CMB Lensing: A New Tool for Cosmology and Astrophysics

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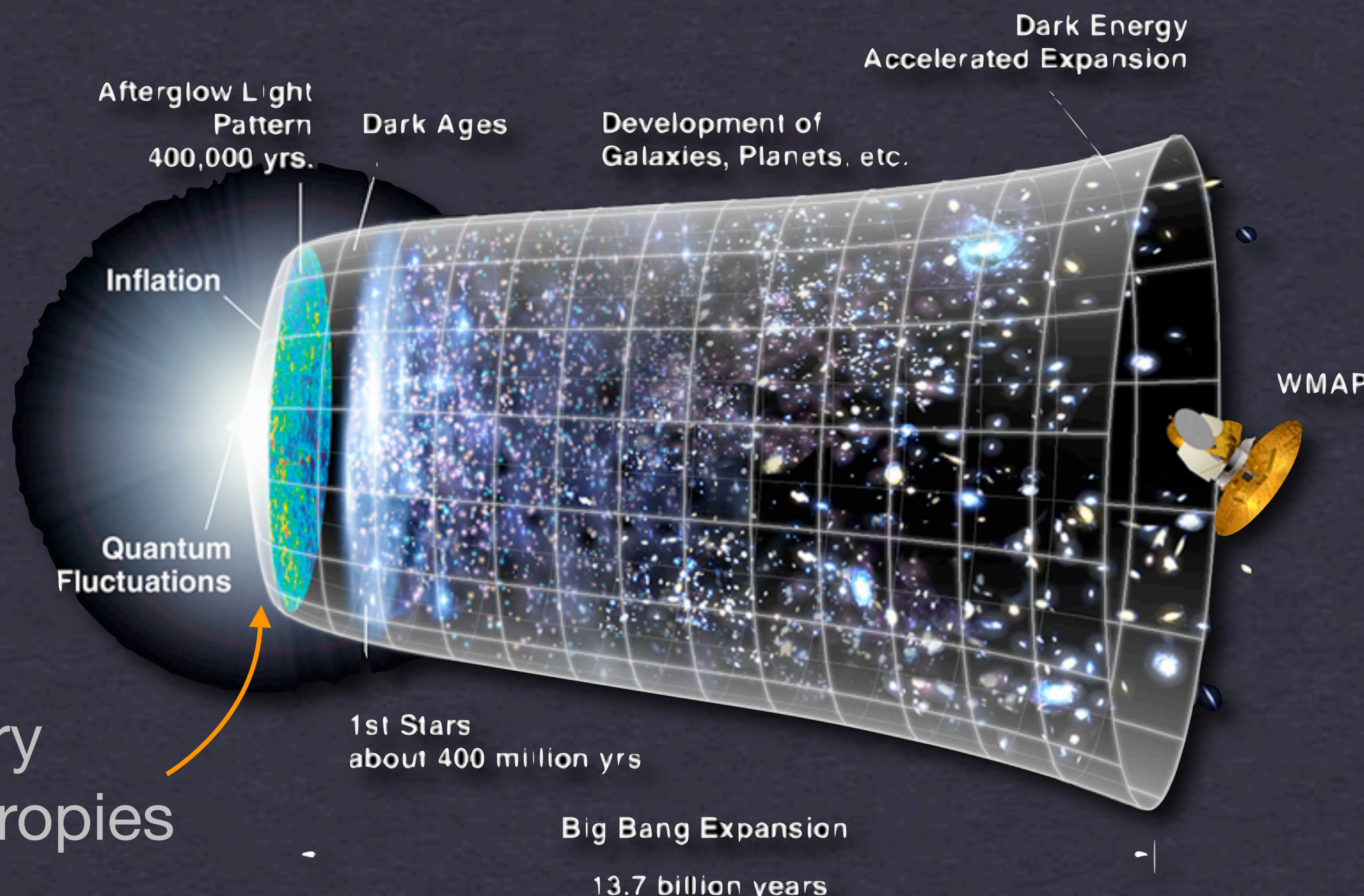
Princeton University

UC Berkeley, Nov 4, 2008.

Introduction

The Importance Of Being Secondary ...



Primary anisotropies

Secondary anisotropies encode information about the **evolution** of the universe and the structure in it.

Secondary Interactions

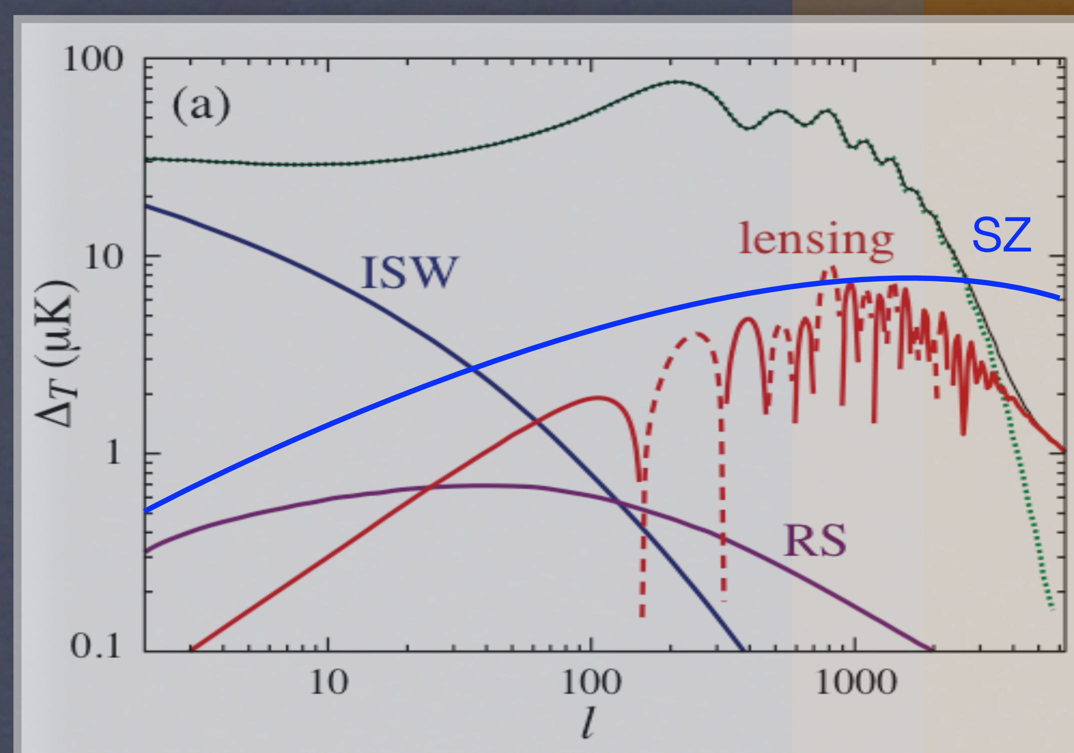
NASA/WMAP Science Team

CMB - A New Era

From Cosmology To Astrophysics

WMAP ACBAR Planck SPT, ACT

At moderate resolutions, dominated by primary signal - probe of cosmology

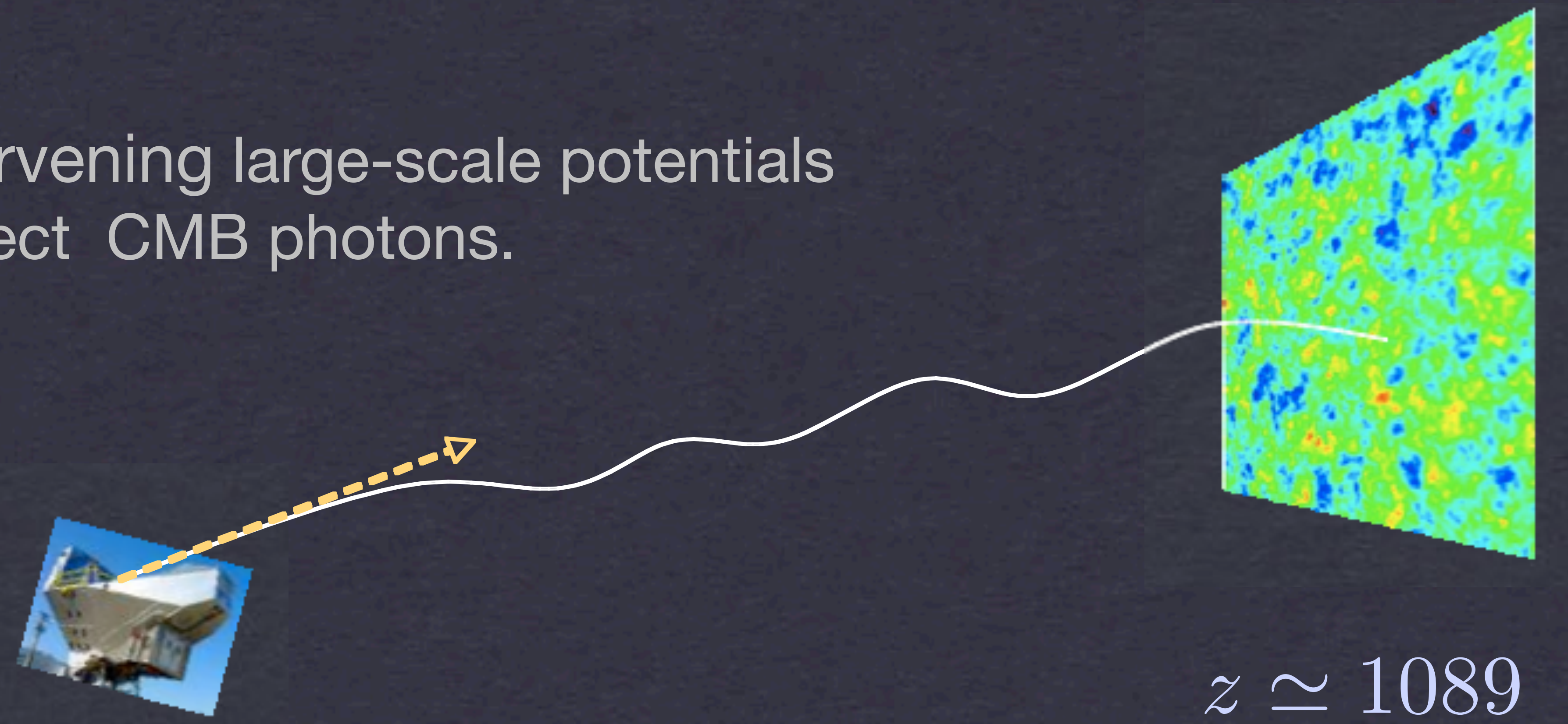


At higher resolutions, appreciable contributions from secondary effects - probe of cosmology and astrophysics.

From Hu and Dodelson (2002) Sims courtesy ACT collaboration

The Secondary We Picked: Gravitational Lensing

Intervening large-scale potentials
deflect CMB photons.



$z \simeq 1089$

$z = 0$

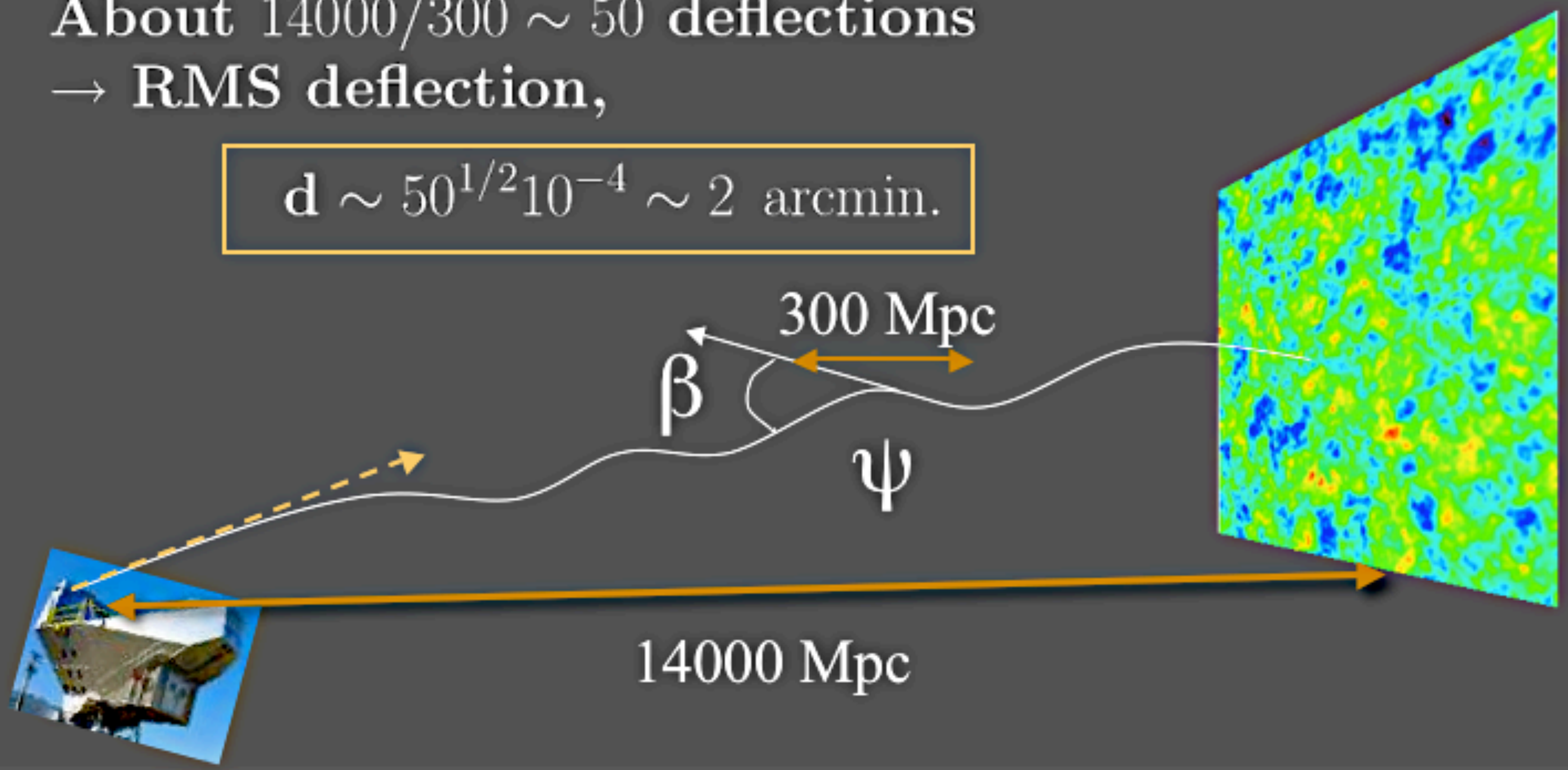
Cool Facts:

CMB is the highest redshift source,
with well understood statistical properties, and
situated at a precisely measured distance.

CMB Lensing: Order Of Magnitude

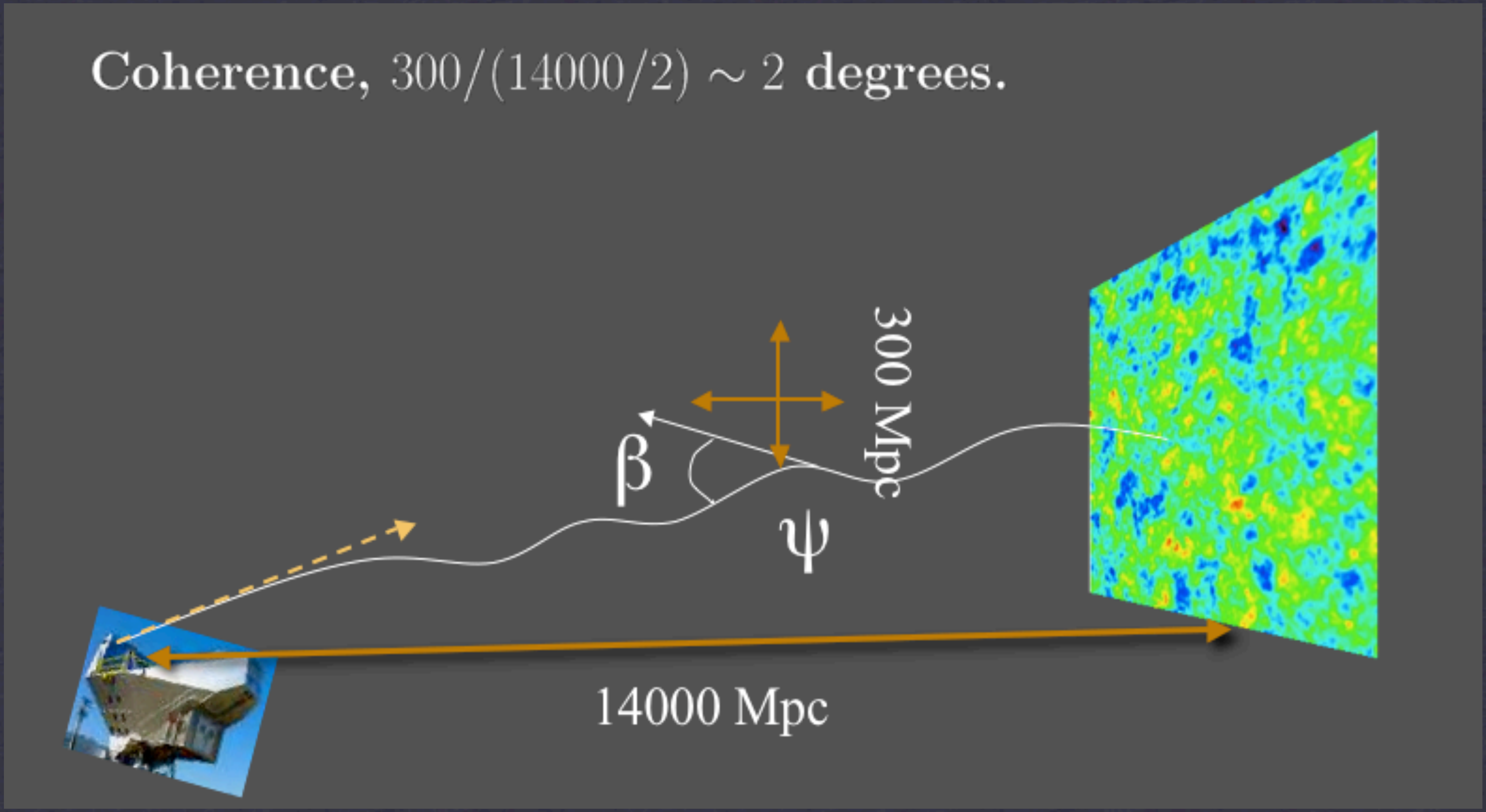
A typical linear potential, $\Psi \sim 2 \times 10^{-5}$
$\rightarrow$ deflection $\beta \sim 4\Psi \sim 10^{-4}$.
About $14000/300 \sim 50$ deflections
$\rightarrow$ RMS deflection,

$$\boxed{\mathbf{d} \sim 50^{1/2} 10^{-4} \sim 2 \ \text{arcmin.}}$$



Lewis and Challinor, (2000)

CMB Lensing: Order Of Magnitude



What Is Different About CMB Lensing?

CMB lensing can be fully described via the deflection field:

$$\Theta(\hat{n}) = \tilde{\Theta}(\hat{n} + \nabla\phi)$$

Lensed Unlensed Deflection Field

ϕ : Effective Lensing Potential

What Is Different About CMB Lensing?

CMB lensing can be fully described via the deflection field:

$$\Theta(\hat{n}) = \tilde{\Theta}(\hat{n} + \nabla\phi)$$

- This is possible because we know the statistical properties of the source screen - so the deflection field can be directly used.

- This makes it a sensitive probe of the large scale modes in the deflection field.

- In case of lensing of galaxies, correlated shape distortions is the observable.

- Second order derivatives of the lensing potential (shear, convergence) are relevant quantities.

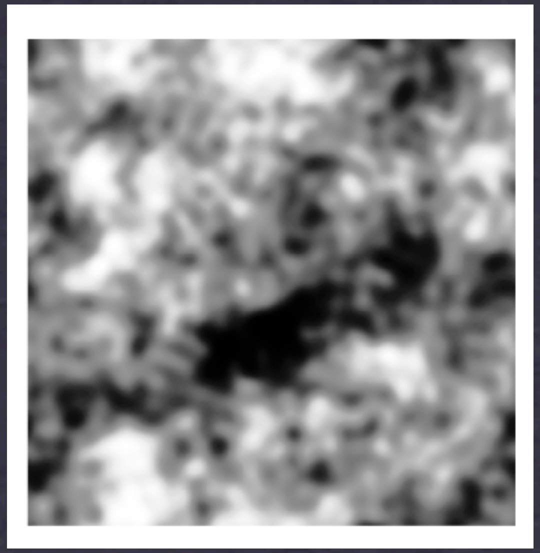
The Deflection Field Can Be Reconstructed!

Lensing correlates the gradient of the temperature field with itself:

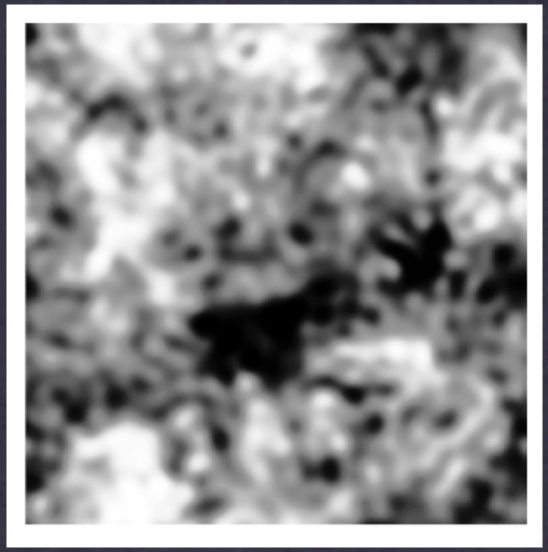
$$\Theta(\hat{n}) = \tilde{\Theta}(\hat{n} + \nabla\phi)$$
$$\simeq \tilde{\Theta}(\hat{n}) + \nabla\tilde{\Theta}(\hat{n}) \cdot \nabla\phi$$

This knowledge can be used to reconstruct the deflection field:

Input Deflection Field



Reconstructed Deflection Field



Seljak & Zaldarriagga (1999), Hu & Okamoto (2002), Hirata & Seljak (2003), Yoo & Zaldarriagga (2008)

Science With CMB Lensing:
The Basics

Lens Reconstruction: The Basis Of All Science With CMB Lensing!

Everything starts with the reconstructed deflection field,

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

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

Deflection field power spectrum.

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

Cross-correlations

LRGs
sub-mm galaxies
Ly-alpha
SZ
cosmic shear

Deflection Field Power Spectrum And Cosmology

Probe of the amplitude of the projected DM potentials between us and the CMB.

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

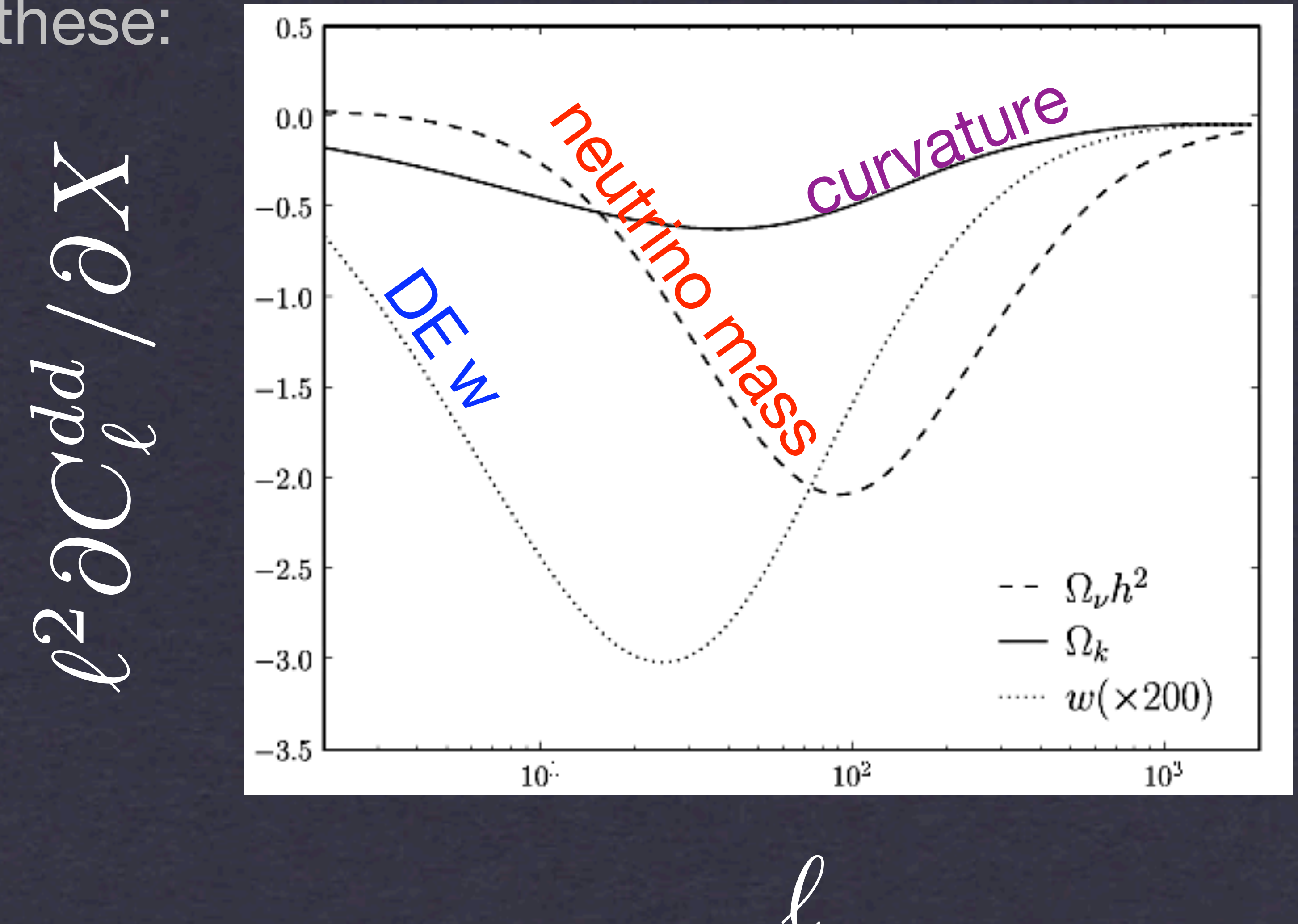
$$\phi = -2 \int \underbrace{\boxed{\frac{d_A(\eta_0 - \eta)}{d_A(\eta) d_A(\eta_0)}}}_{\text{Geometry}} \underbrace{\boxed{\Phi(\eta \hat{n}, \eta)}}_{\text{Matter potential}}$$

Affected by parameters that affect distance scales and growth of structure in the late universe.

Deflection Field Power Spectrum: Parameter Constraints

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!



K. M. Smith, S. Das, O. Dore et al. (2008), CMBPol Lensing White Paper (in prep)

Deflection Field Power Spectrum: Parameter Constraints

Without lensing,

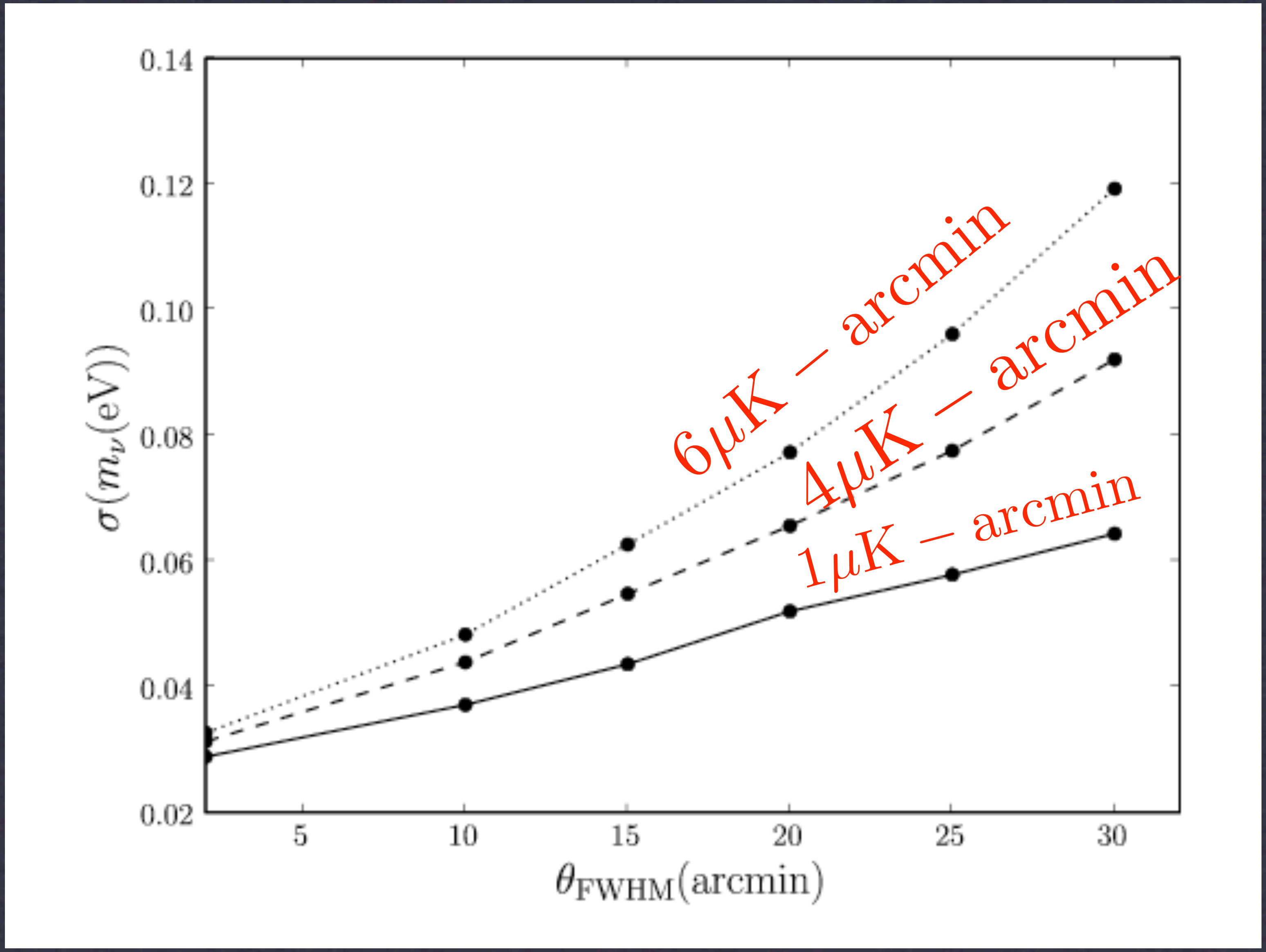
$$\Delta m_\nu \sim 0.16 \text{ eV}$$

With lensing,

$$\Delta m_\nu \sim 0.04 \text{ eV}$$

see also,
Kaplinghat et al . (2003)
Perotto et al. (2006)
Lesgouruges et al. (2006)

Error on Neutrino mass



Beam (arcmin)

K. M. Smith, S. Das, O. Dore et. al (2008), CMBPol Lensing White Paper (in prep)

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!

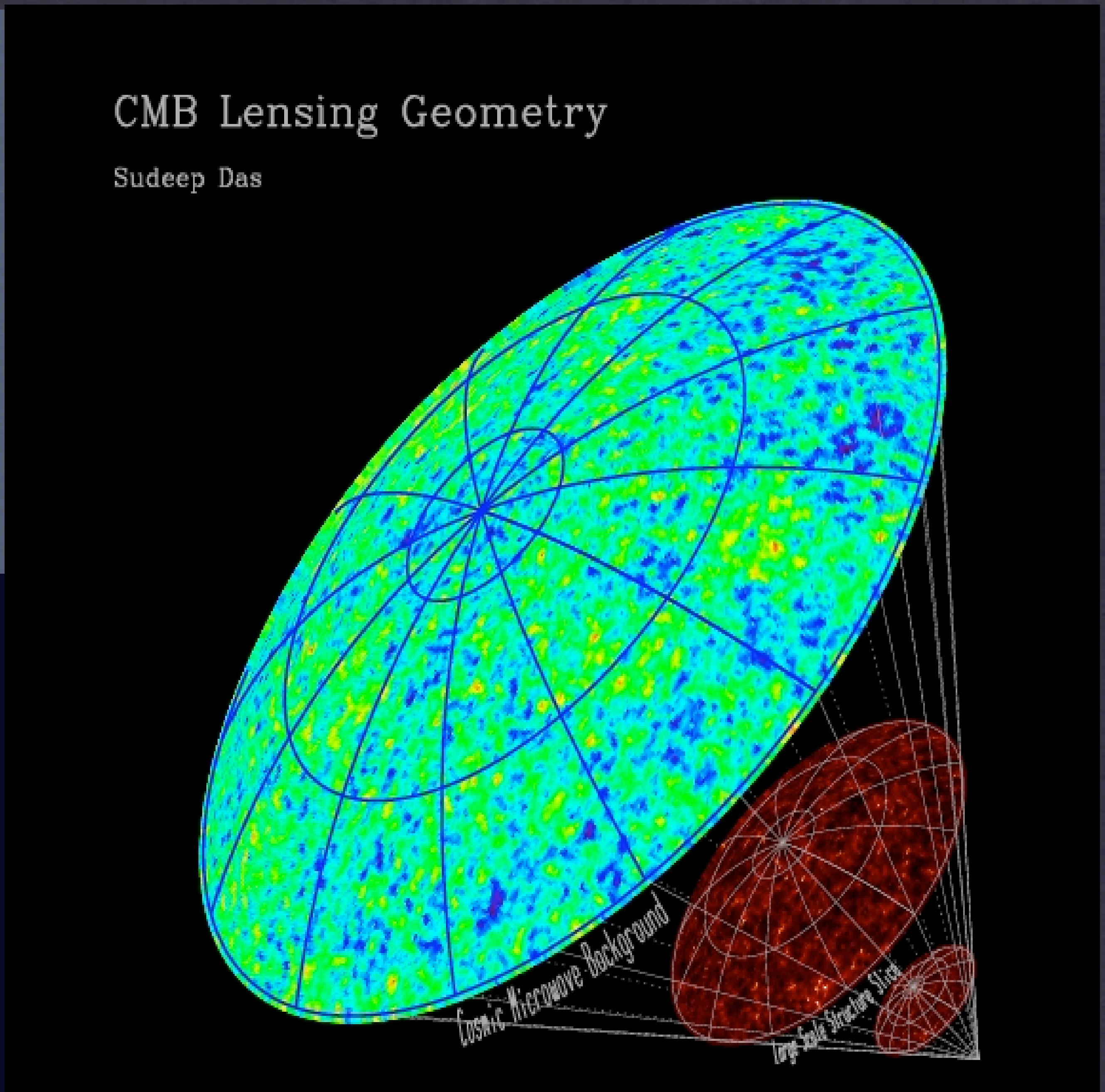
Simulating CMB Lensing

Motivations:

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

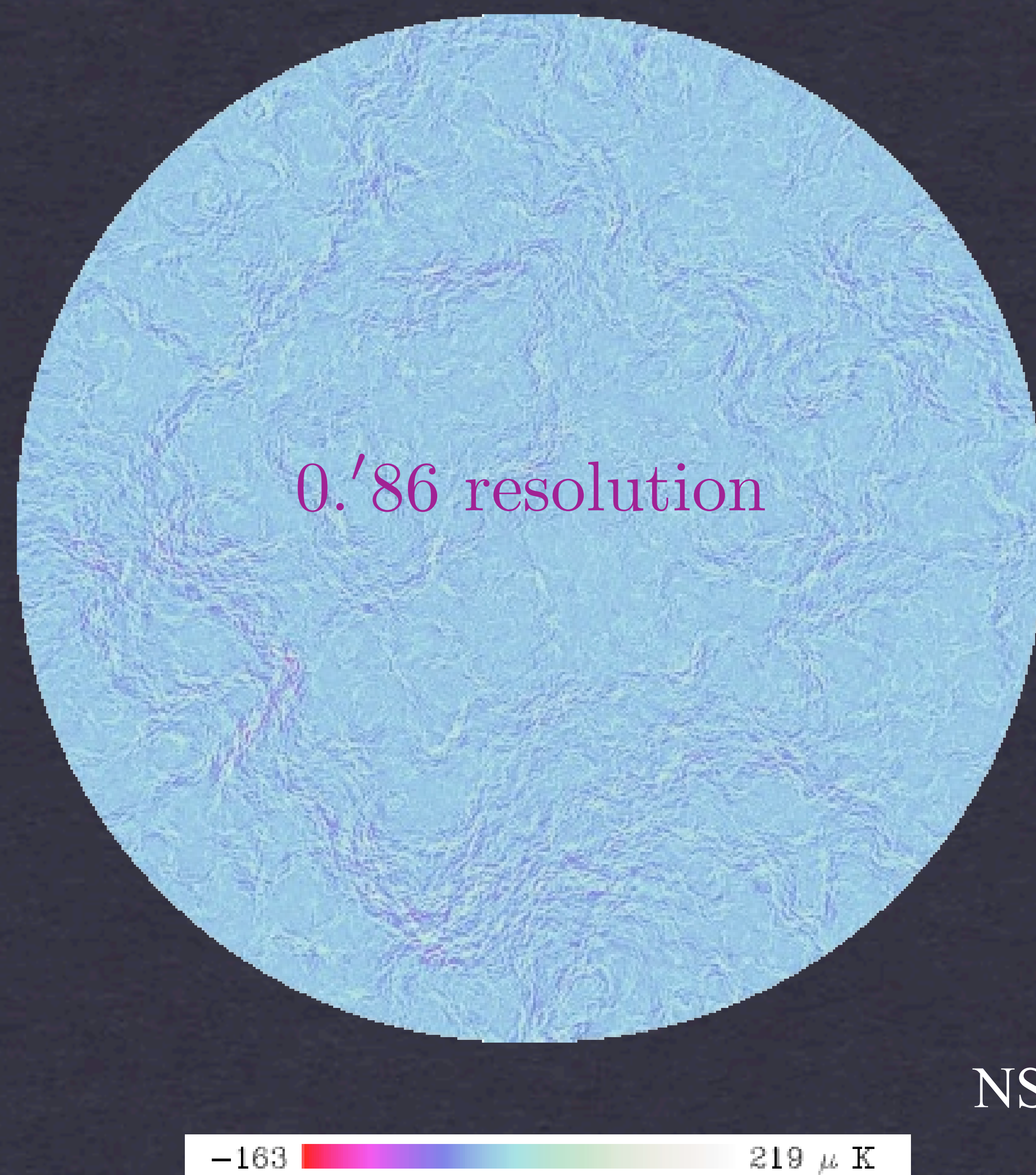
Method:

- 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)

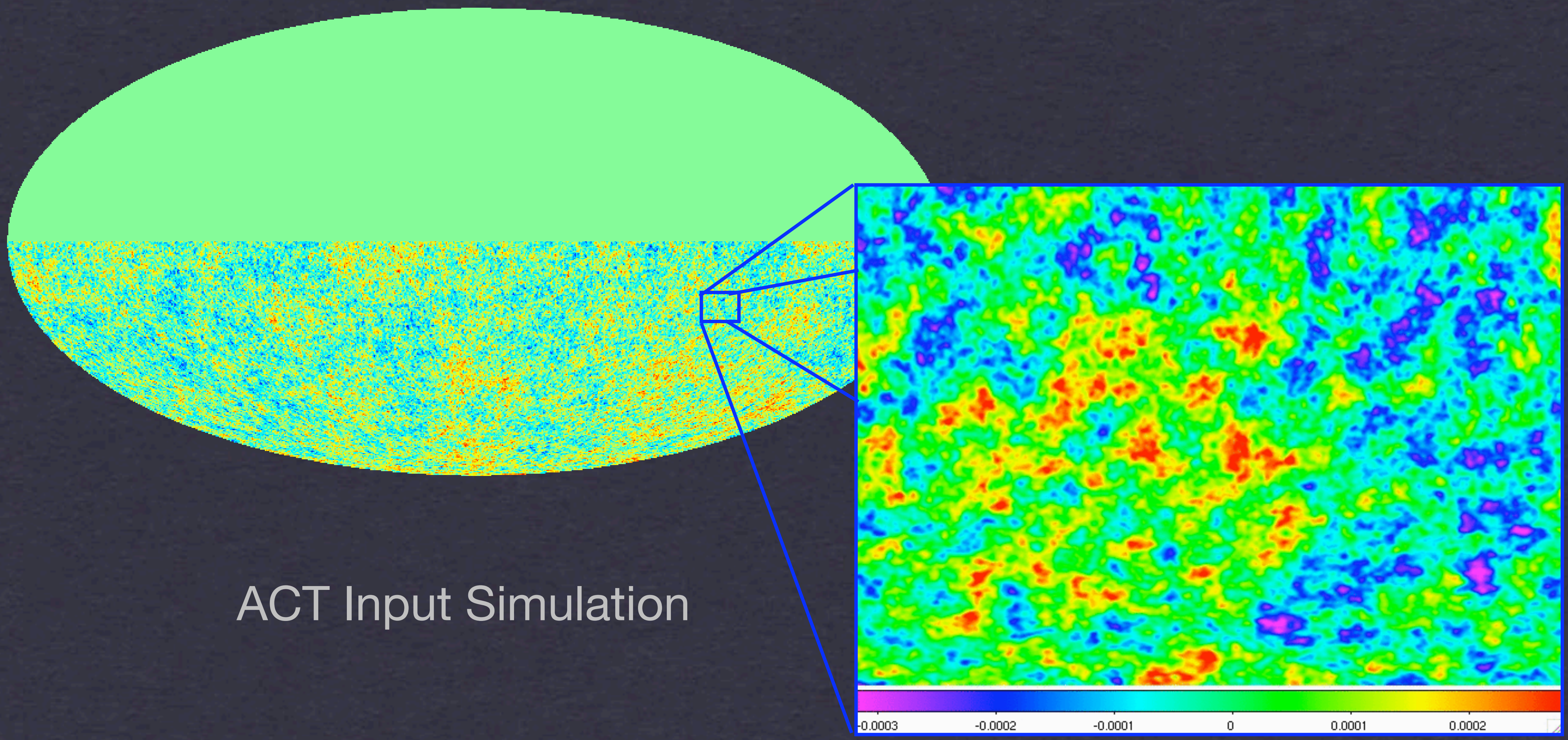
The Lensed - Unlensed Map



NSIDE=4096.

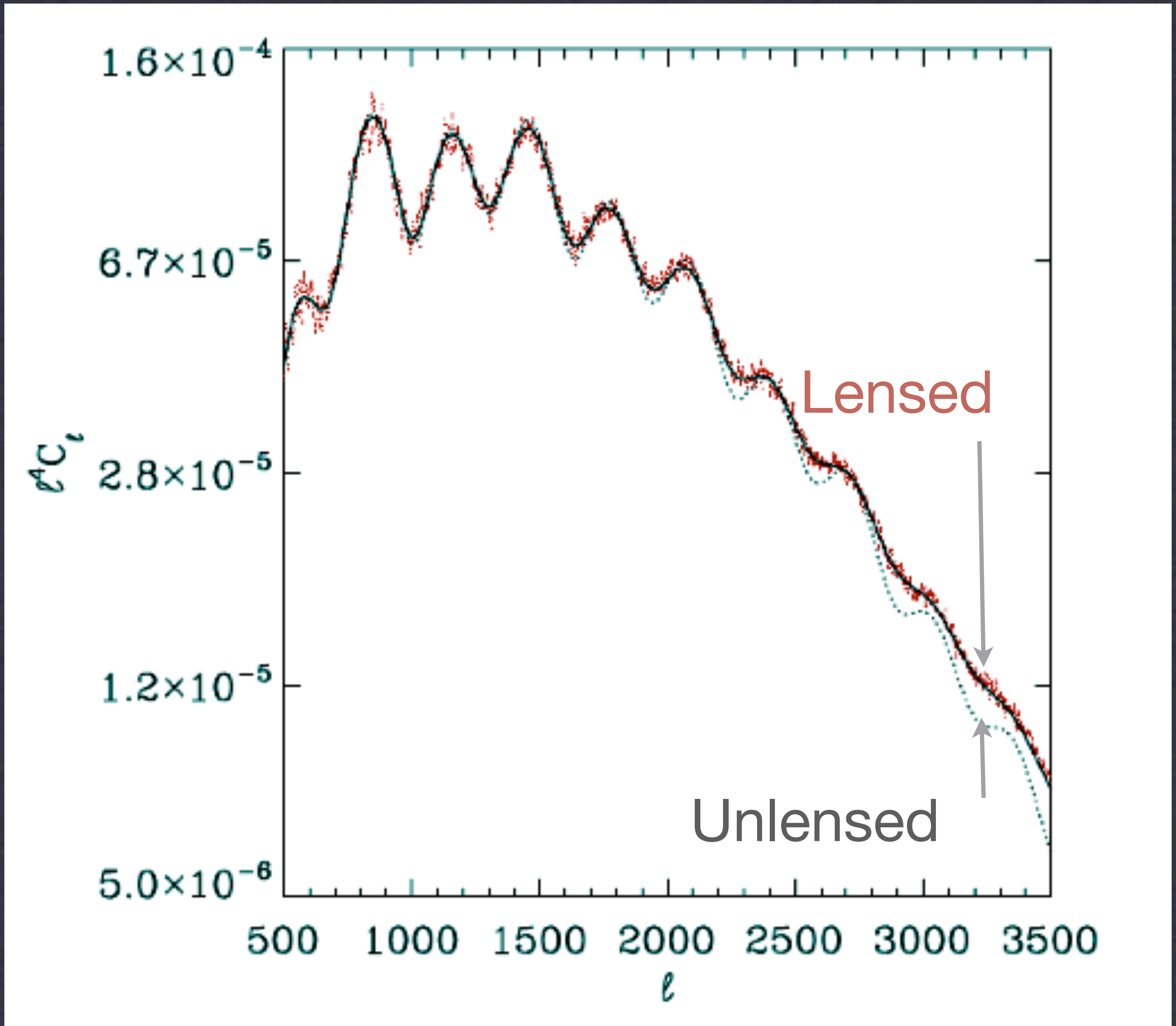
Das and Bode (2008)

Extension To Half And Full-sky



ACT Input Simulation

Large Sky Simulation - Results



Das and Bode (2008)

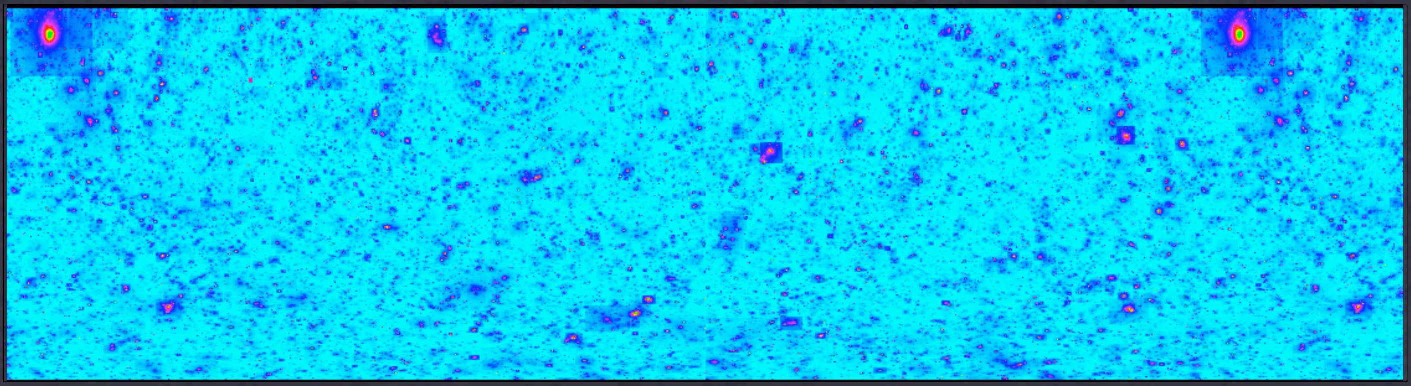
Sub-arcminute resolution lensed CMB maps on full sky.

Excellent match with perturbative theory (black solid line).

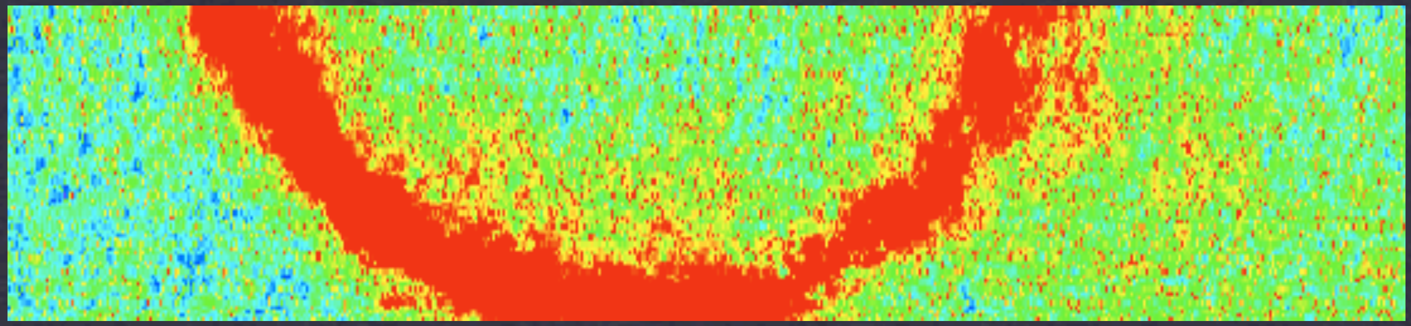
see also:
Carbone et al. (2008)

Auxiliary Simulations

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

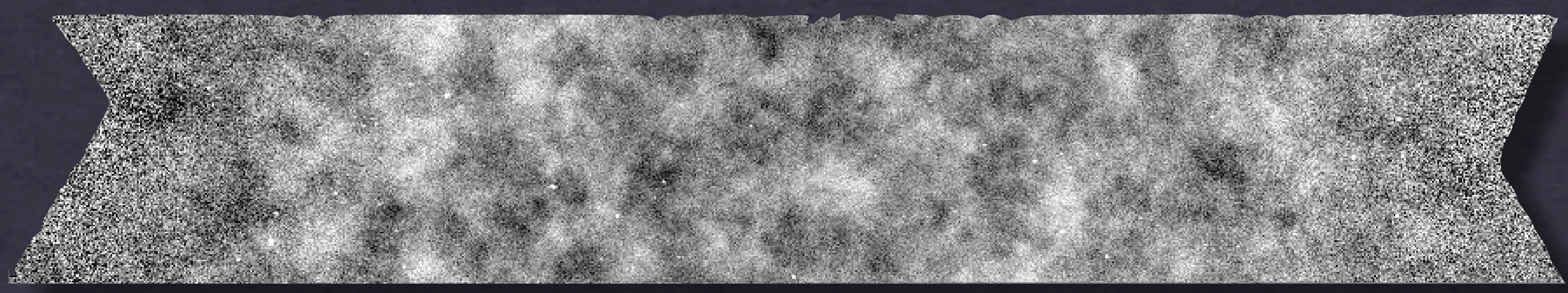


Thermal SZ simulation at 145 Ghz (Sehgal et al. 2007)



A part of the simulated ACT sky at 145 GHz

Simulations > Training Set For Lens Reconstruction



Input simulations run through ACT 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.
- This is work in progress ...
- But we have already run into and solved very similar problems in context of power spectrum estimation ...

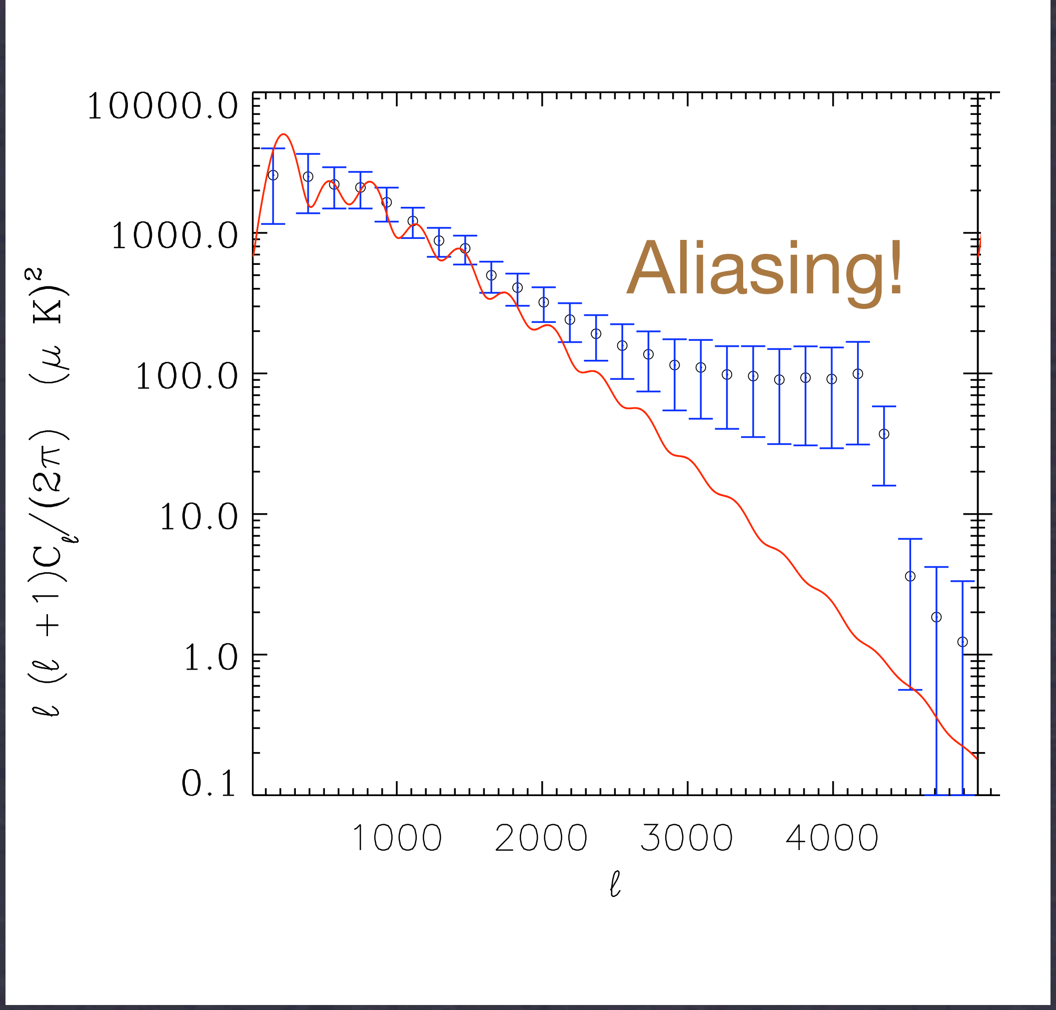
Power Spectrum Estimation:
The Problem

- At high multipoles, CMB power spectrum is very red $C_\ell \propto \ell^{-4}$

- At arcminute resolutions, point sources become a problem and have to be masked.

- Masking and/or hard edges alias power across multipoles.

- Standard deconvolution technique (MASTER; Hivon et al. 2002) de-biases the power spectrum - but produces large errorbars at high ℓ



Aliasing of power in a $4^\circ \times 4^\circ$ map

Power Spectrum Estimation:
The Method

To solve this problem we developed three techniques:

1. The Adaptive Multitaper Method (AMTM)

2. Real-space Prewhitening

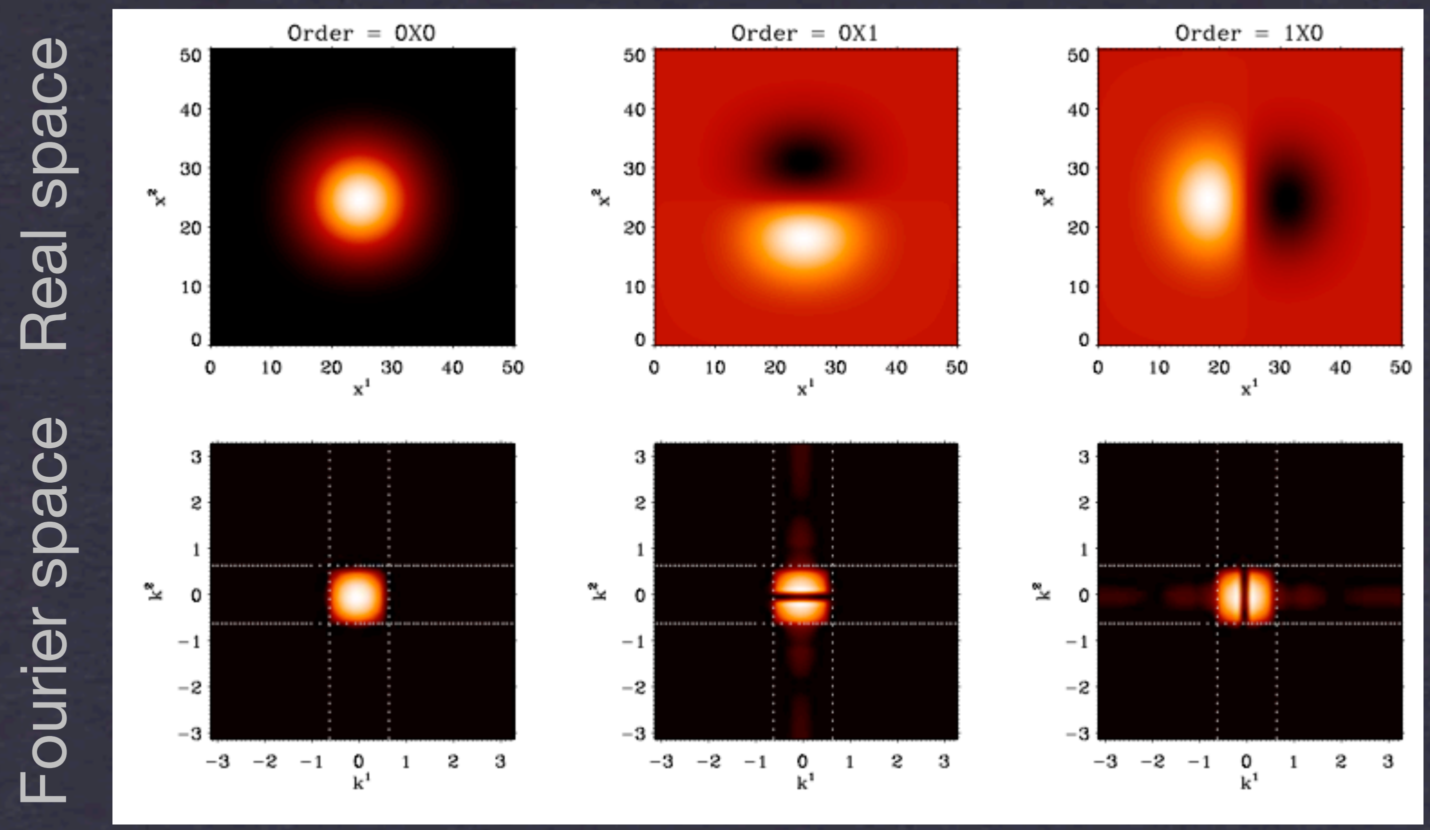
3. Flat sky Deconvolution

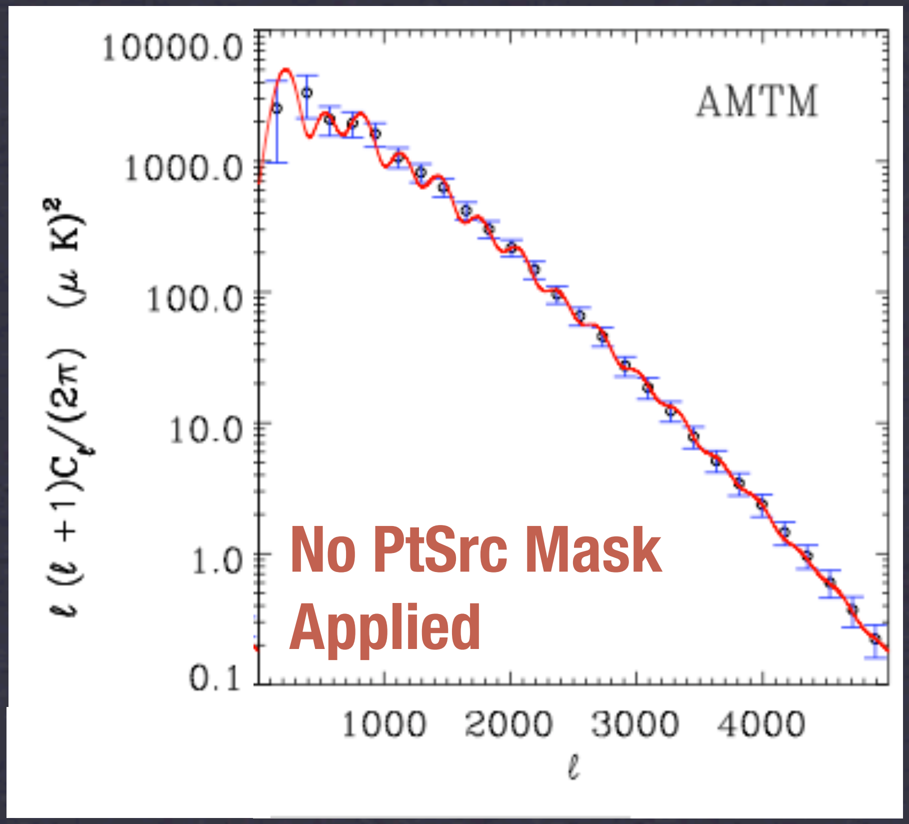
With Amir Hajian, I have written a software called **TaperMaster** to perform these calculations. It will be made public soon.

Das, Hajian and Spergel (2008)

Adaptive Multitaper Method

We multiply the map with a set of tapers designed to have minimal sidelobe power outside a desired frequency width.





Das, Hajian and Spergel (2008)

We compute the adaptively weighted mean of the power spectra of the tapered maps - producing a nearly unbiased estimate of the true PS.

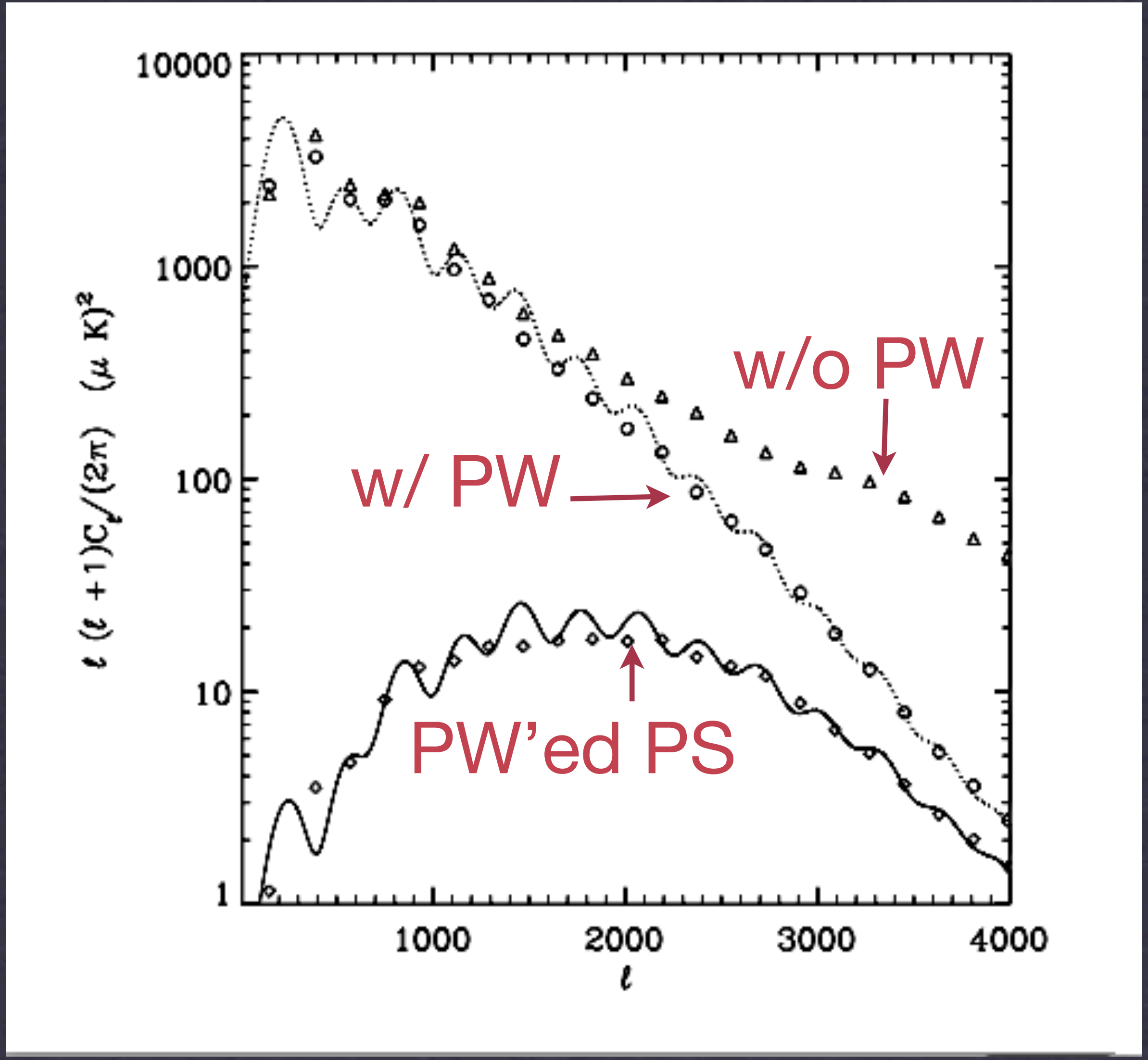
Based on Slepian Sequences (Slepian 1972, Percival and Walden, 1993)

Prewhitening

AMTM breaks in presence of a point source mask.

RECIPE FOR PREWHITENING

- Perform a (series of) real space convolutions so that the resulting map is nearly white.
- Apply mask.
- Estimate its power spectrum with AMTM.
- De-correlate the power spectrum.
- Divide by the Fourier space representation of the prewhitening operation.



Das, Hajian and Spergel (2008)

Deconvolution

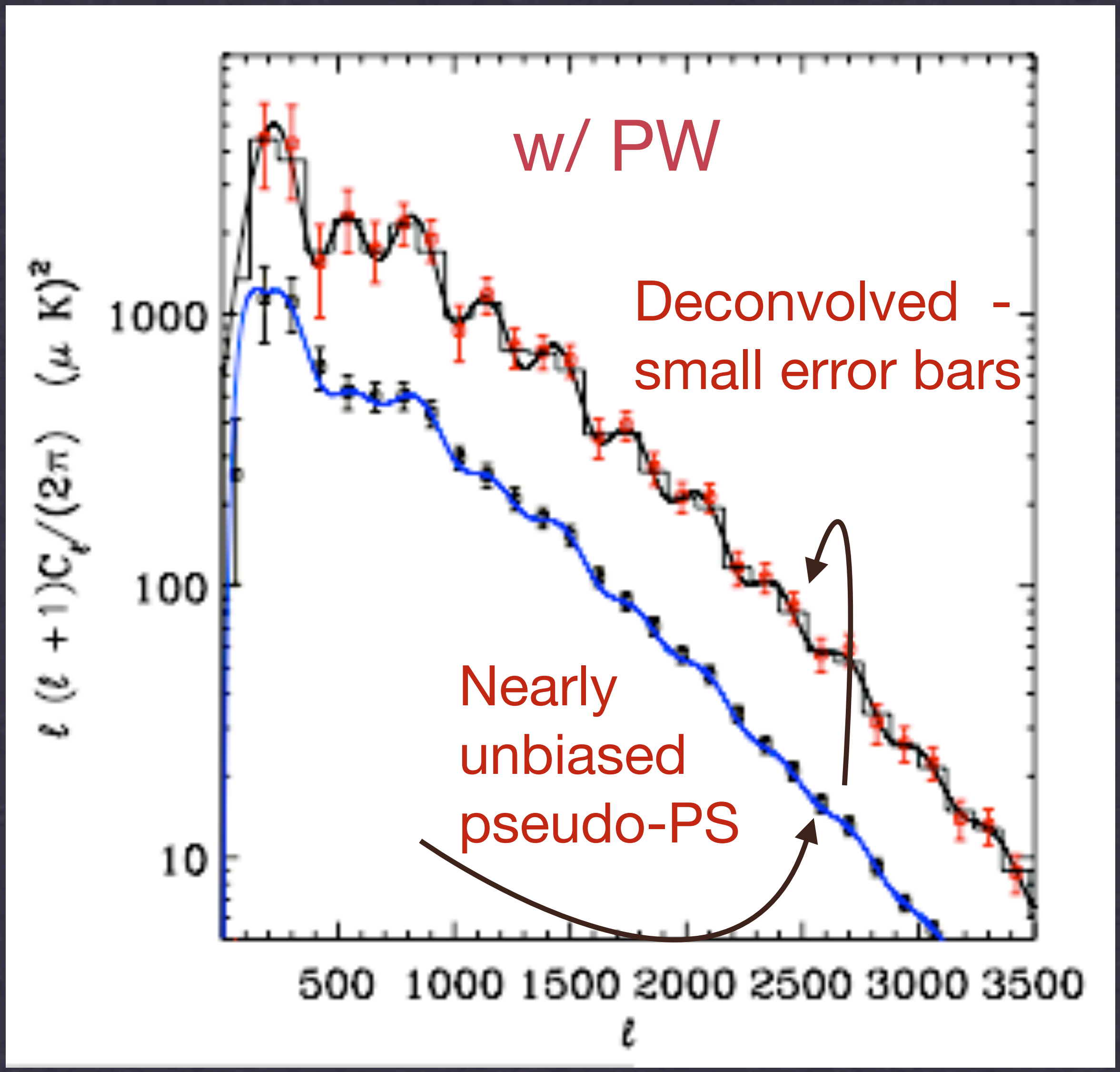
AMTM or PW+ AMTM finally produces a pseudo power spectrum:

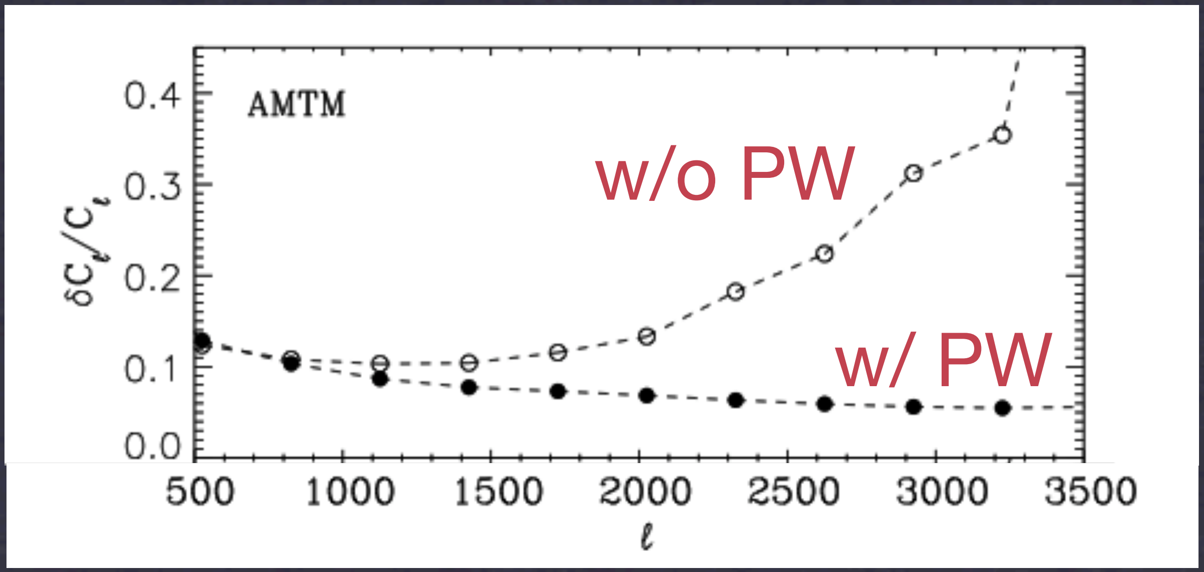
$$\tilde{C}_\ell = M_{\ell\ell'} C_{\ell'}$$

which has smoothed features. This can be deconvolved by inverting M.

Without PW, the pseudo PS is highly biased;

After deconvolution it has 4-5 times larger error bars than the PW case, requiring 16-25 times more observing time!





Stay Tuned For Extensions Of These Methods To Robust Lens Reconstruction Algorithms..

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

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

Great Signal-to-noise!

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

Acquavivia, Hajian, Spergel and Das (2008)

Herschel Galaxies

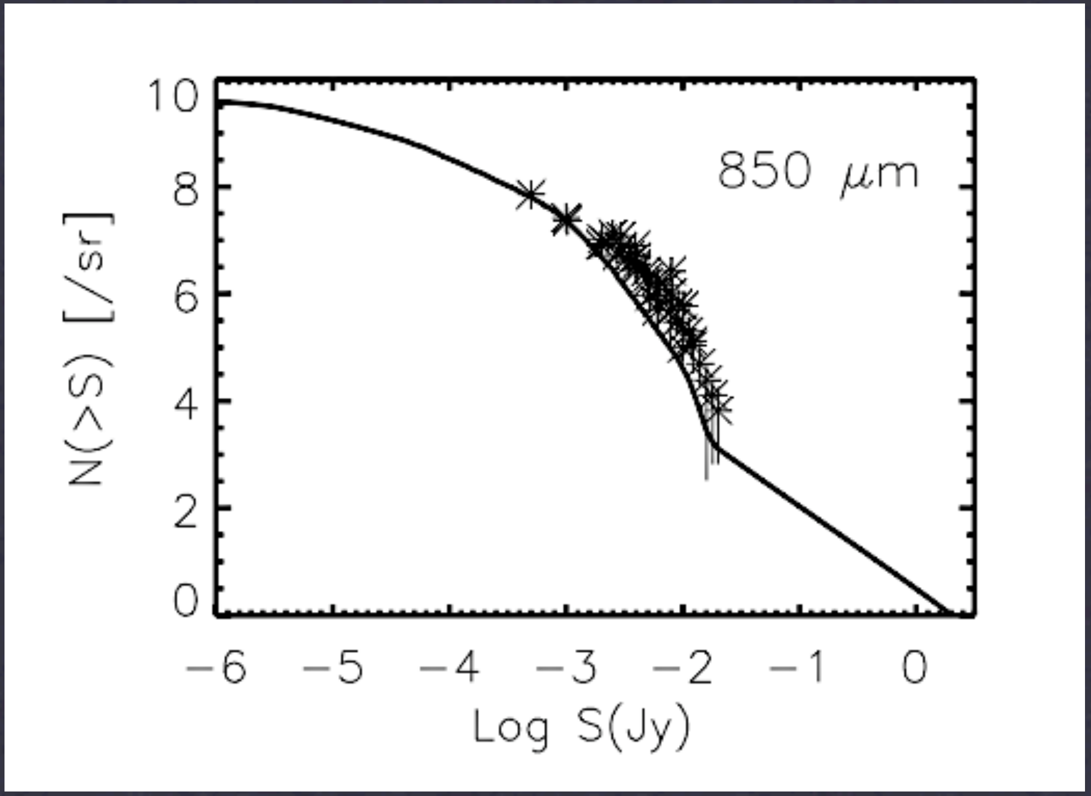
$\hat{\mathrm{d}} \times$ galaxies

- 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)

Similar studies possible with ADEPT, SNAP

Das & Spergel, in prep

Ly-alpha Forest And CMB Lensing

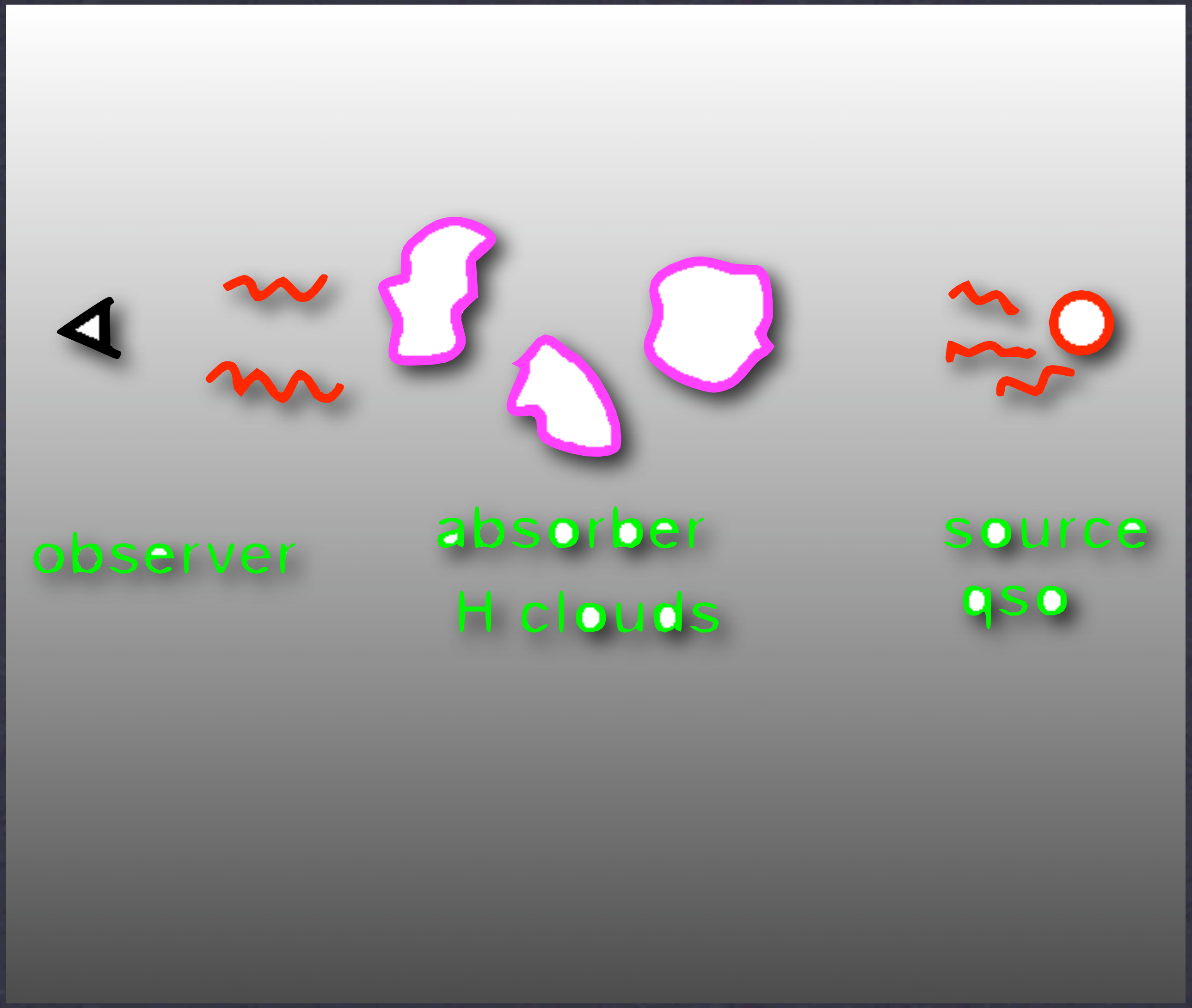
$$\hat{\mathrm{d}} \times \; \mathrm{Ly}-\alpha$$

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

Lensing probes the long wavelength modes.

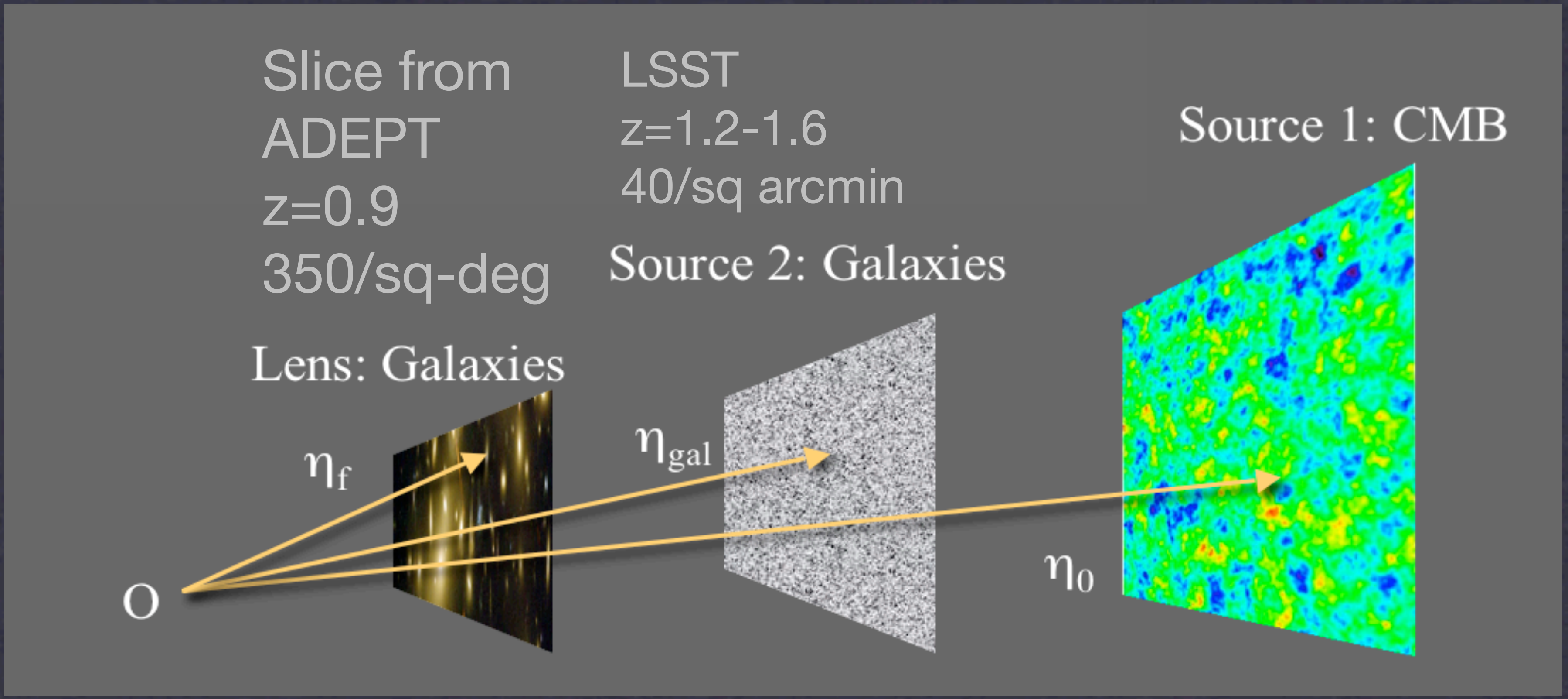
Cross-correlation is a potentially powerful cosmological tool ! Relevant for the BOSS survey: 200,000 QSOs.

Theory project ongoing with Vallinotto, Viel and Spergel.



Vallinotto, Das, Viel, Spergel , in prep

Weak Lensing: Measuring Distance Ratios



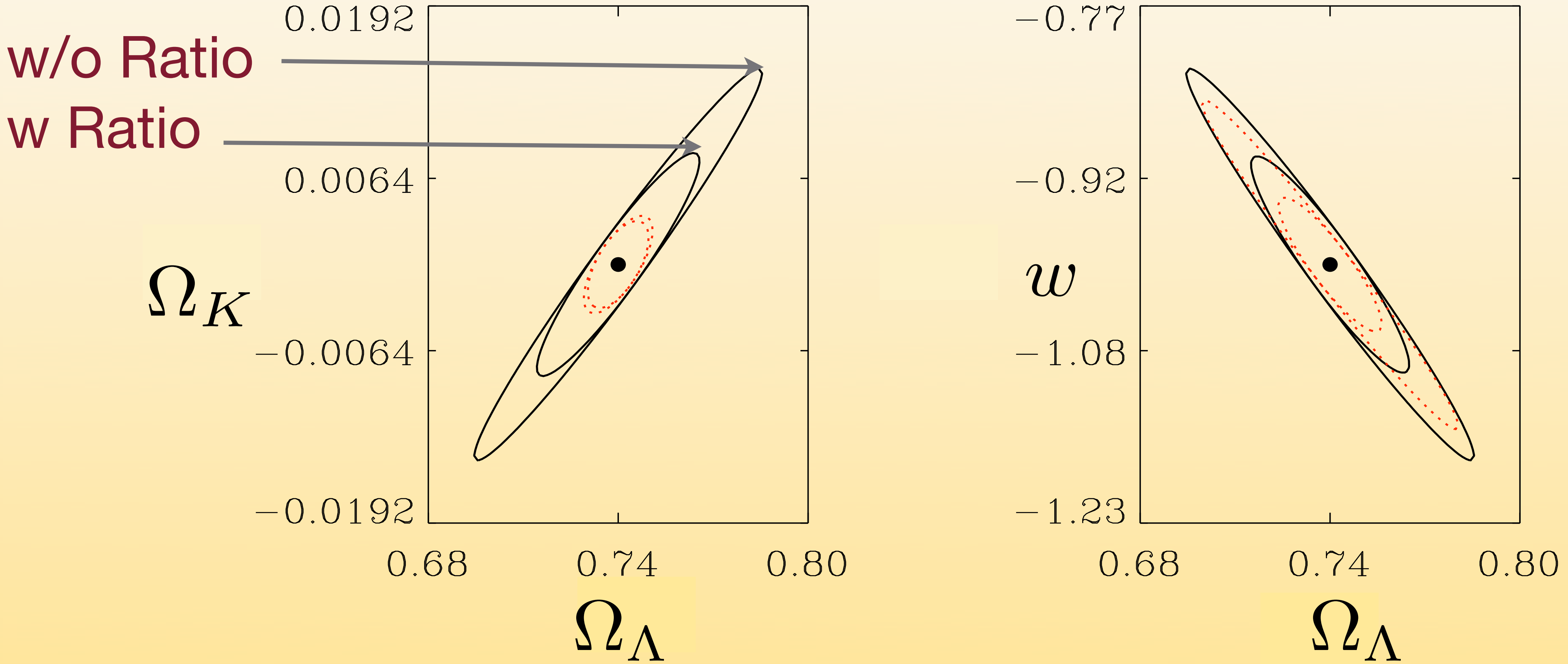
Das & Spergel (2008)

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

$$\rightarrow \frac{d_A(\eta_0 - \eta_f)d_A(\eta_{\rm gal})}{d_A(\eta_{\rm gal} - \eta_f)d_A(\eta_0)}$$ for thin background slice.

(see also Hu et al. arXiv:0708.4391)

Parameter Constraints

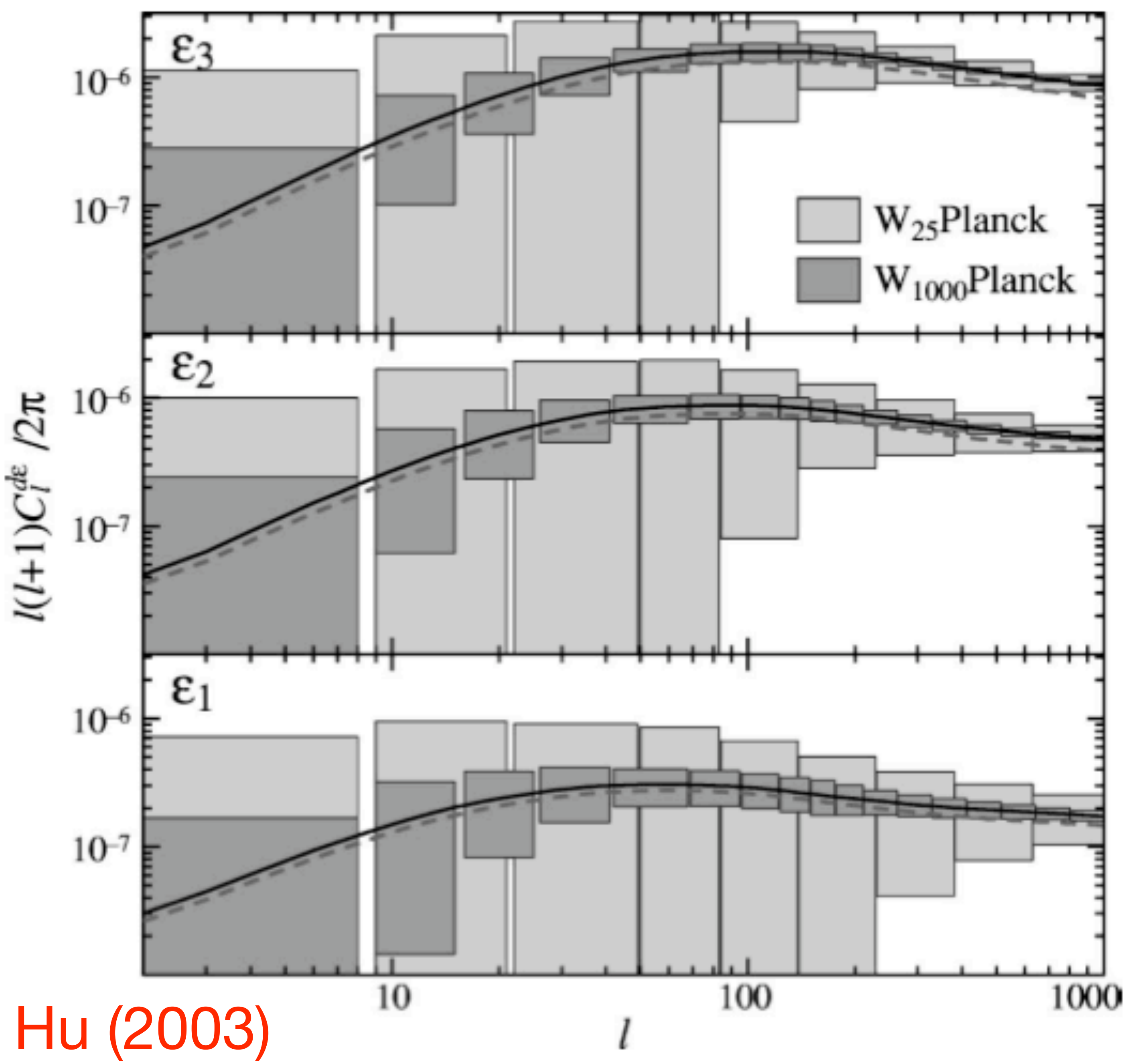


Left Panel: Improvements of constrains in the $\Omega_k - \Omega_\Lambda$ plane for a vacuum energy model with Planck by adding a 1% measurement of the lensing-ratio. The outer solid contour is the 68% confidence interval from primary CMB alone while the inner solid contour is the same after adding the lensing-ratio. The dotted contours have the same interpretation but represent the case where information from lensing extraction has been added to the CMB Fisher matrix. *Right Panel:* Same as left, but for the $w - \Omega_\Lambda$ plane, assuming flatness.

Planck + 1% Ratio. Red dotted curves: After including lensing in CMB Fisher Matrix Das & Spergel (2008) arXiv:0810.3931

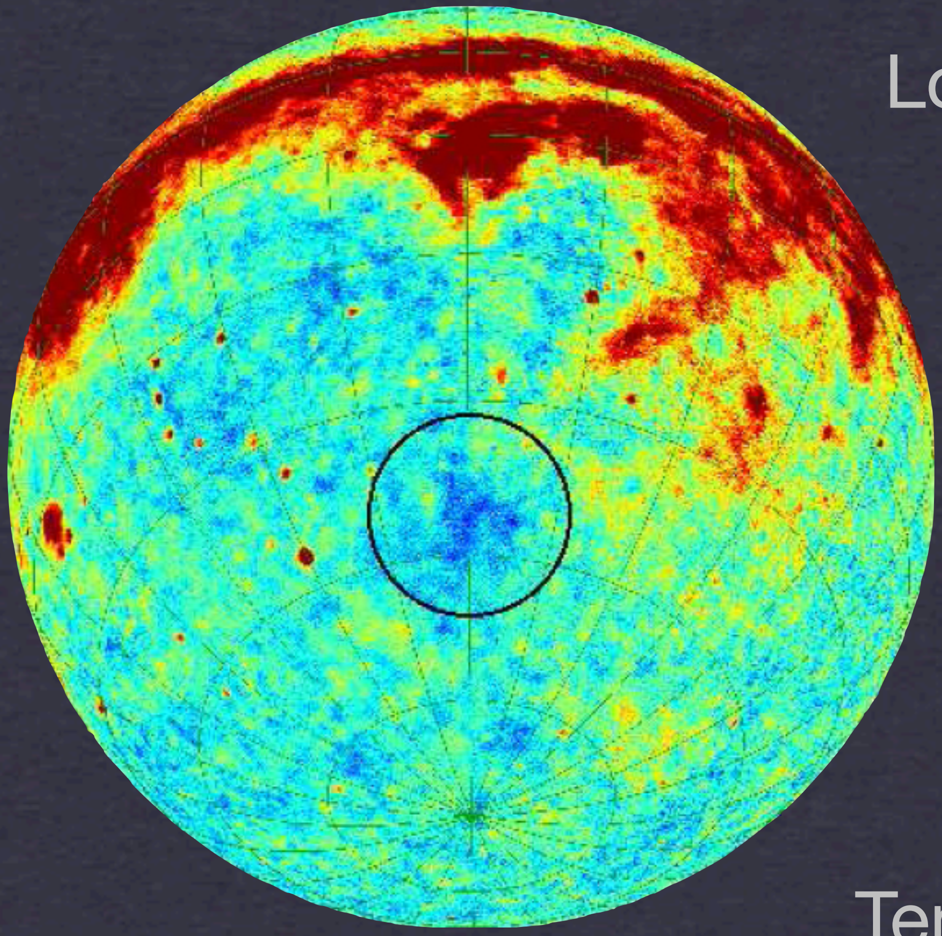
Lensing Tomograpy

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

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

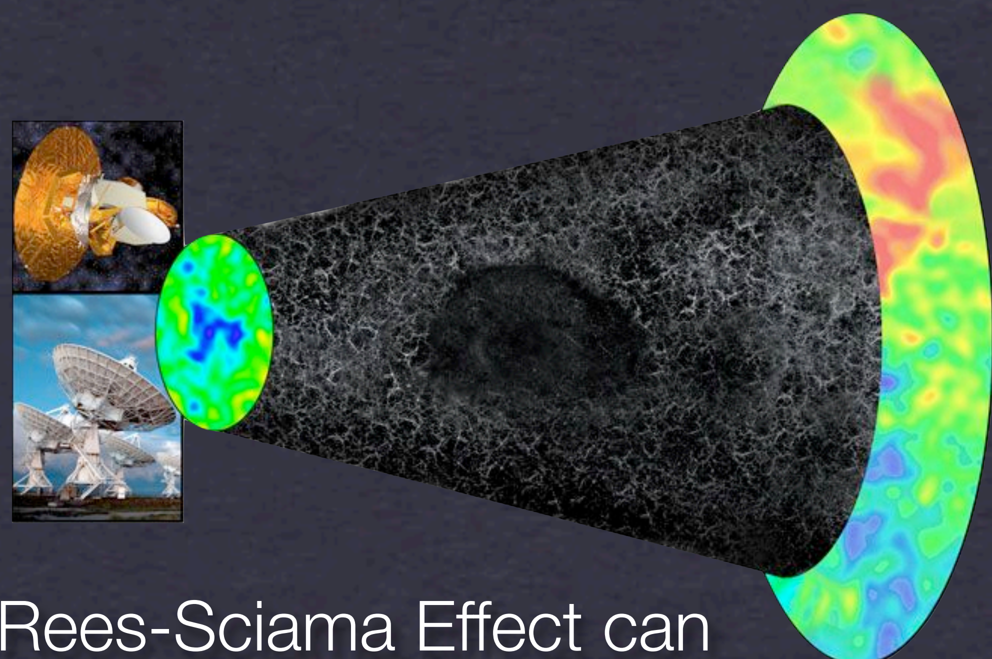
Temperature

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

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)

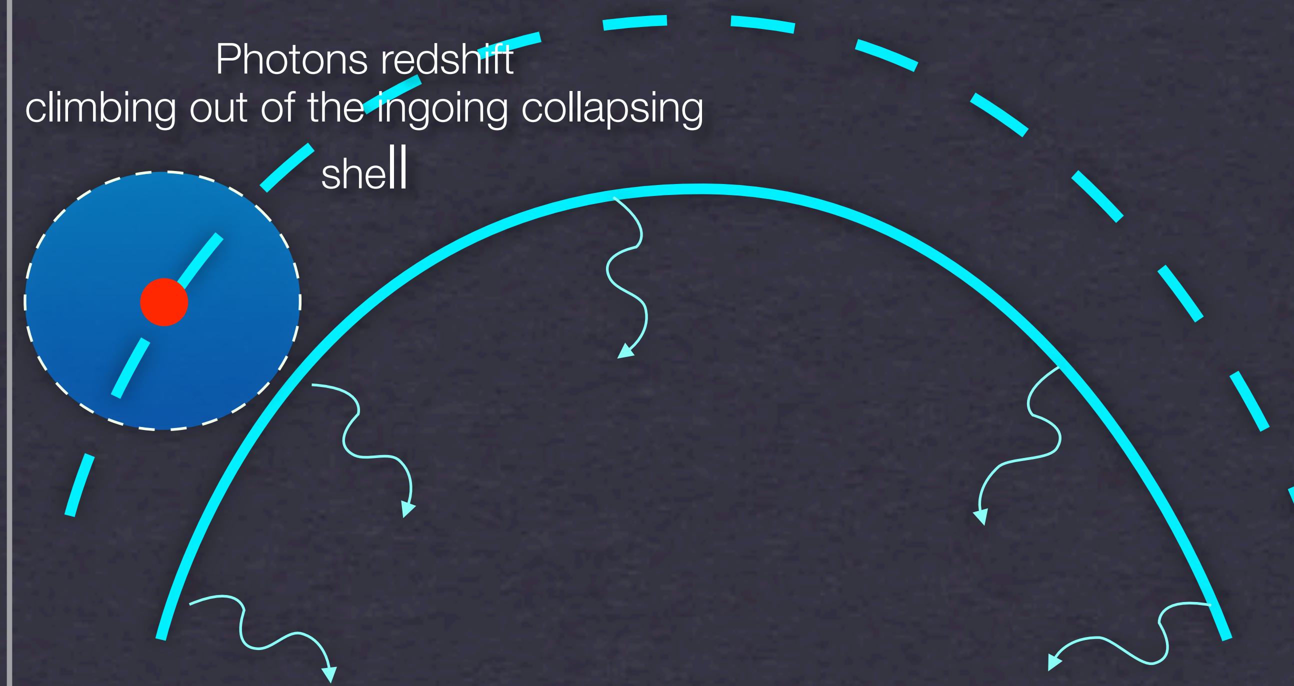


Rees-Sciama Effect can produce a Cold Spot.

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)



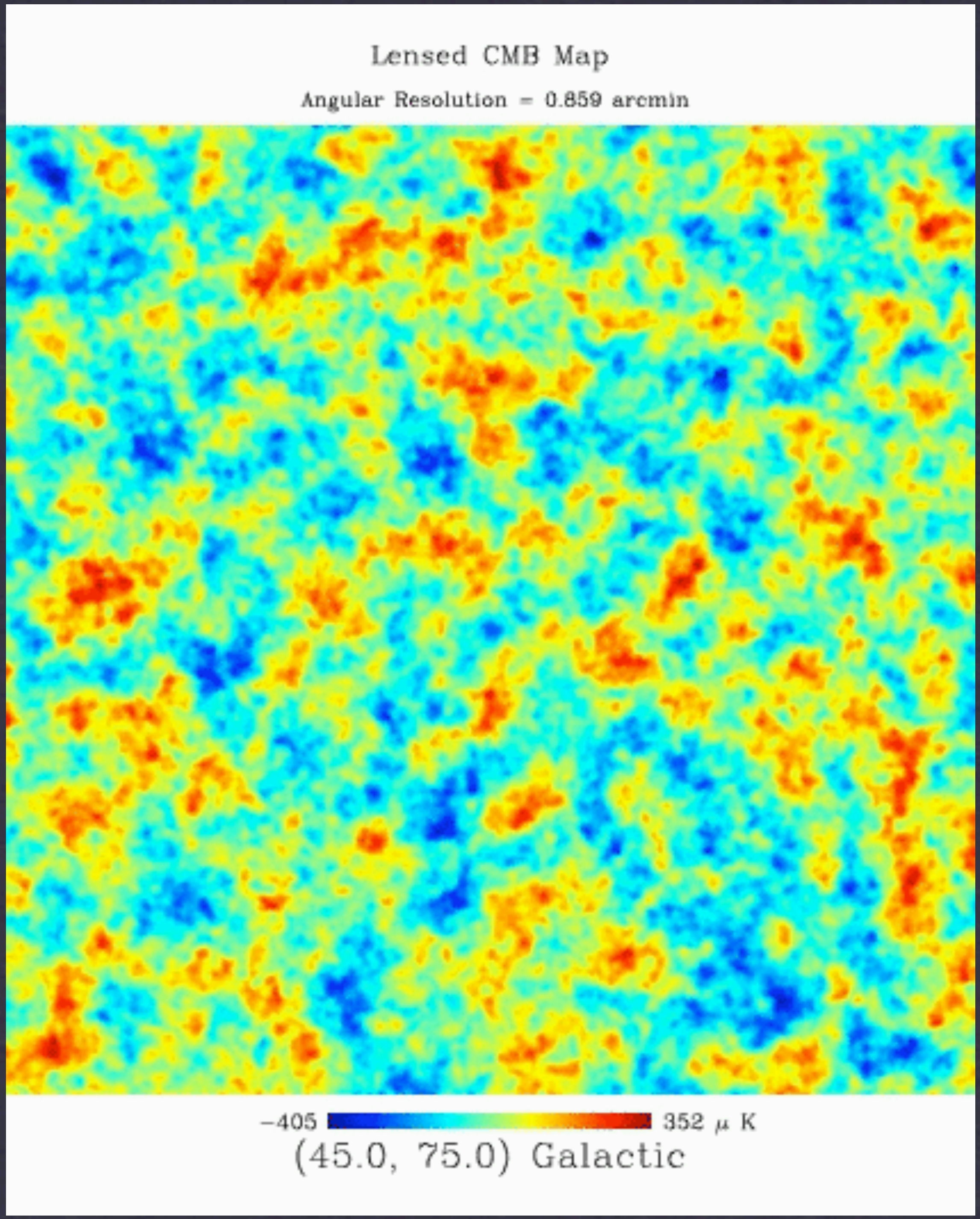
Shell of CMB photons at confomal time τ

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 (2008)
arXiv:0809.4704



Other Projects Underway...

- Constraining Early Dark Energy (EDE) with CMB lensing

Idea: EDE suppresses growth. Use the amplitude of the delfection field is very sensitive to constrain EDE scenarios.

Collaborators: DNS, Viviana Acquaviva

- SZ - CMB lensing cross correlation.

Cross correlate simulated SZ clusters with reconstructed convergence field :constrain gas-pressure fluctuations and matter density parameter (Goldberg & Spergel ,1999)

Collaborators: DNS, Hy Trac

- LRG - CMB lensing cross correlation.

Collaborators: Charlie Conroy

Thank You!
And Looking Forward To Exciting CMB Lensing Science Soon From SPT, ACT, Planck!