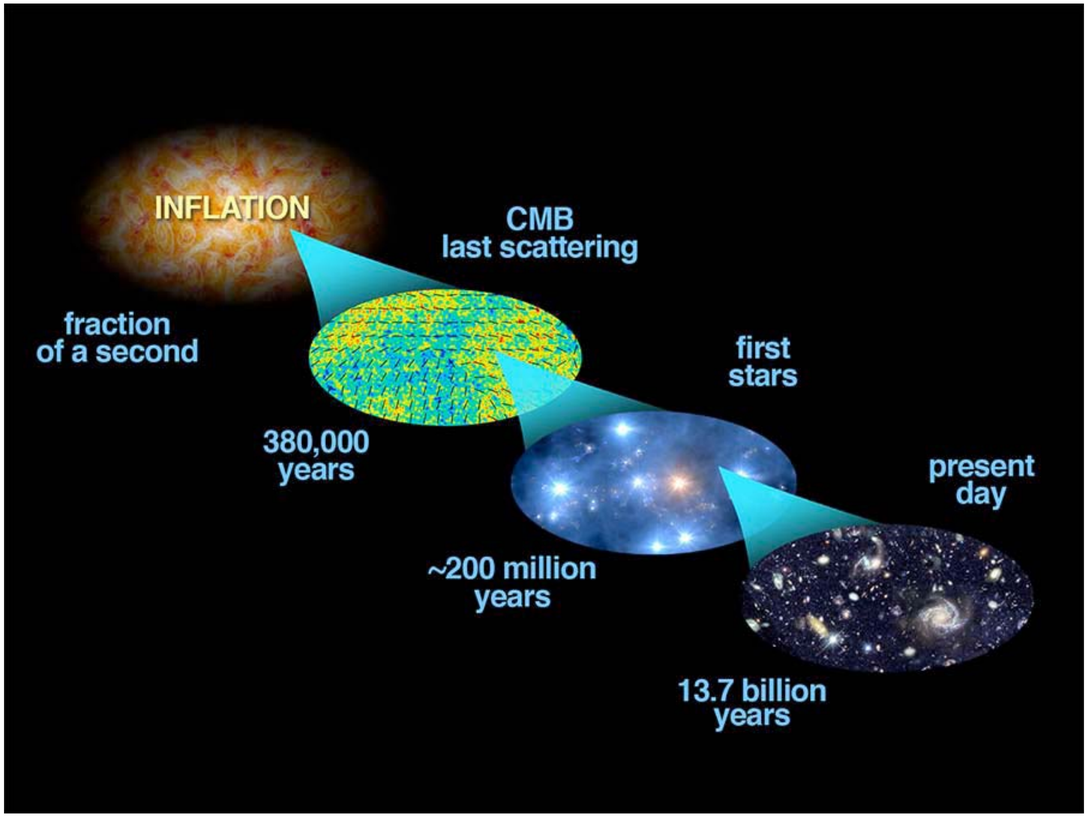
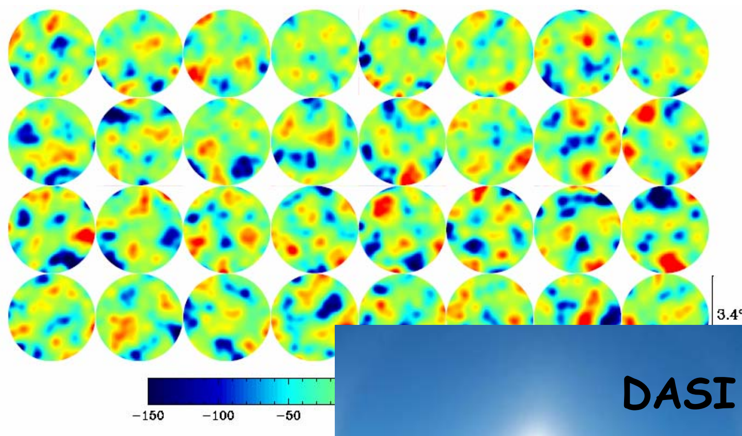
Cosmic Microwave Background Measurements

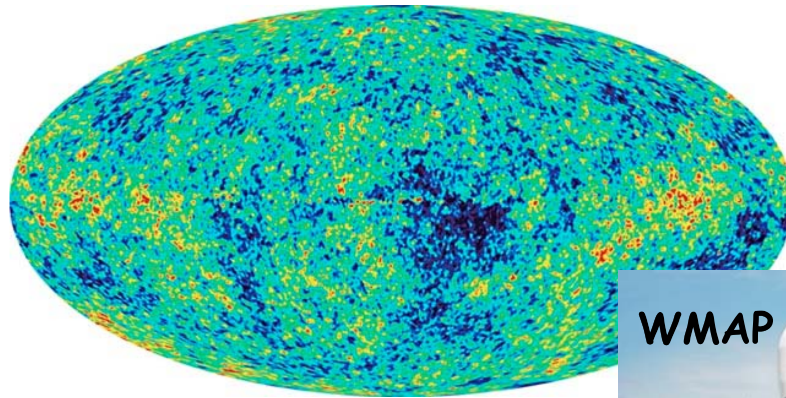
Figure: Task Force CMB Research

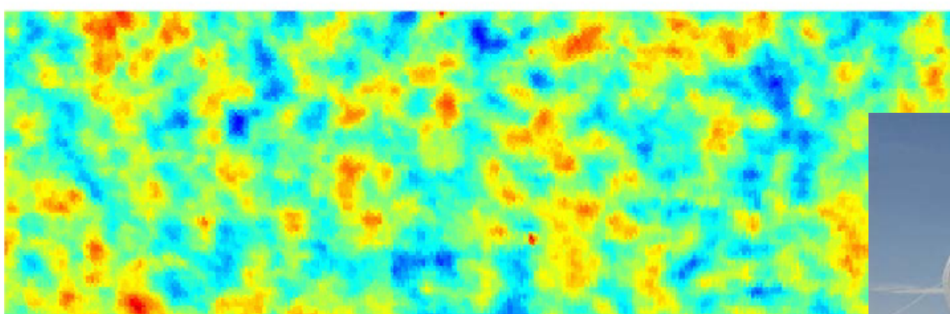


Sarah Church
Stanford University/ KIPAC

Remarkable progress in the last 5 years



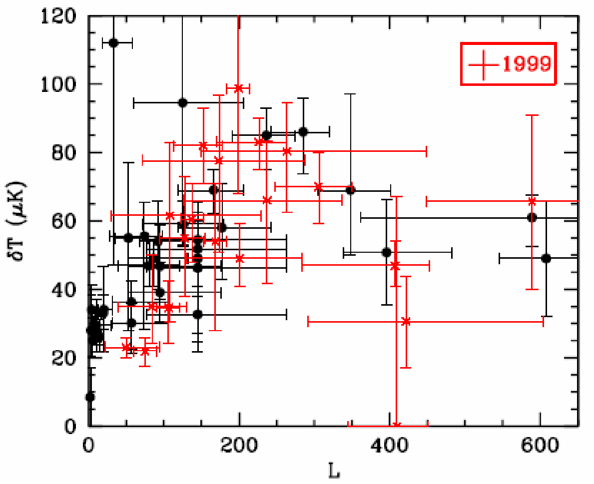




ACBAR, Archeops, CBI, Maxima, VSA + others

Remarkable progress in the last 5 years

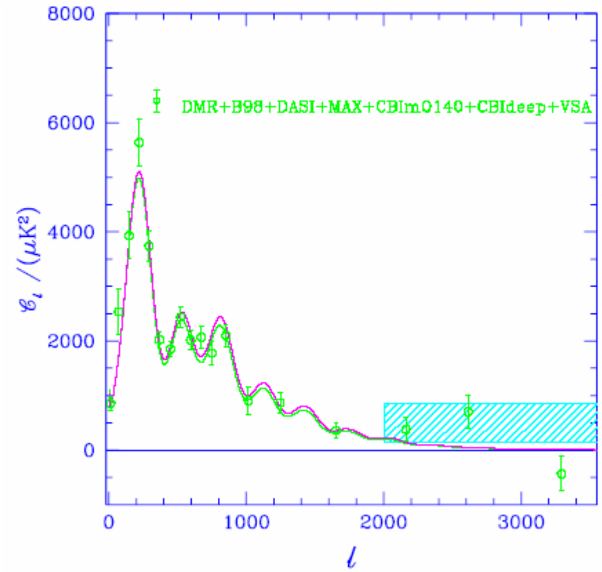
- CMB results pre-2000



Figure

S. Dodelson

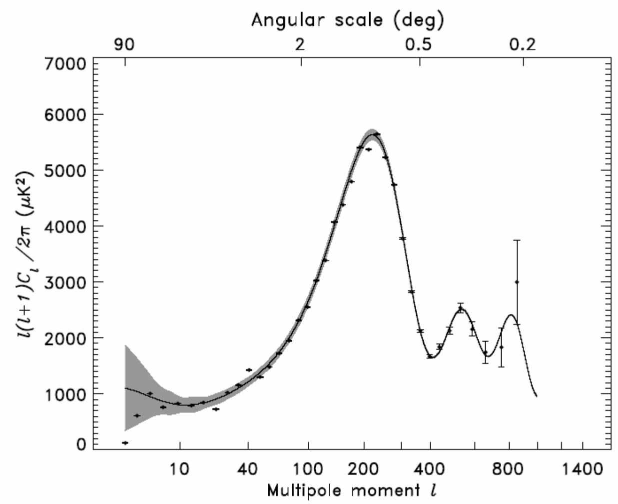
- CMB results 2000-2003 (pre WMAP)



Figure

Bond et al. 2003

- WMAP data 2003



Figure

Hinshaw et al. 2003

Measurements can be matched to a set of cosmological parameters

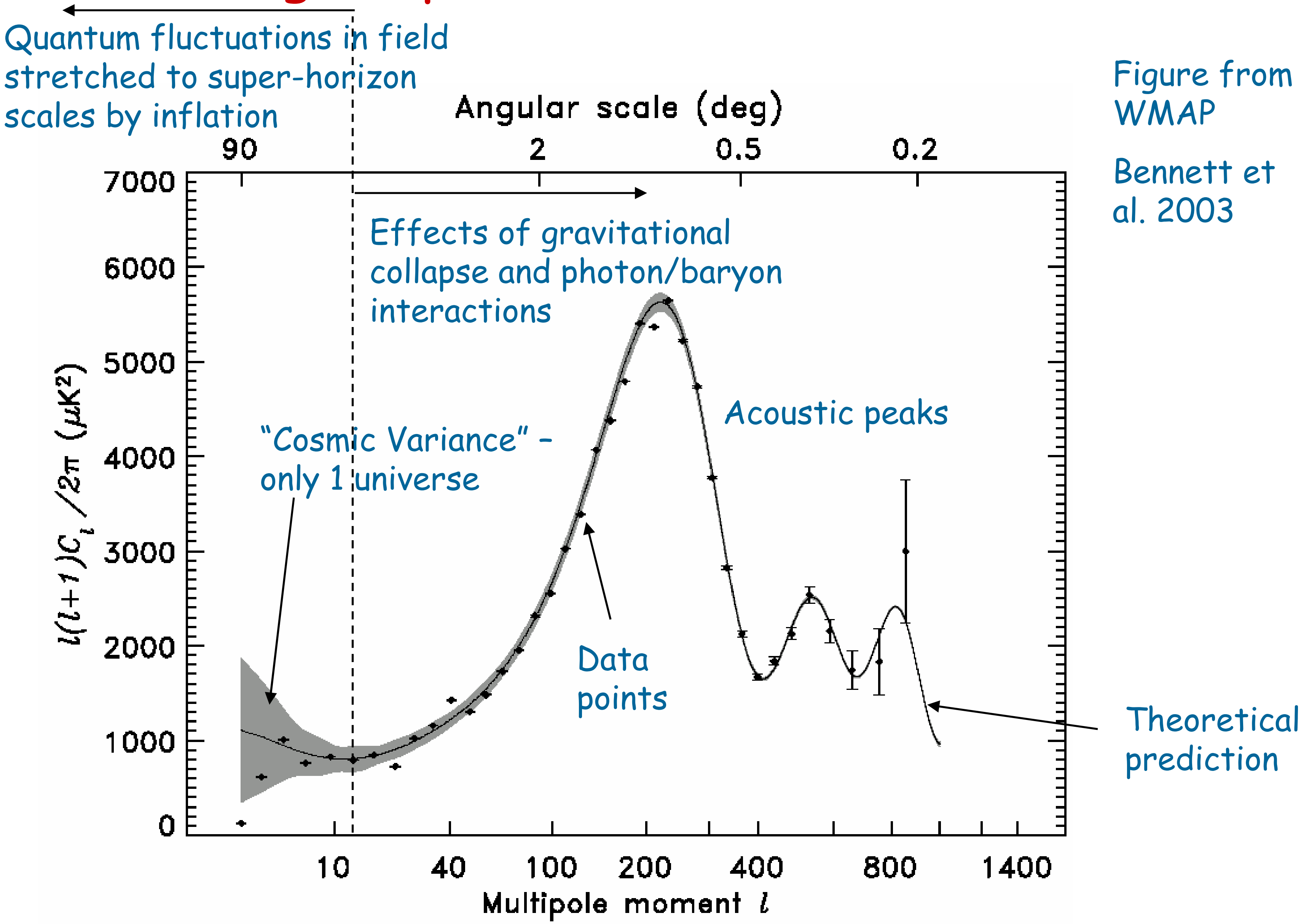


Figure from WMAP

Bennett et al. 2003

The CMB can be used to accurately measure cosmological parameters

- Straightforward physics $\Rightarrow$ accurate theoretical predictions with cosmological quantities as the free parameters
- **Measurements are the key**
- Precision measurements $\Rightarrow$ "precision cosmology"

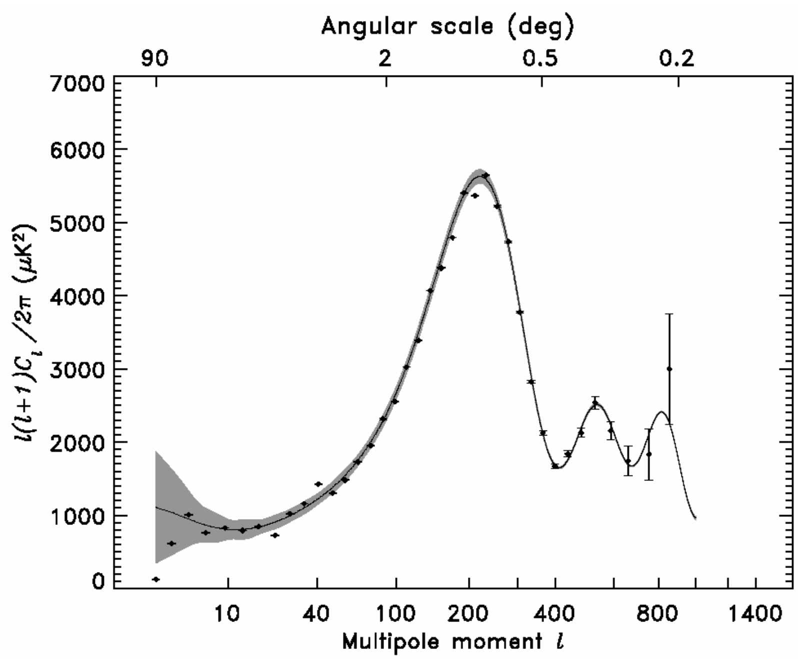


Figure from WMAP

Bennett et al. 2003

"Precision Cosmology"

Scalar spectral index

$$n \approx 1 - 4\epsilon + 2\eta$$

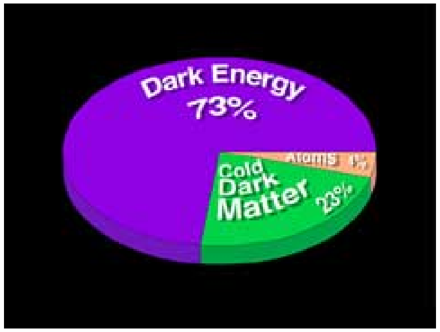
Scalar/tensor ratio

$$r = \frac{P_{\rm tens}(k_0)}{P_{\rm scal}(k_0)}$$

Table 9. Best fit parameters for the running spectral index Λ CDM + Tensors Model

Parameter	WMAPext+2dFGRS	WMAPext+ 2dFGRS+ Lyman α
A	$0.85^{+0.11}_{-0.10}$	$0.84^{+0.10}_{-0.09}$
n_s	0.96 ± 0.04	0.96 ± 0.03
$dn_s/d\ln k$	$-0.046^{+0.030}_{-0.031}$	$-0.042^{+0.021}_{-0.020}$
τ	$0.17^{+0.07}_{-0.06}$	0.17 ± 0.06
h	0.74 ± 0.03	0.74 ± 0.03
$\Omega_m h^2$	0.135 ± 0.006	0.135 ± 0.006
$\Omega_b h^2$	0.023 ± 0.001	0.023 ± 0.001
r	< 0.71	< 0.71
χ^2_{eff}/ν	1465/1379	. . . [a]

[a] Since the Lyman α data points are correlated, we do not quote an effective χ^2 for the combined likelihood including Lyman α data (see Verde et al. (2003)).

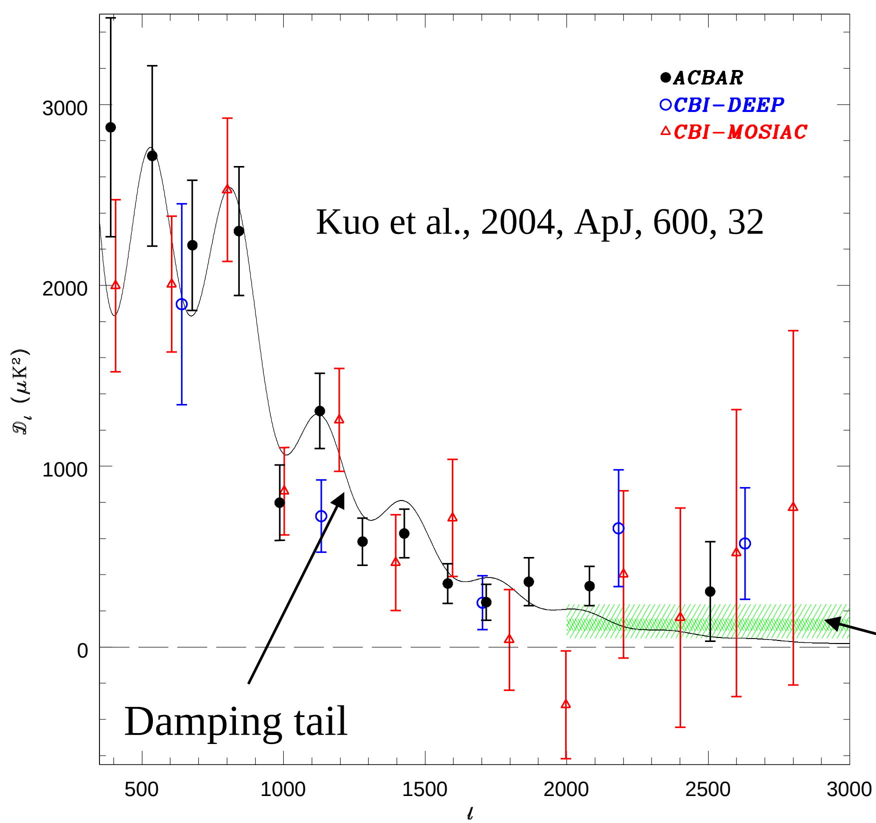


Parameters that can constrain inflationary models

CMB + large scale structure:
Spergel et al. 2003

Status of CMB temperature measurements

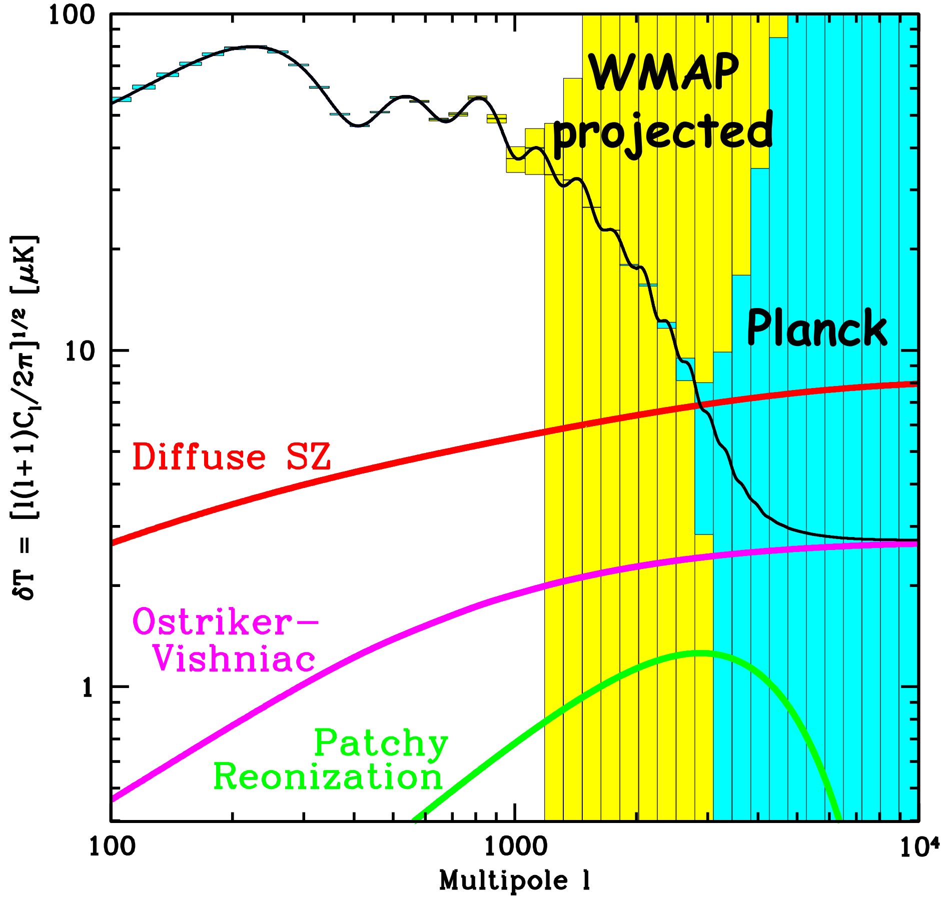
- Expect new WMAP results soon
- New results from small-scale anisotropy experiments



Expected signal from the SZ effect at 150 GHz

- Current small-scale measurements probe:
  - n
  - σ_8
- New ACBAR data release expected in the nest few months

Longer Term: Planck Satellite



Picture credit: de Oliveira-Costa for the CMB taskforce report

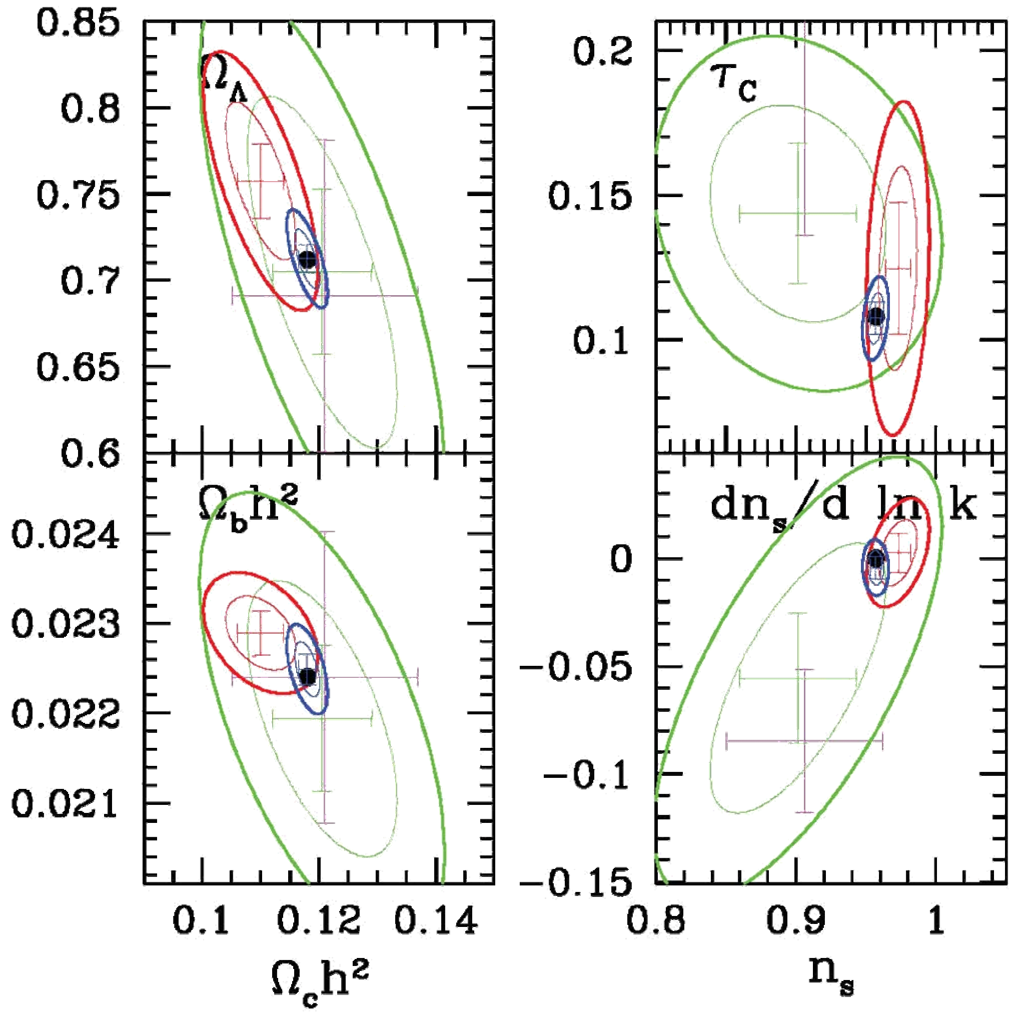
- ESA/NASA satellite (2008)
- All-sky maps 30-850 GHz
- Measure:
  - Temperature
  - Polarization
  - Sunyaev-Zel'dovich Effect in rich clusters (Compton scattering of CMB photons)

Planck Error forecasts (includes polarization measurements)

Current CMB
WMAP 4 years
WMAP 4+ACT
Planck 1 year
Input

7 parameters
A_S, n_s, $dn_s/d\ln k$
+ ω_b, ω_c, h,
+ τ

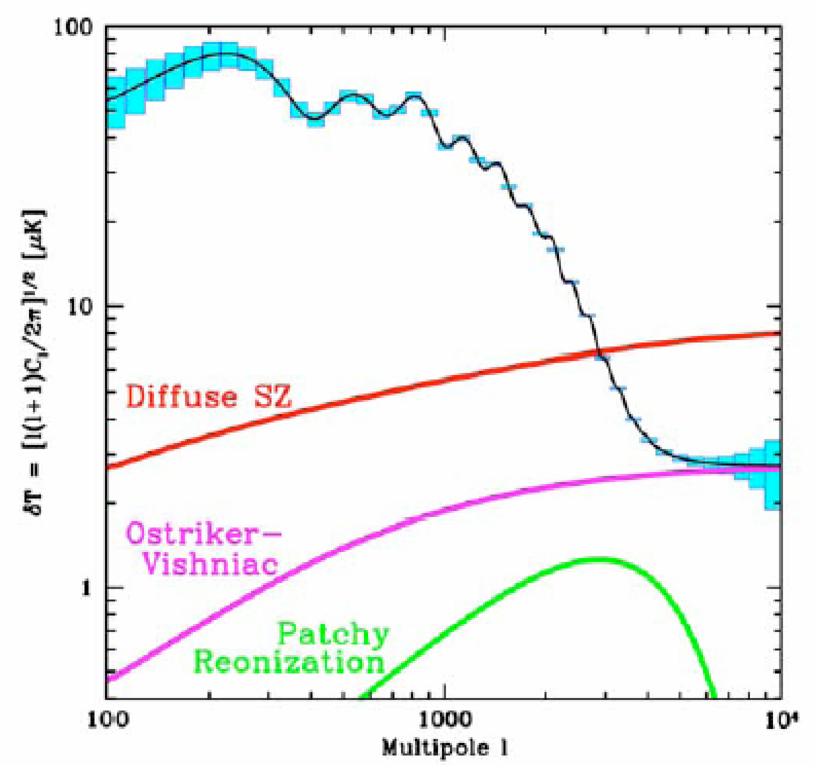
Assumed flat
+ weak priors
(0.45<h<0.9)
(t_U > 10Gyr)



Slide provided by F. Bouchet

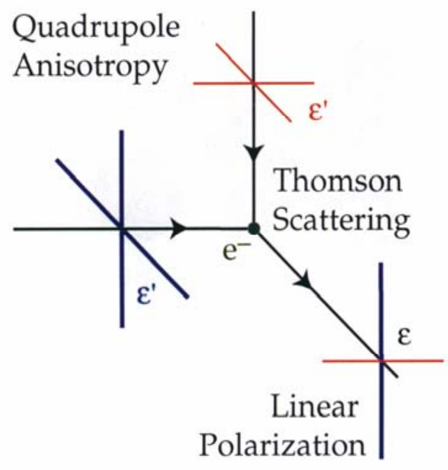
Precise measurements of small Angular Scales from Large Ground-based Telescopes

- Go from 16 pixels of ACBAR to thousand pixel bolometer arrays
  - 6m Atacama Cosmology Telescope
  - 10m South Pole Telescope
- Expected online 2007
- Probe of
  - n_s
  - $dn/d\ln k$
  - Measure cluster abundances using the Sunyaev-Zel'dovich (SZ) effect
  - Measure lensing of the CMB



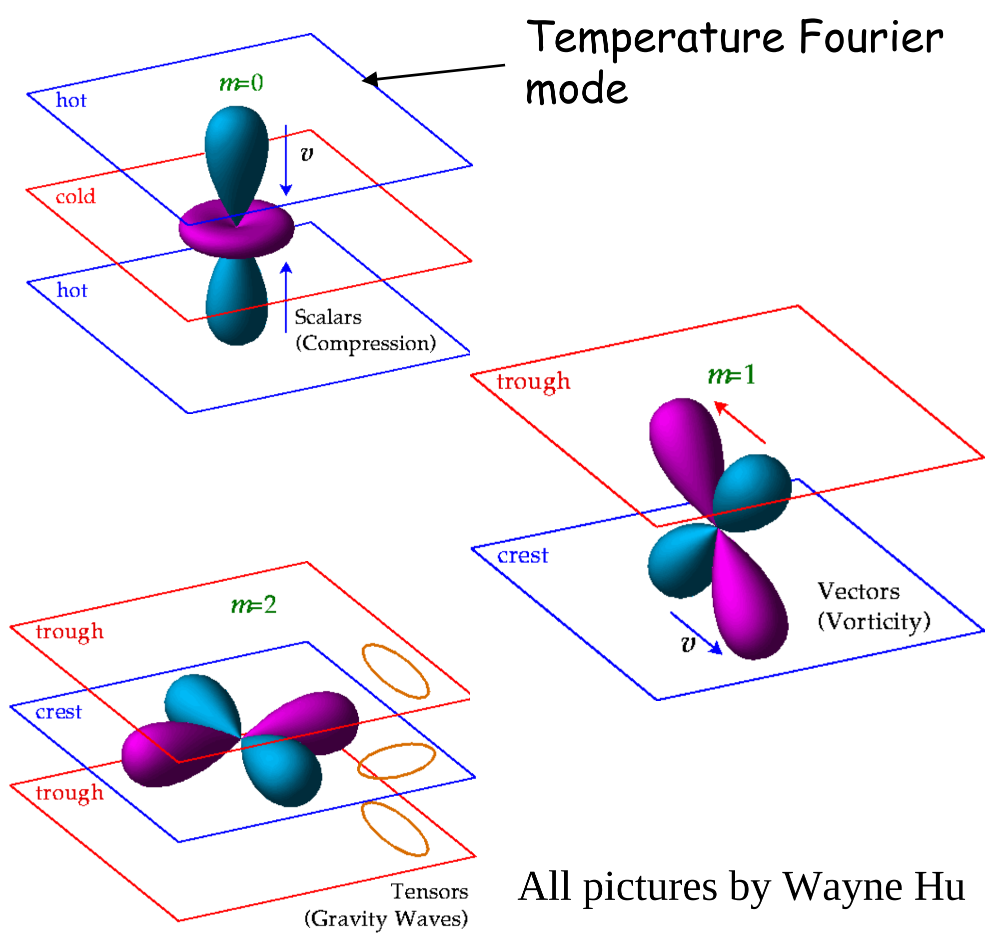
Picture credit de Oliveira-Costa for the CMB taskforce report

CMB polarization anisotropy



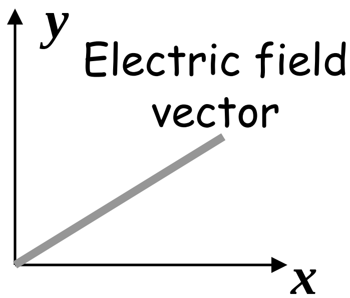
- Only quadrupoles at the surface of last scattering generate a polarization pattern

- Quadrupoles generated by:
  - Velocity gradients in the photon-baryon fluid - SCALAR MODES
  - (Vortices on the surface of last scattering - VECTOR MODES)
  - Gravitational redshifts associated with gravitational waves - TENSOR MODES



All pictures by Wayne Hu

Relating polarization to observables



- The observables are Stokes parameters I, Q and U
  - Circular polarization (parameter V) is not expected

$Q > 0$, $U = 0$

$Q < 0$, $U = 0$

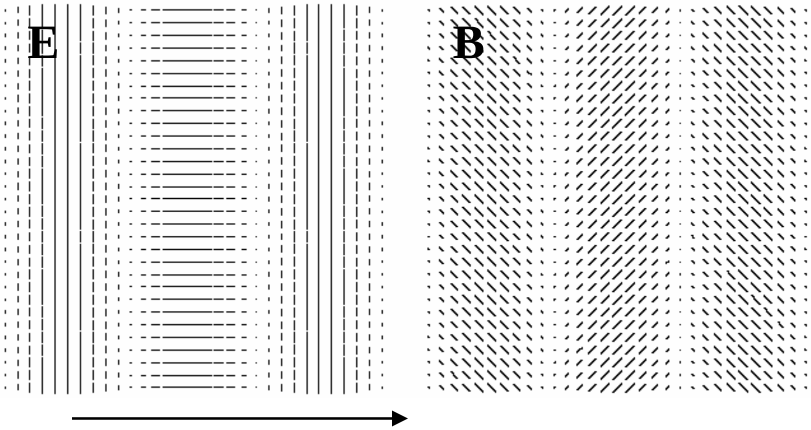
$Q = 0$, $U > 0$

$Q = 0$, $U < 0$

- But Q and U depend on the local coordinate system
  - Rotate coordinates by 45°, Q becomes U and vice versa

Q and U are coordinate dependent but…

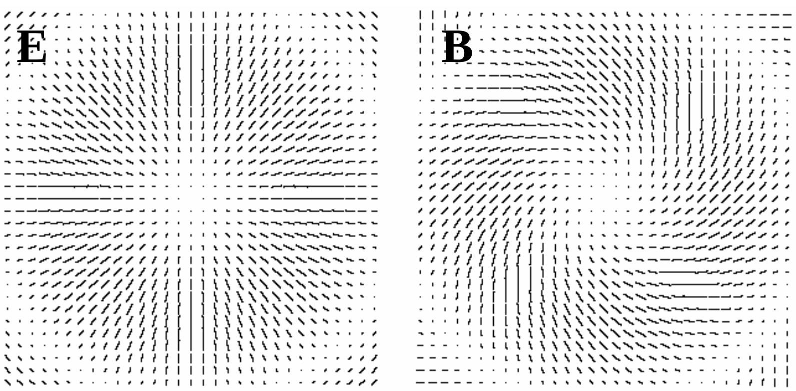
- A single Fourier mode



Plane wave modulation of the CMB temperature
Lines show the polarization field

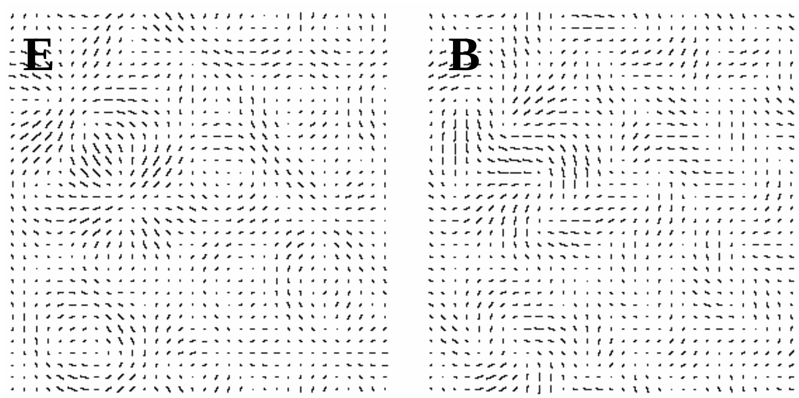
- Spatially varying mixtures of Q and U can be decomposed into patterns that are not coordinate system dependent

- 8 coherently added modes, evenly distributed in angle



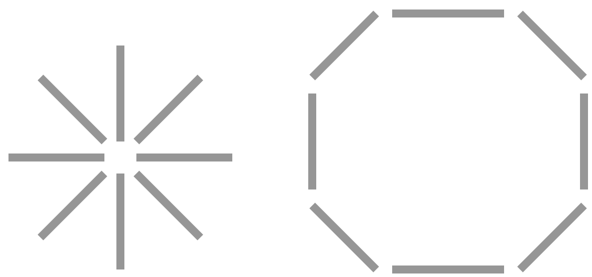
See Bunn (2003)

- Superposed modes with random phases and angle

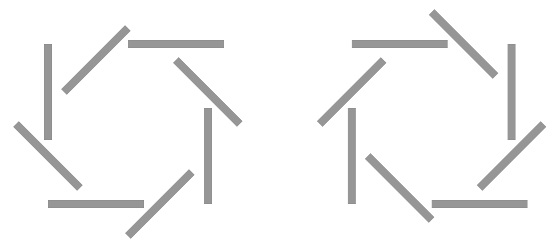


Figures by James Hinderks

E and B modes



E modes

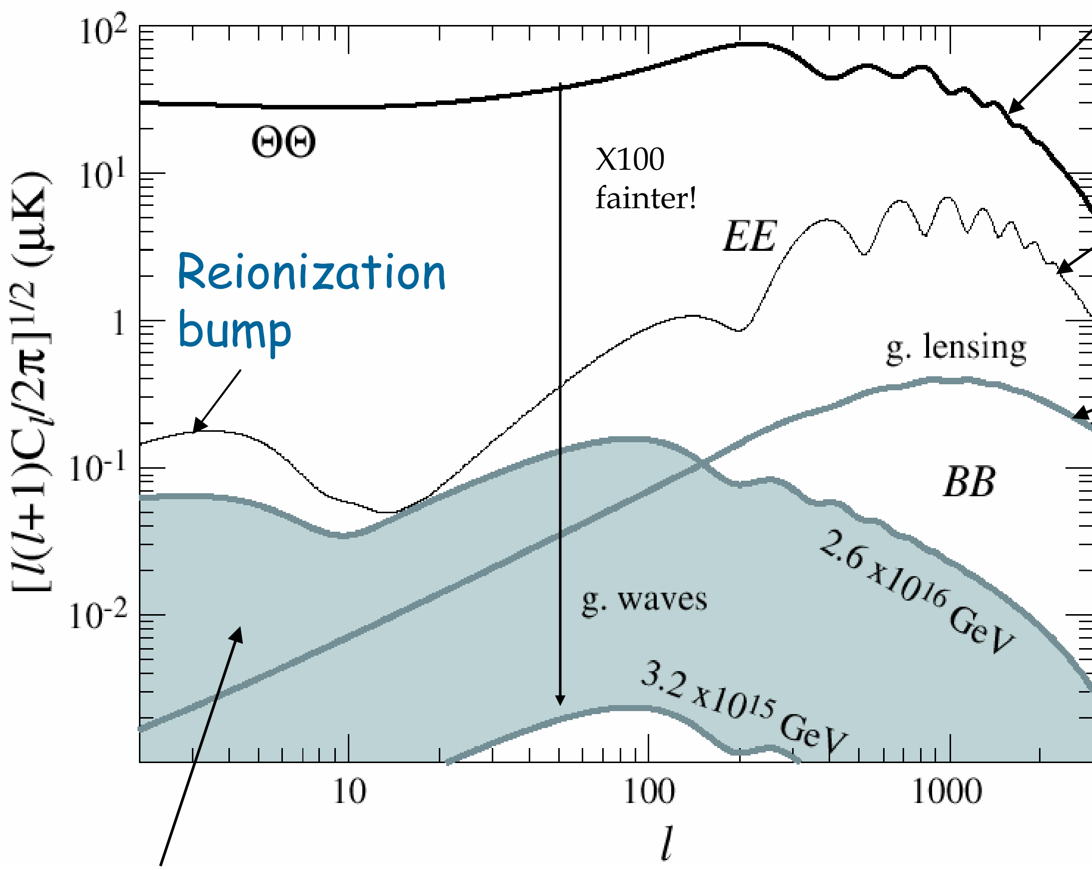


B modes

- These modes retain their character on rotation of the local coordinate system
- E-modes are invariant under a parity change, B modes are not
- Scalar modes (density fluctuations) *cannot* generate B-modes
- Tensor modes generate a mixture of *E* and *B* modes

The CMB polarization power spectra

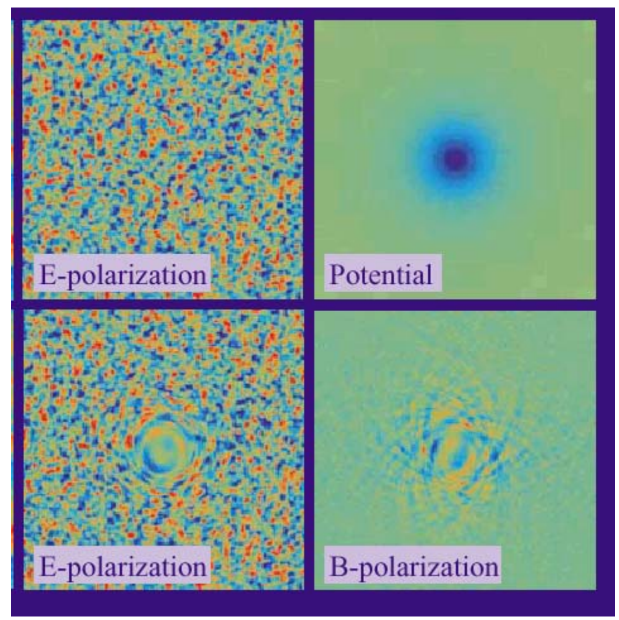
Hu, Hedman, Zaldarriga, 2002



Temperature spectrum

E-modes from scalar perturbations

Gravitationally lensed E-modes



Hu & Okamoto (2001)

B modes from gravitational wave background spanning current limits and minimum detectable from CMB

Science from CMB polarization measurements

- TE cross-correlation
  - measures reionization depth
- E-mode measurements
  - Adds to precision of cosmological parameter measurements, power spectrum index, reionization
- B-modes from lensed E-modes
  - Probes large scale structure out to $z \sim 1100$
  - (Limits on dark energy eq. of state parameter w)
  - Neutrino mass
- B-modes from gravitational waves
  - Probe of inflationary models

Lensing of the CMB measures *all* structure back to the surface of last scattering

- Probes the growth of large scale structure which is sensitive to massive neutrinos and dark energy
- Complements proposed weak lensing surveys

Neutrino mass → m_ν; Dark energy eqn. of state parameter → w_x; Spectral index and rate of change of index → n_S, n'_S

Experiment	m_ν (eV)	w_x	$\ln P_\Psi$	n_S	n'_S
Planck	0.15	0.31	0.017	0.0071	0.0032
SPTpol	0.18	0.49	0.018	0.01	0.006
CMBpol	0.044	0.18	0.017	0.0029	0.0017

Kaplinghat et al, ApJ 583, 24 (2003) Kaplinghat, Knox and Song, astro-ph/0303344
Hu and Holder, PRD 68 (2003) 023001

Allowed parameter space for tensor fluctuations is still large and can be constrained by polarization measurements

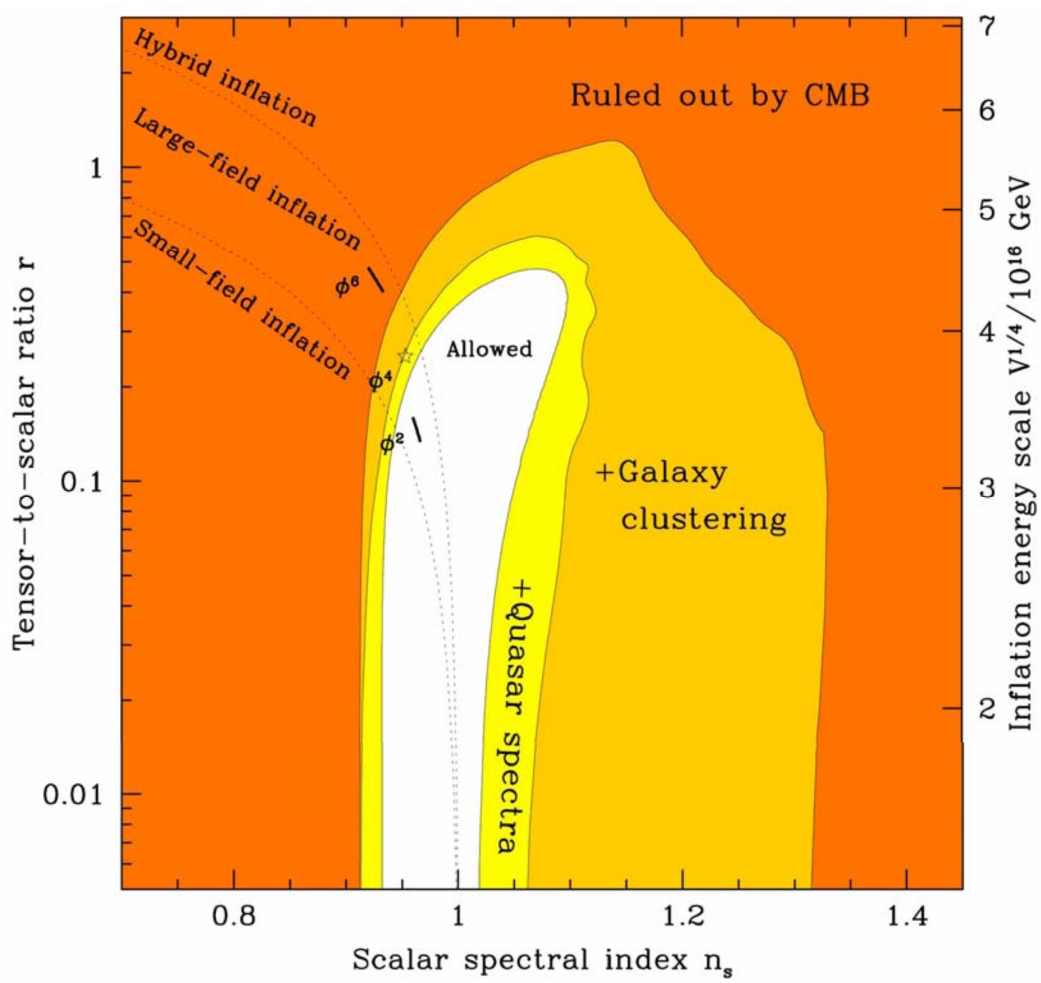
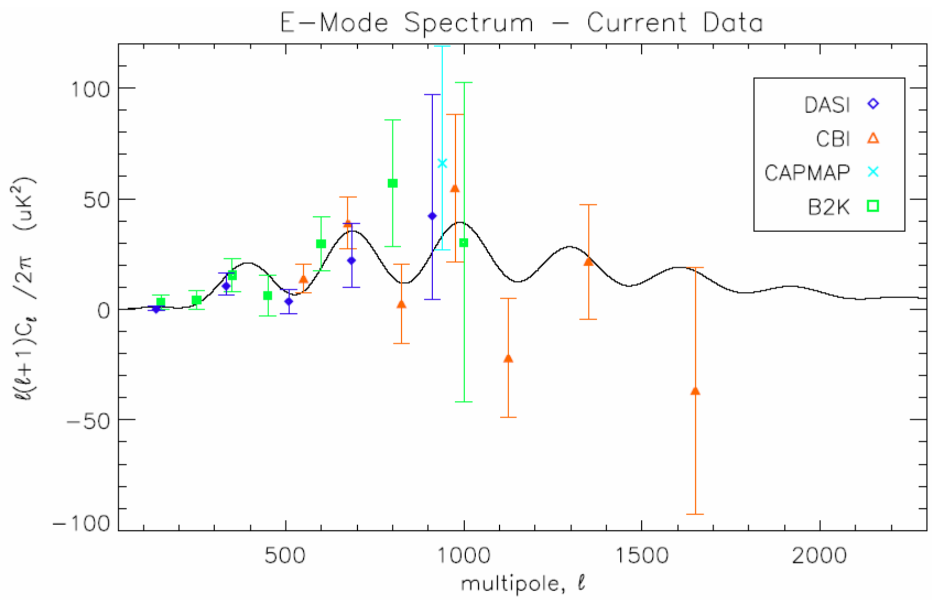
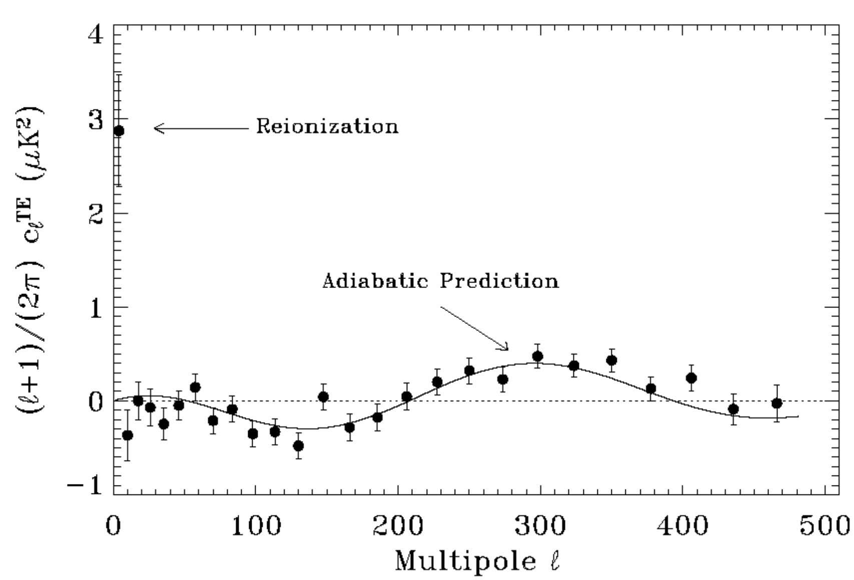


Figure from the CMB taskforce report

Status of Polarization Measurements



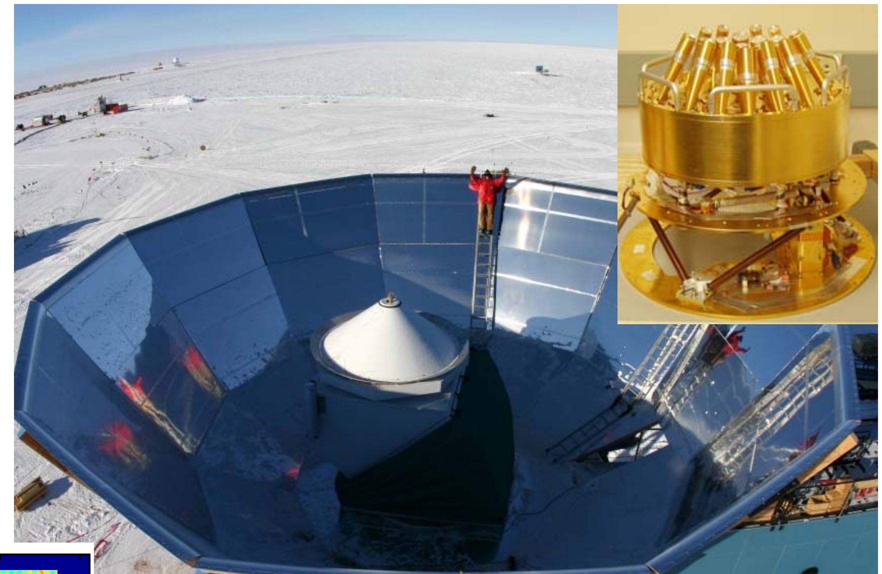
- To date only *E* modes have been detected
- These experiments are finished, except CAPMAP new release expected soon



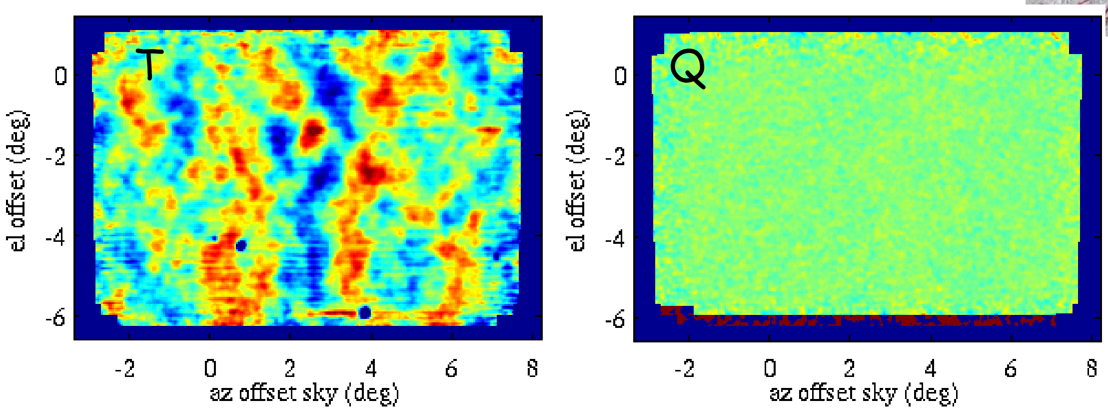
- TE cross-correlation measured by WMAP (Kogut et al. 2003)
- New WMAP release expected soon

The QUaD Experiment

- 31-pixel bolometric array receiver (100, 150 GHz)
- 2.6m telescope at the South Pole, fielded 2005



A subset of data from the QuaD first season



Stanford (PI), Cardiff (PI), Chicago, Caltech/JPL, Edinburgh, Maynooth College, APC Paris

Funding: NSF, PPARC, Enterprise Ireland

- QUaD has demonstrated that a lot of this science will be accessible from the ground
- First results expected in 2006

These are hard measurements!

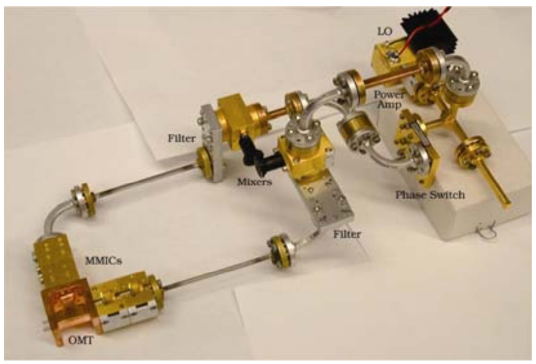
- Detecting each new power spectrum requires roughly an order of magnitude sensitivity improvement

- Requires experiments specifically designed to measure polarization with:
  - High instantaneous sensitivity (many, many detectors)
  - Access to large amounts of sky with low foregrounds
  - Careful design for low systematics
  - Very long integration times (years)

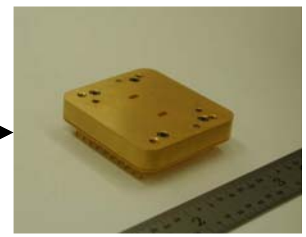
- New experiments being built with very large numbers of detectors

Advancements made possibly by new technologies

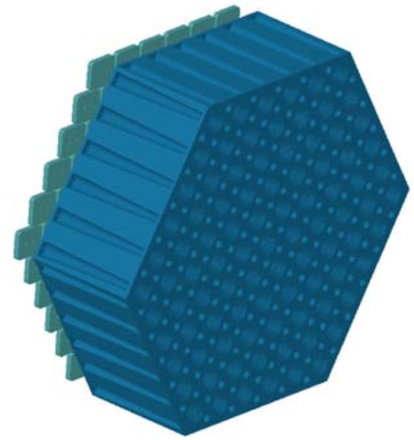
- Small numbers of "hand-built" pixels being replaced by arrays with 100s-1000s of pixels



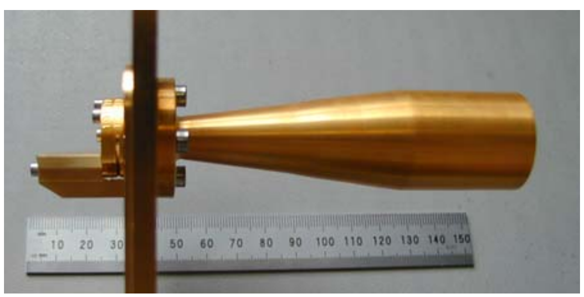
CAPMAP radiometer (90 GHz)



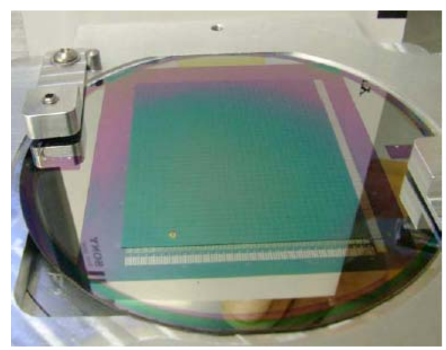
QUIET detector module manufactured by JPL



91-element array



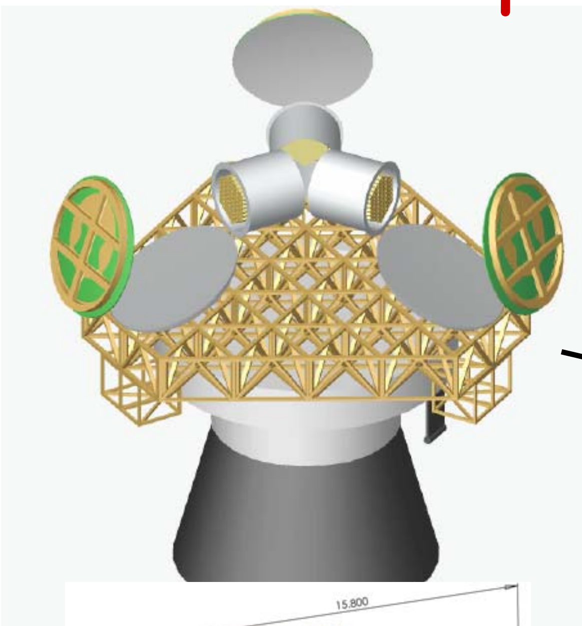
QUaD 90 GHz bolometric pixel



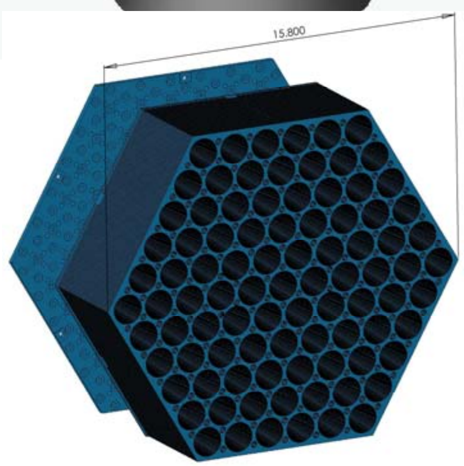
Large format bolometer arrays (NIST array for SCUBA II)

One example -- QUIET

Caltech, Chicago (PI), Columbia, JPL, Oxford, Princeton, Stanford/KIPAC



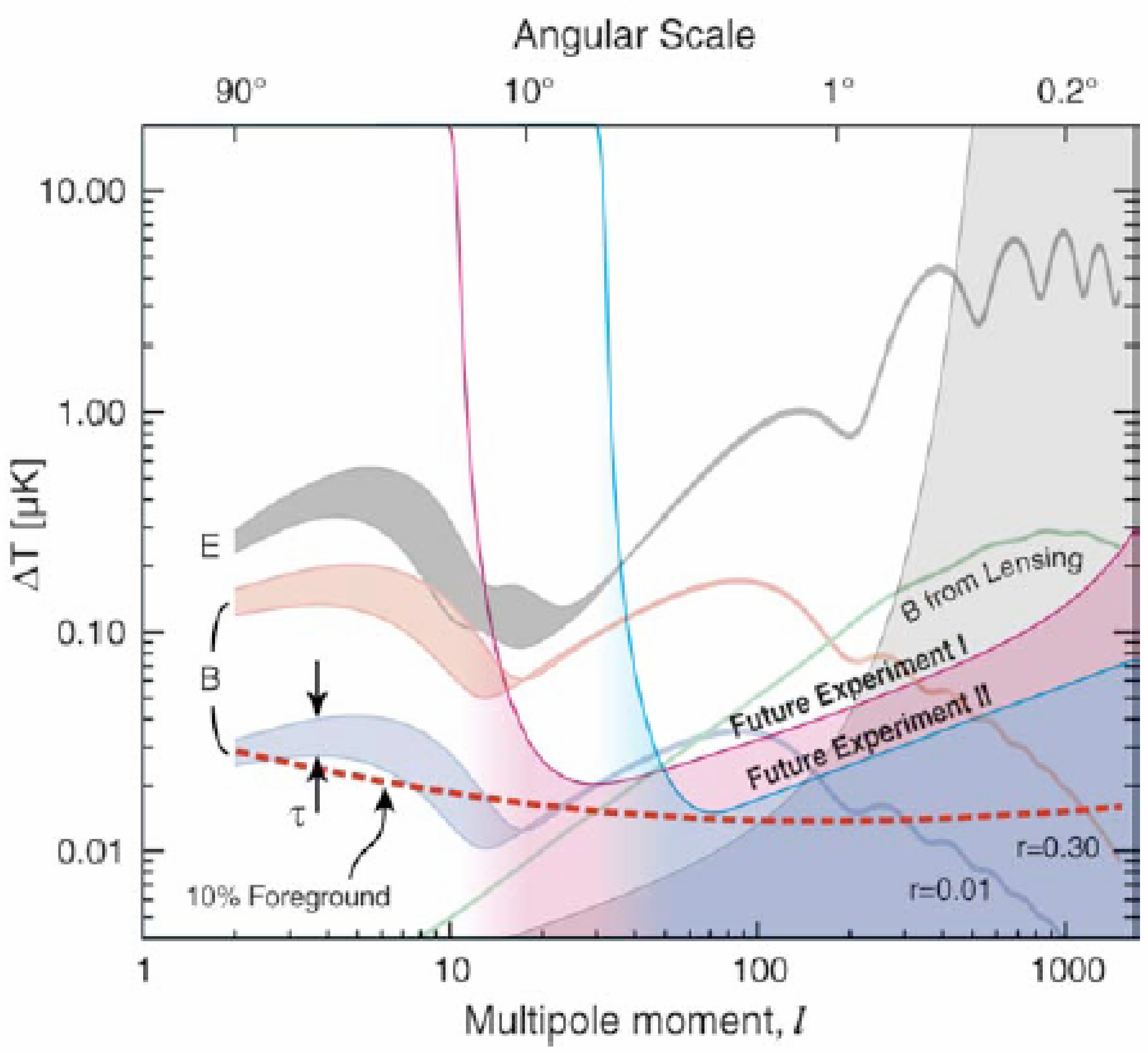
Ultimately three 2m telescopes, each with a large format array, located on the Atacama Plateau in Chile



Large arrays of coherent radiometers. Each pixel sensitive to *Q* and *U* (1000 pixels eventually)

Will also use the CAPMAP 7m telescope to probe *B*-modes from gravitational lensing (will be moved to Chile)

Prospects from Future Polarization Experiments



Shaded regions show an allowed range due to uncertainty of the reionization depth

- Fielded (2005)
  - QUaD, BICEP
- Under Construction (2006-7)
  - QUIET, Clover, EBEX, Polarbear, PAPPA, MBI
- Planned (2007+)
  - Spider, SPTpol, ACTpol
- Satellite (201?)

Figure from the CMB taskforce report

Conclusions

- Both CMB temperature and polarization data will yield exciting science over the next decade and beyond
- Expect
  - More sensitive measurements of a range of cosmological parameters
  - Measurement of n, $dn/d\ln k$
  - Measurements, or limits to the tensor/scalar ratio r

- More information on experimental approaches: Joint NSF/NASA/DOE CMB taskforce report

  http://www.nsf.gov/mps/ast/tfcr_final_report.pdf