COSMIC MICROWAVE BACKGROUND ANISOTROPIES

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Outline: what have we learned from the CMB?

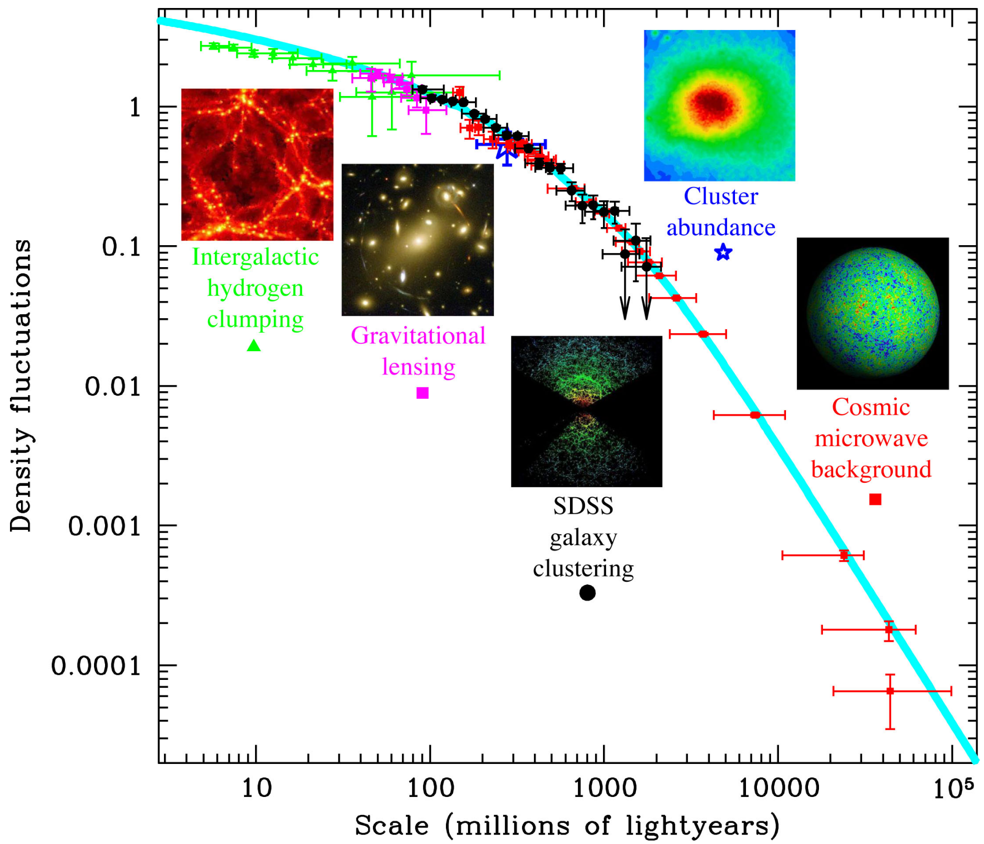
- Parameters from the CMB
- Current measurements
- Major milestones passed
- CMB constraints on inflation
- The future:
  - Planck
  - Secondary anisotropies
  - Gravitational waves

PARAMETERS FROM CMB: MATTER AND GEOMETRY

- Acoustic physics (dark energy and curvature negligible):
  - Peak locations depend on sound horizon r_s at last scattering
  - Damping scale $1/k_D$(roughly geometric mean of horizon and mean free path)
  - Both depend only on $\Omega_b H_0^2$ and $\Omega_m H_0^2$ for fixed T_{CMB}
  - Peak heights depend on baryon loading ($\Omega_b H_0^2$) and gravitational driving ($\Omega_m H_0^2$; see shortly) $\rightarrow r_s$ and k_D then calibrated standard rulers
- Main influence of geometry, dark energy and sub-eV massive neutrinos then through *angular diameter distance* to last scattering
  - d_A accurately determined from angular size of standard rulers r_s and k_D
  - Weak influence on large scales (where cosmic variance bad) through ISW

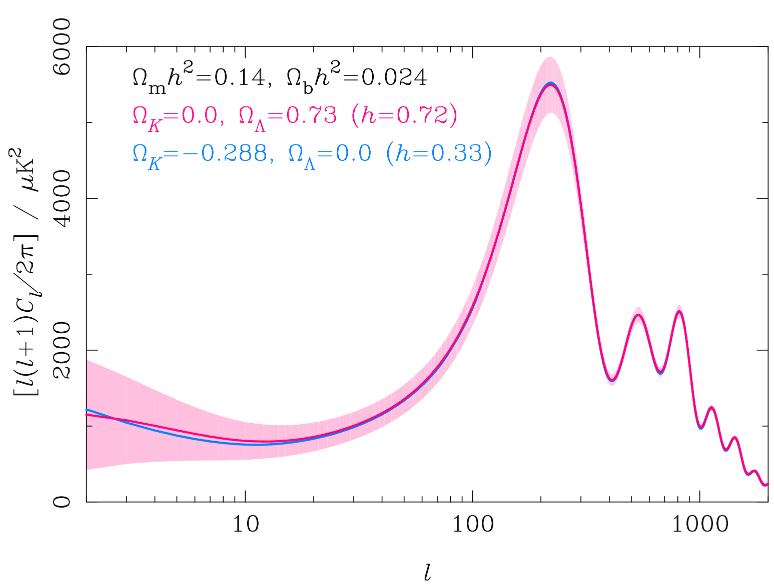
PARAMETERS FROM CMB: PRIMORDIAL POWER SPECTRUM

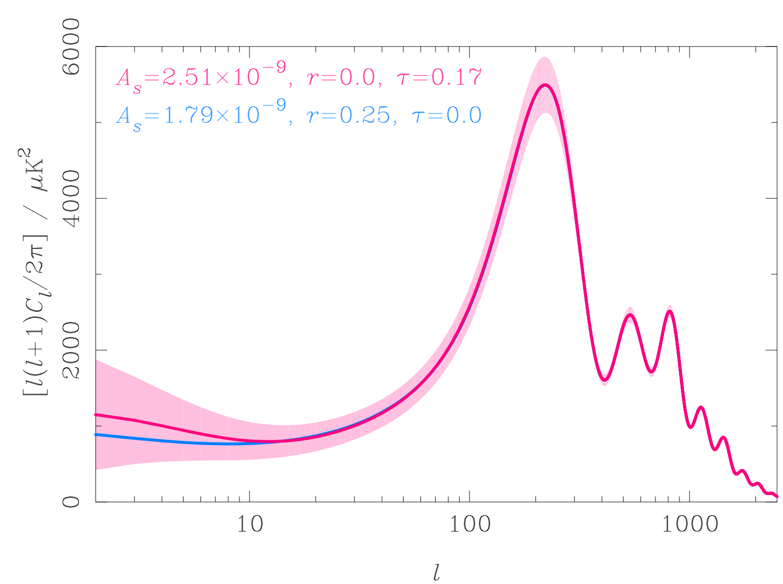
- Scalar power spectrum C_l essentially $e^{-2\tau}\mathcal{P}_{\mathcal{R}}(k)$ at $k \approx l/d_A$ processed by acoustic physics
  - CMB probes scales $7\,\mathrm{Mpc} < k^{-1} < 5000\,\mathrm{Mpc}$
- Tensor power spectra sensitive to $e^{-2\tau}\mathcal{P}_h(k)$



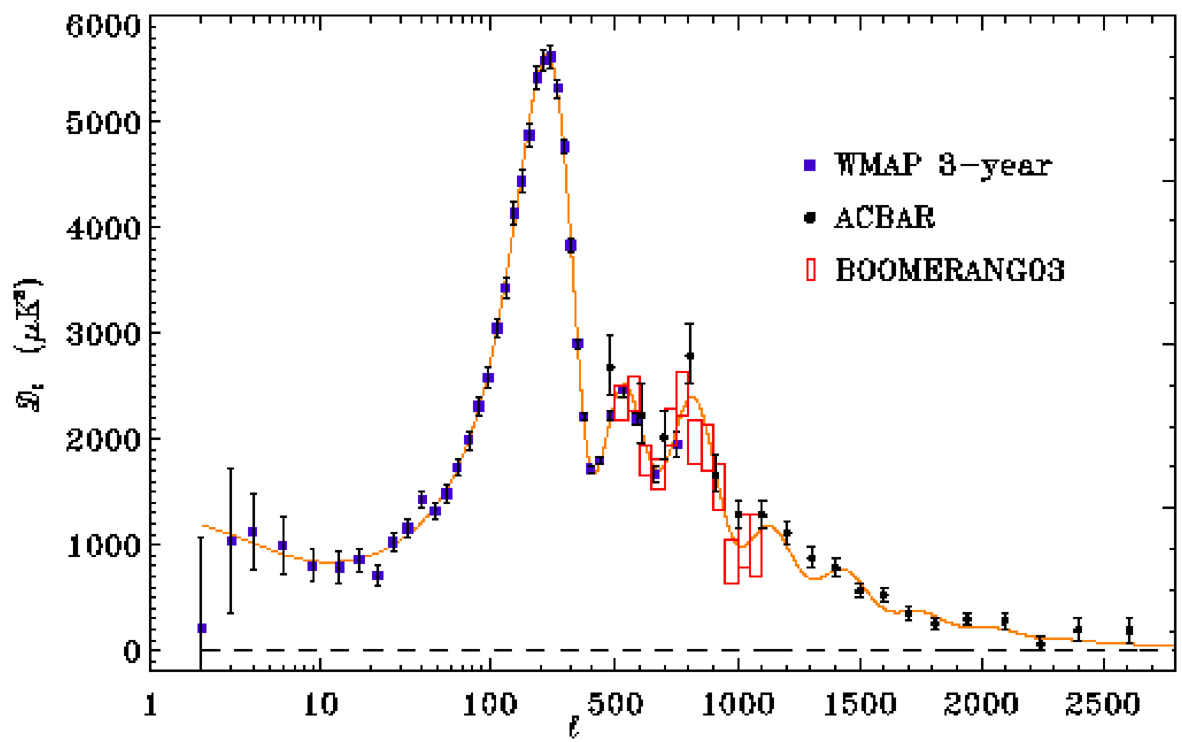
DEGENERACIES

- Some params not determined by linear T anisotropies:
  - Angular diameter test gives only $d_A = d_A(\Omega_K, \Omega_{\rm de}, w, \ldots)$ once matter densities determined from peak morphology
    - Disentangling dark energy and K relies on large-scale anisotropies, where cosmic variance large, or other datasets (e.g. Hubble, supernovae, shape of matter power spectrum or baryon oscillations)
  - Addition of gravity waves and renormalisation mimics reionization but can break with *polarization*



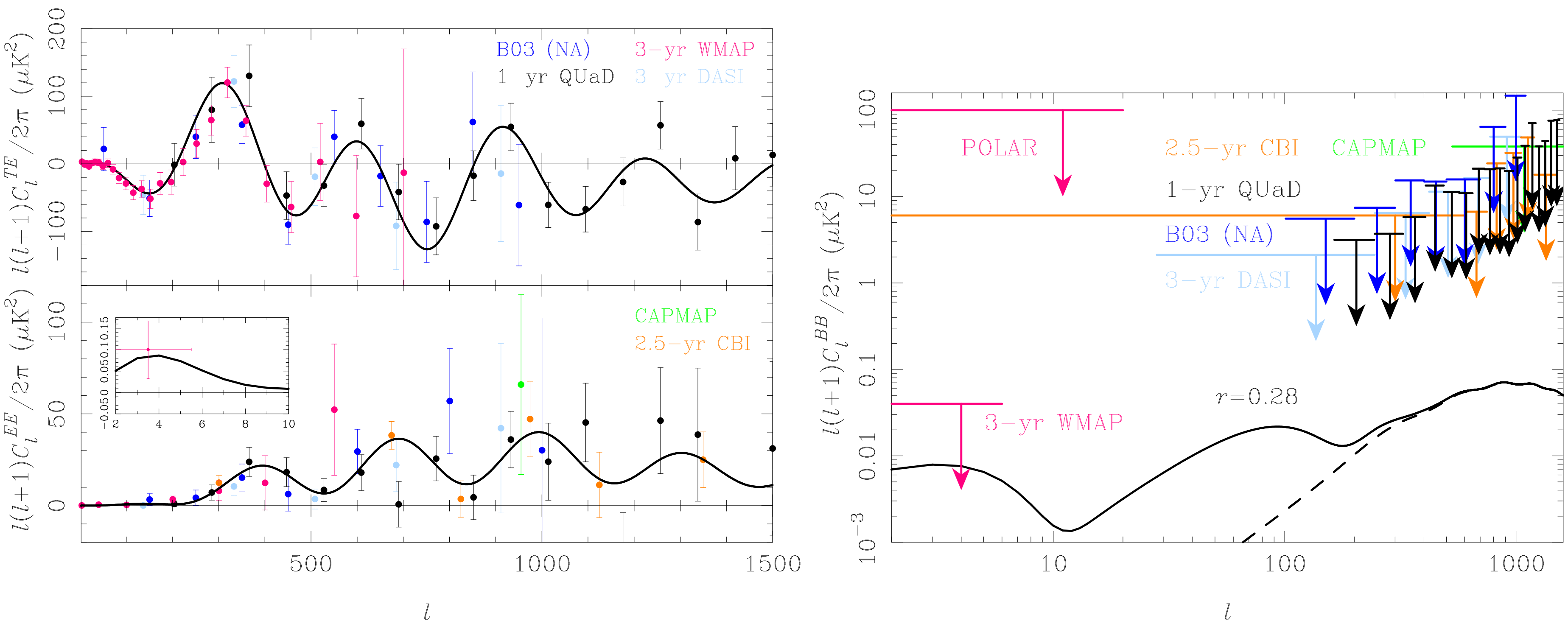


CURRENT TEMPERATURE DATA AND MILESTONES



- Sachs-Wolfe Plateau and late-time ISW effect
- Acoustic peaks at ‘adiabatic’ locations
- Damping tail/photon diffusion
- Weak gravitational lensing (see later)

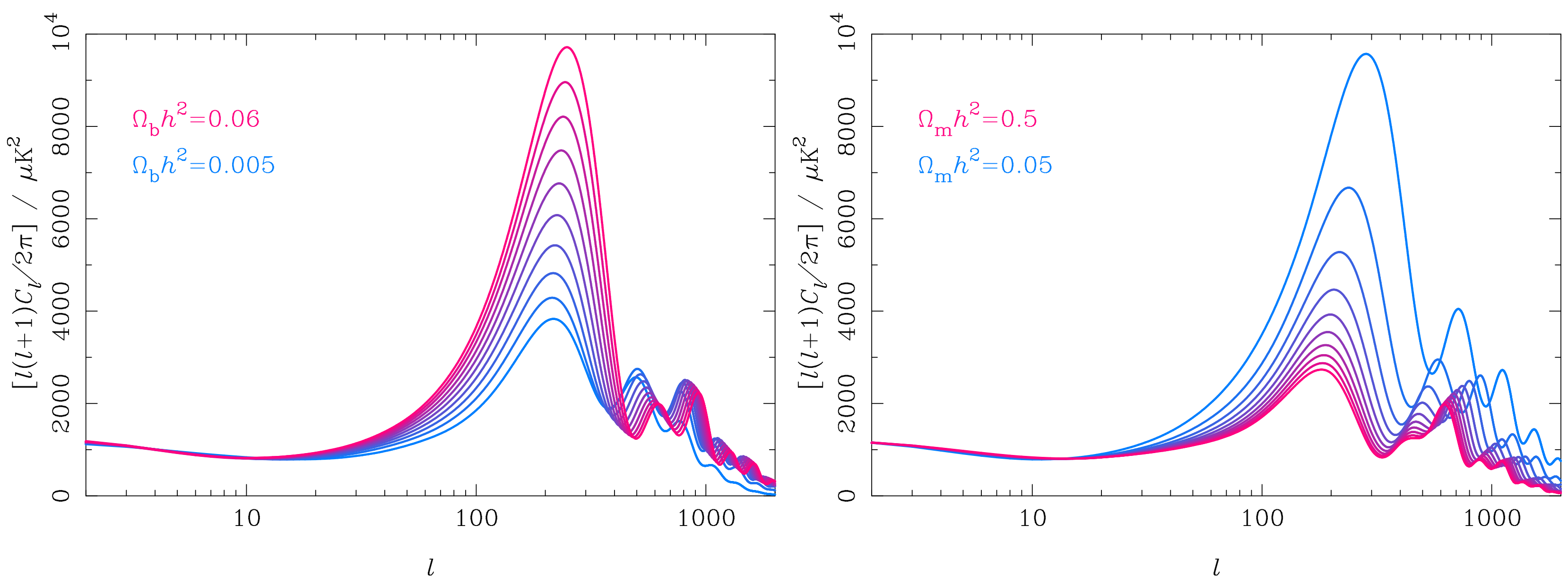
Current polarization data and milestones



- Acoustic peaks at 'adiabatic' locations
- E-mode polarization and cross-correlation with ΔT
- Large-angle polarization from reionization

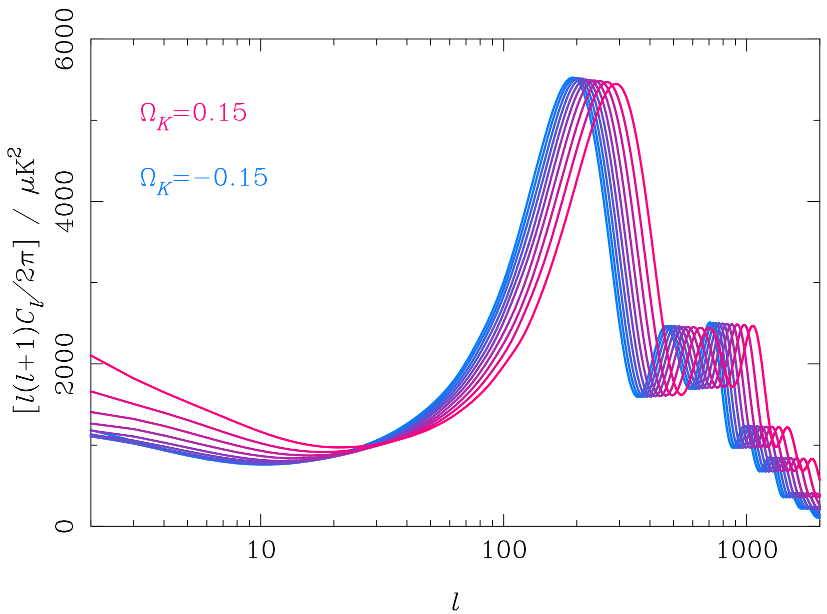
ACOUSTIC PEAK HEIGHTS: BARYON AND CDM DENSITY

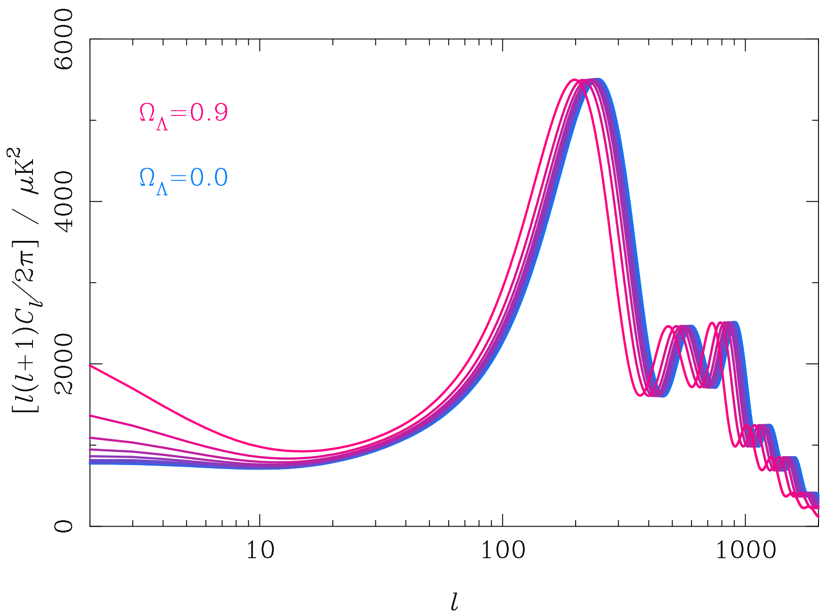
- Peak spacing fixed by $r_s(\Omega_m h^2, \Omega_b h^2)$ and angular diameter distance d_A
  - Peak heights depend on baryon offset of oscillation: increasing baryons at fixed $\Omega_m h^2$ boosts compressional peaks (1, 3 etc. for adiabatic) and reduces r_s
  - Increasing $\Omega_m h^2$ reduces d_A and shifts equality to earlier times reducing resonant driving $\ddot{\phi}$ for low-order peaks
- Current constraints from CMB alone (weak priors): $\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0008}$ and $\Omega_m h^2 = 0.127^{+0.007}_{-0.01}$ (Spergel et al. 2006)
  - Some tension with $\Omega_m h^2$ from CMB and lensing data
  - Should improve to sub-percent level with Planck data



Acoustic peak locations: curvature and dark energy

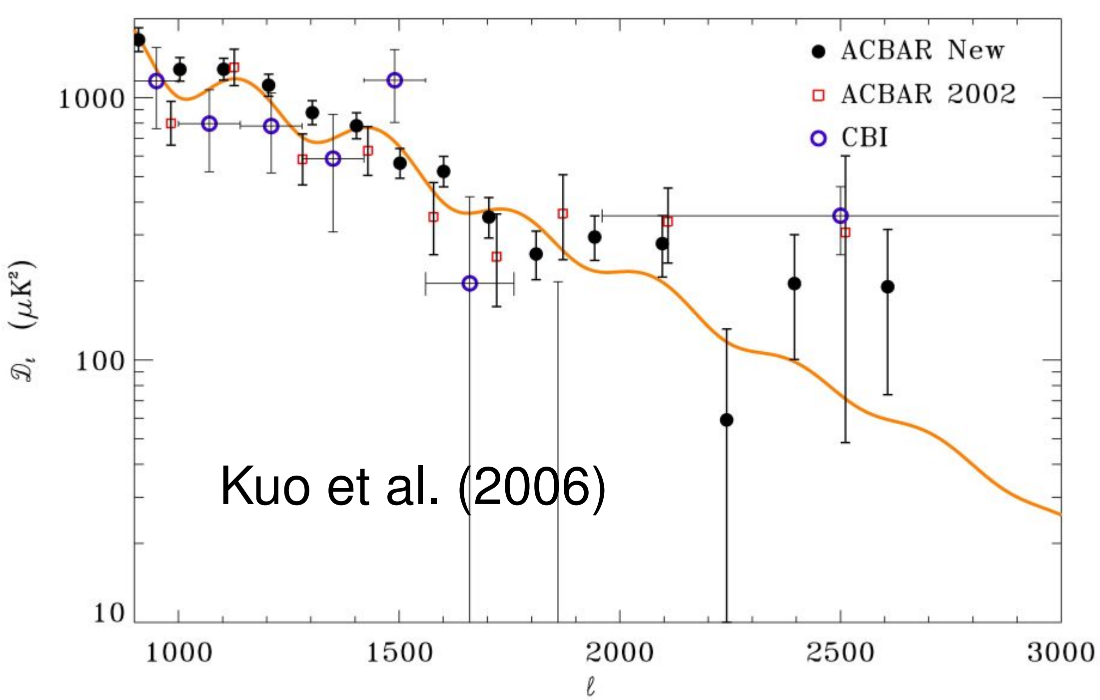
- Mainly affect CMB through d_A; small effects from ISW and mode quantisation for $K > 0$
  - CMB alone only well constrains $d_A = 13.7 \pm 0.5$ Gpc
  - $\Lambda = 0$, closed models fit CMB alone but have very low h, high $\Omega_m h$ cf. LSS, and don't fit ISW-LSS correlation (see later)
  - WMAP3 with HST prior gives $\Omega_K = -0.003^{+0.013}_{-0.017}$ ($w = -1$) and $\Omega_\Lambda = 0.758^{+0.035}_{-0.058}$





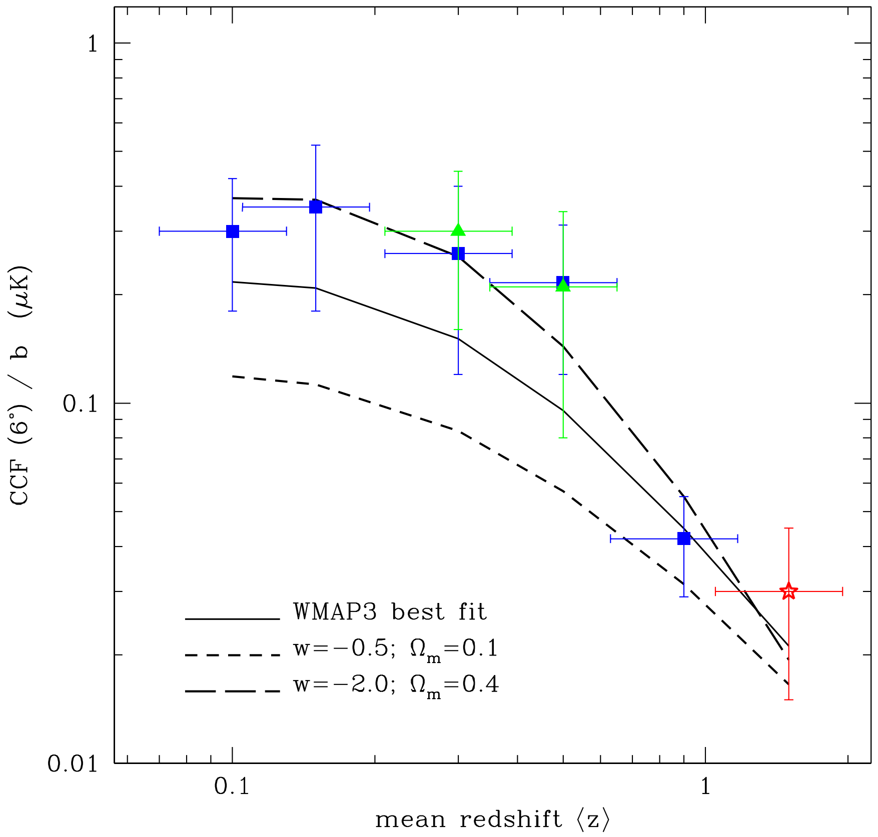
DAMPING TAIL, SZ AND THE AMPLITUDE OF THE FLUCTUATIONS

- Predicted exponential decline due to photon diffusion seen by CBI (30 GHz) and ACBAR (150 GHz)
- CBI and BIMA see significant excess emission at $l > 2000$ not seen by ACBAR
  - Favours non-thermal secondary anisotropy (SZ effect) but then requires $\sigma_8 \approx 0.92 \pm 0.05$
  - Some tension with WMAP3-alone value 0.75 ± 0.06
  - Also some tension with (low) σ_8 from CMB cf. weak lensing and Ly-α forest



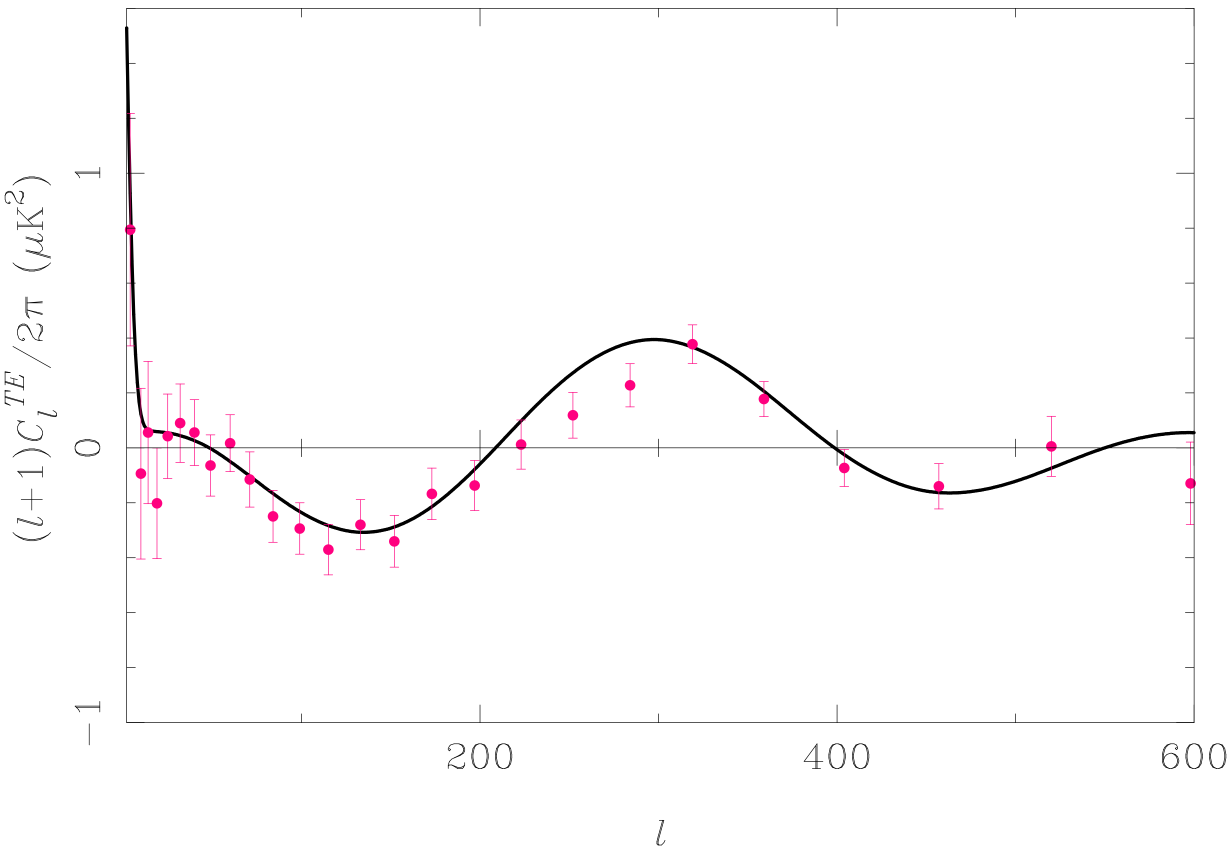
ISW EFFECT AND DARK ENERGY

- Potentials decay once dark energy comes to dominate ⇒ positive correlation of ΔT with LSS tracer on large scales
- Many detections over range of redshifts – highest at $z \sim 1.5$ with quasars from SDSS (Giannantonio et al. 2006)



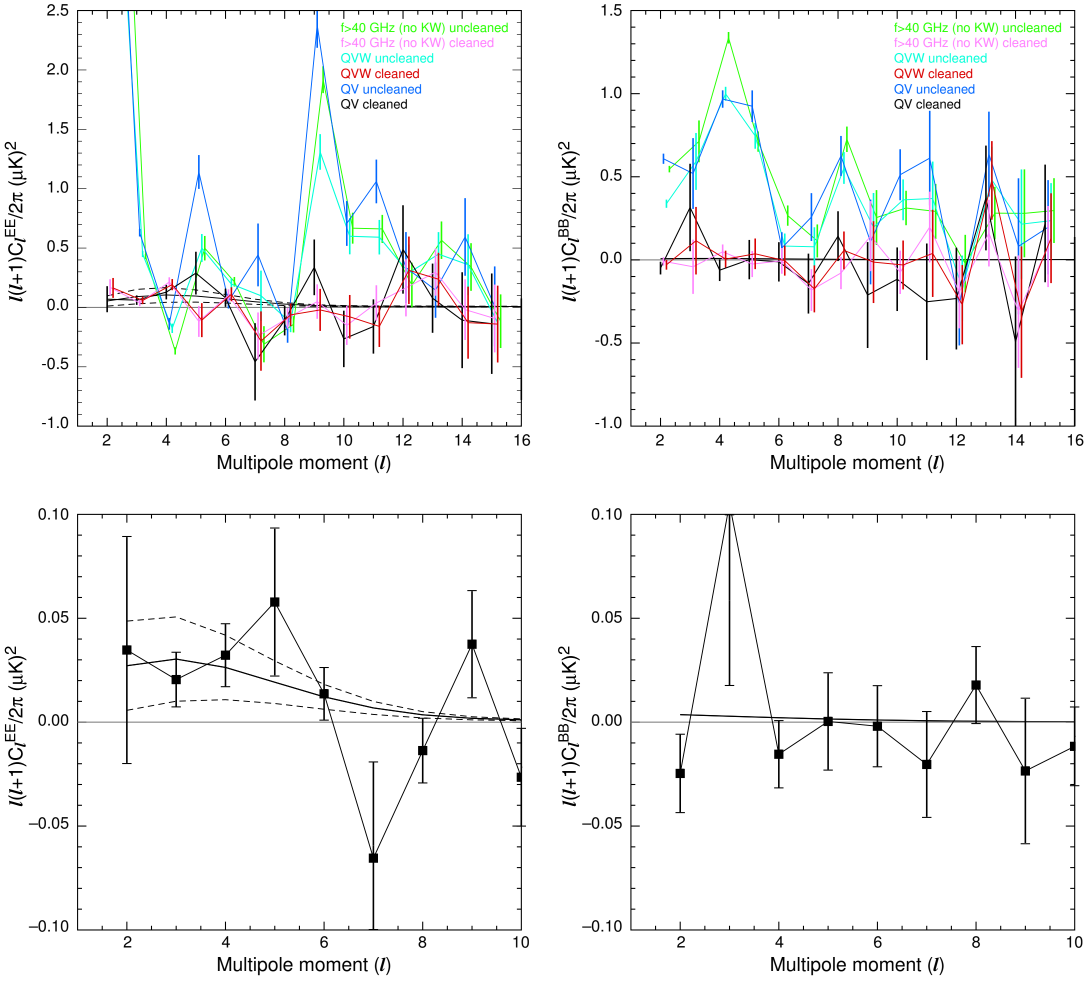
E-MODE POLARIZATION AND THE CHARACTER OF FLUCTUATIONS

- Well-defined peaks $\Rightarrow$ phase coherence (cf. defects)
- Super-horizon correlations at last scattering surface from TE correlation and sign $\Rightarrow$ adiabaticity
- Peak positions in TT, TE and EE consistent with adiabatic models
  - CMB, LSS and BBN still allow $\sim$ 20% CMB contribution from single, uncorrelated isocurvature modes and significantly more for more general cases (Bean et al. 2006), but not favoured over adiabatic



REIONIZATION

- WMAP3 EE large-angle correlation $\Rightarrow \tau = 0.09 \pm 0.03$ (Page et al. 2006)
  - Required aggressive cleaning of polarized Galactic foregrounds (synchrotron and thermal dust emission)



TESTING INFLATION

- Key predictions of *simple* inflation models:
  - Universe should be flat (cf. $\Omega_K = -0.003^{+0.013}_{-0.017}$)
  - Small curvature fluctuations and (possibly) gravitational waves with almost scale-invariant, power-law spectra (see later)
  - Adiabatic initial conditions
  - Fluctuations should be Gaussian (to observational accuracy):

$$\Phi = \Phi_L + f_{\mathrm{NL}} \star (\Phi_L^2 - \langle \Phi_L^2 \rangle) \quad \text{with } f_{\mathrm{NL}} \sim O(1)$$

    * Best constraints on 'local' f_{NL}: $-54 < f_{\mathrm{NL}}^{\mathrm{local}} < 114$ (Spergel et al. 2006)
    * Planck sensitive down to $|f_{\mathrm{NL}}^{\mathrm{local}}| \sim 5$

Constraints on slow-roll inflation

- Observables in $\mathcal{P}_{\mathcal{R}}(k) \approx A_s(k/k_*)^{n_s-1}$ and $\mathcal{P}_h(k) \approx A_t(k/k_*)^{n_t}$ related to slow-roll parameters [≈ parameterise gradient and curvature of $V(\phi)$]

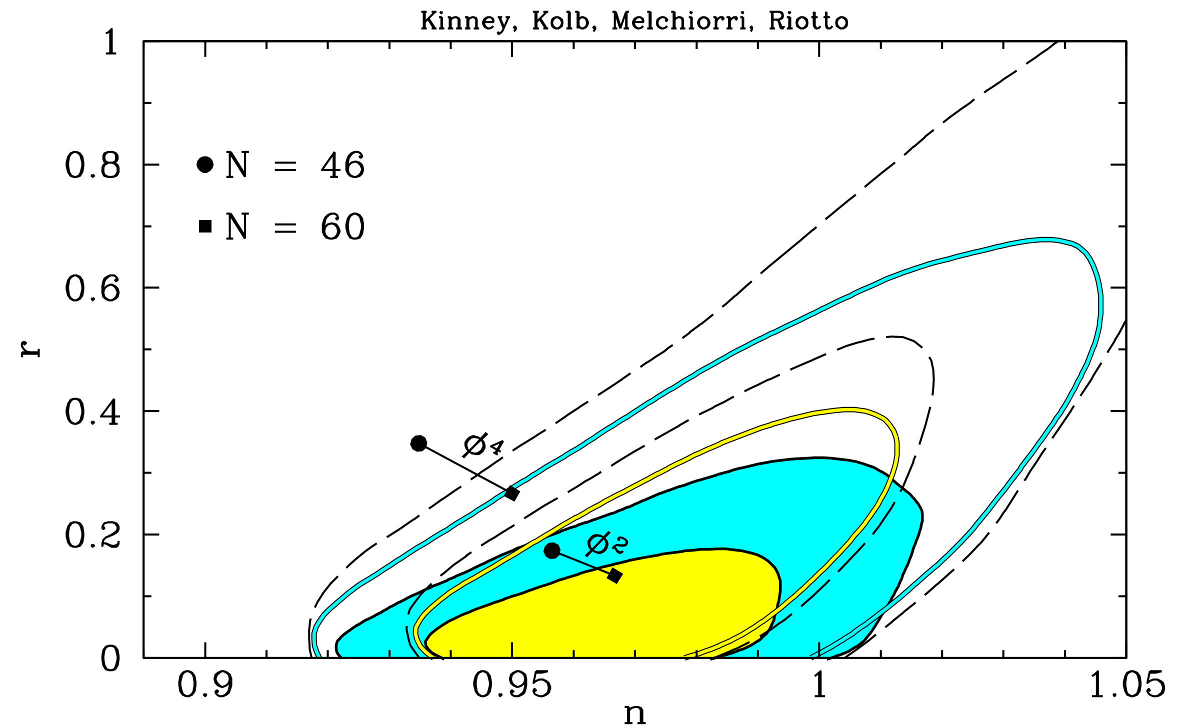
$$A_s = \frac{H^2}{\pi \epsilon m_{\mathrm{Pl}}^2}, \quad n_s - 1 = -4\epsilon + 2\eta, \quad A_t \equiv r A_s = \frac{16 H^2}{\pi m_{\mathrm{Pl}}^2}, \quad n_t = -2\epsilon$$

- $V^{1/4} < 2.4 \times 10^{16}$ GeV from non-detection of gravity waves

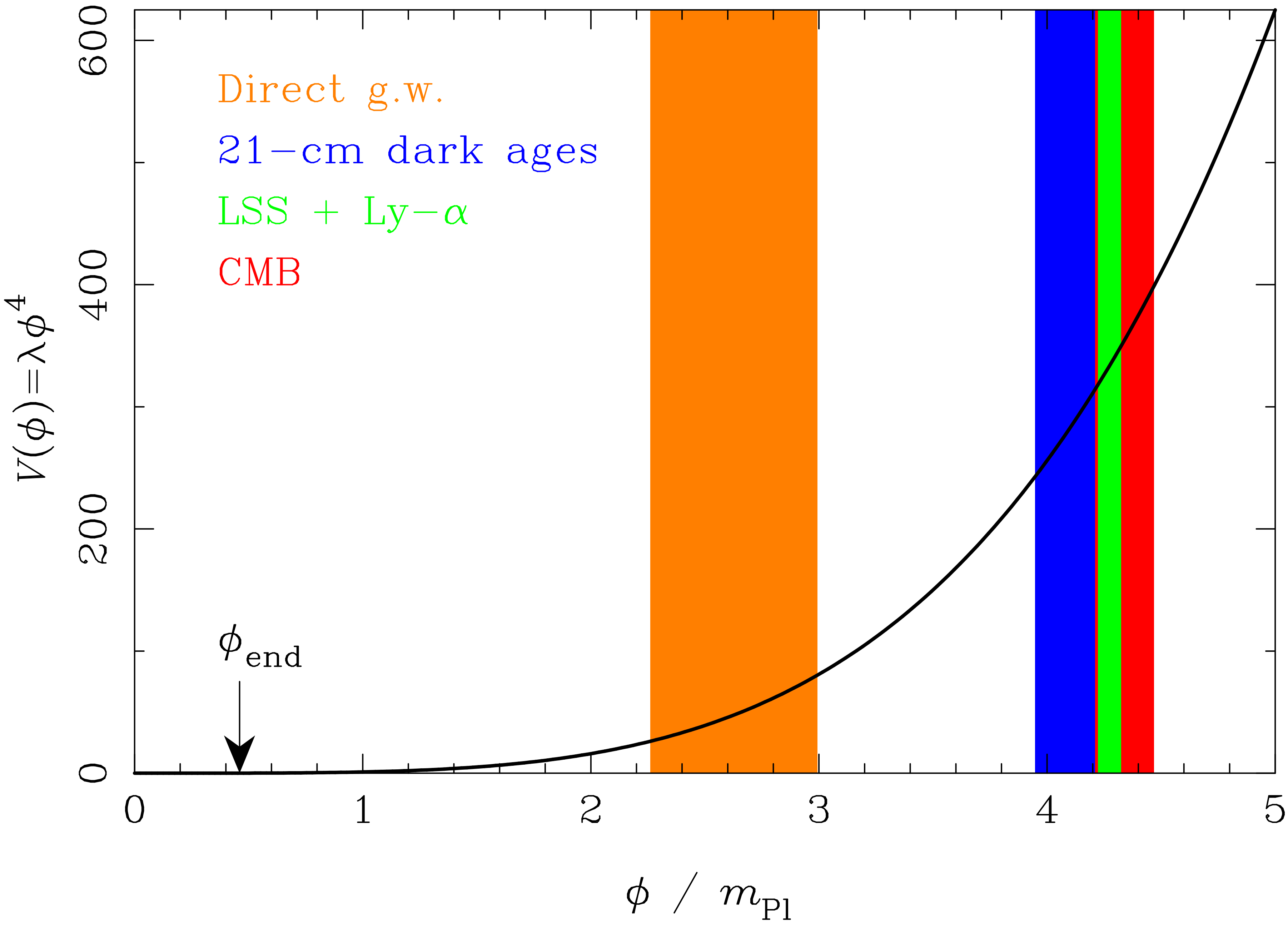
- HZ ($n_s = 1$, $r = 0$) disfavoured but not strongly excluded:

- For *low-energy models*, conditional constraint $n_s = 0.958 \pm 0.016$ is evidence for inflationary dynamics
  - Difficult τ measurement critical!

- Persistent (but weak!) 2σ 'evidence' for curvature in spectrum from CMB; vanishes when add (small-scale) Ly-α



WHAT RANGE OF $V(\phi)$ DOES CMB PROBE DIRECTLY?

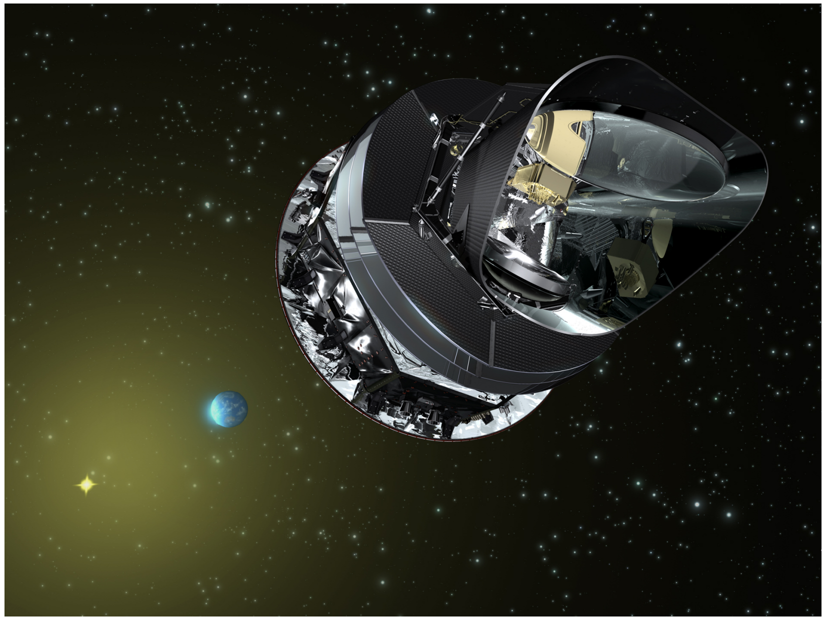


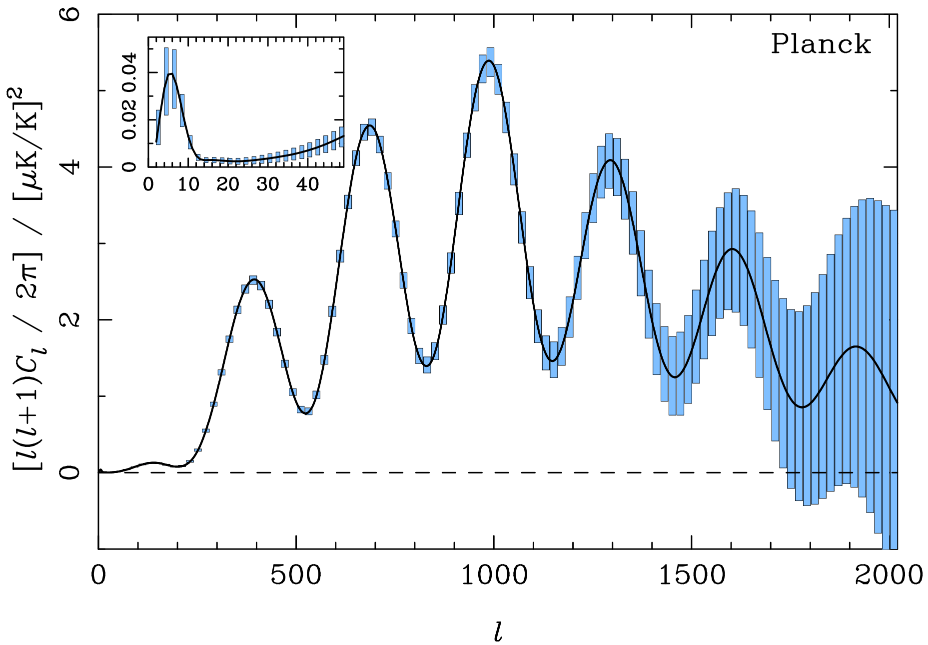
THE FUTURE

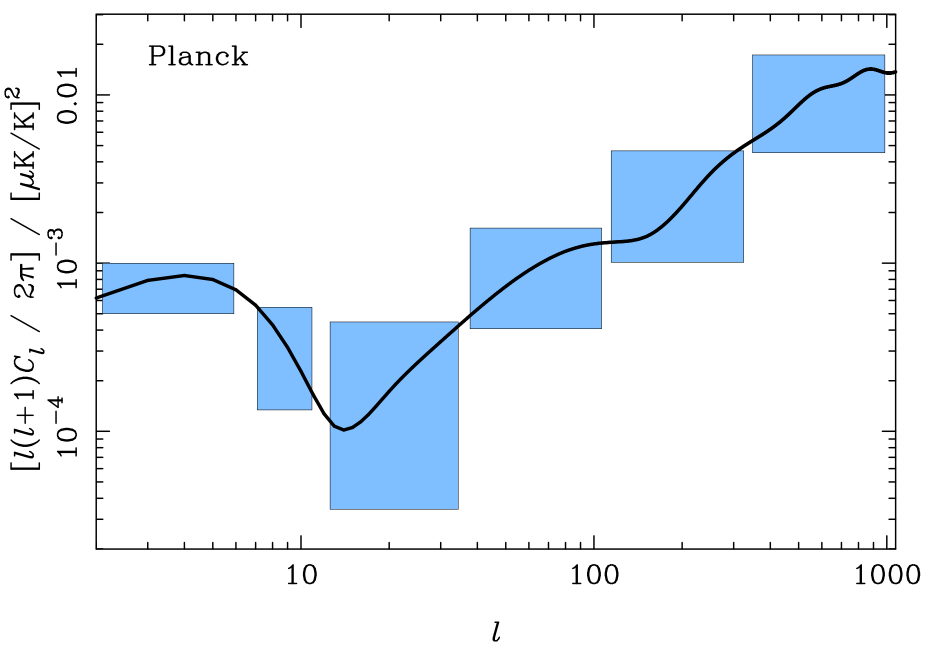
- Planck
- Small-scale CMB (SPT, ACT, AMI, APEX) – using the CMB as a backlight
  - SZ clusters, scattering secondaries and physics of reionization
  - Weak gravitational lensing
- Large-angle CMB polarization (BICEP, Clover, QUIET, EBEX, SPIDER etc.)
  - Gravitational waves

PLANCK

- Launch in late 2008
- Full-sky imaging from L2 in nine frequency bands (30–857 GHz)
- Polarization retro-fitted but may be sensitive to $r \sim 0.1$

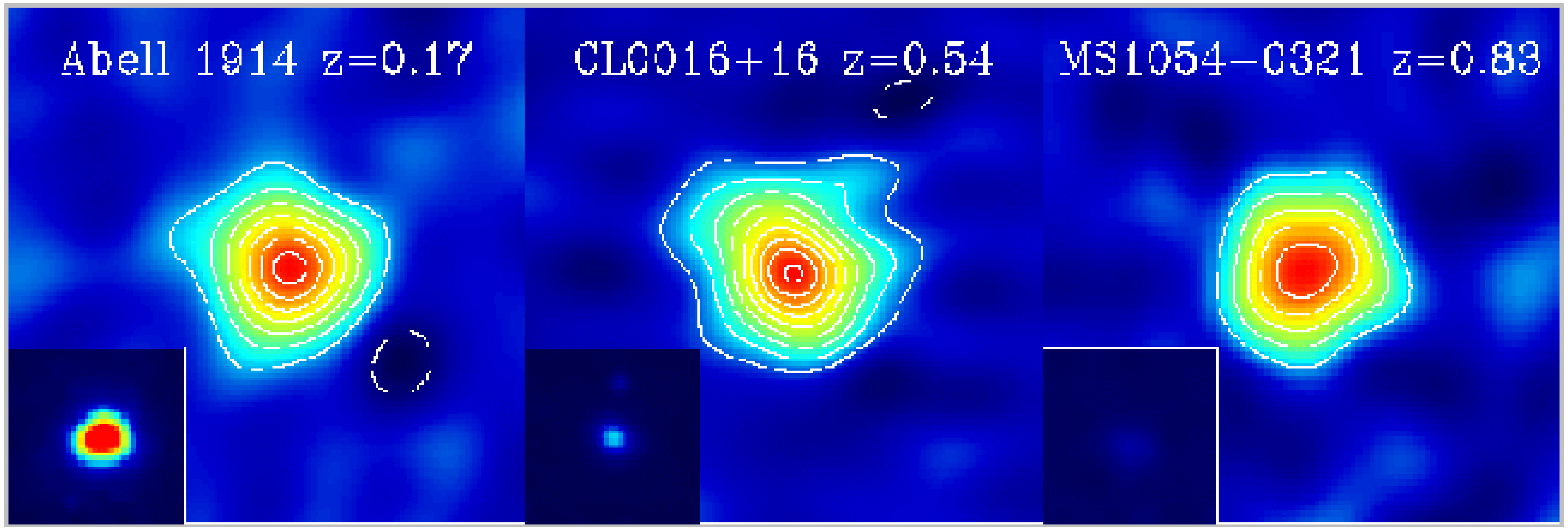






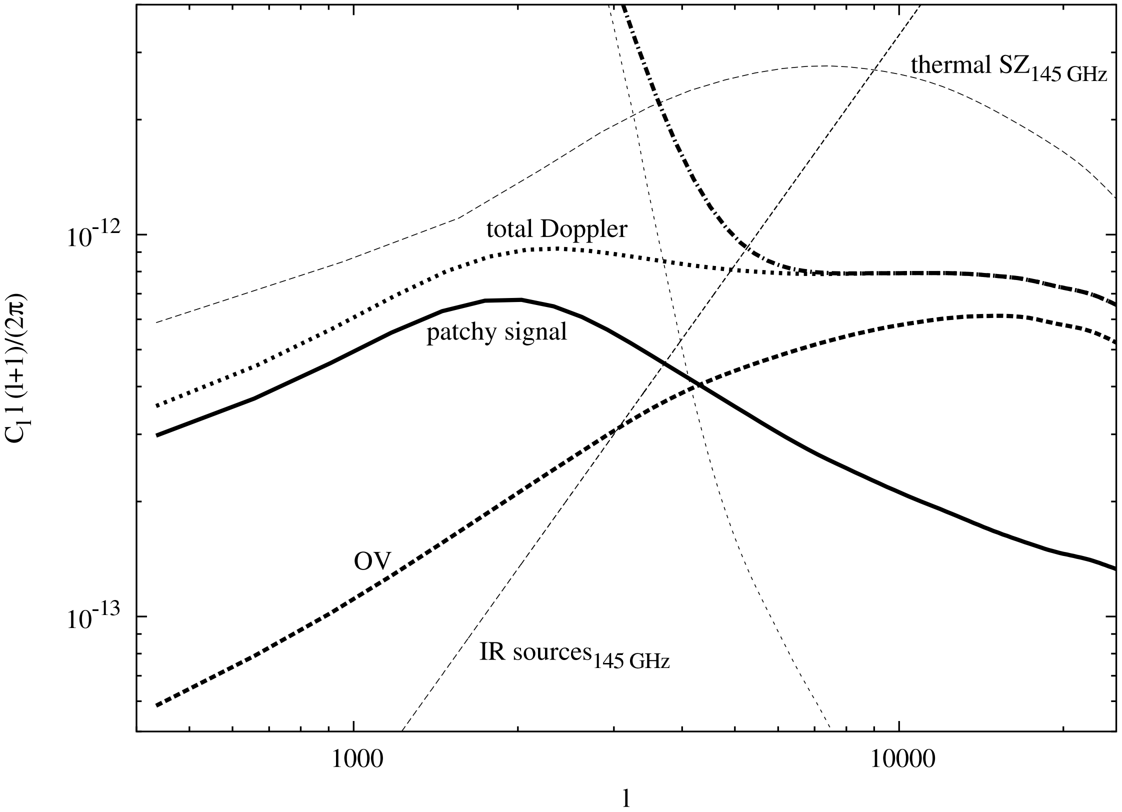
GALAXY CLUSTERS AND THE THERMAL SZ EFFECT

- Free electrons in hot ($\sim$ 10 keV) intra-cluster gas Compton up-scatter CMB photons $\Rightarrow$ decrement below 217 GHz but excess above
- Detected towards known clusters but new arcmin-scale instruments (AMI, SZA, ACT, SPT) soon to start blind surveying for clusters
  - Will produce mass-limited cluster catalogues to all z; evolution of e.g. number counts sensitive to late-time growth of structure (i.e. physics of dark energy)
- Effect from unresolved clusters may already have been seen in small-scale C_l^T



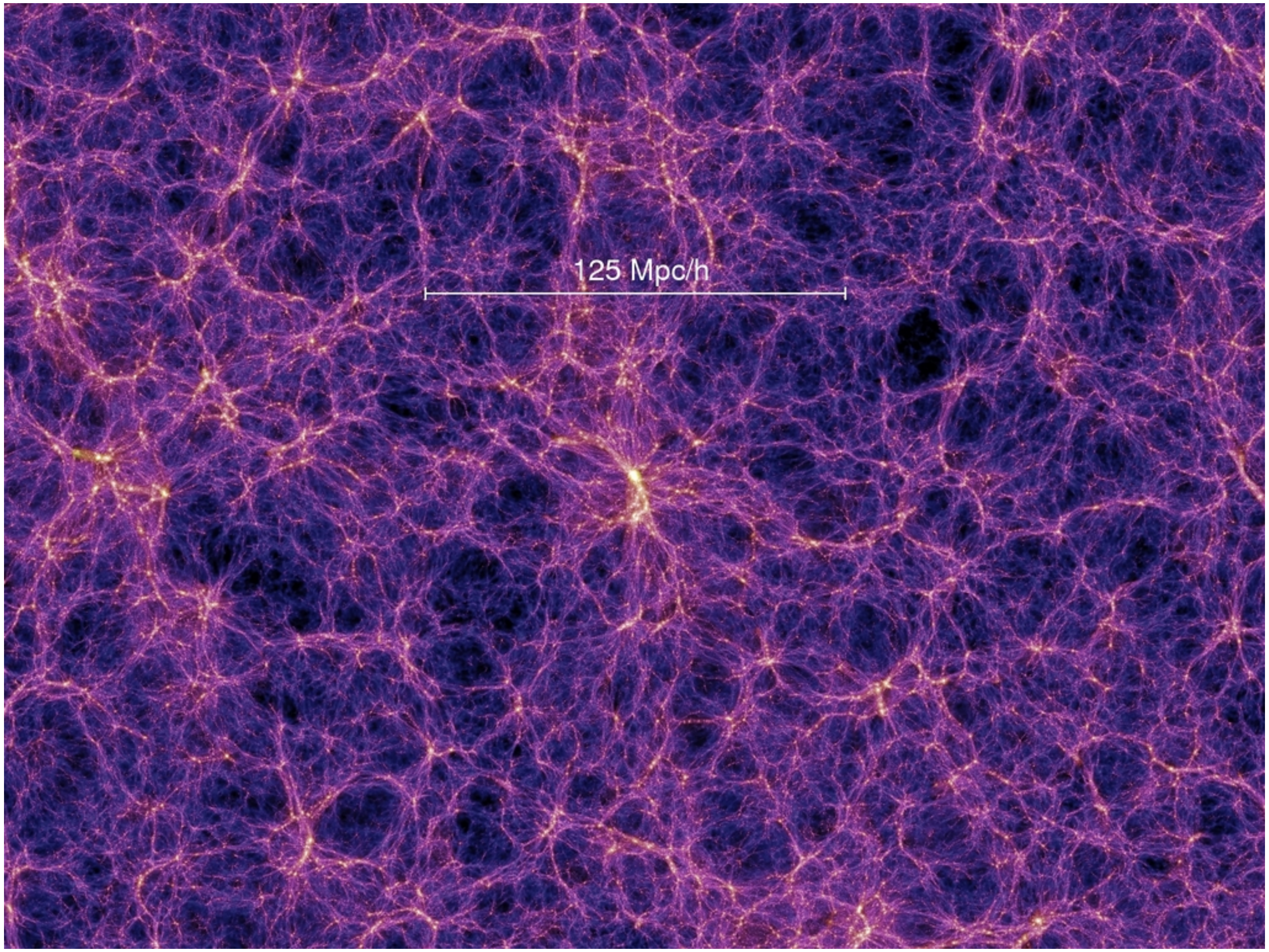
KINETIC SZ AND THE MORPHOLOGY OF REIONIZATION

- Doppler shifts scattering off ionized regions with peculiar velocities
  - Generate small-angle ΔT from *patchy reionization* (probing epoch of reionization) and *kSZ* (mostly from low redshift, high over-densities)



(Zahn et al. 2006)

WEAK GRAVITATIONAL LENSING OF THE CMB



Millenium simulation (VIRGO); $z = 1.5$

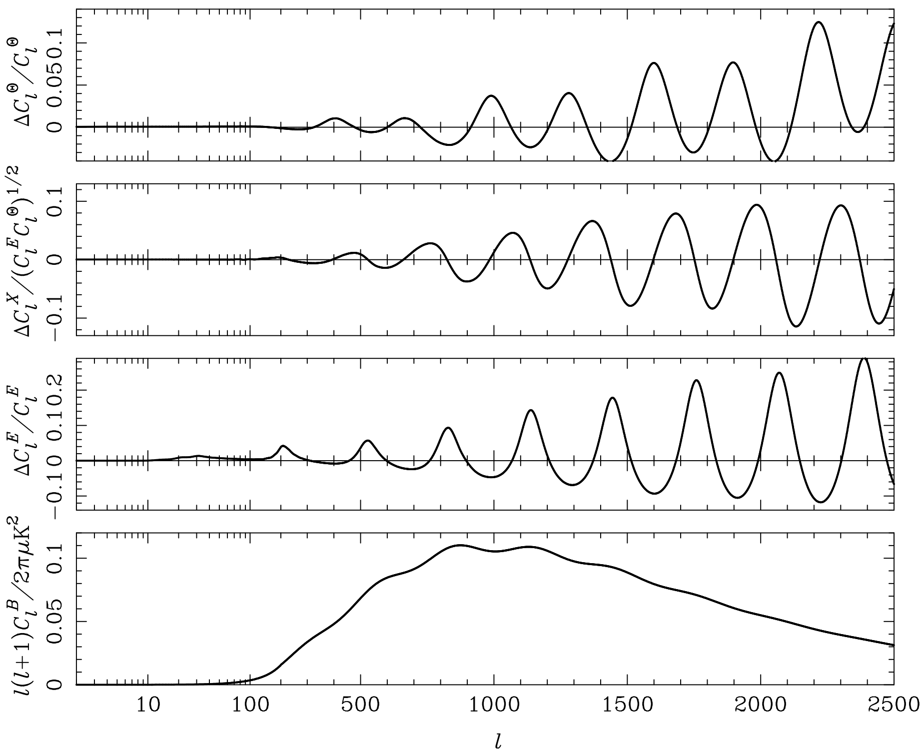
- View CMB through LSS $\Rightarrow$ r.m.s. deflection 2.4 arcmin coherent over several degrees

WEAK GRAVITATIONAL LENSING OF THE CMB

- Weak lensing remaps Θ, Q and U by deflection field $\boldsymbol{\alpha} = \boldsymbol{\nabla}\Psi$:

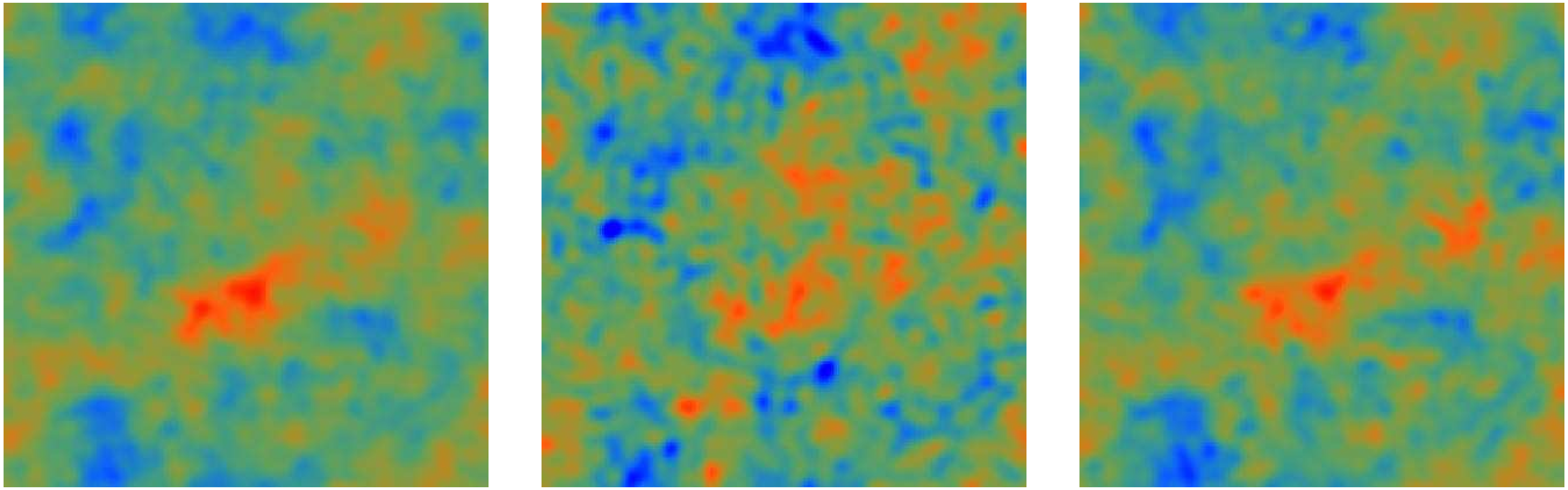
$$\tilde{\Theta}(\hat{\boldsymbol{n}}) = \Theta(\hat{\boldsymbol{n}} + \boldsymbol{\alpha})$$

- Main effects:
  - Smoothing of acoustic peaks and transfers large-scale power to $l > 2000$
  - Generates B-mode polarization from primordial E-mode
  - Introduces non-Gaussianity (which can be used to detect lensing!)



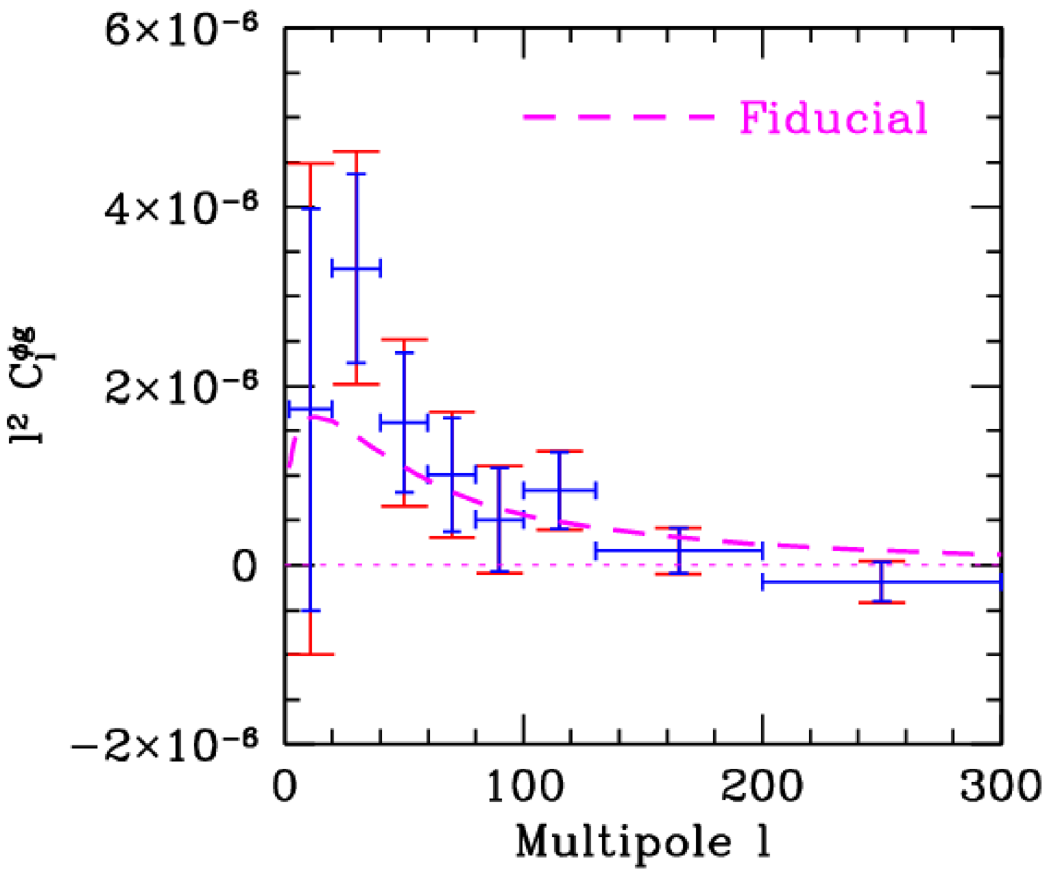
LENSING RECONSTRUCTION

- Within coherence patch of shear, CMB blob-like features all sheared in same way (like galaxy lensing) $\Rightarrow$ non-Gaussianity of observed CMB
  - Can use this non-Gaussianity to reconstruct $\boldsymbol{\alpha}$ (e.g. Hu 2001)
    - $*$ Well-known source plane with well-understood statistics
    - $*$ Sensitive to structure back to $z \sim 10$, though peaks around $z \sim 2$
- Deflection and T-T and E-B reconstruction on $10^\circ \times 10^\circ$ patch (1 μK -arcmin noise on T, 4-arcmin beam; Hu & Okamoto 2001):



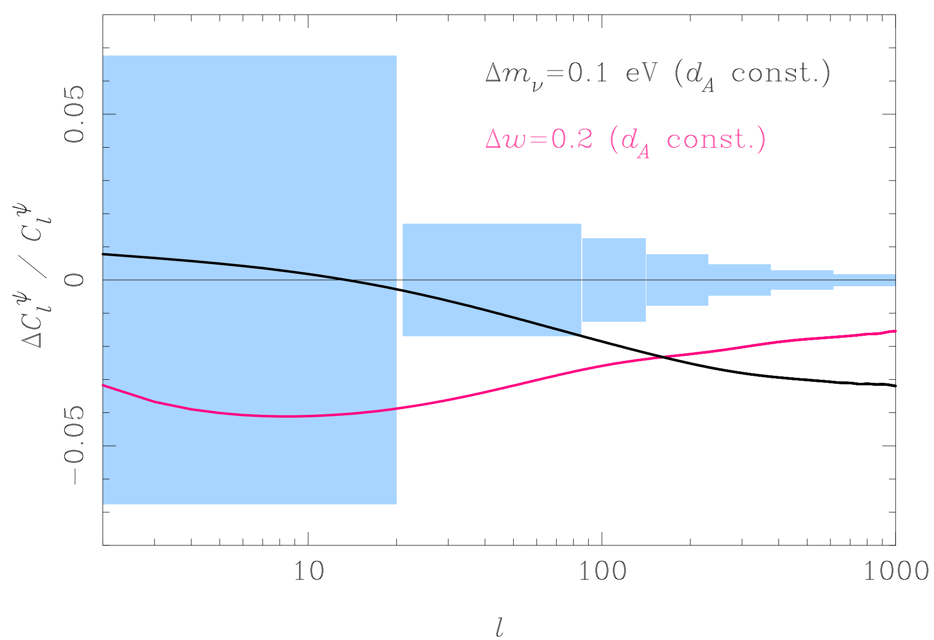
DETECTION OF WEAK LENSING EFFECT ON CMB ΔT

- Smith et al. (2007) reconstruct (very noisy!) deflection map from WMAP3
- Detect signal power at 3.4σ by cross-correlating reconstruction with (less noisy!) LSS tracer (NVSS radio galaxies)

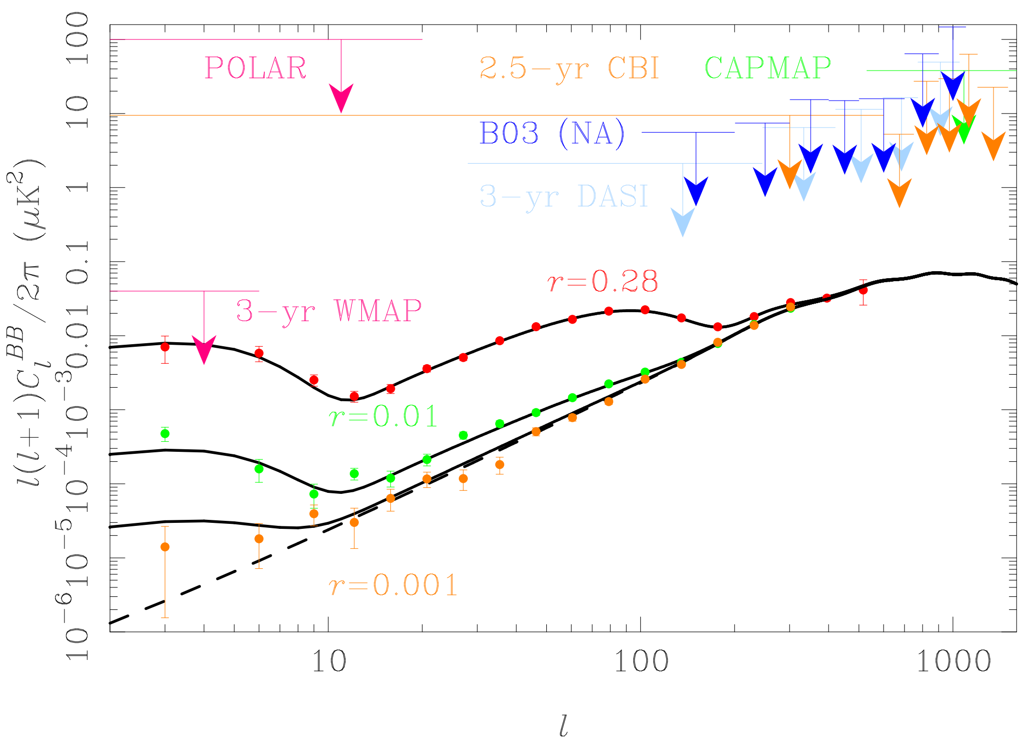


Future applications of CMB lensing

- Lensing potential sensitive to parameters not constrained by primary CMB
  - E.g. dark energy properties and sub-eV massive neutrinos almost degenerate in primary anisotropies (through d_A) but influence lensing potential differently
    - $*$ Future CMB polarization satellite should allow $\Delta m_\nu = 0.04\,\mathrm{eV}$ (marginalised over w; Kaplinghat et al. 2003)
- Lens-induced B-modes are 'noise' for gravity-wave searches
  - Limits $r \sim 10^{-4}$ but can use lens reconstruction to clean out B-modes



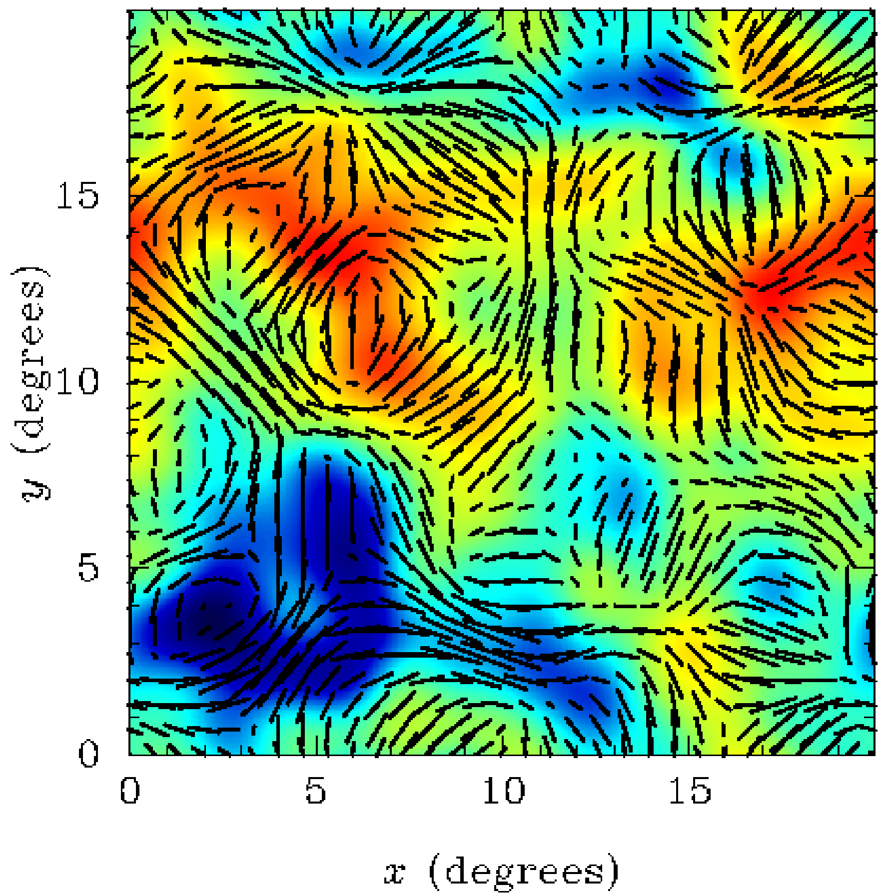
GRAVITY WAVE SEARCHES



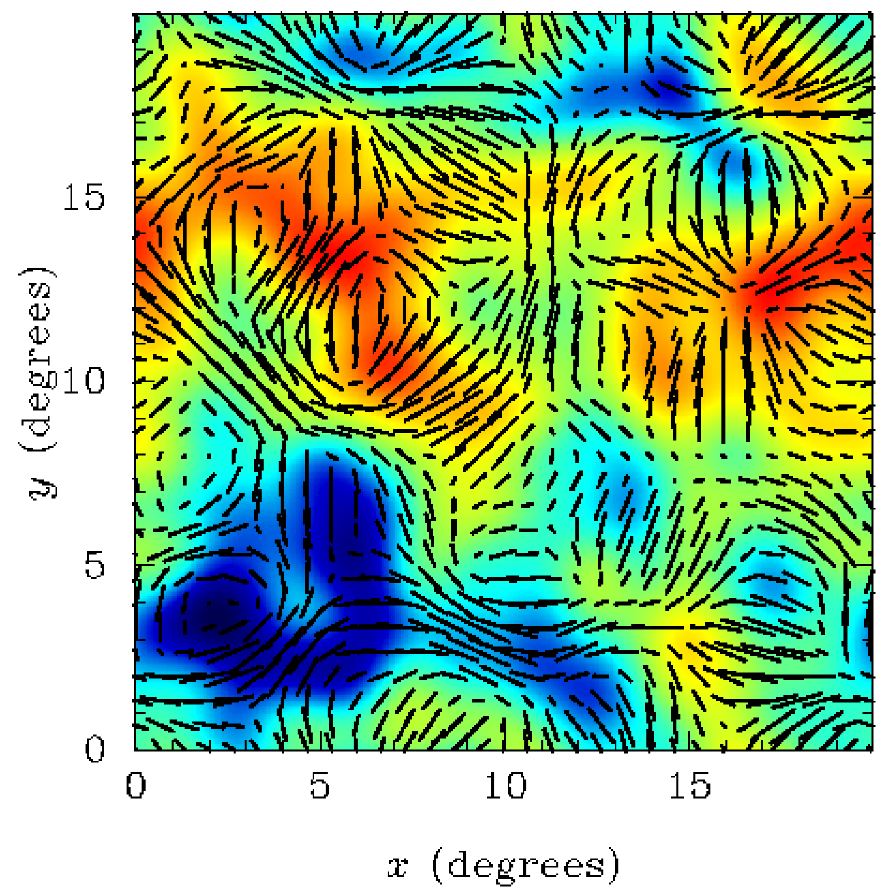
- B-mode polarization circumvents cosmic variance from (dominant) linear density perturbations but current upper limits not competitive with ΔT
- Next generation (Clover, QUIET, SPIDER, EBEX etc.) targeting $r > 0.01$
  - Futuristic full-sky(!) survey limited to $r > 10^{-4}$ *unless* implement lens cleaning
- Will require exquisite control of systematics and accurate removal of synchrotron and dust polarized foregrounds

B-MODE CONTRIBUTION IS SMALL!

- R.m.s. B-mode signal from gravity waves $< 200\,\mathrm{nK}$



$r = 0.28$



$r = 0.0$

SUMMARY

- Basic predictions from CMB now impressively verified:
  - Large-scale Sachs-Wolfe effect and ISW
  - Acoustic peaks and diffusion damping
  - E-mode polarization, correlation with ΔT and reionization in E
  - Weak lensing effect on CMB temperature
- In the (near)-future:
  - Better measurements of 3rd peak and beyond [resolve issues with $\Omega_m h^2$ and $\mathcal{P}_{\mathcal{R}}(k)$?]
  - Better E-mode polarization: essential test but have to work hard to improve parameters *in standard models*
  - Direct detection of weak lensing effect in CMB temperature and polarization (e.g. lens-induced B-mode power)
  - Physics from scattering secondaries (reionization and clusters) and lensing reconstruction
  - Gravity waves from B-mode polarization (E_{inf} and improved inflation phenomenology)?

THINGS I DON'T HAVE TIME TO DISCUSS!

- Non-Gaussianity
- Cosmic (super-)strings
- Magnetic fields
- Large-angle anomalies
- 21-cm emission/absorption against the CMB (reionization and the dark ages)