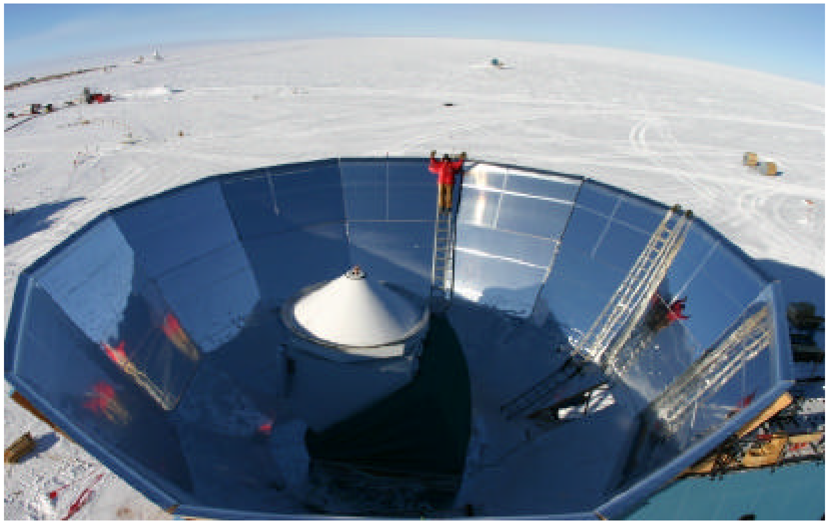
# The QUaD CMB Polarization Experiment

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# 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 the QUaD 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 $10^5$

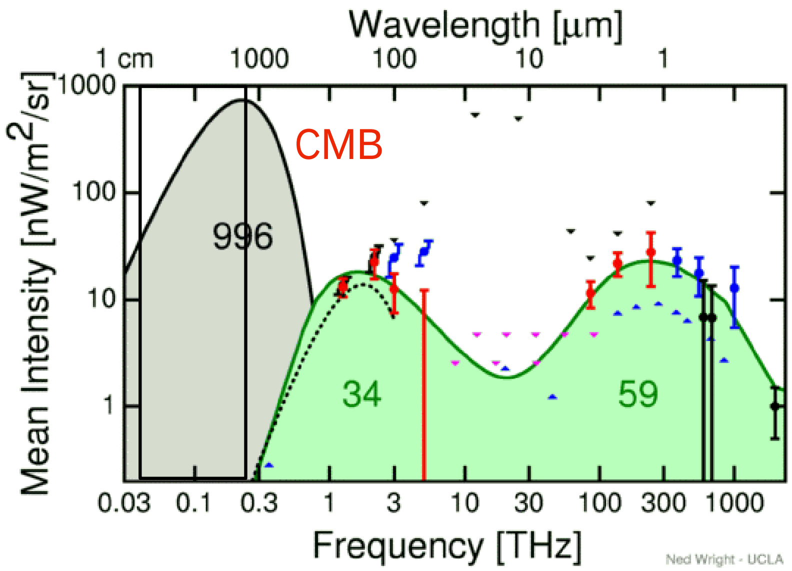
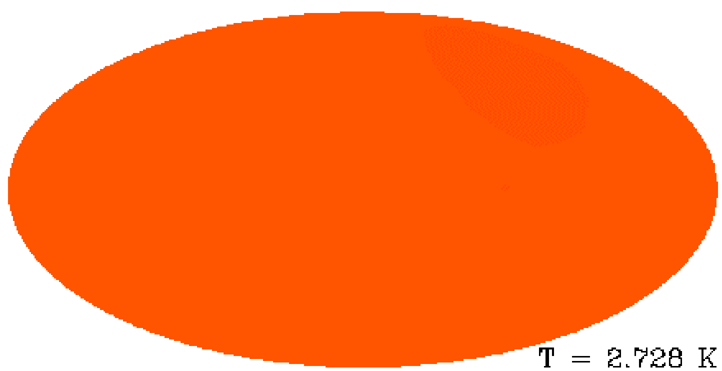
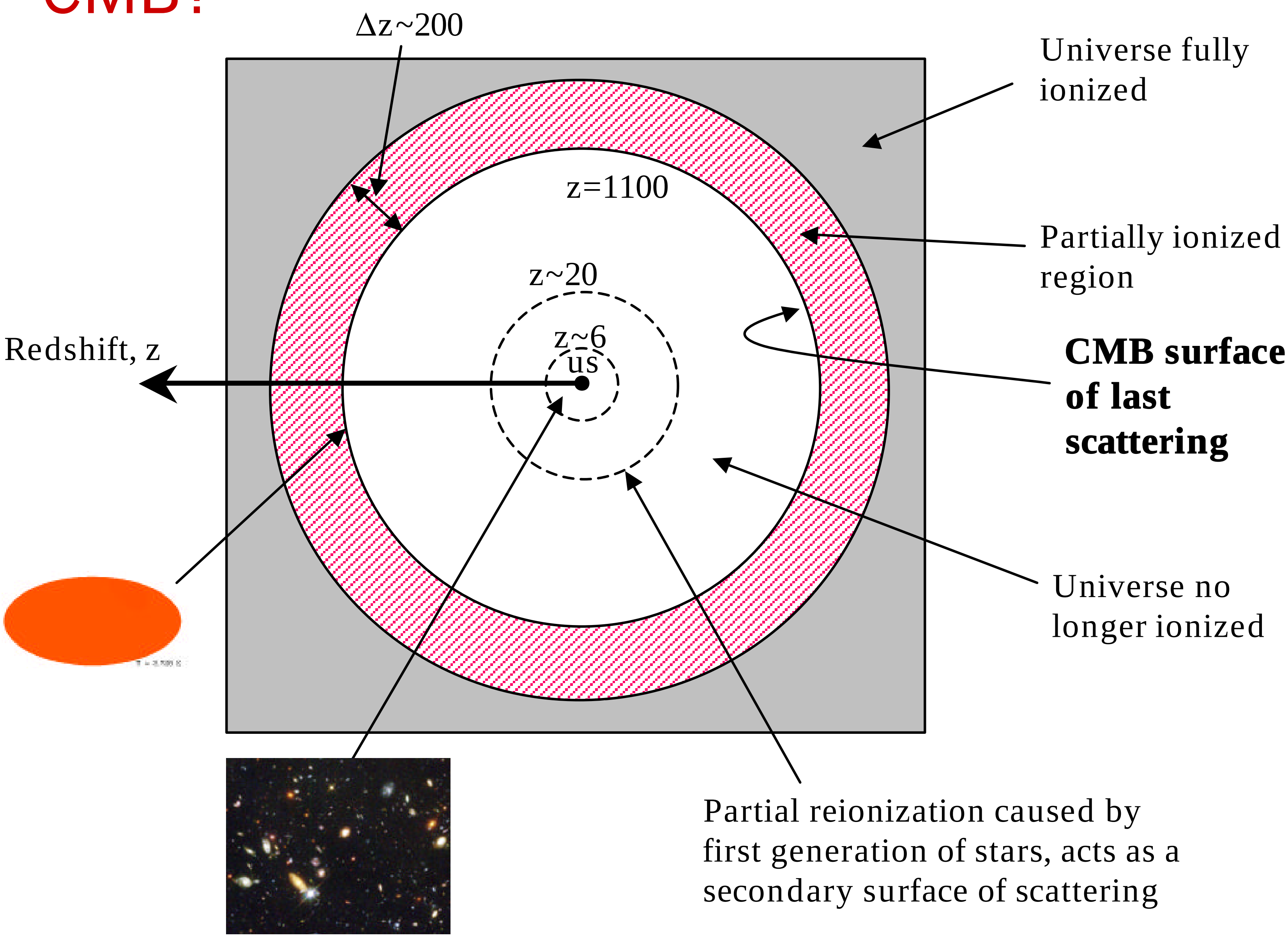



Figure by Ned Wright, UCLA

COBE map of the sky at 33 GHz

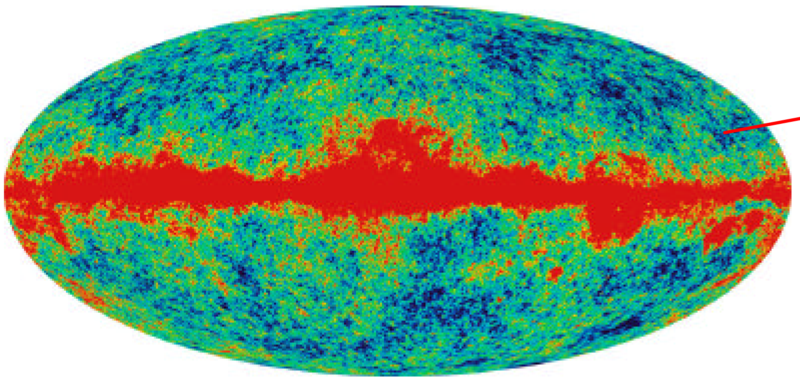


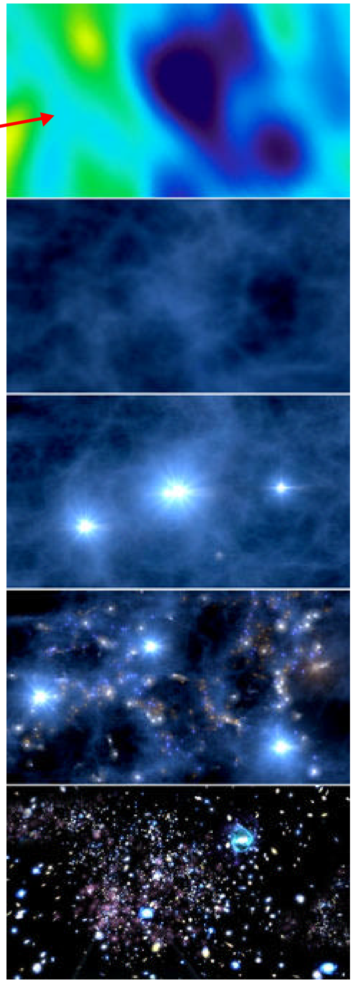
# What are we seeing when we look at the CMB?



# CMB temperature is not completely uniform

WMAP satellite 2003

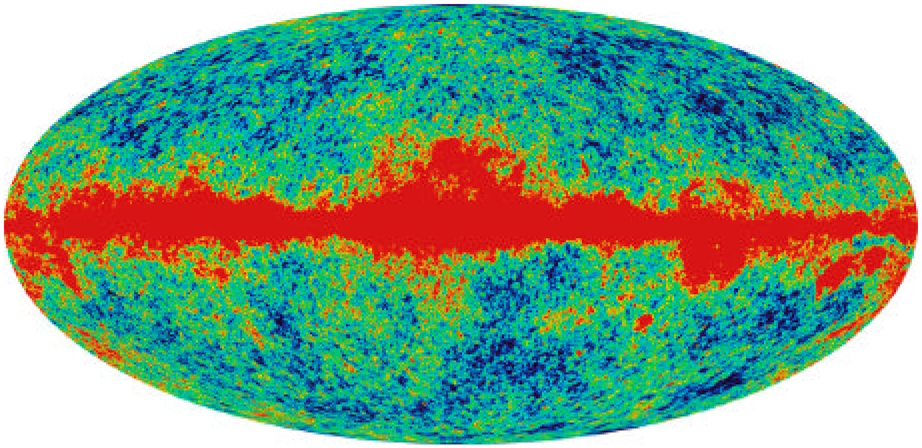




Picture credit: WMAP team

- 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

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

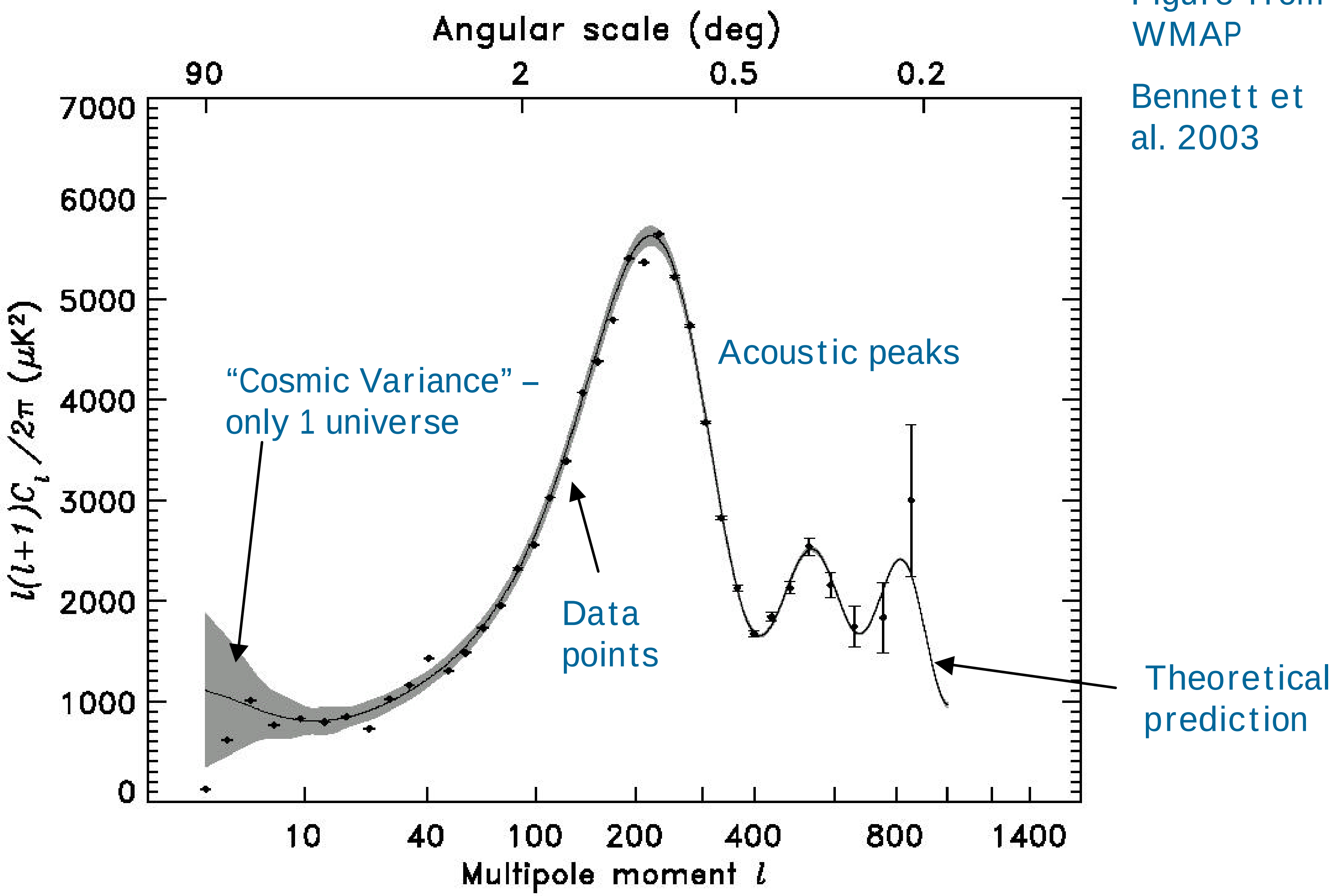
- We can average over *m* values because the universe has no orientation

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

# Theoretical predictions match experiment extremely well

Figure from WMAP

Bennett et al. 2003



# What does this plot mean?

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

Effects of gravitational collapse and photon/baryon interactions

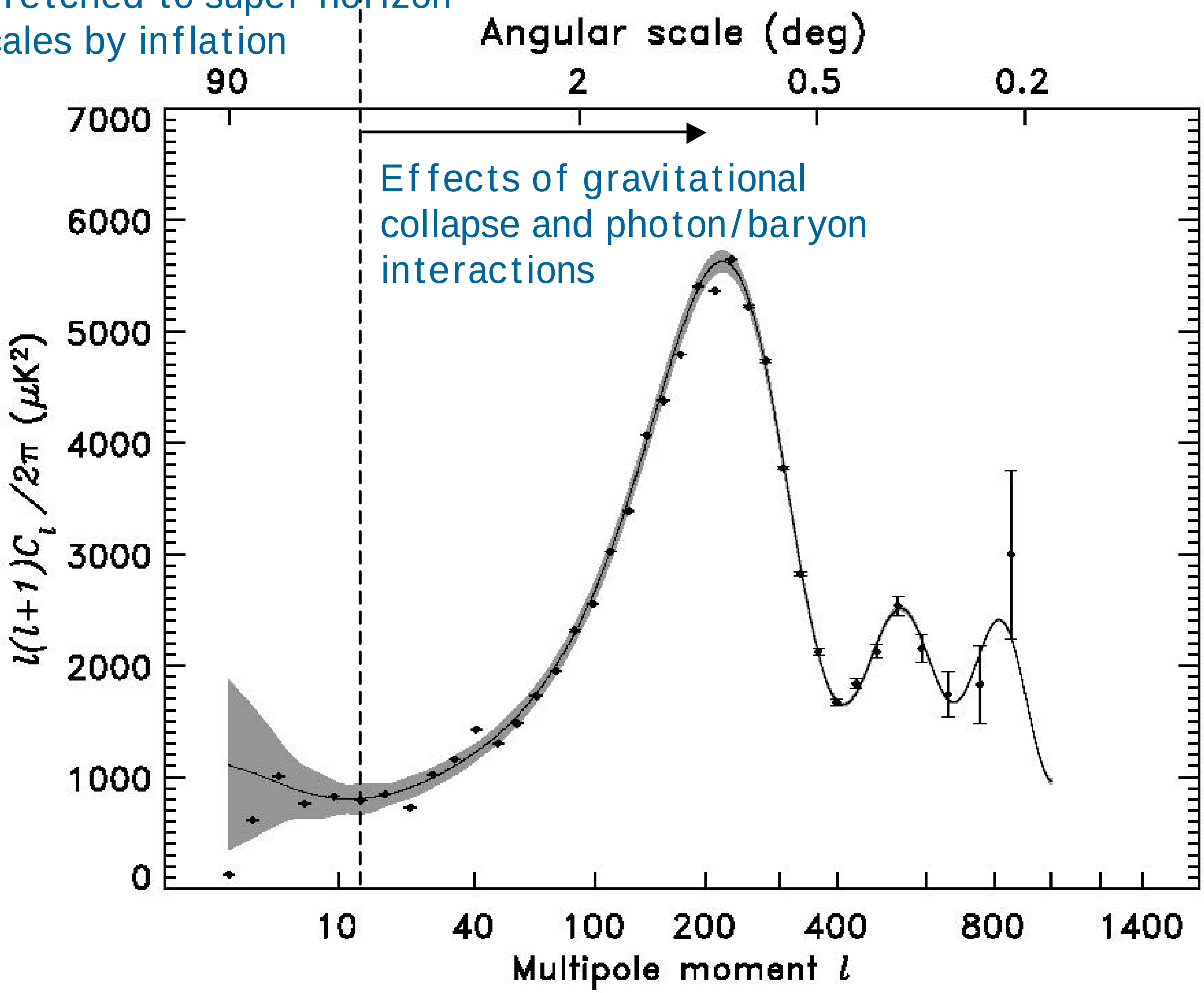
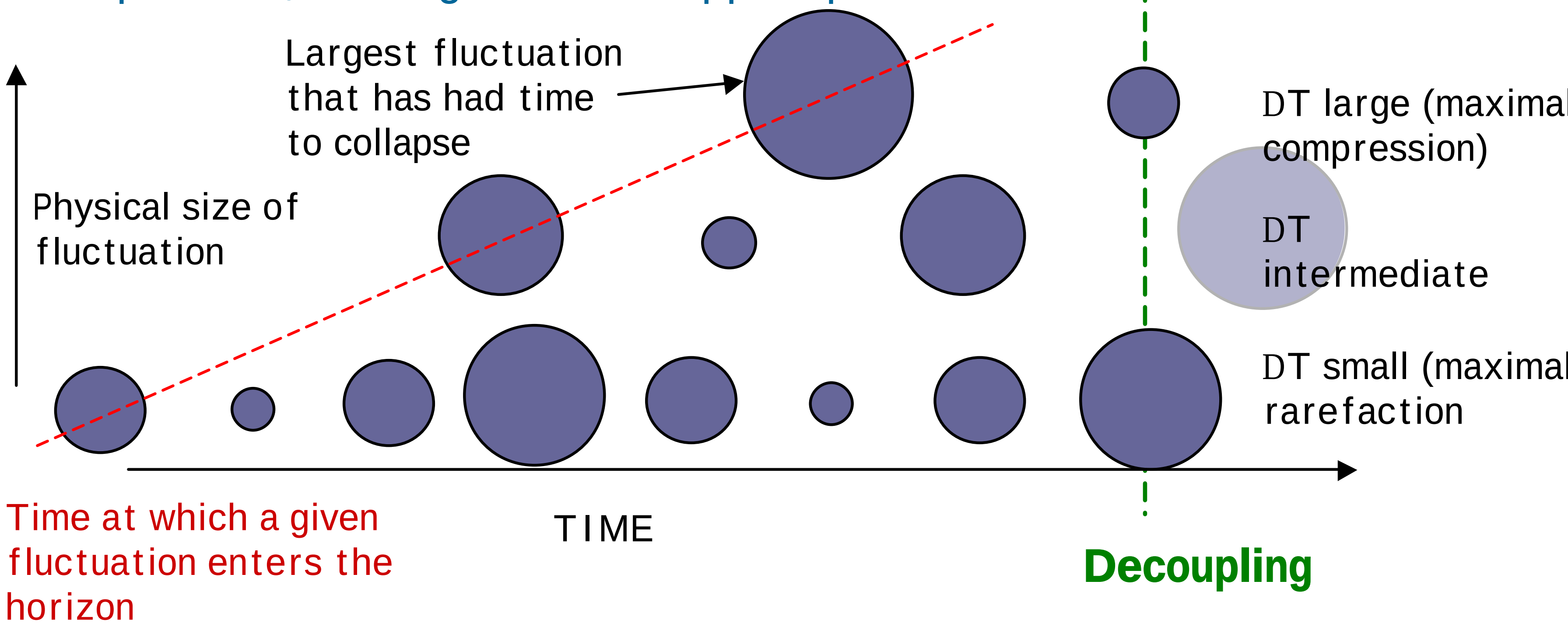



Figure from WMAP

Bennett et al. 2003

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

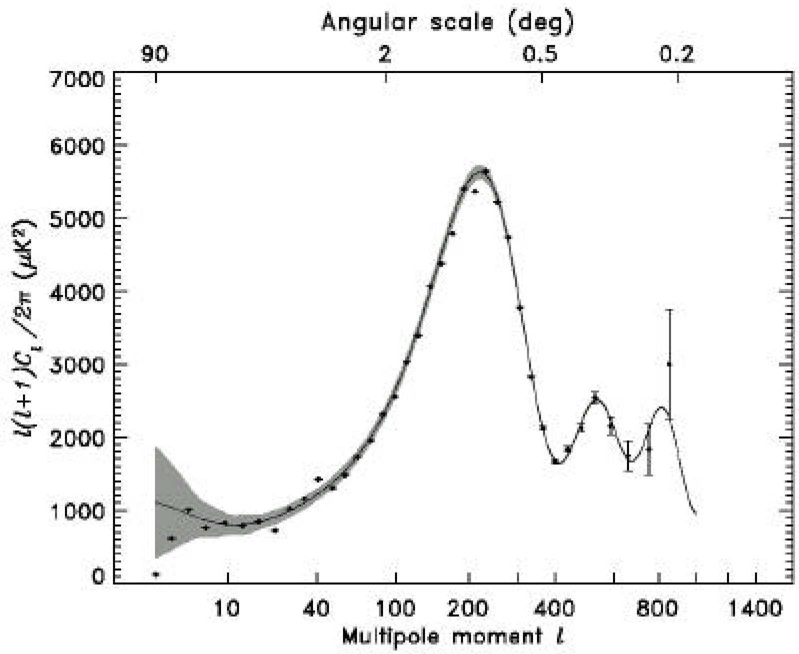



Figure from WMAP

Bennett et al. 2003

# “Precision Cosmology”

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

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

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

**Parameters that can constrain inflationary models**

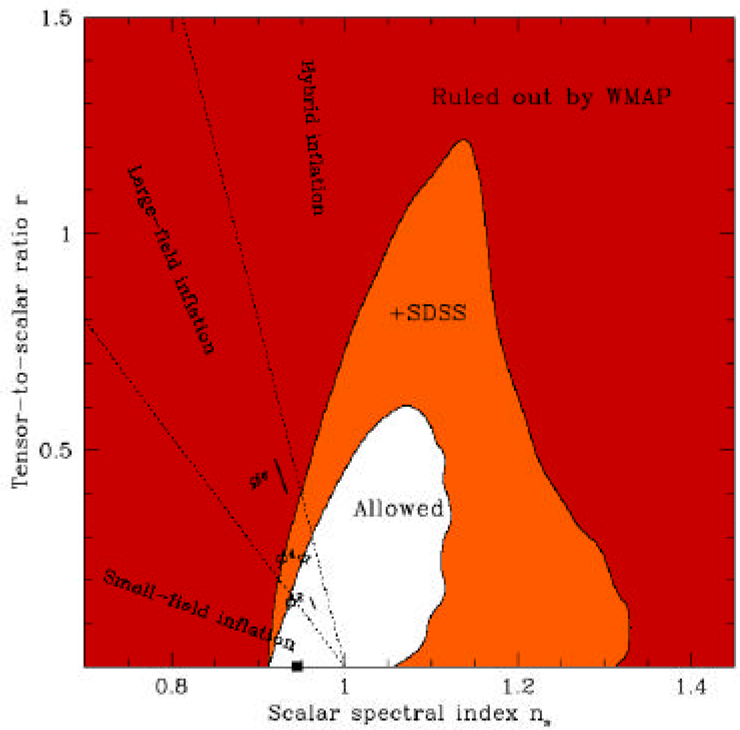
CMB + large scale structure:
Spergel et al. 2004

# Parameterizing inflation

- CMB temperature anisotropy measurements confirm two predictions of inflation
  - A flat universe
  - A close to scale-invariant spectrum of density fluctuations
- However the allowed parameter space remains large

Tegmark et al. (2003)

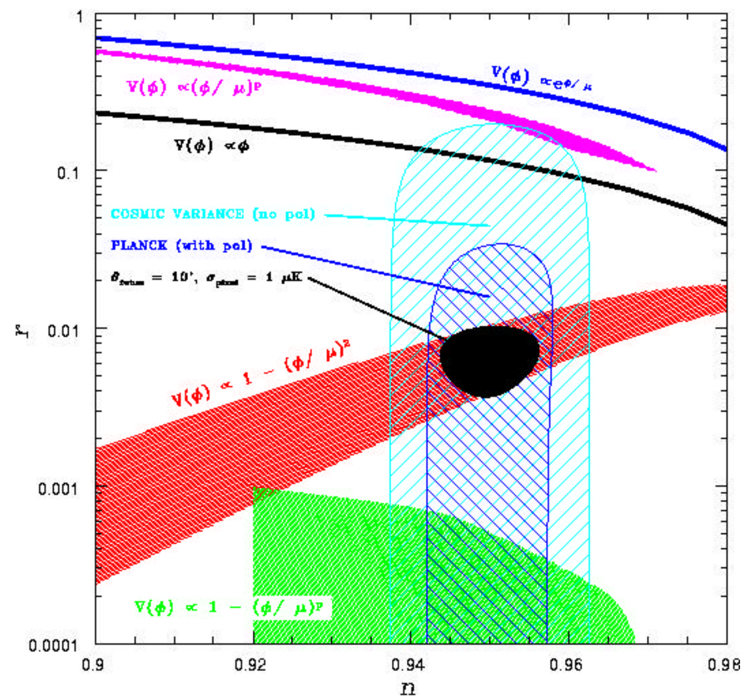
Tensor to scalar ratio




Scalar spectral index

Kinney et al. (2003)

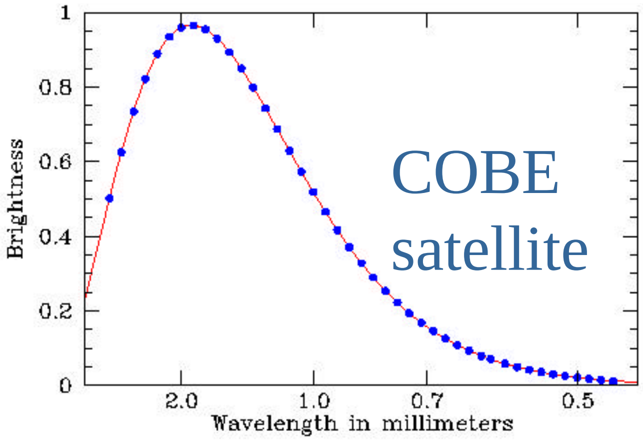
Tensor to scalar ratio



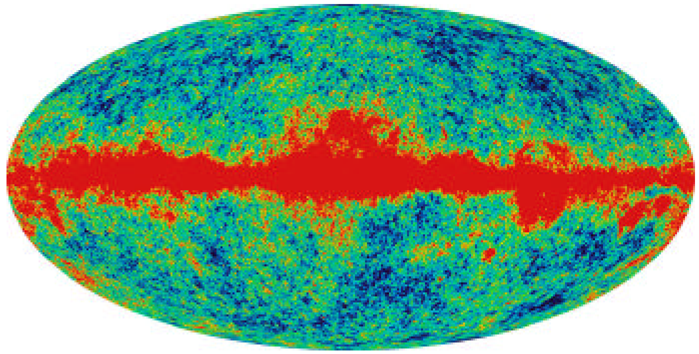

Scalar spectral index

# Polarization is the third measurable property of the CMB

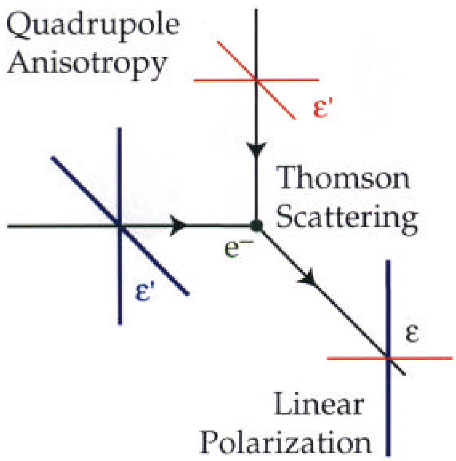
- Frequency spectrum




- Spatial temperature variations:



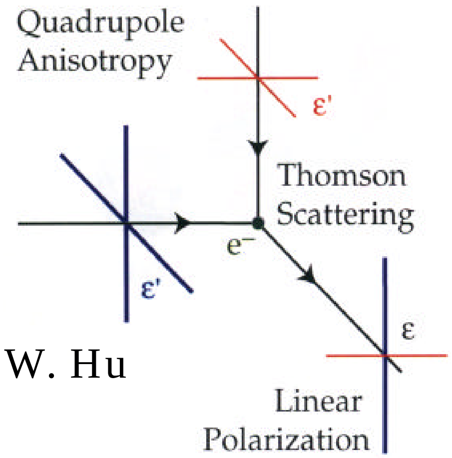
WMAP satellite 2003




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

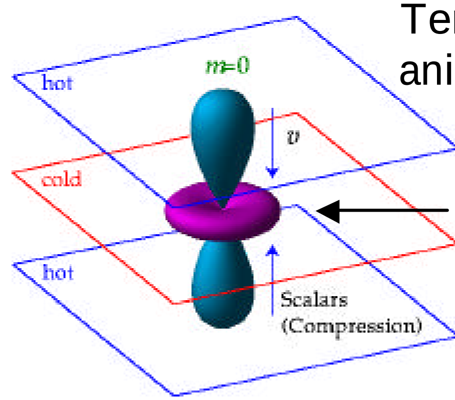
# Origin of CMB polarization anisotropy




Picture by W. Hu

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

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



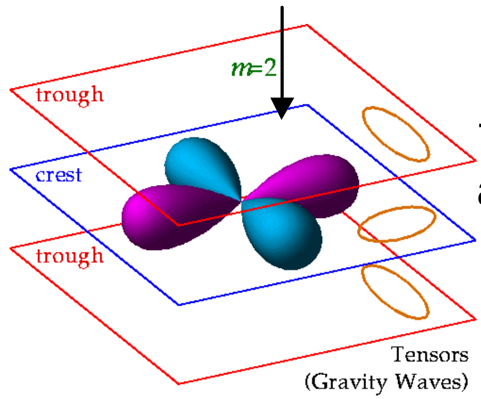

Temperature anisotropy

Quadrupole viewed in this direction

Picture by W. Hu

  - Gravitational redshifts associated with gravitational waves
  - TENSOR MODES

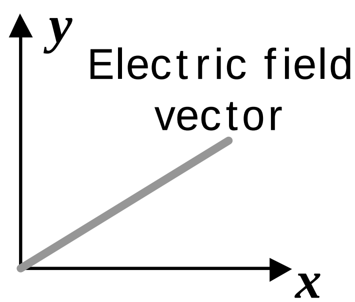
Quadrupole viewed in this direction




Temperature anisotropy

Picture by W. Hu

# Relating polarization to observables




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

$Q > 0$

$U = 0$

$Q < 0$

$U = 0$

$Q = 0$

$U > 0$

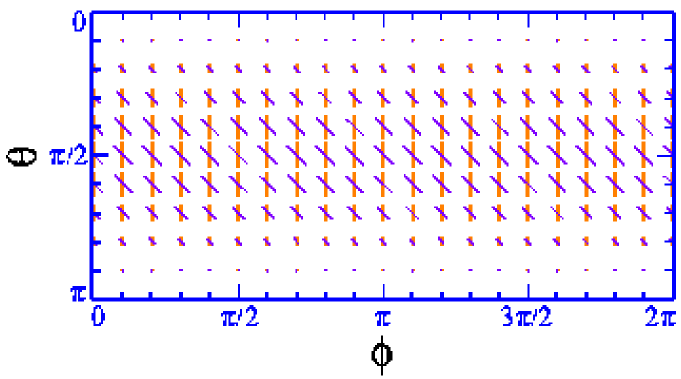
$Q = 0$

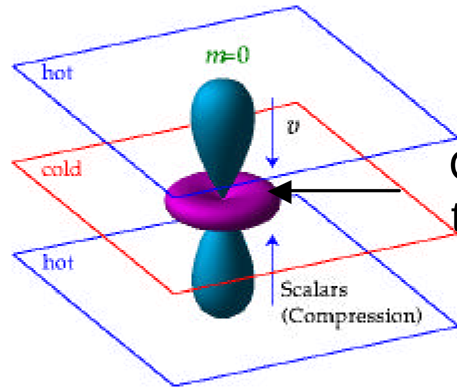
$U < 0$

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

# Different sources of quadrupoles generate different modes

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

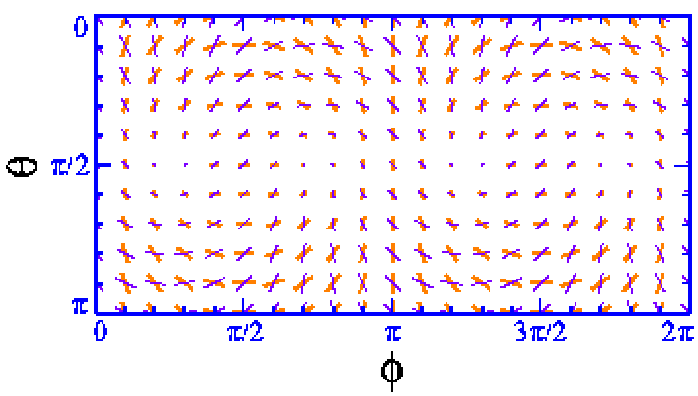


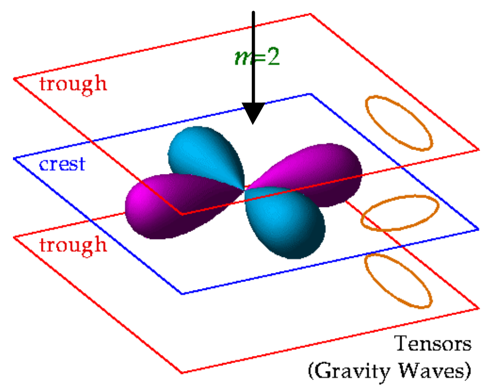

Quadrupole viewed in this direction

*Pictures by Wayne Hu*

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

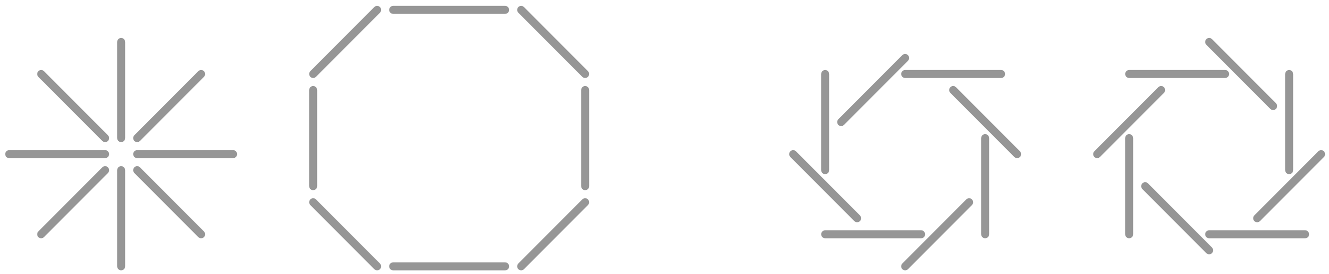



Quadrupole viewed in this direction



# Q and U are coordinate dependent but…

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



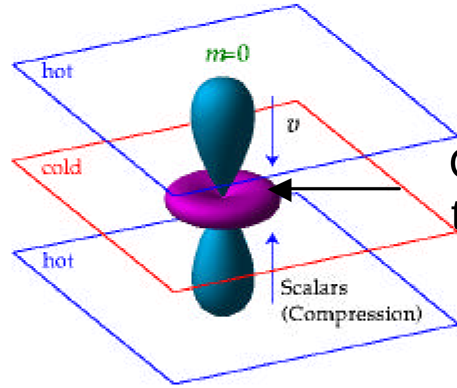
E modes B modes

- These modes retain their character on rotation of the local coordinate system
- E-modes are invariant under a parity change, B modes are not

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

*Pictures by Wayne Hu*

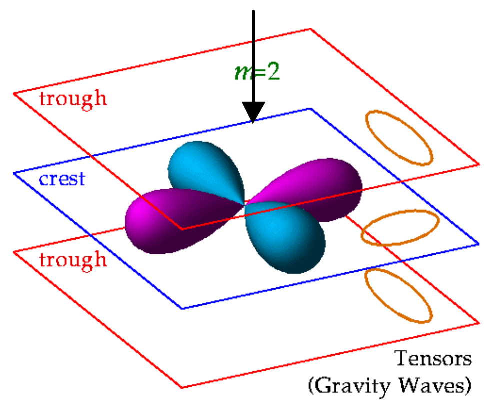
- Scalar modes (density fluctuations) generate *E modes only*




Quadrupole viewed in this direction

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

Quadrupole viewed in this direction

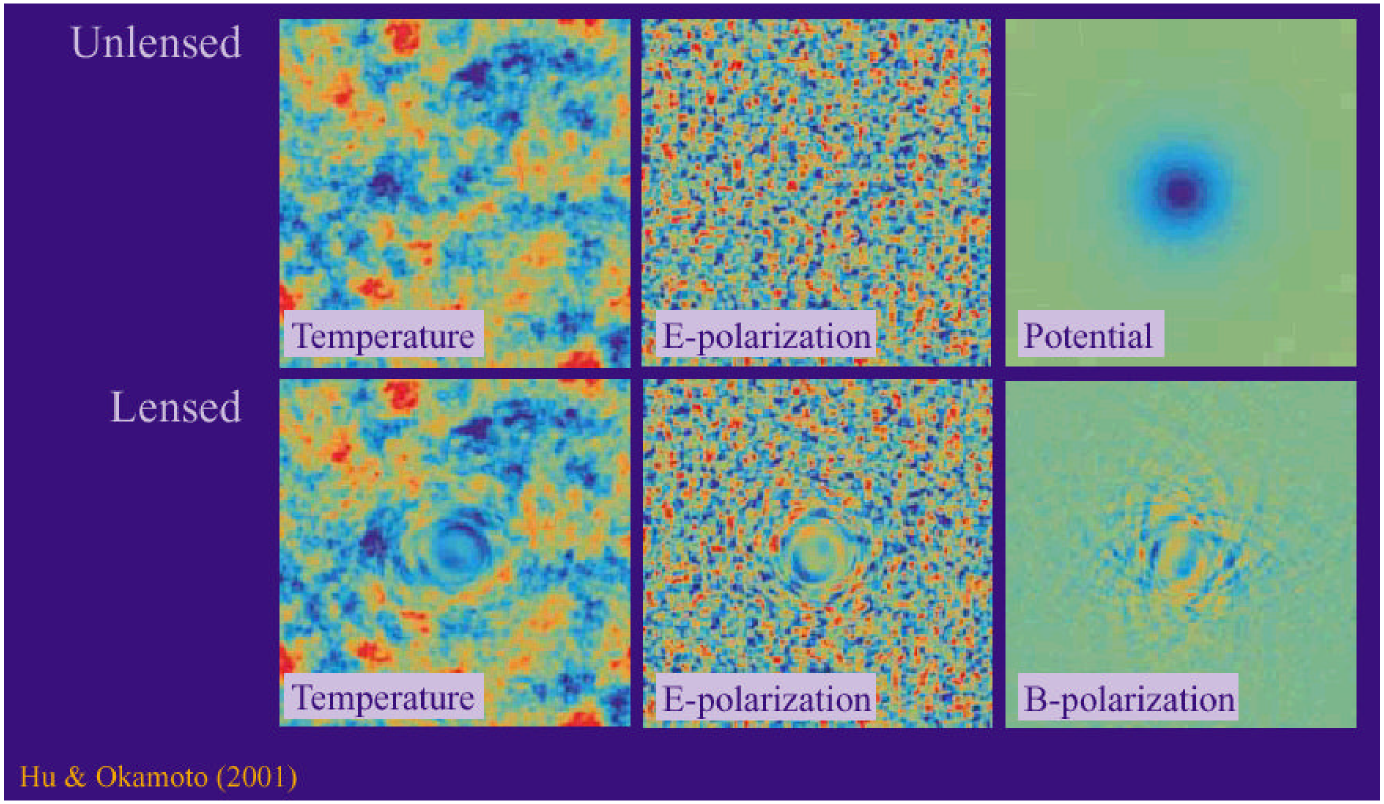



***Only polarization measurements have the potential to uniquely separate scalar and tensor modes***

# 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

# 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

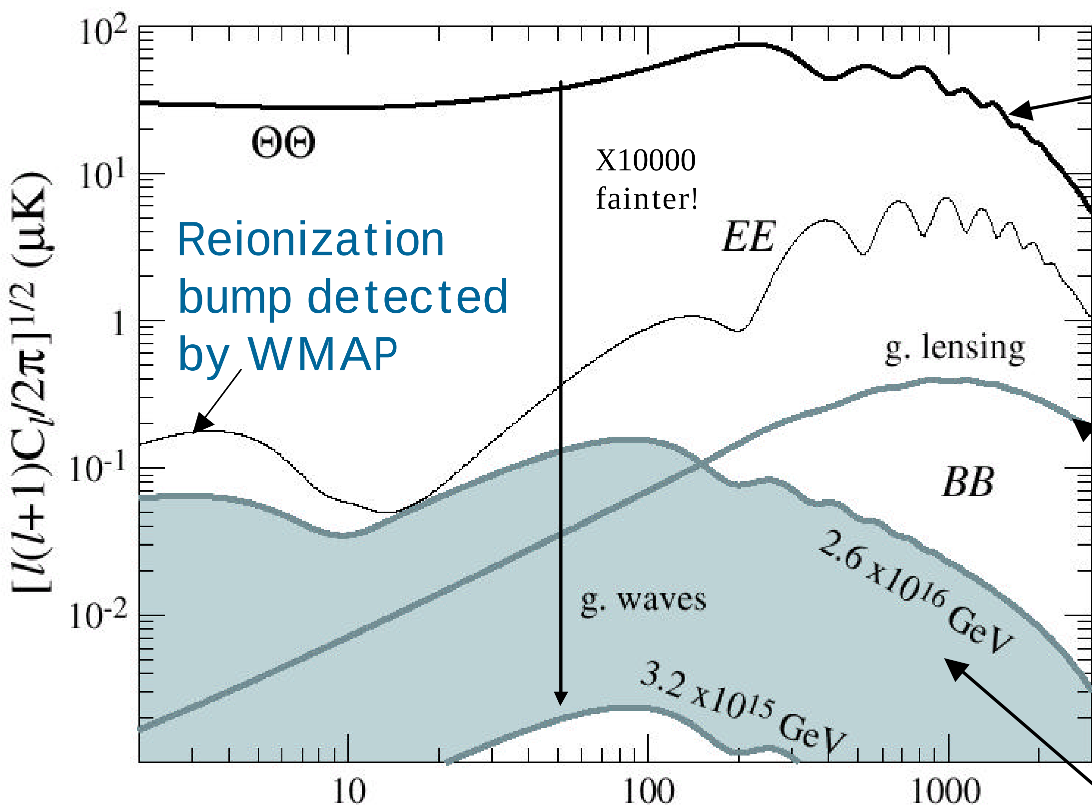
# Lensing of the CMB measures *all* structure back to the surface of last scattering

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

| Experiment | $m_\nu$ (eV) | $w_x$ | ln $P_\Psi$ | $n_S$ | $n'_S$ |
|---|---|---|---|---|---|
| | Neutrino mass | Dark energy eqn. of state parameter | | Spectral index and rate of change of index | |
| 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

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




Temperature spectrum mapped by WMAP

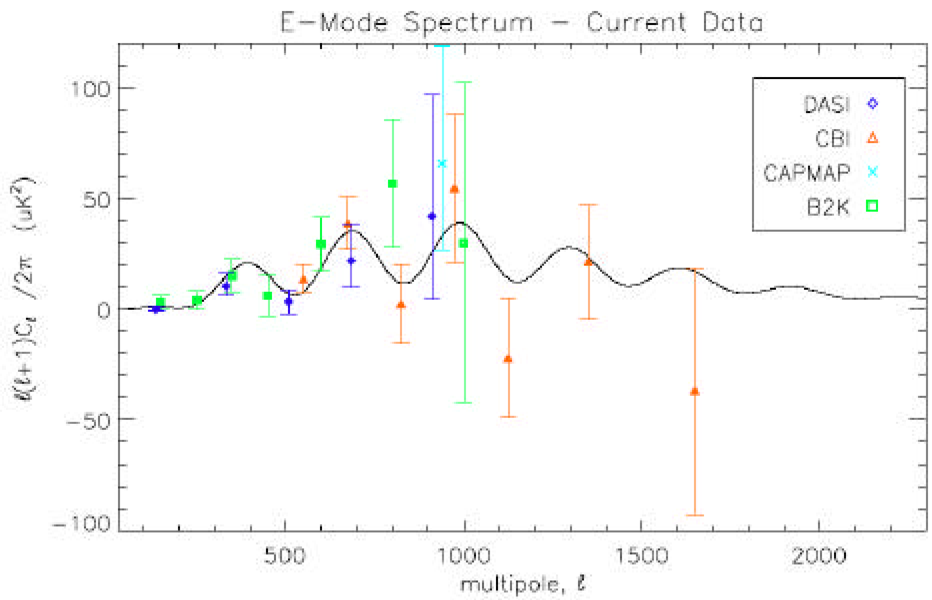
Gravitationally lensed E-modes probe large scale structure formation

Projected effect of a gravitational wave background

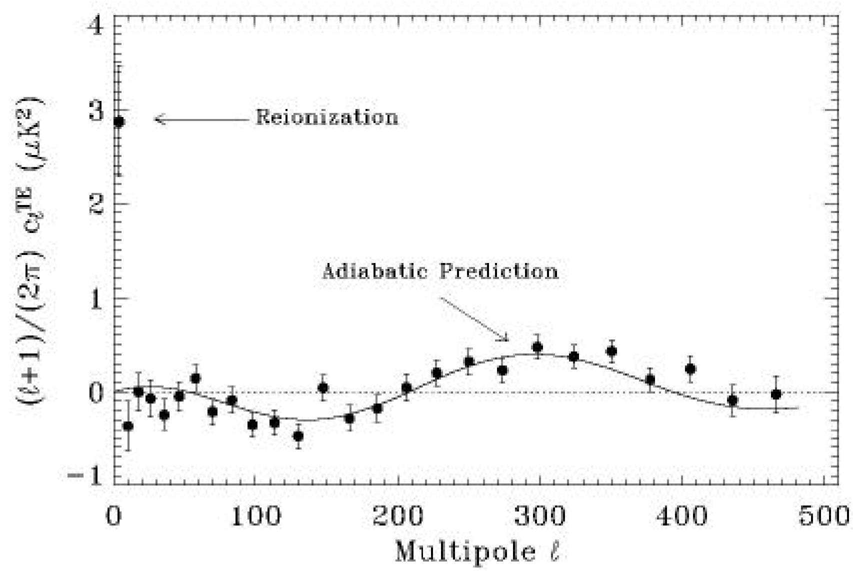
*Picture credit, Wayne Hu*

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

# Status of Polarization Measurements



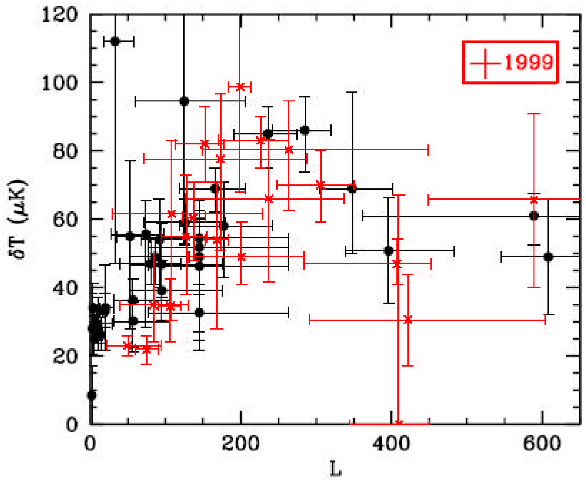

- To date only *E* modes have been detected




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

# Not dissimilar to state of TT measurements a decade ago

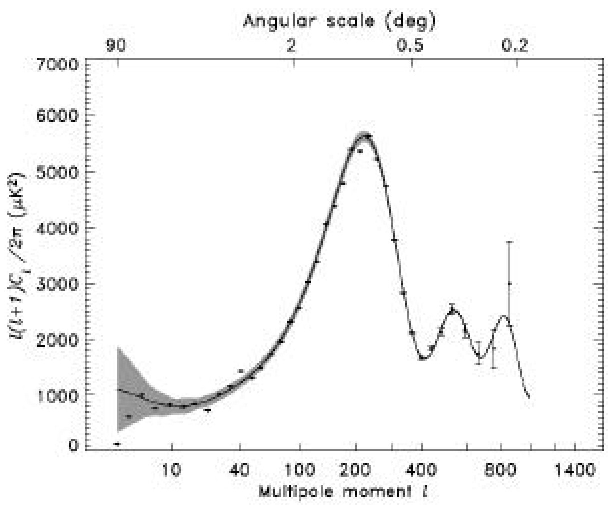
- CMB results pre-2000




Figure

S. Dodelson

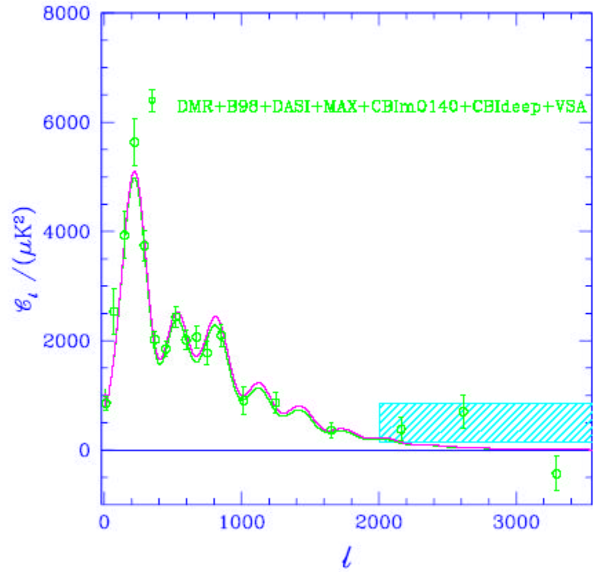
- WMAP data 2003




Figure

Hinshaw et al. 2003

- CMB results 2000- 2003 (pre WMAP)




Figure

Bond et al. 2003

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

# This are hard measurements!

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

- Requires a new generation of 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)

# 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

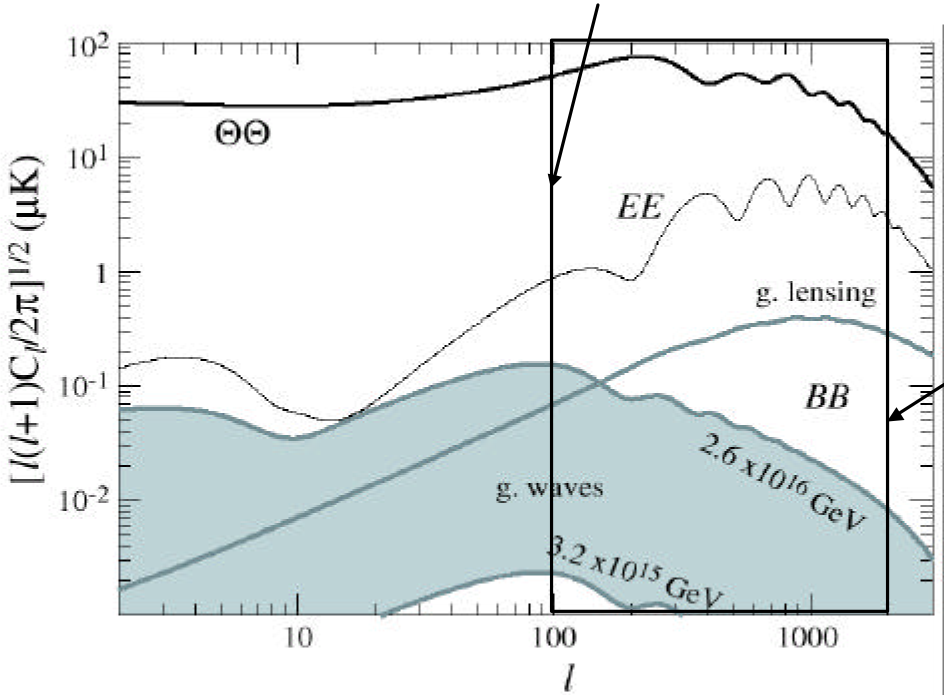

The QUaD Collaboration

- Stanford University
- U. of Wales, Cardiff
- Caltech
- JPL
- U. of Chicago
- N.U.I Maynooth
- U. of Edinburgh
- Collège de France

# 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



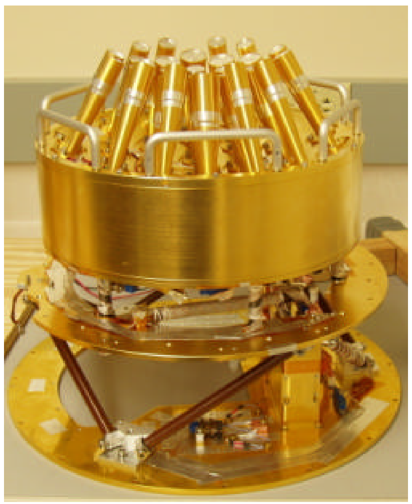

The smallest scales are determined by the angular resolution of the experiment

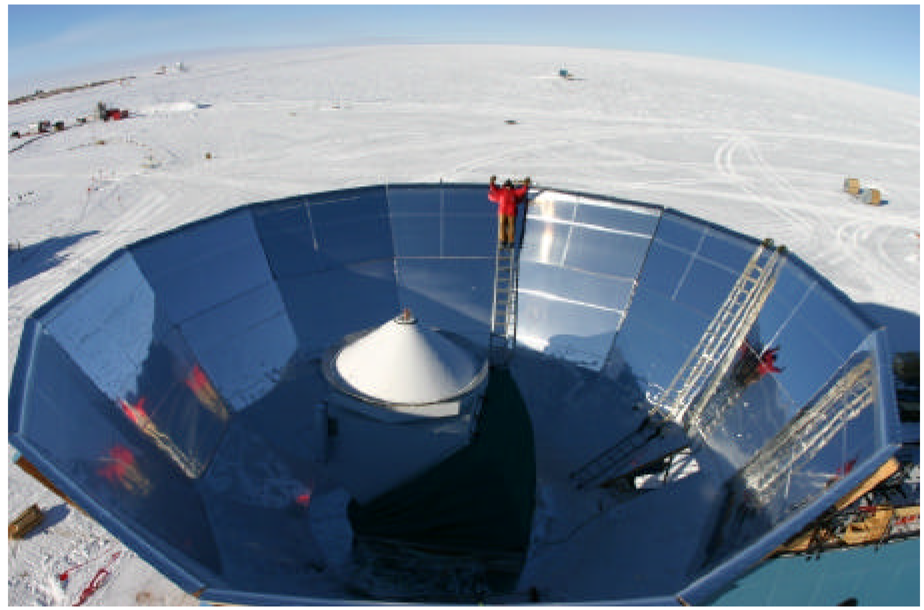
Hu et al. 2002

*l*-space coverage of QUaD

# The QUaD Experiment

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

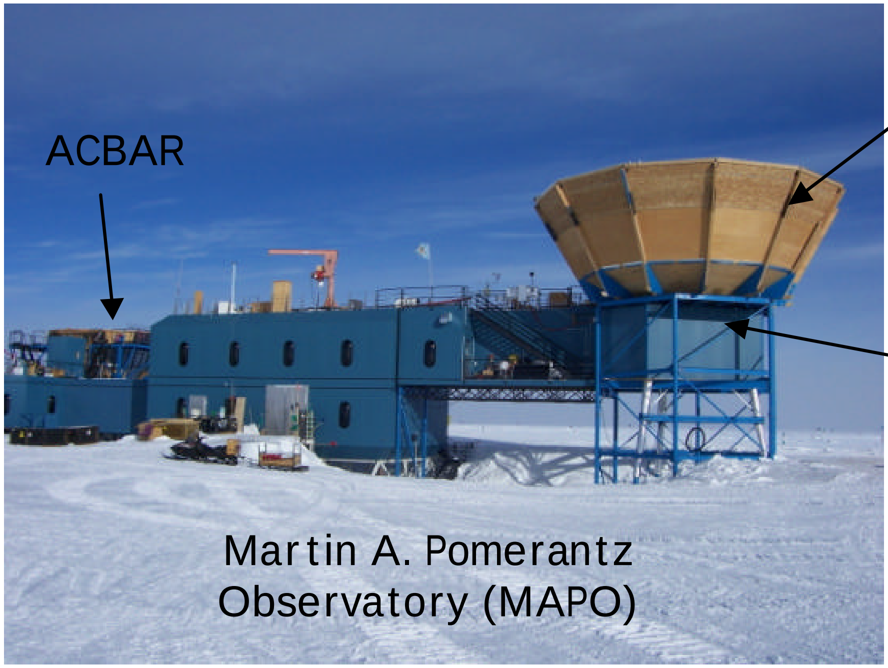




| Freq (GHz) | Beam (arcmin) | No. feeds | Percent Bandwidth | NET per bolometer ($m$K $s^{1/2}$) |
|---|---|---|---|---|
| 100 | 6.3 | 12 (9) | 0.25 | 350 |
| 150 | 4.2 | 19 (17) | 0.25 | 350 |

# Why the South Pole?

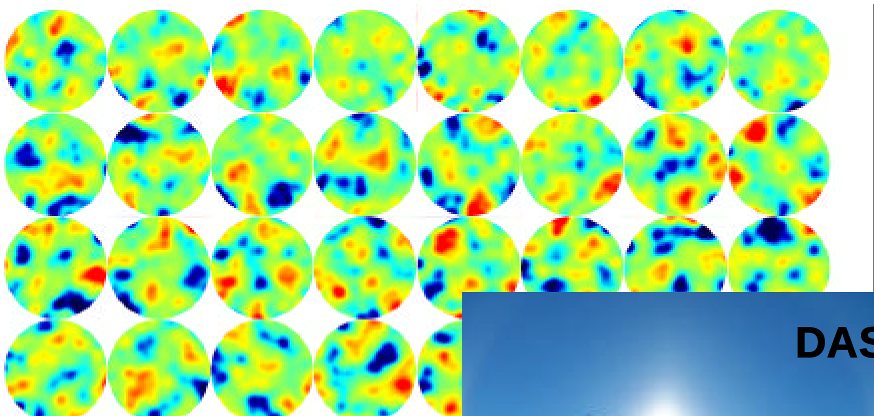
- Very low precipitable water vapor
- Very stable environment (1 day and 1 night)
- Ability to view the same area of sky continuously
- Existing facilities (DASI mount)
- Excellent infrastructure (machine shops, liquid cryogens, etc.)



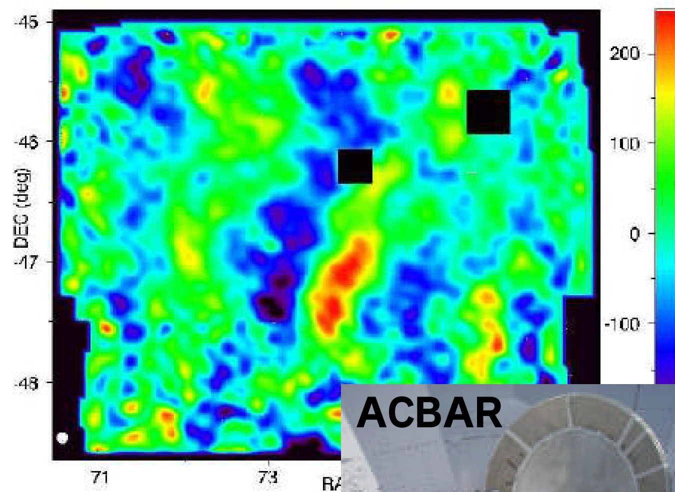

QUaD ground shield

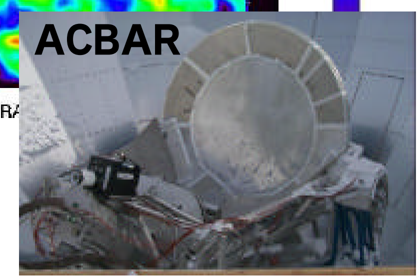
Heated work space behind the telescope

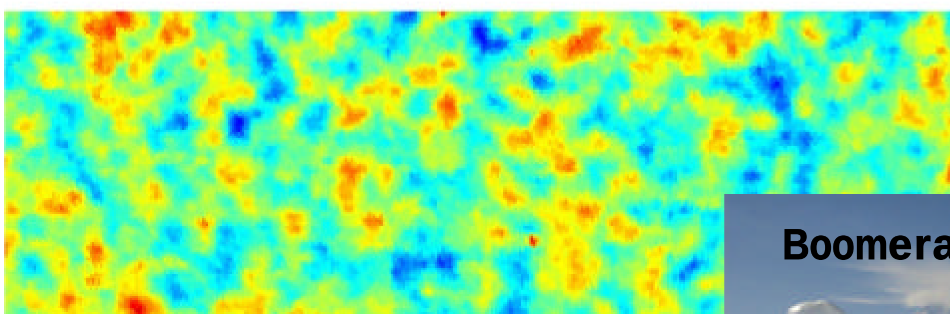
# Antarctica has been used to make a lot of maps of the microwave sky

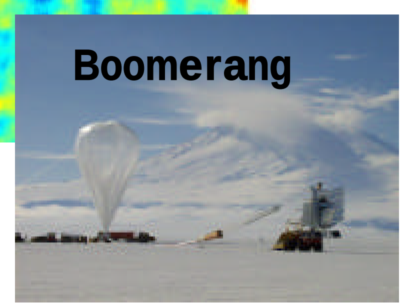




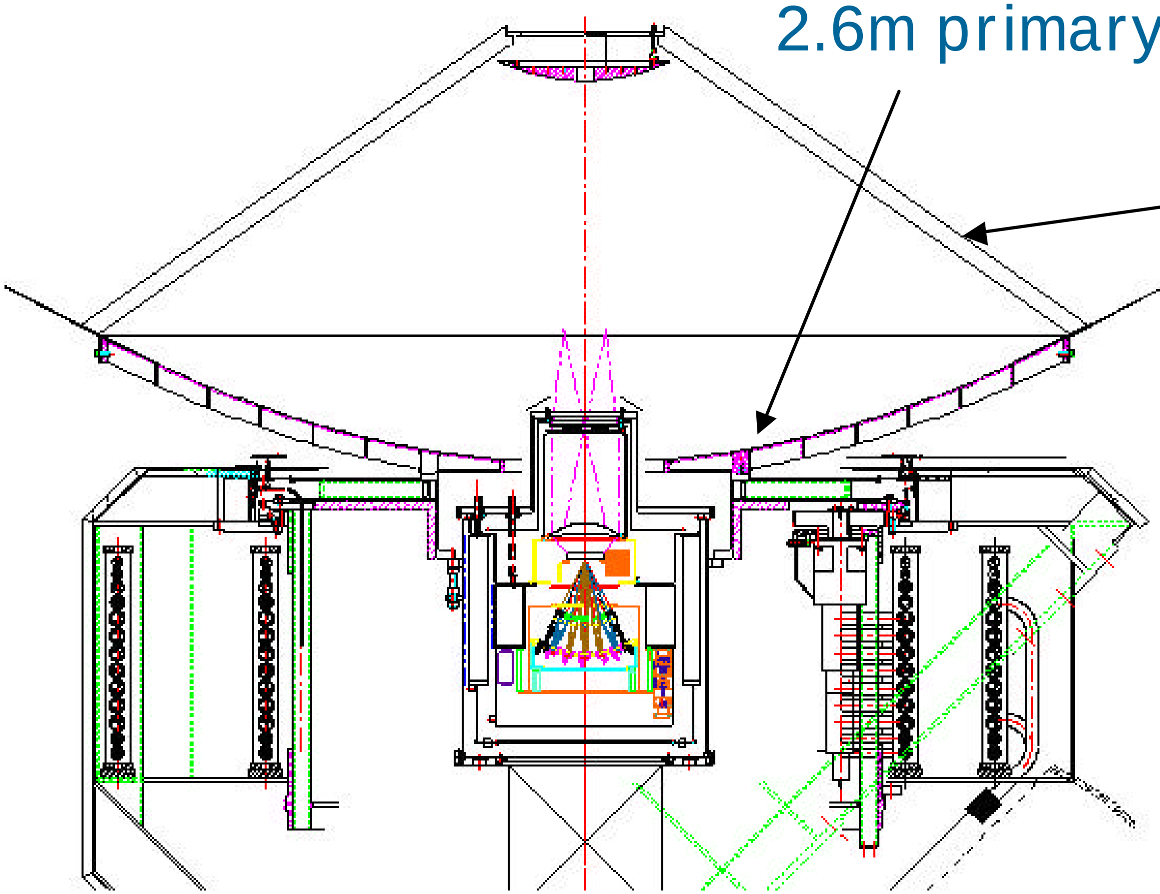




# The QUaD Receiver and CassegrainTelescope

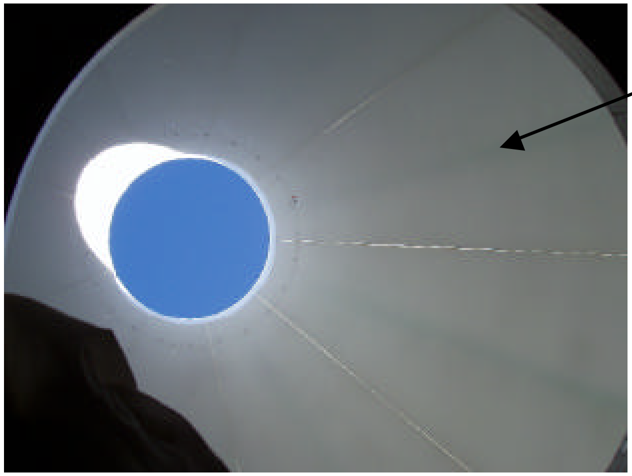



On-axis design minimizes polarization systematics

# Primary installed in late 2003, telescope completed in Jan 2005

Foam cone lift, Jan 2005

Receiver testing, Dec 2004, prior to installation of cone



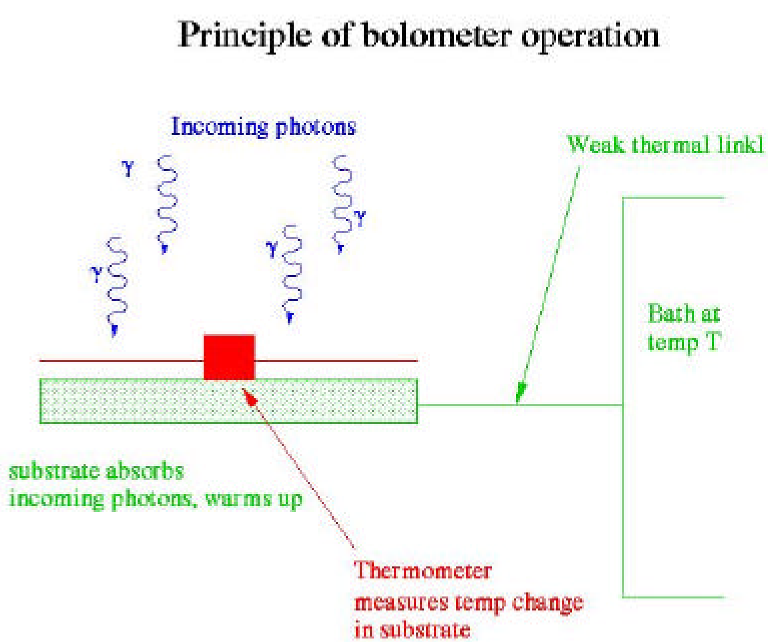
View through the primary hole

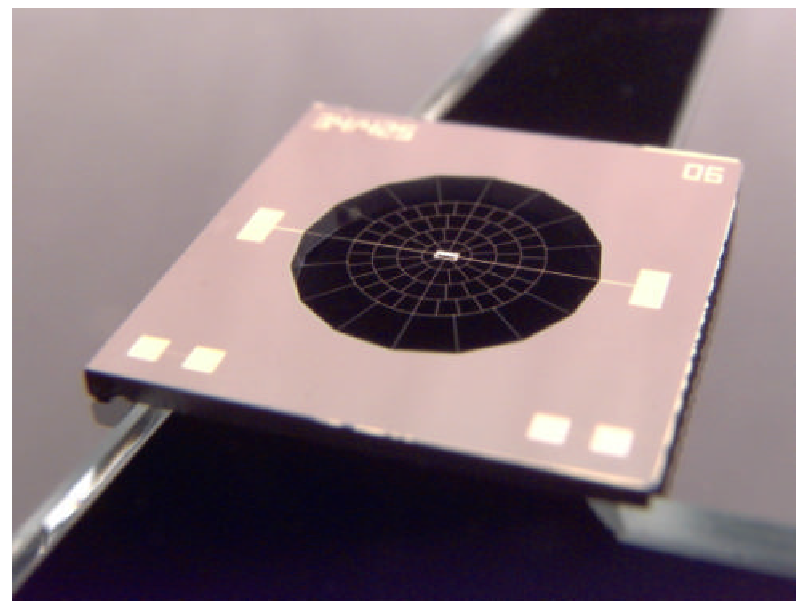
Foam cone comprises a double layer of propazote (Zotefoam).

Low loss, good mechanical strength

# 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

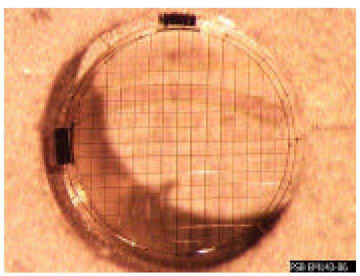
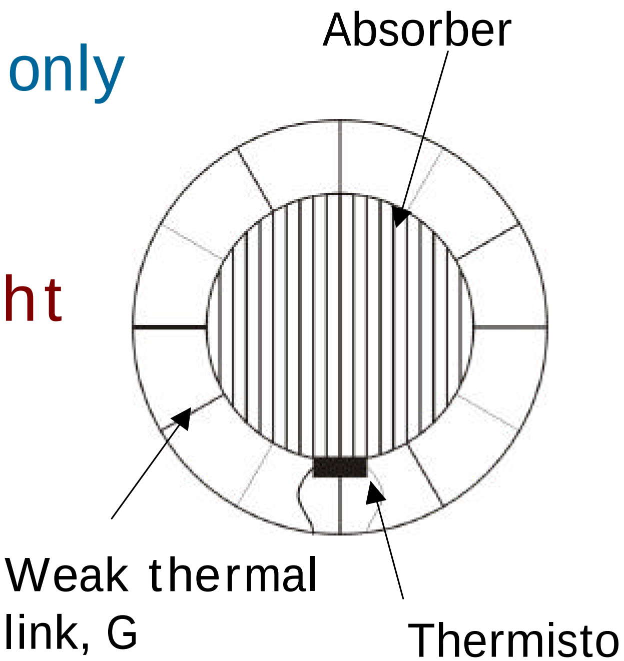


Photo courtesy J. Bock,JPL

- 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

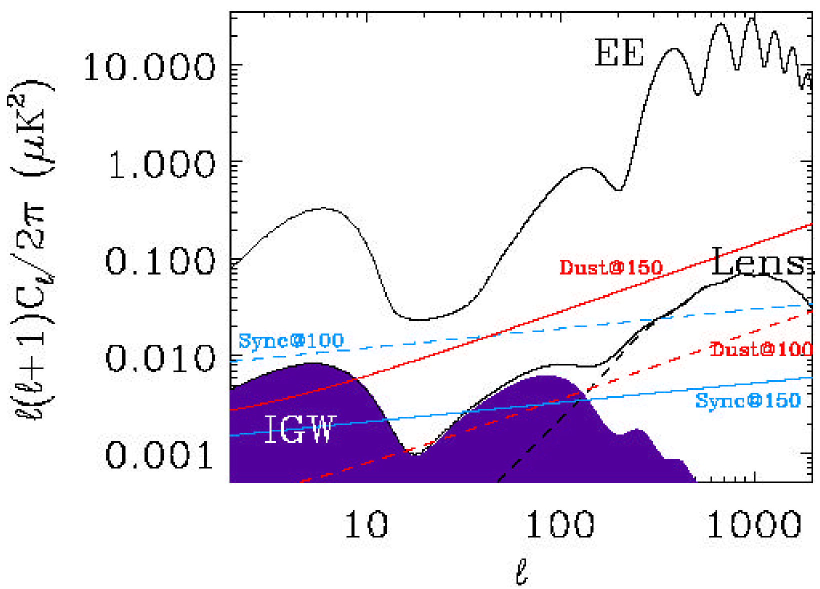
Polarization-sensitive bolometers (PSBs) were developed for Planck and flown on Boomerang (B2K)

# QUaD has two frequencies to characterize foregrounds

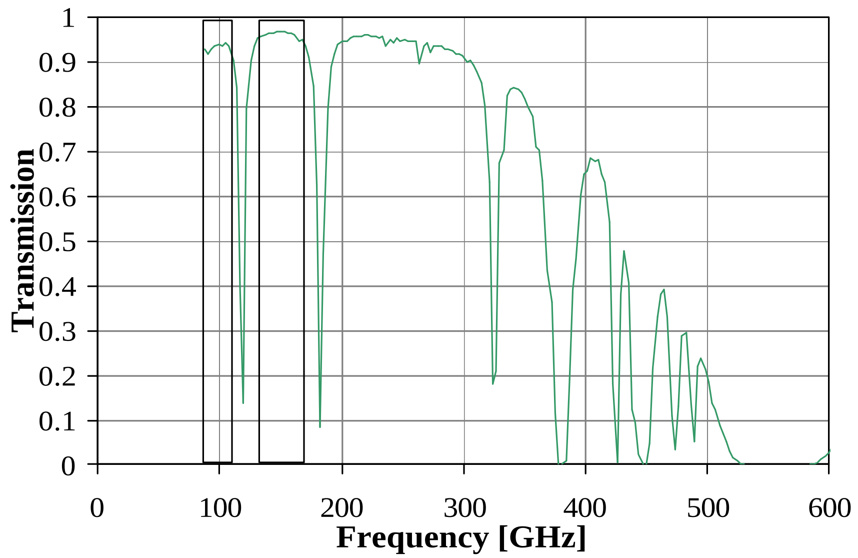
❖ Polarized foregrounds will be dominated by synchrotron and dust emission

- ➢ Extragalactic on small angular scales:
  Point sources – AGN + starburst galaxies
- ➢ Galactic on large angular scales
  Dust and gas, supernova remnants

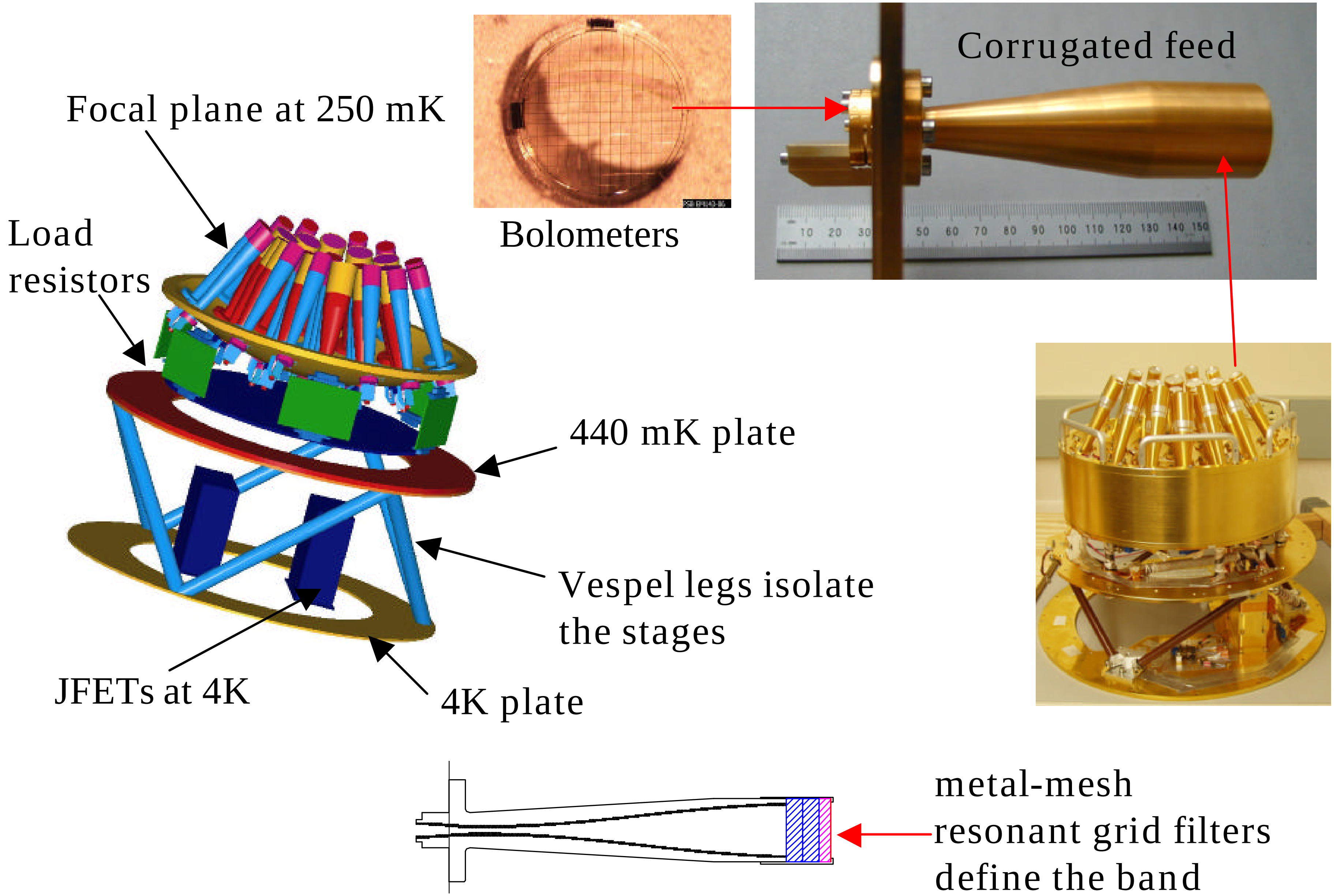
Foreground calculation from Bowden et al. (2003)



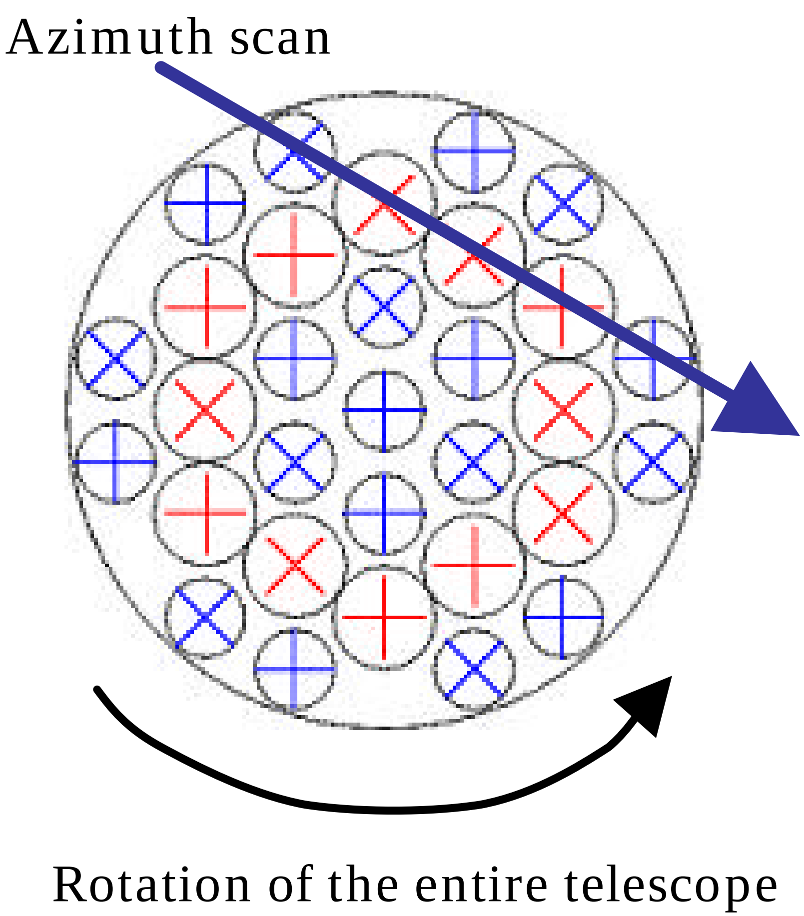

Bands matched to the atmospheric windows



# The QUaD Focal Plane (built at Stanford)



# 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 Receiver Assembled and Tested at Stanford in Summer 2004

Above: Measuring the optical response and polarization efficiency with a chopped cold load

Left: the frequency response was measured with a Fourier Transform Spectrometer

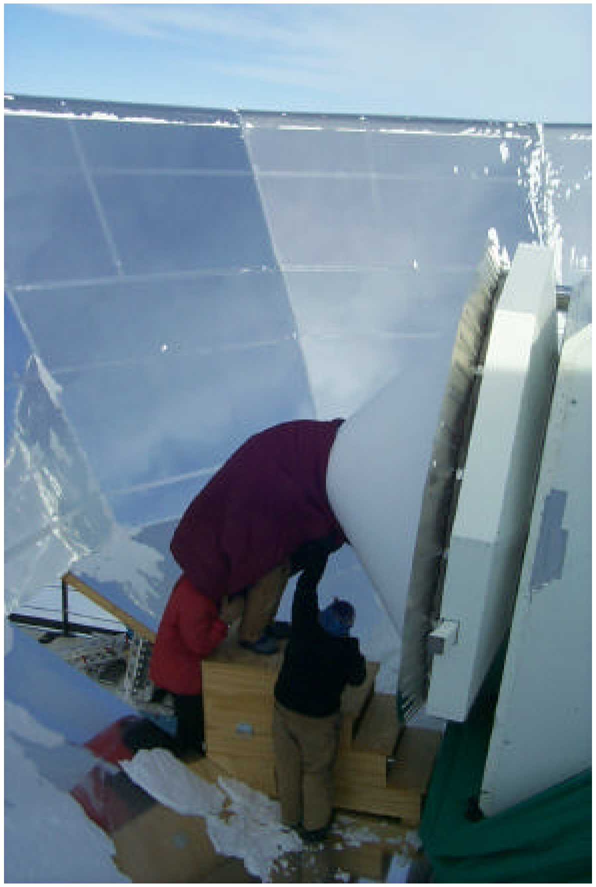
# QUaD installation and commissioning

- 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)

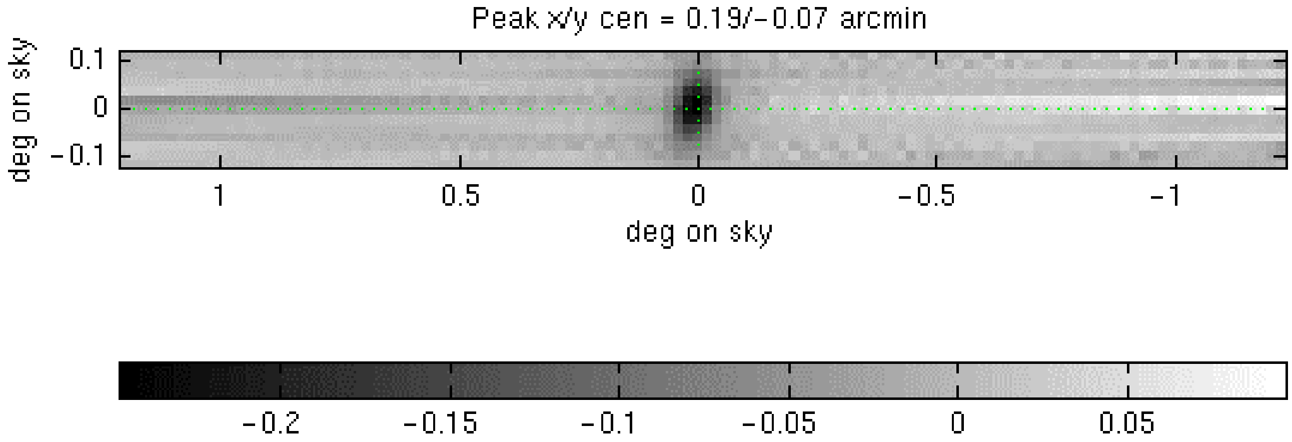


And if you have to work outside, you're grateful for some extra protection

# Receiver was installed in early Feb


First light was obtained on Feb 8th by observing galactic HII region RCW38

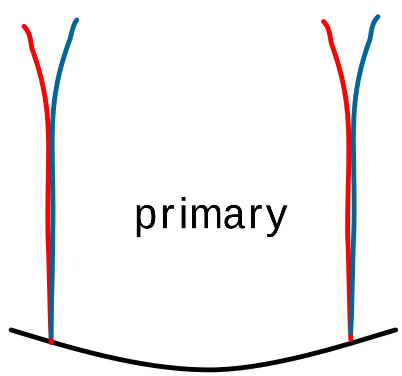
Note: This is an intensity map in arbitrary units



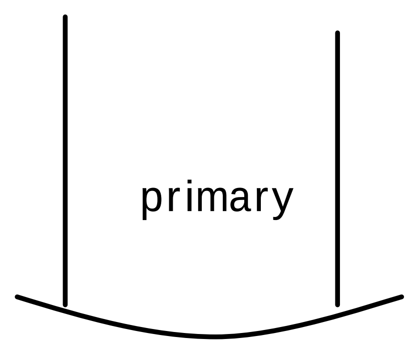
# Atmospheric 1/*f* noise (or why we can do this from the ground)

- Traditionally CMB observations > 30 GHz use balloons or space where atmospheric noise is minimized
- This is because chopping techniques, used to minimize atmospheric noise, remove signal on scales large than the chop
- <u>But</u> polarization experiments are naturally differencing to determine Q and U
- The only signal removed is *unpolarized* CMB and *unpolarized* atmosphere.

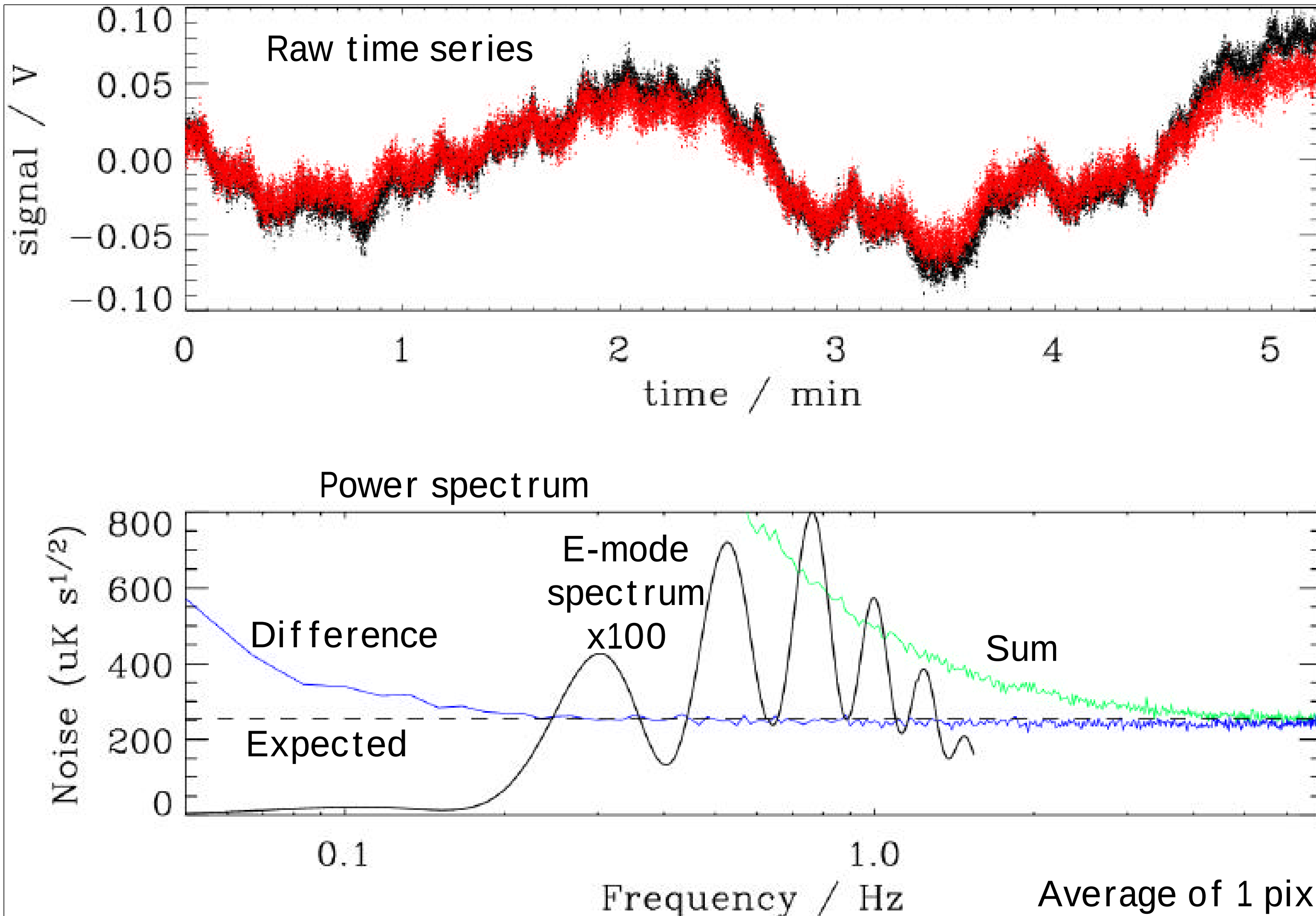
In a spatial chopping experiment, residual atmosphere is caused by beam divergence and mismatch




In a polarization experiment, both detectors look through the same column of atmosphere and so a much cleaner difference is obtained

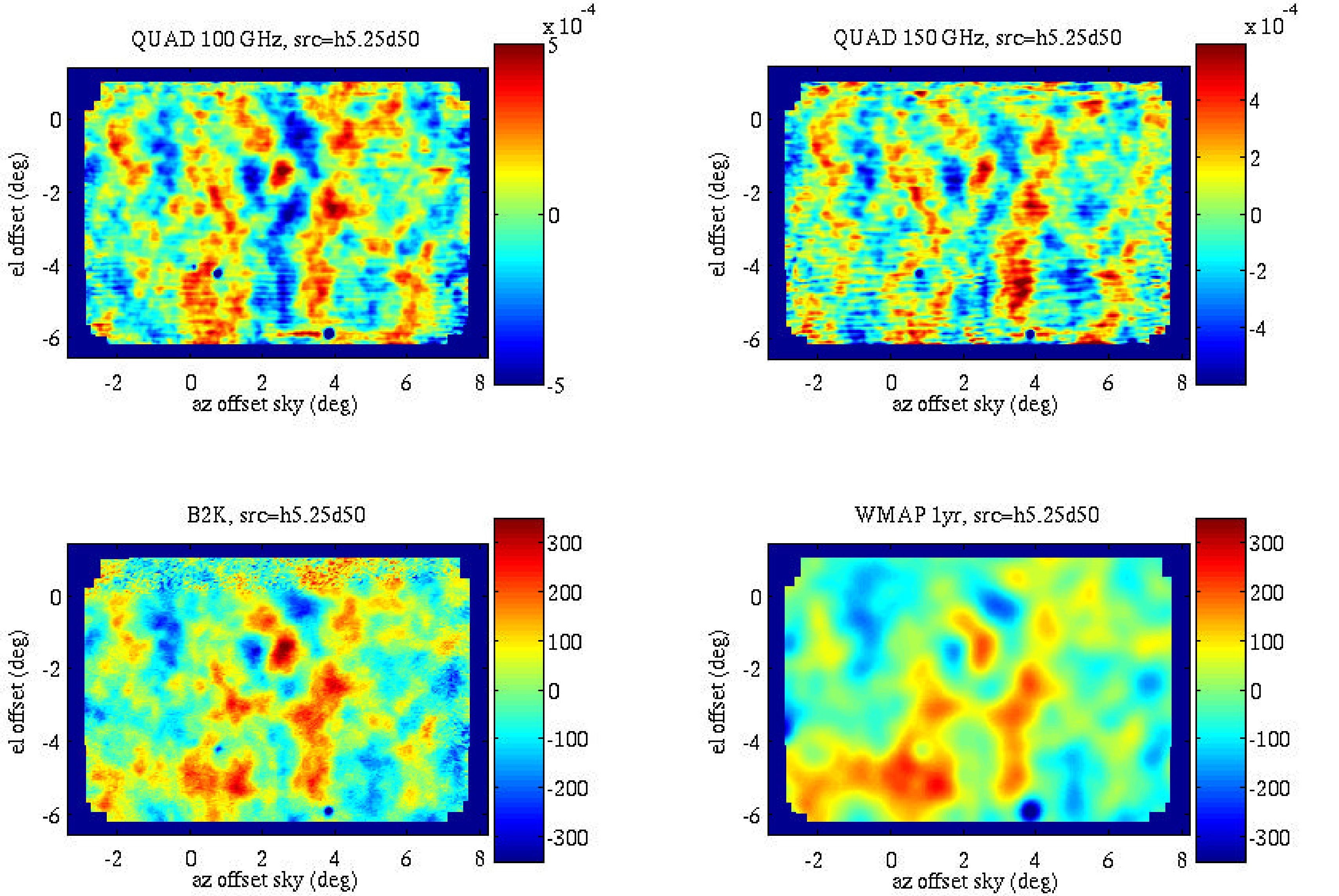


# Atmospheric noise removal works!



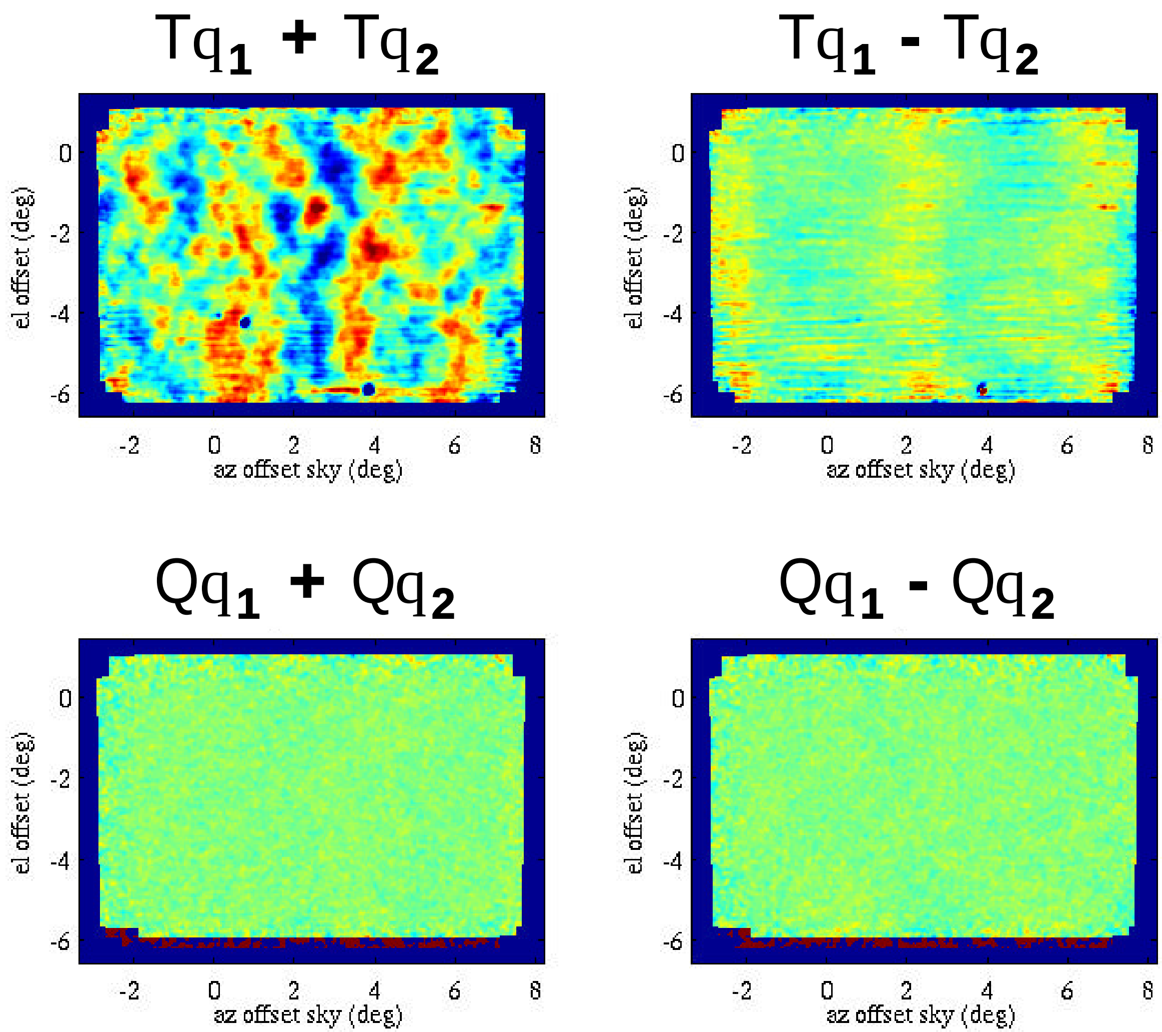

Average of 1 pixel
over 1 day

# Data look good!




Comparison of QUaD, B2K and WMAP temperature maps

# Sum and difference maps

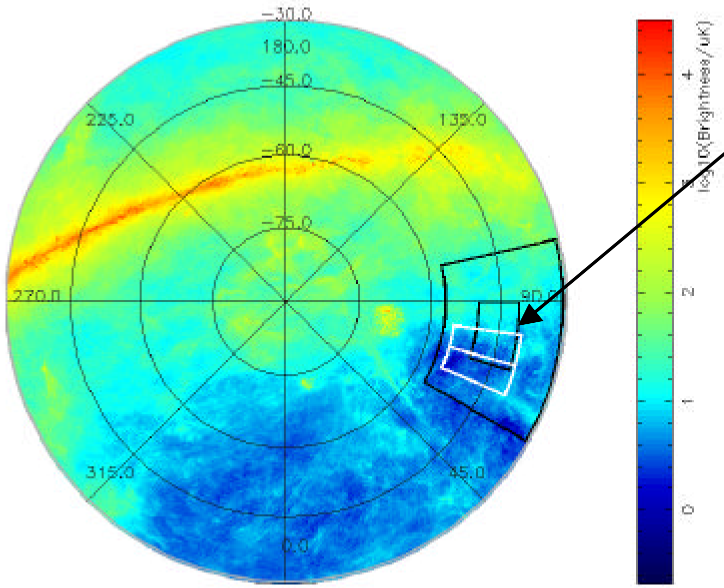



Data taken at two different focal plane orientations, ($0^{\pm}$, $60^{\pm}$) is jack-knifed.

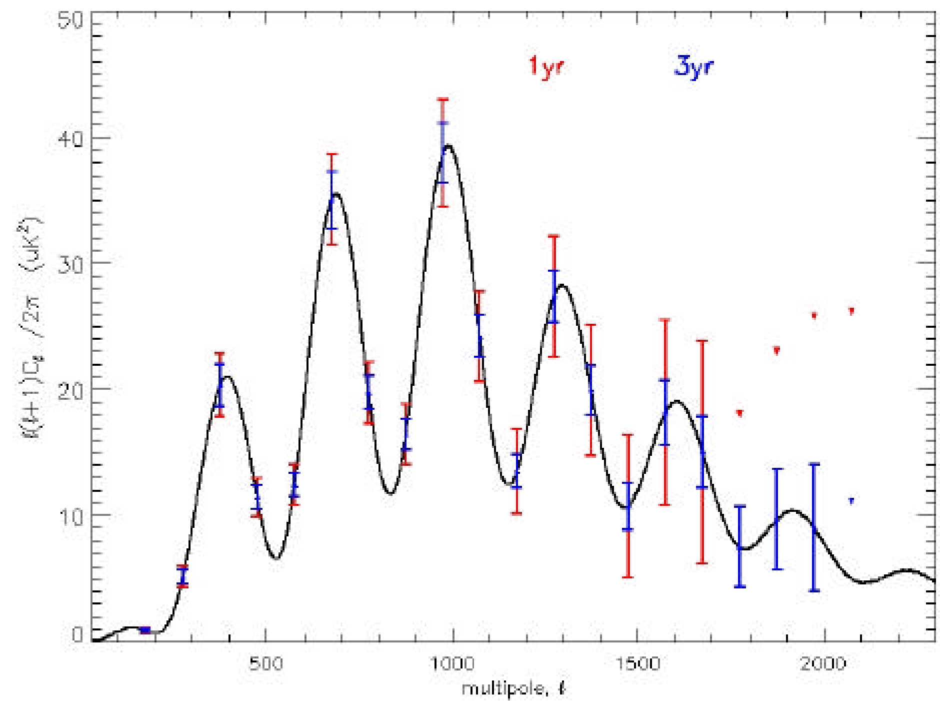
- T data shows residual stripping due to atmosphere.

- Q data consistent with noise. ~10µ K per beam-sized pixel.

# Observation Plans and expected results




Season I: map a region of extremely low foreground sky

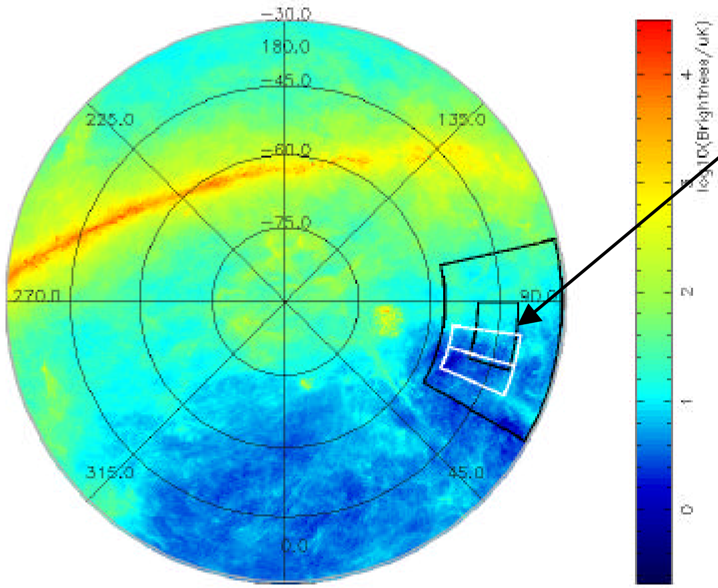



QUaD will be the first experime
to map the E mode power
spectrum in detail

QUaD has sufficient sensitivity to make the first detection of B-mode polarization from gravitational lensing

- Neutrino mass
- Dark energy eq. of state

# Observation Plans and expected results

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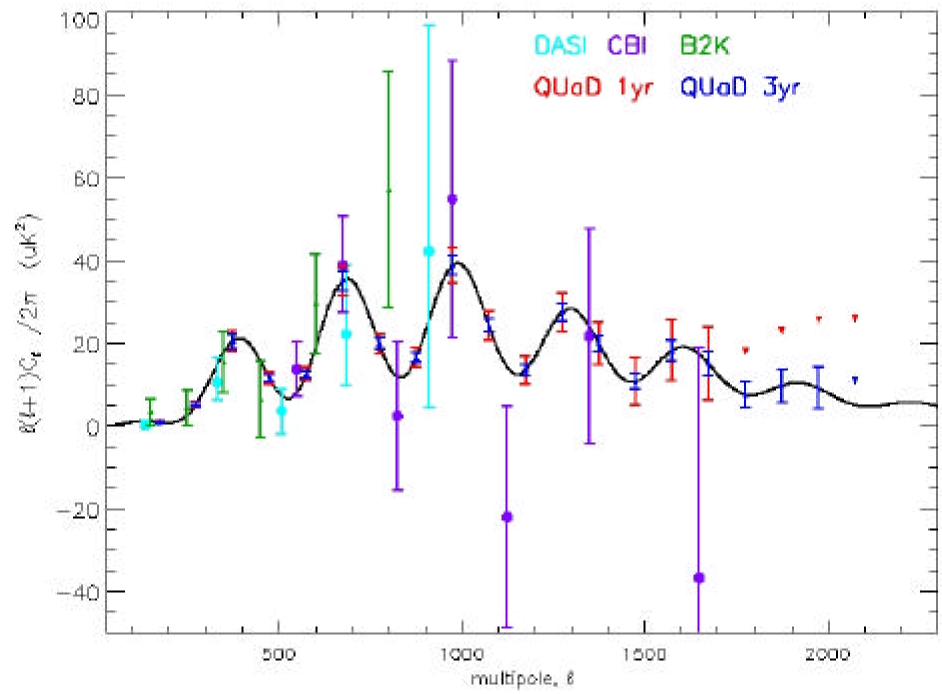


QUaD will be the first experime to map the E mode power spectrum in detail

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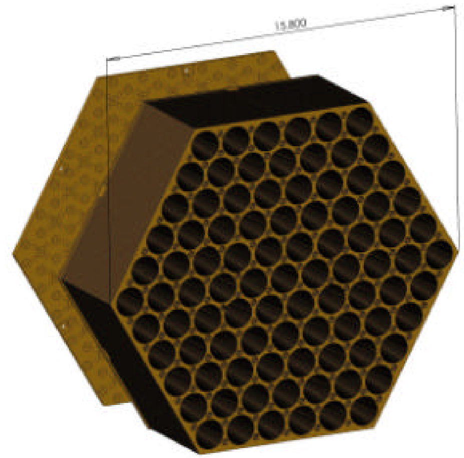
- Dark energy eq. of state

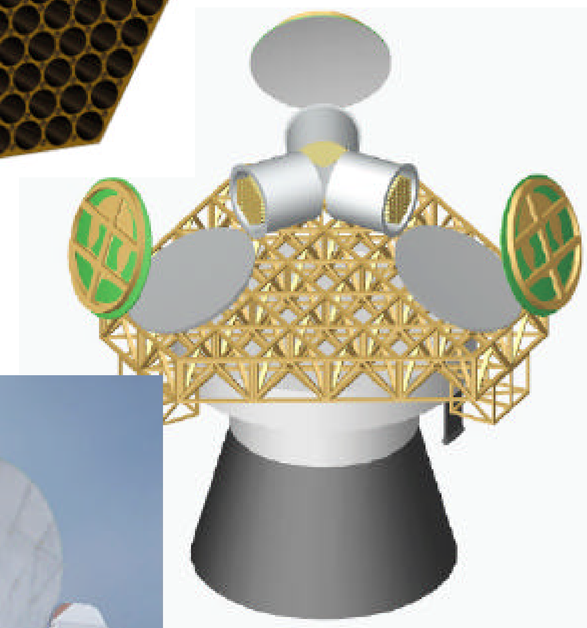
# The future -- QUIET

- Being built by Caltech, Chicago, Columbia, JPL, Oxford, Princeton, **Stanford/KIPAC**

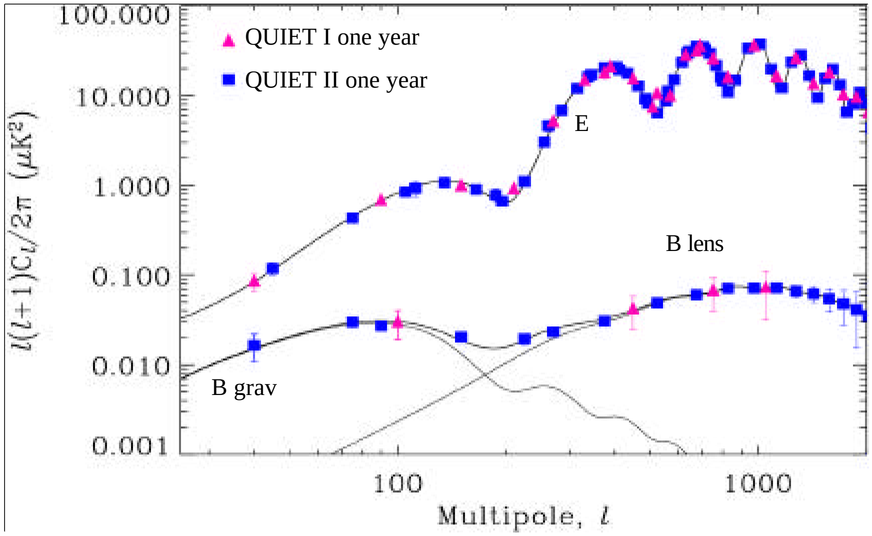
- Stage I (2006)
  - One (two) 1.4m telescope (built by Stanford)
  - 91-element 90 GHz array; 37-element 44 GHz array

- Stage II
  - At least three 2m telescopes
    - 2 x 91-element 44 GHz array
    - 2 x 397 element 90 GHz array
    - (1 x 1000 element 150 GHz array)
  - One 7m telescope
    - 1 x 91-element 90 GHz array
    - 1 x 397 element 44 GHz array





# The Promise of QUIET



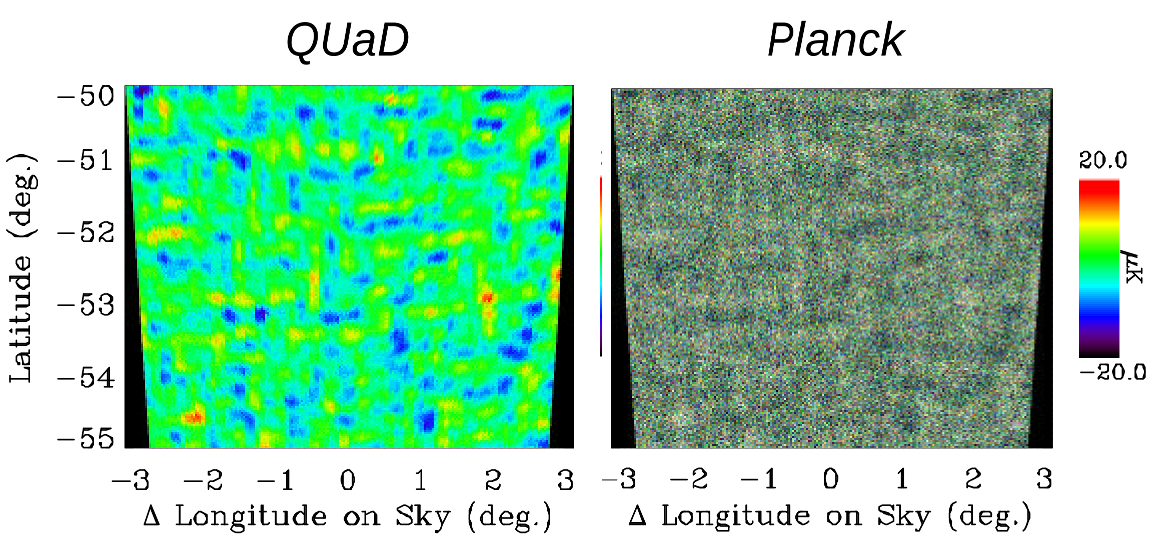

Estimated sensitivities include best estimates of foregrounds

- QUIET I 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 II will have sufficient sensitivity to detect or to set very strong limits on the amount of gravitational waves from inflation

# Also, coming up....Planck

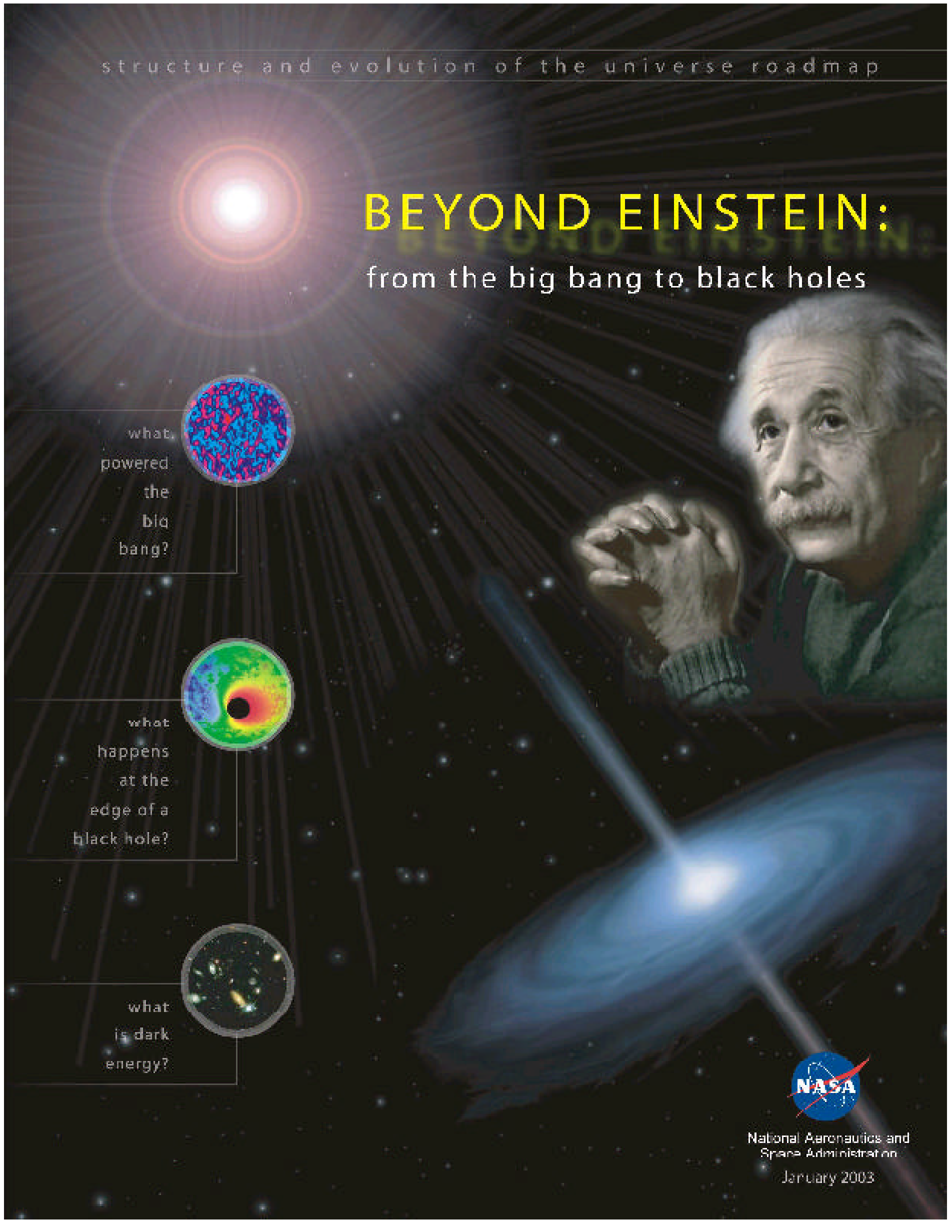
- The ESA/NASA Planck satellite will launch in 2007 and will map the sky in polarization from 30-550 GHz
- Planck's sensitivity to the E-mode power spectrum will exceed QUaD's (because of higher sky coverage), but its signal/noise per point will be inferior (worse pixel noise)
- The Planck and QUaD combination will be a key test for systematics




Simulations by Ken Ganga

- Planck's higher pixel noise makes it unsuitable for B-mode from lensing measurements but it might have a shot at gravity waves

# And eventually there might be a new satellite




- NASA's Universe Roadmap includes a CMB polarization mission but not currently funded
- One of the proposals – EPIC – looks a lot like QUaD in space, but with many thousands of pixels
- Requires a lot of technology development and demonstration via ground-based and balloon-borne programs

# 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.....

# Spare stuff

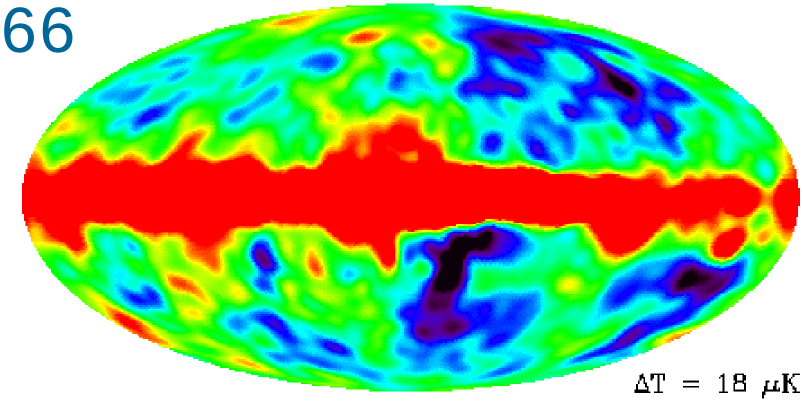
# Trading sky coverage for sensitivity

- 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 a sensitivity of:

Pixel noise term

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

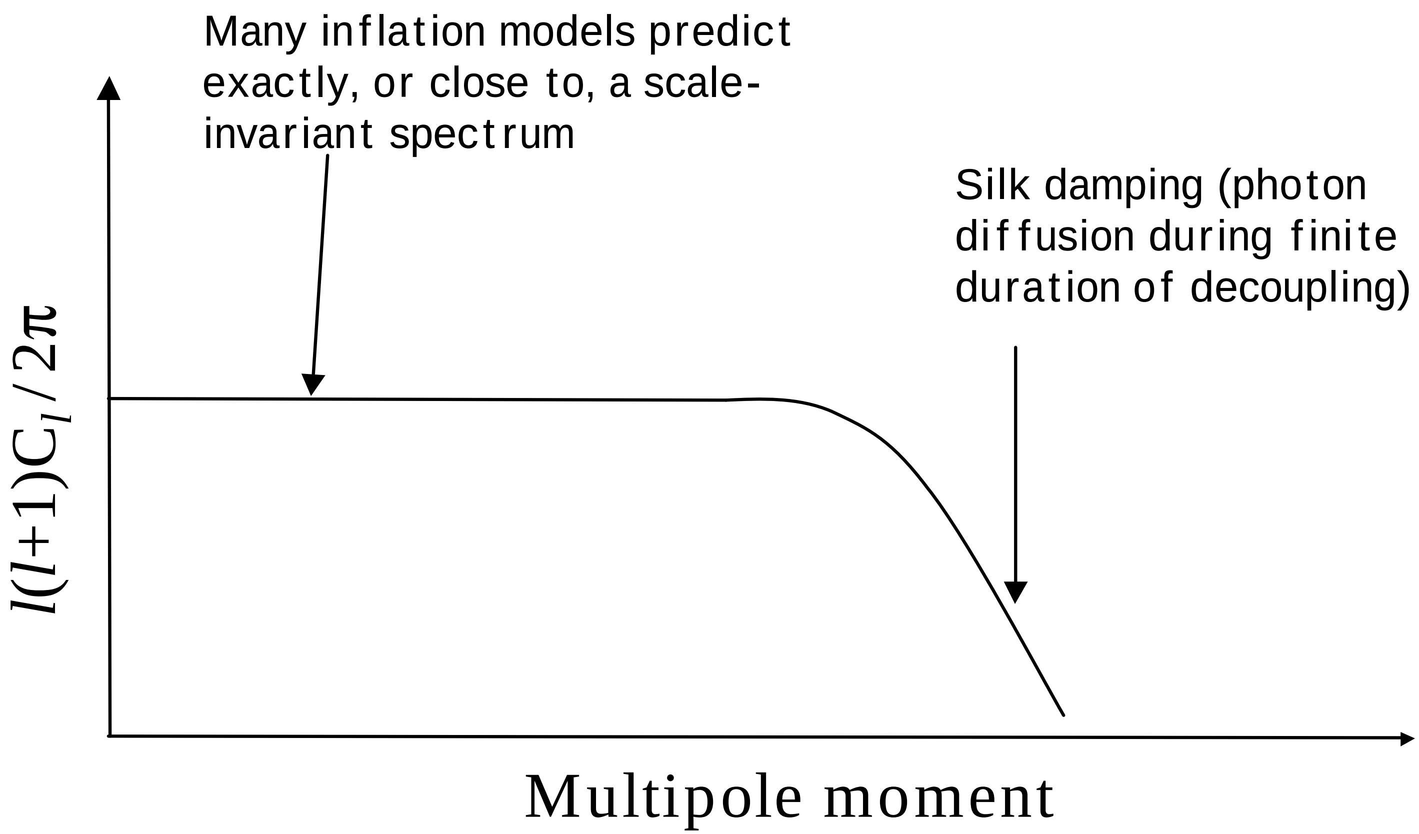
- $\Delta T$ – sensitivity/pixel/Stokes parameter
- $\theta_{\mathrm{pix}}$ – pixel size
- There is a tradeoff between pixel noise and sample variance
- Optimum balance: $\left(\Delta T \theta_{\mathrm{pix}}\right)^2 / C_l = 1$

*QUaD is optimized to measure the CMB polarization power spectra*

*WMAP and Planck optimized to measure T*

# Origin of Acoustic Peaks

- In the absence of any other forces, expect a simple spectrum for the dependence of primordial temperature fluctuations on linear size....

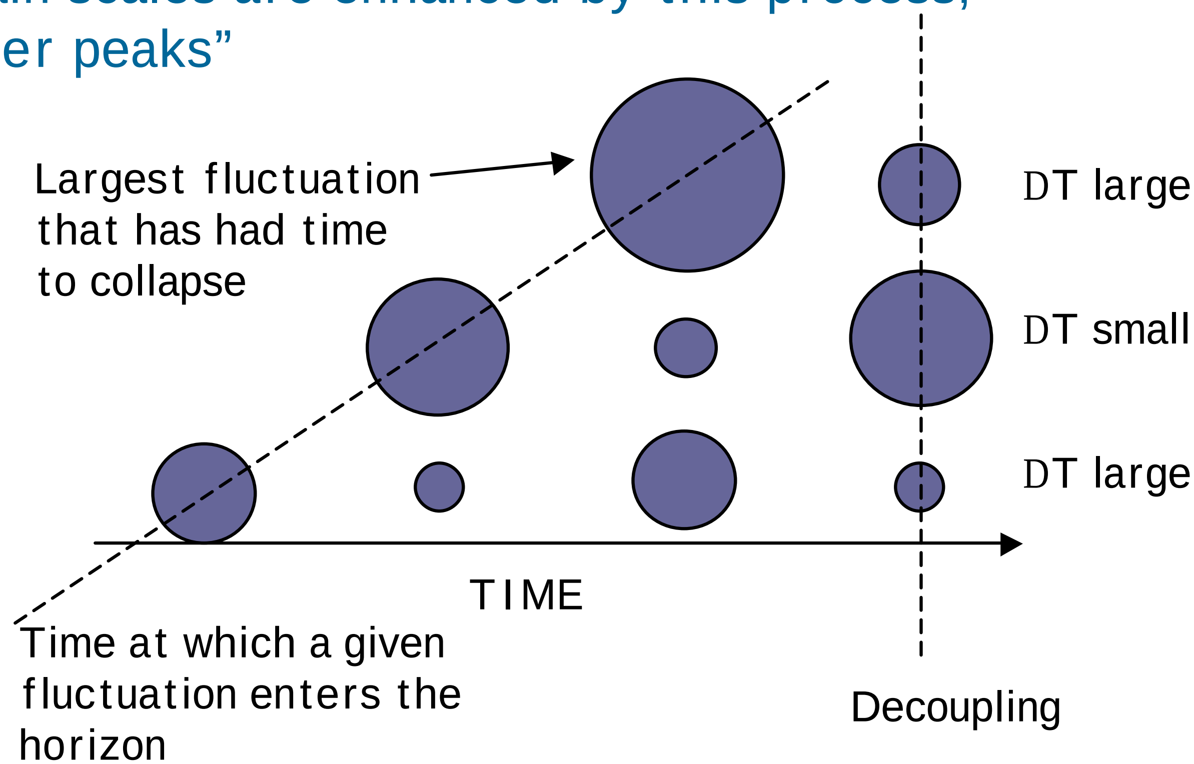


# Simple picture is complicated by the behavior of the photon-baryon fluid

- Gravity + radiation pressure ⇒ oscillations in the photon-baryon fluid
- At decoupling, radiation support is lost and the fluctuations are frozen into the CMB
- Fluctuations on certain scales are enhanced by this process, leading to the “Doppler peaks”

Physics is relatively straightforward ⇒ *accurate theoretical predictions*

*Positions of the peaks determine cosmological parameters*



# Science from polarization of the CMB

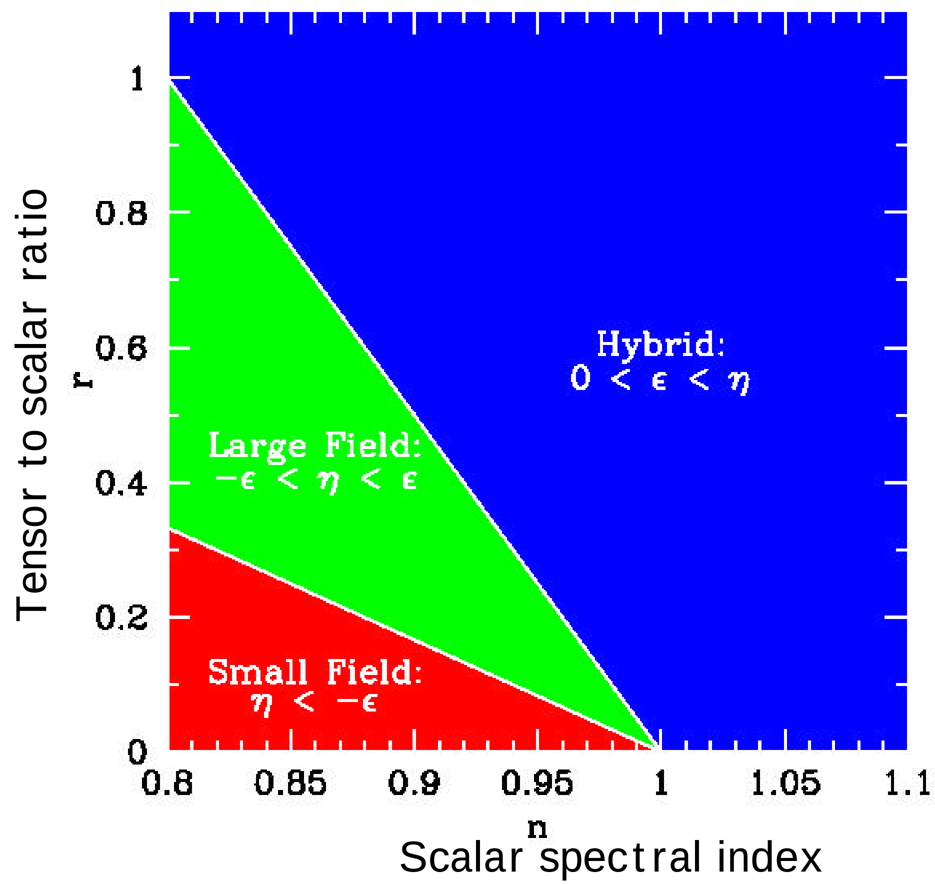
- Small-scale E-mode signal strongly correlated with CMB temperature anisotropy signal (T)
  - Provides an extra probe of cosmological parameters, and tests understanding of recombination physics
  - E-modes detected by DASI, CBI, CAPMAP
  - TE correlation detected by WMAP

- Polarization is enhanced by reionization.
  - Detected in WMAP measurements of TE correlation

- B-mode signal is the signature of the primordial gravitational wave background predicted in many inflationary models.
  - The exact amplitude of this background is proportional to $(V_{inf})^4$ where $V_{inf}$ is the inflaton potential.

# Status of inflationary models

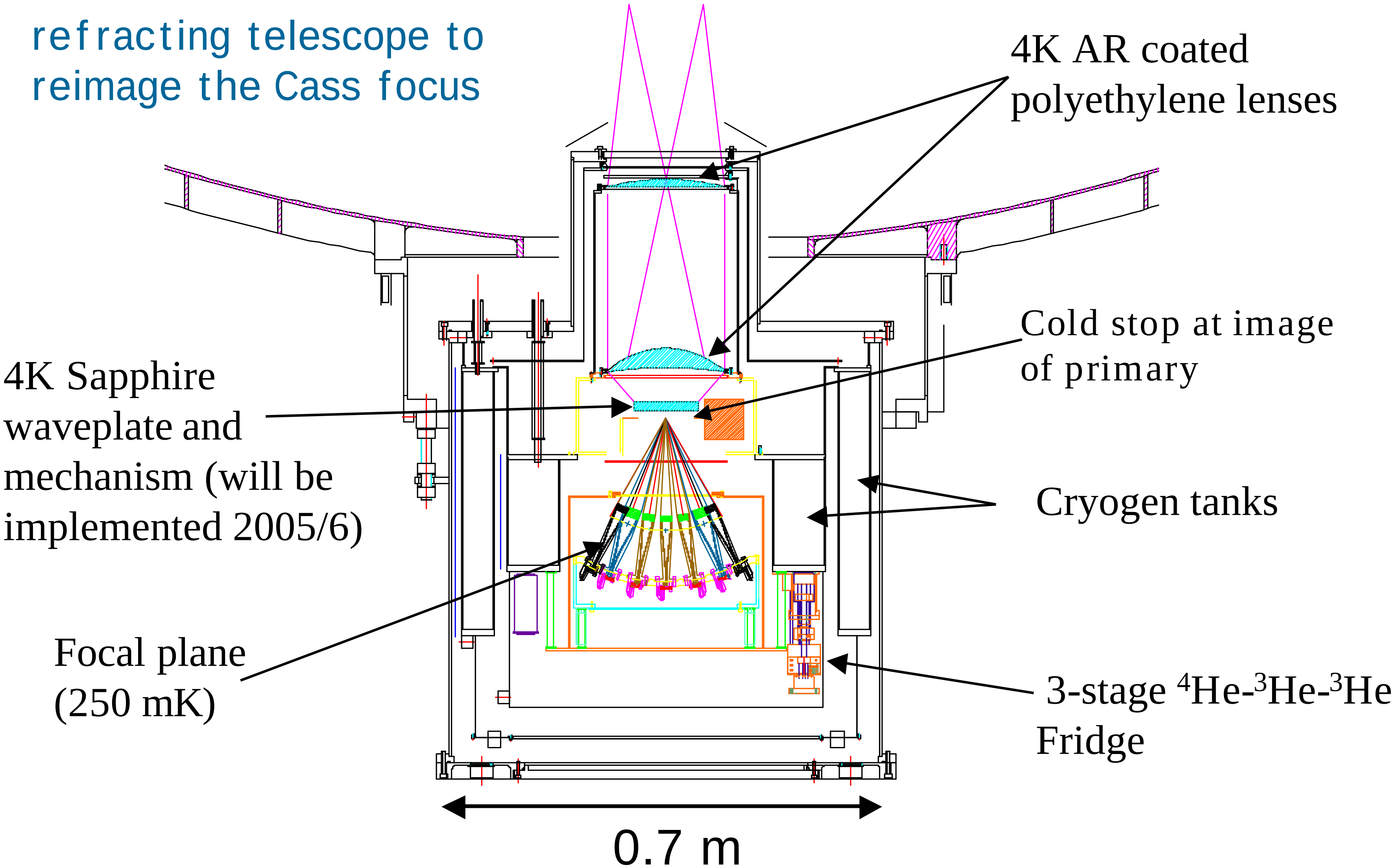
- CMB temperature anisotropy measurements confirm two features of inflation
  - A flat universe
  - A close to scale-invariant spectrum of density fluctuations
- However the allowed parameter space remains large




Kinney et al. (2003)

# QUaD Receiver and Reimaging Optics

Set of lenses form a refracting telescope to reimage the Cass focus



# After QUaD comes Planck

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- Planck's sensitivity to the E-mode power spectrum will exceed QUaD's (because of higher sky coverage), but its signal/noise per point will be inferior (worse pixel noise)
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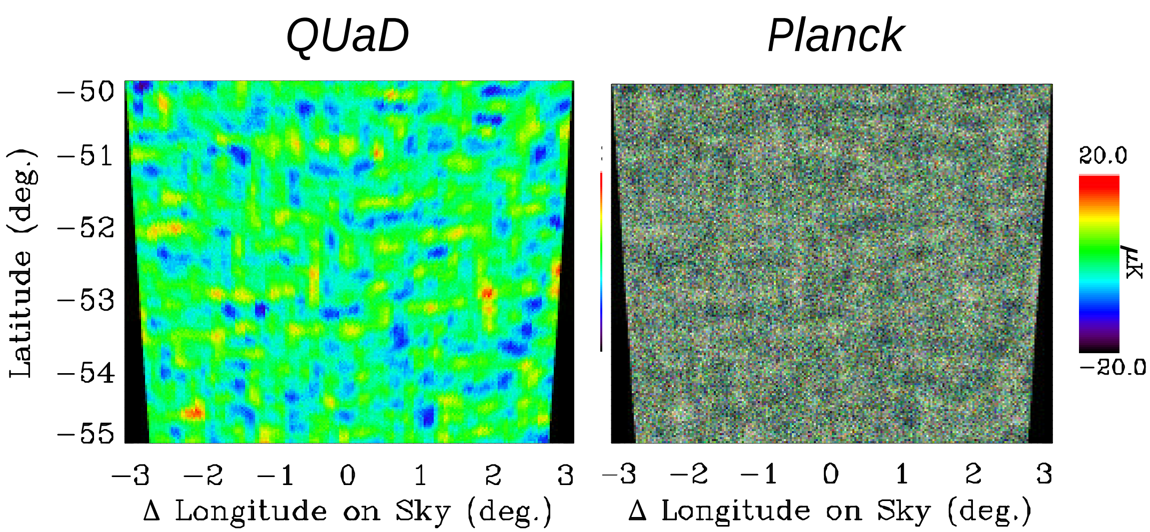
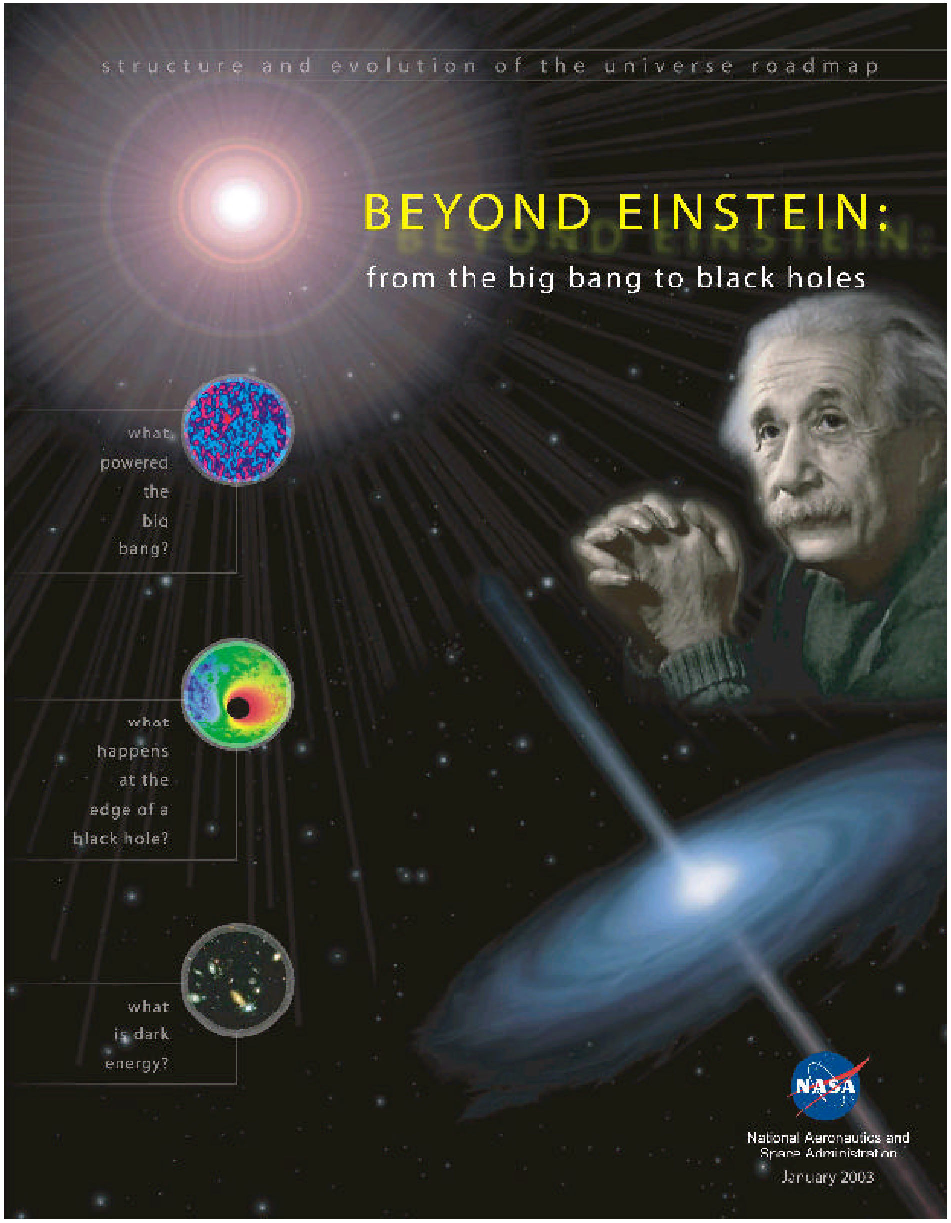



Simulations by Ken Ganga

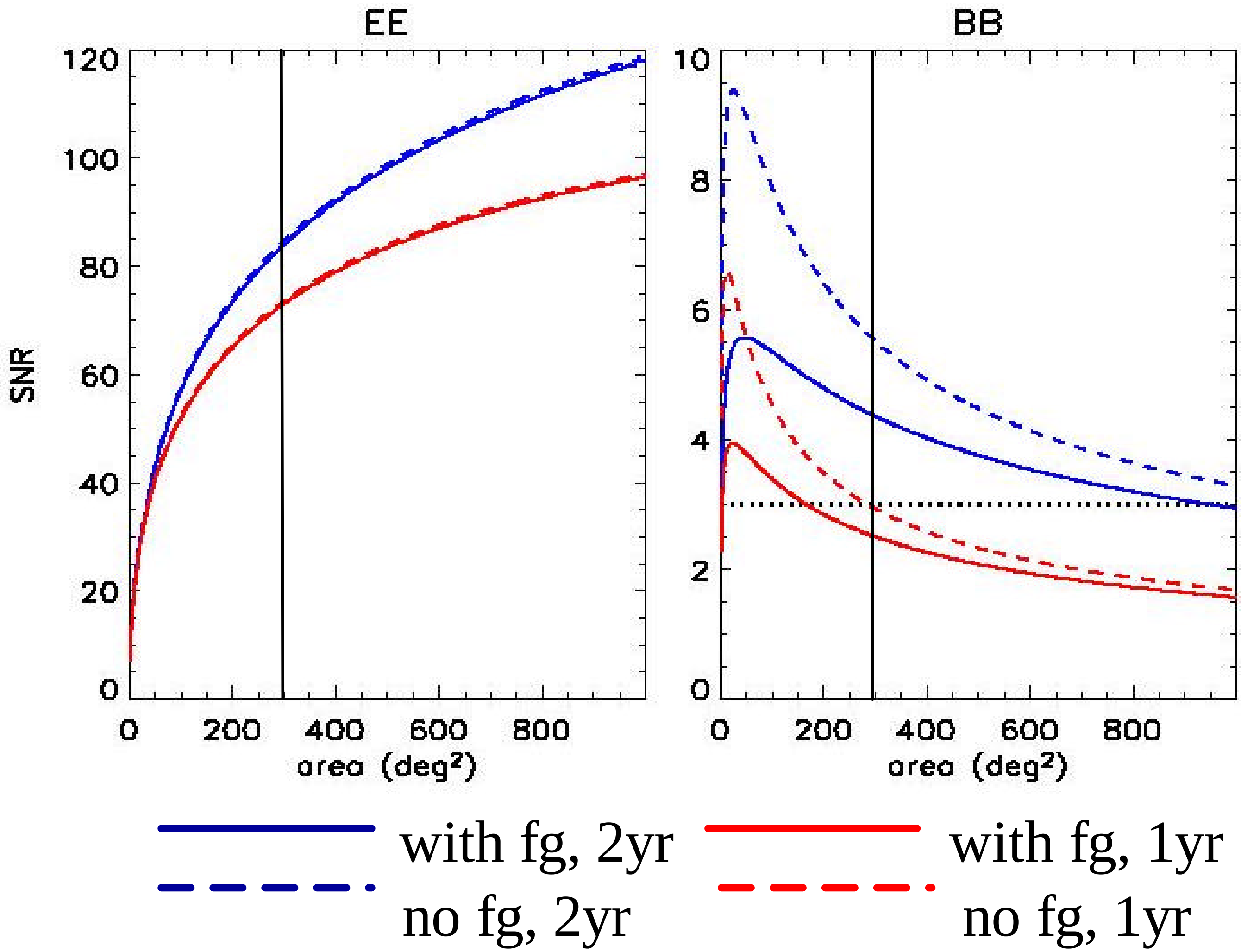
- Planck's higher pixel noise makes it unsuitable for B-mode from lensing measurements but it might have a shot at gravity waves

# But eventually a future satellite is needed




- NASA's Structure & Evolution of the Universe Roadmap includes a CMB polarization mission (no earlier than 2010)
- One of the proposals – EPIC – looks a lot like QUaD in space, but with many thousands of pixels
- Requires a lot of technology development and demonstration via ground-based and balloon-borne programs

# The optimal survey area depends on science goals and expected foreground levels




Bowden et al. (2003) astro-ph/0309610