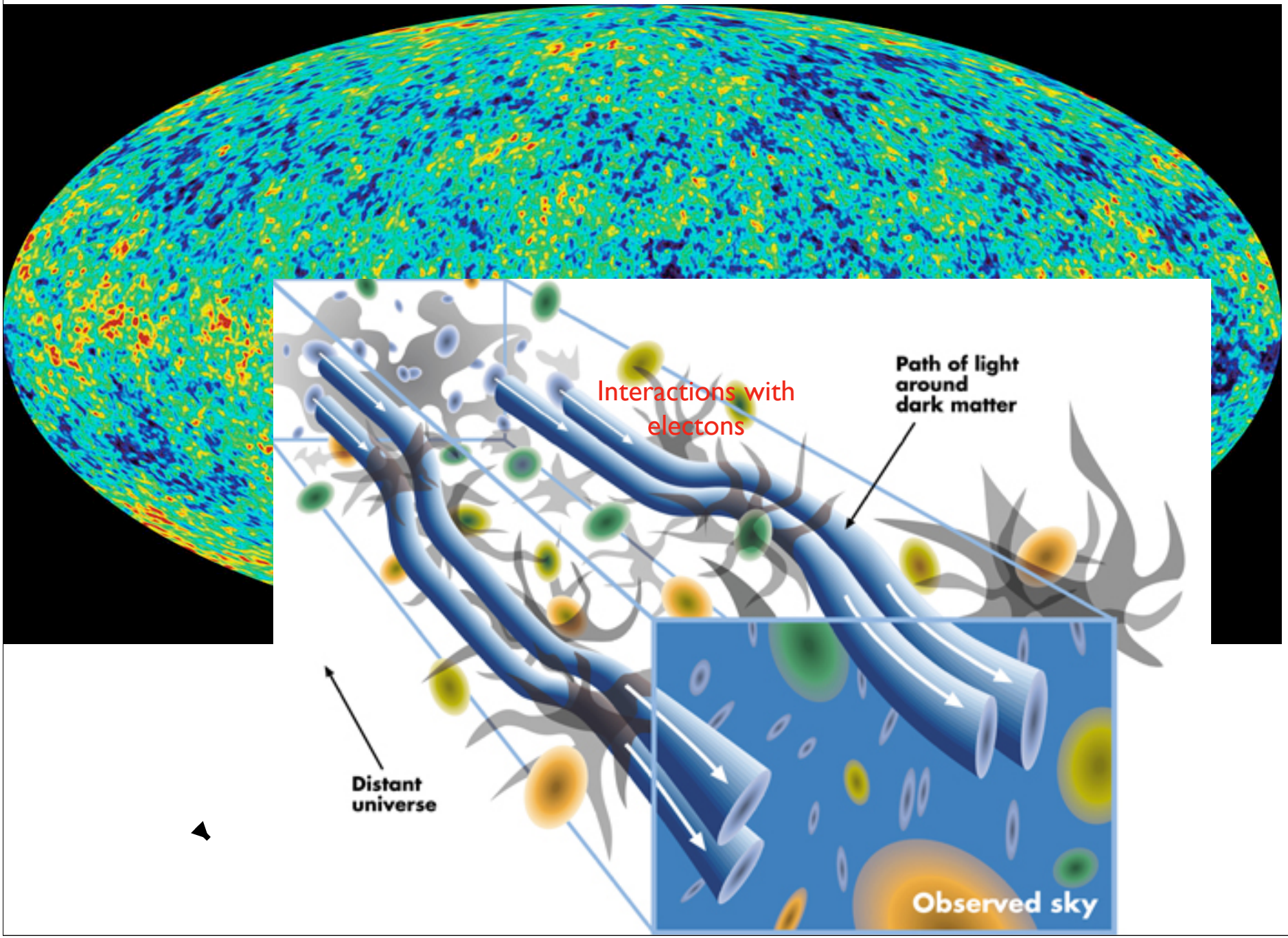
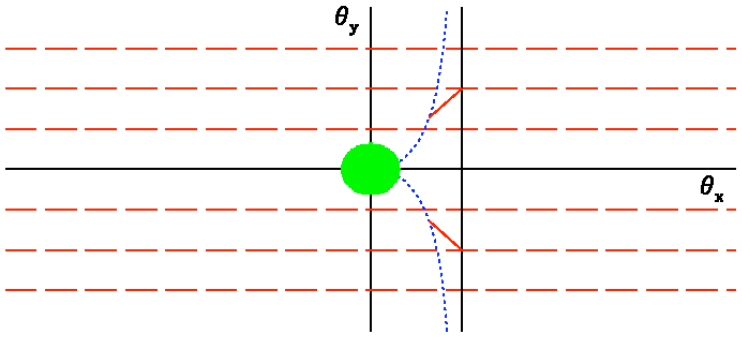
Secondary Anisotropies

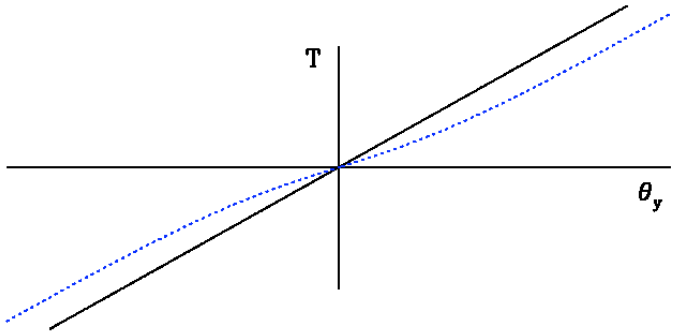
David Spergel


Interactions with electons
Path of light around dark matter
Distant universe
Observed sky

Gravitational Lensing of CMB



- Photons paths are deflected by mass fluctuations
  - Hot spots (and cold spots) behind a cluster are smaller and are



$$T(\boldsymbol{\theta}) = \tilde{T}(\boldsymbol{\theta} + \delta\boldsymbol{\theta})$$
$$\approx \tilde{T}(\boldsymbol{\theta}) + \delta\boldsymbol{\theta} \cdot \nabla\tilde{T}(\boldsymbol{\theta}) + \frac{1}{2}\delta\theta_i\delta\theta_j\partial_{ij}\tilde{T}(\boldsymbol{\theta}).$$

Gravitational Lensing

- Distorts fluctuations, does not generate fluctuations
- Couples large and small scales (produces non-Gaussianities)

$$\kappa \propto (\nabla T)^2 - T\nabla^2 T$$

$$\kappa \propto \rho$$

Power Spectrum

- Acoustic peaks are smeared out
- Additional power on small angular scales
- Lensing signal should correlate with galaxy distribution (just as galaxy lensing-galaxy)

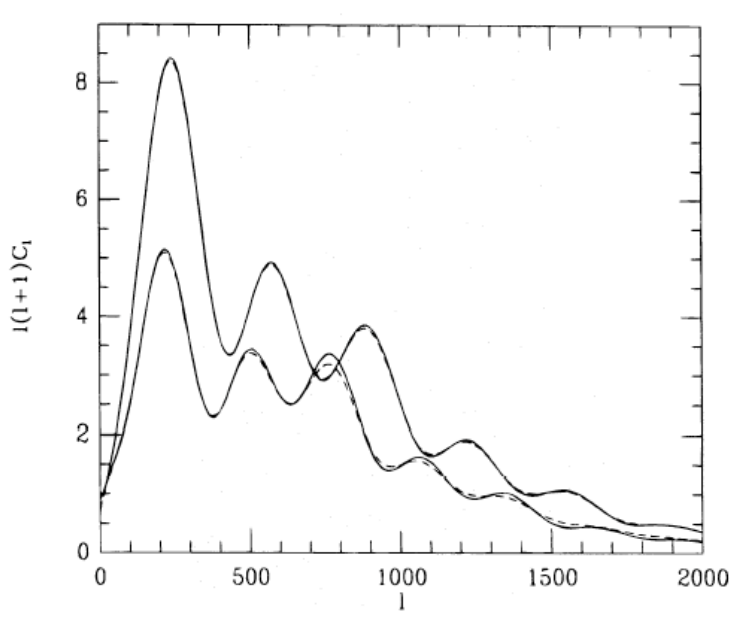


FIG. 2.—CMB anisotropy power spectrum $l(l+1)C_l$ vs. l with lensing (*dashed lines*) and without lensing (*solid lines*). Upper curves are for adiabatic CDM model with $h = 0.5, \Omega_{m0} = 0.4$, and $\Omega_{v0} = 0.6$, lower curves are for adiabatic CDM model with $h = 0.5, \Omega_{m0} = 1$ and $\Omega_{v0} = 0$. Both models are normalized to *COBE*. Lensing smoothes the sharp features in the power spectrum but leaves the overall shape unchanged. The two models show a typical range of the lensing effect on CMB.

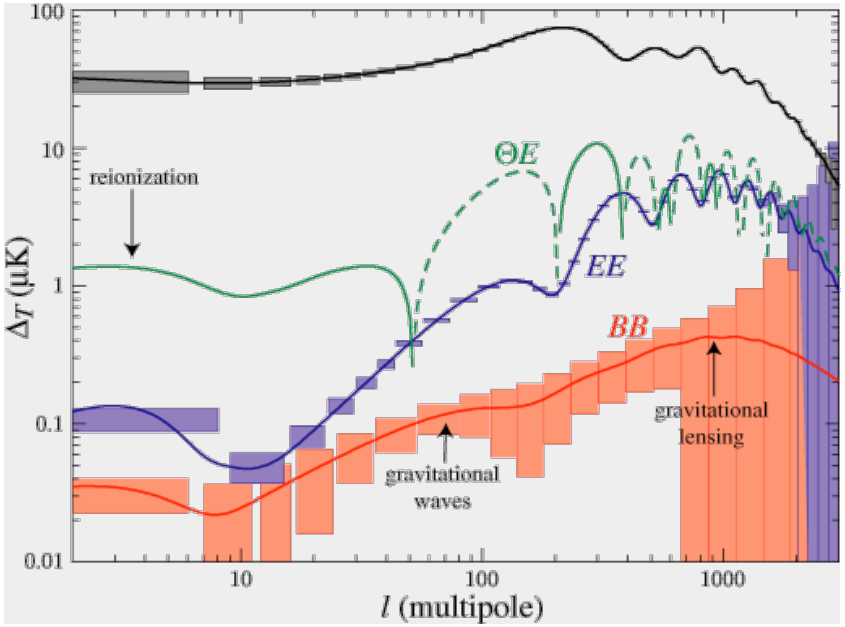
Seljak 1996

Generation of New Fluctuations

E modes are distorted into B modes on small scales

Lensing rotates polarization vectors

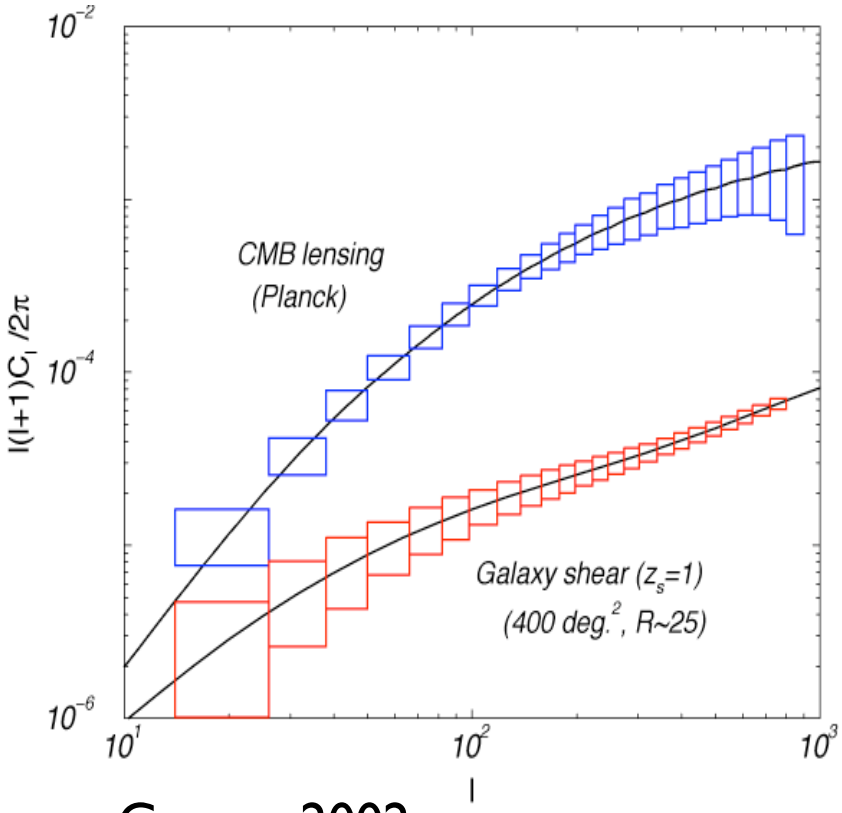
Non-Gaussian fluctuations are generated on small scales (non-trivial 4 point function)



Hu and Dodelson (2002)

Measuring Shear Power Spectrum

- CMB lensing is more sensitive on large angular scales
- Very promising to combine lensing seen by Planck with lensing seen by LSST
  - Independent systematics
  - Multiple lens sheets
- SALT and ACT



Cooray 2002

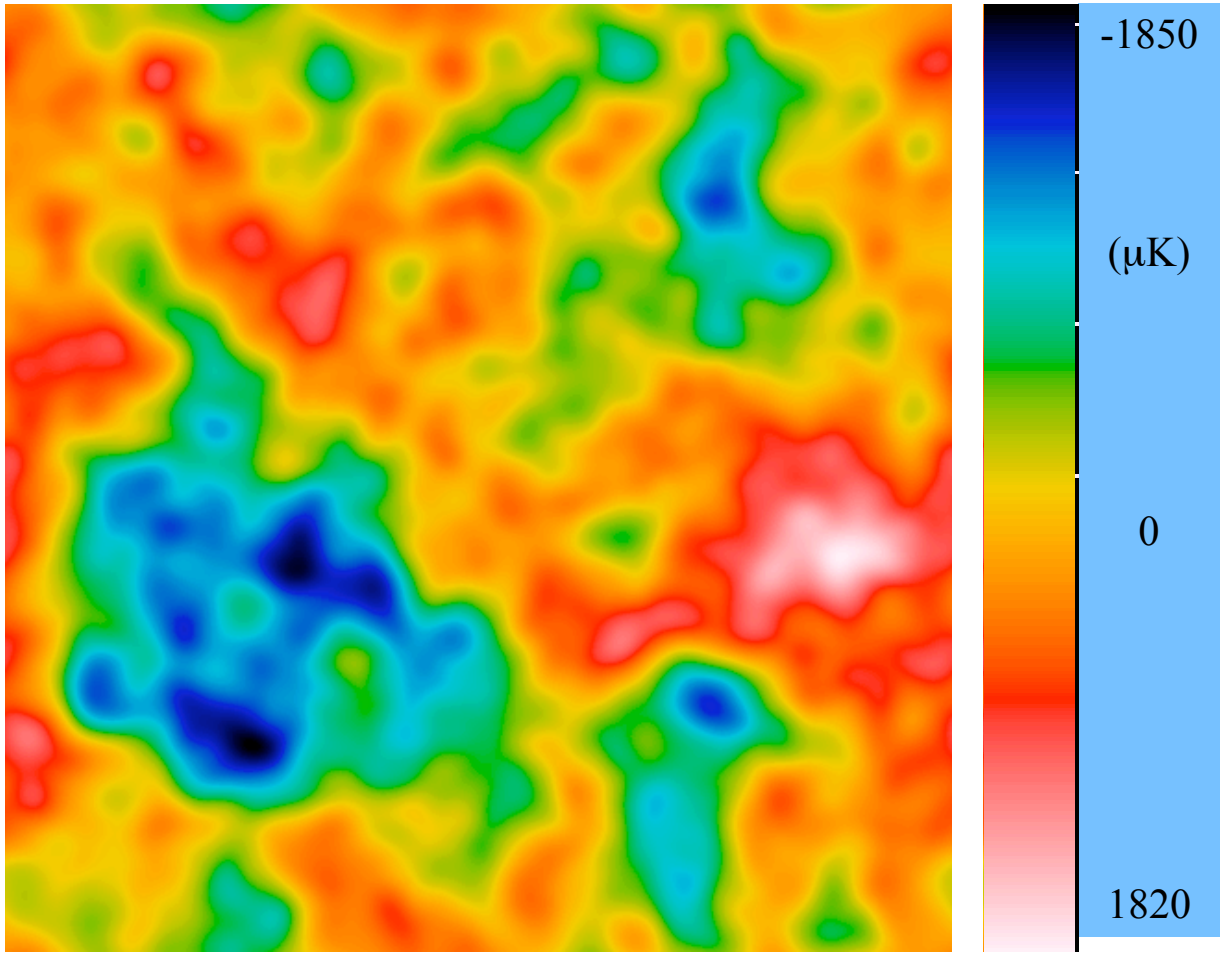
- Lensing arises from integrated mass fluctuations along the line of sight.

- The CMB acts as a fixed distance source, removing the degeneracy inherent to other lensing measurements.

- Signal at l = 1000-3000

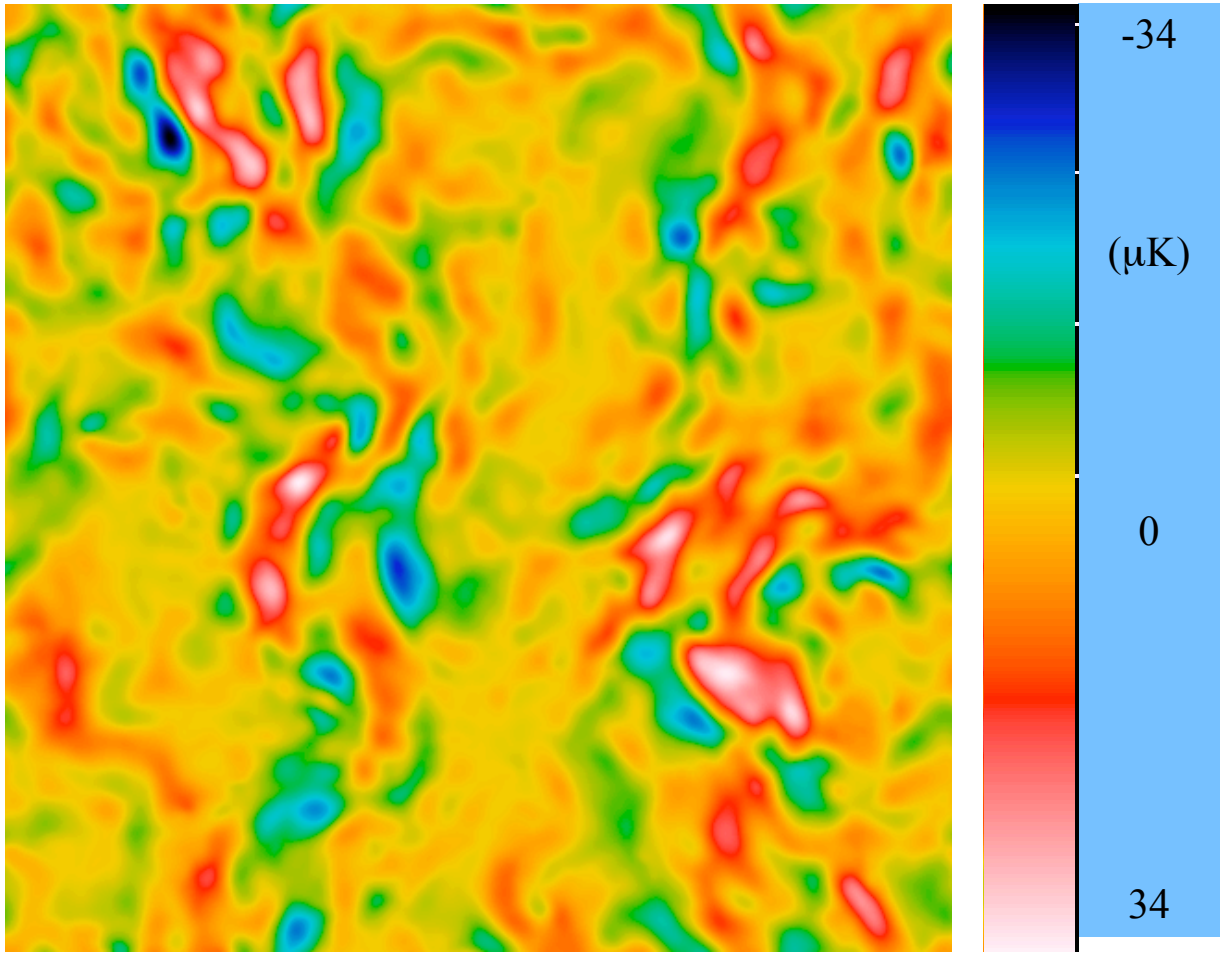
- Image distortion – only a minor effect in the power spectrum.

- *Must* have a deep, high fidelity map to detect this effect.



CMB
1.4°x 1.4°

- RMS signal well above noise floor.
- Isolate from SZ and point sources spectrally.
- Identify with distinctive 4-point function.



Lensing Signal

1.4°x 1.4°

Rees-Sciama Effect

- When density fluctuations become non-linear, the gravitational potential grows with time.
- Amplitude of term depends on cluster mass and on Hubble constant

$$\frac{\delta T}{T} = -2 \int dt \dot{\Phi}$$

$$\Phi \propto \frac{\delta}{a}$$

$$\delta \propto a^3$$

$$\dot{\Phi} \propto H$$

Estimating Rees-Sciama

$$\frac{\delta T}{T} = -2\int dt\dot{\Phi} \simeq \frac{2R}{c}(2H)\Phi \simeq \frac{4R}{ct_0}\frac{v^2}{c^2} \simeq 10^{-7} - 10^{-8}$$

Supercluster

Cluster

- Weak signal to detect through power spectrum
- Much more easily detected by cross-correlating galaxy distribution (or clusters) with CMB map

- CMB and large-scale structure observations measure many highly correlated effects
  - galaxies trace density
  - density field determines velocity field
  - KSZ traces momentum
  - TSZ traces clusters (and thermal pressure)
  - Rees-Sciama traces the evolution of the potential
  - Lensing of the CMB and lensing of the galaxy trace the potential

SALT + ACT can see these cross-correlated effects

Example: 3 pt Function

$$< \kappa T > \propto < ((\nabla T)^2 - T\nabla^2 T)(T_{primordial} + T_{KSZ} + T_{lensing} + T_{RS}) >$$

$$\kappa \propto \rho$$

$$T_{KSZ} \propto \rho v$$

$$T_{RS} \propto H\rho$$

$$< \kappa T > \propto H < \rho^2 >$$

Verde and Spergel 2002

Should be redone using halo model for small scale

Cross-correlations

- If you choose the "right" combination, then you can isolate the interesting cosmological effect

- Maps:
  - galaxy density field
  - TSZ map
  - CMB map
  - CMB convergence map

Galaxy Formation: Open Issues

- How do galaxies affect their environment?
- How does the environment affect galaxies?
- How do galaxies form? Where has all of the gas gone? The baryon/dark matter ratio in galaxies is ~0.25-0.5 times the cosmological model. Where are the missing baryons?
- Galaxy angular momentum problem

SALT observations of ACT clusters!

Dark Energy

- What is the dark energy?
  - measure growth rate of structure
    - Rees-Sciama/galaxy; Rees-Sciama/lensing
    - Kinetic SZ/galaxy

Requires modelling of effectiveness. Potential for SALT/ACT

Early Universe

- CMB observations will measure ns and r. This is a field where fundamental physics touches data. If we are lucky, we may see isocurvature modes or non-Gaussianity. Either detection would severely constrain the inflaton potential.

- Inflation is a powerful idea, but has many problems. There is a lot to work to be done on model building and understanding physics of inflation.

  - initial condition problem
  - reheating
  - fine tuning of potential

Inflation replace a few numbers that we don't understand with a several functions that we don't understand!
-David Schramm

Thank you!

Describe the main effect detected by these cross-correlations where ρ_g is the galaxy density field, T is the CMB sky, κ is the convergence of the CMB sky and T_{SZ} is the thermal SZ map.

$$< \rho_g T^2 > \quad (1)$$

$$< \rho_g \kappa > \quad (2)$$

$$< \kappa T > \quad (3)$$

$$< \rho_g T_{SZ} > \quad (4)$$

Calculating these terms is a paper (e.g., Dore, Hennawi and DNS 2004)

Detecting these effects is a thesis