

astro8405

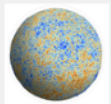
An Introduction to the Cosmic Microwave Background

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eCampus | Lernplattform der Universität Bonn



astro8405: The Cosmic Microwave Background

Aktionen ▼

This course intends to give you a modern and up-to-date introduction to the science and experimental techniques relating to the Cosmic Microwave Background. No prior knowledge of cosmology is necessary, your prerequisite are a basic understanding of electrodynamics and thermal physics and some familiarity with Python programming.

Lecture 12:

CMB Lensing

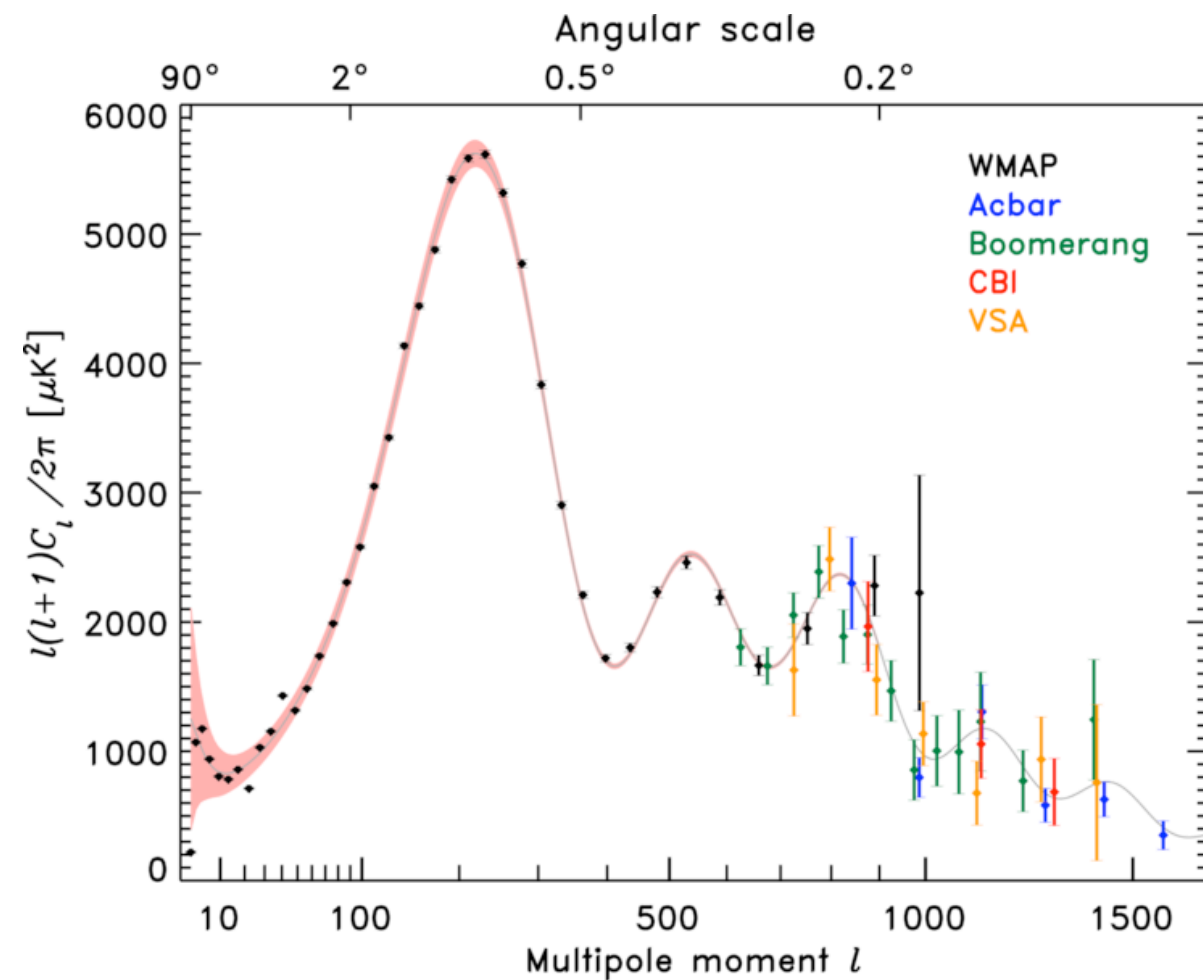
Secondary temperature anisotropies

From the 1995 review
by Max Tegmark

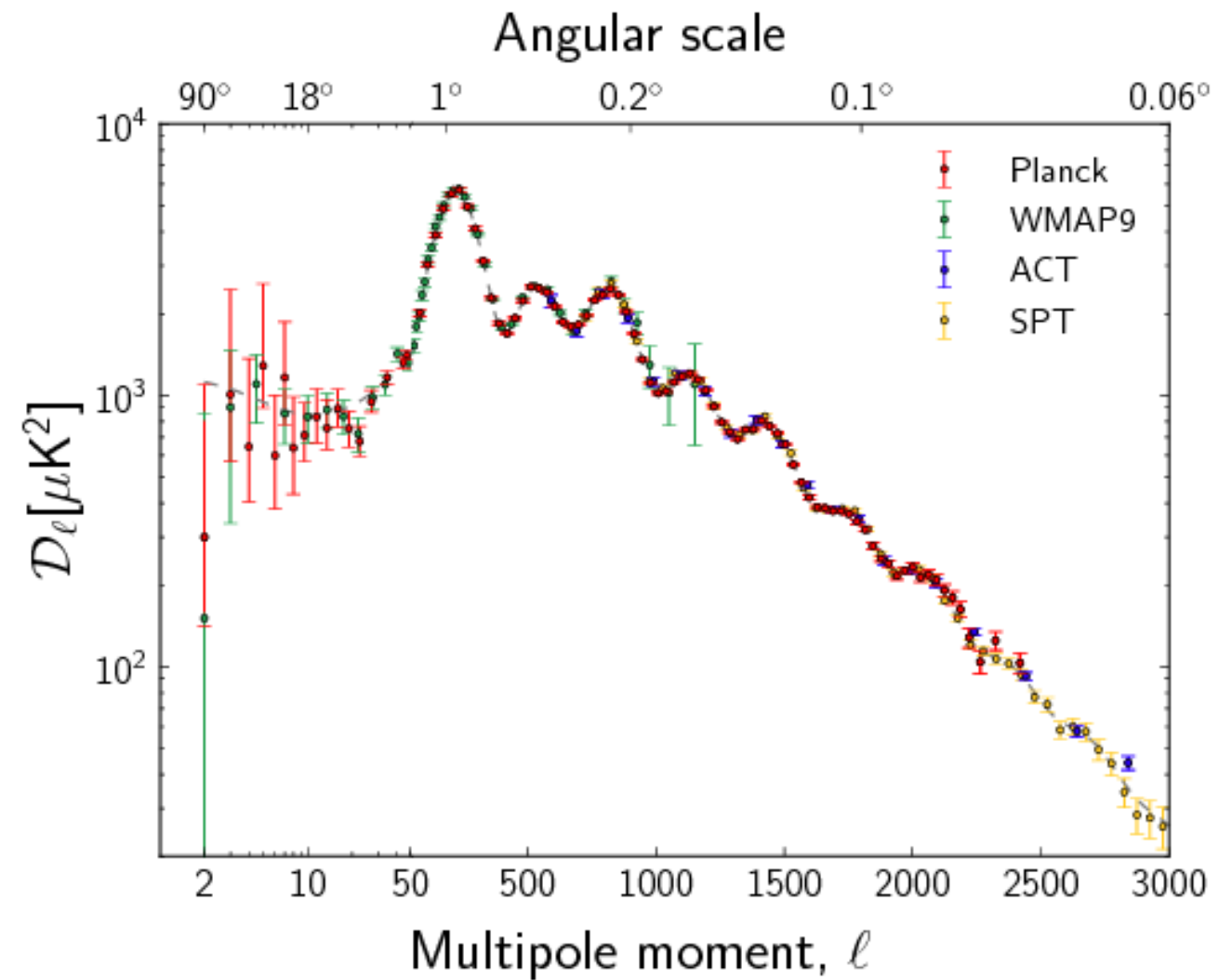
Table 1. Sources of temperature fluctuations.

PRIMARY	Gravity	
	Doppler	
	Density fluctuations	
	Damping	
	Defects	Strings
SECONDARY	Gravity	Textures
		Early ISW
		Late ISW
		Rees-Sciama
	Local reionization	Lensing
		Thermal SZ
		Kinematic SZ
	Global reionization	Suppression
		New Doppler
		Vishniac
“TERTIARY” (foregrounds & headaches)	Extragalactic	Radio point sources
		IR point sources
	Galactic	Dust
		Free-free
		Synchrotron
	Local	Solar system
		Atmosphere
		Noise, <i>etc.</i>

CMB power at small angles

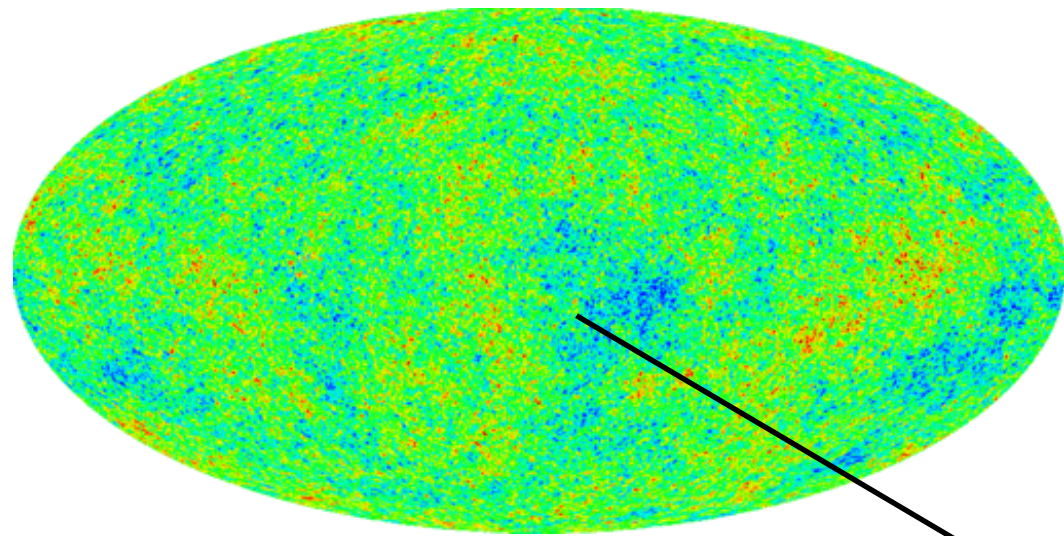


~2006



~2015

CMB photons on their way to us

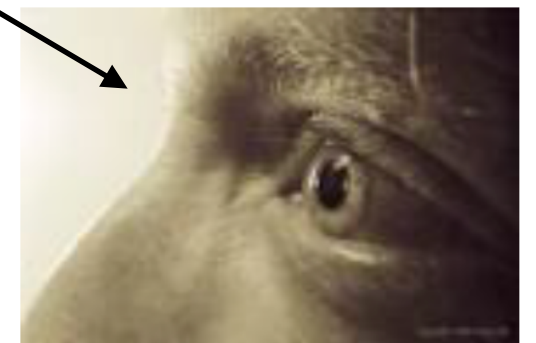


Last scattering surface

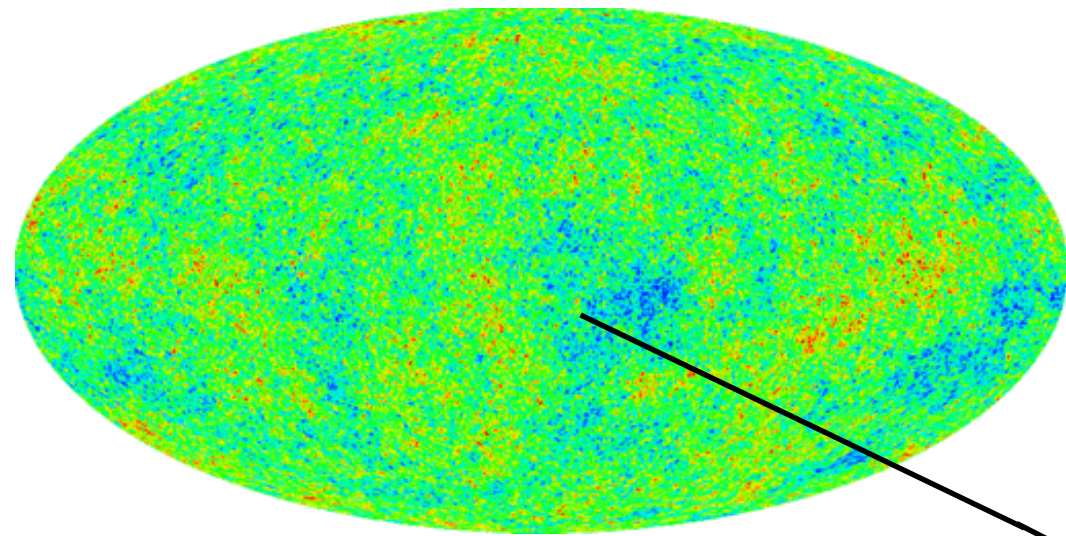
***Two things can happen
to the CMB photons:***

- 1. they are deflected by
gravitational potentials***
- 2. they get scattered off
electrons and atoms***

Observer



CMB photons on their way to us



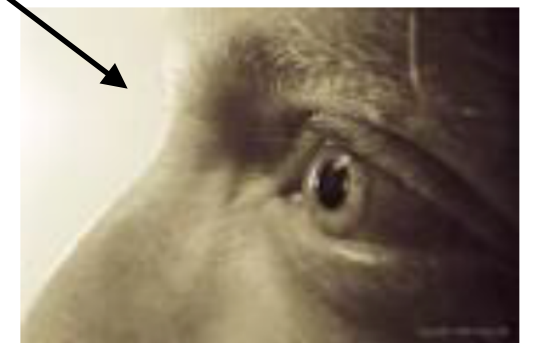
Last scattering surface

Two things can happen to the CMB photons:

- 1. they are deflected by gravitational potentials***
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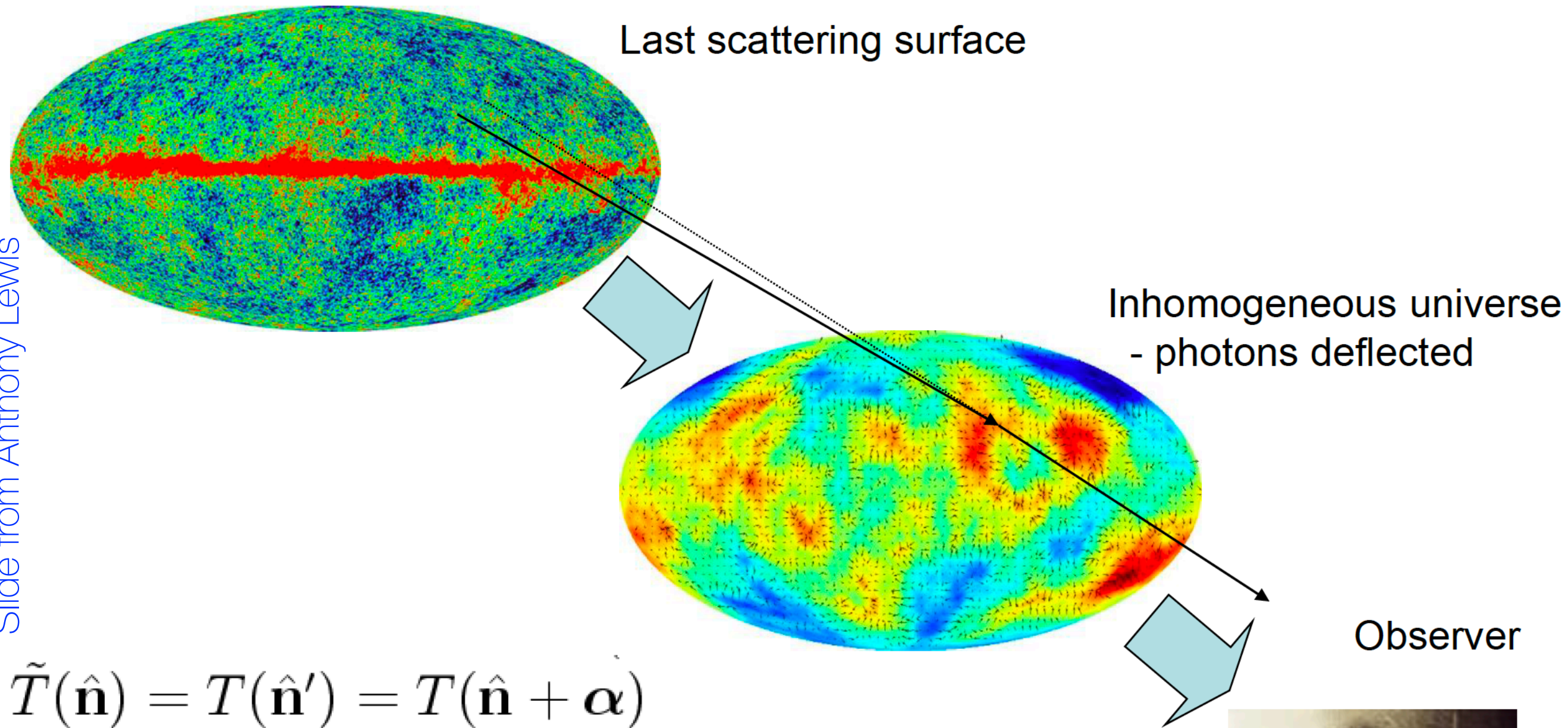


Observer



Lensing of the CMB photons

Slide from Anthony Lewis



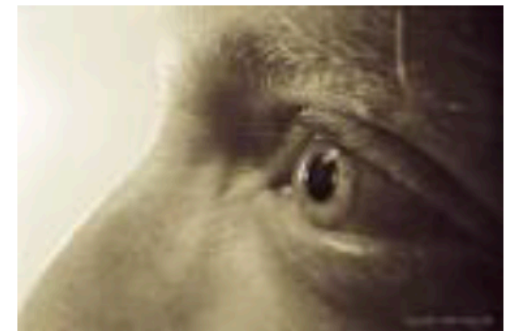
$$\tilde{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}') = T(\hat{\mathbf{n}} + \boldsymbol{\alpha})$$

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

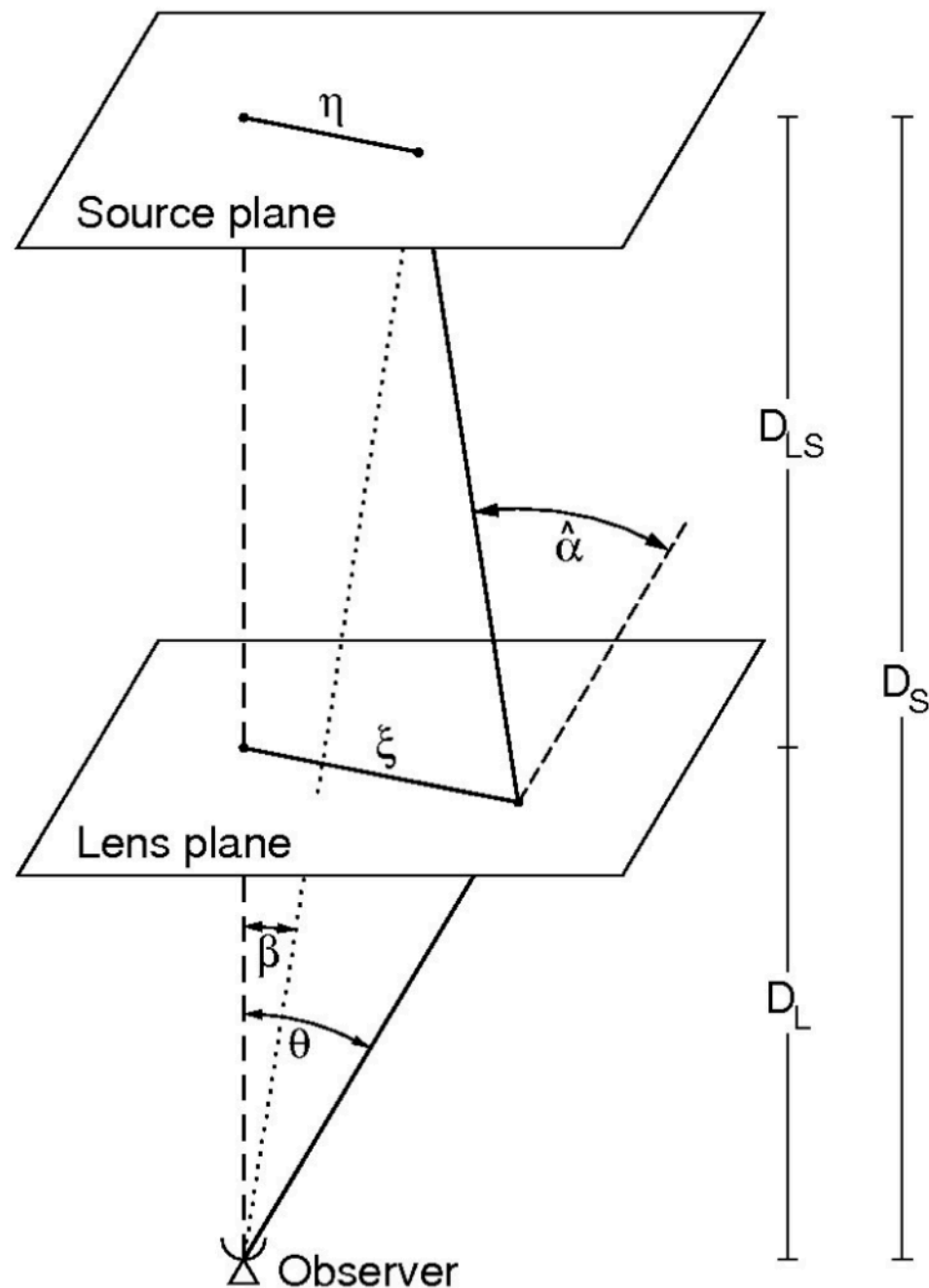
deflection angle

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

lensing potential



Lensing basics. I



The deflection angle α , as the name suggests, is the deflection in the angular position of the source caused by the lens. It is generally a 2D vector, but if the lens is axially symmetric, can be treated as a scalar.

$$\beta = \theta - \alpha(\theta)$$

Since the distance between the observer, lens, and the source is typically much larger than the dimensions of the lens, “thin lens approximation” holds, where the lens is fully described by its surface mass density.

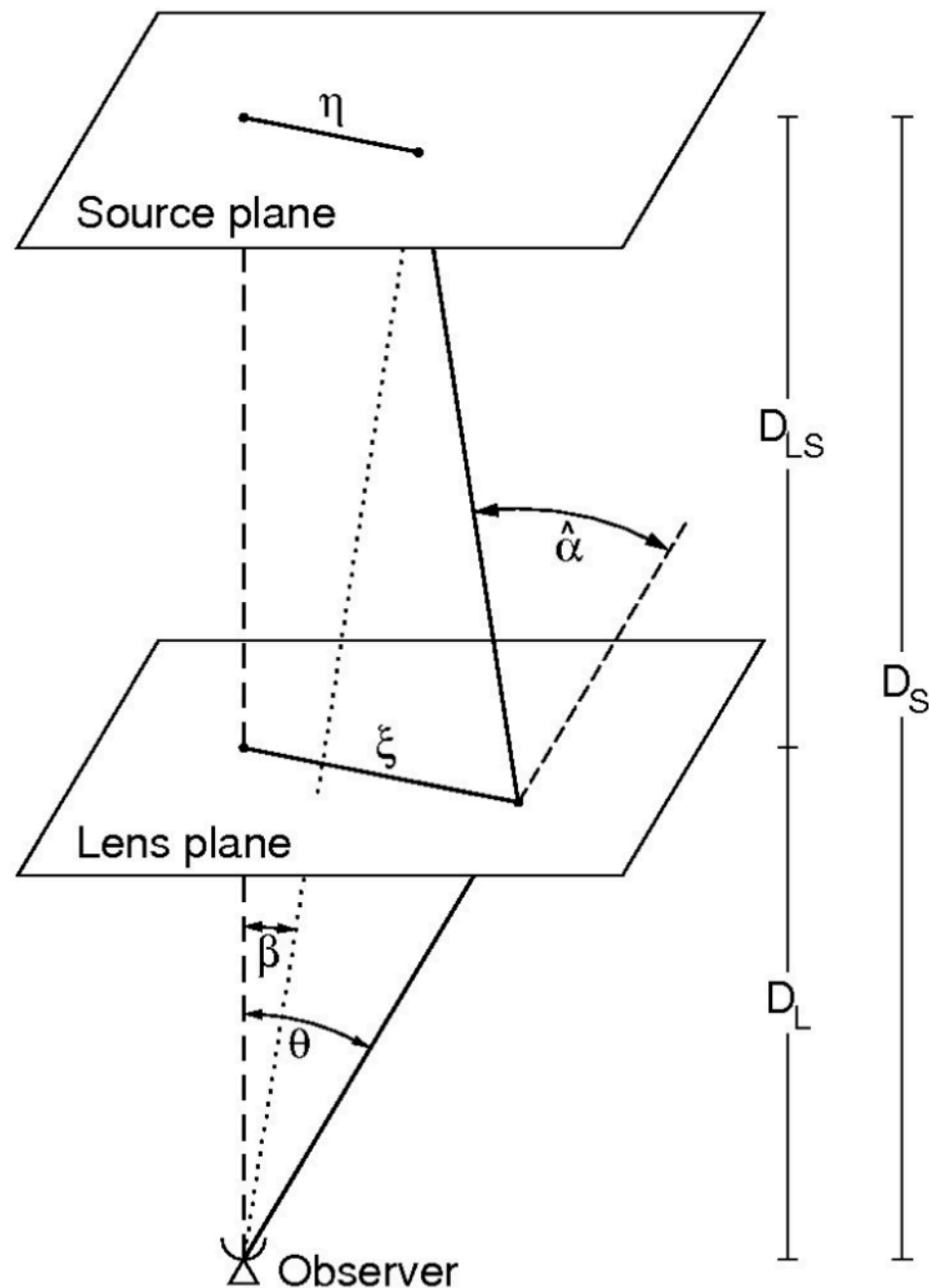
$$\Sigma(\vec{\xi}) = \int \rho(\vec{\xi}, z) dz$$

The total deflection angle is computed by summing all the mass elements, since it is linearly proportional to the mass.

$$\vec{\alpha}(\vec{\xi}) = \frac{4G}{c^2} \int \frac{(\vec{\xi} - \vec{\xi}') \Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2} d^2\xi'$$

Lensing lecture by Massimo Meneghetti

Lensing basics. II



An extended distribution of matter is characterized by its effective gravitational potential, which is the projection of the 3D (Newtonian) potential onto the lens plane

$$\hat{\Psi}(\vec{\theta}) = \frac{D_{LS}}{D_L D_S} \frac{2}{c^2} \int \Phi(D_L \vec{\theta}, z) dz$$

The gradient of Ψ gives the deflection angle

$$\begin{aligned} \vec{\nabla}_x \Psi(\vec{x}) &= \xi_0 \vec{\nabla}_\perp \left(\frac{D_{LS} D_L}{\xi_0^2 D_S} \frac{2}{c^2} \int \Phi(\vec{x}, z) dz \right) \\ &= \frac{D_{LS} D_L}{\xi_0 D_S} \frac{2}{c^2} \int \vec{\nabla}_\perp \Phi(\vec{x}, z) dz \\ &= \vec{\alpha}(\vec{x}) \end{aligned}$$

The Laplacian of Ψ gives twice the convergence, which is defined in terms of the surface mass density

$$\nabla^2 \Psi(\vec{x}) = 2\kappa(\vec{x}) \quad \kappa(\vec{x}) = \frac{1}{2} \vec{\nabla} \cdot \vec{\alpha}$$

All distances are angular diameter distances. Generally, they are not additive: $D_L + D_{LS} \neq D_S$

$$\kappa(\vec{x}) \equiv \frac{\Sigma(\vec{x})}{\Sigma_{cr}} \quad \text{with} \quad \Sigma_{cr} = \frac{c^2}{4\pi G} \frac{D_S}{D_L D_{LS}}$$

The generalized lens equation

The total deflection is calculated by summing over the gravitational potentials along the line-of-sight

$$\alpha(\boldsymbol{\theta}) = \frac{2}{c^2 f_k(\chi)} \int_0^\chi d\chi' \frac{f_k(\chi - \chi')}{f_k(\chi')} \nabla_{\boldsymbol{\theta}} \Phi(f_k(\chi') \boldsymbol{\theta}, \chi')$$

where the comoving angular diameter distances are defined by the cosmology:

$$f_k(\chi) = \begin{cases} \frac{D_H}{\sqrt{\Omega_k}} \sinh(\chi \sqrt{\Omega_k} / D_H) & \Omega_k > 0 \\ \chi & \Omega_k = 0 \\ \frac{D_H}{\sqrt{|\Omega_k|}} \sin(\chi \sqrt{|\Omega_k|} / D_H) & \Omega_k < 0 \end{cases}$$

Note that the above integral is only an approximation, known as the *Born approximation*, where the integration is taken along a straight line connecting the observer and the source, and not along the actual light path. Also, different positions $\boldsymbol{\theta}$ can satisfy the lensing equation, creating multiple images of the source.

Note:
 $\psi \leftrightarrow \phi$

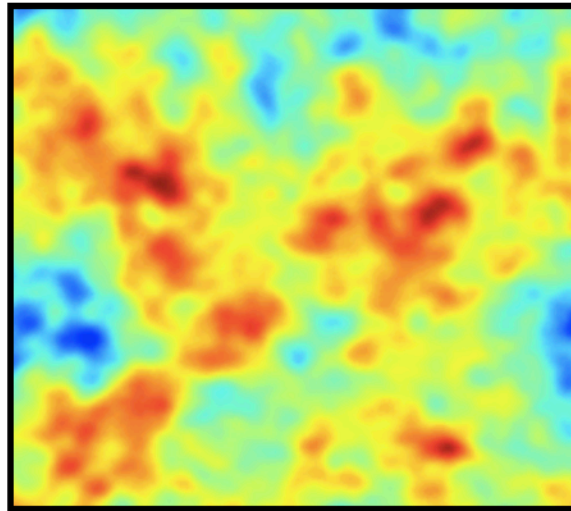
Lensing is a surface brightness conserving **remapping** of source to image planes by the gradient of the **projected potential**

$$\phi(\hat{\mathbf{n}}) = 2 \int \frac{dz}{H(z)} \frac{D_A(D_s - D)}{D_A(D) D_A(D_s)} \Phi(D_A \hat{\mathbf{n}}, D),$$

How to lens the CMB?

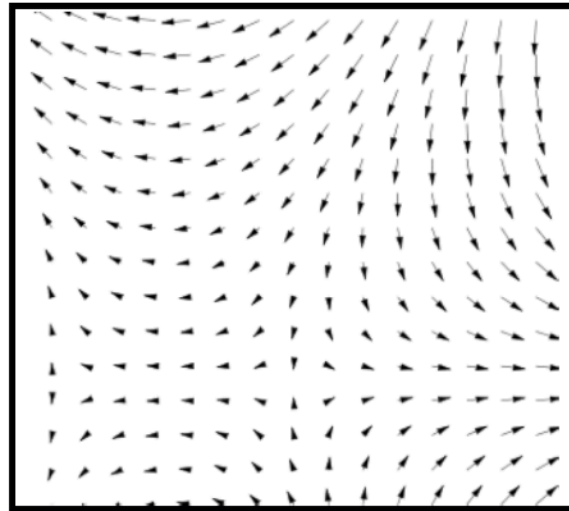
Given the deflection field, remap the points on the CMB.

Unlensed



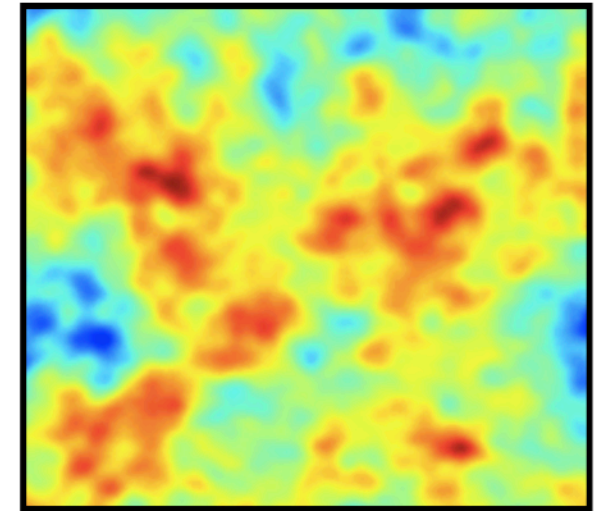
$$\Theta(\hat{n})$$

Deflection



$$\vec{\alpha}(\hat{n})$$

Lensed



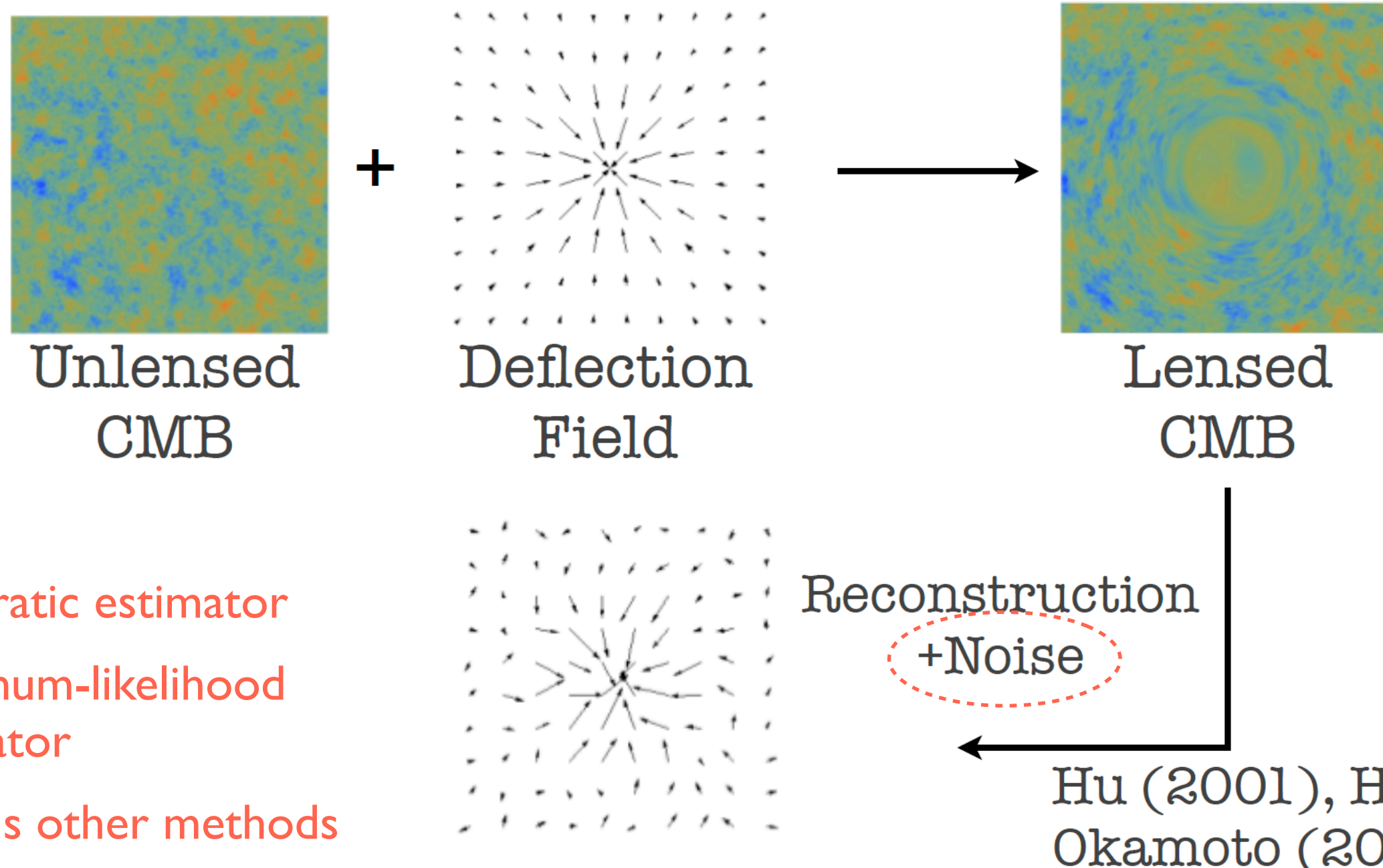
$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \vec{\alpha})$$

CMB lensing can be discussed completely in terms of the deflection field.

Reconstructing the deflection

Slide from Sudeep Das

Given only the lensed CMB sky, can we estimate the deflection field?



- Quadratic estimator
- Maximum-likelihood estimator
- various other methods

The deflection power

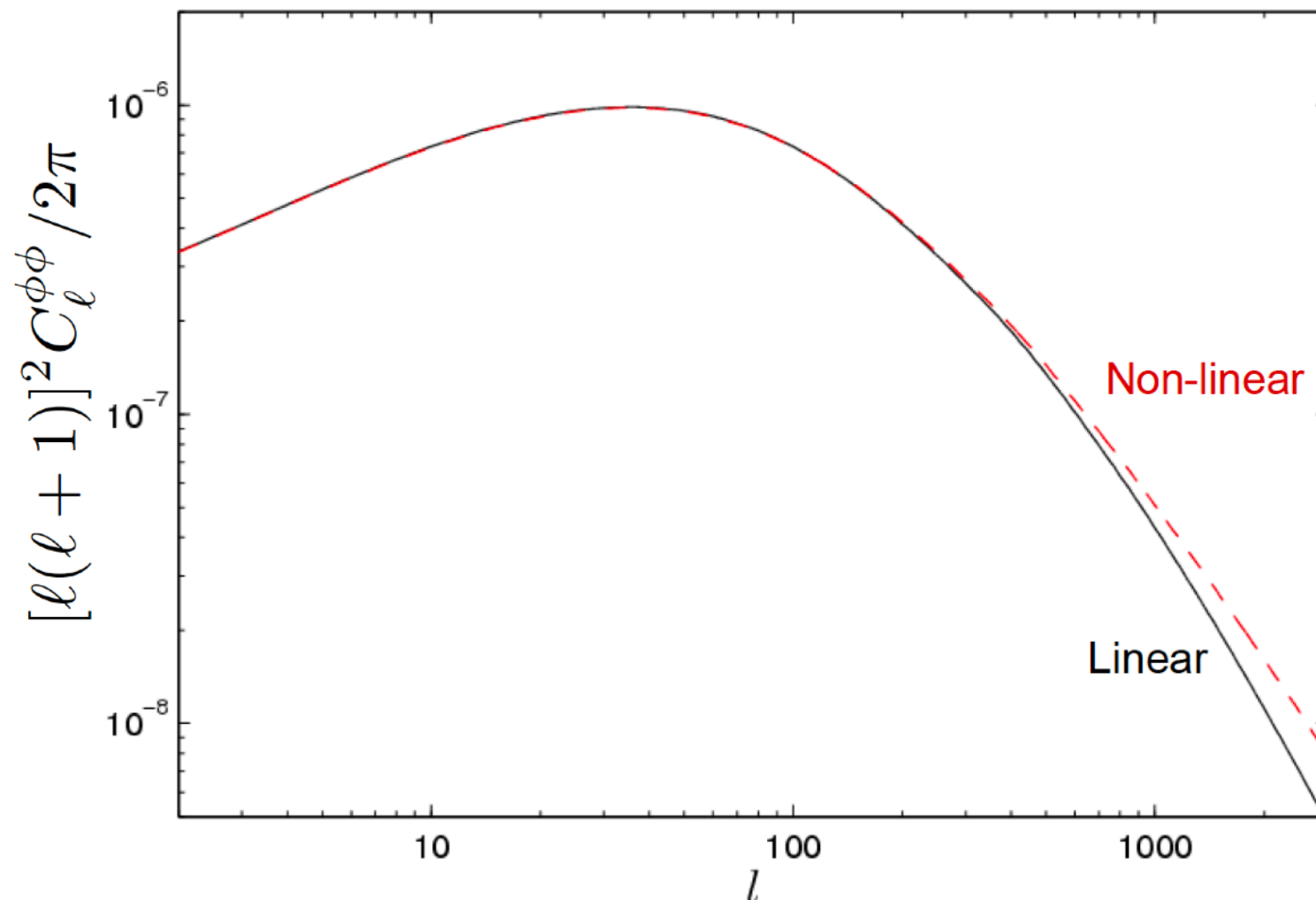
The deflection angle power spectrum is generally shown as the power for the projected lensing potential, ϕ

Note:
 $\psi \leftrightarrow \phi$

$$\vec{\alpha}(\hat{n}) = \nabla_{\hat{n}} \phi(\hat{n})$$

These two are related by the equation: $C_{\ell}^{\alpha\alpha} = \ell(\ell + 1) C_{\ell}^{\phi\phi}$

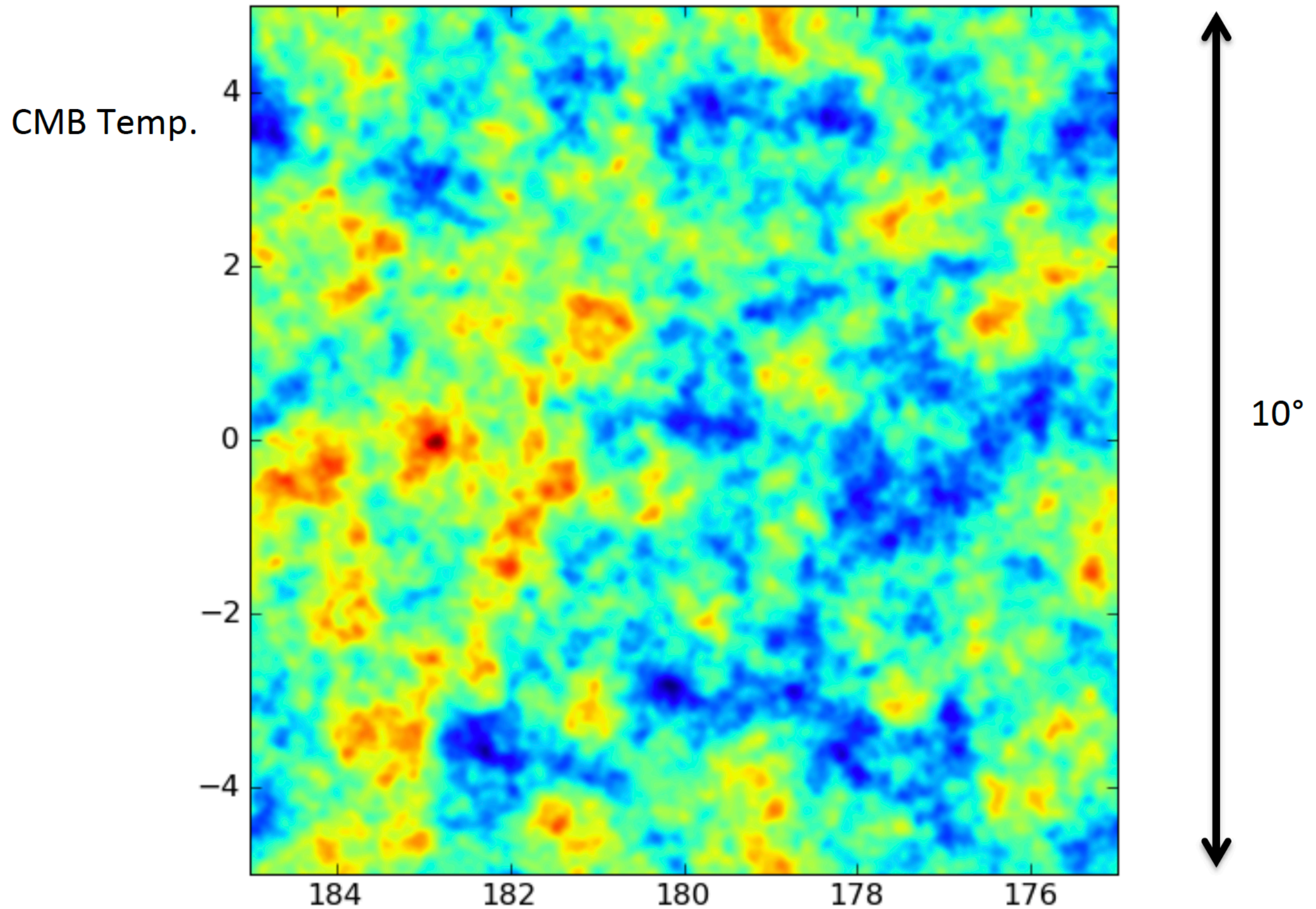
Hence in the Y-axis you will see the quantity plotted as: $[\ell(\ell + 1)]^2 C_{\ell}^{\phi\phi} / 2\pi \approx \ell^4 C_{\ell}^{\phi\phi}$



The deflection PS
peaks at about
 $\ell \sim 60$

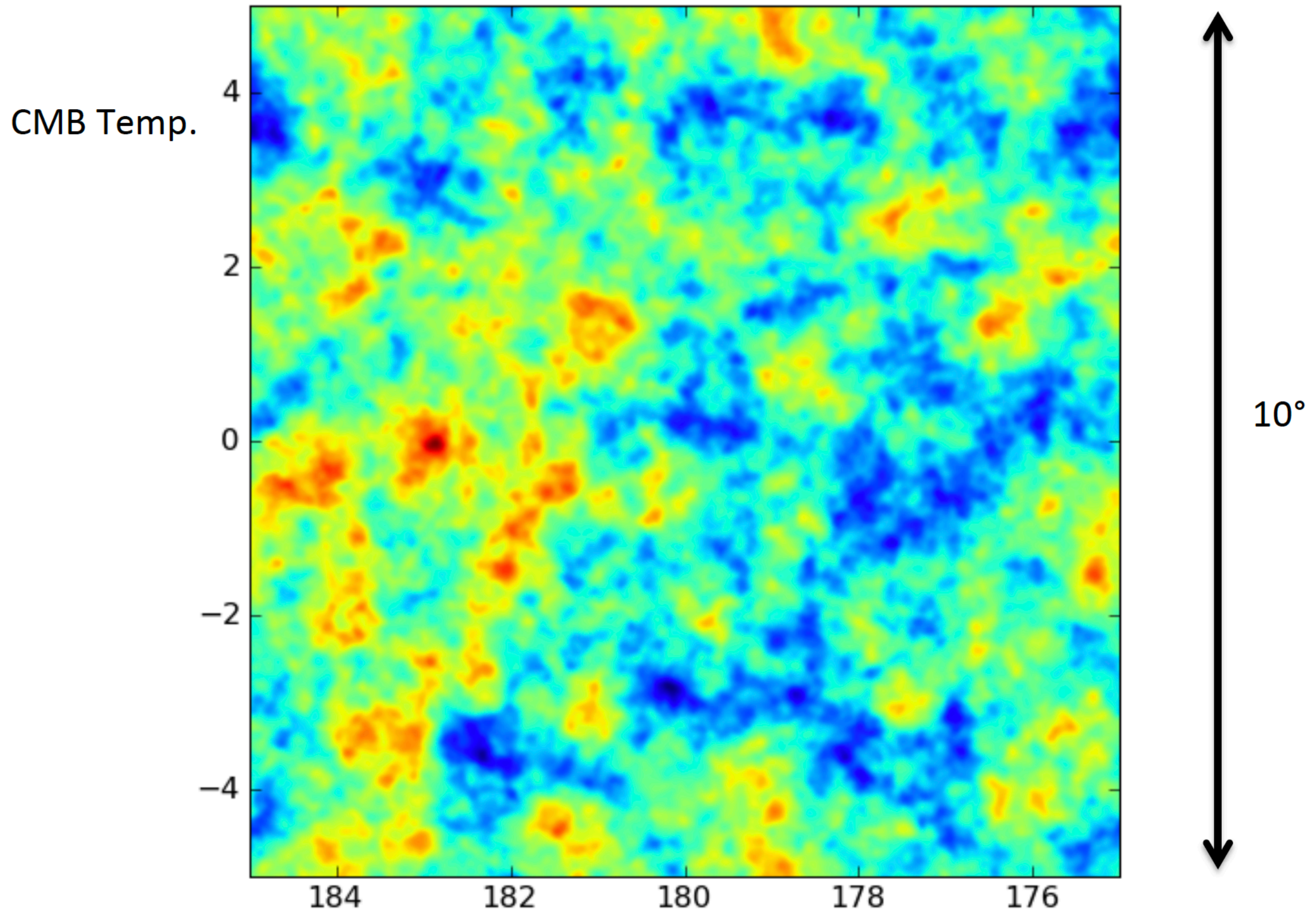
- most power in
degree scale
modes.

Unlensed CMB



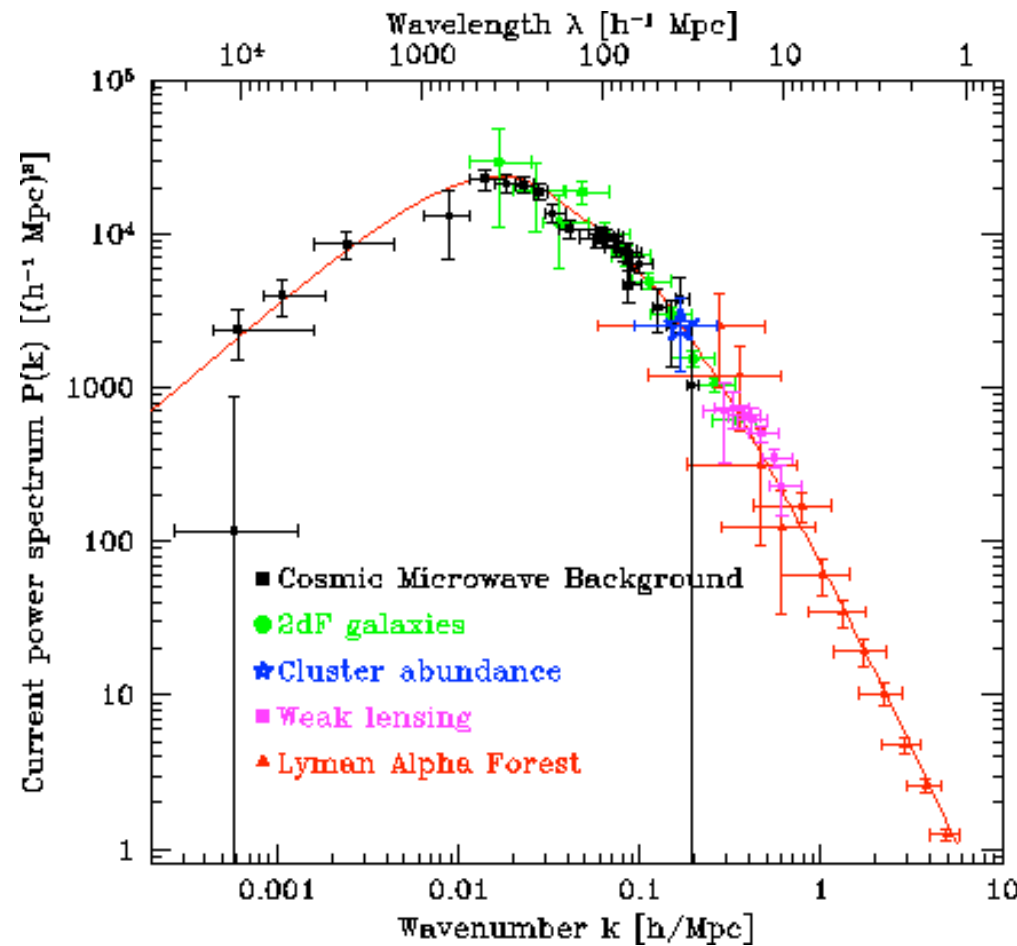
$$T(\hat{\mathbf{n}})_{\text{unlensed}}$$

Lensed CMB



$$T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}}$$

Scale of the lensing peak explained



Peak of matter power spectrum $\sim 300 \text{ Mpc}$.
CMB is at $\sim 14000 \text{ Mpc}$

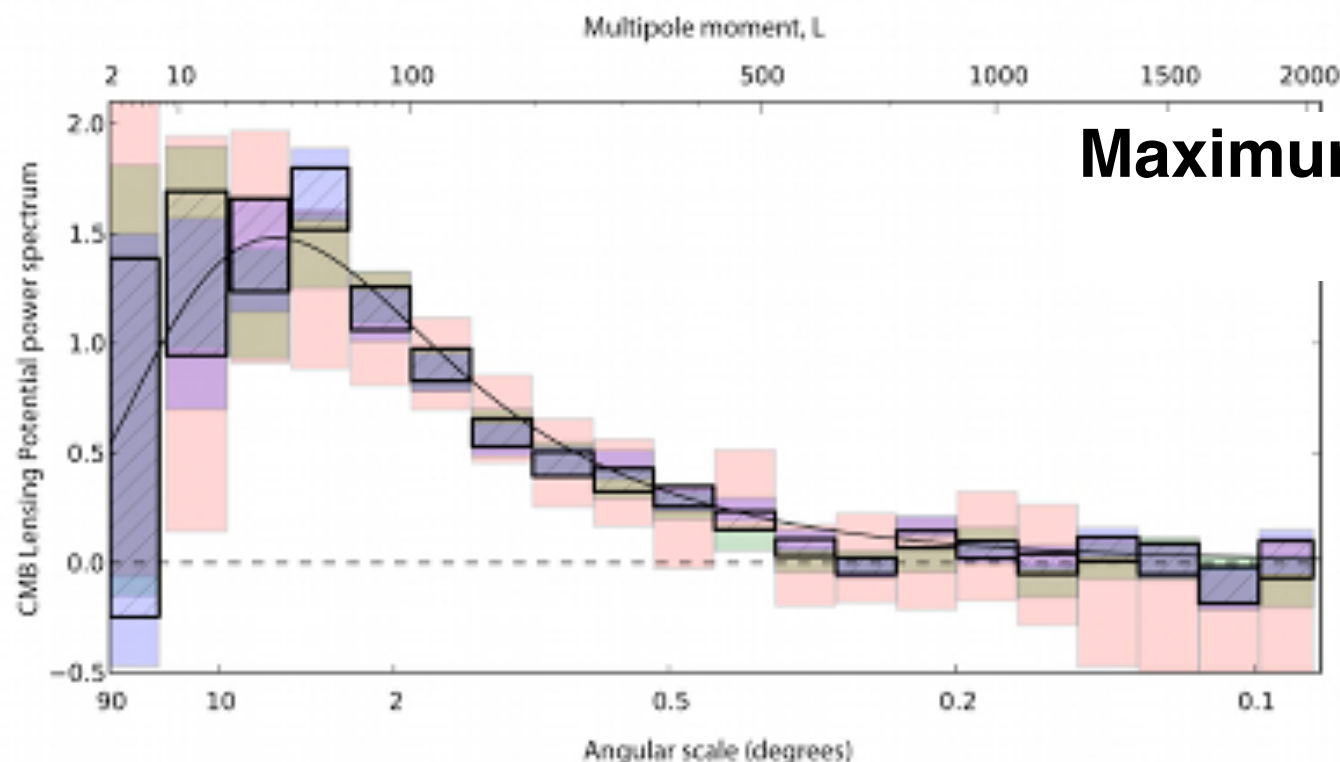
Thus on average, CMB passes through $\sim 14000/300 \sim 50$ lenses

Each lens produce deflection $\alpha \approx 4\Psi \sim 0.3 \text{ arcmin}$

This is a random walk problem for CMB photons!

Total deflection $\sim \sqrt{50} \times 0.3 \sim 2 \text{ arcmin}$

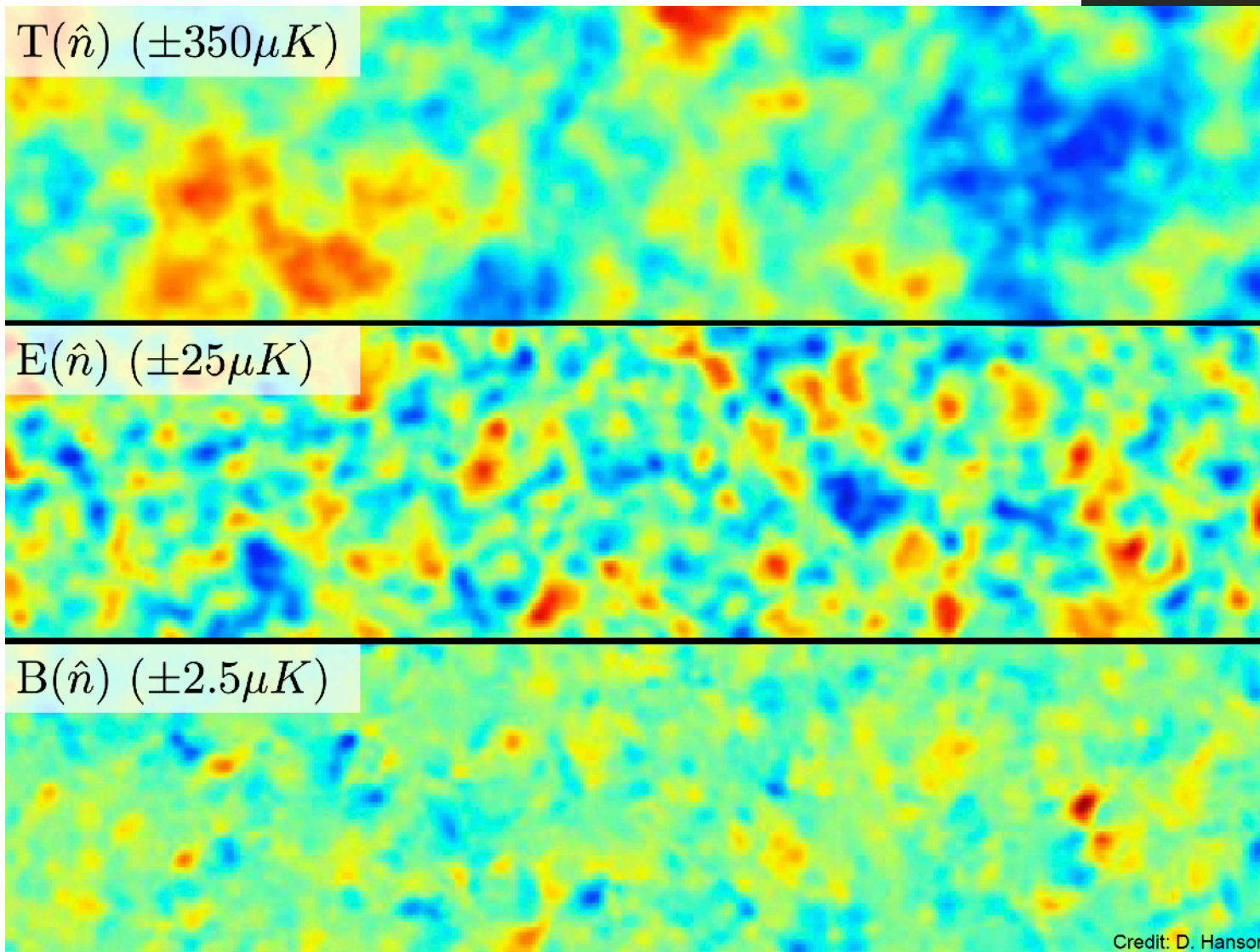
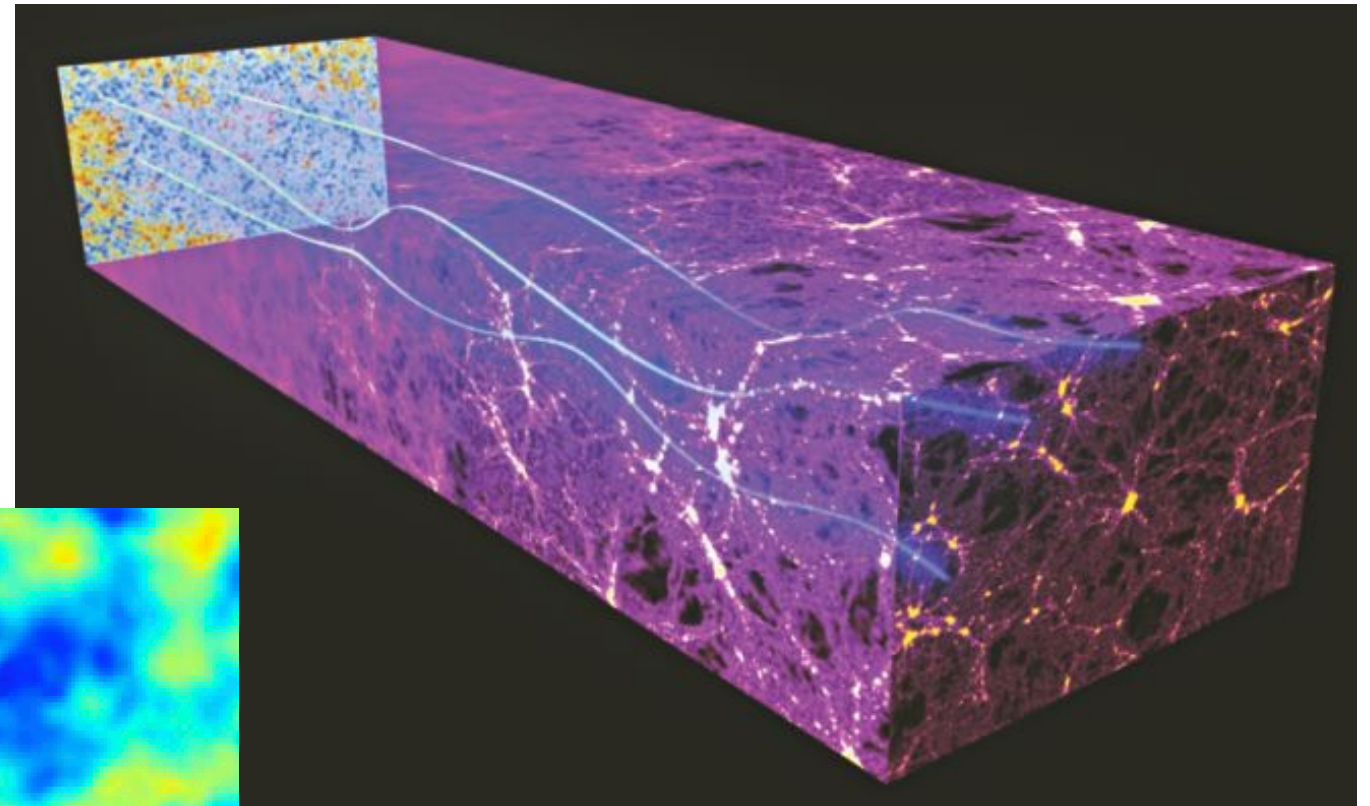
But deflections are coherent on scales of a representative chunk of matter



Maximum power on scales $\sim 300/(14000/2) \sim 2^\circ$

Lensing works on both temp. & pol.

The effect of lensing is quantified by the deflection angle $\alpha = \nabla\psi$ and it works on both temperature and polarization anisotropies in the same way.. with a twist!

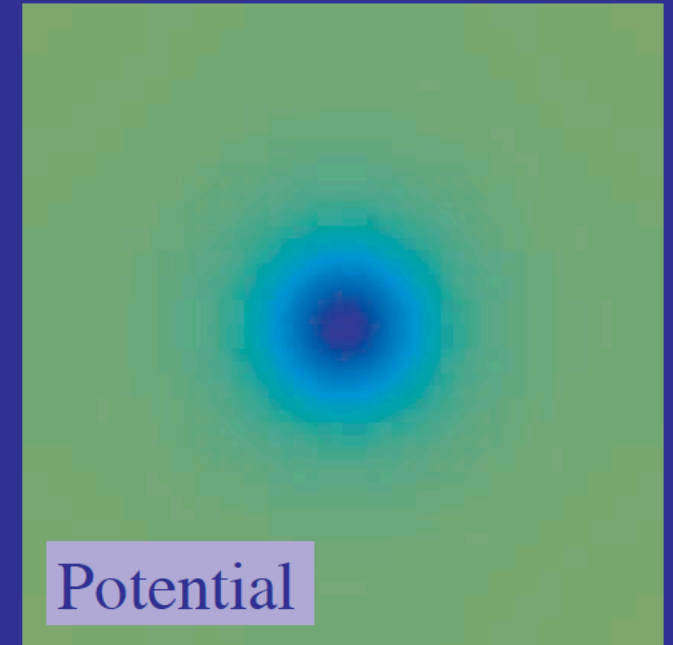
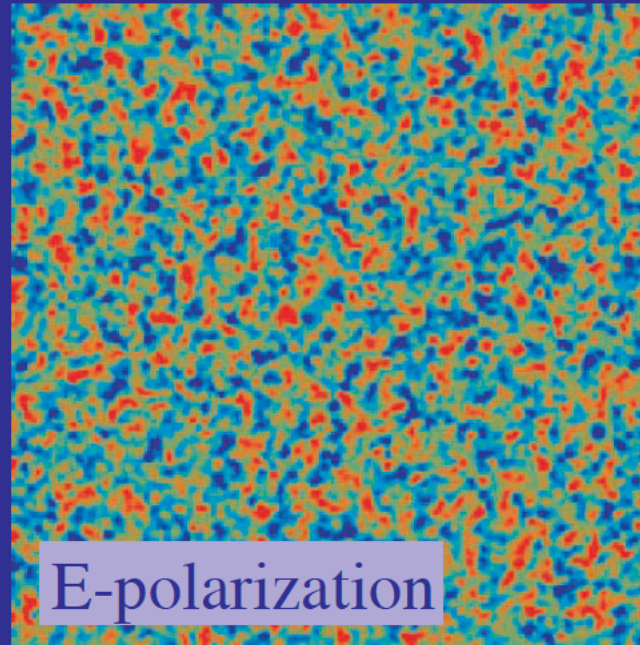
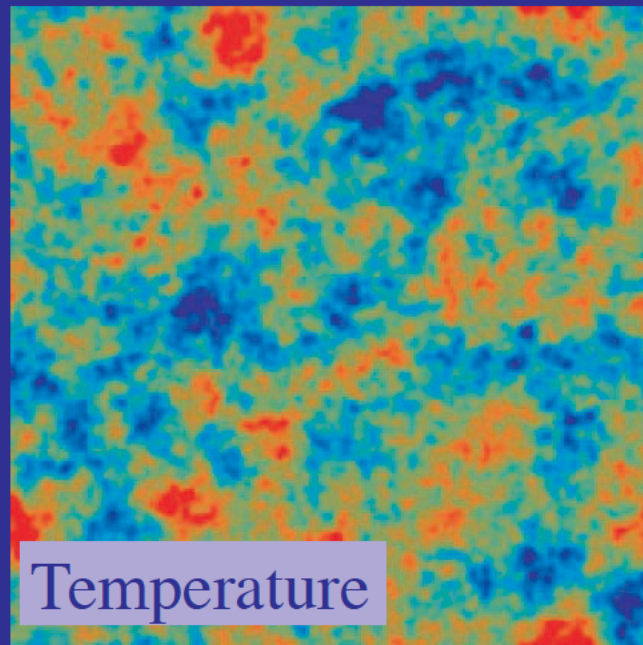


One result of CMB lensing is blurring of temperature and polarization anisotropies, as the angular scales associated with the peaks are smeared.

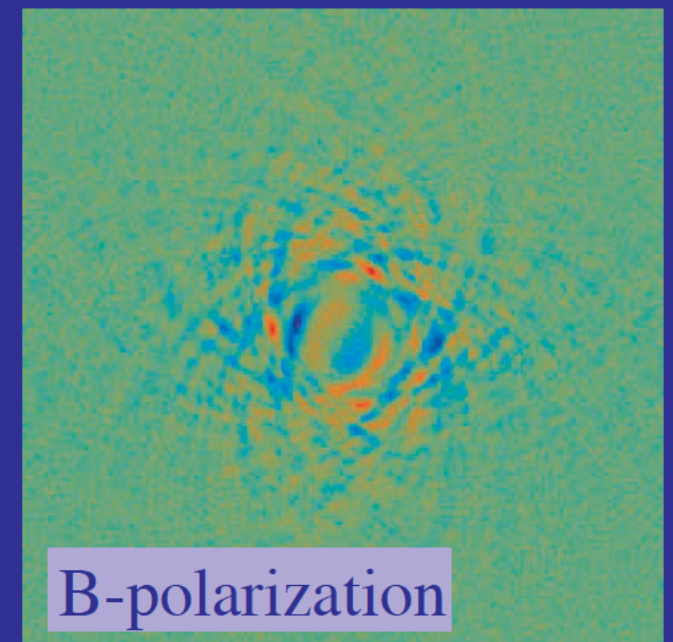
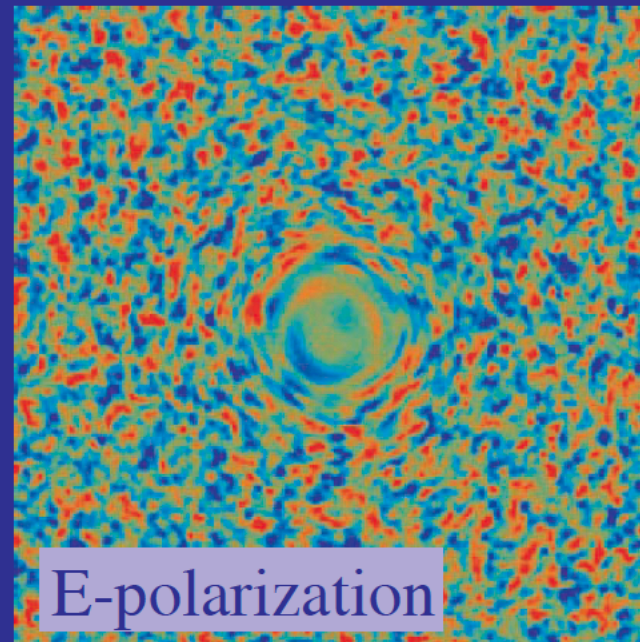
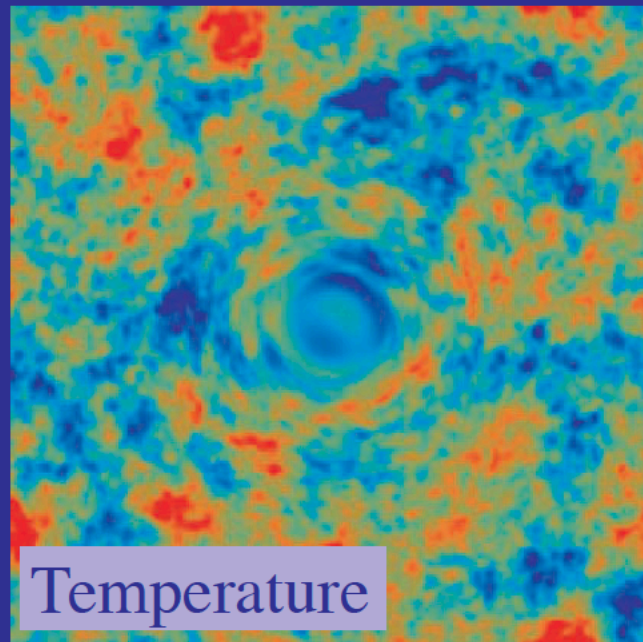
Another result is the creation of B-mode polarization from E-mode (by mixing Stokes Q and U params).

Temperature & polarization after lensing

Unlensed

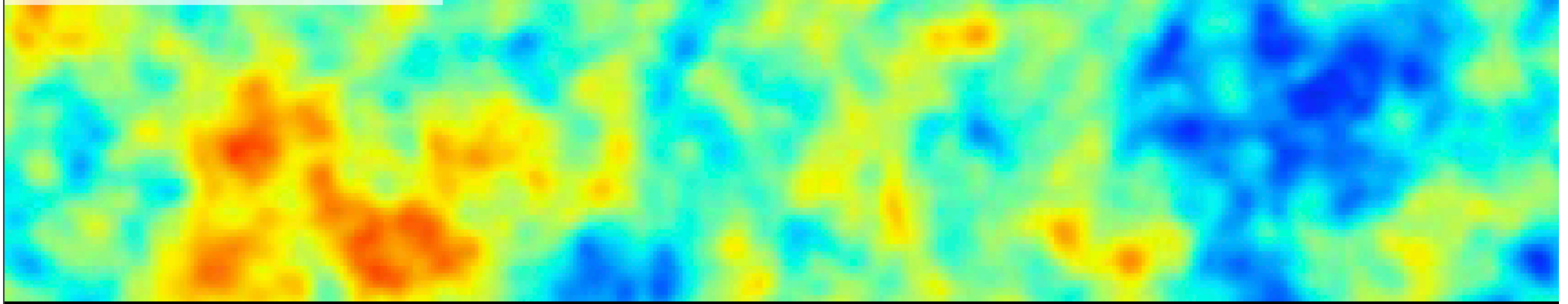


Lensed

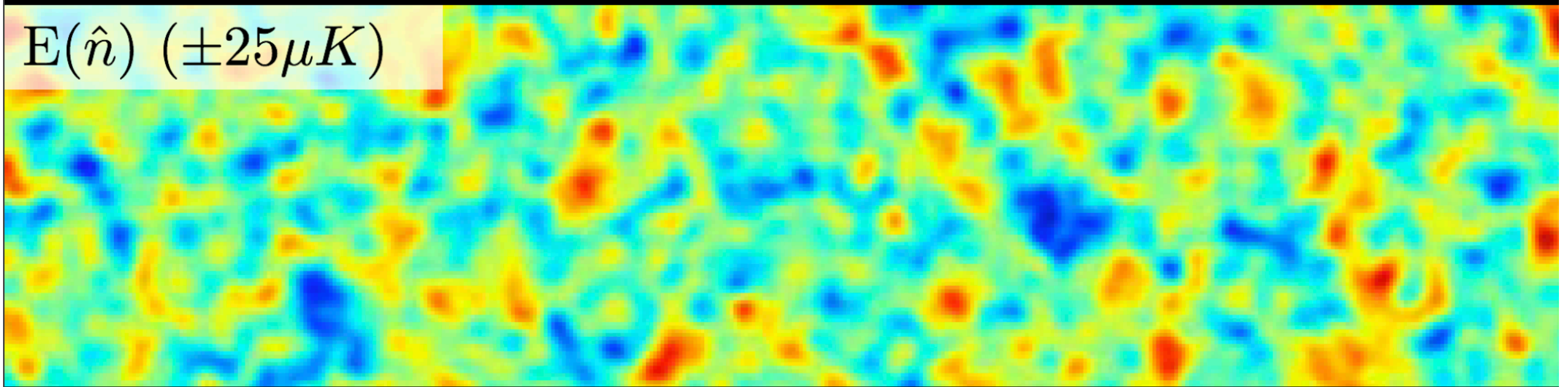


Zaldarriaga & Seljak (1999) [figure from Hu & Okamoto (2001)]

$T(\hat{n}) \ (\pm 350 \mu K)$



$E(\hat{n}) \ (\pm 25 \mu K)$

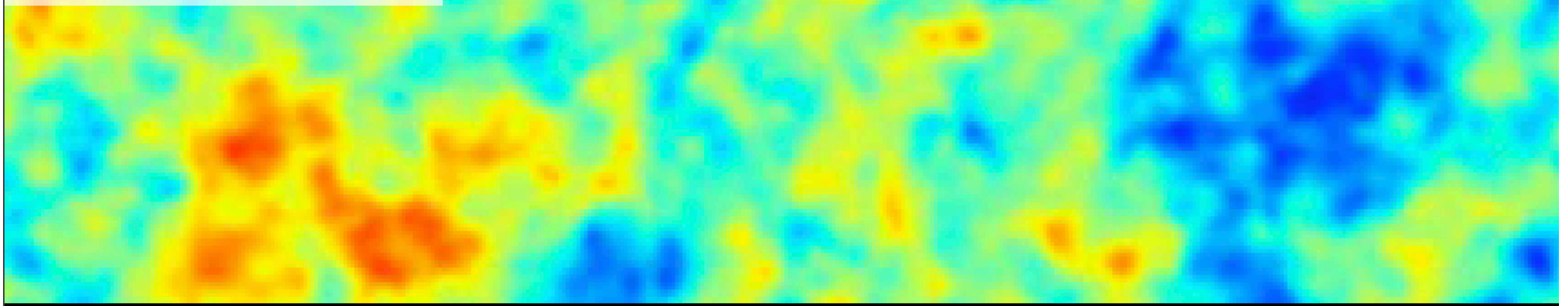


$B(\hat{n}) \ (\pm 2.5 \mu K)$

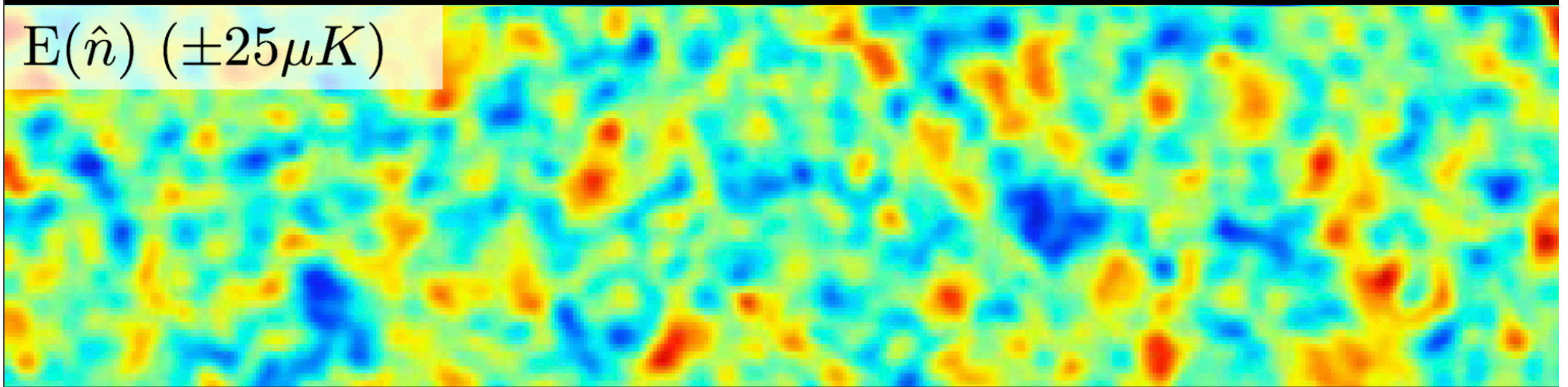


Credit: D. Hanson

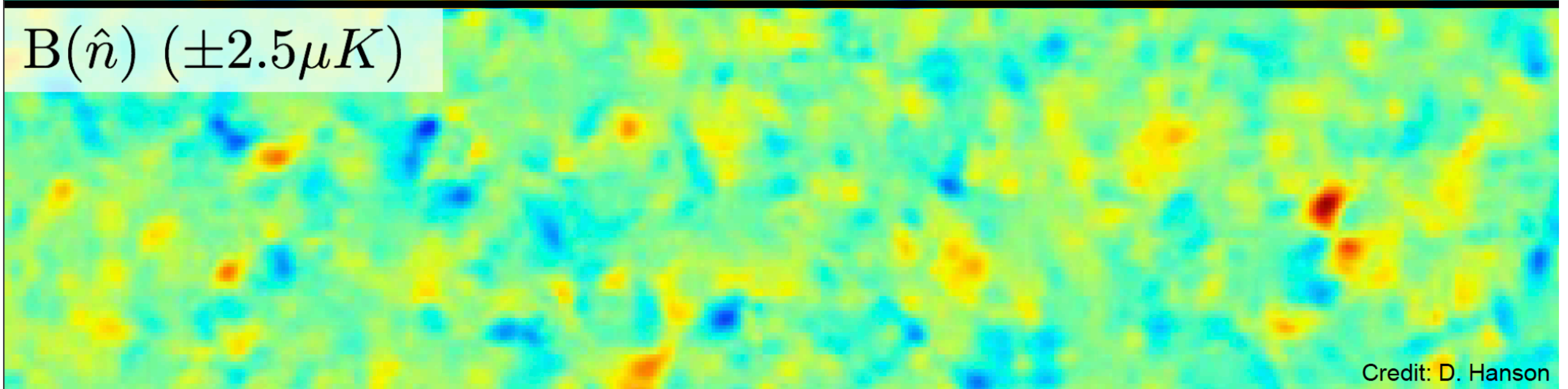
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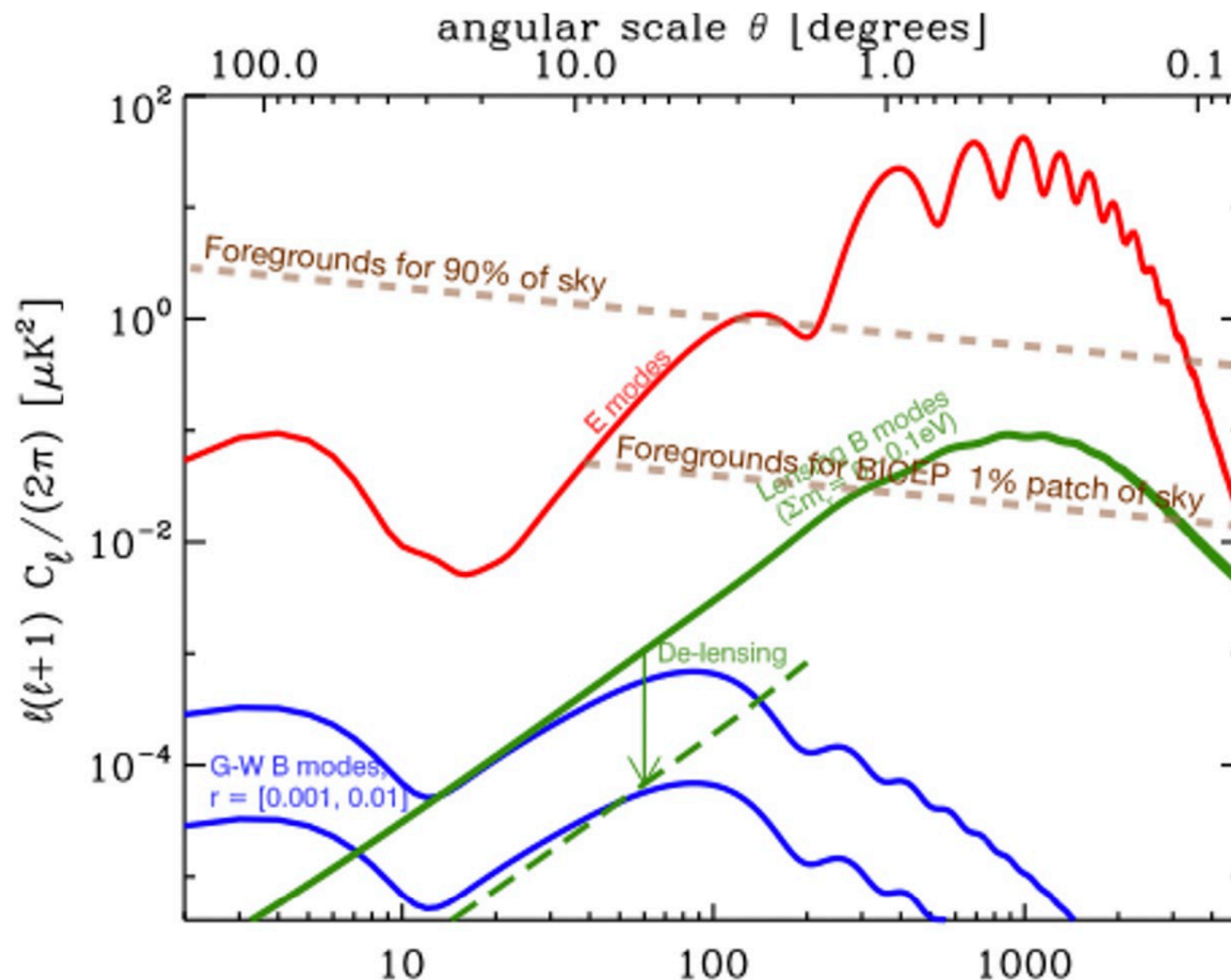


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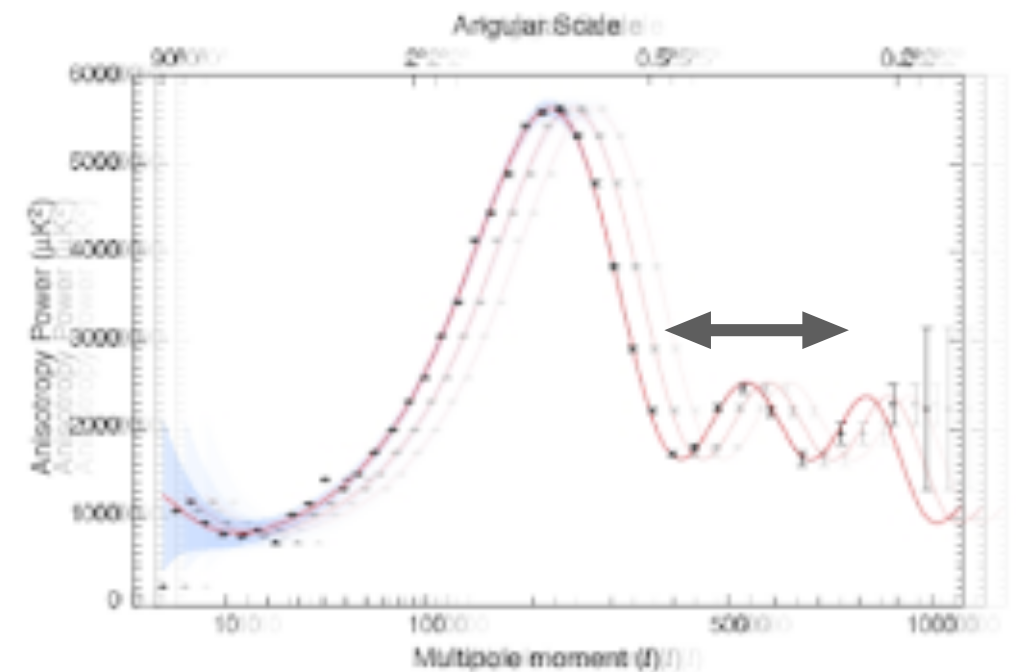
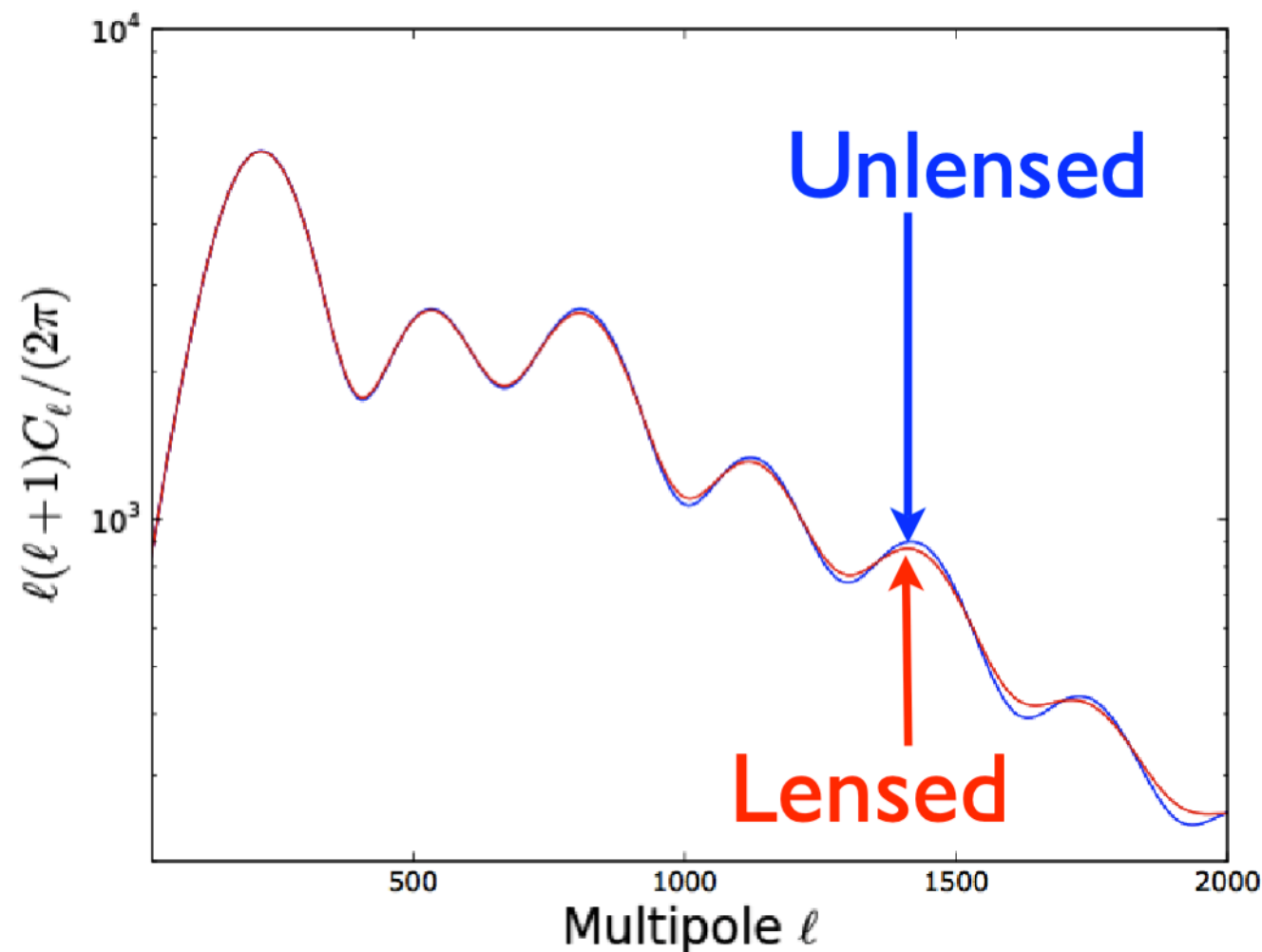
Lensing generates B-mode polarization



The power of the lensing-induced B-mode is much higher than the primordial B-mode generated by gravity waves at all angular scales, with only exception at the very large scales where the primordial B-mode is expected to get boosted by the “reionization bump”. Hence, all ground-based CMB B-mode experiments first need to **de-lens** their measurements, before claiming a possible detection of the primordial signal.

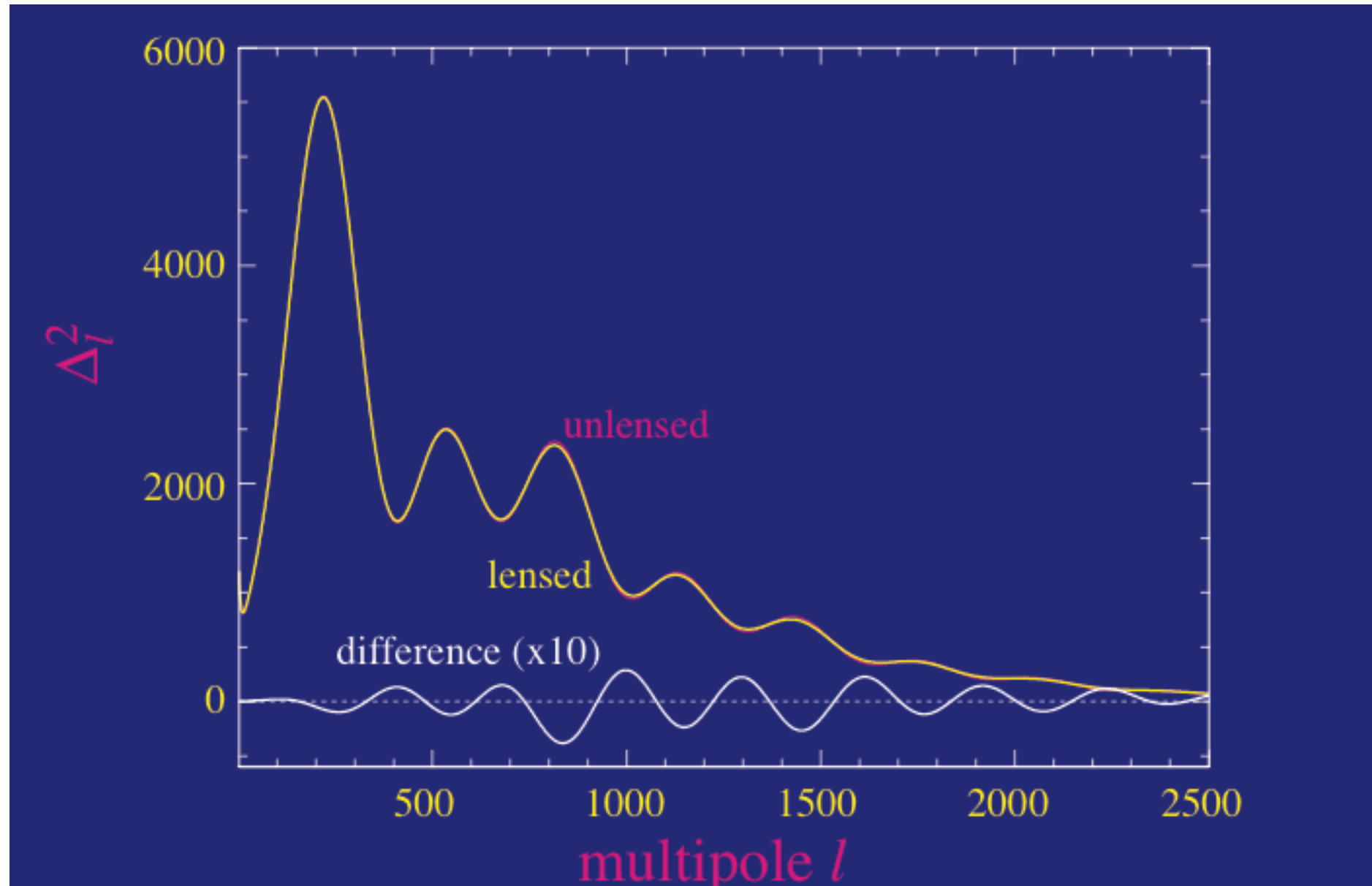
Lensing effect on the temperature power spectrum

Lensing produces two types of modifications to the CMB temperature (and also E-mode polarization) power spectrum. On large to intermediate scales, the effect is to cause a **smoothing of the power spectrum**. This effect arises from averaging of the magnified and de-magnified regions.



effect arises from averaging of magnified and demagnified regions

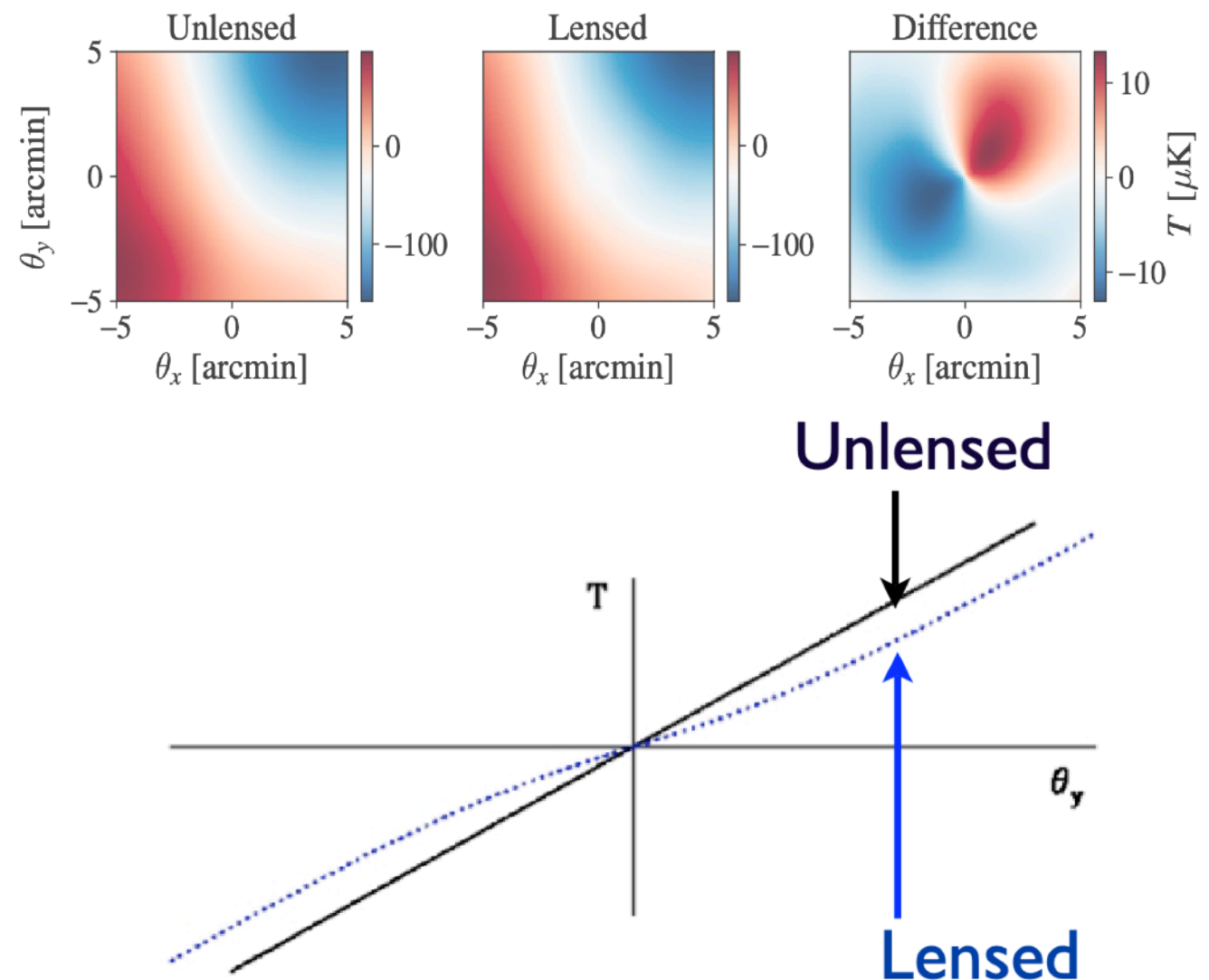
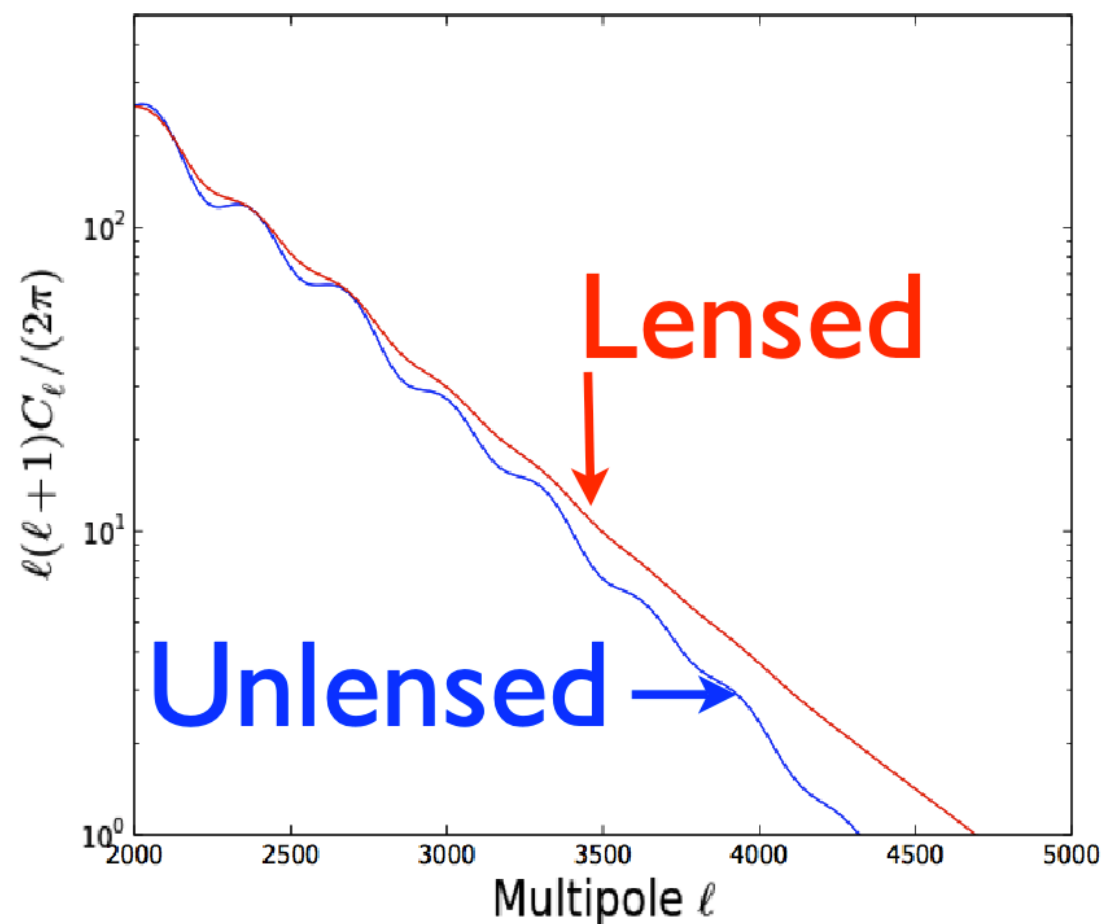
Lensing effect on the temperature power spectrum



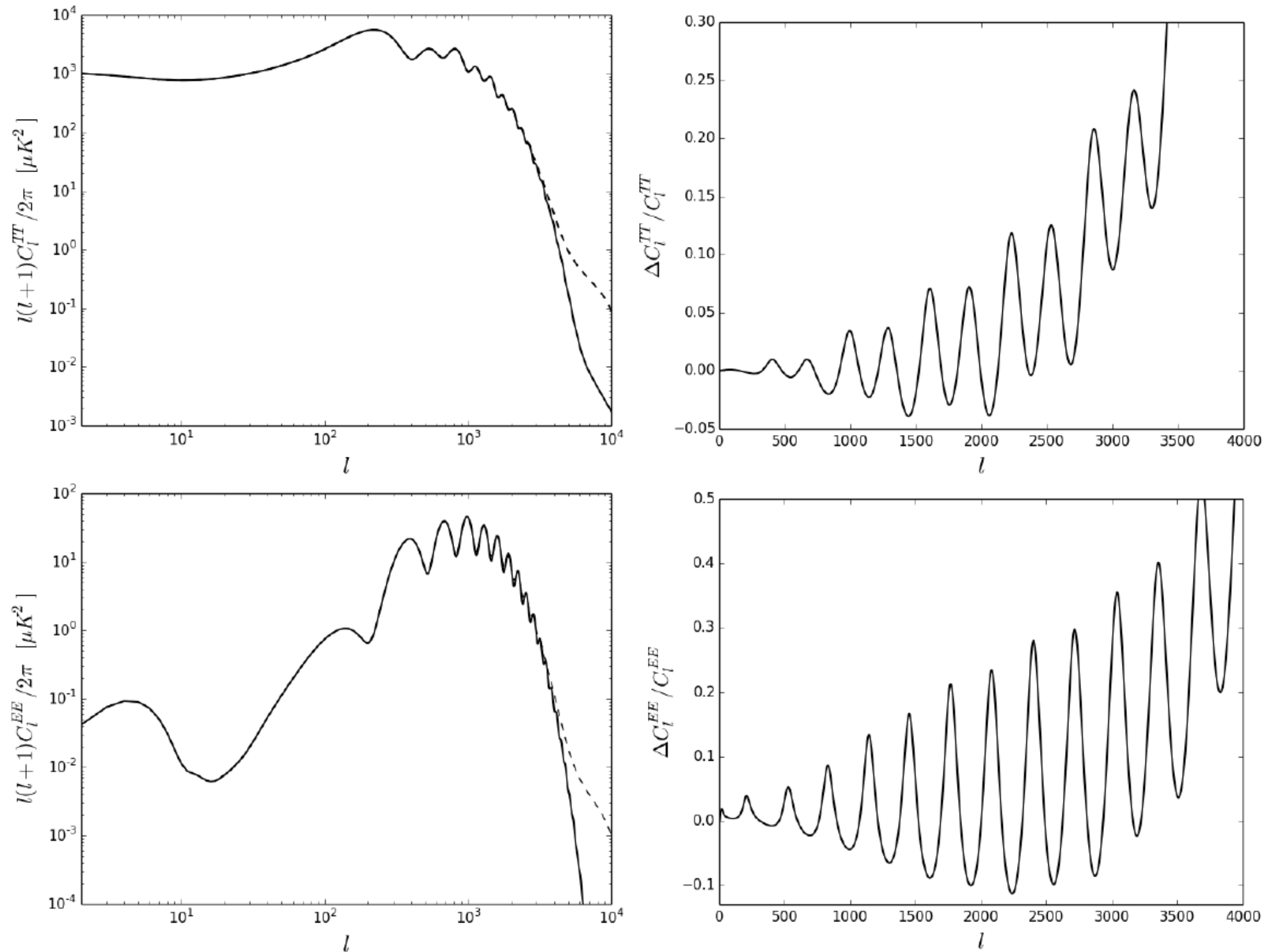
Averaged over the sky, lensing smooths the temperature power spectrum (and also E mode polarization) with a width $\Delta l \sim 60$. This is a small, subtle effect, but reaches up to $\sim 20\%$ at $l \sim 3000$.

Lensing effect on the temperature power spectrum

On small angular scales, lensing generates new power via deflection from massive gravitational structures, like galaxy clusters. This can be understood as the generation of new temperature anisotropies through lensing of a pure CMB gradient by a lump of matter. *More on this later!*



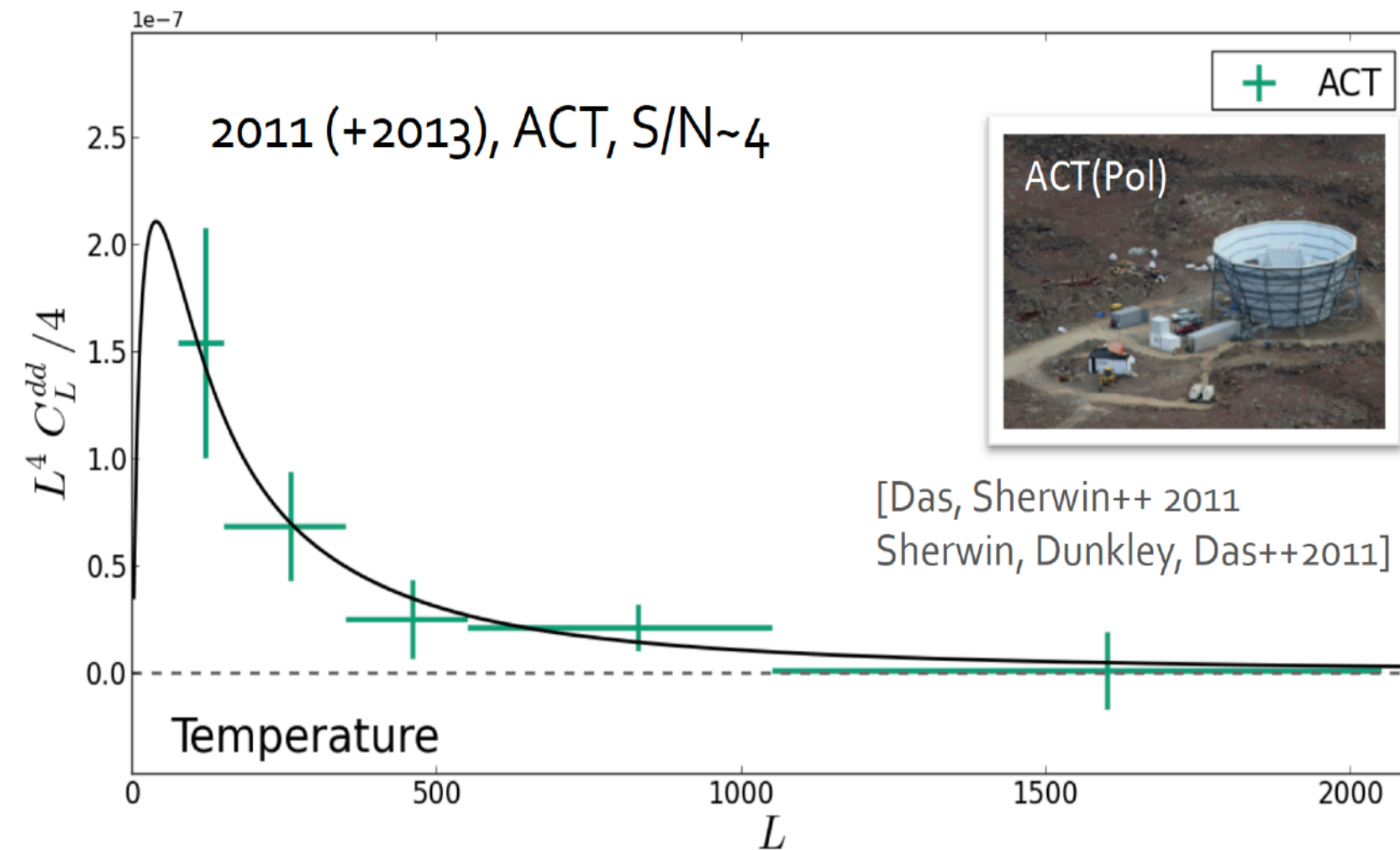
Lensed TT and EE power



The **left panels** show the unlensed (solid) and lensed (dashed) power spectra of the CMB temperature (top) and E mode polarisation (bottom).

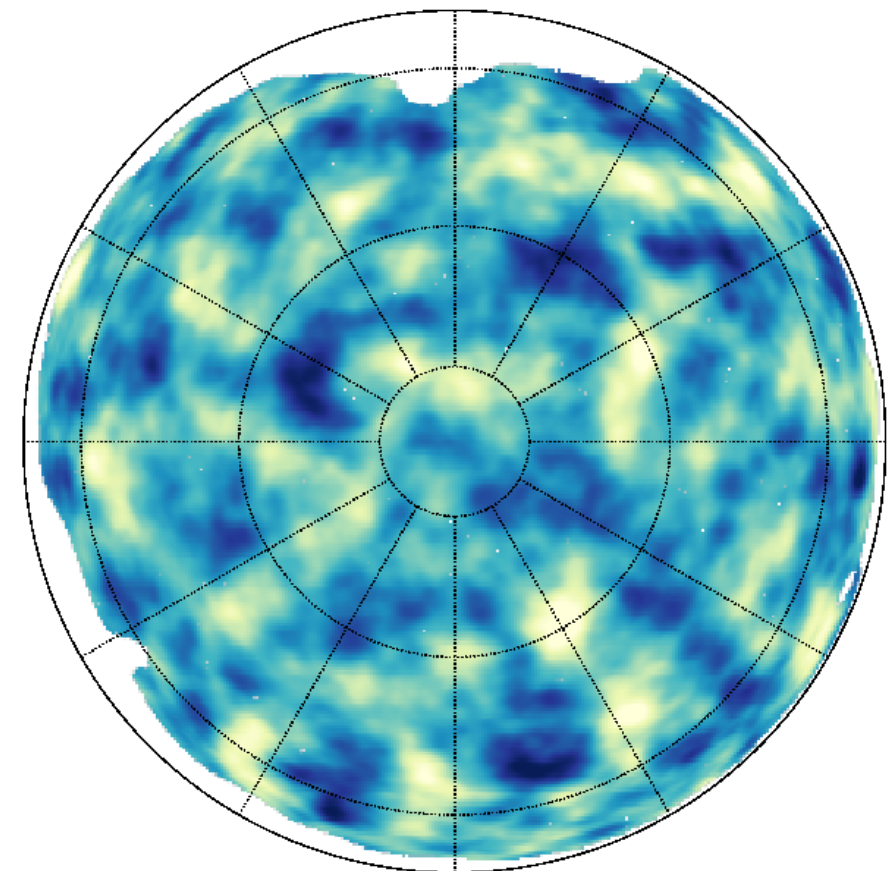
Lensing spreads out the peaks very slightly while transferring power to large l . The **right panels** show the *fractional change* in the power spectrum caused by lensing.

First measurements of lensing power



First measured by ACT,
then Planck and SPT.

2018 Planck results
provide **40 σ detection**
for lensing!

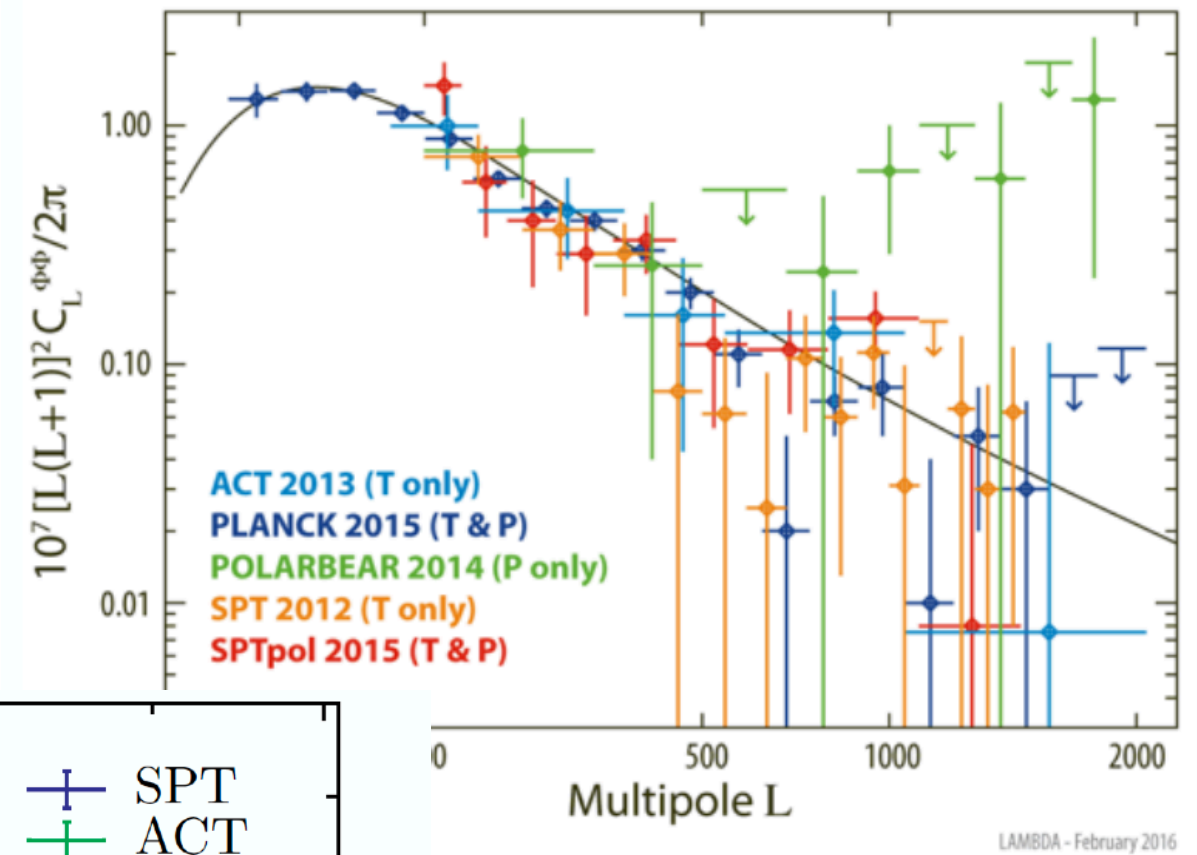


Planck full-sky lensing potential reconstruction

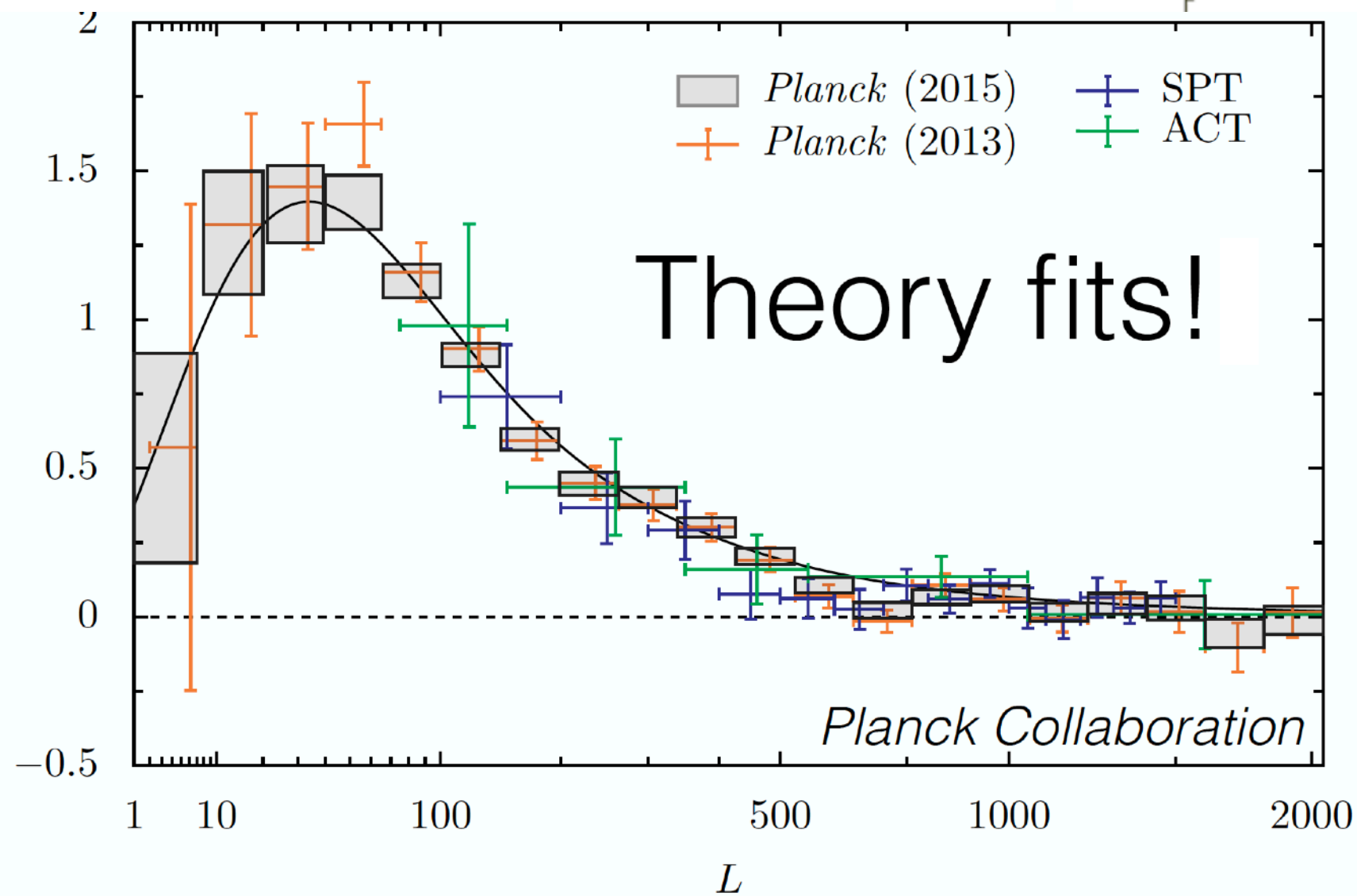
Note – about half signal, half noise,
not all structures are real: map is effectively Wiener filtered

Planck lensing measurements

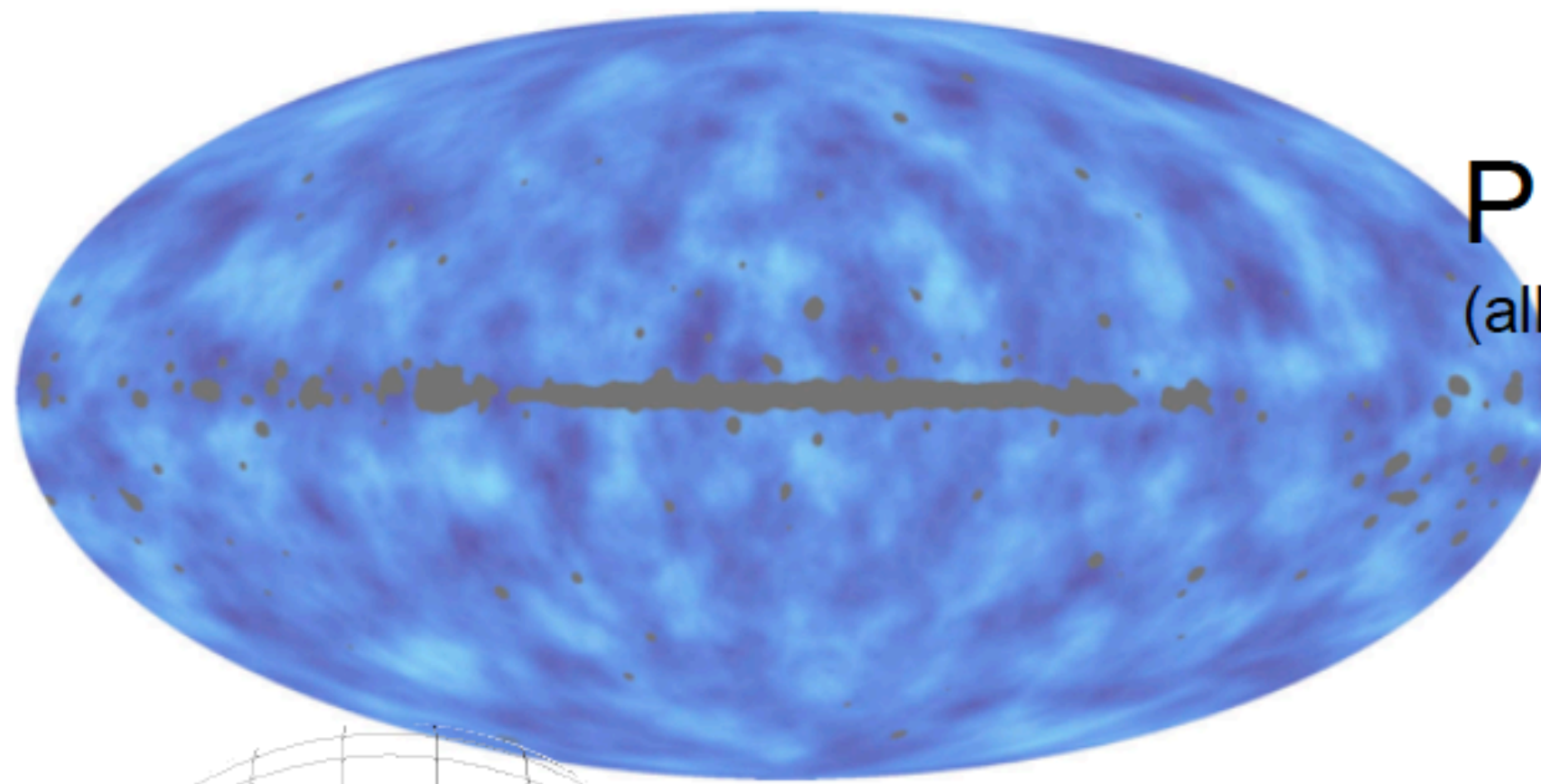
CMB lensing is statistically detectable at high-significance with Planck data, because its all-sky measurement capability suits perfectly with the peak of the lensing power.



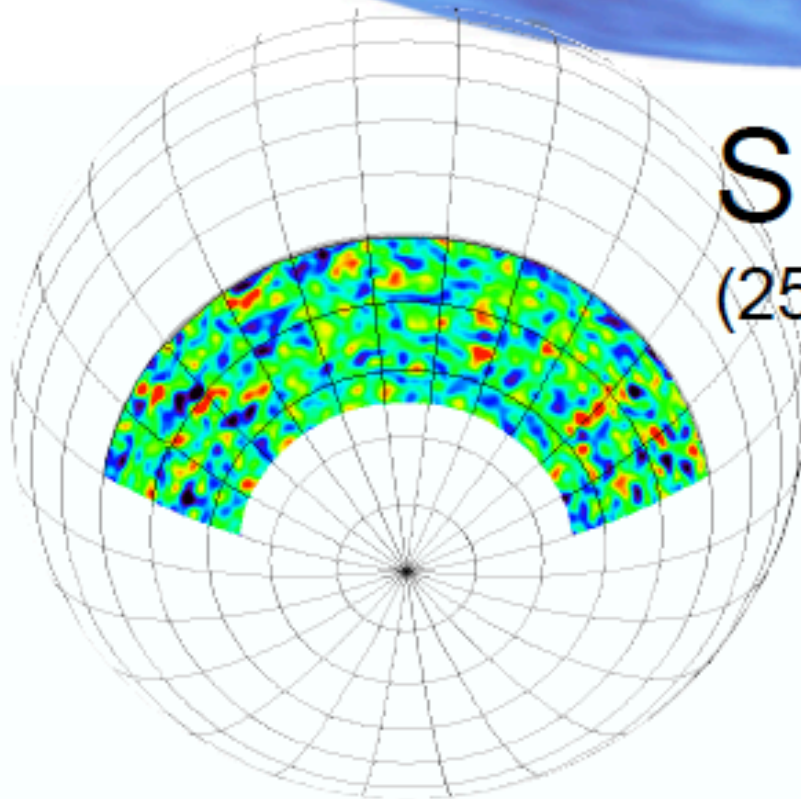
Planck 2015 results



Matter distribution from CMB lensing

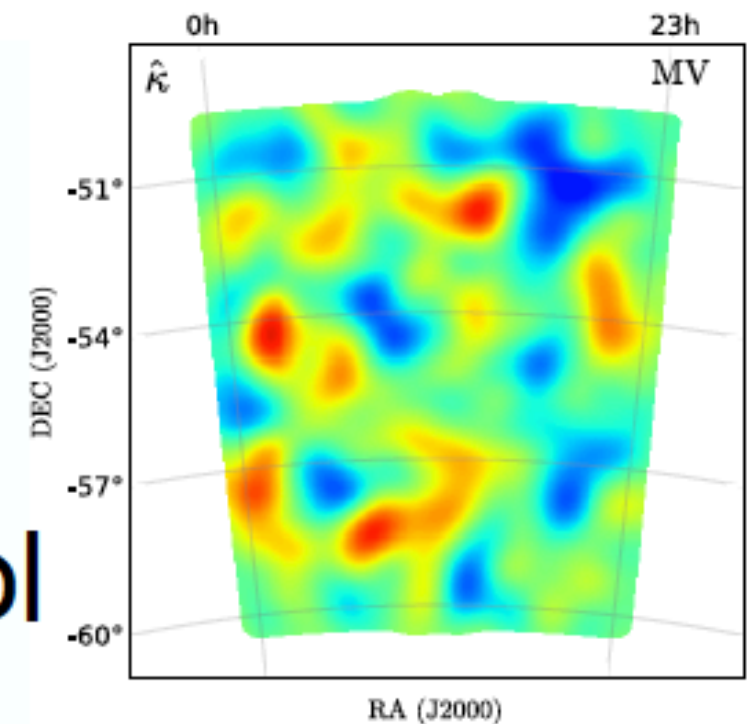


Planck
(all-sky)



SPT
(2500 sq deg)

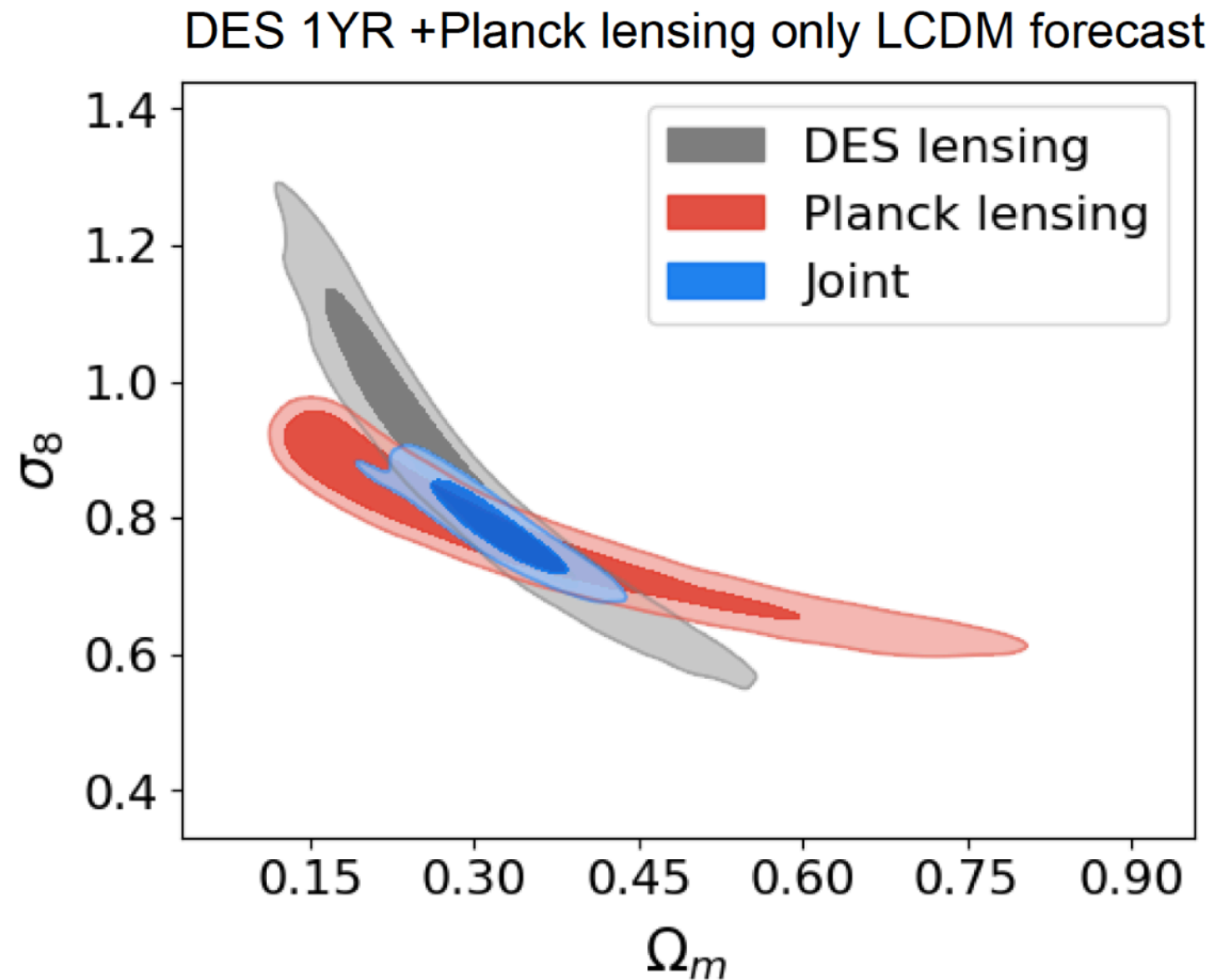
SPT-Pol
(100 sq deg)



Cosmology with CMB lensing

CMB lensing currently competitive with galaxy lensing

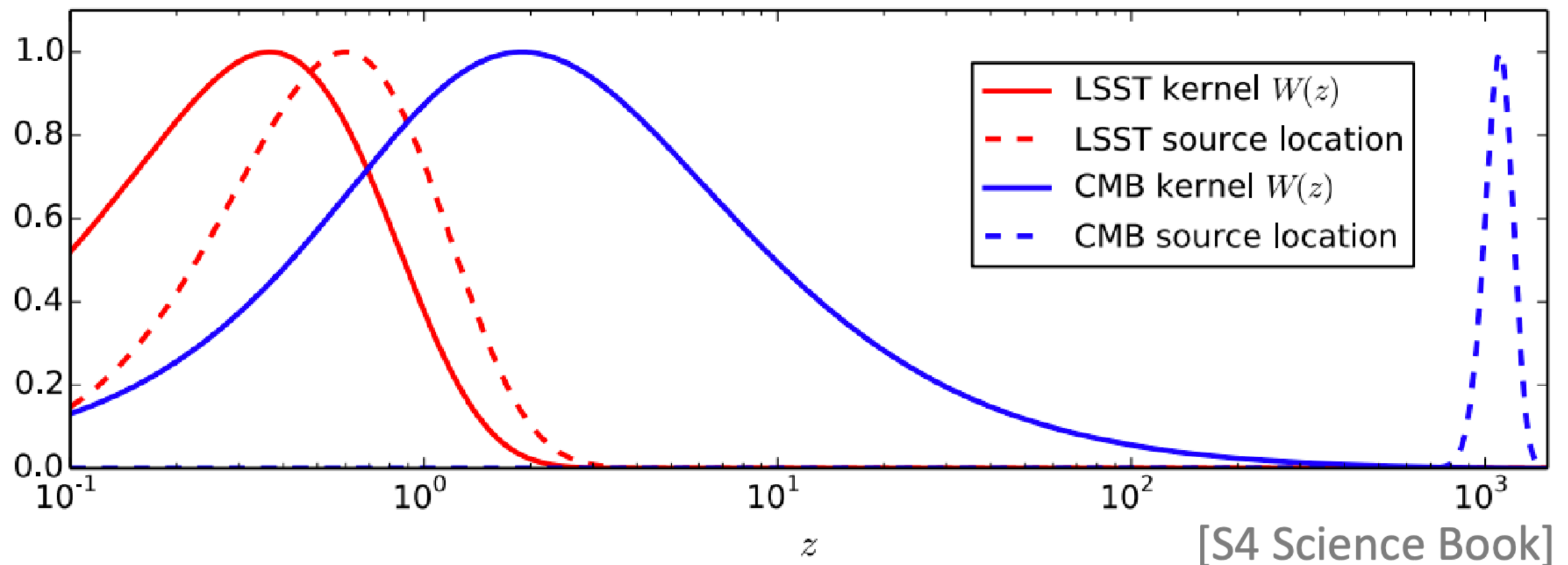
Probes higher redshift $\Rightarrow$ constrains $\Omega_m \sigma_8^{0.25}$ vs. galaxy $\Omega_m \sigma_8^{0.5}$



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 probes higher redshifts

CMB lensing, as a result of the unique and fixed location of its “light source”, probes the mass distribution in a broad redshift range (peaking around $z \sim 2$), which is much higher compared to optical lensing results.



In the above plot (taken from the CMB-S4 science book), the CMB-lensing kernel is compared against the optical lensing kernel and source locations. The optical case is represented by the LSST (now called the Vera-Rubin telescope) survey, which will measure the cosmic shear from a wide-area survey of the sky.

CMB lensing on small angular scales

$$(\ell \gtrsim 3000)$$

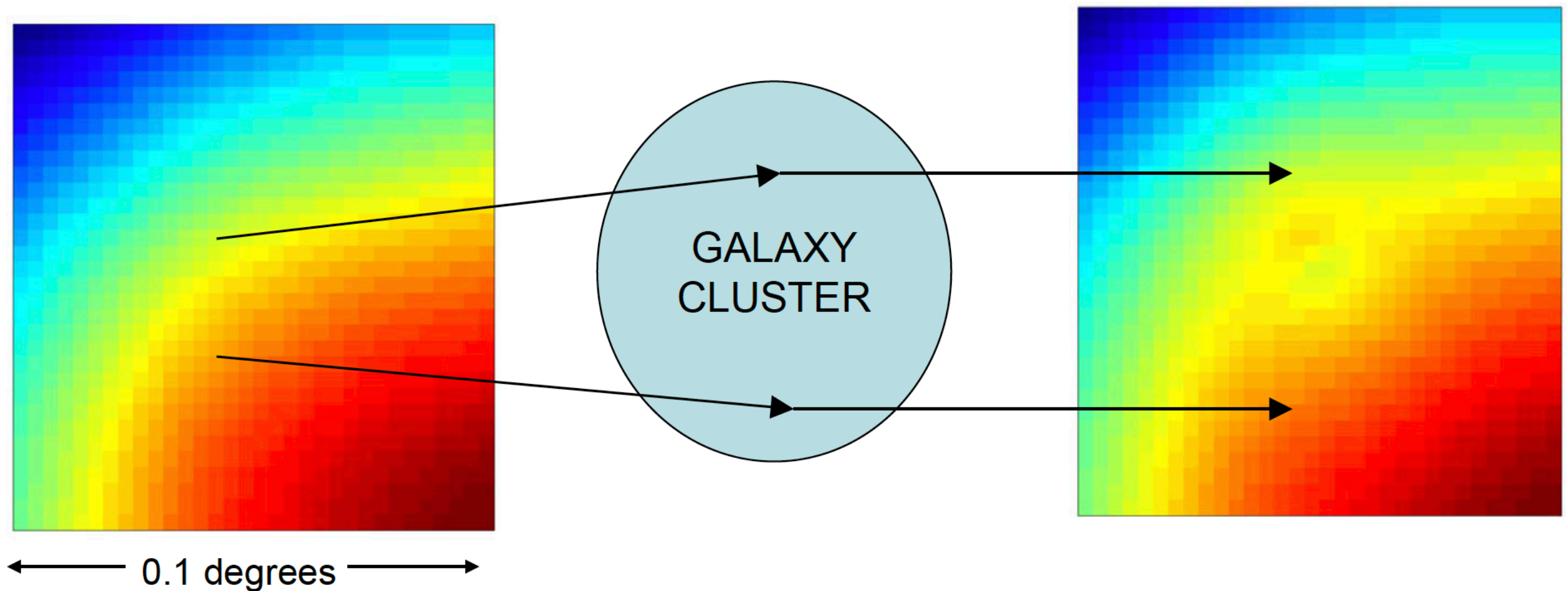
CMB lensing by galaxy clusters

CMB very smooth on small scales: approximately a gradient

$$\tilde{X}(\boldsymbol{\theta}) \approx X(\boldsymbol{\theta}) - \alpha(\boldsymbol{\theta}) \nabla X(\boldsymbol{\theta})$$

Last scattering surface

What we see



Need sensitive ~ arcminute resolution observations

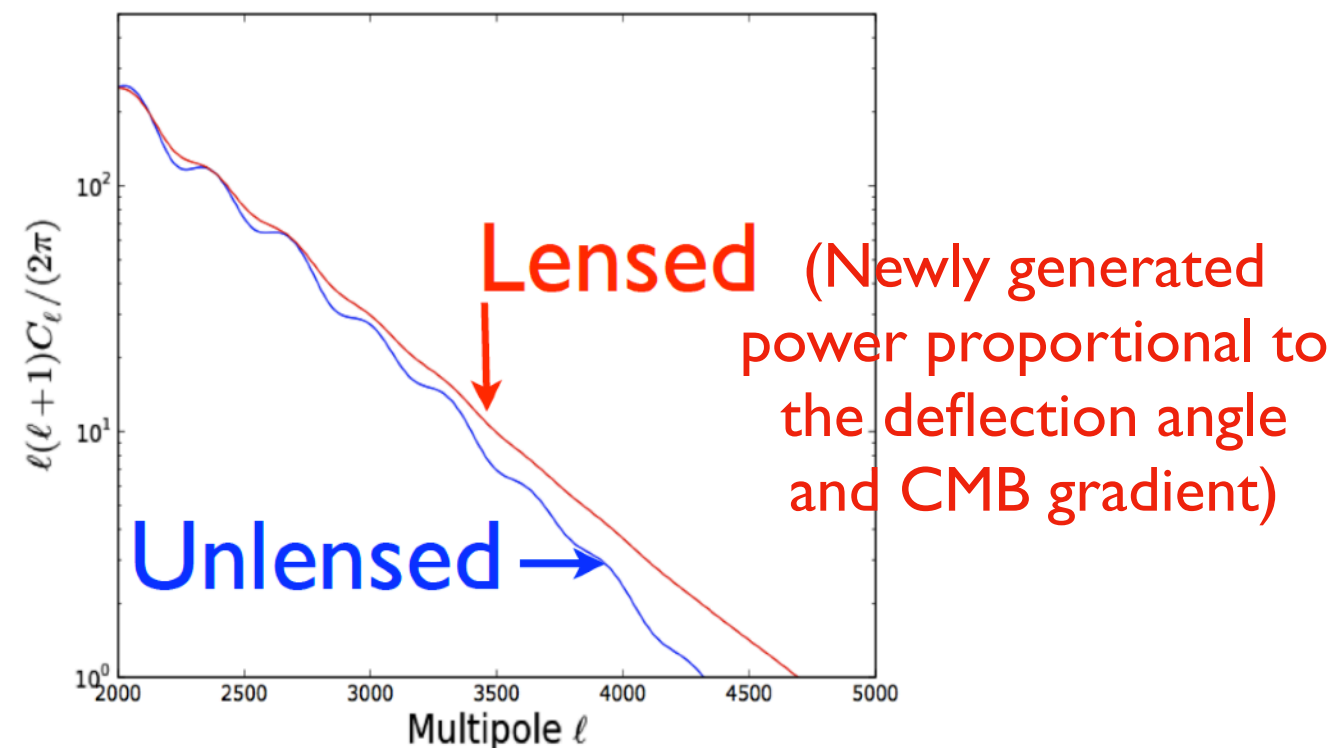
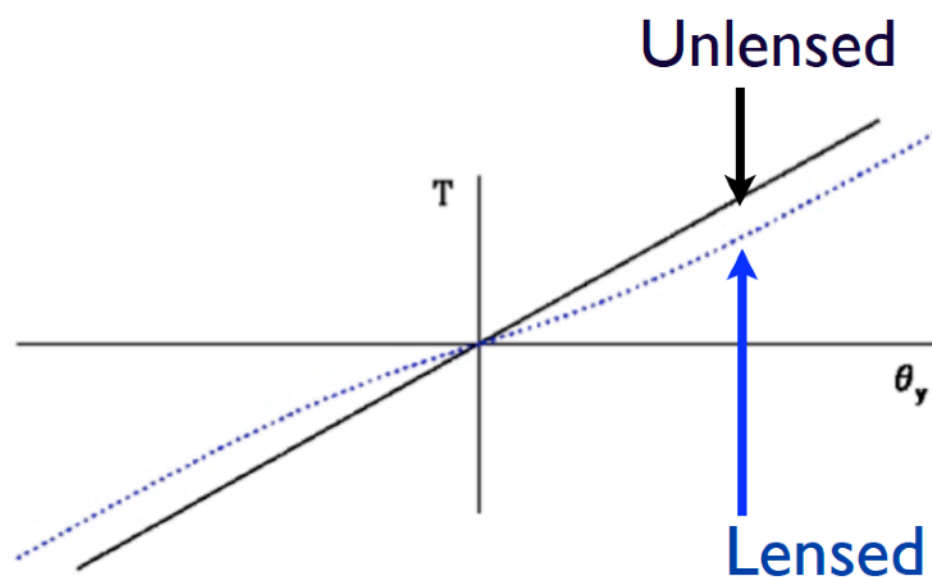
The gradient approximation

The lensed CMB field is a surface-brightness conserving remapping of the unlensed CMB field by the deflection angle

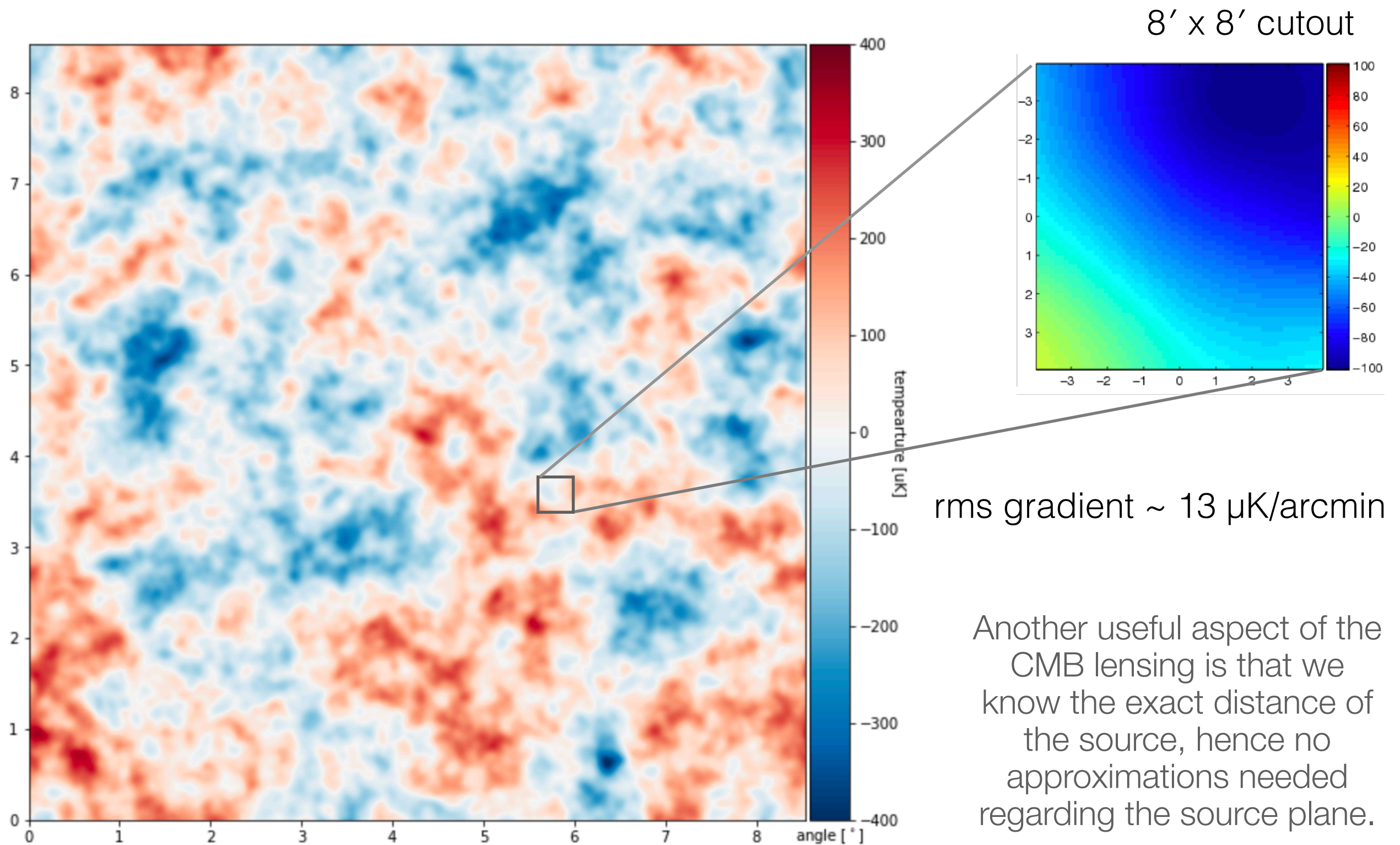
$$\tilde{X}(\boldsymbol{\theta}) = X(\boldsymbol{\beta}) = X(\boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta}))$$

When considering the lensing by galaxy clusters, scales of only few arcminutes are of interest, corresponding to the projected angular sized of galaxy clusters. On these scales the CMB is extremely smooth due to Silk damping and is well described by a gradient field (perturbations in 1st order). Hence, one can Taylor expand the above equation and keep only the linear term. **This is known as the gradient approximation for CMB lensing.**

$$\tilde{X}(\boldsymbol{\theta}) \approx X(\boldsymbol{\theta}) - \boldsymbol{\alpha}(\boldsymbol{\theta}) \nabla X(\boldsymbol{\theta})$$



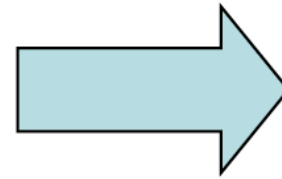
The gradient approximation



$8.5^\circ \times 8.5^\circ$ CMB map

CMB lensing by galaxy clusters

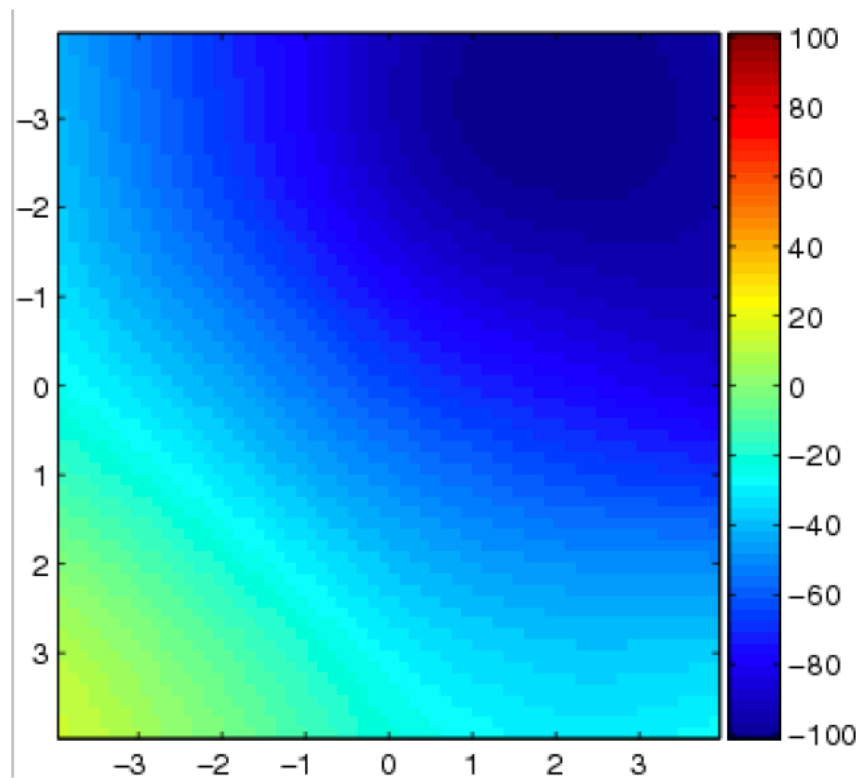
RMS gradient $\sim 13 \mu\text{K} / \text{arcmin}$
deflection from cluster $\sim 1 \text{ arcmin}$
(massive)



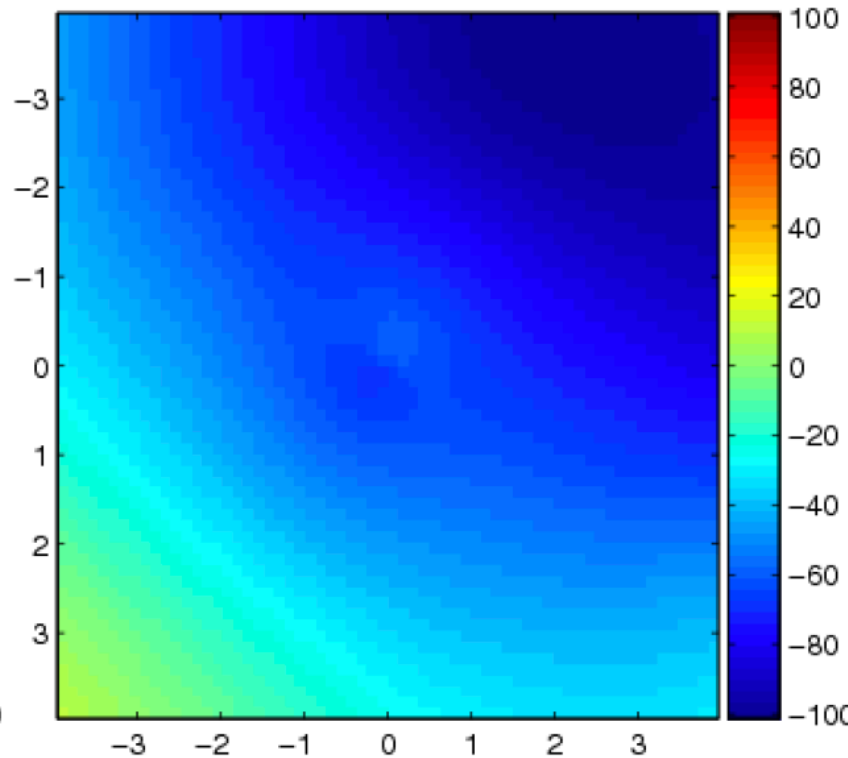
Lensing signal $\sim 10 \mu\text{K}$

BUT: depends on CMB gradient behind a given cluster

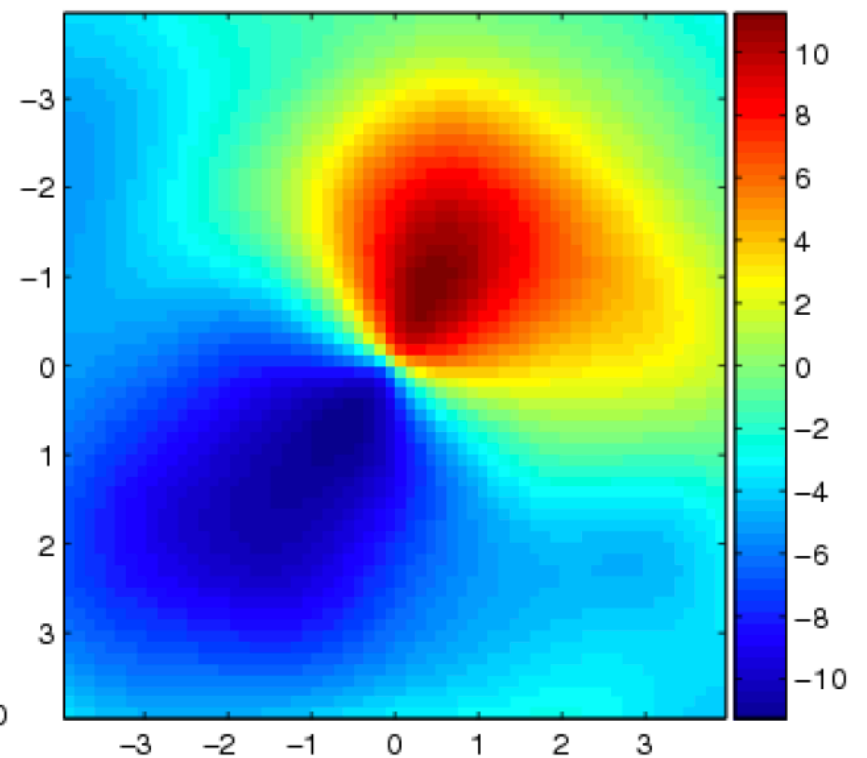
Unlensed



Lensed



Difference



Unlensed CMB unknown, but statistics well understood (background CMB Gaussian) :
can compute likelihood of given lens (e.g. NFW parameters) essentially exactly

Cluster-CMB lensing modelling

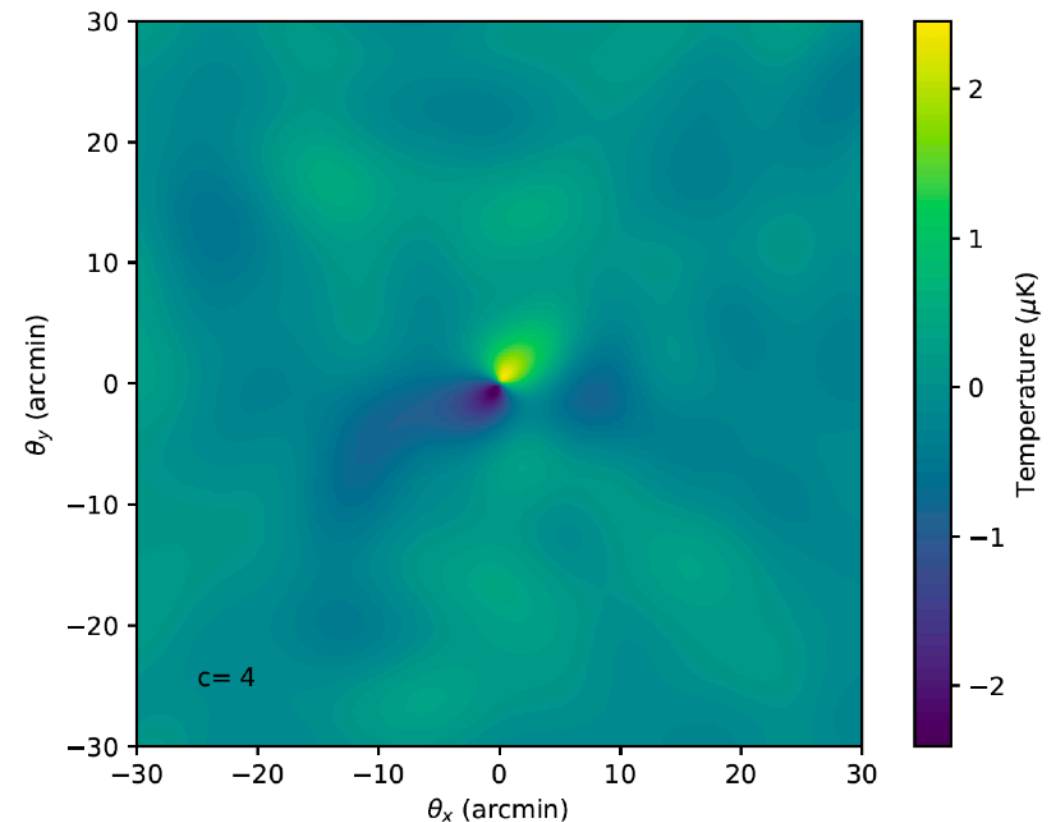
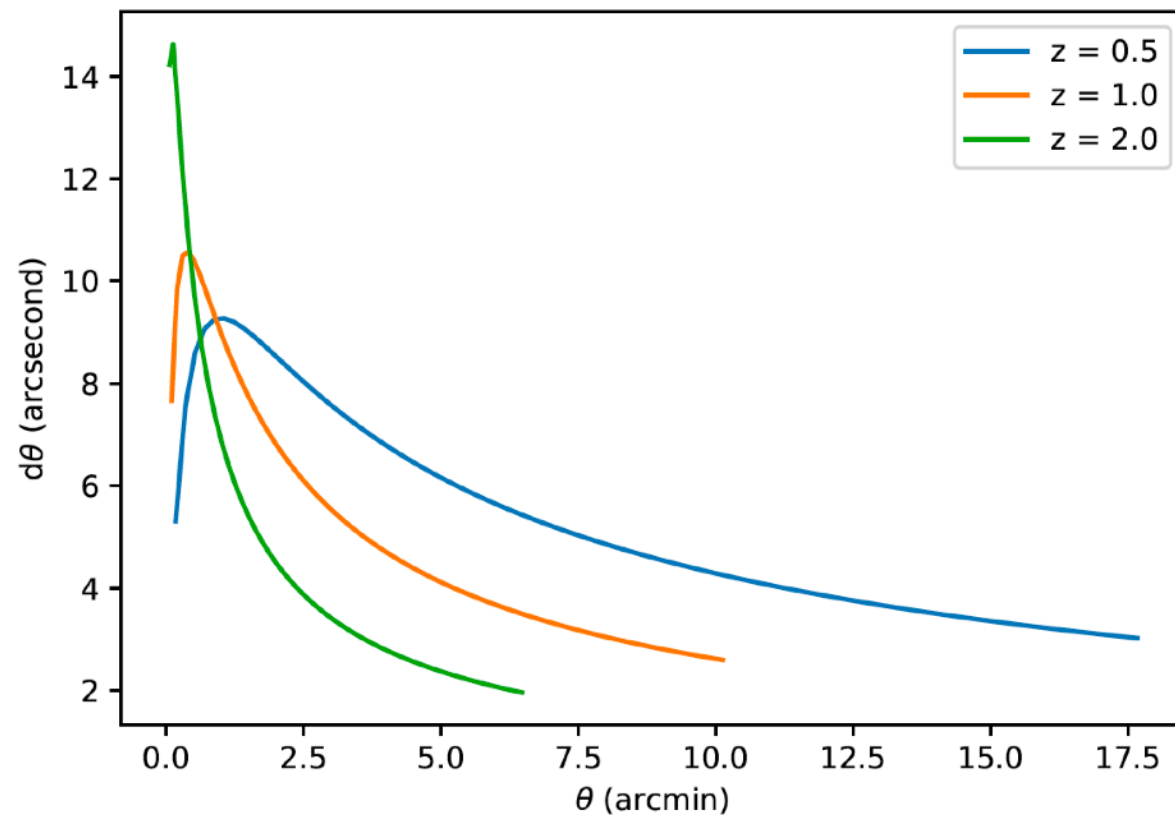
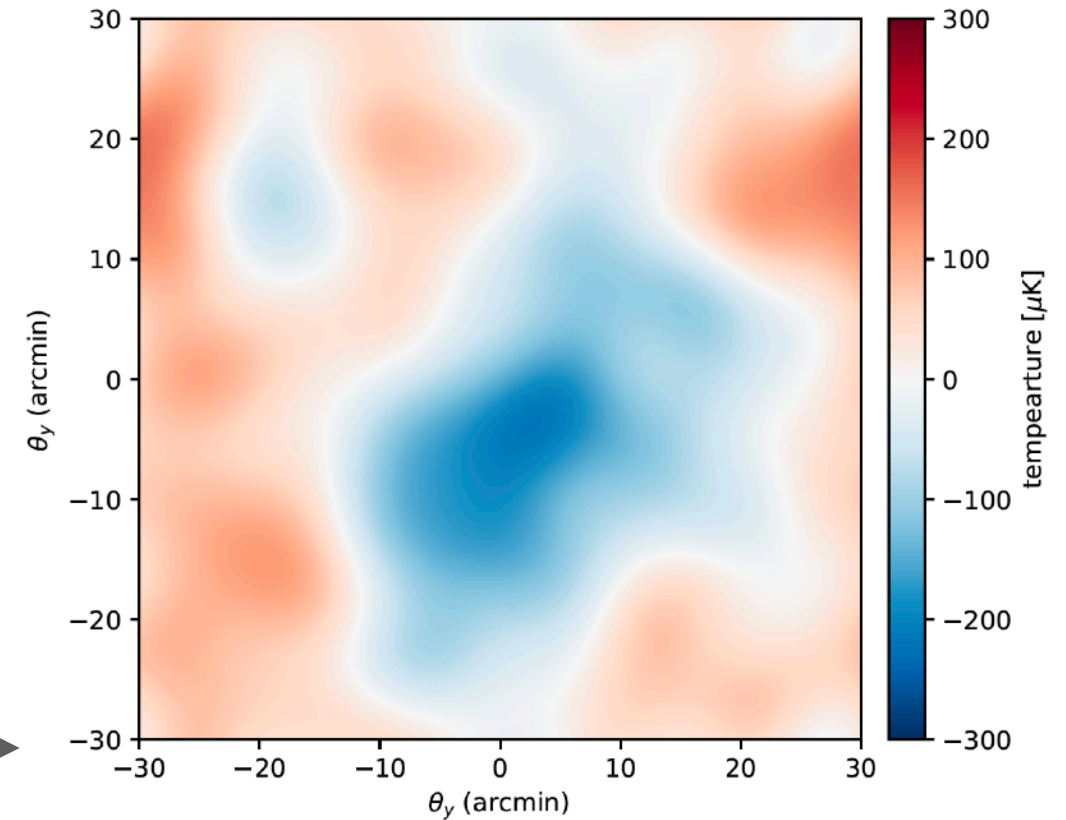
Start with the NFW profile for cluster mass,

$$M = 4\pi\rho_0 R_s^3 \left[\ln\left(\frac{R_s + r}{R_s}\right) - \frac{r}{R_s + r} \right]$$

compute the deflection profile

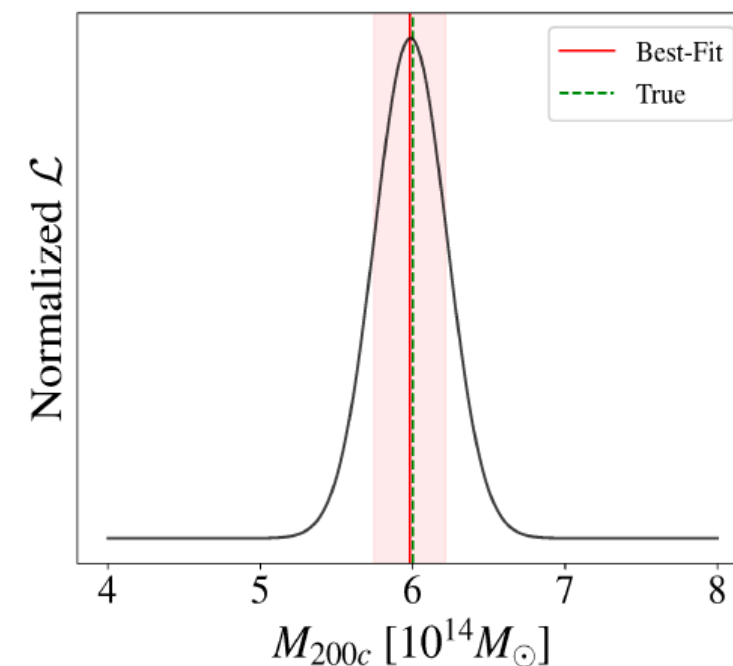
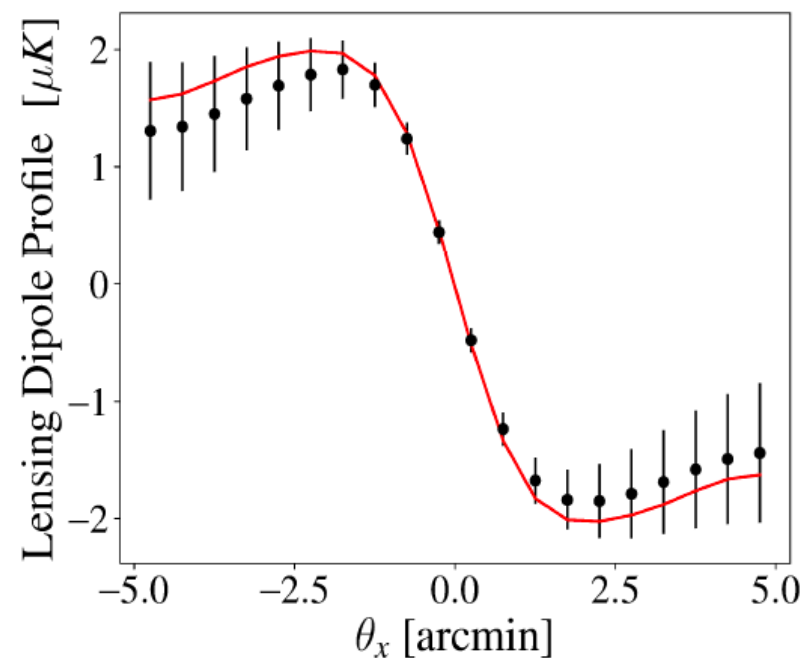
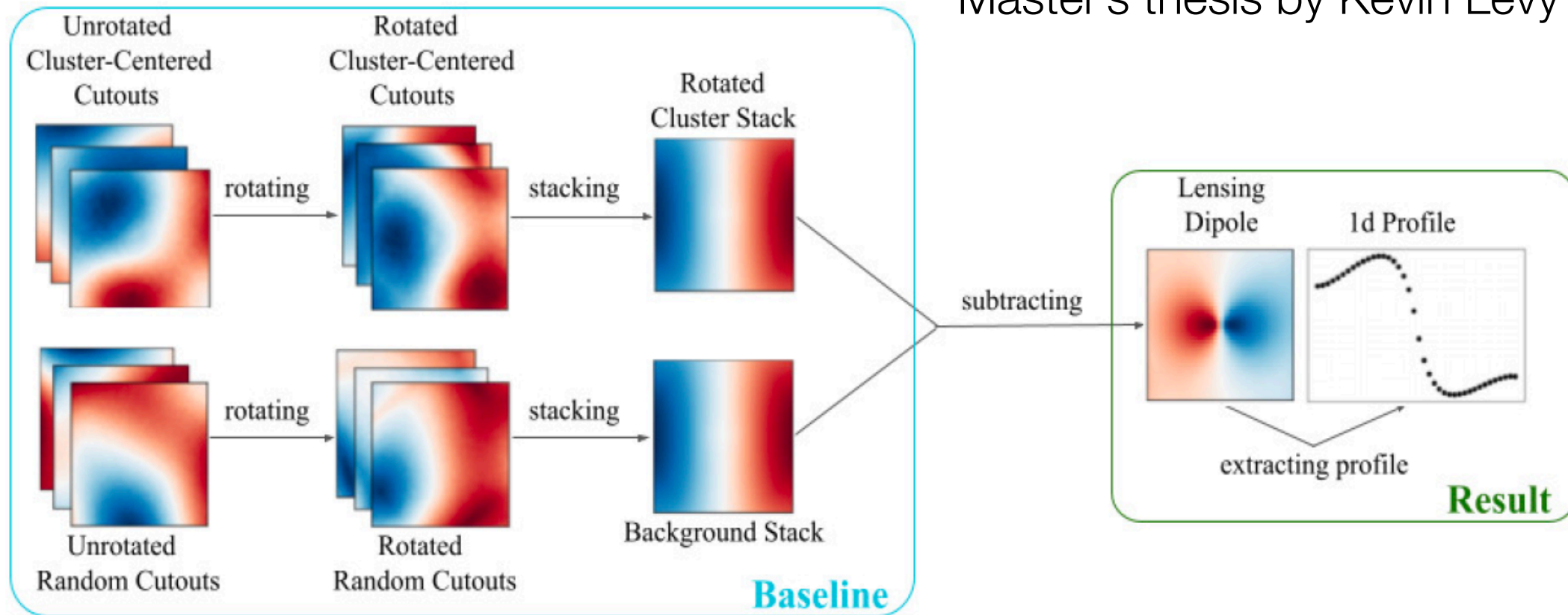
$$\delta\theta = -\frac{8\pi G}{c_l^2} \frac{\theta}{\theta} \frac{(\chi_S - \chi_L)}{\chi_S} \left[\frac{1 + z_L}{\theta \chi_L} \int_0^{\chi_L \theta / (1+z_L)} R \Sigma(R) dR \right]$$

and apply on CMB maps

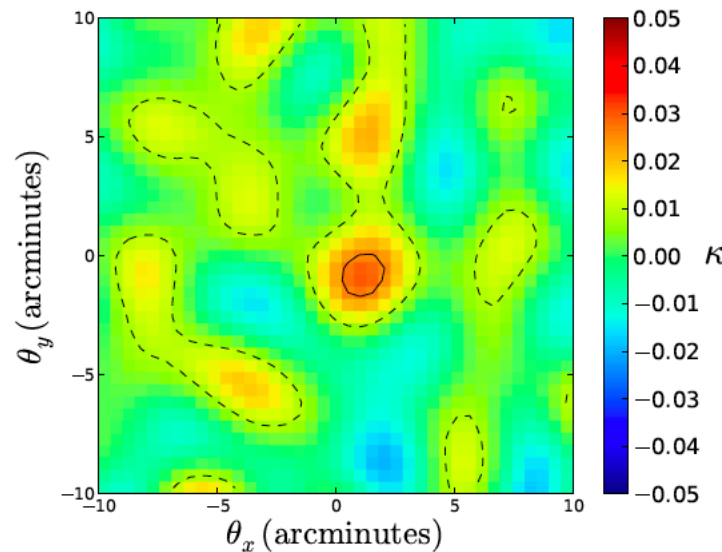
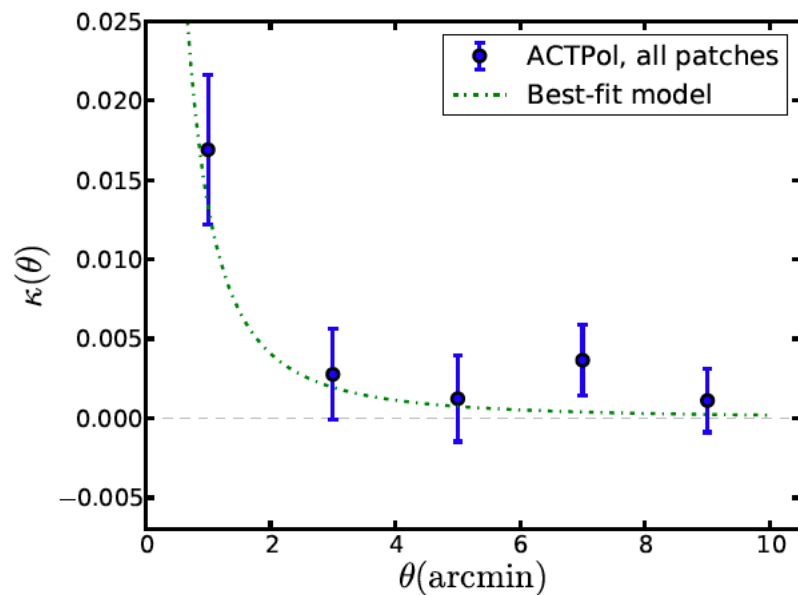


Cluster-CMB lensing modelling

Master's thesis by Kevin Levy (Sep 2021)



Cluster-CMB lensing measurements

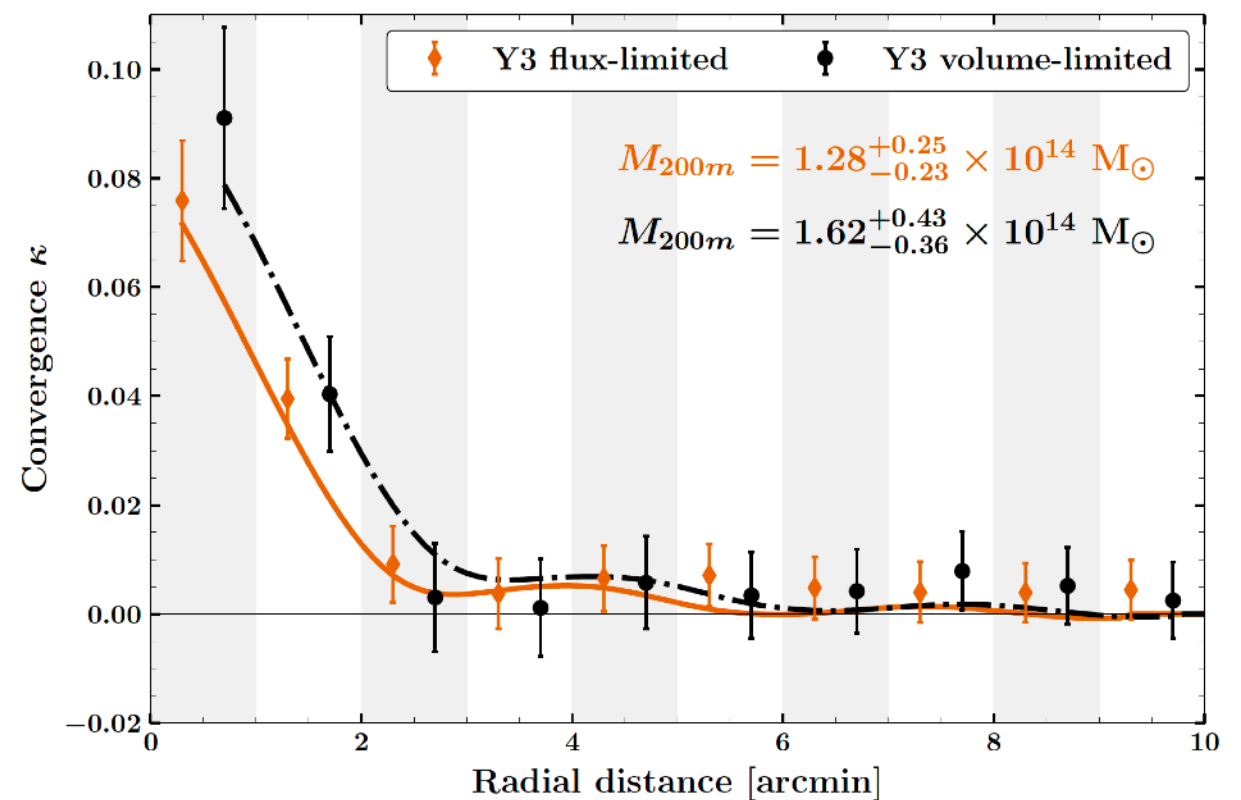
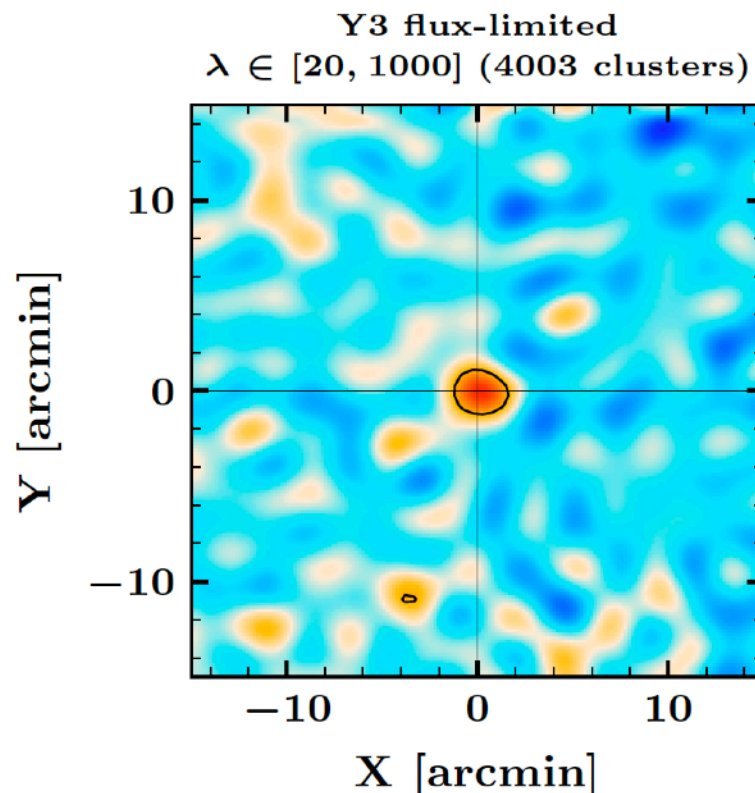


ACTpol data,
Madhavacheril et al. (2015)

~16000 CMASS galaxies

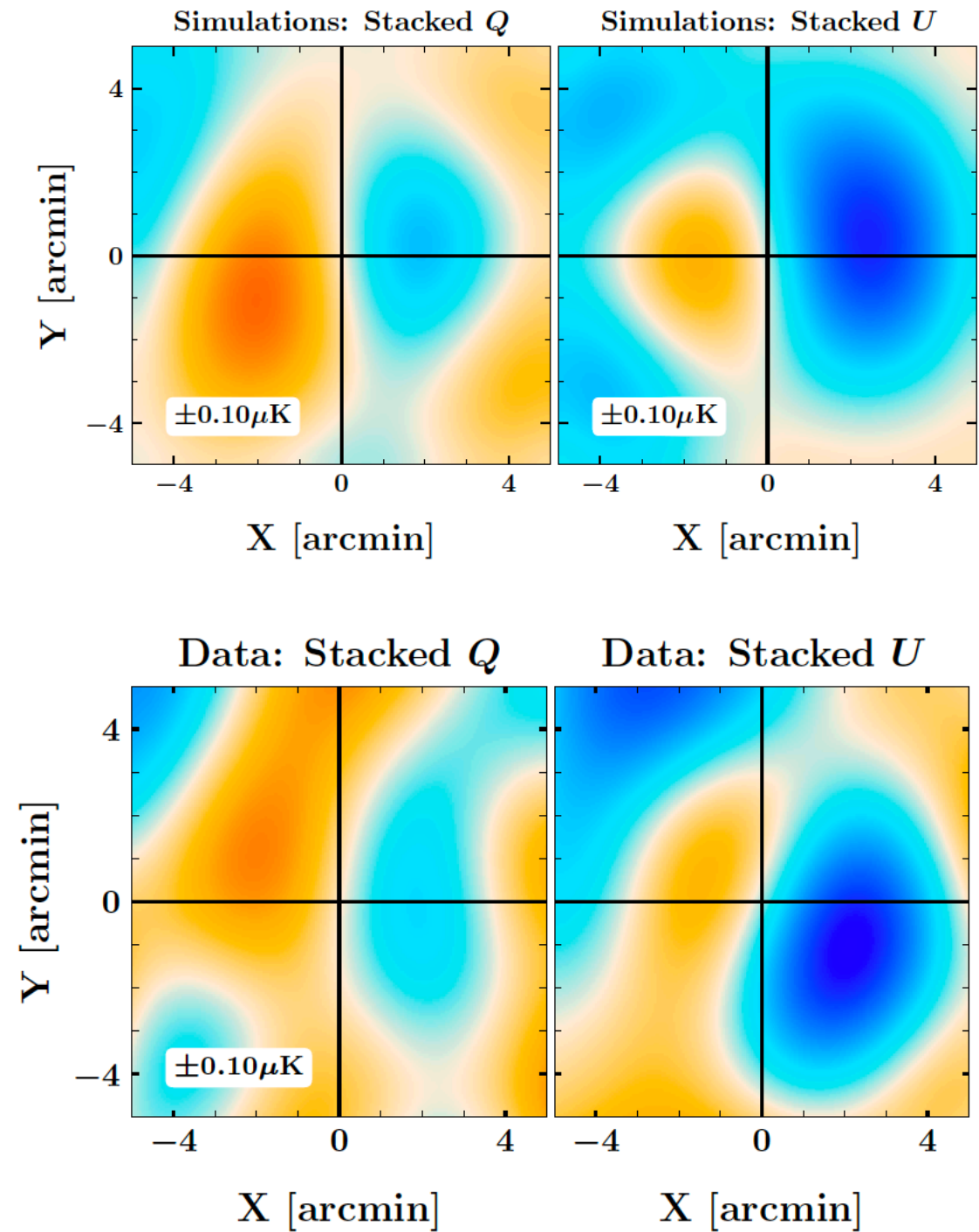
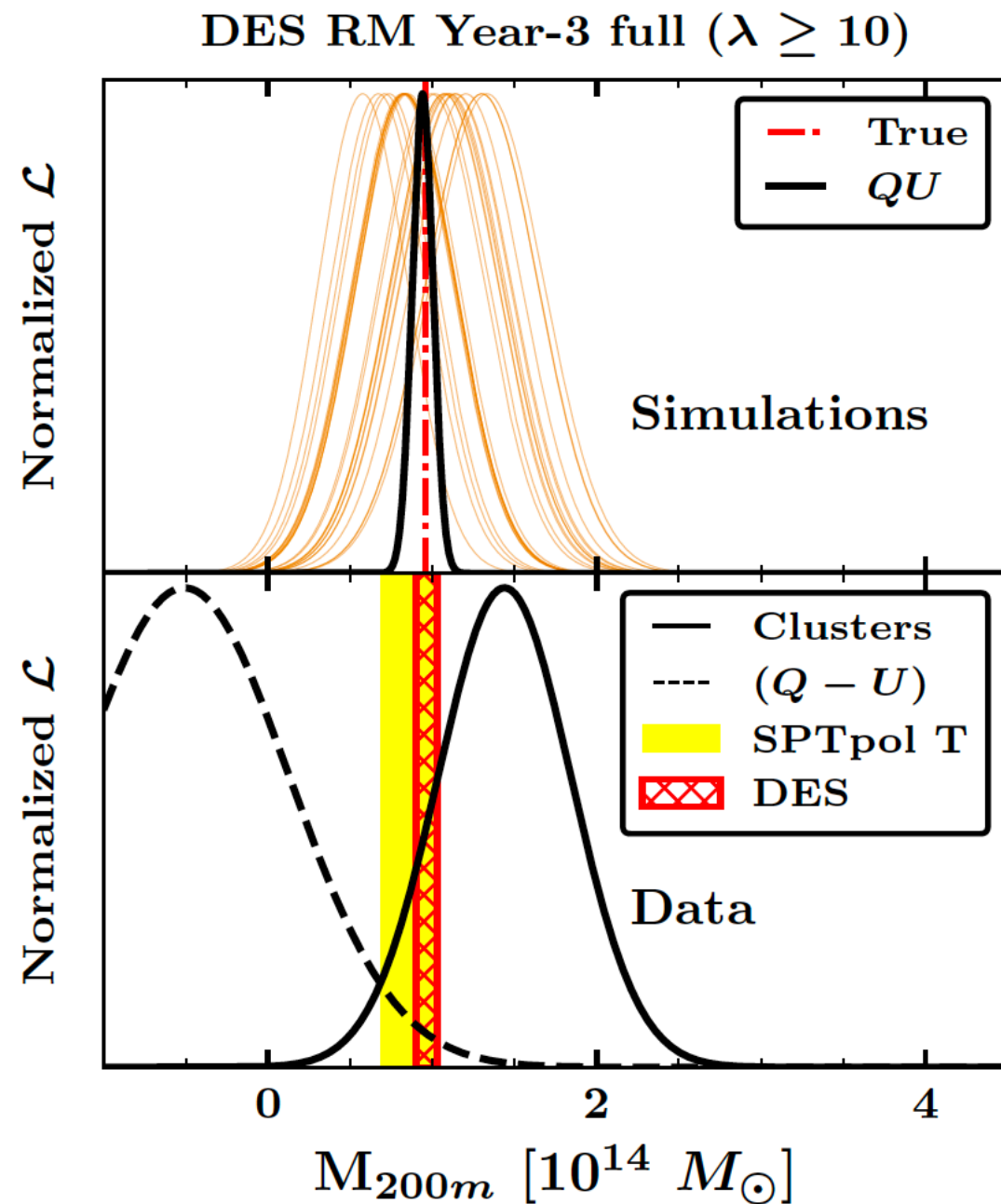
SPTpol TT data, Raghunathan et al. (2018)

~4000 DES clusters in the SPT field



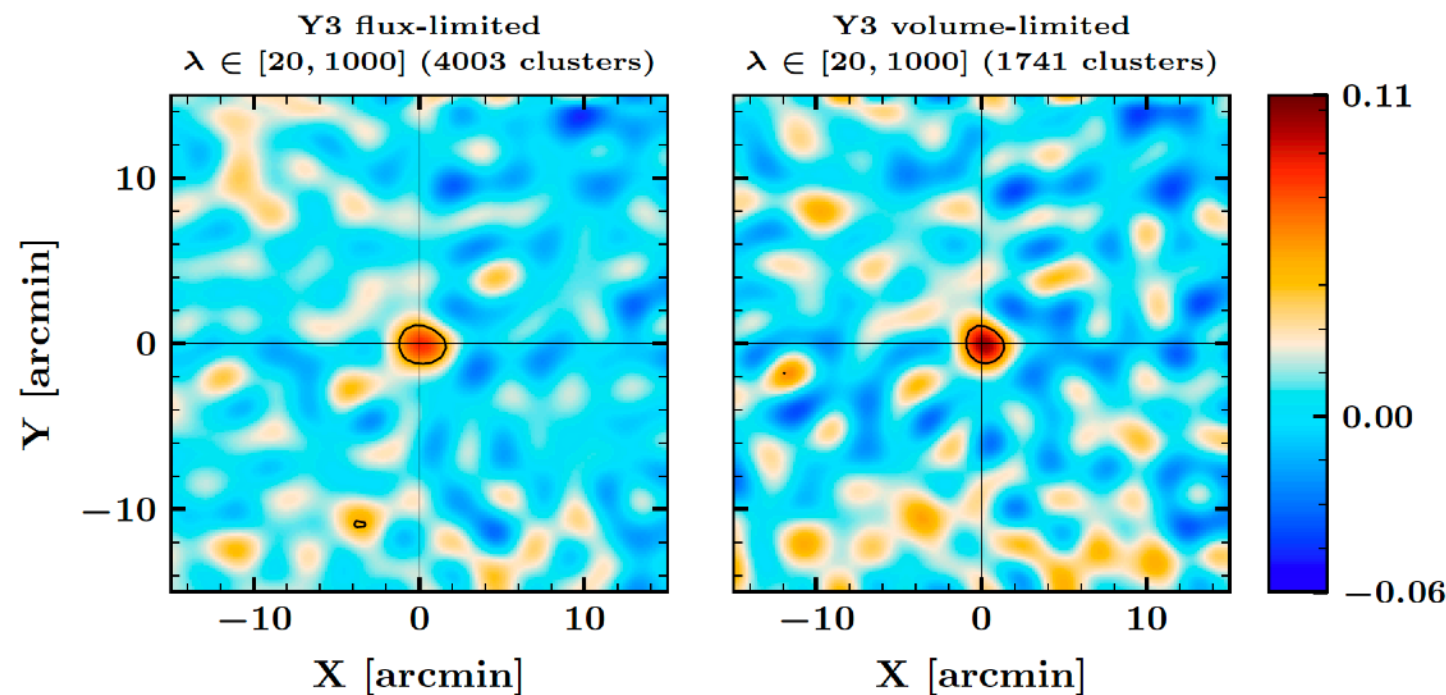
Polarization cluster-lensing measurement

First measurement of the cluster-CMB lensing from polarization, by Raghunathan et al. (2019) using SPTpol data



Cluster-CMB lensing forecasts

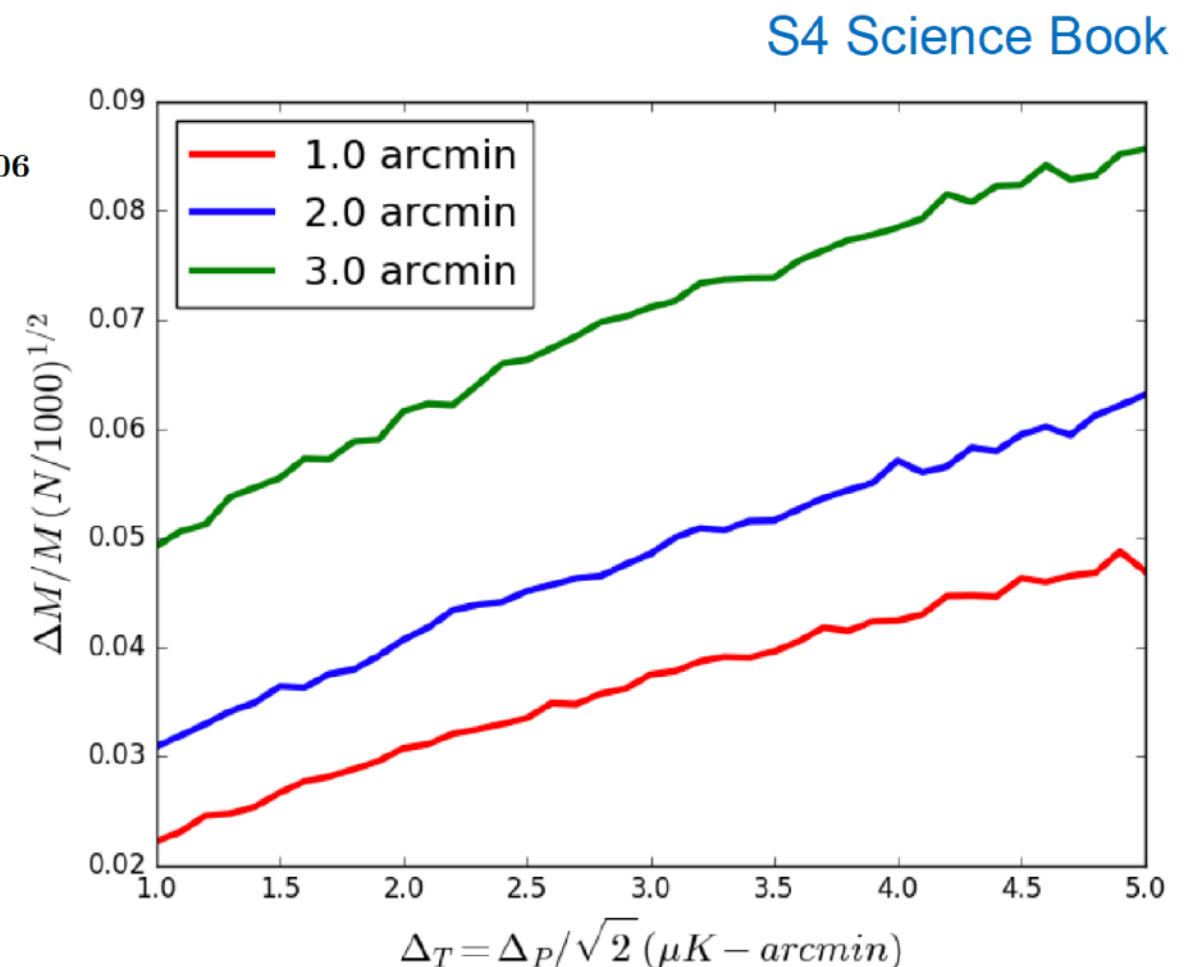
CMB lensing probes mass distribution at high redshifts: $0.5 < z < 6$
Ideal for figuring out high- z cluster masses — probe for dark energy!



Raghunathan et al. (2019): measurements from DES and SPTpol data

Current ground-based CMB experiments (SPT and ACT) are able to measure the lensing convergence from galaxy clusters by stacking 1000s of objects. This precision is expected to improve dramatically in the coming years.

High-sensitivity, high resolution CMB can calibrate mass of 1000 stacked clusters to a few percent.



Questions?



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