CMB lensing measurements and the impact of astrophysical foregrounds

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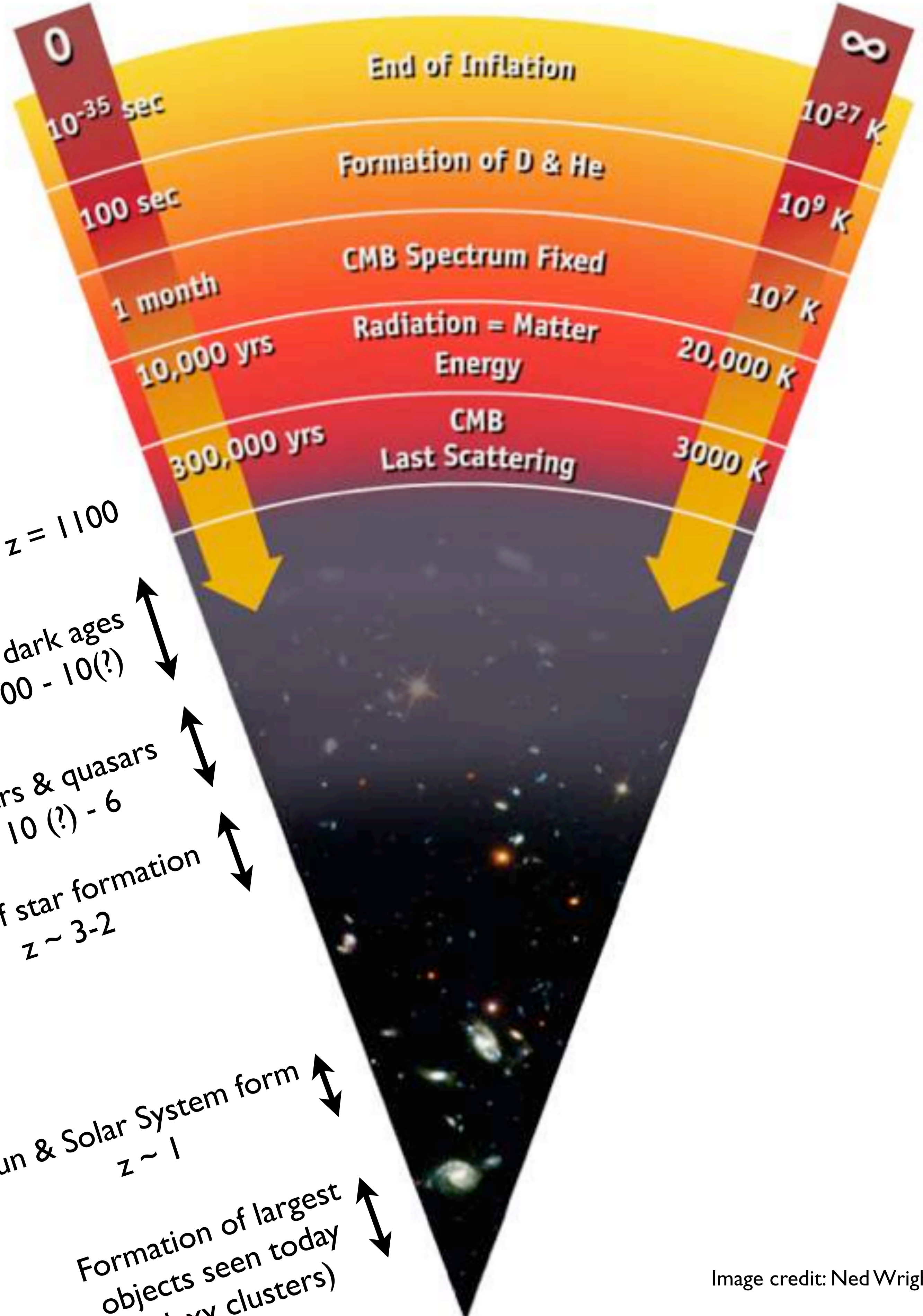
Overview

- CMB lensing and reconstructions
- Science Goals
- Practicalities: astrophysical foregrounds

Brief History of the Universe

(not to scale)



z = 1100

Cosmic dark ages
z = 1100 - 10(?)

First stars & quasars
z ~ 10 (?) - 6

Peak of star formation
z ~ 3-2

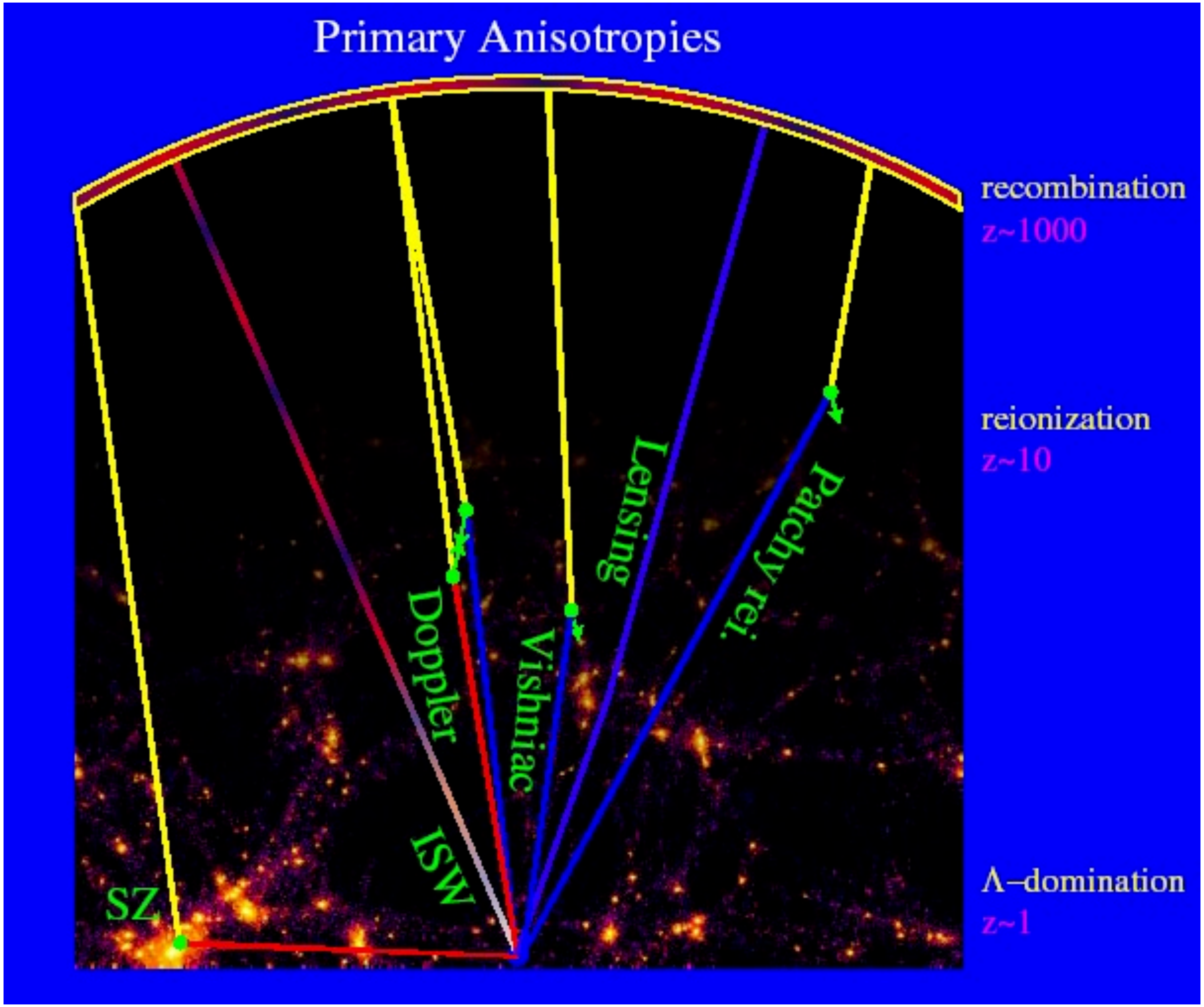
Sun & Solar System form
z ~ 1

Onset of Dark Energy Domination
z ~ 1

Formation of largest objects seen today (galaxy clusters)

Image credit: Ned Wright, UCLA

The CMB as a backlight for nearer objects

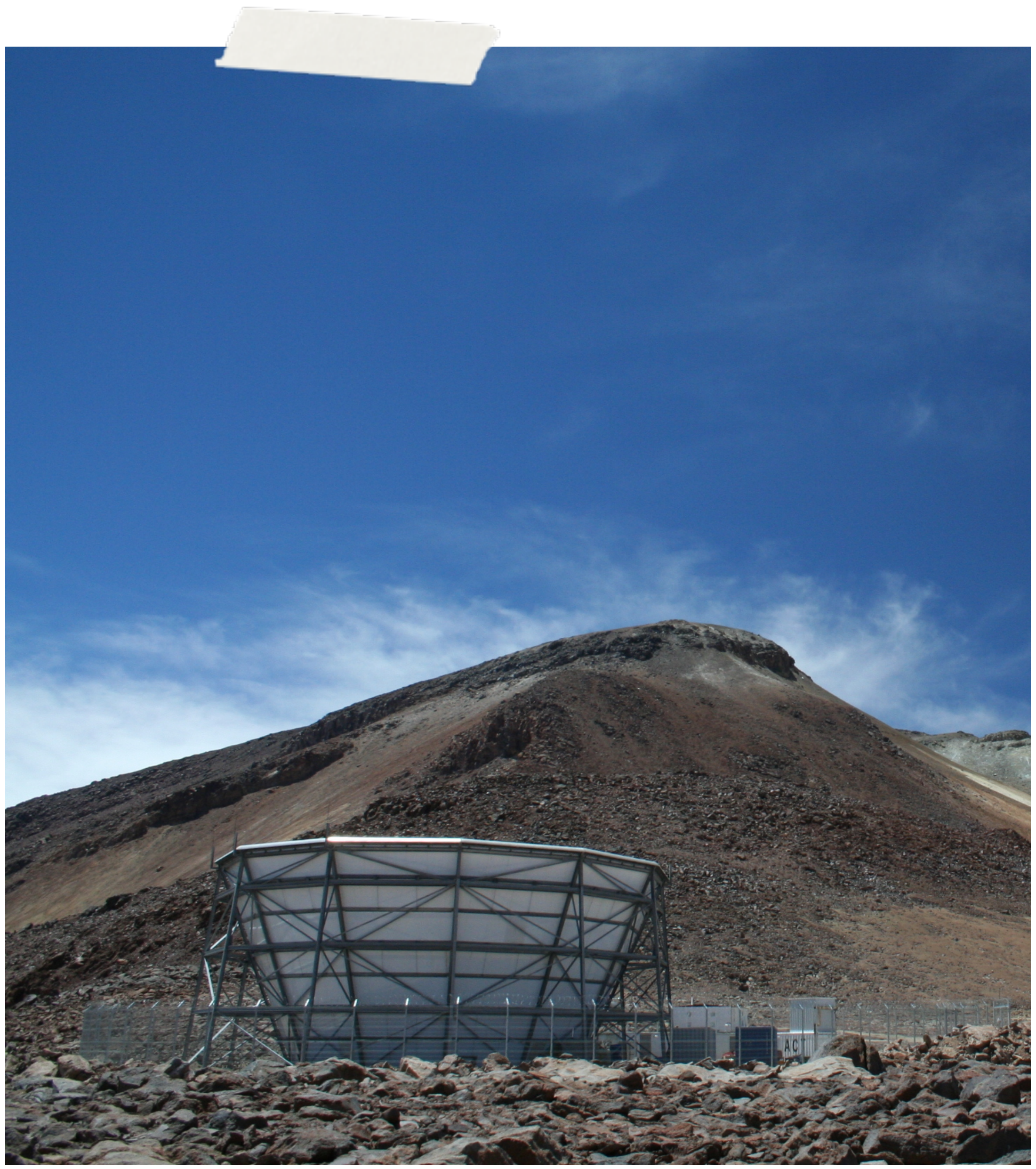


These appear on small angular scales

Wayne Hu's website
background.uchicago.edu/~whu

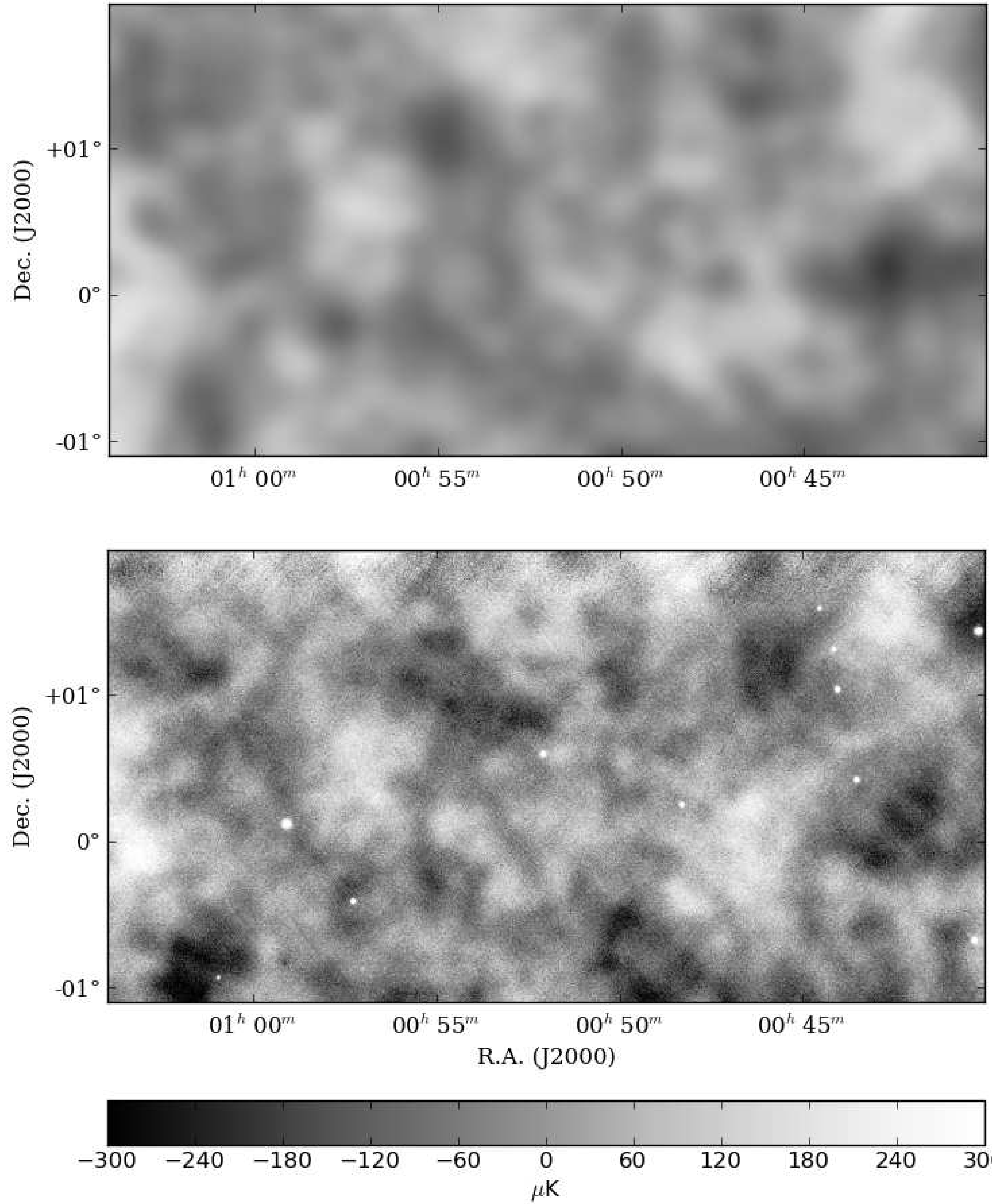
ACT (2007-2010)
ACTpol (2013-...)

- Atacama Plateau, Chile
- Wide-field surveys at 148, 220 GHz
- Small beam (1'.4)
- Low noise



WMAP

ACT

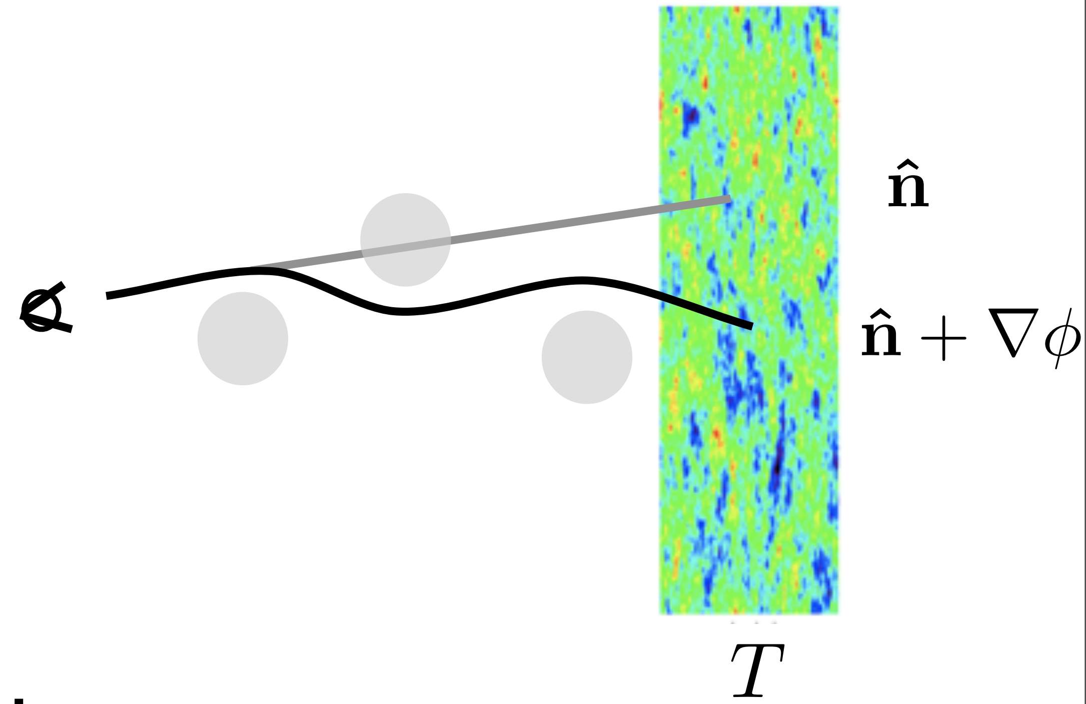


+01°
0°
-01°
Dec. (J2000)
01^h 00^m
00^h 55^m
00^h 50^m
00^h 45^m
R.A. (J2000)
−300 −240 −180 −120 −60 0 60 120 180 240 300
μK

CMB Lensing

Photons get shifted by intervening mass:

$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$



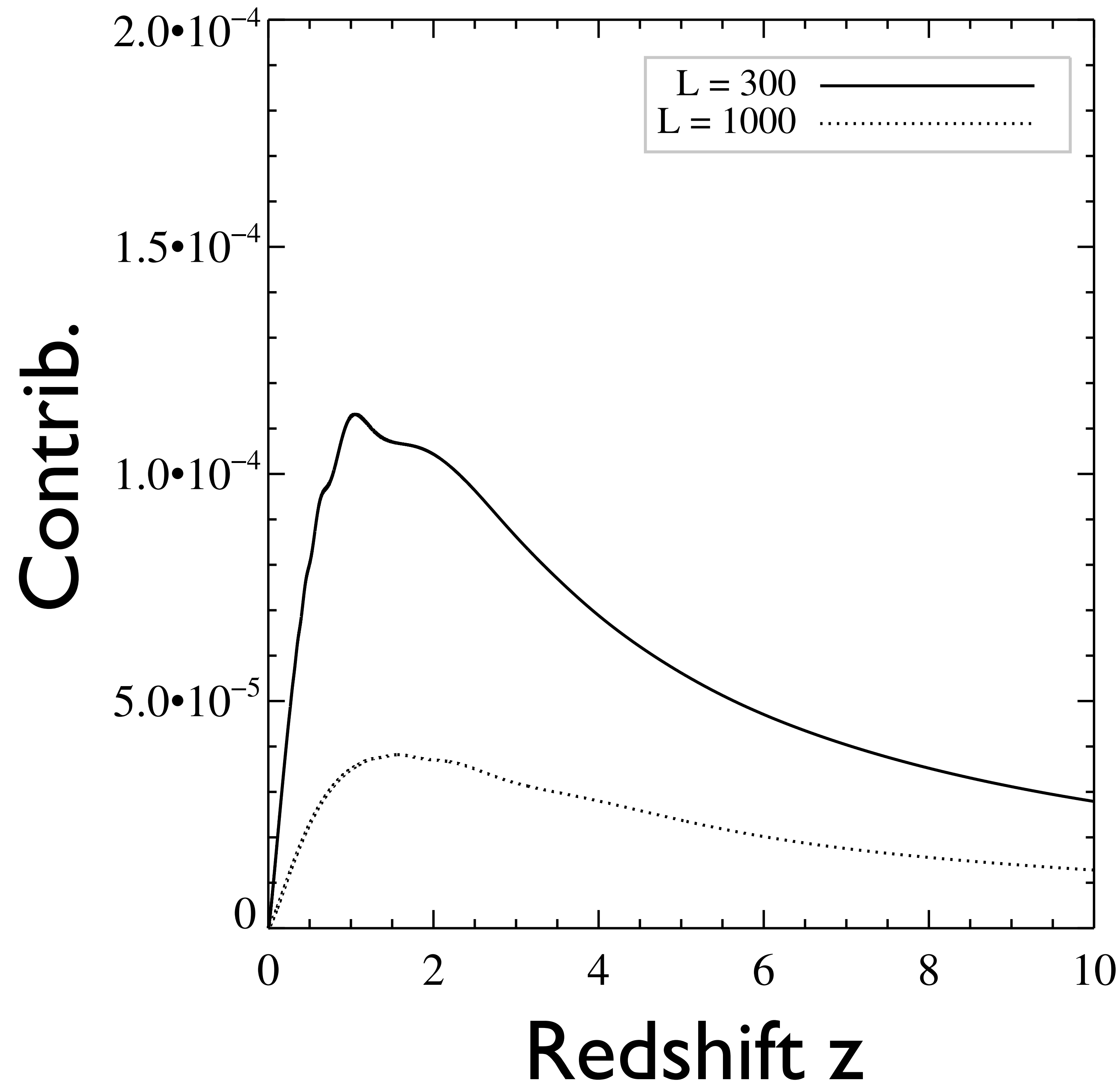
Add many deflections along line of sight:

$$\nabla\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_\star} d\chi\, \frac{\chi_\star - \chi}{\chi_\star \chi} \nabla_\perp \Phi(\chi\hat{\mathbf{n}}, \chi)$$

- CMB is unique for lensing measurements:
  - It's Gaussian, with well-understood power spectrum
  - Its redshift is (a) unique, (b) known, (c) highest

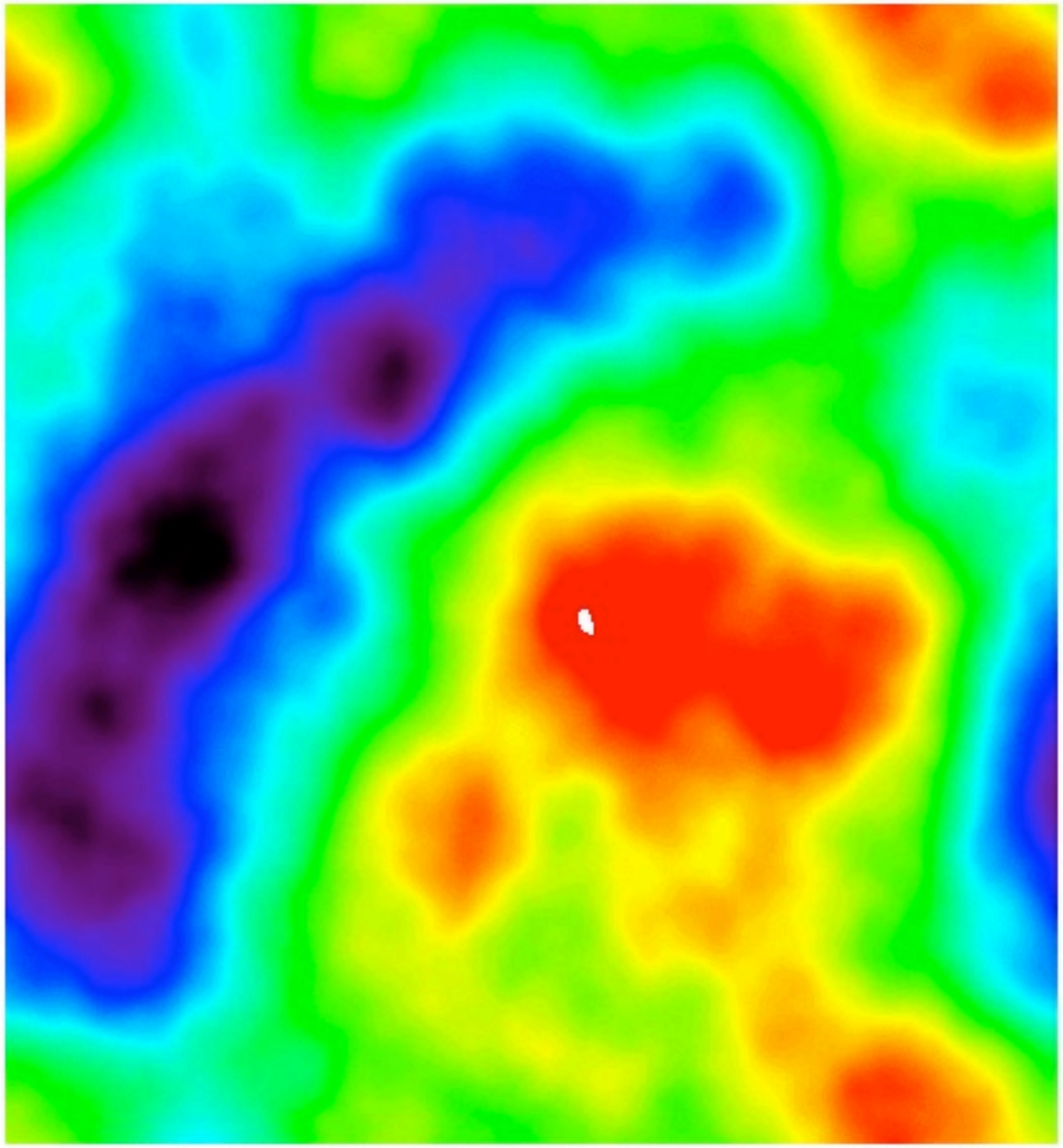
Lensing potential $\phi(\hat{\mathbf{n}})$

- Lensing angle small: $|\nabla\varphi|_{RMS} \sim 2'.7$
- Coherent over large scales (10°)
- Broad kernel in matter, peaks at z ~ 2

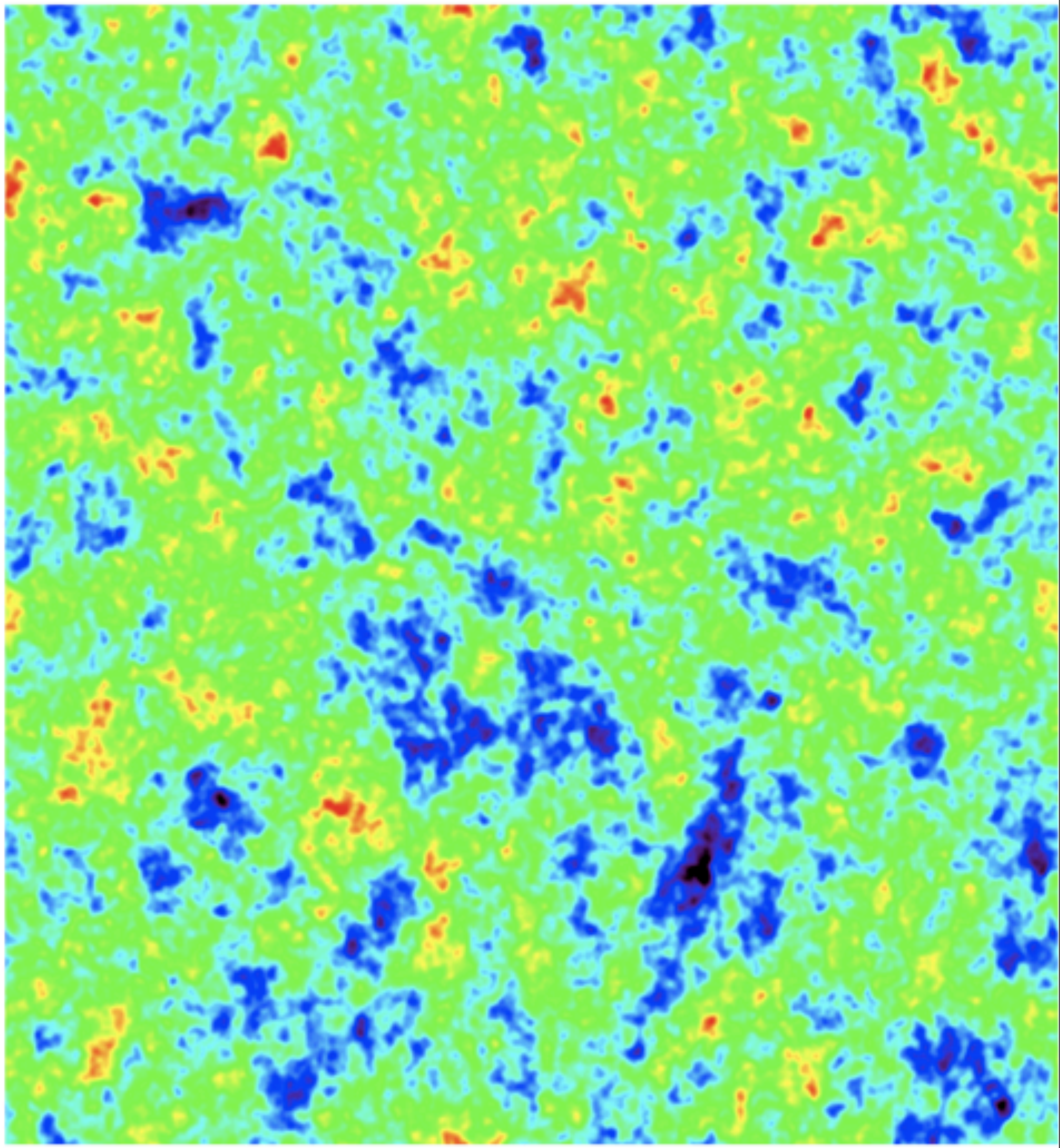


Effect of lensing

17°x17°



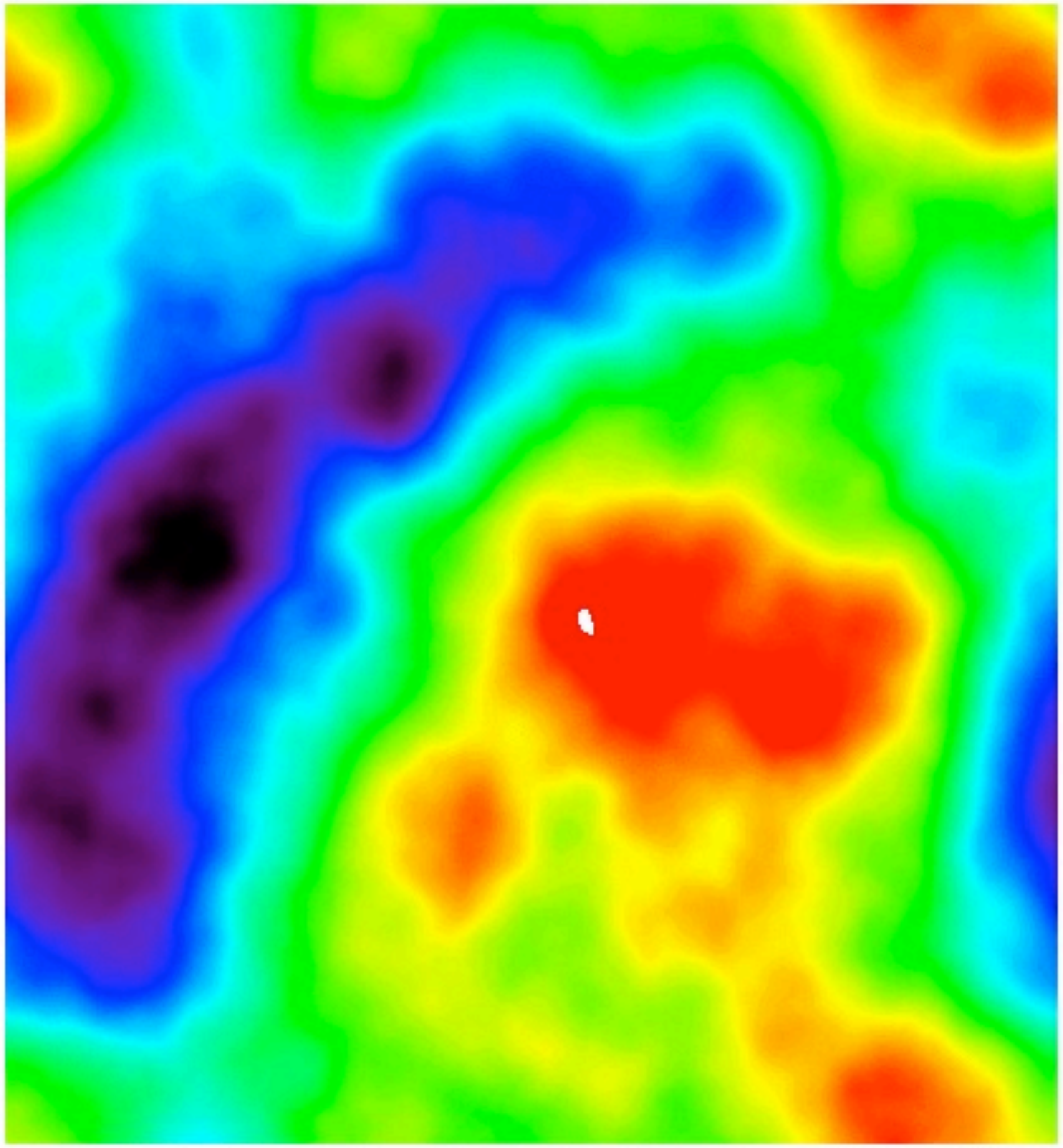
lensing potential



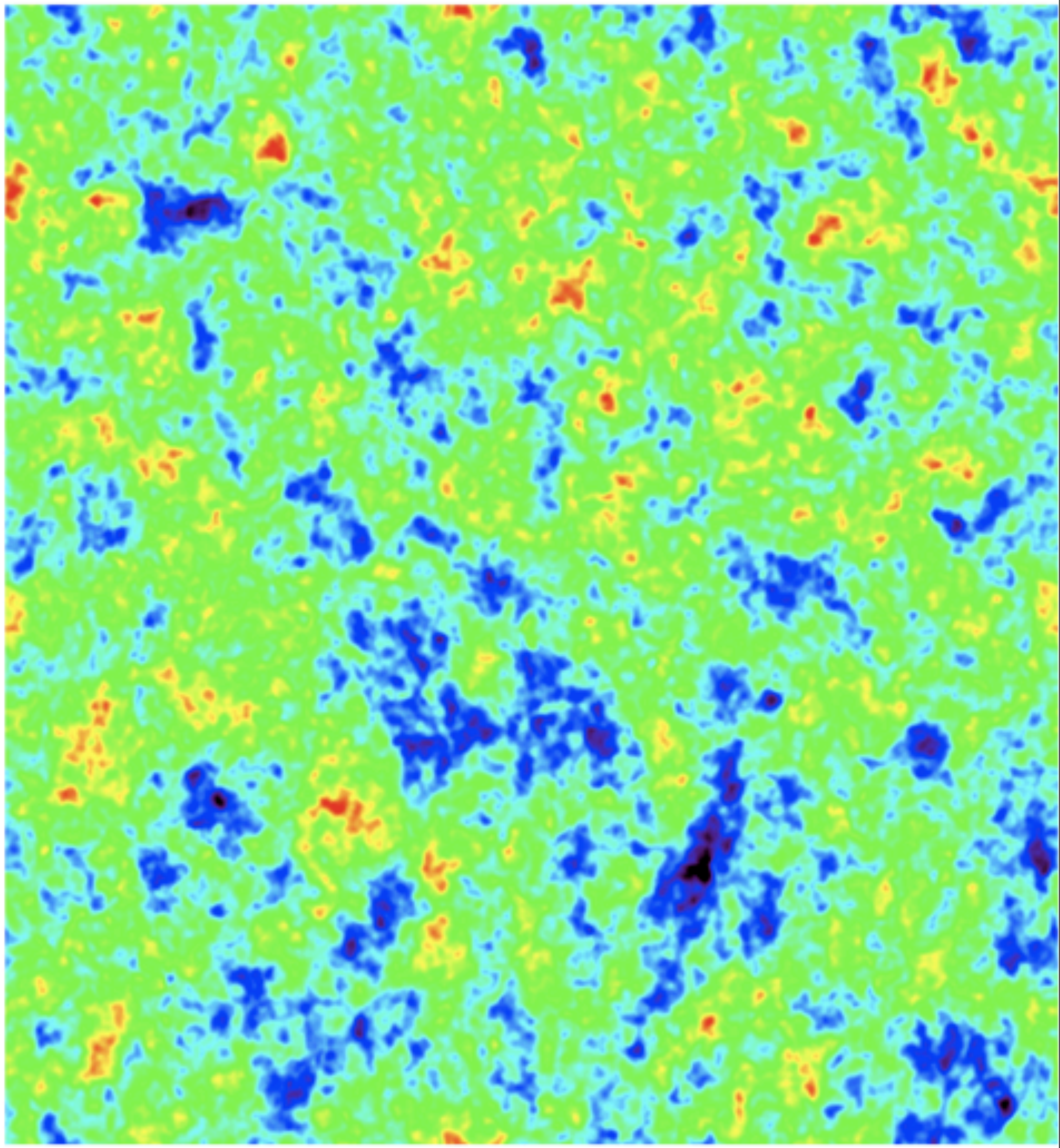
unlensed cmb

Effect of lensing

17°x17°



lensing potential



lensed cmb

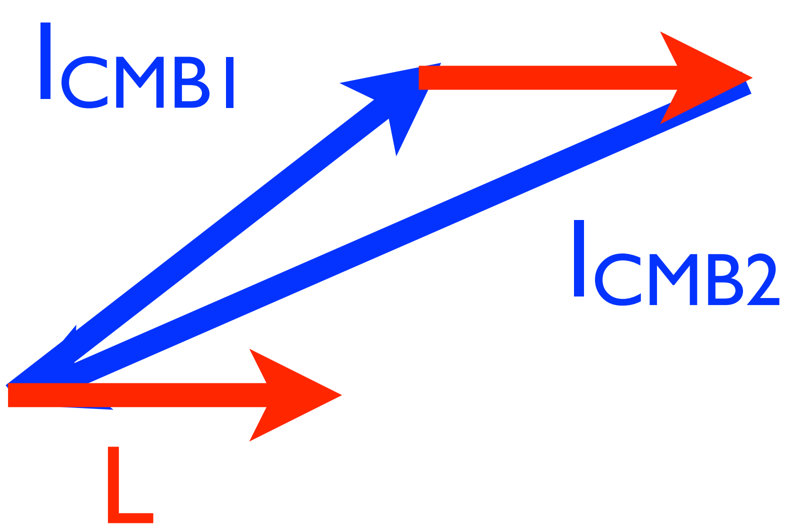
Lens-induced CMB Mode Coupling

$$T(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$
$$= T^U(\hat{\mathbf{n}}) + \nabla T^U(\hat{\mathbf{n}}) \cdot \nabla\phi(\hat{\mathbf{n}}) + \ldots.$$

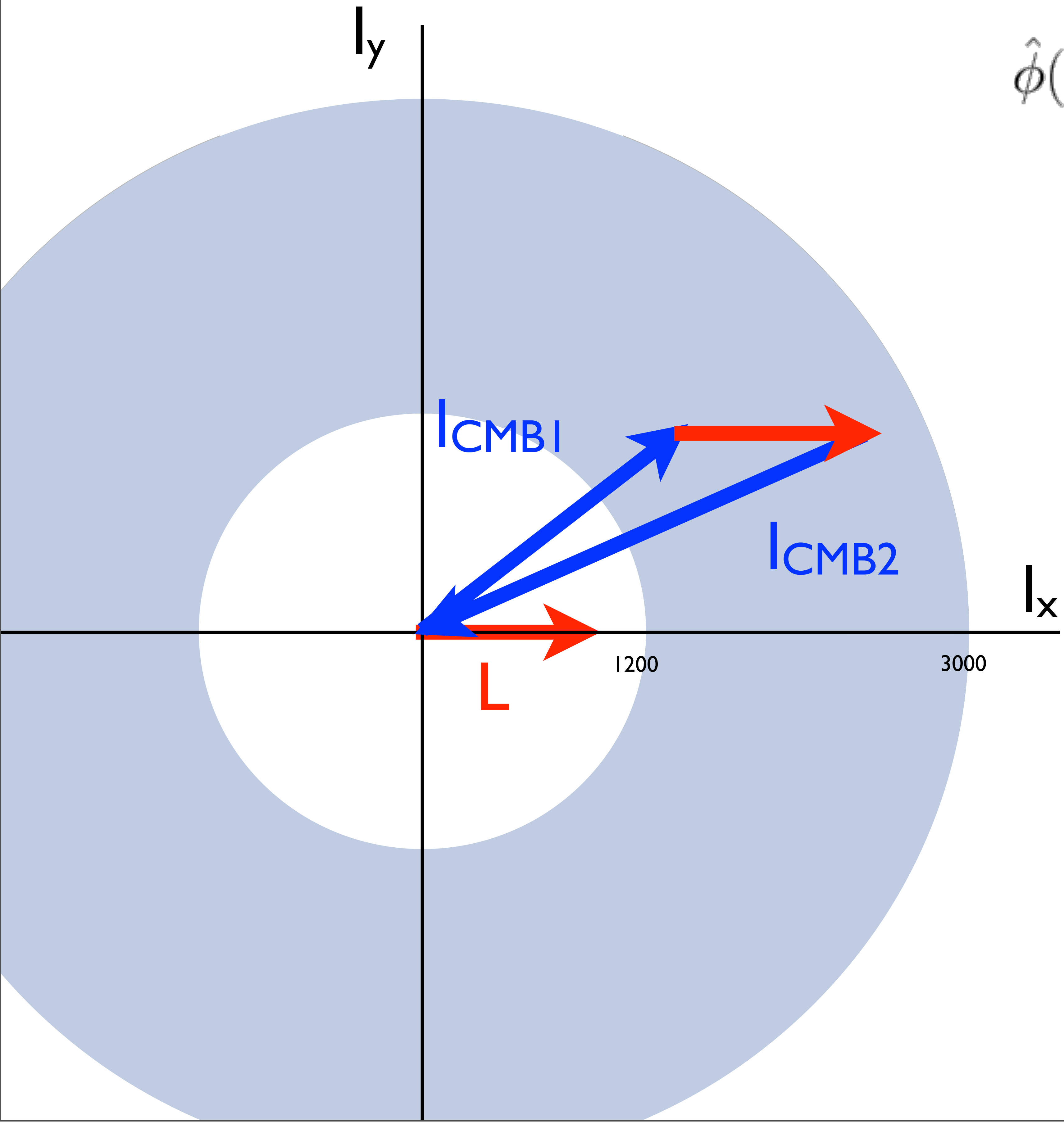
- Lens-induced mode coupling for $\mathbf{l_1} \neq -\mathbf{l_2}$:

$$\langle T(\mathbf{l}_1)T(\mathbf{l}_2)\rangle = f(\mathbf{l}_1, \mathbf{l}_2)\phi(\mathbf{L})$$

$$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$$



Reconstruction idea (Zaldarriaga 1999, Hu 2001)



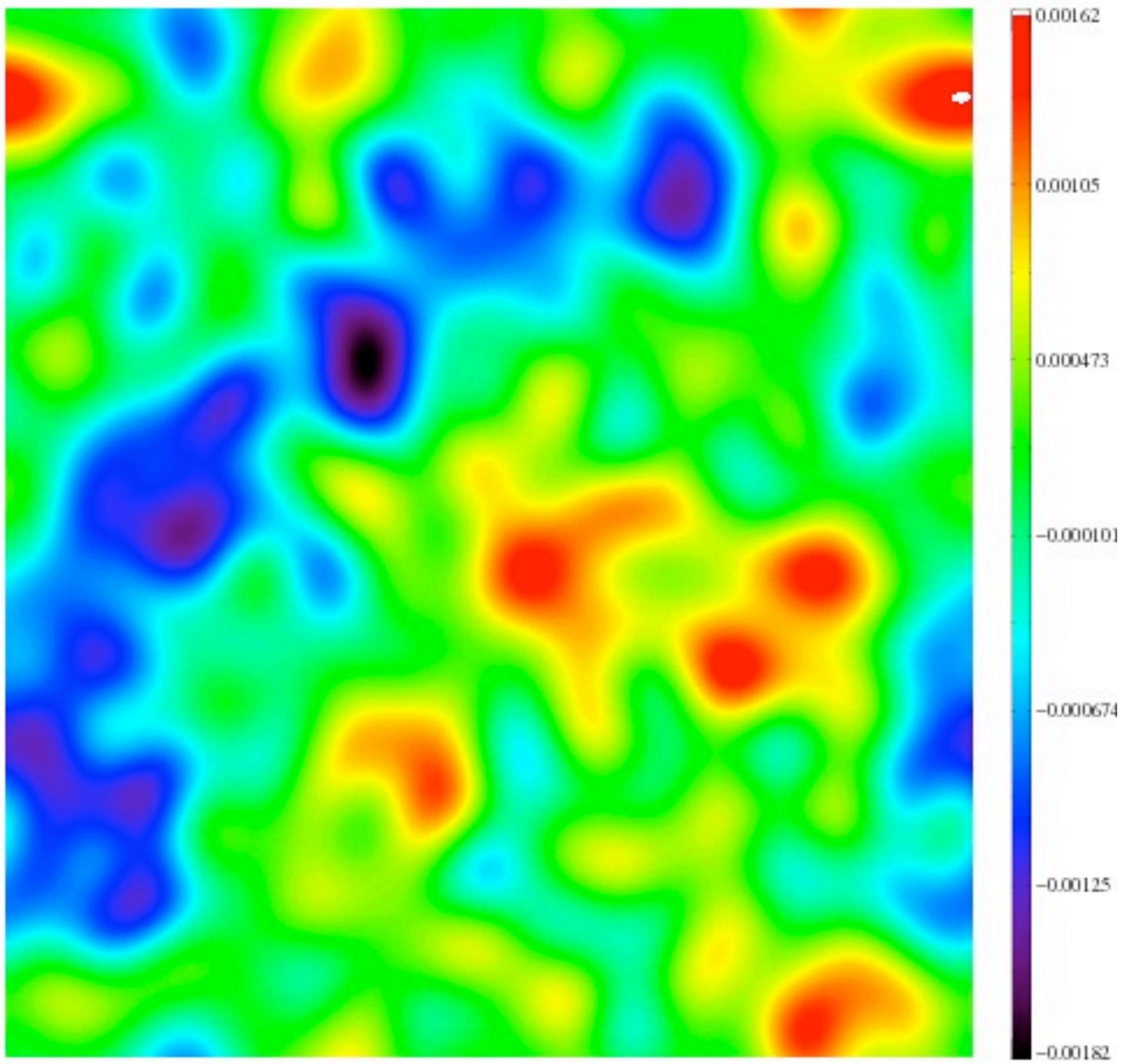
$$\hat{\phi}(\vec{L}) \sim \sum_{\vec{l}} T(\vec{l})T(\vec{L}-\vec{l})$$

quadratic estimator

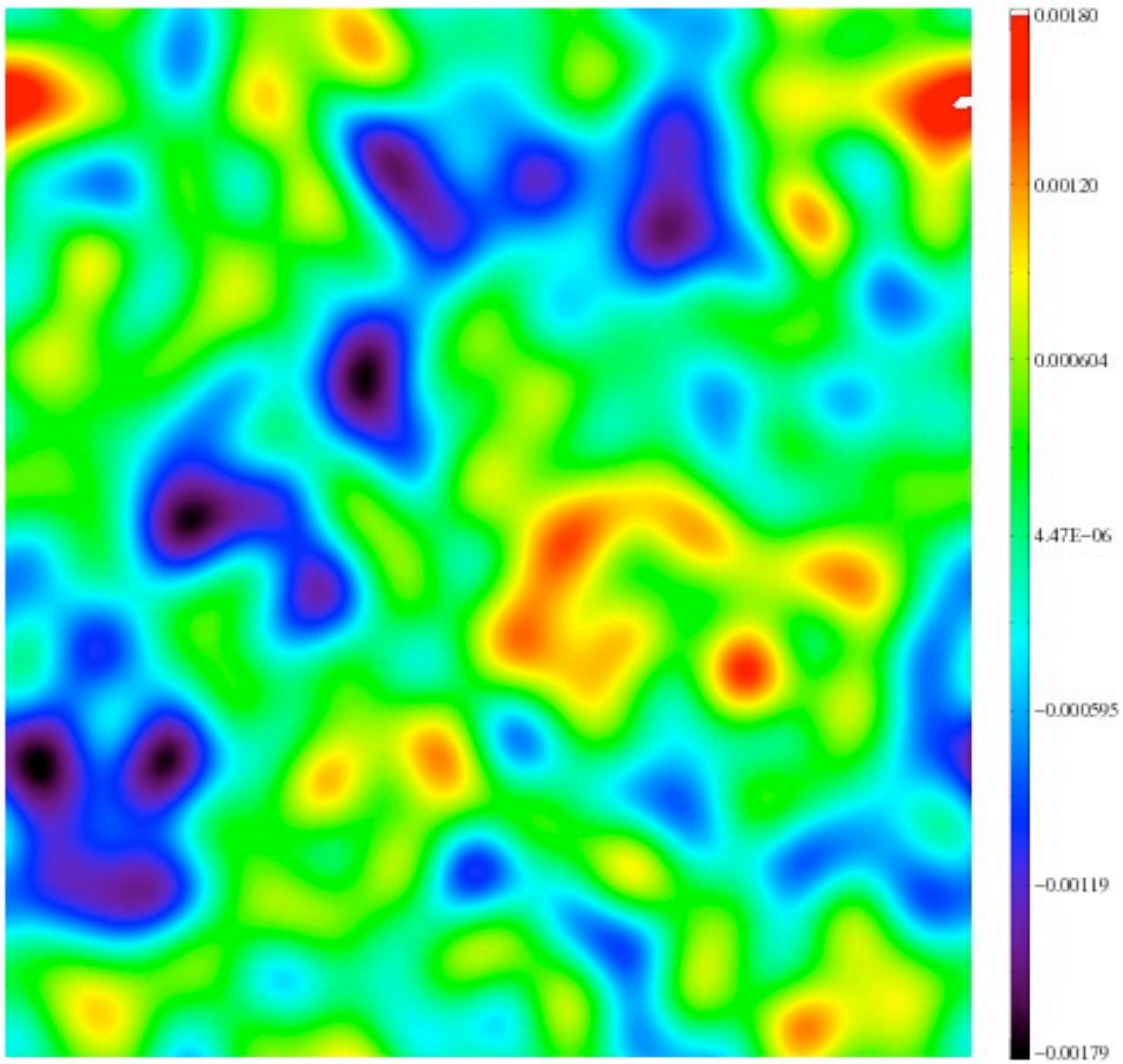
Use small-scale temperature modes to reconstruct large-scale lensing modes

Simulated Reconstruction Results

Input

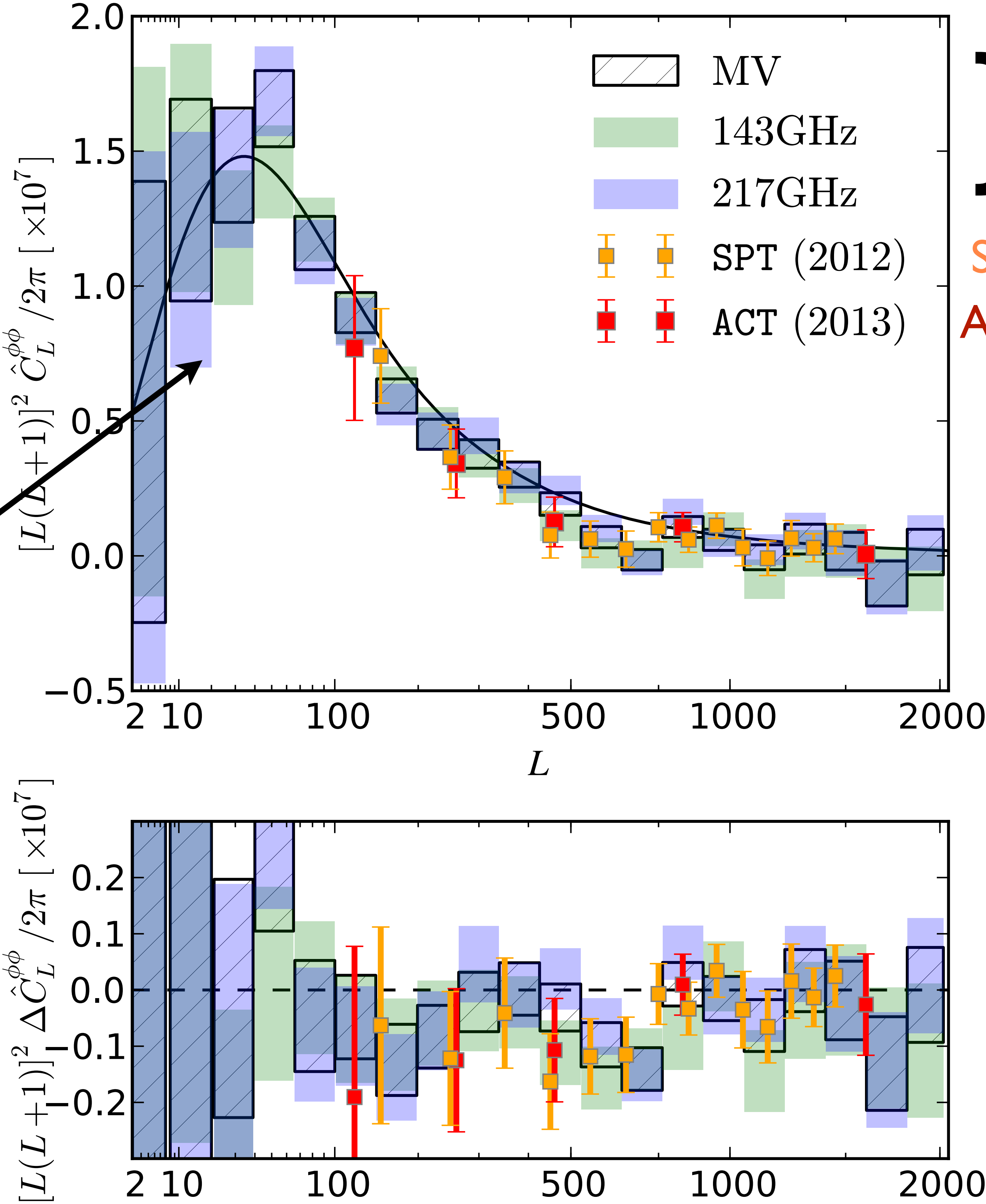


Recovered (filtered for large scales)



17°x17°

Lensing Power Spectrum



Planck 25σ

SPT 6.3σ (van Engelen+ 2012)

ACT 4σ (Das+ 2013)

Theory: predicted by LCDM + 1st order pert. theory

Planck Collab. 2013

Timeline: CMB lensing detections

	φ-gal. crosspower	φ autopower	CMB peak-
2007	WMAP3xNVSS, 3.4 σ, Smith+		ACBAR, ~3σ, Calabrese+, Reichardt+
2008	WMAP3xNVSS, 2.5 σ, Hirata+		
2011		ACT, 4 σ, Das+	ACT, ~3 σ, Dunkley+; SPT, 5 σ, Keisler+
2012	SPT×(WISE, *Spitzer*/IRAC, BCS), 4-5 σ, Bleem+; ACTxSDSSquasars, 3.8 σ, Sherwin+; WMAP5xNVSS, 4 σ, Fang+	SPT, 6.3 σ, van Engelen+; ACT, 4.6 σ, Das+	ACT, ~3 σ, Sievers+; SPT, 8 σ, Story+
2013	SPTx*Herschel*CIB, 7-9 σ, Holder+; *Planck*×*Planck*CIB, 42 σ, Planck Collab.; *Planck*×...., 7-20 σ, Planck Collab.	*Planck*, 25 σ, Planck Collab.	*Planck*, 10 σ, Planck Collab.

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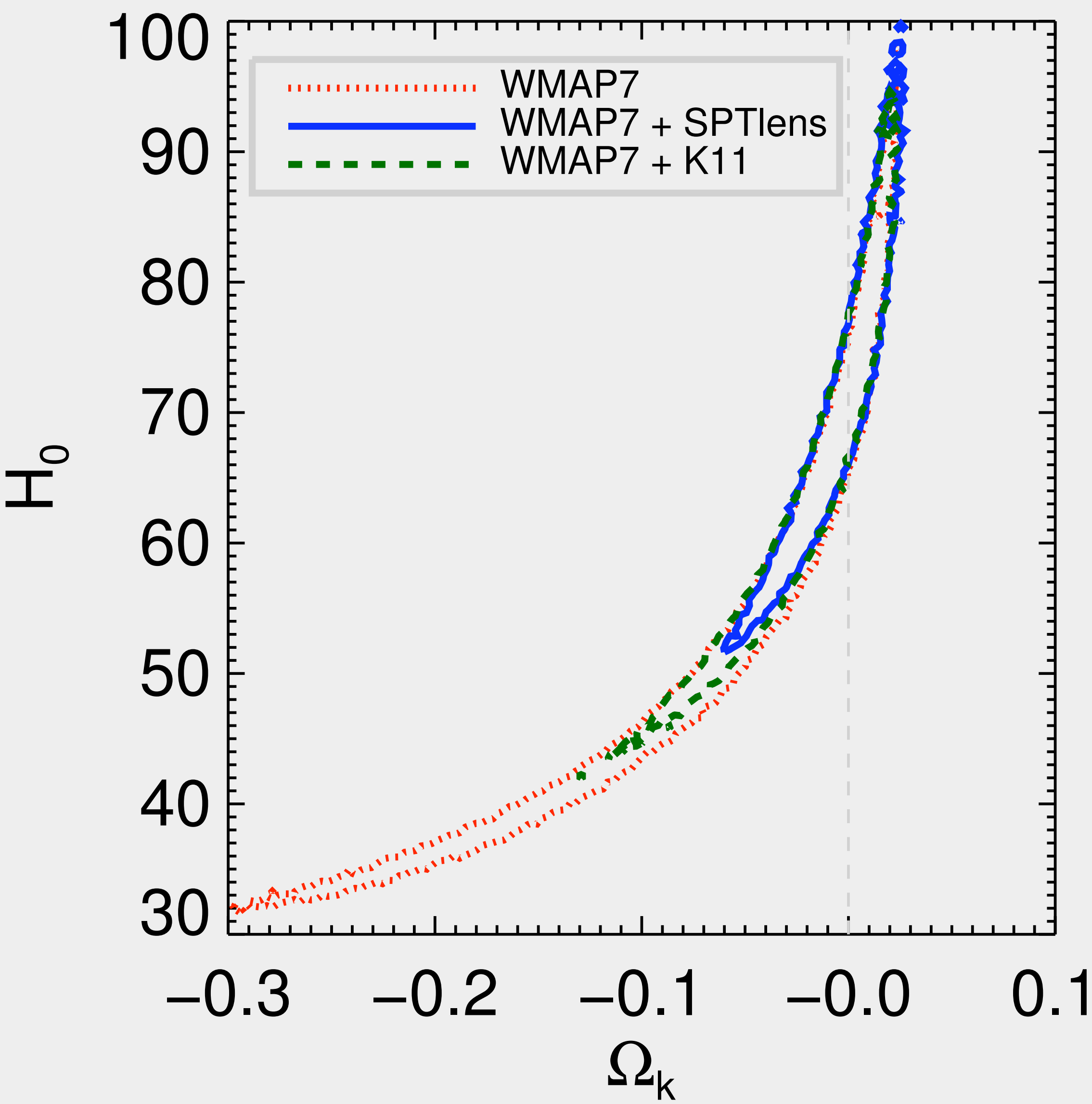
2013	SPTx*Herschel*CIB 7-9 σ Holder+; *Planck*x*Planck*CIB 42 σ Planck Collab.; *Planck*x.... 7-20 σ Planck Collab.	*Planck* 25 σ Planck Collab.	*Planck* 10 σ Planck Collab.
Future		ACTpol, SPTpol ~ 60σ	

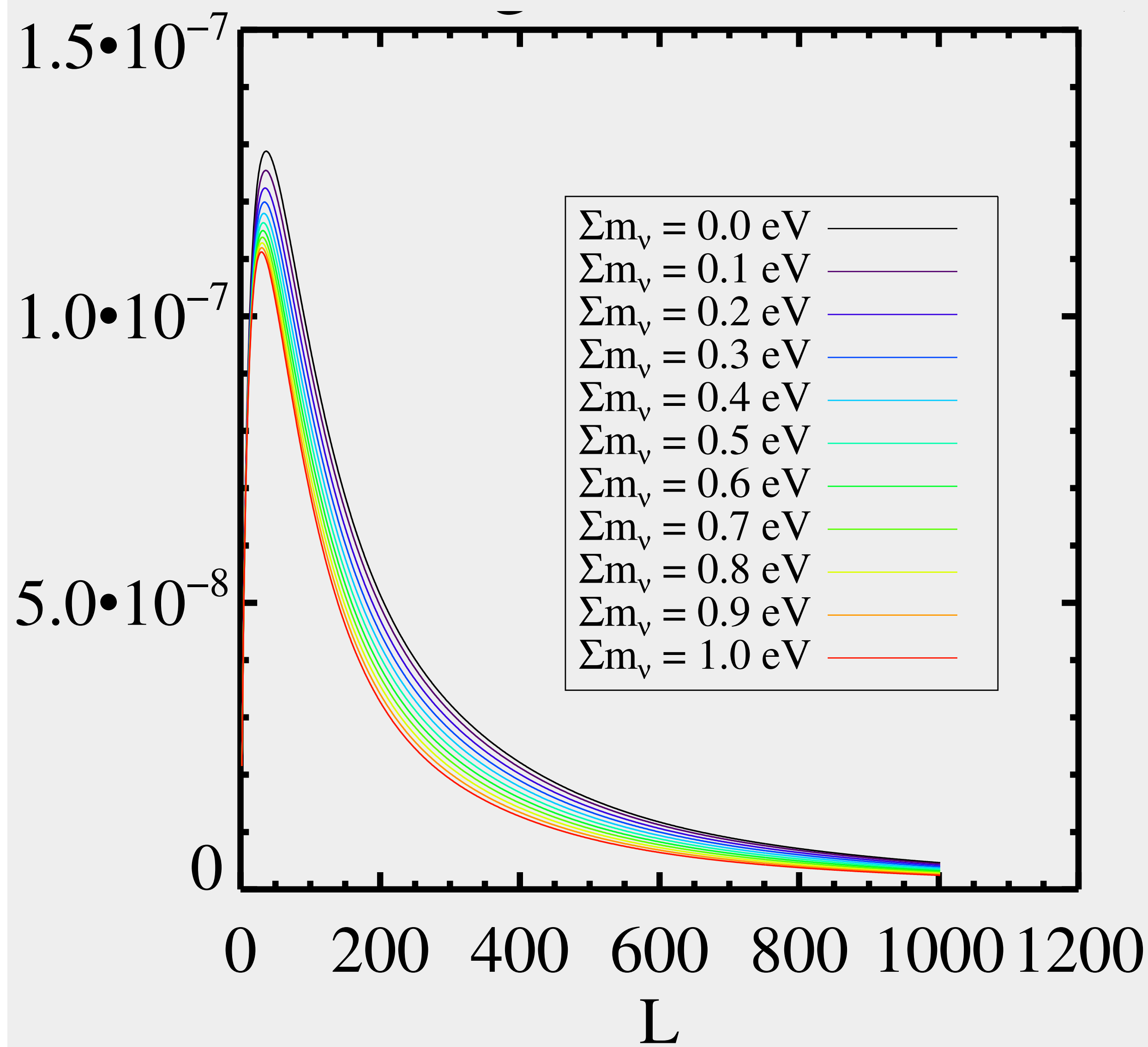
What is it good for?

- Now: curvature



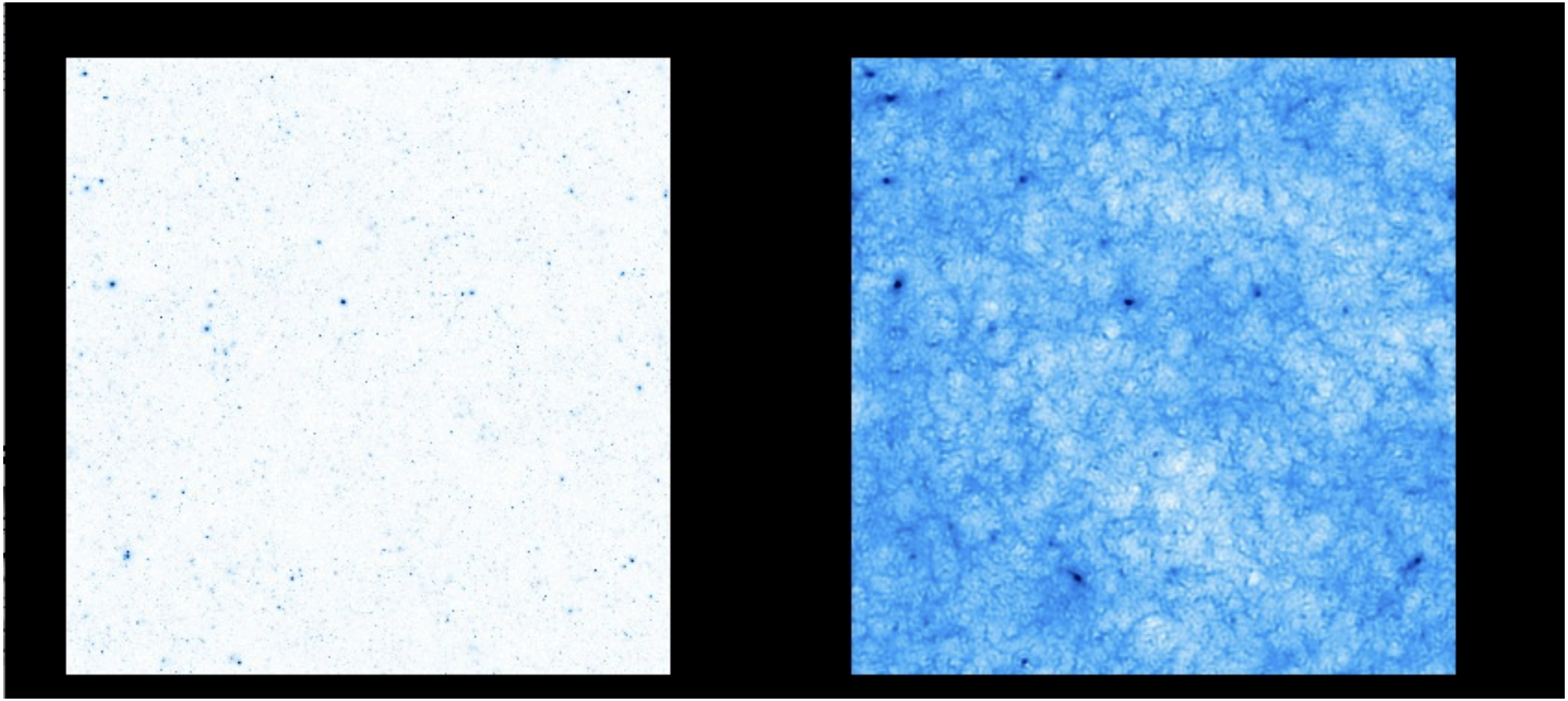
95% C.L.
van Engelen+ 2012
Planck does better; see Duncan's talk

- Future: Σm_ν



Σm_ν of 0.1eV ⟷ 5% in $C_l^{\varphi\varphi}$

Contamination from Astrophysical Foregrounds



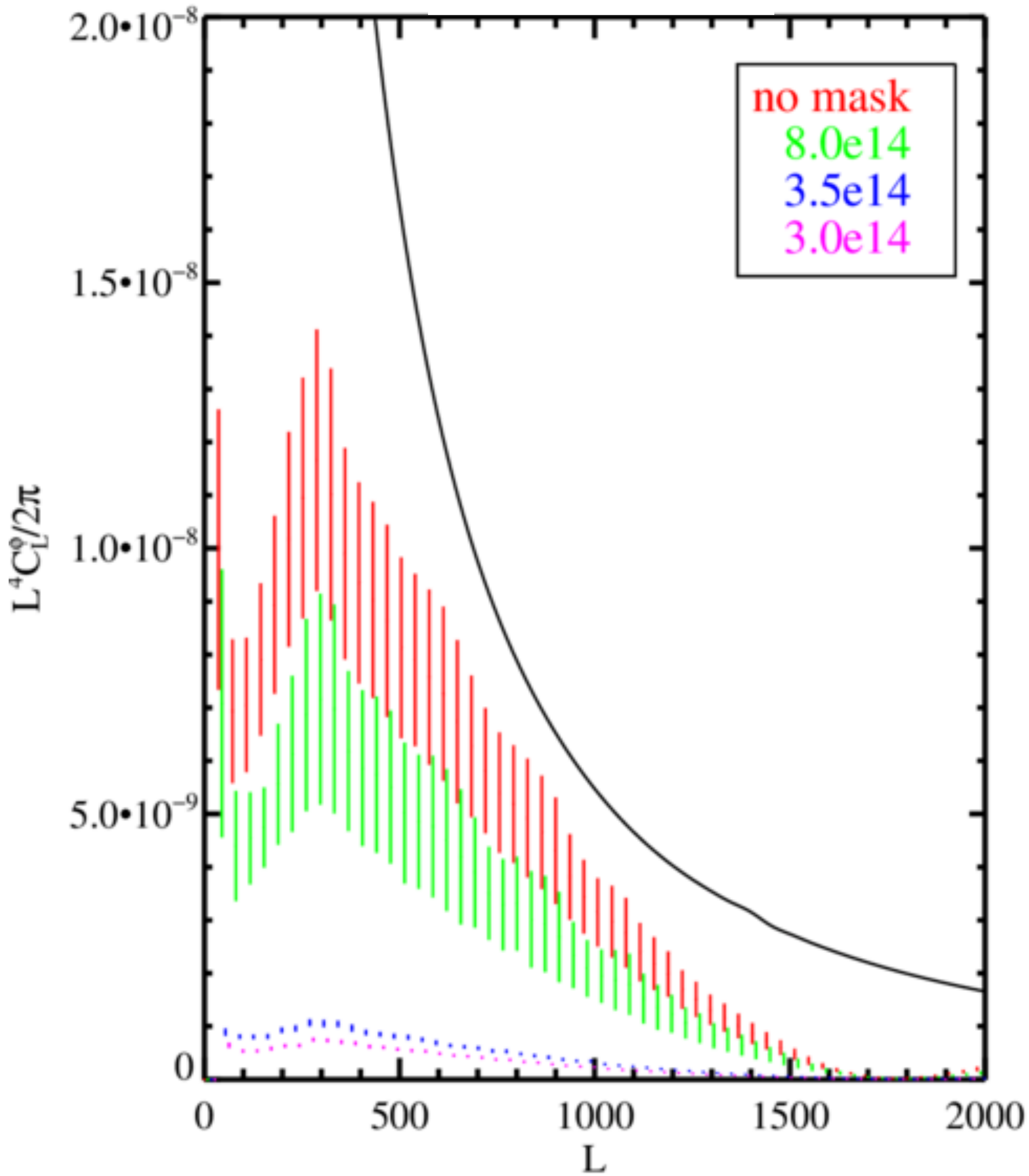
17°x17°

tSZ simulation
(Sehgal et al 2009)
Unmodified

Reconstructed lensing

Contamination from Astrophysical Foregrounds

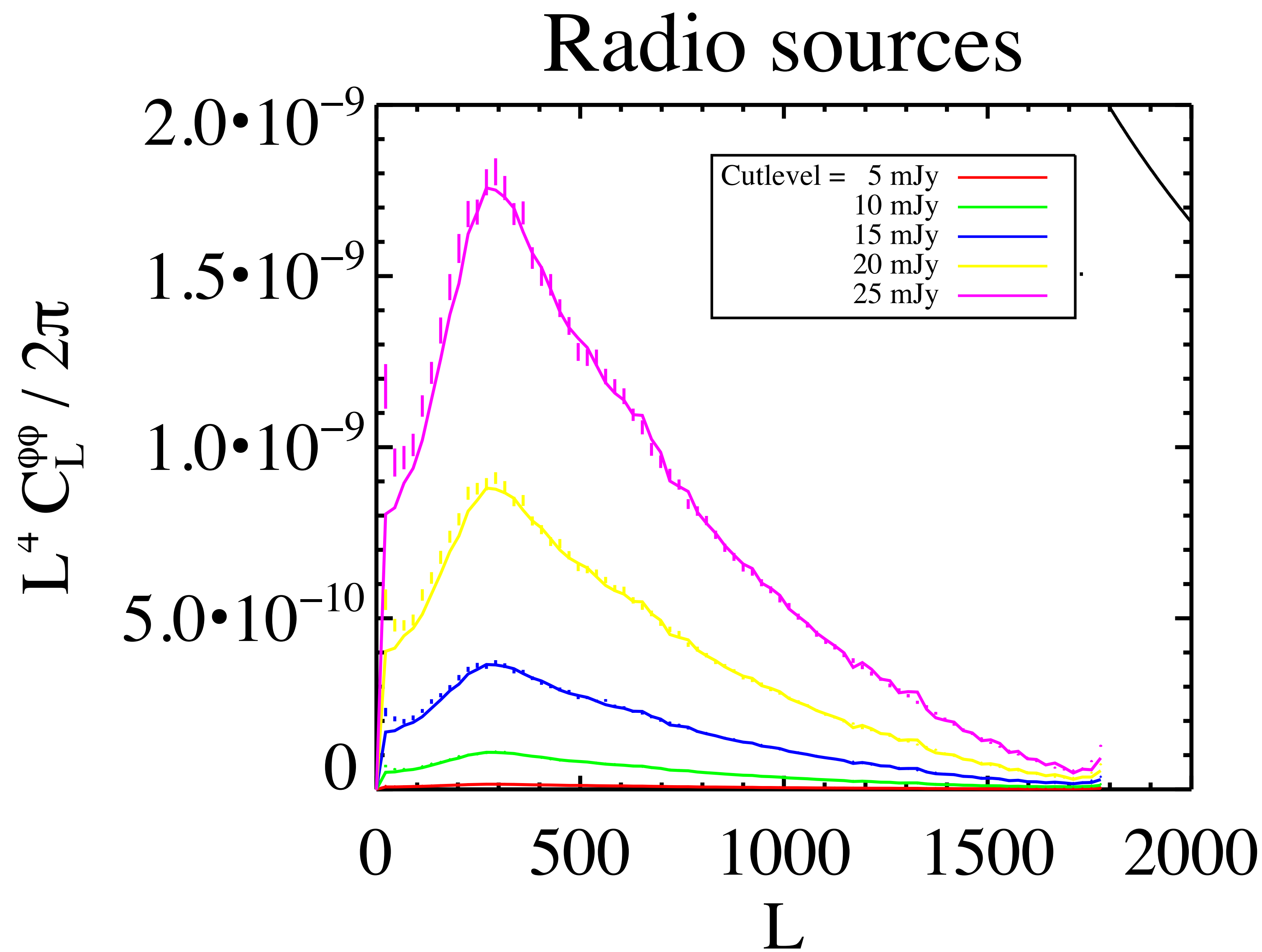
- Sunyaev-Zel'dovich clusters
- Compute bias, using simulations (Sehgal+ 2009 [updated], Bhattacharya+ in prep.) and theory
- Few % bias - needs to be modeled & subtracted



Example: bias from tSZ trispectrum
van Engelen+ in prep.

Contamination from Astrophysical Foregrounds

- Point sources (<1% with masking)
- Also: correlations with lensing (5-10%)
- To do: polarized sources



Example: bias from tSZ trispectrum
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Summary

- Lensing has recently moved from "detection" to "precision measurement"
- ACTpol, SPTpol are coming soon - many 10s of sigmas
- Foreground biases become important for %-level measurements (Σm_ν, w, ...) -- we have a handle on modelling them.