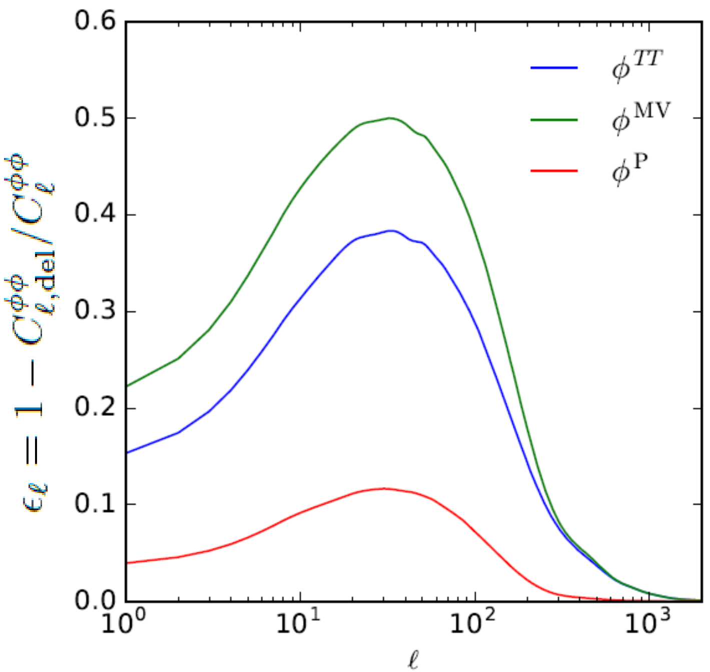
$$\hat{\phi}_{\mathcal{W},\ell m} = \mathcal{W}_\ell \, \hat{\phi}_{\ell m} \qquad \mathcal{W}_\ell = \frac{C_\ell^{\rm fid,\phi\phi}}{C_\ell^{\rm fid,\phi\phi} + N_{\ell,0}}$$

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

c. Remap points using estimated α to get delensed map

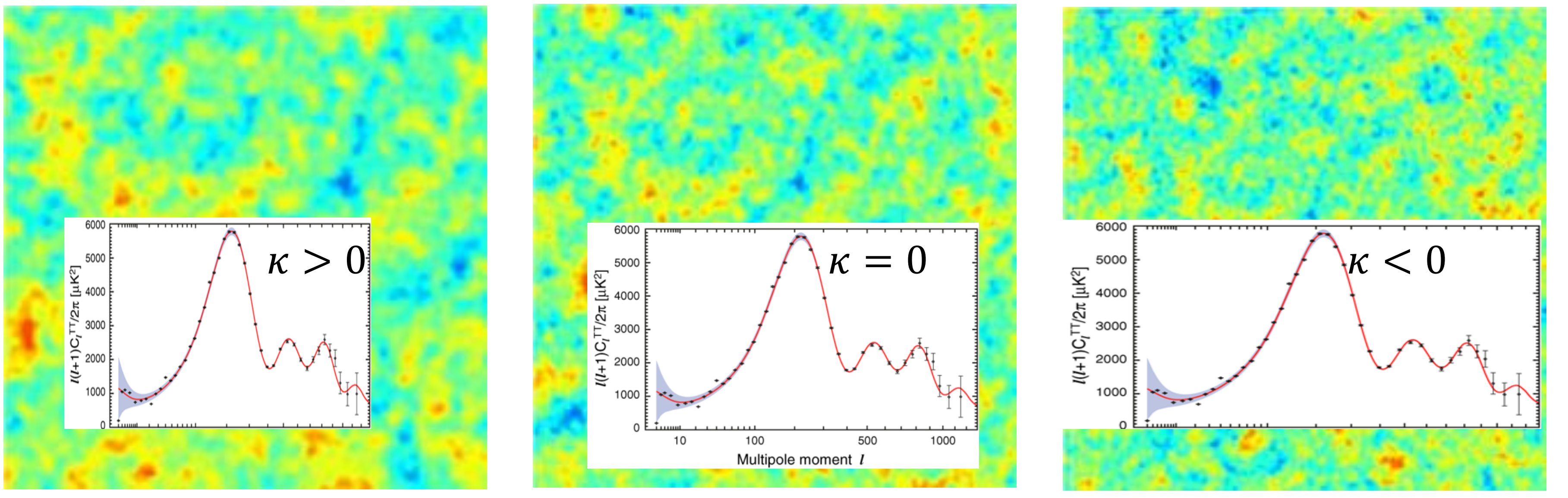
$$X^{\rm del} \equiv X^{\rm dat}(\boldsymbol{n} - \hat{\boldsymbol{\alpha}}_{\mathcal{W}}(\boldsymbol{n}))$$

Expected Planck internal delensing efficiencies

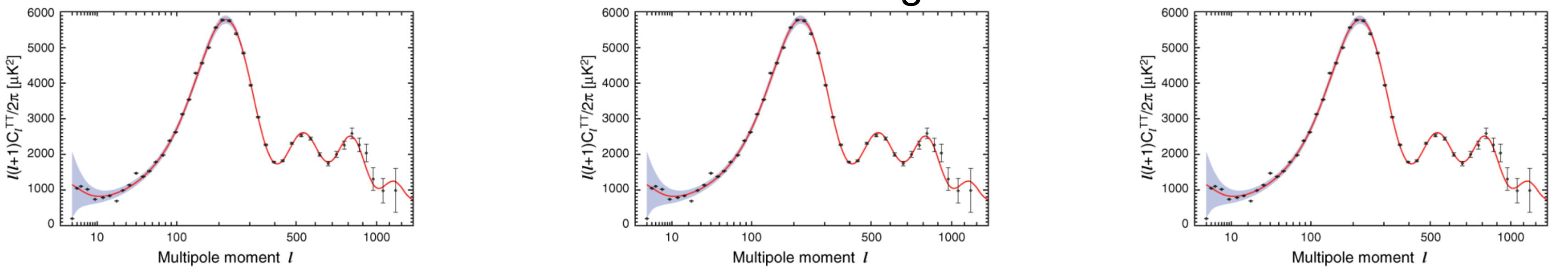


Carron, Lewis, Challinor in prep.

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

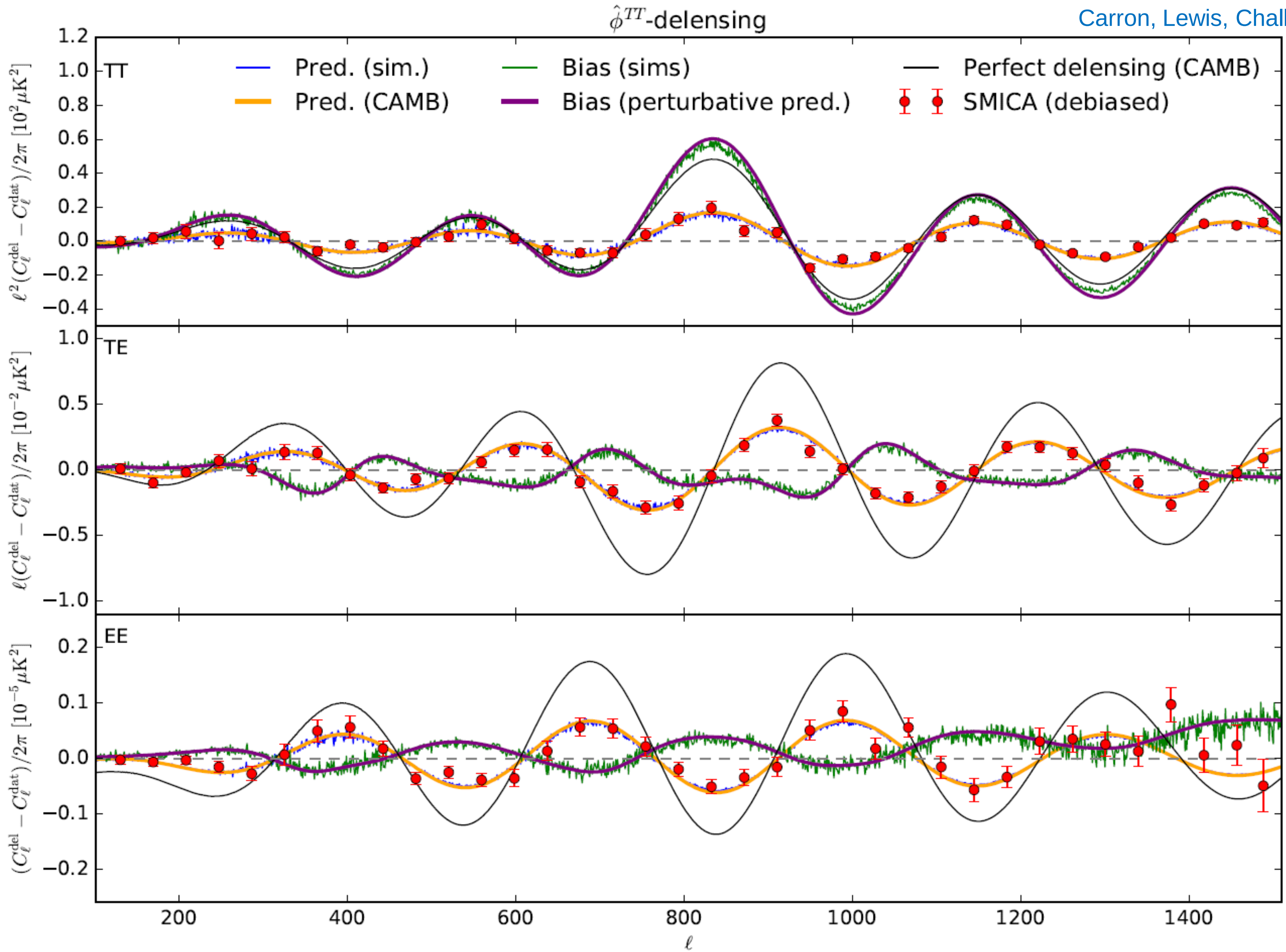
⇒ Delensing *artificially* sharpens the peaks, even with no actual lensing!

⇒ Must subtract bias expected even if no lensing

Power difference after delensing $C_l^{\rm delensed} - C_l^{\rm dat}$

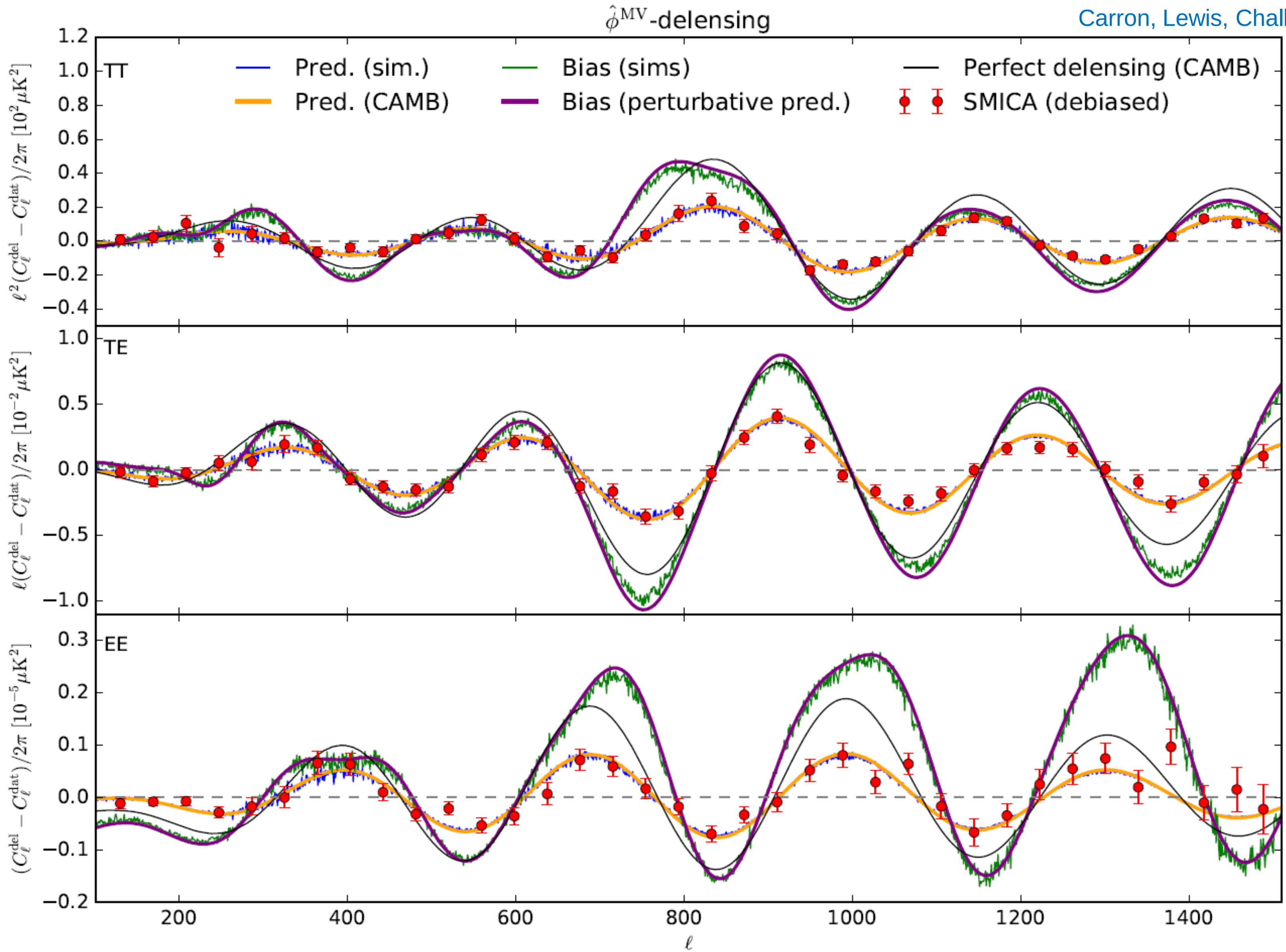
PRELIMINARY

Carron, Lewis, Challinor in prep.



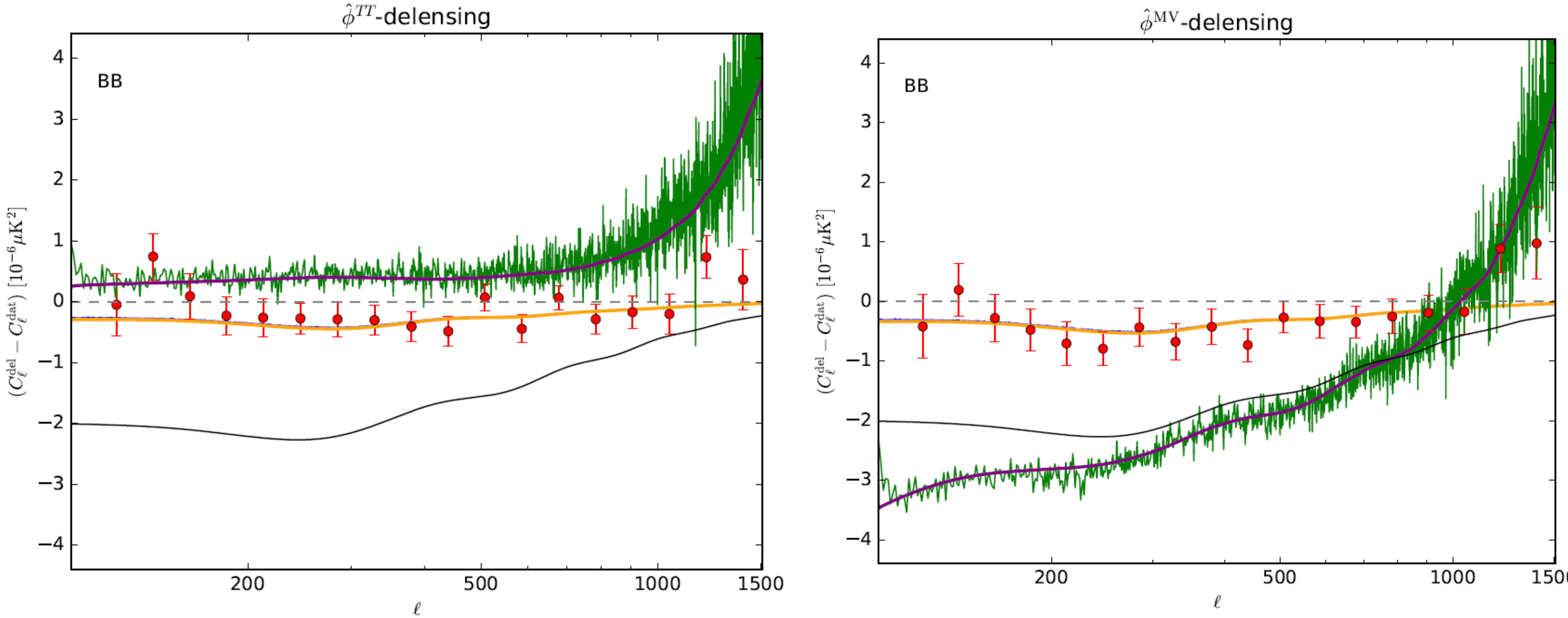
PRELIMINARY

Carron, Lewis, Challinor in prep.



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

Planck delensing of B-mode polarization



Detection of reduction in B-mode lensing power at 3-5σ

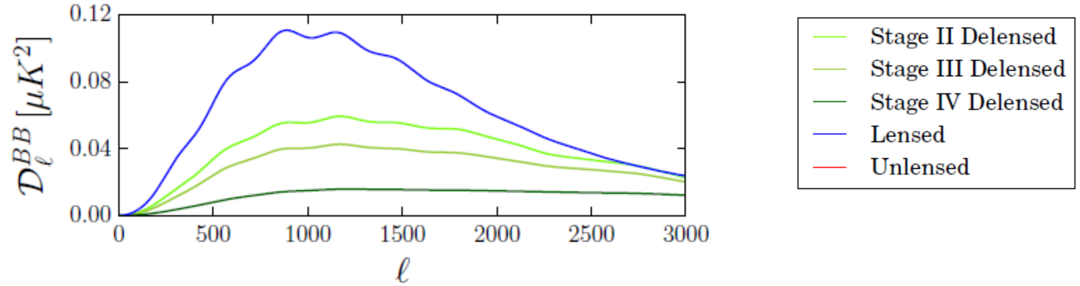
(but noise high, so does not yet help with tensor r constraint)

(VERY) PRELIMINARY

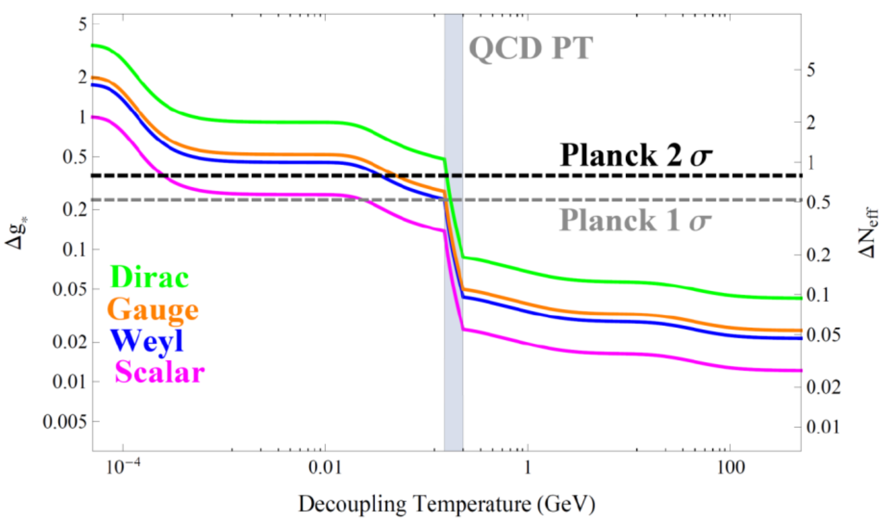
Carron, Lewis, Challinor in prep.

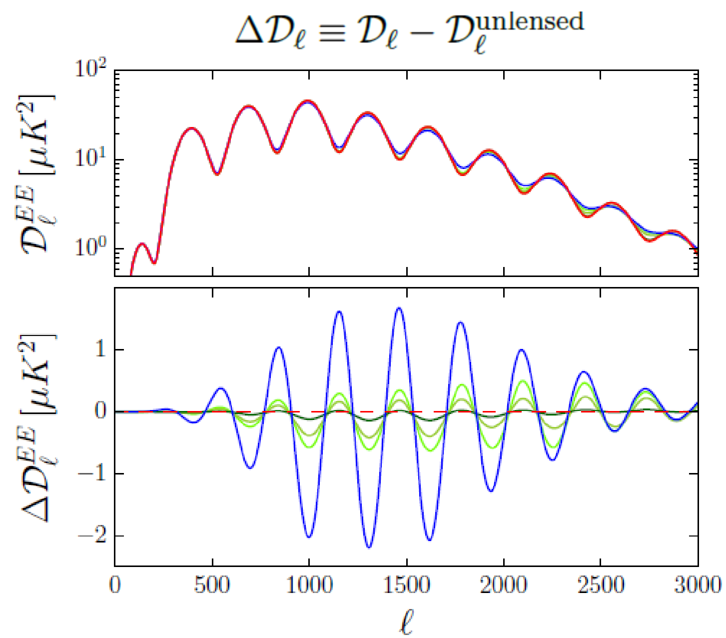
Future prospects

arXiv:1609.08143



Using EE clear physics targets may be (just) within reach of S4… also delens EE



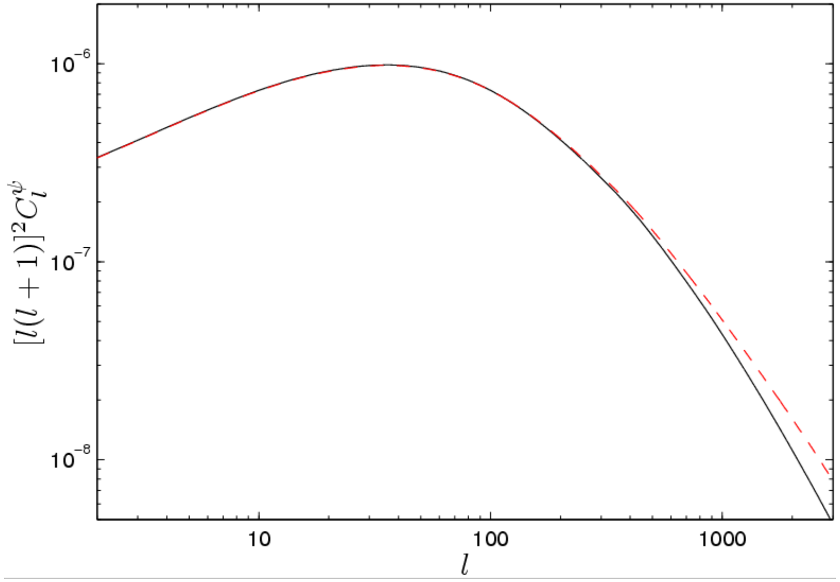


arXiv:1609.08143

Delensing can decrease errors by up to ~ 20%

Theory – how to predict the expected lensing signal?

1. **Linear Theory** (+ approximate non-linear matter power)
   lenses large and high redshift ⇒ nearly linear; Born approximation



2. **Non-linear effects:**
   - Important to quantify
   - Can give interesting new bispectrum and rotation signals

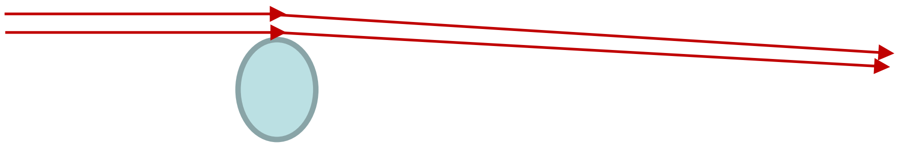
Post-Born lensing + non-linear structure formation

Pratten & Lewis: arXiv:1605.05662

Ray-deflection: first lens changes location of second lensing event

$$\Psi(\mathbf{x}_0 + \delta\mathbf{x}) \approx \Psi(\mathbf{x}_0) + \Psi_{,a}(\mathbf{x}_0)\delta x_a + \frac{1}{2}\Psi_{,ab}(\mathbf{x}_0)\delta x_a \delta x_b + \mathcal{O}(\Psi^4)$$

Linear approximation



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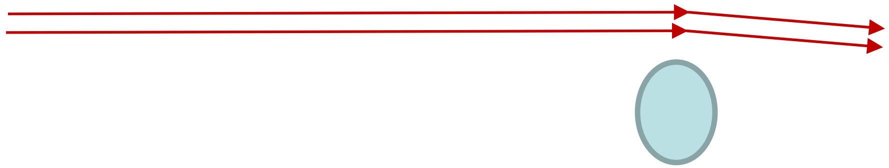

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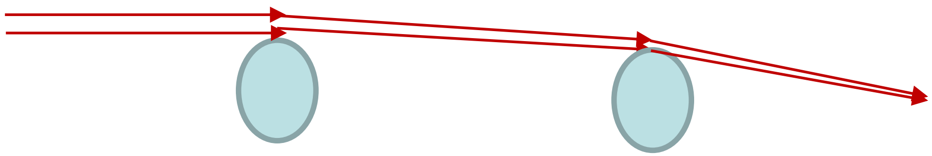
Post-Born lensing

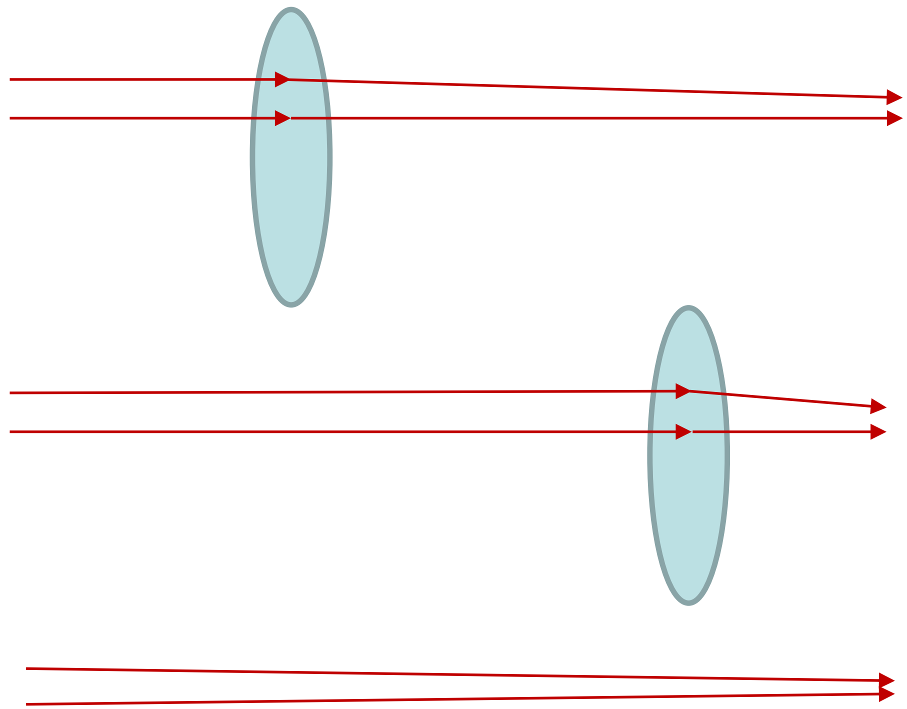
e.g. more net lensing



Lens-Lens coupling: Beam size (and shape) affected by first lensing event

$$\psi_{ab}(\boldsymbol{\theta},\chi) = 2\int_0^{\chi} d\chi'\,\chi'^2\,W(\chi',\chi)\,\Psi_{,ac}(\mathbf{x}')\,[\delta^c_b - \psi^c_b(\boldsymbol{\theta},\chi')]$$

Linear approximation



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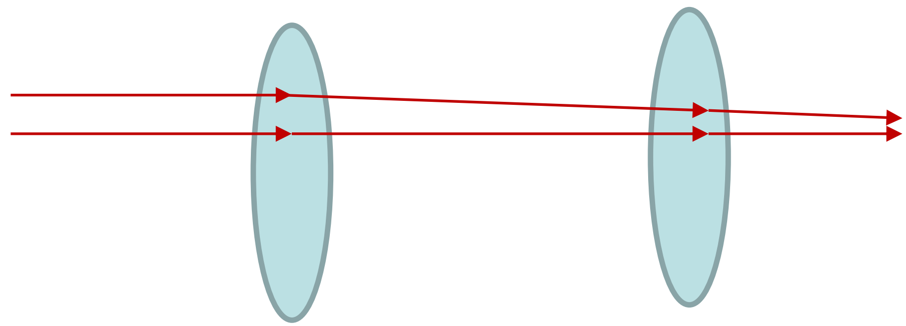
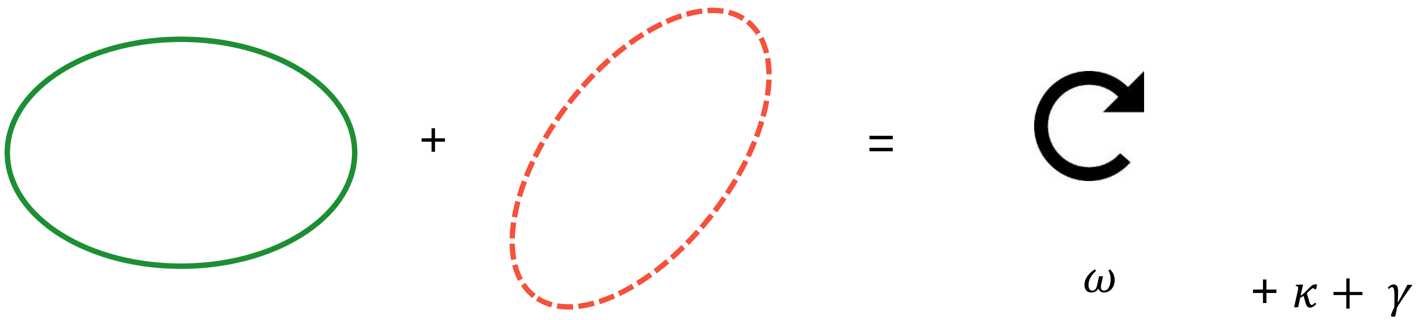
Post-Born lensing



e.g. less net lensing

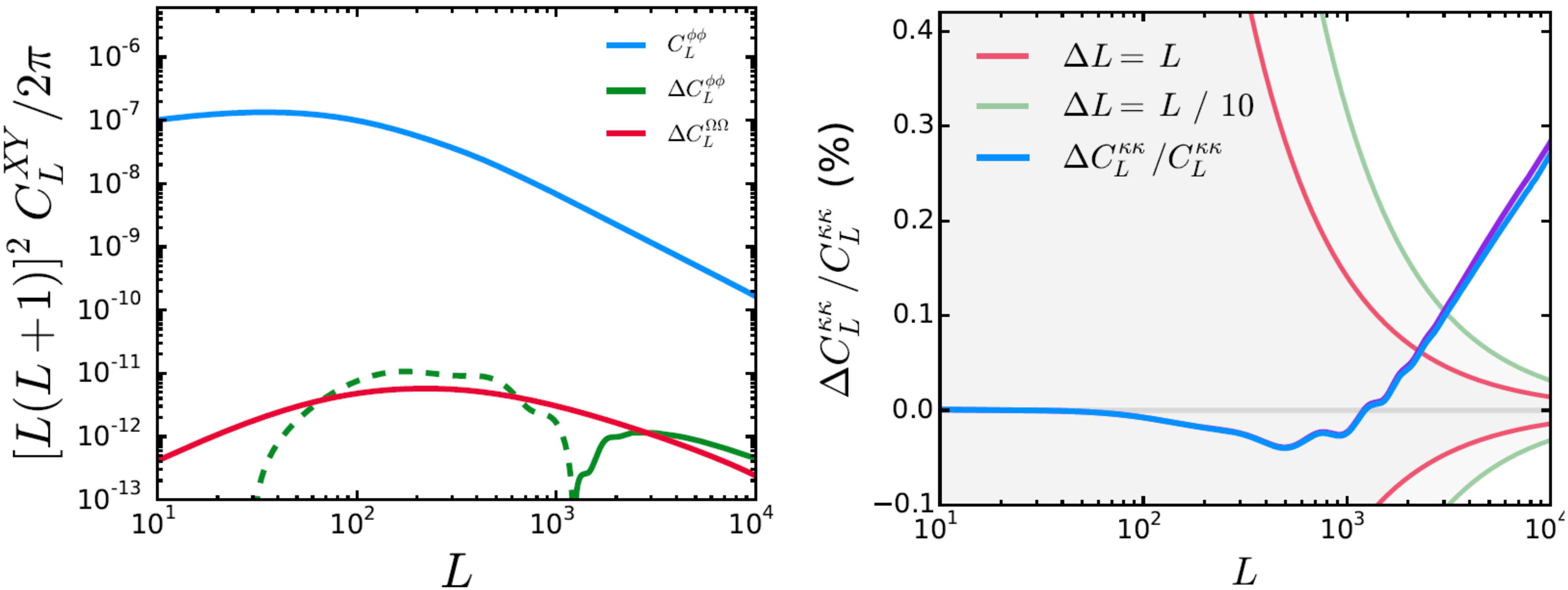
Lens-Lens with two non-aligned shears ⇒ rotation



- Post-Born effects can change power spectra

- Rotation could introduce new source of confusing B-modes

Effect on lensing convergence and rotation power spectra

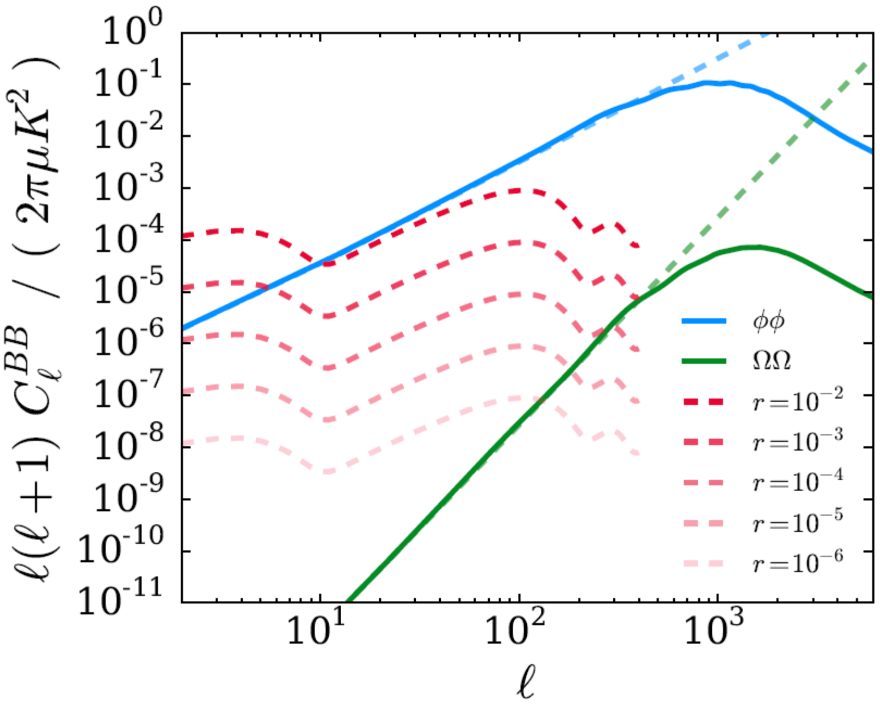


Pratten & Lewis: arXiv:1605.05662

- Negligible change to convergence spectrum
- Non-zero rotation spectrum

Safe to neglect for near future ($< 10^{-3}$)

B-mode signal from rotation



~2.5% of B mode amplitude from rotation

Pratten & Lewis: arXiv:1605.05662

How Gaussian is the lensing potential field?

Non-Gaussianity potentially important:

- Useful extra signal? (Namikawa 2016)
- Biases on lensing quadratic estimators (Boehm et al 2016)
- Corrections to the lensed CMB power spectra (Lewis & Pratten 16)

Expected to be quite small:

Large distance to CMB ⇒ many independent lenses

⇒ Gaussianization by central limit theorem

But how non-Gaussian, and what shape?...

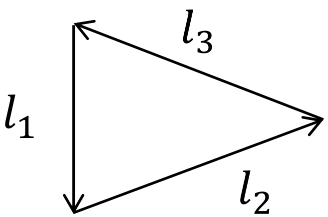
Flat sky approximation: $\kappa(x) = \frac{1}{2\pi}\int d^2l\, \kappa(l) e^{ix\cdot l}$

Gaussian + statistical isotropy

$$\langle \kappa(l_1)\kappa(l_2)\rangle = \delta(l_1 + l_2) C_l^{\kappa}$$

- power spectrum encodes all the information
- modes with different wavenumber are independent

Bispectrum

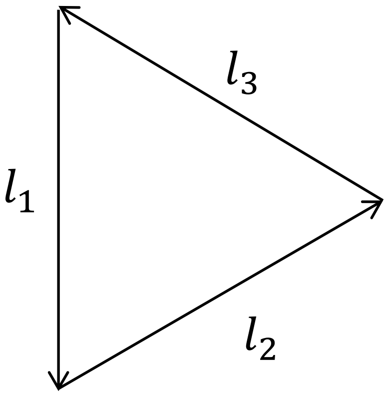


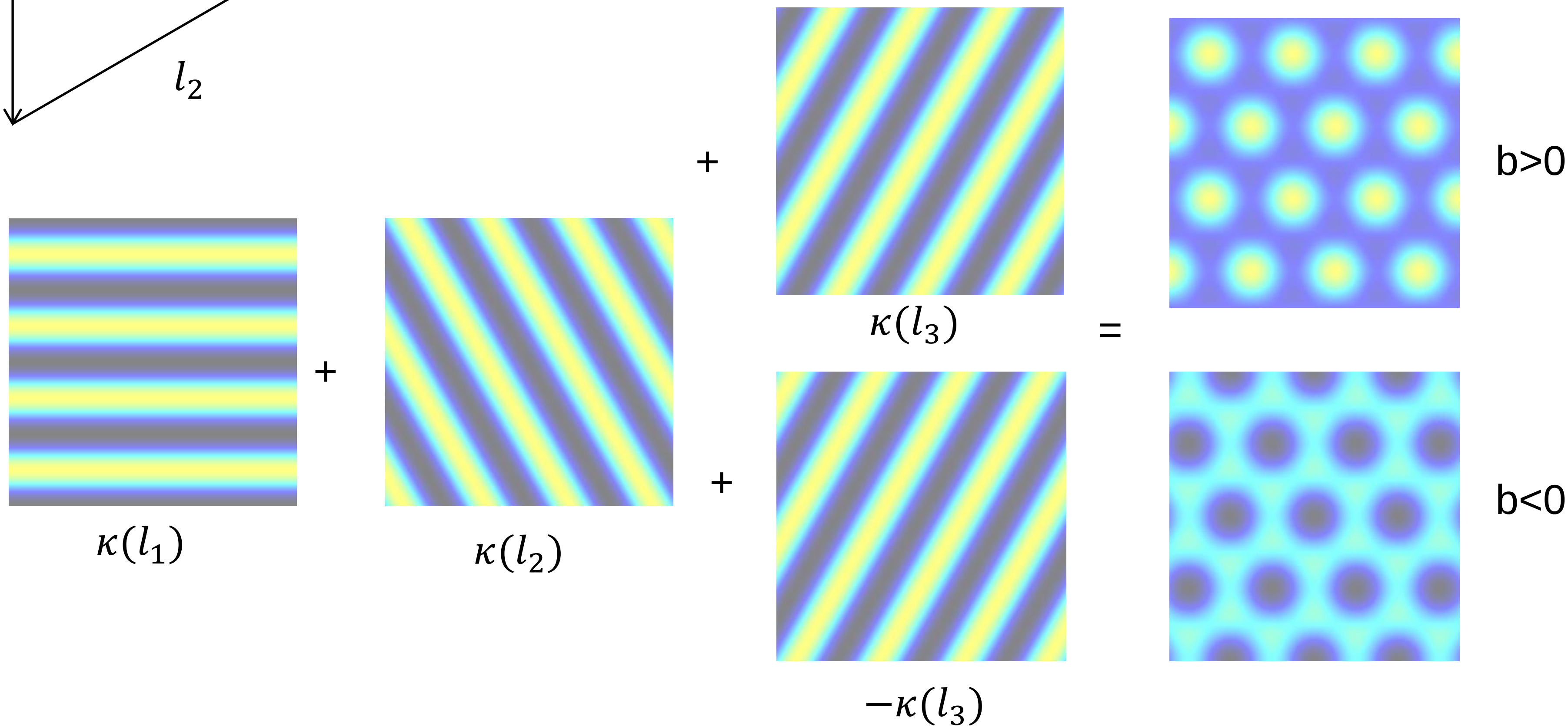
$$\boldsymbol{l_1} + \boldsymbol{l_2} + \boldsymbol{l_3} = \boldsymbol{0}$$

Flat sky approximation: $\langle \kappa(l_1)\kappa(l_2)\kappa(l_3)\rangle = \frac{1}{2\pi}\delta(l_1 + l_2 + l_3) b_{l_1 l_2 l_3}$

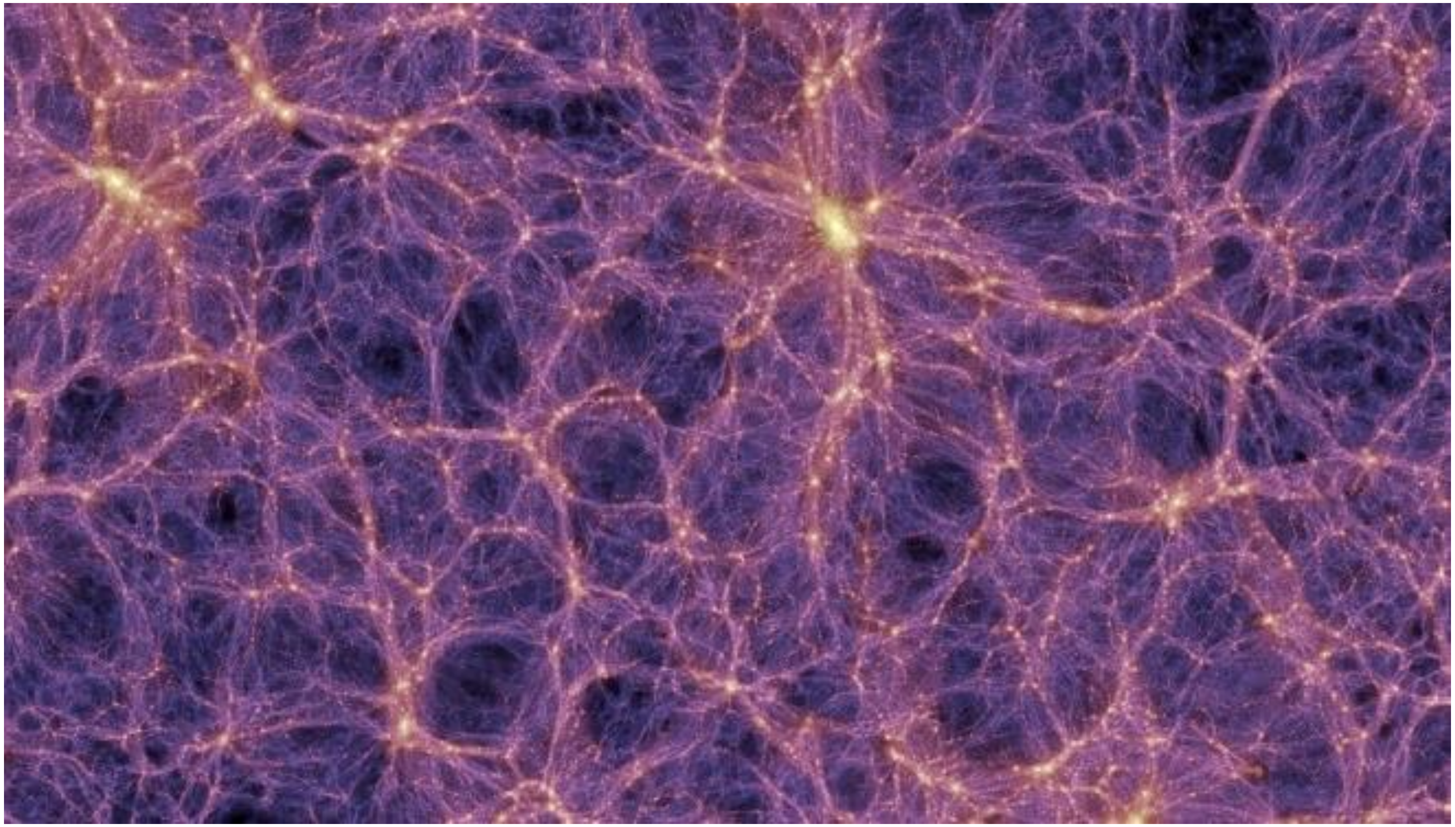
If you know $\kappa(l_1), \kappa(l_2)$, sign of $b_{l_1 l_2 l_3}$ tells you which sign of $\kappa(l_3)$ is more likely

Equilateral $\quad l_1 + l_2 + l_3 = 0, |l_1| = |l_2| = |l_3|$





Lewis: The Real Shape of Non-Gaussianities, arXiv:1107.5431



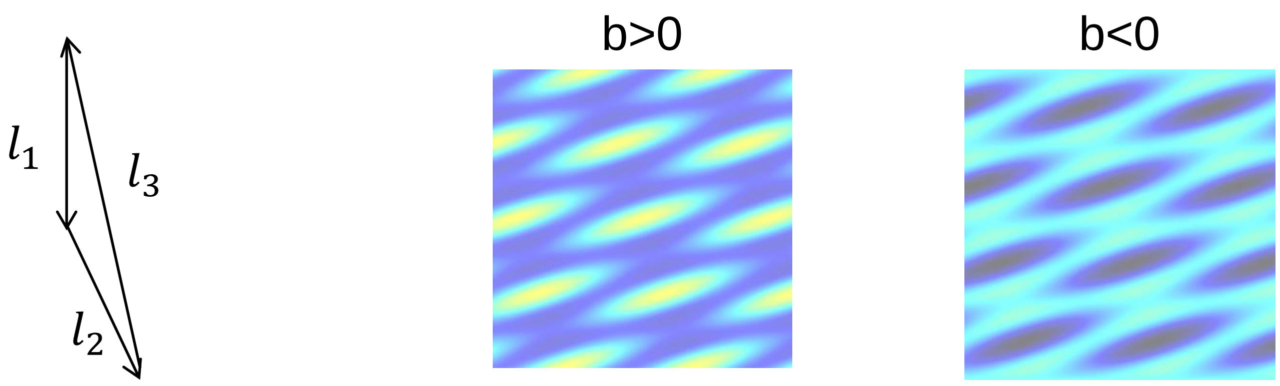
Millennium simulation

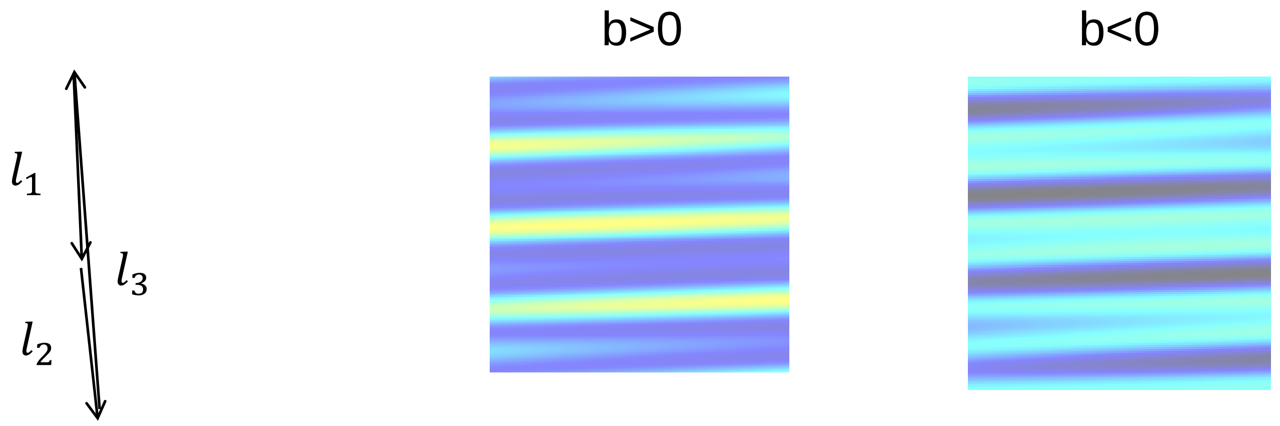
In 2D projection (e.g. lensing)

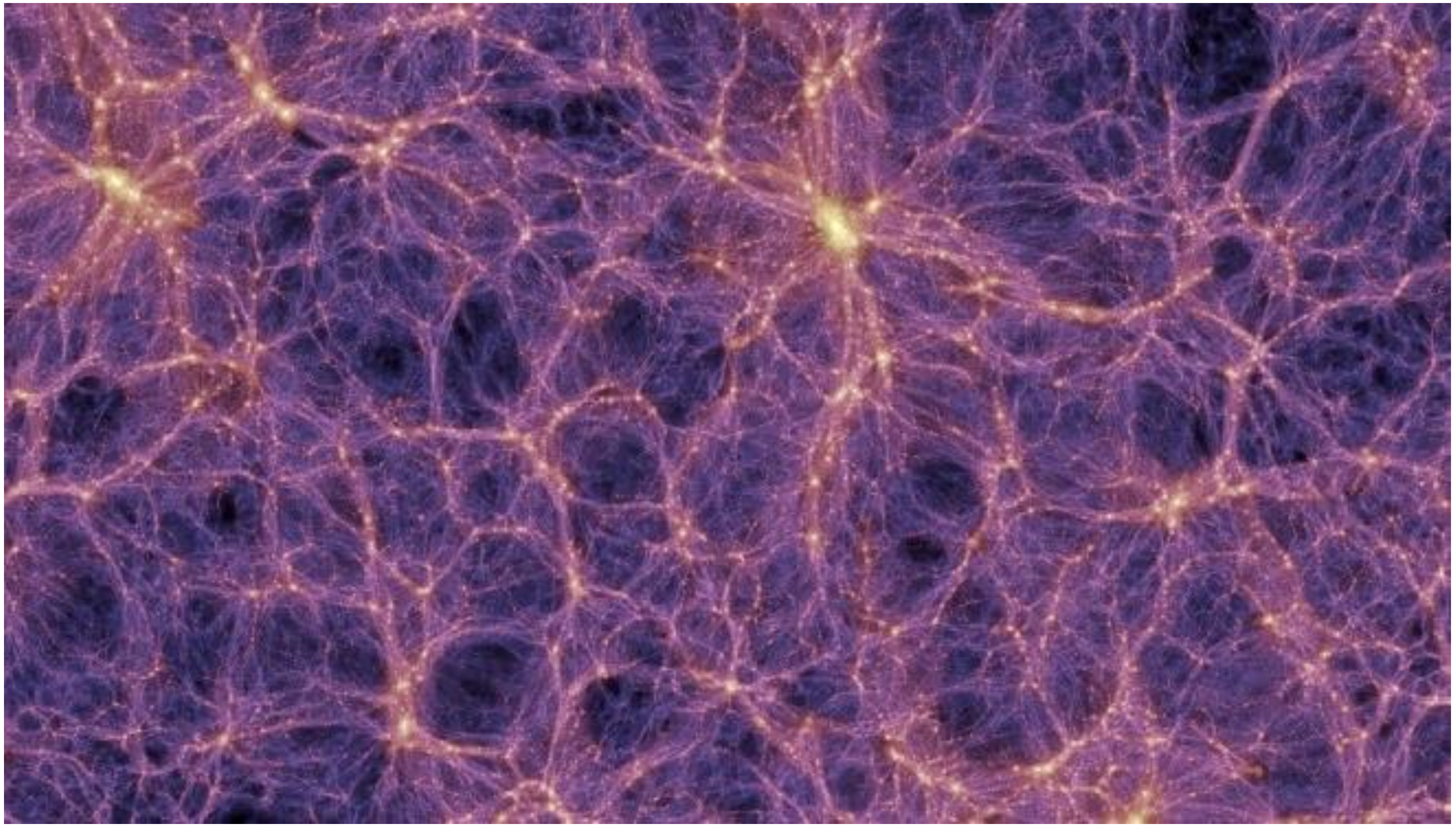
Clusters → Positive equilateral bispectrum

(+sight-aligned filaments)

Near-equilateral to flattened/folded:







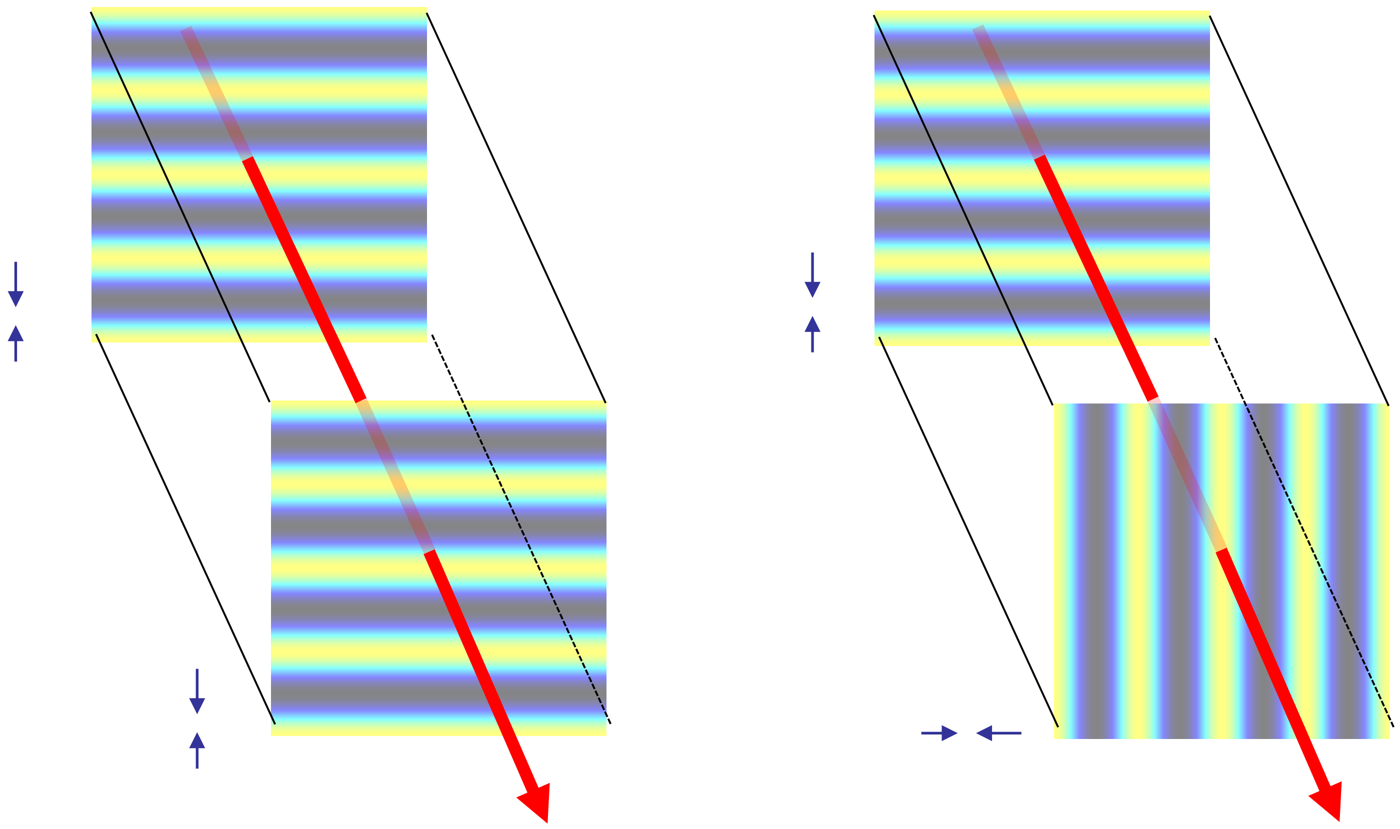
Millennium simulation

In 2D projection (e.g. lensing)

Filaments ⇒ Positive flattened bispectrum

(+sight-aligned sheets)

LSS has positive bispectrum, hence κ bispectrum from LSS also positive.
What about post-Born?



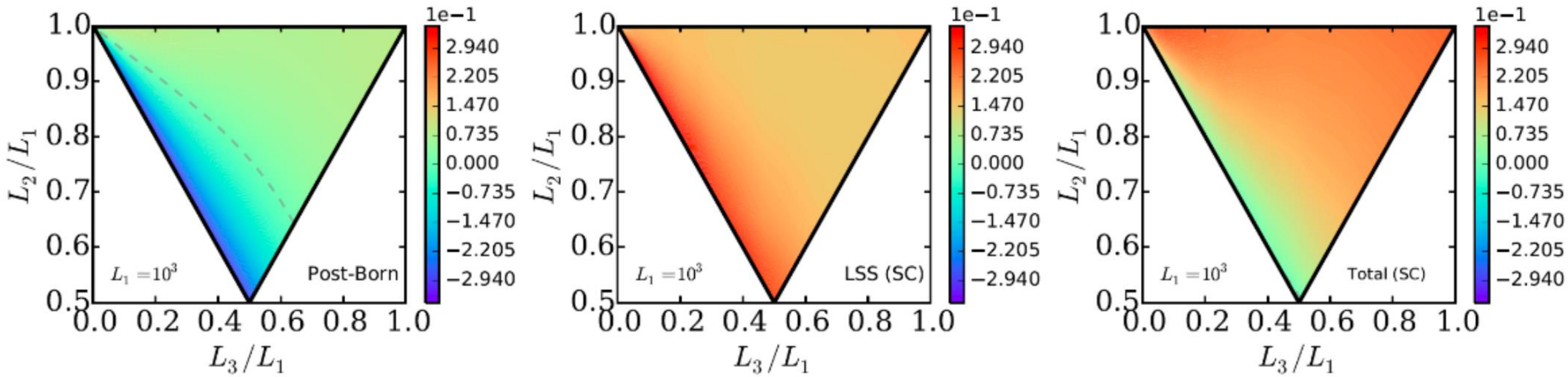
Big negative lens-lens effect

Zero lens-lens effect

Negative flattened bispectrum

Convergence Bispectrum

Post-born + LSS = Total

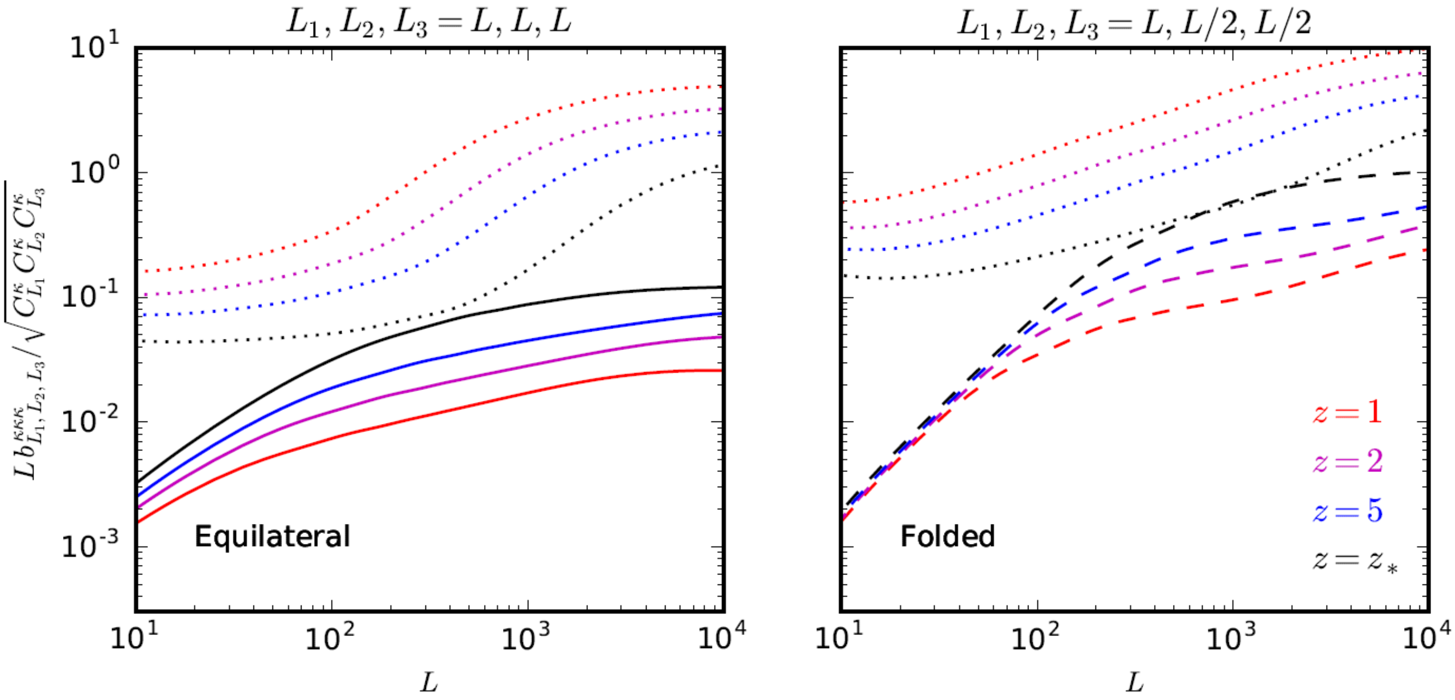


$(L_2 L_3)^{1/2}\, b^{\kappa\kappa\kappa}_{L_1 L_2 L_3} / (C^{\kappa\kappa}_{L_1} C^{\kappa\kappa}_{L_2} C^{\kappa\kappa}_{L_3})^{1/2}$

Unexpectedly small folded Gaussianity of the CMB lensing convergence!

Pratten & Lewis: arXiv:1605.05662

This cancellation is a fluke, LSS dominates at lower redshifts



Pratten & Lewis: arXiv:1605.05662

Naïve S/N for post-Born and total bispectrum

Small but may be important for S4

	noise [μK arcmin]	beam [arcmin]	$\ell_{\rm max}$	$f_{\rm sky}$	$\Delta\kappa\kappa$ S/N	$\omega\omega$ S/N	$\kappa\kappa\kappa$ S/N	$\kappa\kappa\omega$ S/N
Planck	33	5	2000	0.7	0.0	0.0	0.8	0.1
Simons Array	12	3.5	4000	0.65	0.0	0.0	3.4	0.4
SPT 3G	4.5	1.1	4000	0.06	0.0	0.0	2.3	0.4
S4	1	3	4000	0.4	0.2	0.7	25	3.1
S5	0.25	1	4000	0.5	0.8	2.7	99	8.8

Negligible

Can measure ω from its bispectrum with κ?

Pratten & Lewis: arXiv:1605.05662

Conclusions

Lensing the leading secondary effect on the CMB anisotropies

Well measured by Planck
- 2017 release coming up; many others over next 10 years

Test LCDM, constrain parameters, $\sum m_\nu$, dark energy, etc.

Delensing works! Will be important for future tensor mode searches.

Post-Born impact on power spectra negligible for near future

But LSS and post-Born important for CMB convergence bispectrum

- "lucky" cancellation makes CMB lensing remarkably Gaussian
- but bispectrum still detectable with future data
- could also detect lensing rotation using $\kappa\kappa\omega$ bispectrum