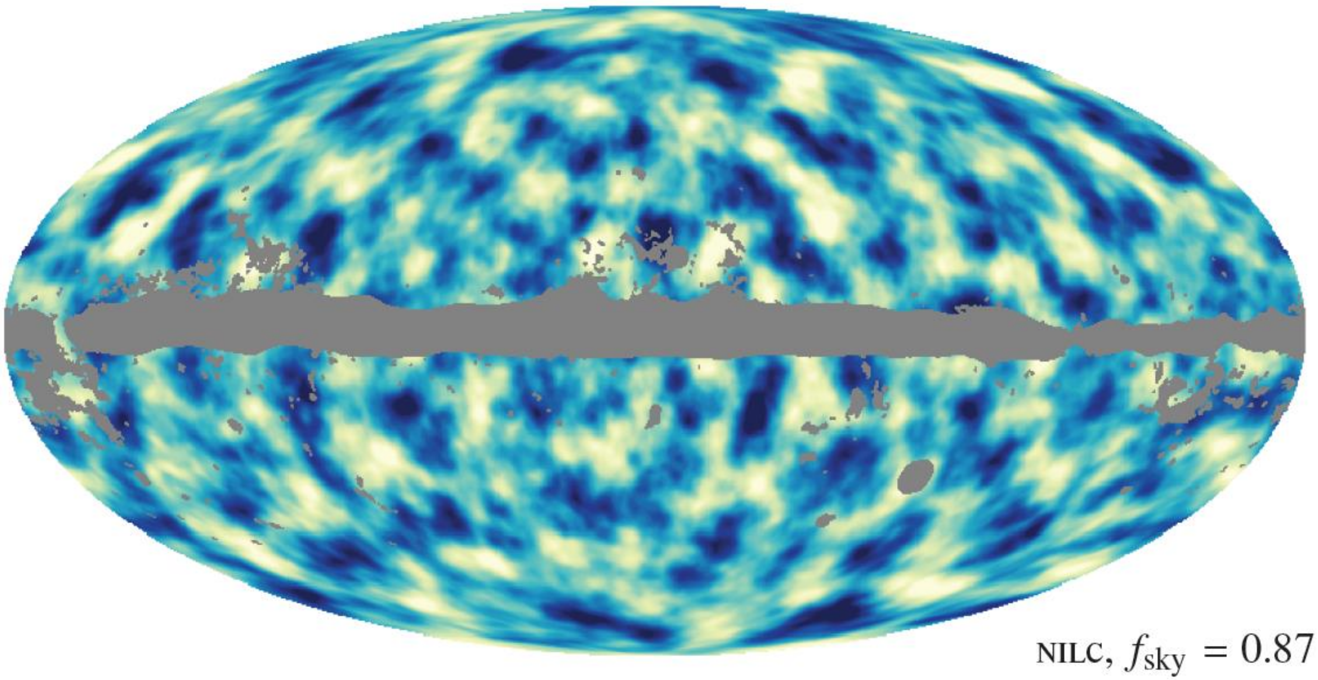
Lensing from Planck

Antony Lewis
On behalf of the Planck Collaboration
(several slides credit Duncan Hanson)

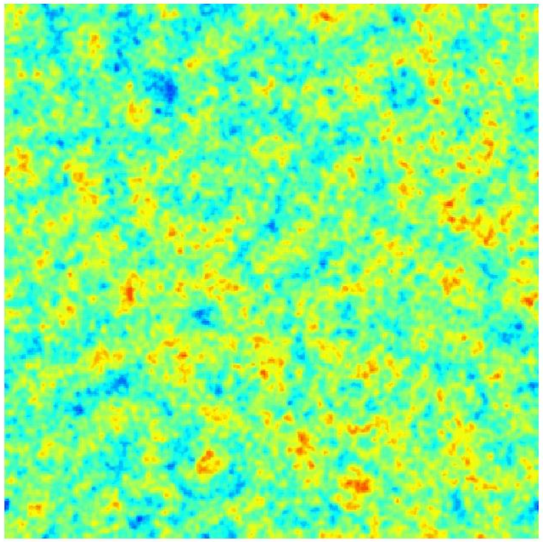


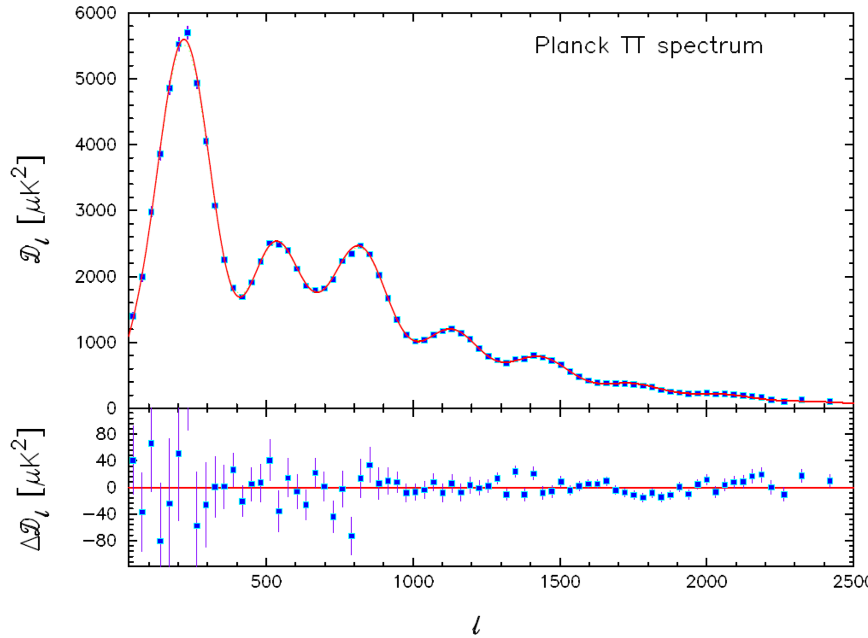
University of Sussex

http://cosmologist.info/

Observed CMB temperature power spectrum

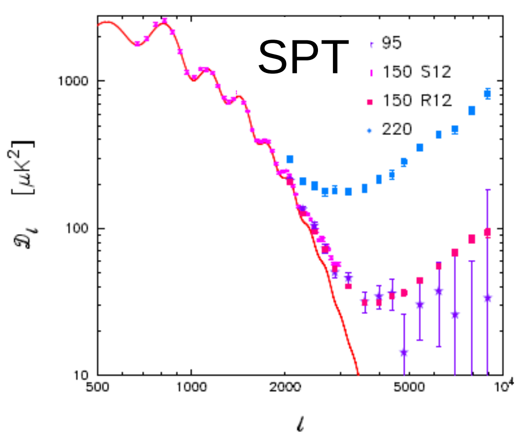
Perturbations accurately linear and Gaussian at last-scattering
- statistics completely described by the power spectrum C_l

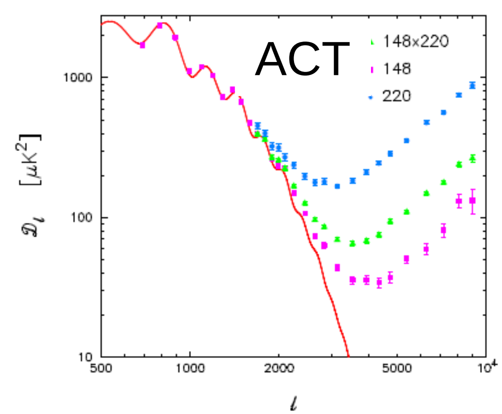




TT well-measured by Planck ($l < 2500$) and smaller scales by ACT and SPT ($l > 500$)

+ large foregrounds at $l \gg 2000$





Planck Collaboration
Story et al, Reichardt et al, Das et al,

Detailed measurement of 6 power spectrum acoustic peaks

⇨ Accurate measurement of cosmological parameters?

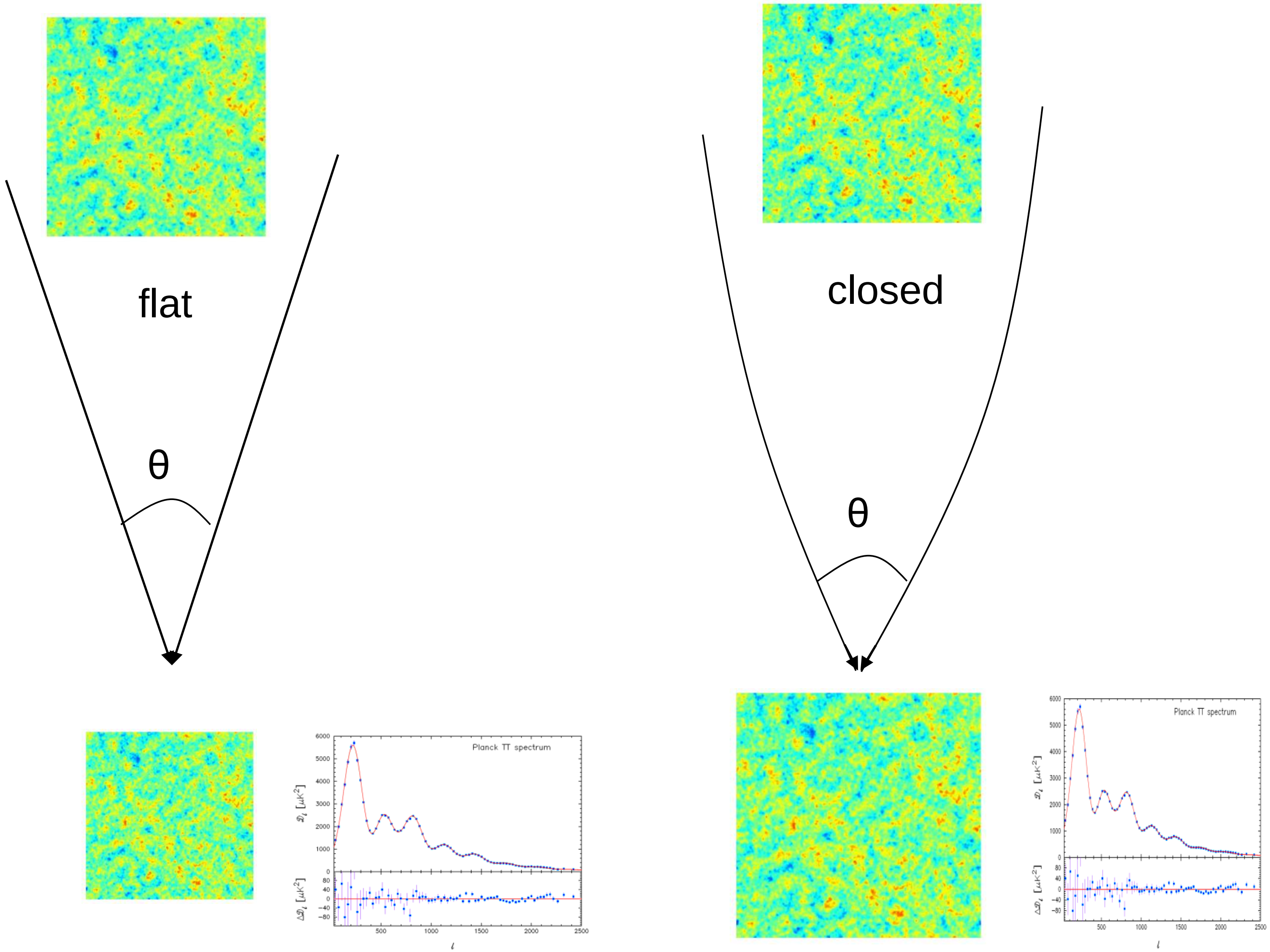
YES: some particular parameters measured very accurately

0.1% accurate measurement of the acoustic scale:

$$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724^\circ \pm 0.00038^\circ.$$

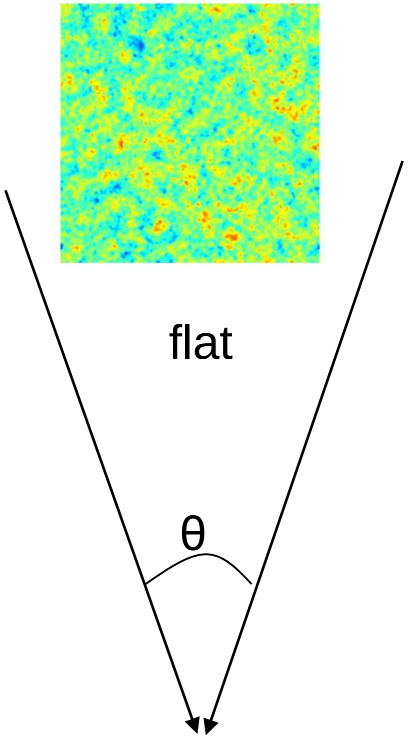
But need full cosmological model to relate to underlying physical parameters..

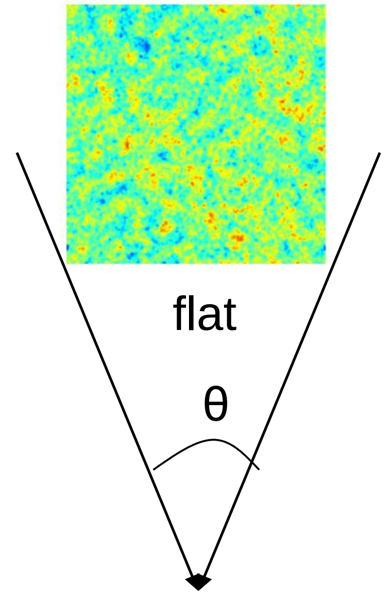
e.g. Geometry: curvature



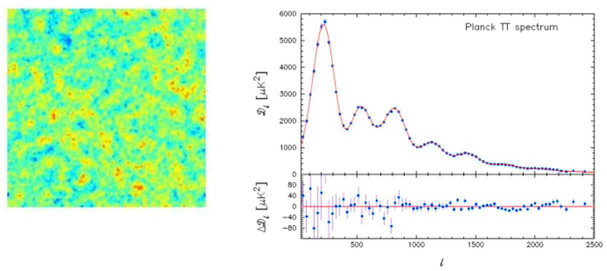
We see:

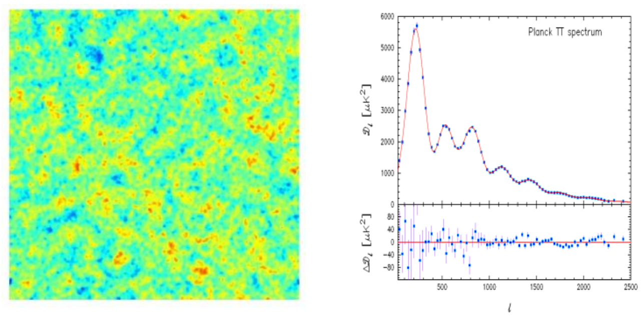
or is it just closer??





We see:





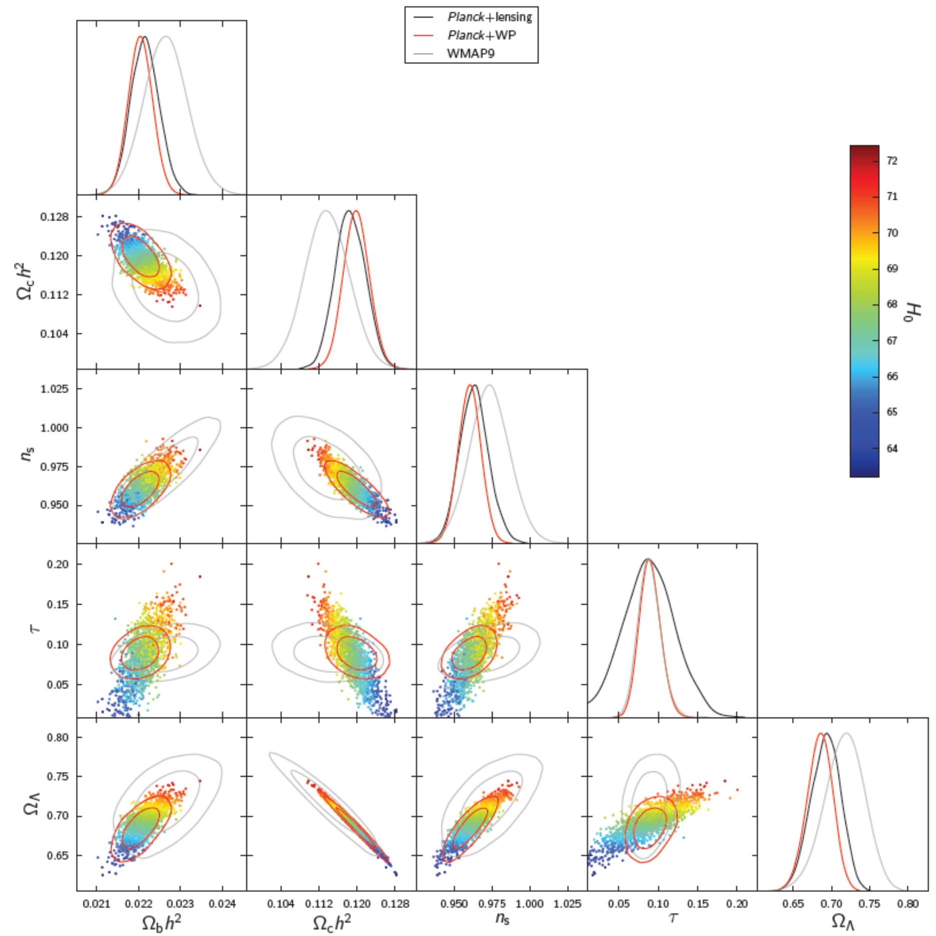
Degeneracies between parameters

1. Assume a model

LCDM baseline model:

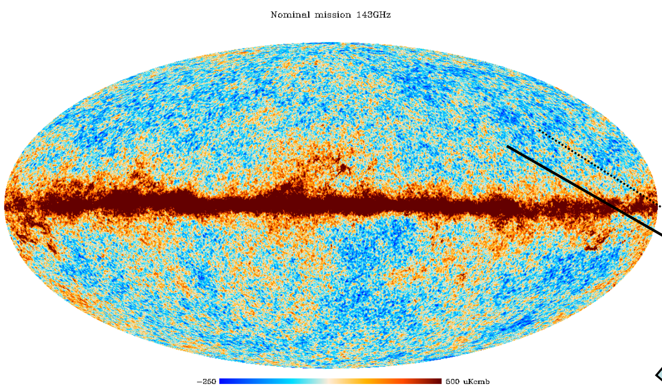
Flat, dark matter, cosmological constant, neutrinos, photons: six free parameters.
Assume 3 neutrinos, minimal-mass hierarchy with $\sum m_\nu = 0.06\text{eV}$.

	Planck	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072
Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020
σ_8	0.8344	0.834 ± 0.027
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$
H_0	67.11	67.4 ± 1.4



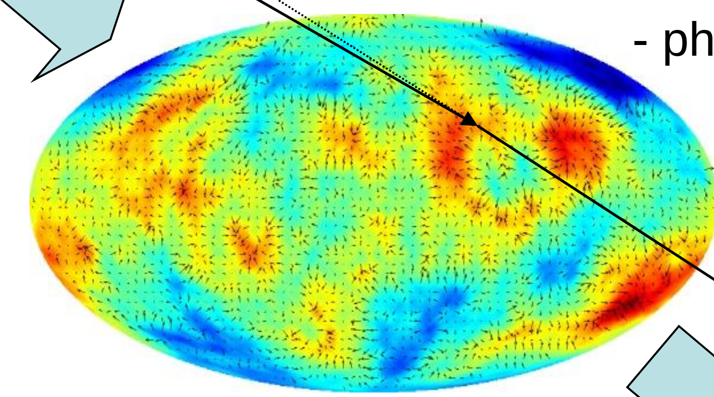
2. Use additional data or non-Gaussianities to break degeneracies

Weak lensing of the CMB perturbations



Last scattering surface

Inhomogeneous universe
- photons deflected



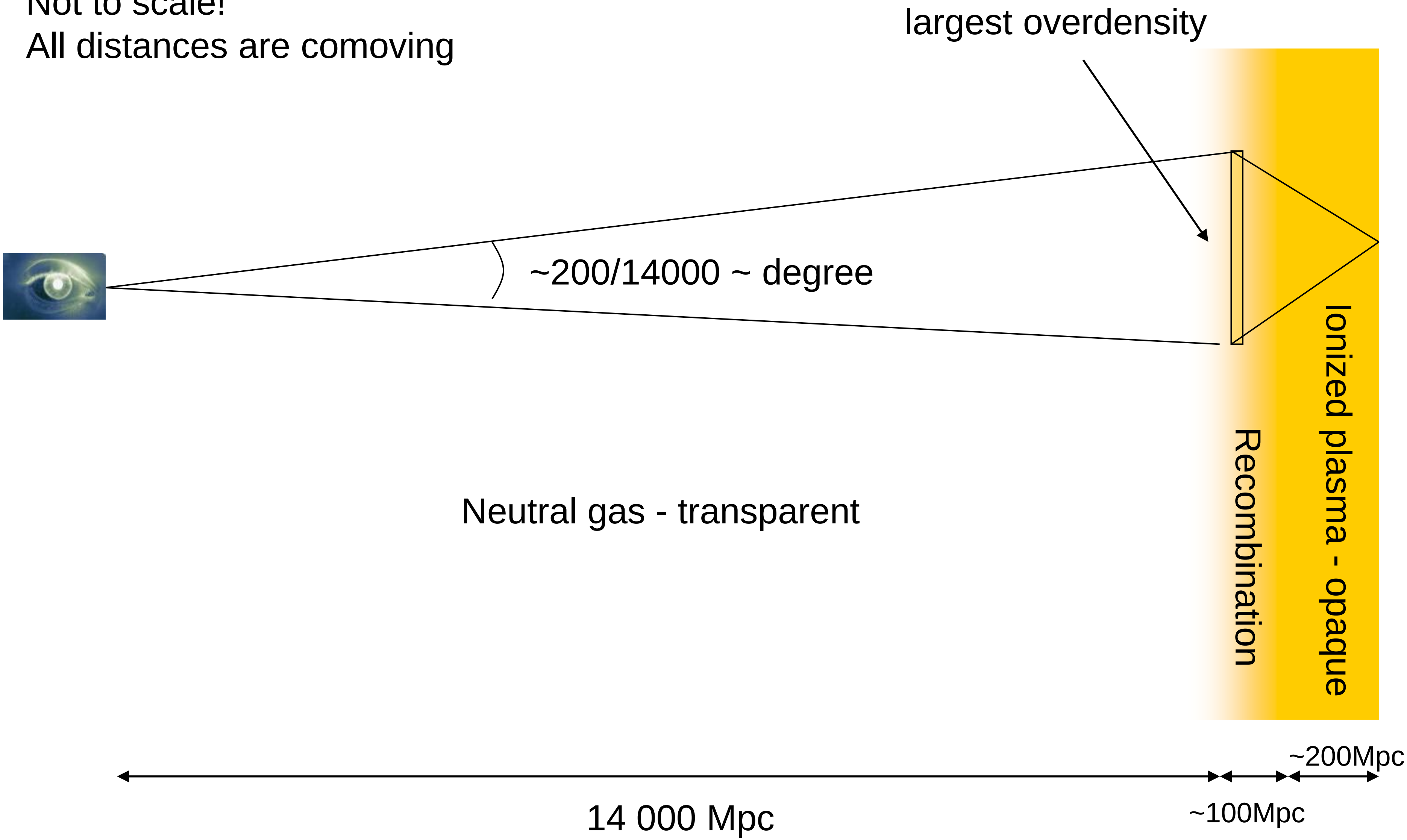
Observer

$$\tilde{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}') = T(\hat{\mathbf{n}} + \boldsymbol{\alpha})$$

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

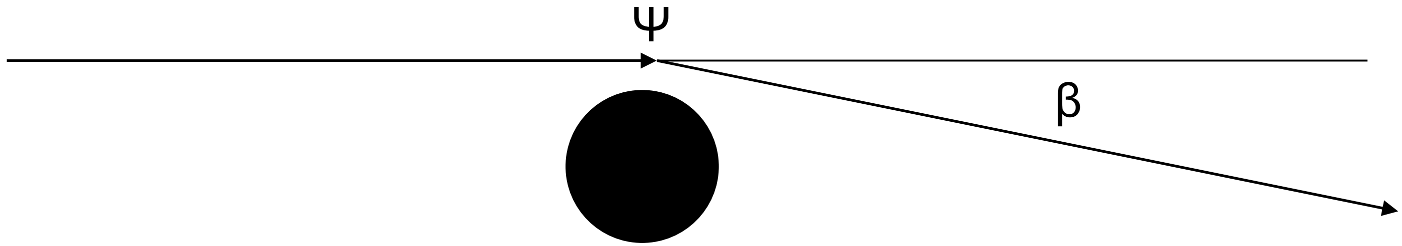
$$\psi(\hat{\mathbf{n}}) = -2\int_0^{\chi_*} \mathrm{d}\chi\, \Psi(\chi\hat{\mathbf{n}}; \eta_0 - \chi)\, \frac{f_K(\chi^* - \chi)}{f_K(\chi^*) f_K(\chi)}$$

Not to scale!
All distances are comoving



Good approximation: CMB is single source plane at ~14 000 Mpc
Angular diameter distance well measured by angle of acoustic peaks

Lensing order of magnitude



General Relativity: $\beta = 4\,\Psi$ $(\beta \ll 1)$

Potentials linear and approx Gaussian: $\Psi \sim 2 \times 10^{-5} \Rightarrow \beta \sim 10^{-4}$

Potentials scale-invariant on large scales, decay on scales smaller than matter-power spectrum turnover:
⇒ most abundant efficient lenses have size ~ peak of matter power spectrum ~ 300Mpc

Comoving distance to last scattering surface ~ 14000 MPc

⇒ pass through ~50 lenses ⇒ total deflection $\sim 50^{1/2} \times 10^{-4}$

assume uncorrelated

~ 2 arcminutes

(neglects angular factors, correlation, etc.)

Why lensing is important

- 2arcmin deflections: $l \sim 3000$
  - On small scales CMB is very smooth so lensing dominates the linear signal at high l

- Deflection angles coherent over 300/(14000/2) ~ 2°
  - comparable to CMB scales
  - expect 2arcmin/60arcmin ~ 3% effect on main CMB acoustic peaks

- Non-linear: observed CMB is non-Gaussian
  - more information
  - potential confusion with primordial non-Gaussian signals

- Does not preserve E/B decomposition of polarization: e.g. $E \to B$
  - Confusion for primordial B modes (“r-modes”)
  - No primordial B ⇒ B modes clean probe of lensing

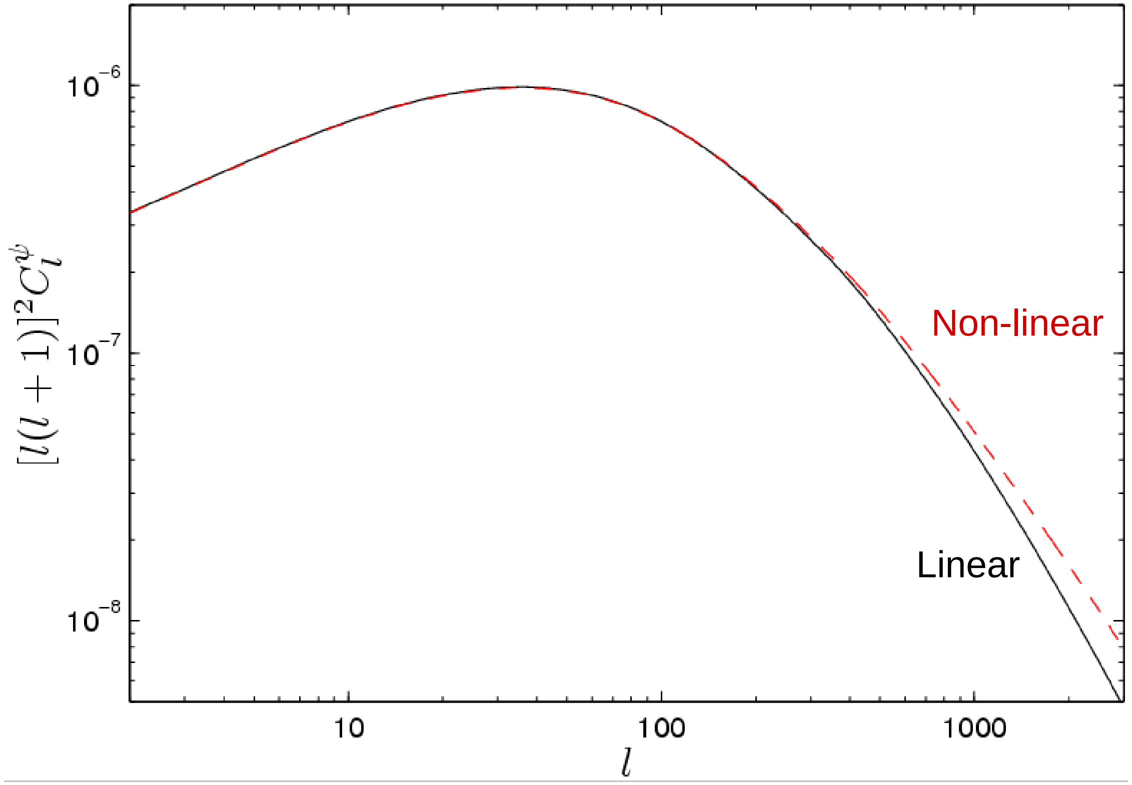
Deflection angle power spectrum

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

Potentials nearly linear ⇒ lensing potential nearly Gaussian

(also central limit theorem on small less-linear scales – lots of small lenses)

Note: In this talk
$\psi = \phi$ in many places

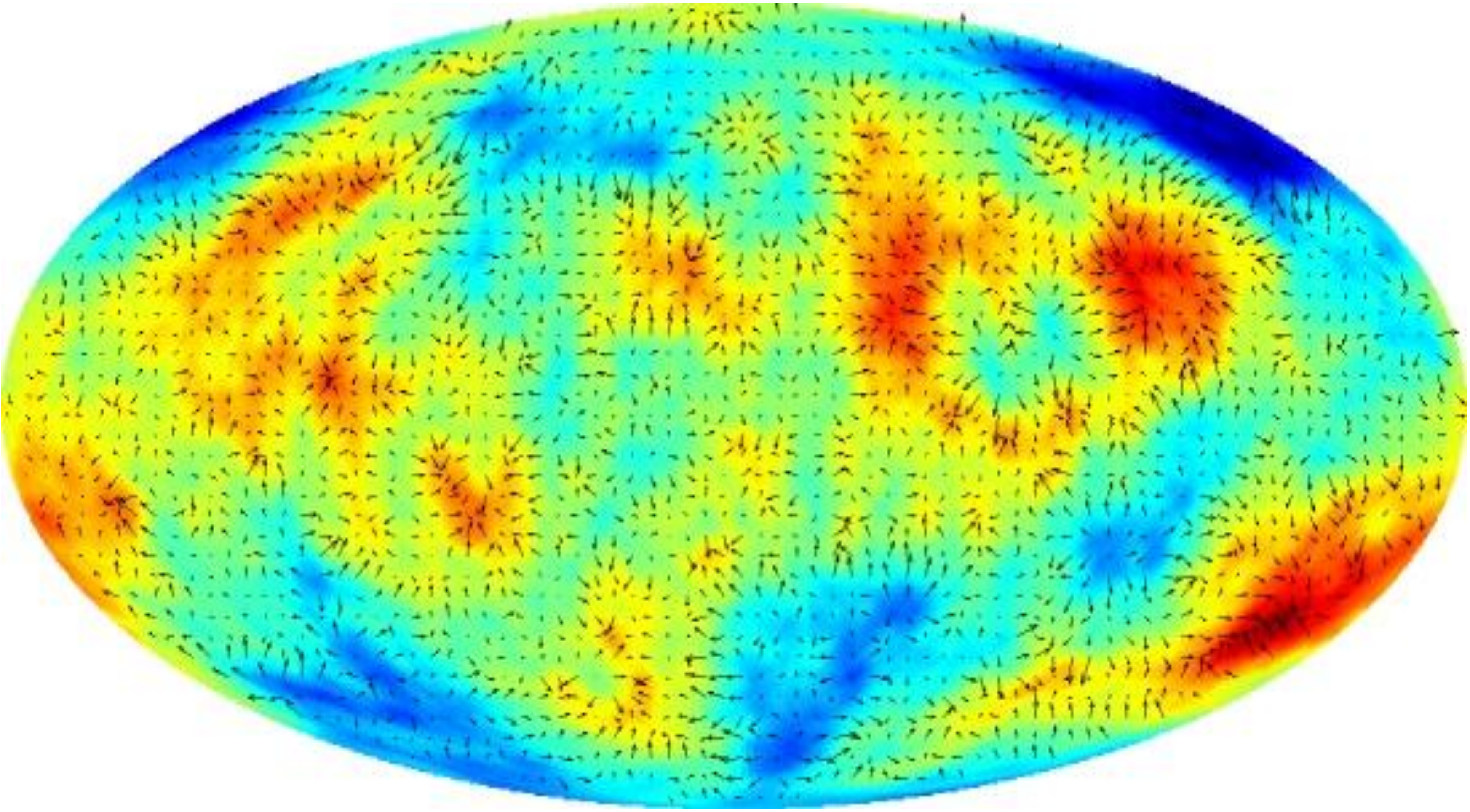


Deflections O(10^{-3}) , but coherent on degree scales

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

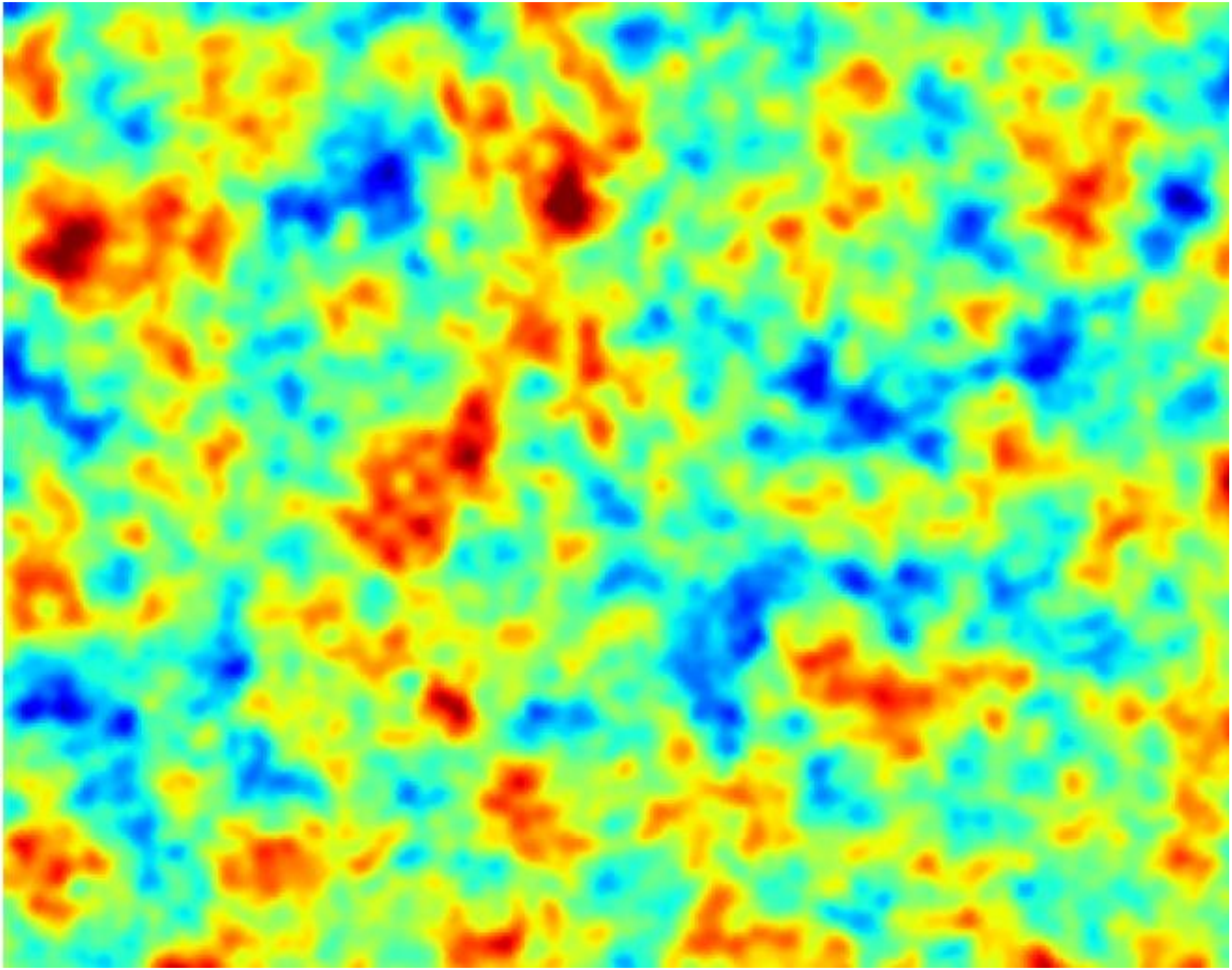
Non-linear structure growth effects important but not a major headache

Simulated full sky lensing potential and (enlarged) deflection angle fields

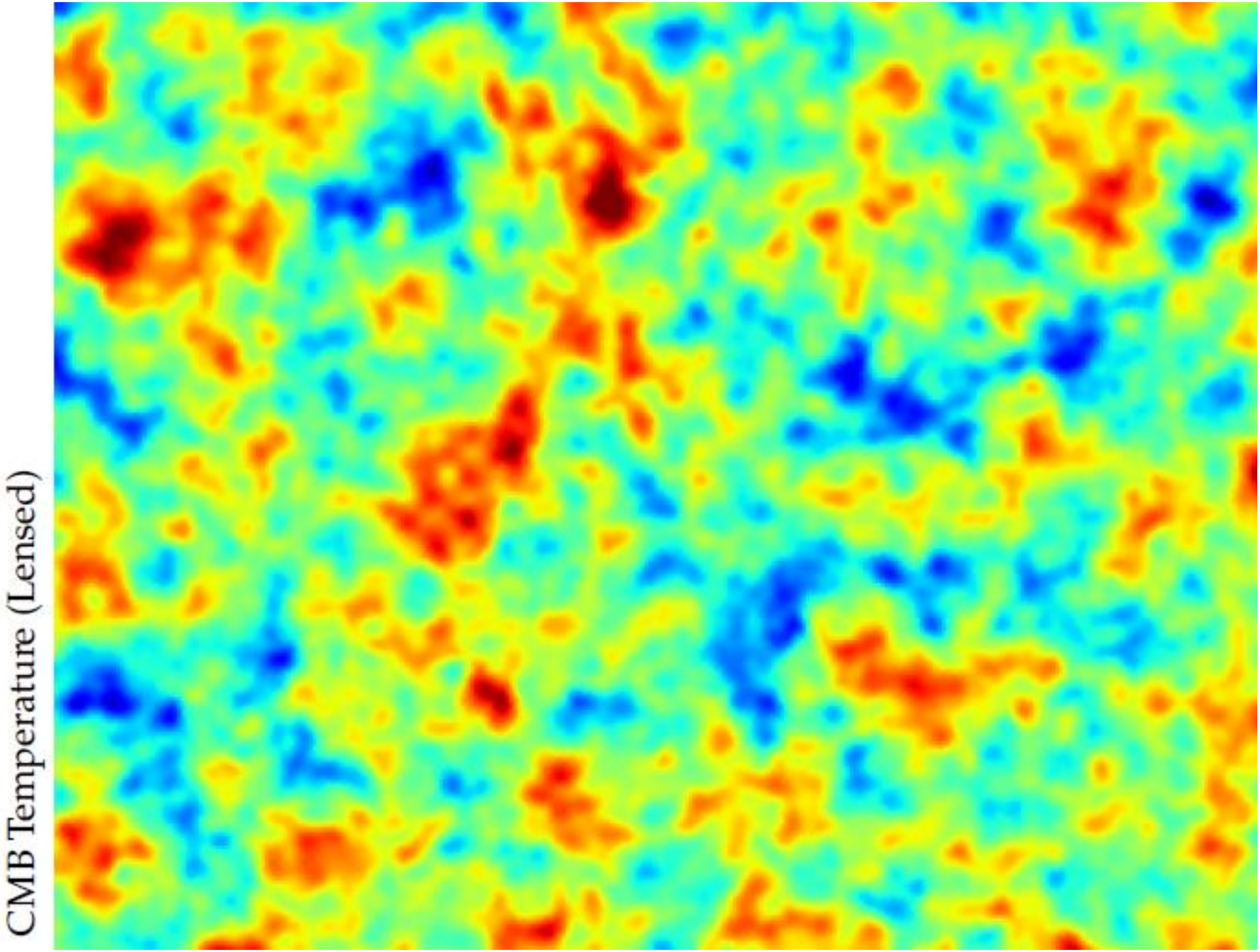


Easily simulated assuming Gaussian fields

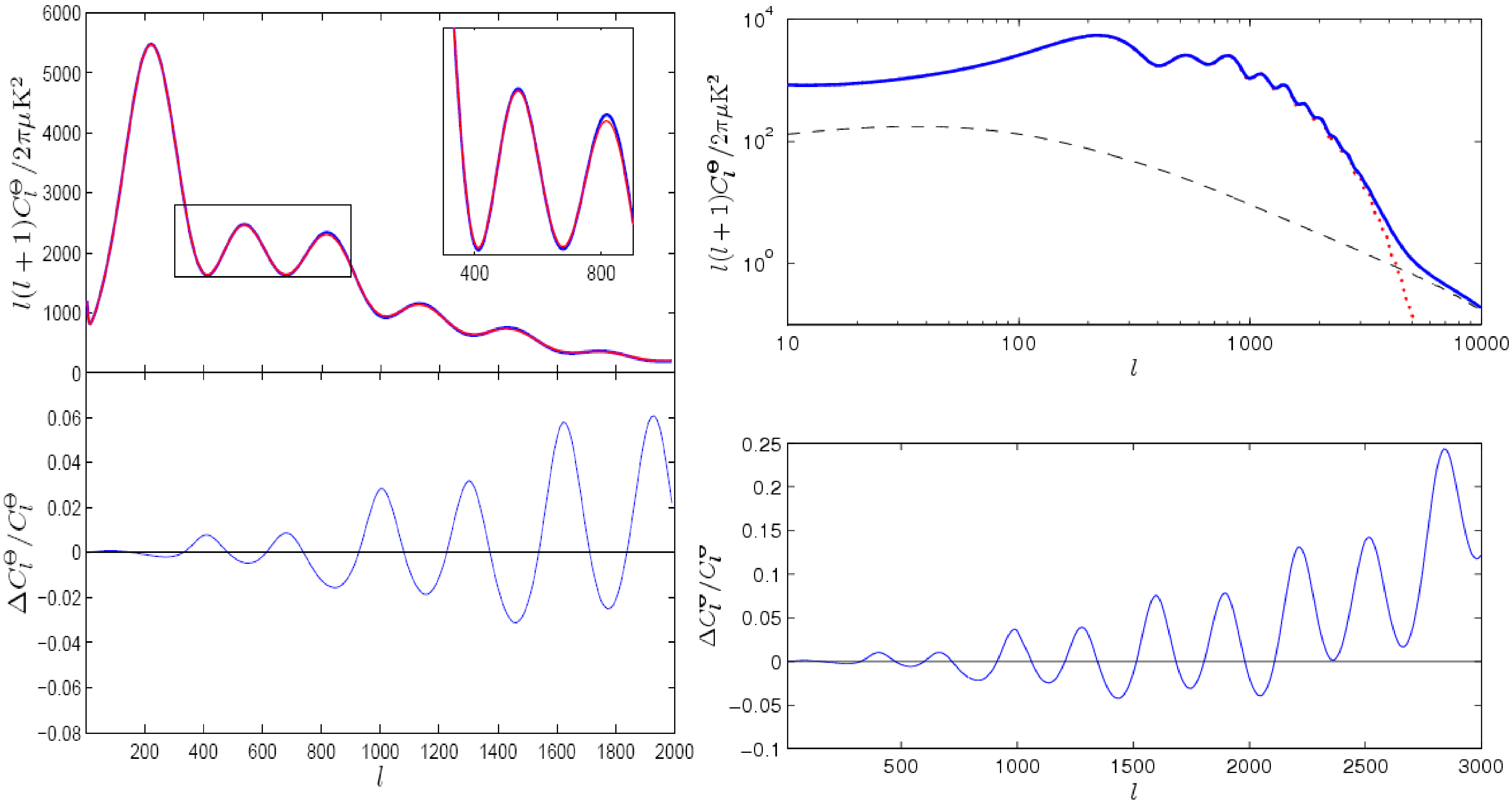
- just re-map points using Gaussian realisations of CMB and potential



CMB Temperature (Unlensed)


CMB Temperature (Lensed)

Lensing effect on CMB temperature power spectrum

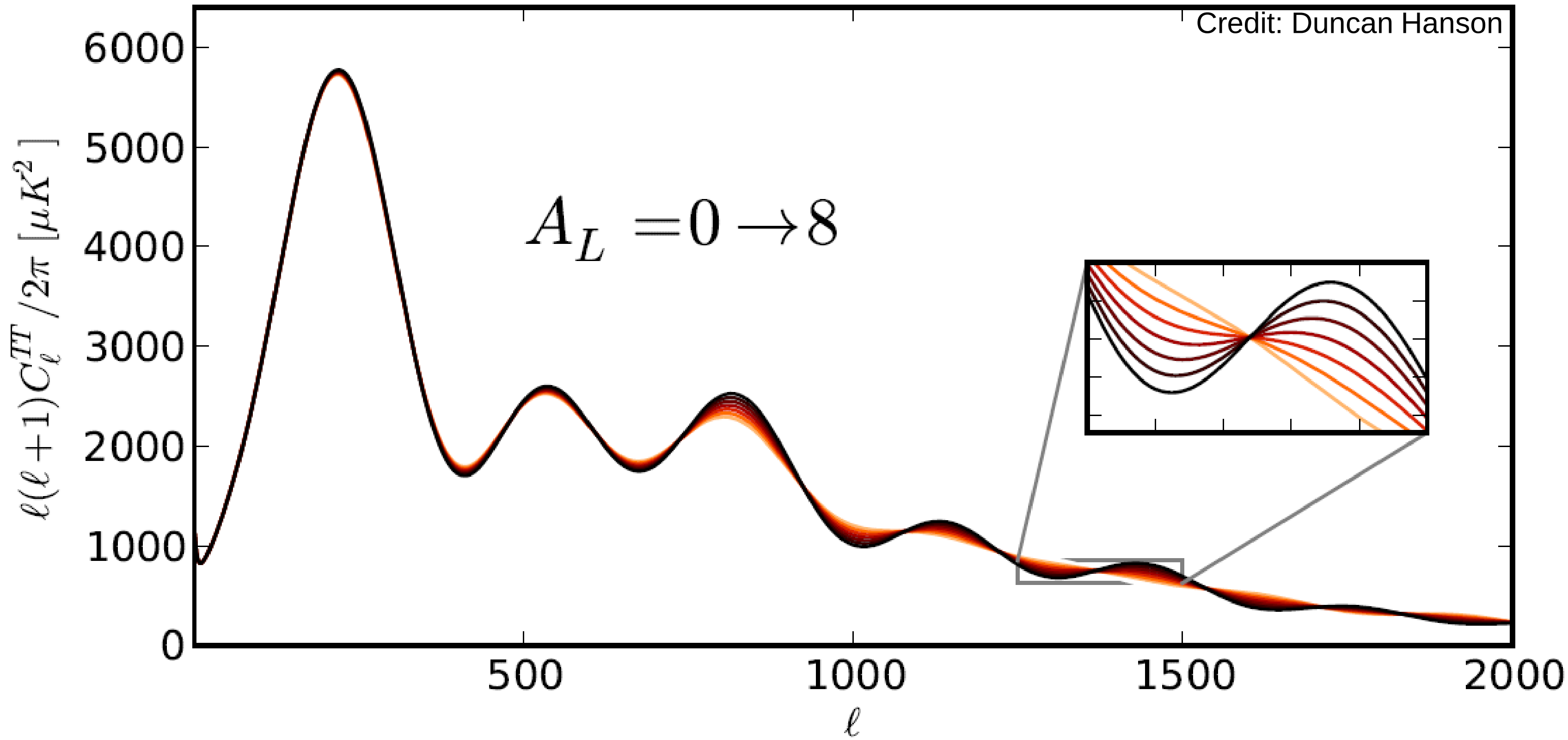


Important, but accurately modelled

Like a convolution with the deflection power spectrum: mainly from peak (L~60) scales

Consistency check, is amount of smoothing at the expected level: $A_L = 1$?

A_L defined so that lensing smoothing calculated using $A_L C_l^{\psi\psi}$ rather than physical $C_l^{\psi\psi}$



- Can we detect preference for $A_L > 0$ in the data?
- Marginalizing over A_L is also a way of “removing” lensing information from C_l

LCDM parameter constraints from Planck alone

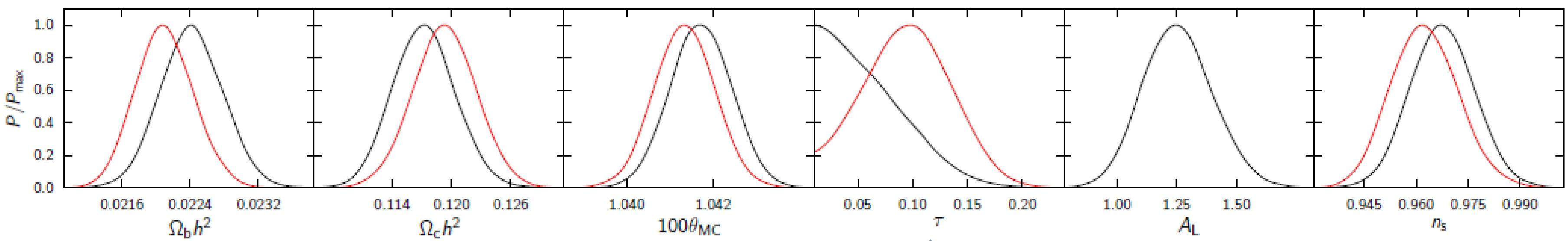
(no WMAP polarization)

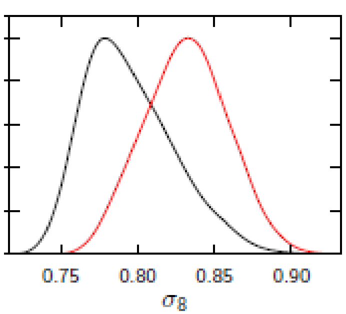
Lensing in the power spectrum is detected at high significance:

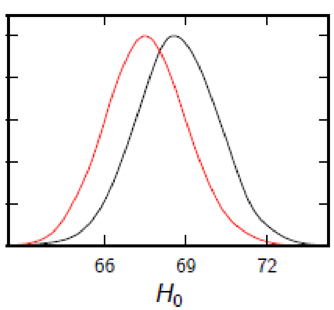
$$A_L = 1.28^{+0.29}_{-0.26} \; (2\sigma)$$

(actually a bit high??)

$A_L = 1$ (physical, main result) A_L varying (non-physical)







Marginalizing A_L (~ remove lensing information) significantly shifts parameters

With lensing – almost a constraint on $\tau > 0$

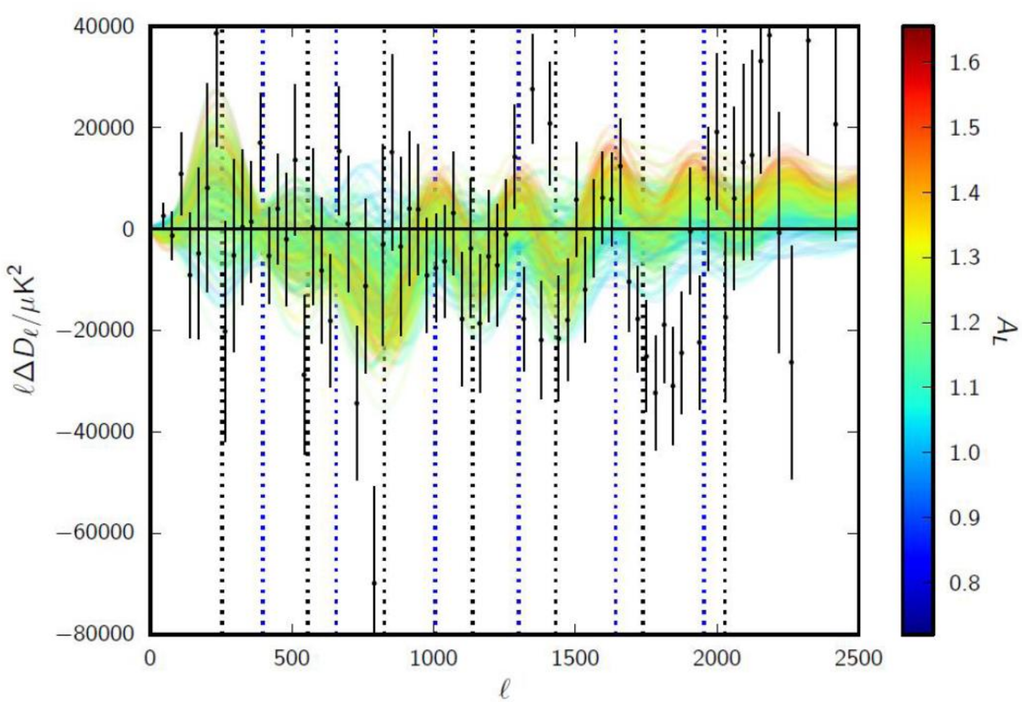
Oddity: power spectrum data seems to like high A_L

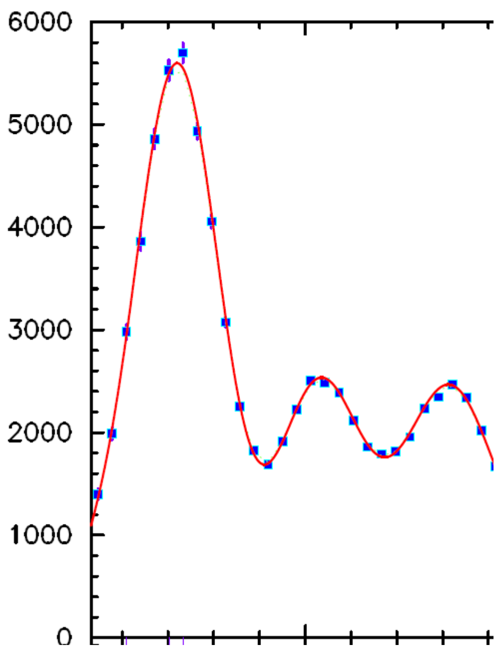
Preference for high A_L?

Varies with data cuts, can be > 3σ discrepant with $A_L = 1$!

Parameter	CamSpec 95% limits	Plik 95% limits	$l_{\max} = 2000$ 95% limits	$l_{\min} = 1200$ 95% limits	no 217×217 95% limits
A_L	$1.23^{+0.22}_{-0.21}$	$1.26^{+0.26}_{-0.25}$	$1.38^{+0.26}_{-0.25}$	$1.31^{+0.24}_{-0.23}$	$1.30^{+0.24}_{-0.22}$

Planck+WP Alens diff to LCDM planck best fit

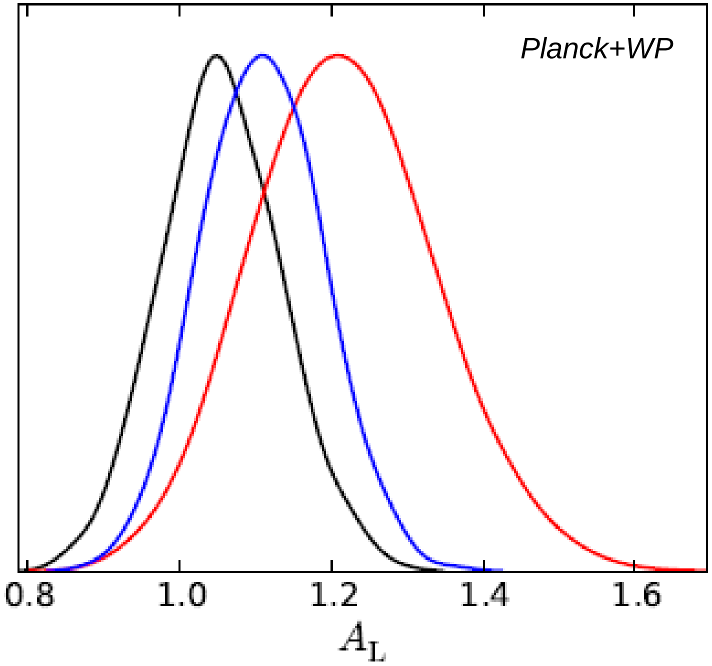




Why does Planck favour high (non-physical) A_L?

- Actual preference for more peak smoothing
- Parameter degeneracies (higher A_L allows higher n_s, better fit at low l)

(note lower $\Omega_c h^2$ or A_s ⇒ less lensing ⇒ higher A_L for same physical smoothing effect)



Vary A_L and 6 other LCDM parameters
(smoothing+degeneracies)

Vary A_L,all other cosmological parameters
fixed to LCDM best fit with $A_L = 1$
(really measuring smoothing wrt best fit)

Vary A_L,all other cosmological parameters
fixed to LCDM best fit when low-l replaced by τ prior
(measuring smoothing wrt best fit which is not
pulled by low low-l power: higher $\Omega_c h^2$ and hence lensing in reference model)

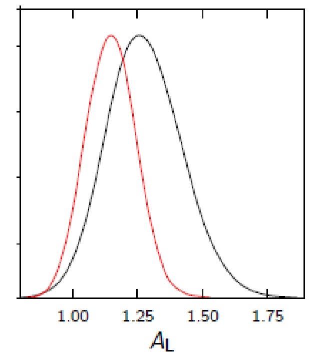
Similarly, could define alternative A_L' to scale amplitude of lensing power w.r.t. fixed value (rather than ratio to physical in each model). E.g.

$$A_L' = \frac{\max\left(l^4 C_l^{\phi\phi}\right)}{8.7\times 10^{-7}}$$

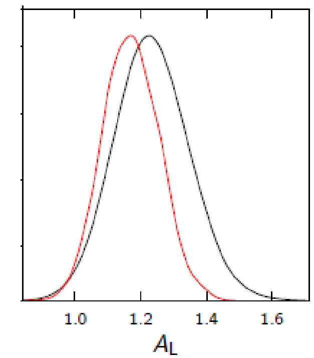
(ratio to LCDM Planck+WP best fit lensing power)

$$A_L = \frac{C_l^{\phi\phi}}{C_l^{\phi\phi}(\text{physical})}$$

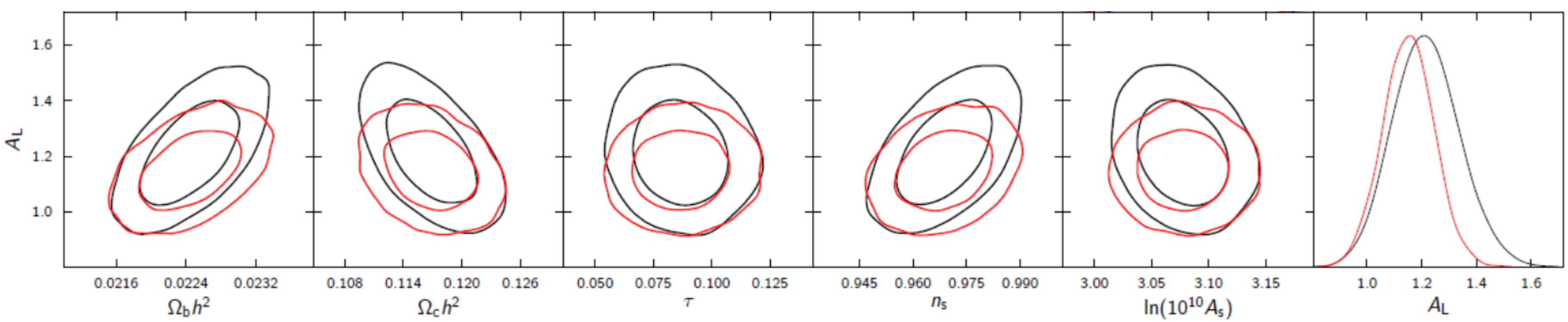
Planck only



Planck+WP+highL



Planck+WP



- High A_L preference is partly driven by degeneracies
- But also some preference for more lensing smoothing
- High A_L models do have significantly better fit
  (may be hint that LCDM is not good fit, systematic, or lensing amplitude is wrong)

Really need to measure the lensing amplitude more directly…

Non-Gaussianity/statistical anisotropy
reconstructing the lensing field

Marginalized over (unobservable) lensing field:

$$T \sim \int P(T,\psi)d\psi$$

- Non-Gaussian statistically isotropic temperature distribution

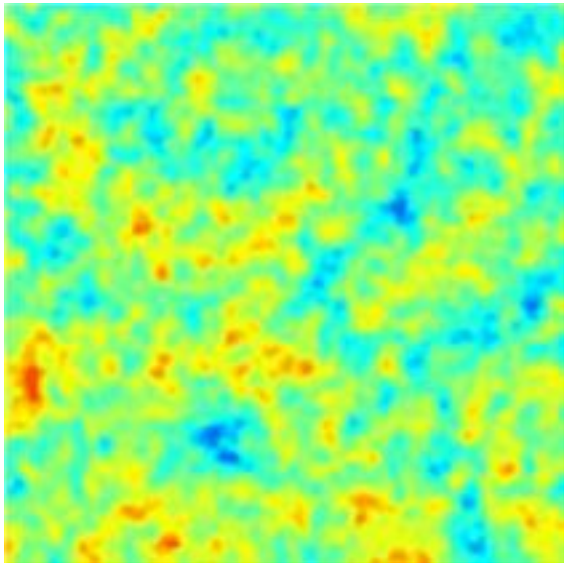
For a given lensing field :

$$T \sim P(T|\psi)$$

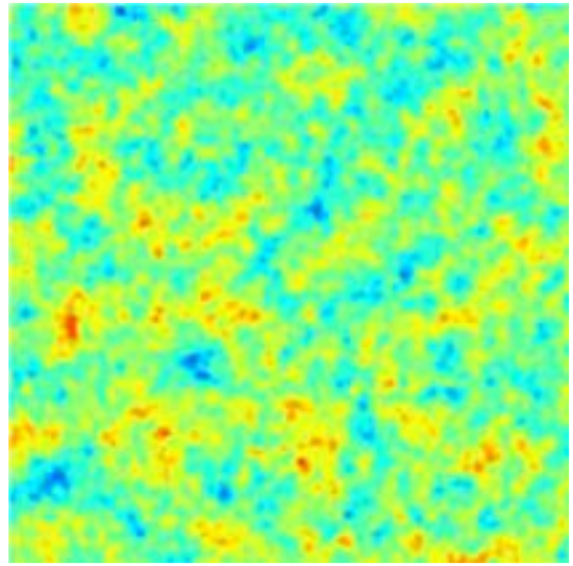
- Anisotropic Gaussian temperature distribution

Fractional magnification ~ convergence $\kappa = -\boldsymbol{\nabla} \cdot \boldsymbol{\alpha}/2$

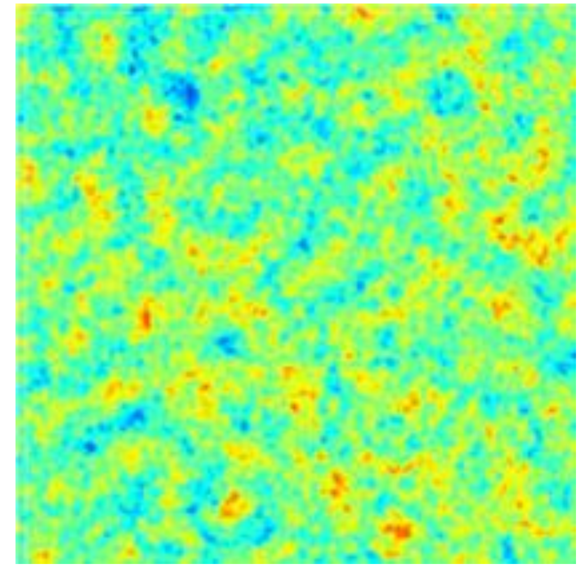
Magnified

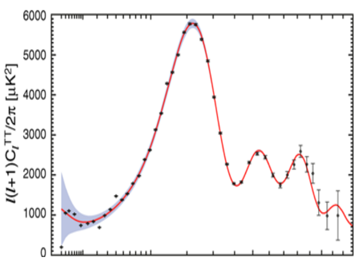


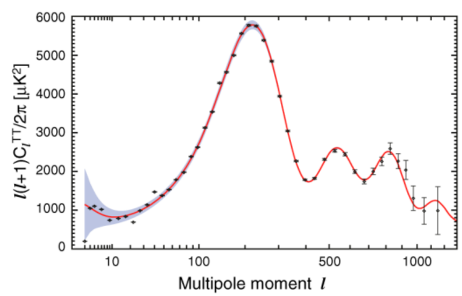
Unlensed

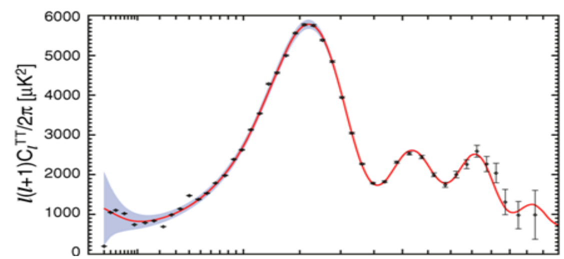


Demagnified









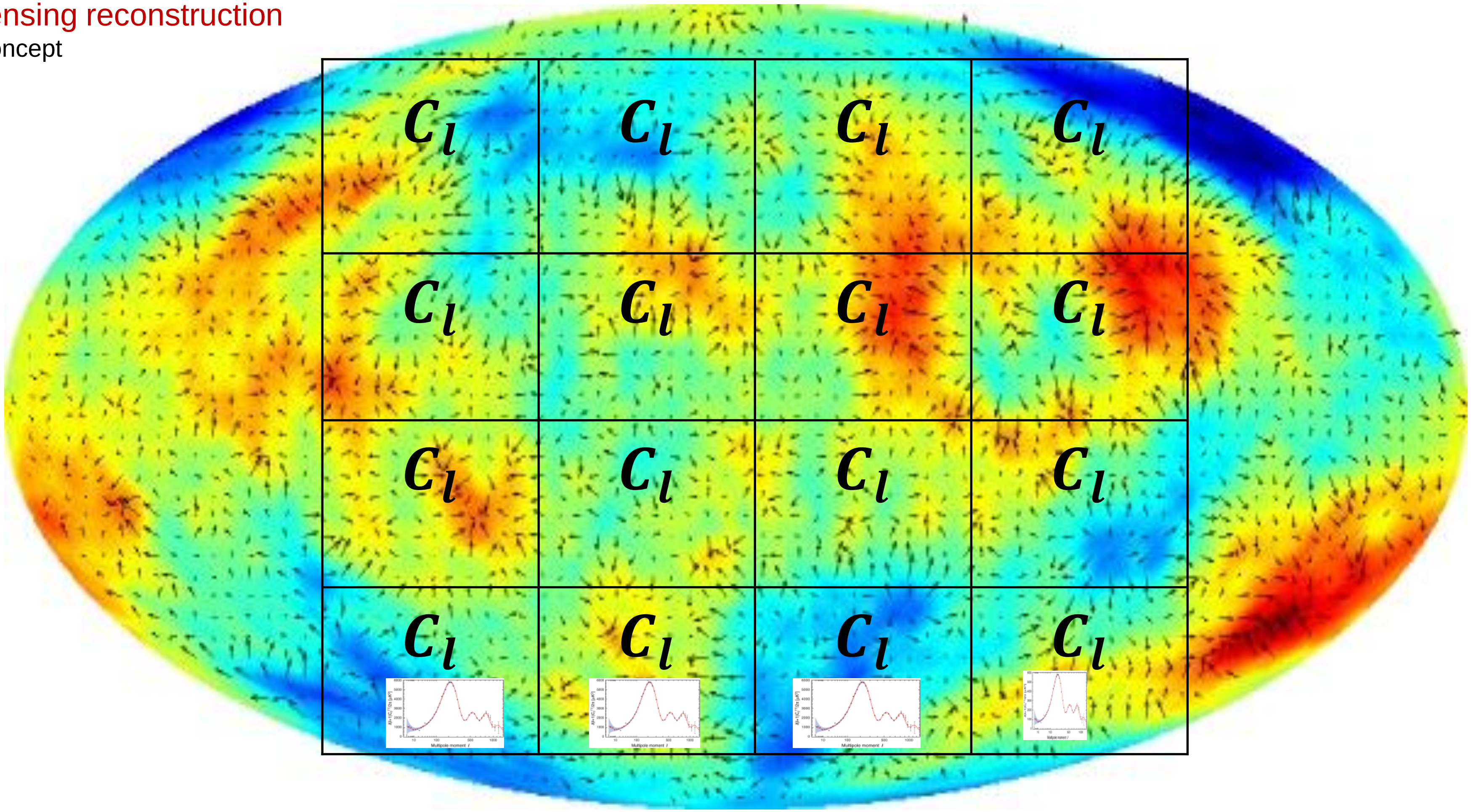
+ shear modulation

$$\langle \tilde{T}(\mathbf{l}_2)\tilde{T}(\mathbf{l}_3)\rangle = C_{l_2}^{TT}\delta(\mathbf{l}_2+\mathbf{l}_3)\left[1+\kappa\frac{\mathrm{d}\ln(l_2^2 C_{l_2}^{TT})}{\mathrm{d}\ln l_2}+\hat{\mathbf{l}}_2^T\gamma\hat{\mathbf{l}}_2\frac{\mathrm{d}\ln C_{l_2}^{TT}}{\mathrm{d}\ln l_2}\right]$$

Bucher et al

Lensing reconstruction

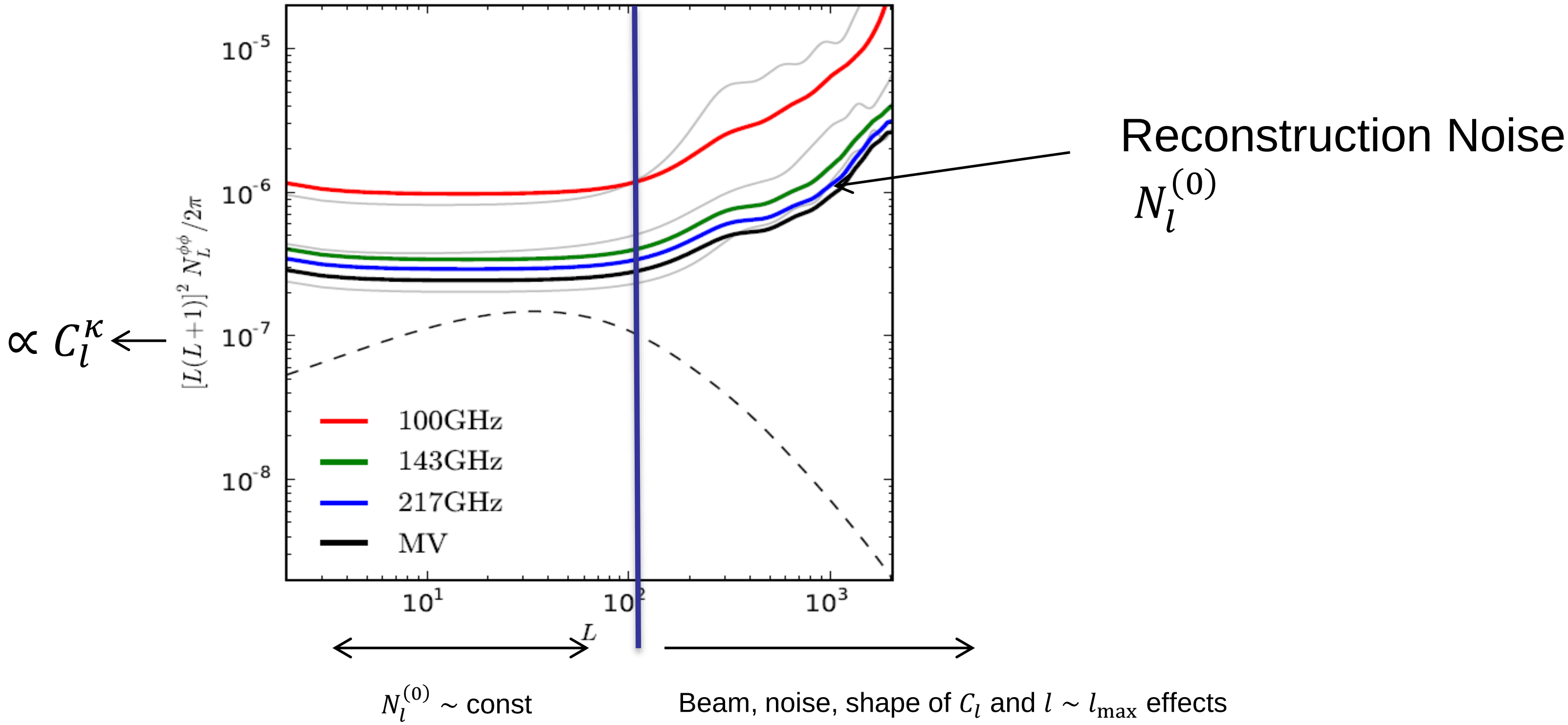
-concept



Variance in each C_l measurement $\propto 1/N_{\text{modes}}$

$N_{\text{modes}} \propto l_{\text{max}}^2$ - dominated by smallest scales

$\Rightarrow$ measurement of angular scale ($\Rightarrow \kappa$) in each box nearly independent
$\Rightarrow$ Uncorrelated variance on estimate of magnificantion κ in each box
$\Rightarrow$ Nearly white ‘reconstruction noise’ $N_l^{(0)}$ on κ , with $N_l^{(0)} \propto 1/l_{\text{max}}^2$



Lensing reconstruction information mostly in the *smallest scales* observed

- Need high resolution and sensitivity
- Almost totally insensitive to large-scale T (so only *small-scale* foregrounds an issue)

  - Use separate frequencies and check consistency
  - Combine (Minimum Variance – MV) for best estimate
  - Also cross-check with foreground cleaned maps

Lensing reconstruction

- Maths and algorithm sketch

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

X here is lensing potential, deflection angle, or κ

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

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

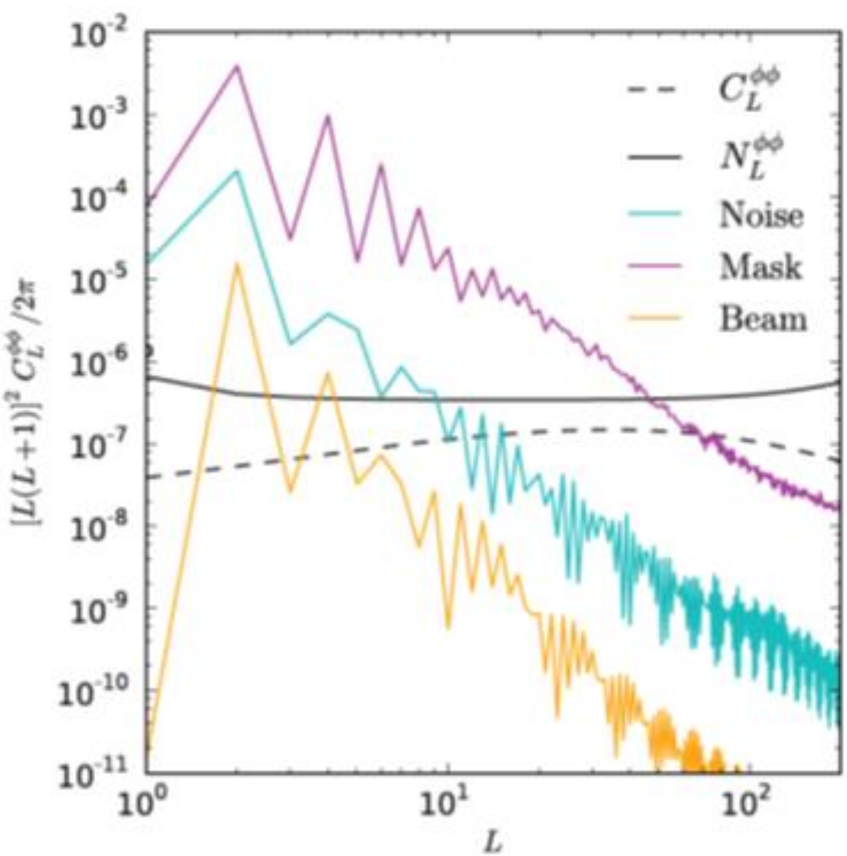
Zaldarriaga, Hu, Hanson, and others.

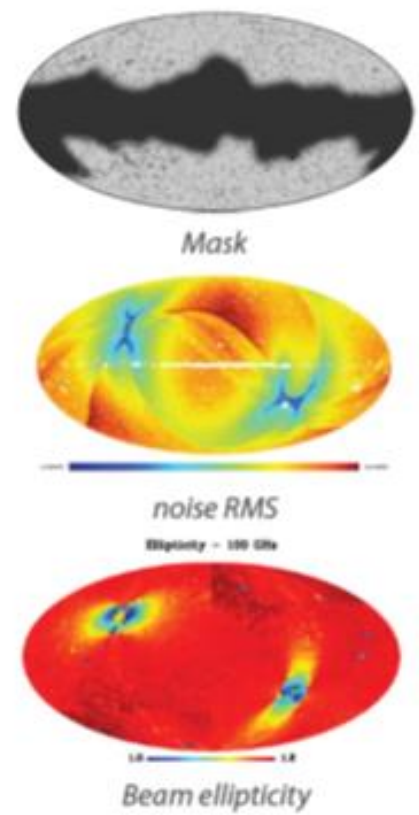
On realistic cut sky can still construct "optimal" quadratic (QML) estimator $\hat{\phi}(K)$

$$\hat{\phi}(L) \sim N_L^{(0)}\left[\sum_{\mathbf{k}_2,\mathbf{k}_3} A(L,k_2,k_3)\,\bar{T}(\mathbf{k}_2)\bar{T}(\mathbf{k}_3) - (\text{Monte carlo for zero signal})\right]$$

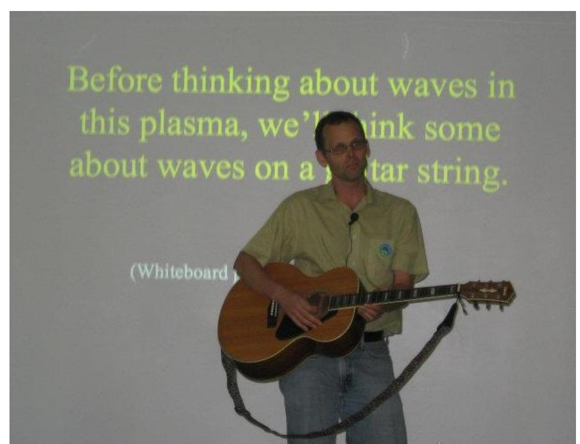
Filtered maps $\bar{T} = (S+N)^{-1}T$
weights for mask and noise anisotropy
(here approx. noise term as diagonal)

"Mean field" – accounts for other sources of anisotropy in the data





- "Mean-field" corrections are very large at low-L. We fail some detailed consistency tests at $L < 10$ (though not very badly!).



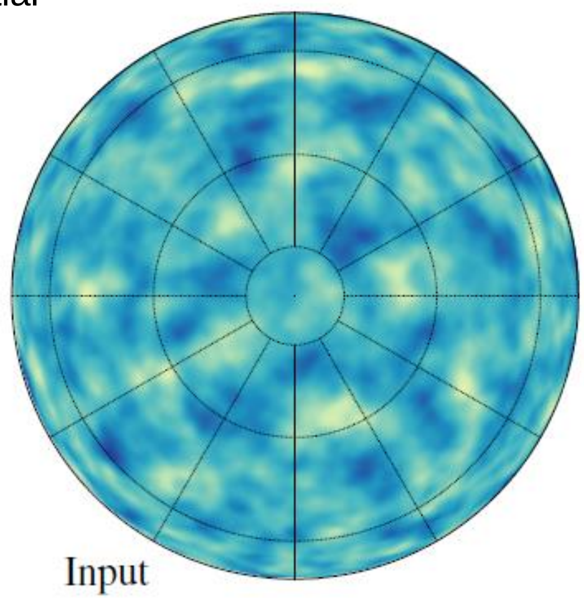
Can also re-write in as fast real-space estimator

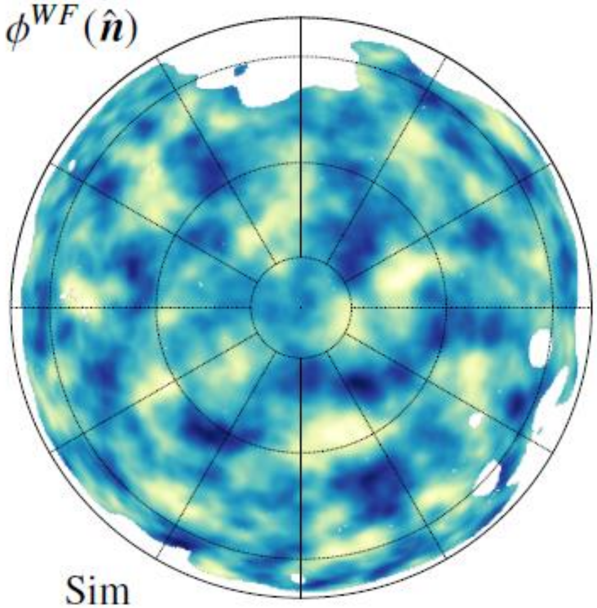
$$\hat{\alpha}_{LM} \propto (\bar{T}\nabla W)_{LM} \qquad W = S\,\bar{T} = S(S+N)^{-1}T \text{ is Wiener-filtered input T map}$$

Planck simulation

S/(S+N) filtered reconstruction

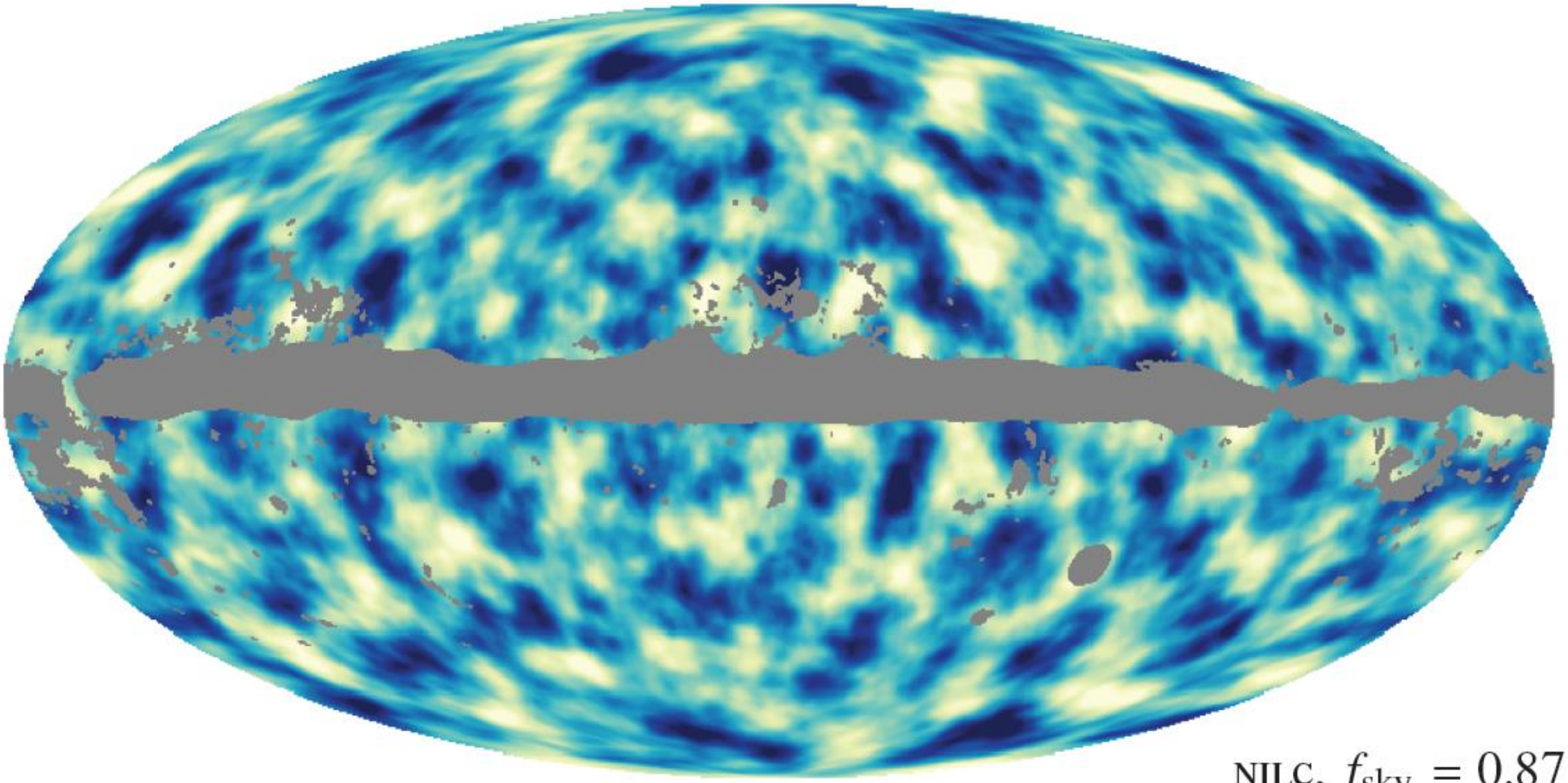
True lensing potential





= input + ‘reconstruction noise’

Planck full-sky lensing potential reconstruction

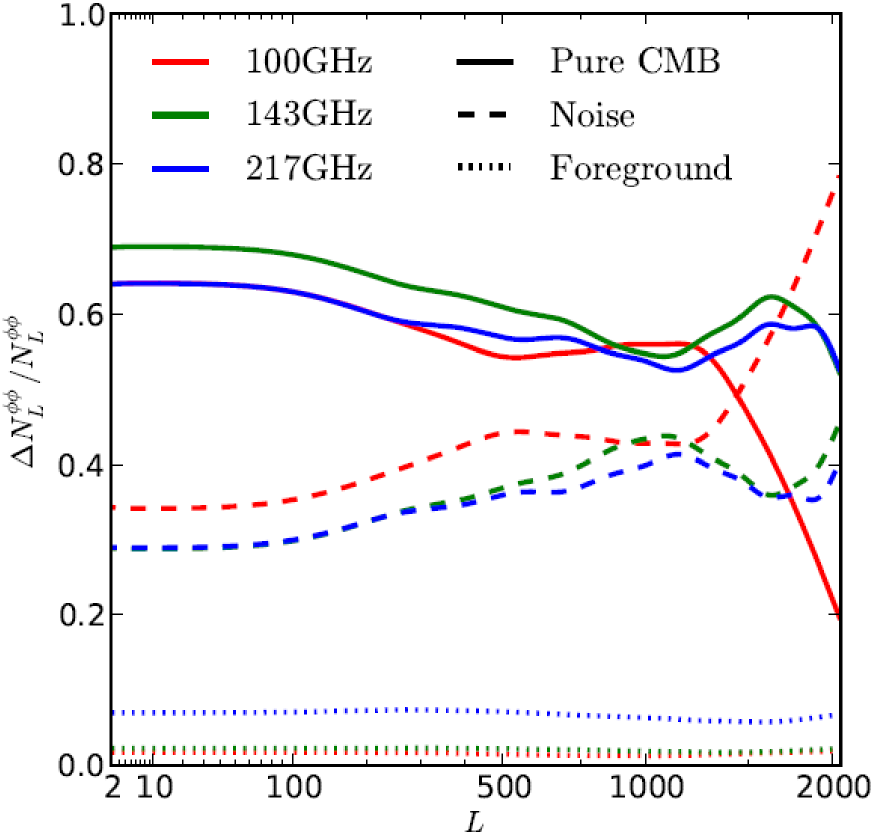


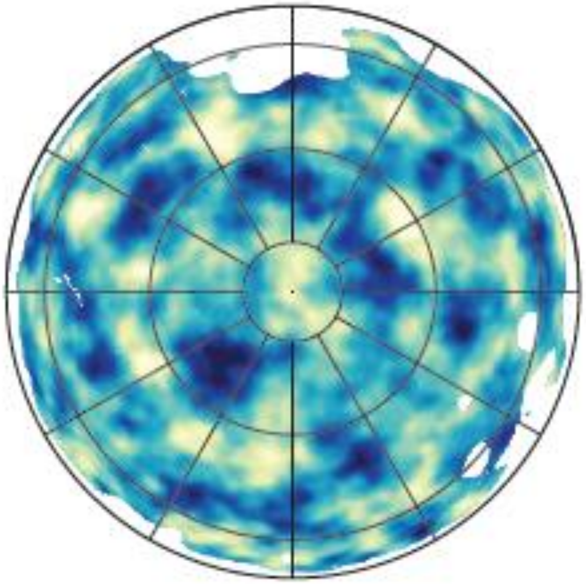
NILC, $f_{\rm sky} = 0.87$

Note – about half signal, half noise,
not all structures are real: map is effectively Wiener filtered

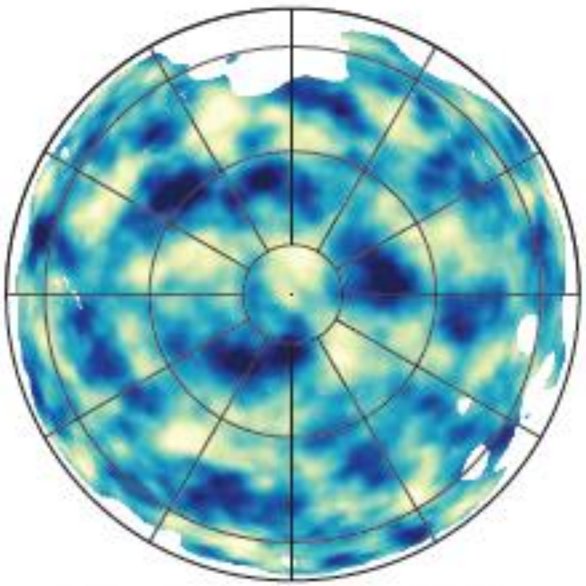
Reconstruction noise budget

Lensing maps are reconstruction noise dominated, but maps from different channels are similar because mainly the same CMB cosmic variance.



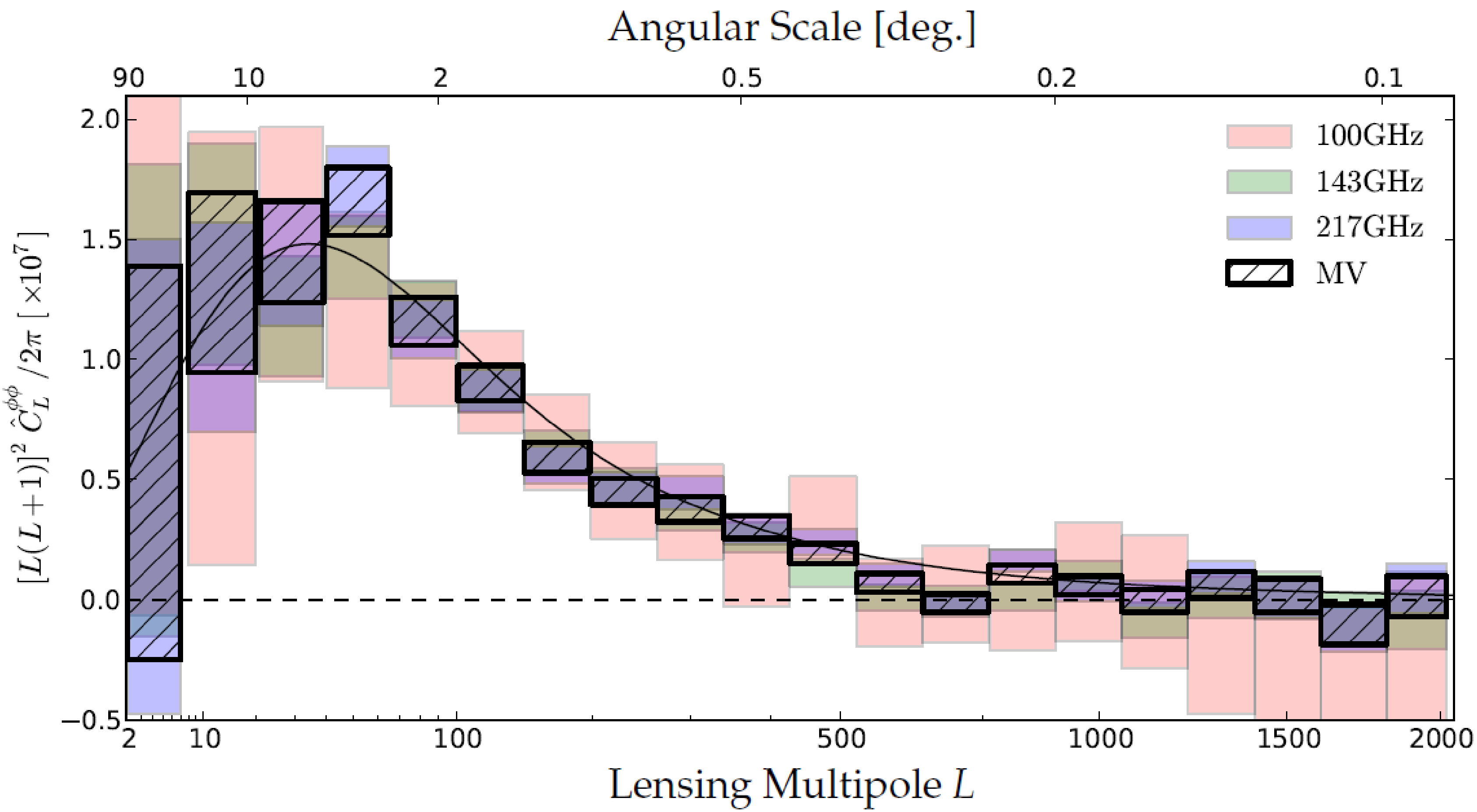


Galactic South - 143 GHz

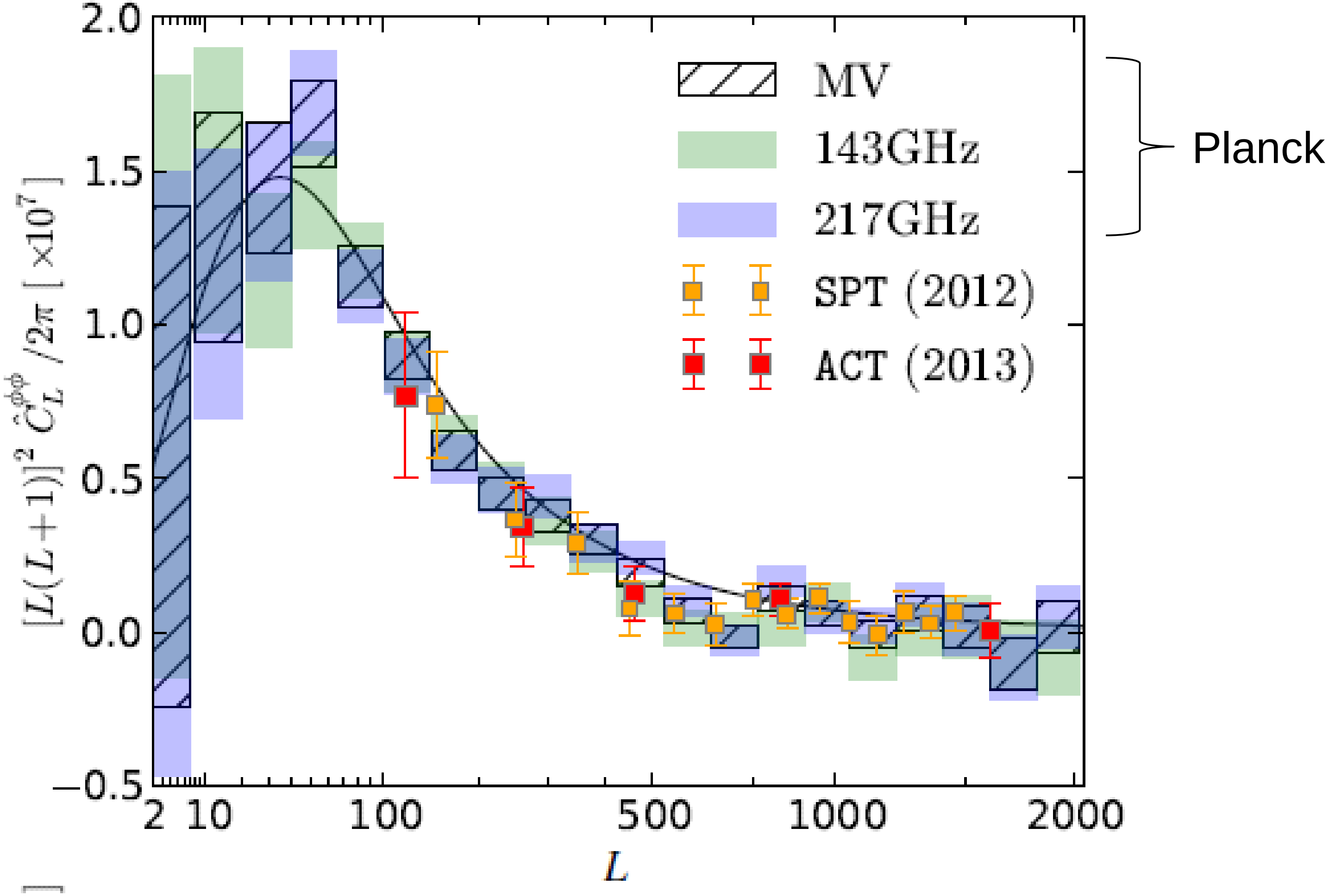


Galactic South - 217 GHz

Power spectrum of reconstruction ⇒ $C_l^{\psi\psi}$

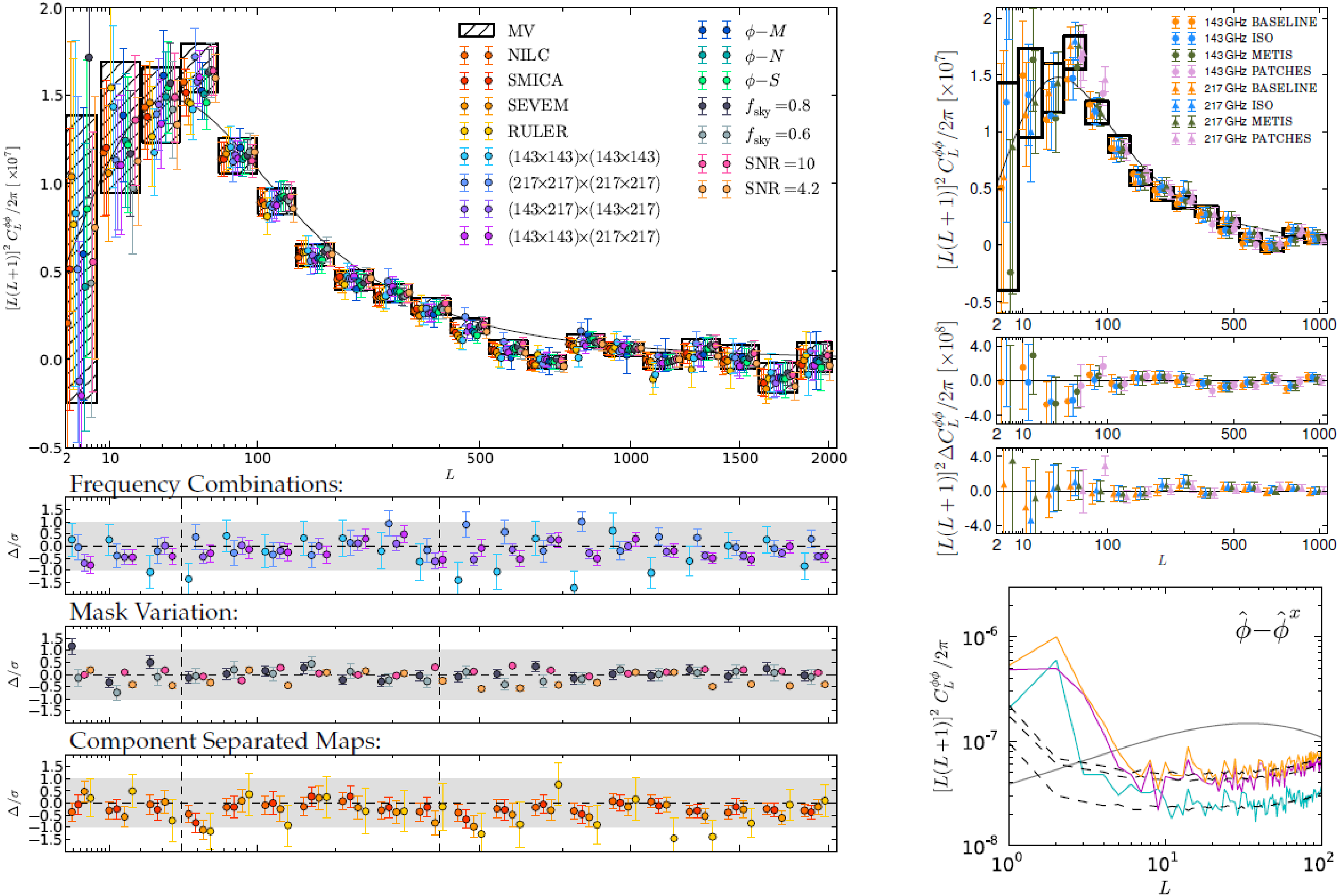


Comparison with ACT/SPT



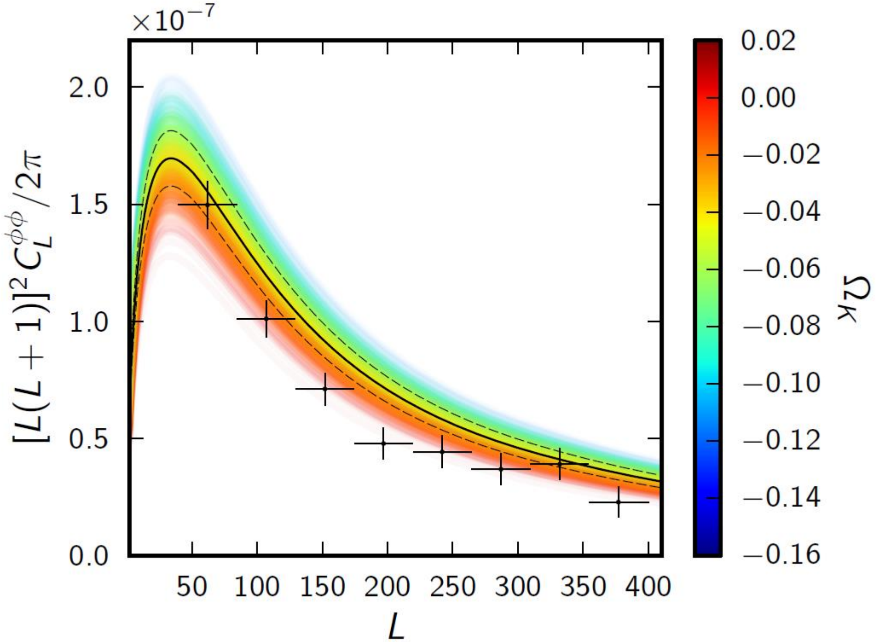
(new SPT data also coming “soon”)

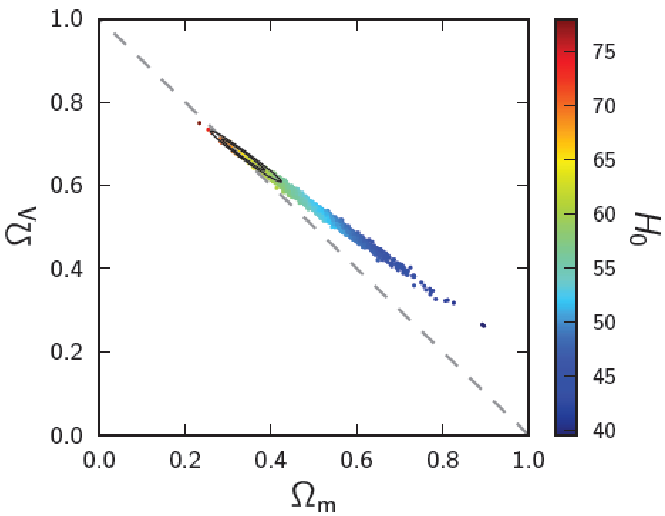
Consistency Tests

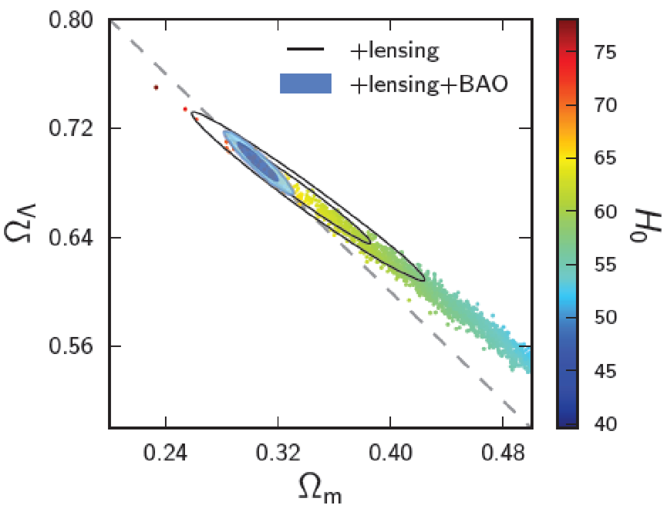


Extra information can help break parameter degeneracies

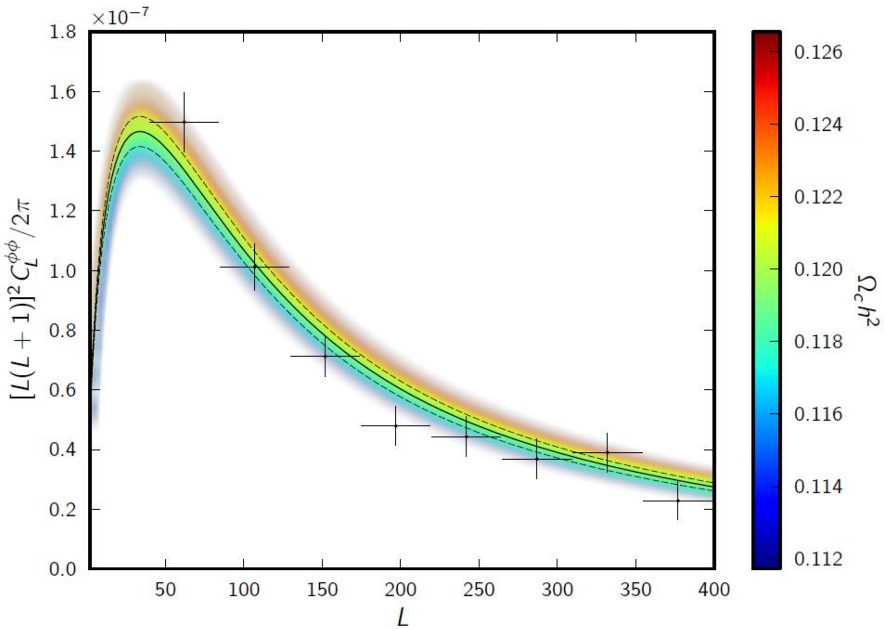
Colour: Planck TT constraint
Crosses: Planck lensing



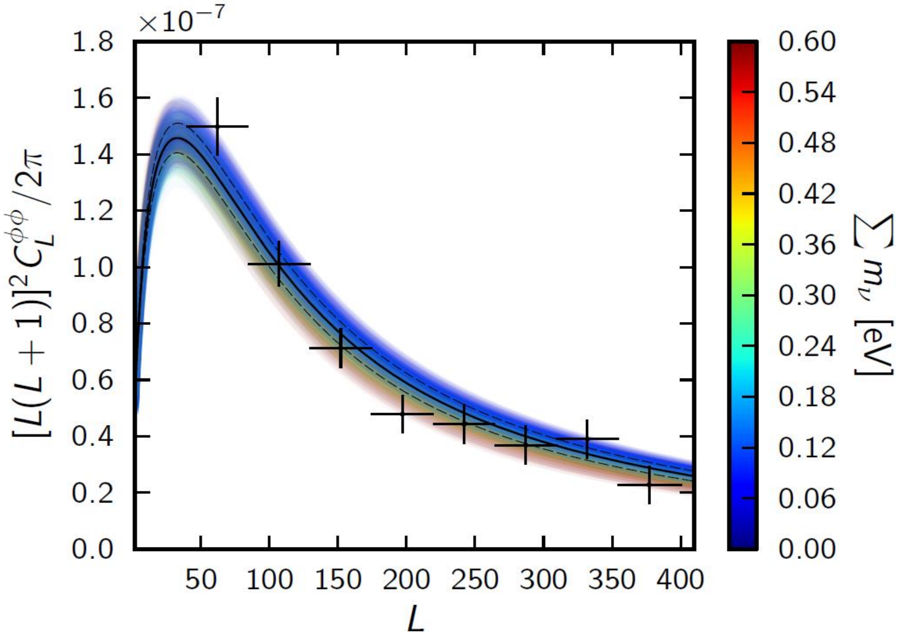




LCDM matter density



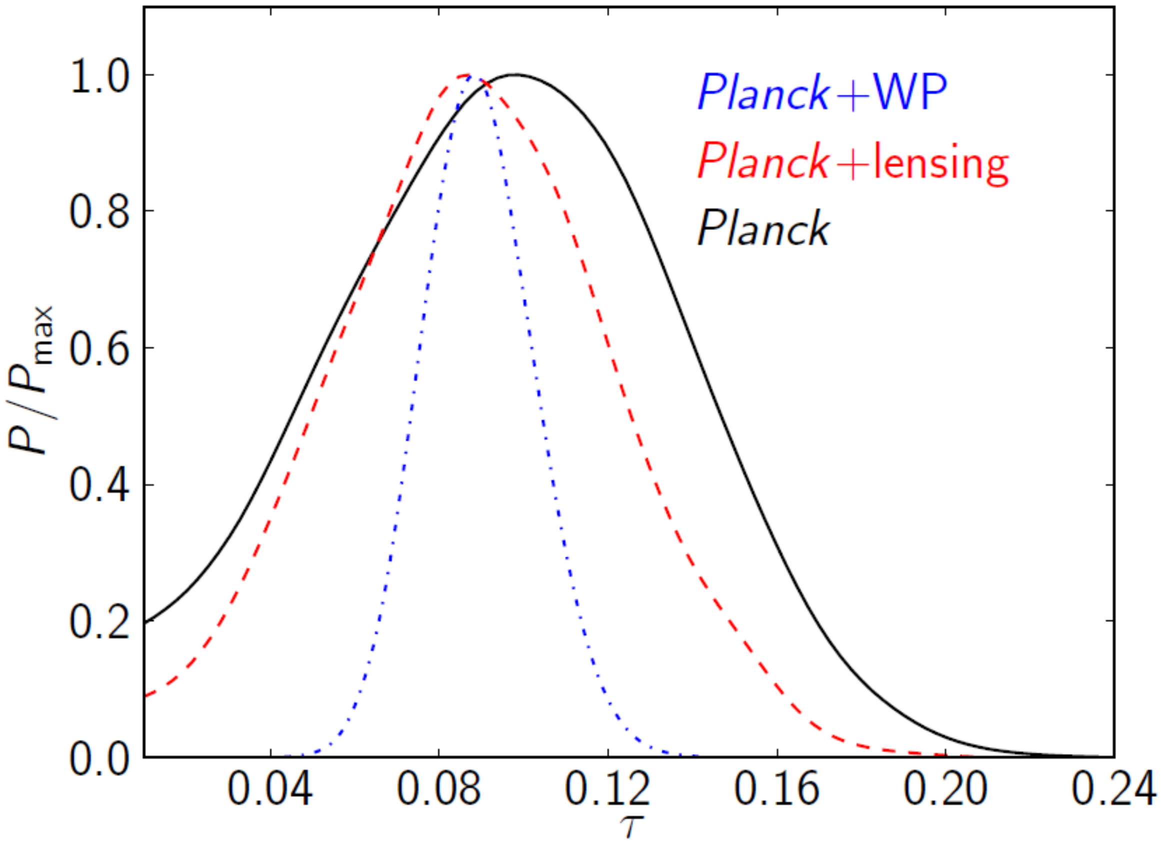
Neutrino mass



Some preference for *lower* lensing power on smaller scales compared to TT LCDM fits (lower $\Omega_c h^2$, higher m_ν)

Reminder: Lensing information enters main parameter results in two ways:

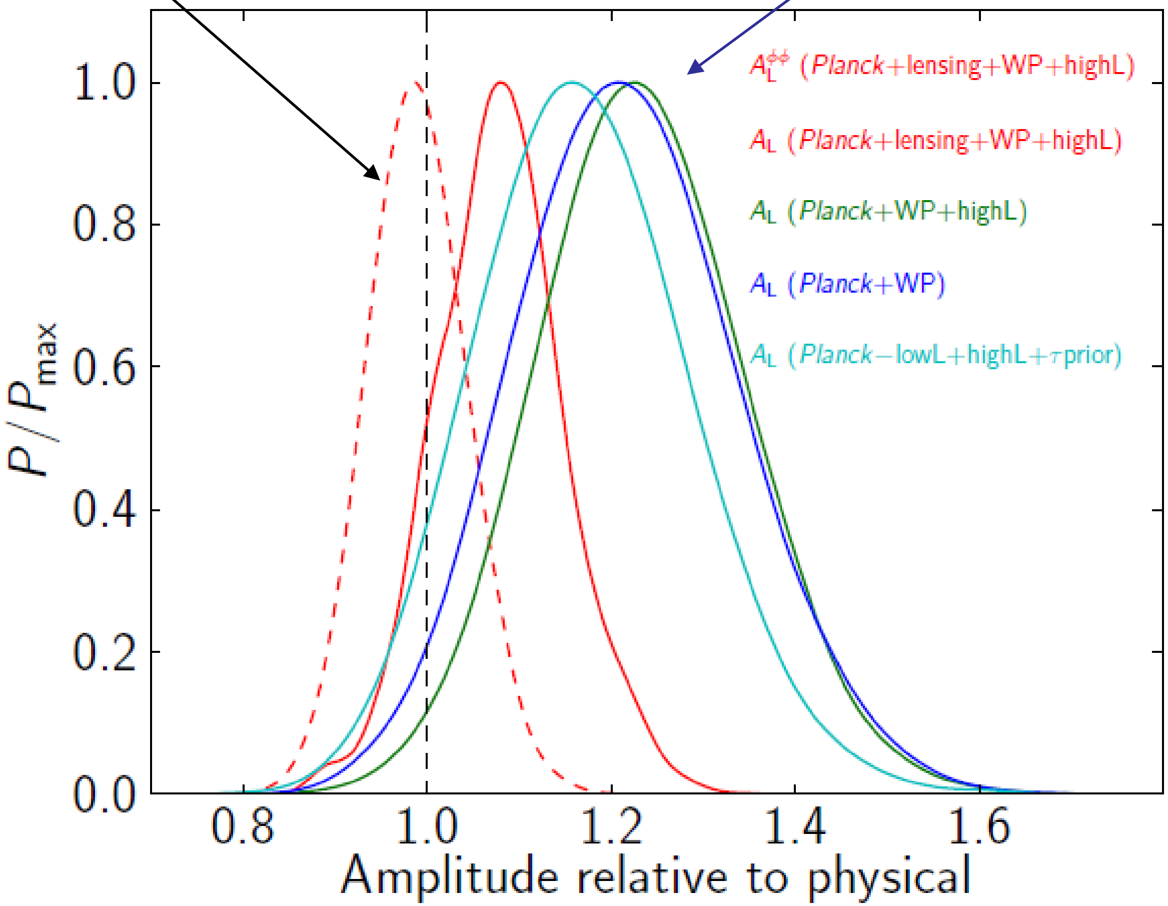
- lensed C_l (always included)
- lensing reconstruction $C_l^{\phi\phi}$ (optionally)



Independent τ constraint (*Planck*+lensing) consistent with WMAP (*Planck*+WP)

Lensing reconstruction perfectly consistent with $A_L = 1$

Lensed power spectrum pulls to higher A_L



Full reason for all high A_L results from power spectrum unclear but

<u>No evidence that actual physical lensing effect is larger than expected</u>

Hang on, aren't we double counting?

Lensed CMB TT signal and lensing reconstruction must be correlated.

But:

- C_l lensing sensitive to broad kernel in $C_L^{\phi\phi}$ a round peak at $L \sim 60$: many modes contribute, so cosmic variance is relatively small compared to reconstruction noise in the same range
  \- *Correlation can be neglected because reconstruction is noise dominated*

- C_l lensing and reconstruction *noise* are also nearly uncorrelated since coming from different parts of the power spectrum (out of phase at low L):

  \- C_l lensing is from smoothing of peak and dip heights

  \- ϕ reconstruction is from *sideways changes* in C_l under magnification/shear:

$$\langle \tilde{T}(\mathbf{l}_2)\tilde{T}(\mathbf{l}_3)\rangle = C_{l_2}^{TT}\delta(\mathbf{l}_2+\mathbf{l}_3)\left[1+\kappa\frac{\mathrm{d}\ln(l_2^2 C_{l_2}^{TT})}{\mathrm{d}\ln l_2}+\hat{\mathbf{l}}_2^T\gamma\hat{\mathbf{l}}_2\frac{\mathrm{d}\ln C_{l_2}^{TT}}{\mathrm{d}\ln l_2}\right]$$

out of phase with peaks and dips

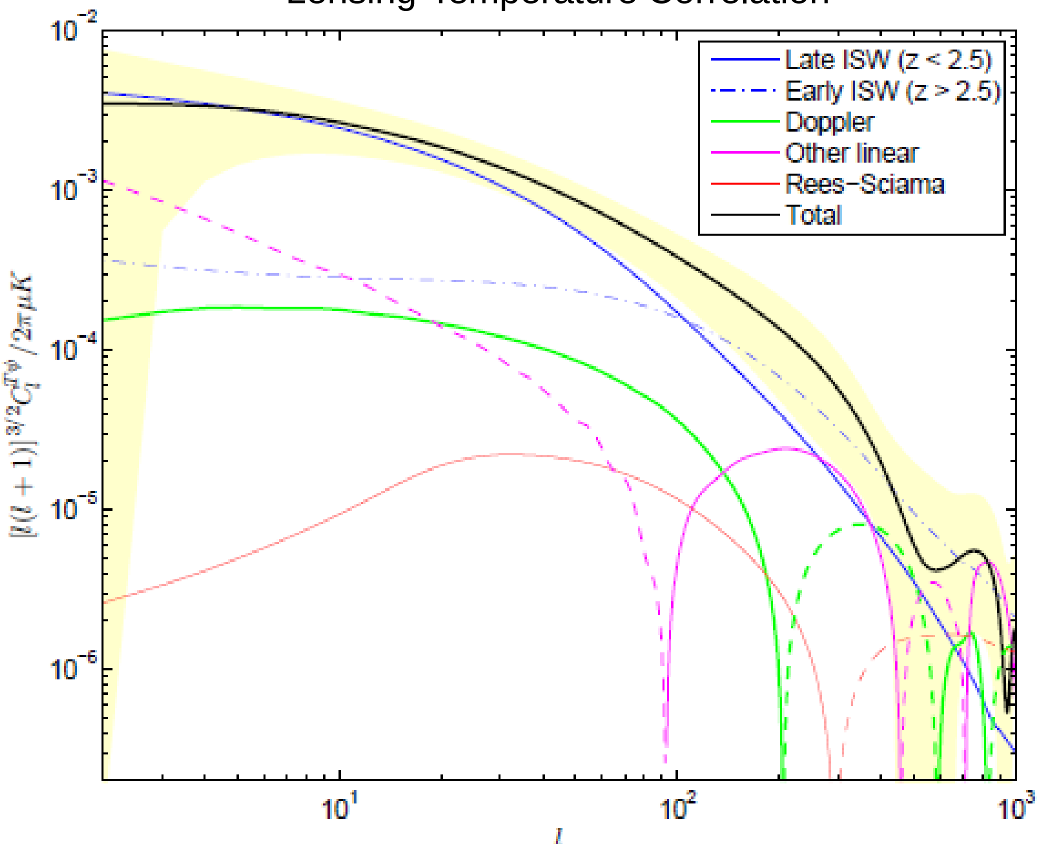
Good approximation to treat lensing reconstruction likelihood as independent

Schmittfull et. al. in prep

Trispectrum: quadratic estimator for $\psi \Rightarrow \quad C_l^{\psi\psi}$ ~trispectrum

Bispectrum: quadratic estimator x temperature $\Rightarrow\ C_l^{T\psi}$

Lensing-Temperature Correlation



Lewis *arXiv:1204.5018*

Large-scale bispectrum from ISW-lensing correlation:

$$\Rightarrow f_{NL} \sim 7$$

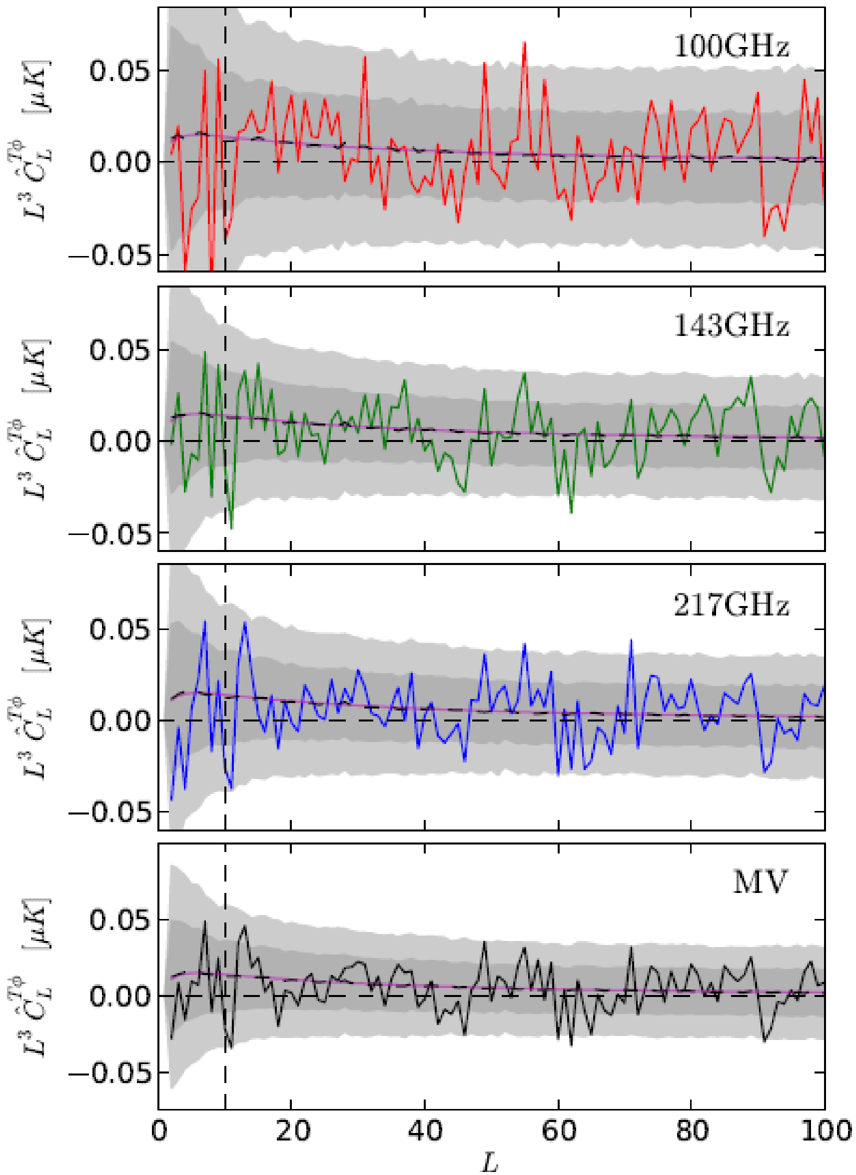
(but very different squeezed shape)

- Must be accounted for in primordial non-Gaussianity results

- Up to 5 sigma detection possible: dark energy information

(note Rees-Sciama contribution is small, numerical problem with much larger result of Verde et al, Mangilli et al.; see also Junk et al. 2012)

Planck lensing bispectrum result

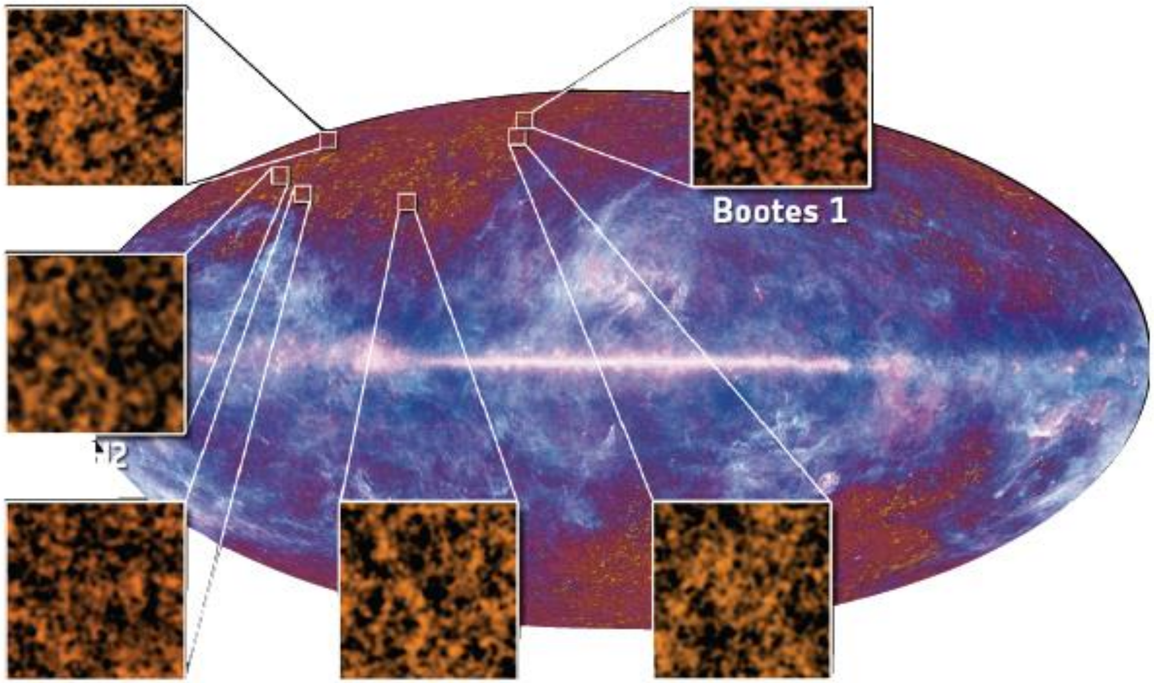


Large cosmic variance and reconstruction noise, but ‘detected’ at $\sim 2.5\sigma$

Table 2. Results for the amplitude of the ISW-lensing bispectrum from the SMICA, NILC, SEVEM, and C-R foreground-cleaned maps, for the KSW, binned, and modal (polynomial) estimators; error bars are 68% CL.

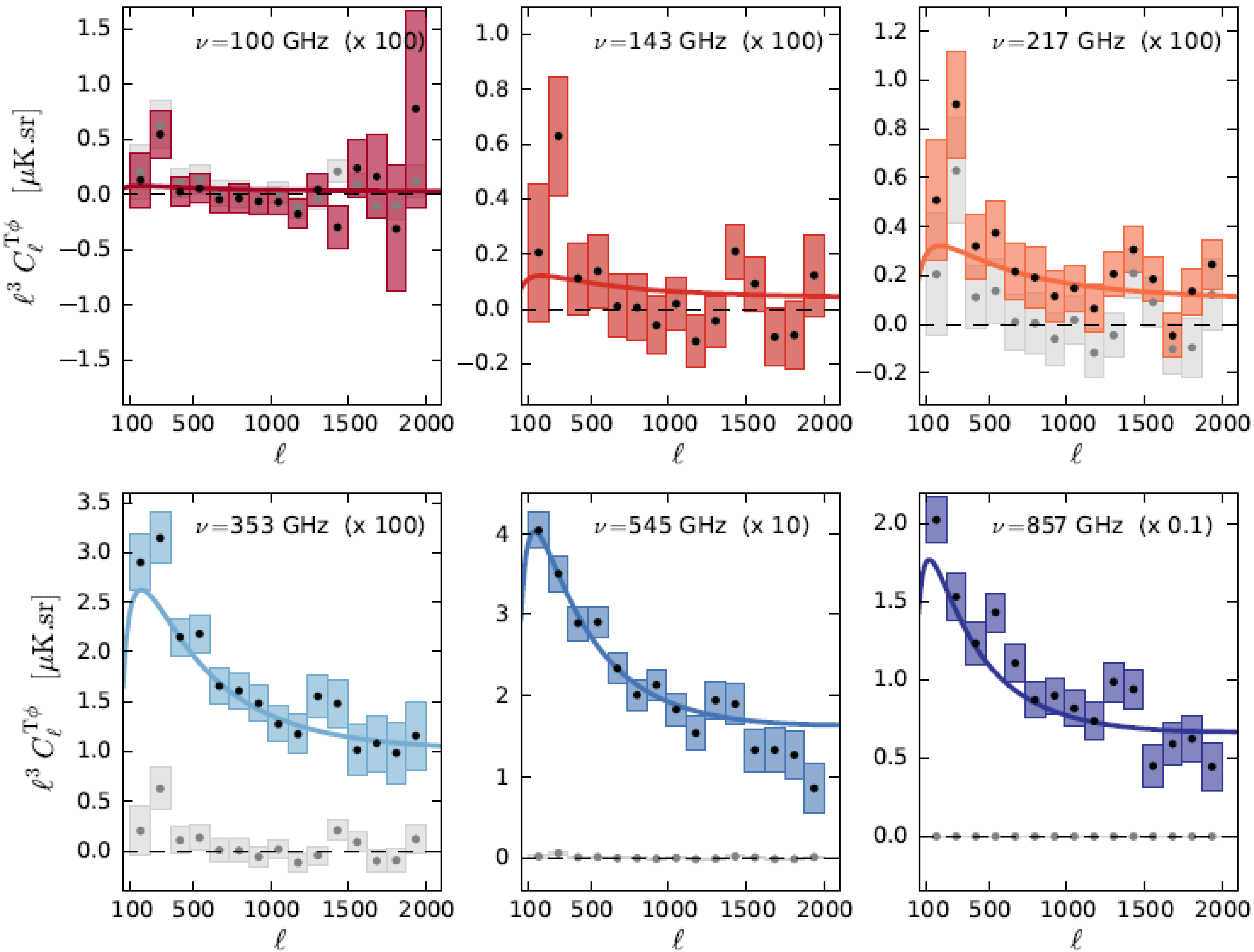
	SMICA	NILC	SEVEM	C-R
KSW	0.81 ± 0.31	0.85 ± 0.32	0.68 ± 0.32	0.75 ± 0.32
Binned	0.91 ± 0.37	1.03 ± 0.37	0.83 ± 0.39	0.80 ± 0.40
Modal	0.77 ± 0.37	0.93 ± 0.37	0.60 ± 0.37	0.68 ± 0.39

Planck 2013 results. XVIII.
Gravitational lensing-infrared background correlation



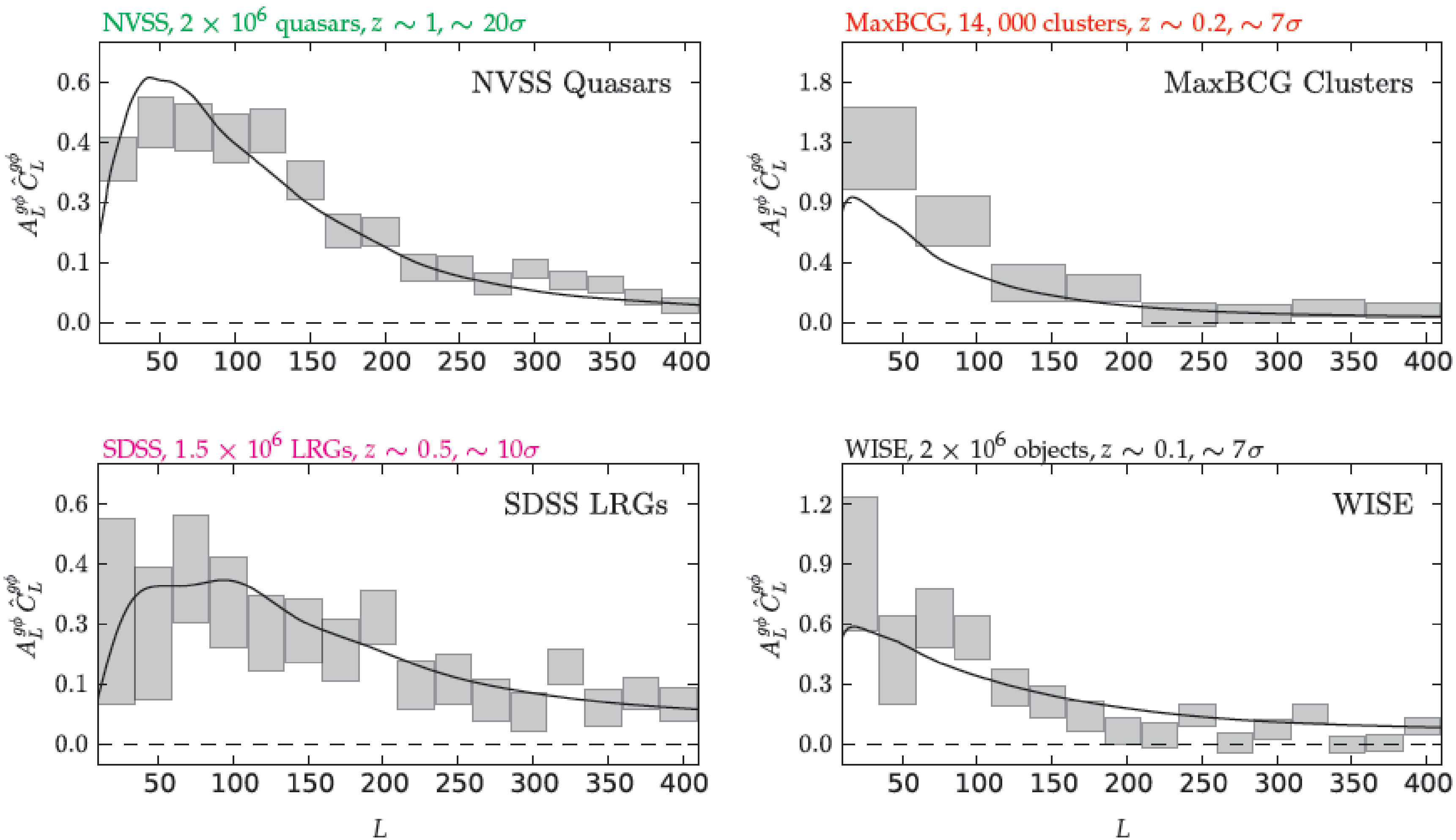
The high-frequency Planck maps trace Cosmic Infrared Background (CIB) fluctuations, primarily sourced by star formation at high-redshift; strong correlations with lensing (Song et. al.).

CIB-CMB lensing bispectrum detection



'42 σ at 545 GHz !

External Correlations



Conclusions

- Planck TT marks the beginning of the end for C_l^{TT}
  - cosmic variance limited to $L \sim 1600$
  - lensing smoothing detected, but possible issues with $A_L > 1$

- Planck lensing marks end of the beginning for $C_l^{\phi\phi}$

  - first nearly fully-sky maps of the lensing potential
  - detected at high significance, by itself and in correlation
  - reconstruction noise dominated
  - can break parameter degeneracies (but not yet competitive with e.g. BAO)
  - broadly consistent with expected amplitude, no preference for $A_L > 1$

Future: SPT TT (~months), Planck full mission (1 yr), ACTpol, SPTpol