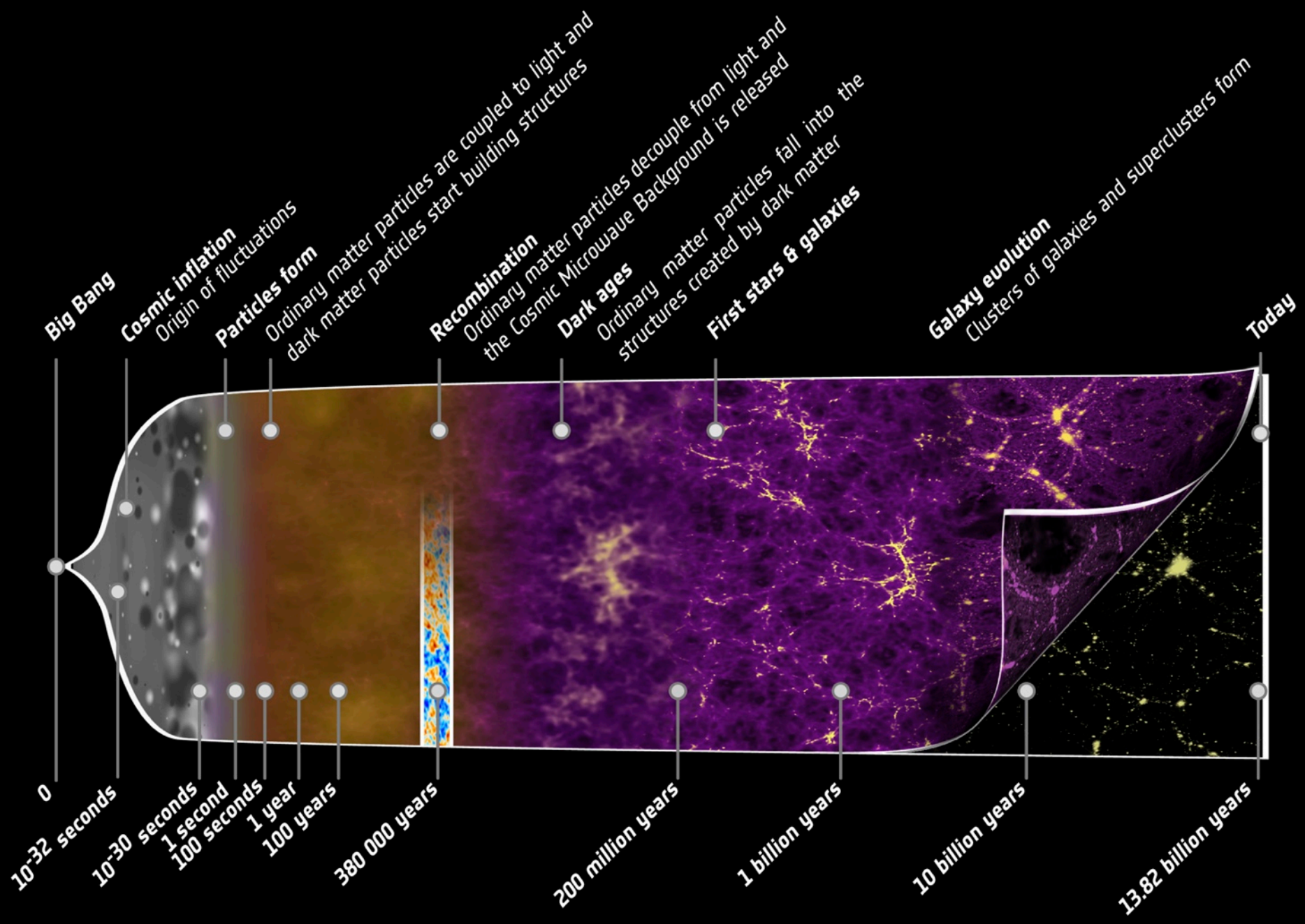
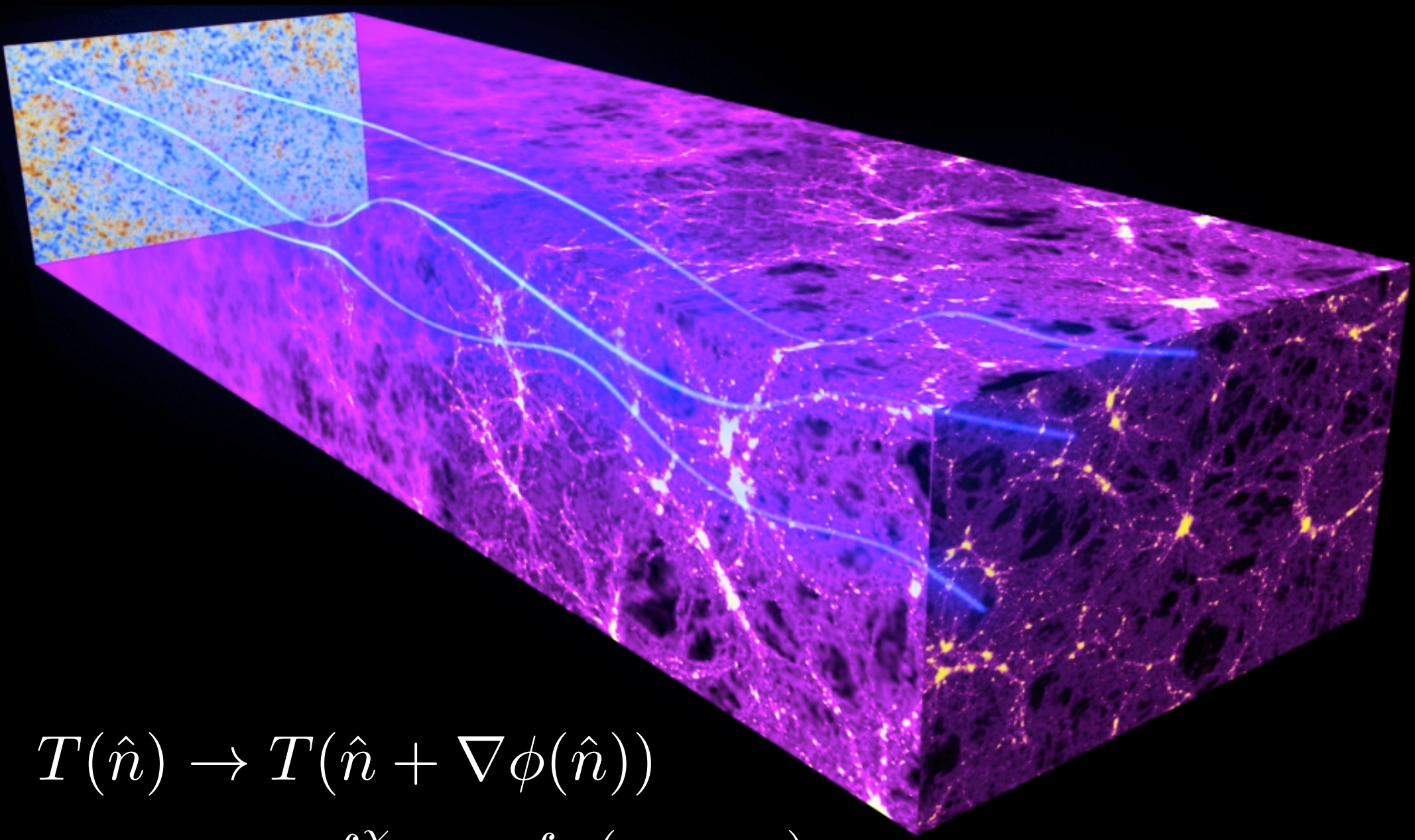
CMB Lensing for «Neutrinos in the Cosmos»

Duncan Hanson

Snowmass on the Mississippi,

July 31st 2013


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

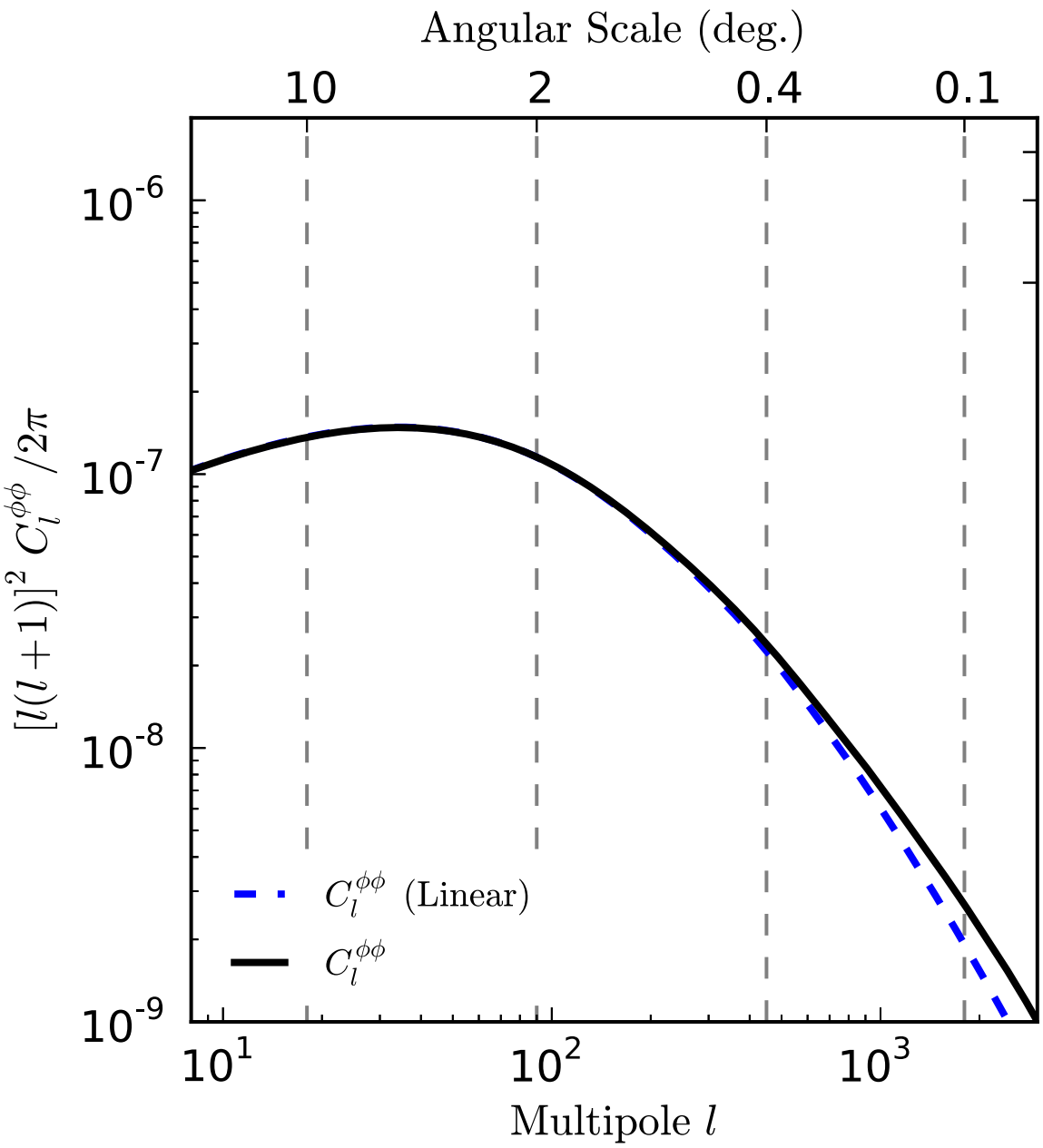


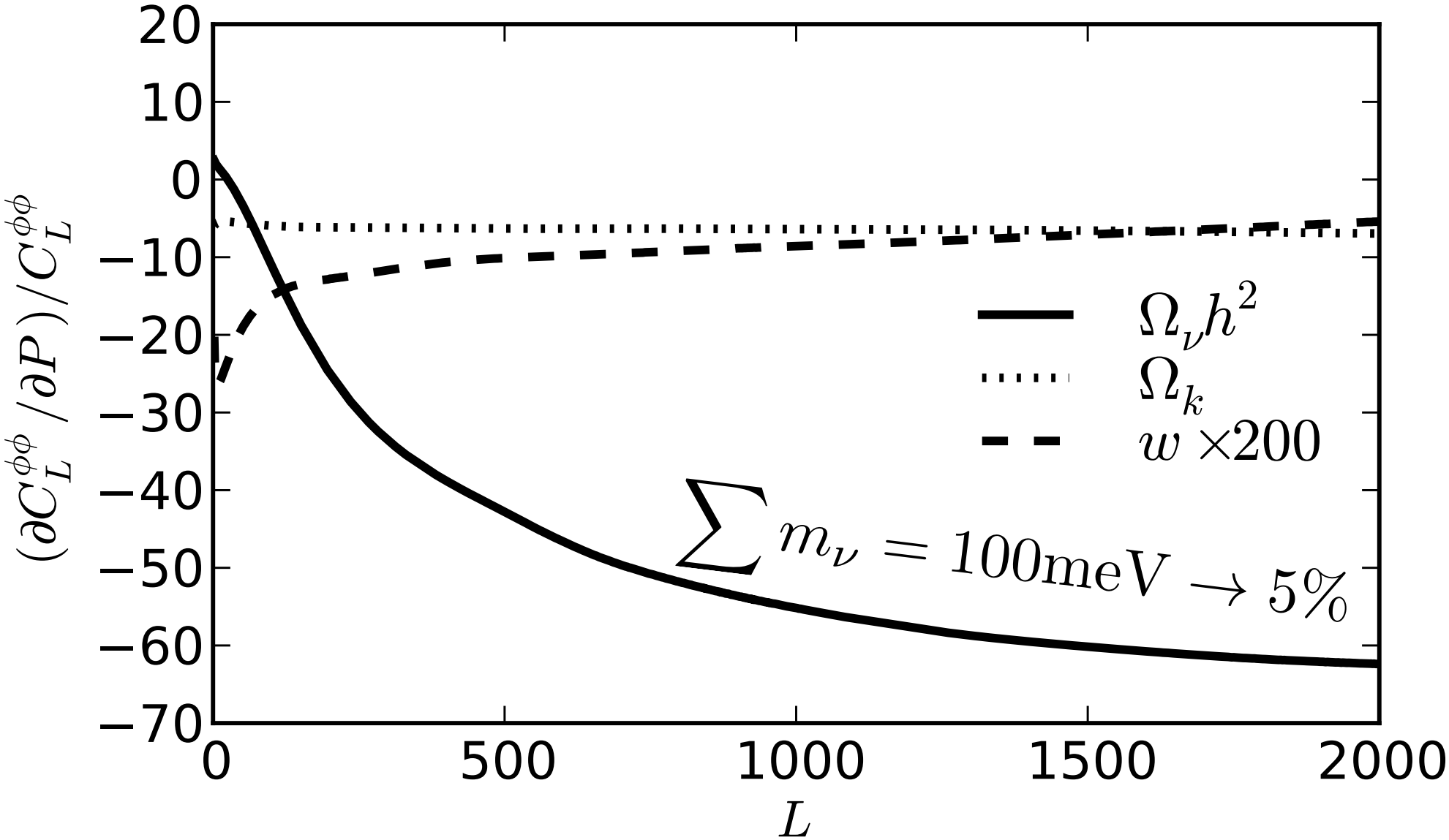
$$T(\hat{n}) \to T(\hat{n} + \nabla\phi(\hat{n}))$$

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

Weak lensing of the CMB by large-scale structure:

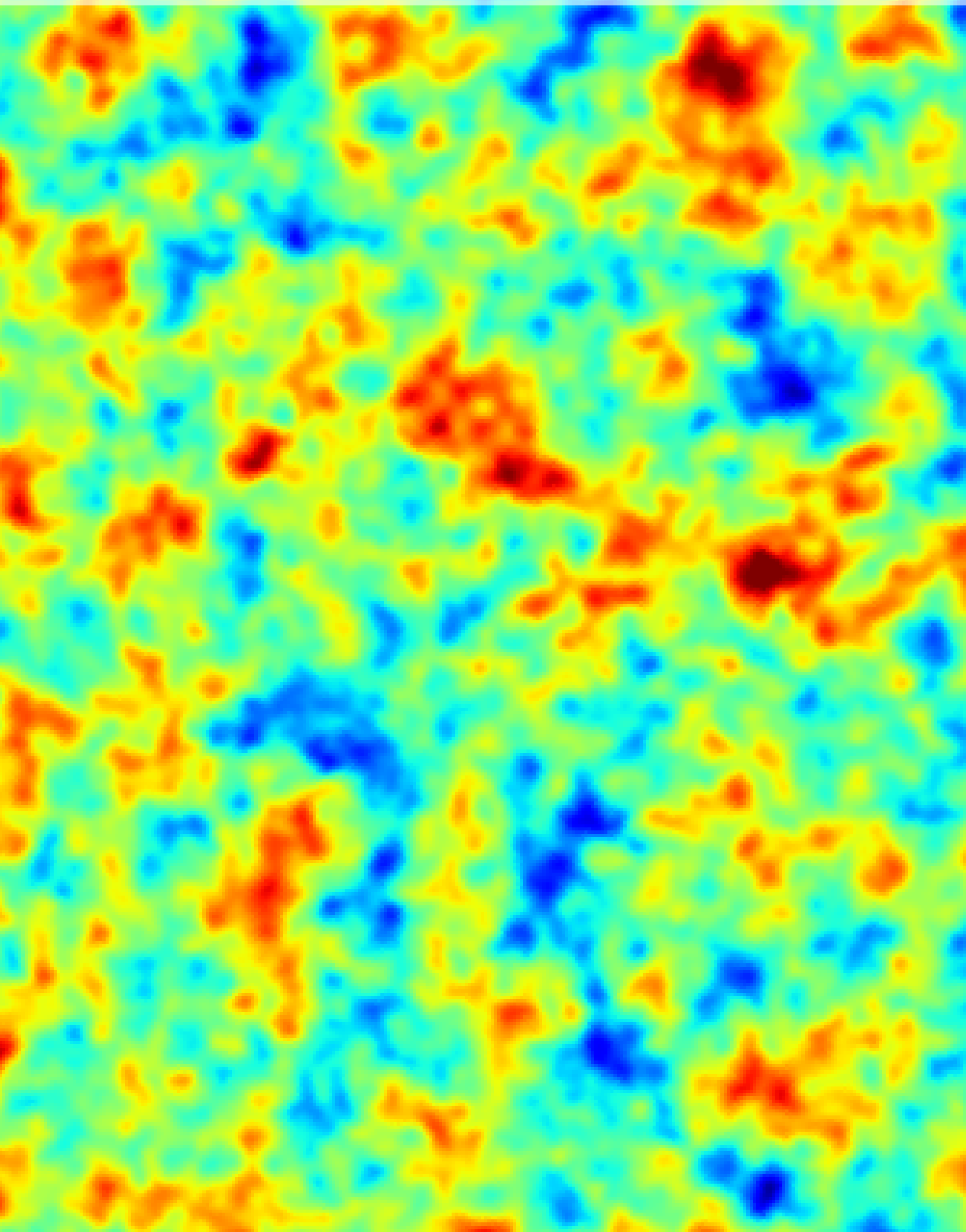
- RMS deflection of 2.4′.
- Peak lensing efficiency halfway to CMB (z~2, or 7000Mpc comoving).
- Coherent over ~300Mpc comoving (δθ~2° on sky).
- (Relatively) Small corrections from non-linearity.



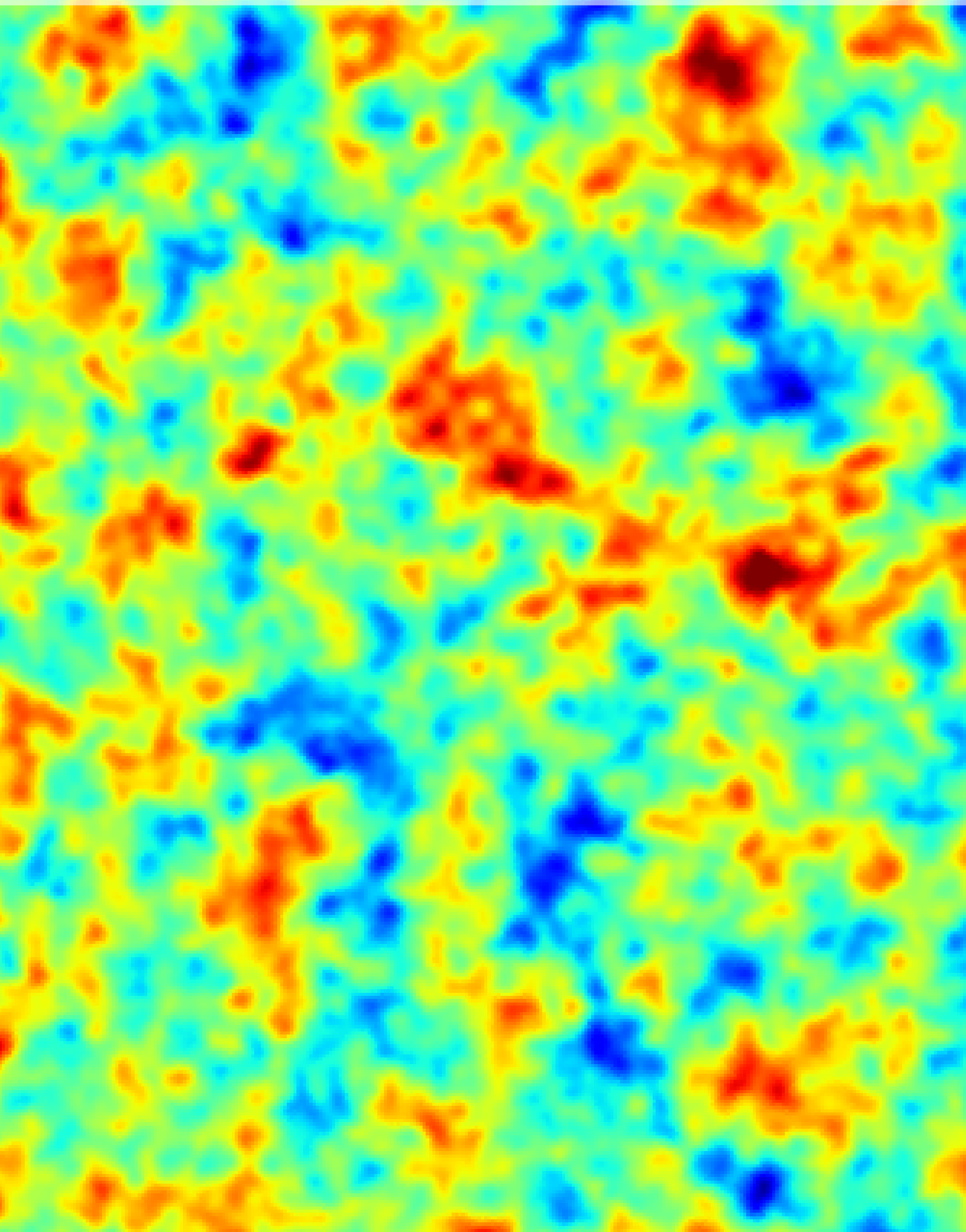


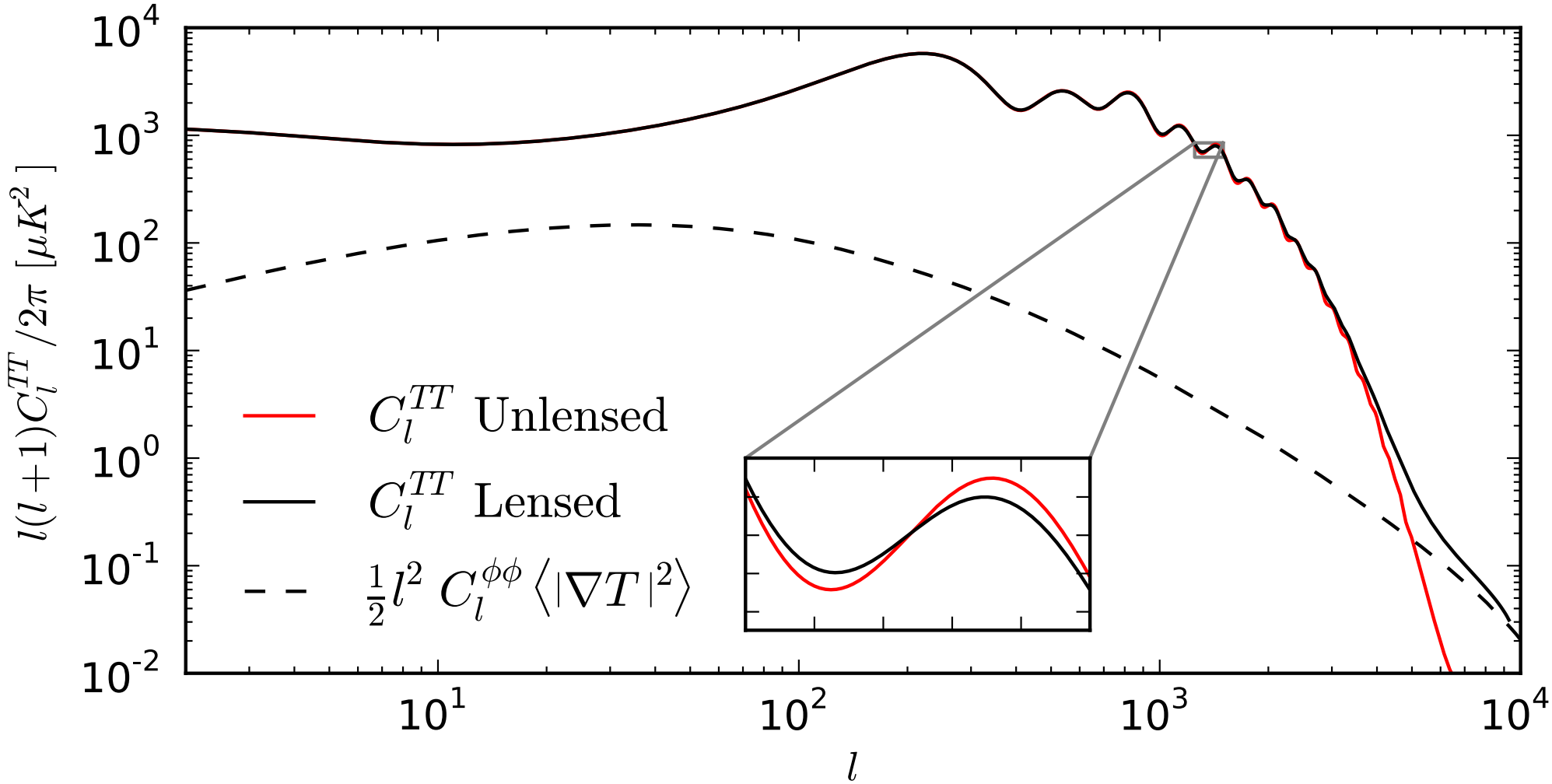
CMBpol Lensing White Paper (2008)

CMB Temperature Unlensed



CMB Temperature Lensed



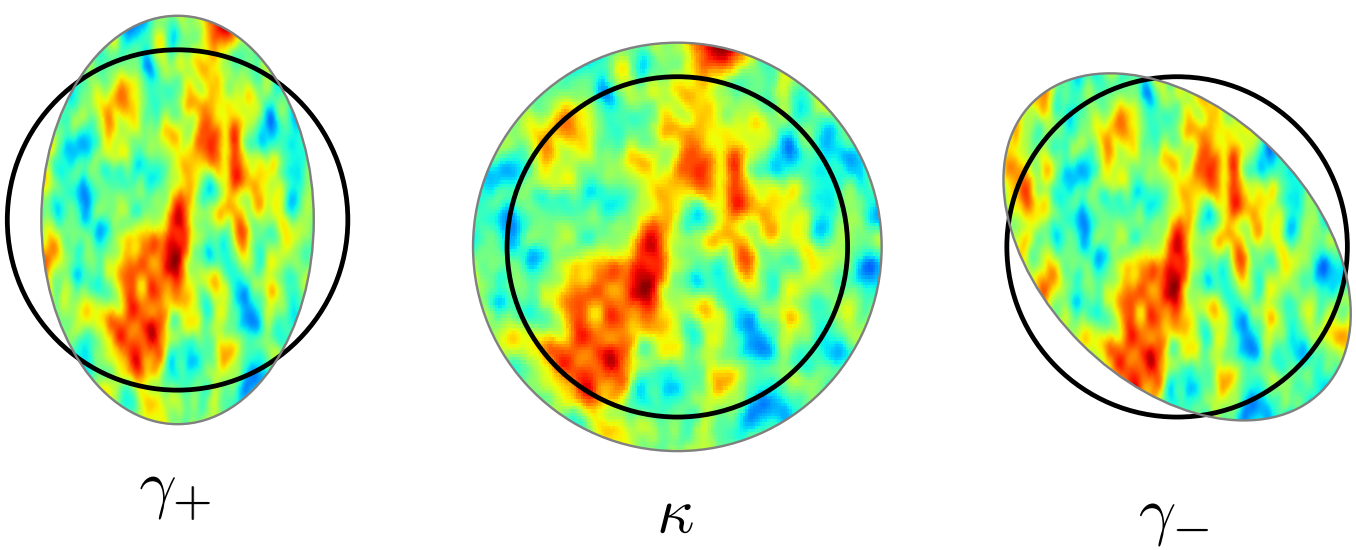


Lensing smooths the accoustic peaks of the CMB Power Spectrum, though smoothing is sensitive only to amplitude of $C_l^{\phi\phi}$.

CMB Lens Reconstruction

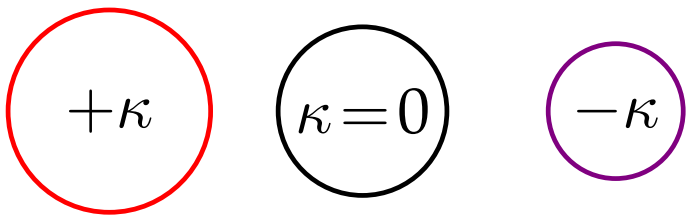
- We can directly reconstruct the lensing potential $\phi(\hat{n})$.
- Idea: as in Galaxy weak lensing, start by decomposing the lensing potential into "observable" convergence and shear modes:

$$-\nabla_{ij}\phi = \begin{bmatrix} \kappa + \gamma_+ & \gamma_- - \omega \\ \gamma_- + \omega & \kappa - \gamma_+ \end{bmatrix}.$$



CMB Lens Reconstruction

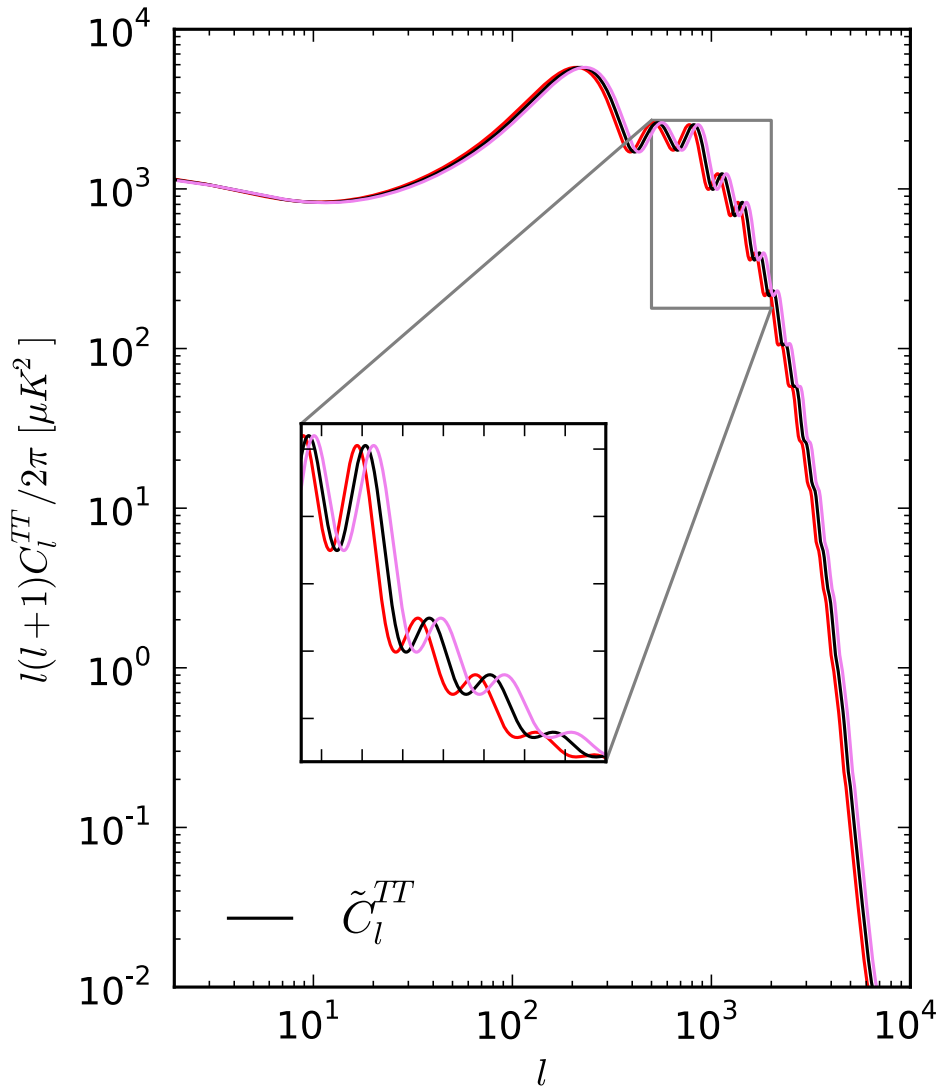
- Consider taking the power spectrum of a small patch with uniform κ.

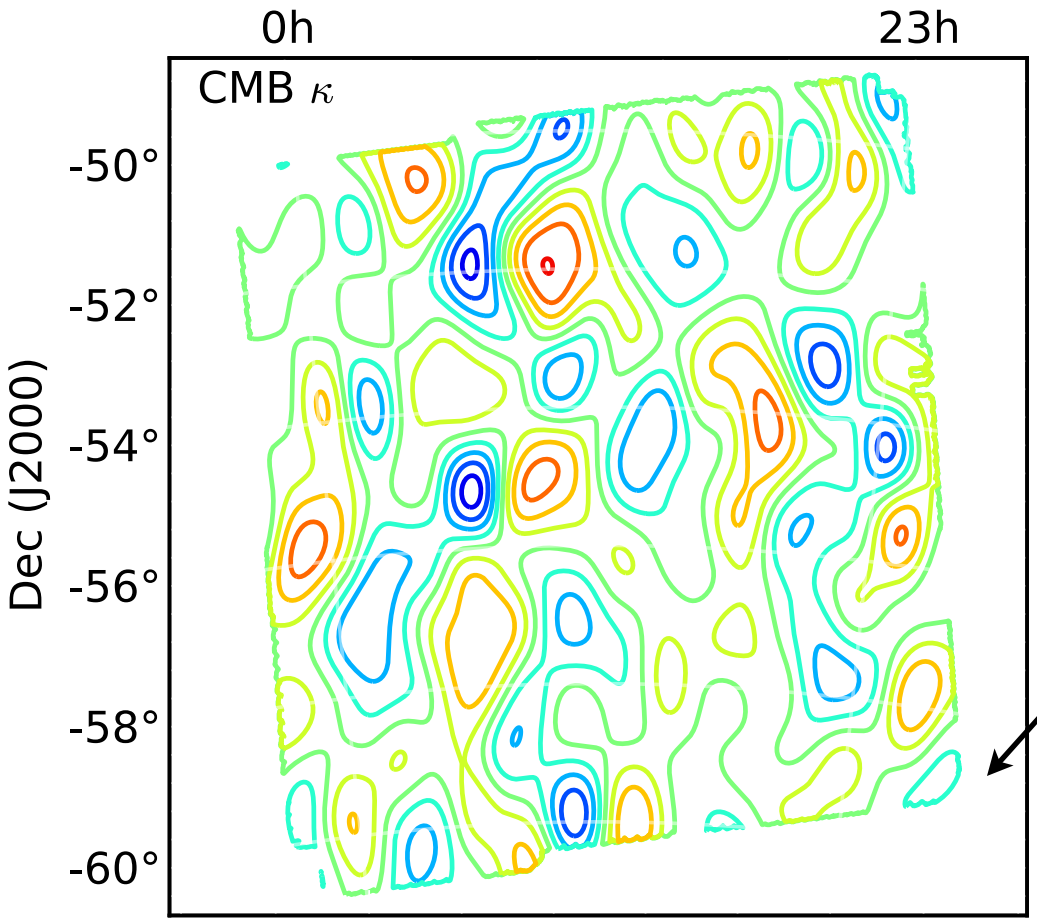


- To first order in κ we have $C_l^{TT} = \tilde{C}_l^{TT} + \kappa\Delta_l^\kappa$, where

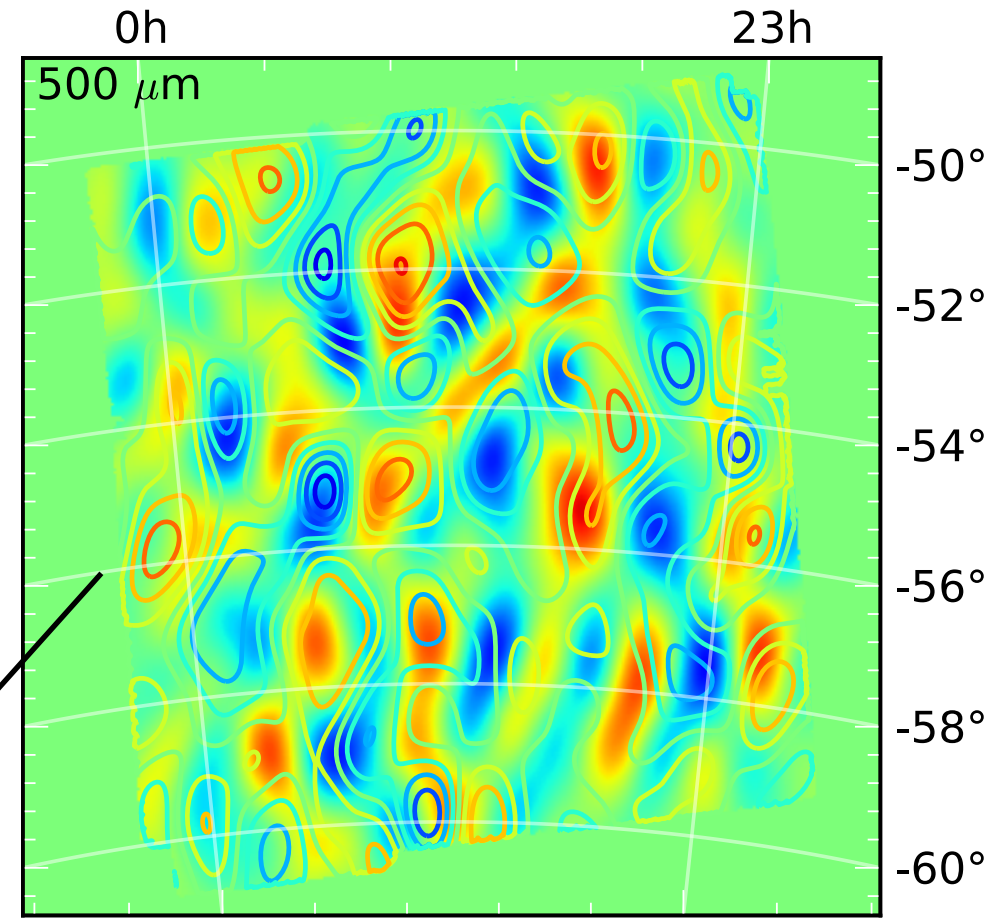
$$\Delta_l^\kappa = \left[l\frac{\partial \tilde{C}_l^{TT}}{\partial l} + 2\tilde{C}_l^{TT} \right].$$

- Look for Δ_l^κ in (localized) estimates of power spectrum, stitch together to get $\kappa(\hat{n})$.

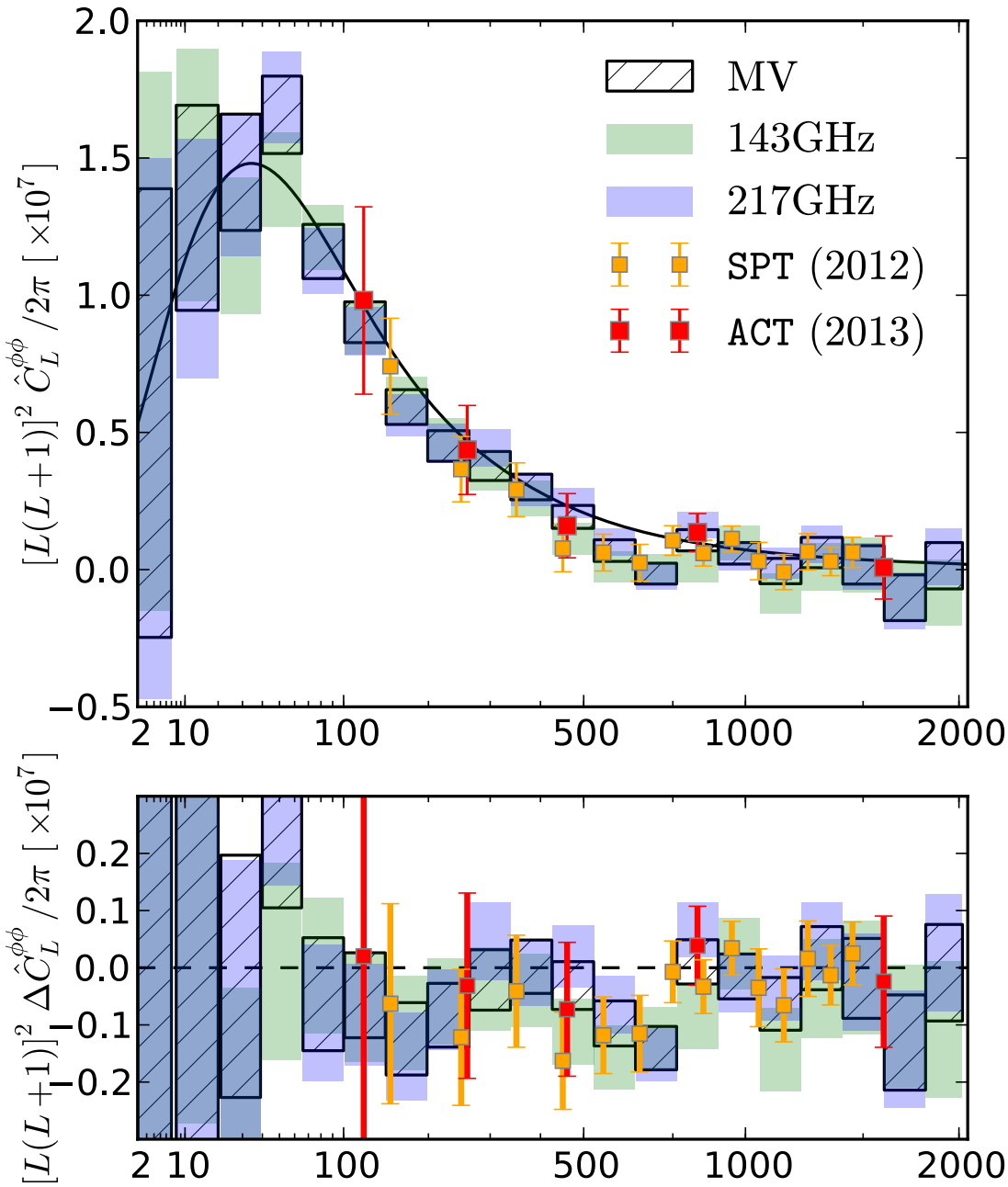




SPT-SZ Mass Map
(Holder et. al. 2012)



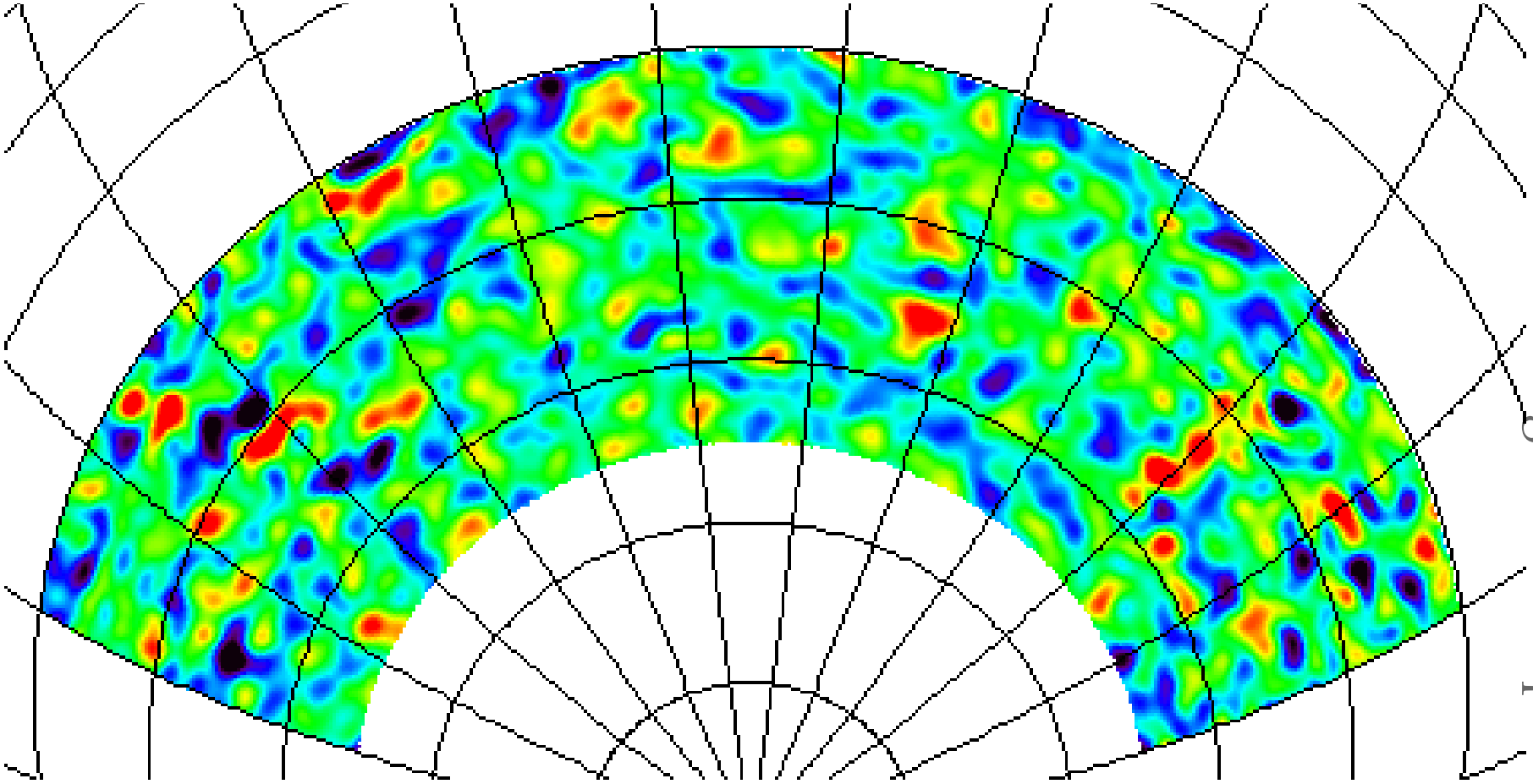
Overlay with Cosmic
Infrared Background
(Herschel-SPIRE)



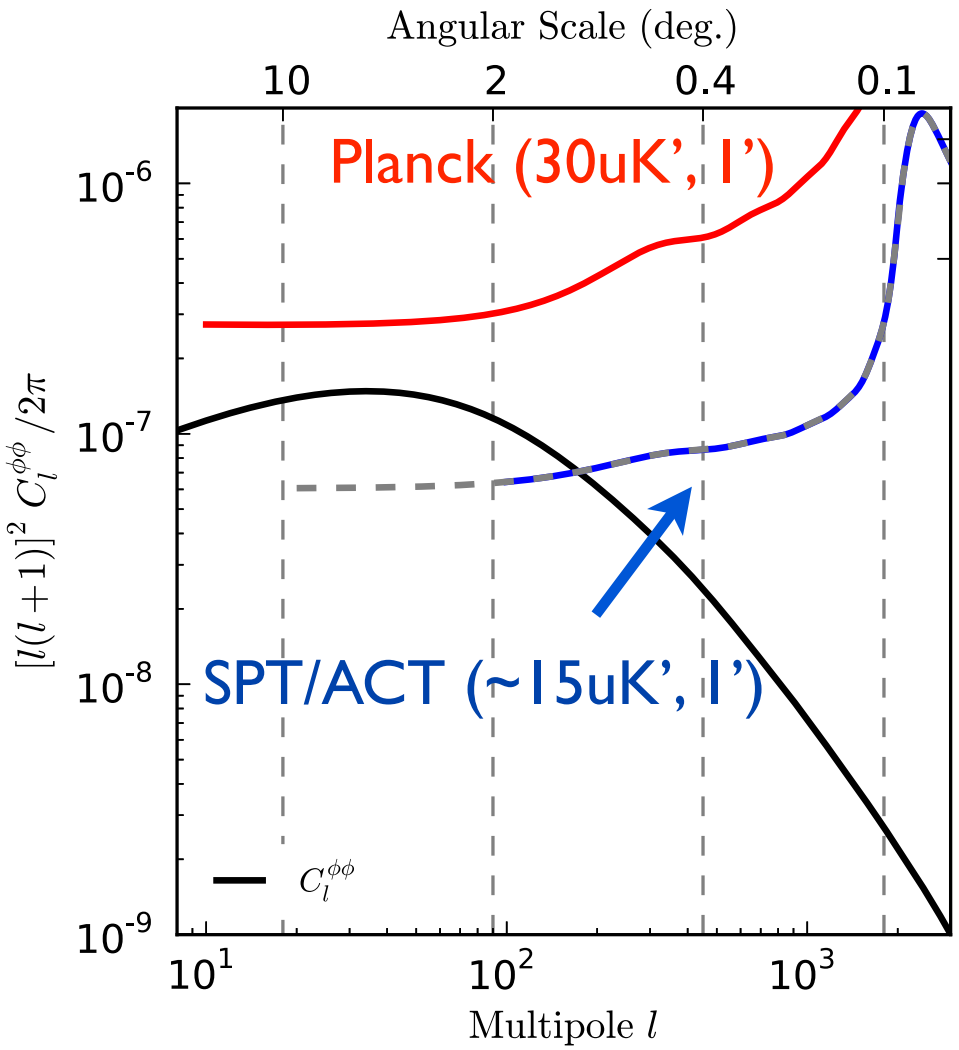
Measurements of the lensing power spectrum have become possible in last two years:

- First ACT in 2011 (4σ)
- SPT in 2012 (6.3σ)
- Planck in 2013 (25σ).

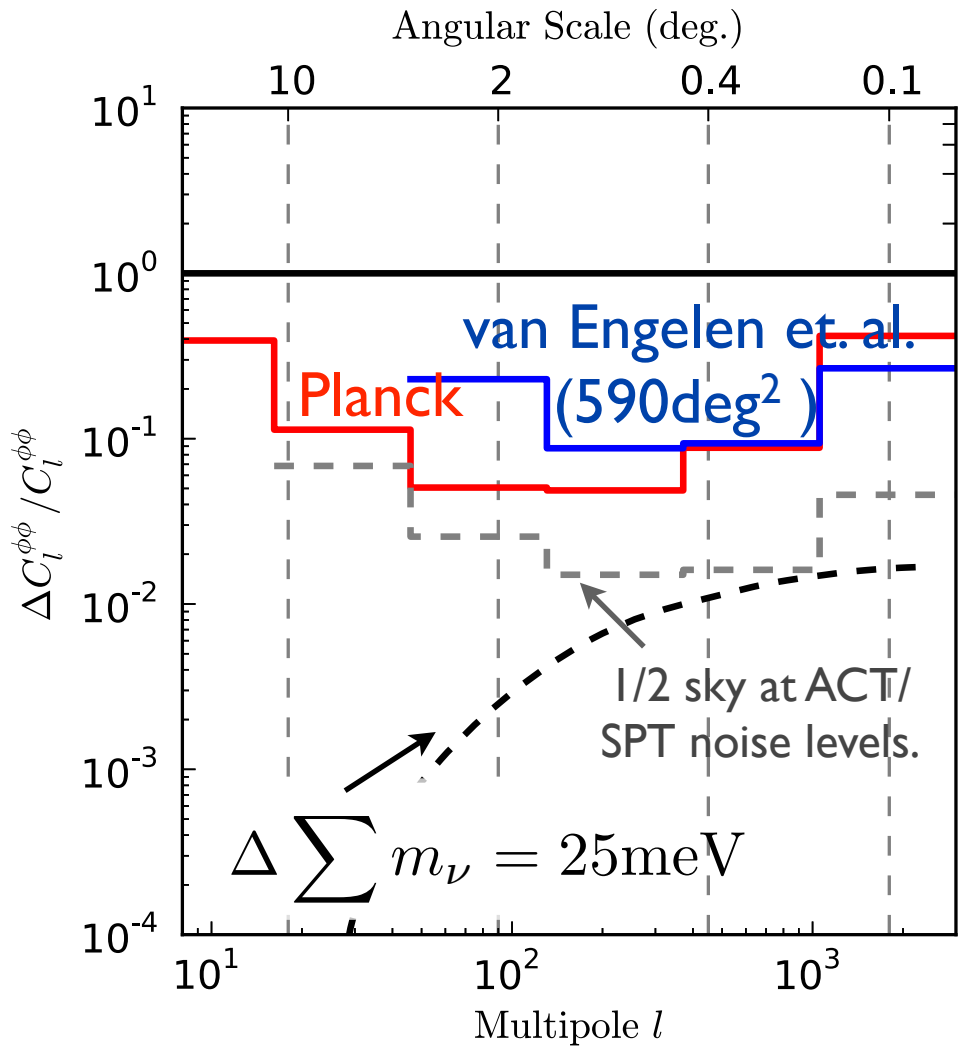
Lensing now a major component of all CMB experiments.



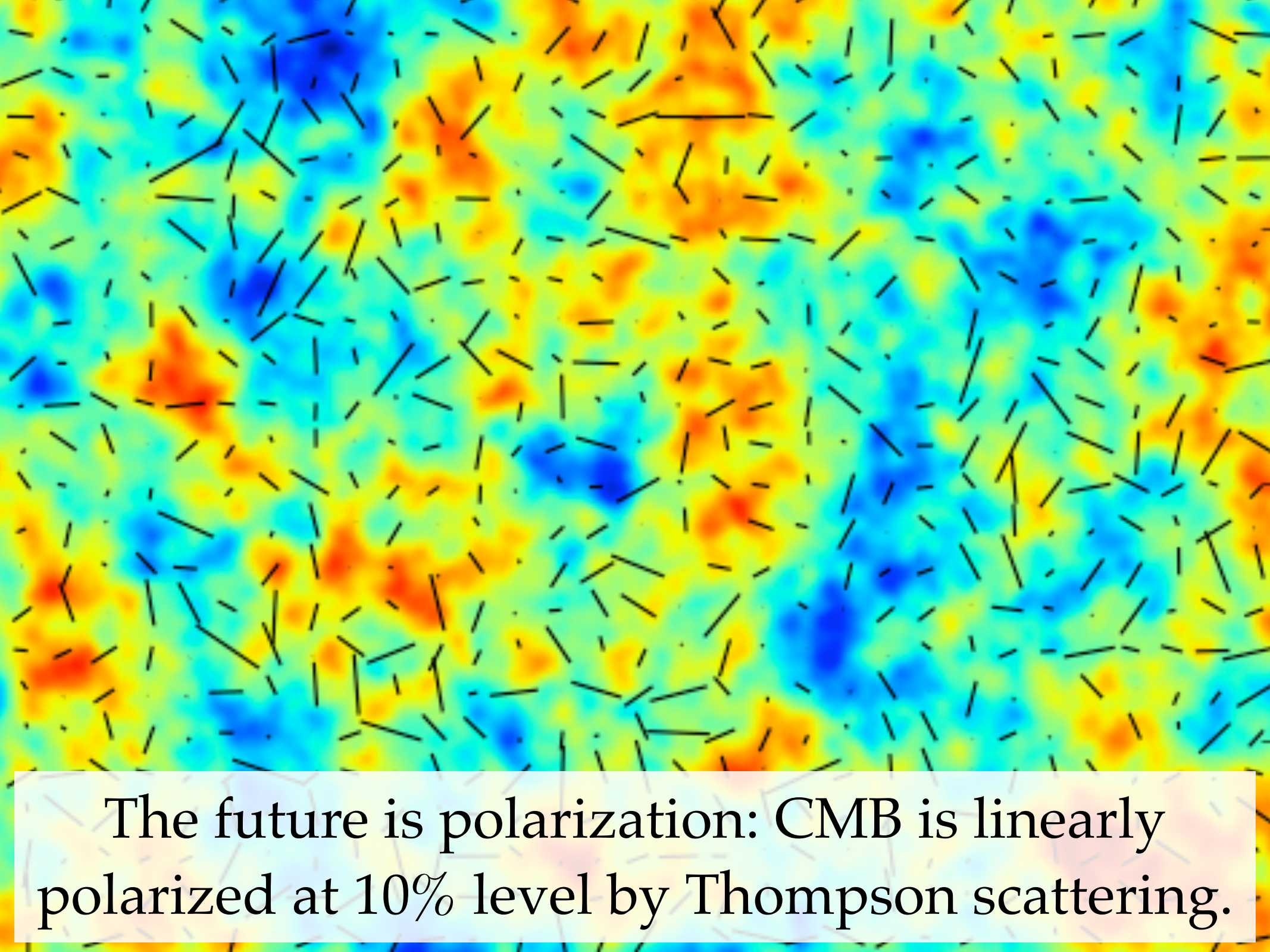
ACT and SPT temperature measurements are now sample/foreground limited. Only way to get more information is to cover more sky.



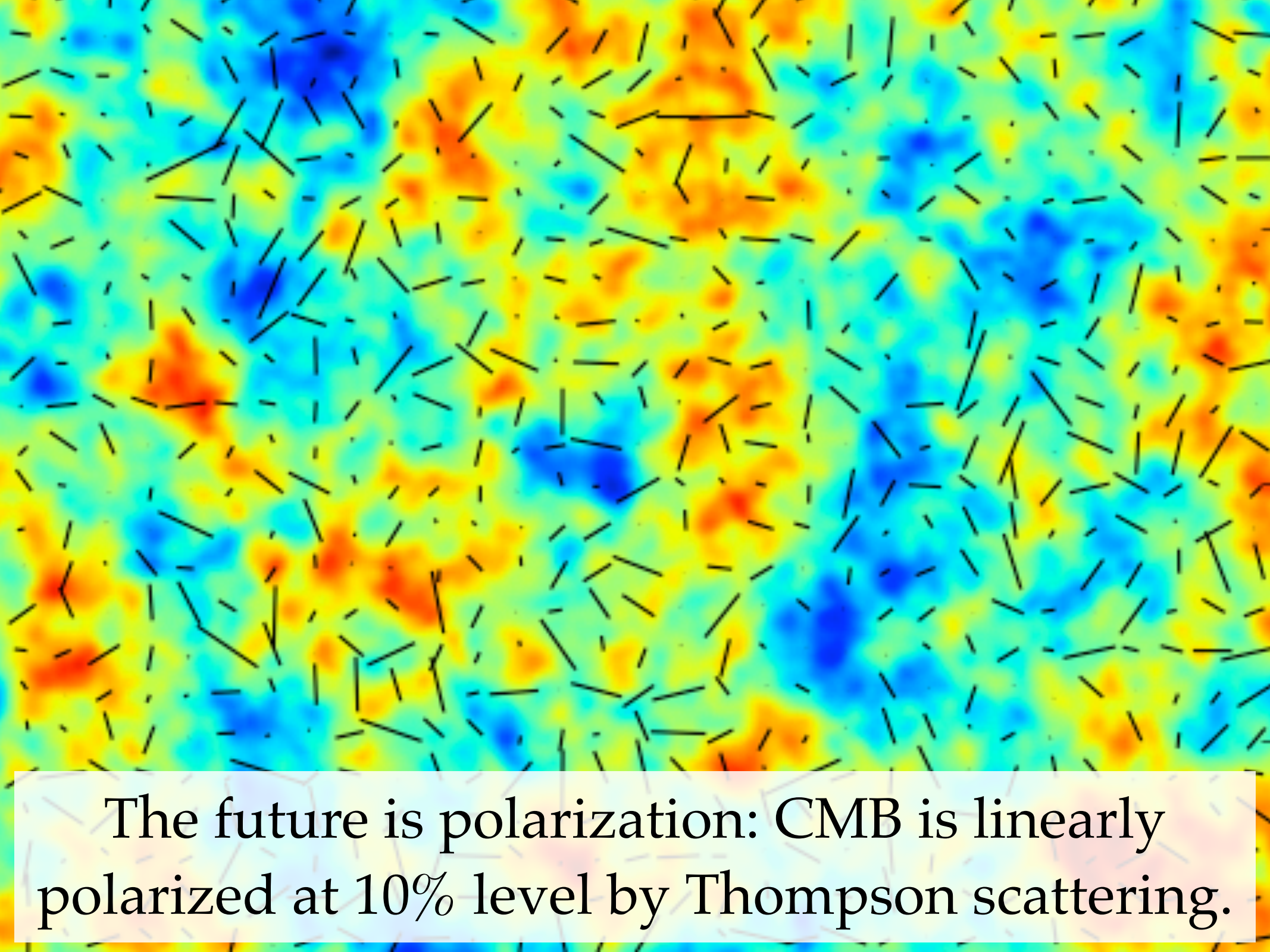
$N_l^{\phi\phi}$



$\Delta C_l^{\phi\phi}/C_l^{\phi\phi}$

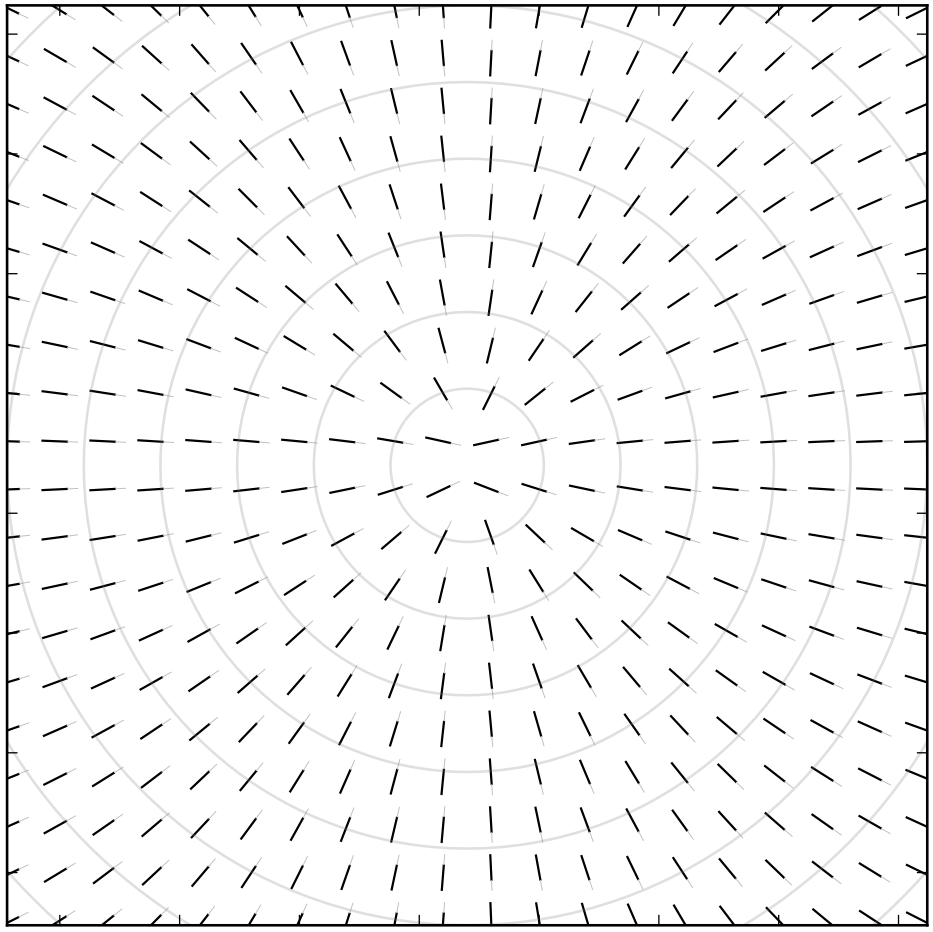


The future is polarization: CMB is linearly polarized at 10% level by Thompson scattering.

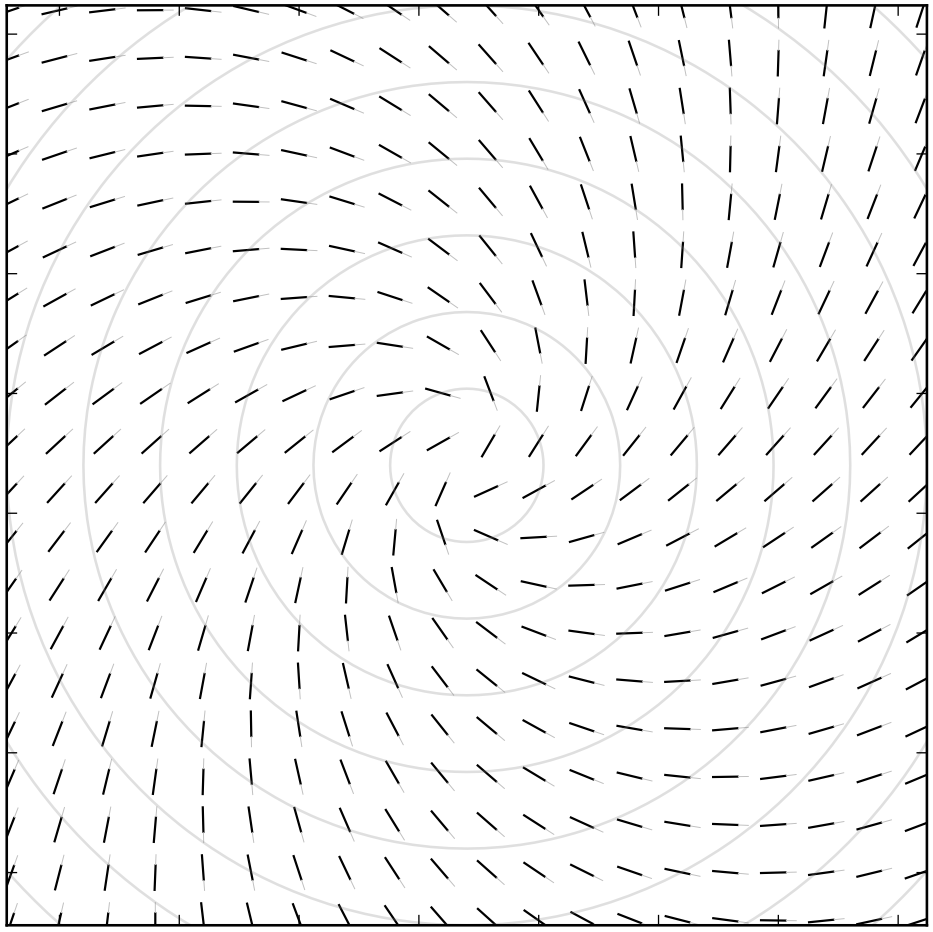


The future is polarization: CMB is linearly polarized at 10% level by Thompson scattering.

Breaking polarization into E- and B-modes, lensing has qualitatively different behaviour in polarization.



«E-mode»



«B-mode»

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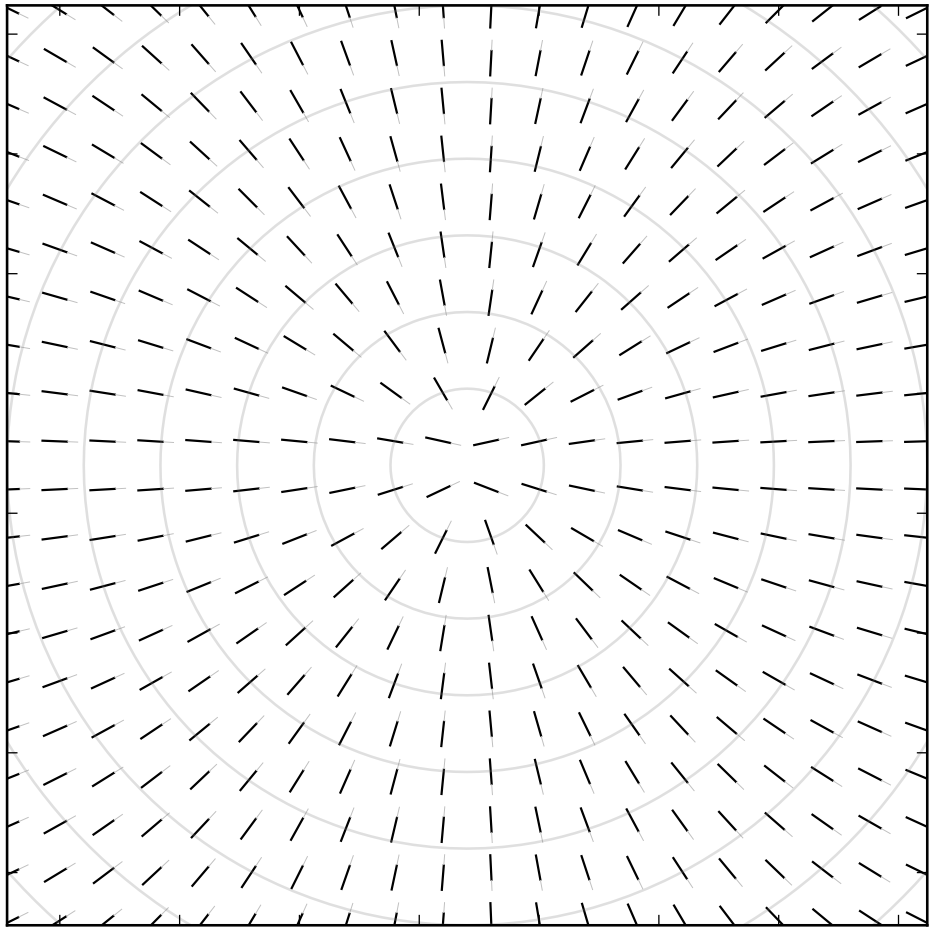

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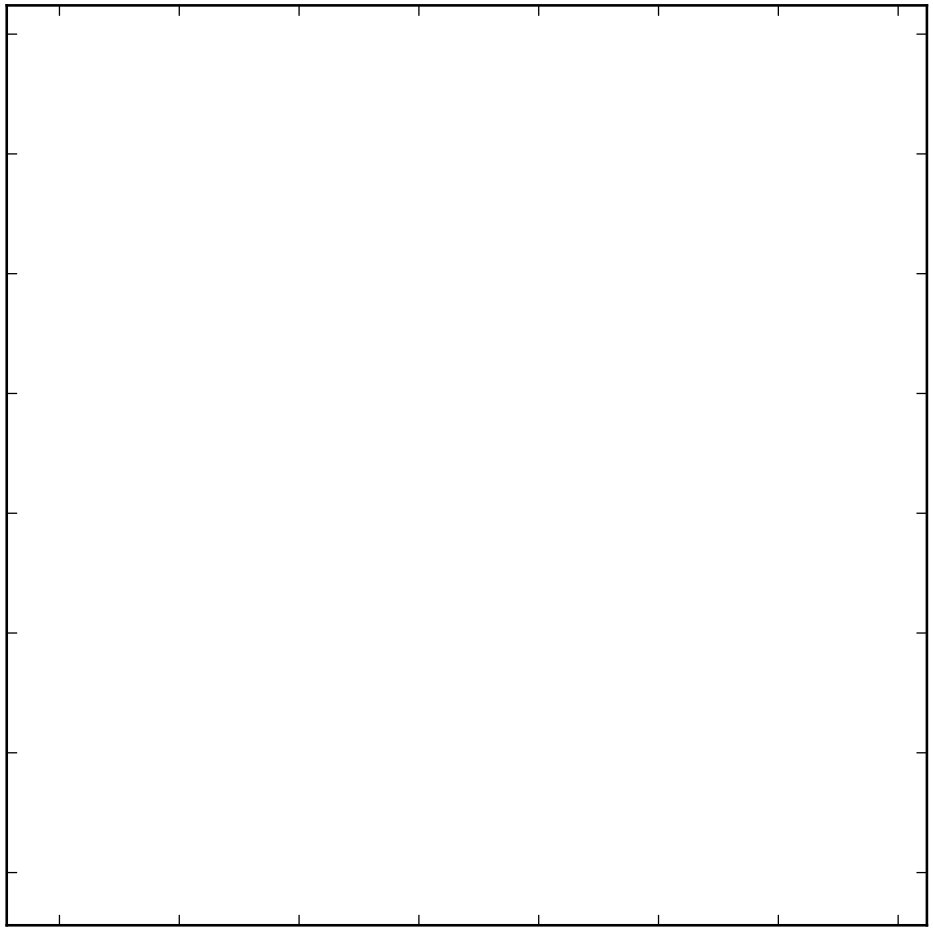

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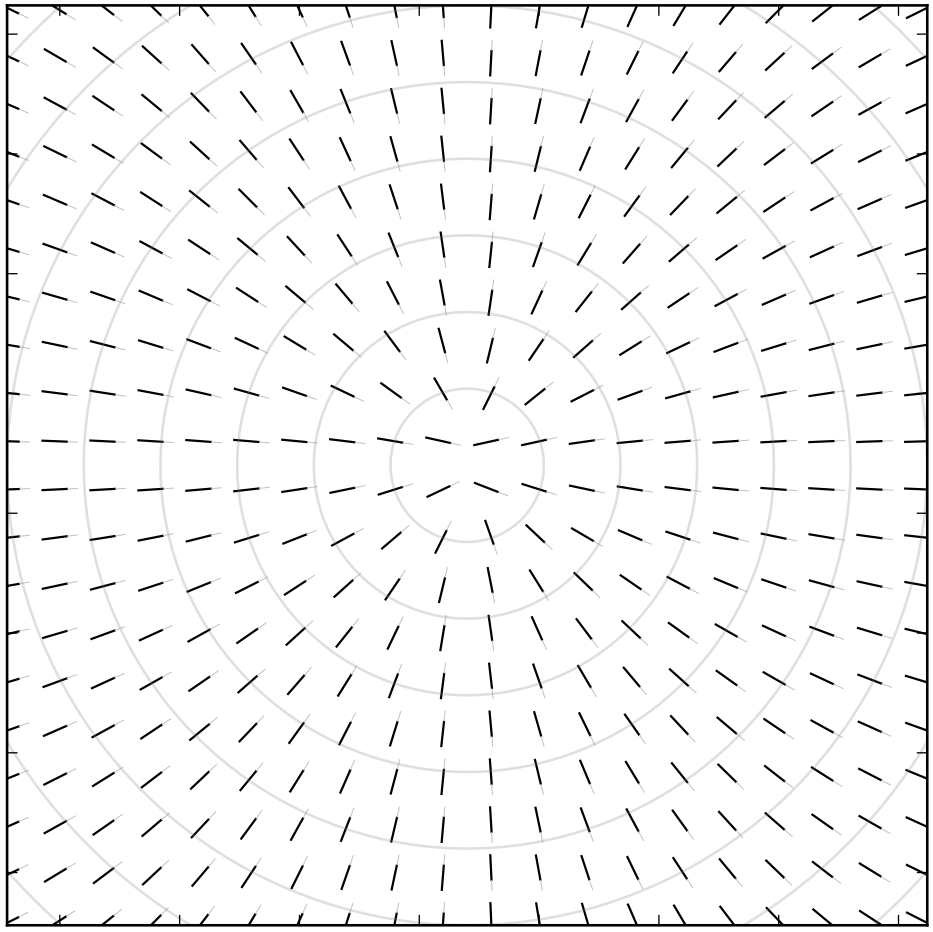

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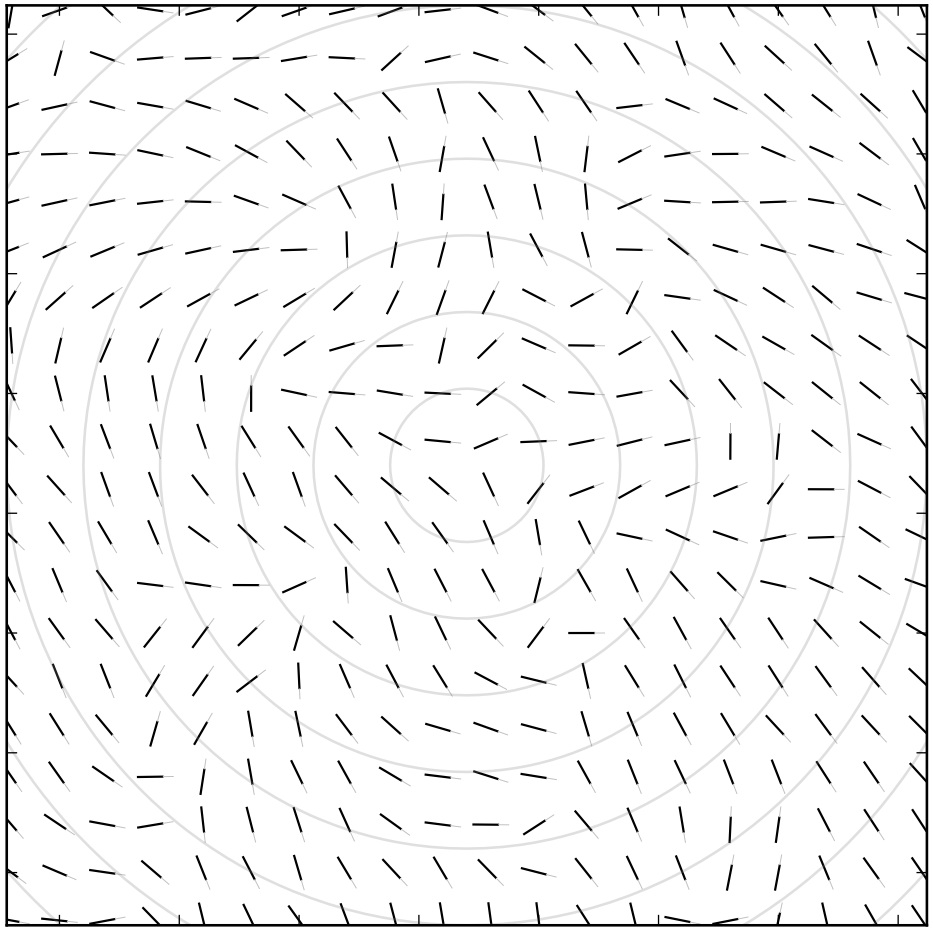

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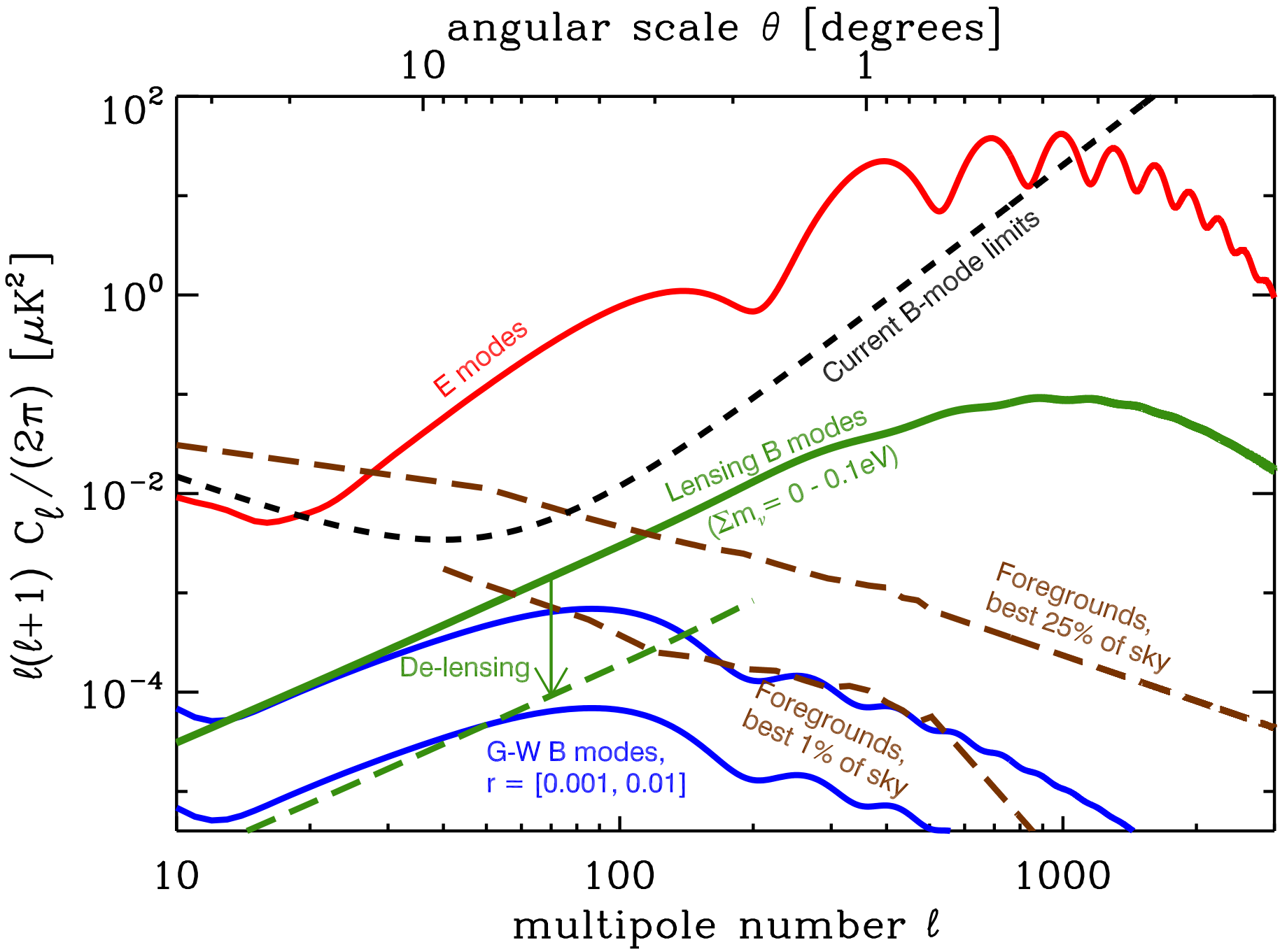
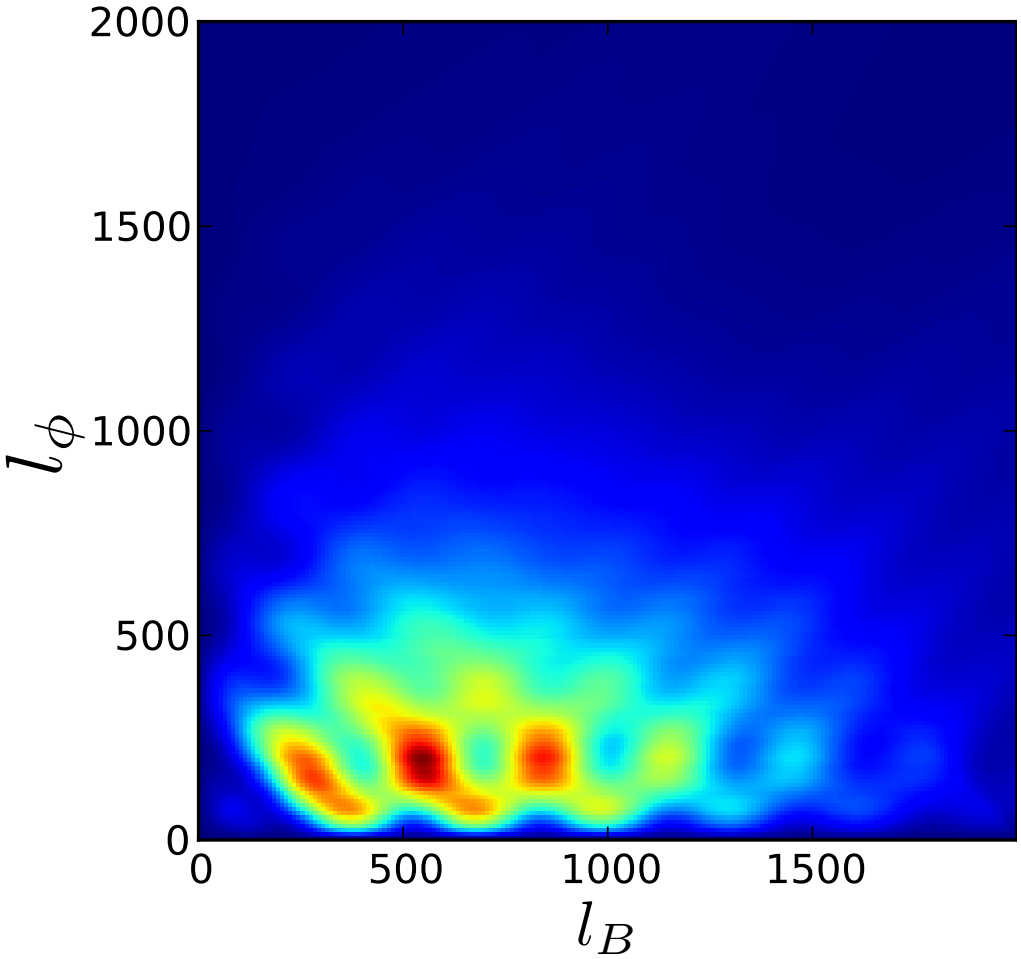
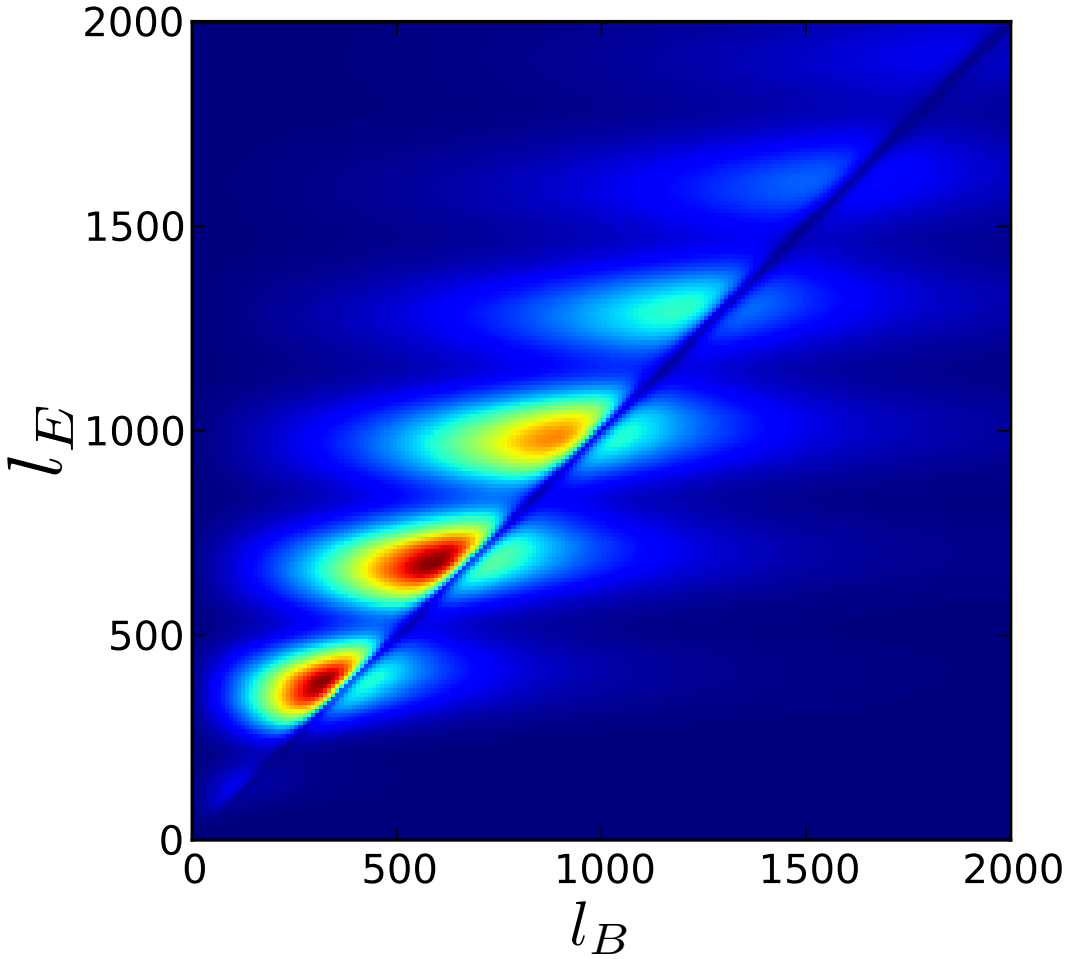


Carlstrom, Lee, ++ «CF5 Inflation Physics from the CMB and LSS»



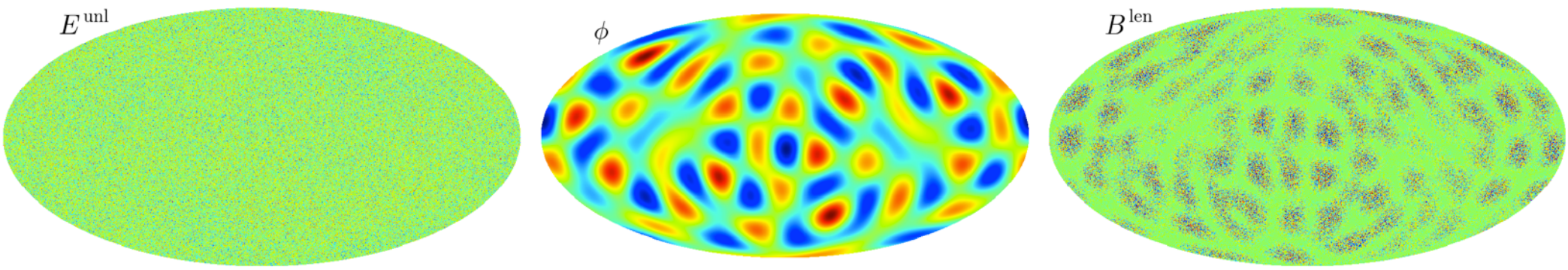


$$l_B \partial C_{l_B}^{BB,\mathrm{lens}} / \partial C_{l_X}^{XX}$$

Lensing B modes are sourced by E and ϕ over a range of scales.

Lens reconstruction in polarization is qualitatively different than in temperature; can be thought of as a process of template fitting.

$$B^{\rm lens}(\vec{l}_B) = \int d^2\vec{l}_E \int d^2\vec{l}_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi)$$



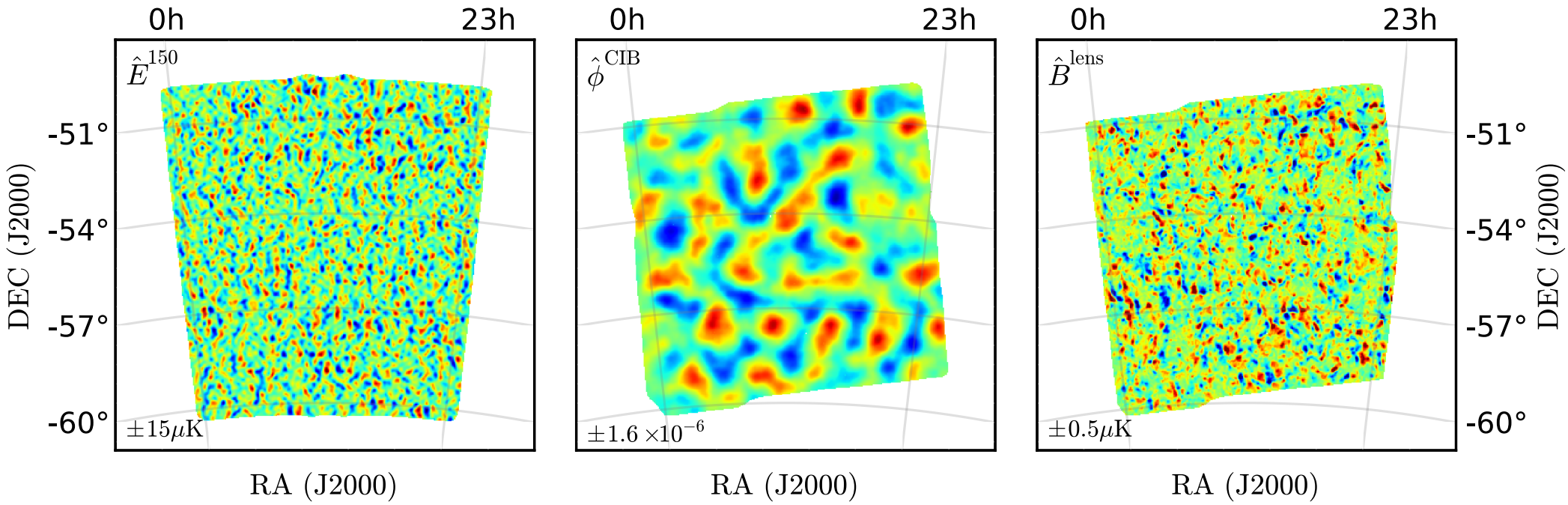
E ϕ $B^{\rm lens}$

Many experiments being built or already operating with target noise levels low enough to see lensing B modes:

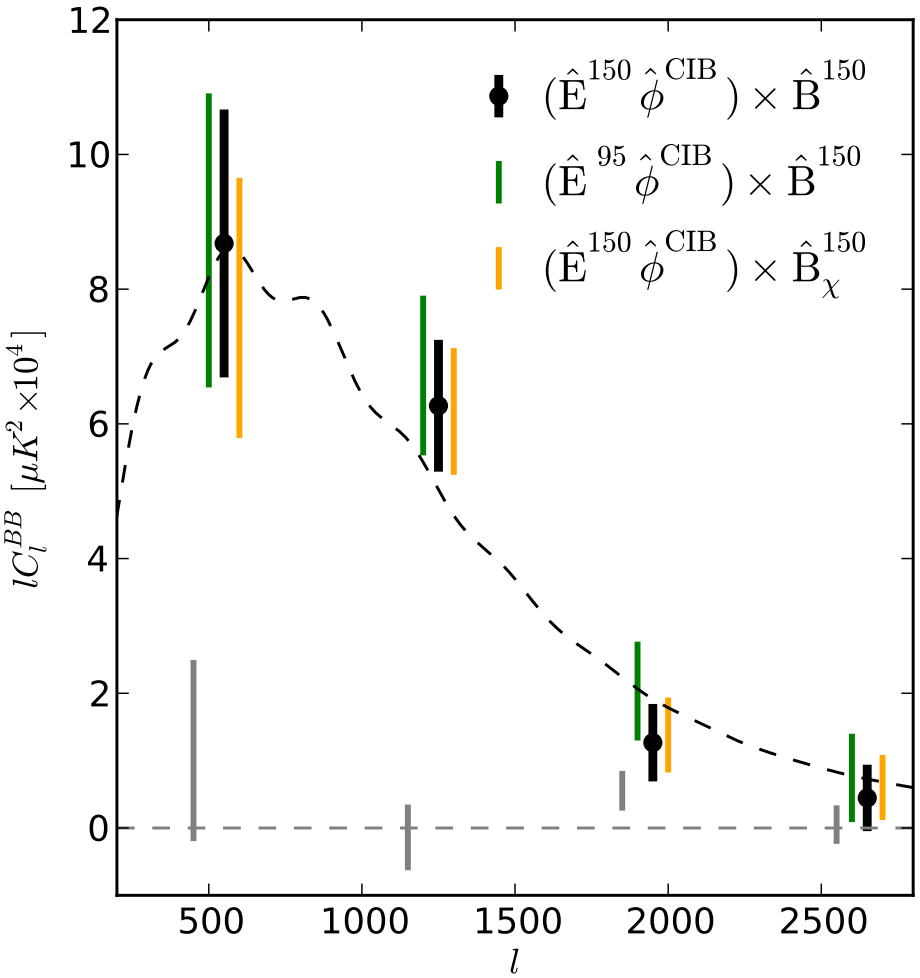
ABS
BICEP
EBEX
SPIDER
LiteBIRD
PolarBear
SPTpol
ACTpol

} Also measure small scale E modes -> can reconstruct ϕ.

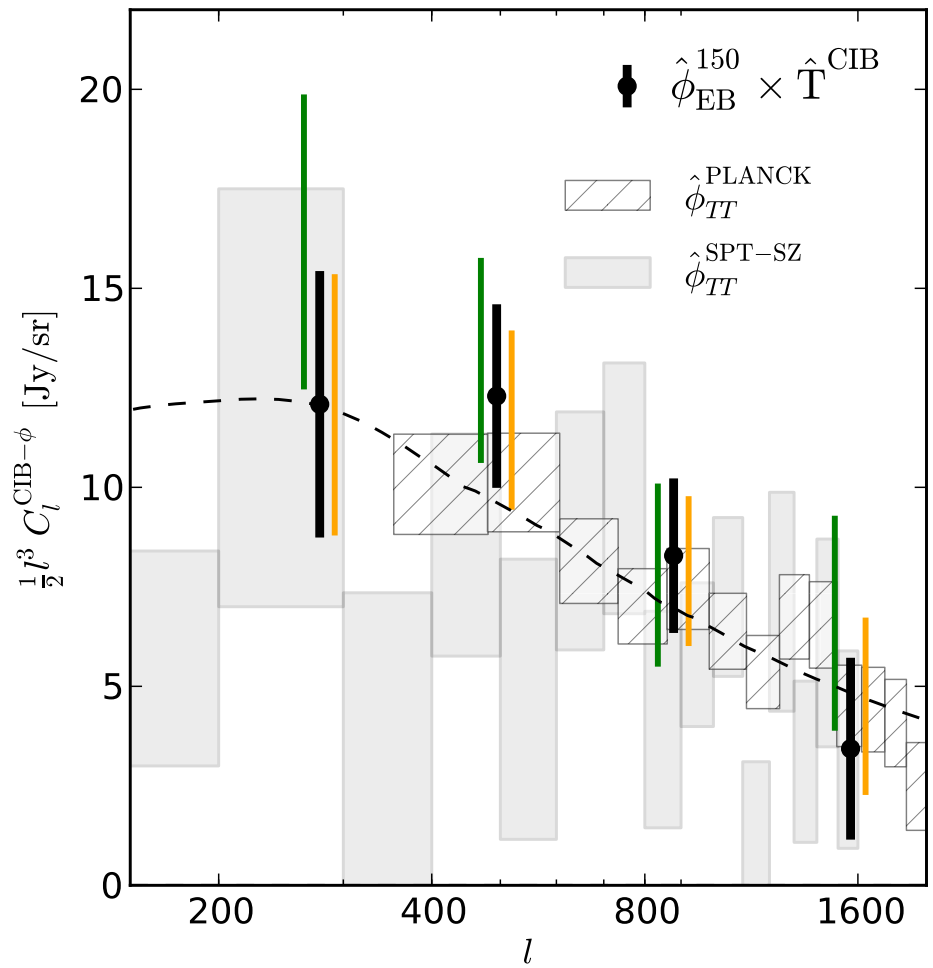
Detection of B-mode Polarization in the Cosmic Microwave Background with Data from the South Pole Telescope



First measurement of lensing B modes (last week!) using three-point EBϕ from SPTpol + Herschel-SPIRE maps of the cosmic infrared background.



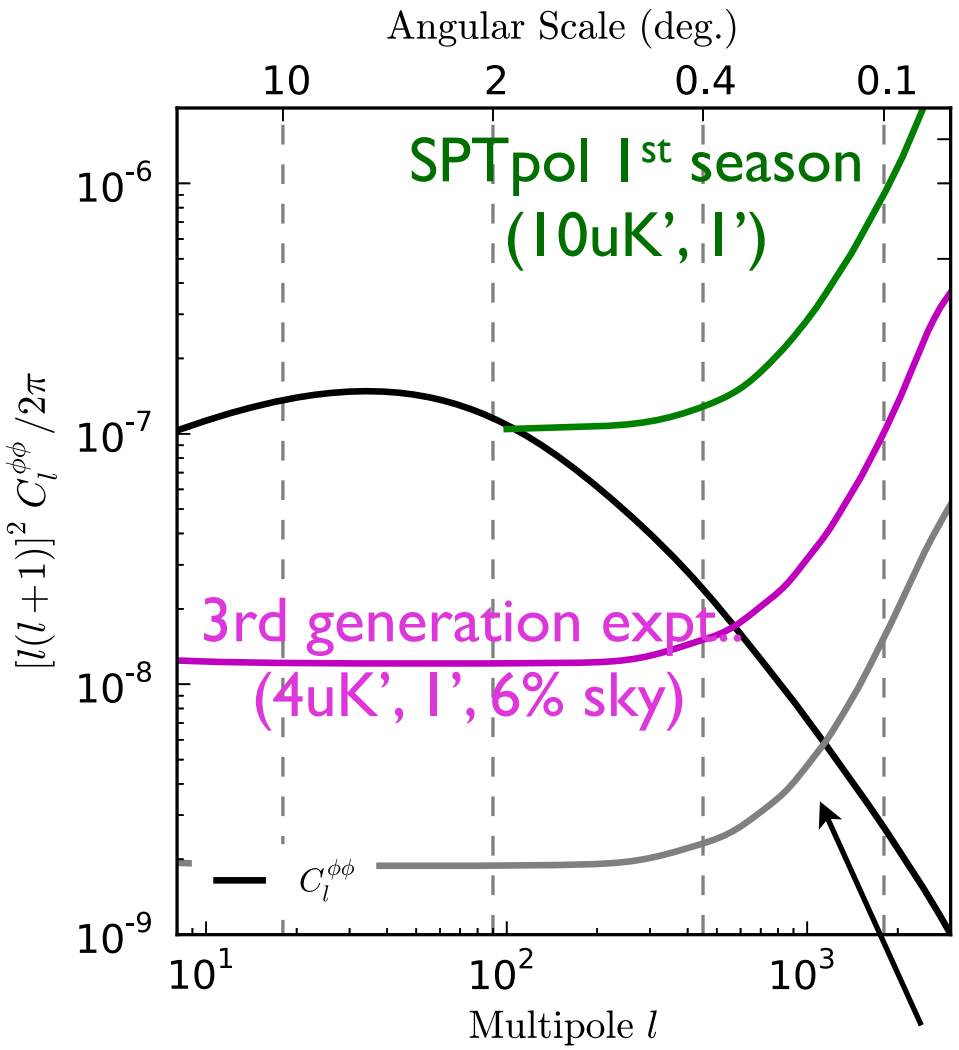
«B mode view»

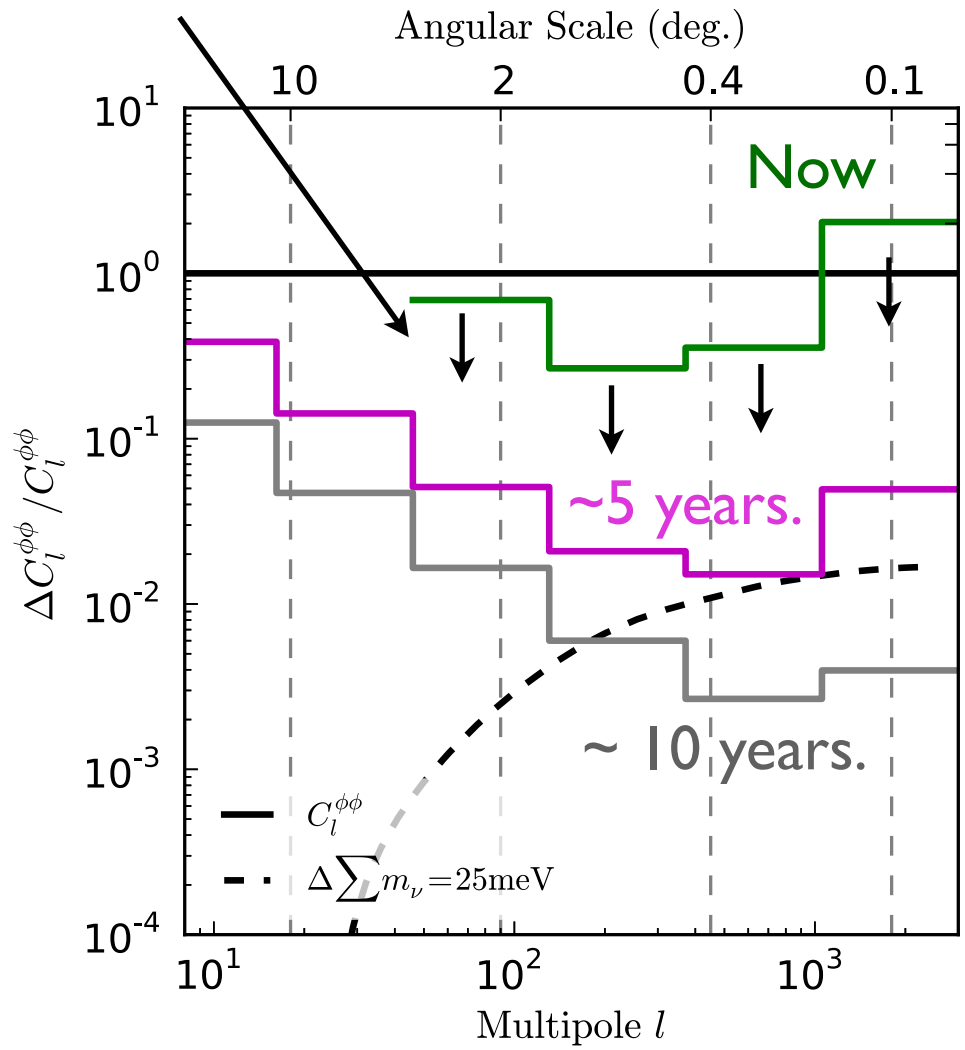


«Lensing view»

Lensing B modes now detected at 7.7σ significance.

Next ~3 years, ACTpol, SPTpol, Polarbear





Stage IV expt.
(1uK', 1', 50% sky)

$N_l^{\phi\phi}$

$\Delta C_l^{\phi\phi}/C_l^{\phi\phi}$