CMB Lensing: A New Tool For Cosmology and Astrophysics

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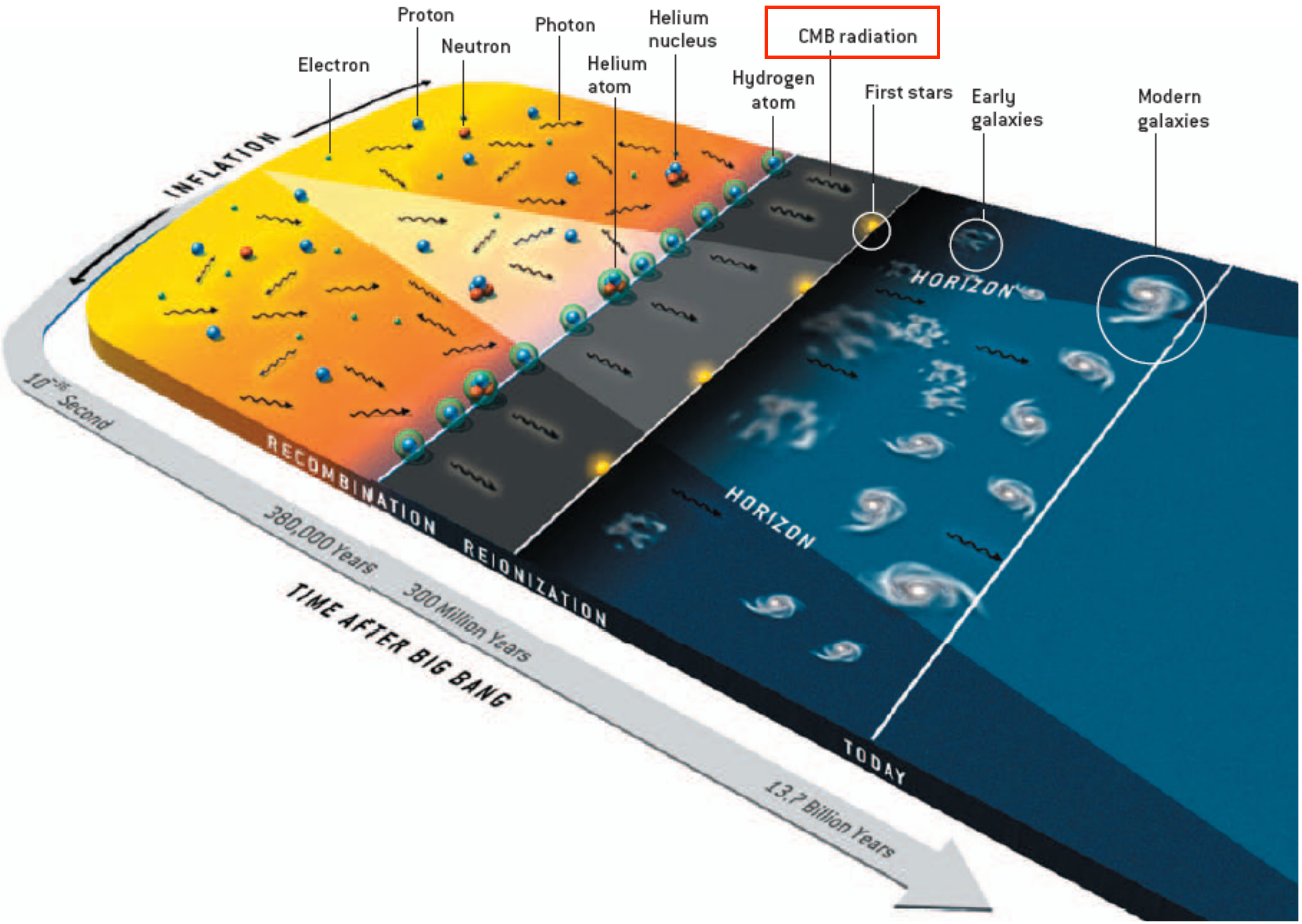
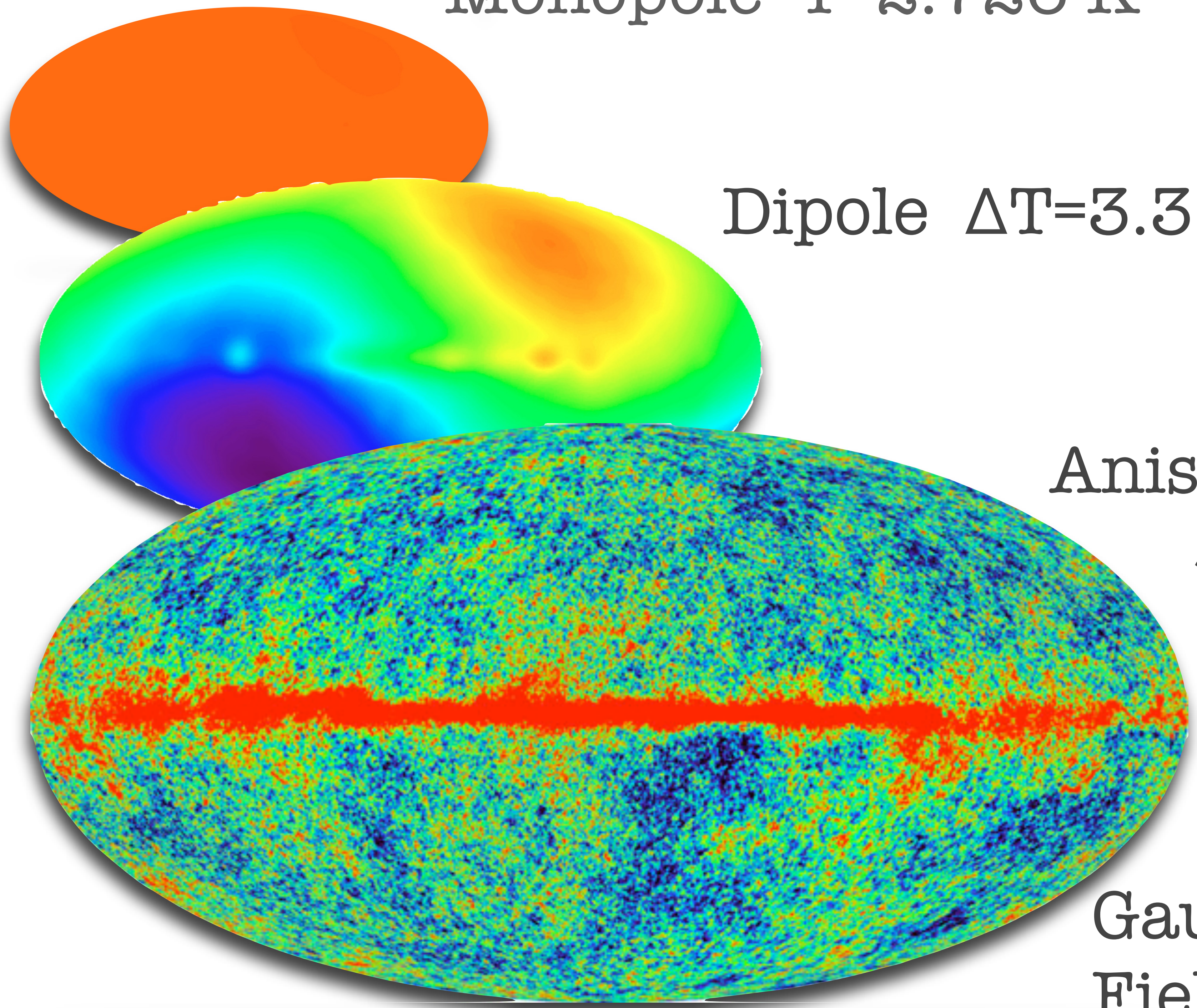
A Timeline of the Universe



The Cosmic Microwave Background

Monopole T=2.726 K



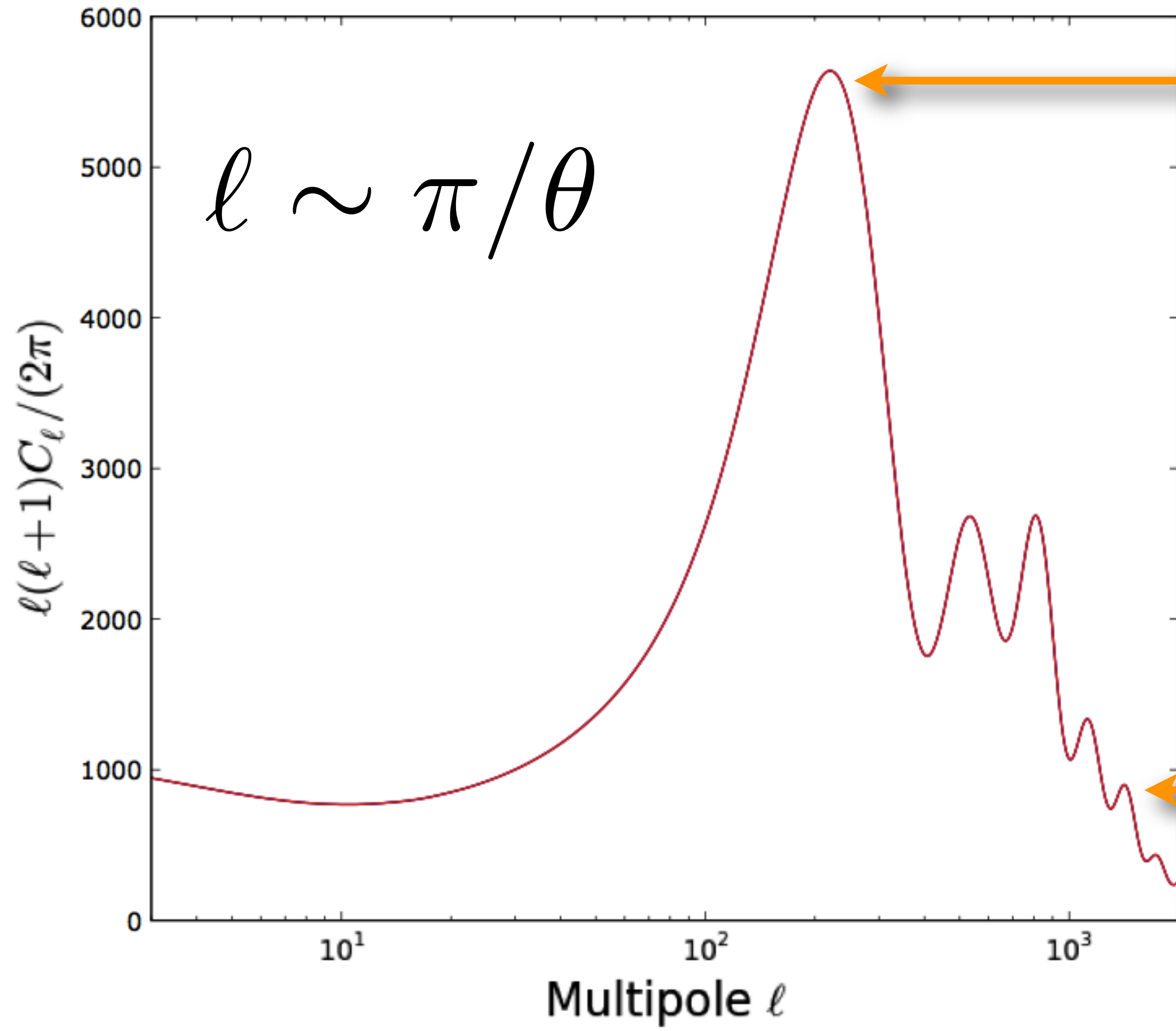
Dipole ΔT=3.353 mK

Anisotropies

~100 μK rms

Gaussian Random Field

The primordial CMB power spectrum

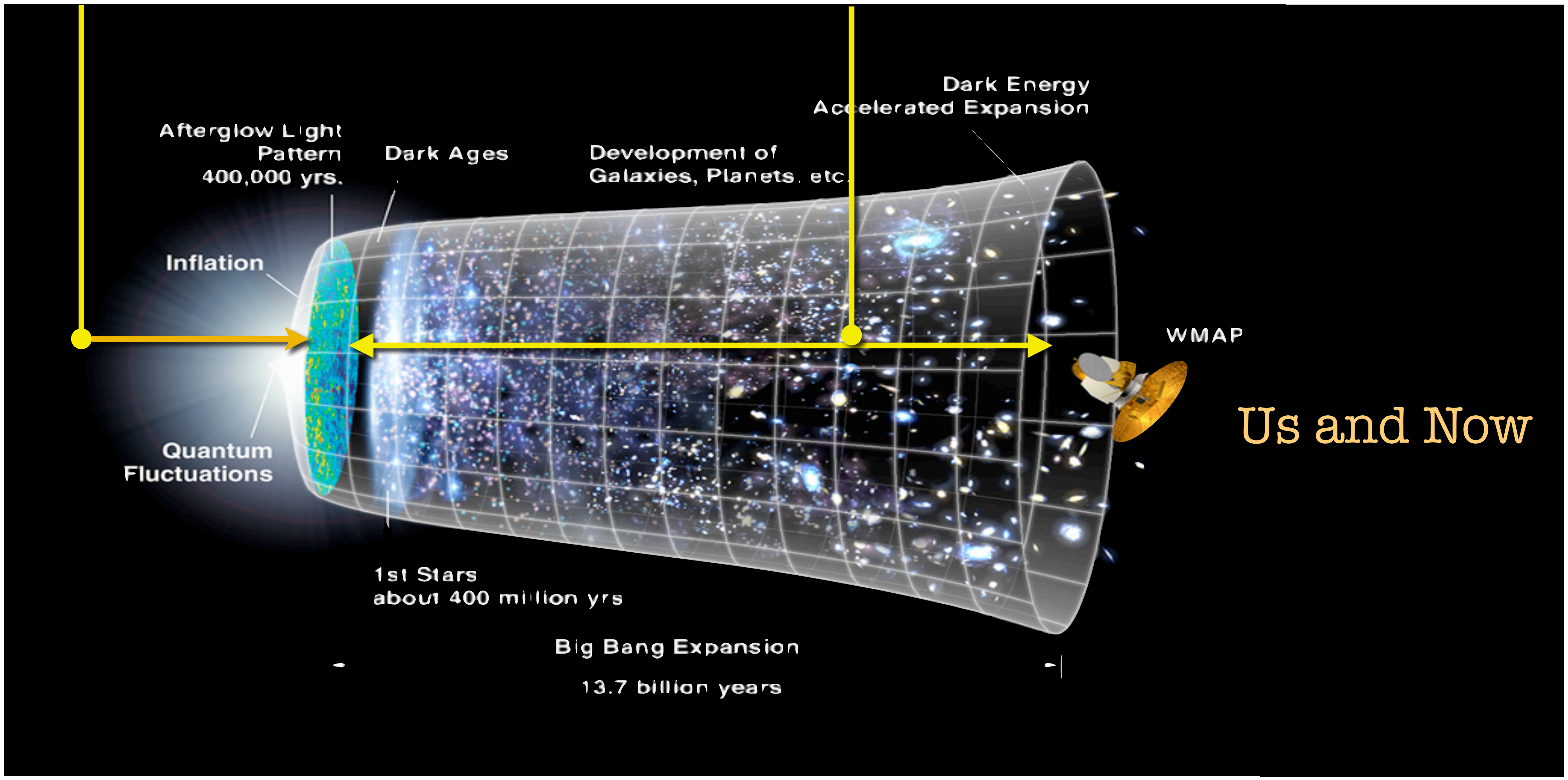


The peak position has been measured very precisely; the angular diameter distance to the CMB is a well measured quantity.

Lensing of the CMB - the basic picture

The last scattering surface ~ 1000 Mpc thick

Intervening LSS spread over 14,000 Mpc



For lensing purposes, the CMB is a thin source sheet.

CMB as a lensing source

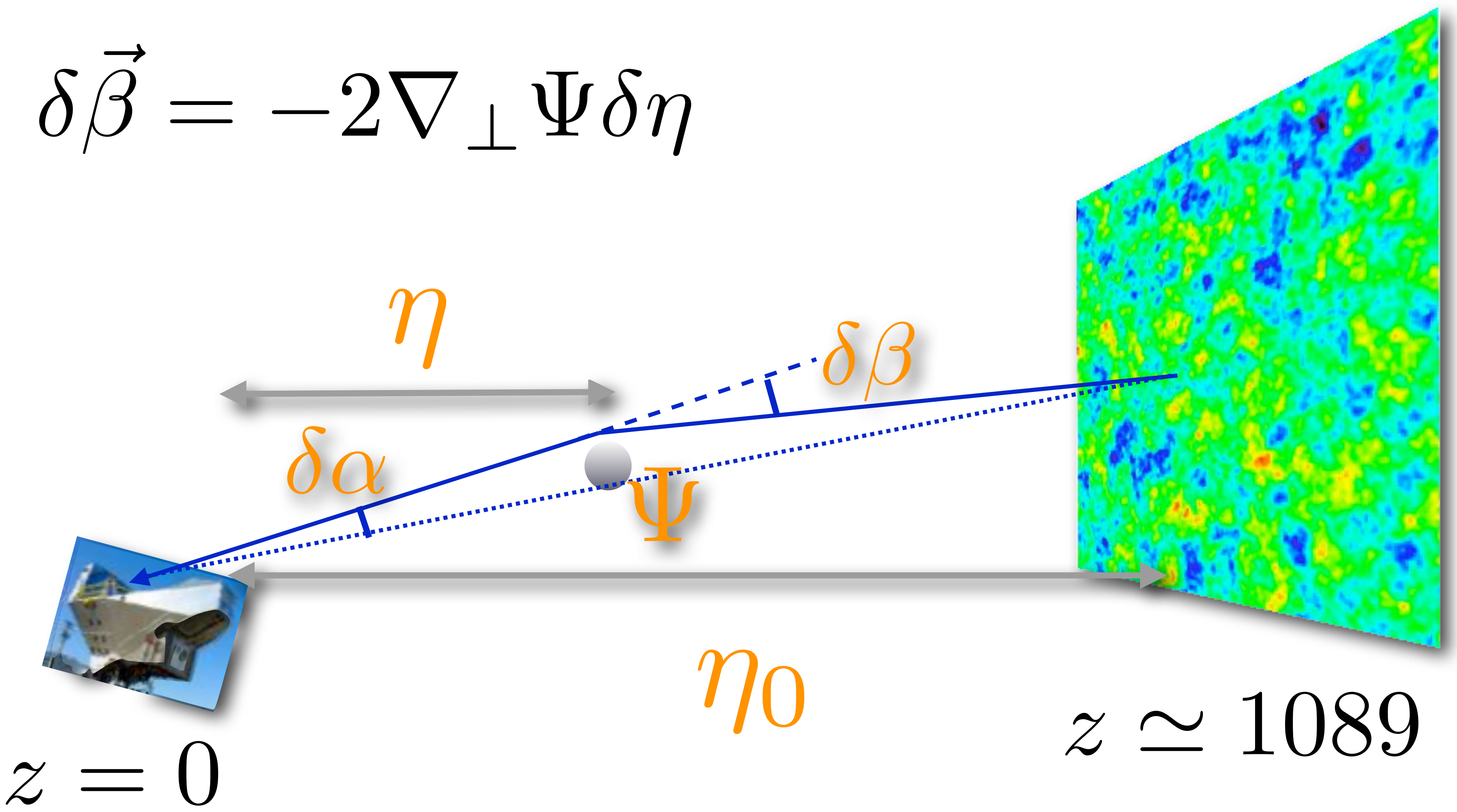
The CMB is a rather unique source for lensing:

- Well approximated as a **single source sheet** ...
- the **distance** to which **precisely calculable** ...
- and the **statistics** on which is well understood.
- It is also the **highest redshift** source !

Deflection of a CMB photon

First, we consider a single potential well:

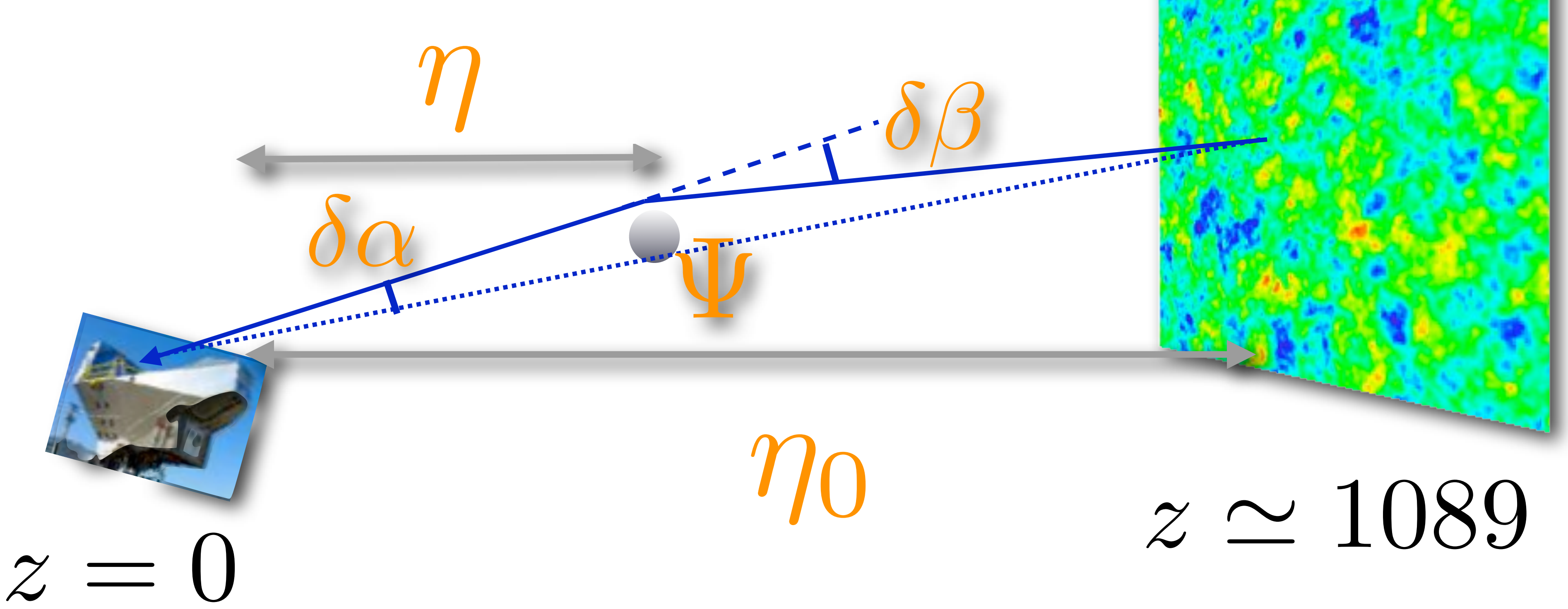
$$\delta\vec{\beta} = -2\nabla_\perp \Psi \delta\eta$$



Deflection of a CMB photon

First, we consider a single potential well:

$$\delta\vec{\alpha} = \frac{d_A(\eta_0 - \eta)}{d_A(\eta_0)}\delta\vec{\beta}$$



The total deflection

For a single potential well:

$$\delta\vec{\alpha} = -2\frac{d_A(\eta_0 - \eta)}{d_A(\eta_0)}\nabla_\perp \Psi \delta\eta$$

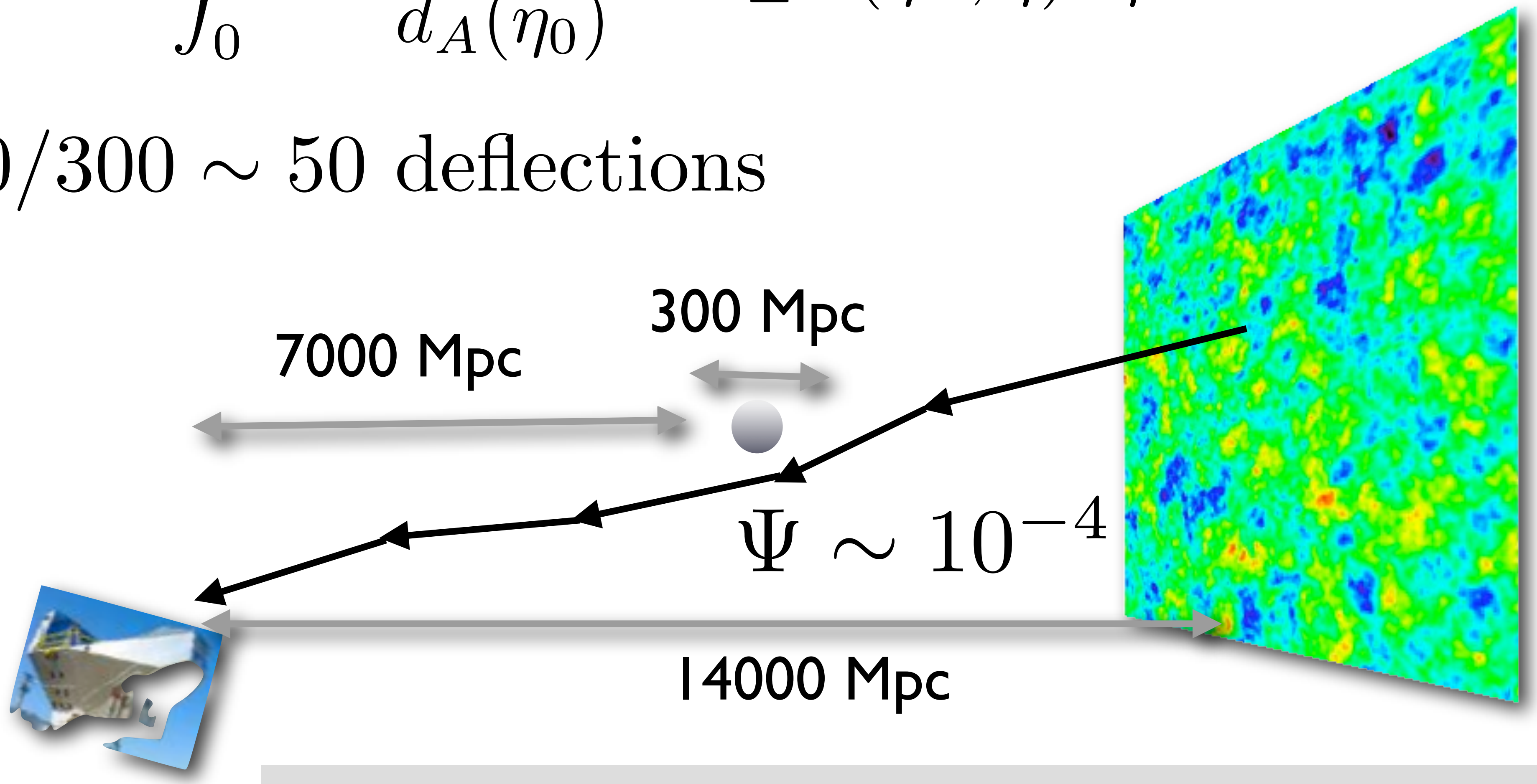
Adding up deflections along the line-of-sight:

$$\begin{aligned}\vec{\alpha}(\hat{n}) &= -2\int_0^{\eta_0} \frac{d_A(\eta_0 - \eta)}{d_A(\eta_0)}\nabla_\perp \Psi(\eta\hat{n}, \eta)d\eta \\ &= -2\int_0^{\eta_0} \frac{d_A(\eta_0 - \eta)}{d_A(\eta_0)d_A(\eta)}\nabla_{\hat{n}} \Psi(\eta\hat{n}, \eta)d\eta\end{aligned}$$

A back of the envelope calculation

$$\vec{\alpha}(\hat{n}) = -2\int_0^{\eta_0} \frac{d_A(\eta_0-\eta)}{d_A(\eta_0)} \nabla_\perp \Psi(\eta\hat{n},\eta)d\eta$$

$14000/300 \sim 50$ deflections



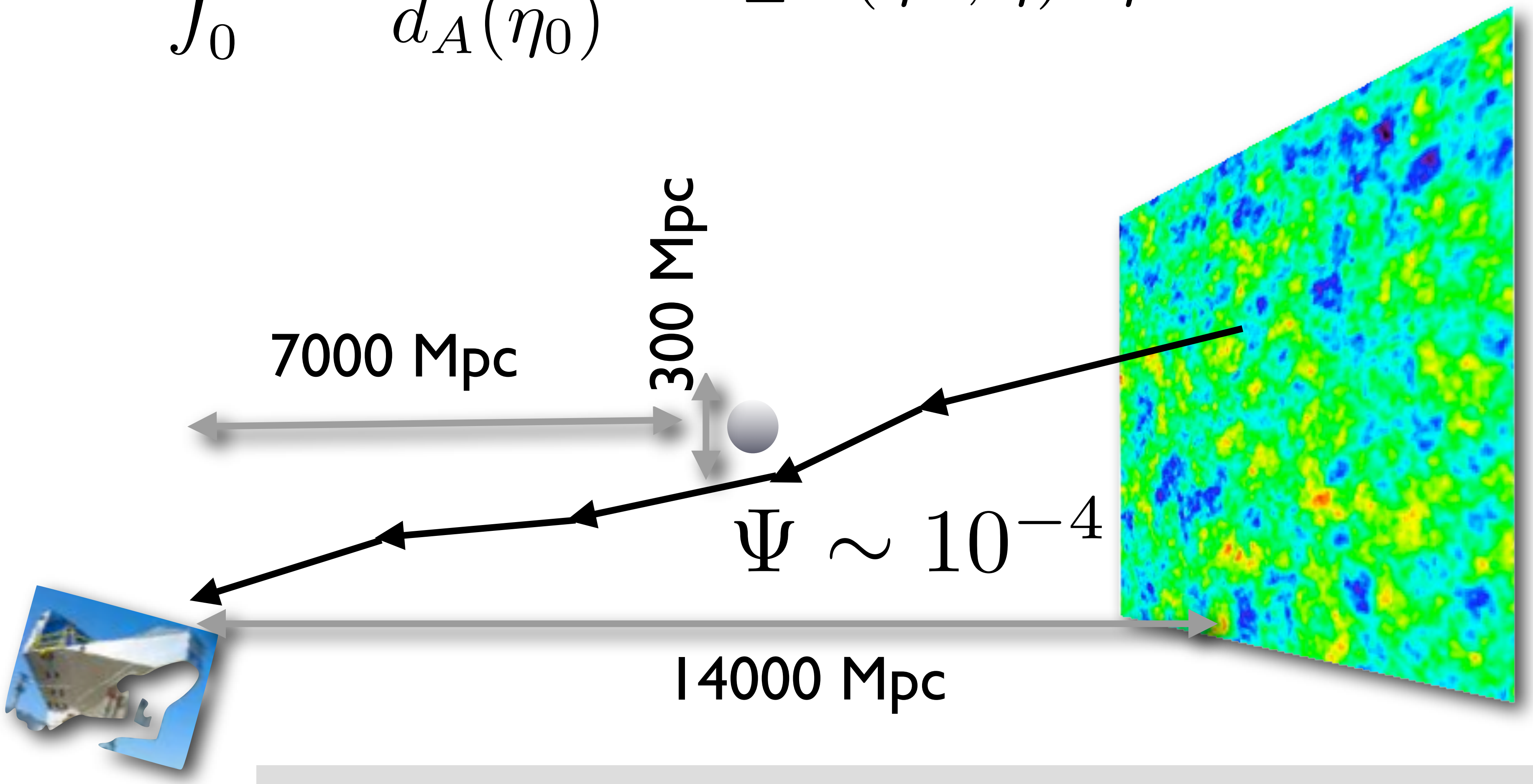
Assume Random Walk:

$$\alpha(\hat{n}) \simeq 2 \times \sqrt{50} \times \frac{1}{2} \times 10^{-4}$$

$$\simeq 7 \times 10^{-4} = 2.4 \text{ arcmin}$$

A back of the envelope calculation

$$\vec{\alpha}(\hat{n}) = -2\int_0^{\eta_0} \frac{d_A(\eta_0-\eta)}{d_A(\eta_0)} \nabla_\perp \Psi(\eta\hat{n},\eta)d\eta$$

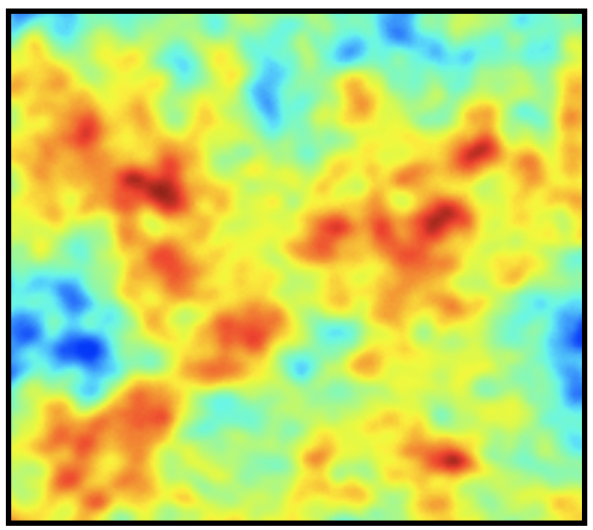


Deflection are coherent over $300/7000 \simeq 2$ degrees.

How do I lens the CMB?

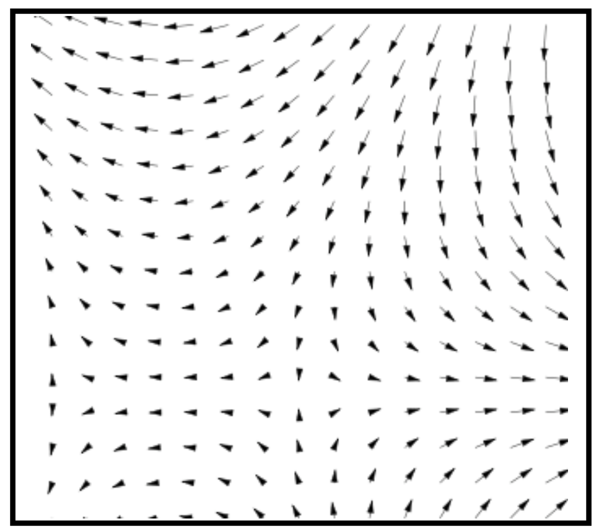
Given the deflection field, remap the points on the CMB.

Unlensed



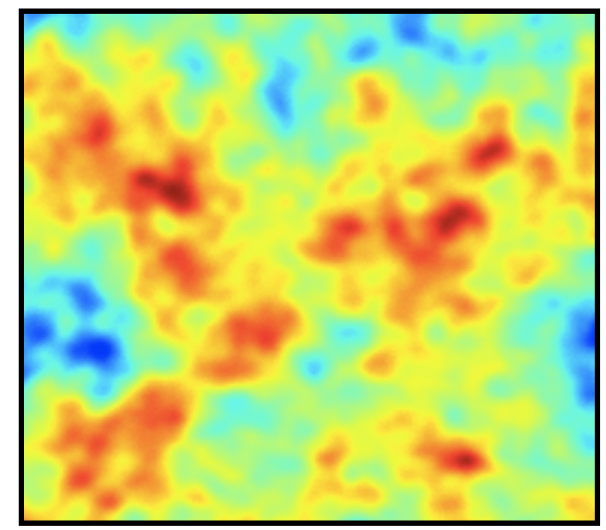
$\Theta(\hat{n})$

Deflection



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

Lensed



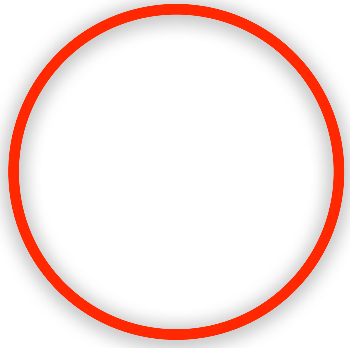
$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \vec{\alpha})$

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

Seeing is believing ....

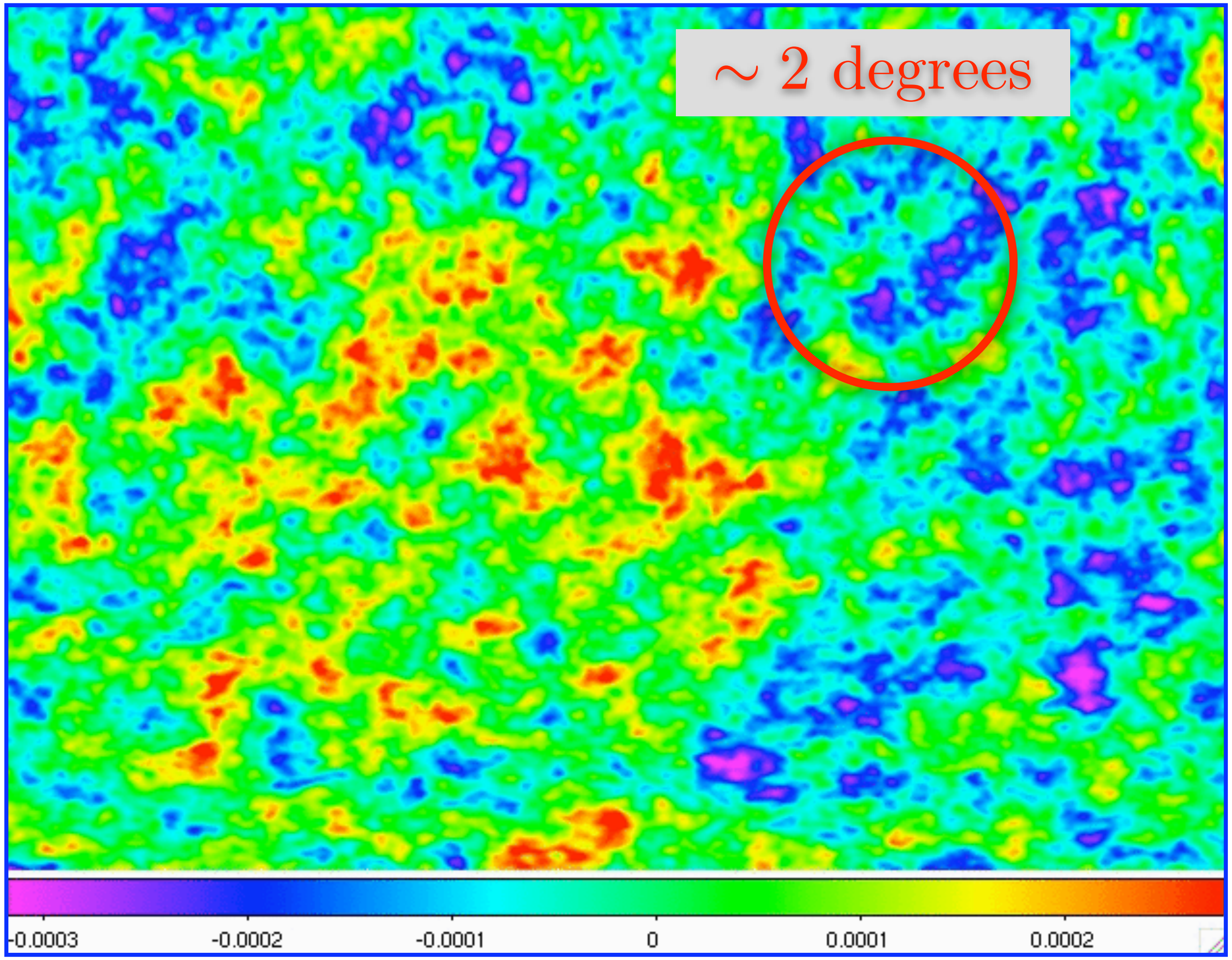
$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \vec{\alpha})$$

~ 2 degrees



Seeing is believing ....

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



Some lensing jargon ...

$$\vec{\alpha}(\hat{n}) = -2 \int_0^{\eta_0} \frac{d_A(\eta_0 - \eta)}{d_A(\eta_0) d_A(\eta)} \nabla_{\hat{n}} \Psi(\eta\hat{n}, \eta) d\eta$$

The lensing potential ϕ:

Define:

$$\phi(\hat{n}) = -2 \int_0^{\eta_0} \frac{d_A(\eta_0-\eta)}{d_A(\eta_0) d_A(\eta)} \Psi(\eta\hat{n}, \eta) d\eta$$

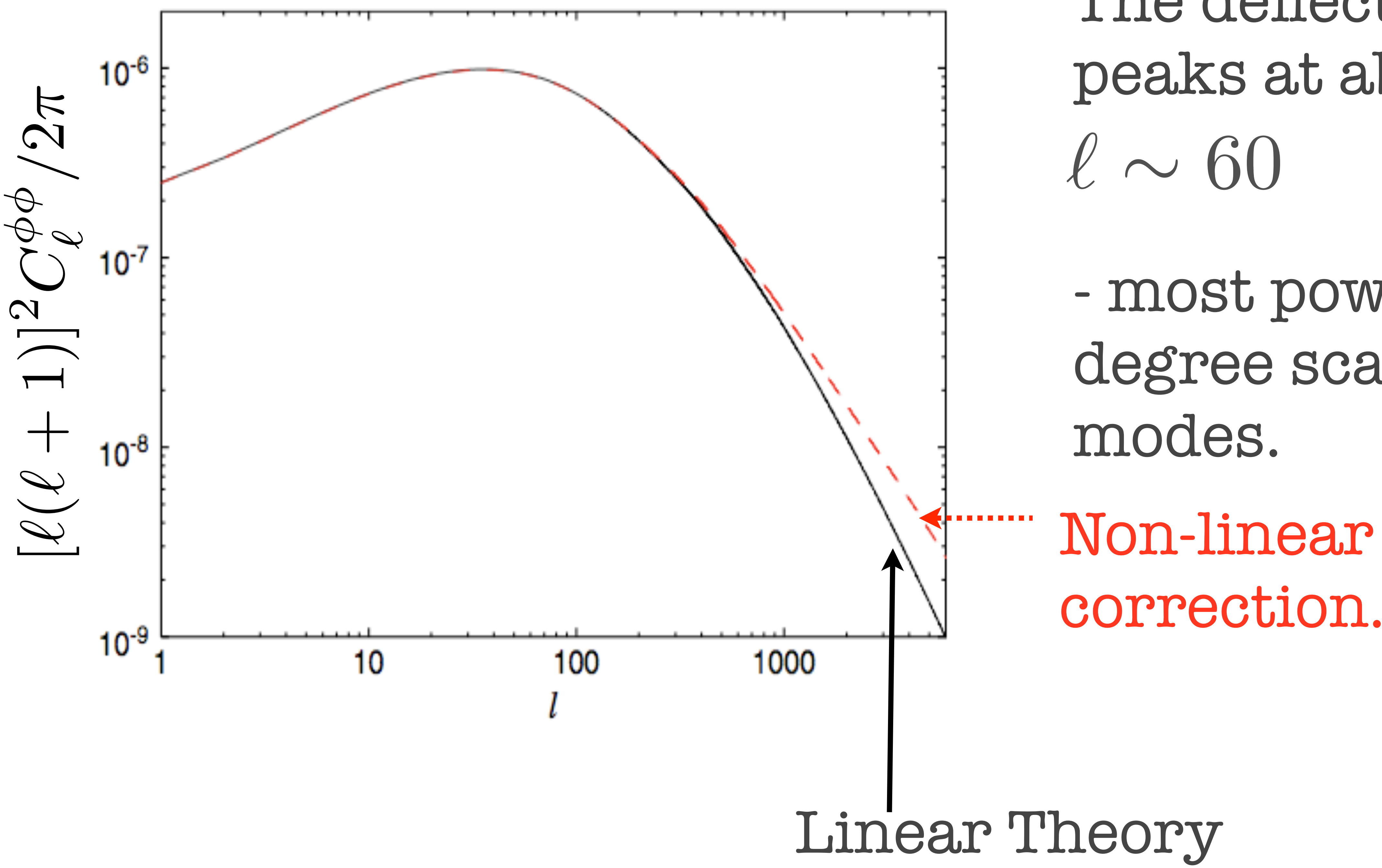
Then,

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

The lensing convergence, $\boldsymbol{\kappa}$:

$$\kappa(\hat{n}) = \frac{1}{2} \nabla \cdot \vec{\alpha} = \frac{1}{2} \nabla^2 \phi$$

Deflection field power spectrum



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

- most power in degree scale modes.

Deflection field power spectrum

Geometry

Growth of Structure

$$C_\ell^{\phi\phi} = \int_0^{\eta_0} \frac{d\eta}{d_A^2} \left[W^{\rm len}\left(\frac{\ell}{d_A},\eta\right)\right]^2 P(\frac{\ell}{d_A},\eta),$$

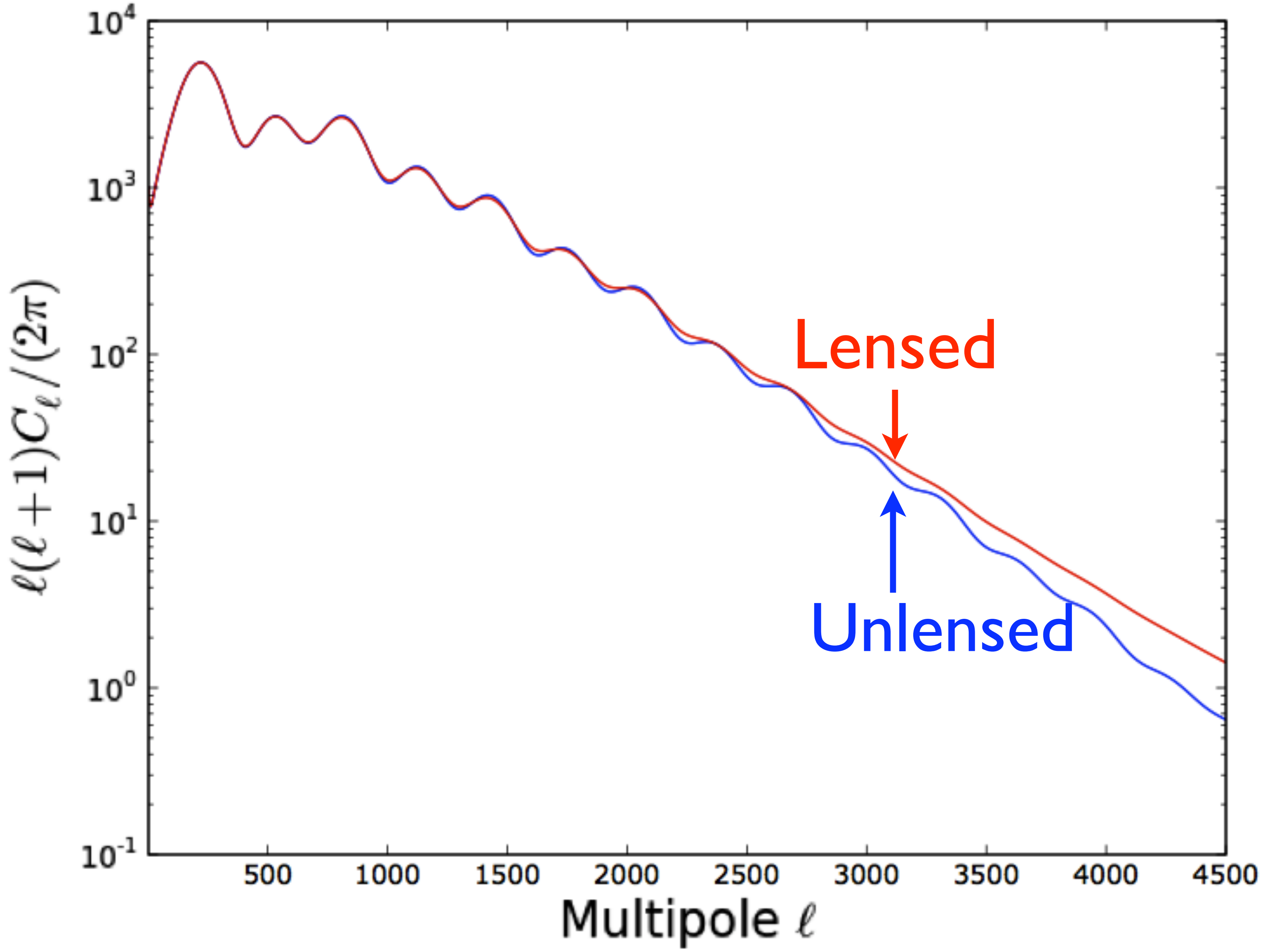
where

$$W^{\rm len}(k,\eta) = -3\frac{\Omega_m}{a}\left(\frac{H_0}{k}\right)^2 \frac{d_A(\eta_0-\eta)}{d_A(\eta)d_A(\eta_0)}.$$

$$C_\ell^{\alpha\alpha} = [\ell(\ell+1)]^2\, C_\ell^{\phi\phi}$$

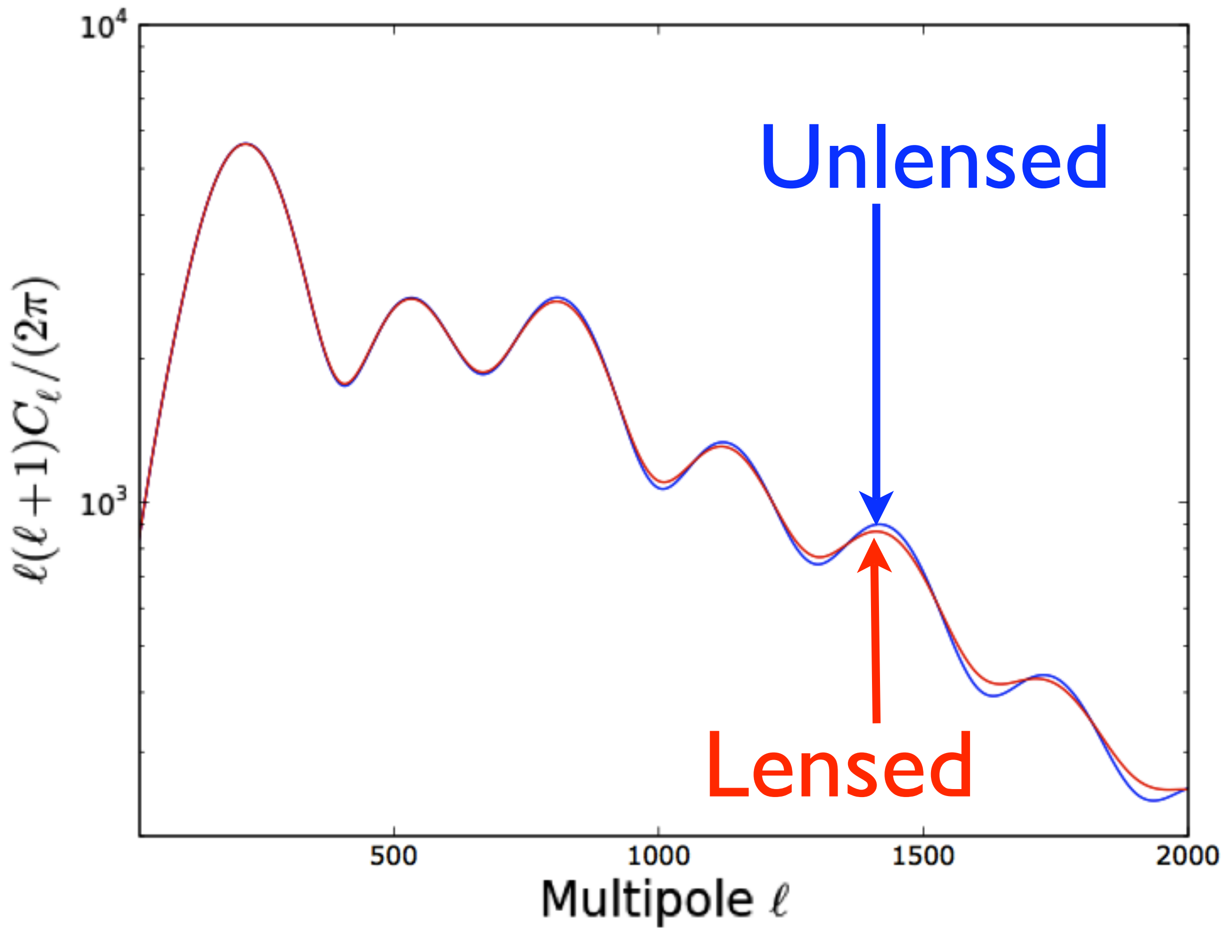
Does lensing affect the CMB PS?

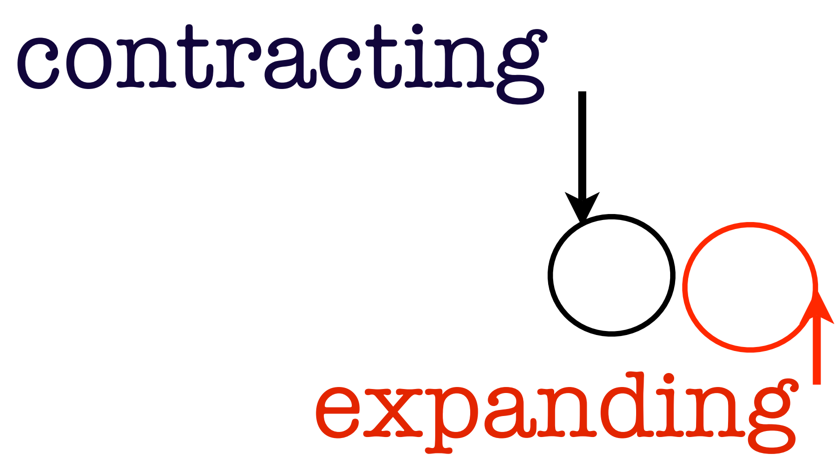
YES!



The Lensed Spectrum at moderate l

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





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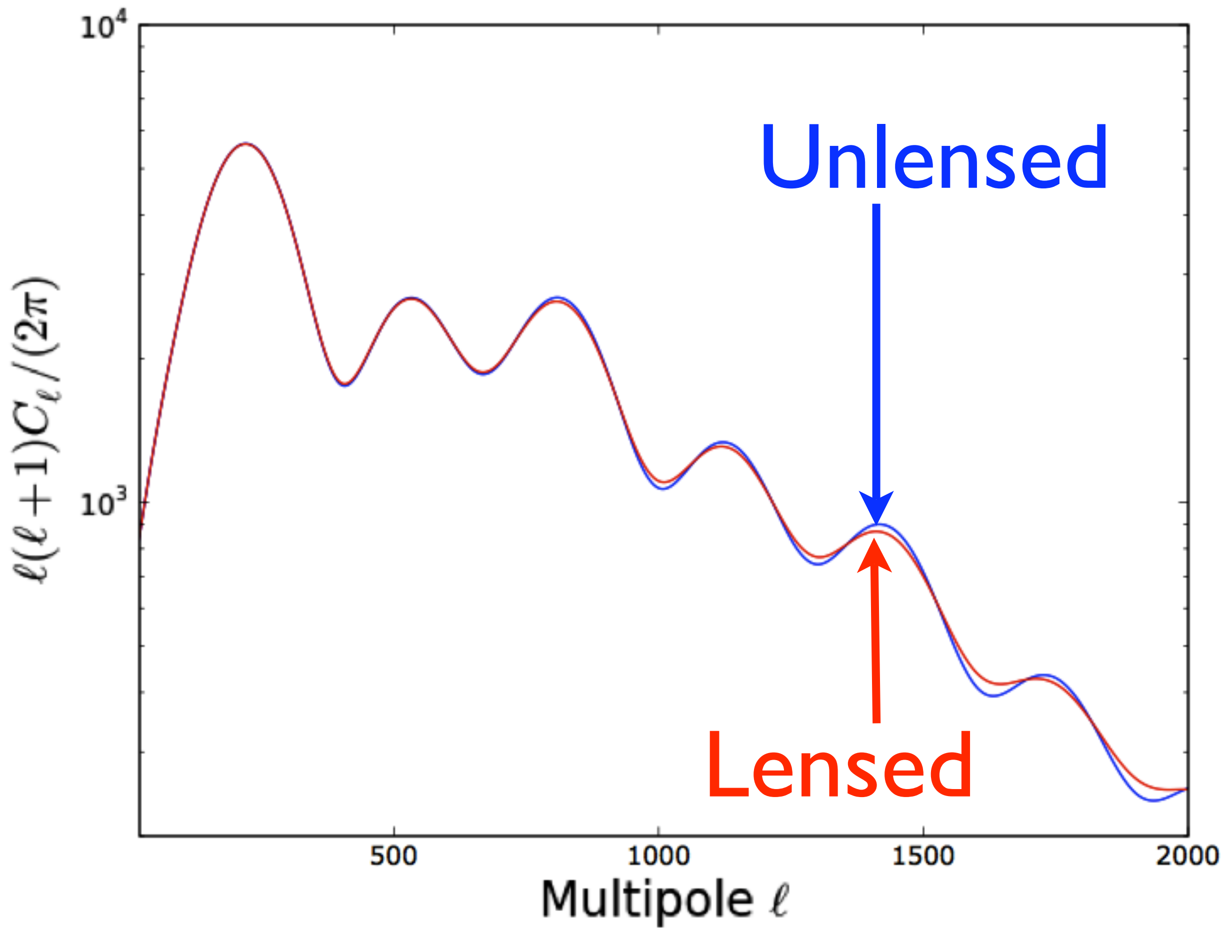
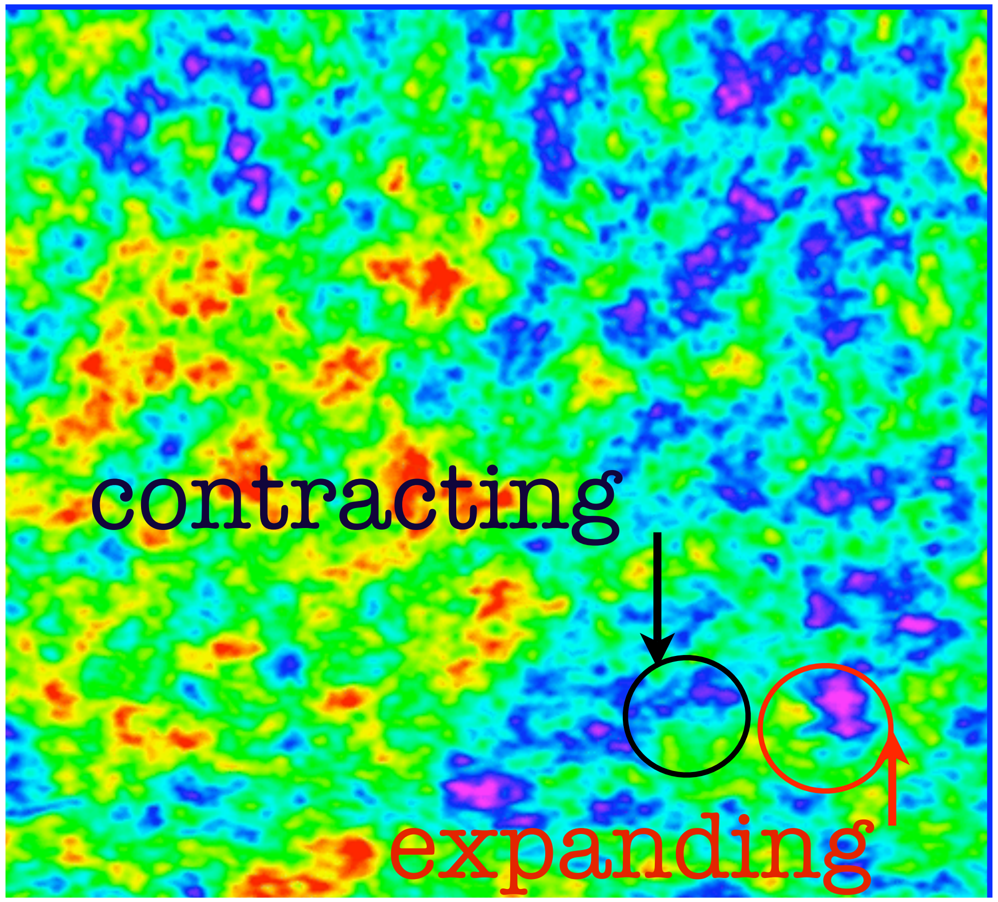
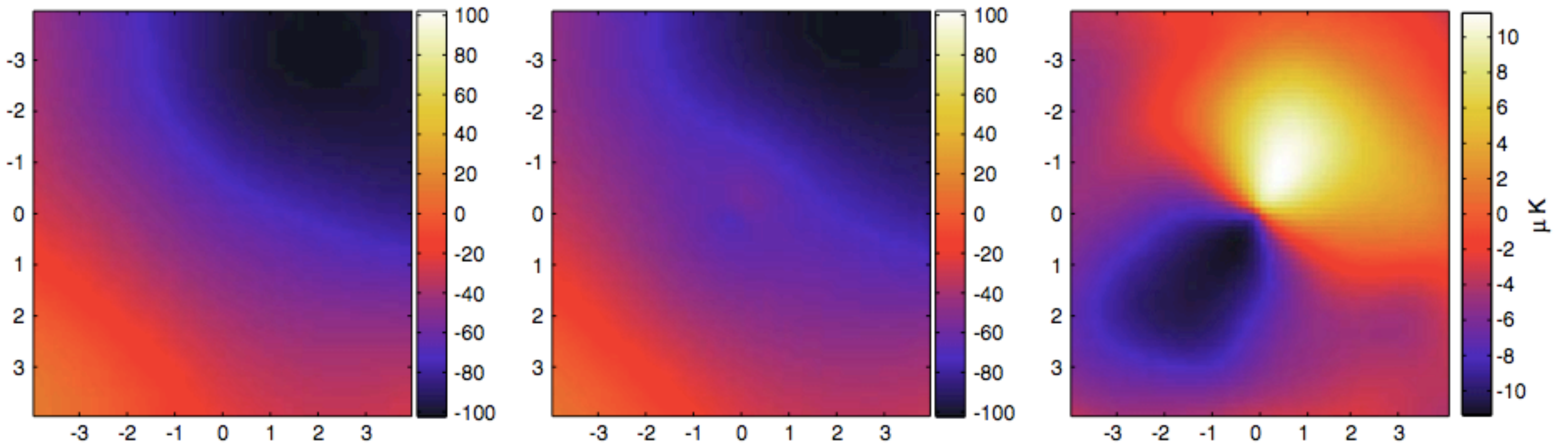




The Lensed Spectrum at high l

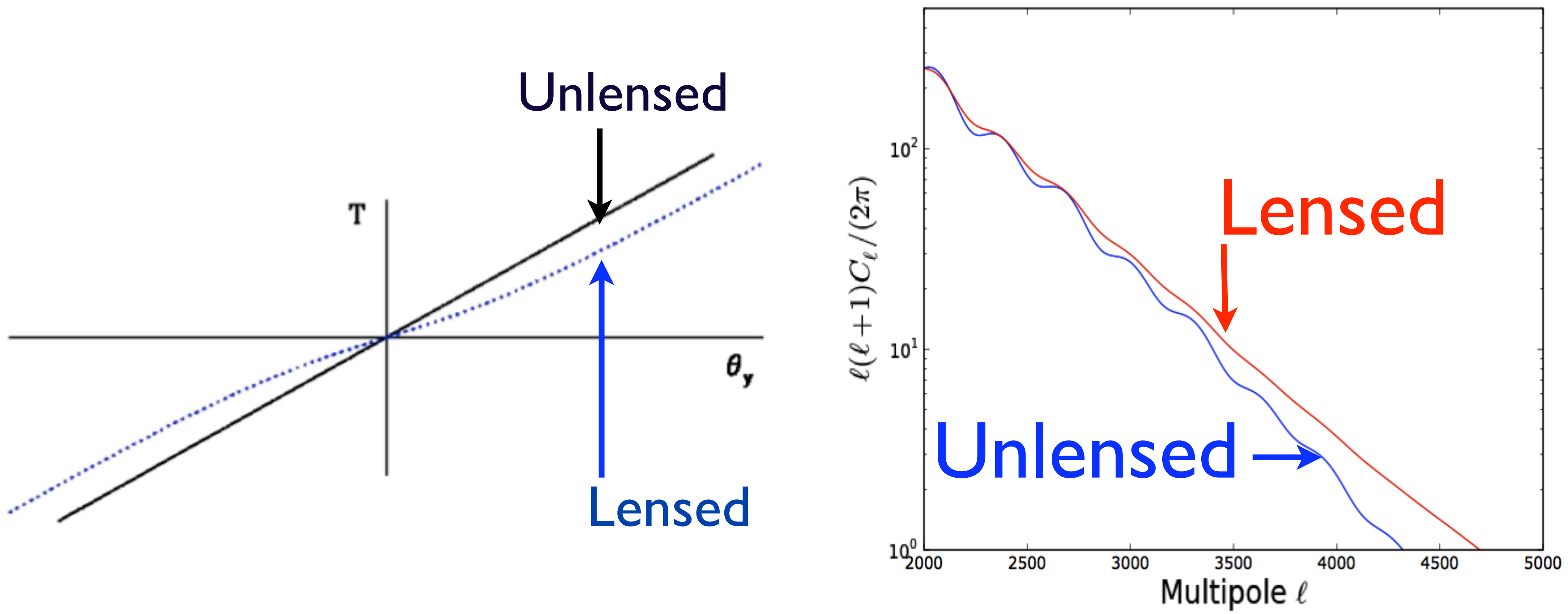
Lensing disturbs the gradient and produces a signal proportional to the deflection angle and the gradient, giving rise to small scale power.

Unlensed Lensed Difference

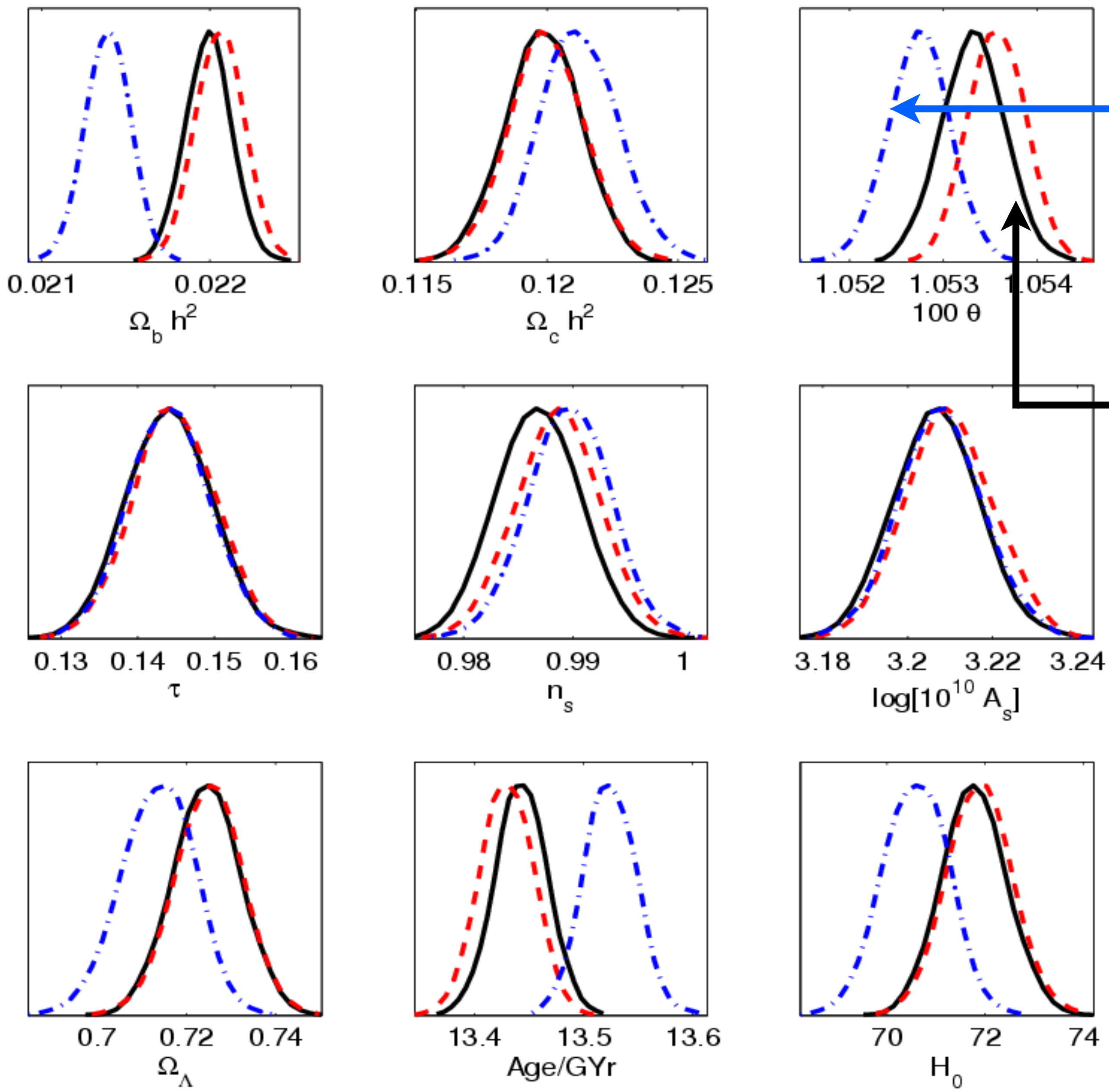


The Lensed Spectrum at high l

The power spectrum at high l can be understood as the lensing of a pure gradient by a small scale clump of matter:



Effect of the lensed PS on Parameters



Lensed Sky +Unlensed PS

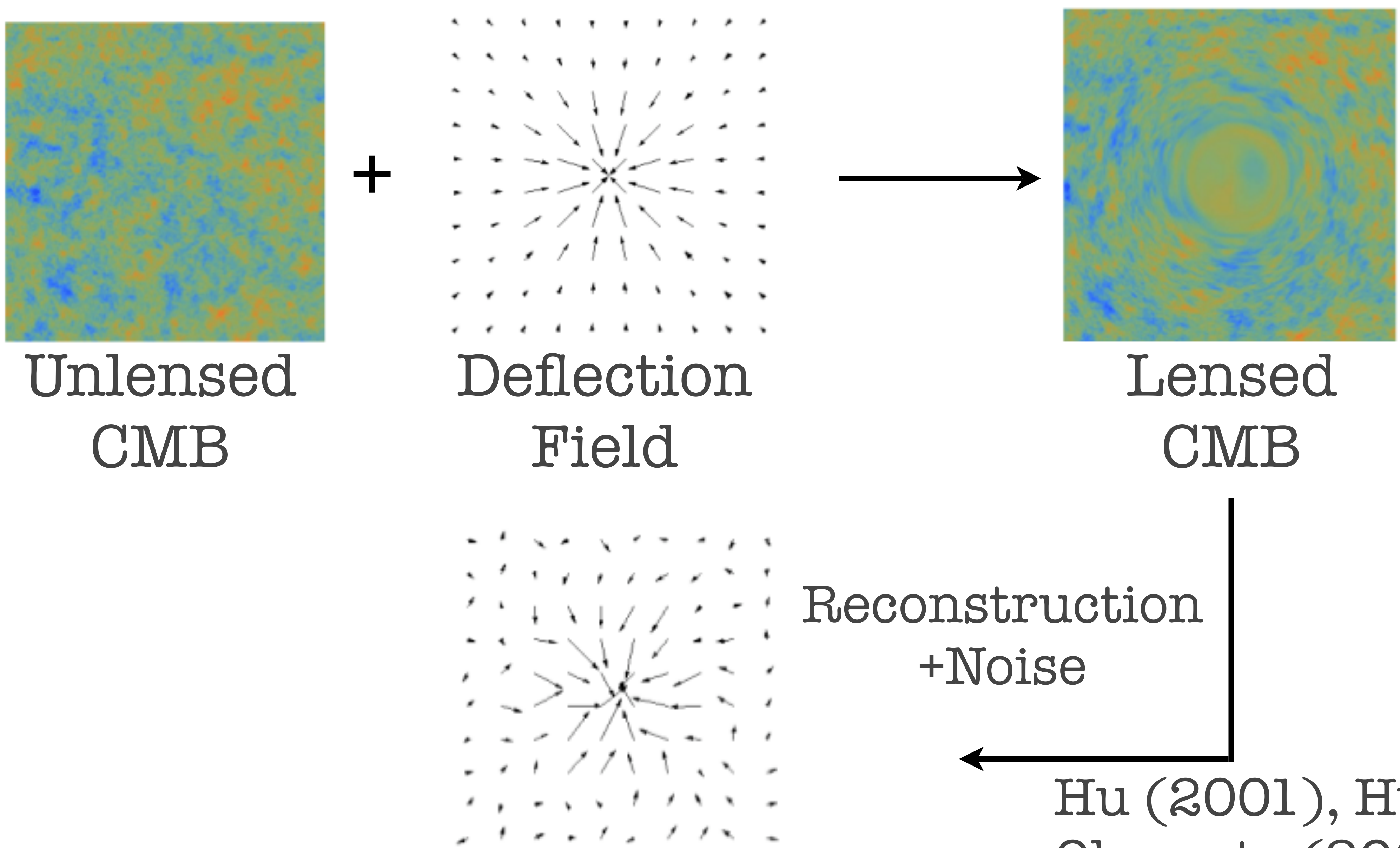
Lensed Sky +Lensed PS

Lensing is important for estimating parameters from the power spectrum.

Simulation for Planck (Lewis 2005)

Lensing Reconstruction

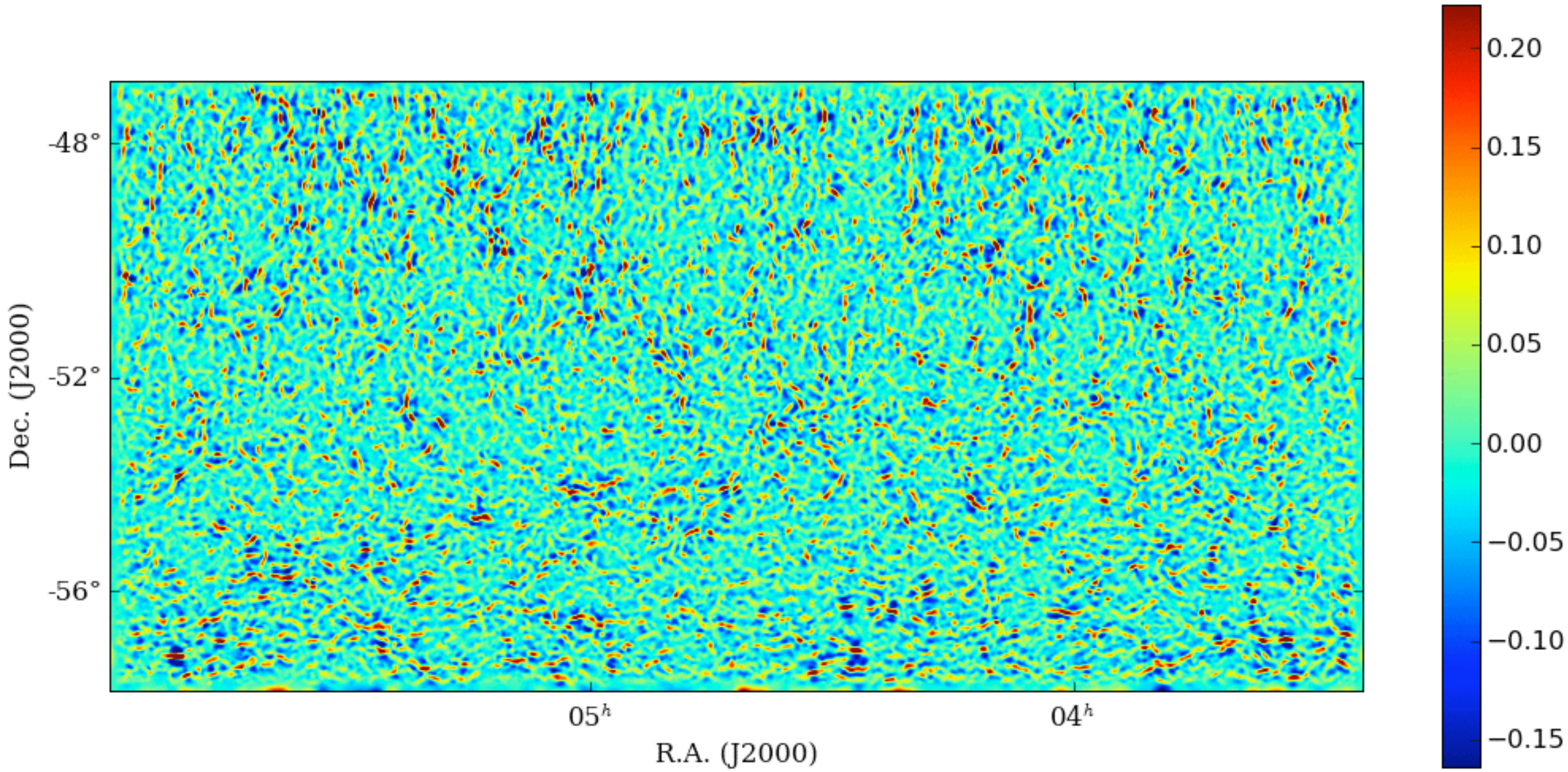
Given only the lensed CMB sky, can we estimate the deflection field?



Hu (2001), Hu & Okamoto (2002)

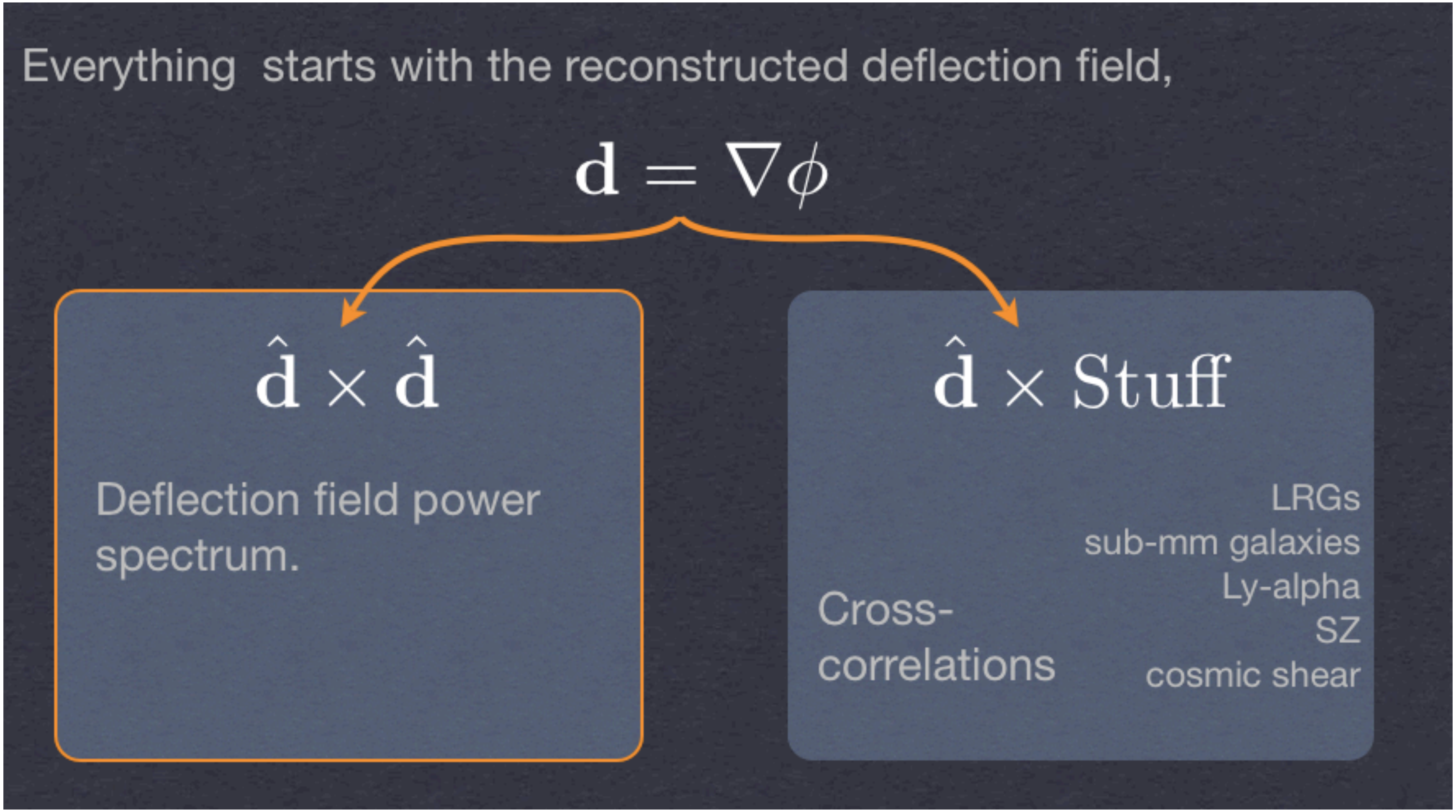
Reconstruction: An example

The reconstructed convergence map:



Das, Sherwin, Spergel, in prep

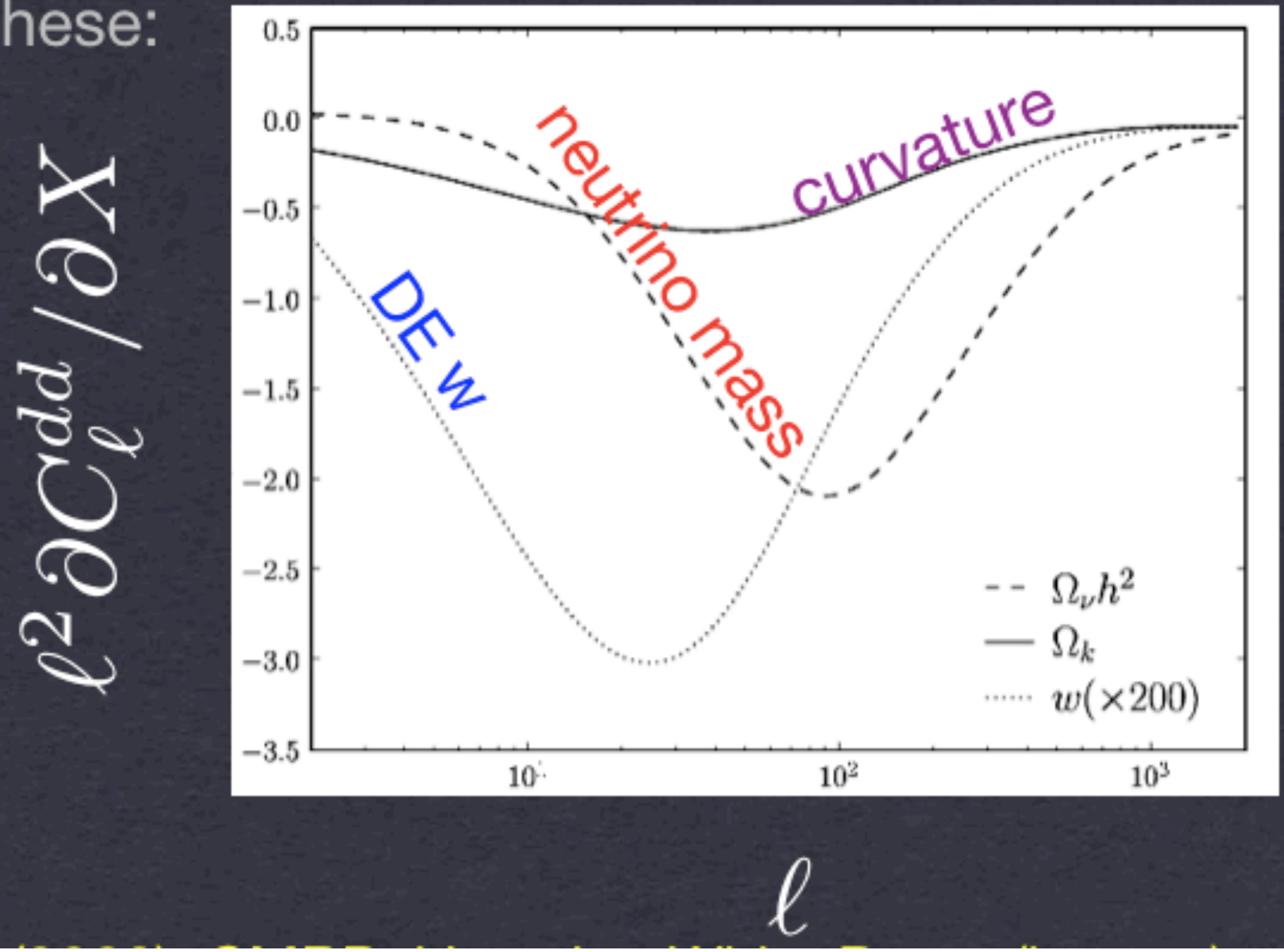
What to do with the reconstruction?



The lensing power spectrum helps

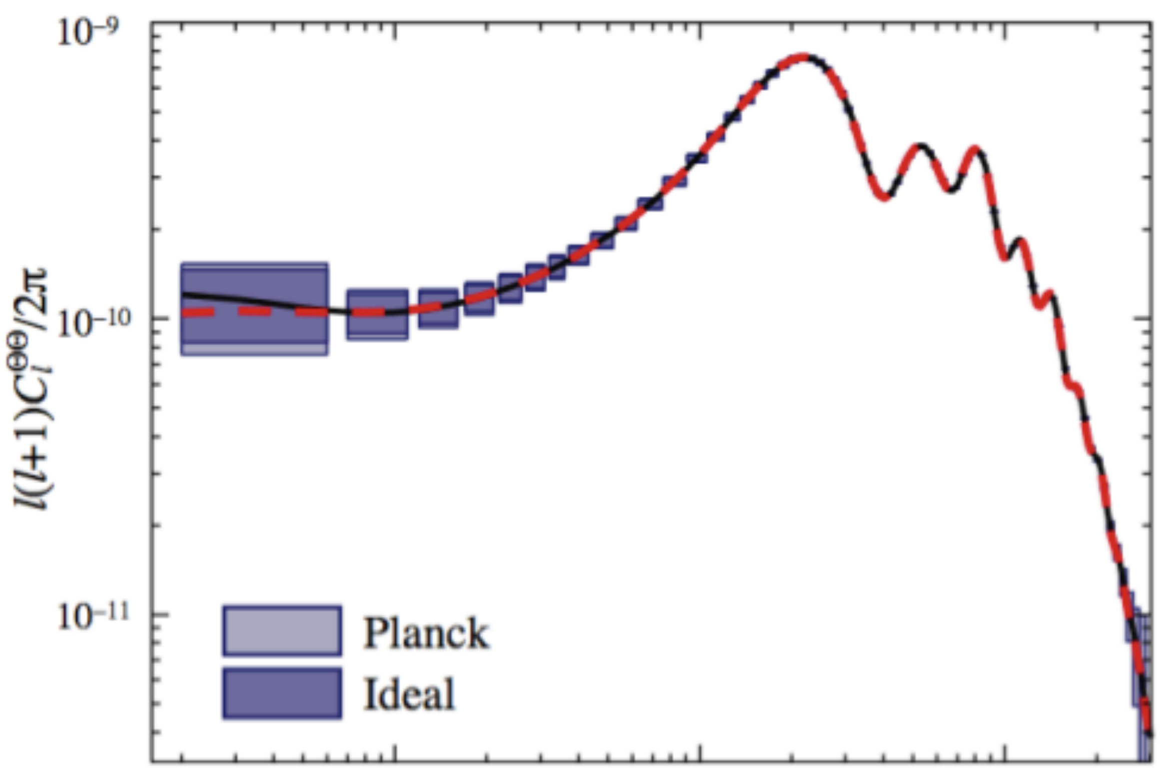
The primary CMB can be kept nearly unchanged under variations of neutrino mass, dark energy equation of state or curvature. But the deflection field cares about these:

Lensing breaks the angular diameter distance degeneracy!

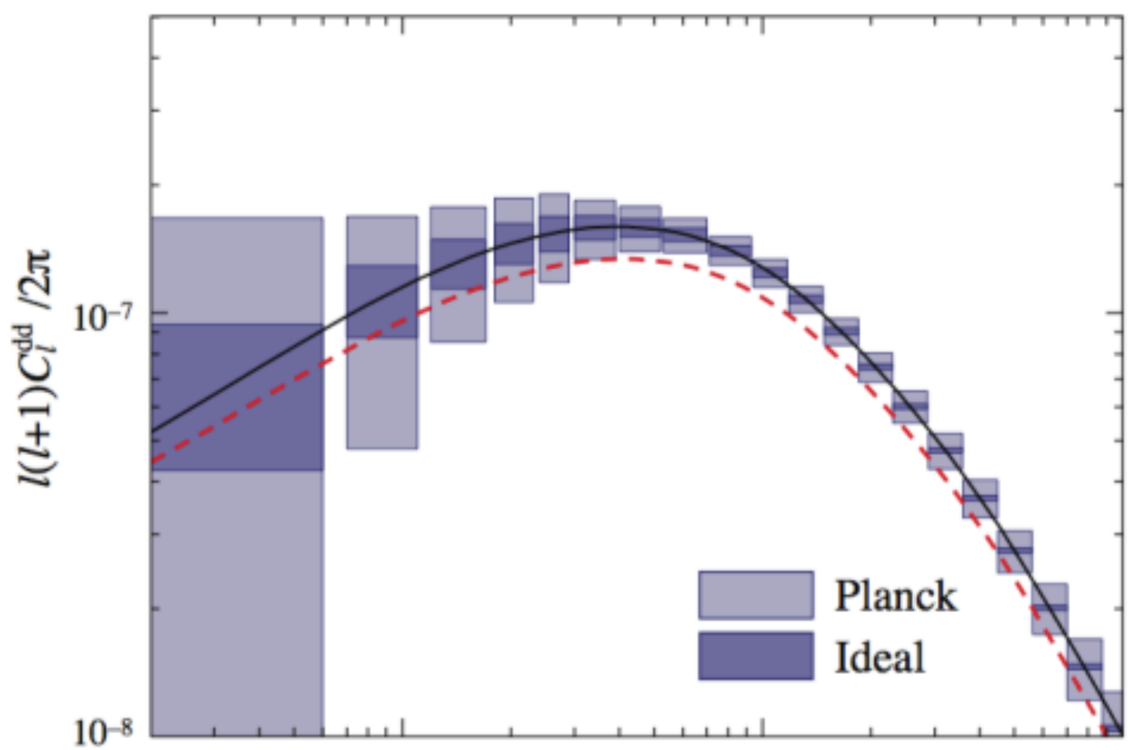


An example

Example from Hu 2001: w=-1 and w=-2/3 models with same D_*



Unlensed CMB PS



Deflection PS

Science With CMB Lensing: Cross Correlations

$$\mathbf{d} = \nabla \phi$$

$$\hat{\mathbf{d}} \times \hat{\mathbf{d}}$$

Deflection field power spectrum.

$$\hat{\mathbf{d}} \times \mathrm{Stuff}$$

Cross-correlations

LRGs
sub-mm galaxies
Ly-alpha
SZ
cosmic shear

Galaxy Bias

$\hat{\mathbf{d}} \times$ galaxies

Large Scale Structure (LSS) surveys measure autocorrelations of galaxies.

From this, we try to infer the correlations among dark matter halos.

Such inferences are limited by our lack of understanding of bias - or how luminous matter traces dark matter.

If we cross-correlate the reconstructed deflection field with the galaxy number counts, we go one step closer to the truth by directly measuring the galaxy-dark matter correlation.

CMB lensing is particularly relevant for high z objects, behind which there are no galaxies to be lensed!

Galaxy Bias

$\hat{\mathbf{d}} \times$ galaxies

Great Signal-to-noise!

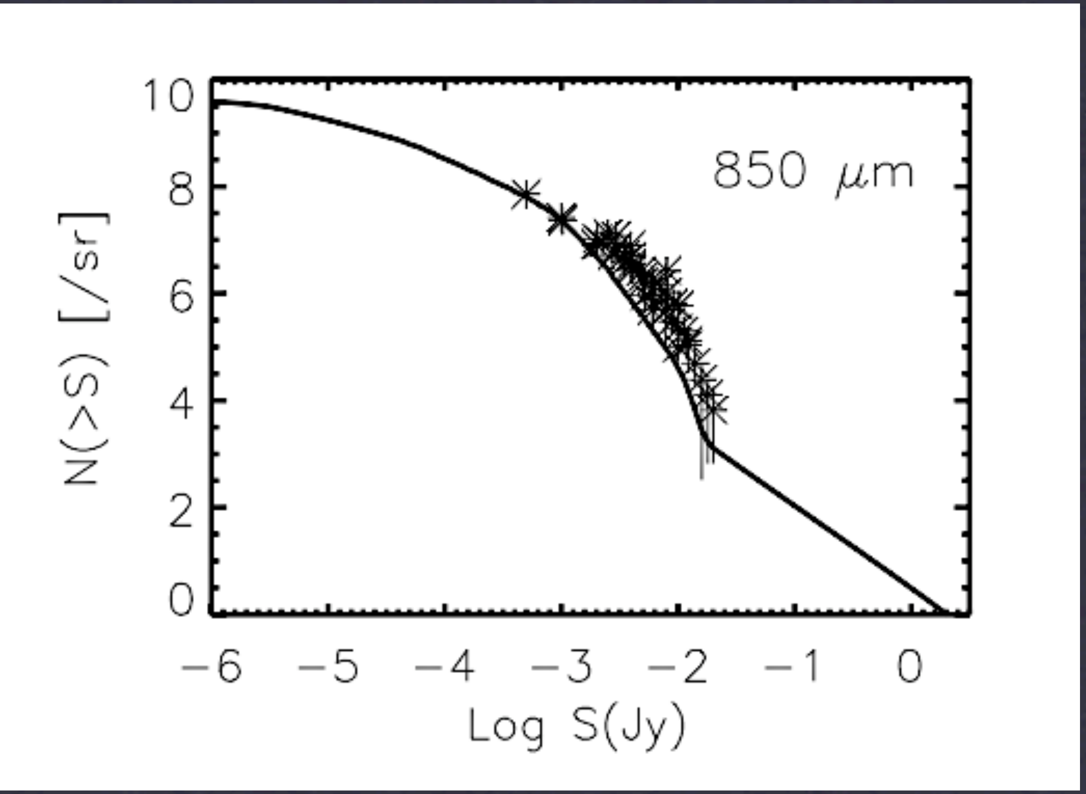
Galaxy Survey	$\hat{n}$	$A/10^3$	z_c	b	CMB Expt.	(S/N)	$\Delta b/b(\%)$
					PLANCK	5.8	17.3
SDSSLRG	12.4	3.8	0.31	2	PACT	11.4	8.8
					IDEAL	20.4	4.9
					PLANCK	10.8	9.3
BOSS1	40.	10	0.3	2	PACT	25.5	3.9
					IDEAL	52.5	1.9
					PLANCK	17.0	5.9
BOSS2	110.	10	0.6	2	PACT	39.4	2.5
					IDEAL	78.2	1.3
					PLANCK	52.8	1.9
ADEPT	3500	27	1.35	1	PACT	107.5	0.9
					IDEAL	228.3	0.4

Acquavivia, Hajian, Spergel and Das,
PRD 78, 043514 (2008)

Herschel Galaxies

$\hat{\mathrm{d}} \times \;\mathrm{galaxies}$

- The Herschel mission will detect Far IR and sub-mm galaxies at $1 < z < 3$.
- Steep number counts imply strong negative K-corrections and magnification bias.
- "Golden" candidates for cross-correlation with Planck lensing reconstruction. (Even for SPT and ACT)
- When coupled to the halo model, this will tell us about typical halo mass of these dusty galaxies.

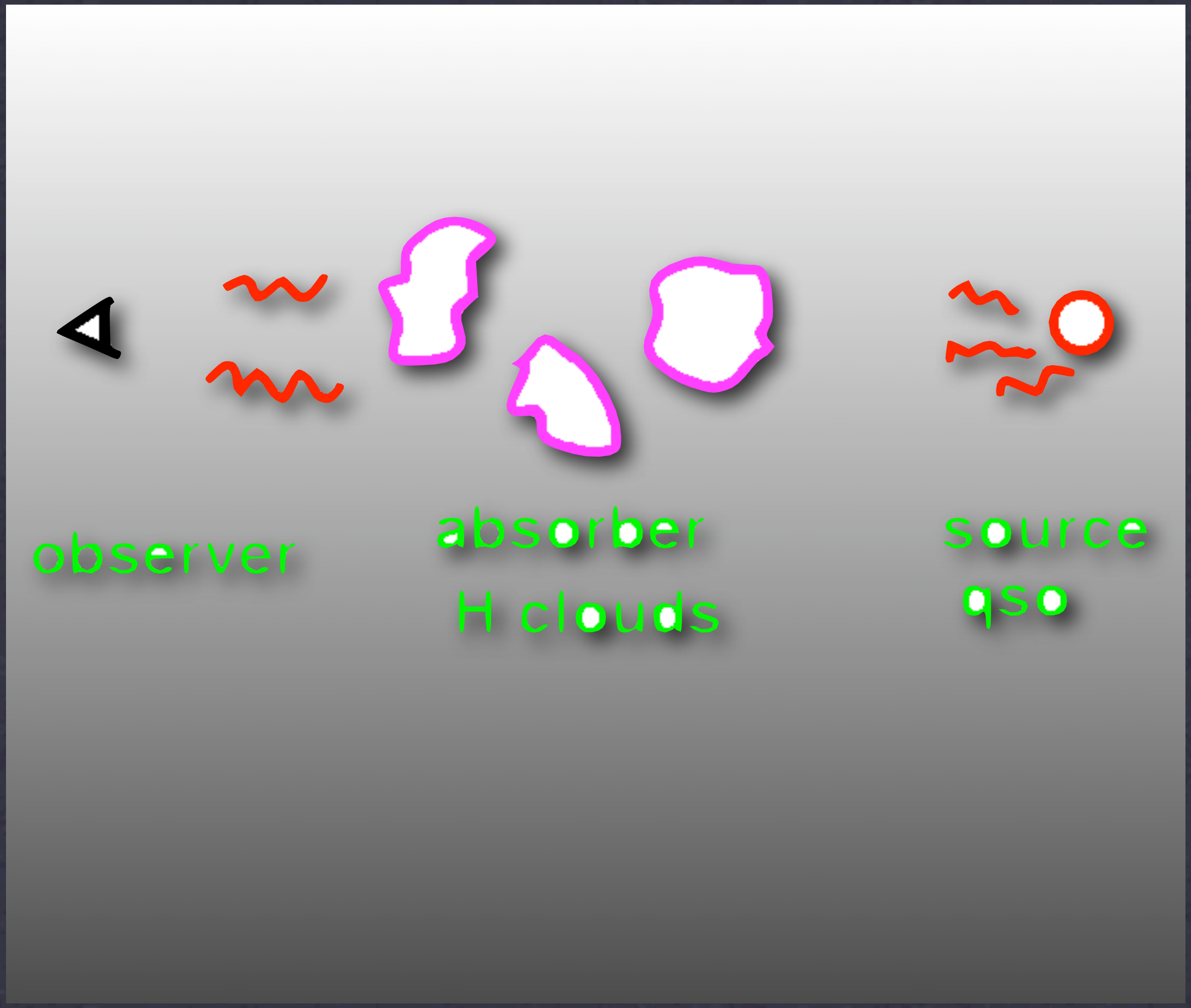


Fernandez-conde etal (2008)

Das, Calvert & Spergel, in prep

Ly-alpha Forest And CMB Lensing

$$\hat{\mathrm{d}} \times \ \mathrm{Ly} - \alpha$$



The Ly-alpha absorption features in quasar spectra probe small scale density fluctuations.

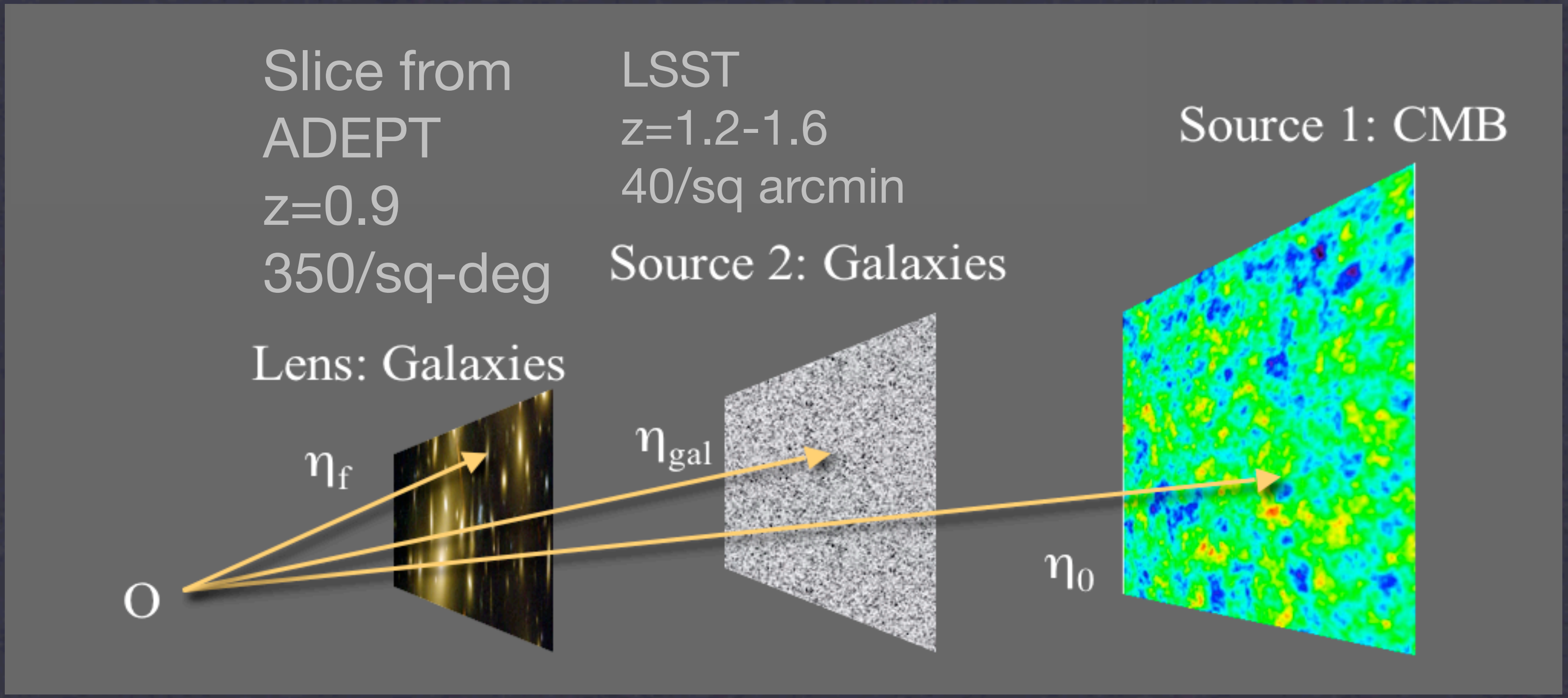
Lensing probes the long wavelength modes.

Cross-correlation is a potentially powerful cosmological tool ! Relevant for the BOSS survey: 200,000 QSOs.

S/N ~ 10 for PLANCK

Vallinotto, Das, Spergel & Viel, PRL,103:091304, 2009

Weak Lensing: Measuring Distance Ratios



Das & Spergel PRD, 79, 043509, (2009)

$$\frac{\text{CMB reconstructed convergence} \times \text{lens surface density}}{\text{Galaxy reconstructed convergence} \times \text{lens surface density}} \equiv \frac{C_\ell^{\kappa_{\rm CMB}\Sigma}}{C_\ell^{\kappa_{\rm gal}\Sigma}} = \frac{g_{\rm CMB}(\eta_f)}{g_{\rm gal}(\eta_f)}$$

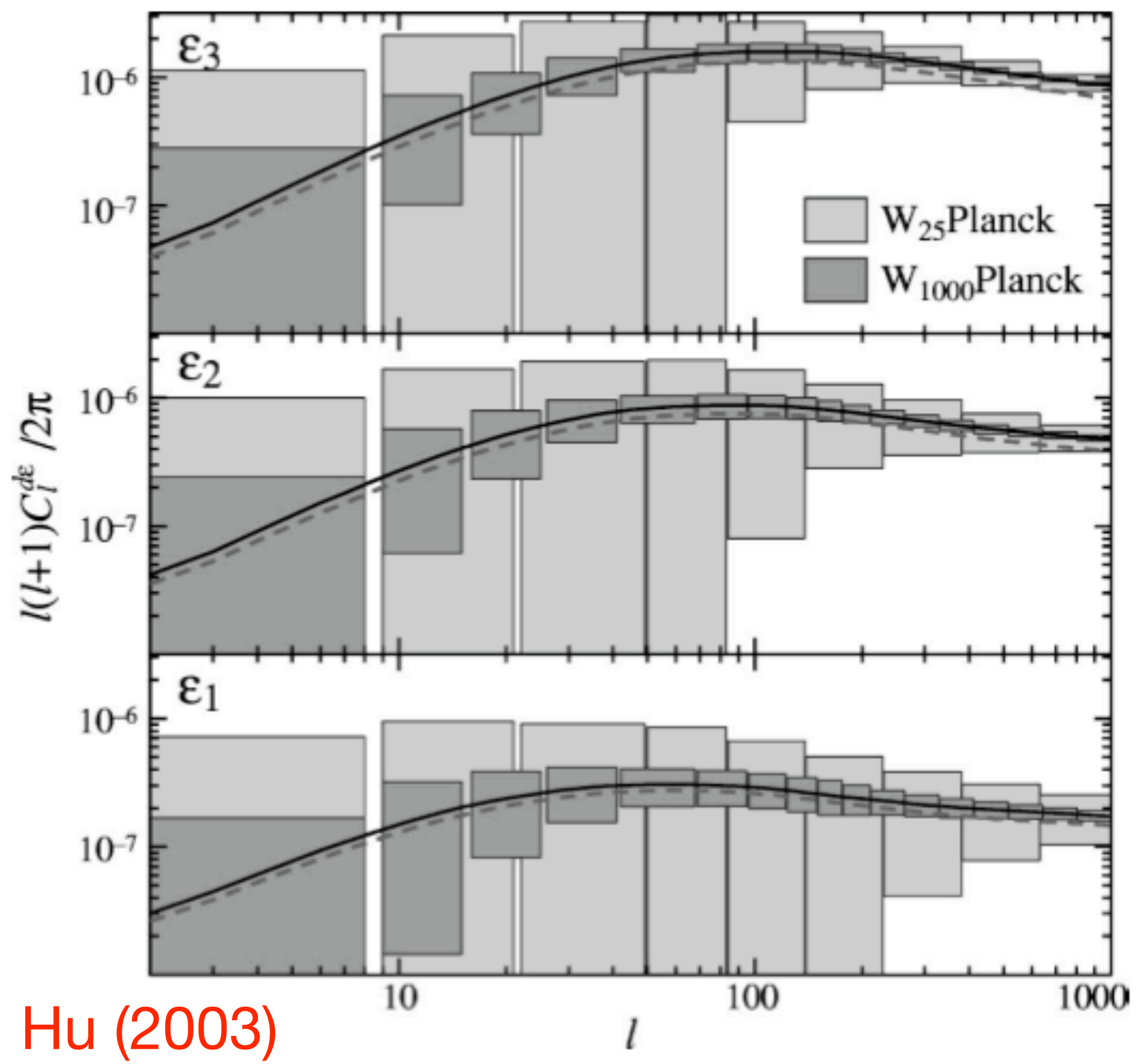
$$\rightarrow \frac{d_A(\eta_0 - \eta_f)d_A(\eta_{\rm gal})}{d_A(\eta_{\rm gal} - \eta_f)d_A(\eta_0)}$$

for thin background slice.

(see also Hu et al. arXiv:0708.4391)

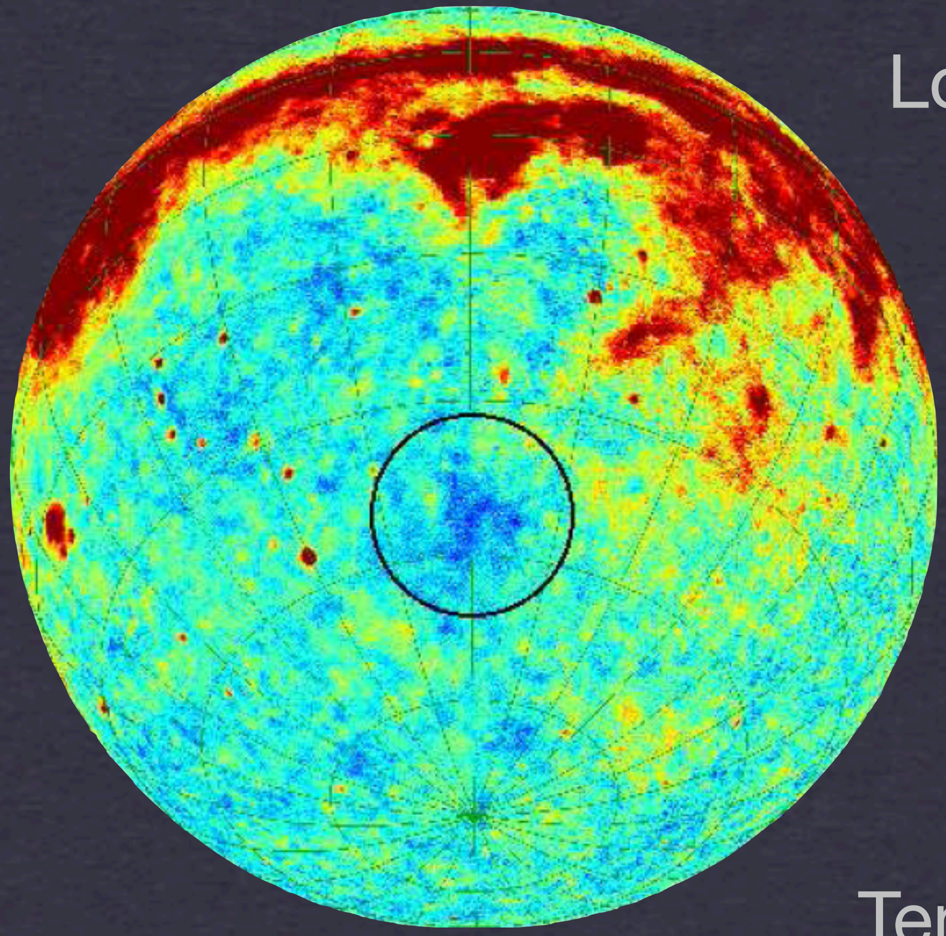
Lensing Tomograpy

Cross-correlating CMB lensing with cosmic shear in redshift slices will probe growth of structure directly!



Hu (2003)

WMAP Cold Spot



Location

$$b = -57^\circ, \quad l = 209^\circ$$

$$(\alpha = 03^h\ 15^m\ 05^s,\ \delta = -19^\circ\ 35'\ 02'')$$

Scale

$$\sim 10^\circ \text{ across}$$

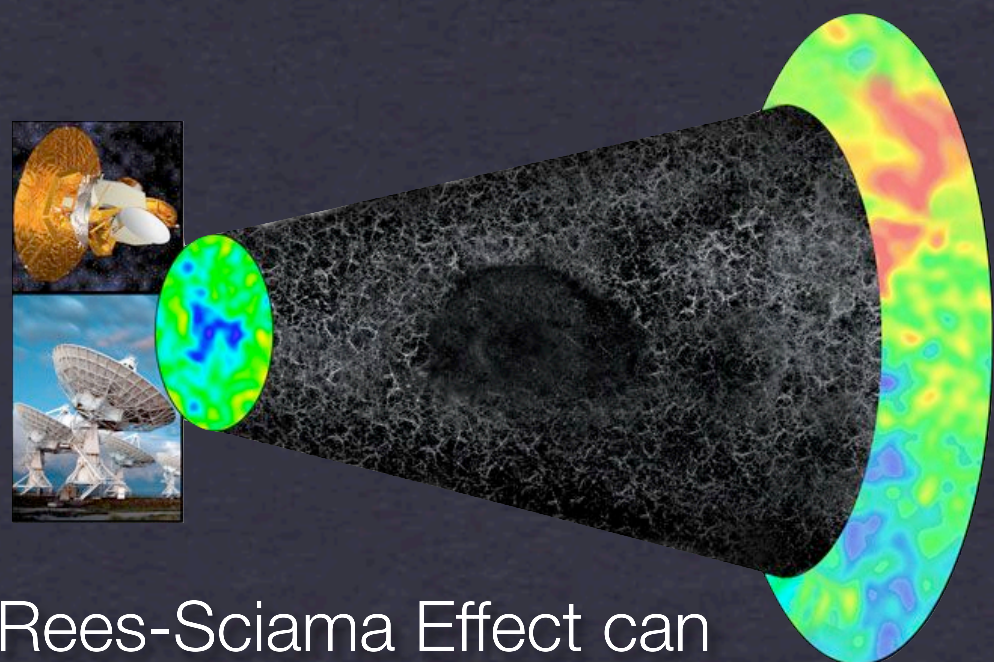
Temperature

$$-78\ \mu K \text{ after smoothing with } 4^\circ \text{ Gaussian}$$

Detected using a Spherical Mexican Hat Wavelet method (Vielva et al. 2004). Cruz et al. 2004 claims that the *a posteriori* probability of finding such a feature by chance is < 2% (Cruz et al. 2004).

The Void Hypothesis

Inoue and Silk (2006,2007)

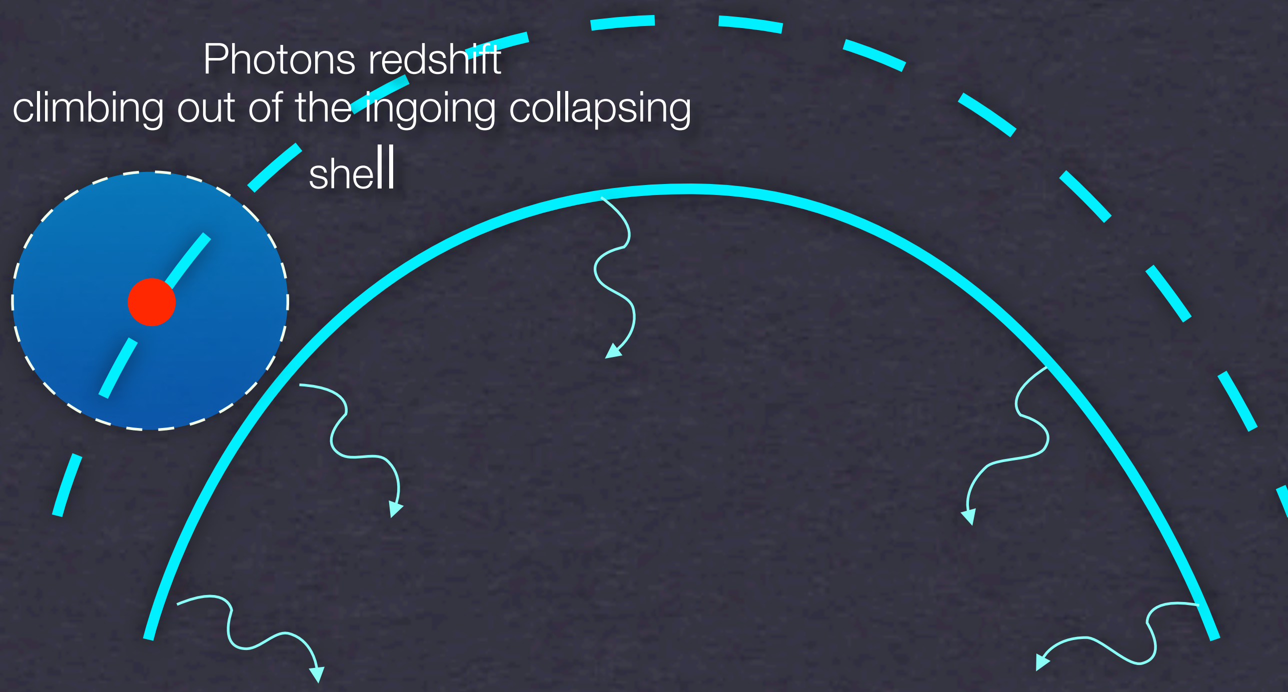


Rees-Sciama Effect can produce a Cold Spot.

But if the underdensity ~ -0.3, one needs a ~300 Mpc radius void at z~ 1 (Inoue and Silk, 2006, 2007)

The Texture Hypothesis

Cruz et al. (2007)



Shell of CMB photons at confomal time τ

Textures are higher dimensional unstable topological defects (Turok and Spergel (1990).

Detectable!

- Voids or textures have distinctive deflection patterns.

- With SPT or ACT, such a void can be easily detected!

- The texture is detectable with longer integration.

Das & Spergel, PRD, 79:043007, 2009

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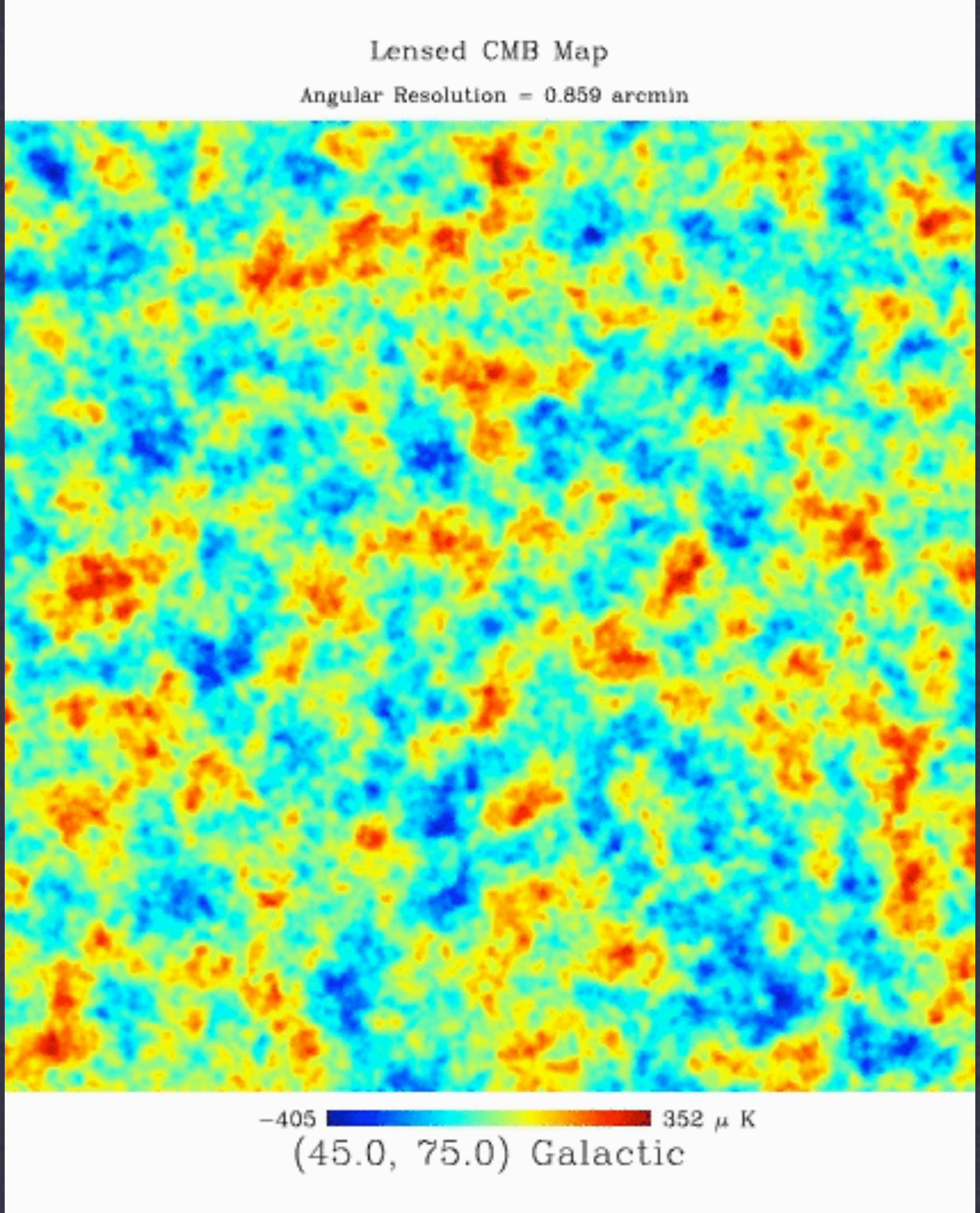
Das & Spergel, PRD, 79:043007, 2009



Tools

Lens Reconstruction Is A Very Important Problem!

Works perfectly under assumptions of an ideal full-sky experiment.

In real life, maps will have partial sky coverage and will be contaminated with astrophysical and instrumental systematics!

Building a realistic lens reconstruction pipeline requires realistic simulations!

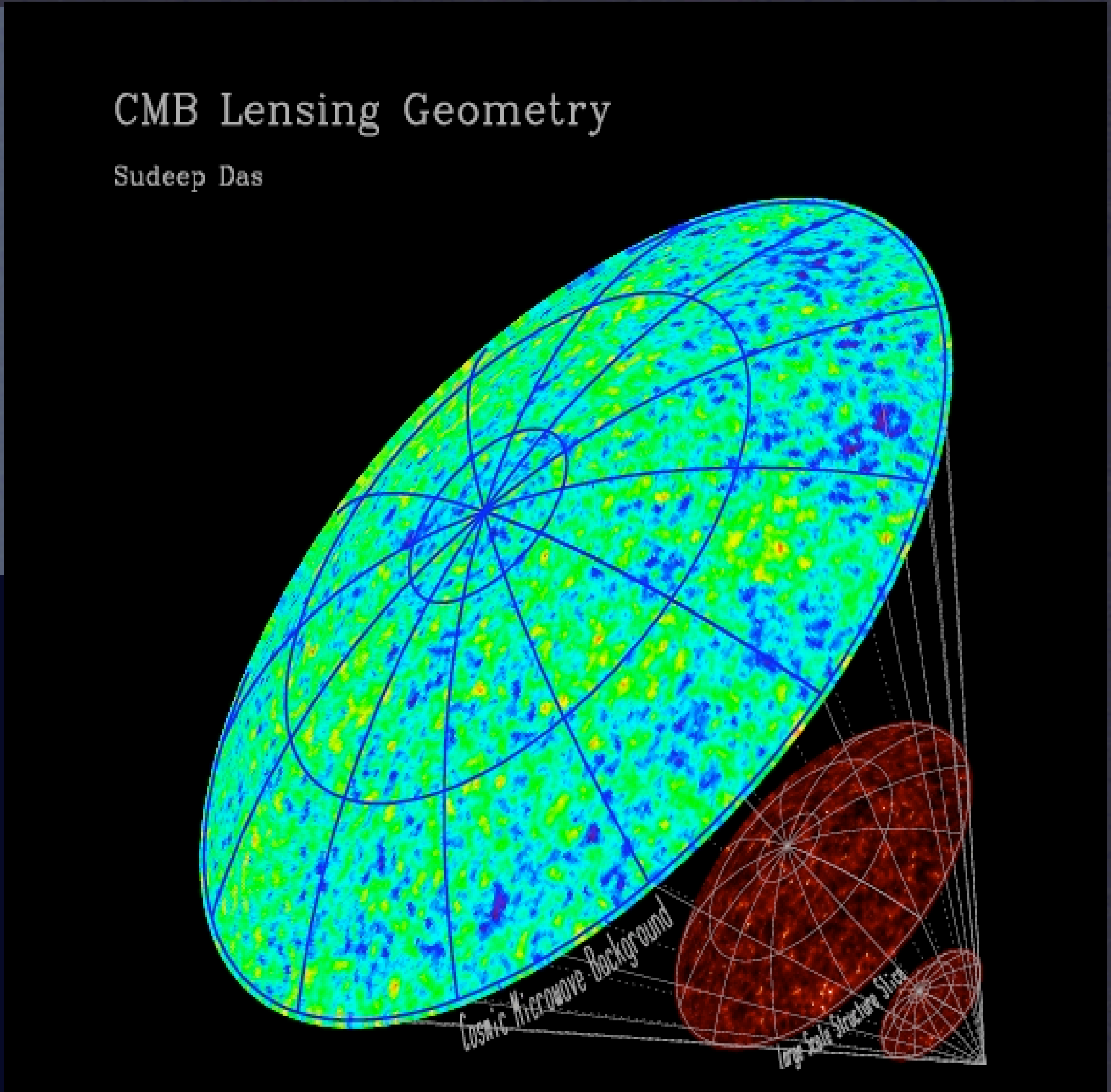
Simulating CMB Lensing

Motivations:

- create arcmin resolution lensed CMB maps
- capture the large scale modes in the deflection field.
- use same LSS for simulating cross-correlation studies.

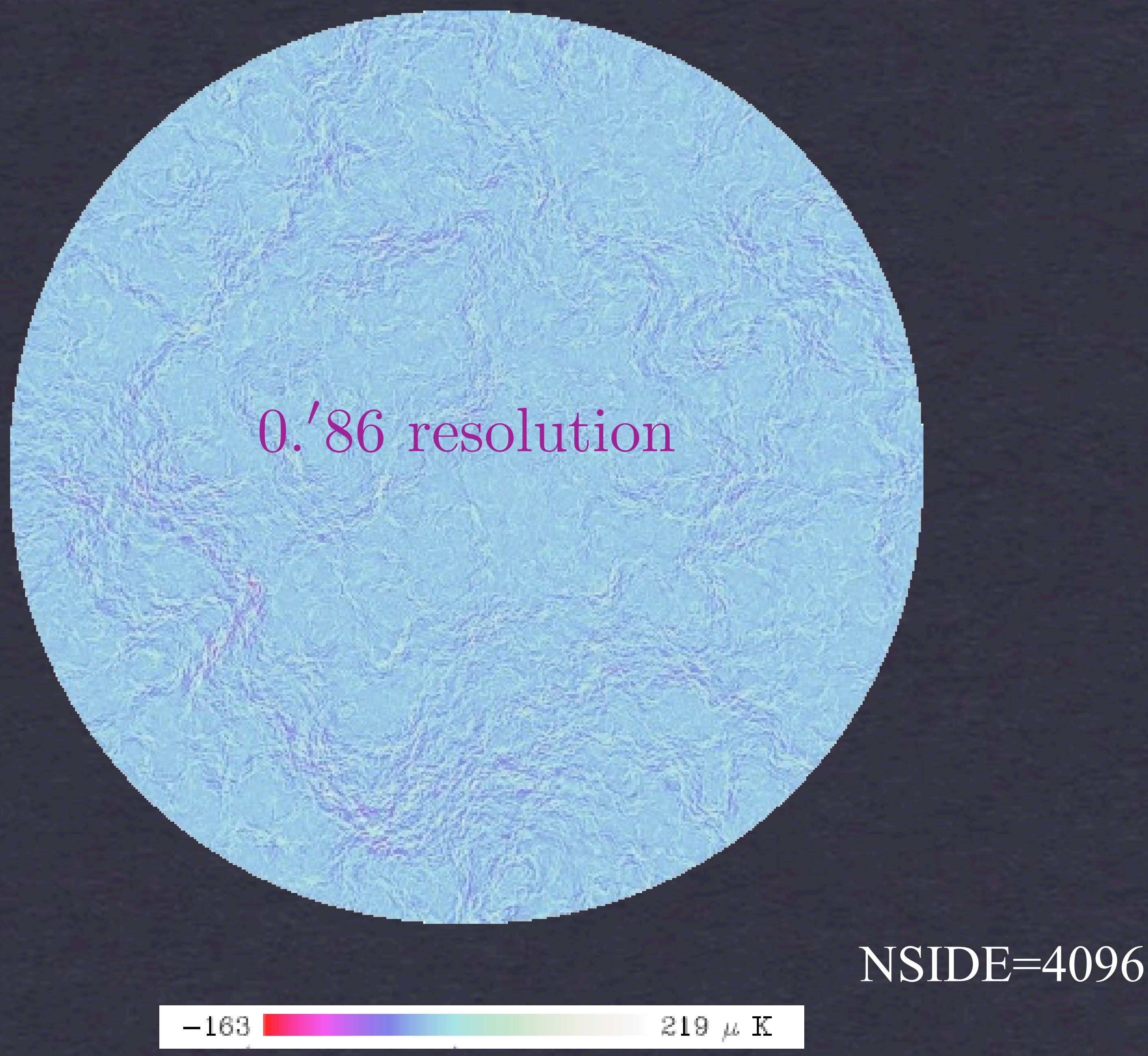
Method:

- Project matter over-density from a light cone Tree-Particle-Mesh simulation onto shells.
- Perform ray-shooting to get lensed map.



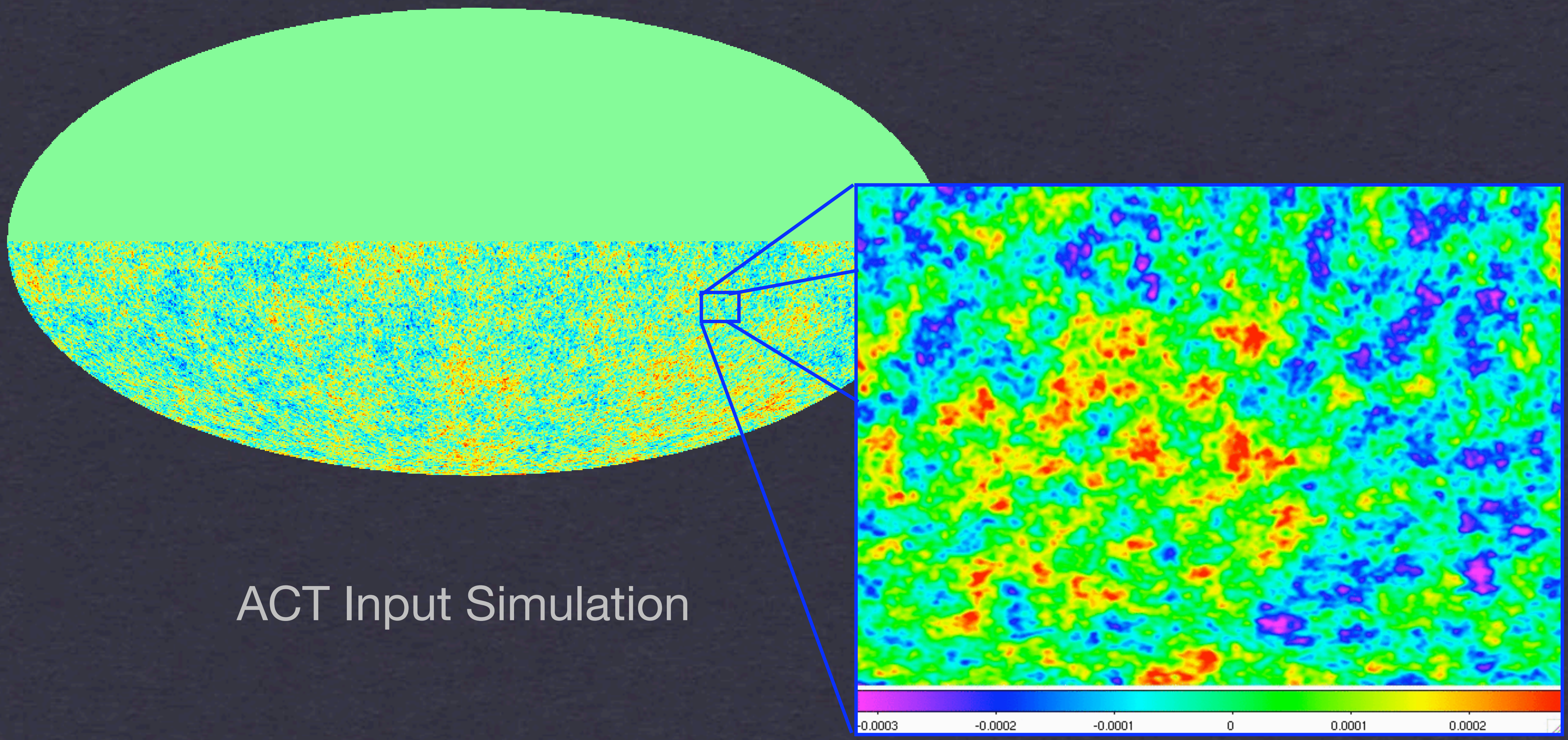
Das and Bode (2008)

The Lensed - Unlensed Map



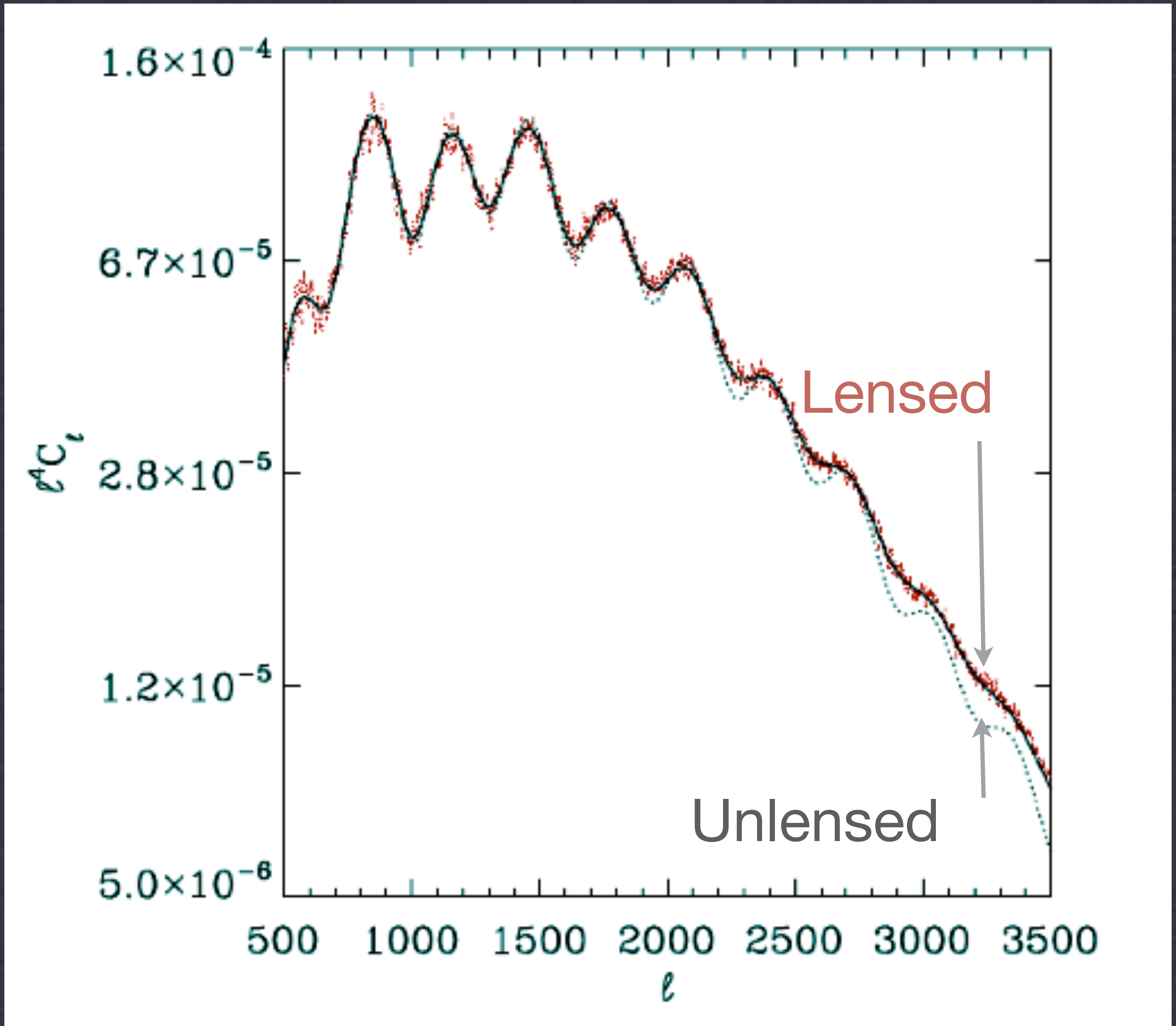
Das and Bode, ApJ, 682, 1 (2008)

Extension To Half And Full-sky



ACT Input Simulation

Large Sky Simulation - Results



Das and Bode (2008)

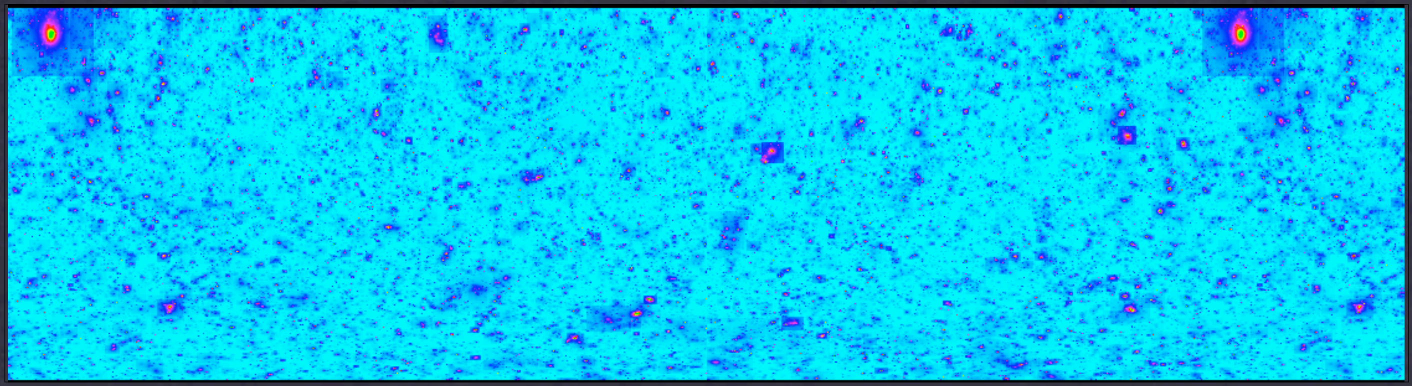
Sub-arcminute resolution lensed CMB maps on full sky.

Excellent match with perturbative theory (black solid line).

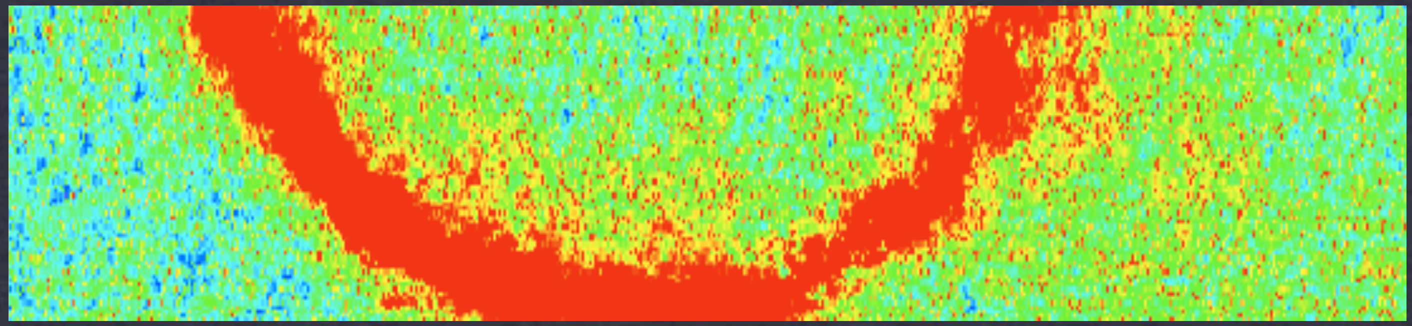
see also:
Carbone et al. (2008)

Auxiliary Simulations

Using the same LSS, we have simulated tSZ, kSZ, Dust, IR and radio point sources.

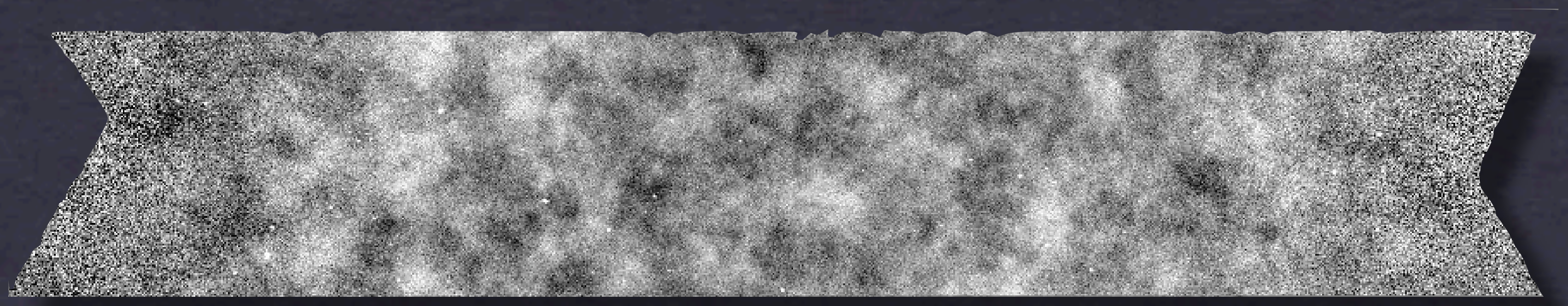


Thermal SZ simulation at 145 Ghz (Sehgal et al. 2007, 2009)



A part of the simulated ACT sky at 145 GHz

Simulations > Training Set For Lens Reconstruction



Input simulations run through Atacama Cosmology Telescope simulator.

- The lens reconstruction algorithm should be robust enough to extract the lensing signal from a map like this!
- Exactly optimal techniques will be numerically expensive.
- We have made good progress on near optimal but fast methods of lensing reconstruction
- This is work in progress ...

Das, Hajian & Spergel (2009); Das, Sherwin, Spergel (in prep)

The Atacama Cosmology Telescope (ACT)

The Atacama Cosmology Telescope (ACT) is a 6-m telescope located in northern Chile. It is currently making observations of the Cosmic Microwave Background at mm-wavelengths with arcminute resolution.

ACT should be able to provide a CMB power spectrum with unprecedented precision at high multipoles, a list of Sunyaev-Zeldovich clusters, and lensing.

Thank You!

And Stay Tuned For Exciting CMB Lensing Science Soon From SPT, ACT, Planck!

References

Lewis and Challinor (2006) Weak Gravitational Lensing of the CMB

Hu and Okamoto (2002) for lensing reconstruction.