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 11:

CMB Lensing

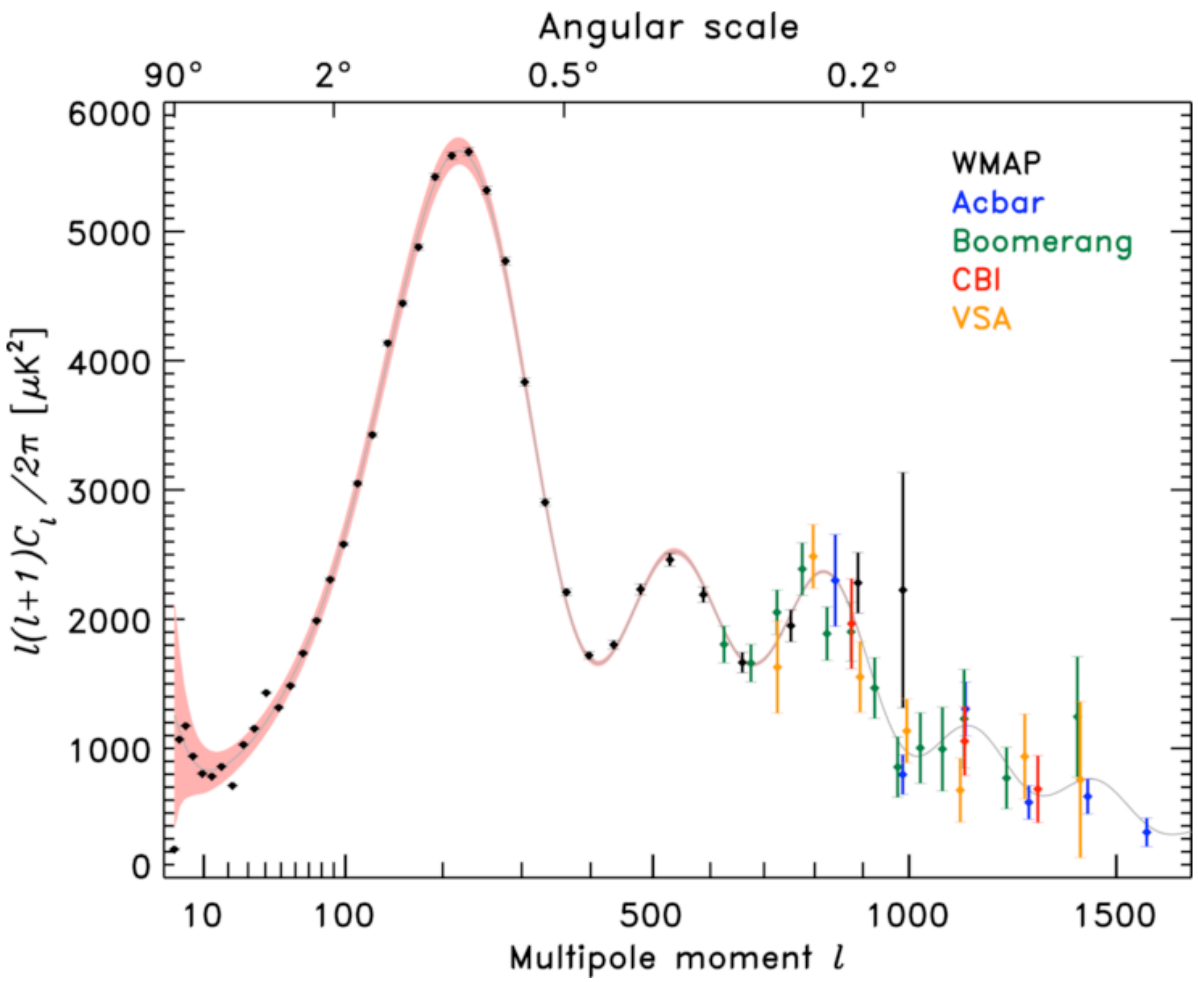
Secondary temperature anisotropies

From the 1995 review by Max Tegmark

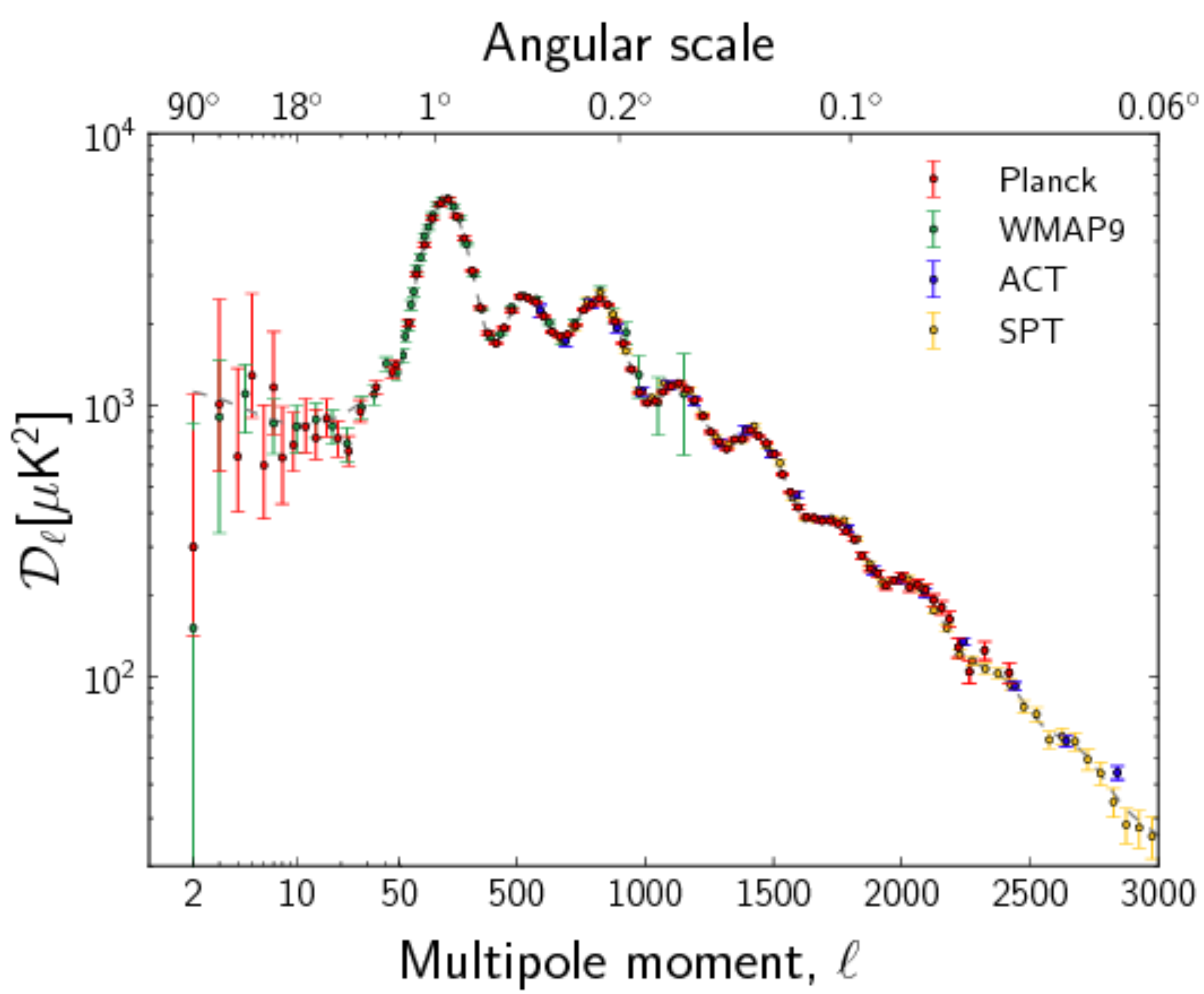
Table 1. Sources of temperature fluctuations.

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

CMB power at small angles

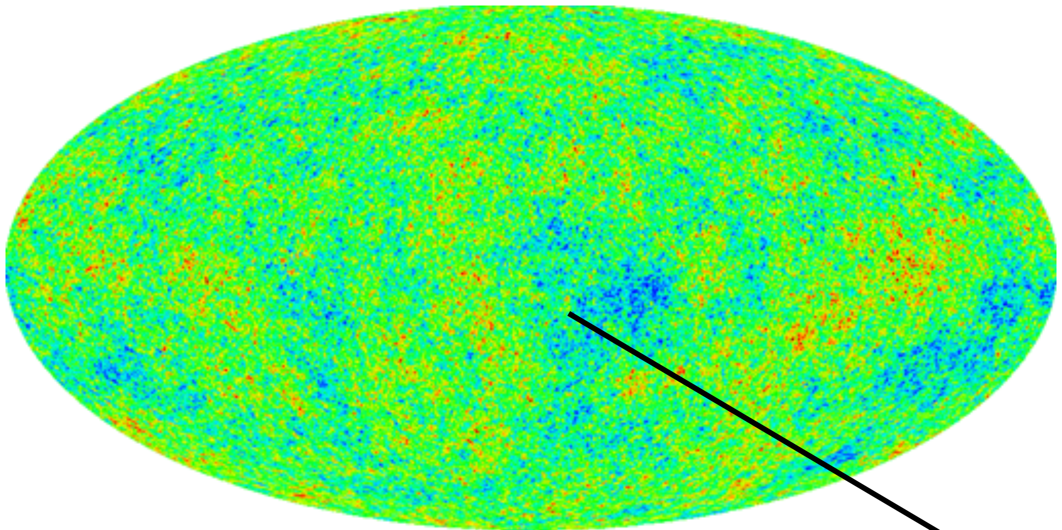


~2006



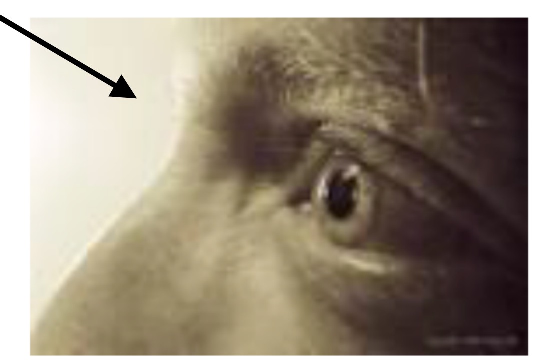
~2015

CMB photons on their way to us



Last scattering surface

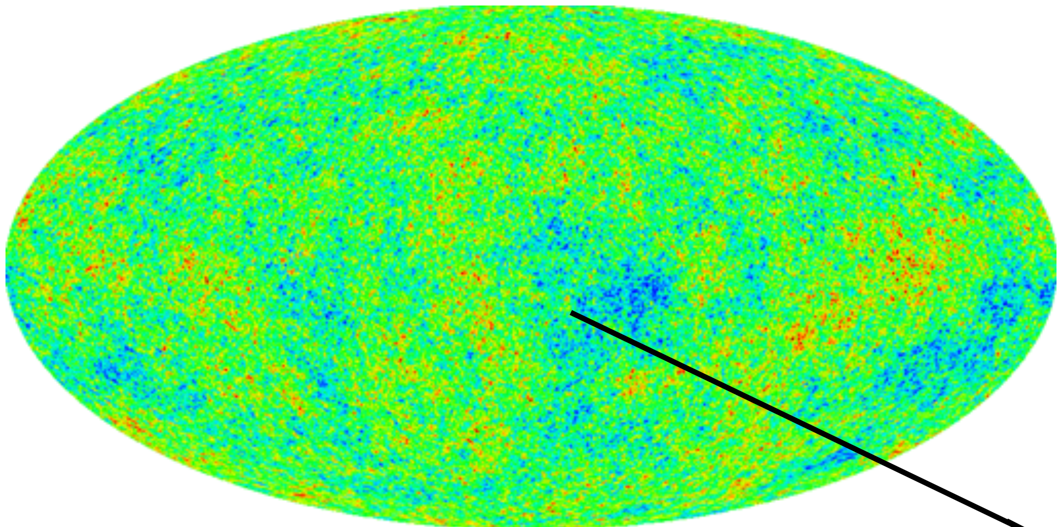
Observer



Two things can happen to the CMB photons:

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

CMB photons on their way to us



Last scattering surface

Observer

Two things can happen to the CMB photons:

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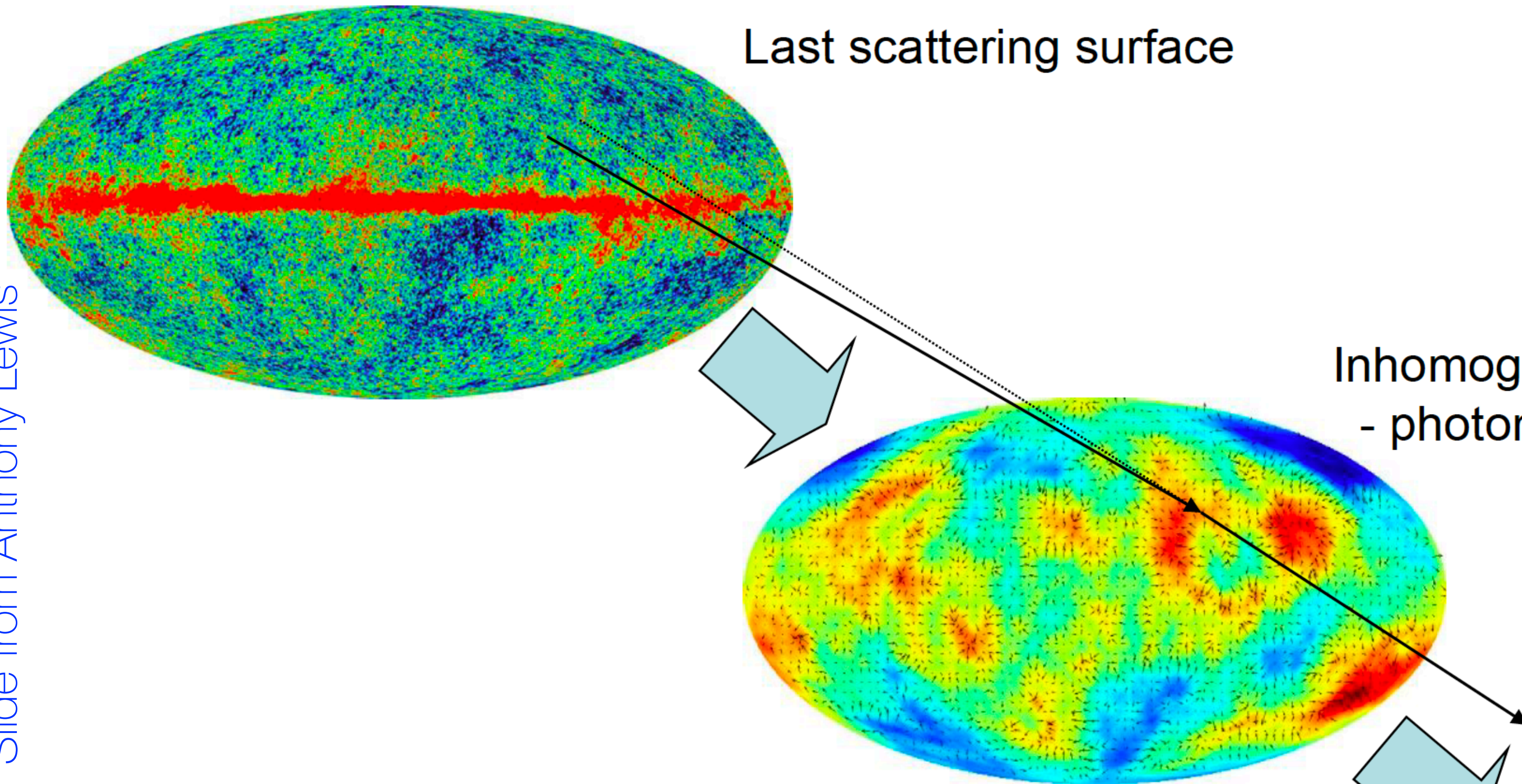
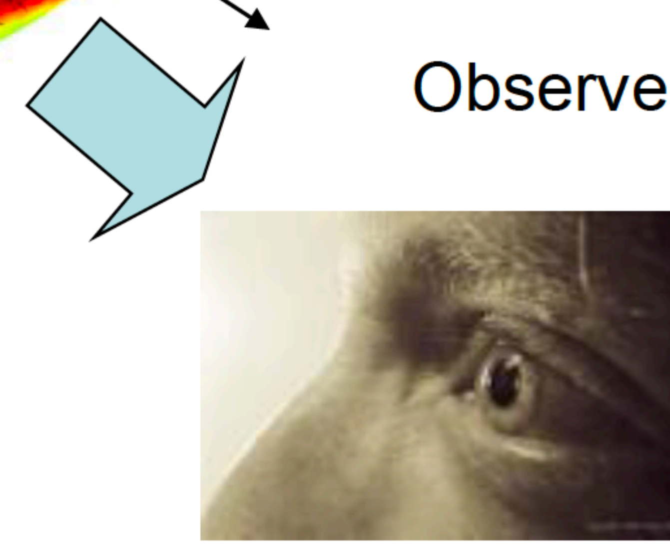
Lensing of the CMB photons





Slide from Anthony Lewis

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

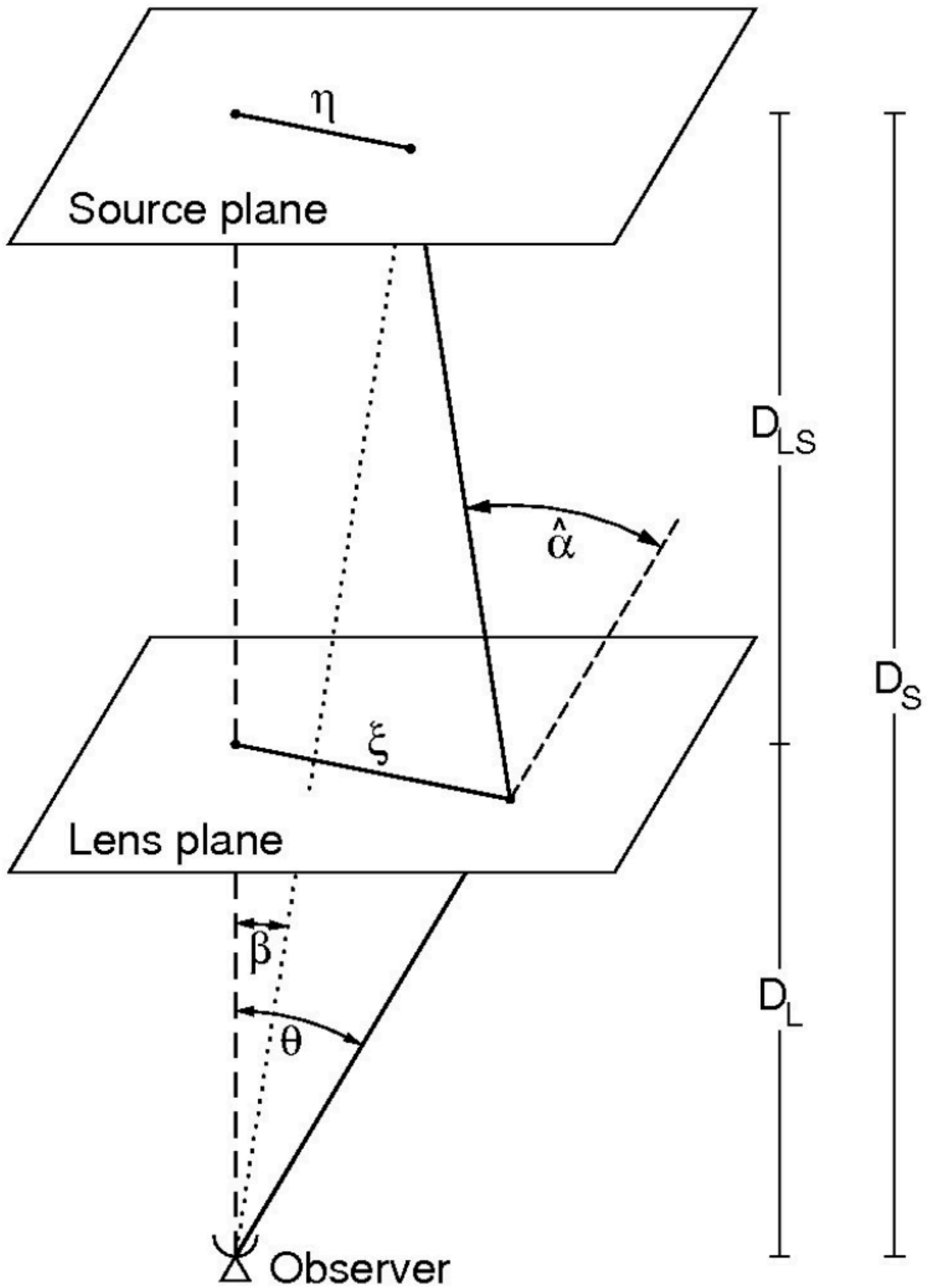
$$\boldsymbol{\alpha} = \nabla\psi$$

deflection angle

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

lensing potential

Lensing basics. I



Lensing lecture by Massimo Meneghetti

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.

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

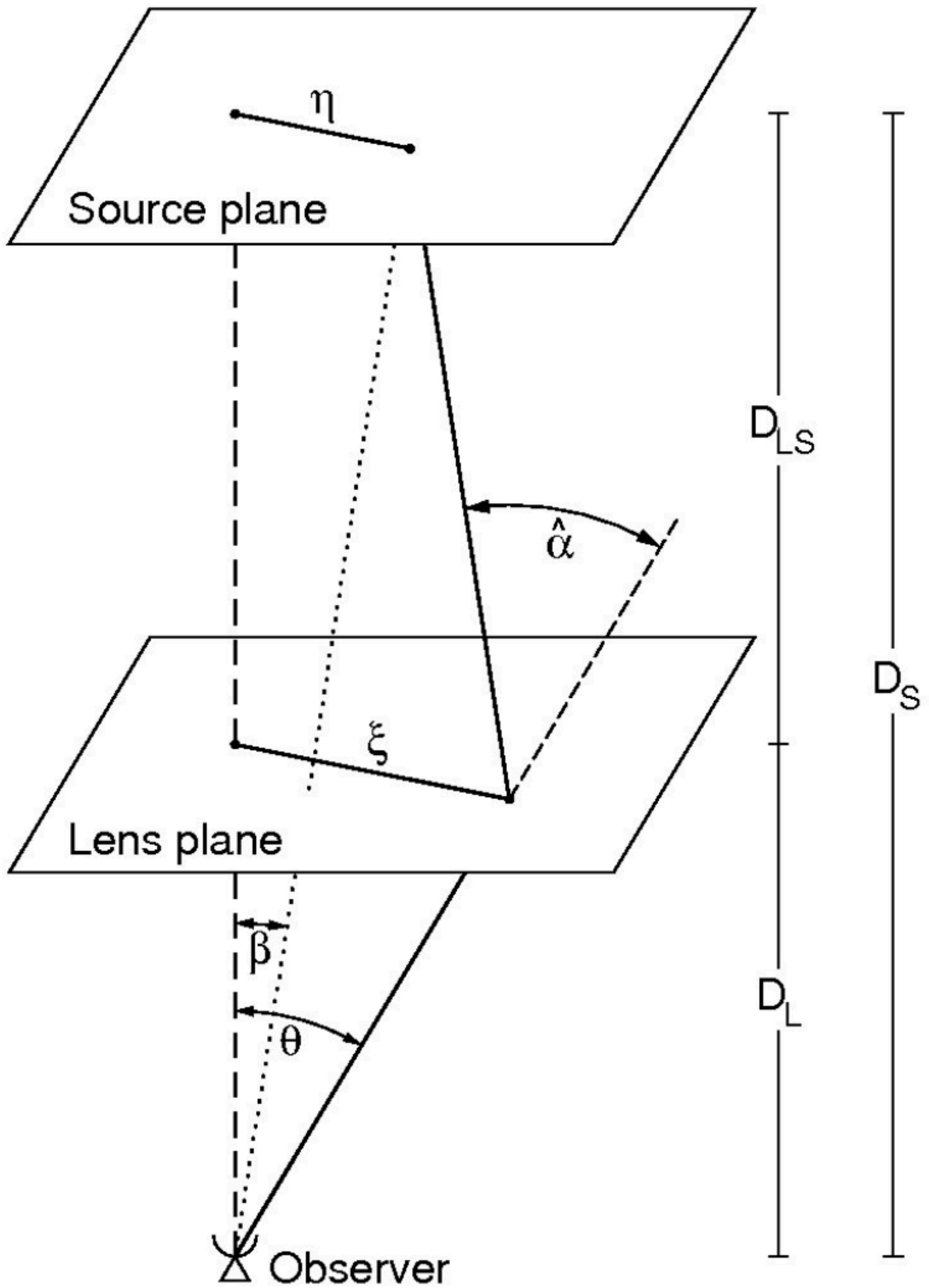
Since the distance between the observer, lens, and the source is typically much larger than the dimensions of the lens, "thin lens approximation" holds, where the lens is fully described by its surface mass density.

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

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

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

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

$$\hat{\Psi}(\vec{\theta}) = \frac{D_{\mathsf{LS}}}{D_{\mathsf{L}} D_{\mathsf{S}}} \frac{2}{c^2} \int \Phi(D_{\mathsf{L}}\vec{\theta}, z)\mathrm{d}z$$

The gradient of ψ gives the deflection angle

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

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

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

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

The generalized lens equation

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

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

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

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

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

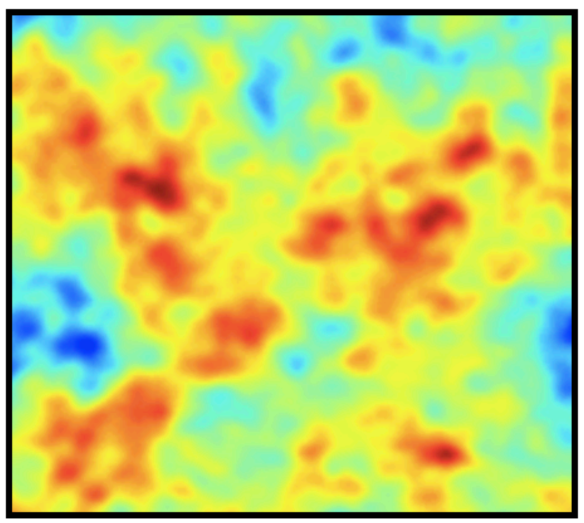
$$\phi(\hat{\mathbf{n}}) = 2\int \frac{dz}{H(z)} \frac{D_A(D_s - D)}{D_A(D)\, D_A(D_s)} \Phi(D_A\hat{\mathbf{n}}, D)\,,$$

How to lens the CMB?

Slide from Sudeep Das

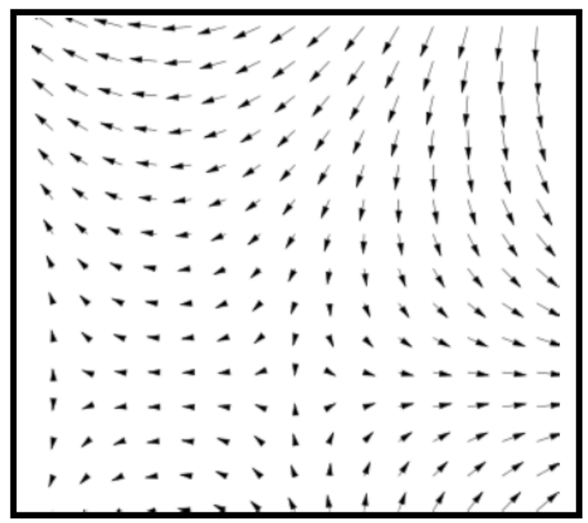
Given the deflection field, remap the points on the CMB.

Unlensed



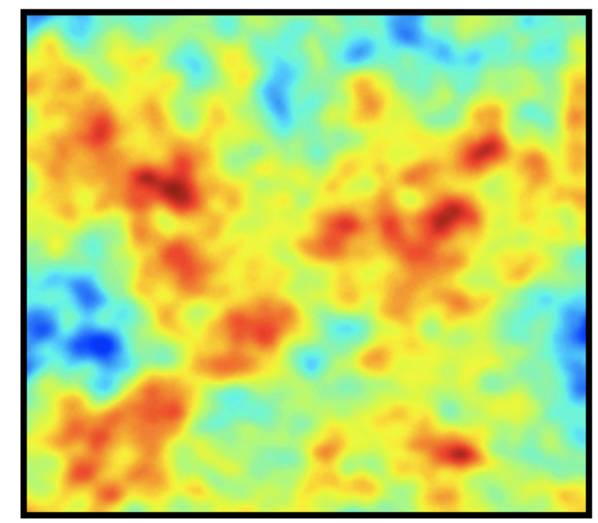
$\Theta(\hat{n})$

Deflection



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

Lensed



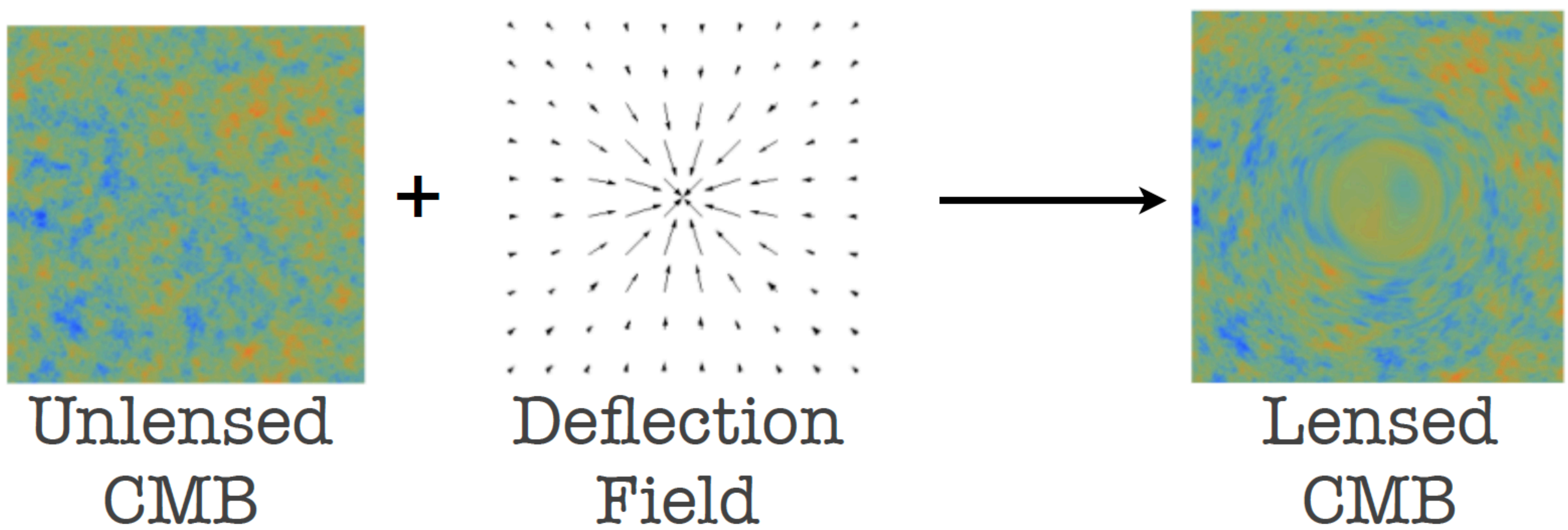
$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \vec{\alpha})$

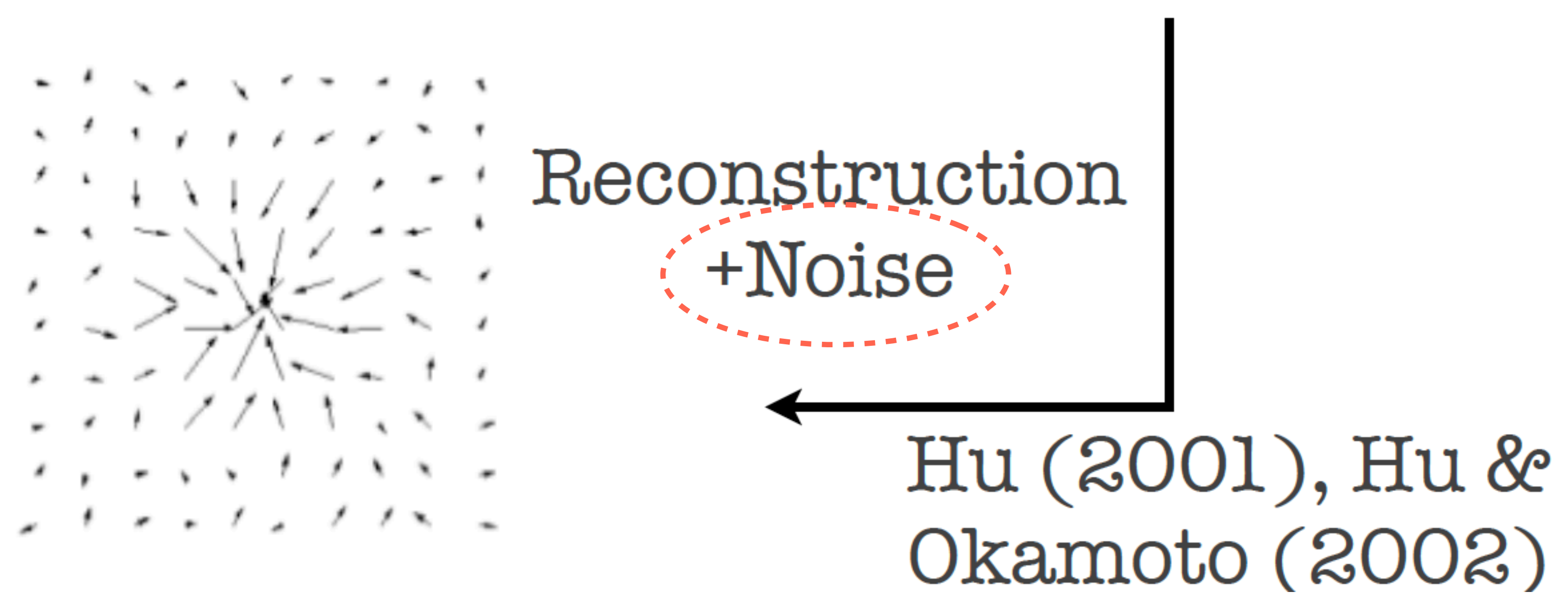
CMB lensing can be discussed completely in terms of the deflection field.

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

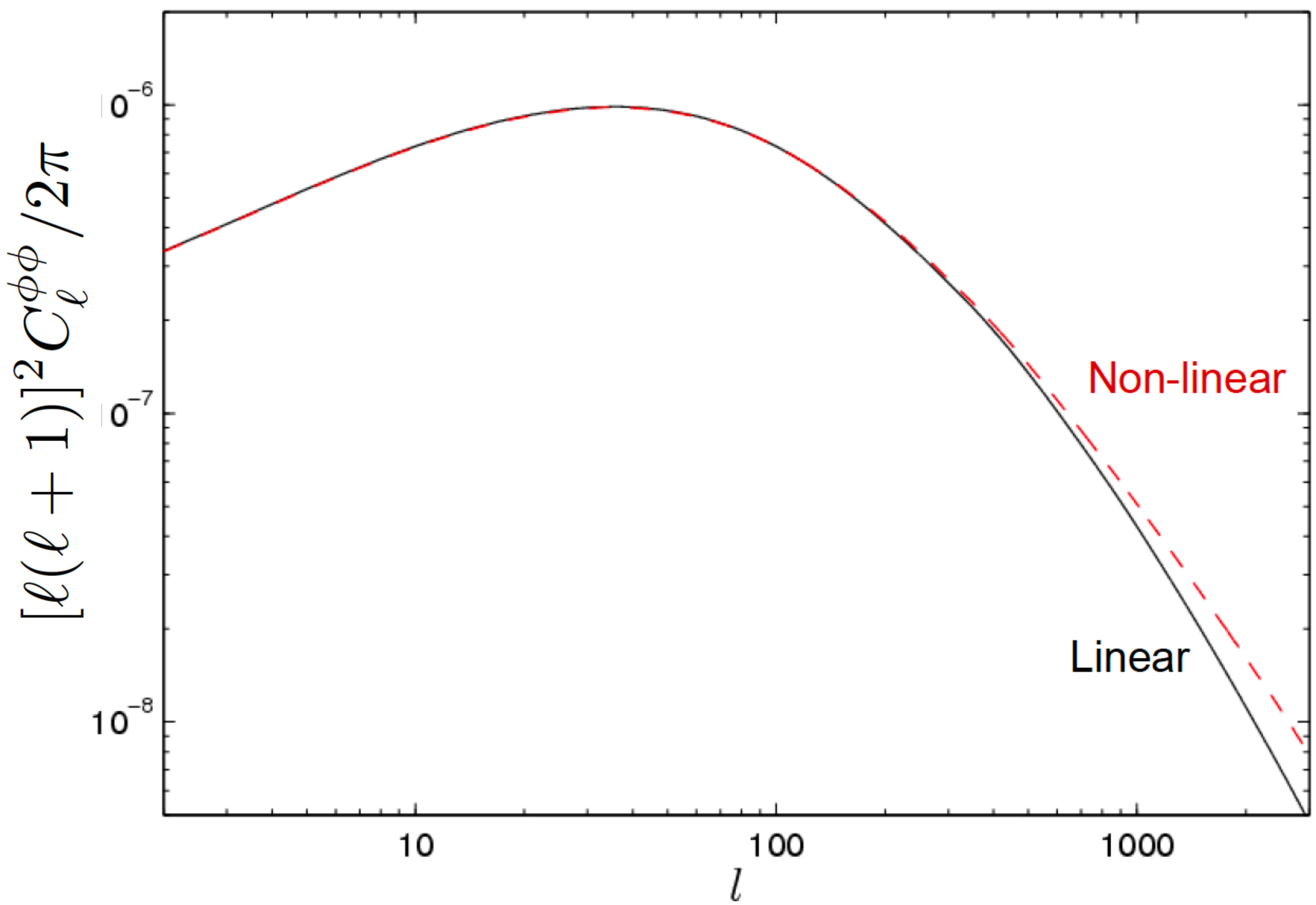
The deflection power

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

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

Note: $\psi \leftrightarrow \phi$

These two are related by the equation: $C_\ell^{\alpha\alpha} = [\ell(\ell+1)]^2 \, C_\ell^{\phi\phi} \approx \ell^4 \, C_\ell^{\phi\phi}$

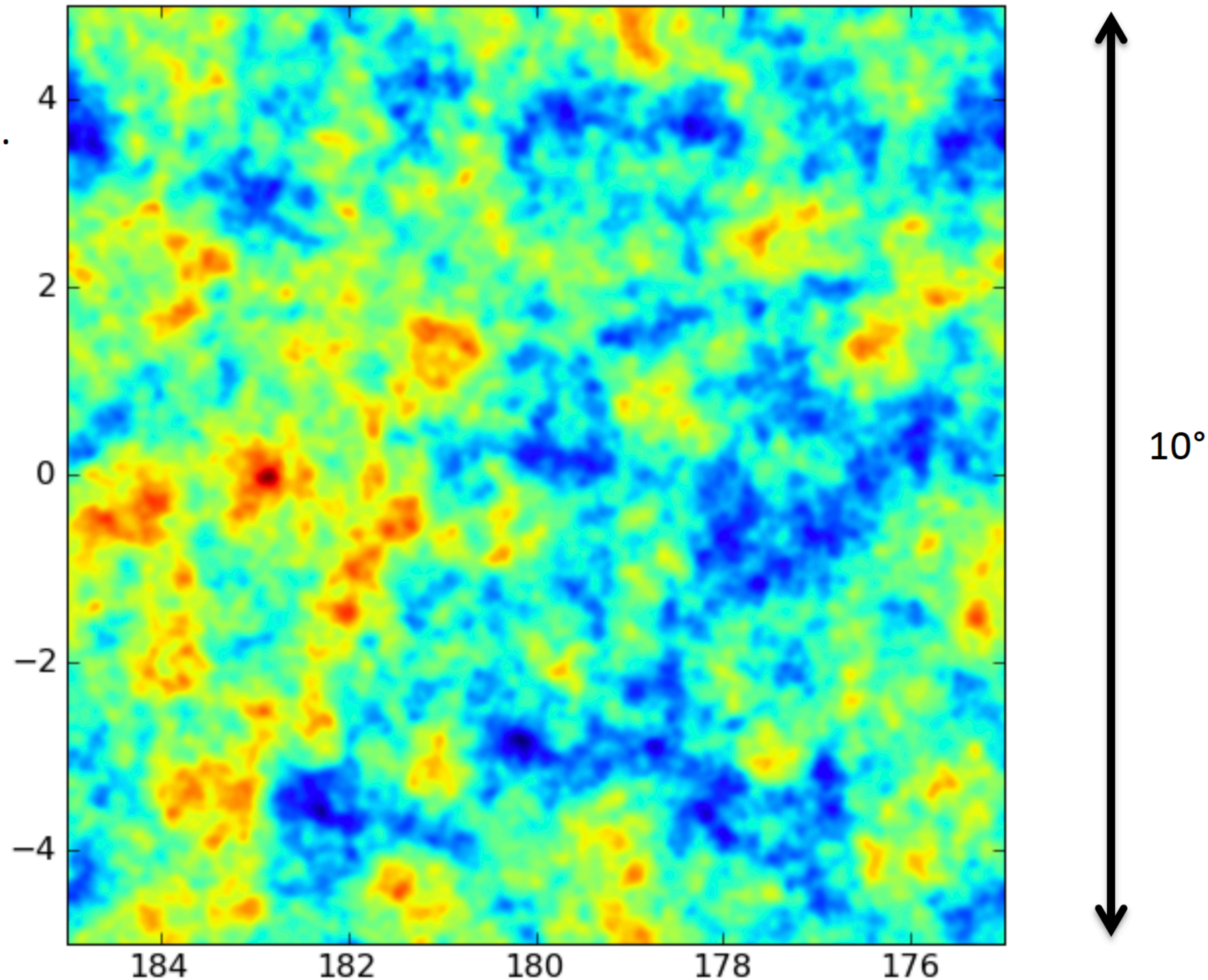


The deflection PS peaks at about $\ell \sim 60$

- most power in degree scale modes.

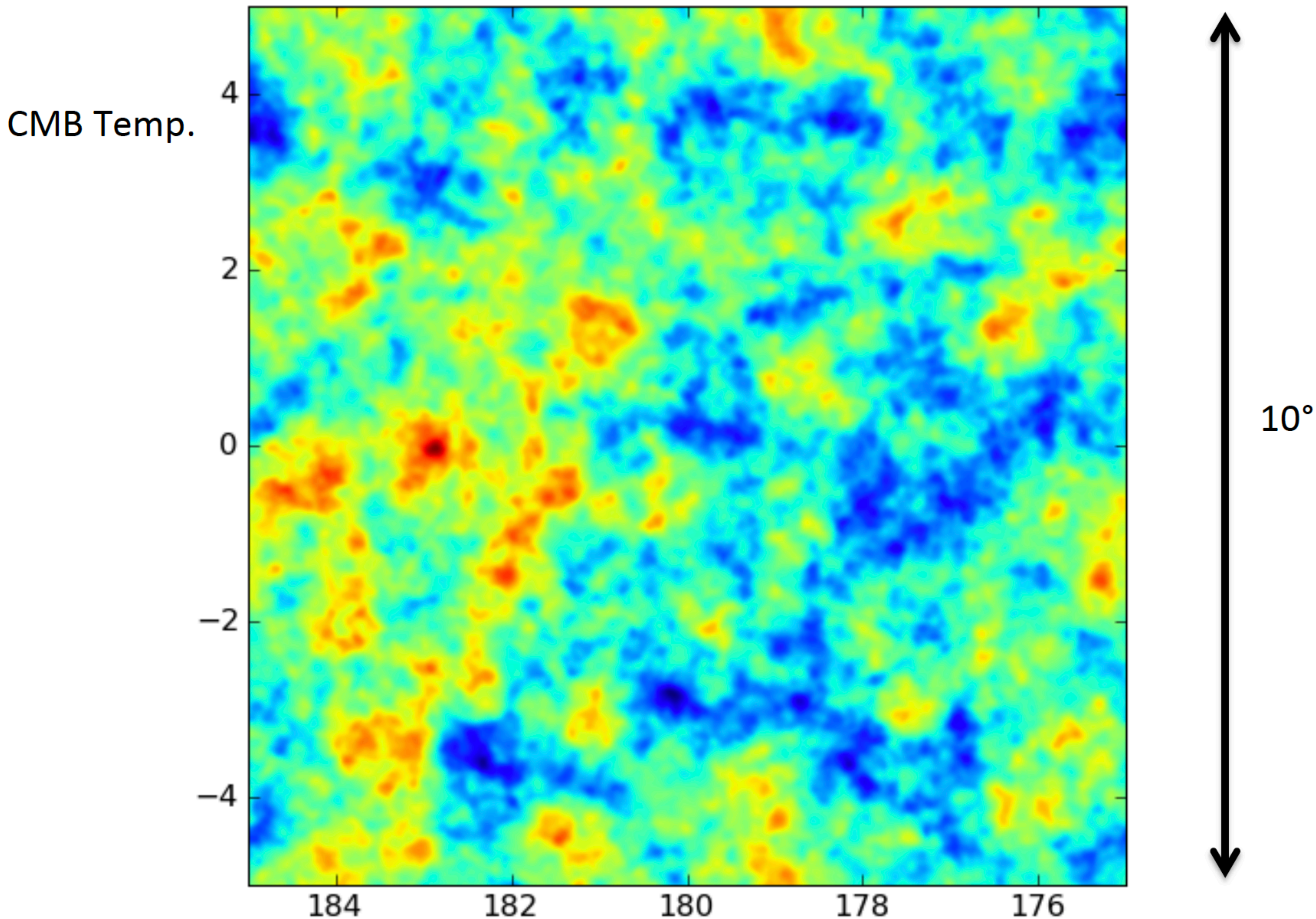
Unlensed CMB

CMB Temp.



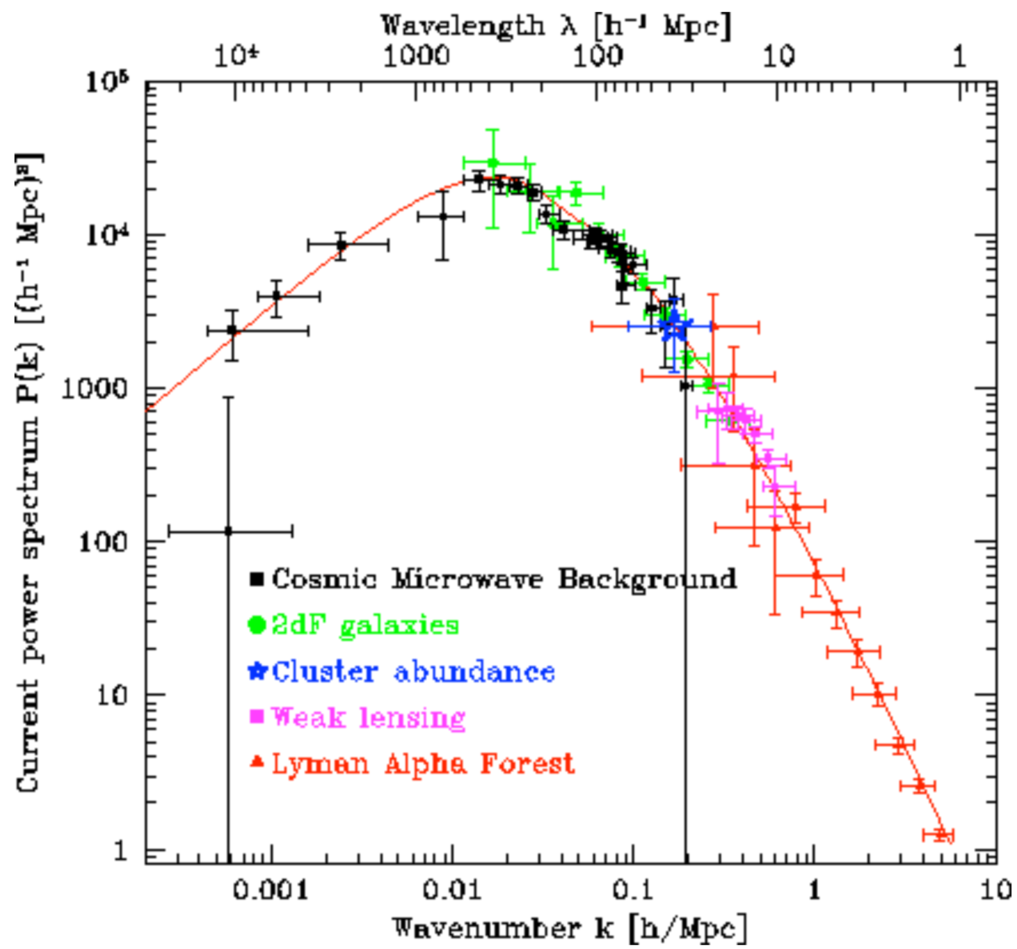
$T(\hat{\mathbf{n}})_{\mathrm{unlensed}}$

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 ~ 300 Mpc.
CMB is at ~ 14000 Mpc

Thus on average, CMB passes through ~ 14000/300 ~ 50 lenses

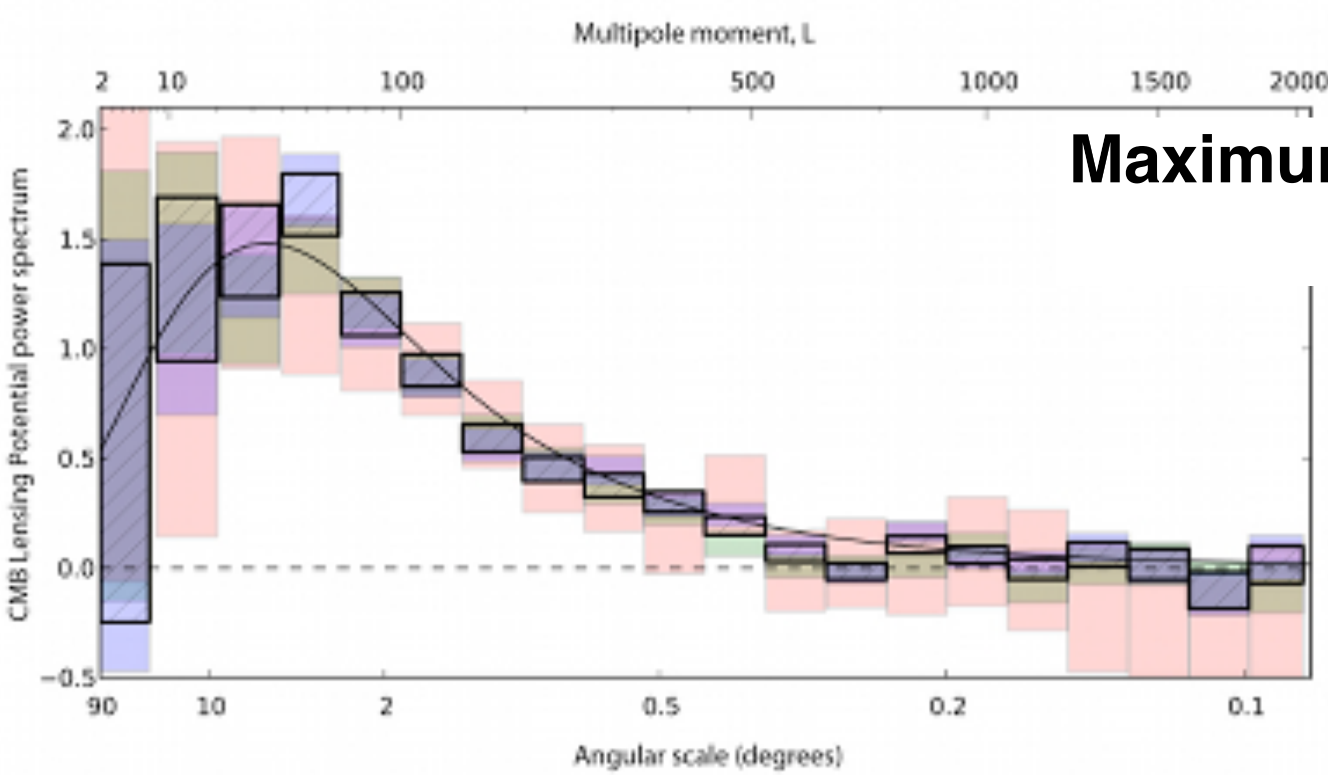
Each lens produce deflection $\alpha \approx 4\Psi$ ~ 0.3 arcmin

This is a random walk problem for CMB photons!

Total deflection ~ √50 x 0.3 ~ 2 arcmin

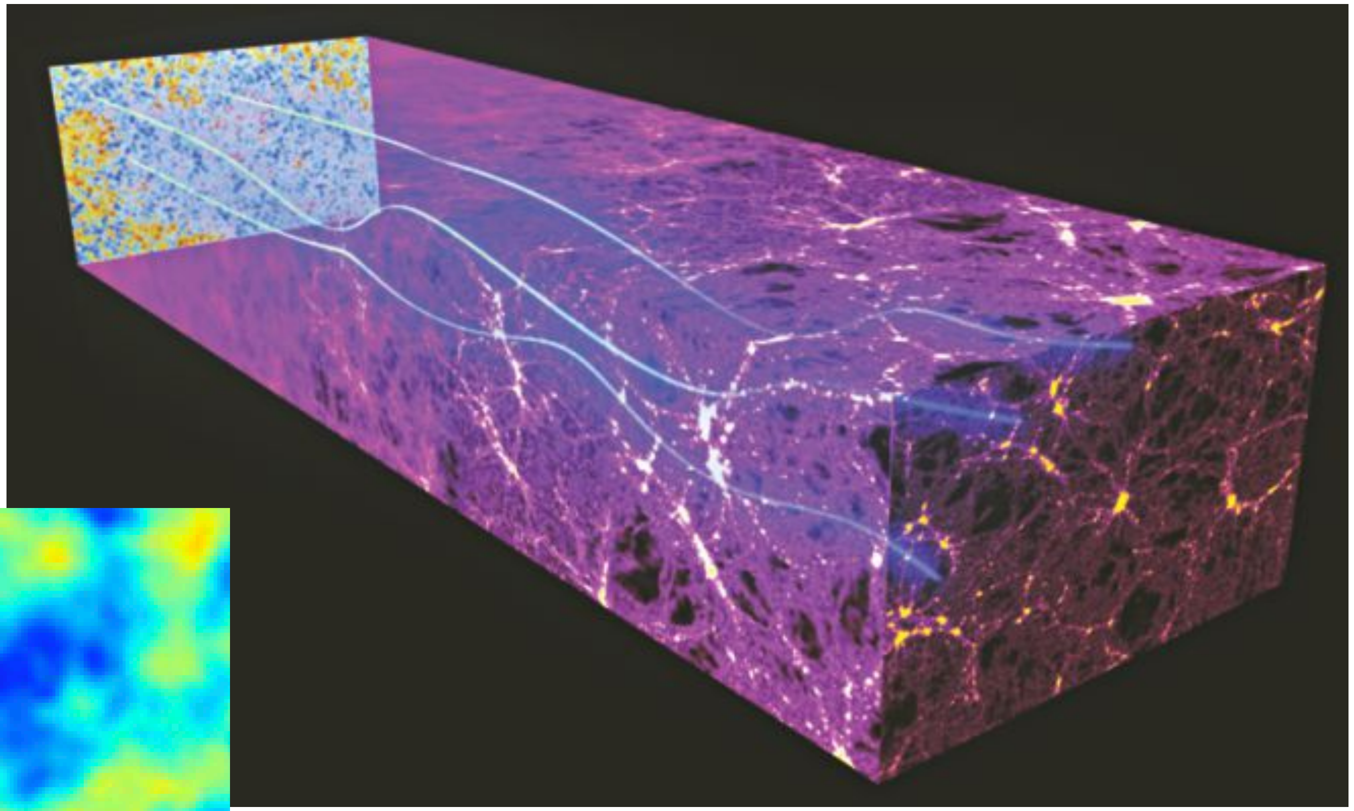
But deflections are coherent on scales of a representative chunk of matter

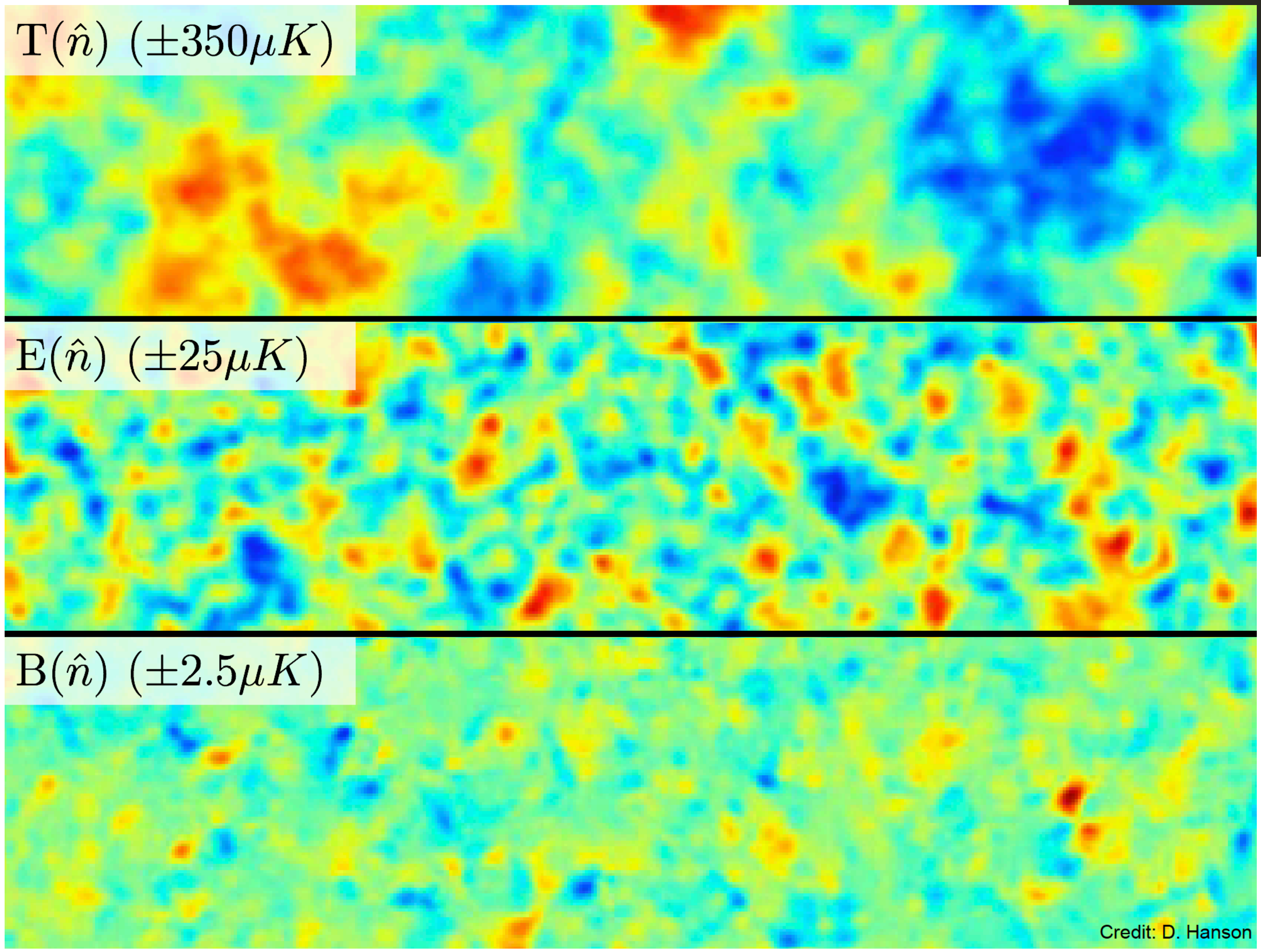
Maximum power on scales ~ 300/(14000/2) ~ 2°



Lensing works on both temp. & pol.

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

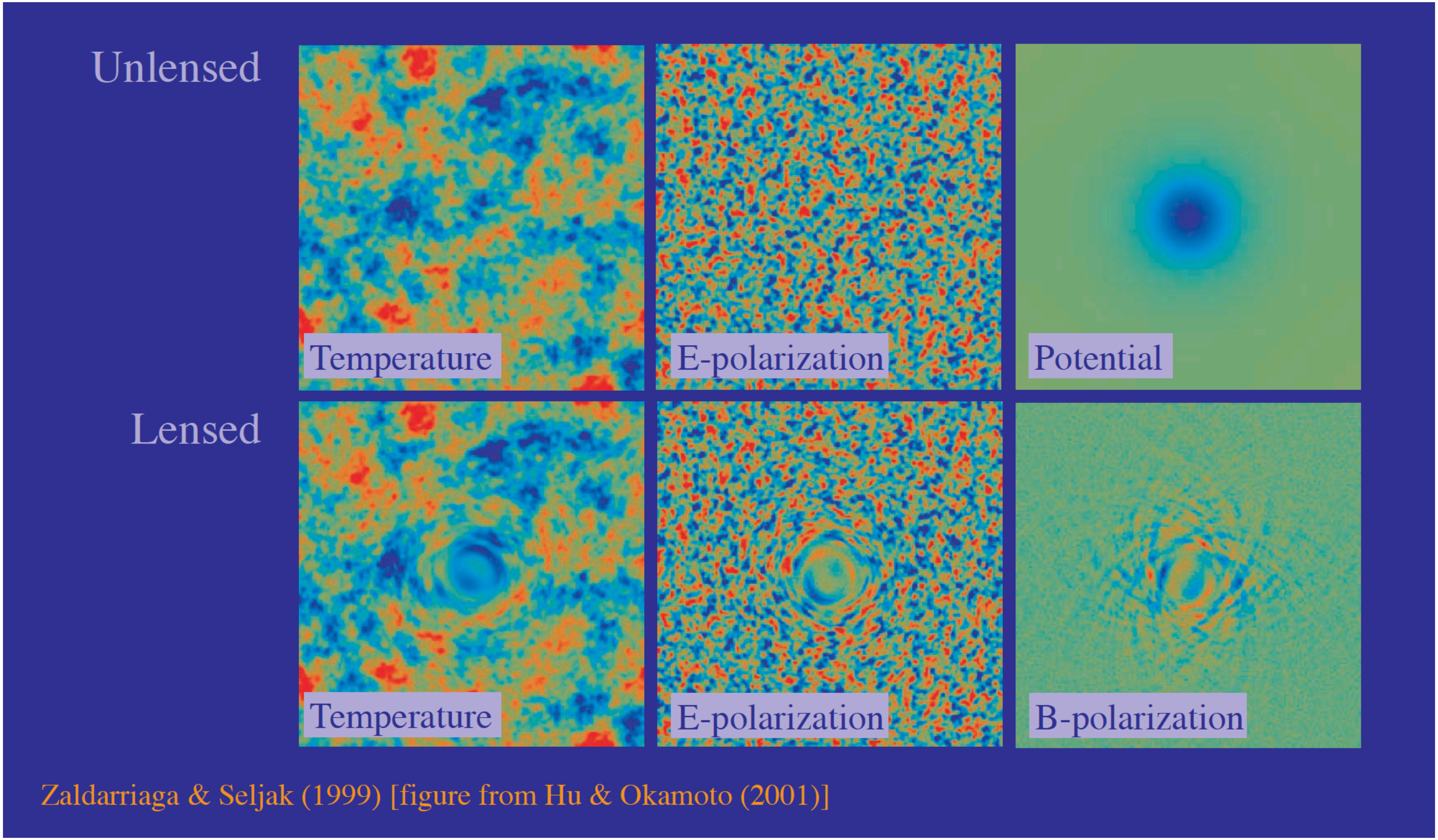


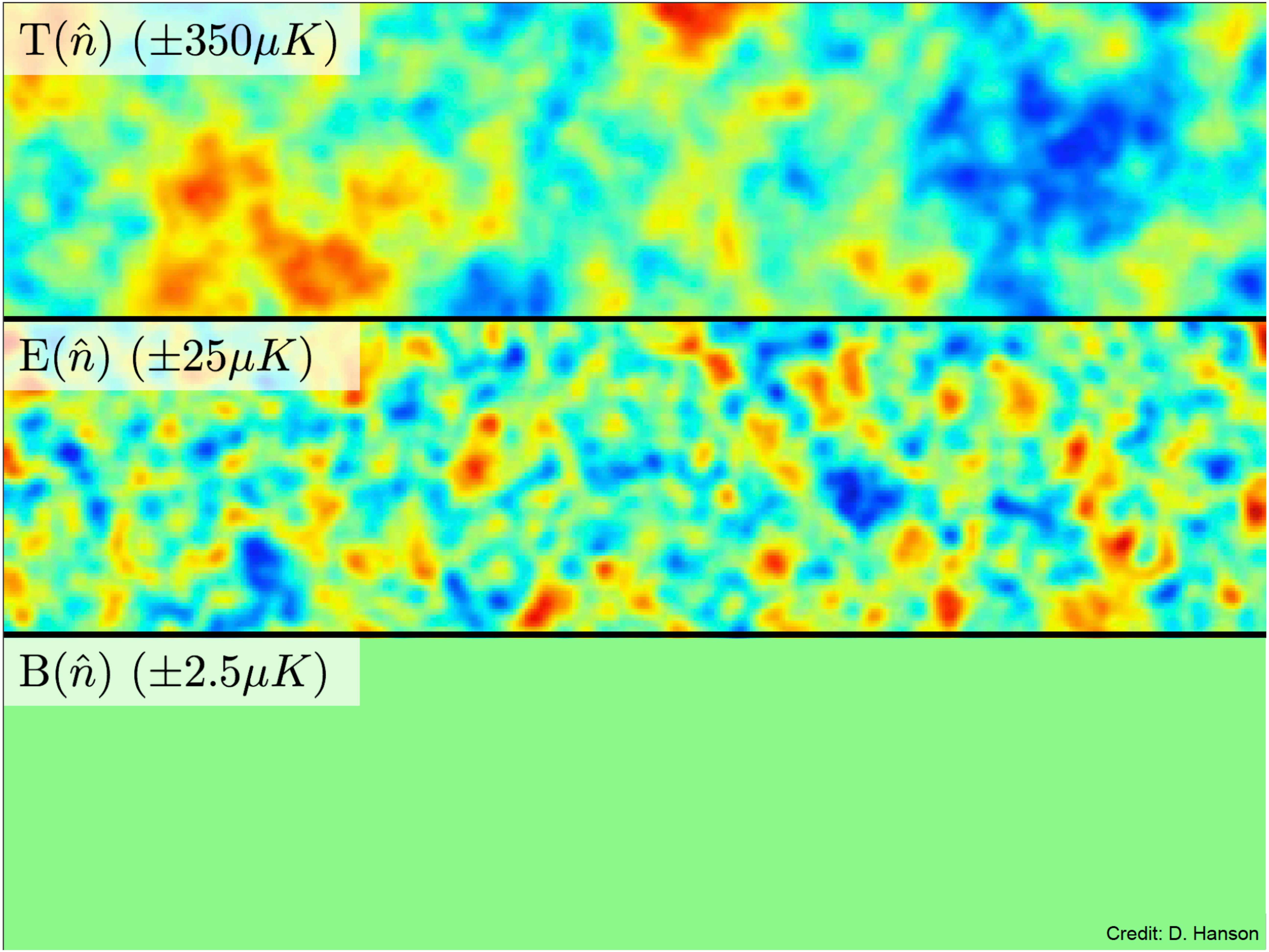


One result of CMB lensing is blurring of temperature and polarization anisotropies, as the angular scales associated with the peaks are smeared.

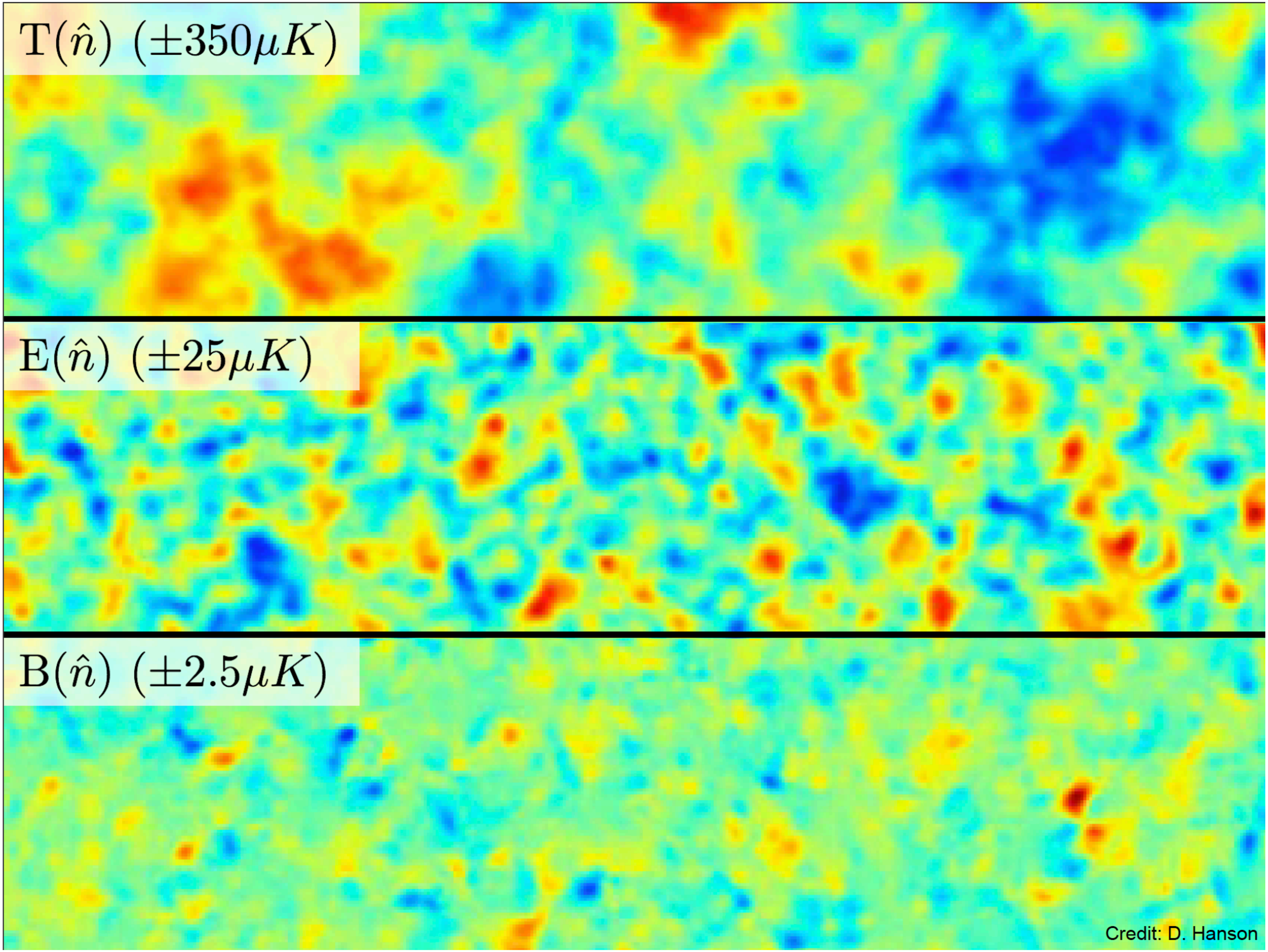
Another result is the creation of B-mode polarization from E-mode (by mixing Stokes Q and U params).

Temperature & polarization after lensing

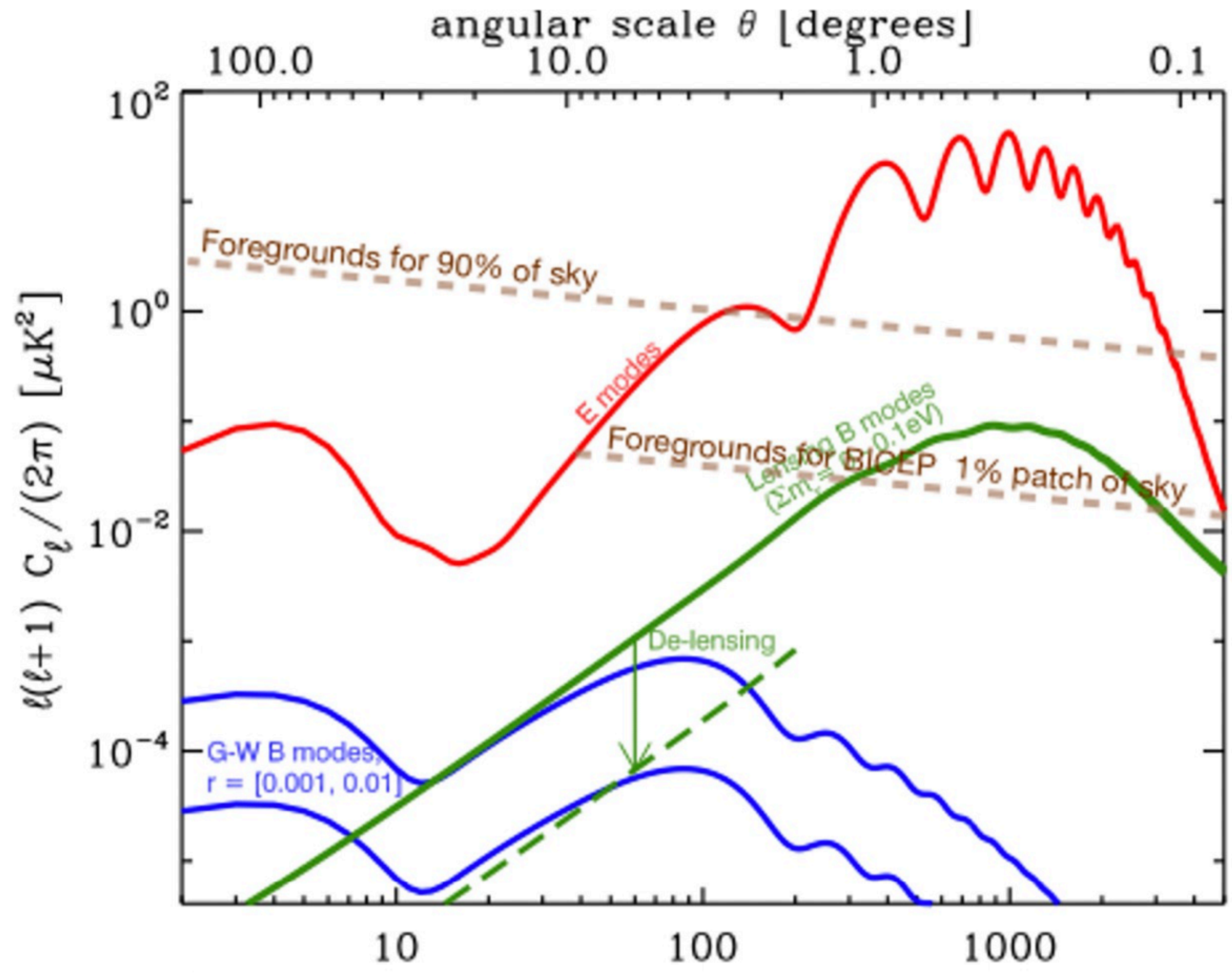




$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Credit: D. Hanson

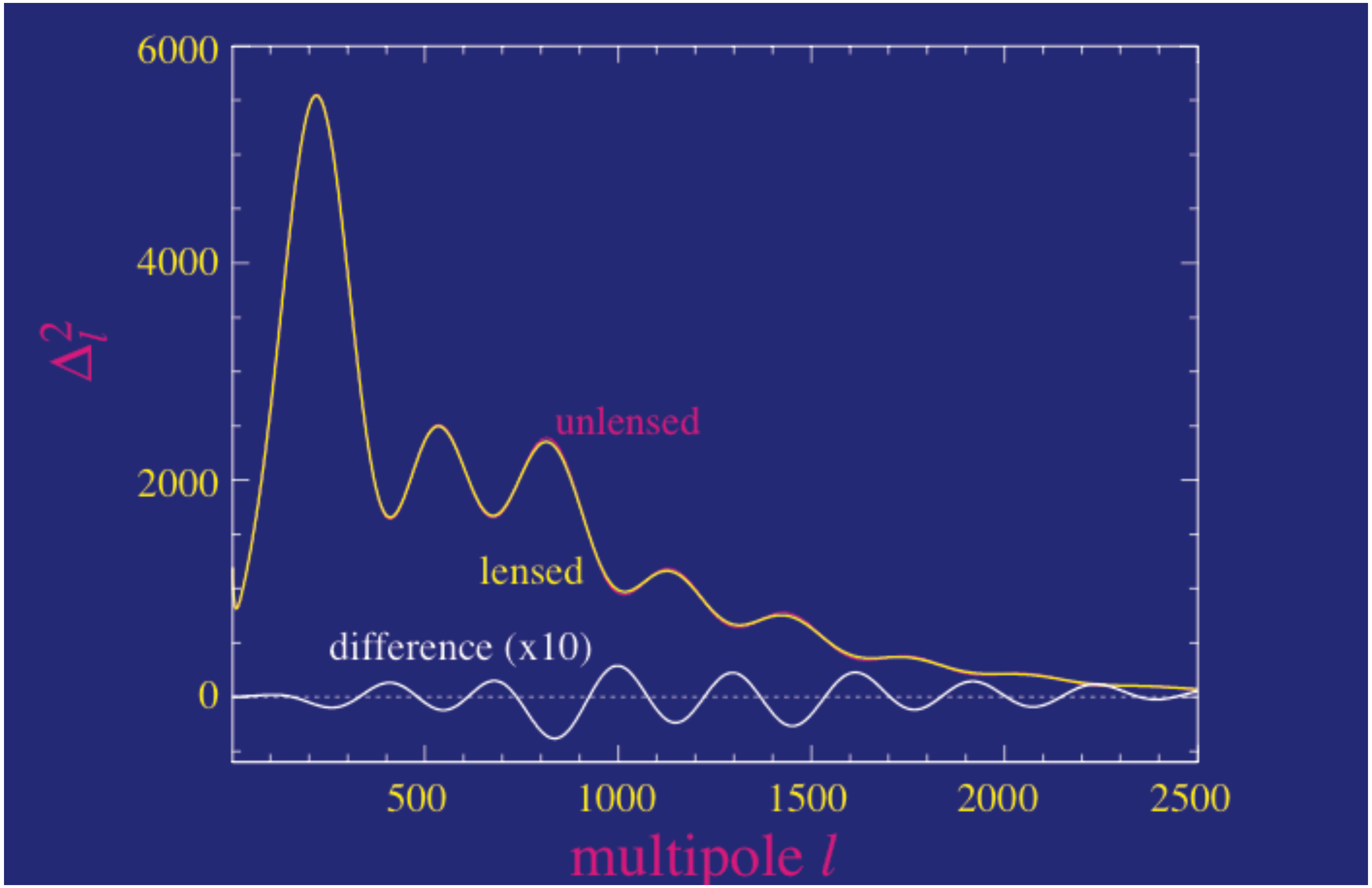

$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Credit: D. Hanson

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 detection of the primordial signal.

Lensing effect on the temperature power spectrum

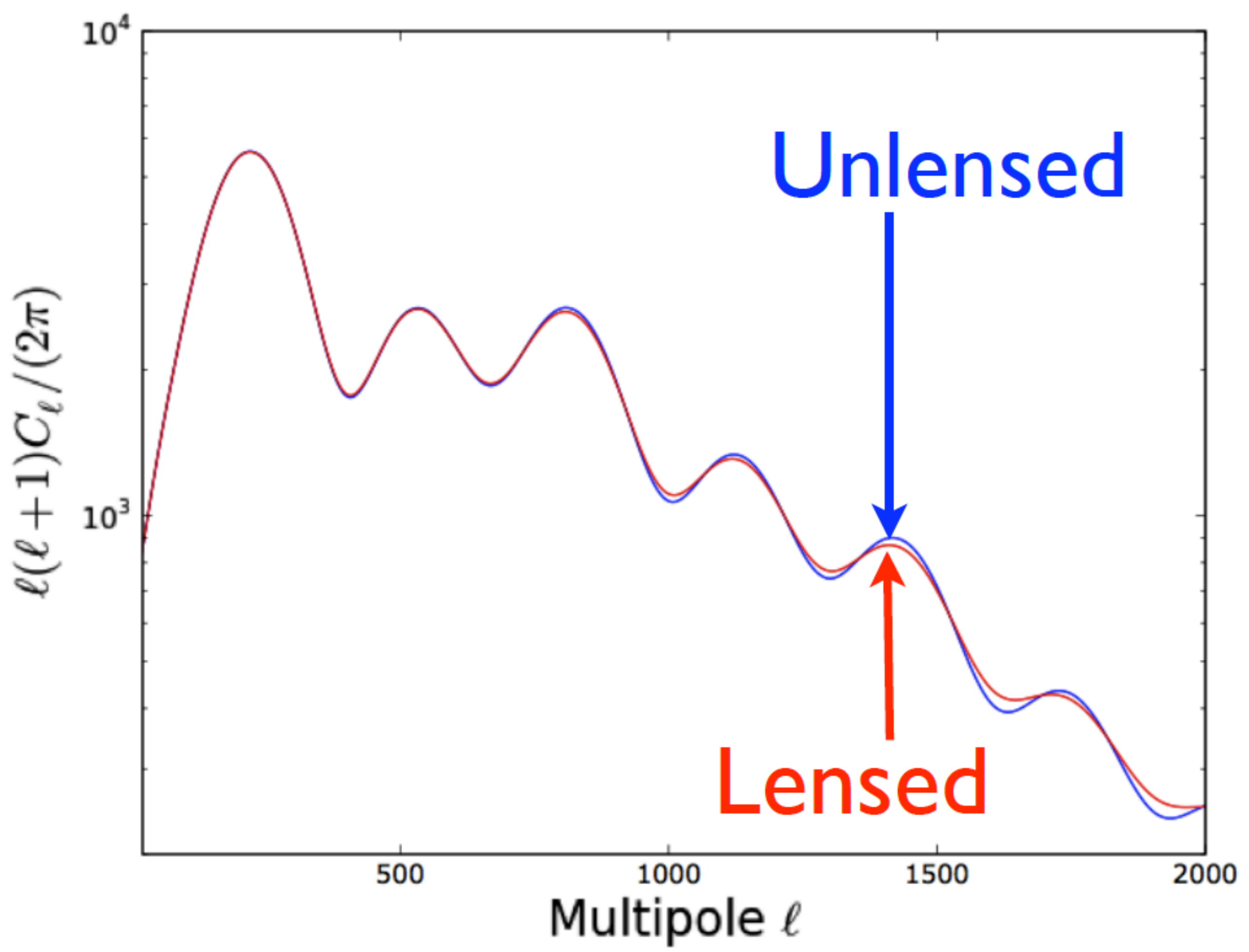


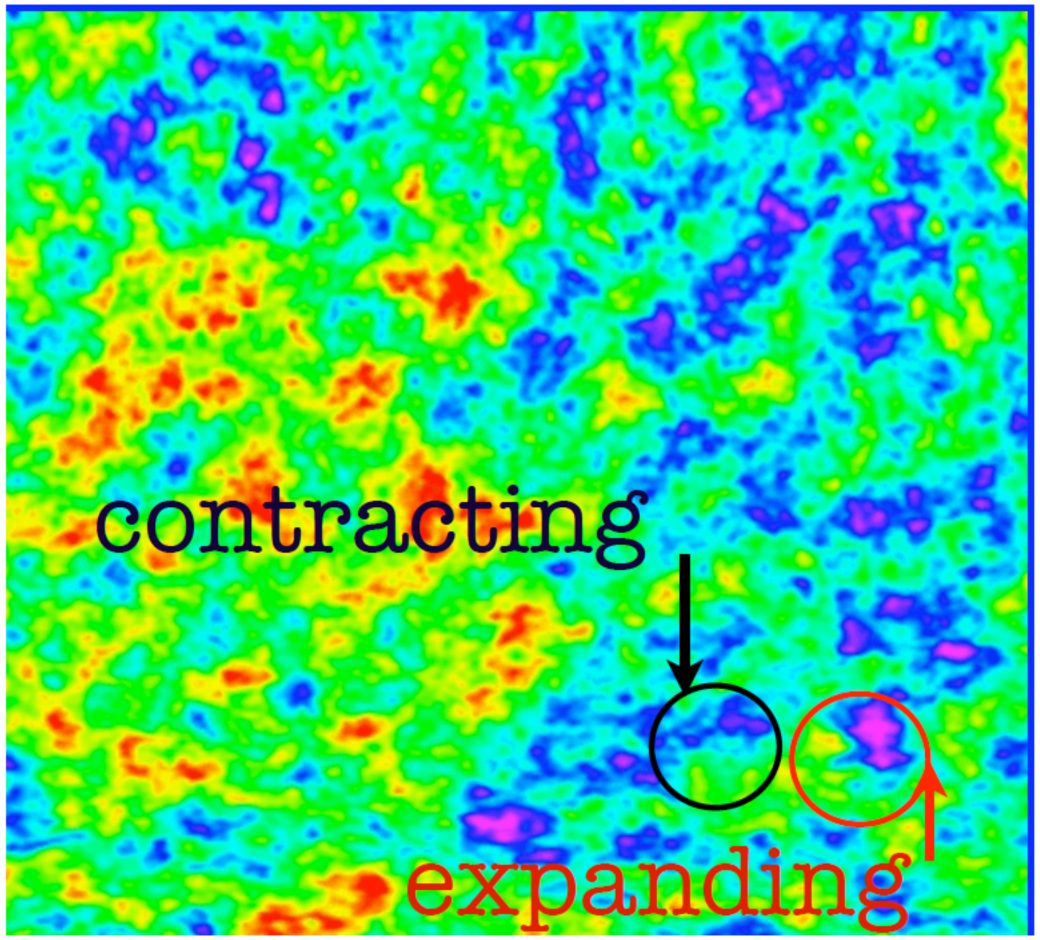
Averaged over the sky, lensing smooths the temperature power spectrum (and also E mode polarization) with a width `Δl~60`.
This is a small, subtle effect, but reaches up to ~20% at `l~3000`.

Lensing effect on the temperature power spectrum

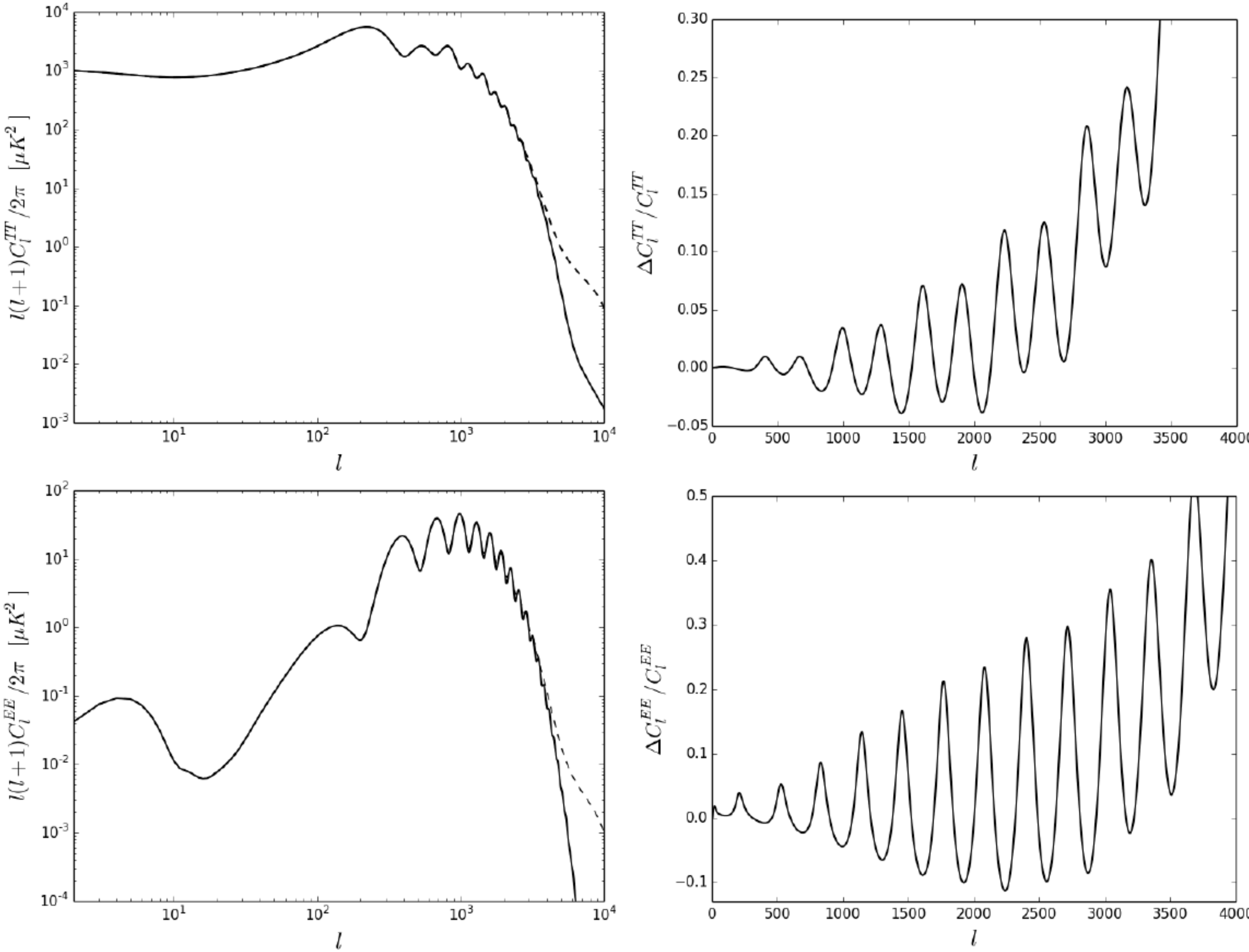
Slide from Sudeep Das

Lensing smoothes acoustic peaks - this can be understood as the broadening of the size distribution of the hot and cold spots.





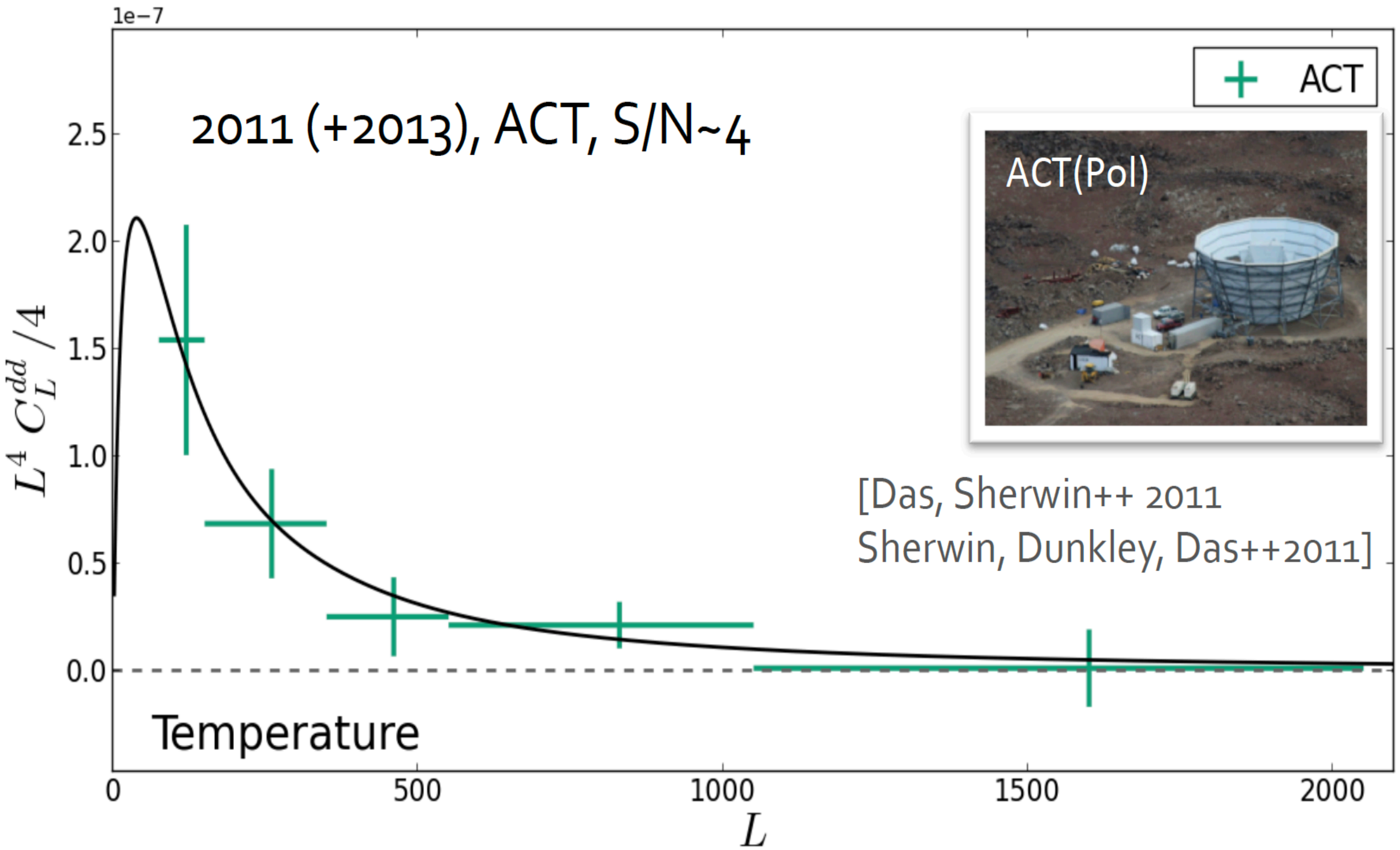
Lensed TT and EE power



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

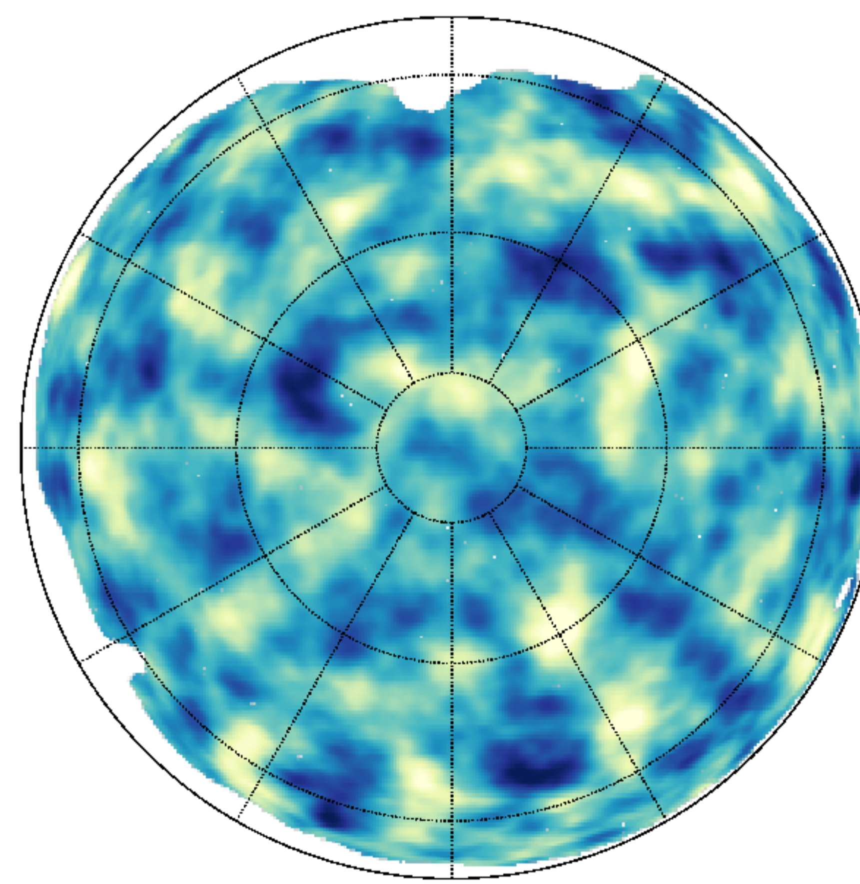
Lensing spreads out the peaks very slightly while transferring power to large l. The right panels show the *fractional change* in the power spectrum caused by lensing.

First measurements of lensing power



First measured by ACT, then Planck and SPT.

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

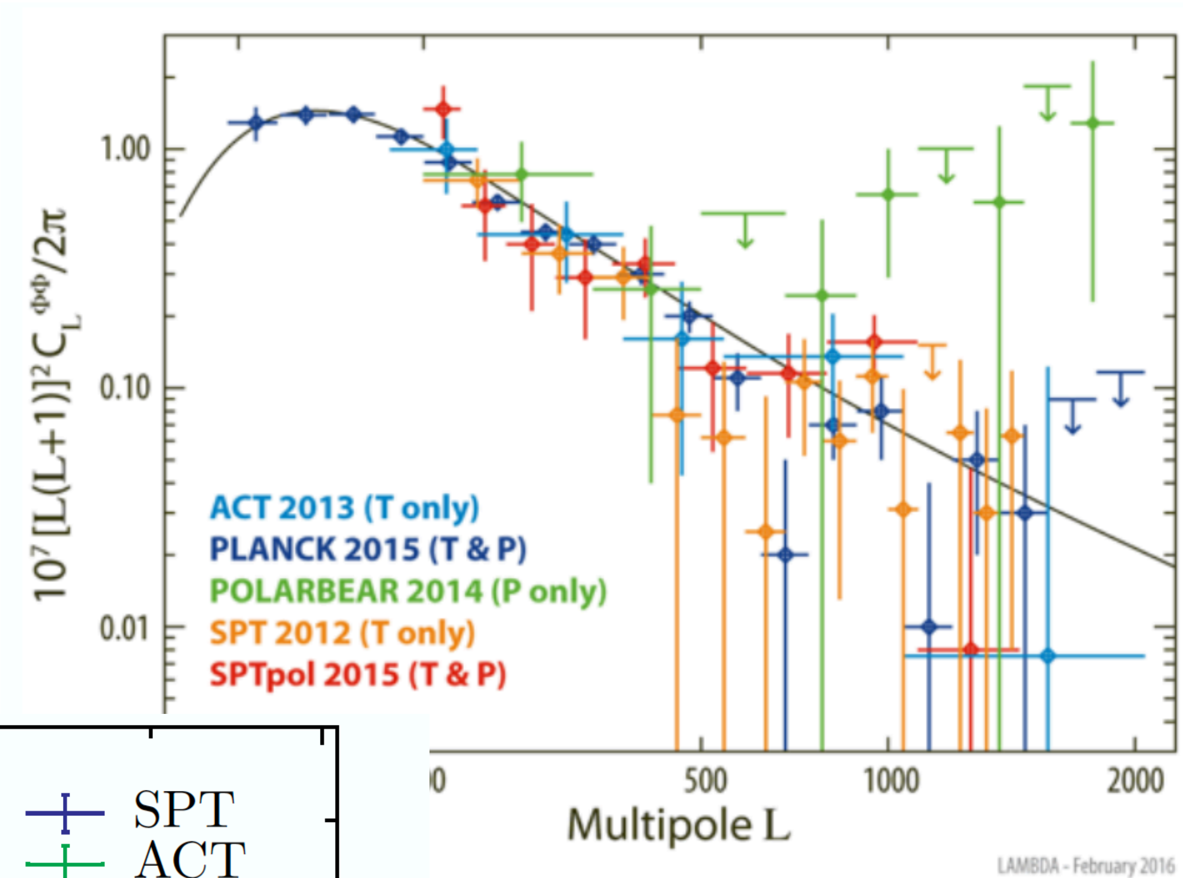


Planck full-sly lensing potential reconstruction

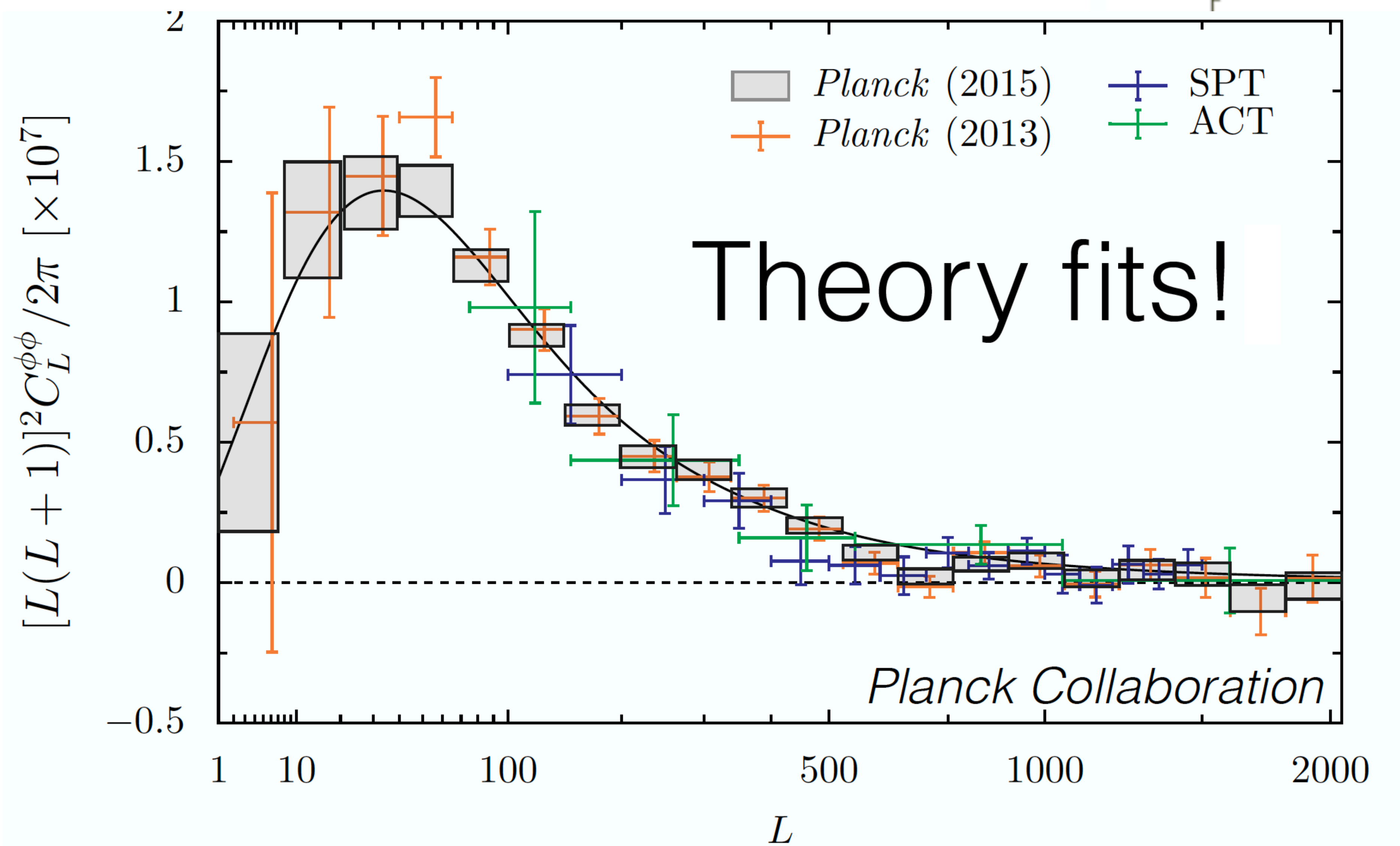
Note – about half signal, half noise,
not all structures are real: map is effectively Wiener filtered

Planck lensing measurements

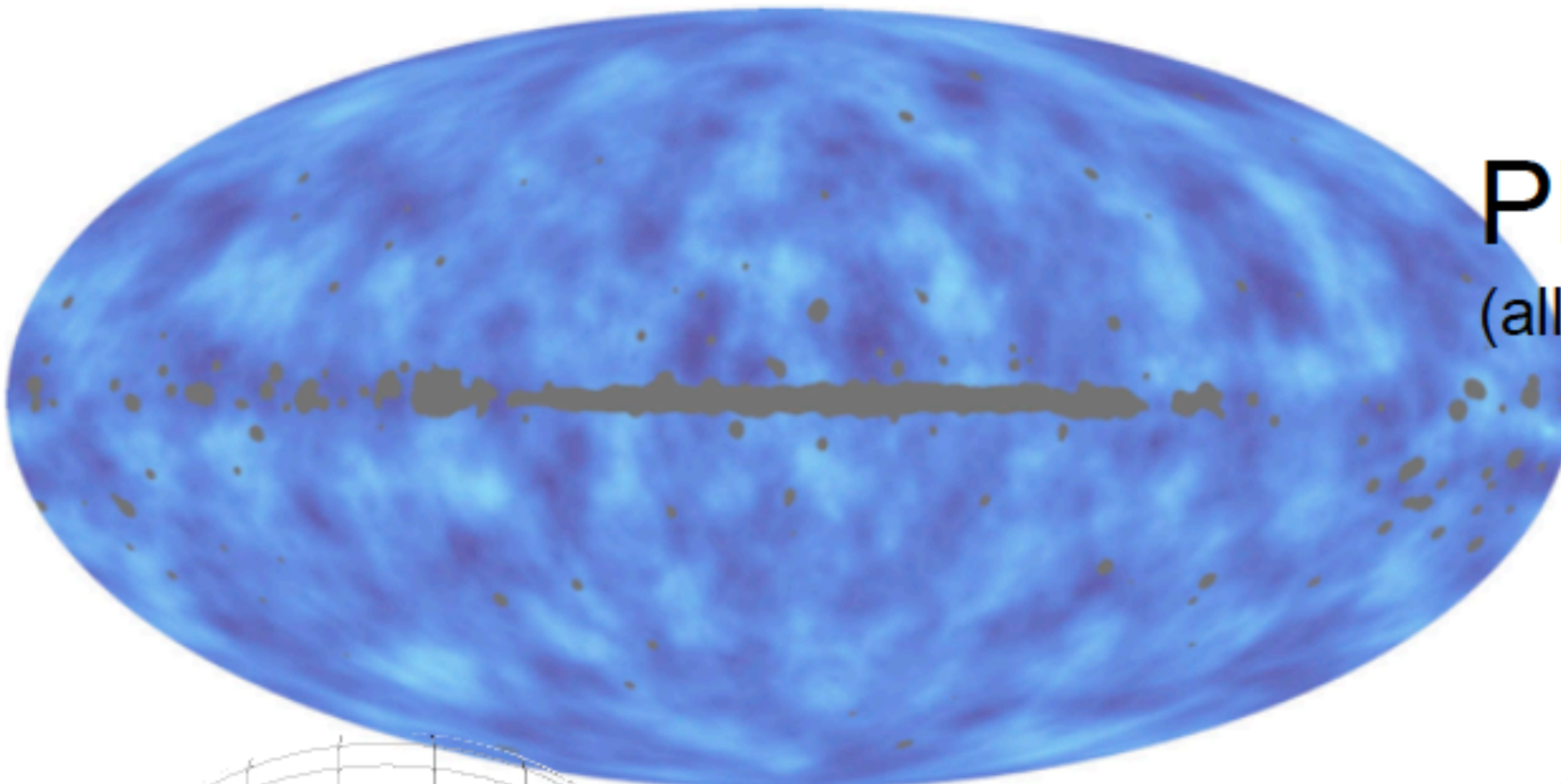
CMB lensing is statistically detectable at high-significance with Planck data, because its all-sky measurement capability suits perfectly with the peak of the lensing power.



Planck 2015 results

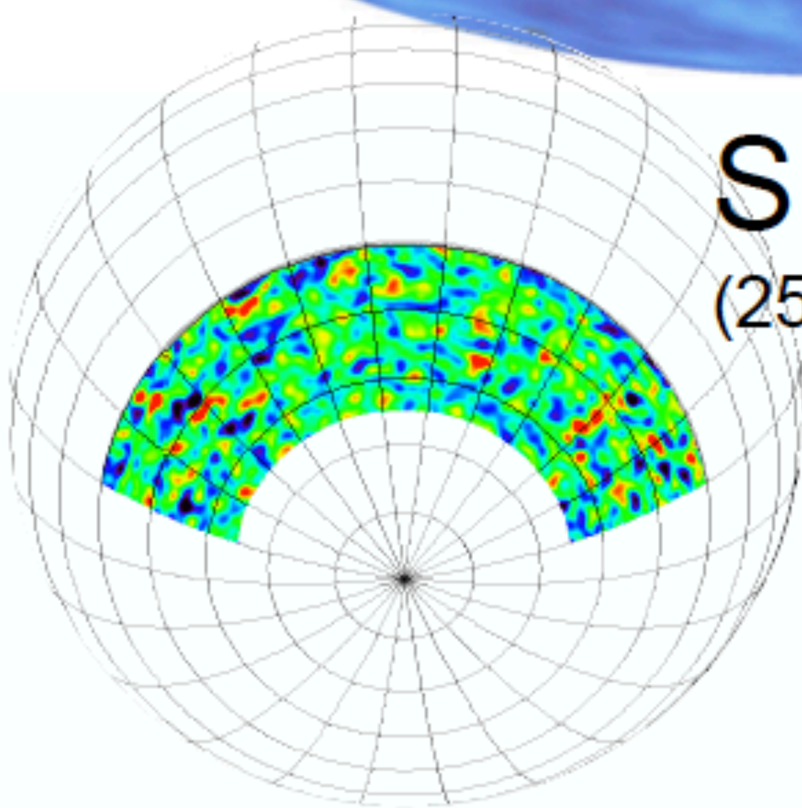


Matter distribution from CMB lensing



Planck

(all-sky)

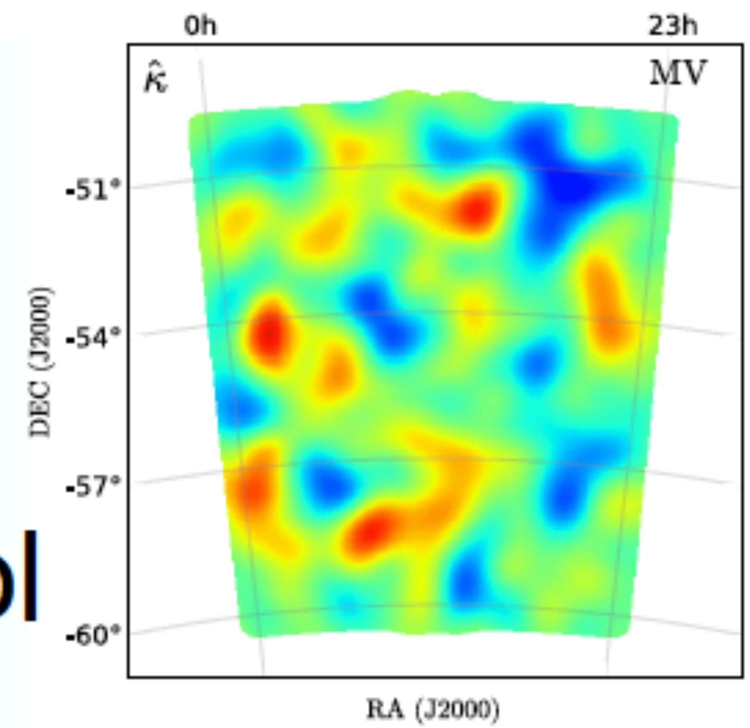


SPT

(2500 sq deg)

SPT-Pol

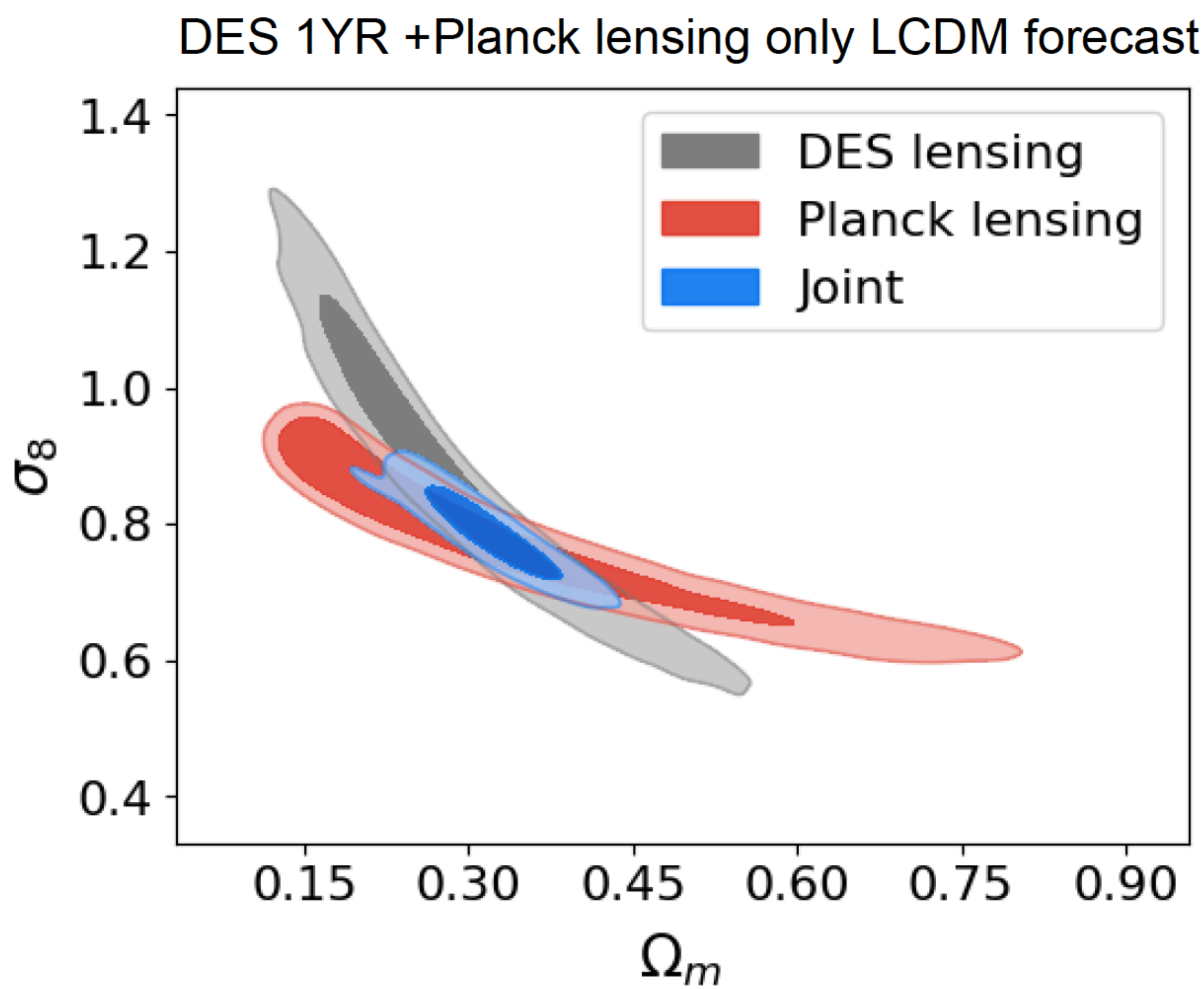
(100 sq deg)



Cosmology with CMB lensing

CMB lensing currently competitive with galaxy lensing

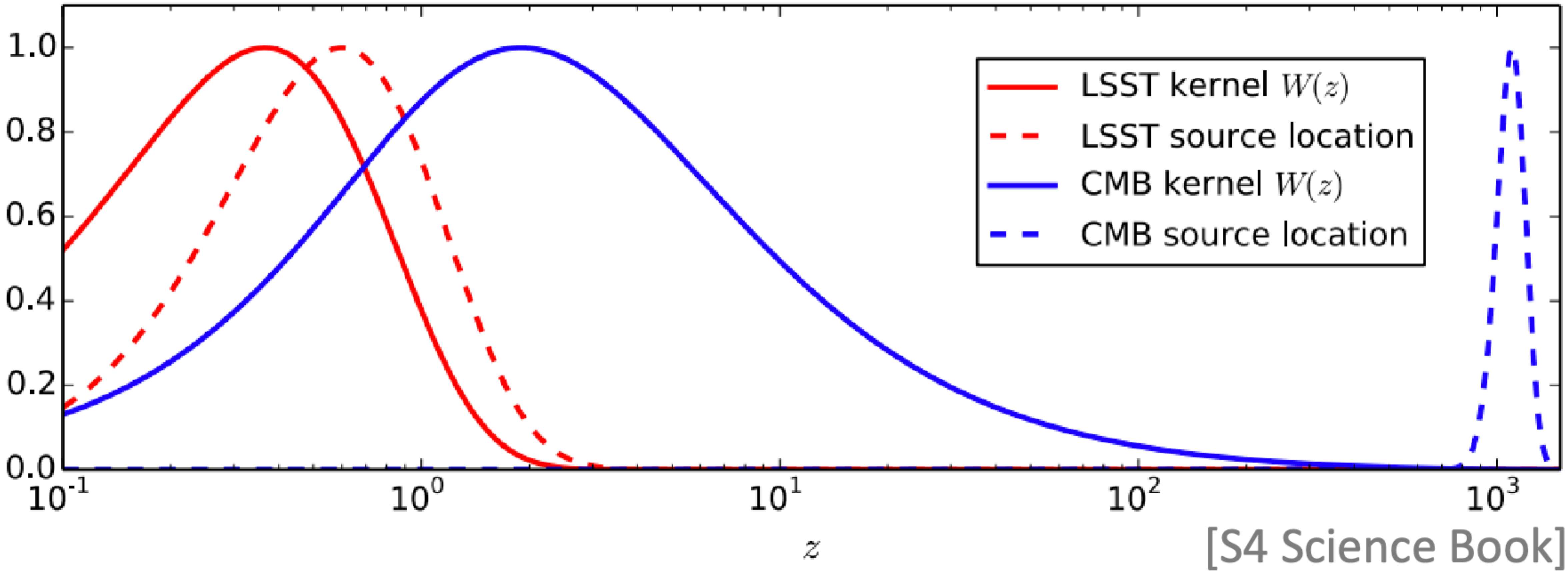
Probes higher redshift ⇒ constrains $\Omega_m \sigma_8^{0.25}$ vs. galaxy $\Omega_m \sigma_8^{0.5}$



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~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 representative of the LSST survey (now called the Vera-Rubin telescope), which will measure the cosmic shear from a wide-area survey of the sky.

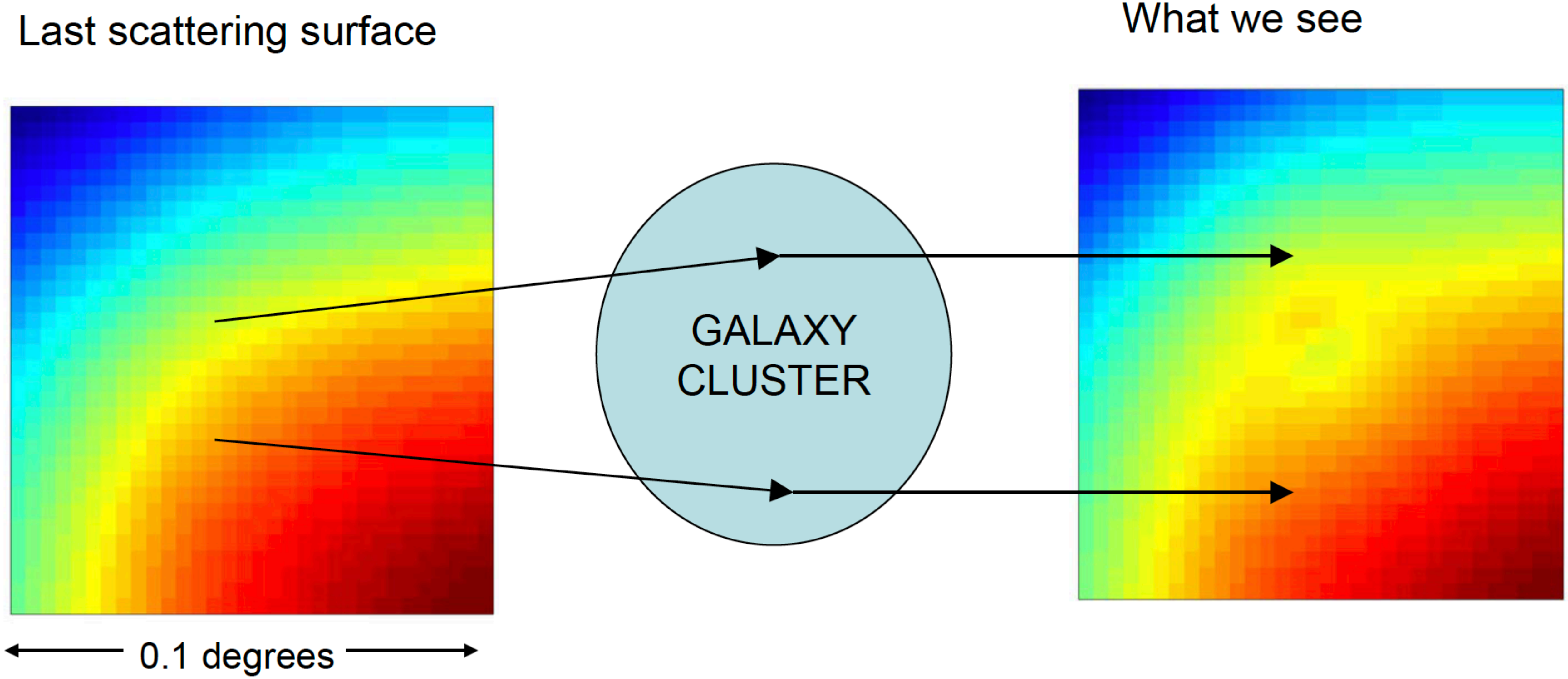
CMB lensing on small angular scales

$$(\ell \gtrsim 3000)$$

CMB lensing by galaxy clusters

CMB very smooth on small scales: approximately a gradient

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



Need sensitive ~ arcminute resolution observations

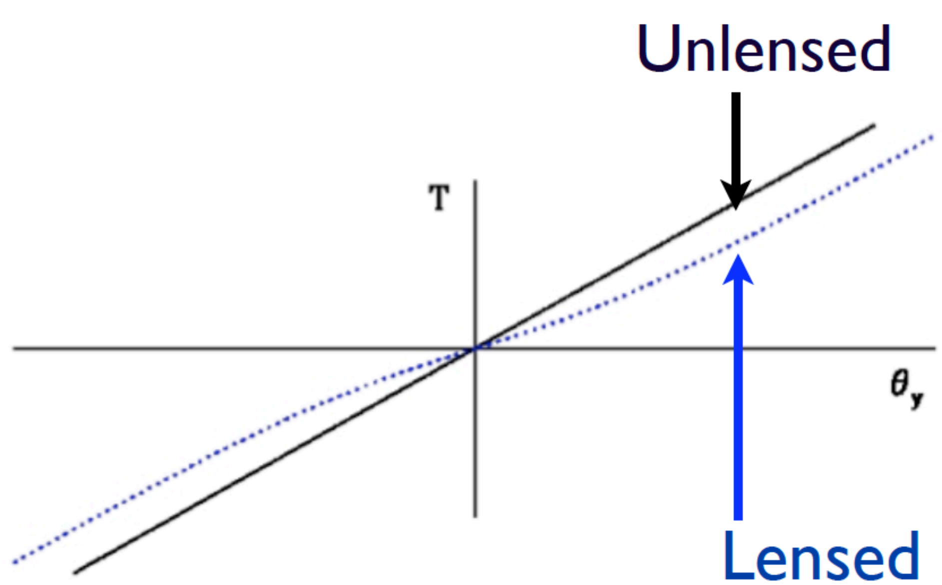
The gradient approximation

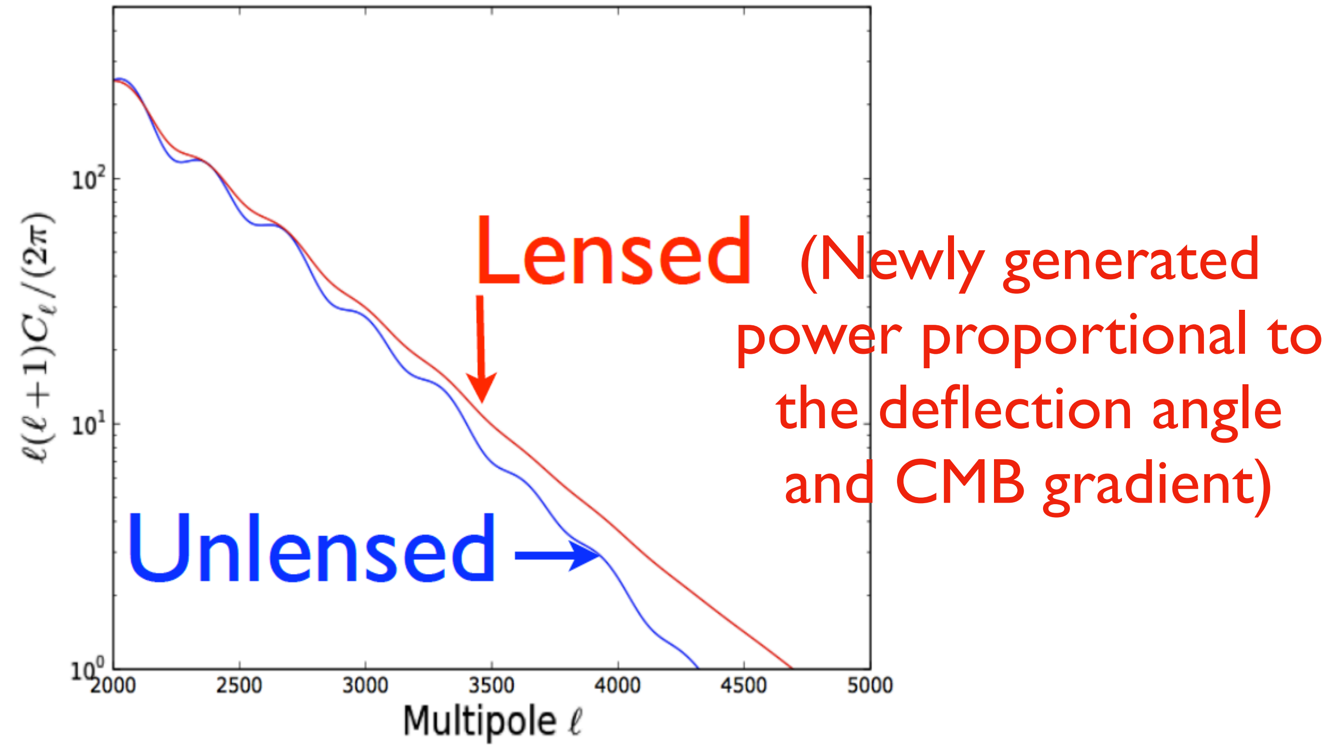
The lensed CMB field is a surface-brightness conserving remapping of the unlensed CMB field by the deflection angle

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

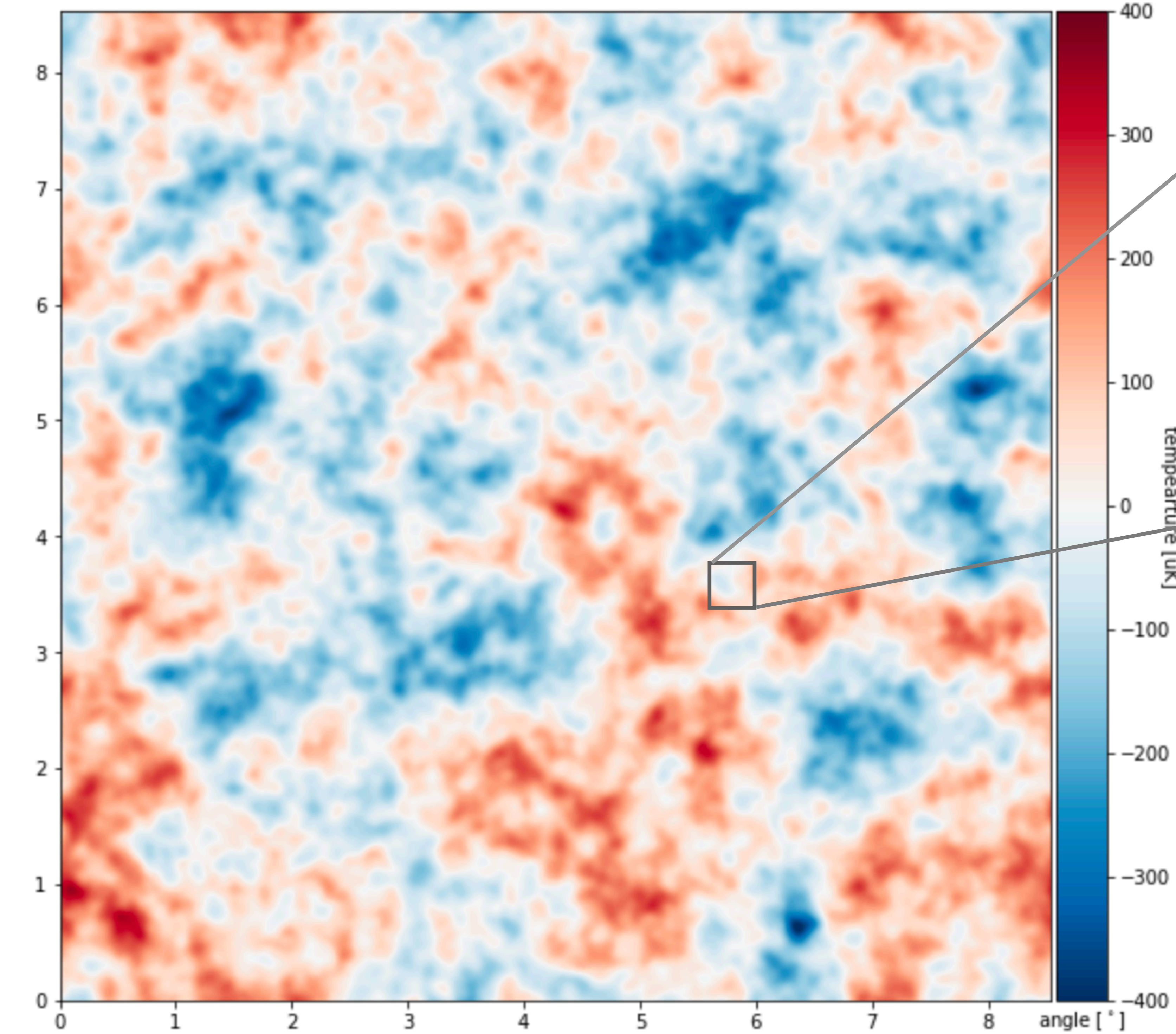
When considering the lensing by galaxy clusters, scales of only few arcminutes are of interest, corresponding to the projected angular sized of galaxy clusters. On these scales the CMB is extremely smooth due to Silk damping and is well described by a gradient field (perturbations in 1st order). Hence,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

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



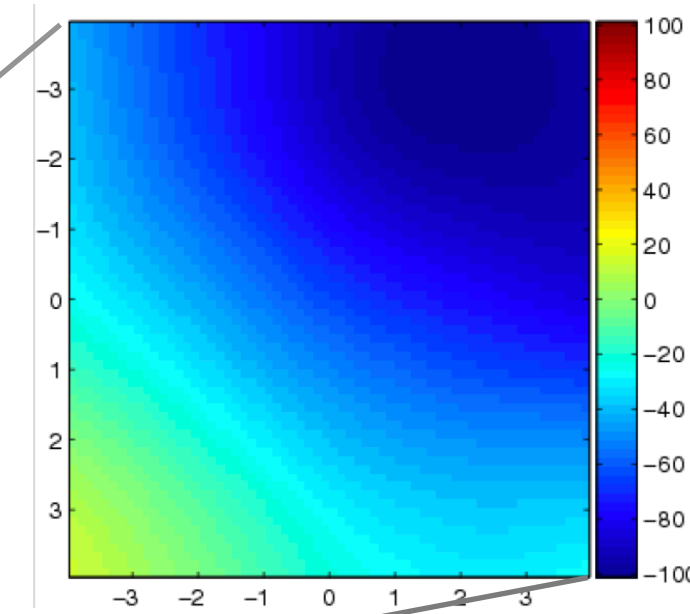


The gradient approximation



8.5° x 8.5° CMB map

8′ x 8′ cutout



rms gradient ~ 13 μK/arcmin

Another useful aspect of the CMB lensing is that we know the exact distance of the source, hence no approximations needed regarding the source plane.

CMB lensing by galaxy clusters

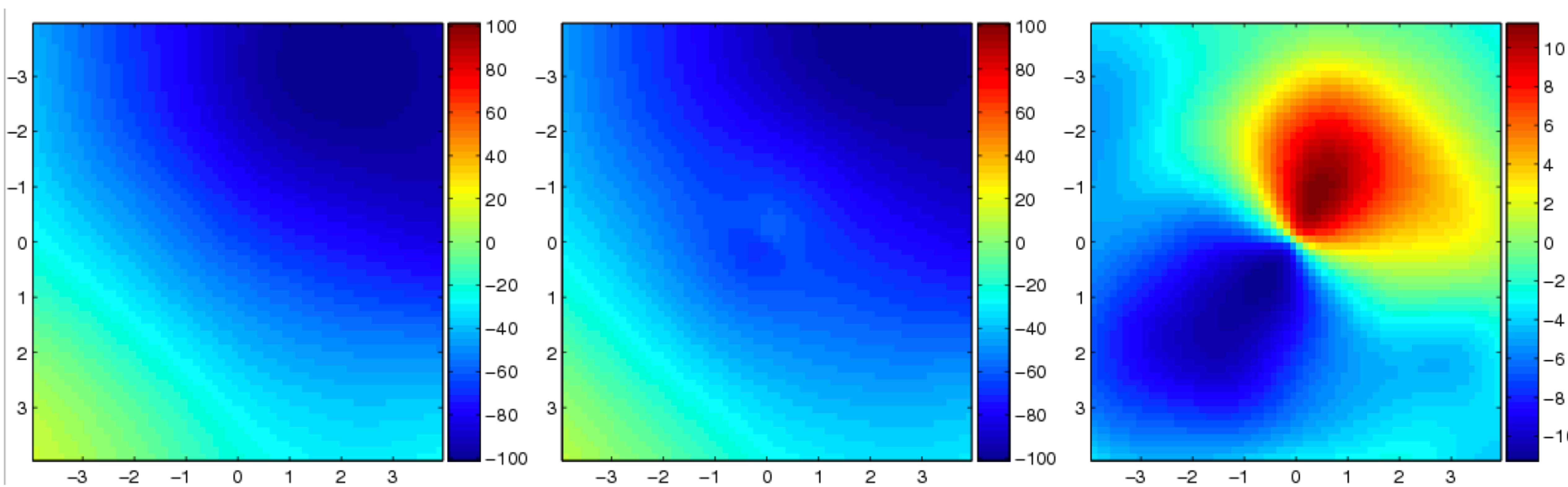
Slide from Anthony Lewis

RMS gradient ~ 13 μK / arcmin
deflection from cluster ~ 1 arcmin

Lensing signal ~ 10 μK

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

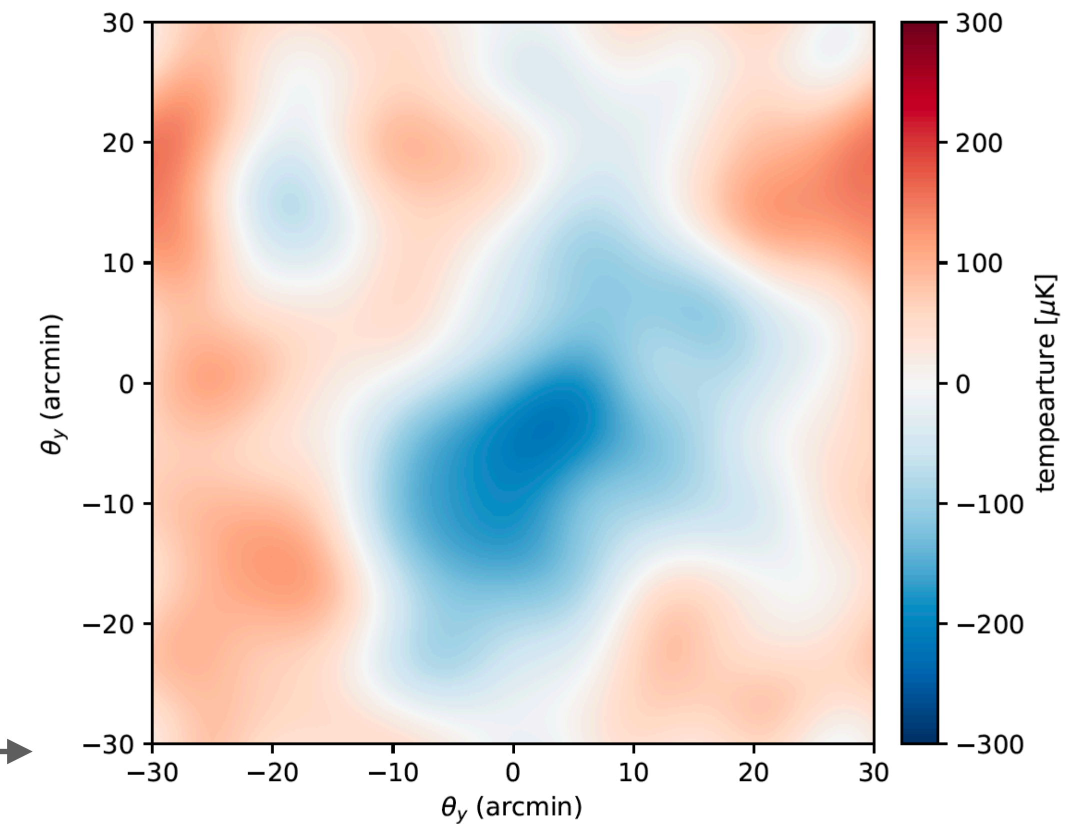
Start with the NFW profile for cluster mass,

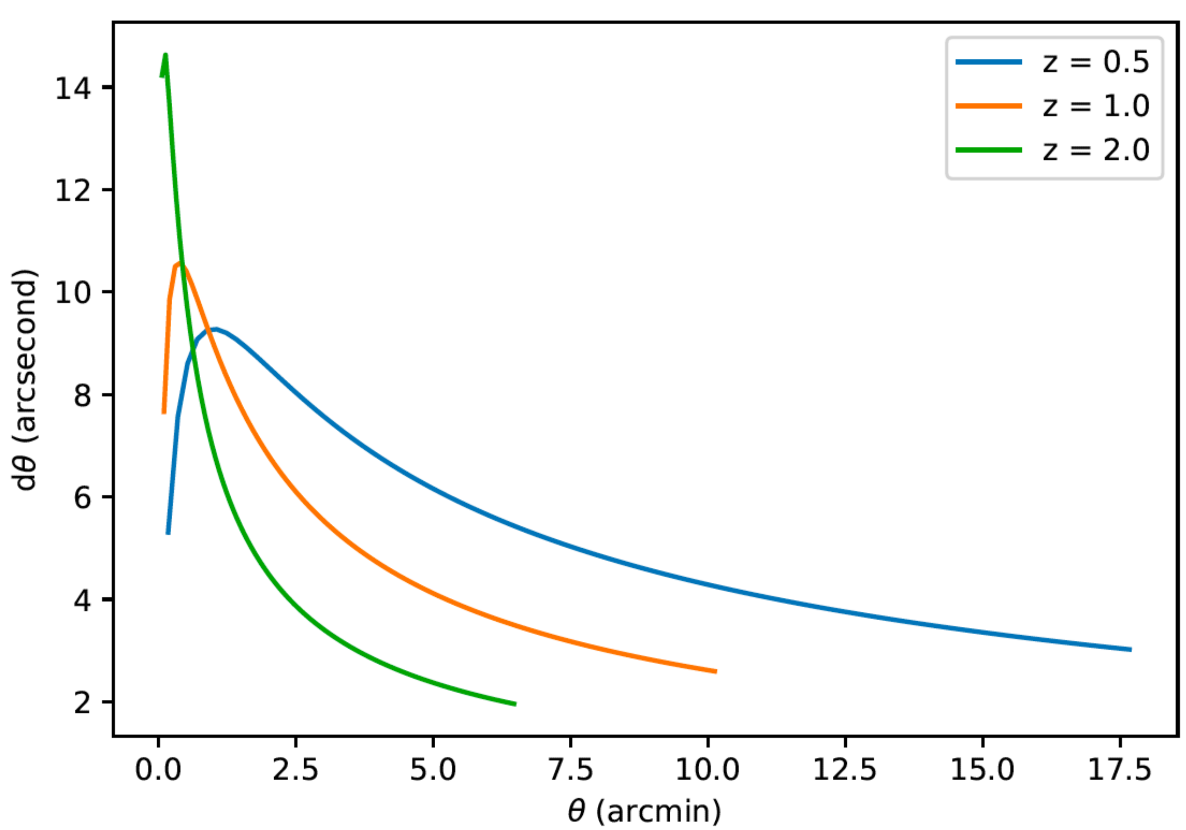
$$M = 4\pi\rho_0 R_s^3 \left[\ln\left(\frac{R_s + r}{R_s}\right) - \frac{r}{R_s + r} \right]$$

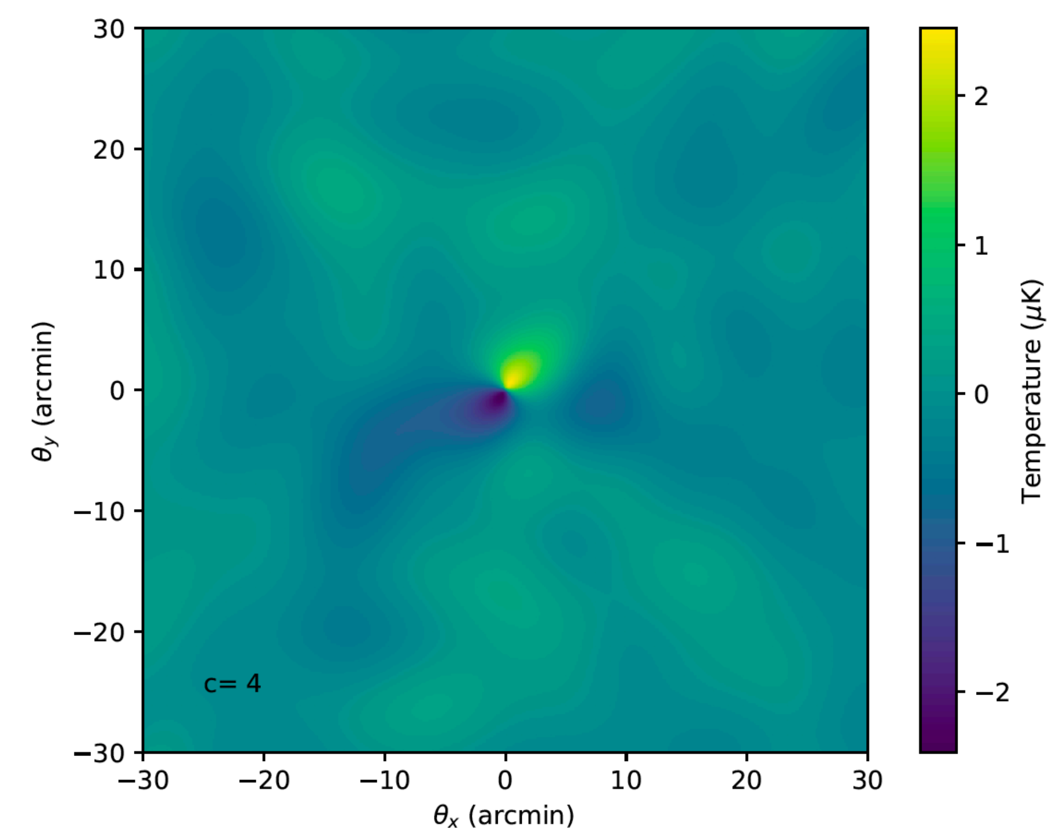
compute the deflection profile

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

and apply on CMB maps



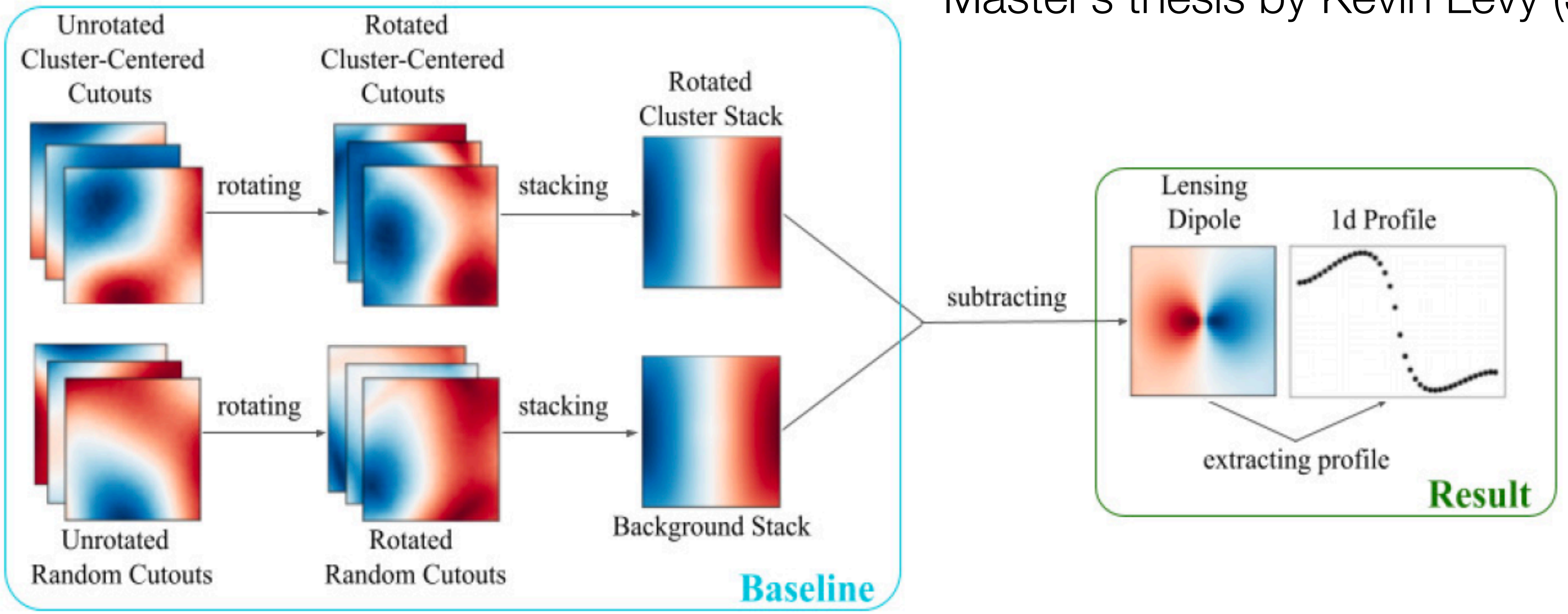


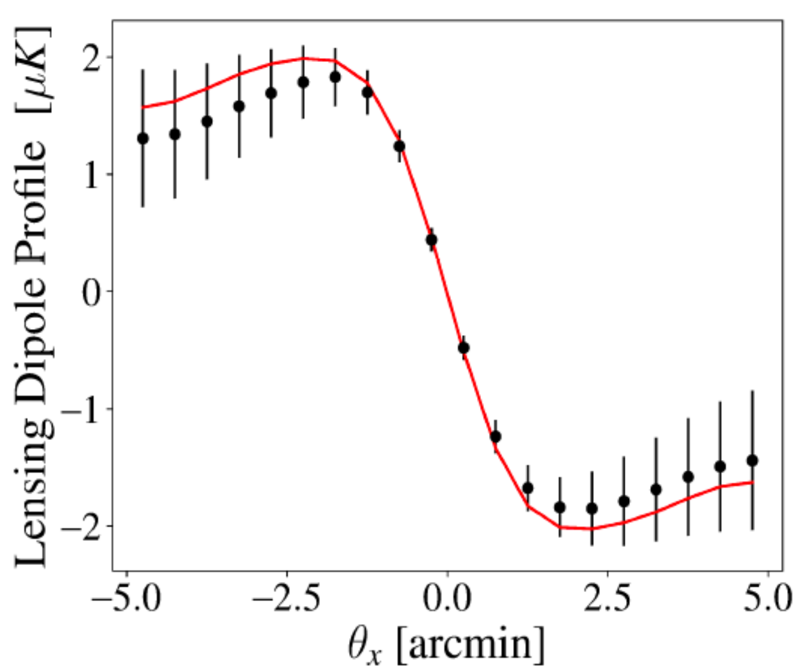


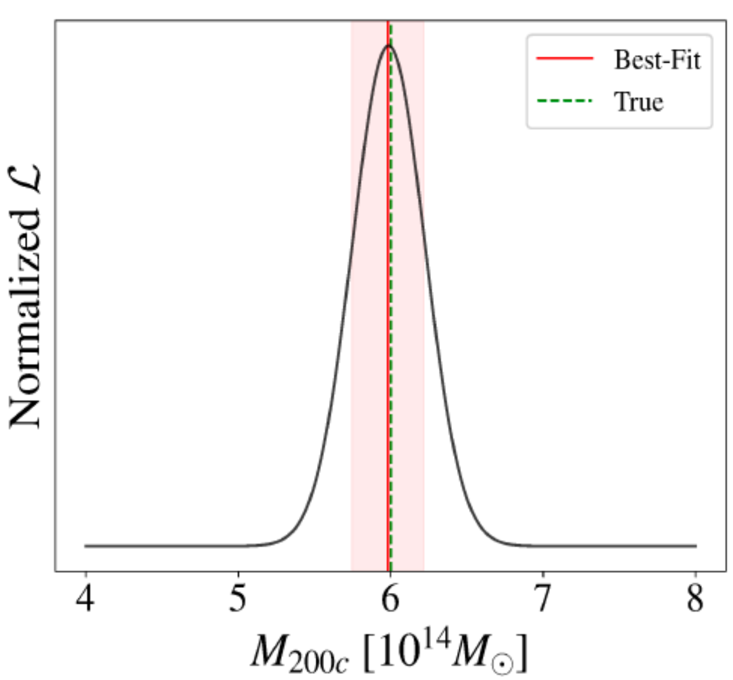
Internship by Awais Mirza

Cluster–CMB lensing modelling

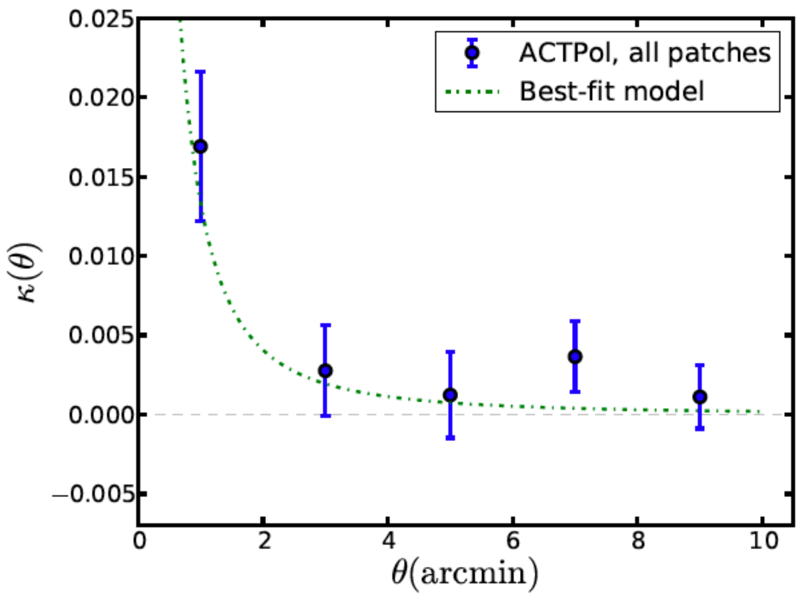
Master's thesis by Kevin Levy (Sep 2021)

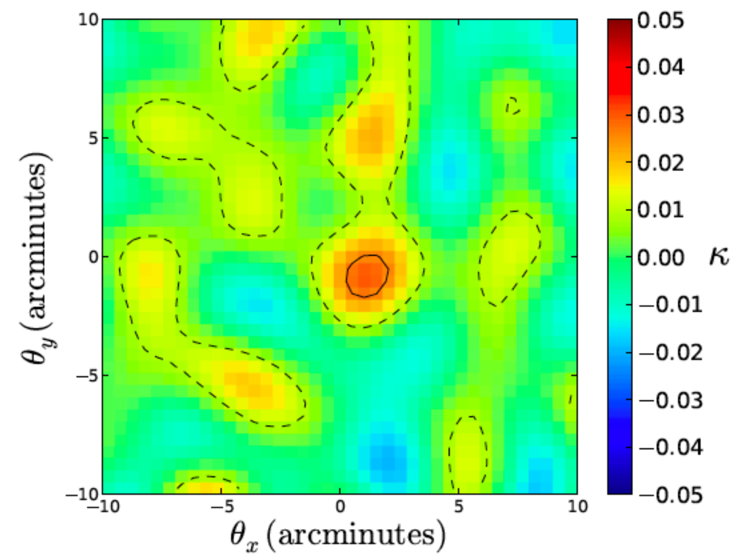






Cluster-CMB lensing measurements



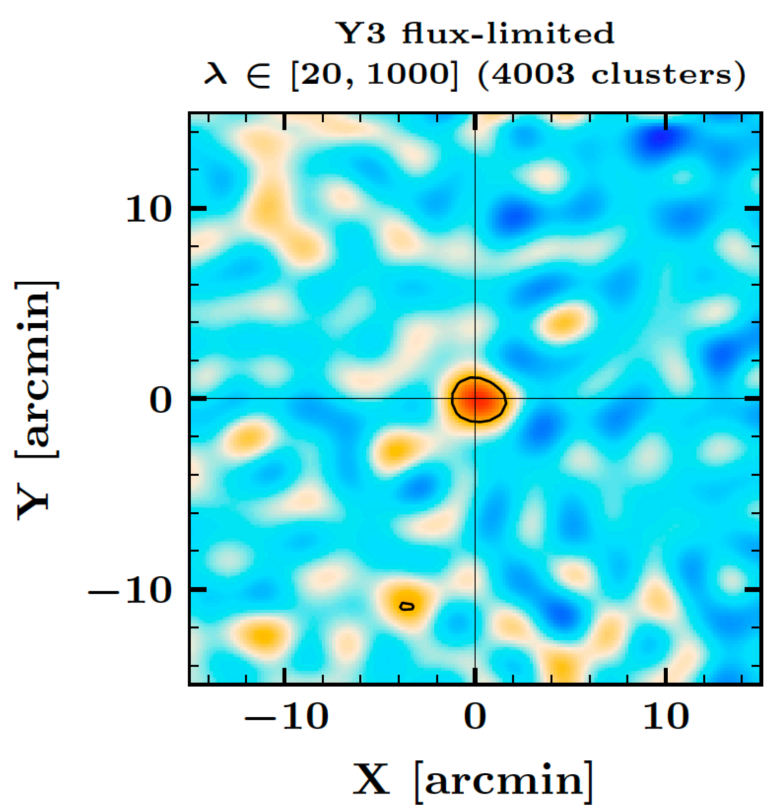


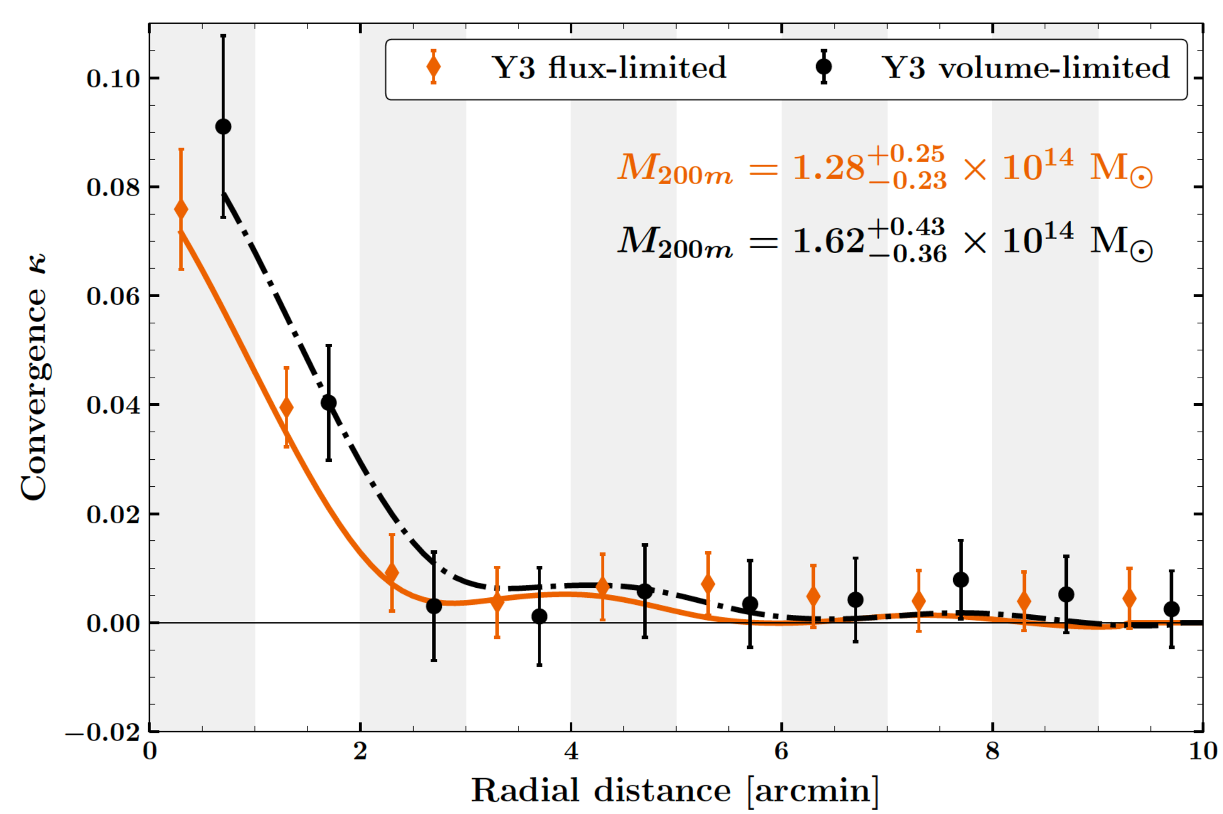
ACTpol data,
Madhavacheril et al. (2015)

~16000 CMASS galaxies

SPTpol TT data, Raghunathan et al. (2018)

~4000 DES clusters in the SPT field

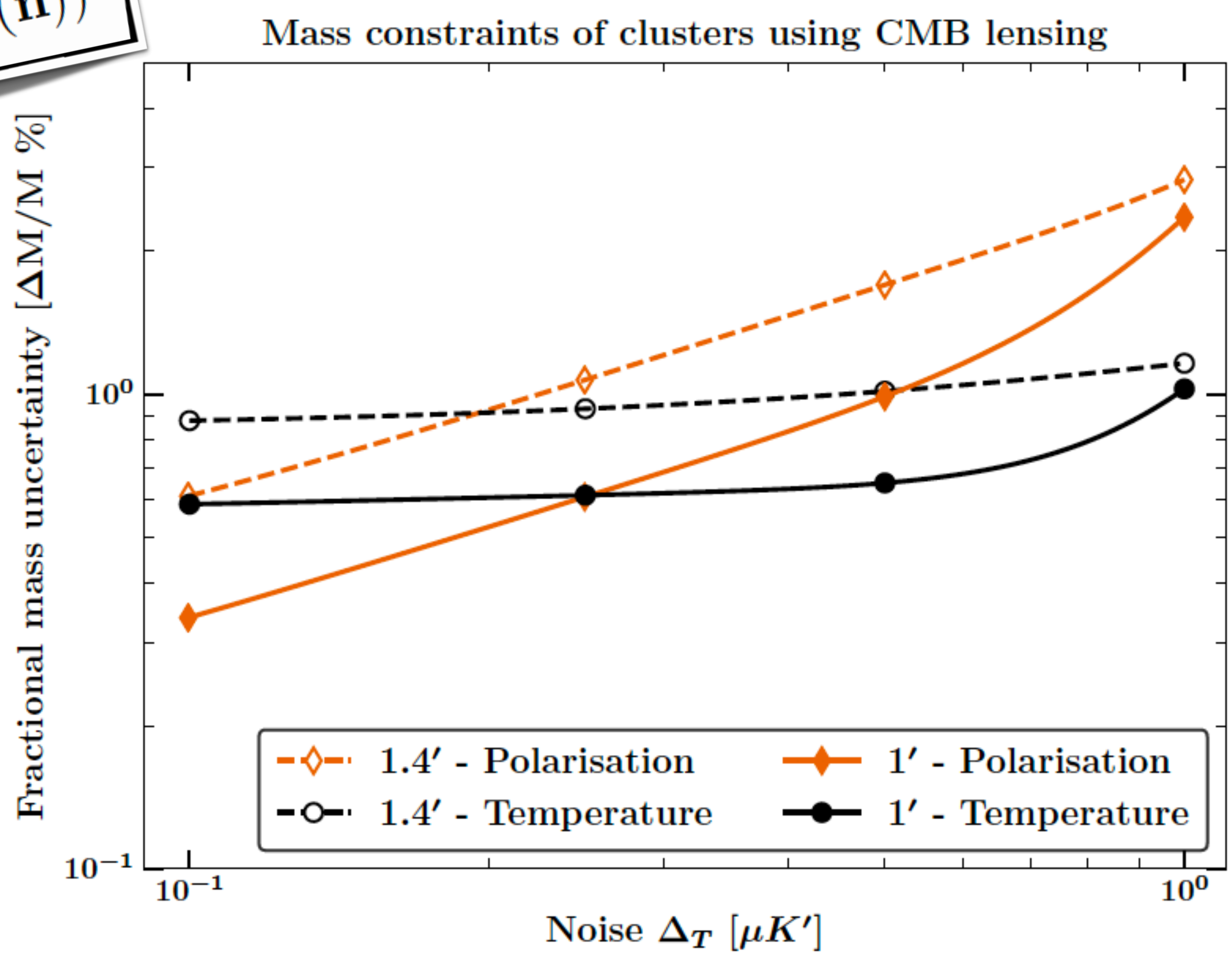




Works also on polarization

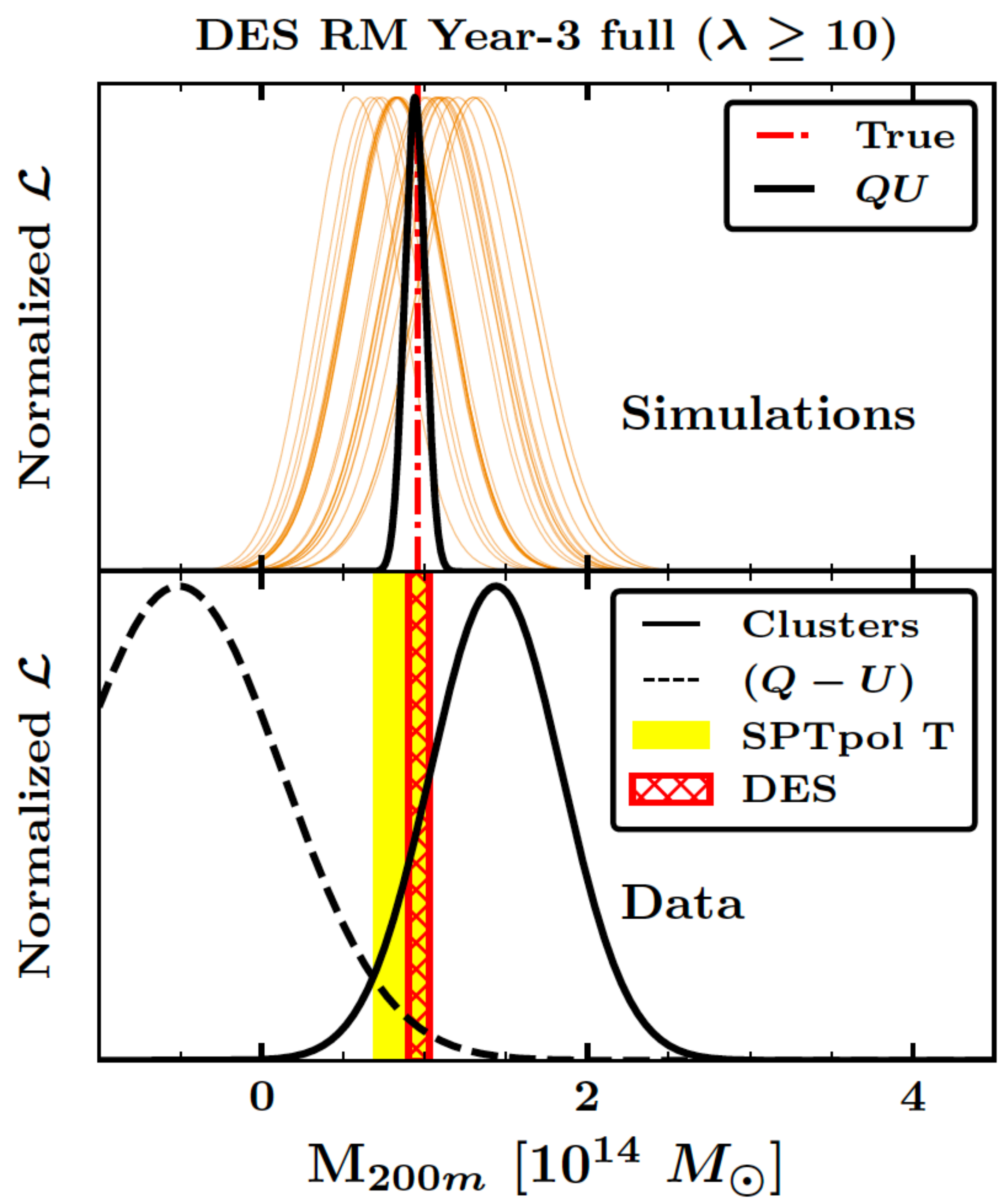
$$T(\hat{\mathbf{n}}) = \widetilde{T}(\hat{\mathbf{n}} + \vec{\alpha}(\hat{\mathbf{n}}))$$
$$Q(\hat{\mathbf{n}}) = \widetilde{Q}(\hat{\mathbf{n}} + \vec{\alpha}(\hat{\mathbf{n}}))$$
$$U(\hat{\mathbf{n}}) = \widetilde{U}(\hat{\mathbf{n}} + \vec{\alpha}(\hat{\mathbf{n}}))$$

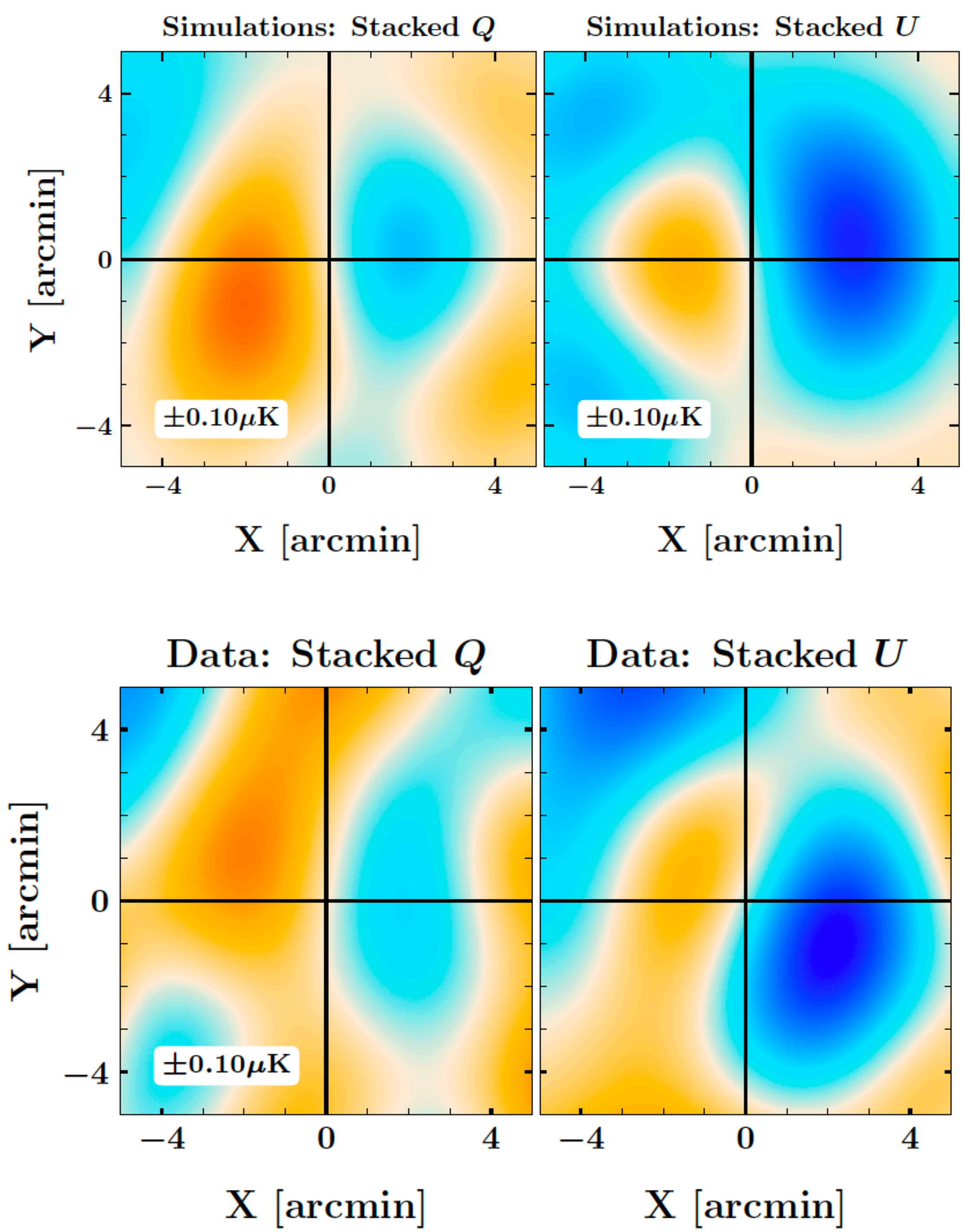
Even though the polarization signal is small, several foreground signals are absent from the polarized signal, so lensing reconstruction is cleaner. Fig. from our Voyage 2050 paper.



Polarization cluster-lensing measurement

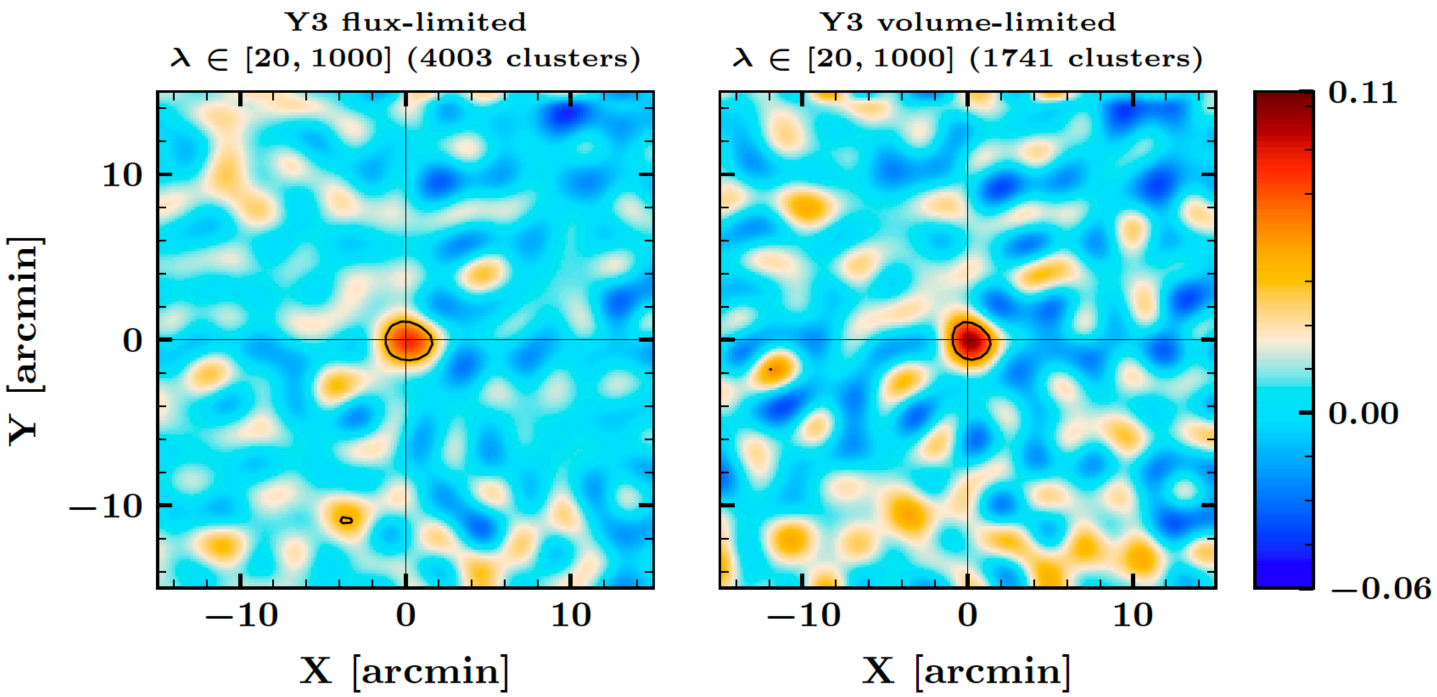
First measurement by Raghunathan et al. (2019) using SPTpol data





Cluster-CMB lensing forecasts

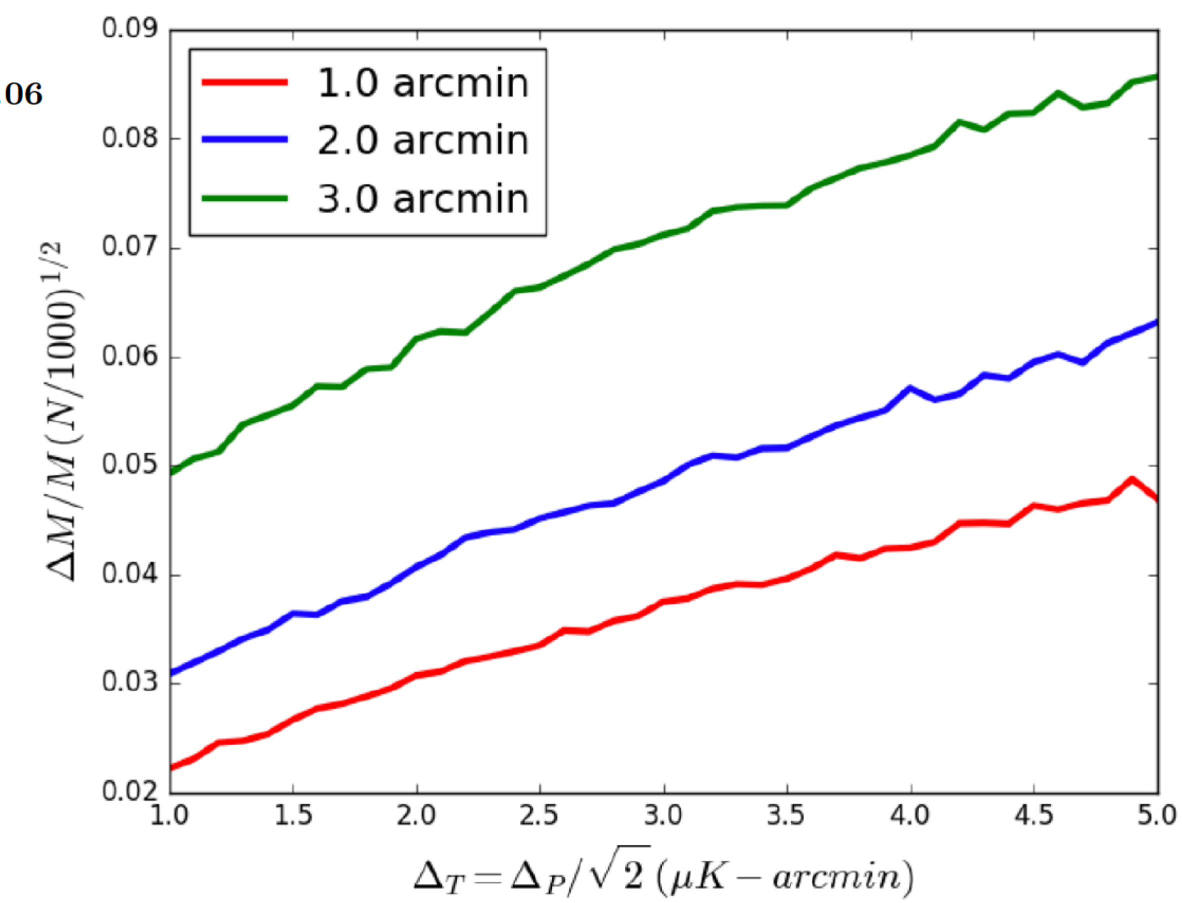
CMB lensing probes mass distribution at high redshifts: 0.5 < z < 6
Ideal for figuring out high-z cluster masses — probe for dark energy!



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

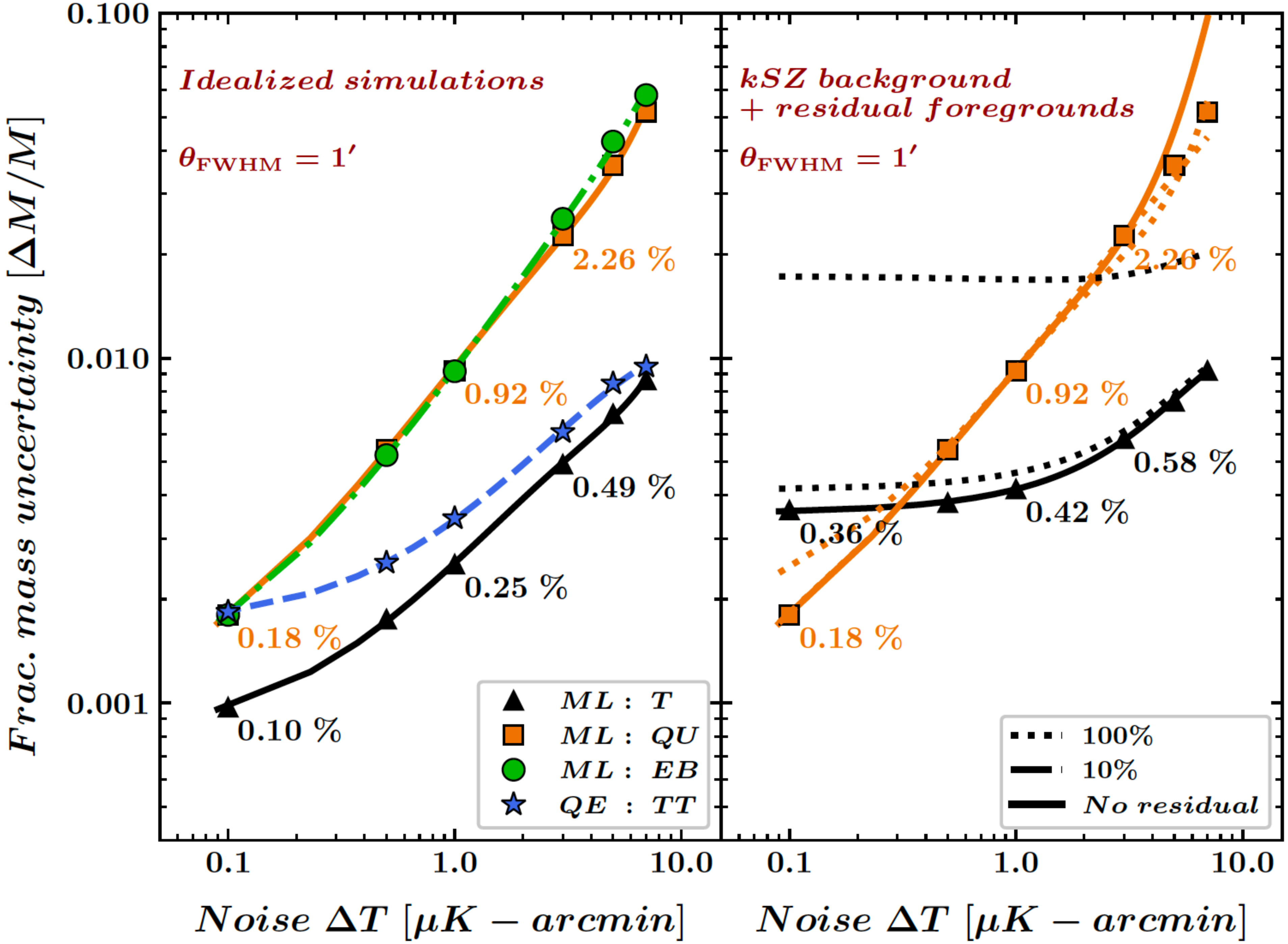
High-sensitivity, high resolution CMB can calibrate mass of 1000 stacked clusters to a few percent.

S4 Science Book



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.

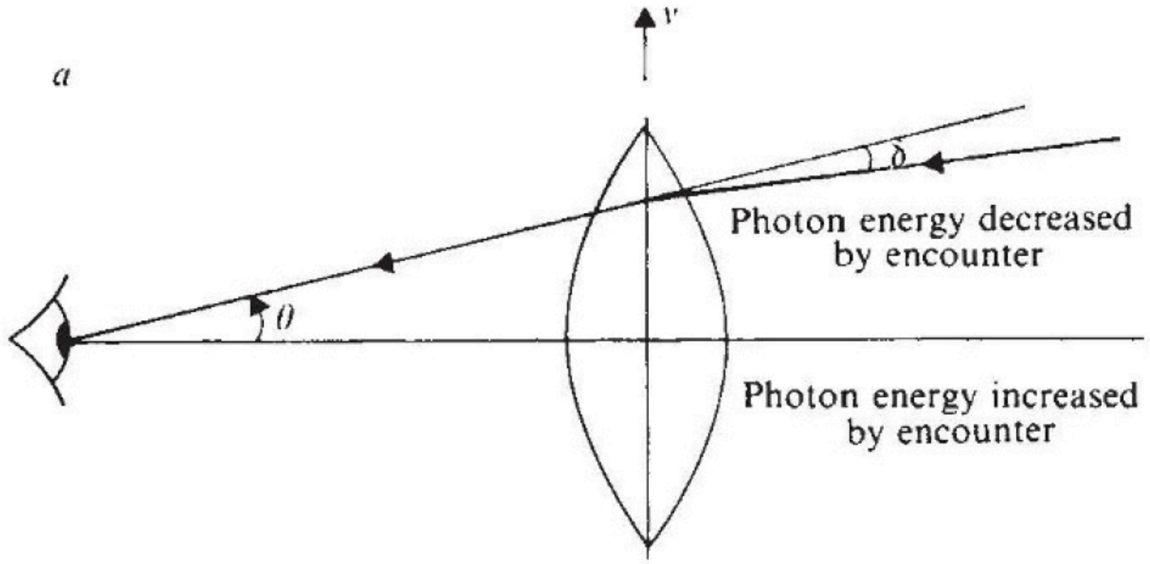
Cluster-CMB lensing forecasts



From Raghunathan et al. (2017), forecast for stacking of 100,000 clusters

Another lensing effect: Moving

Birkinshaw & Gull (1983)

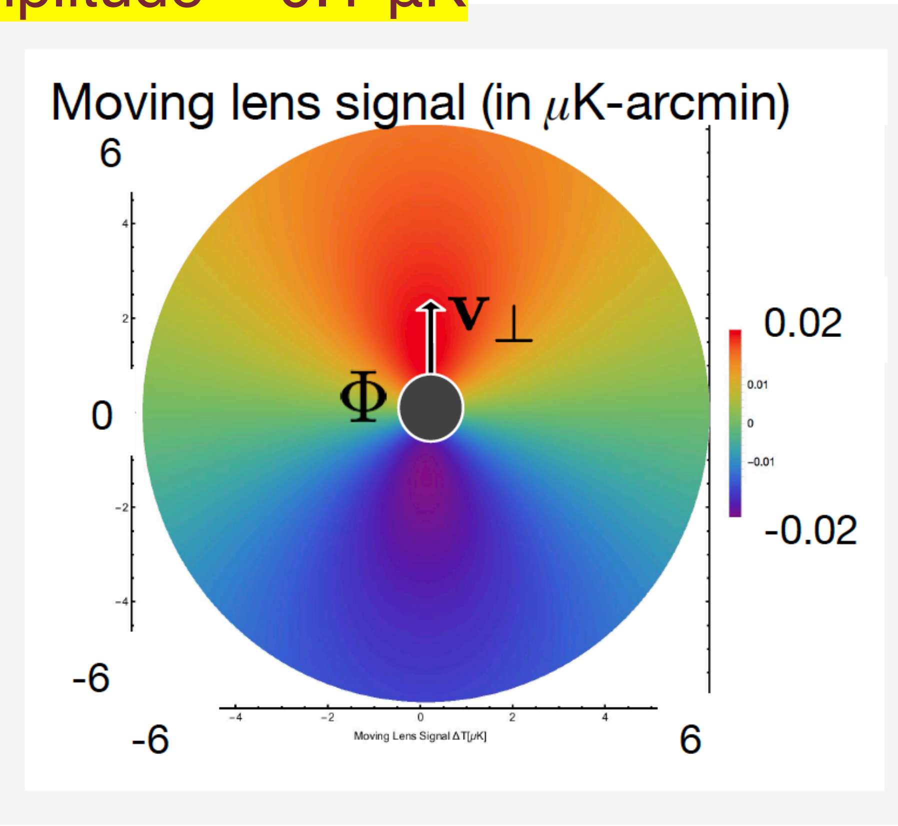


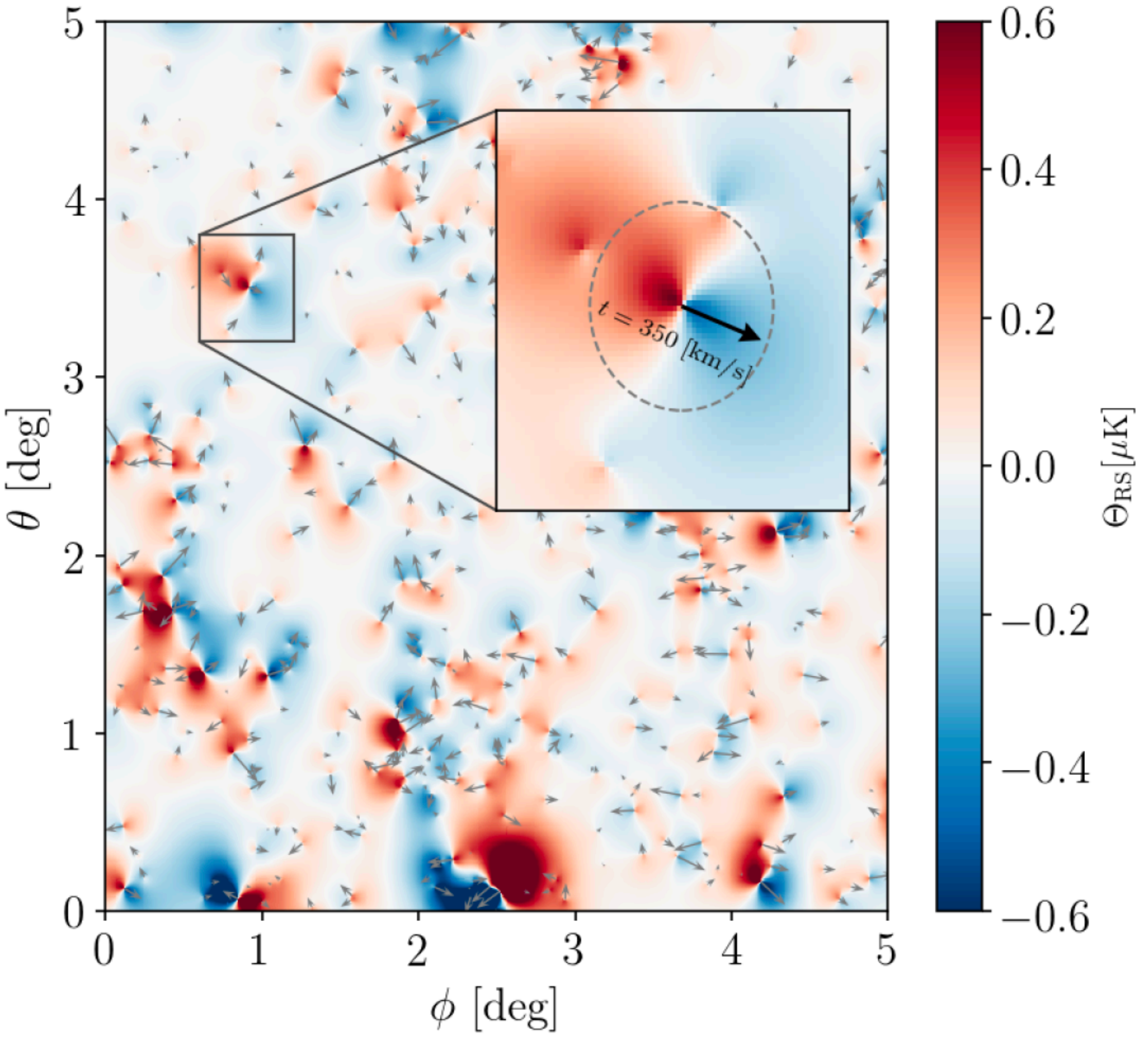
$$\frac{\Delta T(\hat{\mathbf{n}})}{T_{\rm CMB}} = \mathbf{v}_\perp \cdot \nabla\psi$$

Yasini et al. (2019)

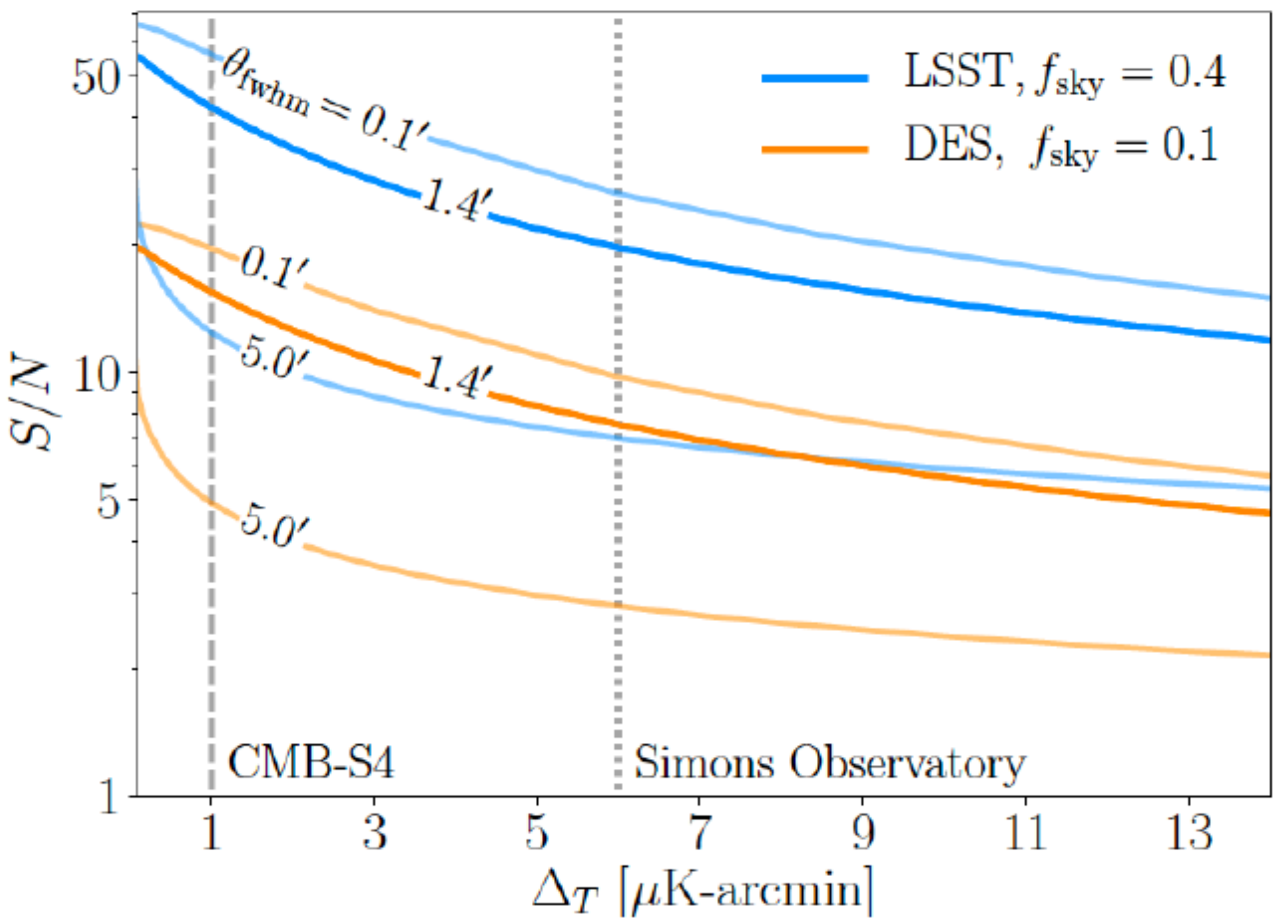
Hotinli et al. (2019)

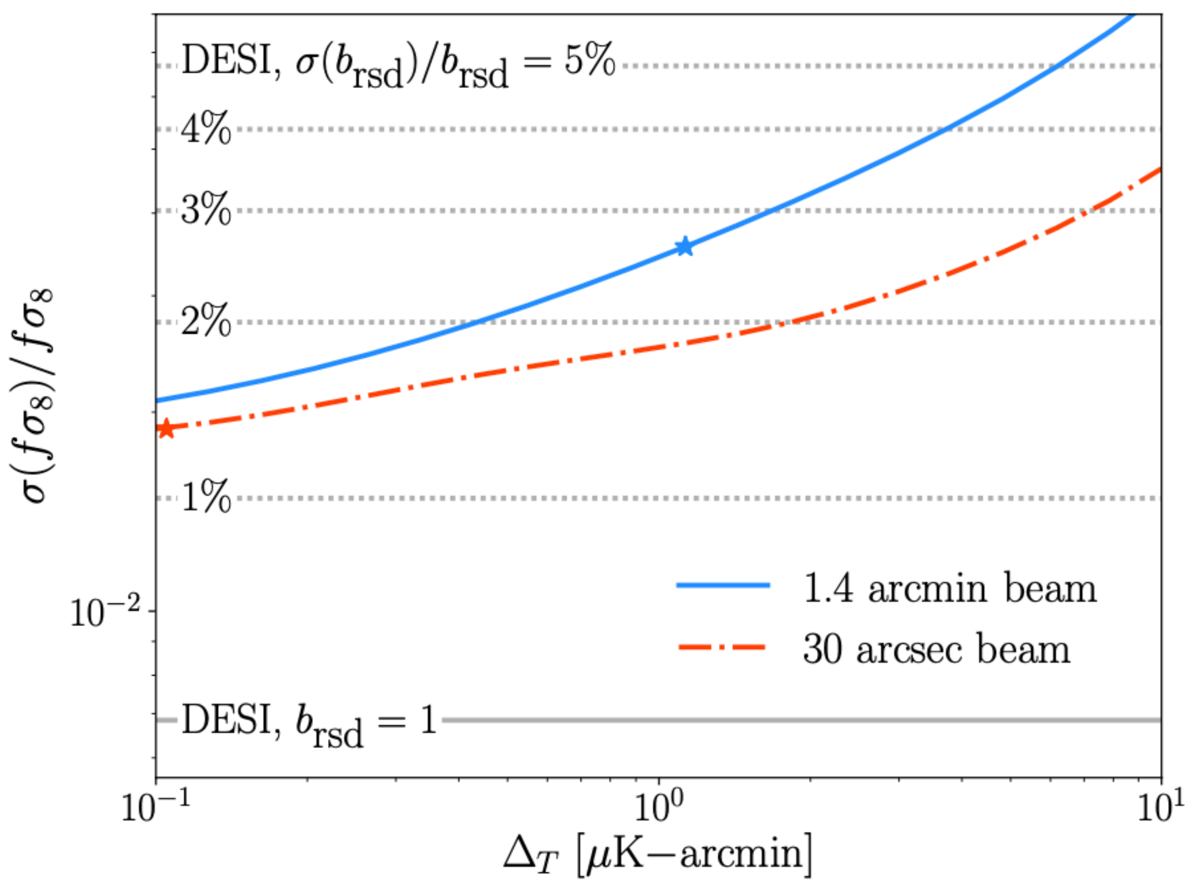
Signal amplitude ~ 0.1 μK





Forecasts for the moving-lens effect





Predicted signal-to-noise for a transverse velocity estimator, obtained via the moving-lens effect, for a range of angular resolution and sensitivity of the upcoming CMB experiments. Figure from Hotinli et al. (2019).

Relative measurement uncertainty on the product $f\sigma_8$ (where f is the linear growth rate) from moving-lens effect measurements, with the same range of CMB experiment noise as in left figure. Figure from Hotinli et al. (2021).

Questions?

Feel free to email me or ask questions in our eCampus Forum