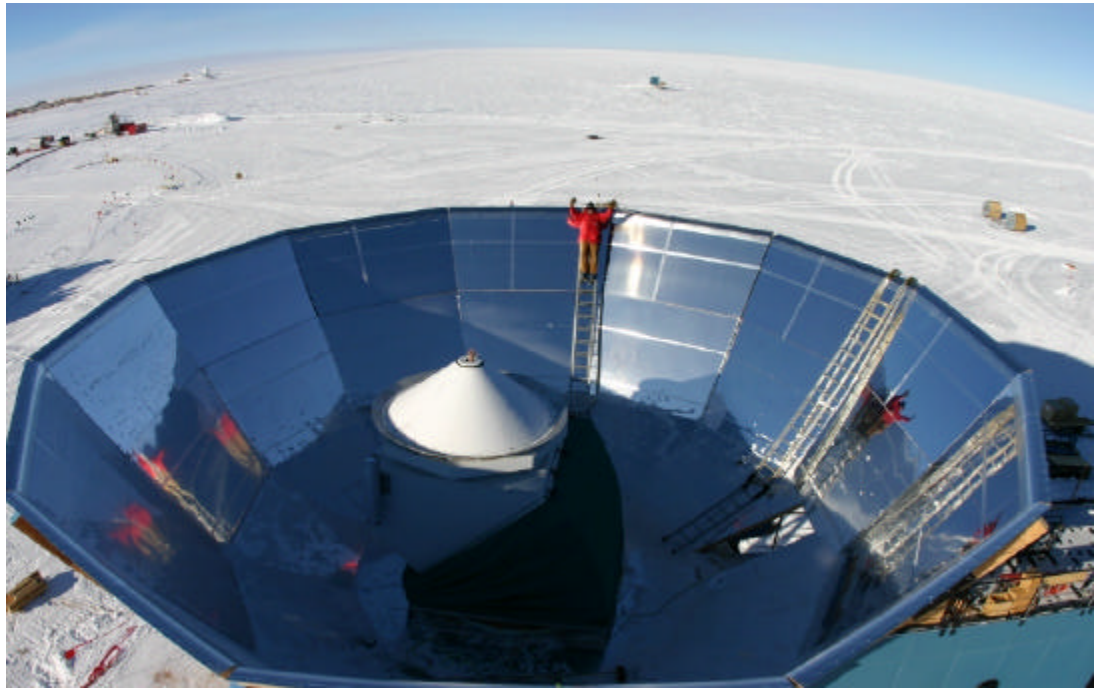
Probing Gravity with Observations of the Cosmic Microwave Background



Sarah Church

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http://www.stanford.edu/~schurch

Outline

- Brief review of the importance of the Cosmic Microwave Background (CMB) radiation for measuring cosmological parameters
- Why we would like to measure CMB polarization
- A description of some experiments
- Conclusions and future prospects

Origin of the Cosmic Microwave Background

- Universe initially in a hot dense state; expands and cools.
- Photons and baryons decouple approximately 400,000 years after the Big Bang
- Photon background visible as the Cosmic Microwave Background (CMB)
- Dominates energy density of universe
- Temperature is isotropic to few parts in 10^5

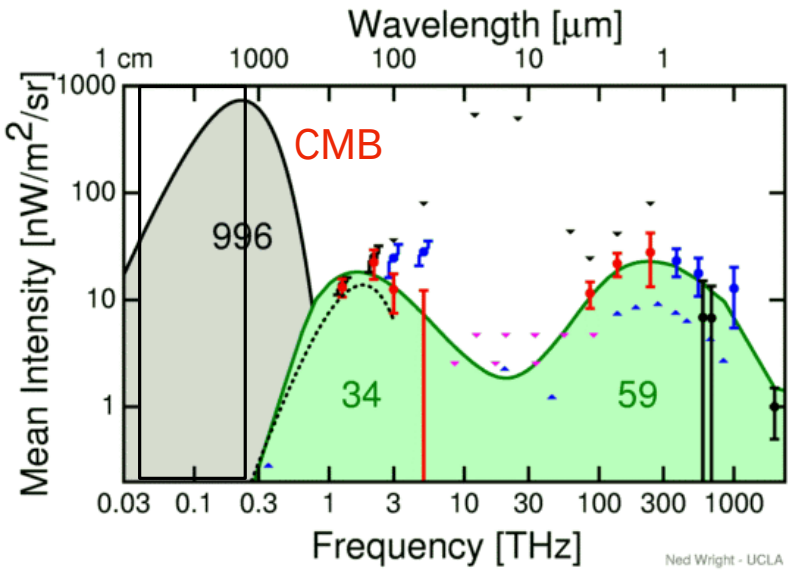
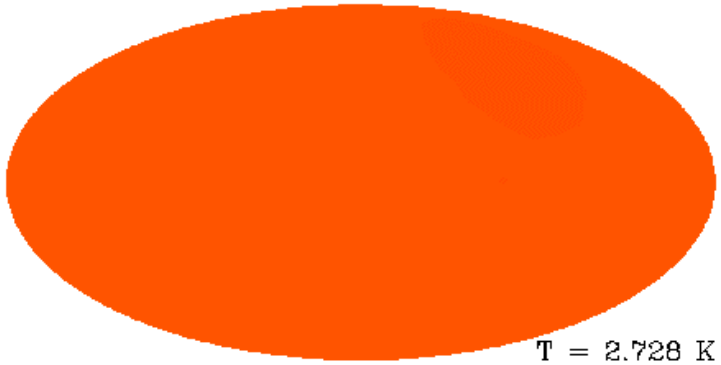
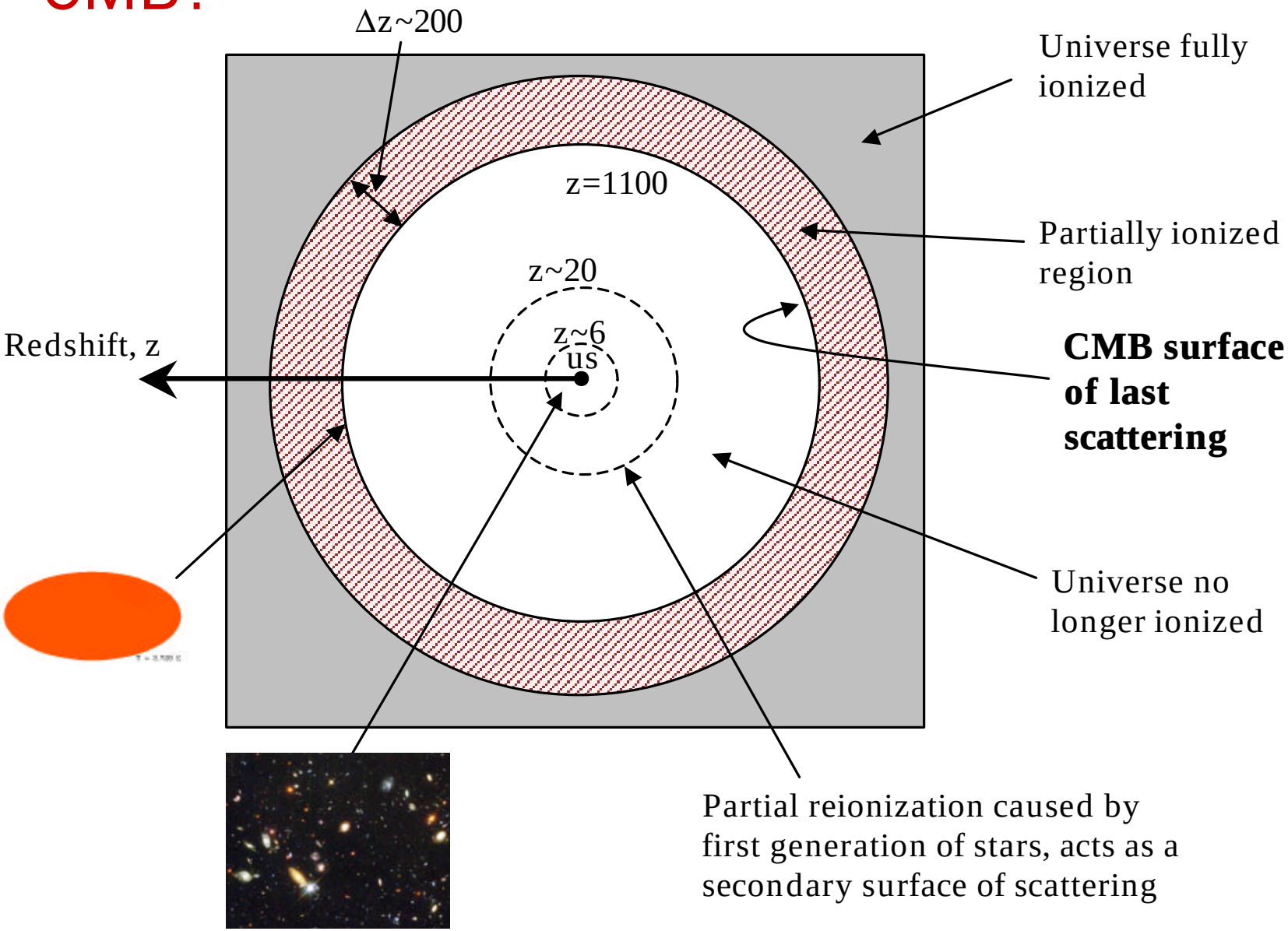


Figure by Ned Wright, UCLA

COBE map of the sky at 33 GHz

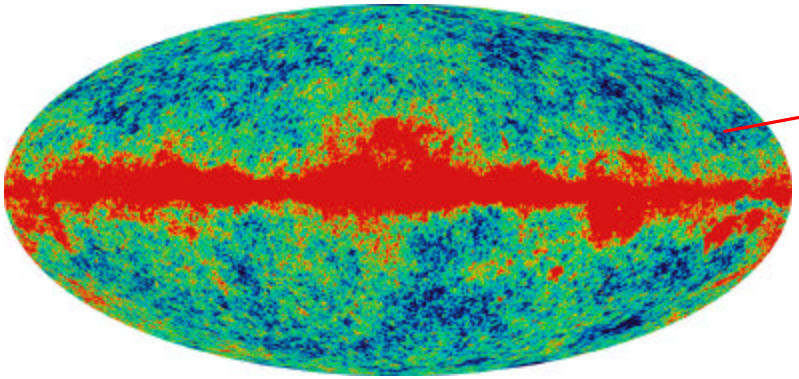


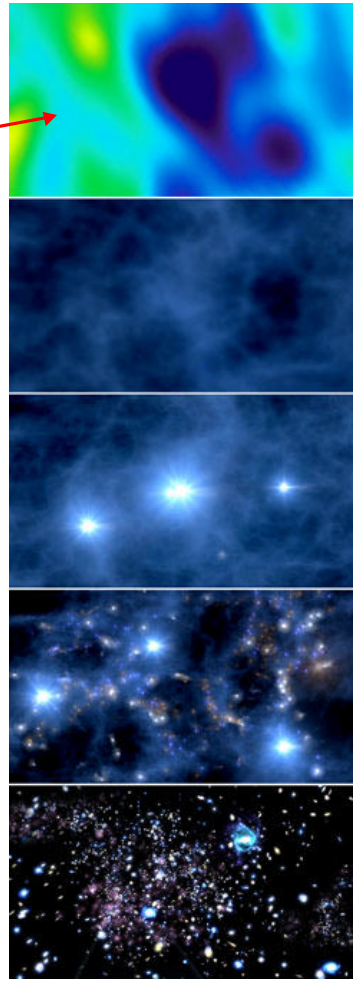
What are we seeing when we look at the CMB?



CMB temperature is not completely uniform

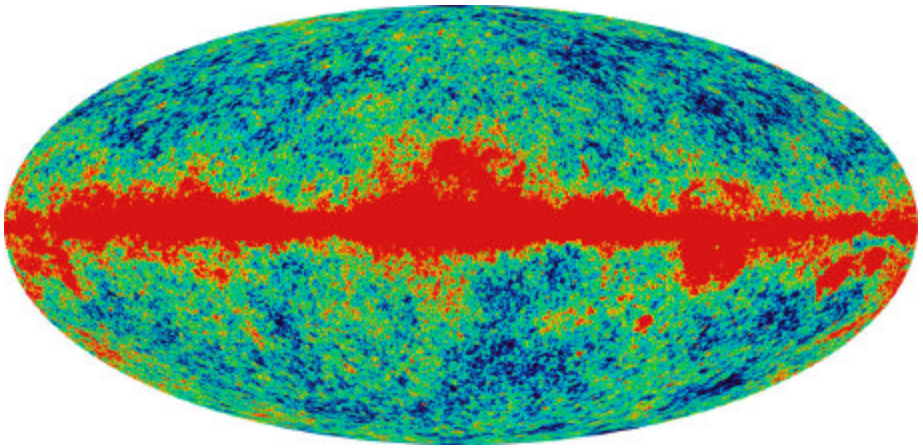
WMAP satellite 2003





- Temperature anisotropies are caused by:
  - Spatial variations in the baryon density (dominant effect, seeds of structure we see today) SCALAR PERTURBATIONS TO THE METRIC
  - Primordial gravity waves (produced by an epoch of inflation) TENSOR PERTURBATIONS TO THE METRIC
  - Secondary effects (scattering by hot gas generated by reionization, or in clusters of galaxies)

CMB temperature maps yield precision measurements of cosmological parameters



WMAP 2003

- Let the temperature in any direction be $T(\hat{n})$
- Analyze statistics of maps using a multipole expansion

$$\frac{\Delta T}{T}(\hat{n}) = \sum_{l,m} a_{lm} Y_{lm}(\hat{n})$$

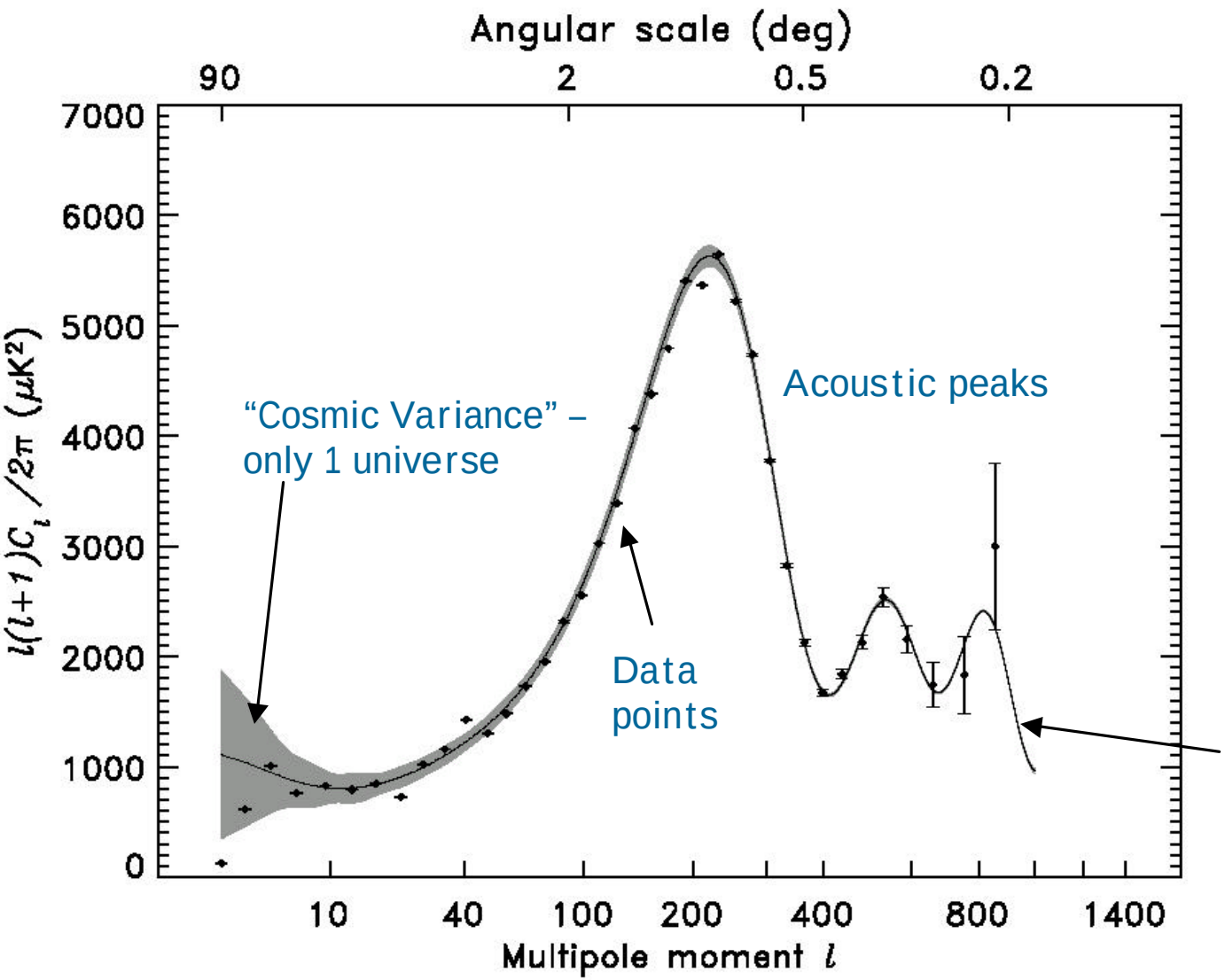
- We can average over *m* values because the universe has no preferred orientation

$$\Delta T_l^2 = C_l = \langle a_{lm} a_{l'm'} \rangle$$

Theoretical predictions match experiment extremely well

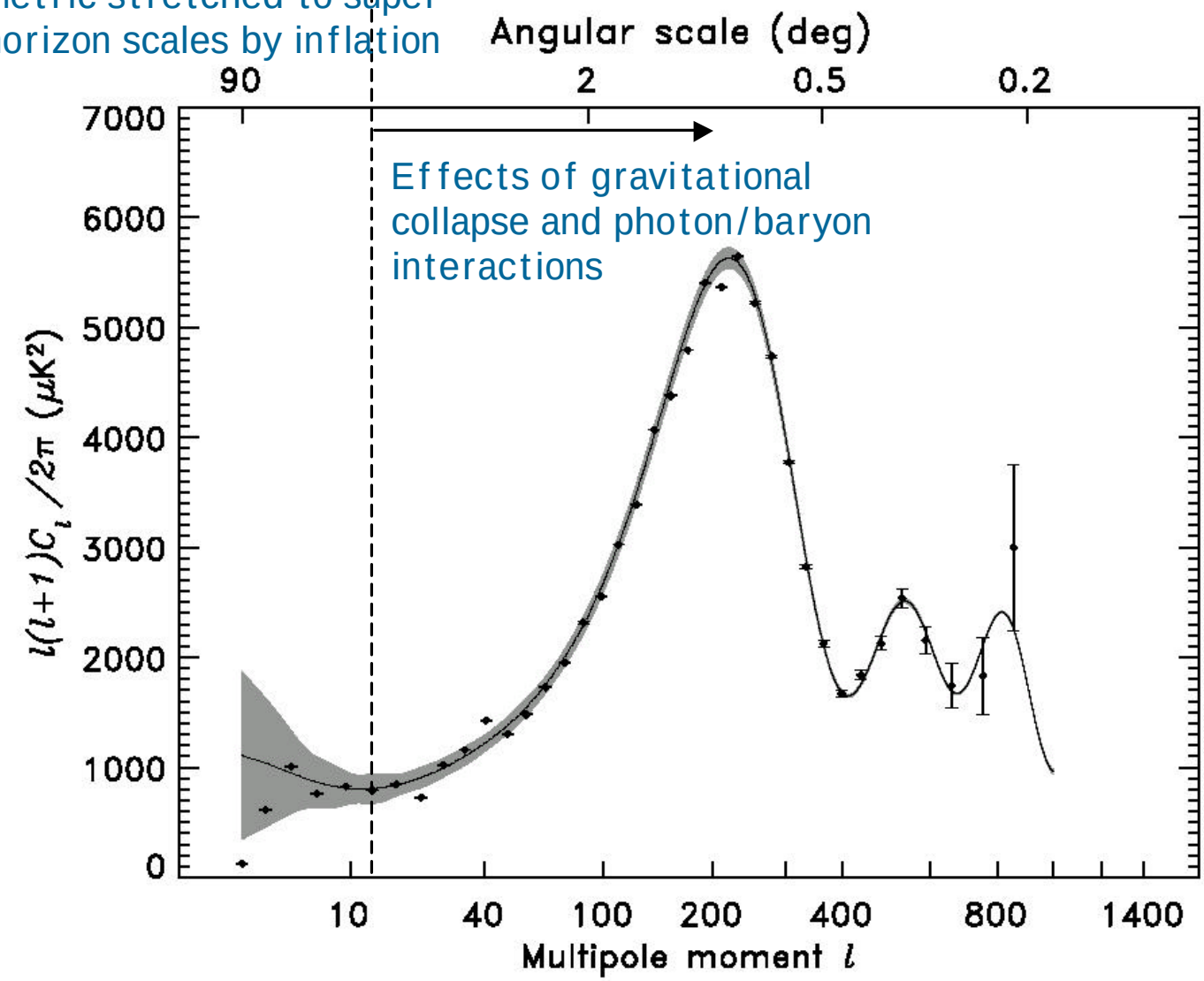
Figure from WMAP

Bennett et al. 2003



What does this plot mean?

Quantum fluctuations in metric stretched to super-horizon scales by inflation



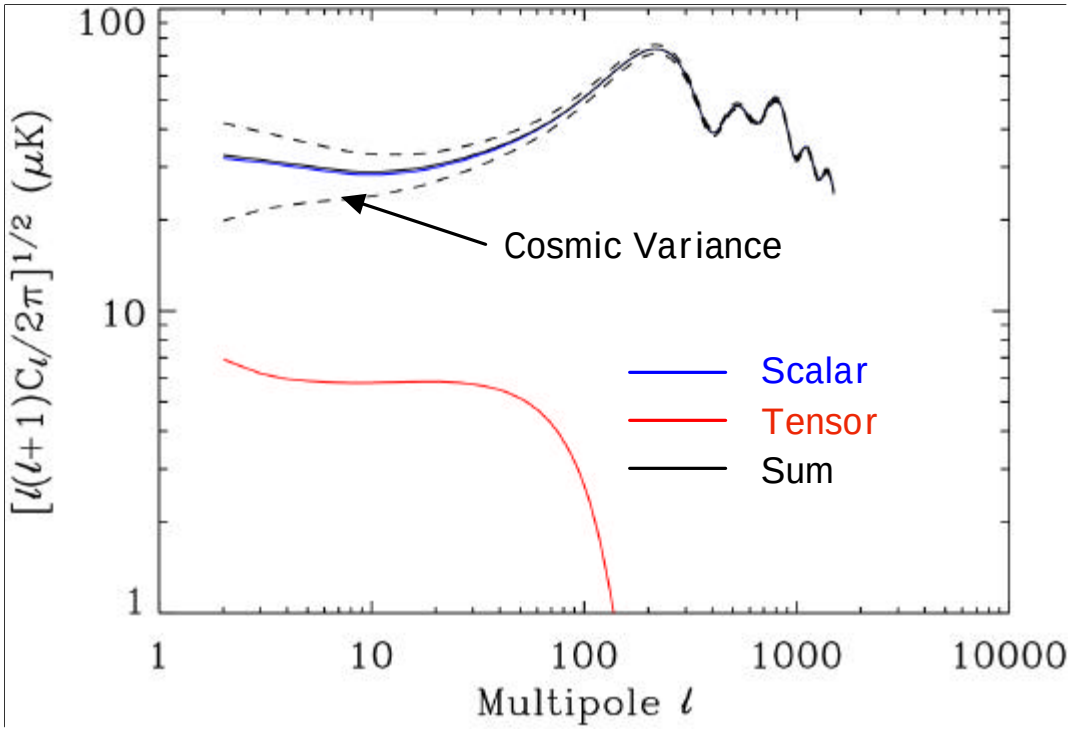
Effects of gravitational collapse and photon/baryon interactions

Figure from WMAP

Bennett et al. 2003

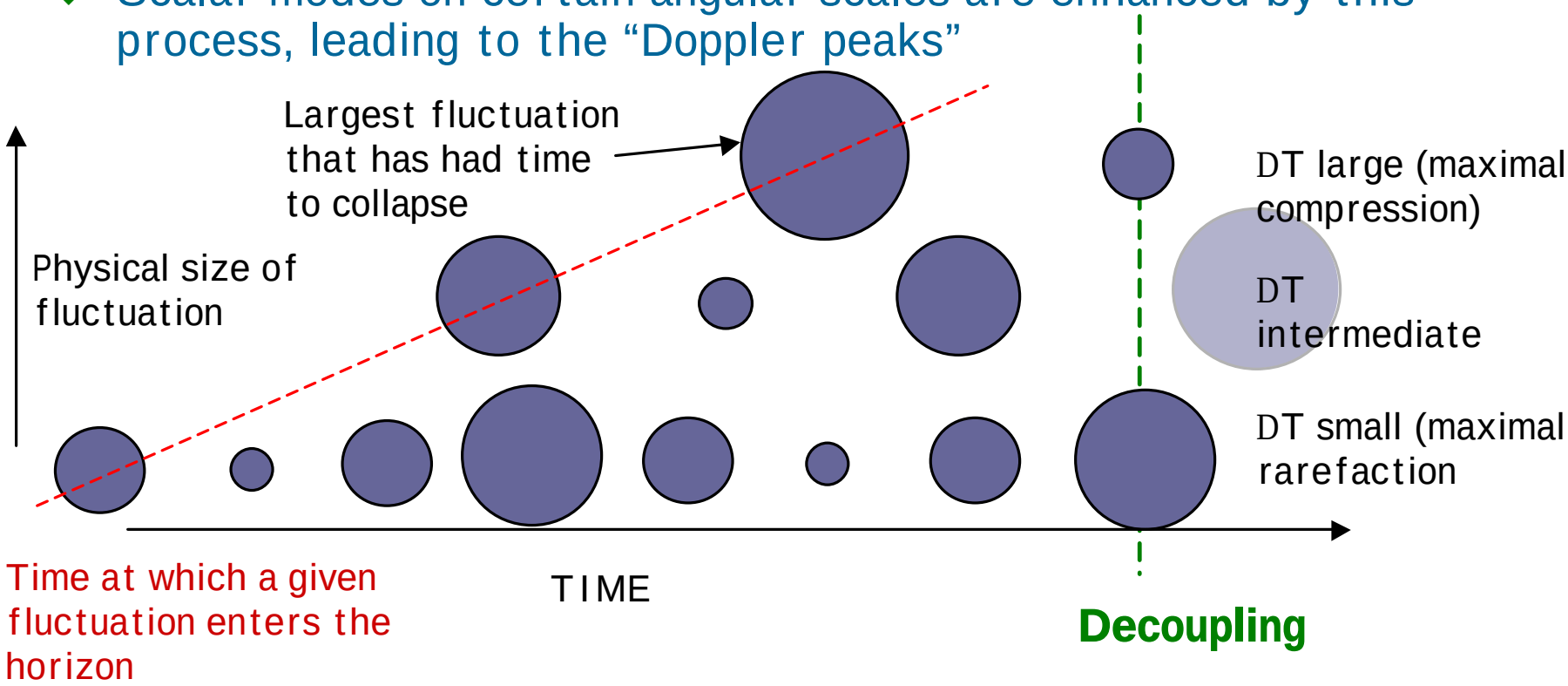
How can the CMB be used to probe gravity in the early universe?

- Tensor fluctuations (gravitational waves) generated during inflation
- Gravitational redshift of photons cause CMB temperature fluctuations, but effect on anisotropies is small



The physics of CMB fluctuations are straightforward

- Initial power spectrum of scalar modes and tensor modes (arise naturally from quantum fluctuations stretched out by inflation)
- Matter fluctuations begin to collapse as they enter the horizon
- Gravity + radiation pressure couple the baryons and the photon background ⇒ oscillations in the photon-baryon fluid
- Decoupling removes radiation support; matter fluctuations are frozen into the CMB
- Scalar modes on certain angular scales are enhanced by this process, leading to the "Doppler peaks"



The CMB can be used to accurately measure cosmological parameters

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

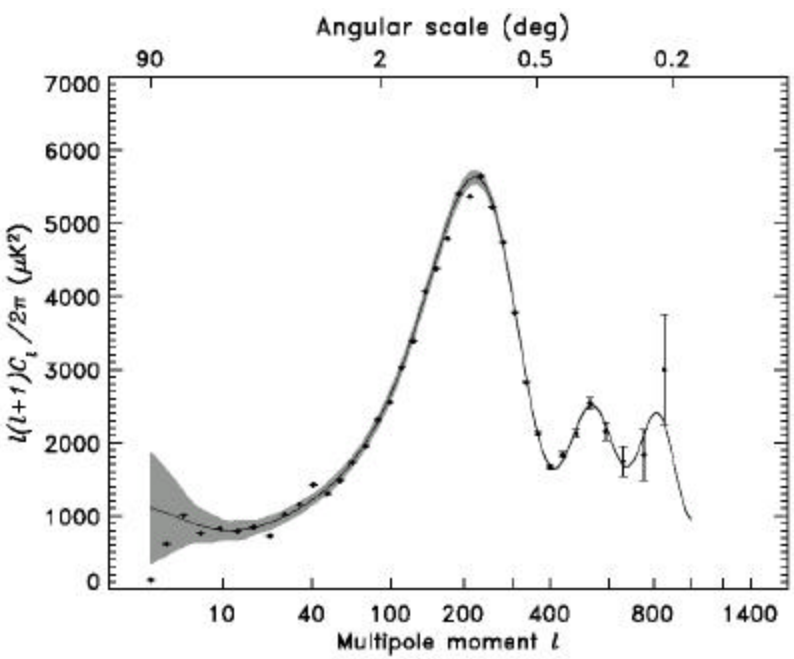


Figure from WMAP

Bennett et al. 2003

“Precision Cosmology”

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)).

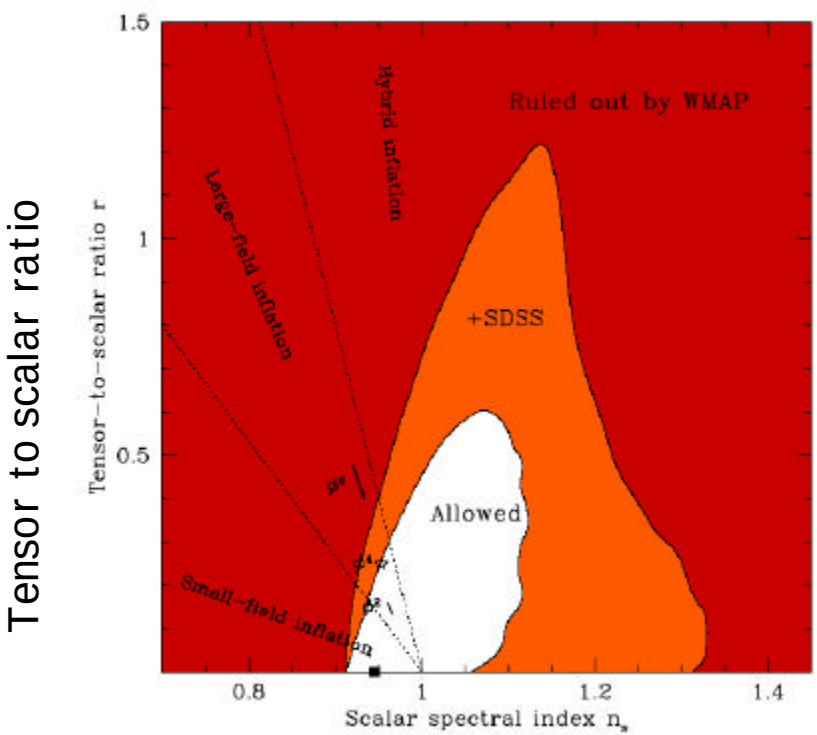
Parameters that can constrain inflationary models

CMB + large scale structure:
Spergel et al. 2004

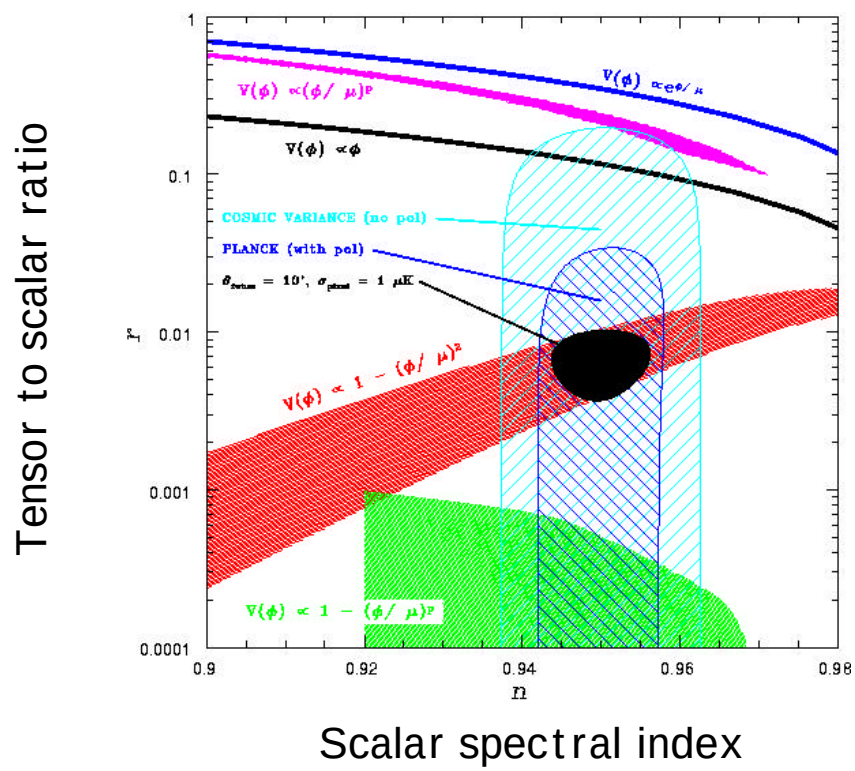
Parameterizing inflation

- A better characterization of the gravitational wave background could constrain inflationary models
- May also be observable effects of some string models (e.g. Freivogel et al. hep-th/0505232, Kaloper et al. 2002)

Tegmark et al. (2003)

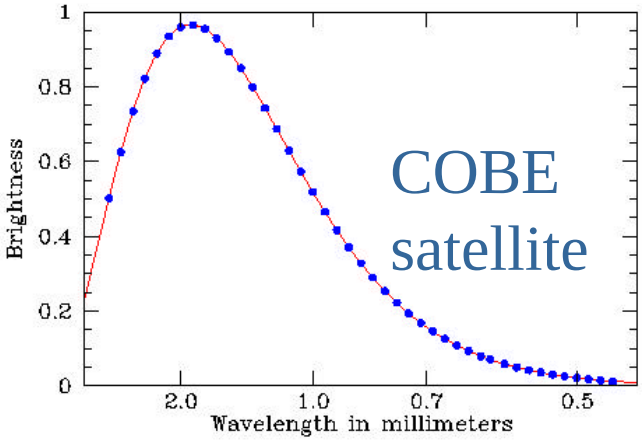


Kinney et al. (2003)

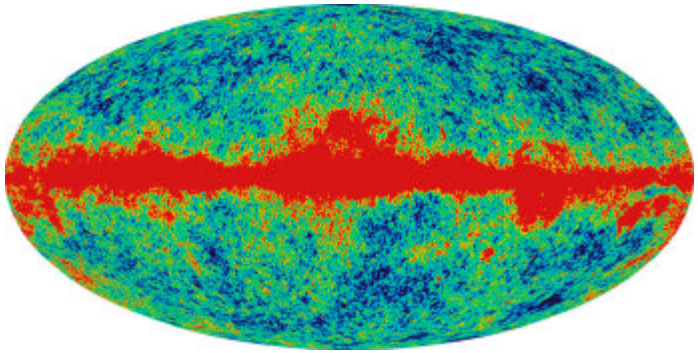


Polarization is the third measurable property of the CMB

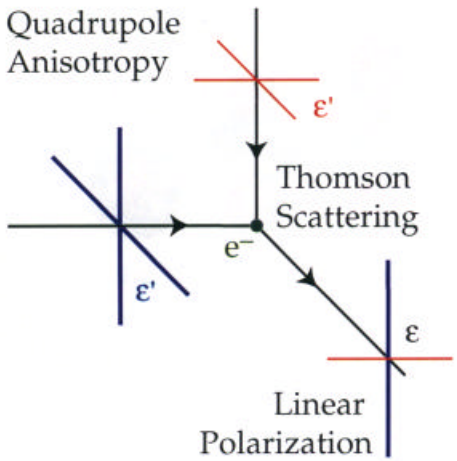
- Frequency spectrum



- Spatial temperature variations:



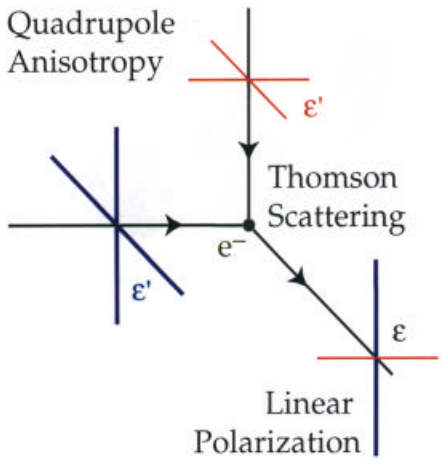
WMAP satellite 2003



Picture by W. Hu

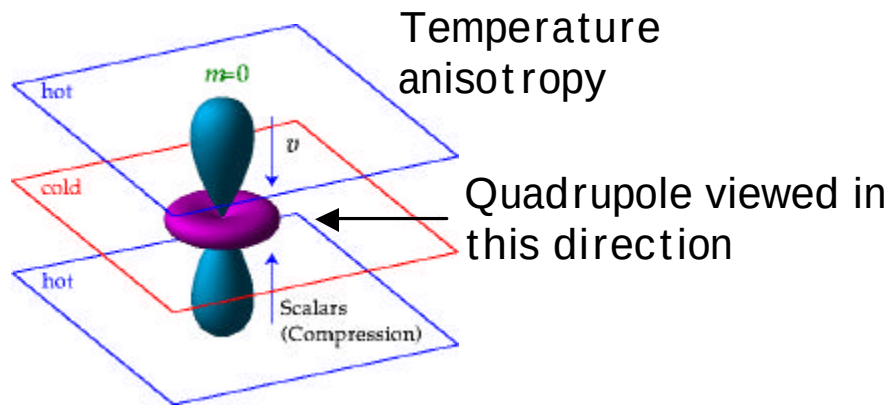
- Polarization generated by anisotropic Thomson scattering
- The polarization percentage is high (around 10%), but the signal is still very weak
- Once again the physics is well-understood
- Precision cosmology equally feasible using polarization

Origin of CMB polarization anisotropy

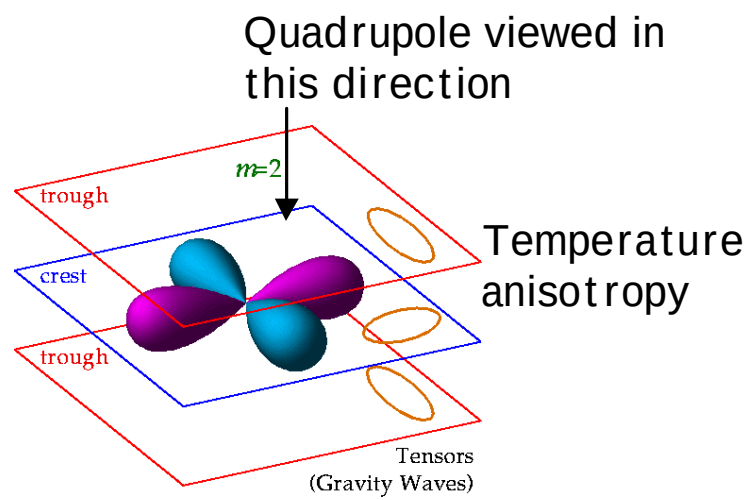


- Only quadrupoles at the surface of last scattering generate a polarization pattern

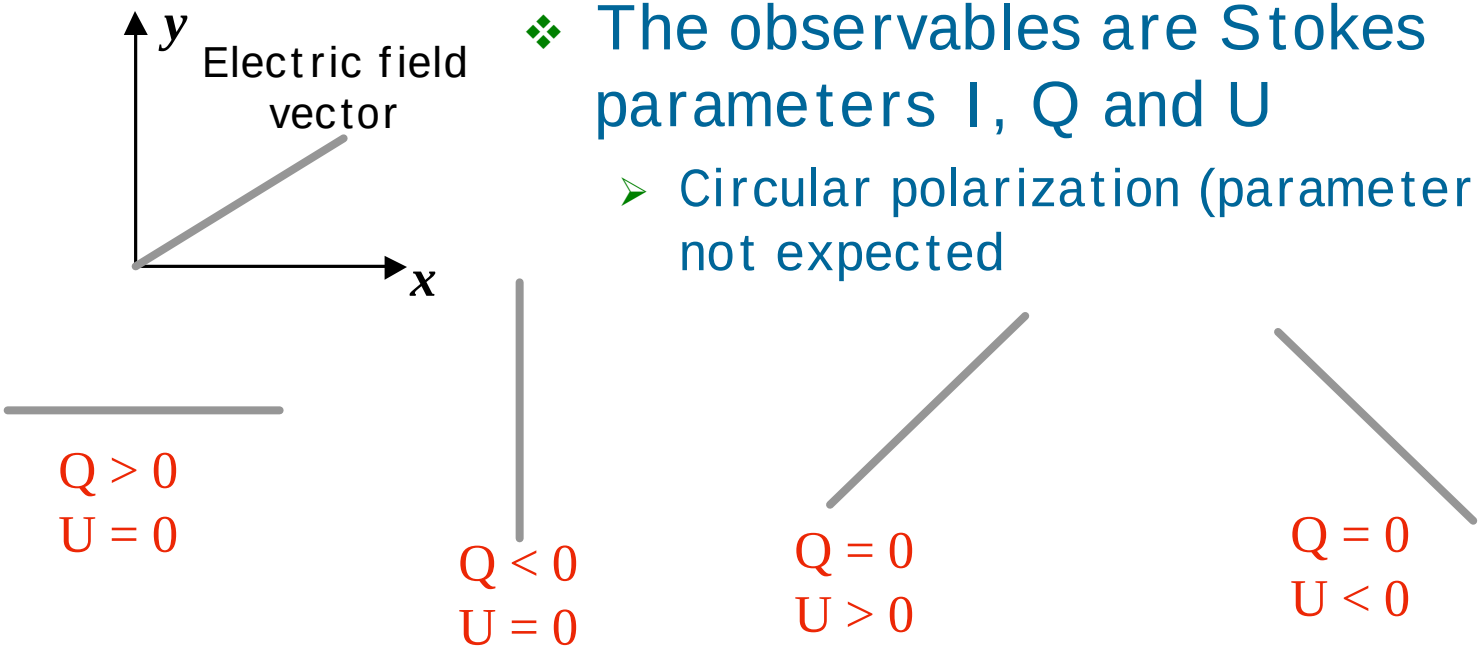
- Quadrupoles generated by:
  - Velocity gradients in the photon-baryon fluid
  - SCALAR MODES



  - Gravitational redshifts associated with gravitational waves
  - TENSOR MODES



Relating polarization to observables



- The observables are Stokes parameters I, Q and U
  - Circular polarization (parameter V) is not expected
- But Q and U depend on the local coordinate system
  - Rotate coordinates by 45°, Q becomes U and vice versa
- Q and U form the components of the polarization tensor

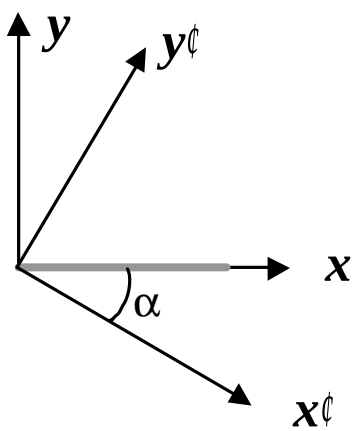
$$\mathcal{P}_{ab}(\hat{n}) = \frac{1}{2}\begin{pmatrix} Q(\hat{n}) & -U(\hat{n})\sin q \\ -U(\hat{n})\sin q & -Q(\hat{n})\sin^2 q \end{pmatrix}$$

in spherical polar coordinates

Symmetric, trace-free $\mathcal{P}_{ab} = \mathcal{P}_{ba}$ $\quad g^{ab}\mathcal{P}_{ab} = 0$

Coordinate-Independent Formalism I

See for example Zaldarriaga & Seljak (1996); Challinor (2005)



$$Q' = Q cos(2\alpha) + U sin(2\alpha)$$

$$U' = -Q sin(2\alpha) + U cos(2\alpha)$$

From which:

$$Q'(\hat{n}) + iU'(\hat{n}) = e^{-2i\alpha}[Q(\hat{n}) + iU(\hat{n})]$$

$$Q'(\hat{n}) - iU'(\hat{n}) = e^{+2i\alpha}[Q(\hat{n}) - iU(\hat{n})]$$

This form suggests an expansion in terms of spin-weighted spherical harmonics:

$${}_sY'_{lm} = e_s^{-is\alpha} Y_{lm}$$ (Note sign reversed in Challinor 2005)

Then:

$$Q(\hat{n}) + iU(\hat{n}) = \sum_{lm} a_{2,lm}\, {}_2Y_{lm}(\hat{n})$$

$$Q(\hat{n}) - iU(\hat{n}) = \sum_{lm} a_{-2,lm}\, {}_{-2}Y_{lm}(\hat{n})$$

Just as: $T(\hat{n}) = \sum_{lm} a_{lm}\, Y_{T,lm}(\hat{n})$

Coordinate Independent Formalism II

$$a_{E,lm} = \frac{(a_{2,lm} + a_{-2,lm})}{2}$$

Scalar; invariant under a parity change – "Electric modes"

$$a_{B,lm} = \frac{(a_{2,lm} - a_{-2,lm})}{2i}$$

Pseudo-scalar; changes sign under a parity change – "Magnetic modes"

Then:

$$Q(\hat{n}) + iU(\hat{n}) = \sum_{lm} (E_{lm} + iB_{lm})\, {}_2Y_{lm}(\hat{n})$$

$$Q(\hat{n}) - iU(\hat{n}) = \sum_{lm} (E_{lm} - iB_{lm})\, {}_{-2}Y_{lm}(\hat{n})$$

Four parity-independent power spectra can then be formed:

$$C_{TT} = \frac{1}{2l+1} \sum_m \left\langle a^*_{T,lm}\, a_{T,lm} \right\rangle \qquad C_{BB} = \frac{1}{2l+1} \sum_m \left\langle a^*_{B,lm}\, a_{B,lm} \right\rangle$$

$$C_{EE} = \frac{1}{2l+1} \sum_m \left\langle a^*_{E,lm}\, a_{E,lm} \right\rangle \qquad C_{TE} = \frac{1}{2l+1} \sum_m \left\langle a^*_{T,lm}\, a_{E,lm} \right\rangle$$

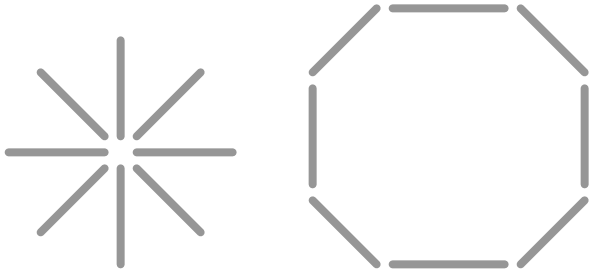
Coordinate Independent Formalism III

- Note that instead of spin-weighted spherical harmonics, the polarization tensor can be written in terms of "tensor harmonics"
  - Kamionkowski, Kosowsky & Stebbins 1997; Challinor 2005

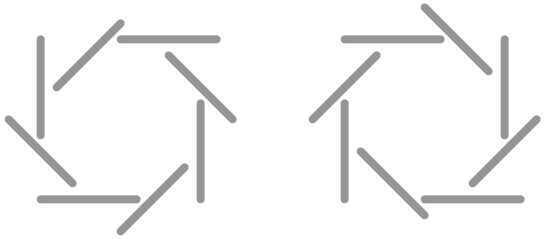
$$\mathcal{P}_{ab} = \sum_{l} \sum_{m=-l}^{l} \left[a^{G}_{lm} Y^{G}_{(lm)ab} + a^{C}_{lm} Y^{C}_{(lm)ab} \right]$$

- The functions $Y^{G}_{(lm)ab}$ and $Y^{C}_{(lm)ab}$ are calculated using covariant differentiation on a 2-sphere
- Process is analogous to decomposing a vector field into the gradient of a scalar field and the curl of a vector field
- So E and B polarization often referred to as "gradient" and "curl"

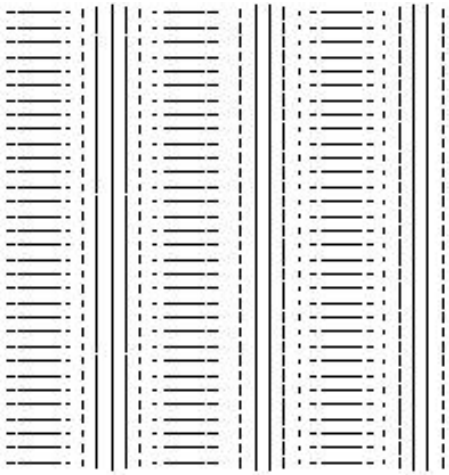
“E” and “B” modes



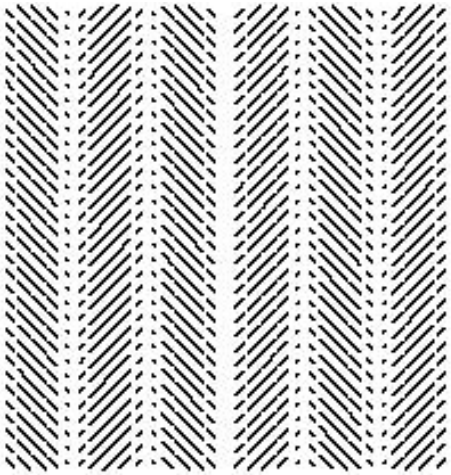
E modes



B modes



E Fourier mode

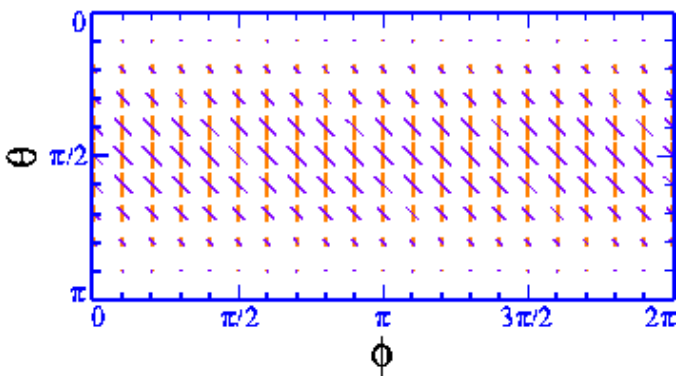


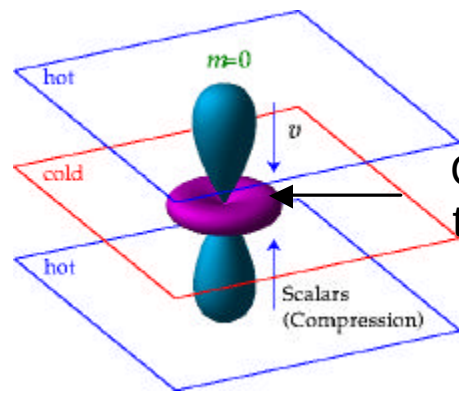
B Fourier mode

See, e.g. Bunn, 2005

Different sources of quadrupoles generate different modes

- Density fluctuations generate pure *Q* or *U*

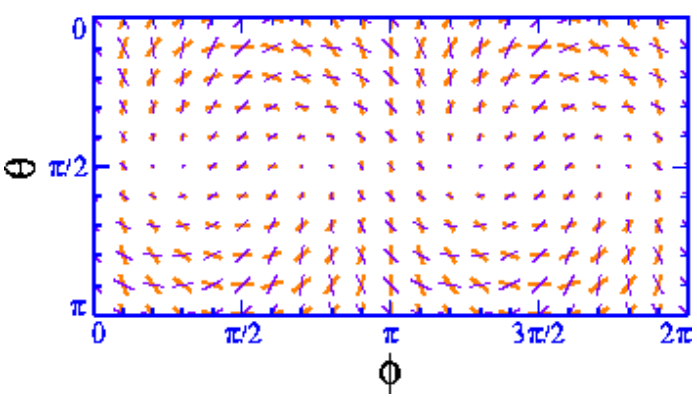




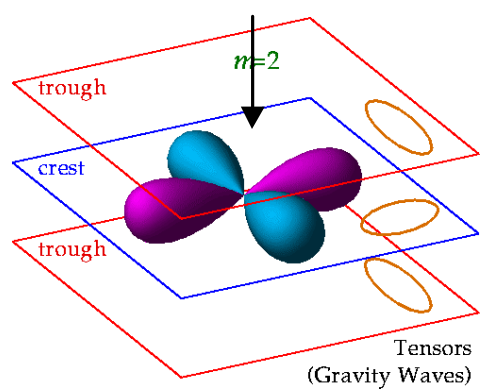
Quadrupole viewed in this direction

Pictures by Wayne Hu

- Gravitational waves generate a mixture of *Q* and *U*



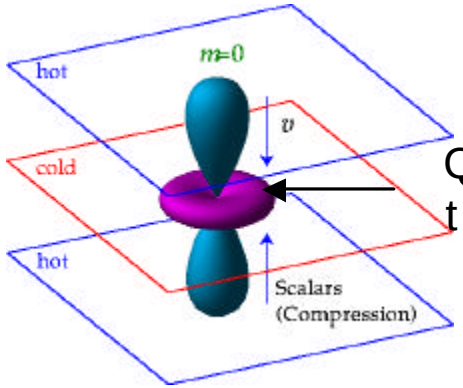
Quadrupole viewed in this direction



Different sources of quadrupoles generate *E* or *B*

Pictures by Wayne Hu

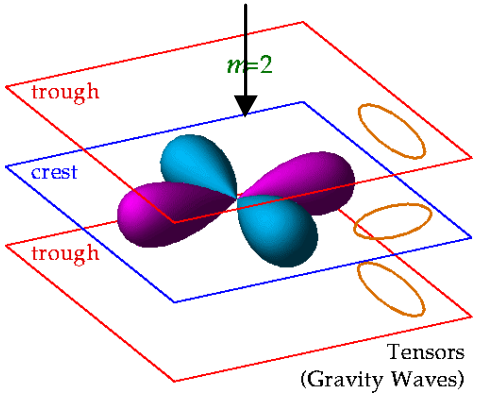
- Scalar modes (density fluctuations) generate *E* *modes only*



Quadrupole viewed in this direction

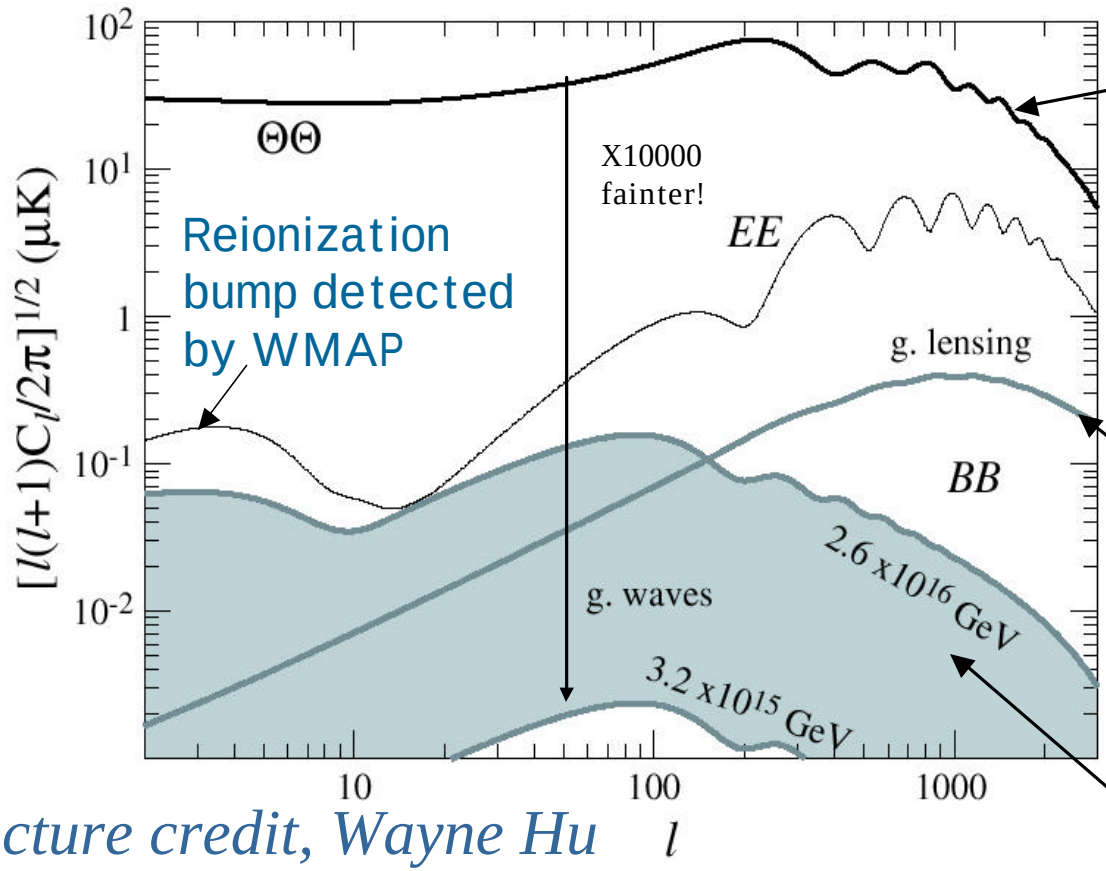
Quadrupole viewed in this direction

- Tensor modes (gravitational waves) generate equal amounts of *E* and *B*



Only polarization measurements have the potential to uniquely separate scalar and tensor modes

Polarization measurements will be even harder than temperature measurements...



Picture credit, Wayne Hu

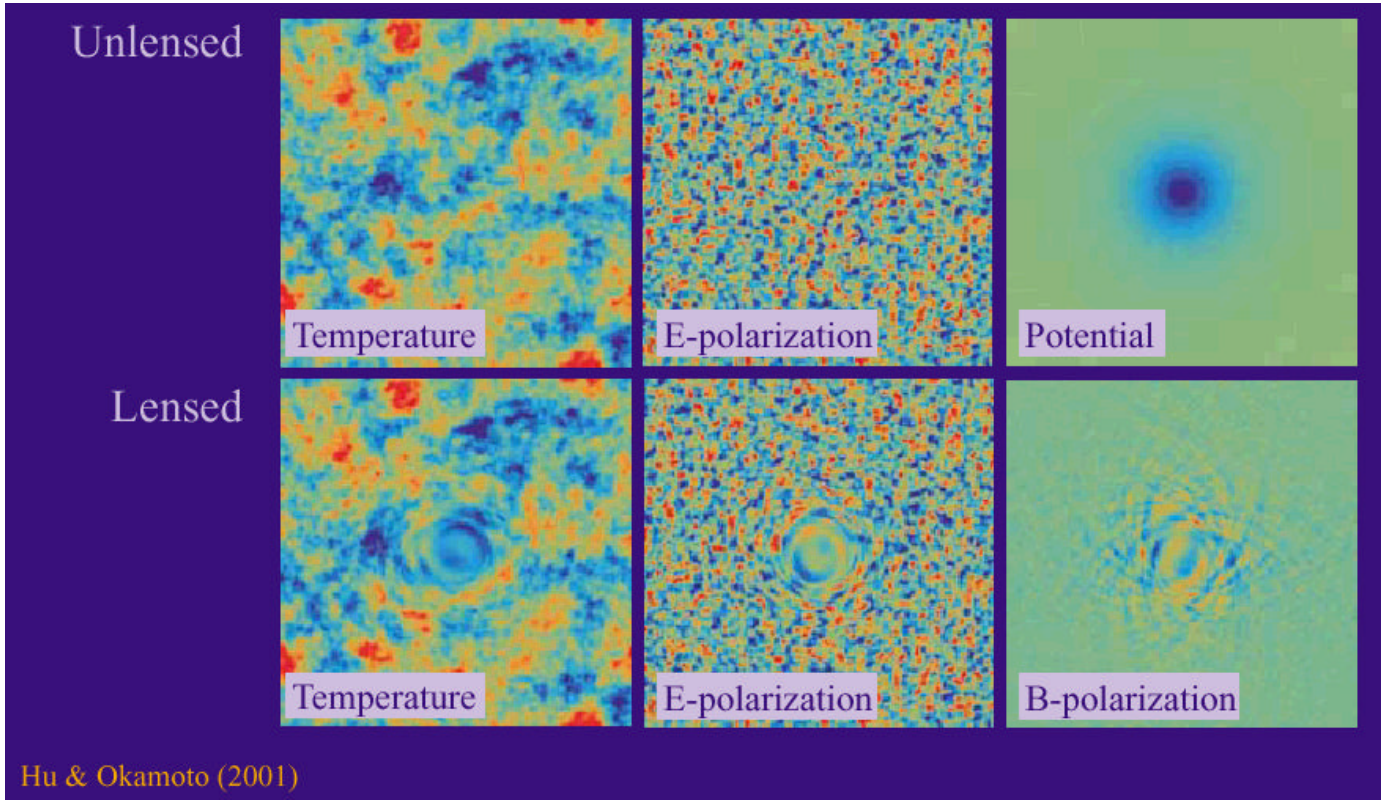
Temperature spectrum mapped by WMAP

Gravitationally lensed E-modes probe large scale structure formation

Projected effect of a gravitational wave background

The range shown for the gravitational wave background spans the maximum allowable level from COBE, and the minimum detectable from CMB measurements

Gravitational lensing of the CMB makes things more complicated….



- Converts E-modes to B-modes
  - Confusion limit to measuring the gravitational wave component
  - Interesting signal in itself, probing growth of structure from present-day to epoch of decoupling

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

Dark energy eqn. of state parameter

Spectral index and rate of change of index

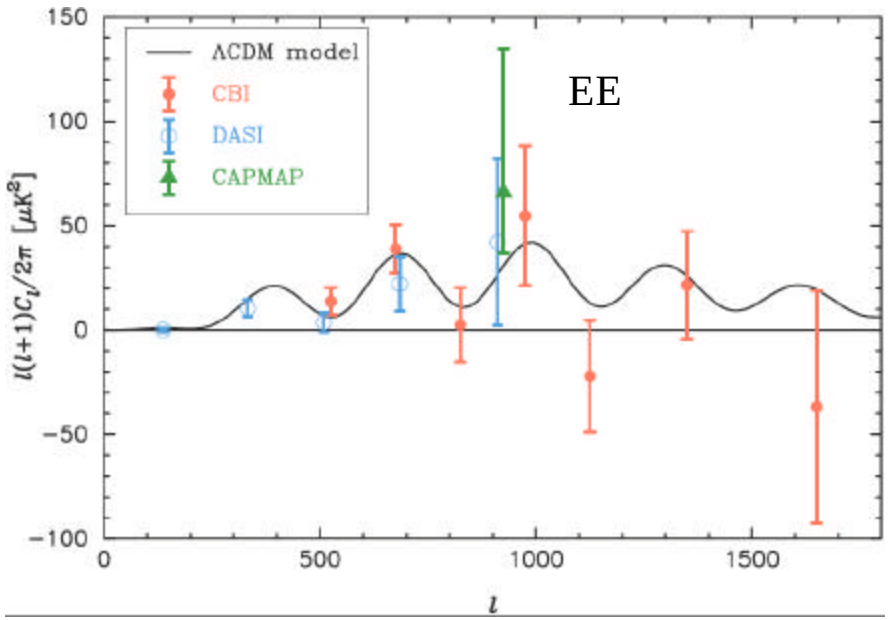
Experiment	m_ν (eV)	w_x	$\ln P_\Psi$	n_S	n'_S
Planck	0.15	0.31	0.017	0.0071	0.0032
SPTpol	0.18	0.49	0.018	0.01	0.006
CMBpol	0.044	0.18	0.017	0.0029	0.0017

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

Aim of CMB polarization measurements

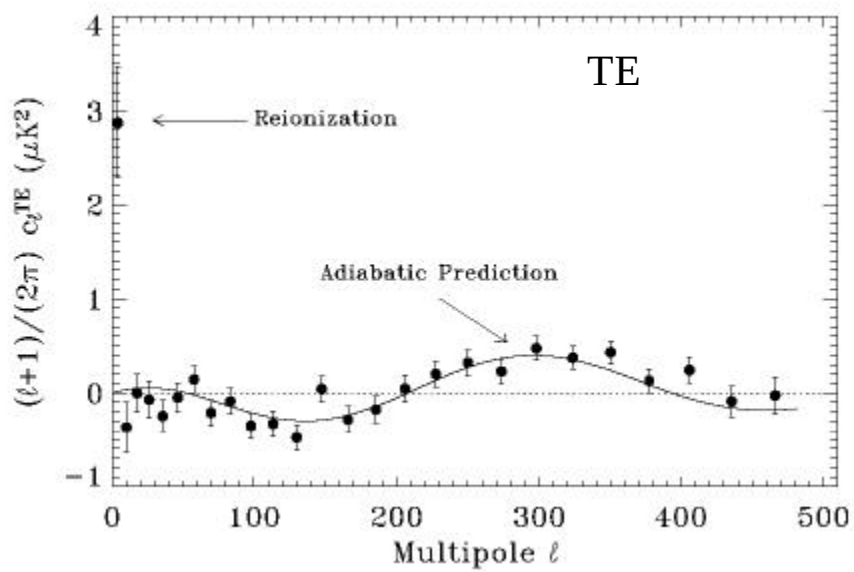
- Stronger constraints on a host of cosmological parameters from *E*-modes
  - Optical depth and redshift of reionization
- Measure (or set limits to) parameters of inflation from *B* modes:
  - Ratio of tensor/scalar modes, r
  - Spectral index of scalar fluctuations, n_s
- Probe dark energy parameters and neutrino mass through lensing of *E*-modes to *B*-modes

Status of Polarization Measurements



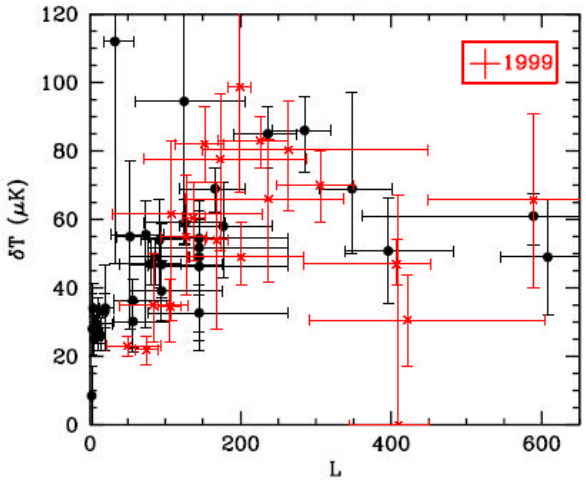
- EE power spectrum
- First detection by U. Chicago DASI experiment in 2002 (Kovac et al. 2002)
- Several other experiments reported data in 2004

- TE cross-correlation measured by WMAP (Kogut et al. 2003) shows evidence for reionization
- WMAP second release expected soon



Not dissimilar to state of TT measurements a decade ago

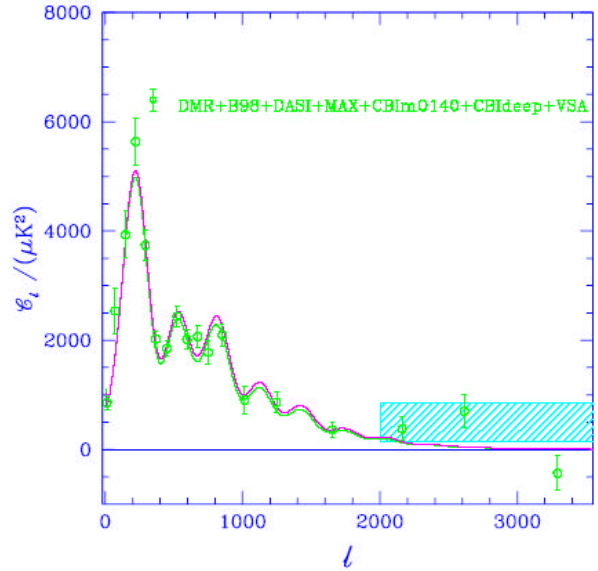
- CMB results pre-2000



Figure

S. Dodelson

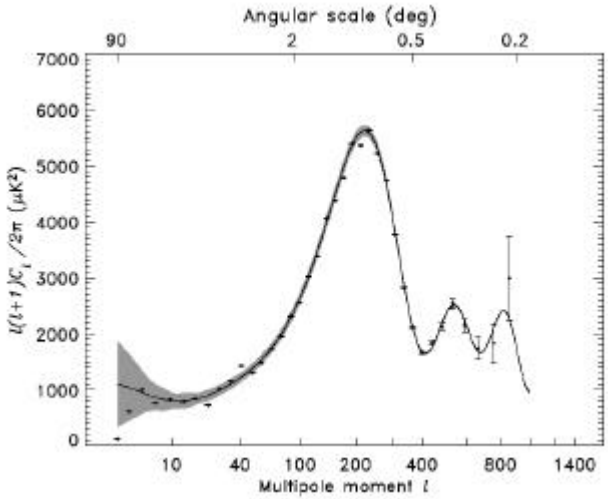
- CMB results 2000- 2003 (pre WMAP)



Figure

Bond et al. 2003

- WMAP data 2003



Figure

Hinshaw et al. 2003

.. with one exception; improvements in polarization measurements will come from increases in number of detectors, not from improvements in detector sensitivity

These experiments are close to or have reached their limits

- Detecting each new power spectrum requires roughly 1 order of magnitude sensitivity improvement

- New experiments are 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)

QUaD (QUEST at DASI)

- Experiment that was commissioned at the South Pole in the Austral summer 2004/2005
- Specifically designed to measure both E and B mode polarization

Stanford (US PI Institution)
Focal plane design and assembly
Warm and cold electronics
Integration and testing

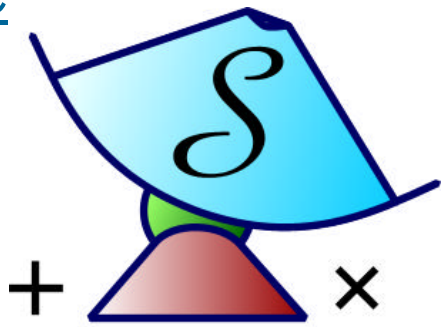
U. Chicago
Telescope mount and software

Maynooth College, Ireland
Optics design and testing

University of Edinburgh, UK
Software and science definition

Cardiff (UK PI Institution)
Telescope design and assembly
Cryostat and fridge
Filters and optical components

JPL/Caltech/IPAC
Bolometers
Cold JFETs
Software

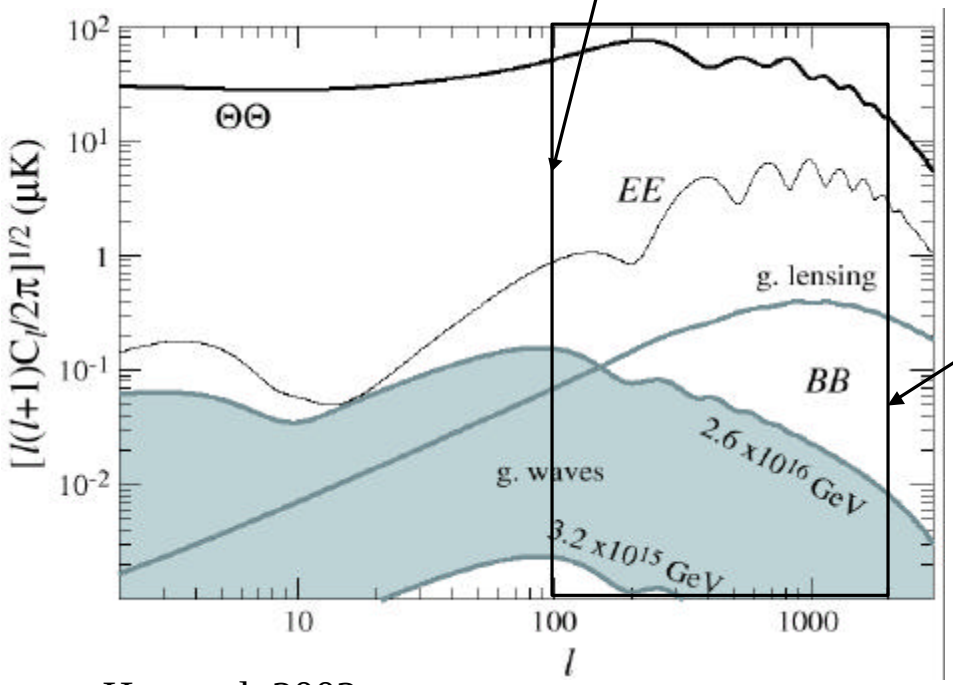


QUaD

QUaD Science Goals

- To map CMB polarization on angular scales > 4′
- Optimized to map *E*-modes, and *B*-modes produced by gravitational lensing
- Detect or improve limits on primordial *B*-modes

The largest scales are determined by scan strategy and noise stability



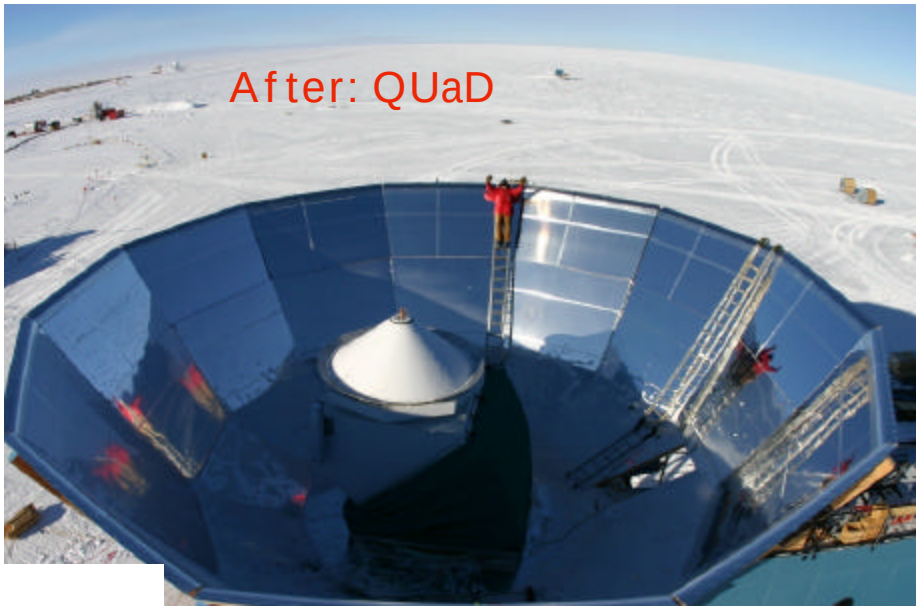
The smallest scales are determined by the angular resolution of the experiment

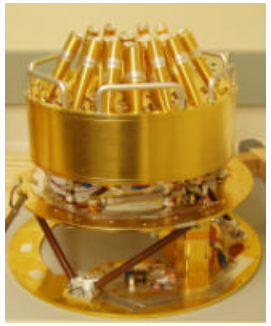
l-space coverage of QUaD

Hu et al. 2002

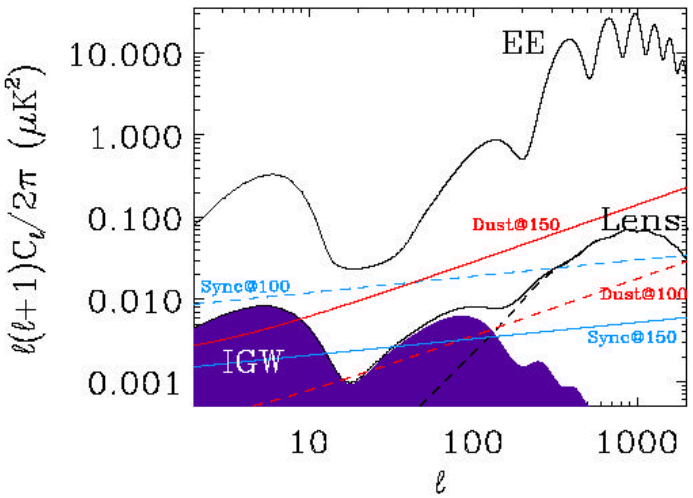
The QUaD Experiment

- Bolometric array receiver mounted on a 2.6m telescope
- Telescope is located on the DASI mount at the South Pole





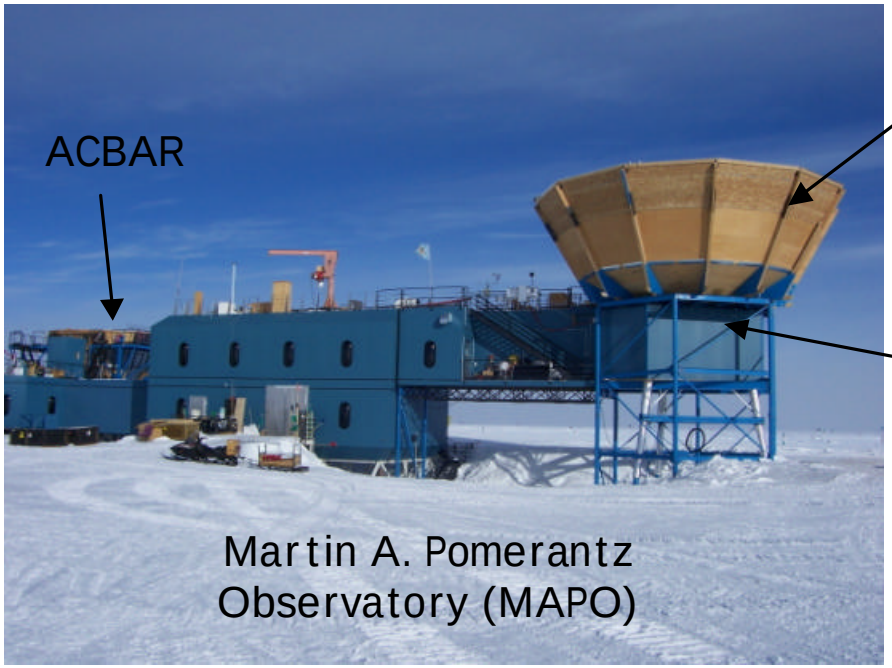
QUaD Camera



Freq (GHz)	Beam (arcmin)	No. feeds
100	6.3	12 (9)
150	4.2	19 (17)

Why the South Pole?

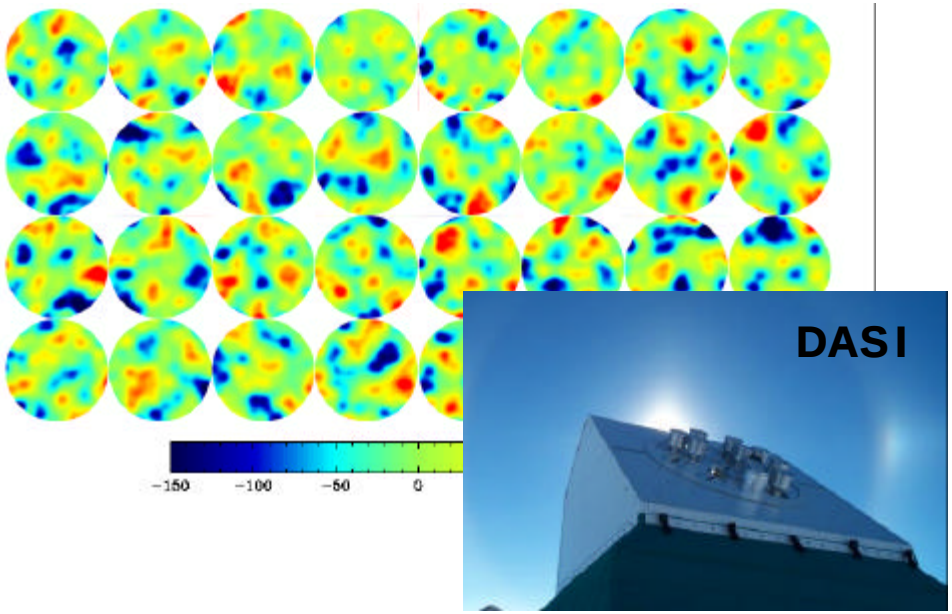
- Very low precipitable water vapor
- Very stable environment (1 day and 1 night)
- Ability to view the same area of sky continuously
- Existing facilities (DASI mount)
- Excellent infrastructure (machine shops, liquid cryogens, etc.)

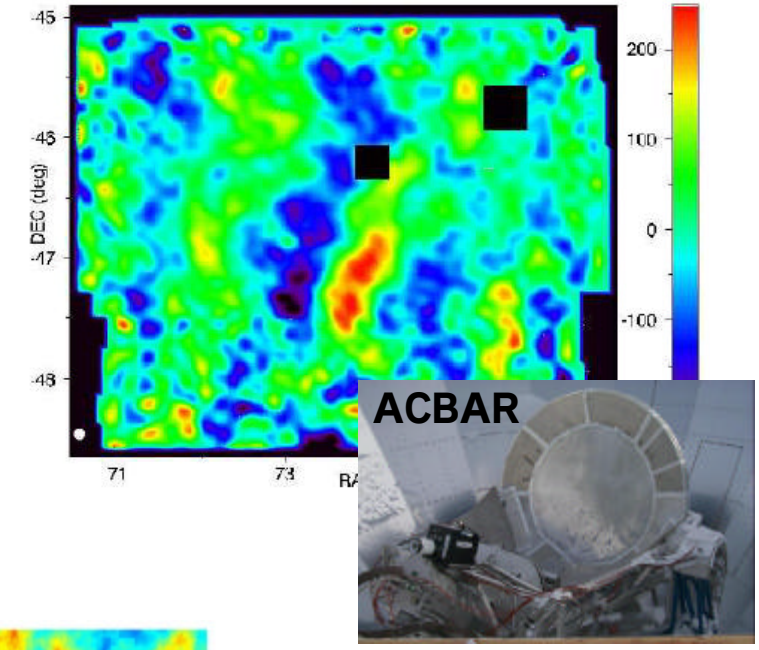


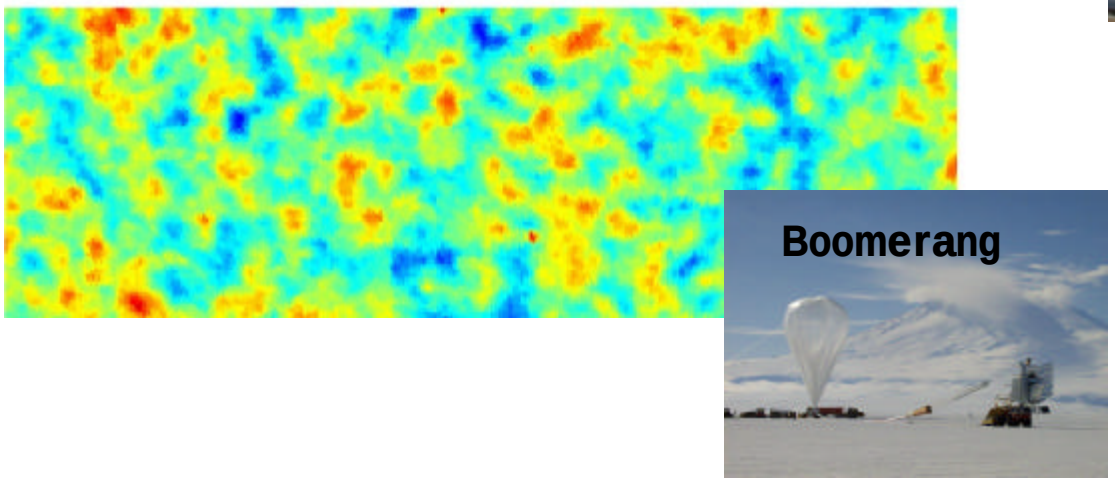
QUaD ground shield

Heated work space behind the telescope

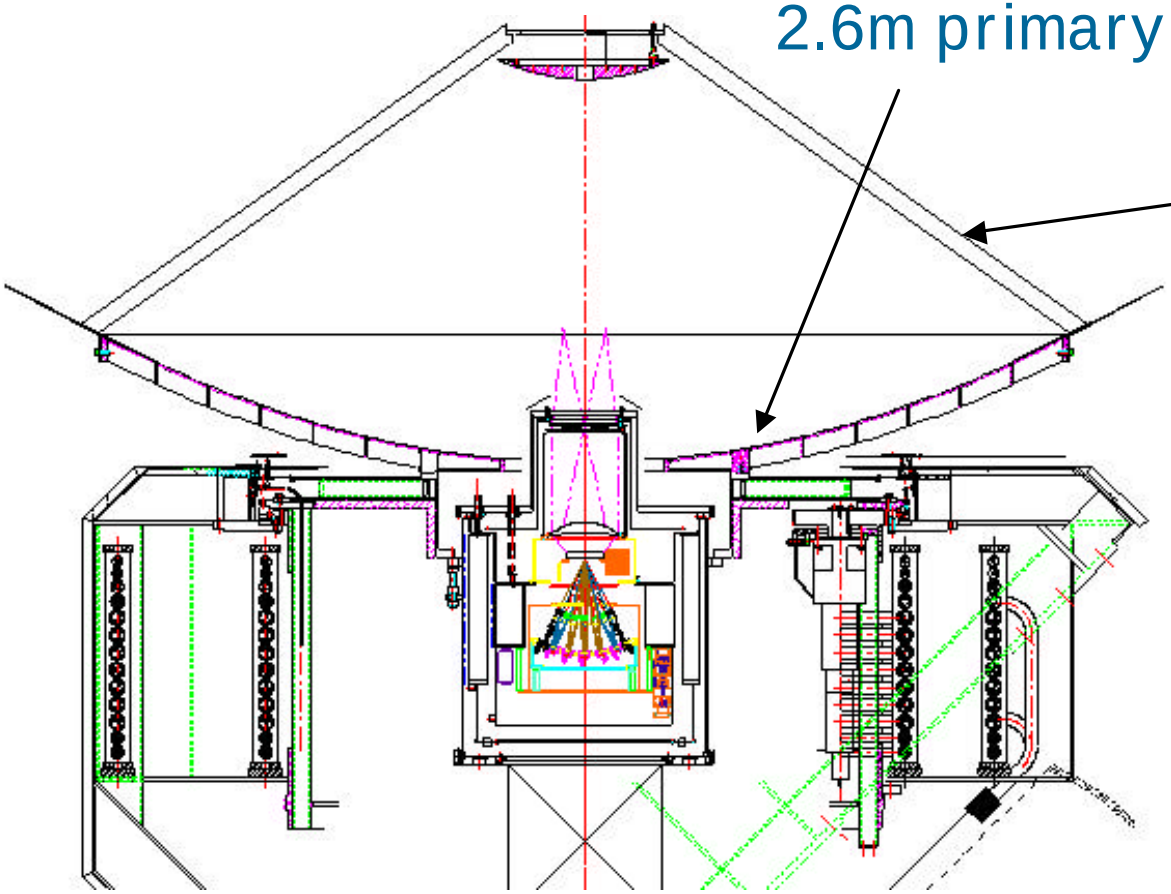
Antarctica has been used to make a lot of maps of the microwave sky







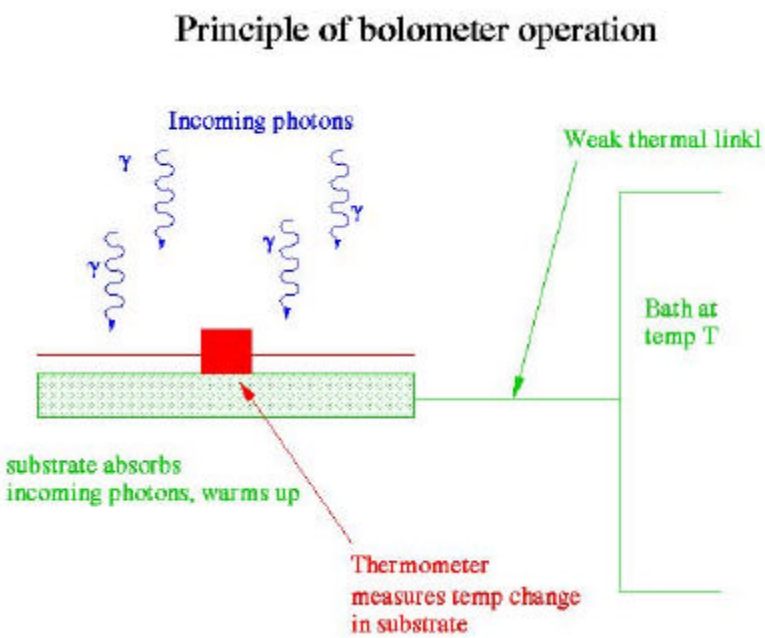
The QUaD Receiver and CassegrainTelescope

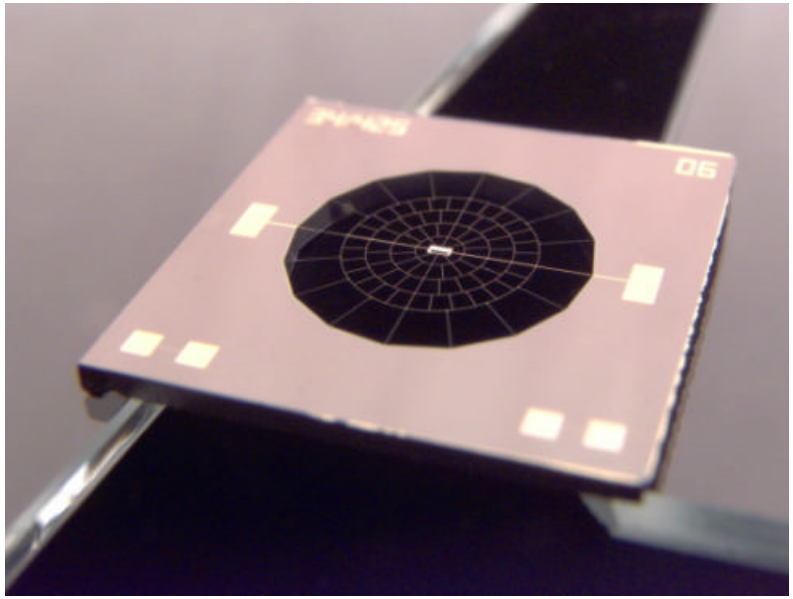


On-axis design minimizes polarization systematics

The QUaD detectors

- We use bolometers because of their high instantaneous sensitivity
- Bolometers can be operated close to the photon noise limit – sensitivity determined primarily by the photon background





Boomerang detector

Photo courtesy J. Bock, JPL

How do you make a bolometer polarization sensitive?

- Make the substrate polarization sensitive
- The linear absorbing grid detects only one direction of polarization

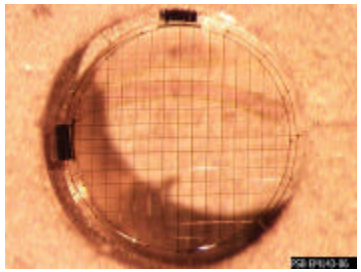
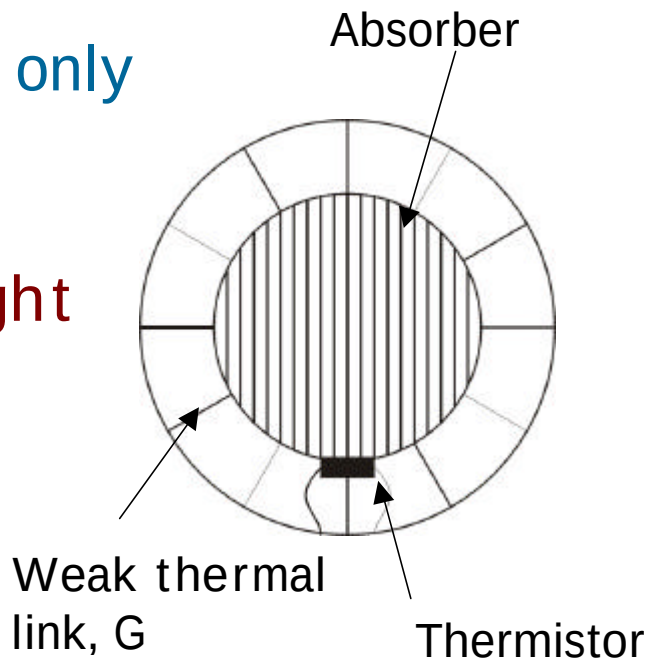


Photo courtesy J. Bock,JPL

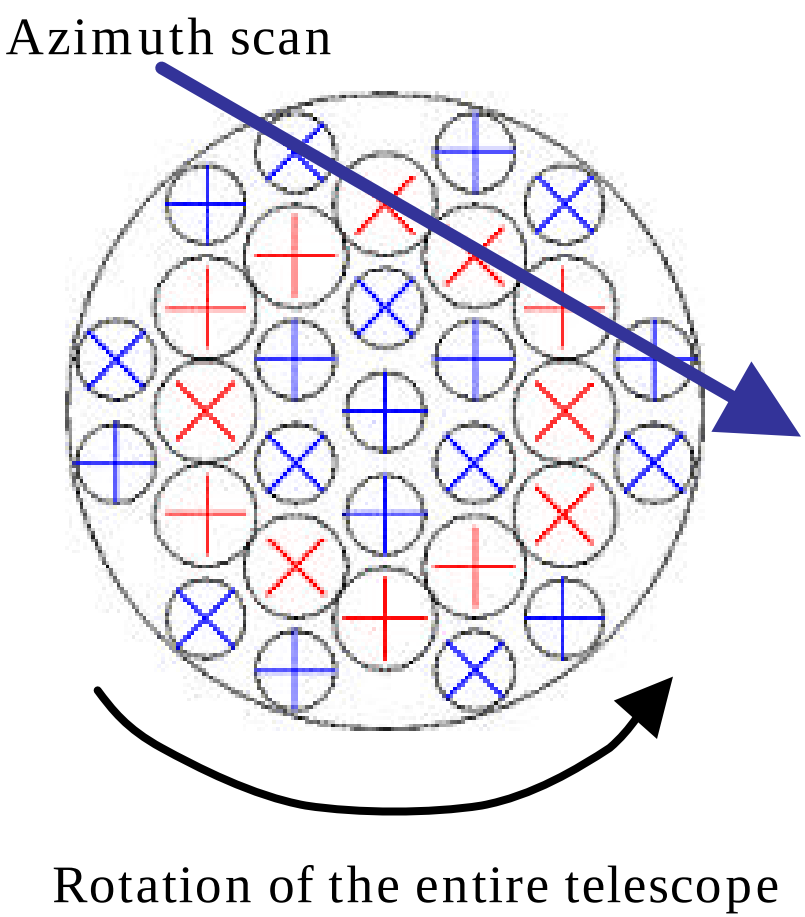
- Put two of them at right angles and you detect both directions!



- Difference the two signals to get Q or U depending on the orientation of the detector pair

Polarization-sensitive bolometers (PSBs) were developed for Planck and flown on Boomerang (B2K)

Stokes Sampling



- Difference 2 PSBs to get Q or U, depending on orientation
- Rotate telescope and instrument about the optic axis (allowed rotation is +/- 60 degrees) to change the orientation of instrumental polarization with respect to sky.
- Scan in azimuth, reacquire source, rescan.

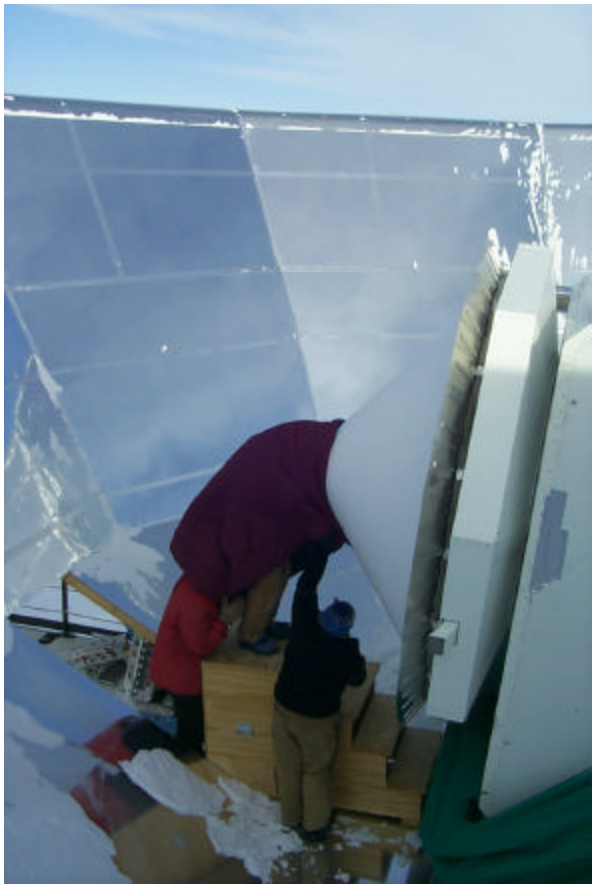
QUaD installation and commissioning

- The QUaD receiver was shipped to Pole in October 2004 with 84% of the detectors installed
- Team deployed from mid-Nov 2004 to mid-Feb 2005

This involves taking one plane from Christchurch, NZ, to McMurdo station…

..and a second, ski-equipped plane to the Pole

Getting to the telescope is 15-min trek (including crossing the runway)



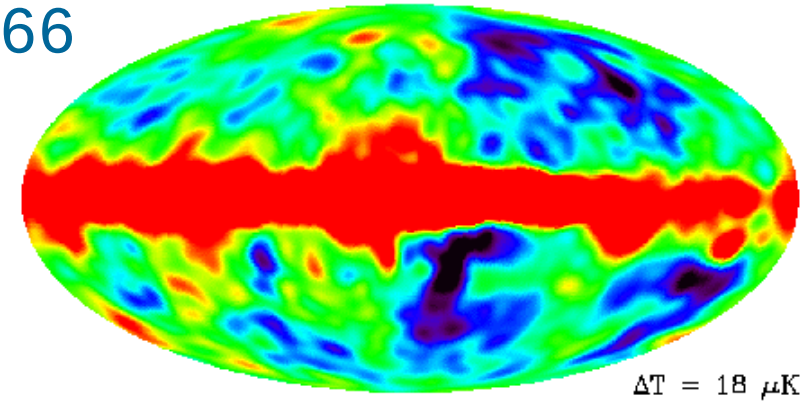
And if you have to work outside, you're grateful for some extra protection

Trading sky coverage for sensitivity

- For a noiseless experiment, the sensitivity to a given multipole is:

$$\frac{\Delta C_l}{C_l} \approx \left[\frac{2}{(2l+1)}\right]^{1/2} \frac{1}{\sqrt{f_{sky}}}$$

  where f_{sky} is the fractional sky coverage of the experiment
- If fsky = 1 an experiment is *cosmic variance* limited
- In practice maximum f_{sky} = 0.66 due to foregrounds
- An experiment with fsky < 0.66 is *sample variance* limited



Sometimes being sample variance limited is good

- A *real* experiment has an approximate sensitivity of:

$$\frac{\Delta C_l}{C_l} \approx \left[\frac{2}{(2l+1)}\right]^{1/2}\left[1+\frac{\left(\Delta T q_{\mathrm{pix}}\right)^2}{C_l}\right]\frac{1}{\sqrt{f_{sky}}}$$

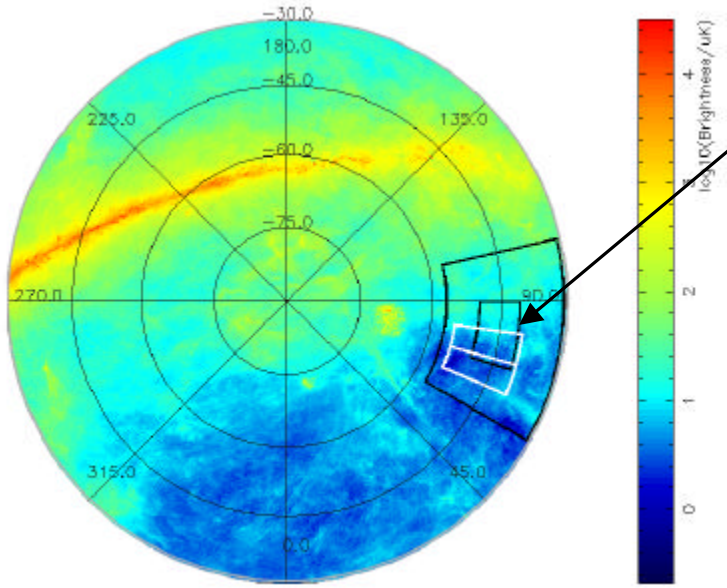
Pixel noise term

- ΔT – sensitivity/pixel/Stokes parameter
- q_{pix} – pixel size
- There is a tradeoff between pixel noise and sample variance
- Optimum balance: $\left(\Delta T q_{\mathrm{pix}}\right)^2 / C_l = 1$

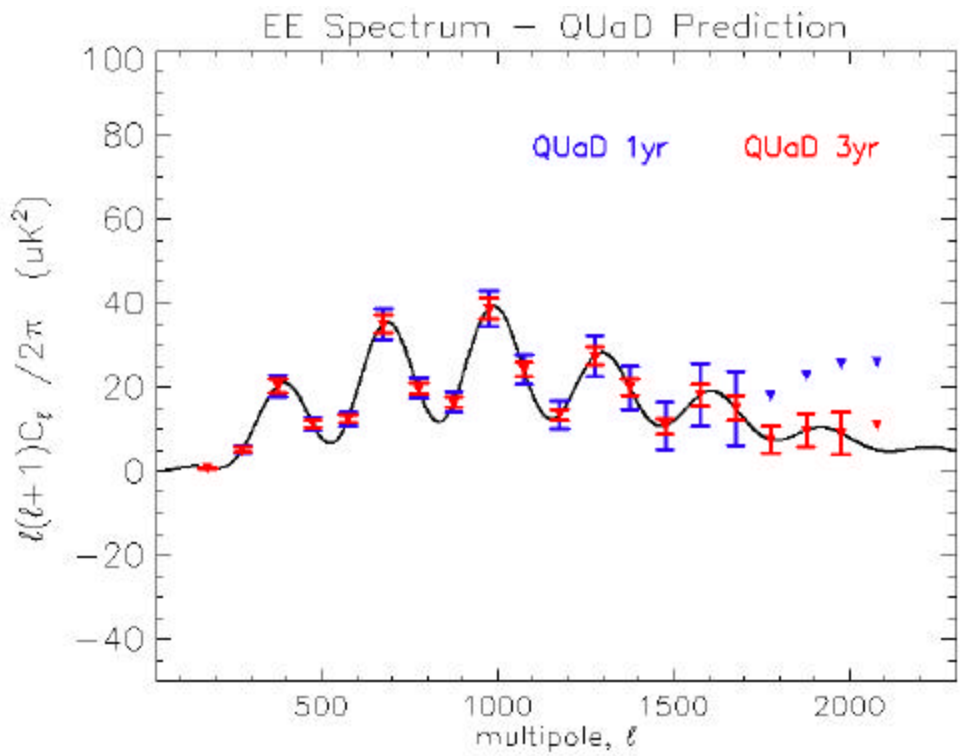
QUaD is optimized to measure the CMB polarization power spectra

WMAP optimized to measure T

Observation Plans and expected results



Season I: map a region of extremely low foreground sky



QUaD will be the first experiment to map the E mode power spectrum in detail

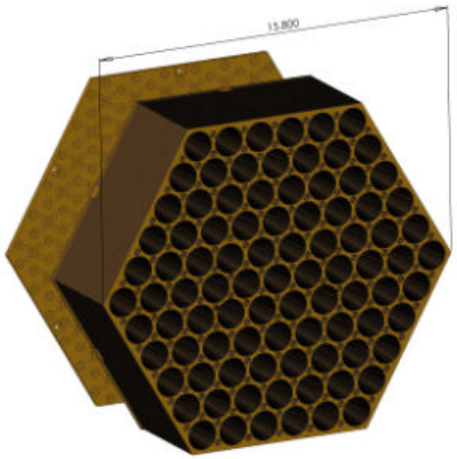
More sensitivity required to detect B-modes

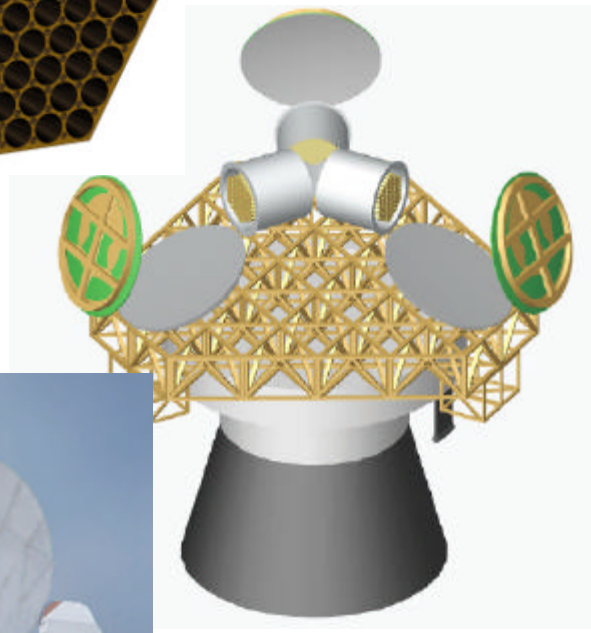
The future -- QUIET

- Berkeley, Caltech, Chicago, Columbia, JPL, NASA Goddard, Oxford, Princeton, **Stanford/KIPAC**

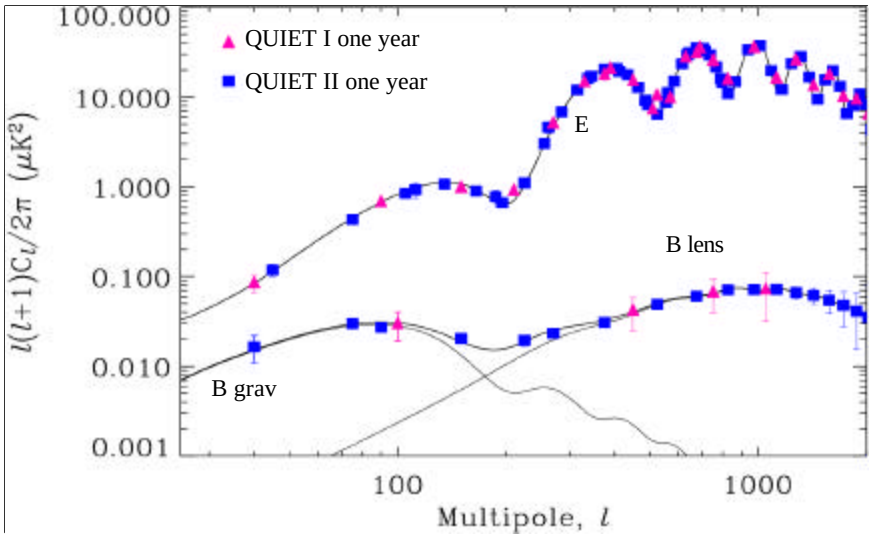
- Stage I (2006)
  - One 1.4m telescope (built by Stanford)
  - 91-element 100 GHz array

- Stage II
  - Three 2m telescopes
    - 2 x 91-element 40 GHz array
    - 2 x 397 element 100 GHz array
  - One 7m telescope
    - 1 x 91-element 40 GHz array
    - 1 x 397 element 100 GHz array





The Promise of QUIET



- QUIET has strong synergy with QUaD
  - Observe same sky at 100 GHz with *totally different instrument*
  - Combined experiment has 40-150 GHz coverage which is important for foreground removal

- QUIET I
  - 91 element 100 GHz receiver
  - 1 telescope
- QUIET II
  - Full instrument
  - 40, 100 GHz on 3 x 2m telescopes and one 7m telescope
- Estimated sensitivies include best estimates of foregrounds

Conclusions

- The long-term promise of CMB polarization is the possibility of a direct measurement of the inflaton potential, allowing us to select between competing models
- The next 20 years of CMB research will be hard, but potentially even more exciting than the last!
- Look for first QUaD results coming soon.....