Cosmology:
Observations of the Cosmic Microwave Background

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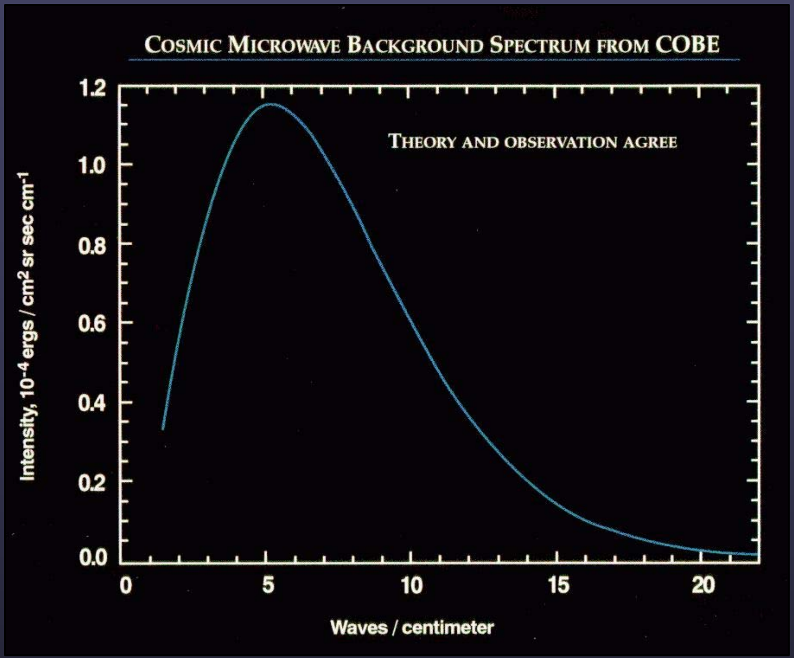
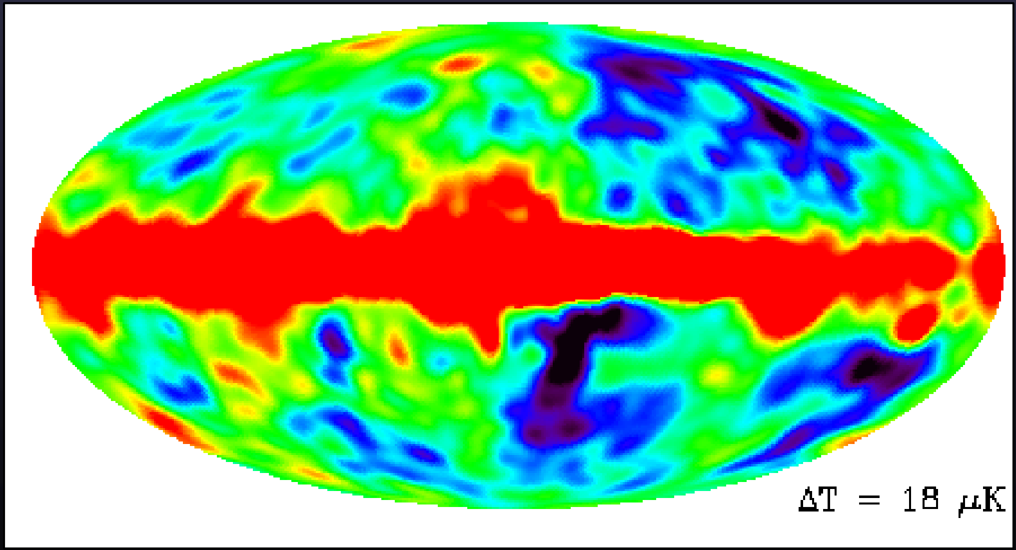
Some history…

The Cosmic Microwave Background

- Discovered 1965 (Penzias & Wilson)
  - 2.7 K blackbody
  - Isotropic (<1%)
  - Relic of hot “big bang”
- 1970’s and 1980’s
  - 3 mK dipole (local Doppler)
  - $\delta T/T < 10^{-5}$ on arcminute scales

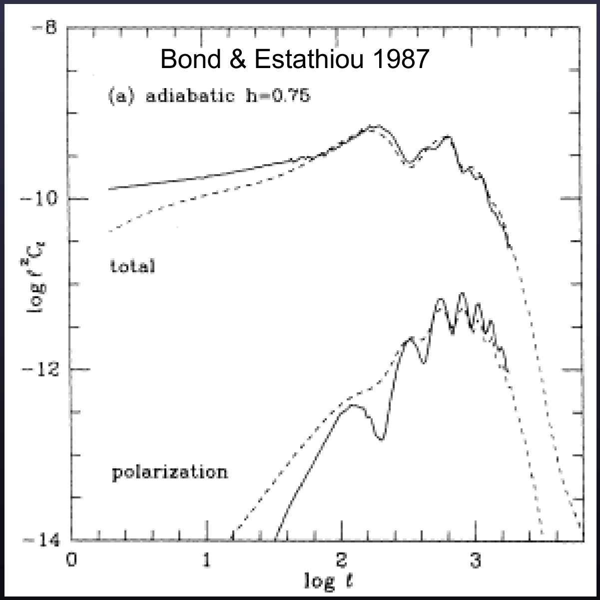




- COBE 1992
  - Blackbody 2.728 K
  - $\ell < 30 : \delta T/T \approx 10^{-5}$

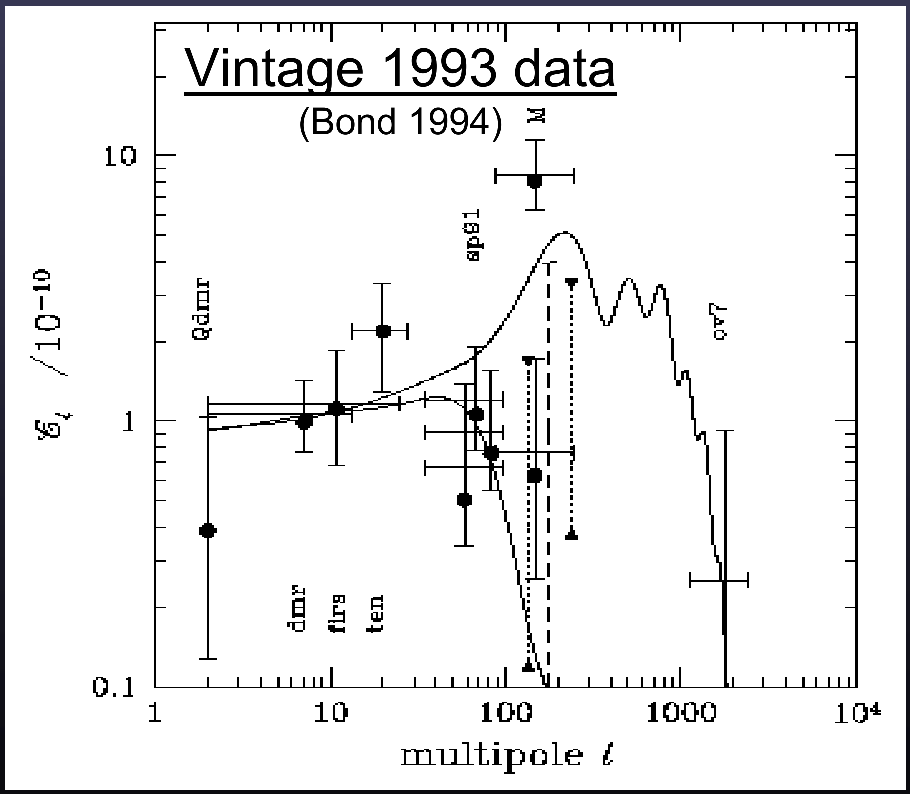
Search for Anisotropies in 1980s

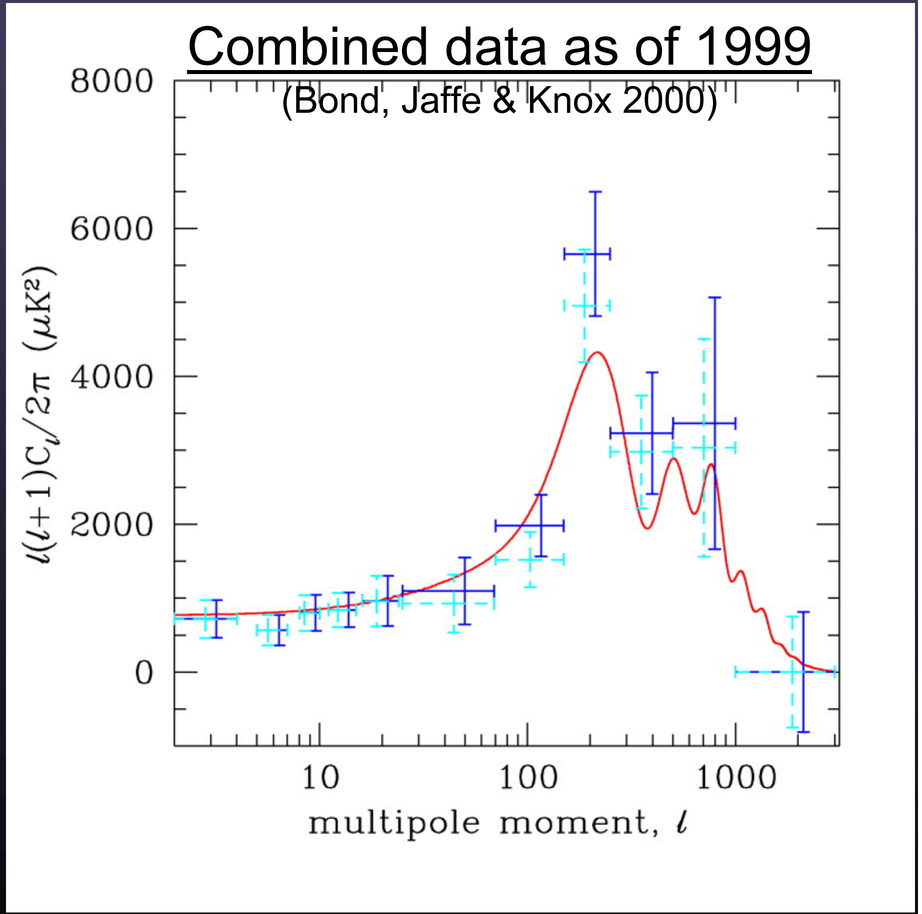
- Aside from dipole, only upper limits on anisotropy
  - Sensitivity limited by microwave technology
- Best limits on small (arcminute) angular scales
  - Uson & Wilkinson 1984; Readhead et al. 1989
    - $\Delta T/T < 2 \times 10^{-5}$ on 2'-7' scales
    - requires dark matter for reasonable $\Omega_0 > 0.2$
- Theory of CMB power spectra (e.g. Bond & Esthathiou 1987)



In the 1990's

- Better receivers (e.g. HEMT) = first detections!
- COBE satellite: FIRAS (spectrum), DMR (anisotropies)
- Ground and Balloon-based
- Hint of first peak detection!



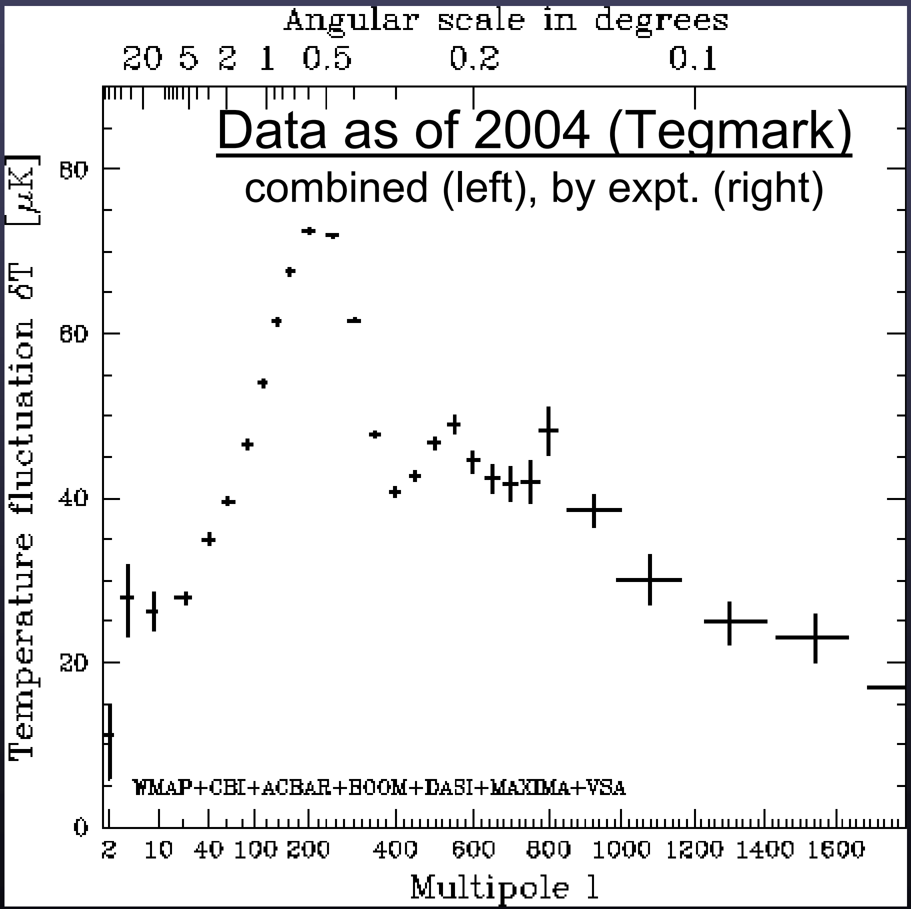


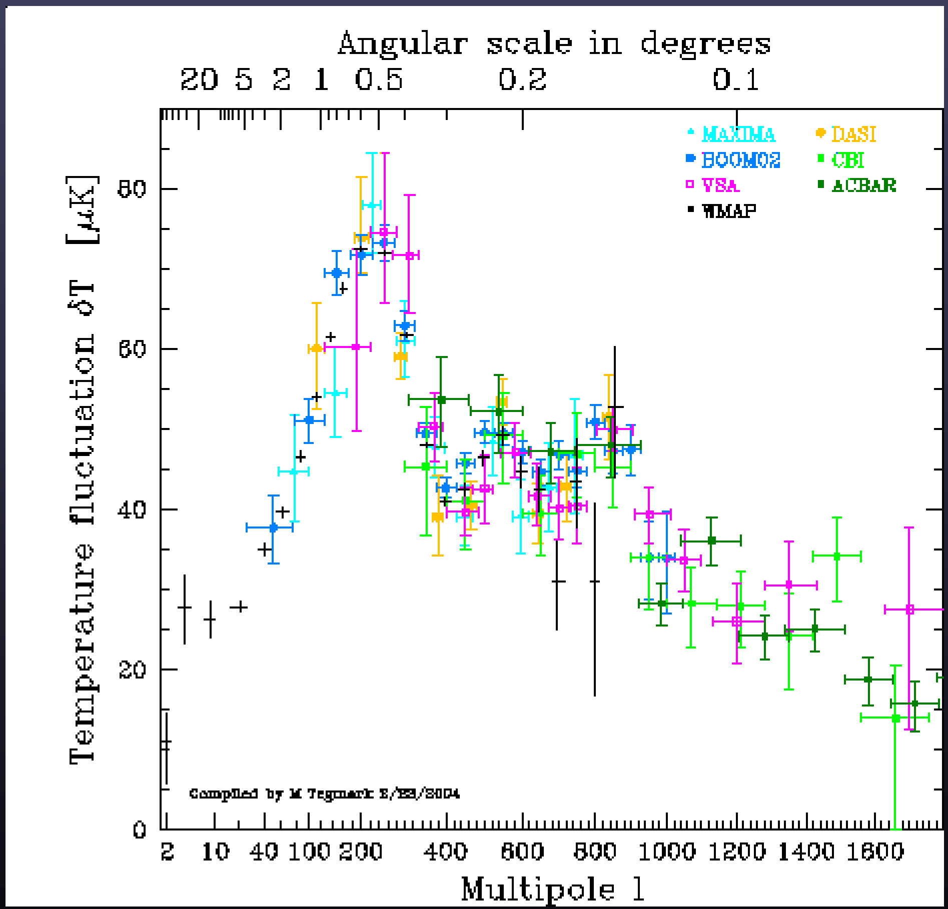
Turn of the Century: 2000 onwards

- Balloon results (Boomerang, Maxima); Interferometers (CBI, DASI, VSA); Satellites (WMAP)
  - Measurement of first 2-3 peaks and damping tail

Data as of 2004 (Tegmark)

combined (left), by expt. (right)

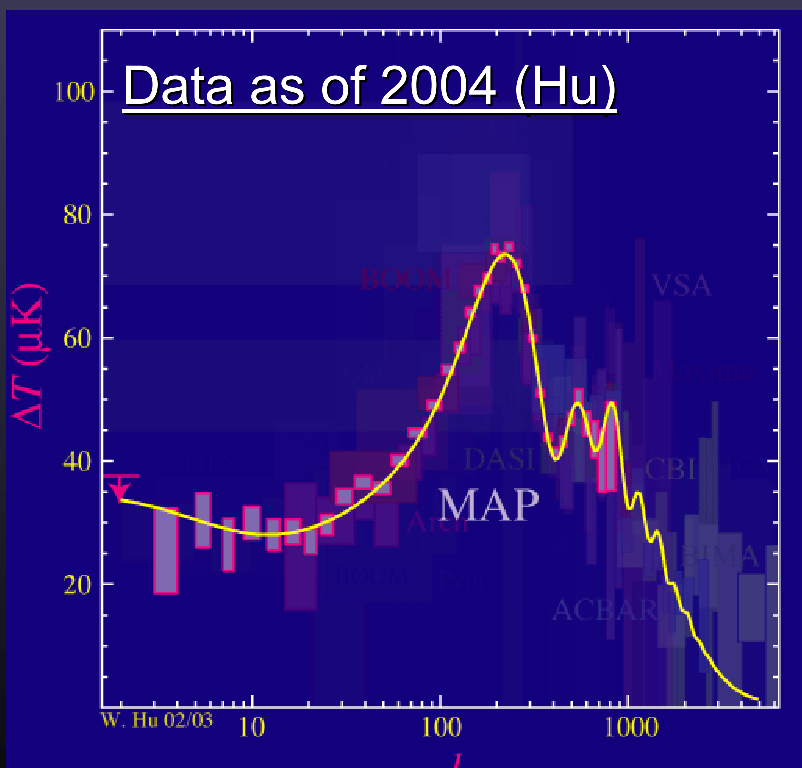


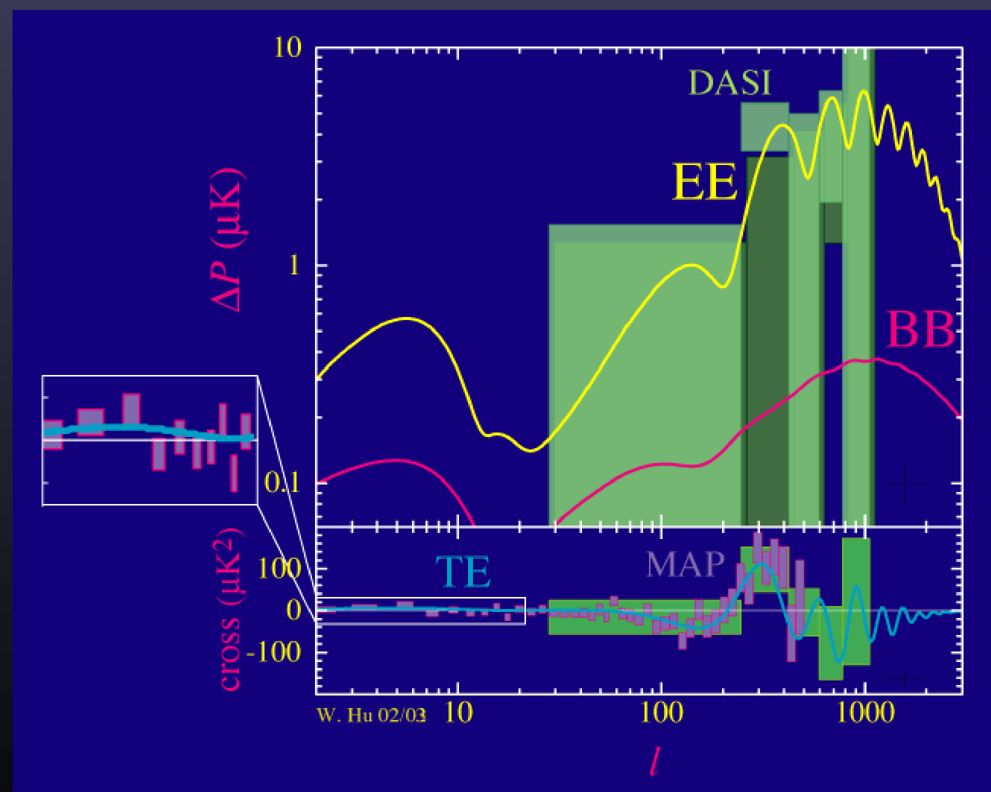


Courtesy Max Tegmark – *http://space.mit.edu/home/tegmark/cmb/experiments.html*

Turn of the Century: 2000 onwards

- Balloon results (Boomerang, Maxima); Interferometers (CBI, DASI, VSA); Satellites (WMAP)
  - Measurement of first 2-3 peaks and damping tail
  - Detection of E-mode polarization
  - Dawn of Precision Cosmology!

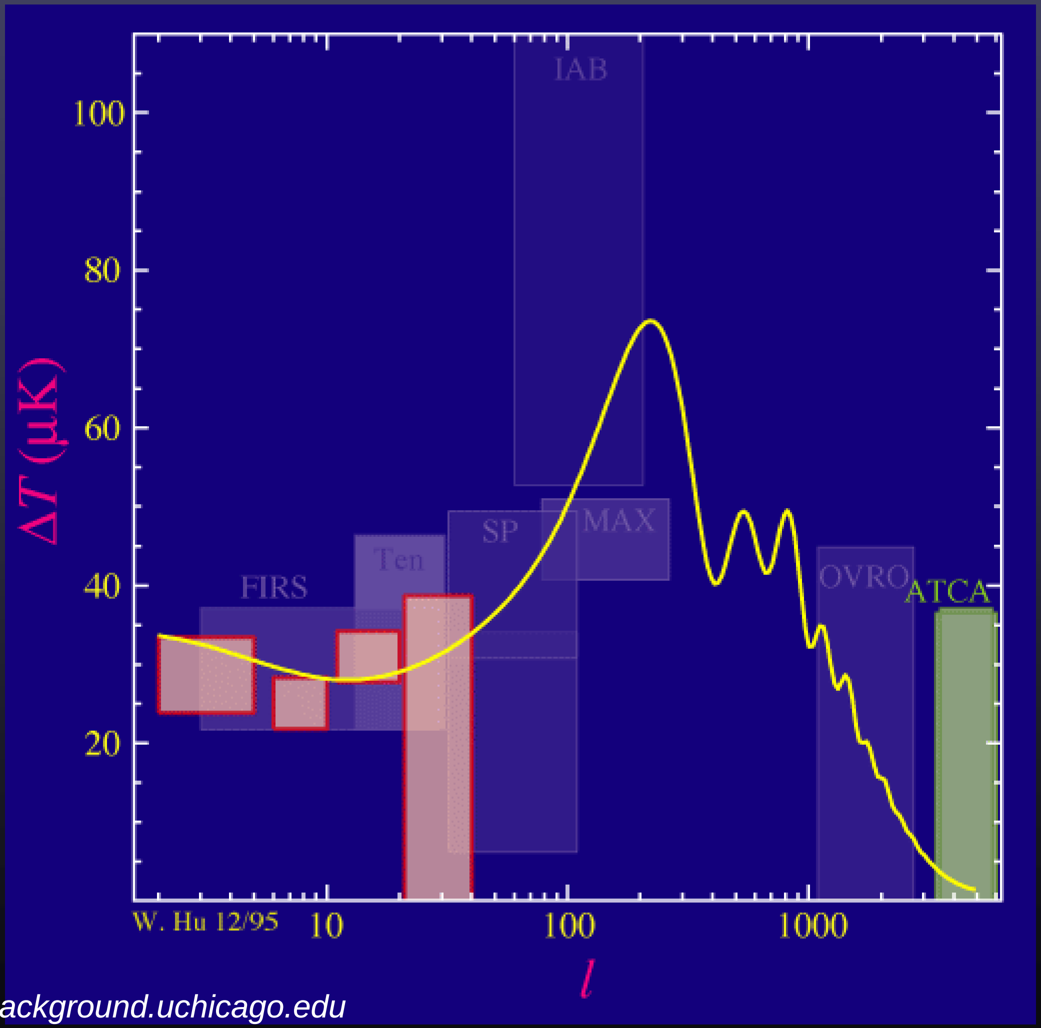




Courtesy Wayne Hu – *http://background.uchicago.edu*

The March of Progress

- Continual improvements in observational technology and technique (ground, balloon, space):

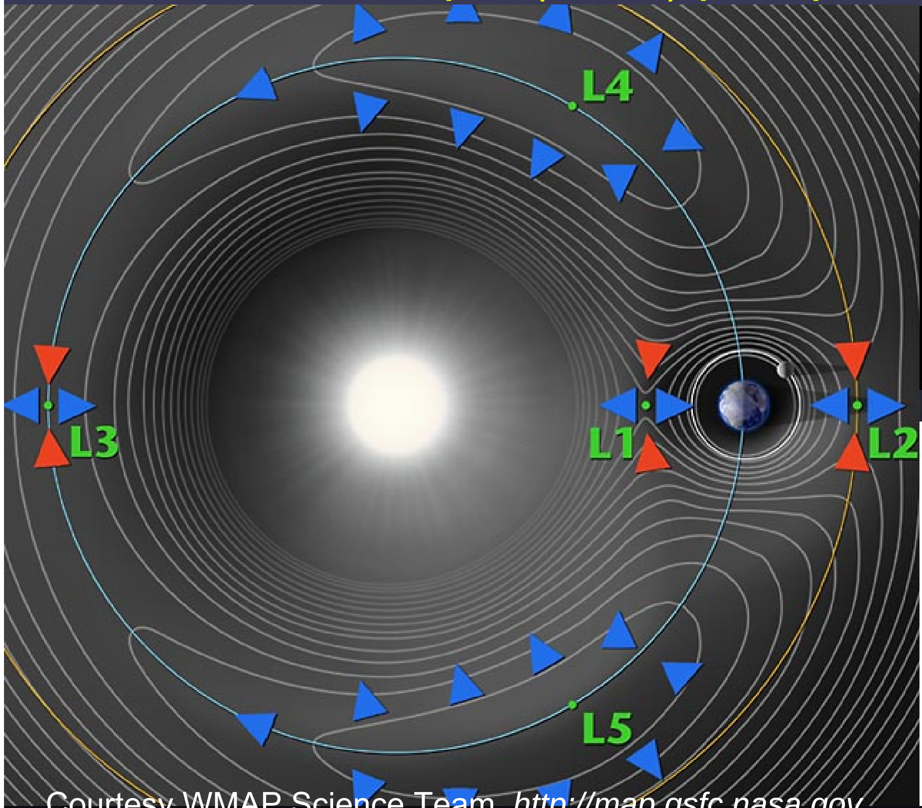


Courtesy Wayne Hu – *http://background.uchicago.edu*

WMAP

The WMAP Mission

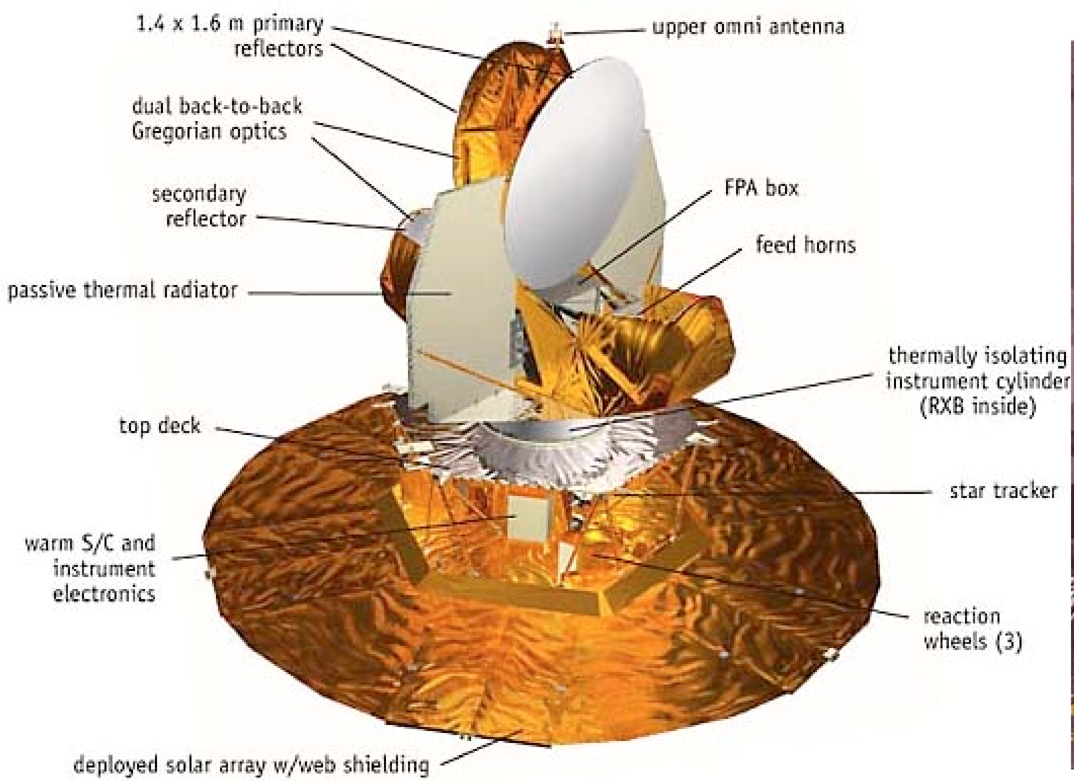
- Wilkinson Microwave Anisotropy Probe
  - proposed 1995, selected by NASA 1996, launched June 2001
  - at L2 point (Sun and Earth shielded), scan full sky in 1 year
  - fast spin (2.2m) plus precession (1hour), scan 30% sky in 1 day



Courtesy WMAP Science Team *http://map.gsfc.nasa.gov*

The WMAP Telescope

- 1.4m × 1.6m Gregorian mirrors (0.3° – 0.7° resolution)
  - two telescopes pointed 140° apart on sky – differential radiometry
  - HEMT microwave radiometers (built by NRAO), orthogonal linear polarizations
  - 5 Bands: K (23GHz), Ka (33GHz), Q (41GHz), V (61GHz), W (94GHz)



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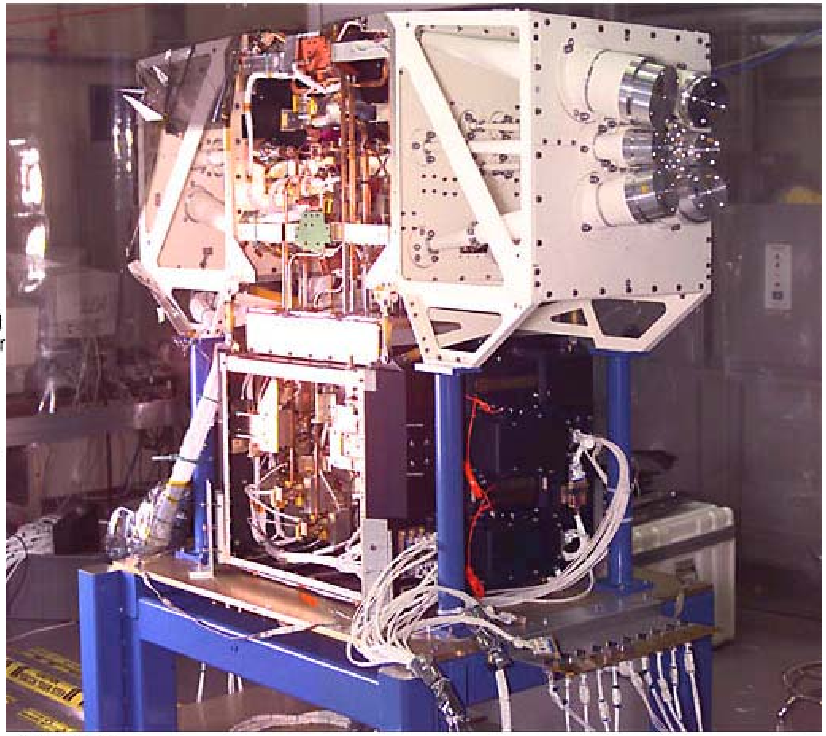

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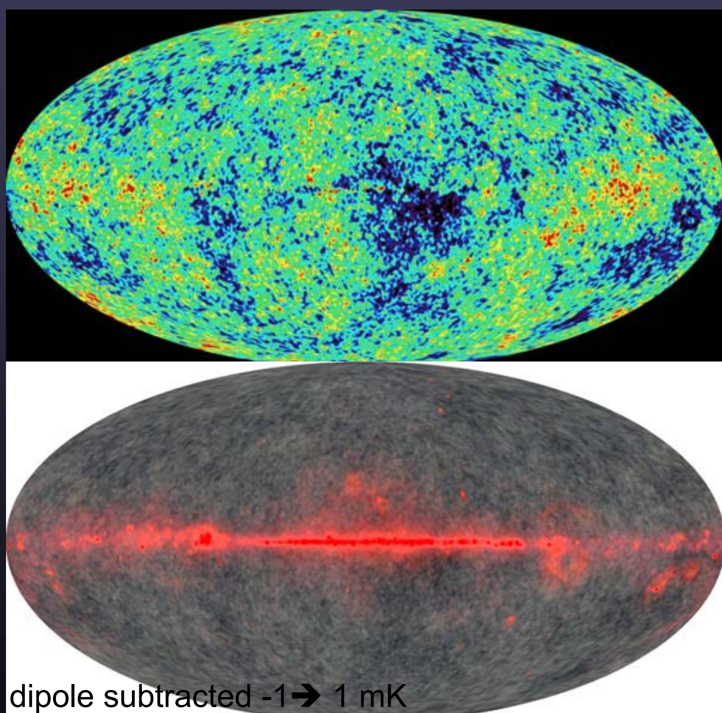
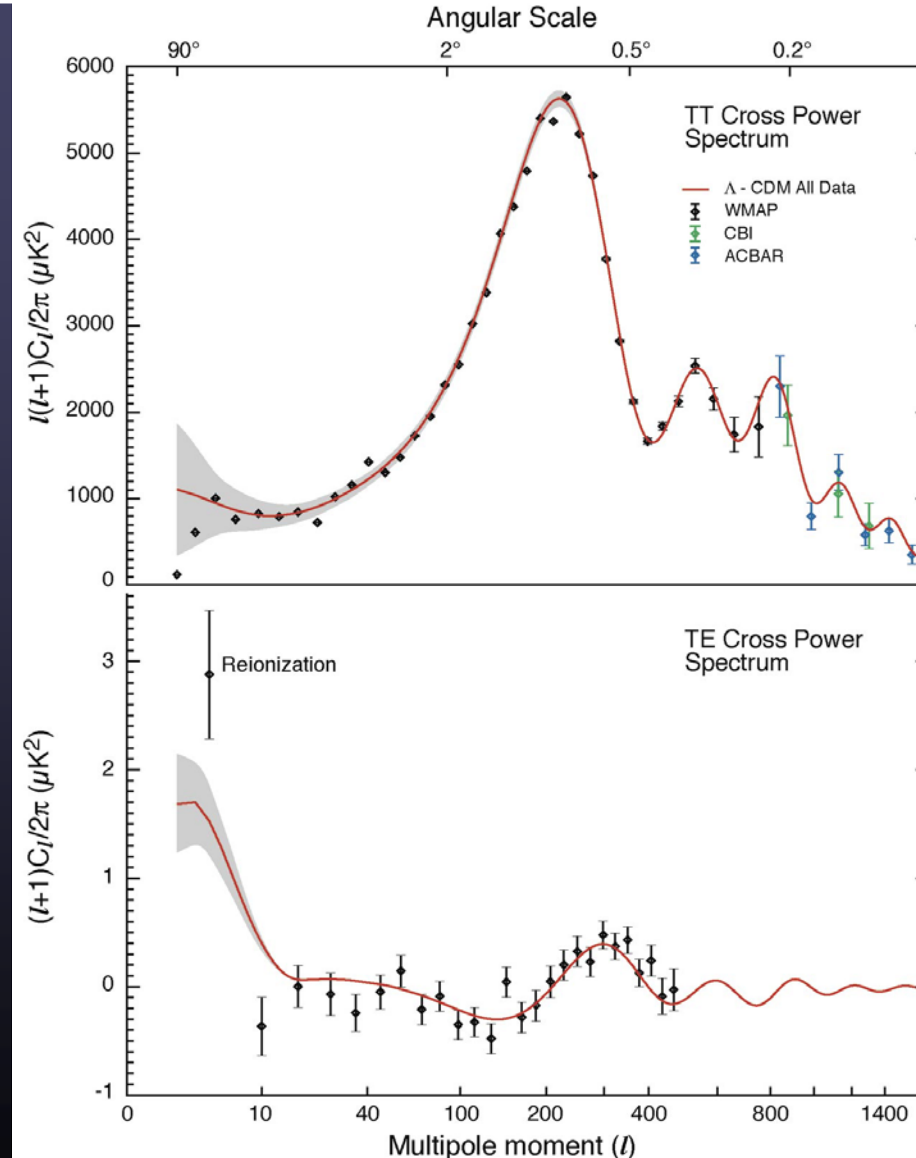
WMAP 1-yr data release (2003)

- Bennett et al. (2003) ApJS, 148, 1
- TT spectrum
- TE spectrum
- ILC vs. 41/61/94GHz image





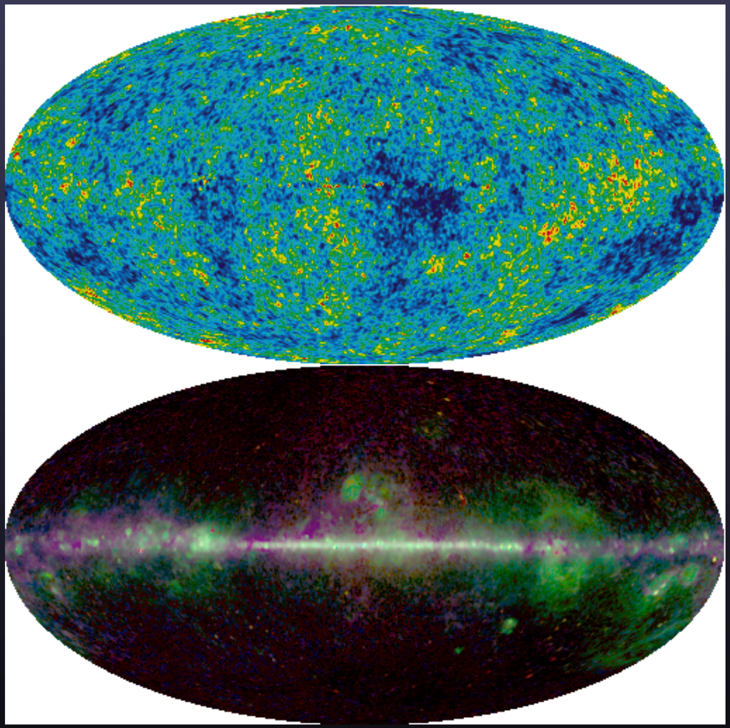
Courtesy WMAP Science Team *http://lambda.gsfc.nasa.gov*

Mission so far

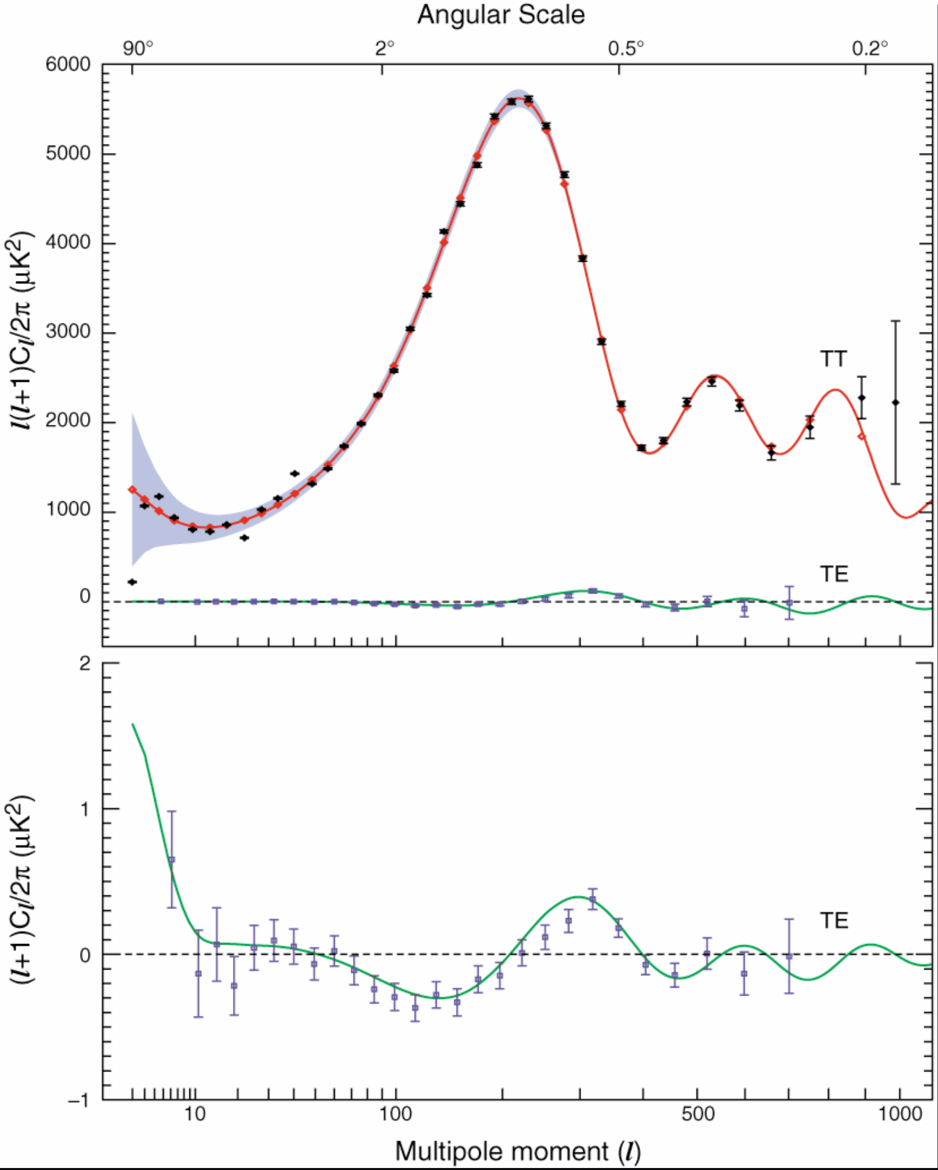
- First year data release (2003)
  - first and second peaks in TT
  - low-ℓ anomalies & cold spots: geometry? foreground? variance?
  - first peak in TE polarization (but no EE or BB results reported)
  - confirmation of nearly flat Universe
  - consistent with scale-invarinat $n_{S} \approx 1$, hint of running α_S (w/Lyα)
  - high TE < 10 ➔ τ=0.17 early reionization (z~20)

WMAP 3-yr data release (2006)

- Hinshaw et al. (2006) submitted
- TT & TE spectrum
- EE spectrum (not shown)
- ILC vs. 61GHz foreground model



Courtesy WMAP Science Team *http://lambda.gsfc.nasa.gov*



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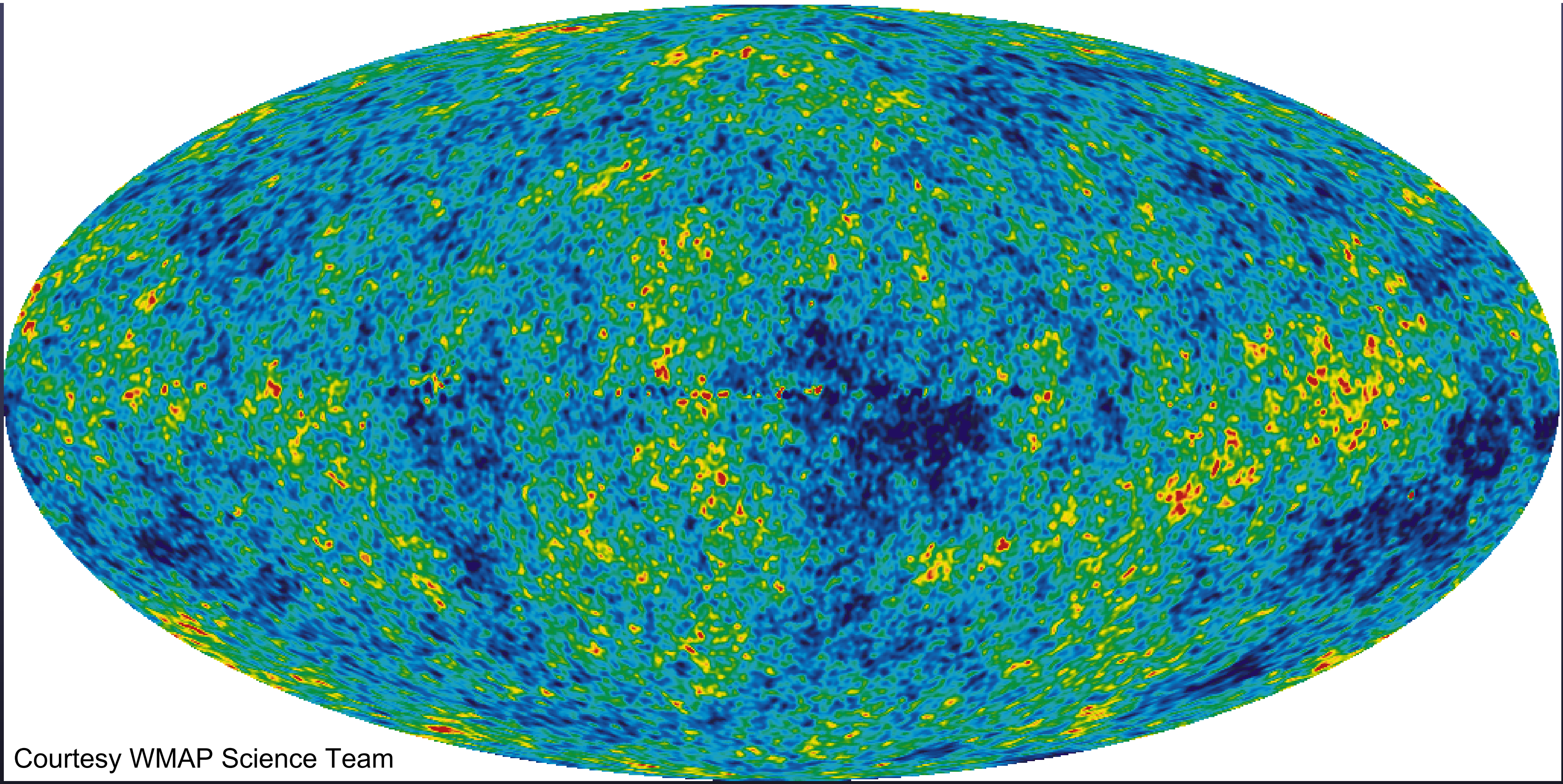
- Third year data release (2006)
  - rise to third peak (hint of lower σ_8 ~ 0.7)
  - better models for galactic (polarized) foregrounds!!!
  - EE & BB : lower τ=0.09 standard reionization (z<10)
  - $n_{S} \approx 0.95 \pm 0.02$, no hint of running α_S in WMAP alone

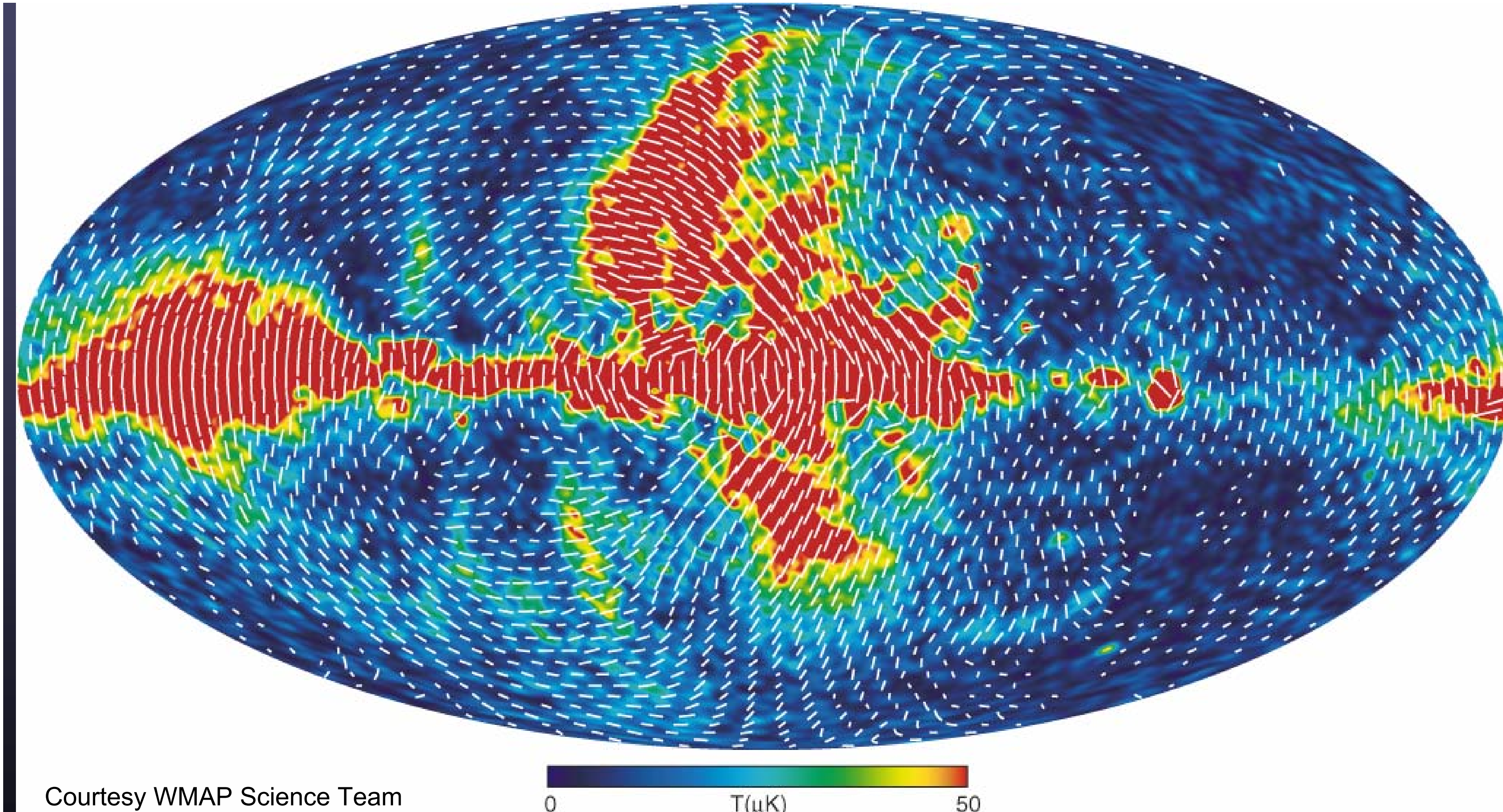
WMAP 3 - ILC



Courtesy WMAP Science Team

WMAP 3yr internal linear combination (ILC) temperature map (CMB -200 to 200 μK)

WMAP 3 - polarization

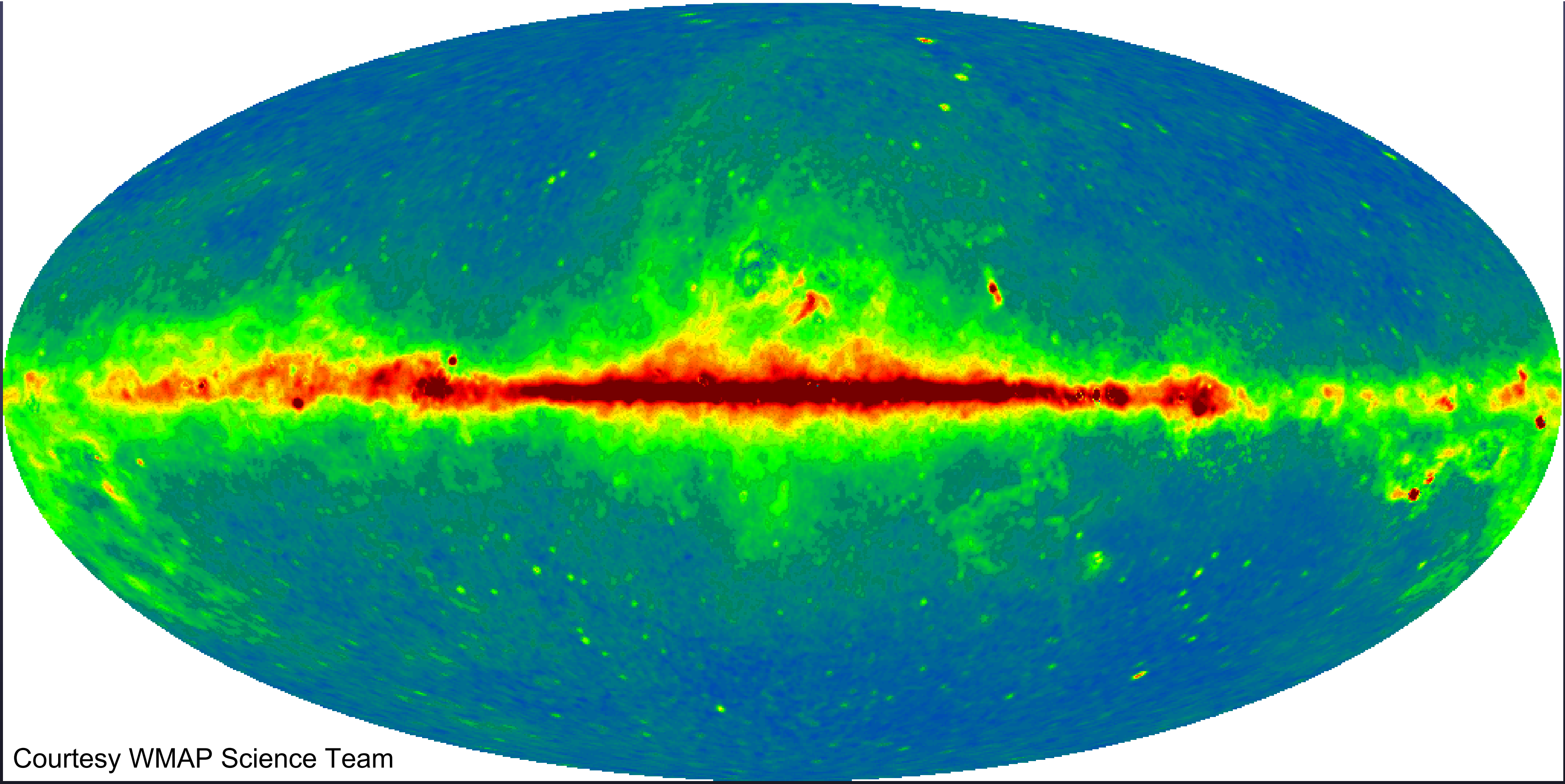


Courtesy WMAP Science Team

WMAP 3-yr 22 GHz polarization map (galaxy)

- linear scale 0 to 50 μK

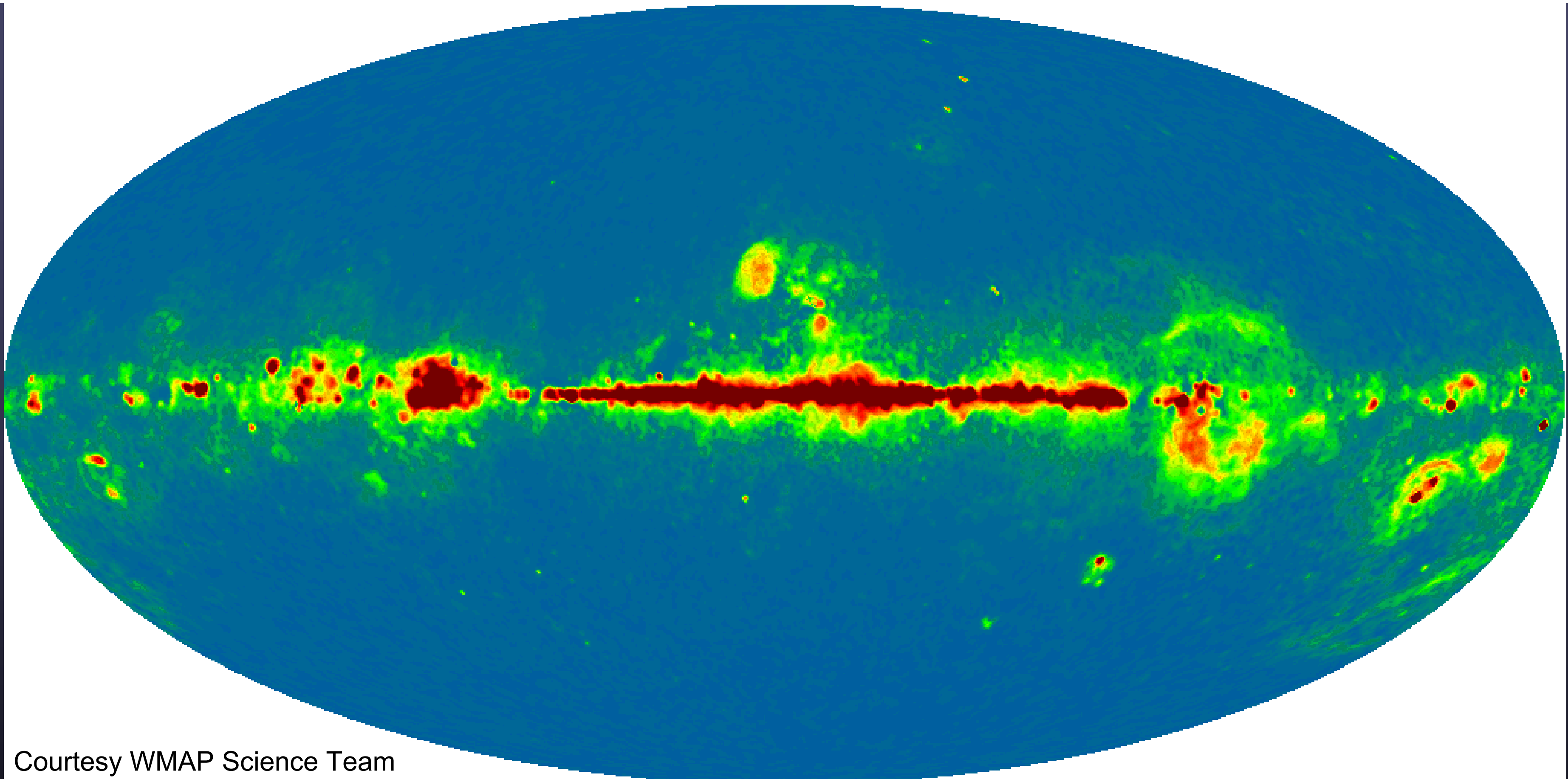
WMAP 3 - synchrotron


Courtesy WMAP Science Team

WMAP 3-yr 23 GHz synchrotron map (galaxy)

– model derived using MEM (linear scale -1 to 5 mK)

WMAP 3 – free-fee

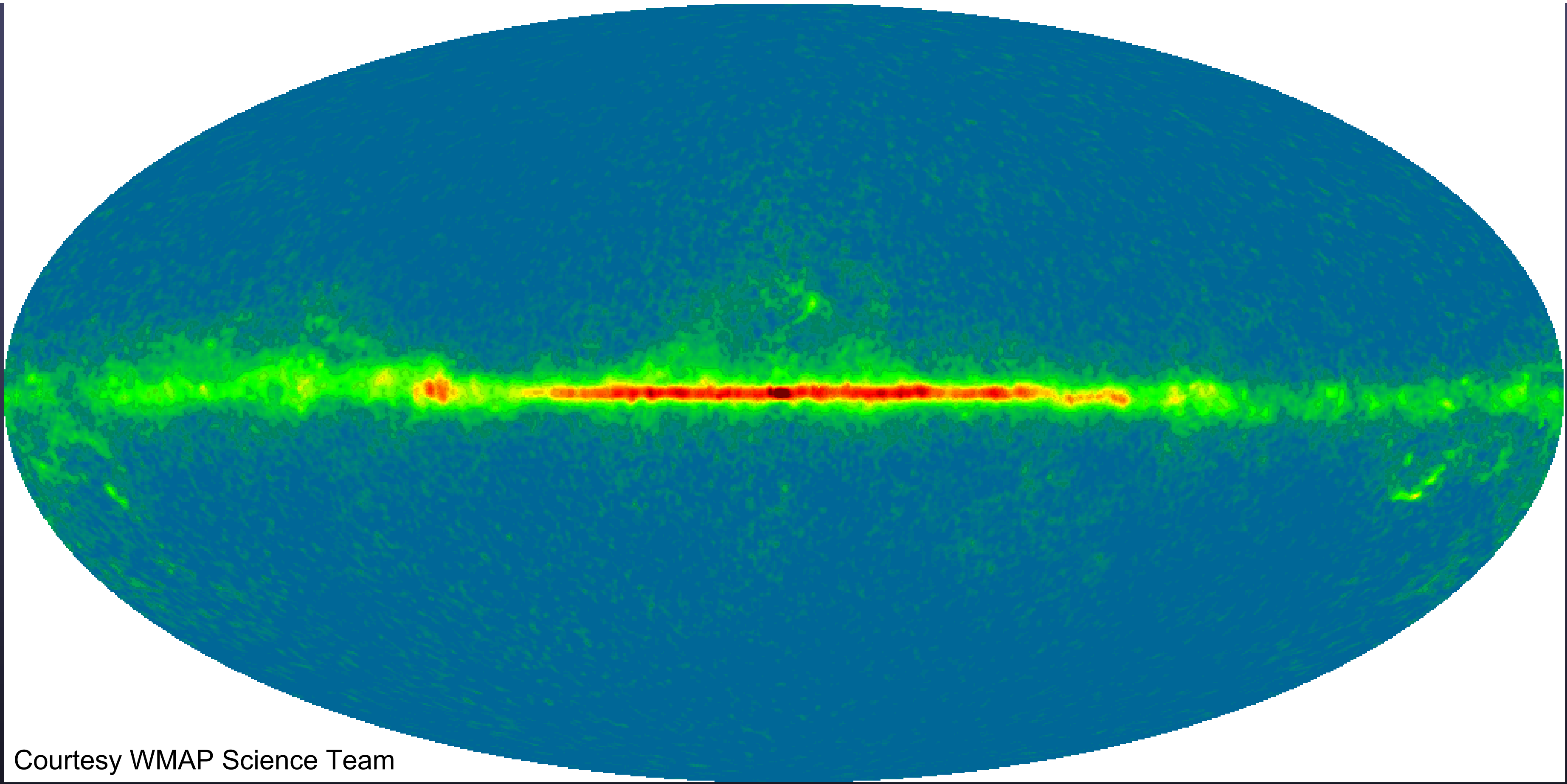


Courtesy WMAP Science Team

WMAP 3-yr 23 GHz free-free map (galaxy)

– model derived using MEM (linear scale: -1.0 to 4.7 mK)

WMAP 3 - dust

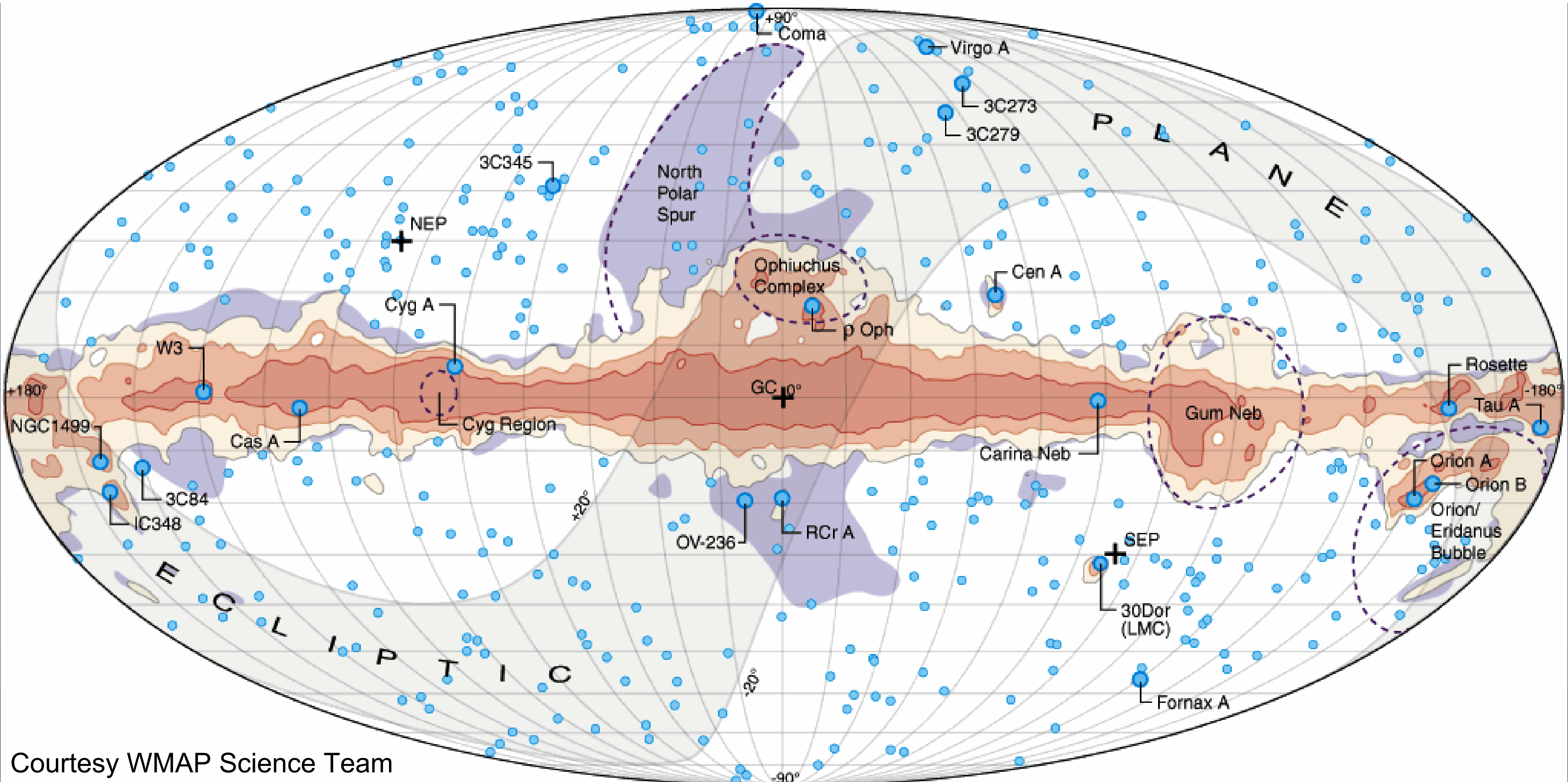


Courtesy WMAP Science Team

WMAP 3-yr 94 GHz dust map (galaxy)

– model derived using MEM (linear scale: -0.5 to 2.3 mK)

WMAP 3 galaxy

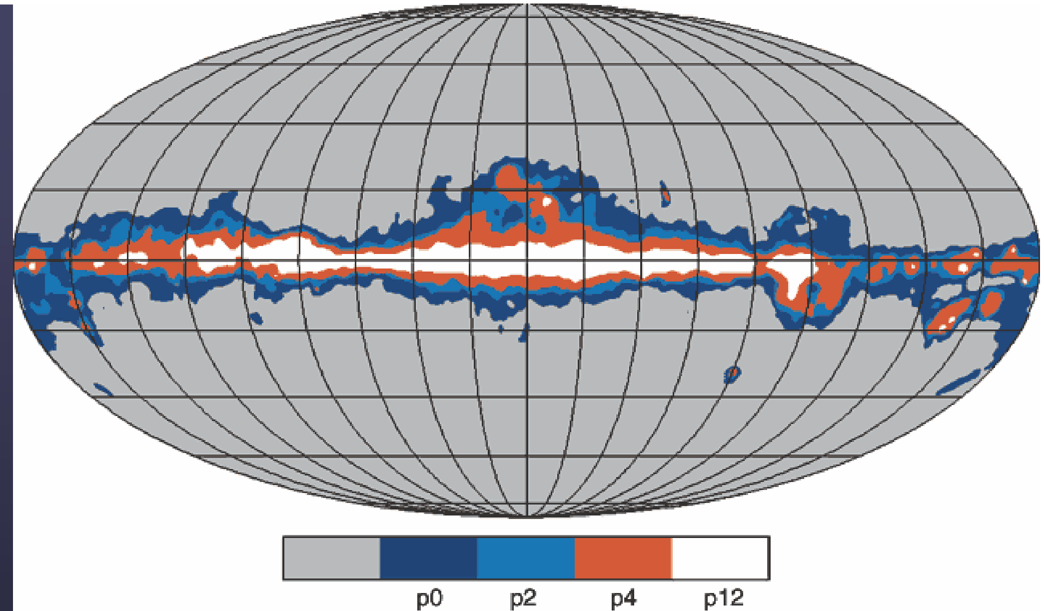


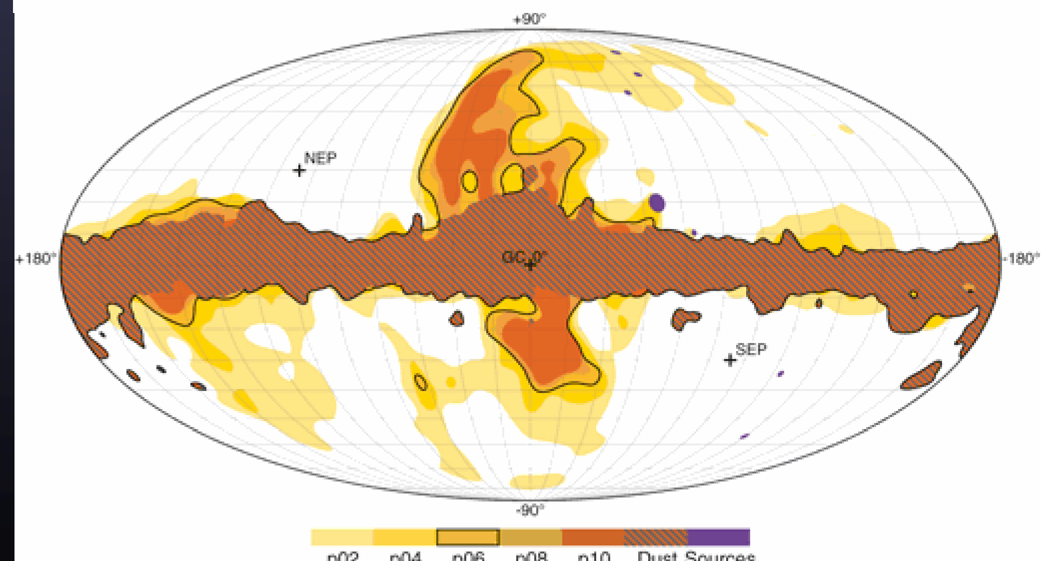
Courtesy WMAP Science Team

Galactic microwave map for orientation

WMAP3 - masks

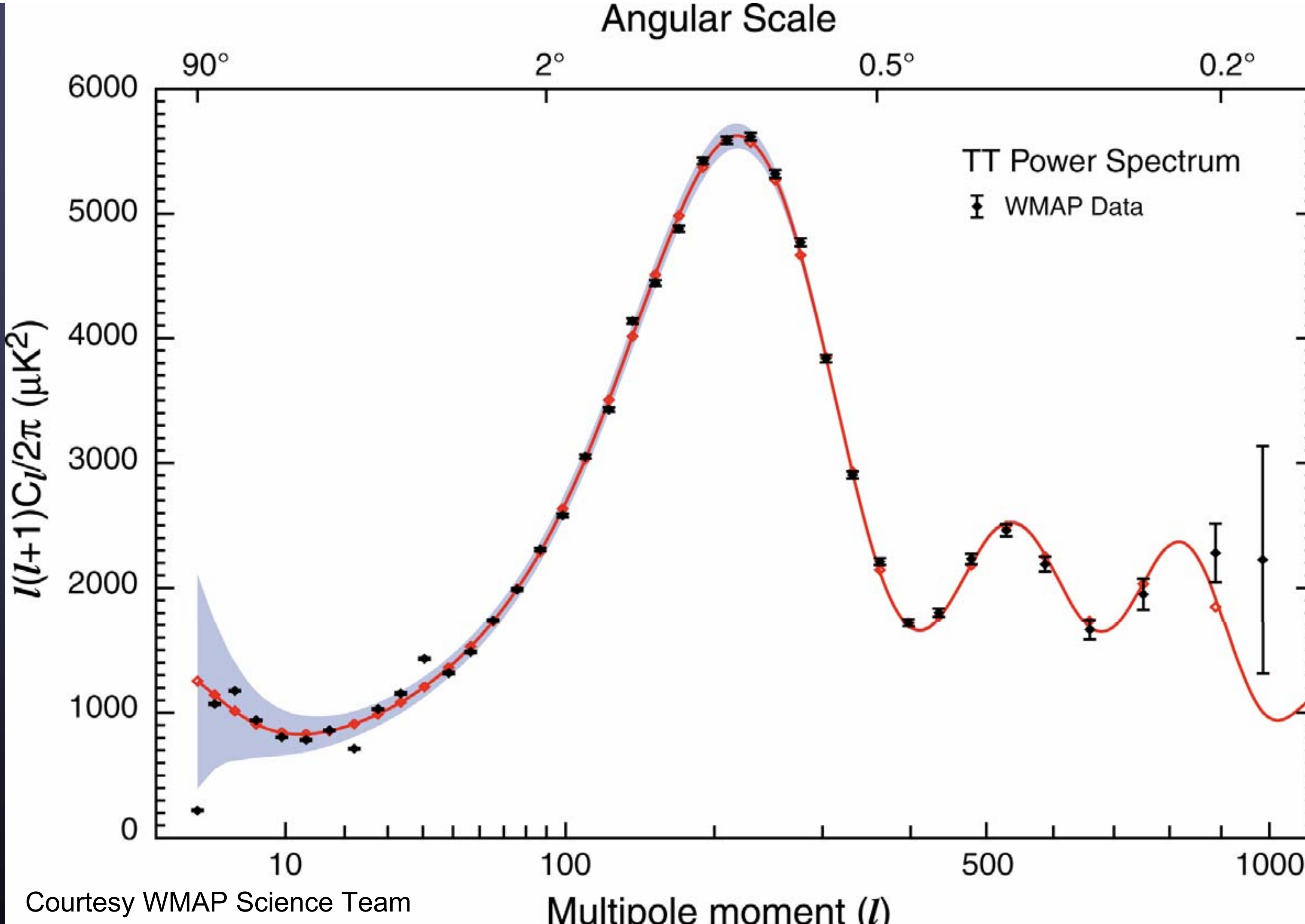
- To compute power spectrum and determine cosmological parameter constraints the WMAP team used <u>galactic masks</u>
  - *top panel* – the Kp2 mask was used for temperature data analysis. This was derived from the K-band (23GHz) total intensity image.
  - *bottom panel* - the P06 (black curve) was used for polarization analysis. The mask was derived from the K-band (23GHz) polarized intensity.





Courtesy WMAP Science Team *http://lambda.gsfc.nasa.gov*

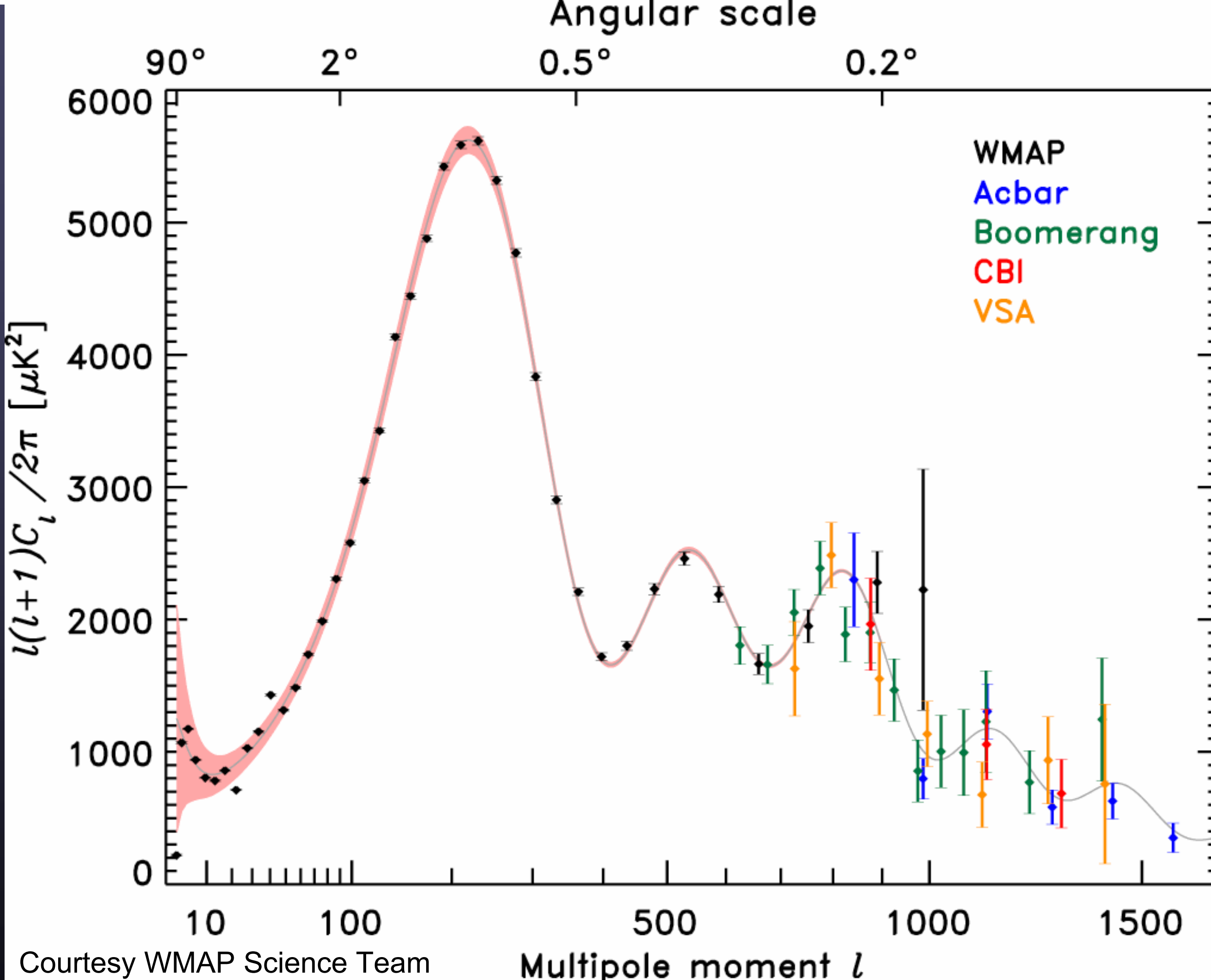
WMAP 3 – TT power spectrum



Courtesy WMAP Science Team

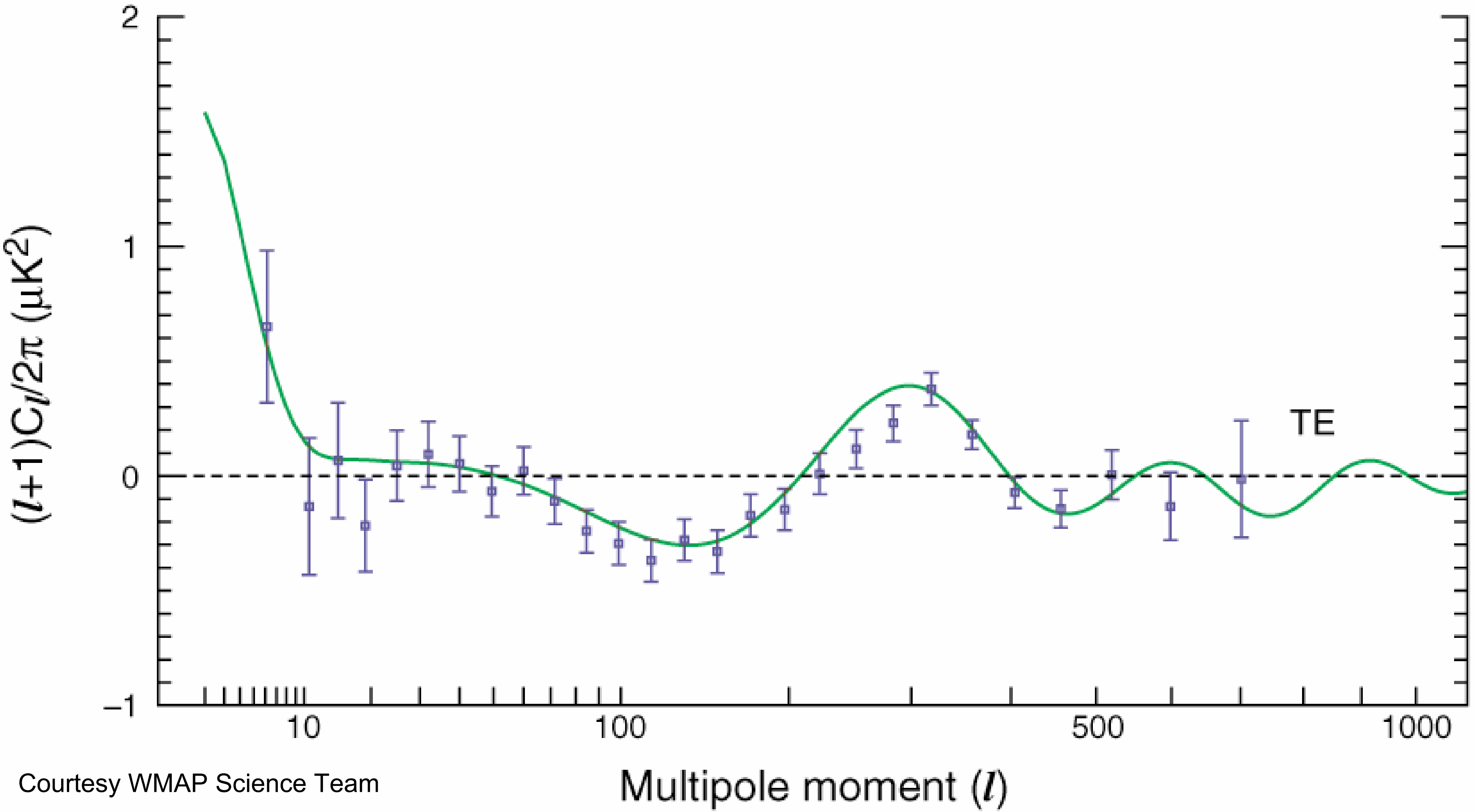
WMAP 3yr TT power spectrum (Hinshaw et al. 2006)

WMAP 3 – TT vs. all expts.



WMAP+ 3yr TT power spectrum (Hinshaw et al. 2006)

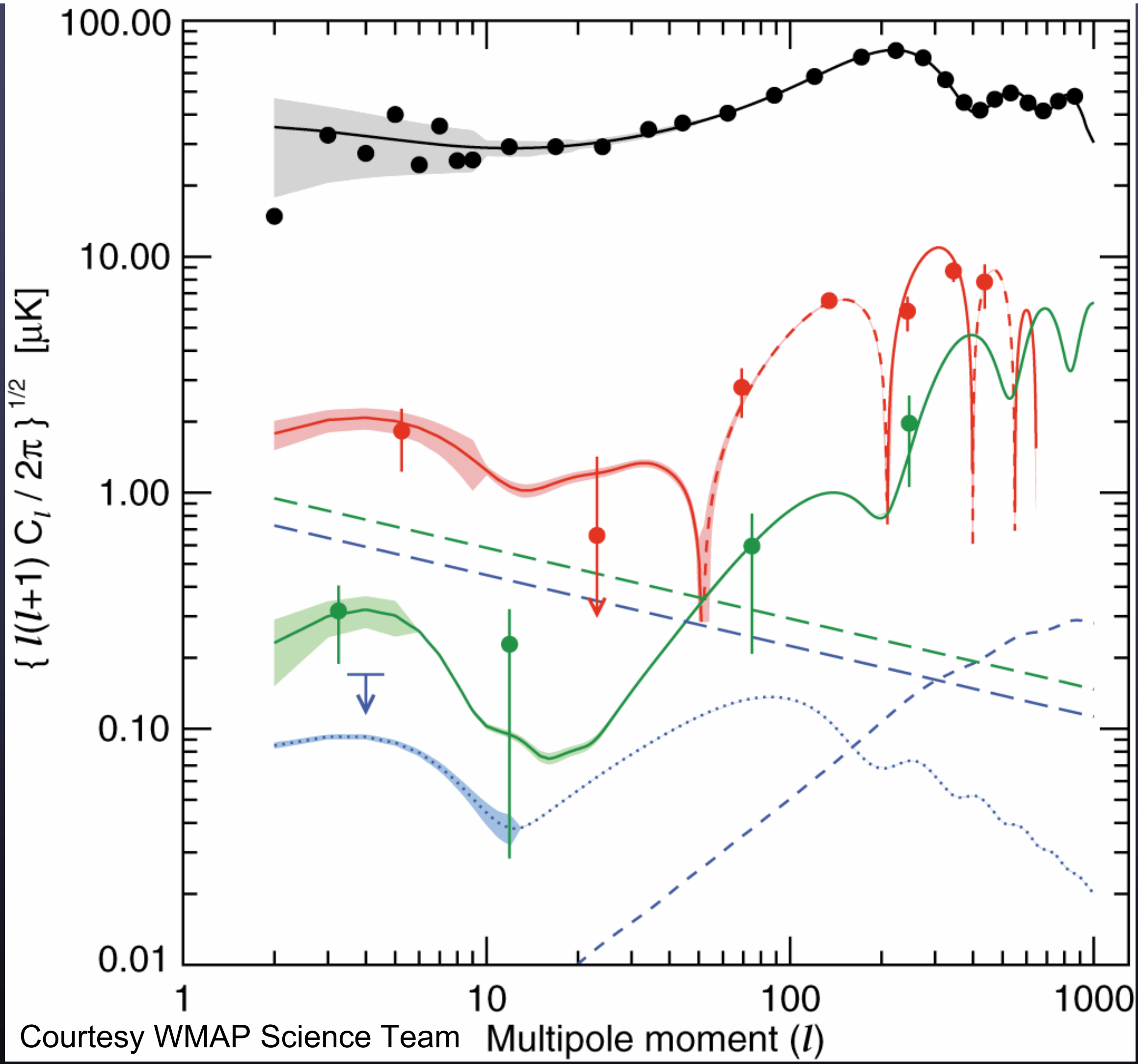
WMAP 3 – TE power spectrum



Courtesy WMAP Science Team

WMAP 3yr TE power spectrum (Hinshaw et al. 2006)

WMAP 3 – TT/TE/EE spectrum



WMAP 3yr power spectra (Page et al. 2006)

WMAP 3 – Cosmological Parameters

- Cosmological parameters (ΛCDM) from WMAP3 alone

Ω_c	$=$	$0.20^{+0.02}_{-0.04}$
$\Omega_c h^2$	$=$	$0.104^{+0.007}_{-0.010}$
Ω_Λ	$=$	$0.76^{+0.04}_{-0.03}$
Ω_m	$=$	$0.24^{+0.03}_{-0.04}$
$\Omega_m h^2$	$=$	$0.127^{+0.007}_{-0.009}$
σ_8	$=$	$0.74^{+0.05}_{-0.06}$
$\sigma_8 \Omega_m^{0.6}$	$=$	$0.31^{+0.04}_{-0.05}$
A_{SZ}	$=$	$0.99^{+0.92}_{-0.99}$
t_0	$=$	$13.7^{+0.1}_{-0.2}$ Gyr
τ	$=$	$0.088^{+0.028}_{-0.034}$
θ_A	$=$	$0.595 \pm 0.002\ ^\circ$
z_{eq}	$=$	3036^{+168}_{-250}
z_r	$=$	$10.9^{+2.7}_{-2.3}$

$10^2 \Omega_b h^2$	$=$	$2.23^{+0.07}_{-0.09}$
A	$=$	$0.68^{+0.04}_{-0.06}$
$A_{0.002}$	$=$	$0.80^{+0.04}_{-0.05}$
$\Delta^2_{\mathcal{R}}$	$=$	$(20^{+1}_{-2}) \times 10^{-10}$
$\Delta^2_{\mathcal{R}}(k = 0.002/Mpc)$	$=$	$(24^{+1}_{-2}) \times 10^{-10}$
h	$=$	$0.73^{+0.03}_{-0.04}$
H_0	$=$	73^{+3}_{-4} km/s/Mpc
ℓ_A	$=$	$302.6^{+0.9}_{-1.4}$
n_s	$=$	$0.951^{+0.015}_{-0.019}$
$n_s(0.002)$	$=$	$0.951^{+0.015}_{-0.025}$
Ω_b	$=$	$0.042^{+0.003}_{-0.005}$
$\Omega_b h^2$	$=$	$0.0223^{+0.0007}_{-0.0009}$

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  - EE & BB : lower τ=0.09 standard reionization (z<10)
  - $n_S \approx 0.95 \pm 0.02$, no hint of running α_S in WMAP alone
- Funded for six years (asking for eight)
  - passive cooling, no consumables except for L2 station-keeping

CMB Interferometry: the CBI

Statistics of the CMB revisited

- Power Spectrum
  - power vs. multipole l (independent of m)
  - information is in power spectrum C_l

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \delta_{\ell\ell'} \delta_{mm'}$$

- Fourier analysis
  - small angles: $(l,m) = 2\pi(u,v)$
    - spherical harmonics ➔ Fourier transform (u,v conjugate coordinates)
  - uv-plane is quantized, each (u,v) mode independent

$$\tilde{T}(\mathbf{u}) = \int d^2\mathbf{x}\, e^{-i2\pi\mathbf{u}\cdot\mathbf{x}}\, T(\mathbf{x})$$

$$\langle \tilde{T}(\mathbf{u})\tilde{T}^*(\mathbf{u}') \rangle = C_\ell \delta^2(\mathbf{u}-\mathbf{u}') \qquad \ell = 2\pi|\mathbf{u}|$$

  - T is real: uv-plane has Hermitian symmetry

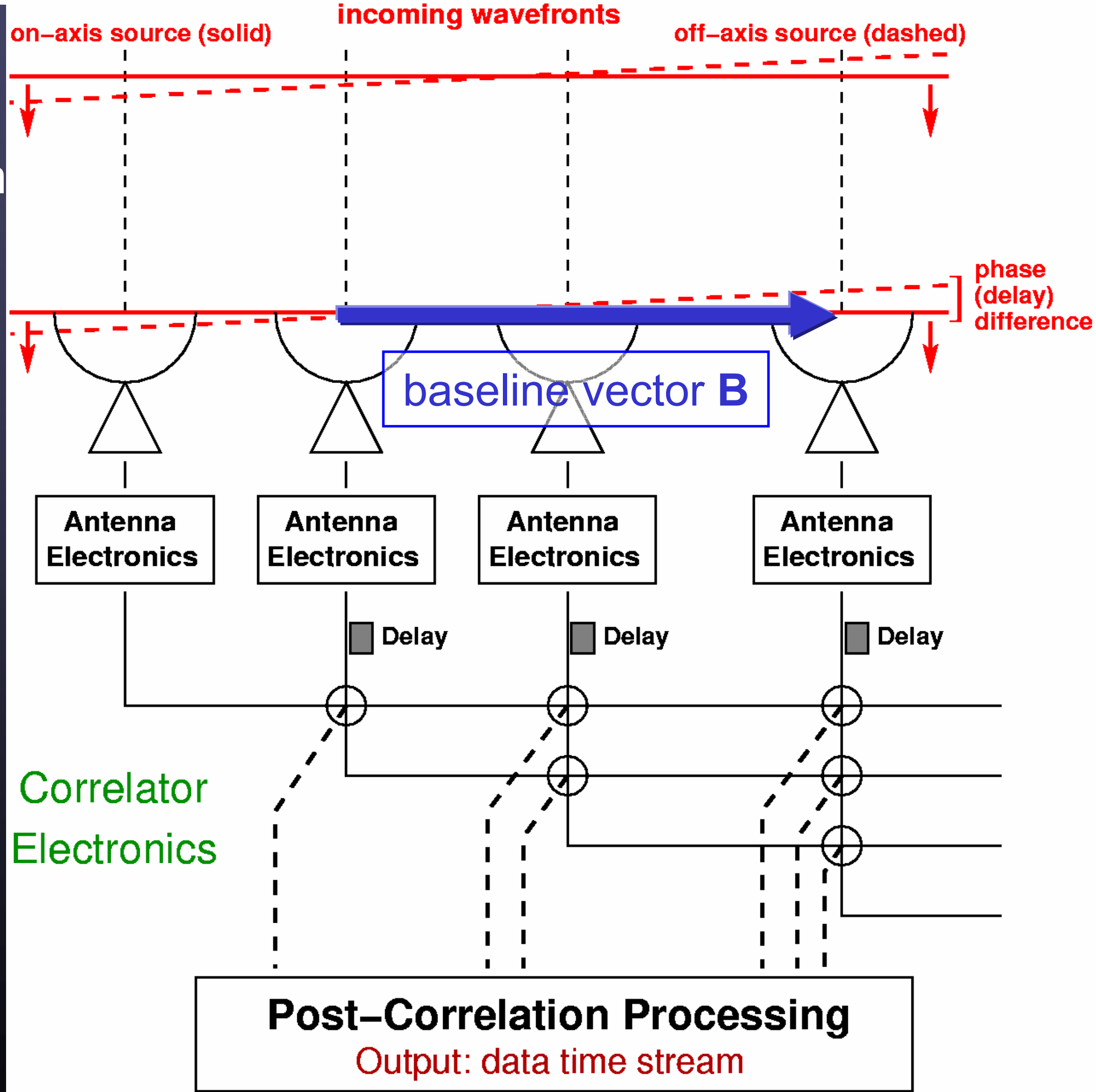
$$\tilde{T}(-\mathbf{u}) = \tilde{T}^*(\mathbf{u})$$

$$\langle \tilde{T}(\mathbf{u})\tilde{T}(\mathbf{u}') \rangle = C_\ell \delta^2(\mathbf{u}+\mathbf{u}') \qquad \ell = 2\pi|\mathbf{u}|$$

CMB is ideal for interferometry!

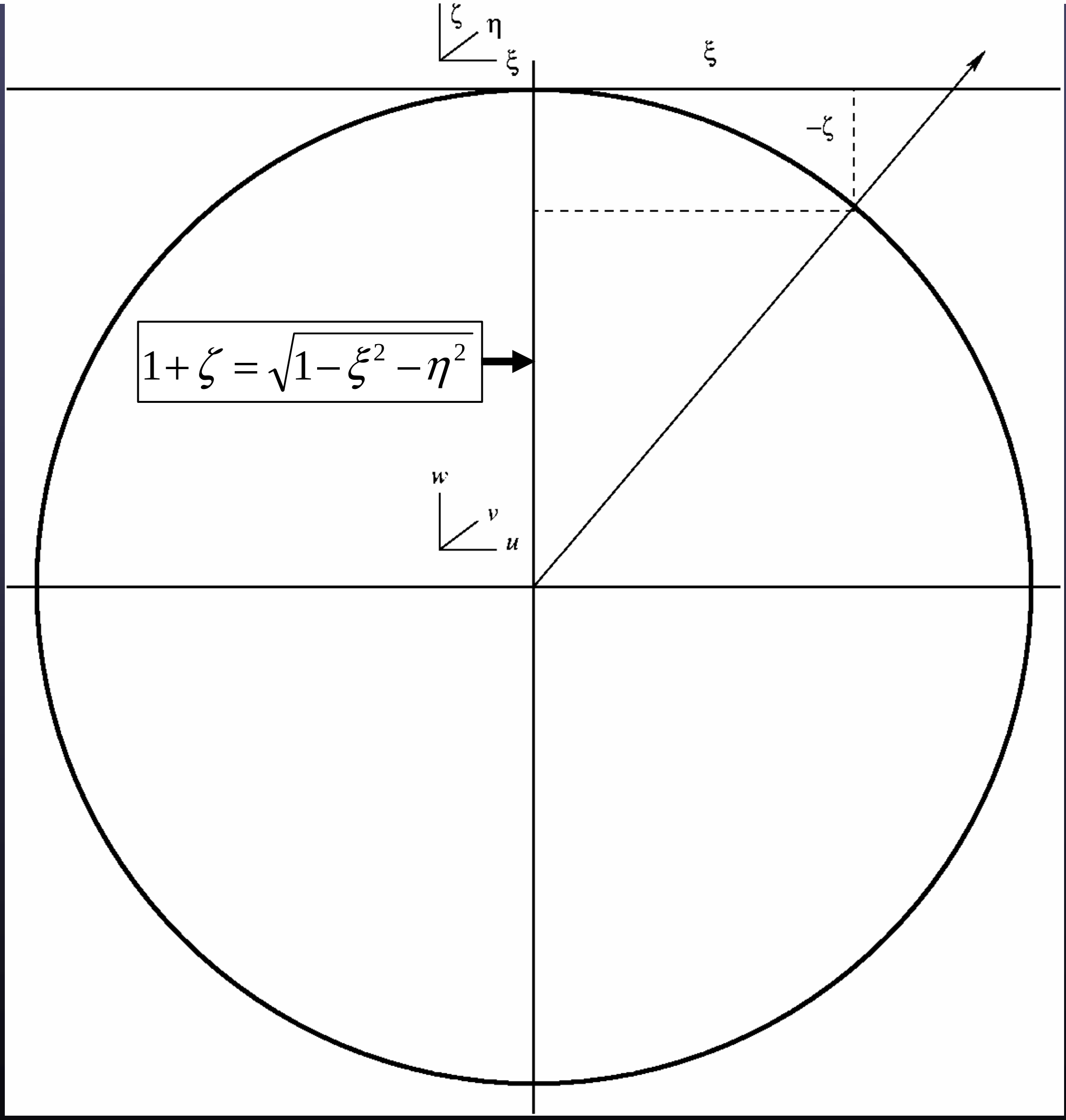
CMB Interferometer – schematic

- Spatial coherence of radiation pattern contains source structure information
  - wave-front correlations
- Correlate pairs of antennas
  - "visibility" = correlated fraction of total signal, calibrated as flux density
  - correlate real (cosine) and imaginary (90° shift=sine)
  - measure amplitude and phase of each product
- Function of baseline **B**
  - measures spatial frequencies $\boldsymbol{u} = \boldsymbol{B} / \lambda$
  - longer baselines = higher resolution



Standard sky geometry

- sky:
  - unit sphere
  - tangent plane
  - direction cosines
  - $\boldsymbol{\xi} = (\xi, \eta, \zeta)$
- interferometer:
  - $\mathbf{u} = \mathbf{B} / \lambda$
  - $\mathbf{u} = (u, v, w)$
- project plane-wave onto baseline vector
  - phase $2\pi\, \boldsymbol{\xi} \cdot \mathbf{u}$



Wavefront correlations

- Sum wavefronts over (incoherent) source distribution

$$V(u,v,w) = \iint \frac{d\xi\, d\eta}{1+\zeta} I(\xi,\eta)\, e^{i2\pi \boldsymbol{\xi}\cdot\mathbf{u}}$$

Visibility in *uv*-plane

Intensity field on sky

$$\boldsymbol{\xi} = (\xi,\eta,\zeta) \qquad \mathbf{u} = (u,v,w)$$

$$1+\zeta = \sqrt{1-\xi^2-\eta^2}$$

- for small fields-of-view can ignore w term, treat as 2D Fourier transform pair (Van Cittert-Zernicke theorem)

$$V(u,v) = \int dx\,dy\, I(x,y)\, e^{i2\pi(ux+vy)}$$

Basic Interferometry

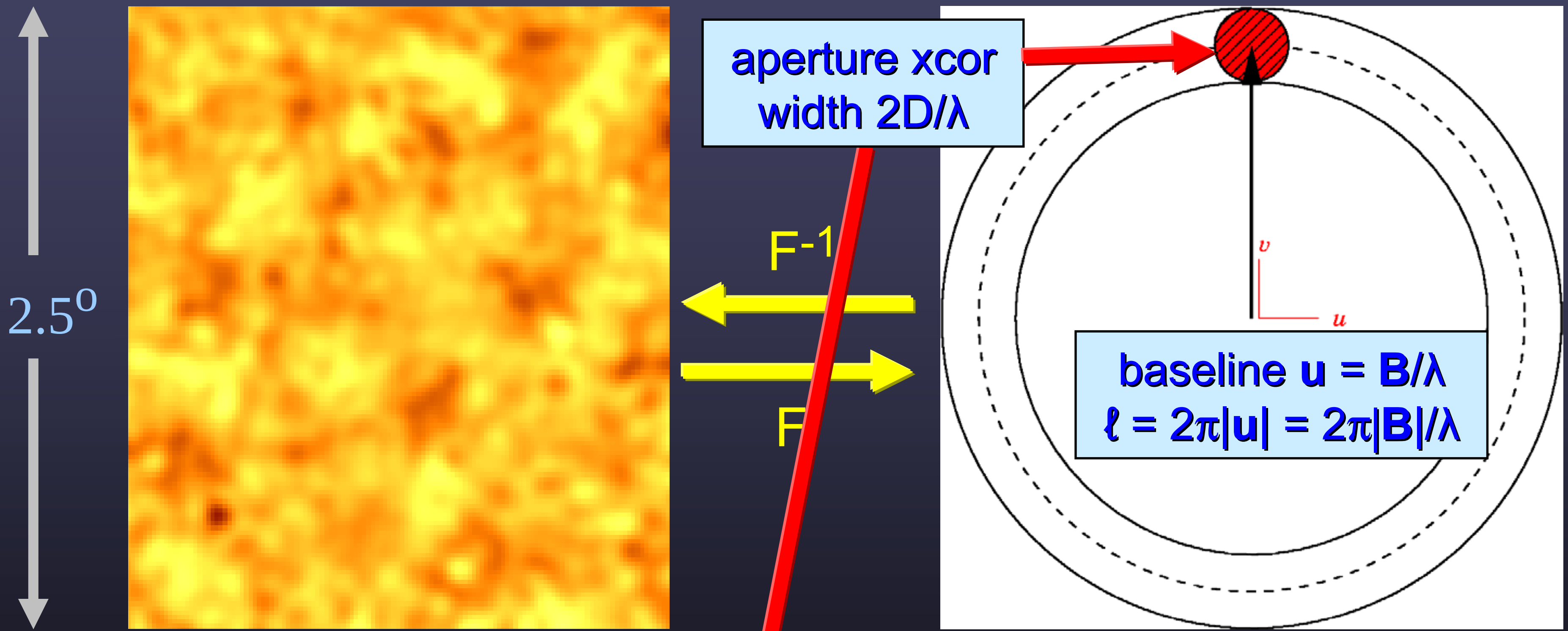
- For small (sub-radian) scales the spherical sky can be approximated by the Cartesian tangent plane
  - Similarly, the CMB spherical harmonics can be approximated as a Fourier transform for ℓ>>1
  - The conjugate variables are customarily (*u,v*) in radio interferometry, with $|\mathbf{u}| = l\,/\,2\pi$
- An interferometer naturally measures the transform of the sky intensity in l space convolved with aperture
  - cross-correlation of aperture voltage patterns in uv-plane
  - its tranform on sky is the primary beam with FWHM ~ λ/D

$$V(\mathbf{u}) = \int d^2\mathbf{x}\, A(\mathbf{x}-\mathbf{x}_p)\, I(\mathbf{x})\, e^{-2\pi i\,\mathbf{u}\cdot(\mathbf{x}-\mathbf{x}_p)} + \mathrm{e}$$

$$= \int d^2\mathbf{v}\, \tilde{A}(\mathbf{u}-\mathbf{v})\, \tilde{I}(\mathbf{v})\, e^{2\pi i\,\mathbf{v}\cdot\mathbf{x}_p} + \mathrm{e}$$

From sky to uv-plane

The uv-plane is the Fourier Transform of the tangent plane to the sky



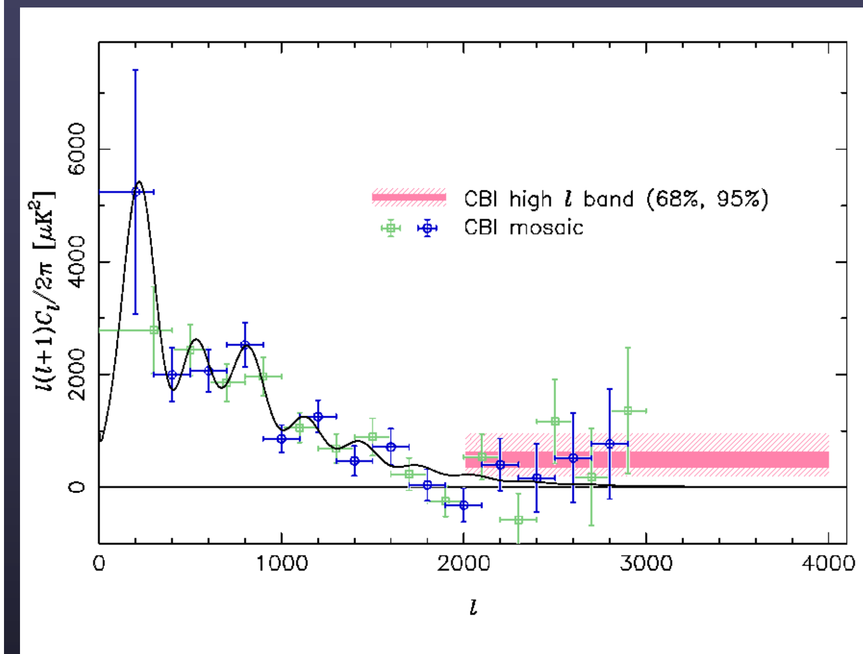
Sky Plane **x** = (x,y)

Fourier Plane **u** = (u,v)

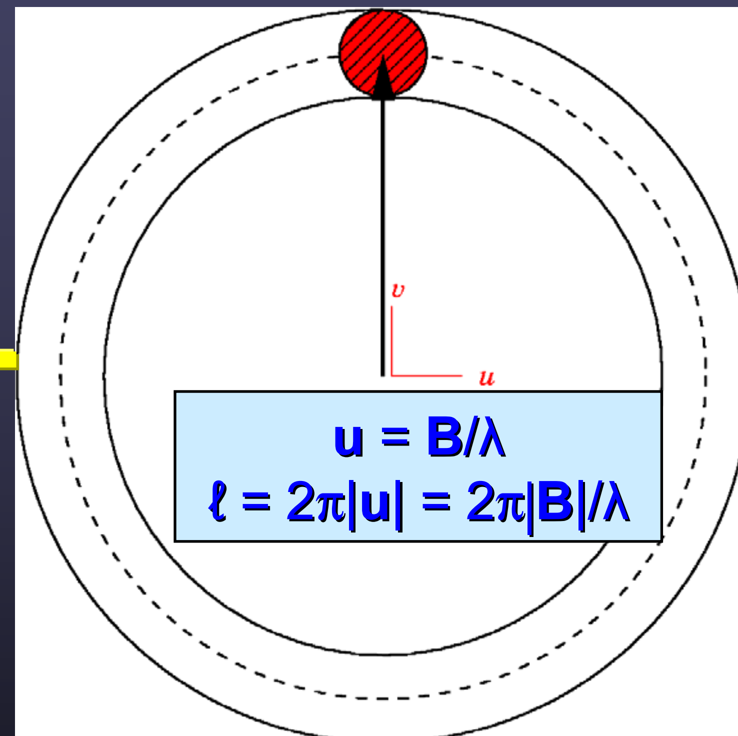
$$V(\mathbf{u}) = \int d^2\mathbf{v}\, \tilde{A}(\mathbf{u}-\mathbf{v})\, \tilde{I}(\mathbf{v})\, e^{2\pi i \mathbf{v}\cdot\mathbf{x}_p} + \mathrm{n}$$

From uv-plane to C_ℓ

The angular power spectrum is <u>square</u> of the Fourier Transform of CMB intensity



V^2



Power Spectrum C_ℓ

Fourier Plane **u** = (u,v)

$$C_\ell \approx \left\langle V^2(\mathbf{u}) \right\rangle_{2\pi|\mathbf{u}|=\ell}$$

<u>power spectrum easily extracted from interferometer visibilities!</u>

Polarization – Stokes parameters

- CBI (or VLA) receivers can observe either RCP or LCP
  - cross-correlate RR, RL, LR, or LL from antenna pair
- Correlation products (RR,LL,RL,LR) to Stokes (I,Q,U,V) :

$$\begin{pmatrix} \langle e_R e_R^* \rangle \\ \langle e_R e_L^* \rangle \\ \langle e_L e_R^* \rangle \\ \langle e_L e_L^* \rangle \end{pmatrix} = \begin{pmatrix} I+V \\ (Q+iU)e^{-i2\theta} \\ (Q-iU)e^{i2\theta} \\ I-V \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & e^{-i2\theta} & ie^{-i2\theta} & 0 \\ 0 & e^{i2\theta} & -ie^{-i2\theta} & 0 \\ 1 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

  - parallel hands RR, LL measure intensity I
  - cross-hands RL, LR measure linear polarization Q, U
    - modulated by parallactic angle θ of receiver on sky (AZEL) - derotate
    - R-L phase gives Q, U electric vector position angle
      - EVPA $\Phi = \frac{1}{2} \tan^{-1} (U/Q)$ (North through East)
    - Q “points” North, U 45 toward East ➔ coordinate system dependent

Polarization Interferometry : Q & U

- Parallel-hand & Cross-hand correlations
  - for visibility *k* (antenna pair *ij* , time, pointing *x*, and channel ν) :

$$V_k^{RR}(\mathbf{u}_k) = \int d^2\mathbf{v}\, \tilde{A}_k^{RR}(\mathbf{u}_k - \mathbf{v})\, \tilde{I}_\nu(\mathbf{v})\, e^{2\pi i \mathbf{v}\cdot\mathbf{x}_k} + \mathrm{e}_k^{RR}$$

$$V_k^{RL}(\mathbf{u}_k) = \int d^2\mathbf{v}\, \tilde{A}_k^{RL}(\mathbf{u}_k - \mathbf{v})\, \tilde{P}_\nu(\mathbf{v})\, e^{-i2\psi_k}\, e^{2\pi i \mathbf{v}\cdot\mathbf{x}_k} + \mathrm{e}_k^{RL}$$

  - where kernel A is the aperture cross-correlation function, and

$$\tilde{P}(\mathbf{v}) = \tilde{Q}(\mathbf{v}) + i\tilde{U}(\mathbf{v}) = \left|\tilde{P}(\mathbf{v})\right| e^{i2\phi(\mathbf{v})}$$

  - and ψ the baseline parallactic angle (w.r.t. deck angle 0°)

$$\psi_k = \tan^{-1}(v_k / u_k) - \psi_{ij0}$$

E and B modes

- Decomposition into E and B Fourier modes:

$$\tilde{Q}(\mathbf{v}) + i\,\tilde{U}(\mathbf{v}) = \left[\tilde{E}(\mathbf{v}) + i\,\tilde{B}(\mathbf{v})\right] e^{i2\chi_{\mathbf{v}}}$$

$$\tilde{E}(\mathbf{v}) + i\,\tilde{B}(\mathbf{v}) = \left|\tilde{P}(\mathbf{v})\right| e^{i2[\phi(\mathbf{v}) - \chi_{\mathbf{v}}]}$$

where

$$\chi_{\mathbf{v}} = \tan^{-1}(v/u)$$

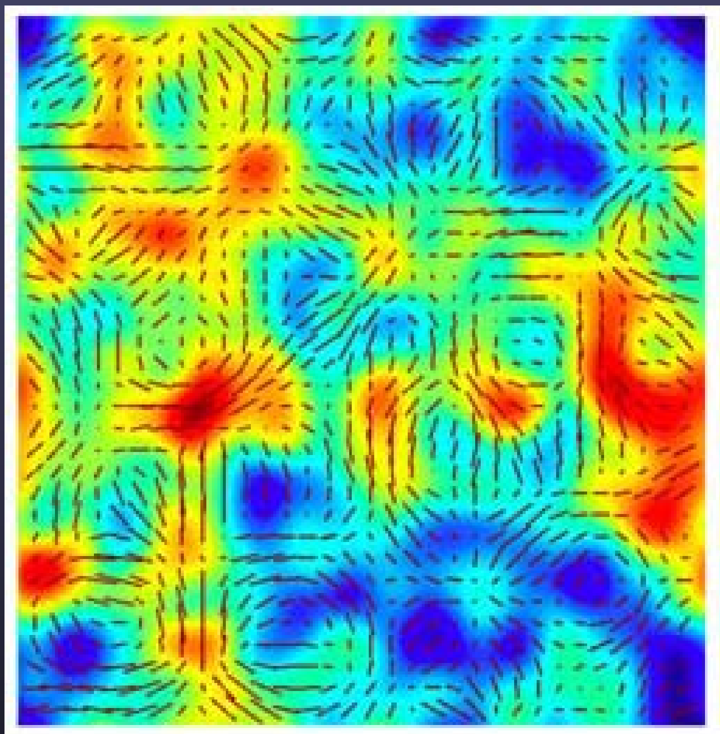
E : ϕ-χ=0,π/2
B : ϕ-χ=±π/4

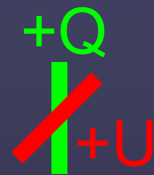
E and B measure alignment of plane-wave polarization with wave vector

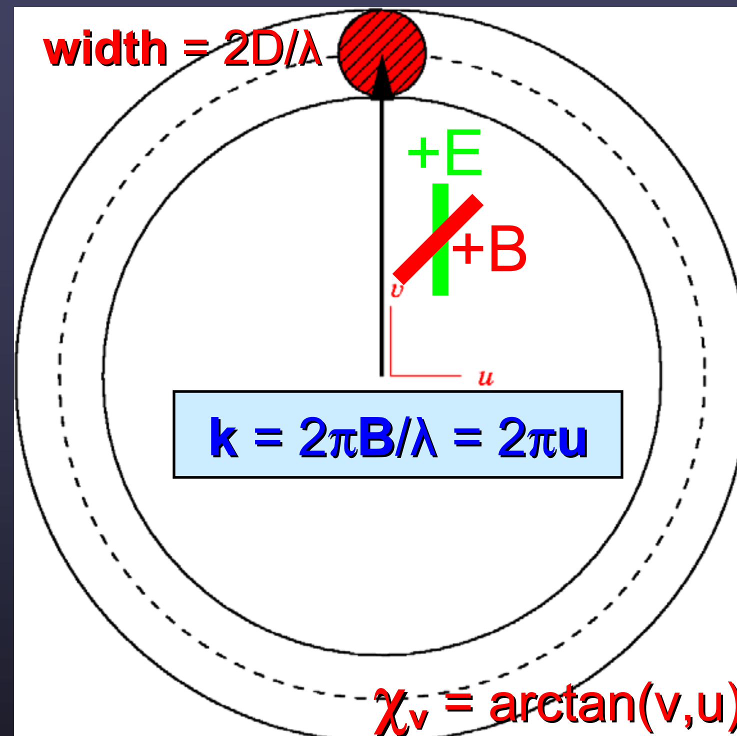
Q,U Cartesian vs. E,B polar coordinate frame in uv-plane

Polarization Interferometry : E & B

Stokes Q,U in image plane transform to E,B in *uv*-plane







$$Q + i\,U = [\,E + i\,B\,]e^{i2\chi_v}$$

$$V_k^{RL}(\mathbf{u}_k) = \int d^2\mathbf{u}\,\tilde{A}_k^{RL}(\mathbf{u}_k - \mathbf{u})[\tilde{E}(\mathbf{u}) + i\,\tilde{B}(\mathbf{u})]\,e^{i2(\chi_{\mathbf{v}} - \chi_k)}\,e^{2\pi i\,\mathbf{u}\cdot\mathbf{x}_k}$$

RL interferometer “directly” measures E & B in Fourier domain!

Visibility covariances

- RR, RL products → T, E, B fields

$$V^{RR}=\mathbf{A}^{RR}\ T + e^{RR} \qquad V^{RL}=\mathbf{A}^{RL}\ [E+iB] + e^{RL}$$

- RR, RL covariances → TT,EE,BB,TE covariances

$$< V^{RR}V^{RR\dagger} > = \mathbf{A}^{RR} < TT^{\dagger} > \mathbf{A}^{RR\dagger} + \mathbf{N}^{RRRR}$$

$$< V^{RR}V^{RL\dagger} > = \mathbf{A}^{RR} < TE^{\dagger} > \mathbf{A}^{RL\dagger} + \mathbf{N}^{RRRL}$$

$$< V^{RL}V^{RL\dagger} > = \mathbf{A}^{RL} [< EE^{\dagger} > + < BB^{\dagger} >]\ \mathbf{A}^{RL\dagger} + \mathbf{N}^{RLRL}$$

$$\left\langle X(\mathbf{v})Y^{*}(\mathbf{v}')\right\rangle = C_{\ell}^{XY}\delta^{2}(\mathbf{v}-\mathbf{v}') \quad X,Y=T,E,B$$

Power spectrum estimation

- for perfect data (all sky, no noise), estimator is trivial:

$$a_{\ell m} = \int d^2\hat{\mathbf{n}}\, Y_{\ell m}(\hat{\mathbf{n}})\, T(\hat{\mathbf{n}})$$

$$\hat{C}_\ell = \frac{\sum_m |a_{\ell m}|^2}{2\ell+1}$$

$$\tilde{T}(\mathbf{u}) = \int d^2\hat{\mathbf{n}}\, Y(\mathbf{u},\hat{\mathbf{n}})\, T(\hat{\mathbf{n}})$$

$$\hat{C}_\ell = \frac{2\pi \int d^2\mathbf{u}\, \tilde{T}^2(\mathbf{u})\, \delta\left(2\pi|\mathbf{u}| - \ell\right)}{\ell(\ell+1)}$$

  - multipole $l = 2\pi$ B / λ for interferometer baseline B
- polarization → cross-power spectra:
  - <TT> , <TE>, <EE>, <BB> (parity: <TB>=<EB>=0)
- limitation: cosmic variance
  - only one sky available to observe!
  - only $2l$+1 “m” values at each l, limits low l precision
  - e.g. WMAP TT limited for l < 354, will not improve!

Power Spectrum and Likelihood

- Break C_l into bandpowers q_B:

$$C_\ell = \sum_B q_B C_\ell^{\text{shape}} \chi_{B\ell}$$

fiducial power spectrum shape (e.g. $2\pi/\ell^2$)

χ=1 if l in band B; else χ=0

- Covariance matrix **C** sum of individual covariance terms:

noise

fitted

projected

$$C = C^{\text{N}} + \sum_\kappa \sum_B q_B^\kappa C_B^\kappa + q_{\text{src}} C^{\text{src}} + q_{\text{res}} C^{\text{res}} + q_{\text{scan}} C^{\text{scan}}$$

$$\kappa = TT, TE, TB, EE, EB, BB$$

known foregrounds (e.g point sources)

residual (statistical) foreground

scan (ground) signal

- maximize Likelihood for gridded estimators Δ :

$$\ln \mathcal{L}(\{q_B\} \mid \Delta) = -n \ln \pi - \ln(\det \mathbf{C}) - \Delta^{+} \mathbf{C}^{-1} \Delta$$

Maximum Likelihood Estimate (MLE)

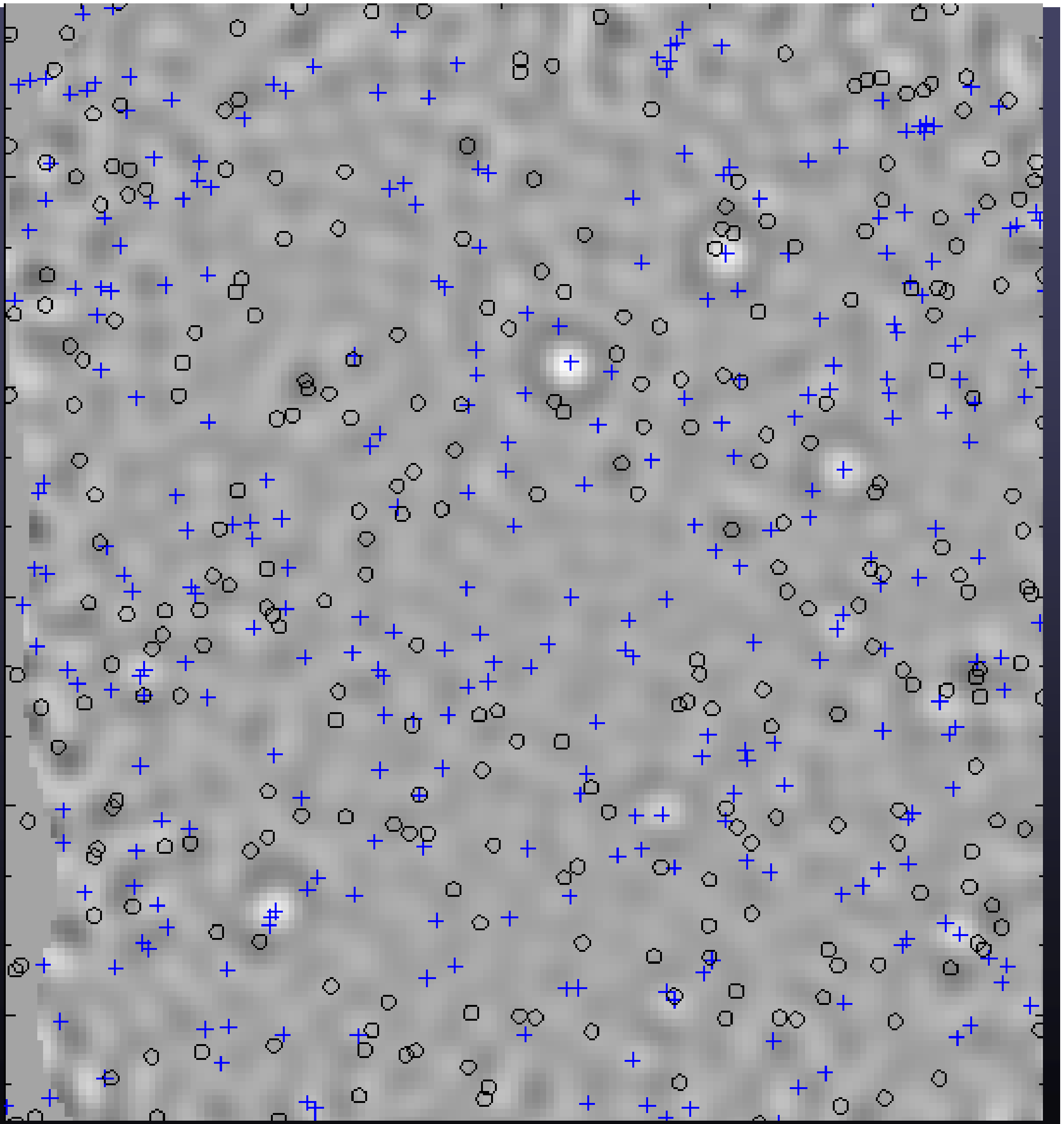
- data **d** = real,imaginary parts of gridded visibilities ***V***
- maximize the likelihood:

$$\mathcal{L}(C_\ell \,|\, \mathbf{d}) = \frac{\exp\left[-\frac{1}{2}\mathbf{d}^T\left(\mathbf{S}(C_\ell)+\mathbf{N}\right)^{-1}\mathbf{d}\right]}{\left[(2\pi)^{N_d}\det\left(\mathbf{S}(C_\ell)+\mathbf{N}\right)\right]^{1/2}}$$

  - note: the exponential term is $\chi^2/2$ (quadratic = easy!)
  - but: the determinant is expensive!
- O(N^3) determinant is costly!
  - S + N may not be sparse (size N_d^2)
  - need data compression or approximations
  - almost all real methods use some "lossy" procedure
- construct efficient pipeline to take V ➔ C^{XX} (STM)

Foreground Projection – Sources

- Foreground radio sources
  - Located in NVSS at 1.4 GHz, VLA 8.4 GHz
- Construct source covariance matrix
  - use know positions of radio sources
  - equivalent to masking out these directions from the Likelihood
  - BUT, lots (100's) of sources from NVSS



Other effects: leakage

- Leakage of R ⇔ L (d-terms):

"true" signal

$$V_{ij}^{RR} = \int_{sky} E_{ij}^{RR}(l,m)[(\mathrm{I}+\mathrm{V})e^{i(\chi_i-\chi_j)}$$

$$+ d_i^R e^{-i(\chi_i+\chi_j)}(\mathrm{Q}-i\mathrm{U}) + d_j^{*R} e^{i(\chi_i+\chi_j)}(\mathrm{Q}+i\mathrm{U})$$

$$+ d_i^R d_j^{*R} e^{-i(\chi_i-\chi_j)}(\mathrm{I}\text{-}\mathrm{V})](l,m)e^{-i2\pi(u_{ij}l+v_{ij}m)}dldm$$

2nd order: D•P into I

2nd order: D²•I into I

$$V_{ij}^{RL} = \int_{sky} E_{ij}^{RL}(l,m)[(\mathrm{Q}+i\mathrm{U})e^{i(\chi_i+\chi_j)}$$

$$+ d_i^R(\mathrm{I}-\mathrm{V})e^{-i(\chi_i-\chi_j)} + d_j^{*L}(\mathrm{I}+\mathrm{V})e^{i(\chi_i-\chi_j)}$$

$$+ d_i^R d_j^{*L}(\mathrm{Q}-i\mathrm{U})e^{-i(\chi_i+\chi_j)}](l,m)e^{-i2\pi(u_{ij}l+v_{ij}m)}dldm$$

1st order: D•I into P

3rd order: D²•P* into P

  - 1st Order: TT unaffected; TT leaks into TE; TE into EE, BB
  - can include in gridding

CMB Interferometers: DASI, VSA, CBI

- DASI @ South Pole

- VSA @ Tenerife

CMB interferometers have small apertures (antennas) to match the angular scales of the CMB (arcminutes or larger)!

The Cosmic Background Imager is…

- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
  - reconfigurable
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Tnoise 8K, Tsys 15 K
- Single polarization (R or L)
  - U. Chicago polarizers < 2% leakage
- Analog correlators
  - 780 complex correlators
  - pol. product RR, LL, RL, or LR
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin

Traditional Inteferometer – The VLA

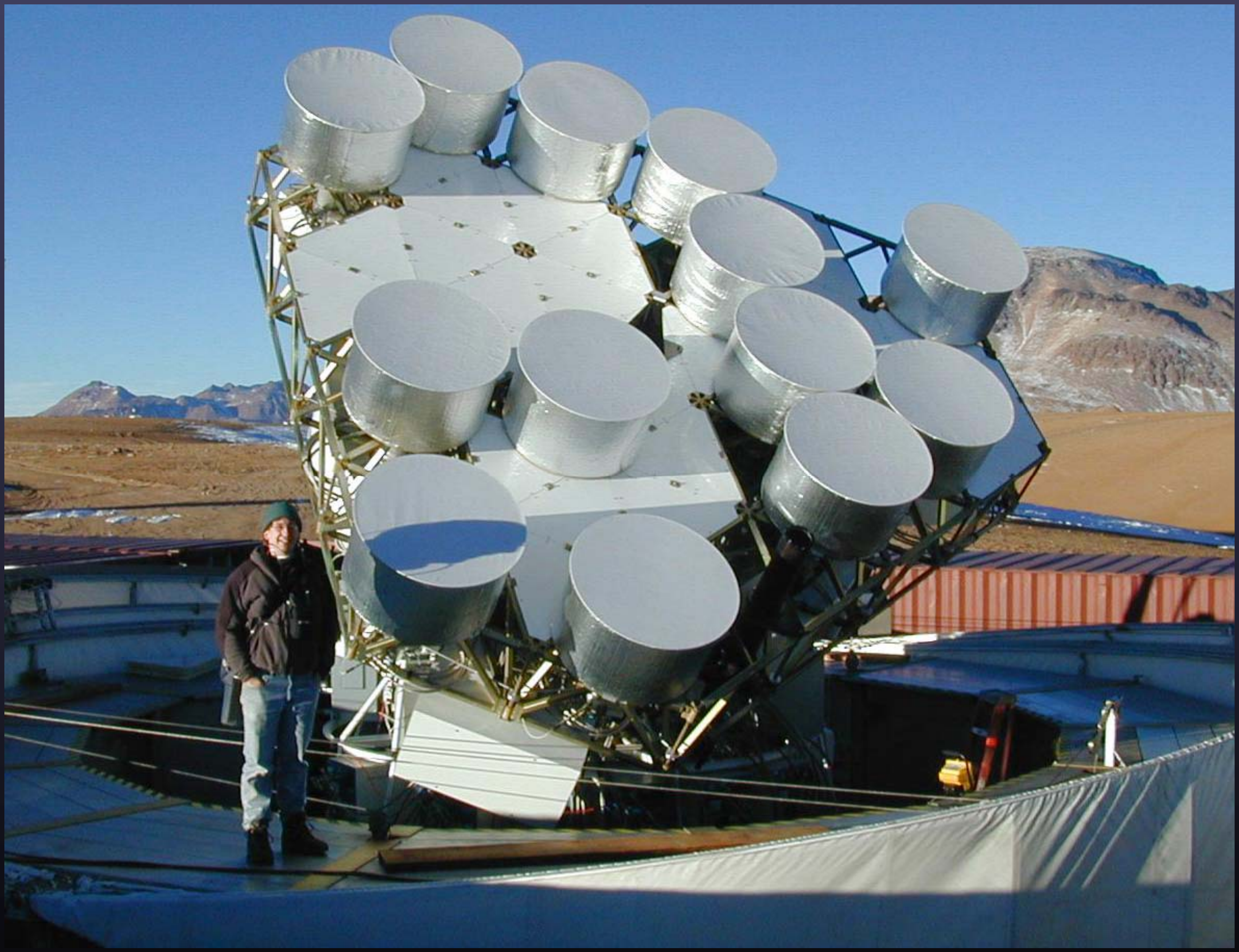
- The Very Large Array (VLA)
  - 27 elements, 25m antennas, 74 MHz – 50 GHz (in bands)
  - independent elements ➔ Earth rotation synthesis

CMB Interferometer – the CBI

- Antennas fixed to <u>3-axis</u> platform (alt, az, deck)
  - rotate deck to rotate baselines ➔ telescope rotation synthesis!

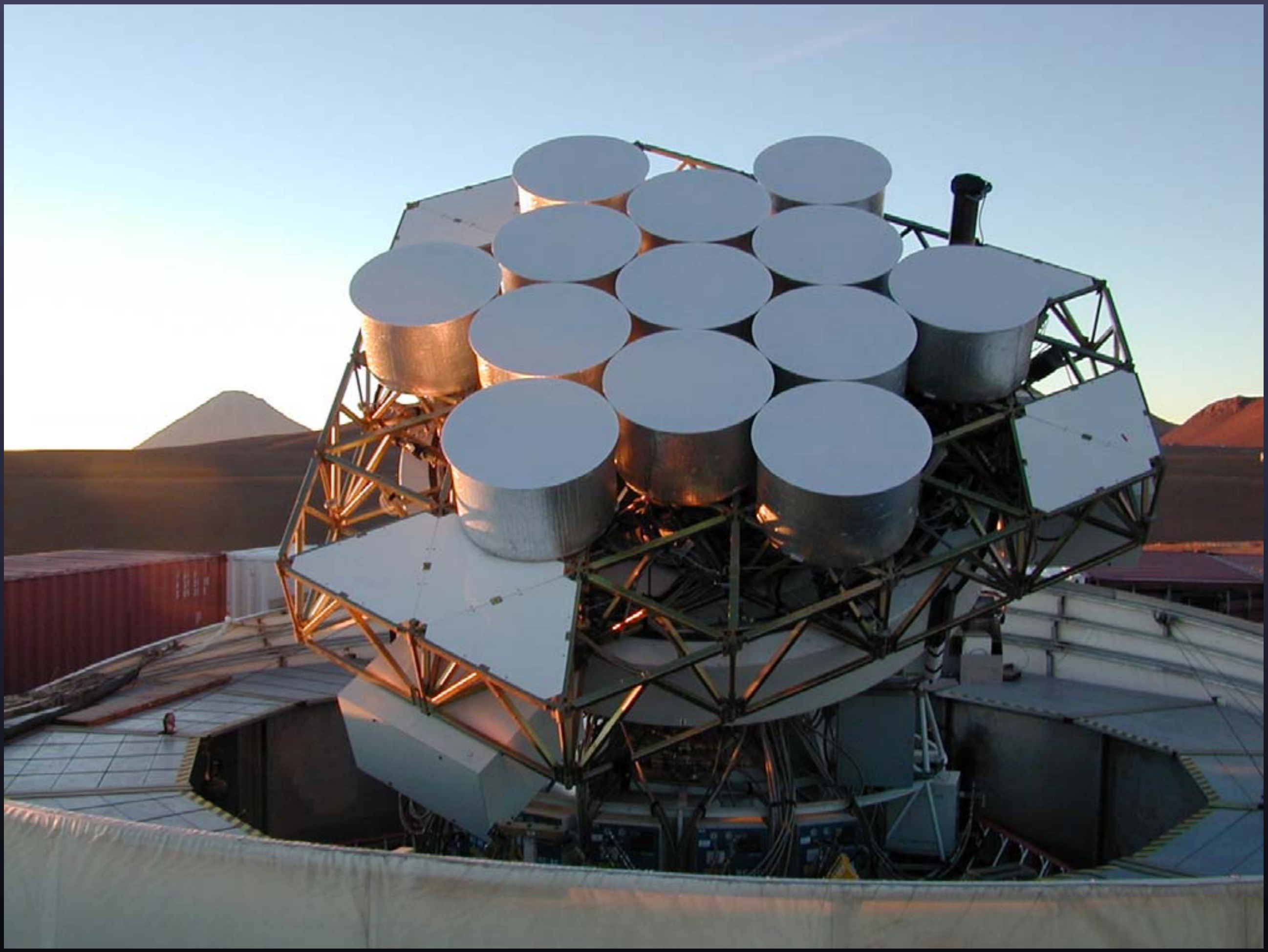
CBI Temperature Observations

- Observed January 2000 to June 2002
  - extended configuration, reach higher ℓ



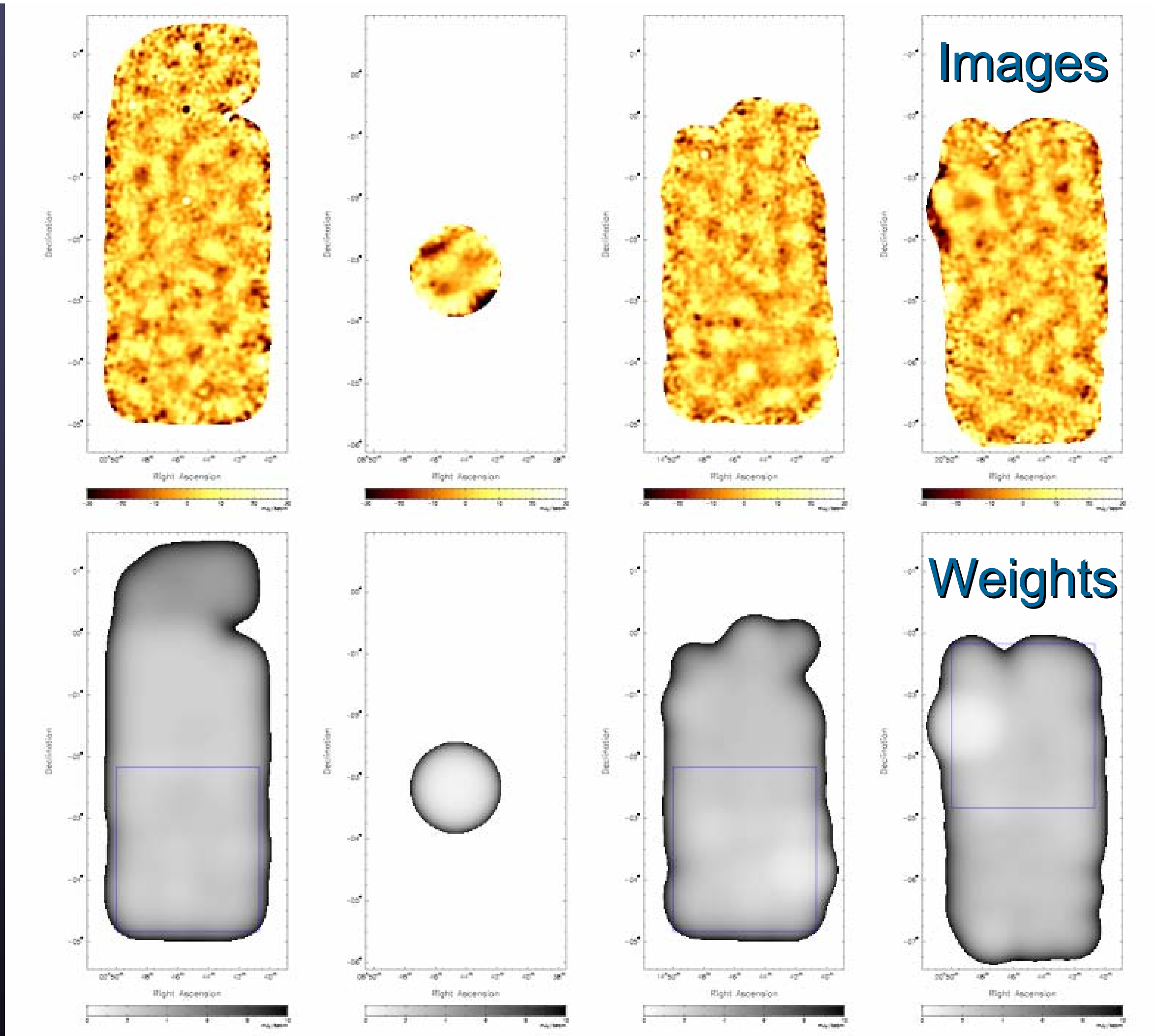
CBI Polarization Program

- Observed September 2002 to April 2005
  - compact configuration, maximum sensitivity



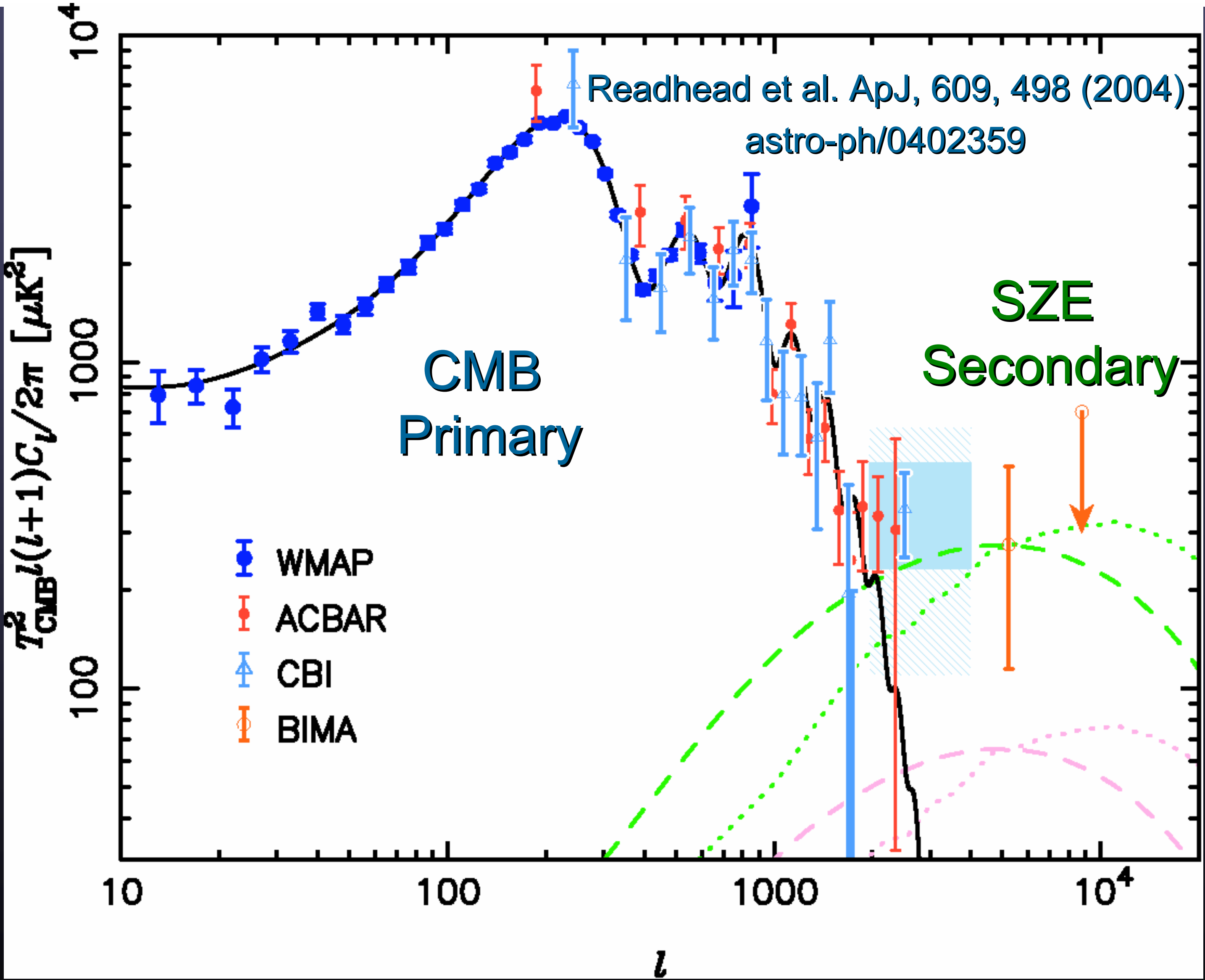
CBI 2000-2001 Mosaics

- Emission from ground
  - dominant on 1-meter baselines
- Observe 2 fields separated by 8^m of RA
  - about 2° on-sky
  - lead for 8 min followed by trail for 8 min (tracks each field through same AZEL)
  - subtract corresponding visibilities so ground emission cancels
- Images show lead field minus trail field
- Also eliminates low-level spurious common-mode signals

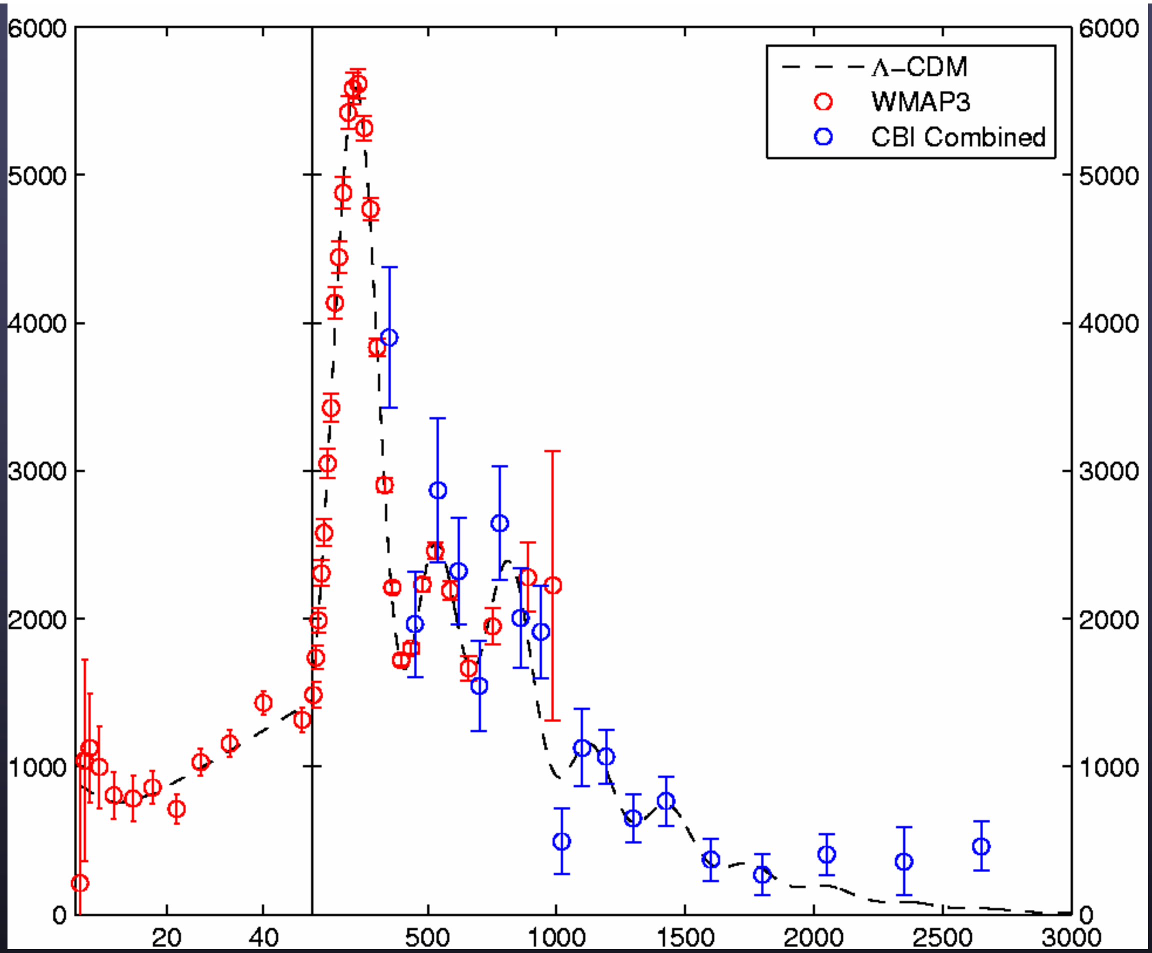


Note also deep fields: 8^h and in14^h,20^h mosaics

CBI 2000-2001, WMAP1, ACBAR, BIMA

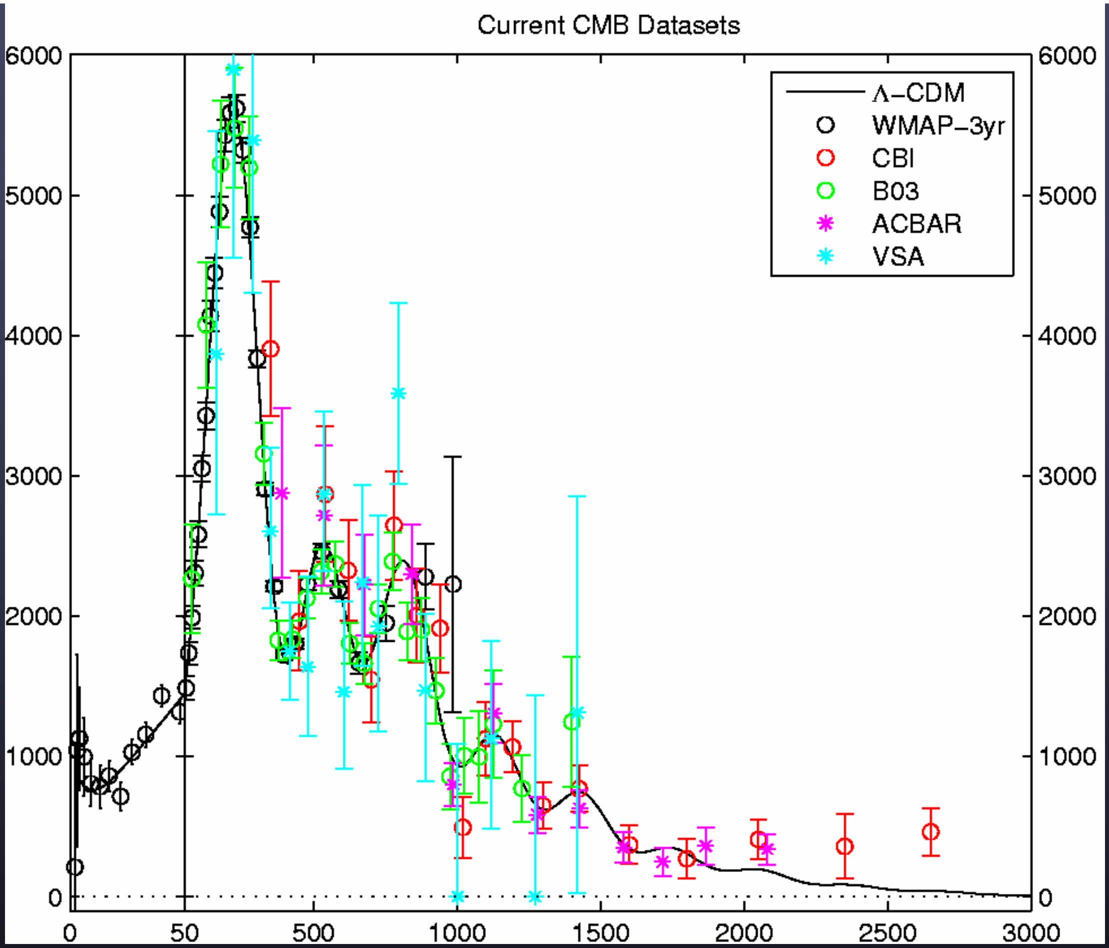


NEW: CBI 2000-2005 Temperature



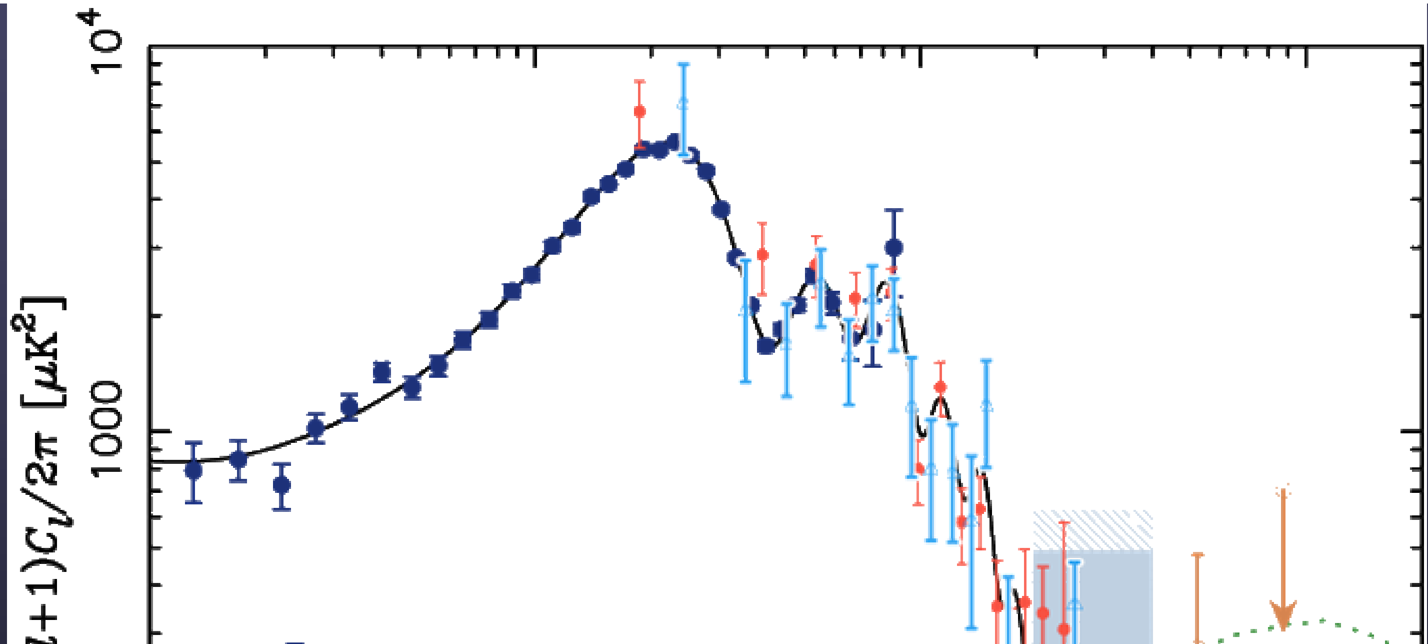
- Combined 2000-2001 and 2002-2005 mosaics
- 5th acoustic peak (barely) visible, plus excess!

NEW: CBI 2000-2005 Temperature



- also including new Boomerang (B03), plus VSA and ACBAR

CBI Temperature high-ℓ excess



- <u>At 2000 < l <3500, CBI finds power ~ 3 sigma above the standard models</u>
  - Not consistent with any likely model of discrete source contamination
  - Suggestive of secondary anisotropies, especially the SZ effect
- <u>Comparison with predictions from hydrodynamical calculations:</u>
  - strong dependence on amplitude of density fluctuations, σ_8^7
  - CBI observed amplitude suggests σ_8~0.9-1.0
  - BUT, significant non-Gaussian corrections (dominated by nearby clusters)

SZ Hydro Simulations

- CBI Paper 6 [Bond et. al. 2005]
  - [ApJ, 626, 12 (2005); astro-ph/0205386]
- Simulations:
  - Smooth Particle Hydrodynamics (512^3) [Wadsley et al. 2002]
  - Moving Mesh Hydrodynamics (512^3) [Pen 1998]

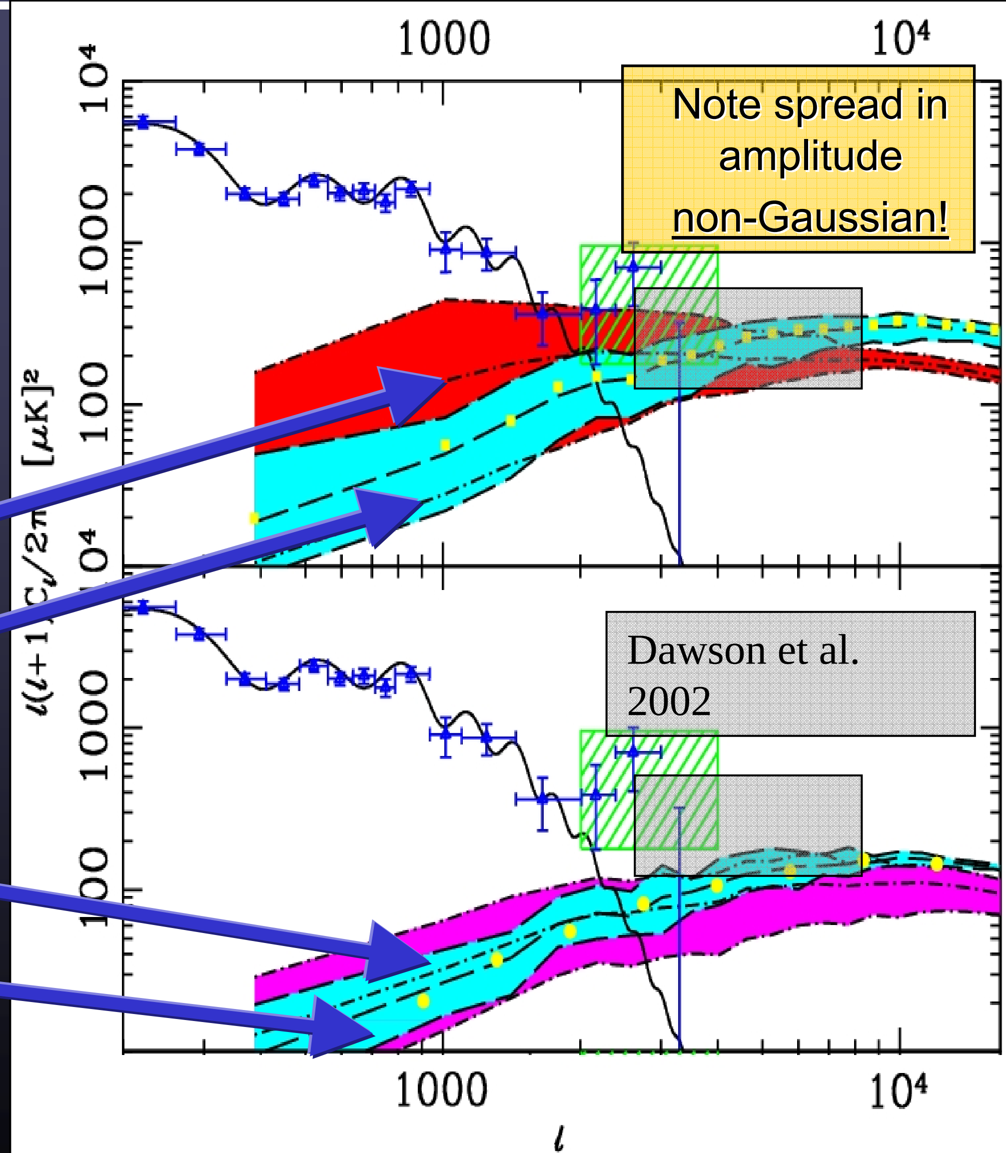
•143 Mpc σ_8=1.0

•200 Mpc σ_8=1.0

•200 Mpc σ_8=0.9

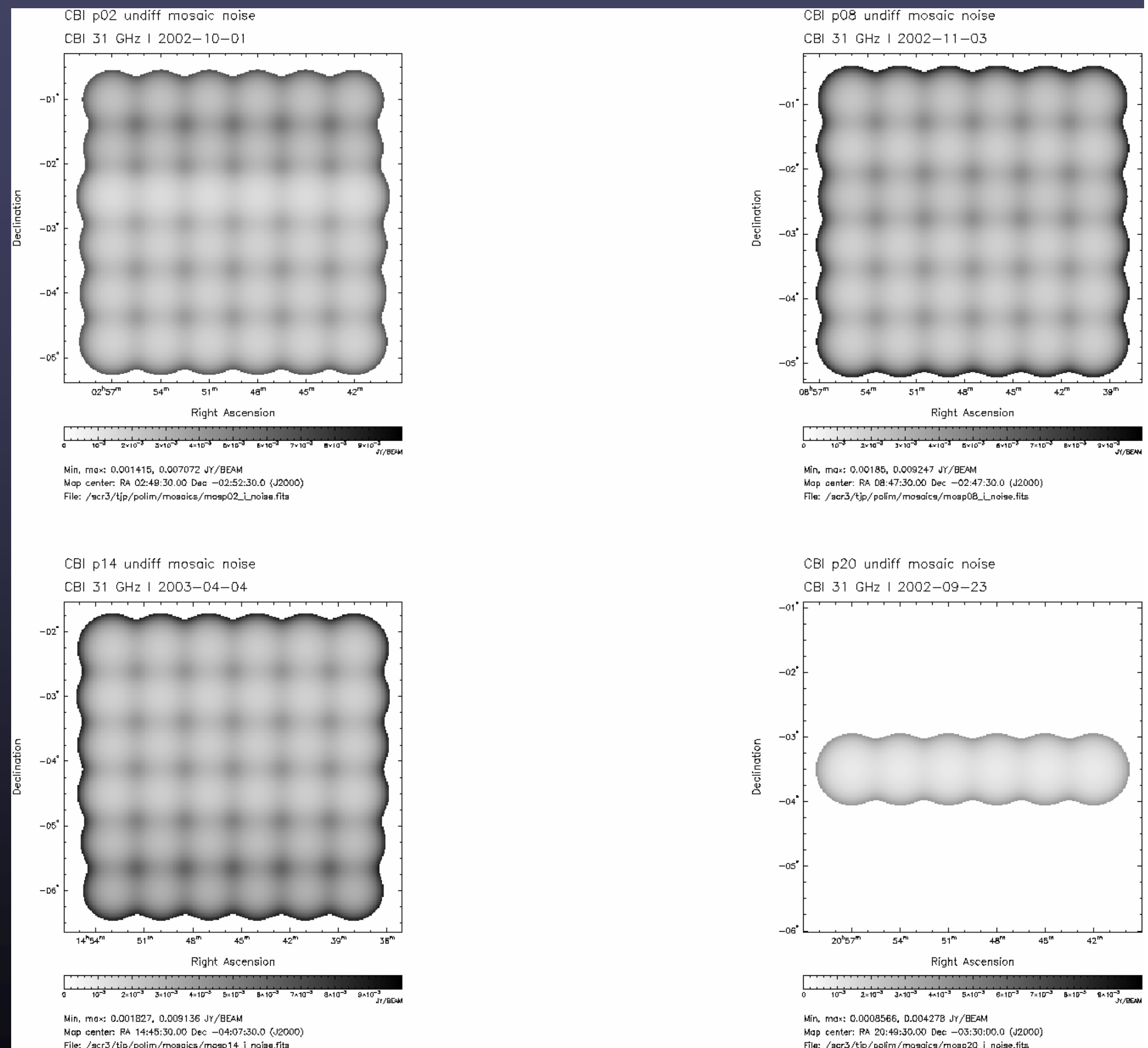
•400 Mpc σ_8=0.9

$$C_\ell^{SZ} \sim \sigma_8^7 (\Omega_b h^2)^2$$



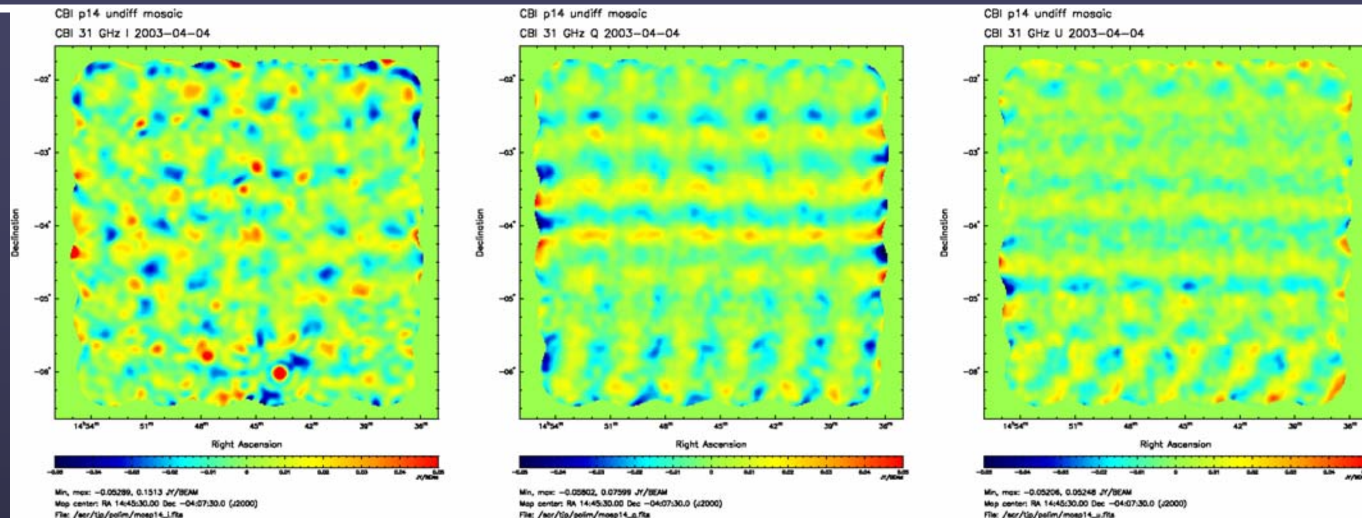
CBI Polarization Mosaic Fields

- On celestial equator at 2^h, 8^h, 14^h, 20^h
  - overlap with 2000-2001 mosaics
- Raster 6 fields 3^m in RA
  - 45' on sky separation
  - Note: sub-Nyquist compared to FWHM, will produce Fourier aliasing (sidelobes)
- Deep strip at 20^h, the remainder 6x6 mosaics
- Undifferenced
  - project out common mode in analysis (similar to source projection)

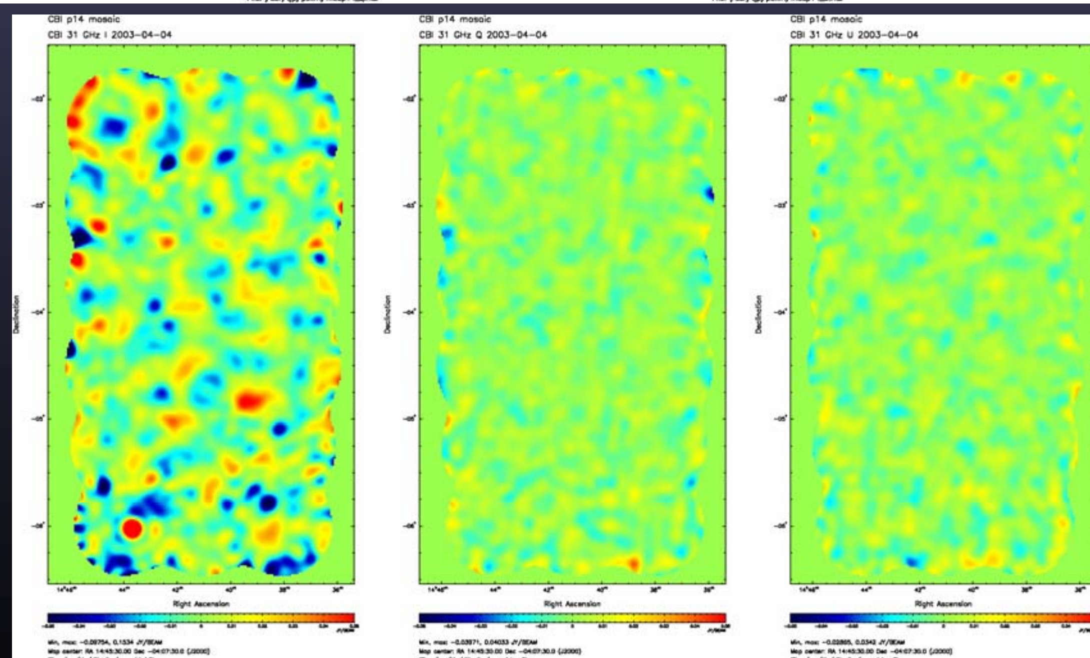


CBI Polarization Mosaic Fields

Ground emission (from horizon) is polarized!



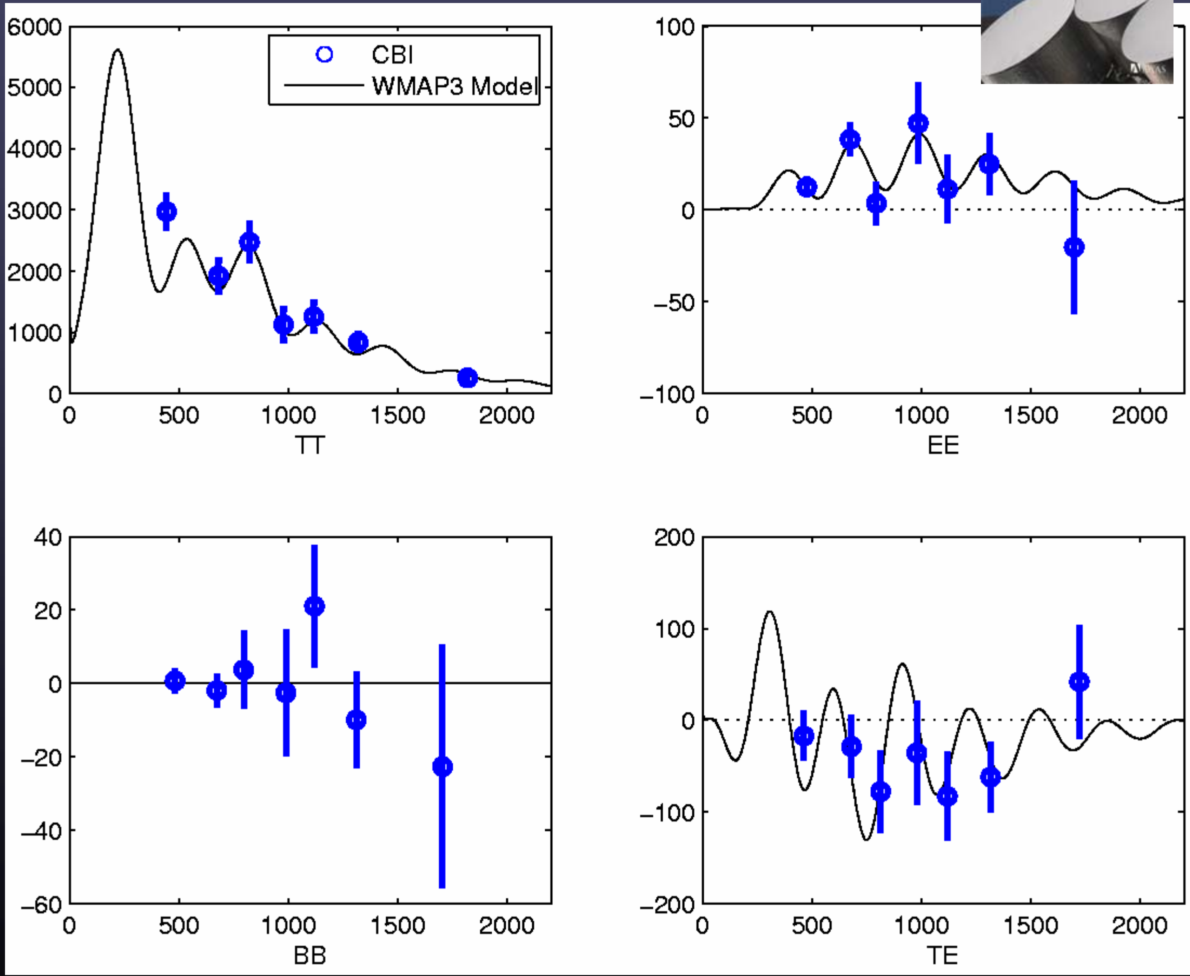
- Shown: the 14^h 6x6 mosaic
  - I (left), Q (middle), U(right)
  - top panels: raw mosaic
  - bottom panels: differenced halves 9min RA apart
  - NOTE: power spectrum analysis uses undifferenced data with scan mean projected out



NEW: CBI Polarization Power Spectra

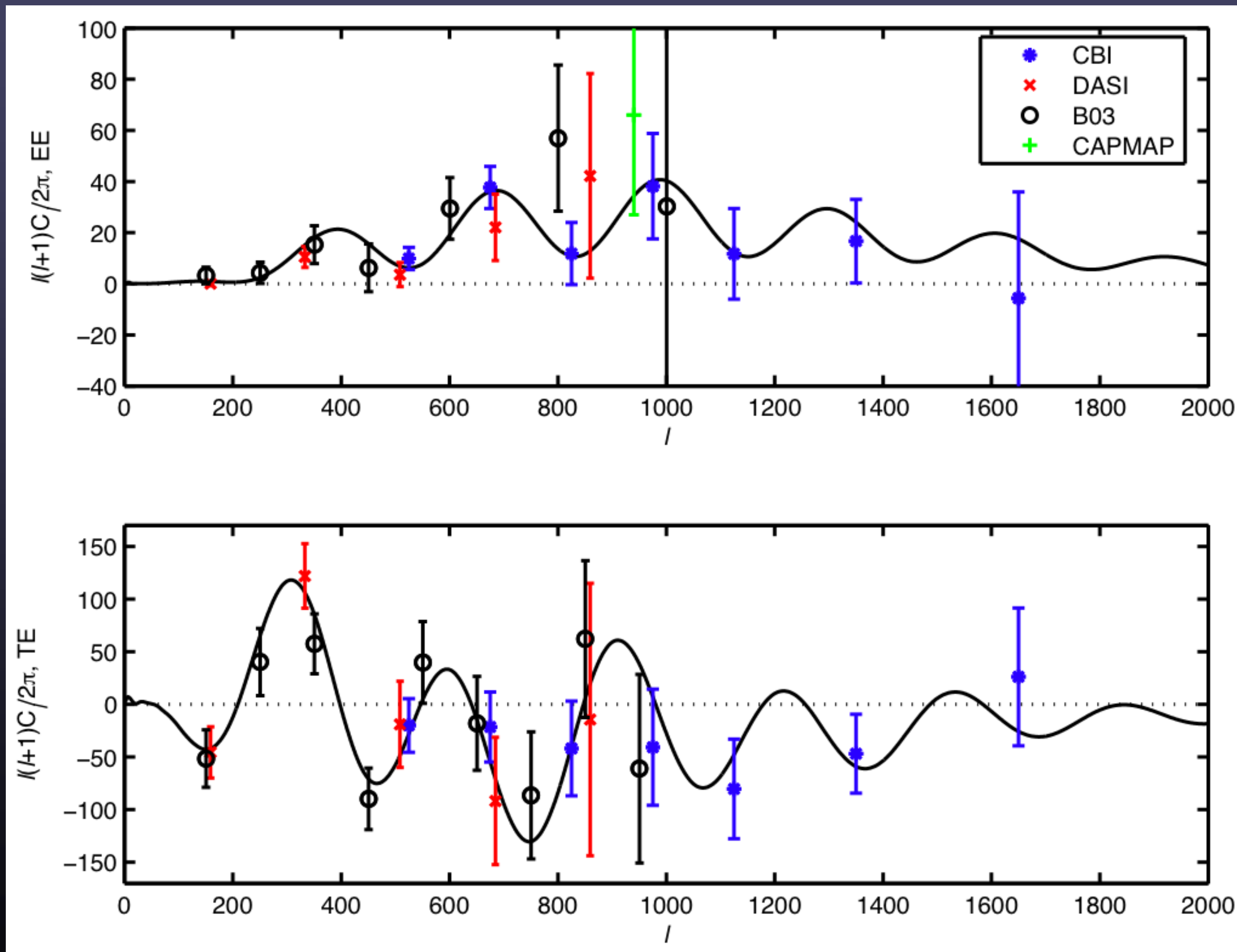
- First reported in Paper 8: Readhead et al. 2004b, Science 306,836;
  - updated in Paper 9: Sievers et al. 2005 (astro-ph/0509203)

- All CBI Polarization data
  - 2002-2005
- Significances (shaped vs. zero, from likelihoods)
  - EE 12.0σ
  - TE   4.25σ

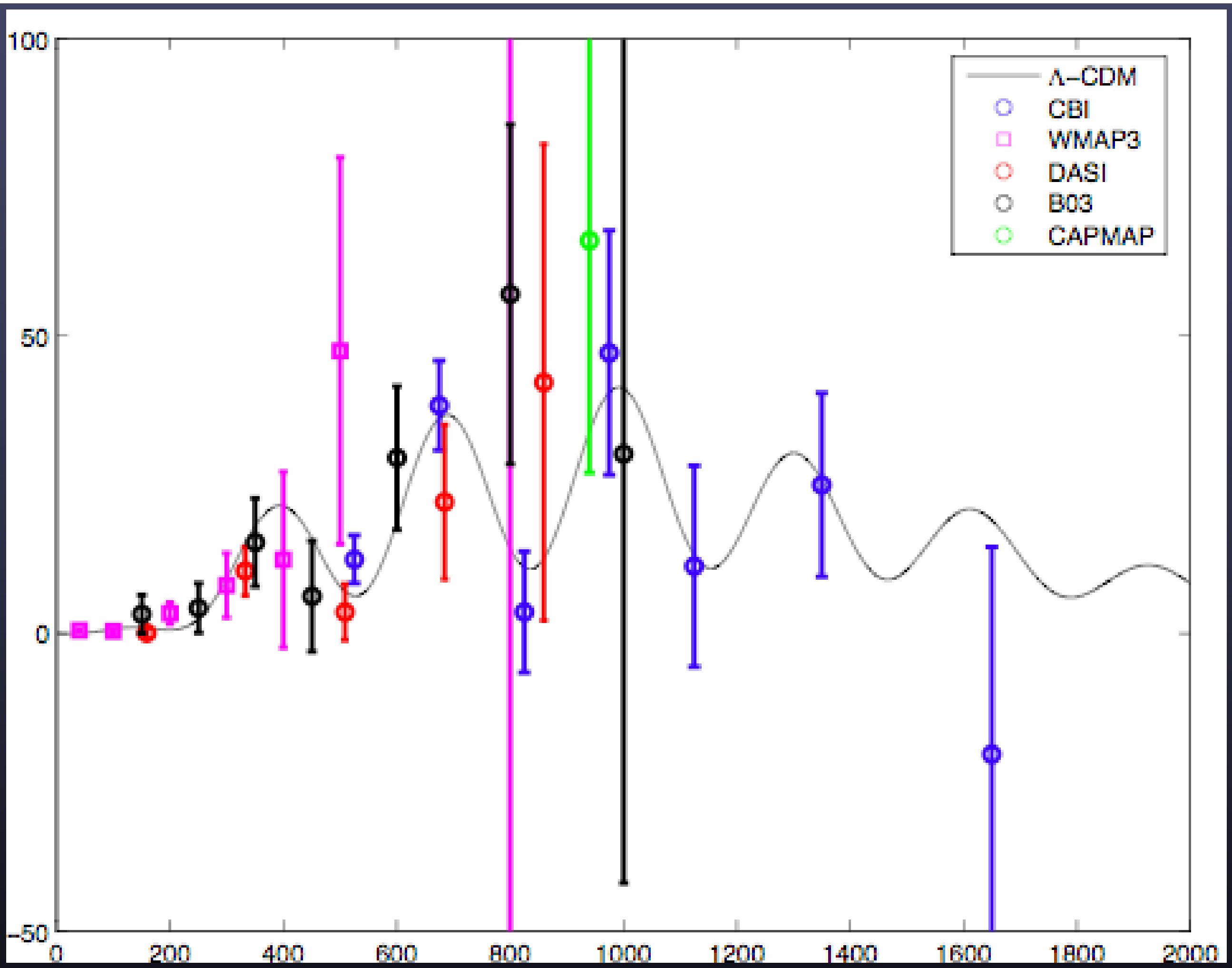


EE & TE: Comparison of Experiments

- New CBI and pre-WMAP3 experiments:

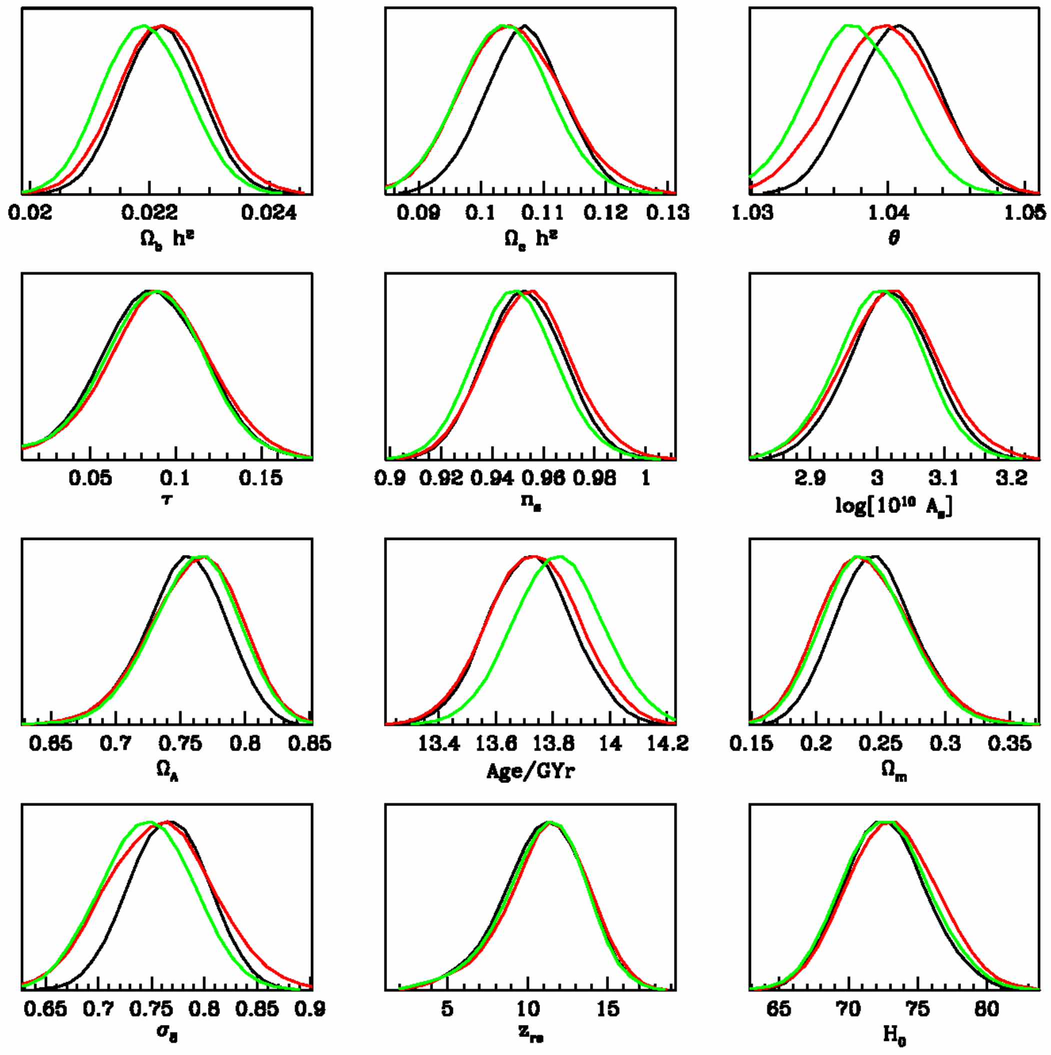


EE: Comparison of Experiments



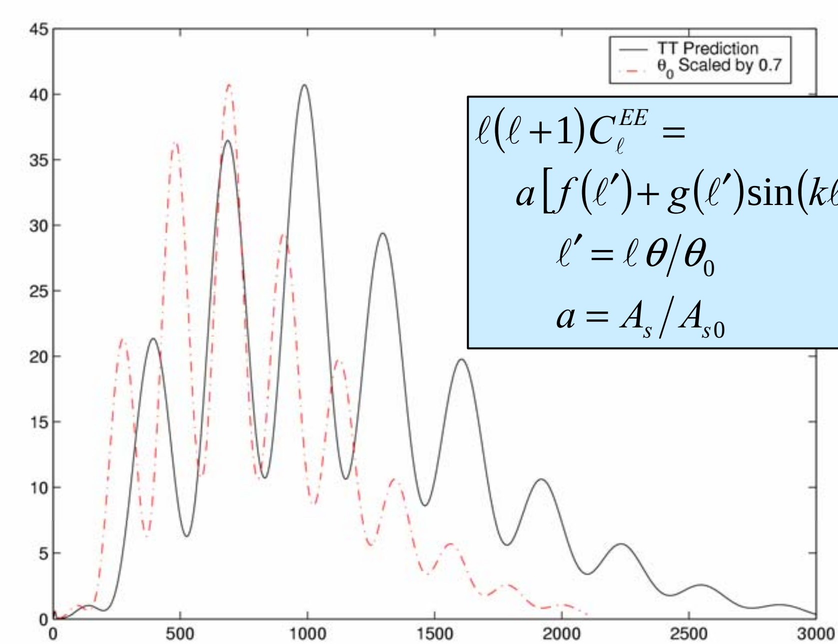
NEW: CBI01-05 + all parameters

- COSMOMC runs
  - 1-d likelihood plots
- WMAP3 (red)
- WMAP3 + CBI01-05 TT & Pol (green)
- all = plus VSA, B03, ACBAR, Maxima (black)



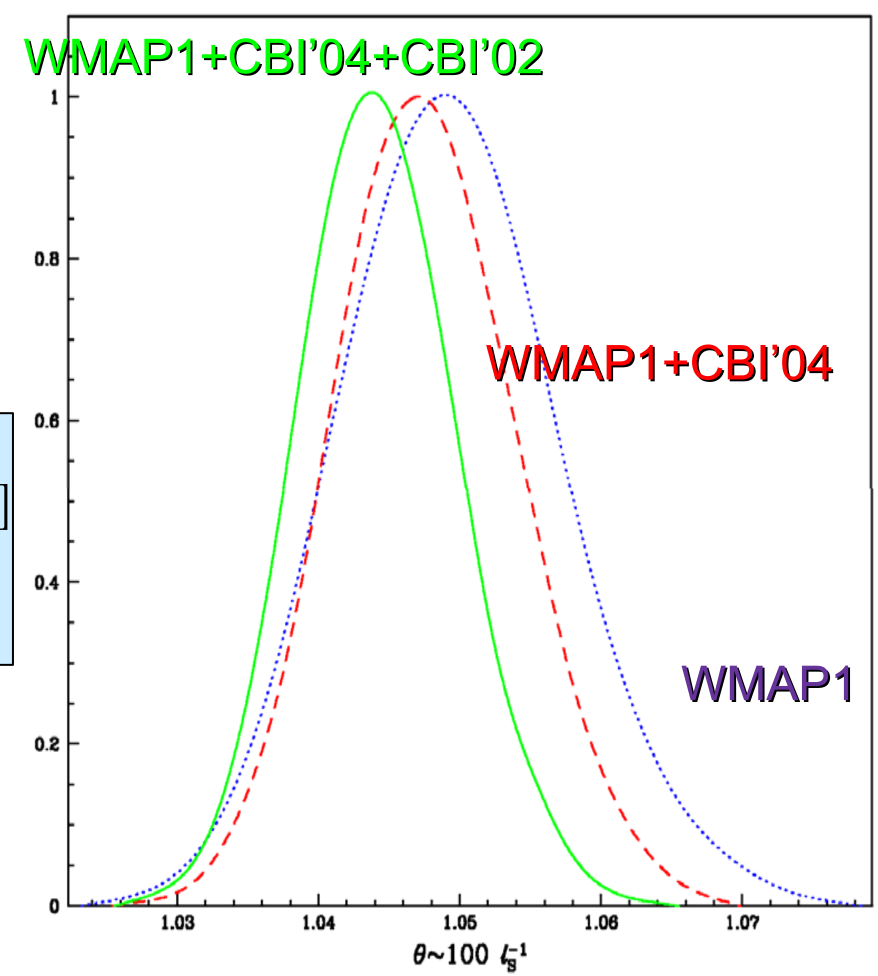
CBI EE Acoustic Oscillations

- Should be predictable from TT oscillations
  - from velocity, EE 90° out-of-phase vs. TT [sin(ks) vs. cos(ks)]
  - plot in terms of scaling $\theta=100/\ell_s$ vs. sound horizon [Papers 8 & 9]



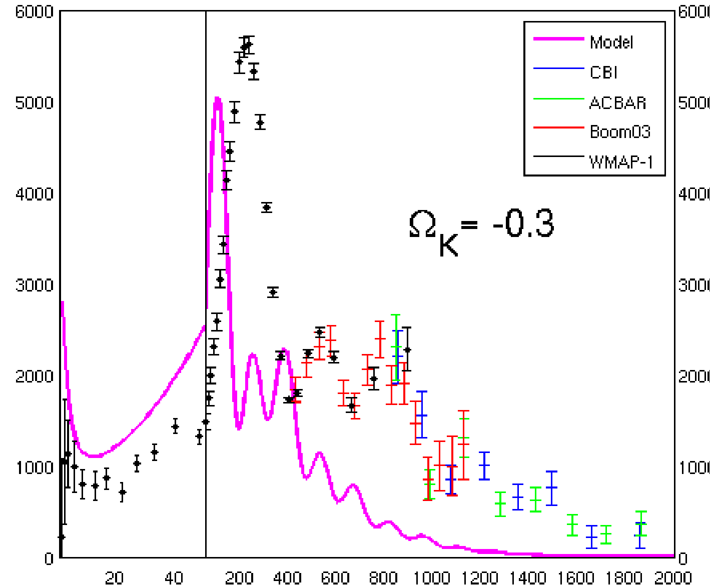
$$\ell(\ell+1)C_\ell^{EE} = a\left[f(\ell')+g(\ell')\sin(k\ell')\right]$$
$$\ell' = \ell\,\theta/\theta_0$$
$$a = A_s/A_{s0}$$

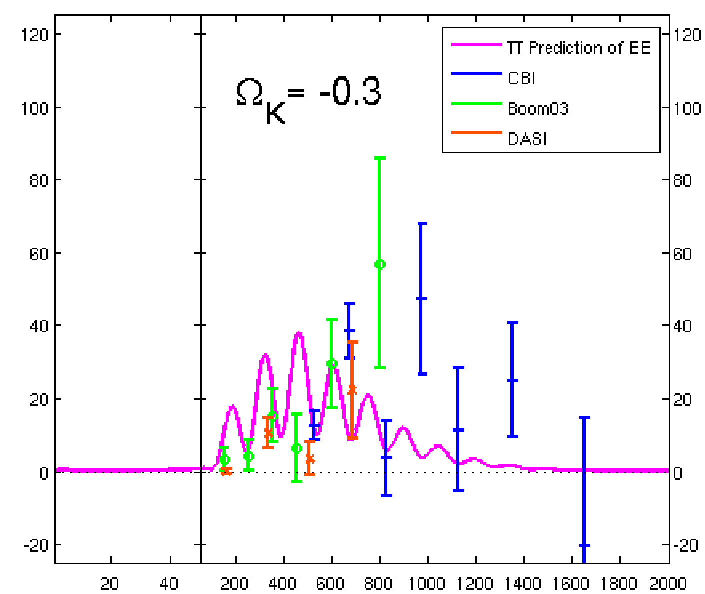
Fiducial model: θ_0= 1.046 ("WMAP+ext")



CBI EE Acoustic Os

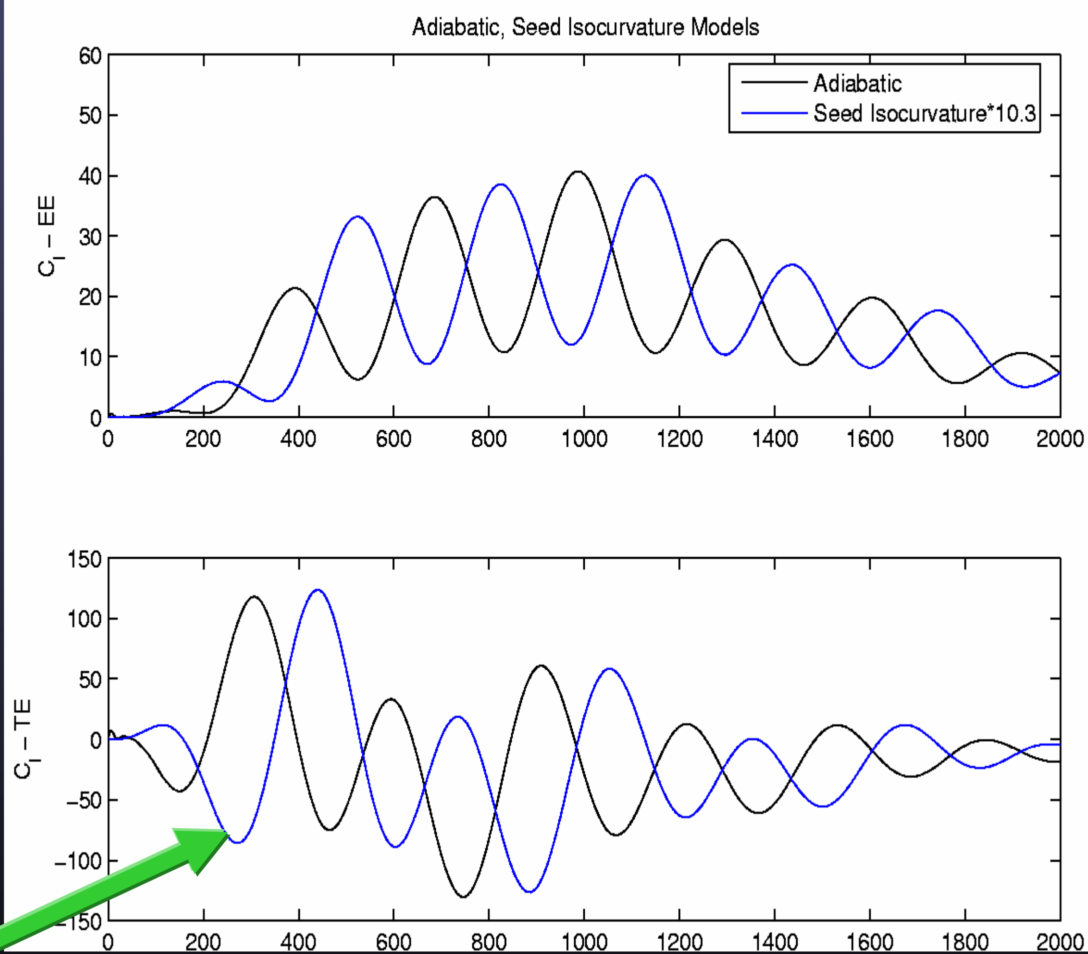
- Should be predictable from TT oscillations
  - from velocity, EE 90° out-of-phase vs. TT [sin(ks) vs. cos(ks)]
  - plot in terms of scaling $\theta = 100/\ell_s$ vs. sound horizon [Papers 8 & 9]
- Primarily controlled by curvature





Tweaking the Model: Isocurvature

- Are there curvature fluctuations?
  - if standard model then matter/photon ratio preserved (adiabatic)
  - some inflation and most defect models predict isocurvature modes
    - matter & radiation anti-correlated, acoustic peaks not shifted



isocurvature mode: polarization peaks aligned w/TT

Constraining Isocurvature Modes

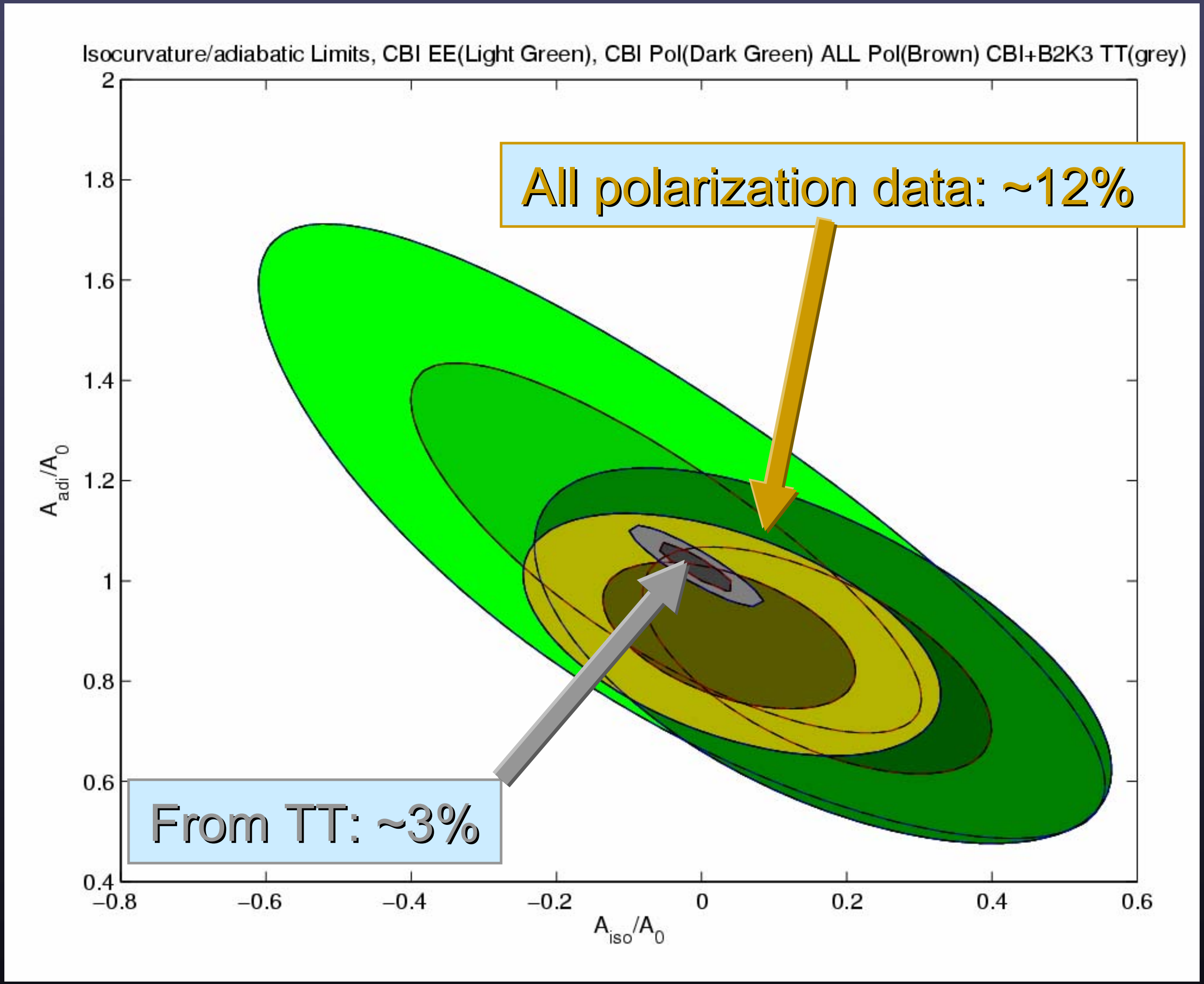
CBI Pol – green

All Pol – brown

CBI+B03 - grey

Note – strongest constraints from TT

parameters are better constrained by T (but model dependent!)



Mapmaking: Wiener filtered images

- estimators can be Fourier transformed back into filtered images

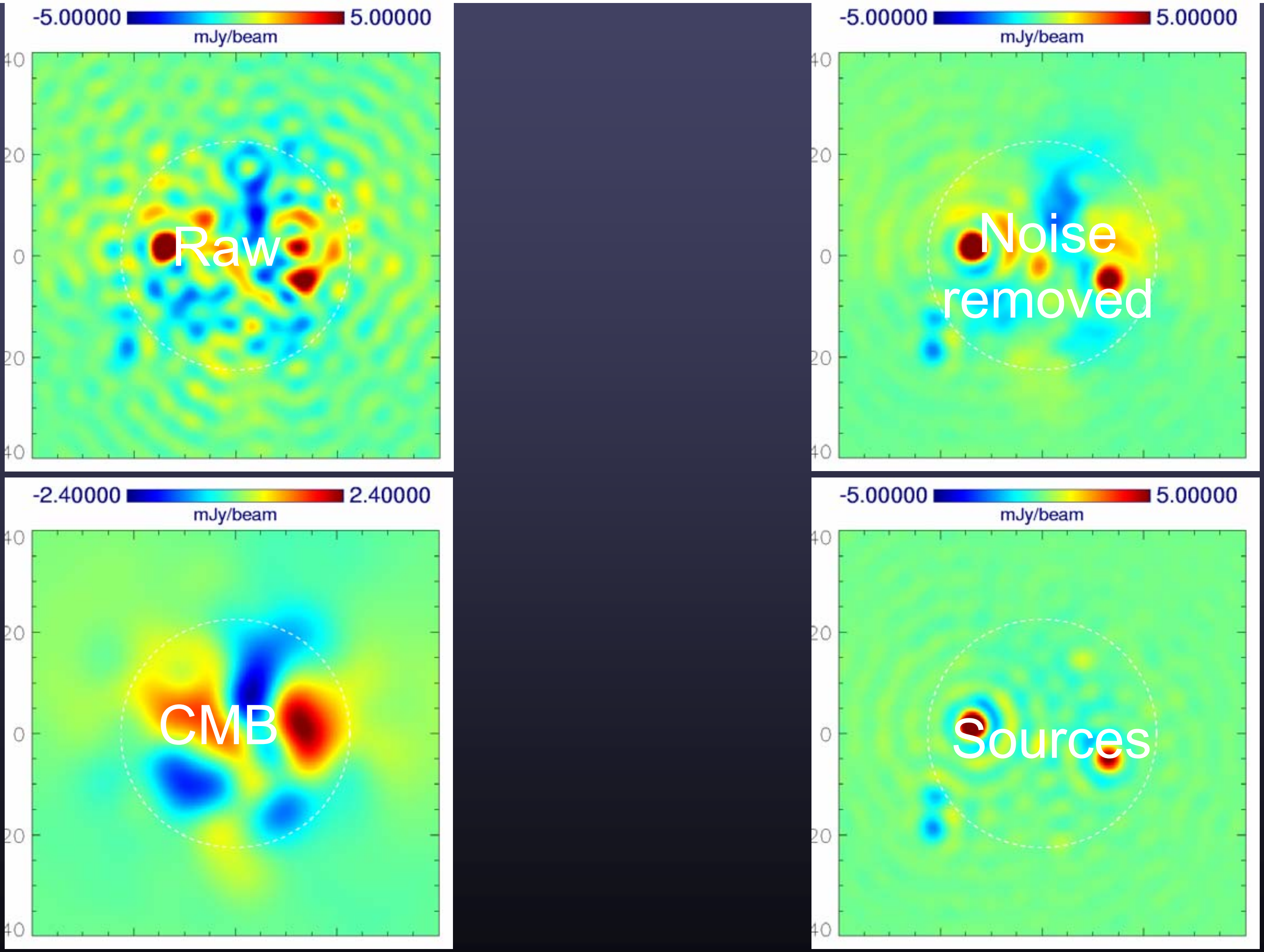
$$m = \mathbf{F}\,\Delta$$

- covariance matrices can be applied as Wiener filter to gridded estimators

$$\boldsymbol{\Delta}^{\mathrm{X}} = \mathbf{C}^{\mathrm{X}}\,\mathbf{C}^{-1}\,\boldsymbol{\Delta}$$

- filters C^X can be tailored to pick out specific components
  - e.g. CMB, SZE, foregrounds
  - just need to know the shape of the power spectrum
  - can make T,E,B (or Q,U) estimators
  - can also image foregrounds using the "β" estimators from MFS

Example – Mock CBI deep field



E & B Mode Images

Grid visibilities into ℓ-space estimators (e.g. Myers et al. 2003).

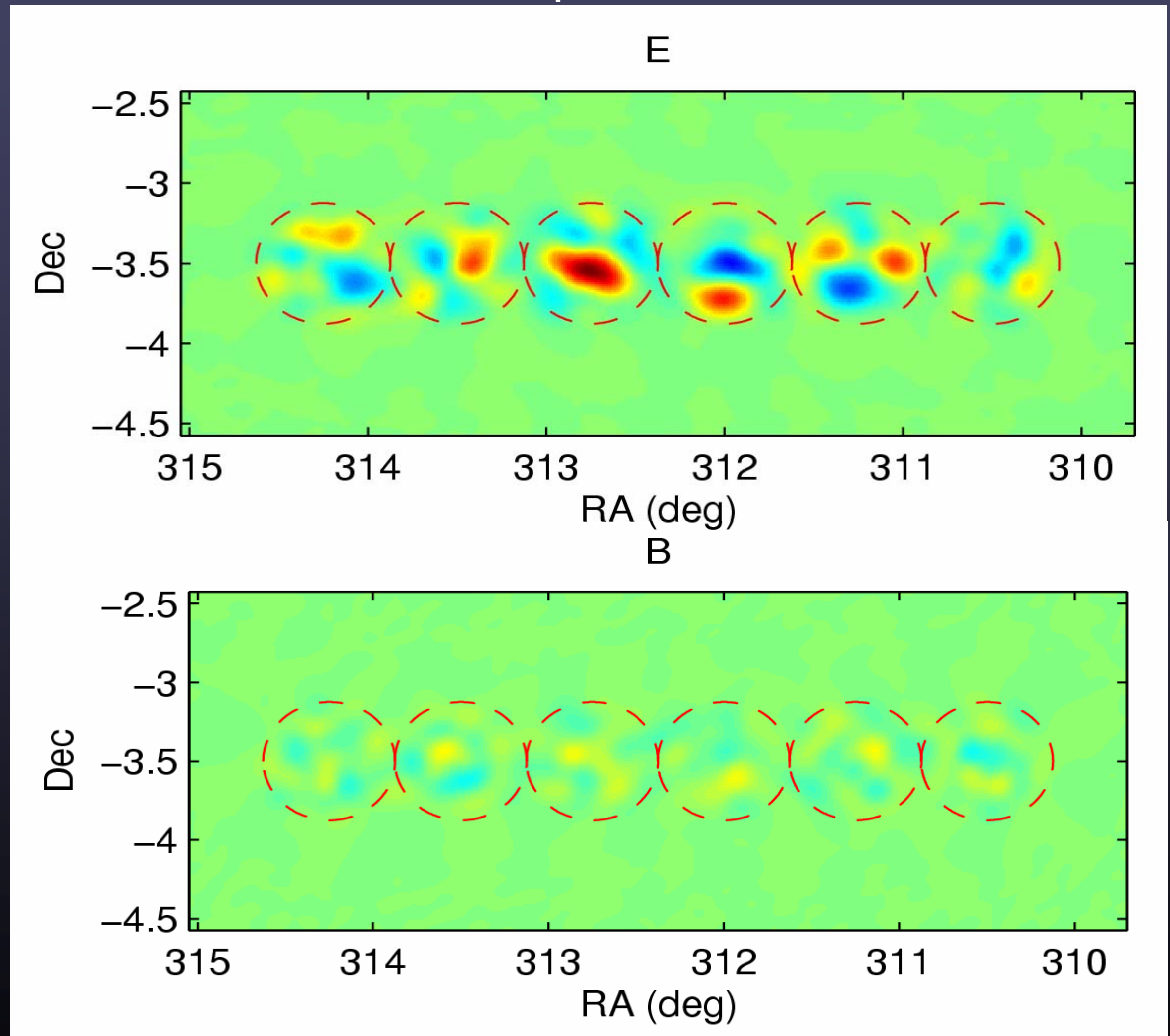
Variance of E in raw data 2.45 times B (ℓ<1000). B is consistent with noise.

Mixing between E,B Is ~5% in power.

NOTE: <u>Peaks in E/B are not peaks in P!</u>

Sievers et al. 2005, submitted to ApJ (astro-ph/0509203)

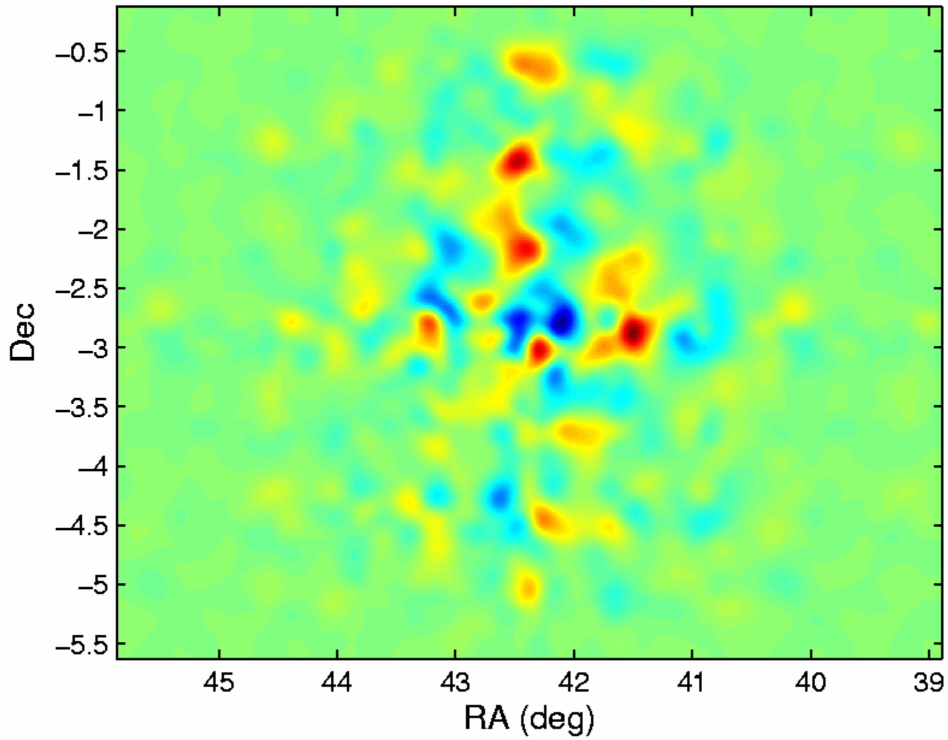
CBI 20h strip: gridded FT($E + i\,B$) transformed to

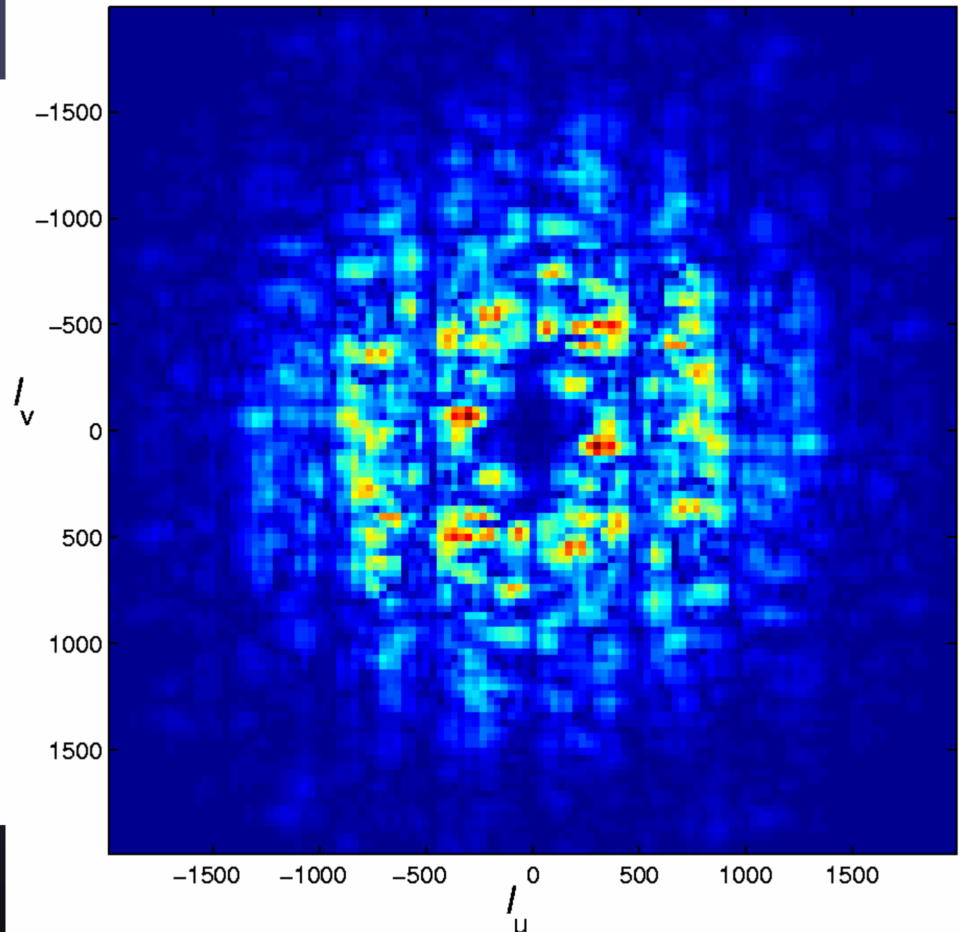


ℓ-space maps

- use gridded visibilities to reconstruct T,E,B in ℓ-space

CBI 02^h 6x6 field mosaic





T image ⇔ ℓT_ℓ

➔test for non-Gaussianity in ℓ-space

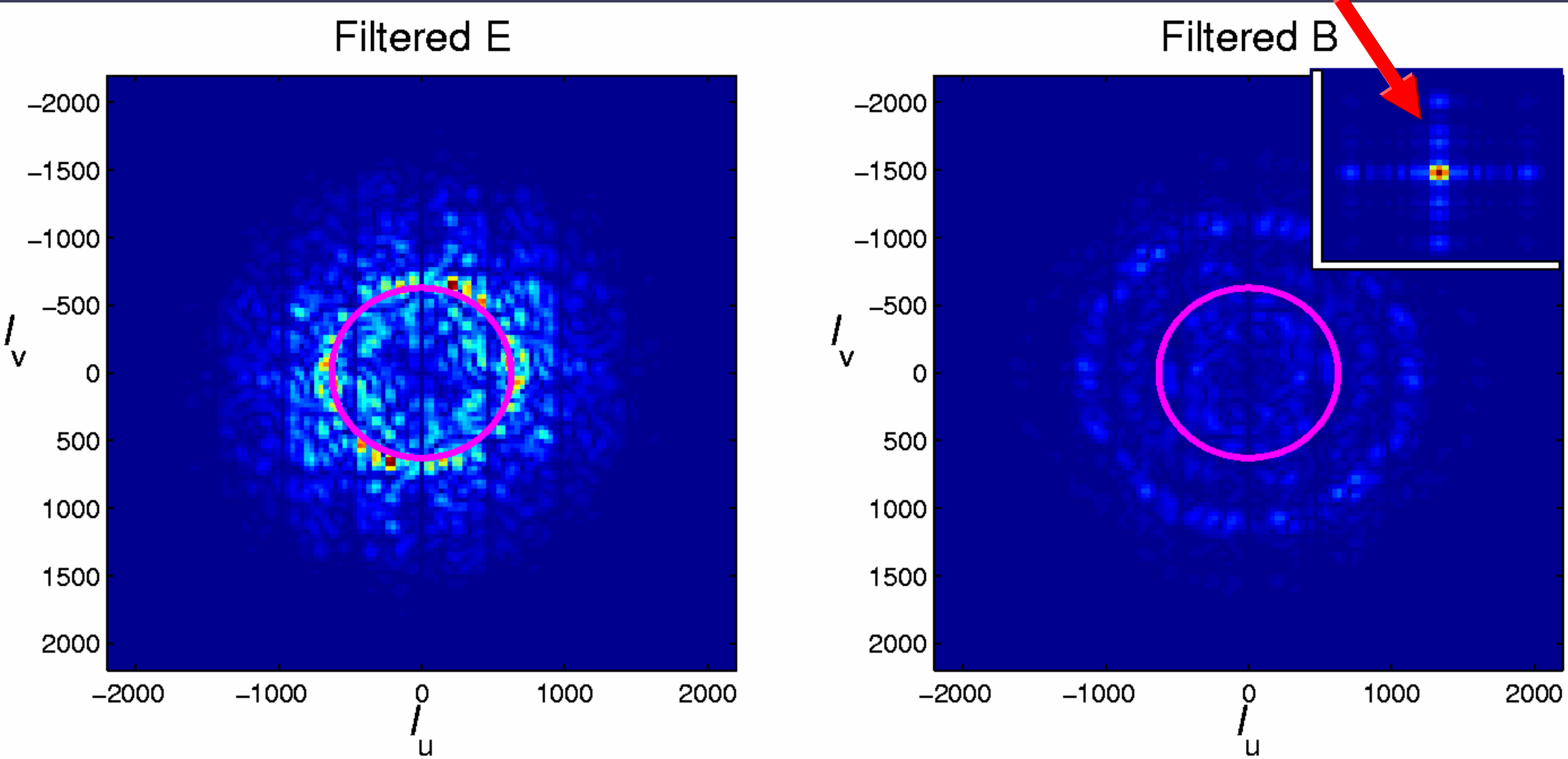
ℓ -space CLEAN deconvolved!

ℓ-space maps

use gridded visibilities to reconstruct T,E,B in ℓ-space

linear Wiener filtered reconstruction

sub-Nyquist mosaic pattern ➔ "sidelobes" in ℓ-space



Summary

CMB Checklist

Primary predictions from inflation-inspired models:

- acoustic oscillations below horizon scale
  - √– nearly harmonic series in sound horizon scale
  - √– signature of super-horizon fluctuations
  - √– even-odd peak heights baryon density controlled
  - √– a high third peak signature of dark matter at recombination
- nearly flat geometry
  - √– peak scales given by comoving distance to last scattering
- primordial plateau above horizon scale
  - √– signature of potential fluctuations
  - √– nearly scale invariant with slight red tilt ($n \approx 0.96$) and small running
- damping of small-scale fluctuations
  - √– baryon-photon coupling plus delayed recombination (& reionization)

CMB Checklist (continued)

Secondary predictions from inflation-inspired models:

- late-time dark energy domination
  - √ – low ℓ ISW bump correlated with large scale structure (potentials)
- late-time non-linear structure formation
  - gravitational lensing of CMB
  - ? – Sunyaev-Zeldovich effect from deep potential wells (clusters)
- late-time reionization
  - ? – overall supression and tilt of primary CMB spectrum
  - doppler and ionization modulation produces small-scale anisotropies

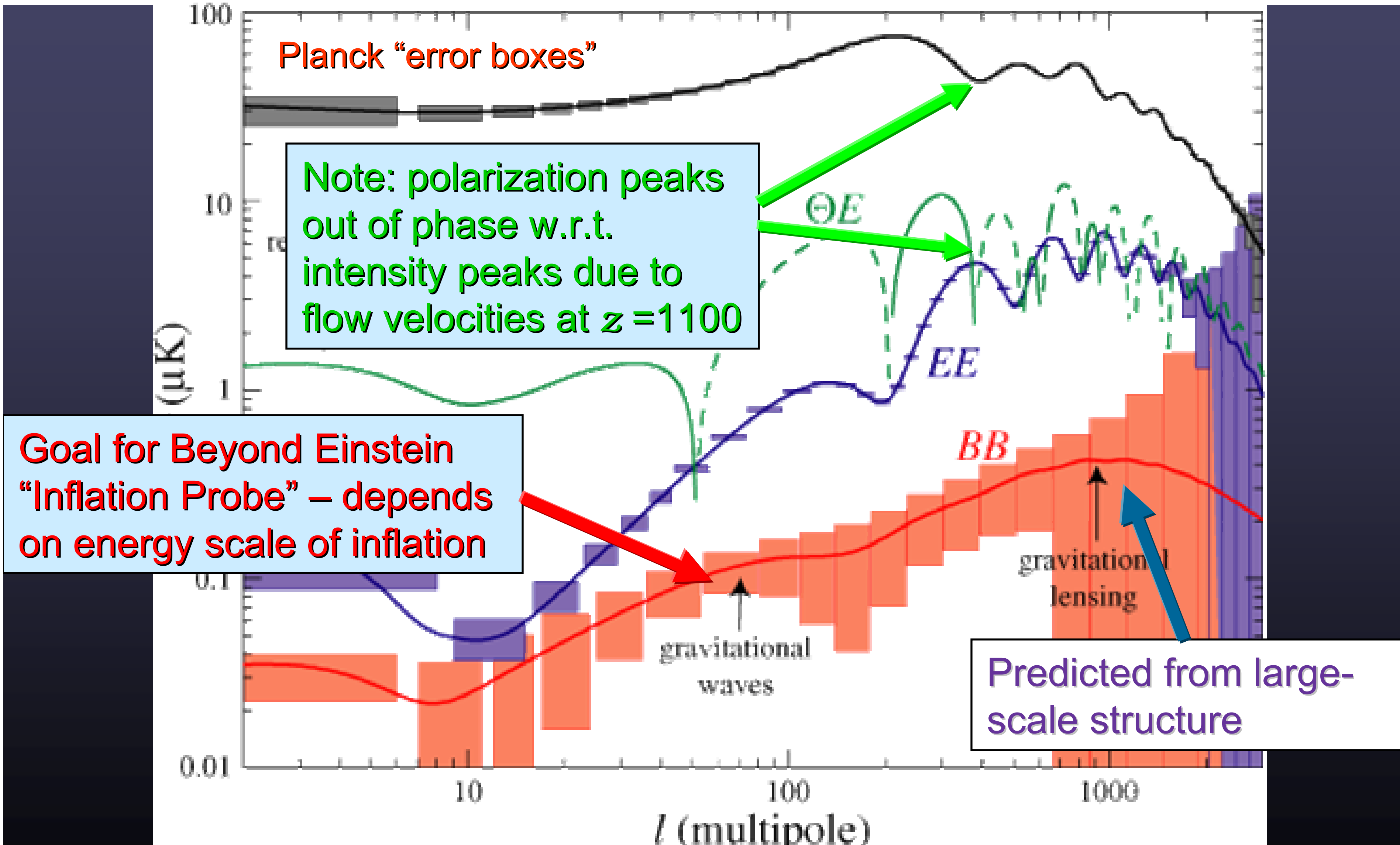
CMB Checklist (continued)

Polarization predictions from inflation-inspired models:

- CMB is polarized
  - √ – acoustic peaks in E-mode spectrum from velocity perturbations
  - √ – E-mode peaks 90° out-of-phase for adiabatic perturbations
  - √ – vanishing small-scale B-modes
  - √ – reionization enhanced low ℓ polarization
- gravity waves from inflation
  - B-modes from gravity wave tensor fluctuations
  - very nearly scale invariant with extremely small red tilt ($n \approx 0.98$)
  - decay within horizon ($\ell \approx 100$)
  - tensor/scalar ratio r from energy scale of inflation ~ $(E_{inf}/10^{13}\ \mathrm{GeV})^4$

Our inflationary hot Big-Bang theory is standing up well to the observations so far! Now for those gravity waves…

Planck: The next big thing in CMB!



Hu & Dodelson *ARAA 2002*