The Cosmic Microwave Background

Theoretical and Experimental Overview

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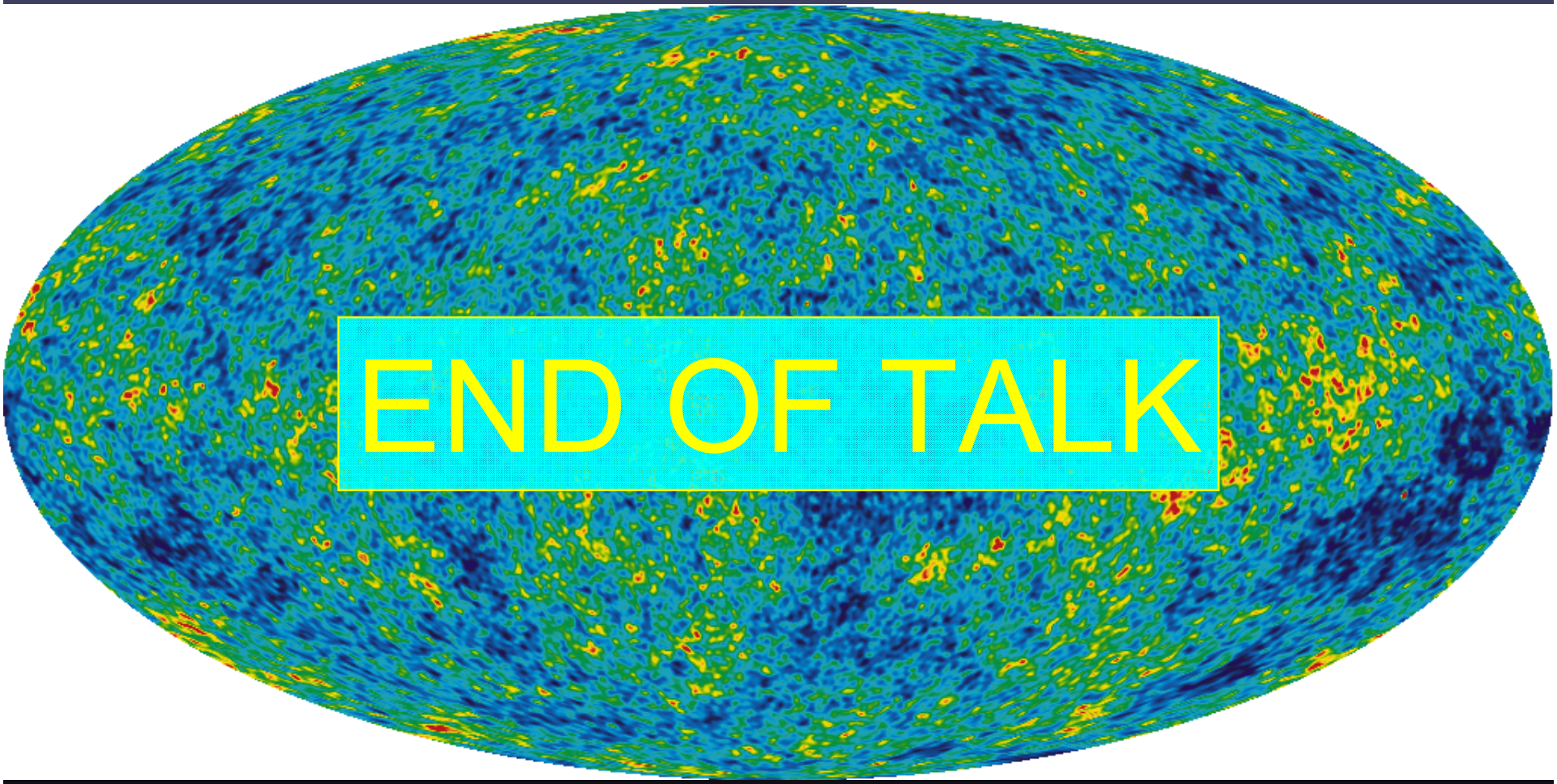
What is the CMB?

- WMAP says: a lot of Gaussian random noise…



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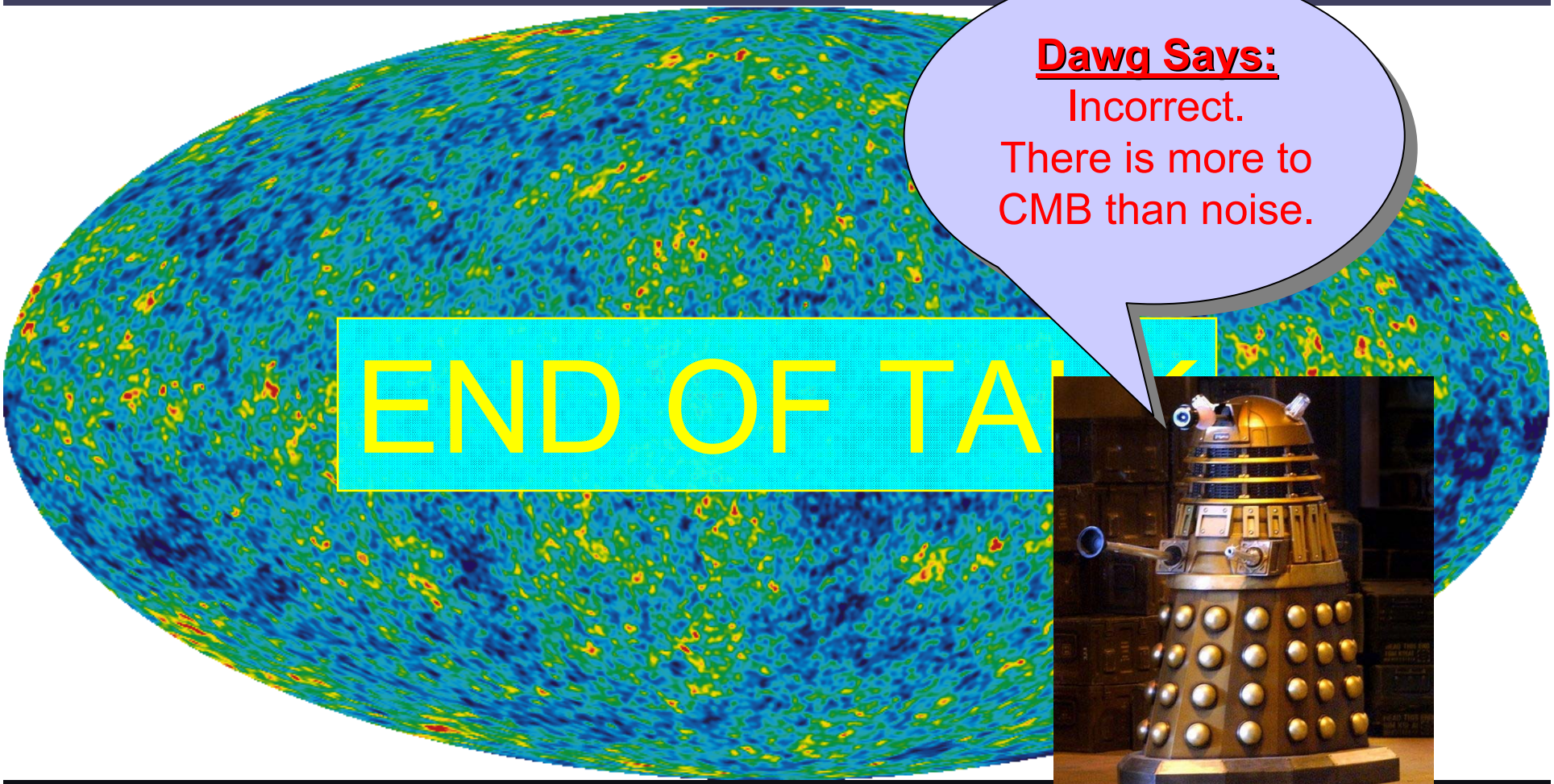


Remarkable things about the CMB

- Indistinguishable from perfect blackbody with T ~ 2.728K
- It is remarkably isotropic, except for 3 mK dipole
  - anisotropies < 0.01%
- Nearly isotropic even on scales outside horizon
  - horizon ~ 2° at z=1000 "last scattering"
  - for causality must have had "inflationary epoch" in past
- CMB fluctuations appear to be a Gaussian Random Field
- Extremely good fit to our theoretical models
  - "Hot Big Bang" model
  - inflationary generation of adiabatic fluctuations
  - transition from radiation to matter domination around z~10000
  - recombination at z~1000, dark matter domination
  - dark energy domination around z~1

Your alternative model had better fit better than this!

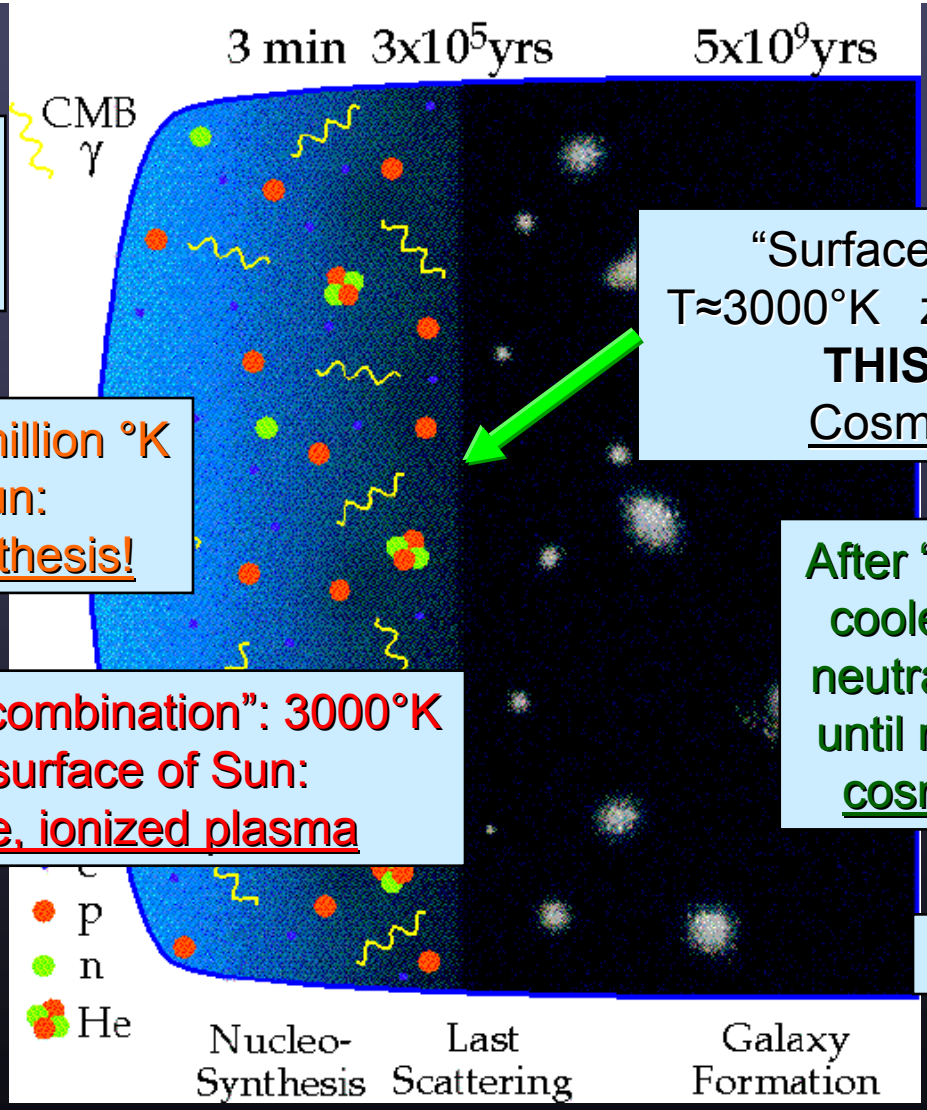
Cosmological Parameters

and their effect on the angular power spectrum of the Cosmic Microwave Background

Thermal History of the Universe

A Hot Big Bang

Planck time?
Inflation?
Baryogenesis



"First 3 minutes": 10 million °K
like interior of Sun:
Big Bang Nucleosynthesis!

Before "recombination": 3000°K
like surface of Sun:
opaque, ionized plasma

"Surface of last scattering"
T≈3000°K z≈1000 t=400,000 yrs
THIS IS THE CMB!
Cosmic Photosphere

After "recombination":
cooler, transparent,
neutral hydrogen gas
until reionization z~6
cosmic Dark Ages

CMB: T≈3°K now

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

Genesis of the CMB

- Based on a Standard Cosmological Model™ (~10 parameters)

$\Omega_k, \Omega_b, \Omega_m, \Omega_\Lambda, h, n_s, r, \tau, \sigma_8$

$\Omega_\Lambda \rightarrow \Omega_e, w_e$

  - e.g. energy densities in fluids relative to critical $\Omega=\rho/\rho_{cr}$

- Quantum fluctuations from Inflation
  - quantum fluctuations in inflaton field
    - gravitational potential perturbations
  - fluctuations pushed outside horizon by exponential inflation
  - inflaton decays into matter and radiation (pre- and re-heating)
  - fluctuations re-enter horizon at late times
    - we see inflation "played back"
  - standard models adiabatic fluctuations (vs. isocurvature)
    - matter and radiation perturbed together = curvature fluctuations
  - Gaussian fluctuations ➔ Gaussian random field

$\delta^2_\Phi(k) = A\, k^{n_s-1} \rightarrow A, n_s$

$n_s \approx 1$

The CMB statistics should reflect physics of inflation

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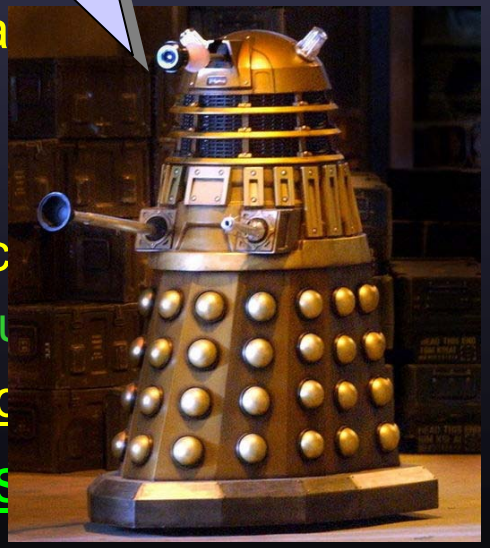
The CMB statistics should reflect phys

Dawg Says:
Incomplete.
There is more to inflation than this.



Statistics of the CMB

- Density fluctuations @ z~1000: linear regime
  - independent plane waves ➔ spherical harmonics on sky

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

- Angular Power Spectrum
  - Gaussian random field
  - cosmological principle - homogeneous & isotropic
  - each mode $a_{\ell m}$ is independent ➔ power spectrum C_ℓ

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

The CMB Angular Power Spectrum C_ℓ contains the physics!

Acoustic Waves

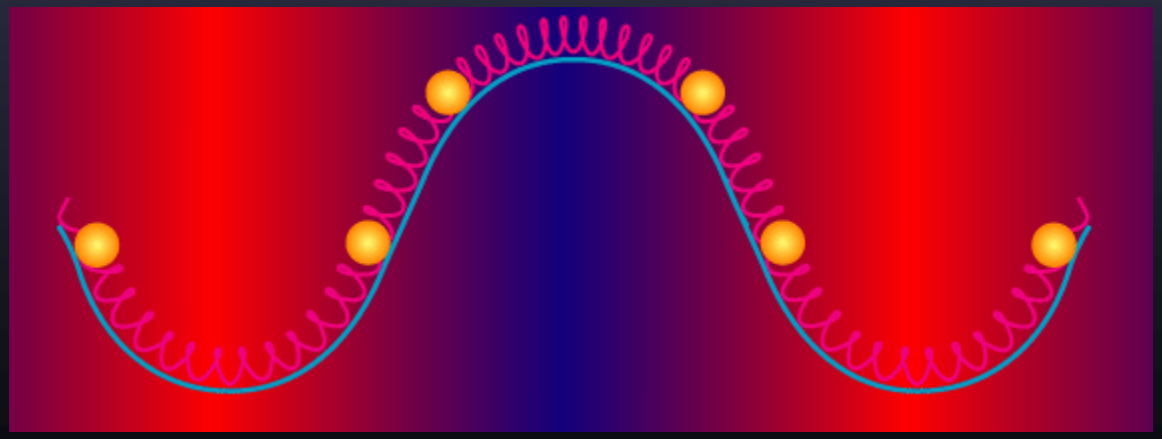
- Before recombination: Photon – Baryon Fluid
  - linear perturbations to photons ➔ harmonic oscillator
  - solution $\delta T/T = (\delta T/T)_0 \cos(ks)$ s=sound horizon

    ➔ harmonic series of peaks in $(\delta T/T)^2$
- Potential fluctuations seeded from inflation
  - drive photon oscillator ➔ $(\delta T/T)_0 = \Phi/3$
- Baryons tightly coupled to photons
  - loading of oscillator ➔ increase effective mass

sound speed ~$c/\sqrt{3}$

$\rho_b/\rho_\gamma \sim 0.3$

Ω_b



$\rho_m/\rho_\gamma \sim 4$

Ω_m

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Acoustic Waves

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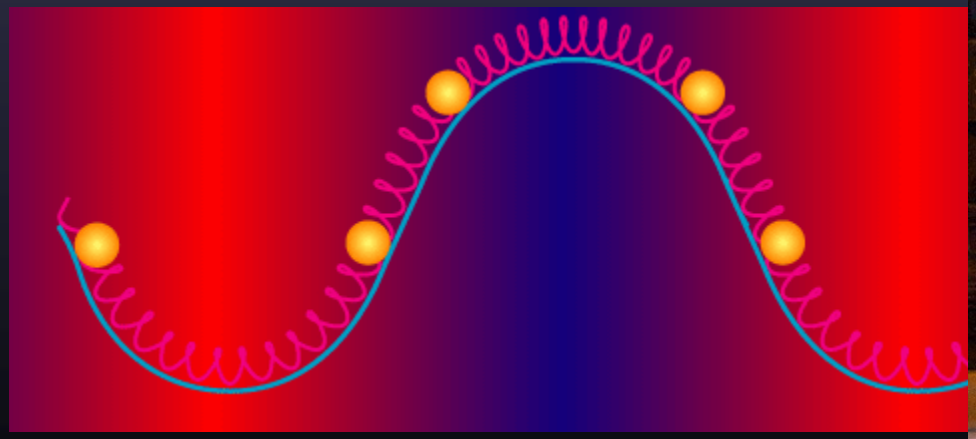
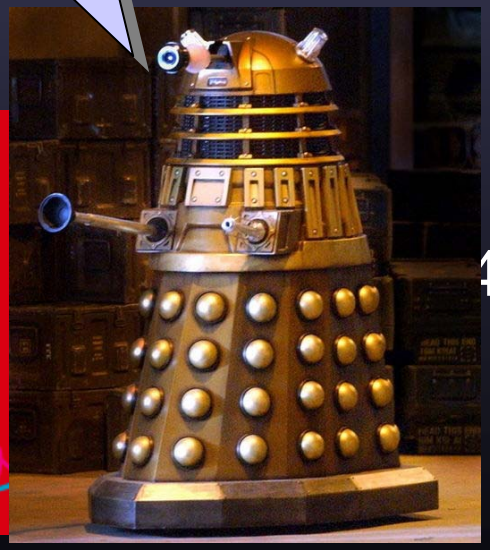
Dawg Says:
Inadequate.
Must solve the
Boltzmann equation.

sound speed
~c/√3

ρ_b/ρ_γ~0.3

Ω_b





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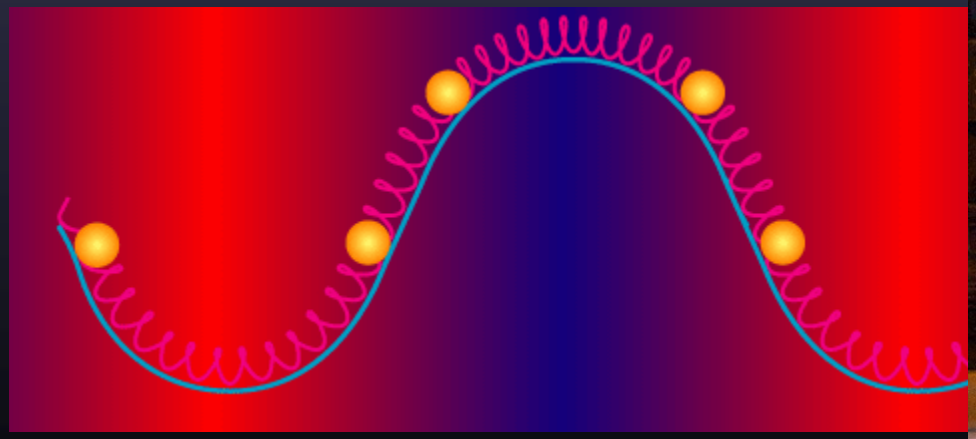
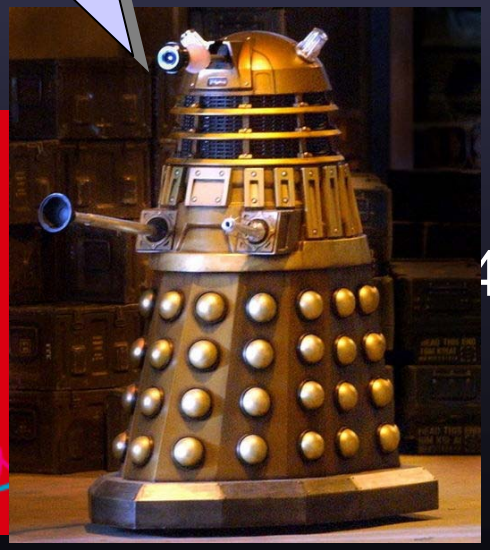
$$\frac{Df(\mathbf{x},\mathbf{p},\eta)}{D\eta} = 0$$

sound speed ~c/√3

ρ_b/ρ_γ~0.3

Ω_b

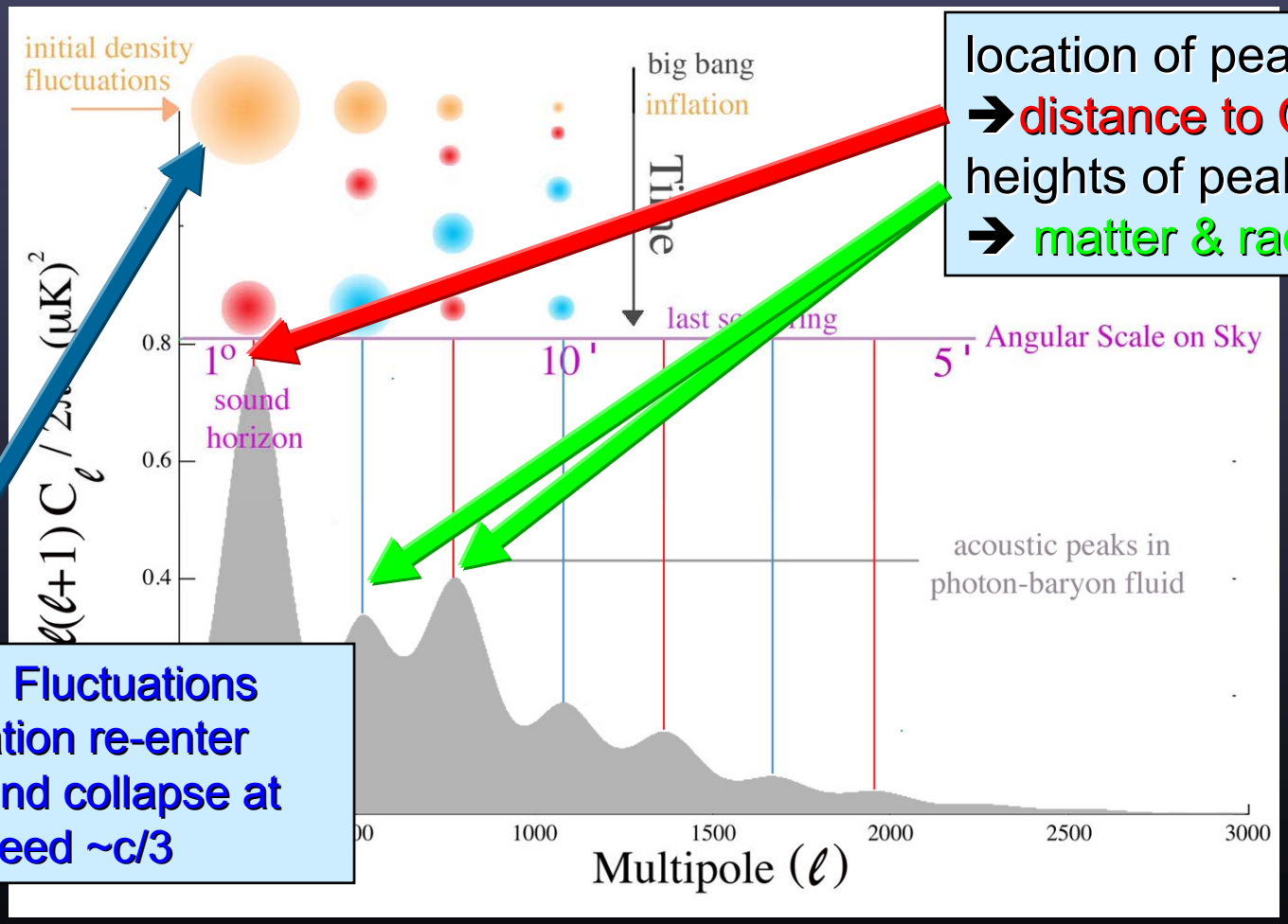




Courtesy Wayne Hu – *http://background.uchicago.edu*

CMB Acoustic Peaks

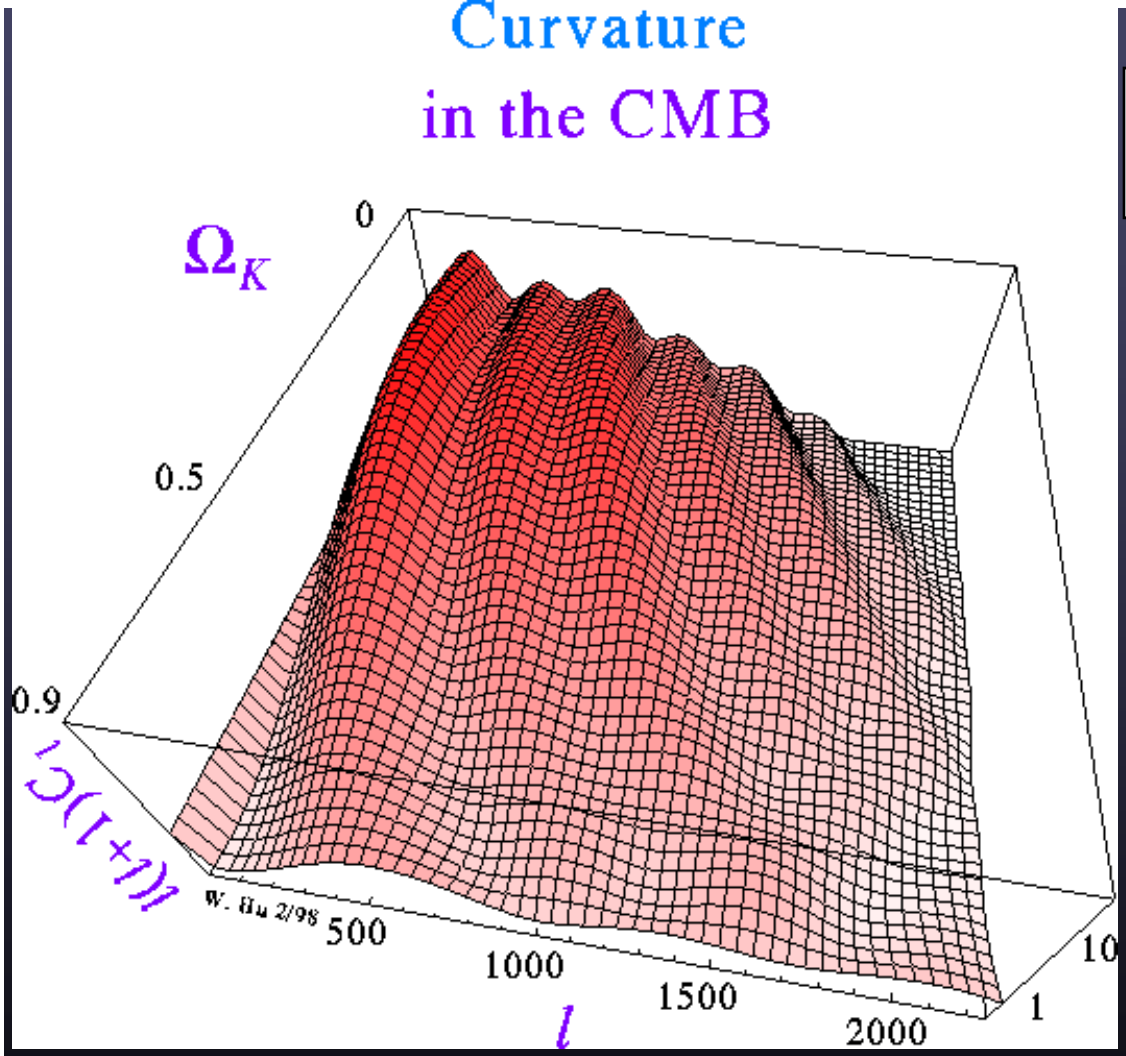
- Compression driven by gravity, resisted by radiation
  - ≈ seismic waves in the cosmic photosphere: $\cos(kc_s\eta)$



location of peaks
➔ distance to CMB
heights of peaks
➔ matter & radiation

Quantum Fluctuations from Inflation re-enter horizon and collapse at sound speed ~c/3

Peaks and Curvature



Changing distance to z =1100 shifts peak pattern

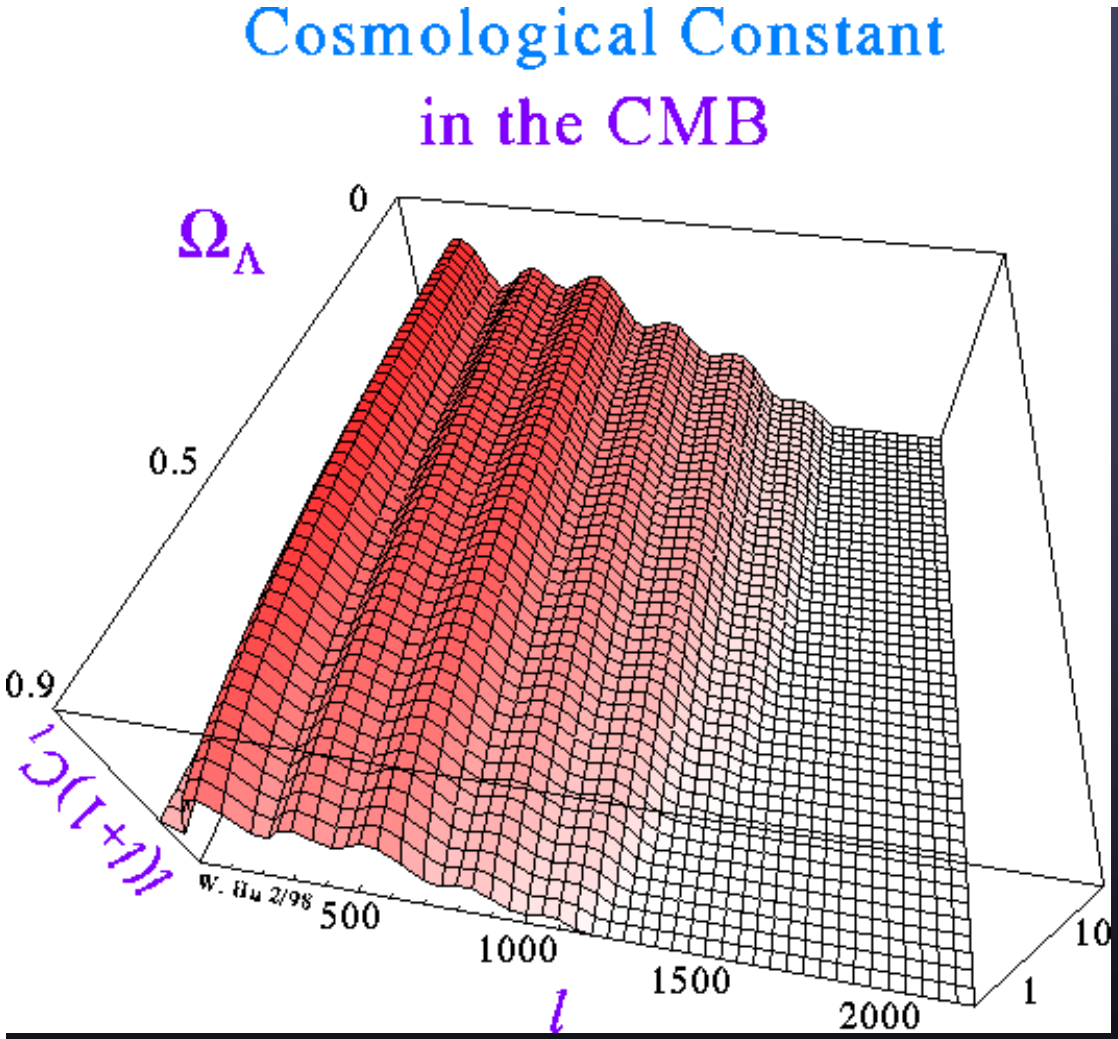
- Location of acoustic peaks
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant) – smaller effect

Ω_k ,h, Ω_Λ

- Relative heights of peaks
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

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

Peaks and Dark Energy



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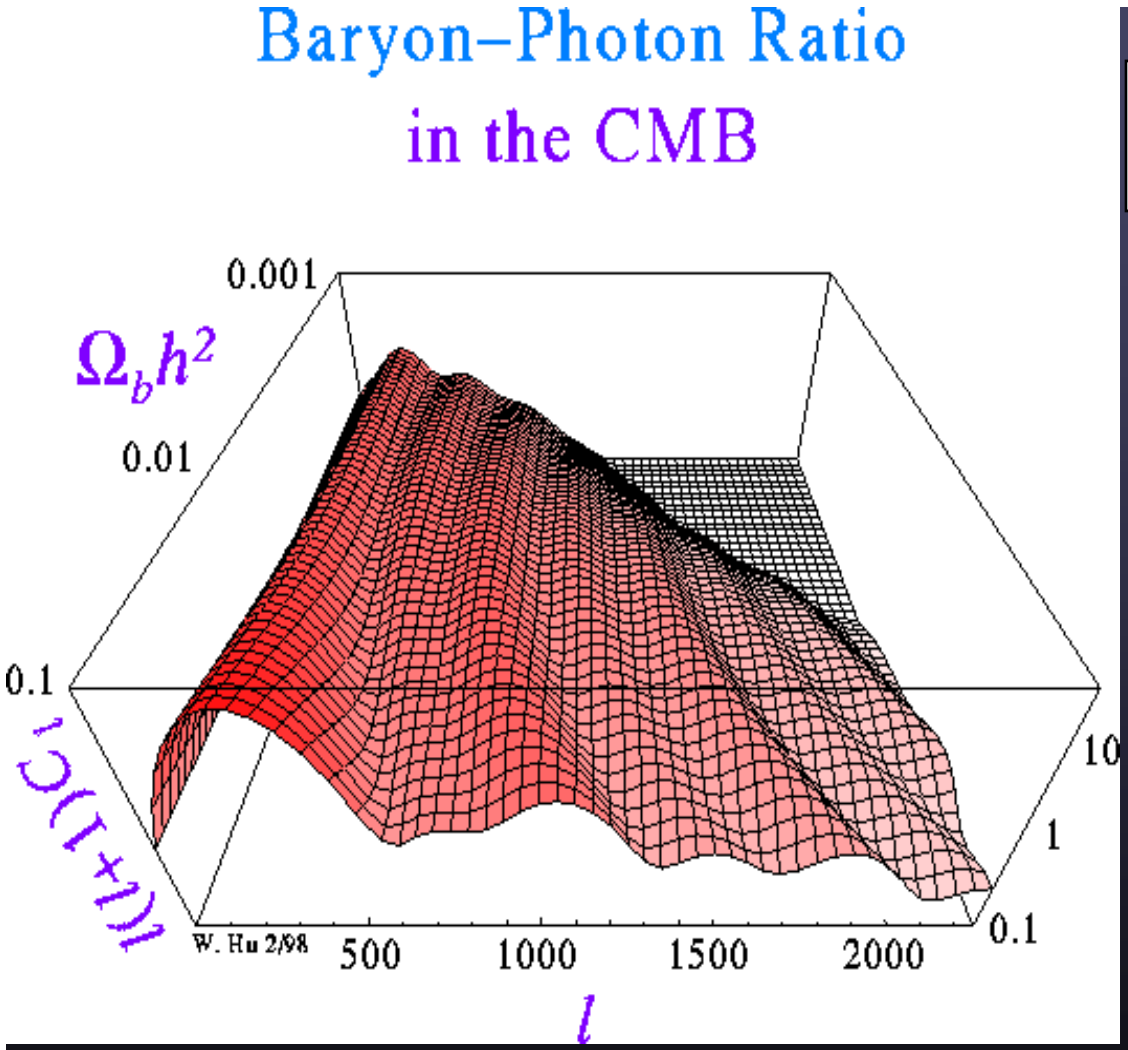
Peaks and Baryon Density



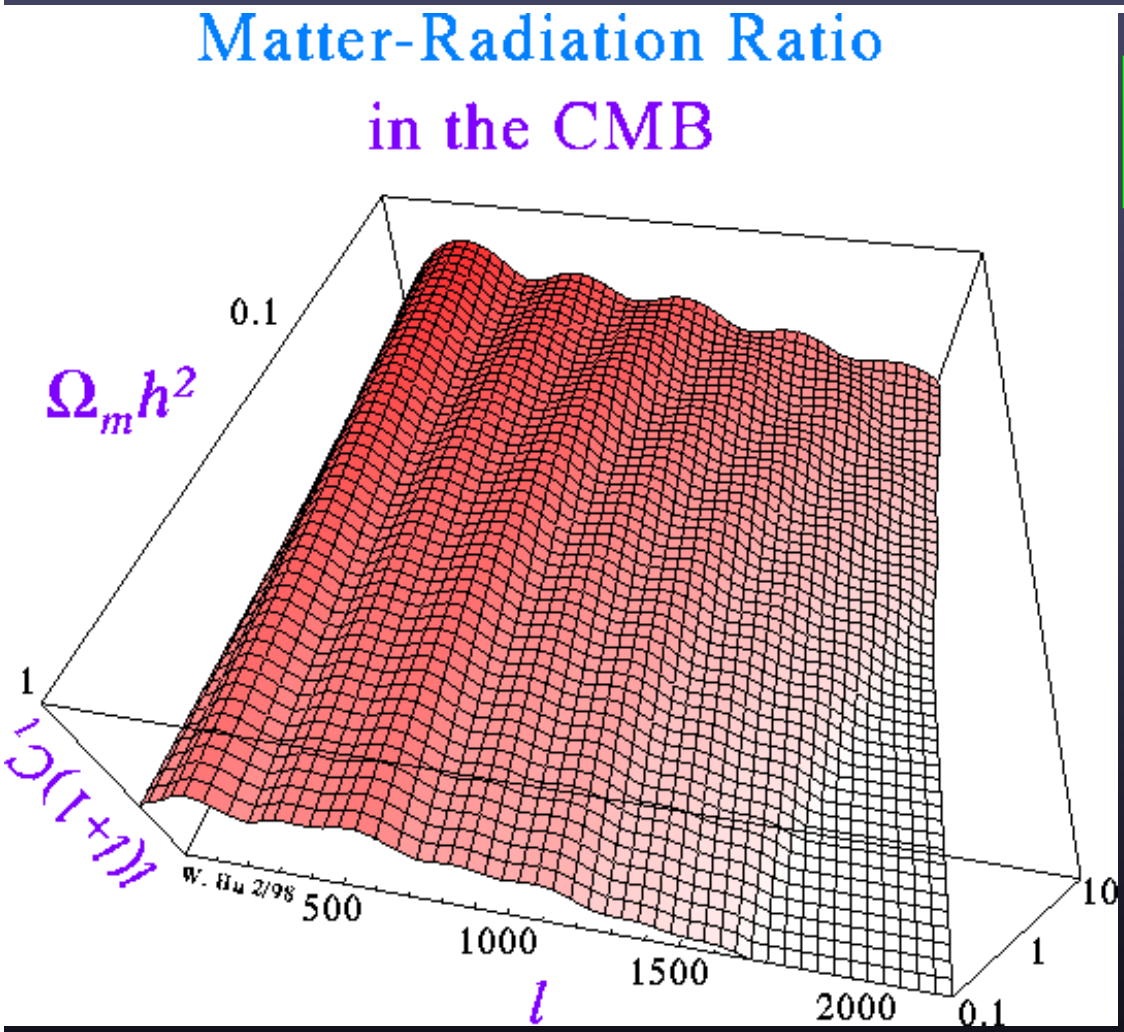
Increasing baryon density enhances odd over even peaks

- Location of acoustic peaks
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
- Relative heights of peaks
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

$\Omega_b h^2$

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

Peaks and Matter Density



Increasing dark matter density supresses 2nd peak vs, 3rd

- Location of acoustic peaks
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
- Relative heights of peaks
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

$\Omega_m h^2$

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

CMB Checklist

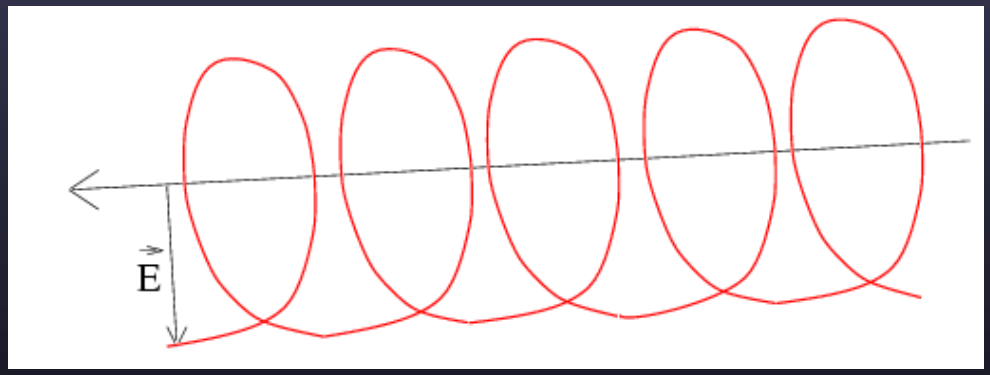
Primary predictions from inflation-inspired models:

- acoustic oscillations below horizon scale
  - nearly harmonic series in sound horizon scale
  - signature of super-horizon fluctuations (horizon crossing starts clock)
  - 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 super-horizon potential fluctuations (Sachs-Wolfe)
  - 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)

Polarization
of the Cosmic Microwave Background Radiation

Physics of polarization

- Maxwell's Equations + Wave Equation
  - E•B=0 (perpendicular) ; $E_z = B_z = 0$ (transverse)
- Electric Vector – 2 orthogonal independent waves:
  - $E_x = E_1 \cos(k z - \omega t + \delta_1)$ $\quad k = 2\pi / \lambda$
  - $E_y = E_2 \cos(k z - \omega t + \delta_2)$ $\quad \omega = 2\pi \nu$
  - describes helical path on surface of a cylinder…



  - parameters E_1, E_2, $\delta = \delta_1 - \delta_2$ define <u>ellipse</u>
    - electric vector traces ellipse viewed along ***k*** direction

The Polarization Ellipse

- Axes of ellipse E_a, E_b
  - $S_0 = E_1^2 + E_2^2 = E_a^2 + E_b^2$ (Poynting flux)
  - $E_\xi = E_a \cos(\tau + \delta) = E_x \cos\psi + E_y \sin\psi$
  - $E_\eta = E_b \sin(\tau + \delta) = -E_x \sin\psi + E_y \cos\psi$

δ phase difference

$\tau = k\,z - \omega\,t$

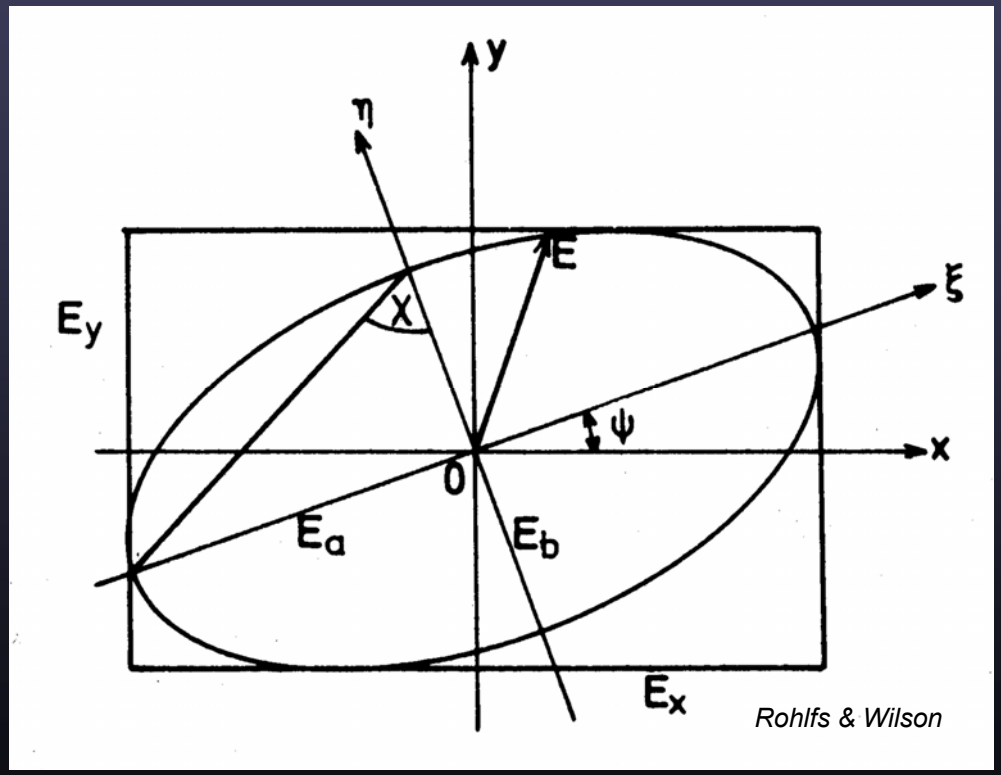
  - $E_1 / E_2 = \tan\alpha$
  - $E_a / E_b = \tan\chi$
  - <u>two angles:</u>

    $\tan 2\psi = -\tan 2\alpha \cos\delta$

    $\sin 2\chi = \sin 2\alpha \sin\delta$
  - <u>special cases:</u>

    linear ($\delta = \delta_1 - \delta_2 = m\,\pi$)

    circular ($\delta = ½\,(1 + m)\,\pi$)

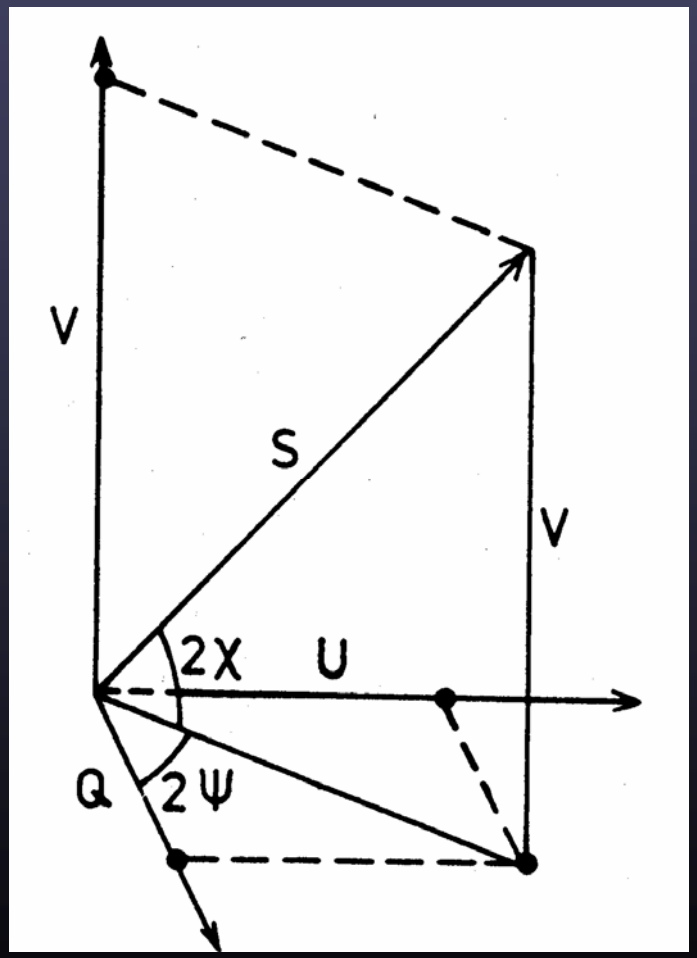


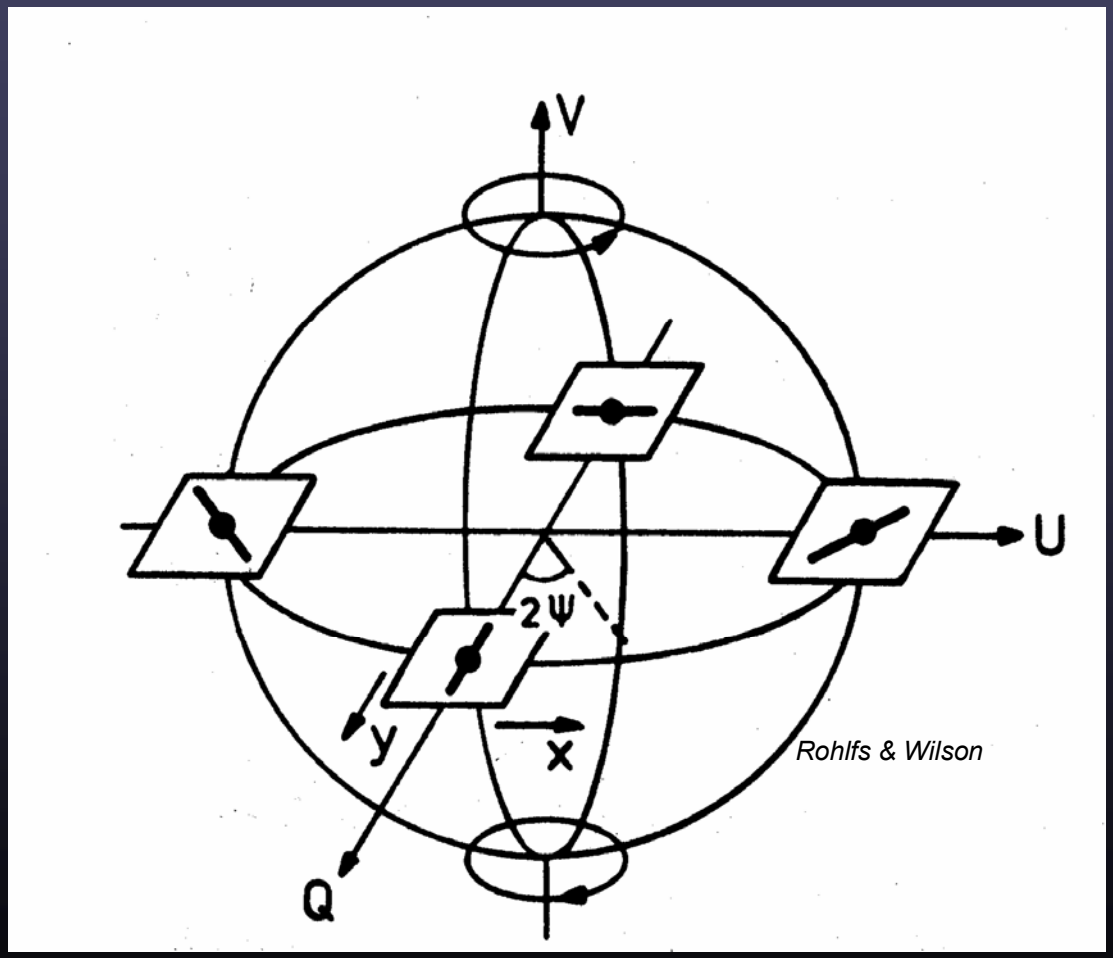
Rohlfs & Wilson

  - handedness ($\sin\delta > 0$ or $\tan\chi > 0$ ➔ *right-handed*)

The Poincare Sphere

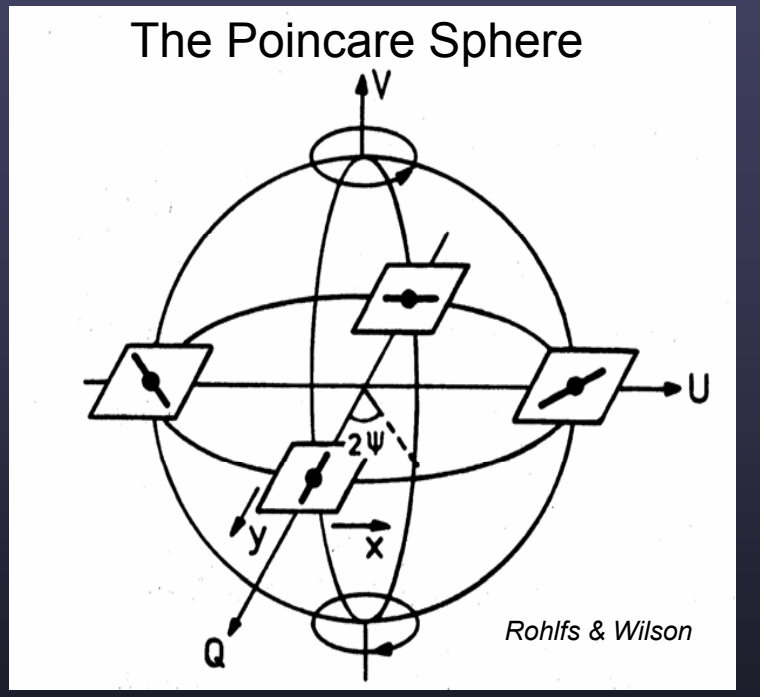
- Treat 2ψ and 2χ as longitude and latitude on sphere of radius S_0





Stokes parameters

- Spherical coordinates: radius I, axes Q, U, V
  - $S_0 = I = E_a^2 + E_b^2$
  - $S_1 = Q = S_0 \cos 2\chi \cos 2\psi$
  - $S_2 = U = S_0 \cos 2\chi \sin 2\psi$
  - $S_3 = V = S_0 \sin 2\chi$
- Only 3 independent parameters:
  - $S_0^2 = S_1^2 + S_2^2 + S_3^2$
  - $I^2 = Q^2 + U^2 + V^2$



- Stokes parameters I,Q,U,V
  - form complete description of wave polarization
  - NOTE: monochromatic wave MUST be fully polarized!
  - for non-monochromatic sources: <u>partial polarization</u>
    - $I^2 > Q^2 + U^2 + V^2$

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Q,U depend on choice of "North" (plus handedness)

- Q "points" North, U 45 toward East
- $\Phi = \frac{1}{2} \tan^{-1} (U/Q)$ (North through East)

Note: because of coordinate system dependence, Q and U are not useful for CMB statistics in homogeneous and isotropic Universe!

Stokes parameters

- Spherical coordinates: radius I, axes Q, U, V
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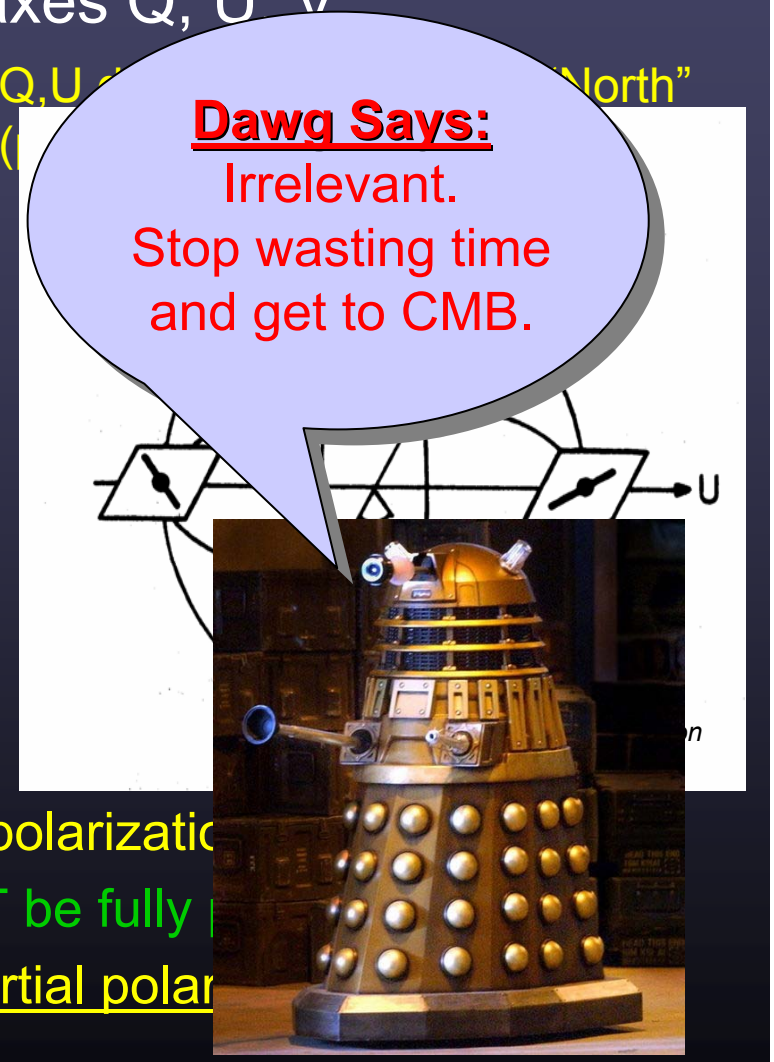
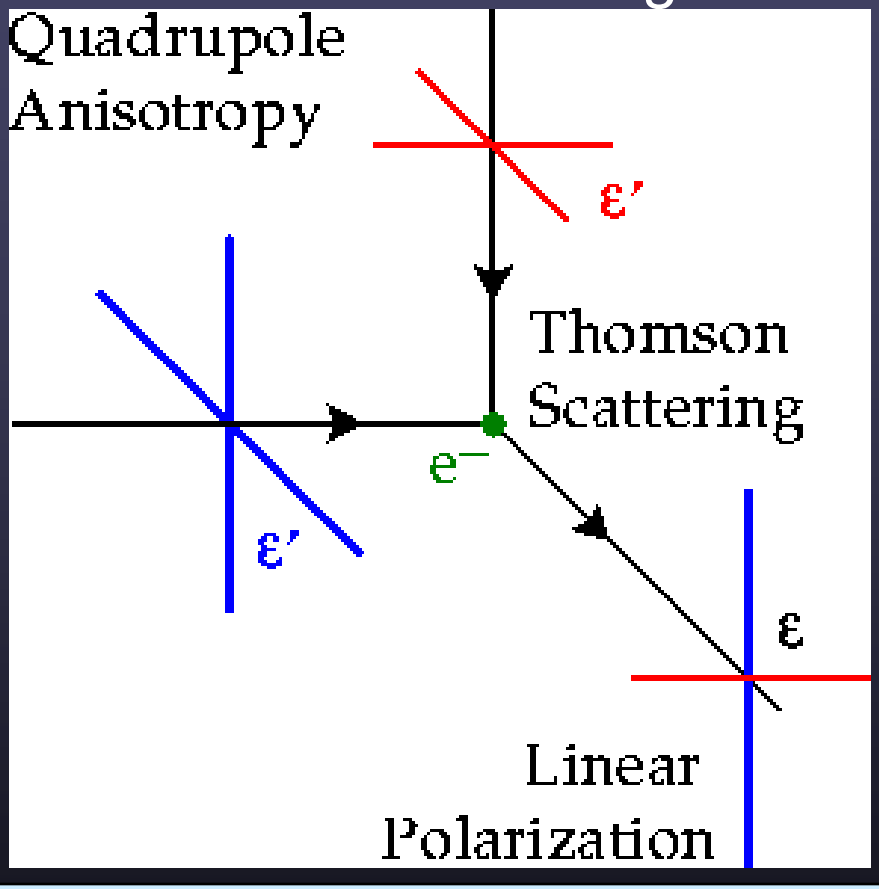
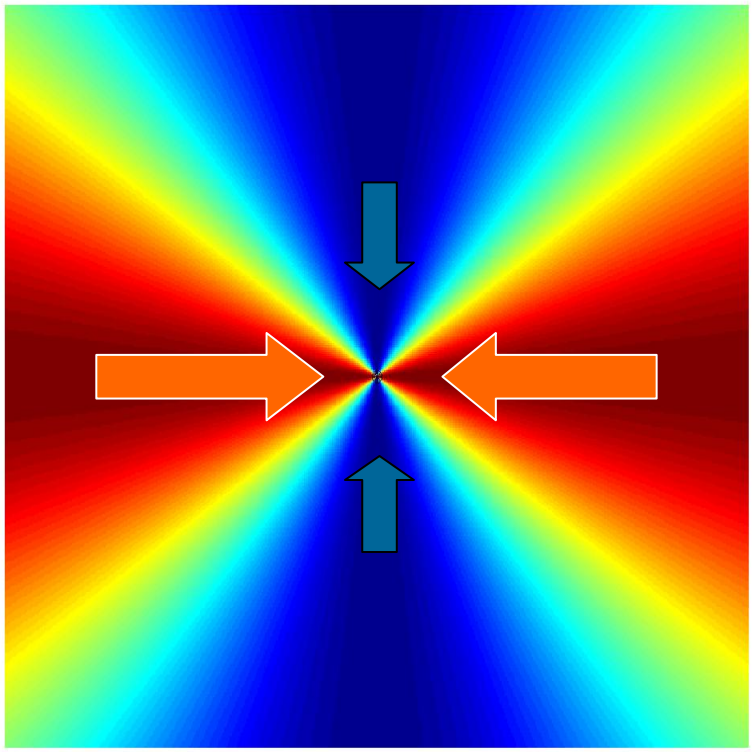


- Stokes parameters I,Q,U,V
  - form complete description of wave polarizatio
  - NOTE: monochromatic wave MUST be fully
  - for non-monochromatic sources: partial polar
    - $I^2 > Q^2 + U^2 + V^2$

The CMB is Polarized

Thomson scattering:





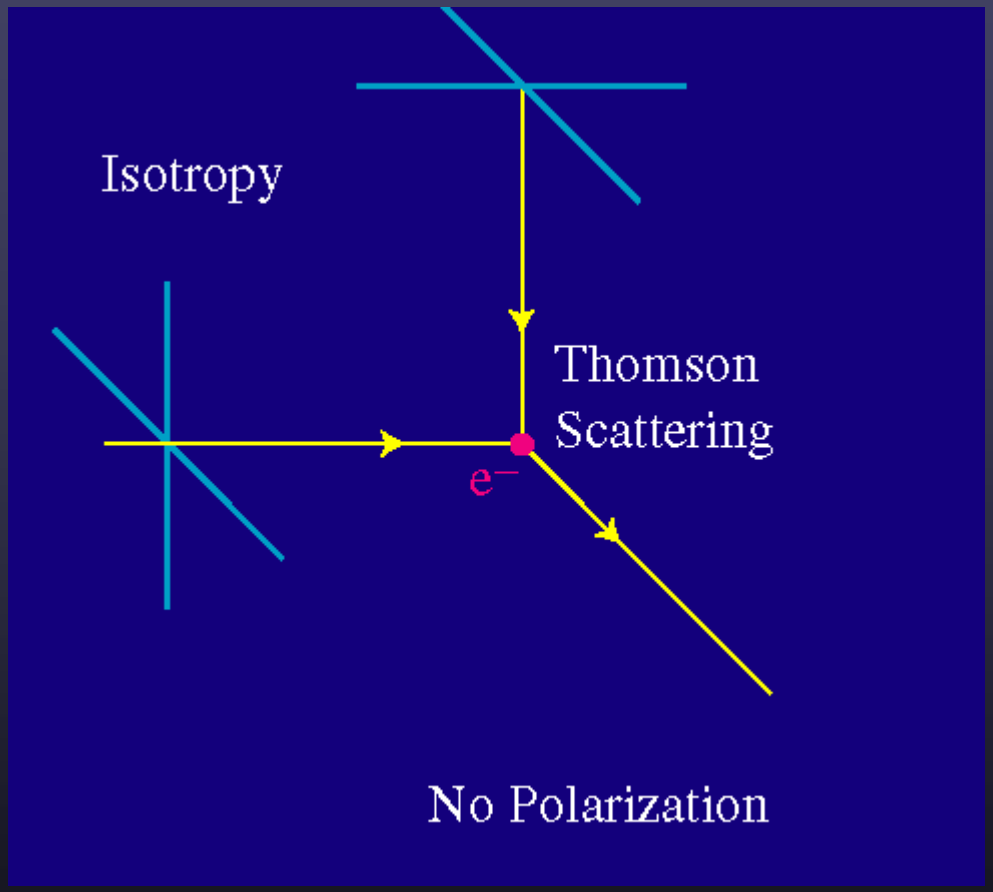
polarization transverse to line-of-sight transmitted on scattering!

more radiation from horizontal (hot) than vertical (cold)

➔ outgoing polarization net vertical

Above figure courtesy Hu & White 1997

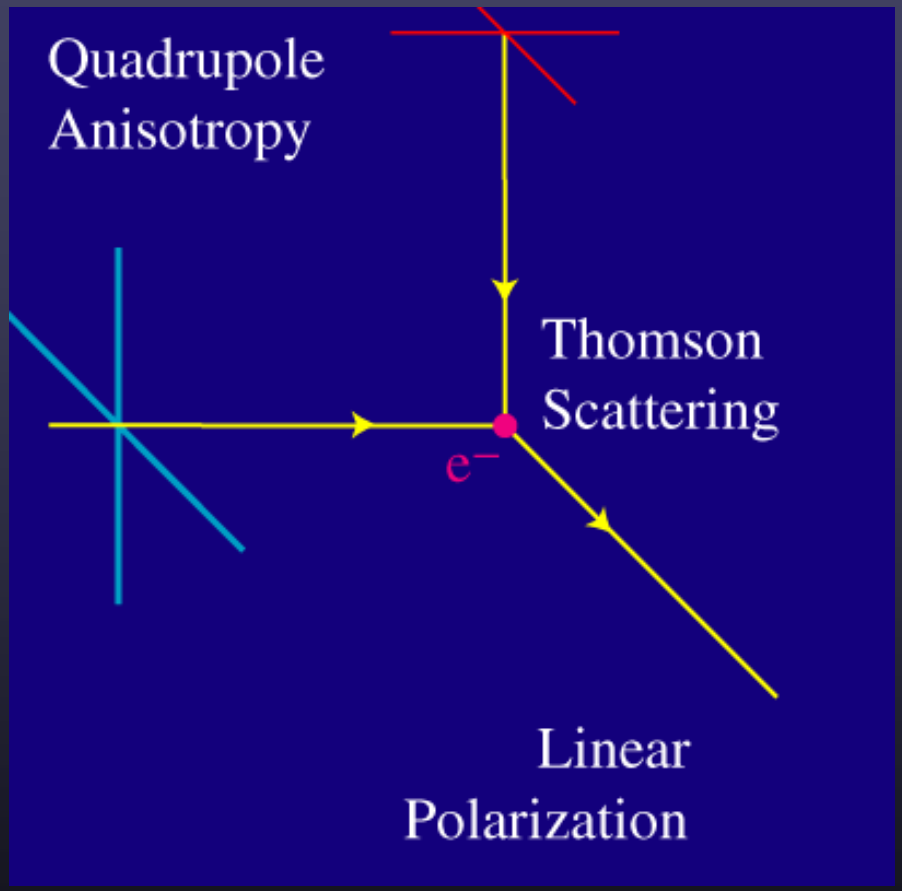
Isotropic (monopolar) Scattering



➔ NO net linear polarization

animations from Wayne Hu

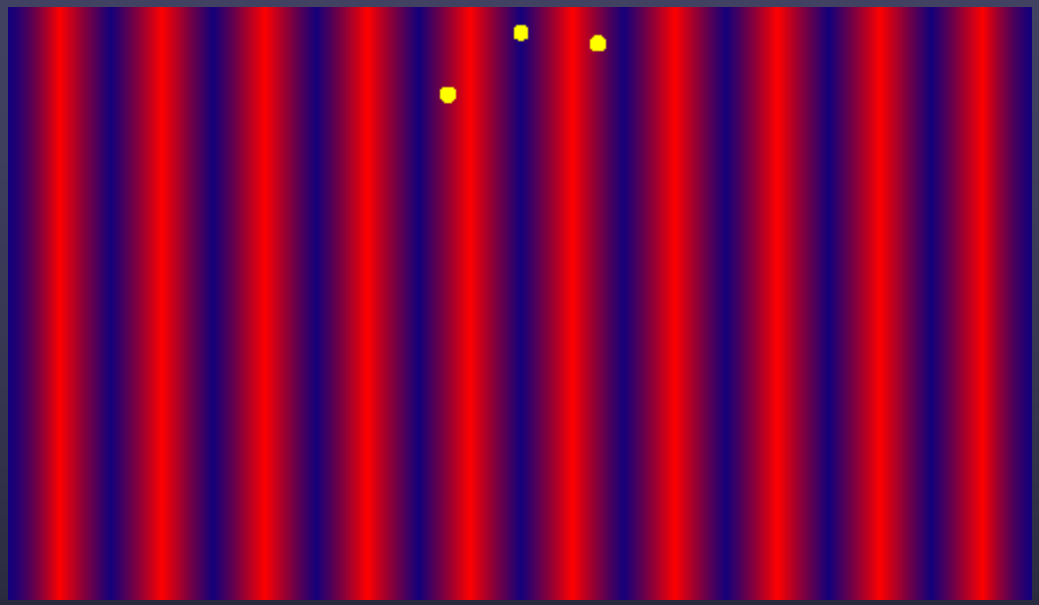
Quadrupolar Scattering



➔ <u>net linear polarization</u>

Animations from Wayne Hu

Quadrupole and plane wave



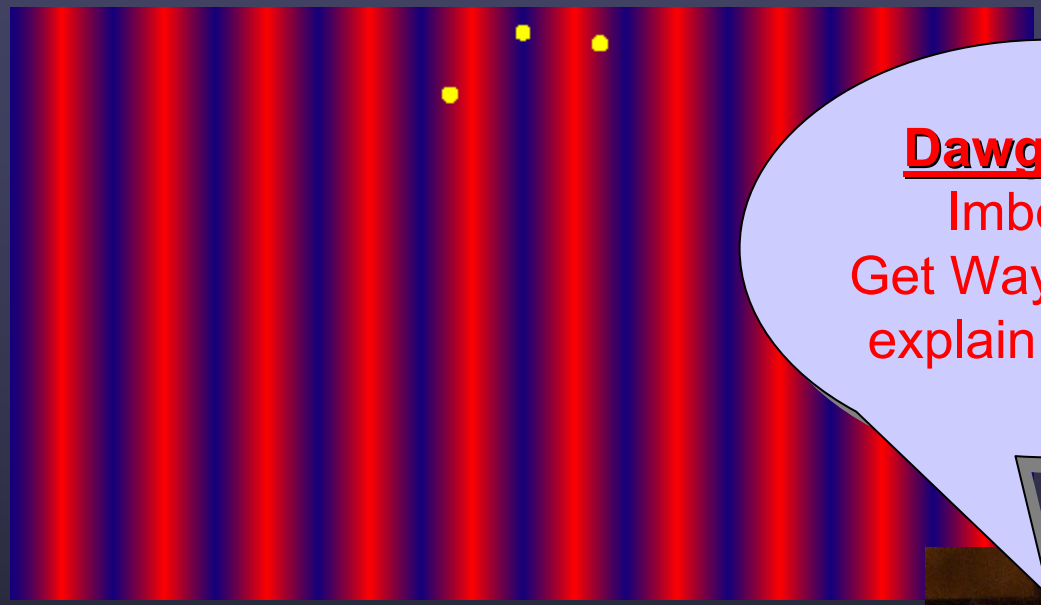
electrons forced to move normal to or parallel to wave in convergent or divergent flows (scalars)

➔ net linear polarization

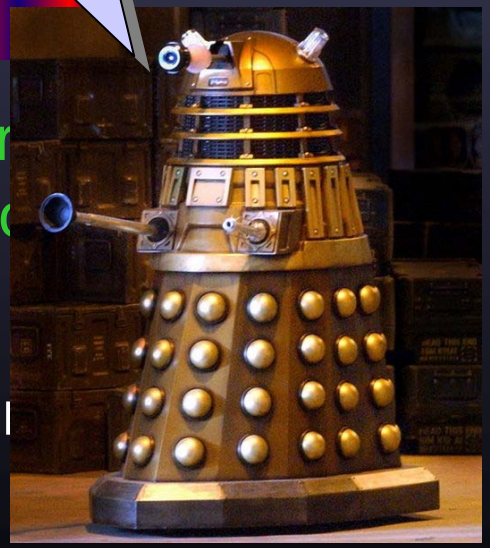
is oriented along cold axis of quadrupole

Animations from Wayne Hu

Quadrupole and plane wave



Dawg Says:
Imbecile.
Get Wayne Hu to explain instead.



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➔ net linear polarization

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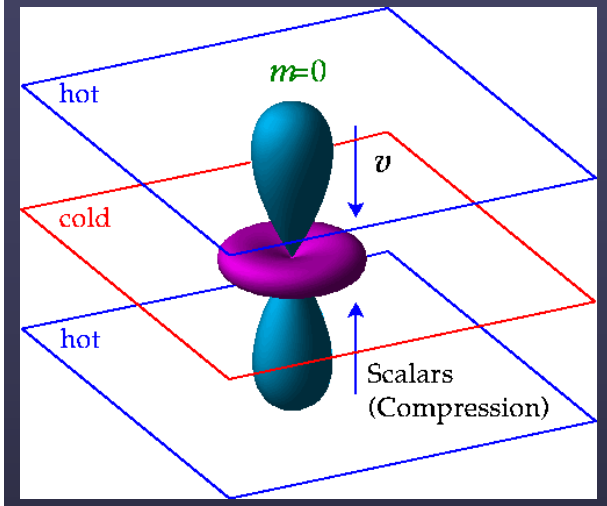
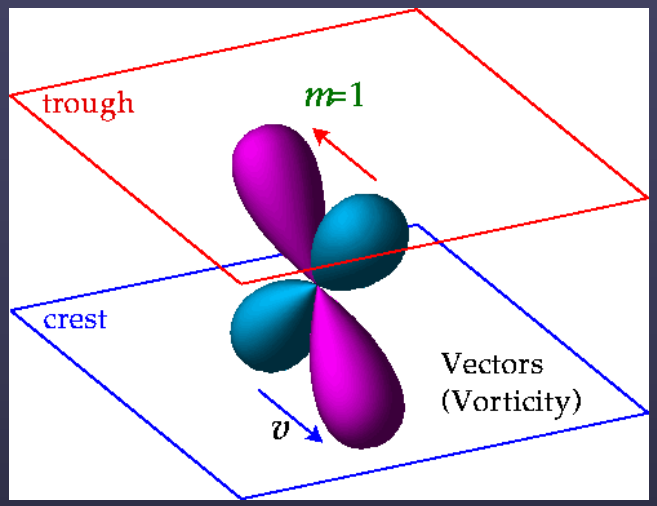
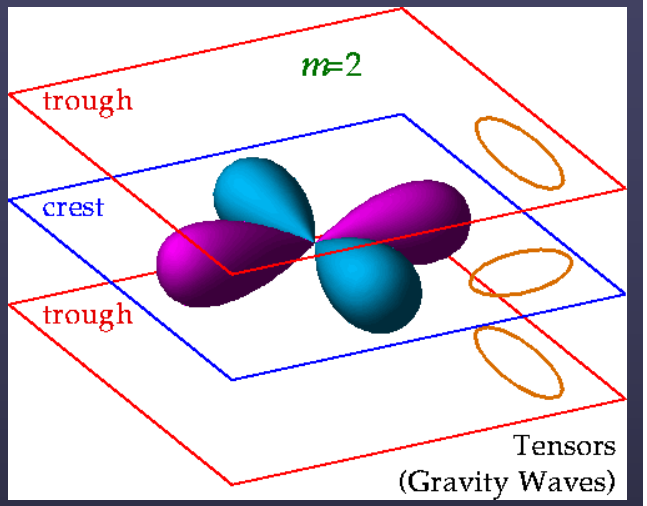
Animations from Wayne Hu

The local quadrupole at scattering







Scalar modes

Vector modes

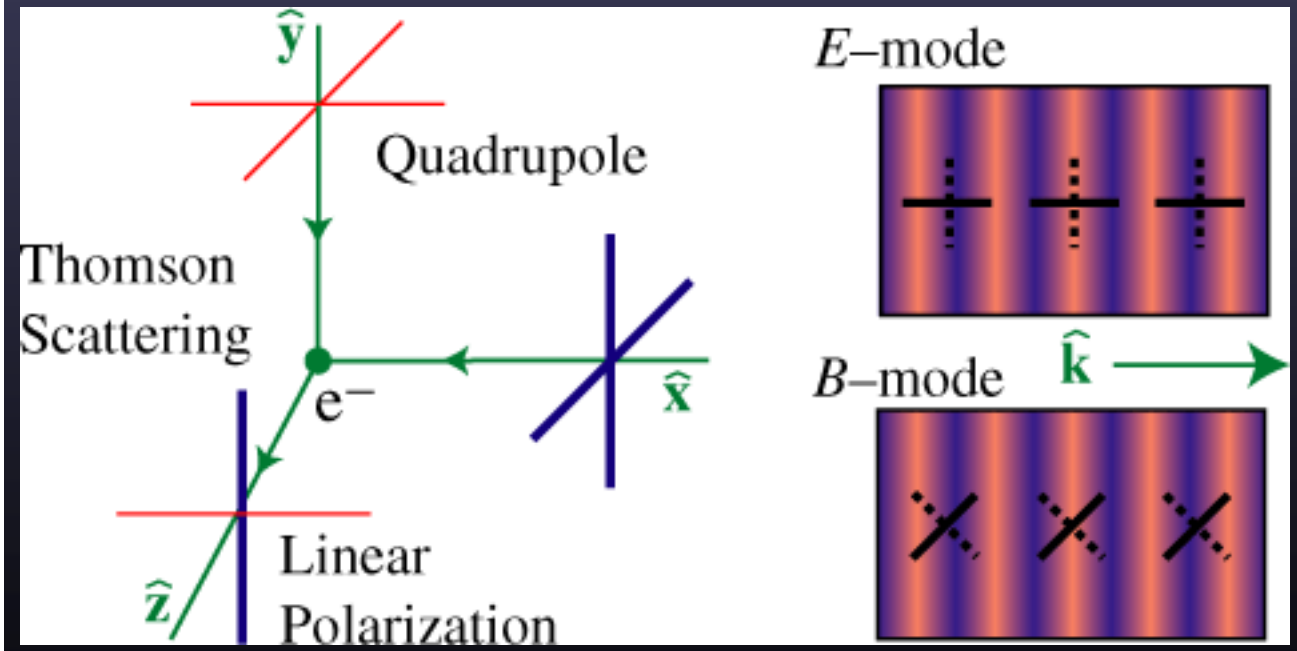
Tensor modes

- Quadrupole (ℓ=2) has 8 components: m=0, m=±1, m=±2
- Density perturbations (from potential fluctuations H) produce scalar modes
- Vector modes indicate vorticity, and can be produced by defects (e.g. cosmic strings)
- Tensor modes are produced by gravity waves

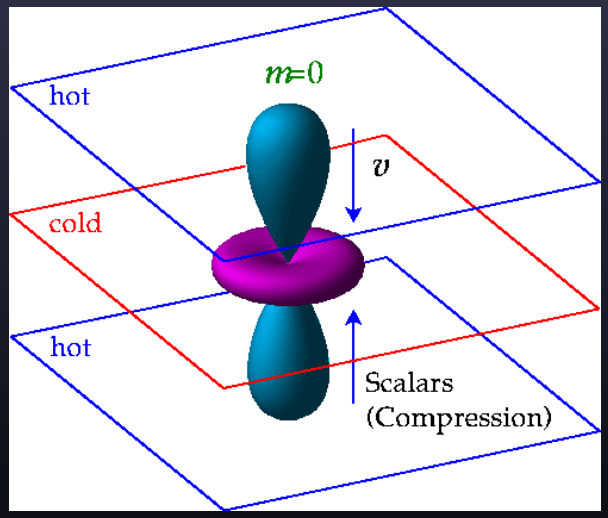
Courtesy Hu & White– *http://background.uchicago.edu*

E-modes from Scalars

- Linear polarization "vectors" for plane waves
  - E (even parity = aligned 0° or 90° to k-vector)
    - from scalar density fluctuations ➔ predominant in standard model!



Density waves produce "E-mode" polarization:



Figures courtesy Hu & White 1997, Hu & Dodelson 2002

E-modes from Scalars

- Linear polarization "vectors" for plane waves
  - E (even parity = aligned 0° or 90° to k-vector)
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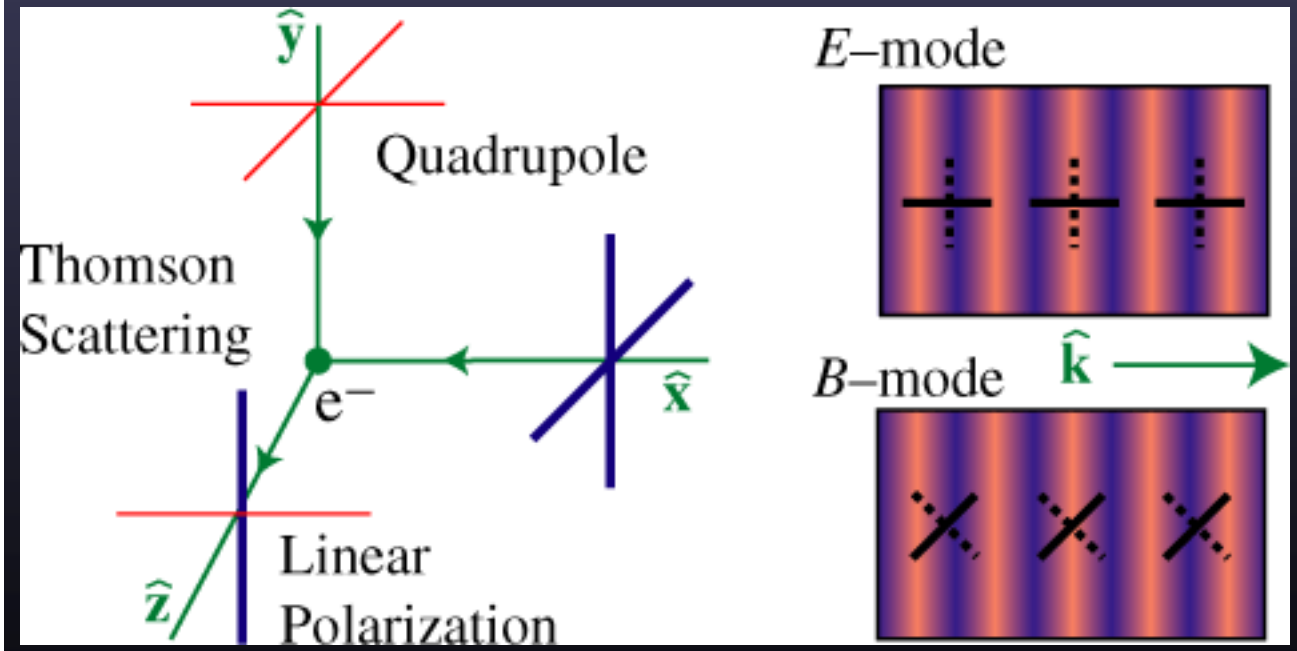
  - B (odd parity = at ±45° to k-vector)



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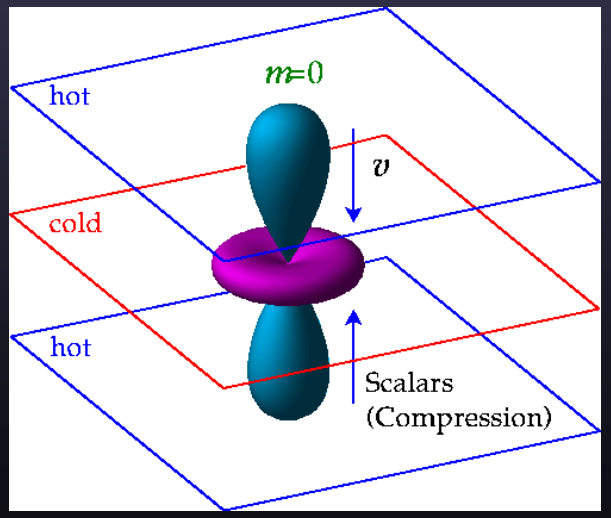
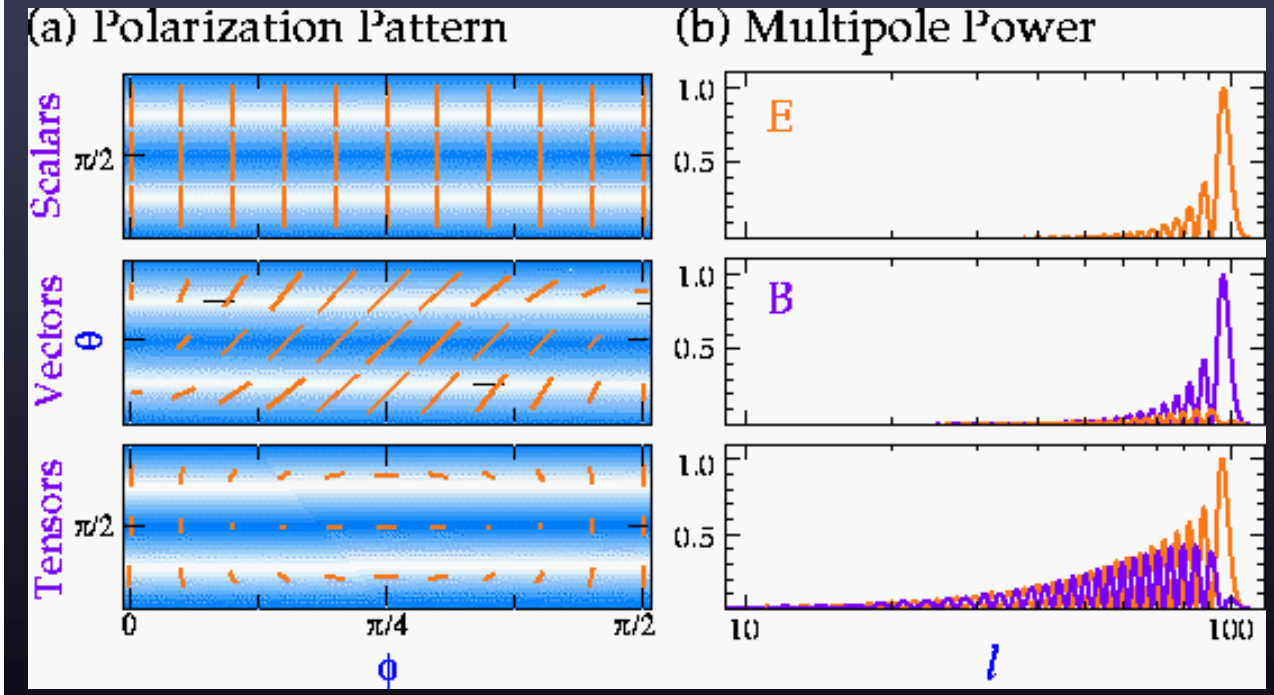


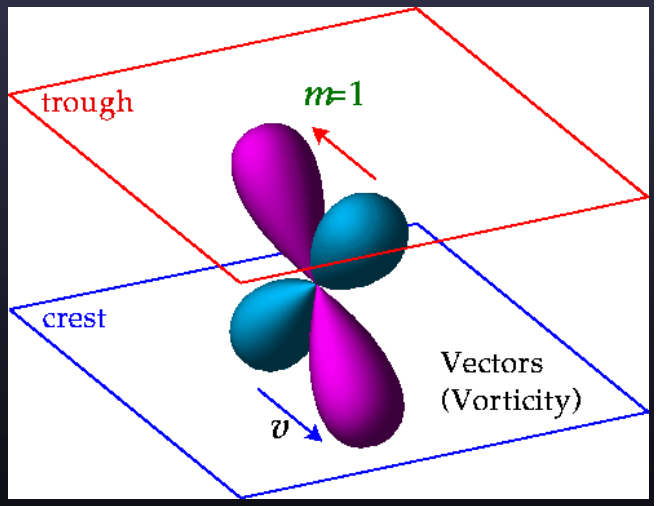
Figures courtesy Hu & White 1997, Hu & Dodelson 2002

E & B modes from Tensors

- Linear polarization "vectors" for plane waves
  - E (even parity = aligned 0° or 90° to k-vector)
    - from scalar density fluctuations ➔ predominant in standard model!
  - B (odd parity = at ±45° to k-vector)
    - vector perturbations (vorticity or defects) produce only **B**-modes



Vorticity produces "B-mode" polarization:

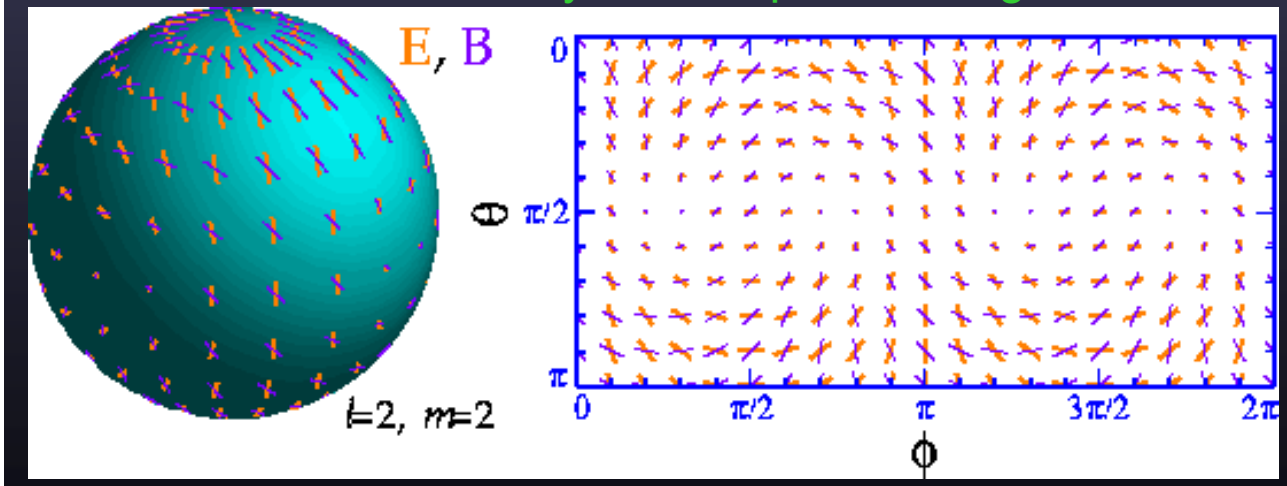


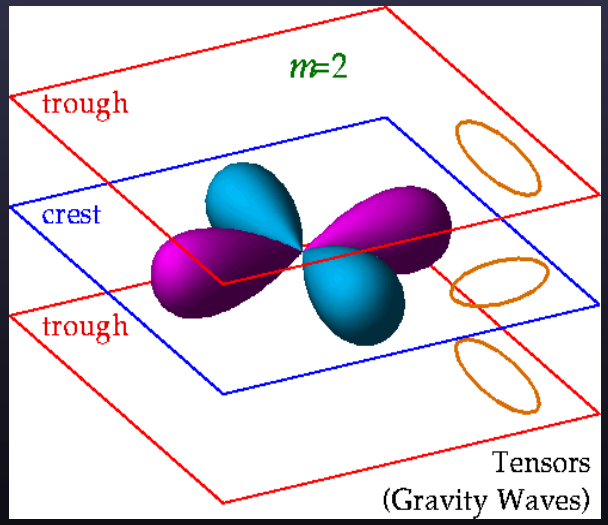
Figures courtesy Hu & White 1997

E & B modes from Tensors

- Linear polarization "vectors" for plane waves
  - E (even parity = aligned 0° or 90° to k-vector)
    - from scalar density fluctuations ➔ predominant in standard model!
  - B (odd parity = at ±45° to k-vector)
    - vector perturbations (vorticity or defects) produce only **B**-modes
    - tensors (gravity waves) produces <u>both **E** & **B**</u>
    - lensing makes **B** modes from **E** modes
    - also secondary anisotropies & foregrounds

Gravity waves produce "B-mode" polarization:

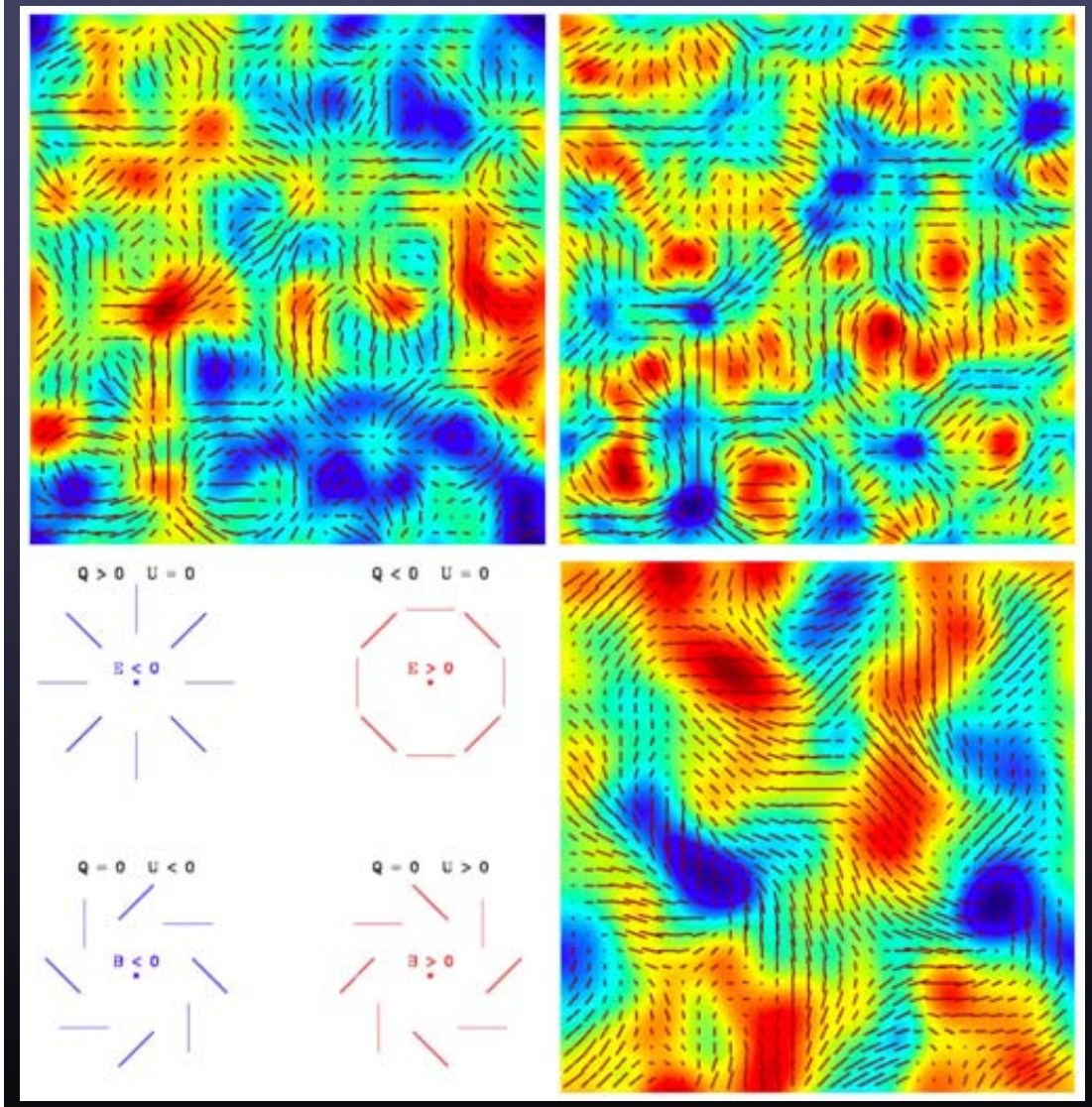




Figures courtesy Hu & White 1997

E & B modes on the sky

P



E

B

Plane waves add up or interfere on the sky to make “hot” and “cold” spots.

E-mode polarization vectors line up as radial “hedgehog” or tangential patterns.

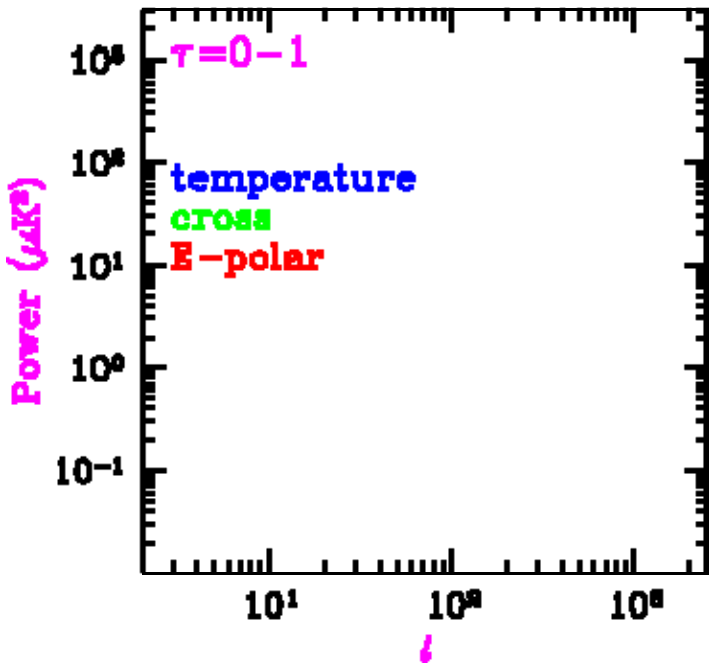
B-mode polarization vectors “pinwheel” or curl around peaks/holes.

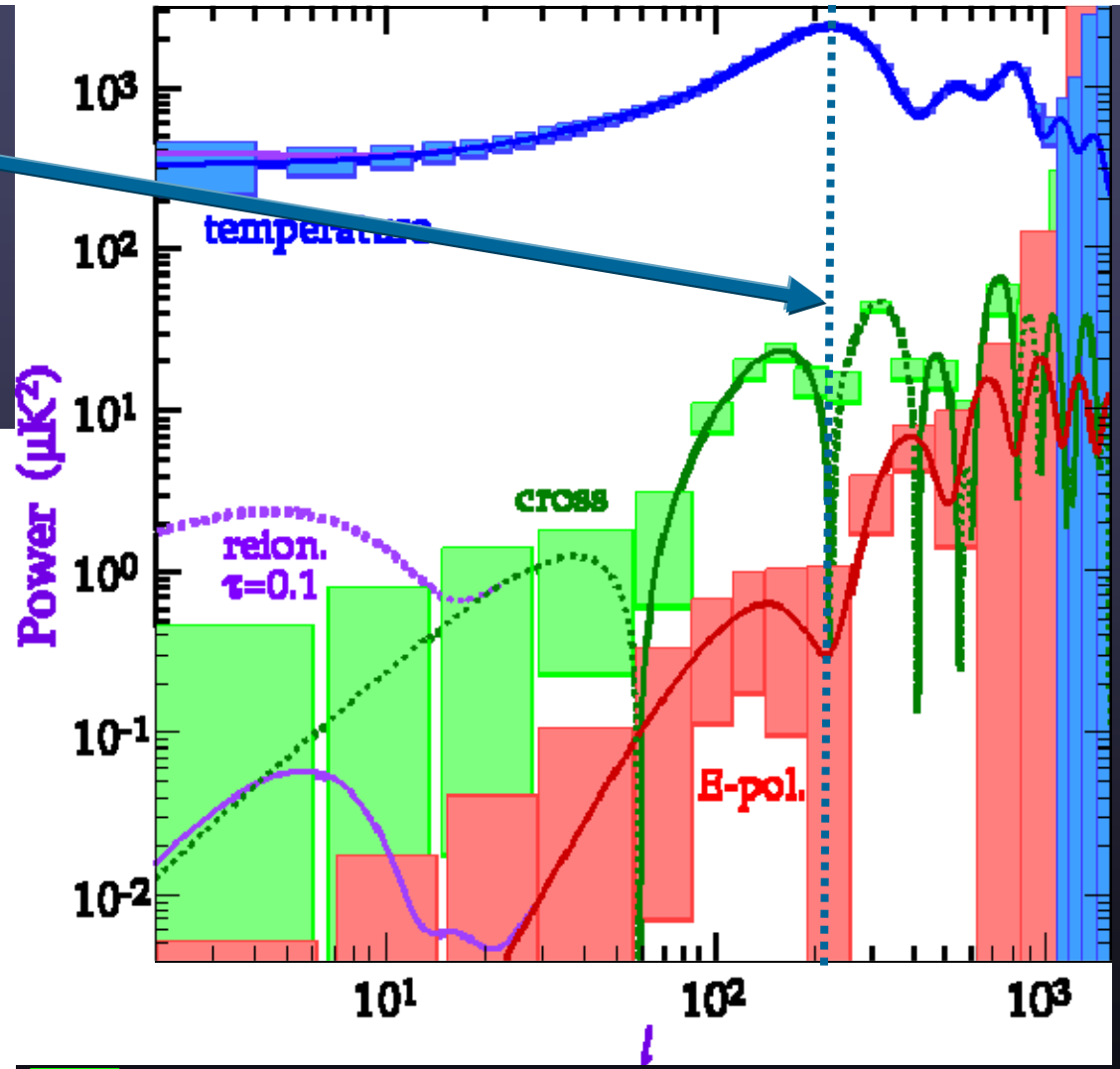
Maxima in E/B are not P maxima – but measure non-local coherences in P

<u>E & B live in wave-space!</u>

Scalar Power Spectrum

- Sourced from velocities
  - E-pol oscillations 90° out-of-phase with density
- Only E modes
  - confirmation of physics
- Enhanced by reionization





τ

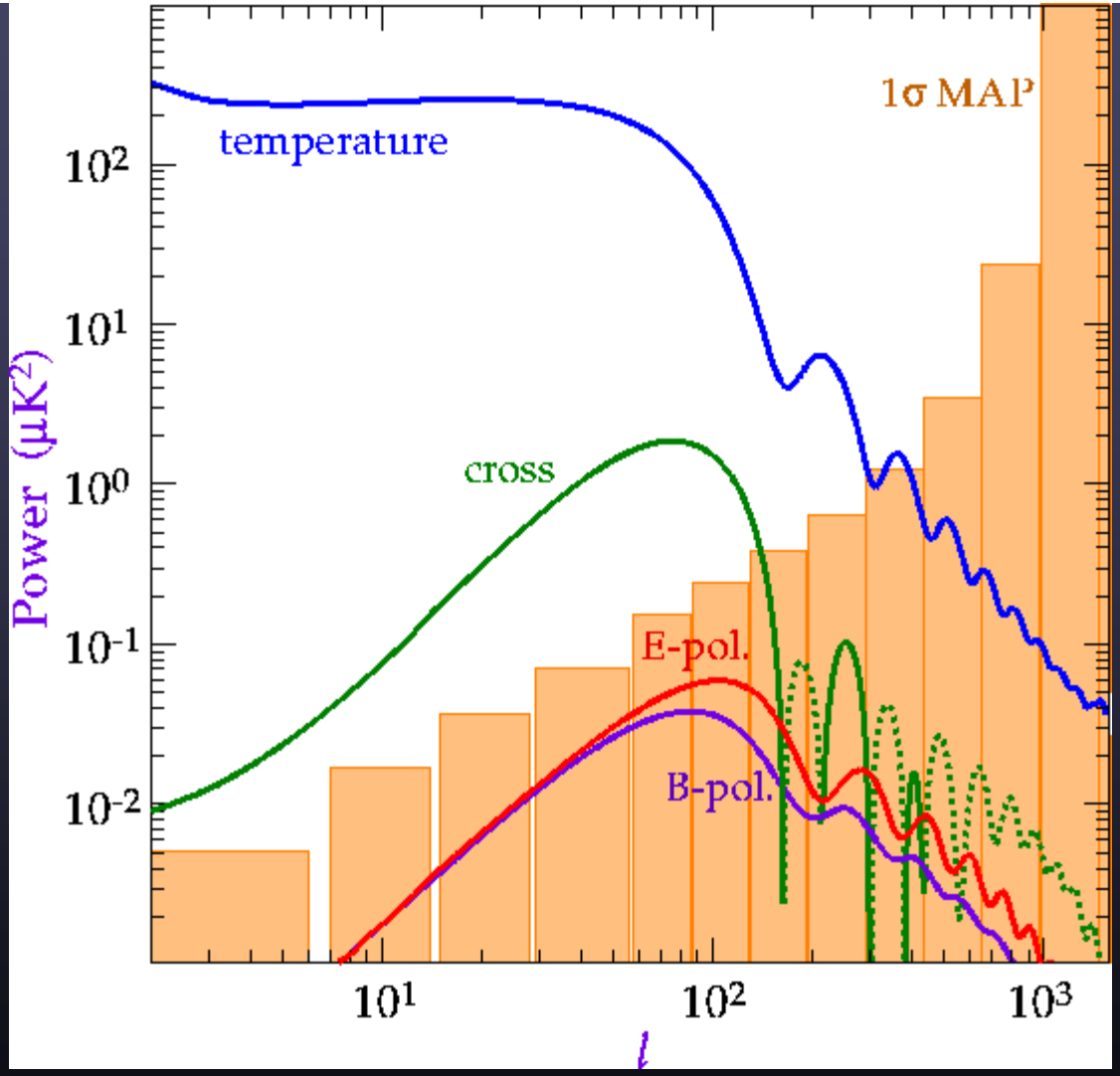
Hu & White 1997 – WMAP errors

Tensor Power Spectrum

- Gravity waves from inflation

$$\delta^2_\Phi(k) = A\, k^{n_s-1} \rightarrow A,\ n_s$$
$$\delta^2_h(k) = rA\, k^{n_T} \rightarrow r,\ n_T$$

- Sharp fall $\ell > 100$
  - tensor perturbations decay within horizon
- Both E and B modes
  - B-modes unique to GW
- Enhanced by reionization
- Amplitude (r=tensor/scalar) reflects energy scale of inflation
- <u>Not within reach of current generation of experiments</u>
  - Planck and beyond…



Hu & White 1997 – WMAP errors

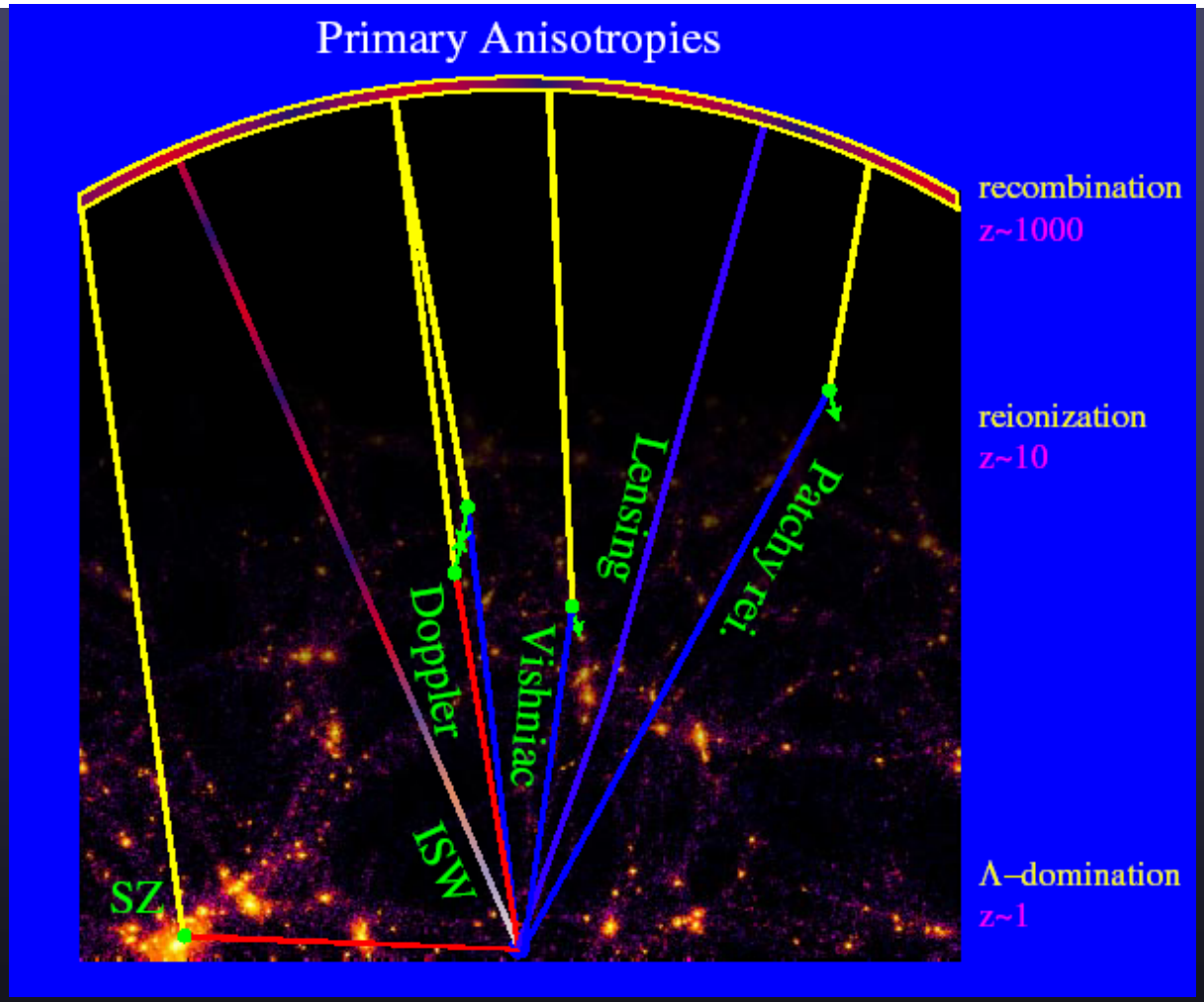
CMB Polarization Checklist

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 ($n \approx 0.98$) for most popular models
  - decay within horizon ($\ell \approx 100$)
  - tensor/scalar ratio r from energy scale of inflation ~ $(E_{inf}/10^{16}\ \mathrm{GeV})^4$

Secondary Anisotropies

The CMB After Last Scattering…

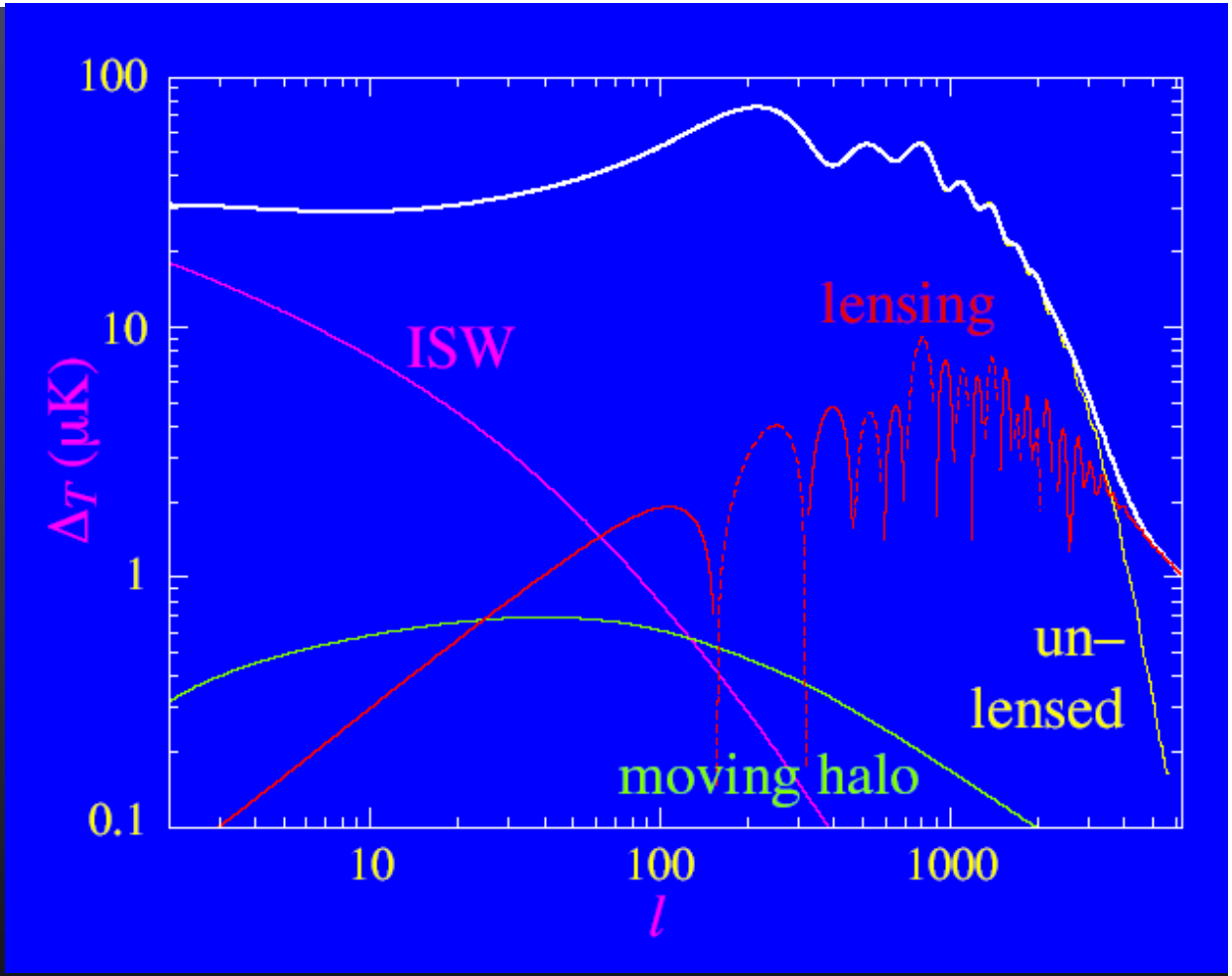


Secondary Anisotropies from propagation and late-time effects

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

Gravitational Secondaries

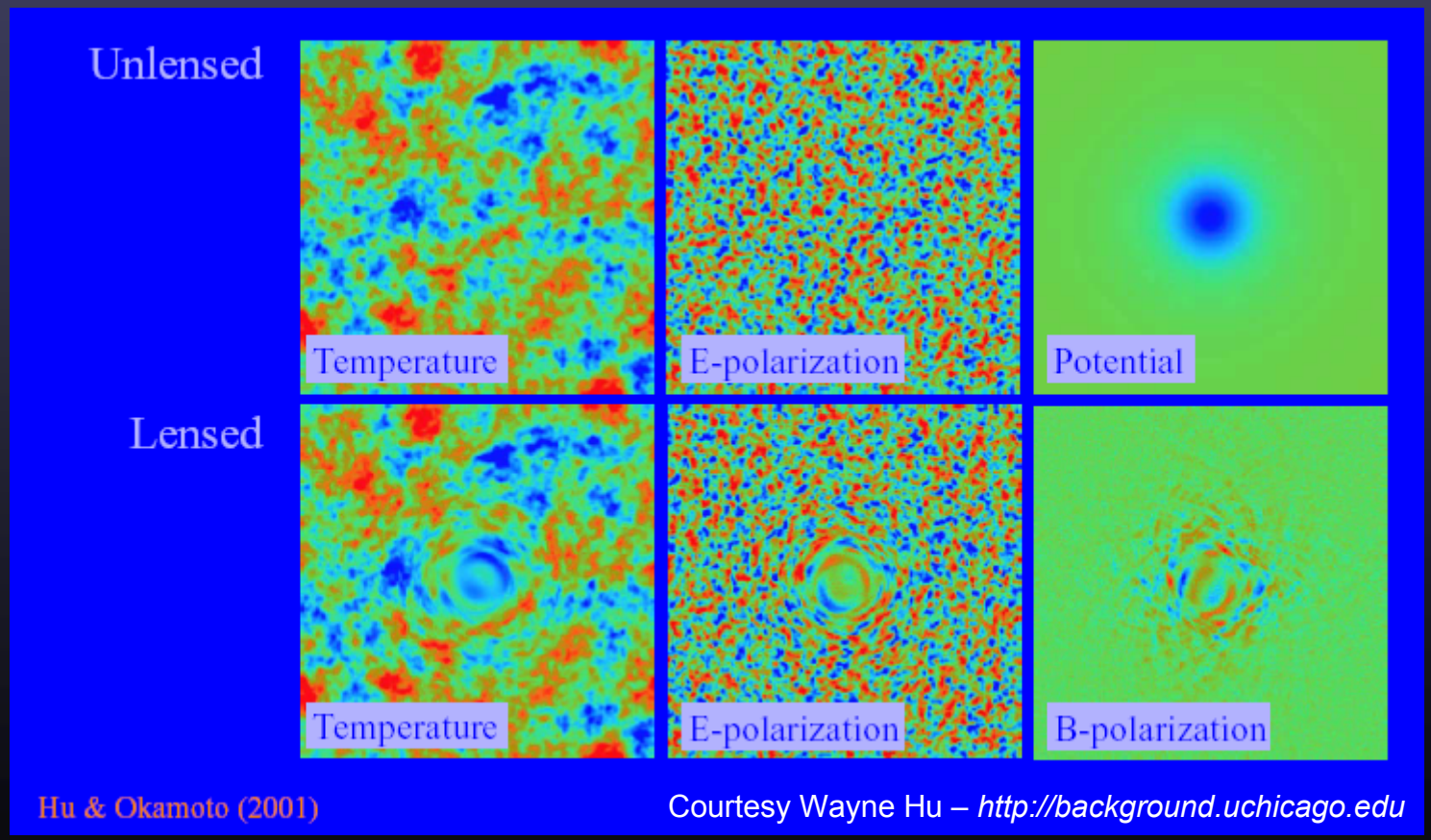
- Due to CMB photons passing through potential fluctuations (spatial and temporal)
- Includes:
  - Early ISW (decay, matter-radiation transition at last scattering)
  - Late ISW (decay, in open or lambda model)
  - Rees-Sciama (growth, non-linear structures)
  - Tensors (gravity waves, 'nuff said)
  - Lensing (spatial distortions)



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

CMB Lensing

- Distorts the background temperature and polarization
- Converts E to B polarization
- Can reconstruct from T,E,B on arcminute scales
- Can probe clusters



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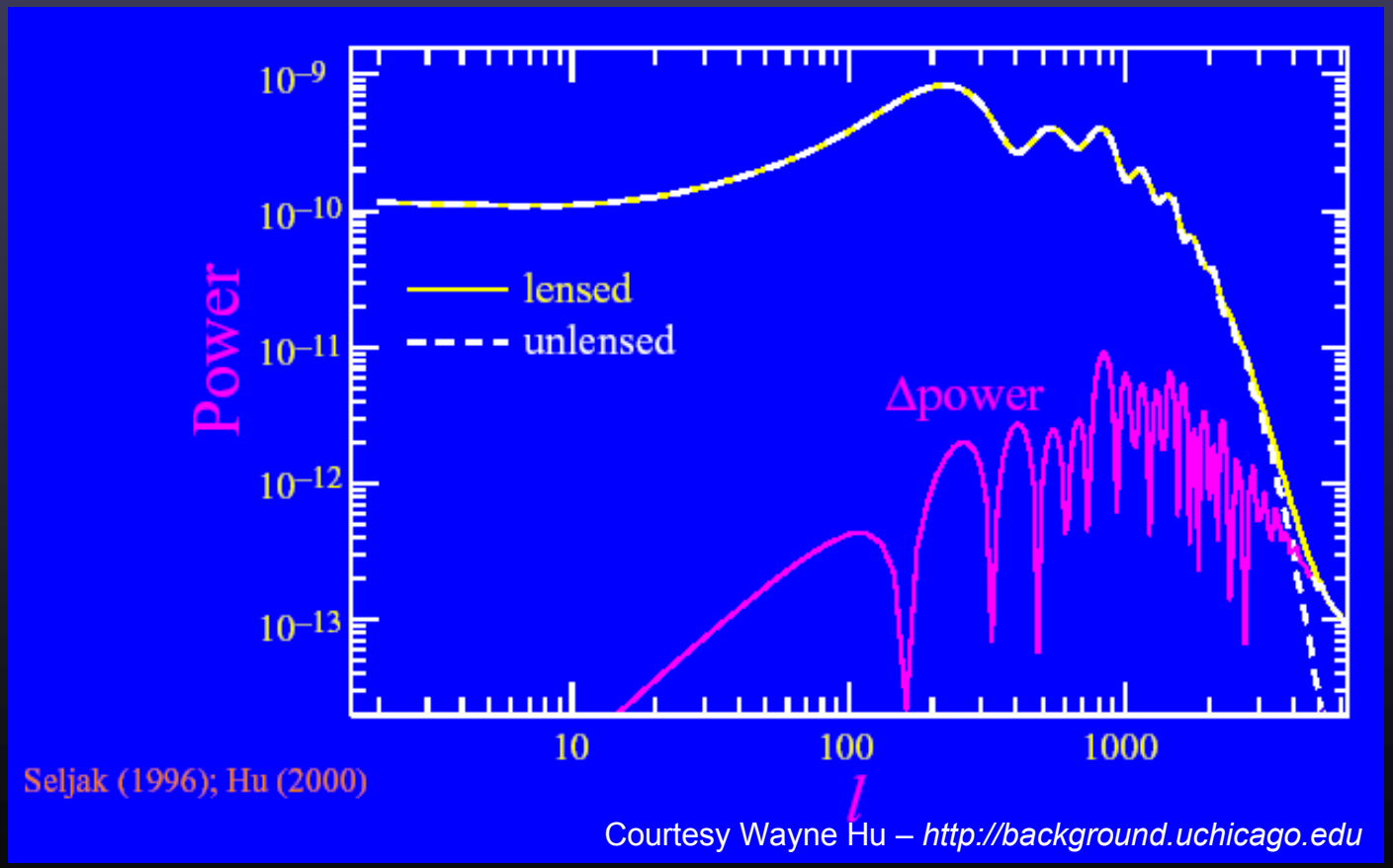
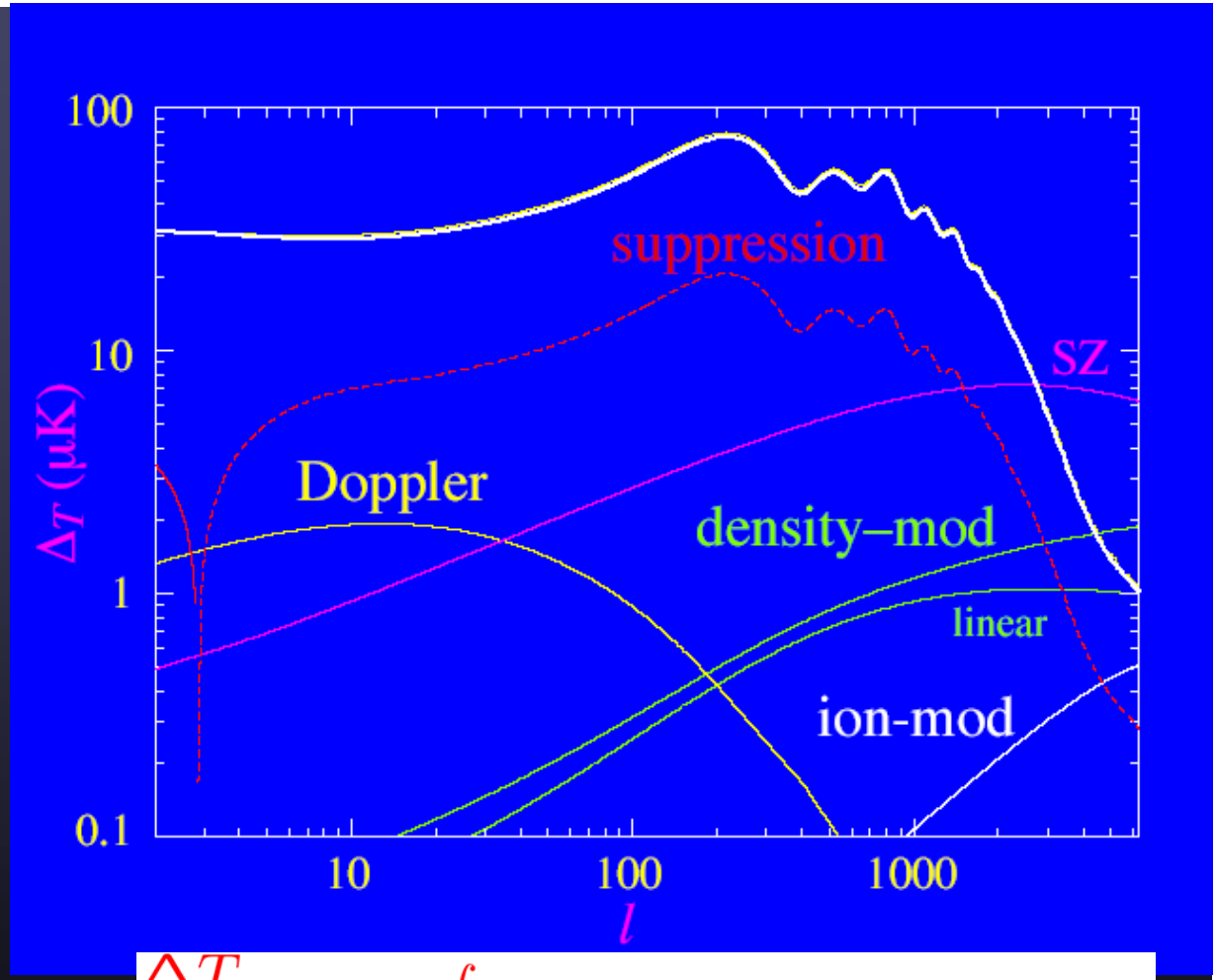
Detected?
See Smith,Zahn & Dore
arXiv:0705.3980



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

Scattering Secondaries

- Due to variations in:
  - Density
    - Linear = Vishniac effect
    - Clusters = thermal Sunyaev-Zeldovich effect
  - Velocity (Doppler)
    - Clusters = kinetic SZE
  - Ionization fraction
    - Coherent reionization suppression
    - "Patchy" reionization



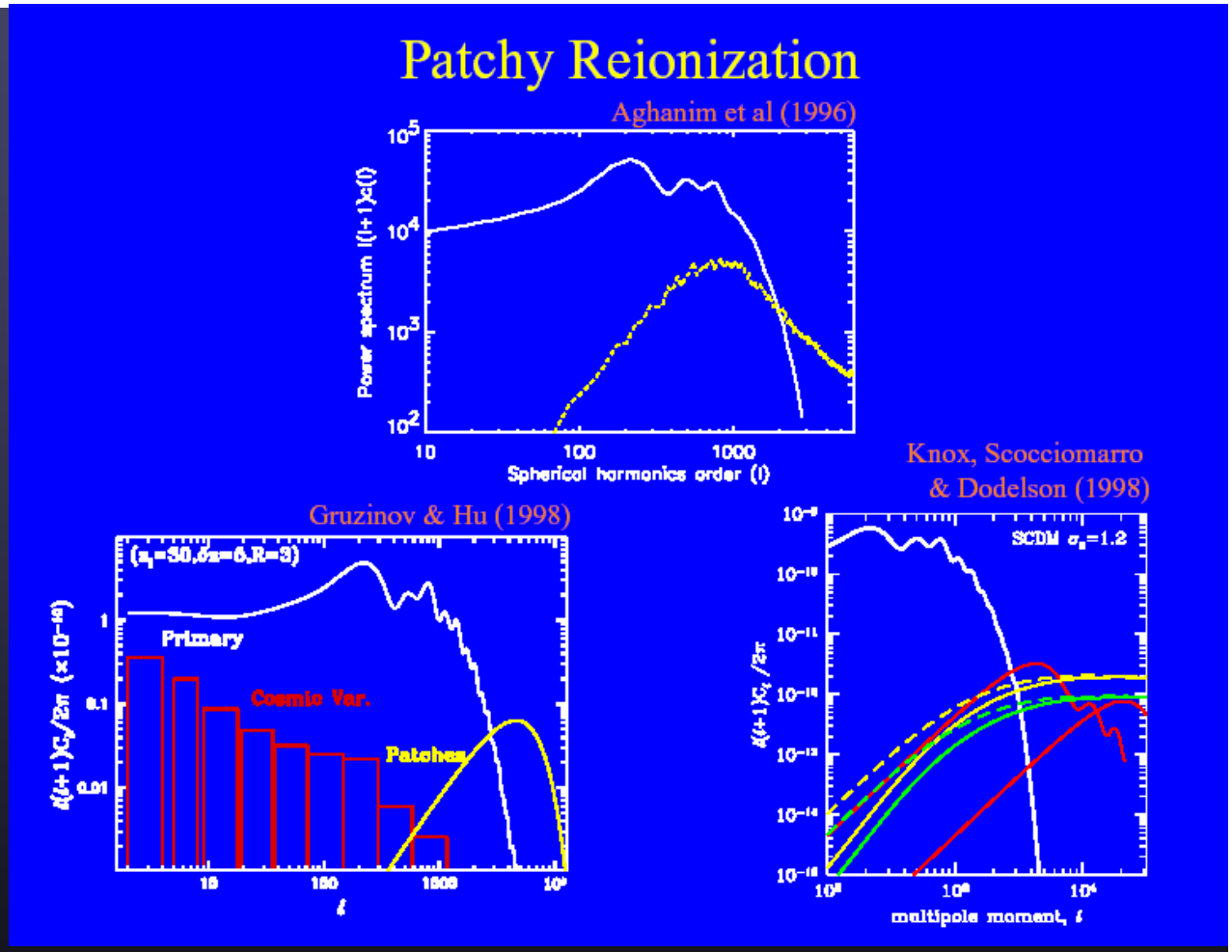
$$\frac{\Delta T}{T}(\hat{n}) = \int dx\,(n_e\,\sigma_T\,e^{-\tau})\,\hat{n}\cdot\mathbf{v}(\mathbf{x},z)$$

$$n_e = X_e\,n_p = \bar{X}_e\,\bar{n}_p(1+\delta_x+\delta_b)$$

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

Patchy Reionization

- Structure in ionization
  - Can distinguish between ionization histories
  - Confusion, e.g. kSZ effect
  - e.g. Santos et al. (0305471)
- Effects similar
  - kSZ, OV, PRel
  - Different z's, use lensing?



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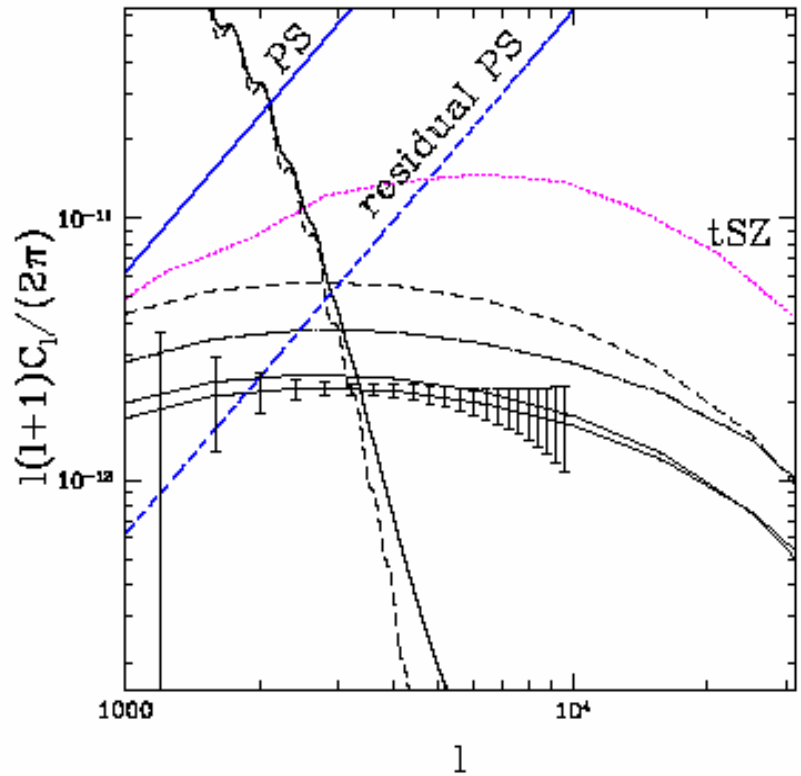
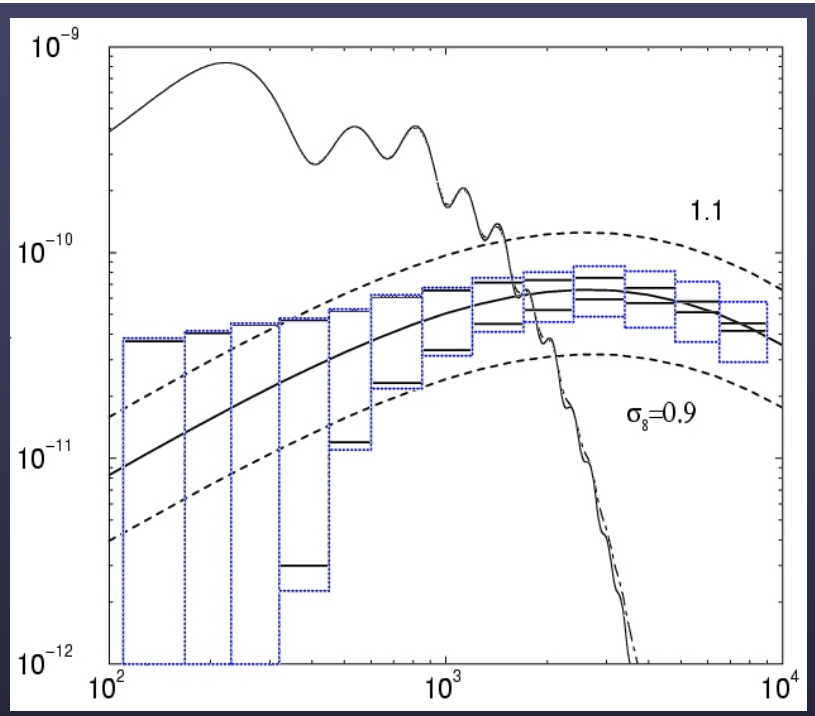


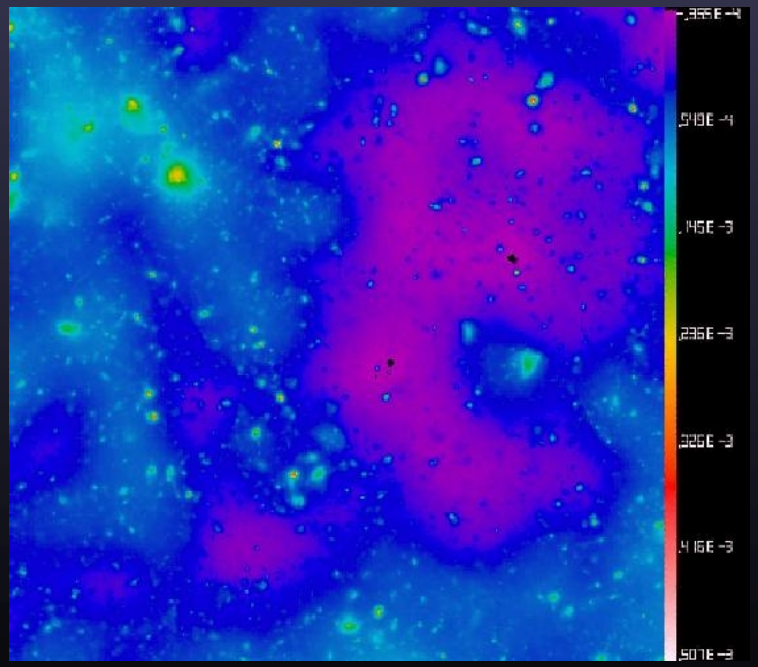
FIG. 5.— Patchy power spectra for the reionization models in Figure 3 (same line styles), together with other astrophysical contributions and expected measurement errors (see text). The solid (dashed) straight line is the the point source contribution at 217 GHz before (after) multi-frequency cleaning. The primary unlensed (dashed) and lensed (solid) CMB power spectra are also shown as is the thermal SZ power spectrum from White et al. (2002) (dotted) with its expected amplitude at lower frequencies. The thin line close to the solid one shows the patchy power spectrum for a model with $\tau = 0.11$ but large bias.

Sunyaev-Zeldovich Effect (SZE)

- Spectral distortion of CMB
- Dominated by massive halos (galaxy clusters)
- Low-z clusters: ~ 20'-30'
- z=1: ~1' → expected dominant signal in CMB on small angular scales
- Amplitude highly sensitive to σ_8



A. Cooray (astro-ph/0203048)



P. Zhang, U. Pen, & B. Wang (astro-ph/0201375)

CMB Checklist (continued)

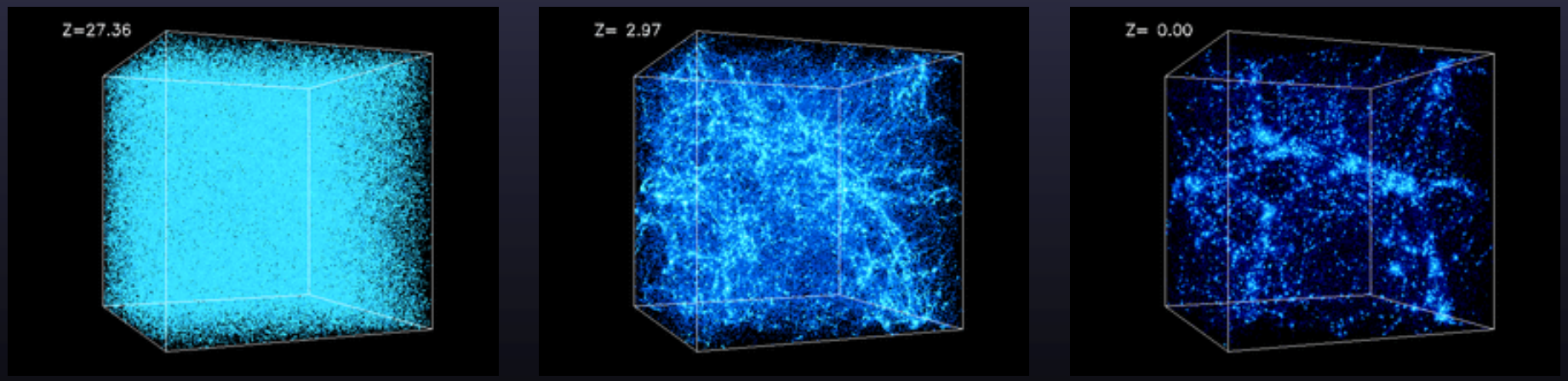
Secondary predictions from inflation-inspired models:

- 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

Matter Spectrum and Large Scale Structure

After recombination …

- Potential fluctuations grow to form Large Scale Structure
  - overdensities collapse to form galaxies and galaxy clusters
  - underdensities expand into voids, with cosmic web between
  - acoustic peaks appear as Baryon Oscillations in matter spectrum
- Current overdensities in non-linear regime
  - $\delta\rho/\rho \sim 1$ on 8 h^{-1} Mpc scales (σ_8 parameter)
  - linear potential growth: $\delta\rho/\rho \sim 10\text{-}3$ at recombination ($z \approx 1500$)

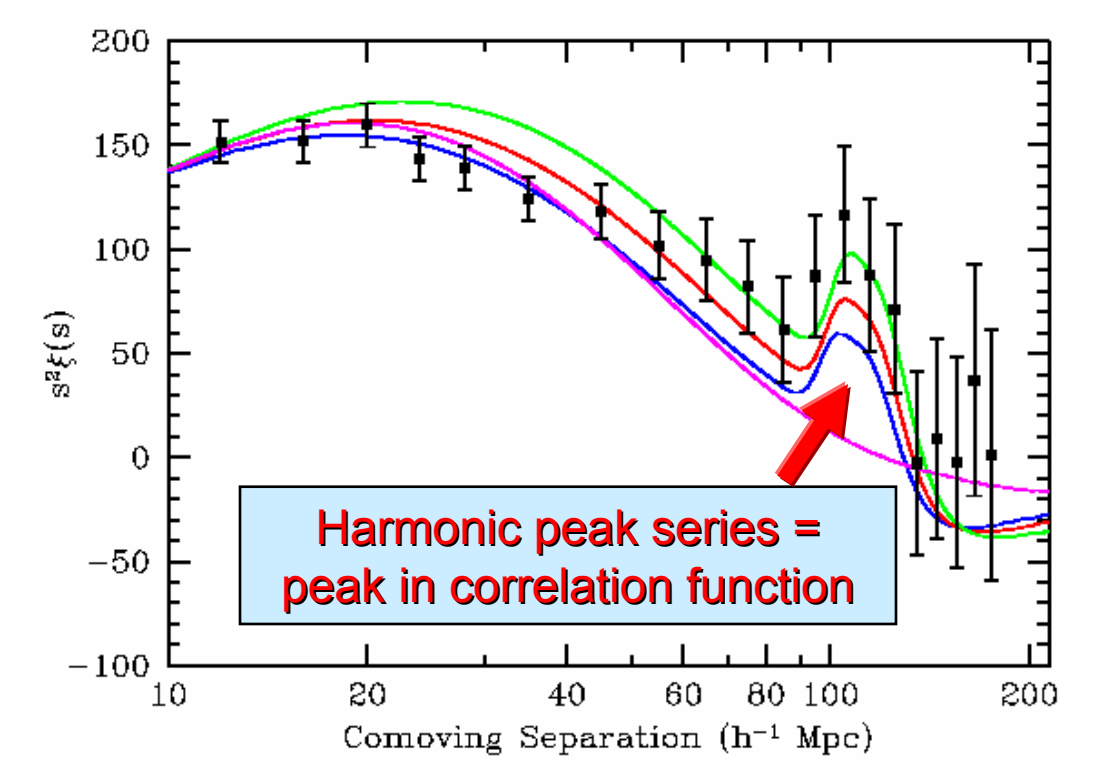


Simulation courtesy A. Kravtsov – *http://cosmicweb.uchicago.edu*

Late Times: Matter Power Spectrum

- matter power spectrum P(k)
  - related to angular power spectrum (via transfer function)

- <u>large scale structure</u>
  - non-linear on small scales
  - imprint of CMB acoustic peaks retained on large scales
  - "baryon oscillations" measured by SDSS



Eisenstein et al. 2005, astro-ph/0501171

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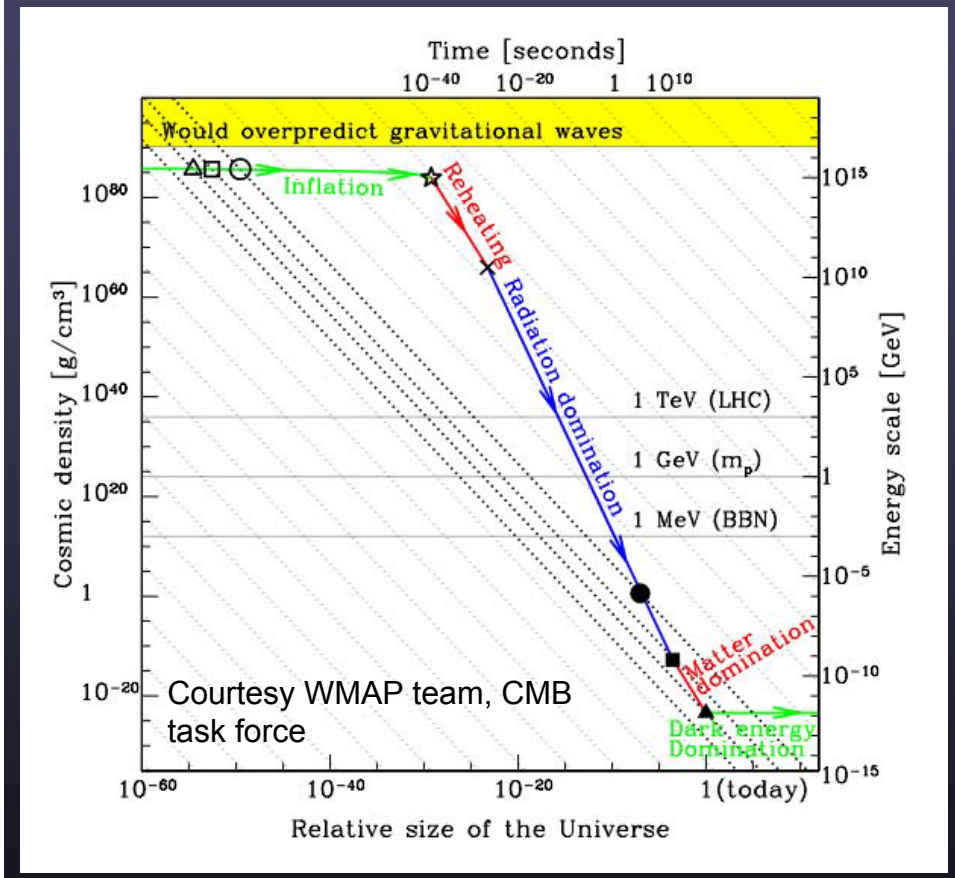
- late-time reionization
  - overall supression and tilt of primary CMB spectrum
  - doppler and ionization modulation produces small-scale anisotropies
- growth of matter power spectrum
  - primordial power-law above current sound horizon
  - CMB acoustic peaks as baryon oscillations

Summary: The Standard Model

Over the past decade we have arrived at a Standard Cosmological Model™



Courtesy WMAP team, CMB task force

THE PILLARS OF INFLATION

1) super-horizon (>2°) anisotropies
2) acoustic peaks and harmonic pattern (~1°)
3) damping tail (<10')
4) Gaussianity
5) secondary anisotropies
6) polarization
7) gravity waves

But … to test this we need to measure a signal which is 3×10^7 times weaker than the typical noise!

The (scalar) cosmological parameters:

Ω_k	Ω_b	Ω_{cdm}	n_s	Ω_Λ	Ω_m	h	τ
geometry of the universe	baryonic fraction protons, neutrons	cold dark matter not protons and neutrons	primordial fluctuation spectrum	dark energy negative pressure of space	matter fraction	Hubble Constant size & age of the universe	optical depth to last scattering of cmb

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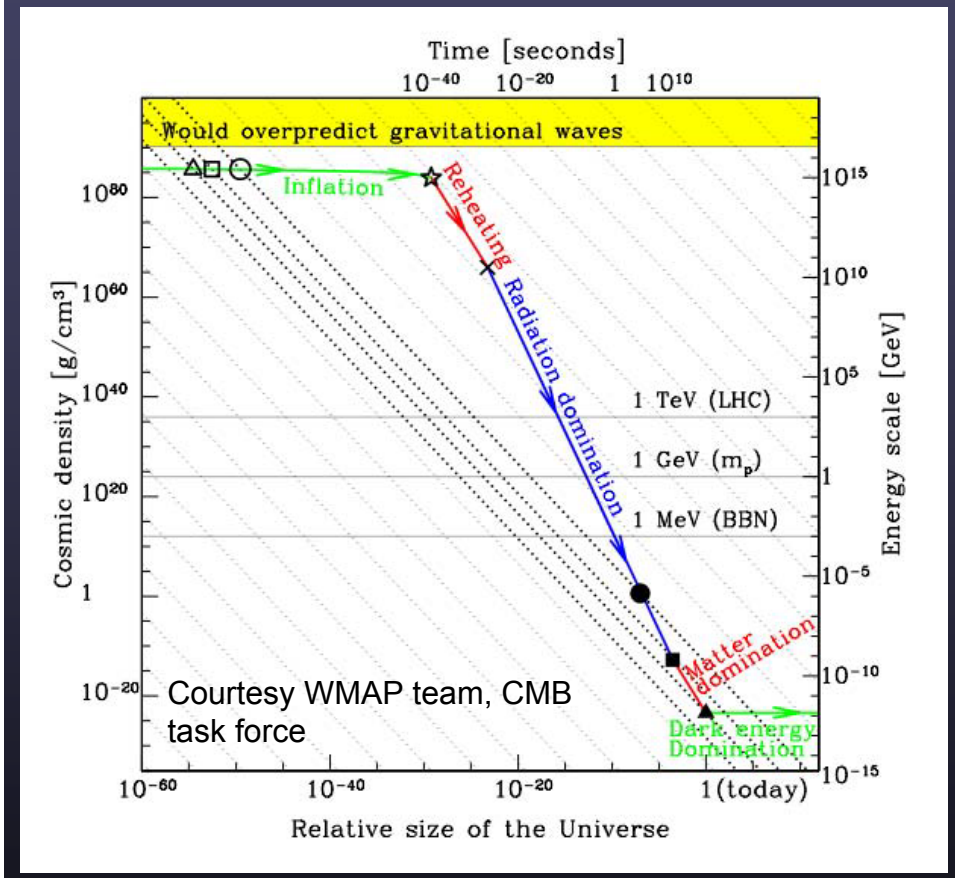

Courtesy WMAP team, CMB task force

THE PI ... ATION

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2) acoustic ...)
3) damping ta
4) Gaussianity
5) secondary anisoti
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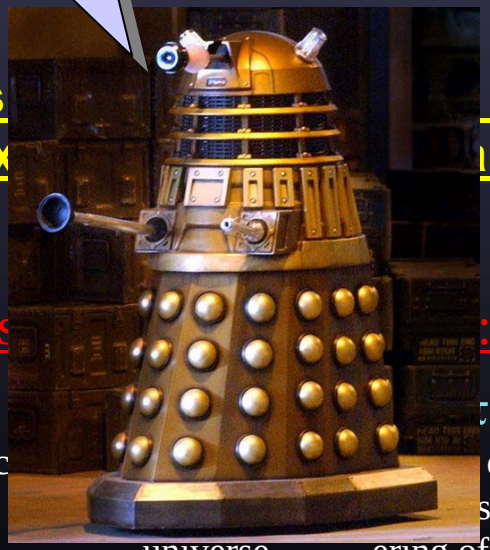
But … to test this ... a signal which is 3x ... n the typical noise!

Dawg Says:
Impertinent.
This is too difficult for puny humans.



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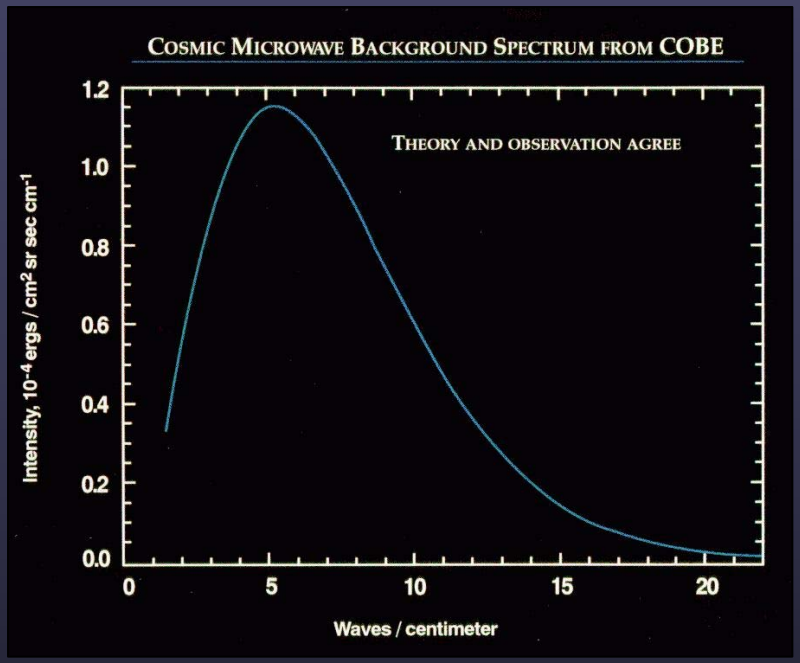
geometry of the universe	baryonic fraction protons, neutrons	cold dark matter not protons and neutrons	primordial fluctuation spectrum	dark energy negative pressure of space	matter frac ... universe	depth scattering of cmb

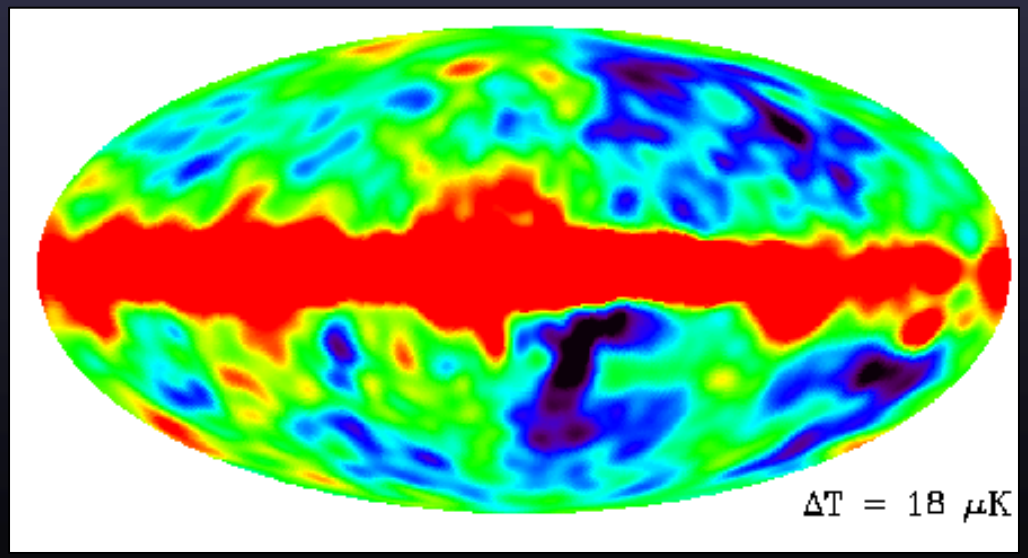
Observations
of the Cosmic Microwave Background Radiation

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

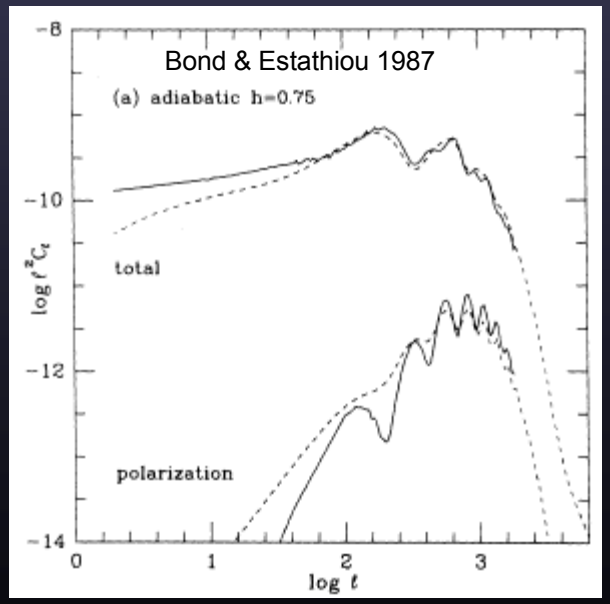




- COBE 1992
  - Blackbody 2.728 K
  - $\ell < 30 : \delta T/T \approx 10^{-5}$

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)



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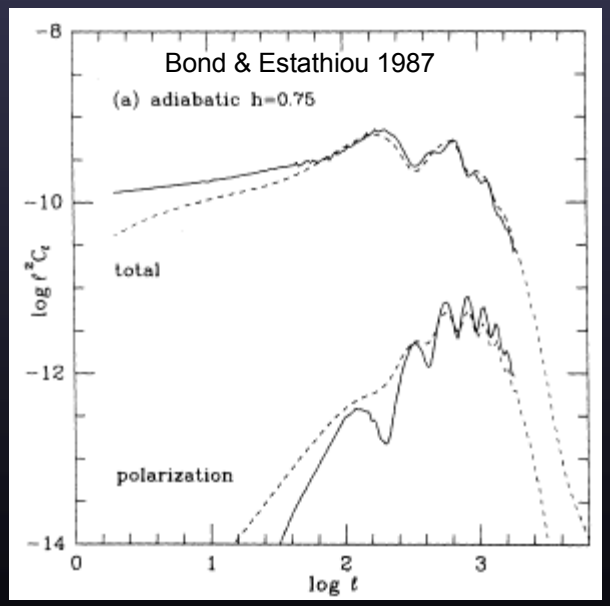
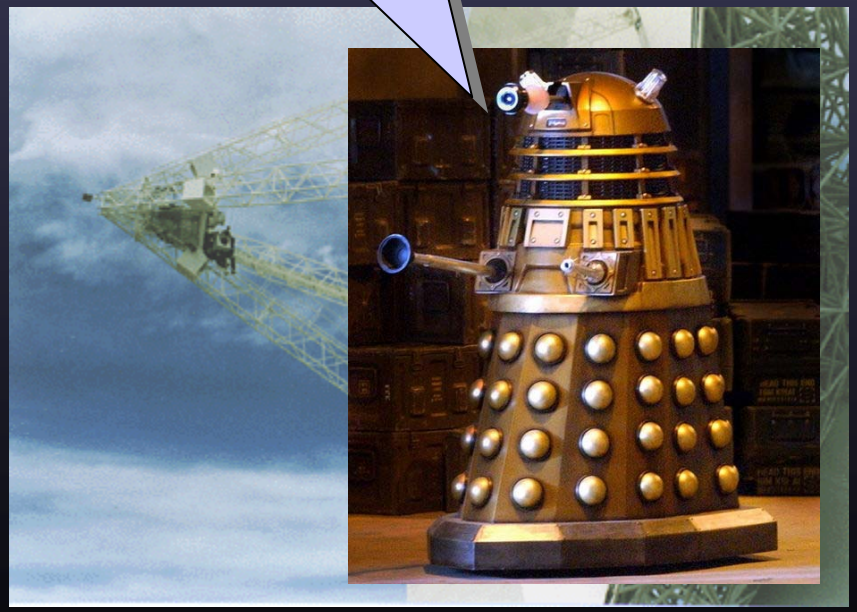
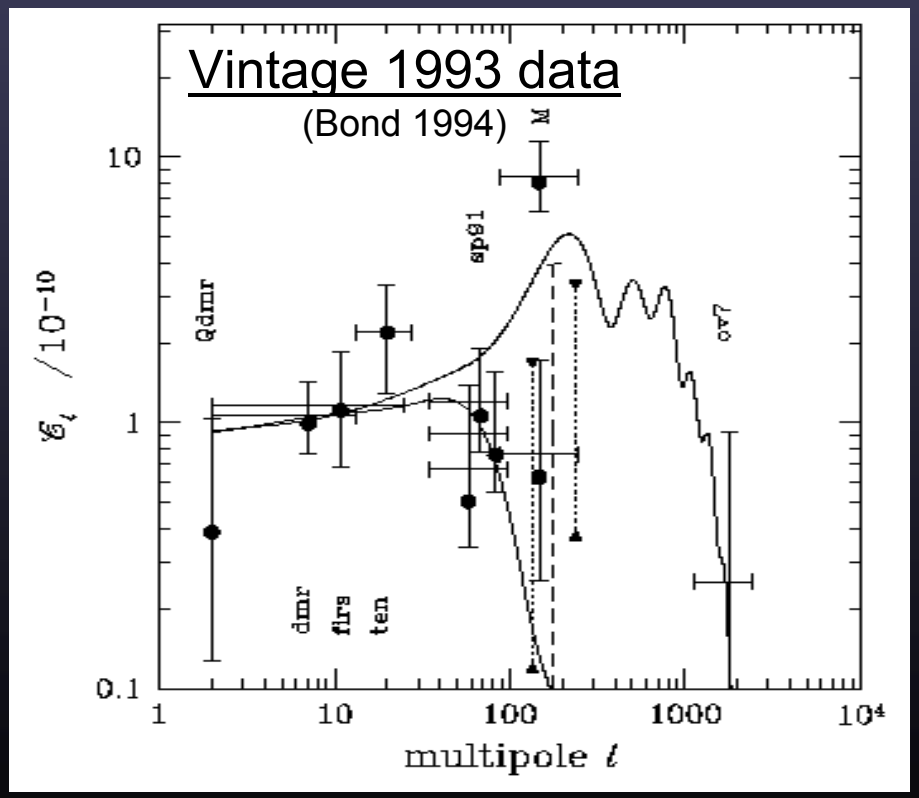
Dawg Says:
Impossible.
The theorists cannot be right.

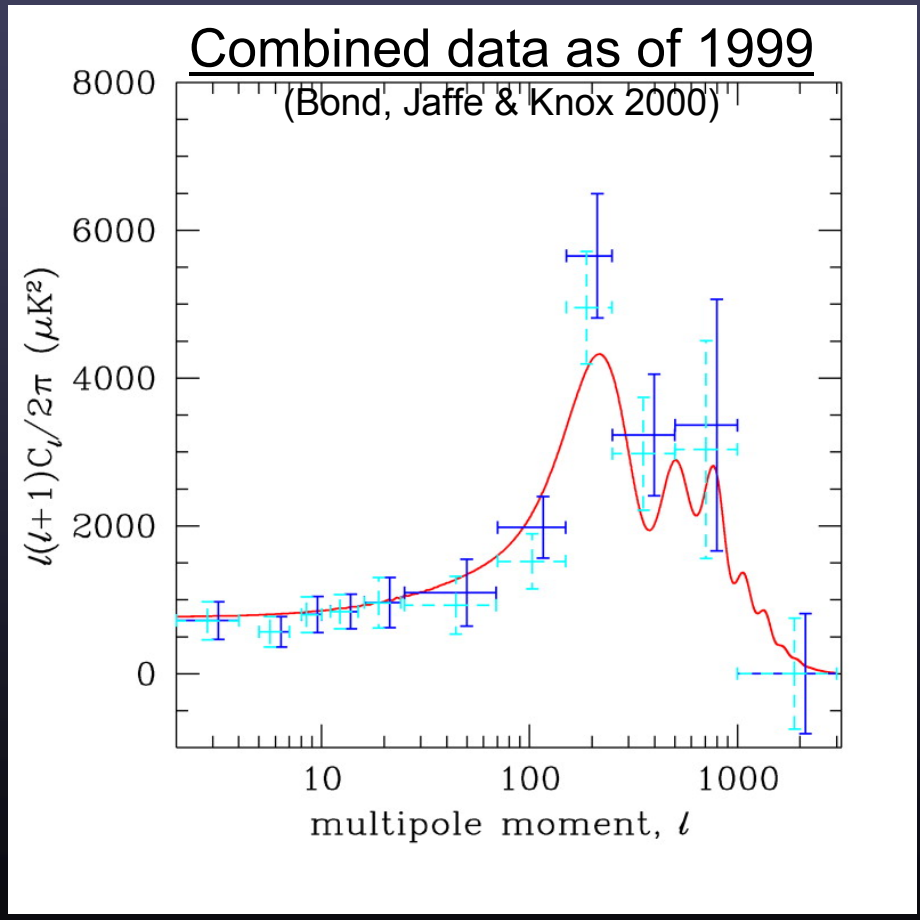




In the 1990's

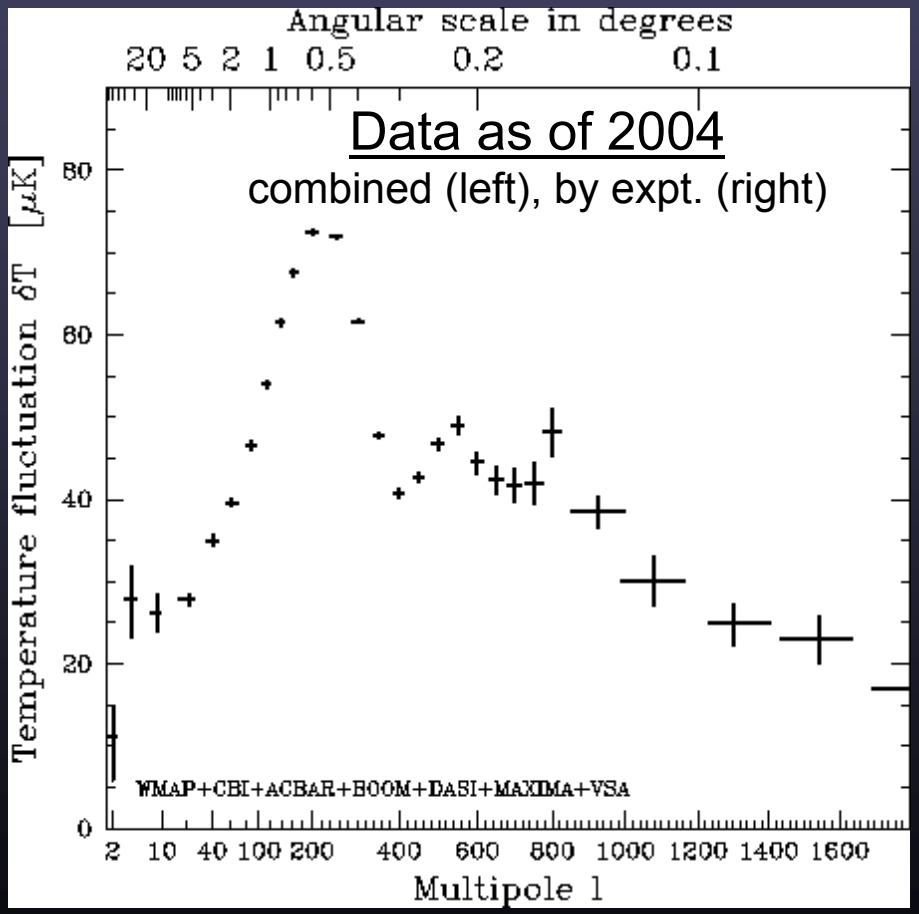
- Better receivers (e.g. HEMT) = first detections!
- COBE satellite: FIRAS (spectrum), DMR (anisotropies)
- Ground and Balloon-based
- Hint of first peak detection!

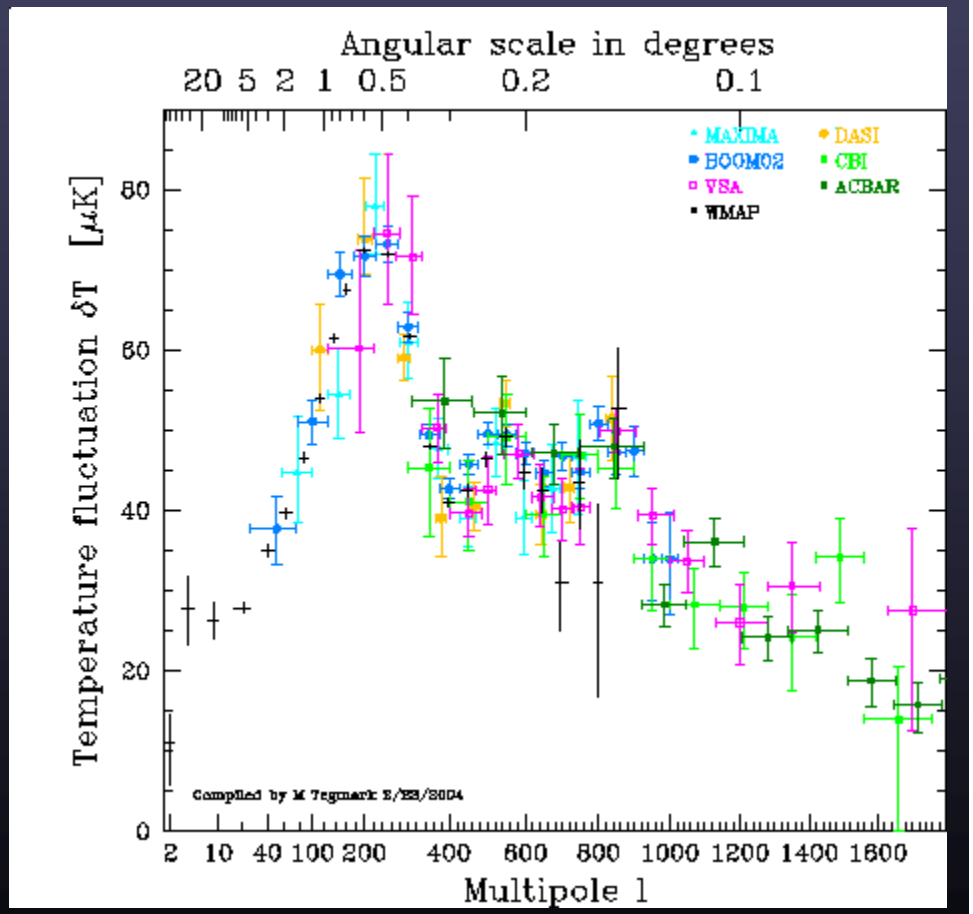




Turn of the Century: 2000 onwards

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

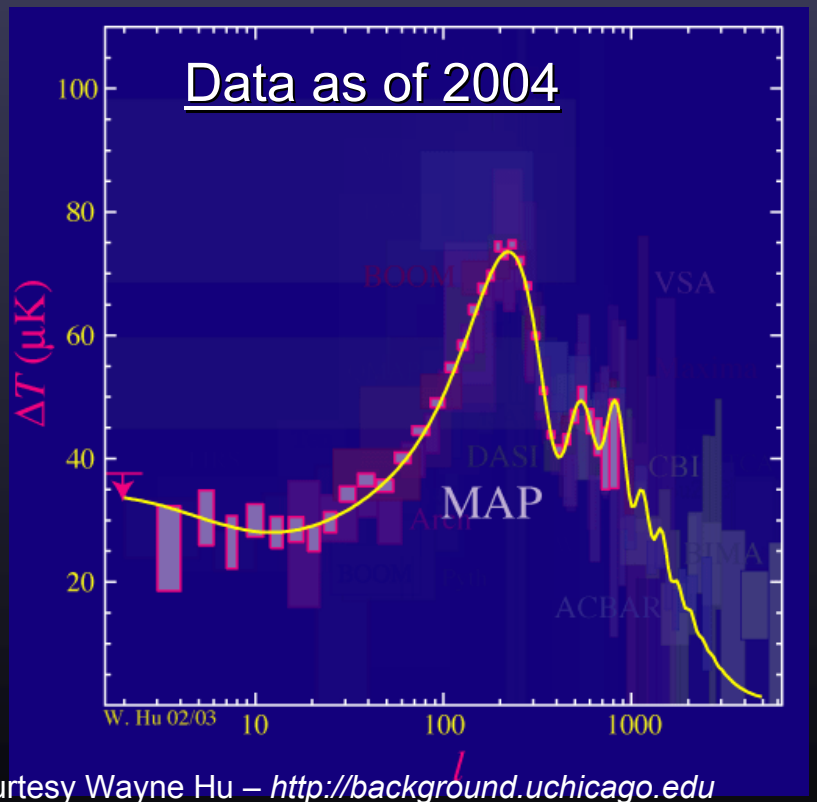


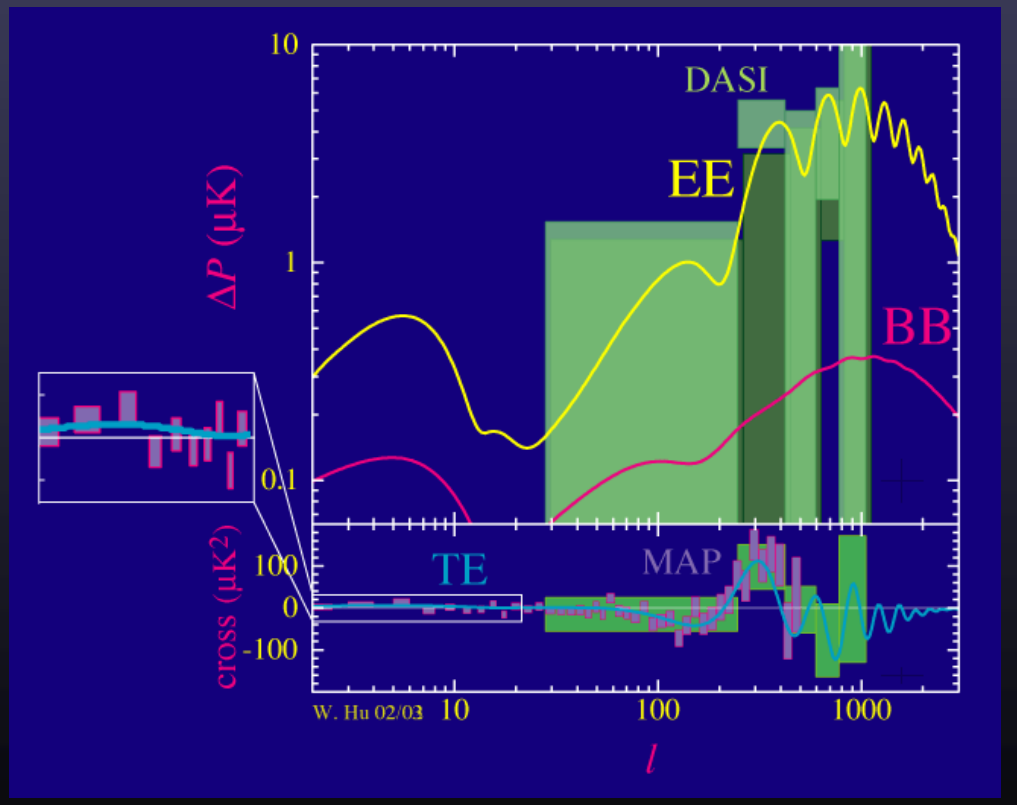


Courtesy Max Tegmark – *http://space.mit.edu/home/tegmark/cmb/experiments.html*

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 (DASI)
  - Dawn of Precision Cosmology!

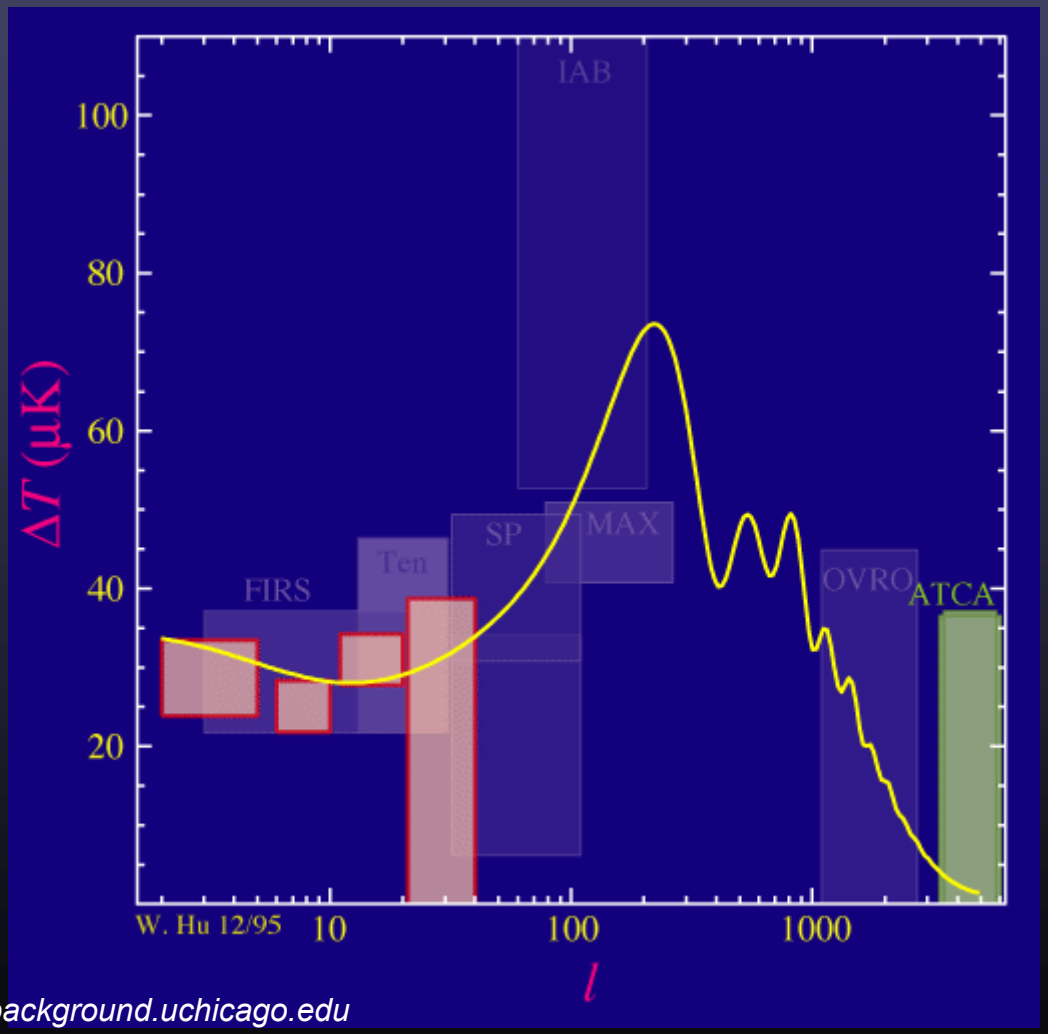




Courtesy Wayne Hu – *http://background.uchicago.edu*

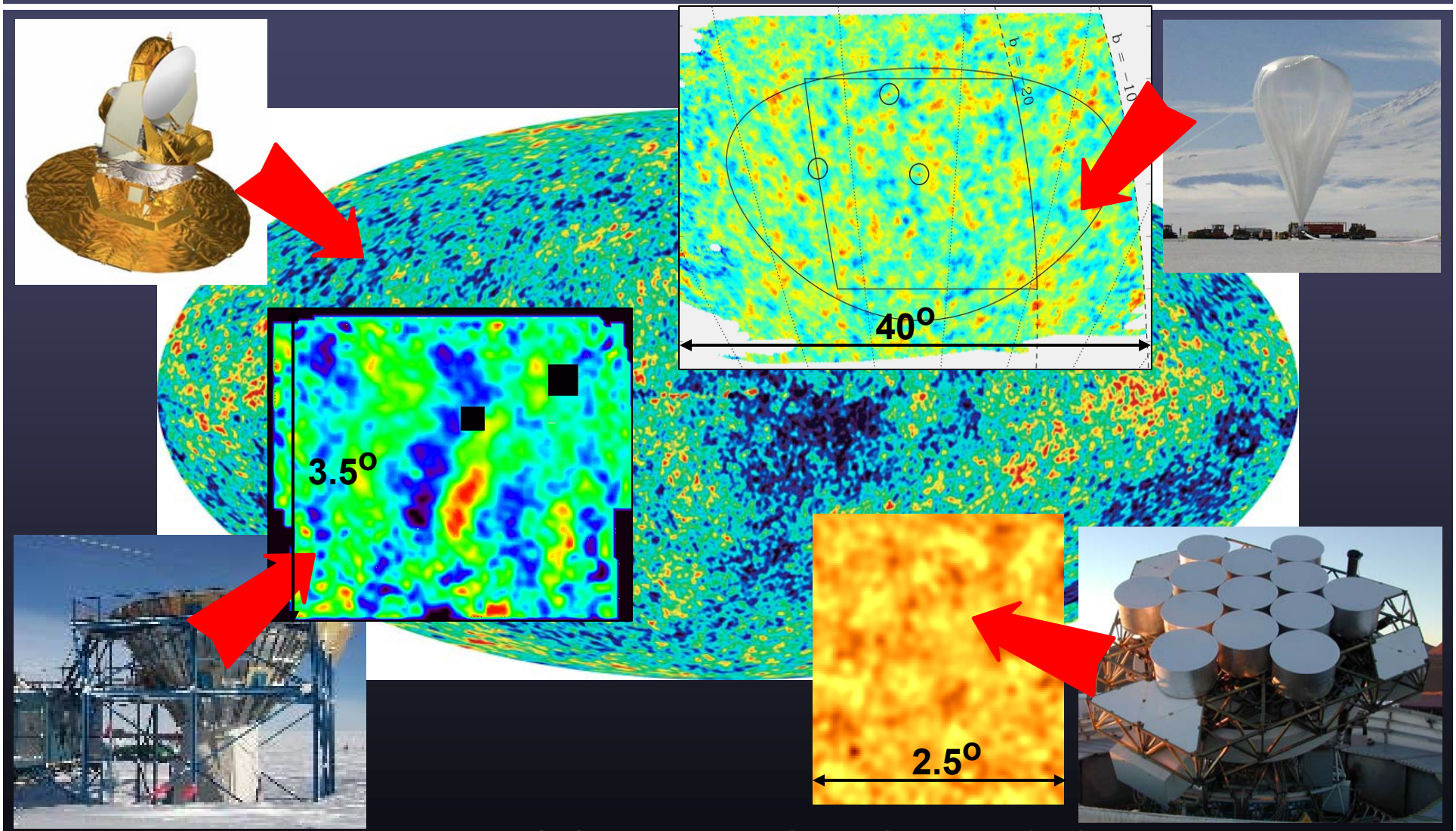
The March of Progress

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



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

CMB Experiments: Ground to Space

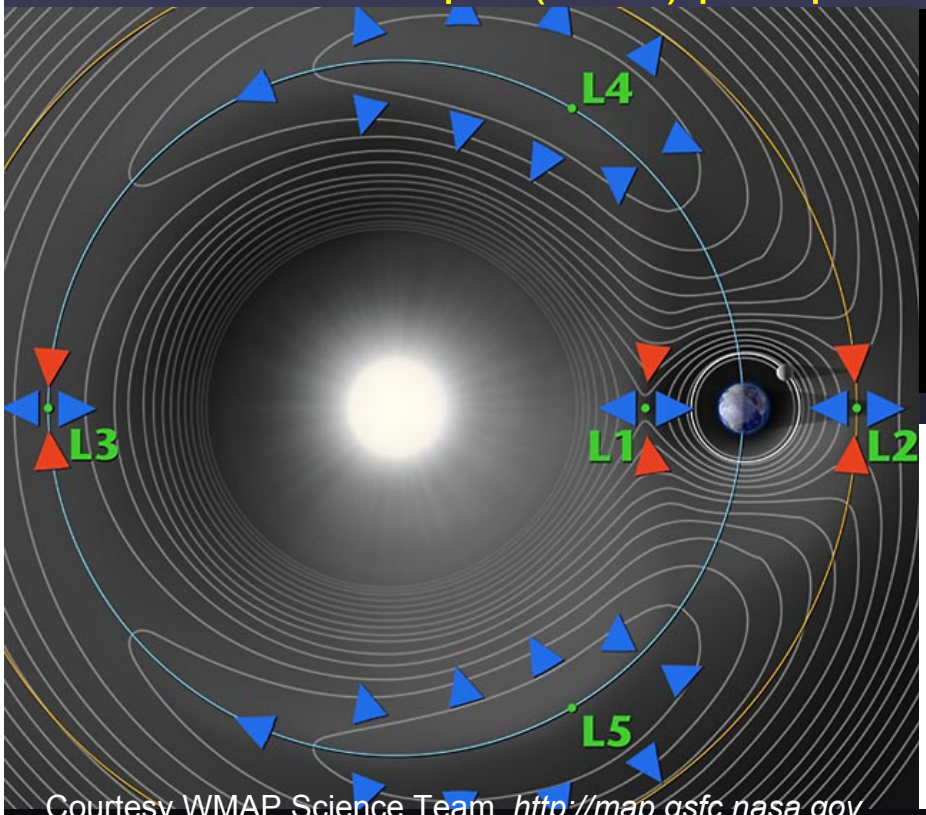


WMAP, BOOMERANG, ACBAR & CBI

WMAP

The WMAP Mission

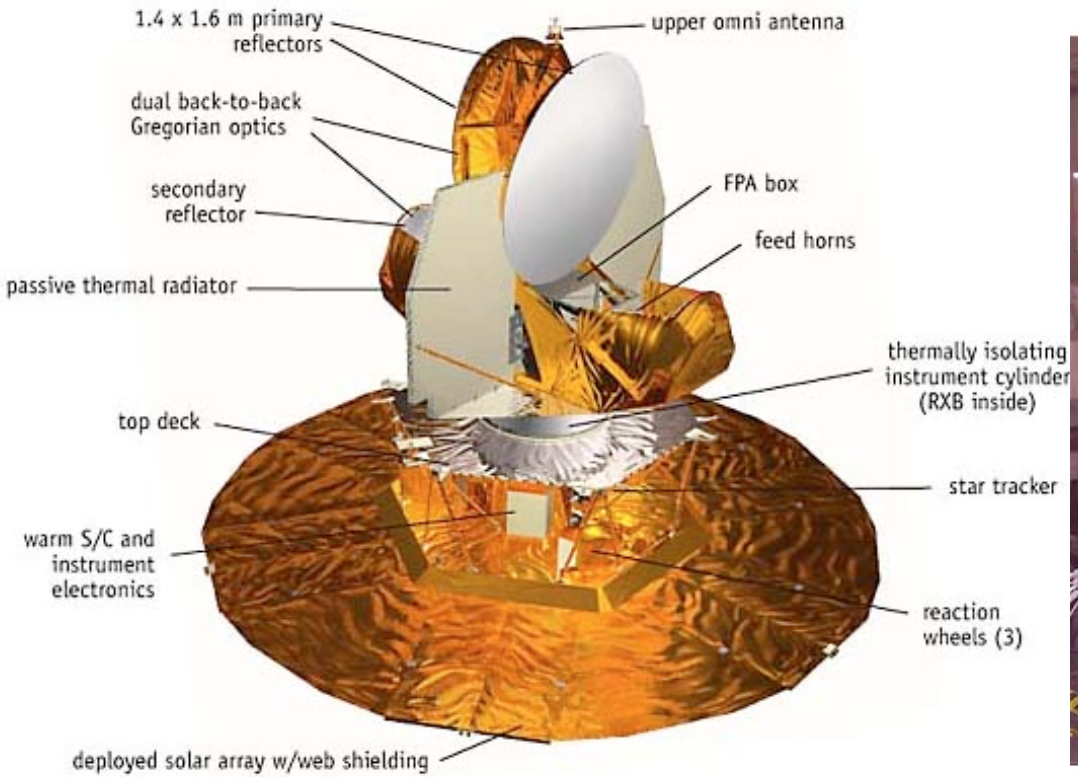
- Wilkinson Microwave Anisotropy Probe
  - proposed 1995, selected by NASA 1996, launched June 2001
  - at L2 point (Sun and Earth shielded), scan full sky in 1 year
  - fast spin (2.2m) plus precession (1hour), scan 30% sky in 1 day

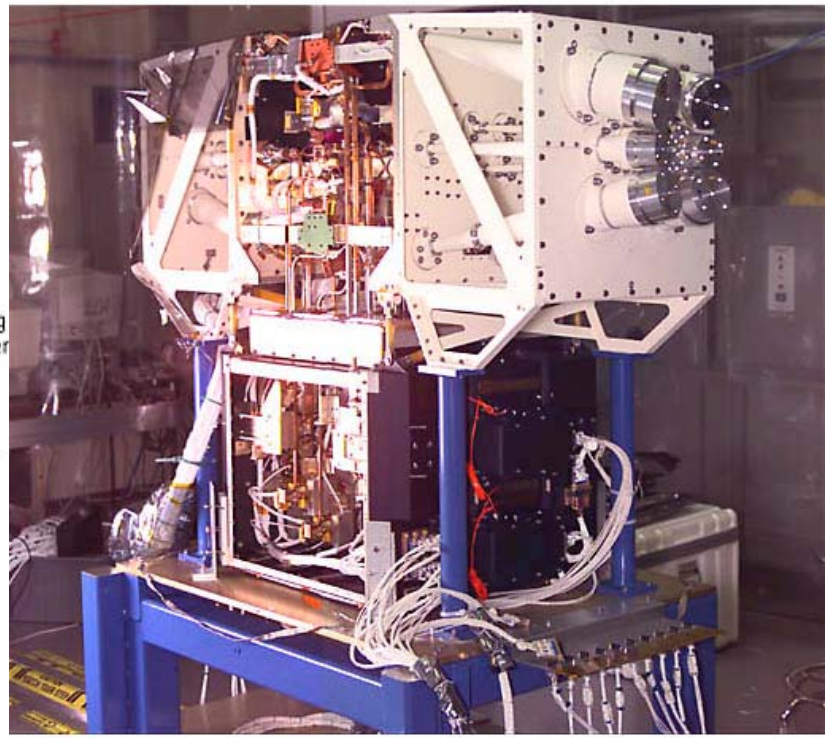


Courtesy WMAP Science Team *http://map.gsfc.nasa.gov*

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)

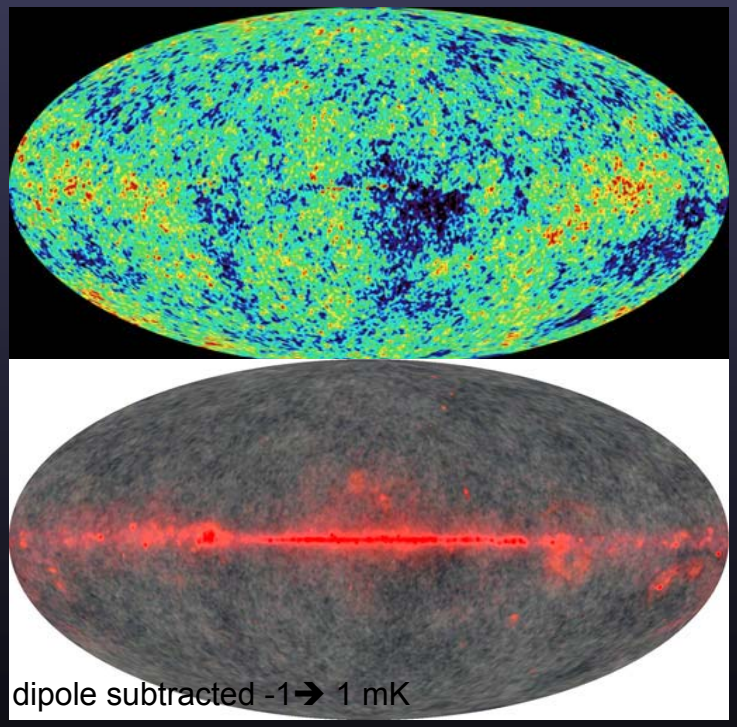




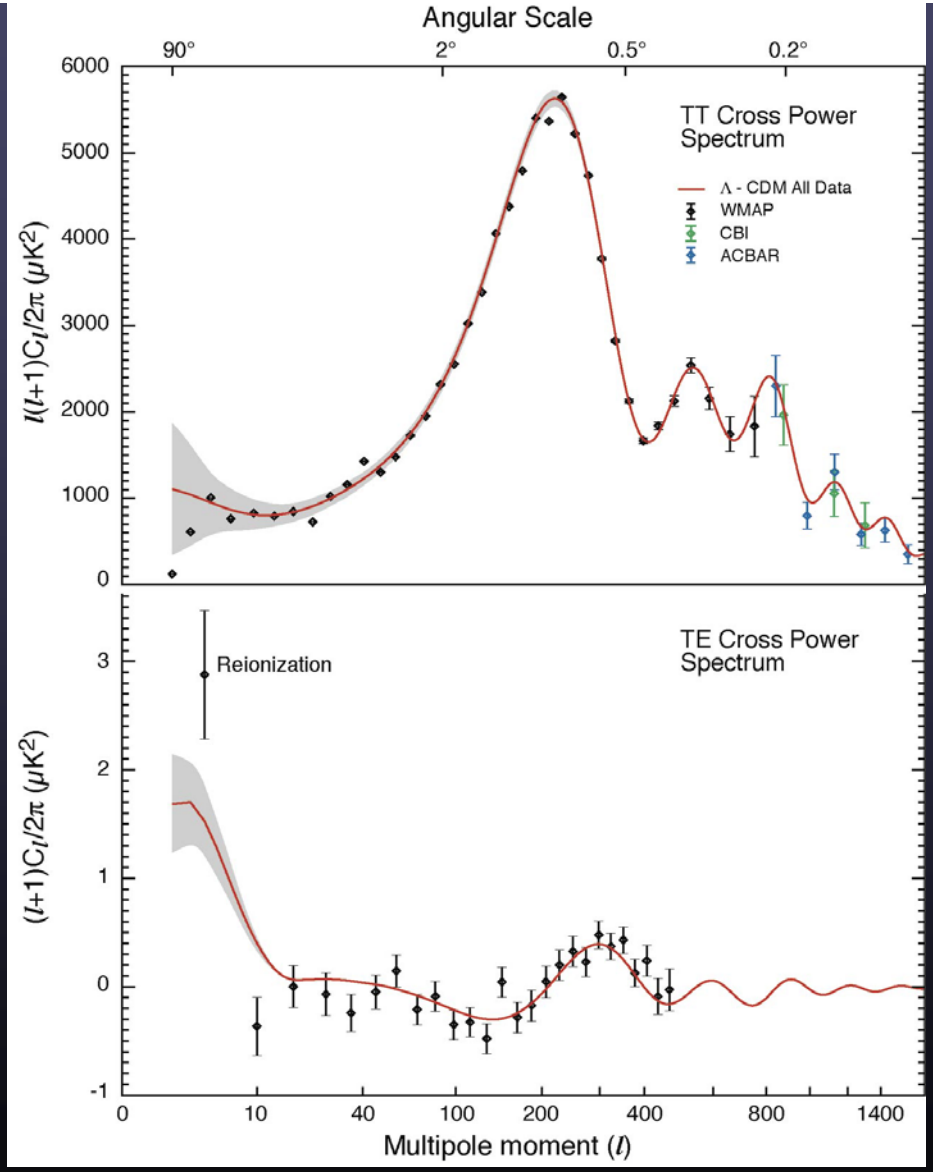
Courtesy WMAP Science Team *http://map.gsfc.nasa.gov*

WMAP 1-yr data release (2003)

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

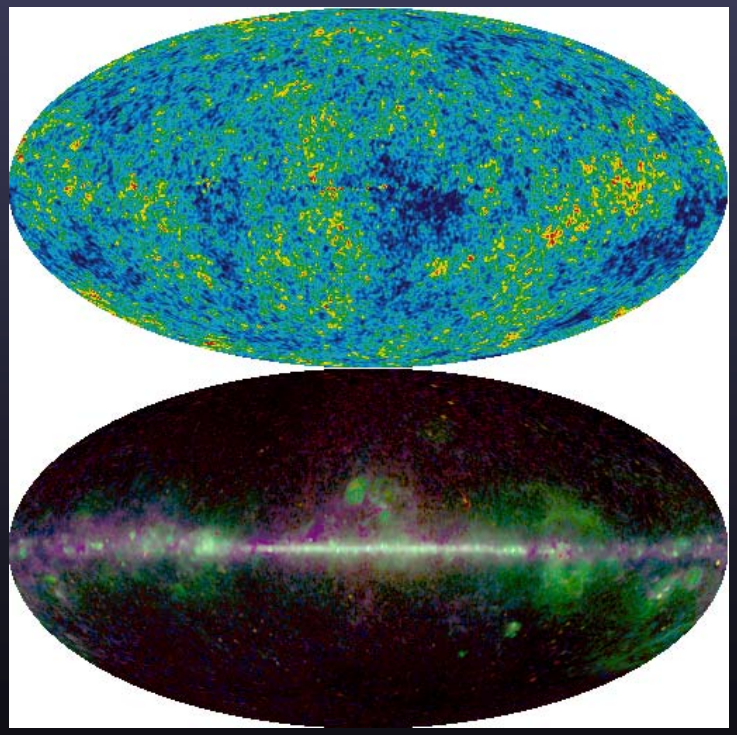


Courtesy WMAP Science Team *http://lambda.gsfc.nasa.gov*

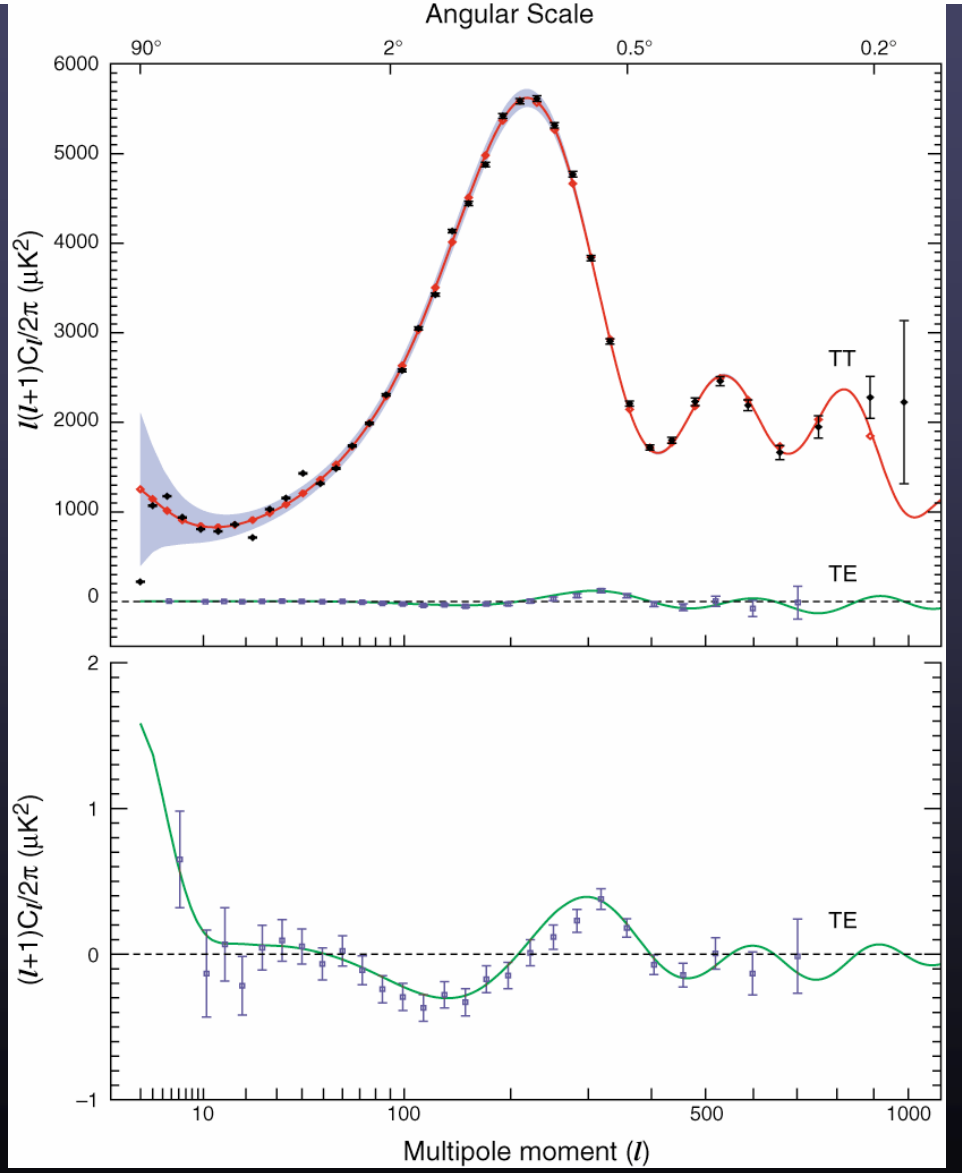


WMAP 3-yr data release (2006)

- Hinshaw et al. (2007) ApJS, **170**, 288
- TT & TE spectrum
- EE spectrum (not shown)
- ILC vs. 61GHz foreground model



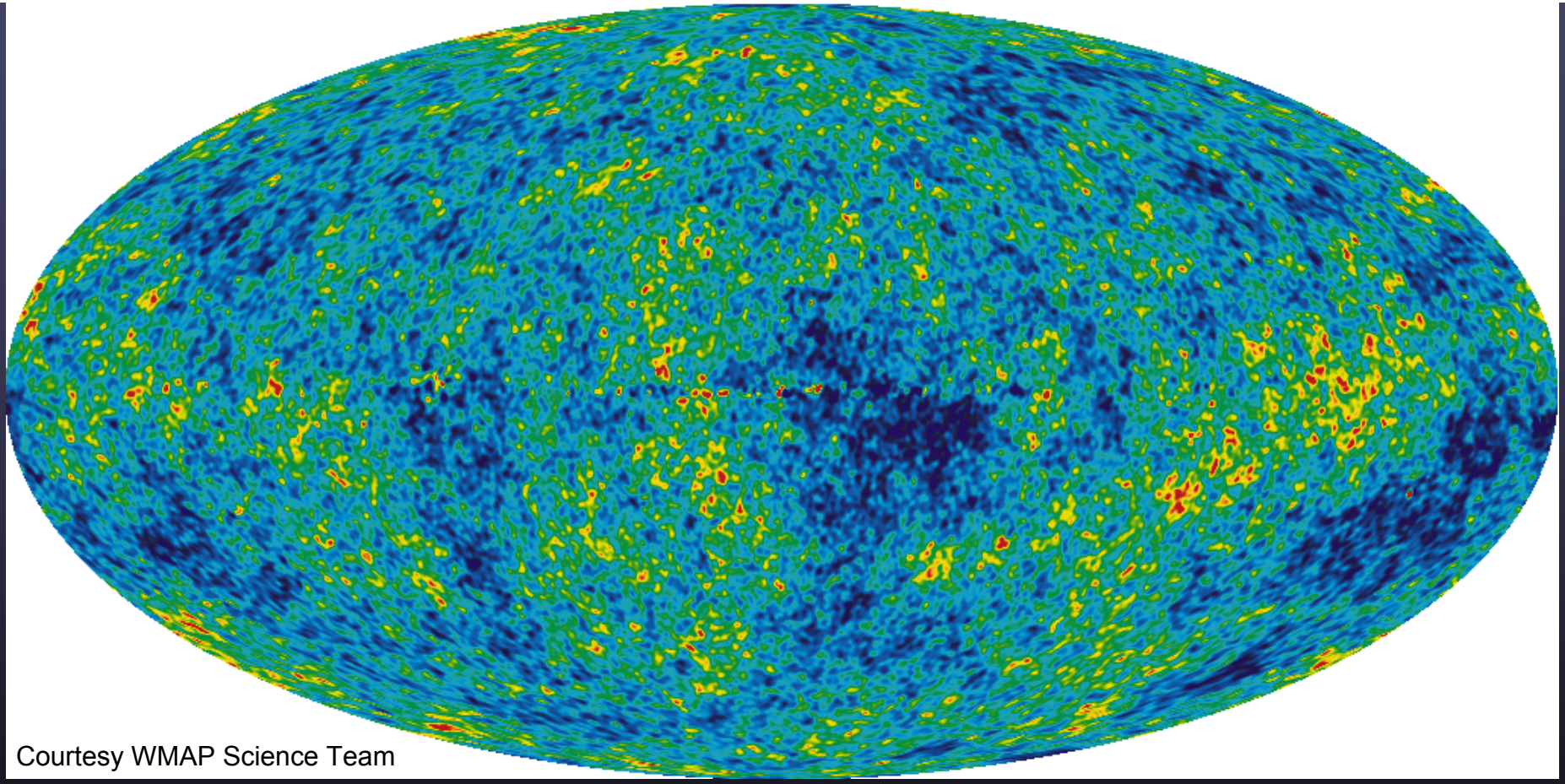
Courtesy WMAP Science Team *http://lambda.gsfc.nasa.gov*



Mission so far

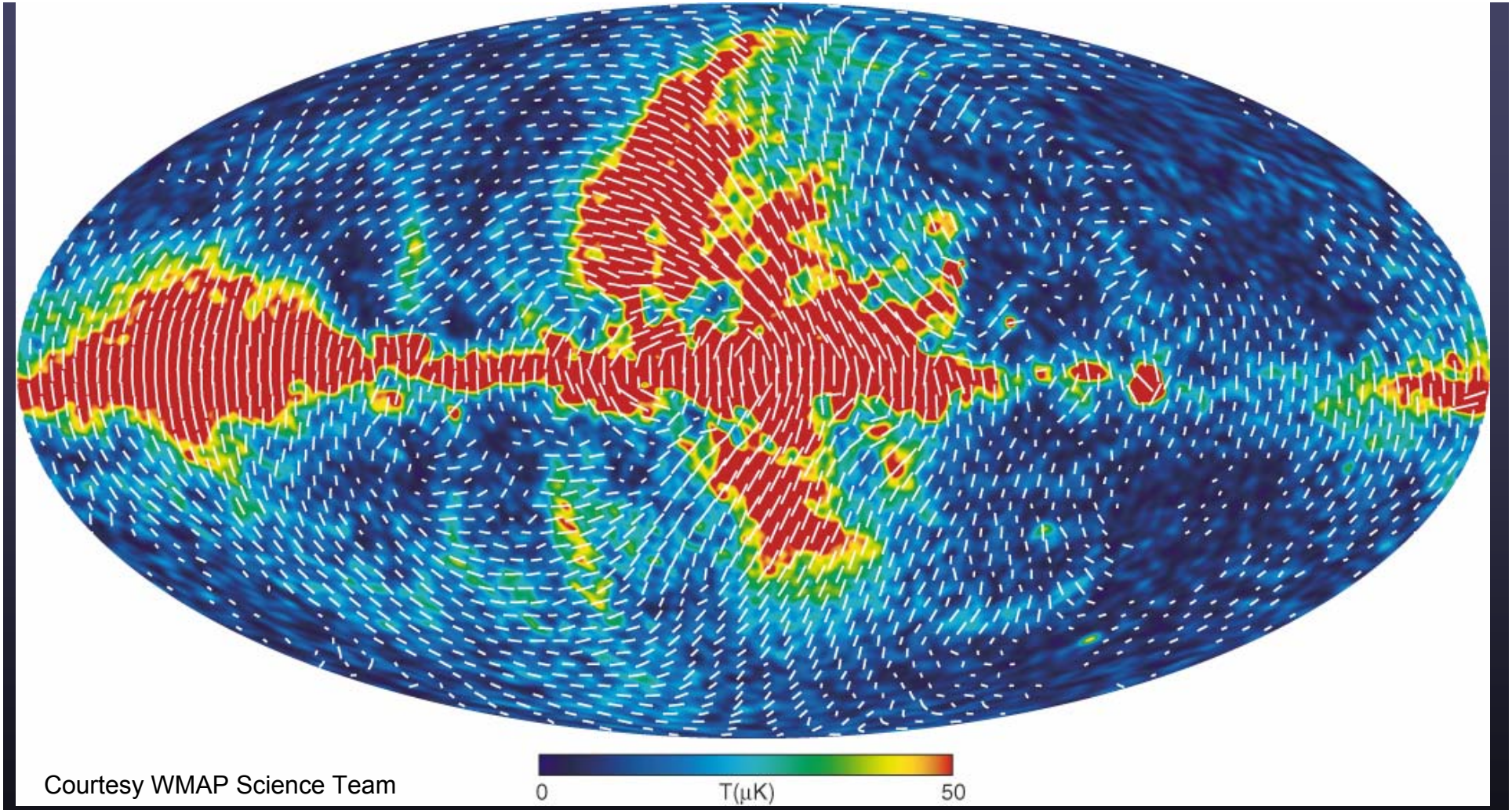
- First year data release (2003)
  - first and second peaks in TT
  - low-ℓ anomalies & cold spots: geometry? foreground? variance?
  - first peak in TE polarization (but no EE or BB results reported)
  - confirmation of nearly flat Universe
  - consistent with scale-invarinat $n_s \approx 1$, hint of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



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

WMAP 3 - polarization

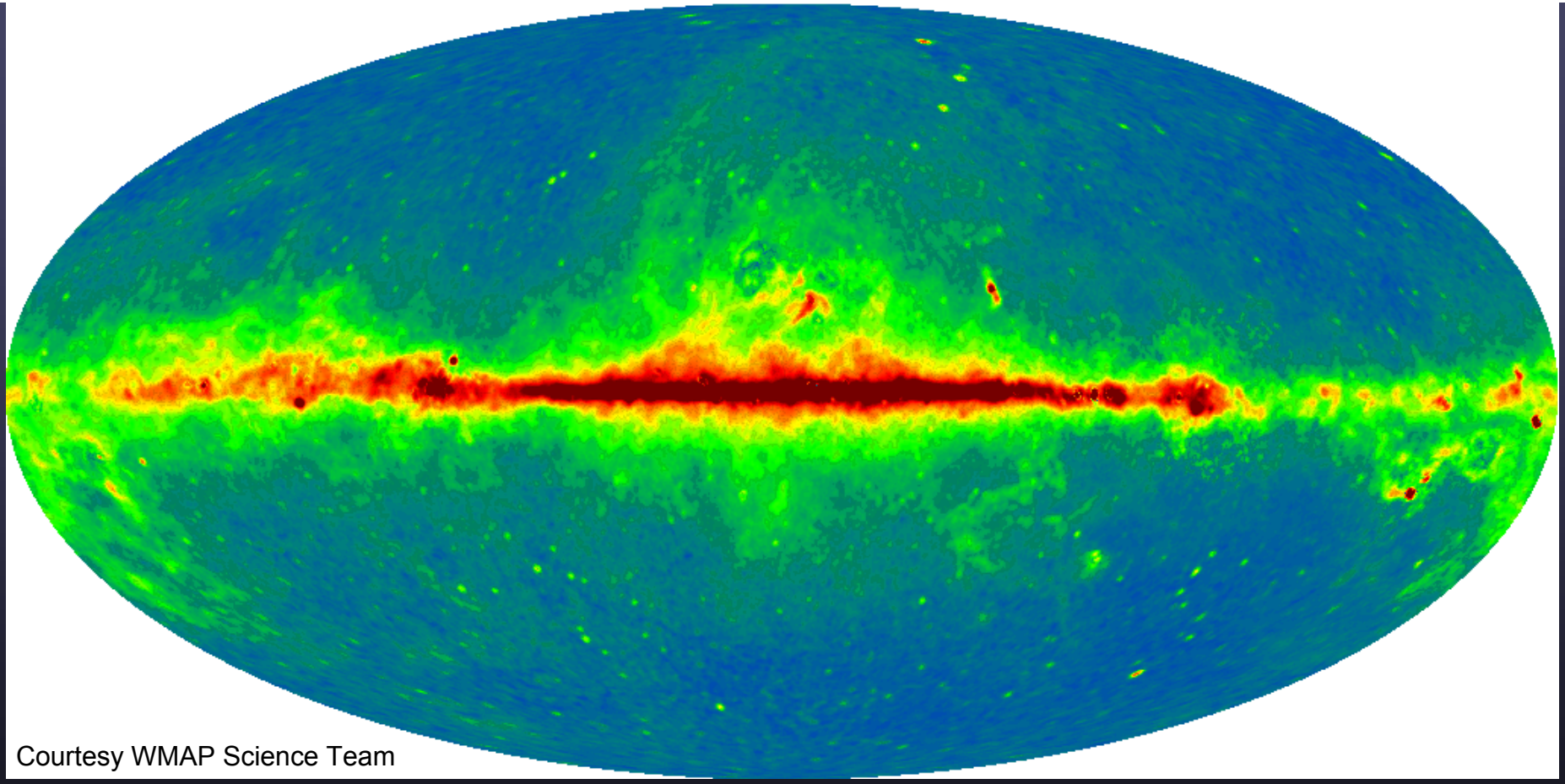


Courtesy WMAP Science Team

WMAP 3-yr 22 GHz polarization map (galaxy)

- linear scale 0 to 50 μK (Page et al. 2007)

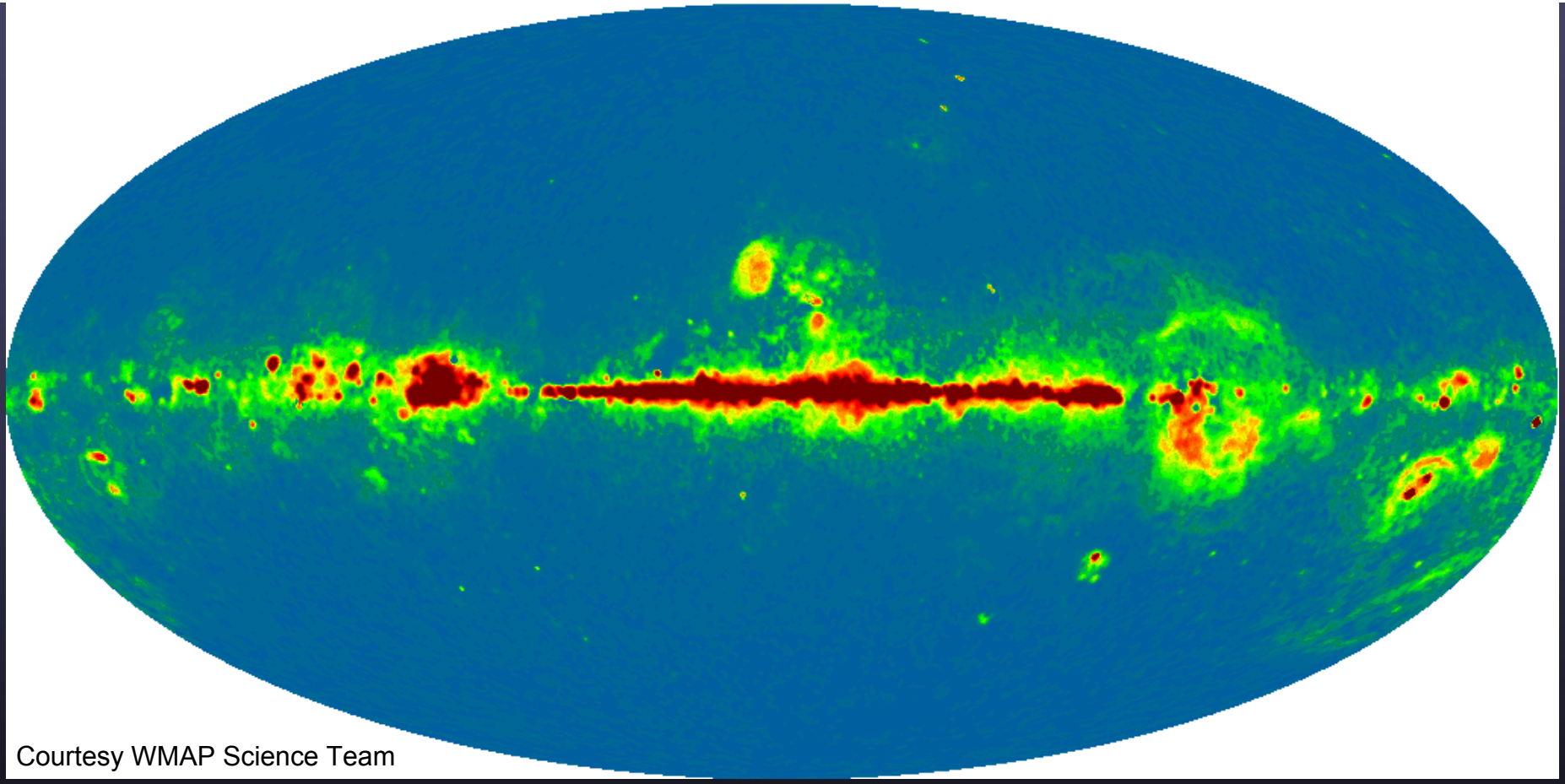
WMAP 3 - synchrotron



WMAP 3-yr 23 GHz synchrotron map (galaxy)

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

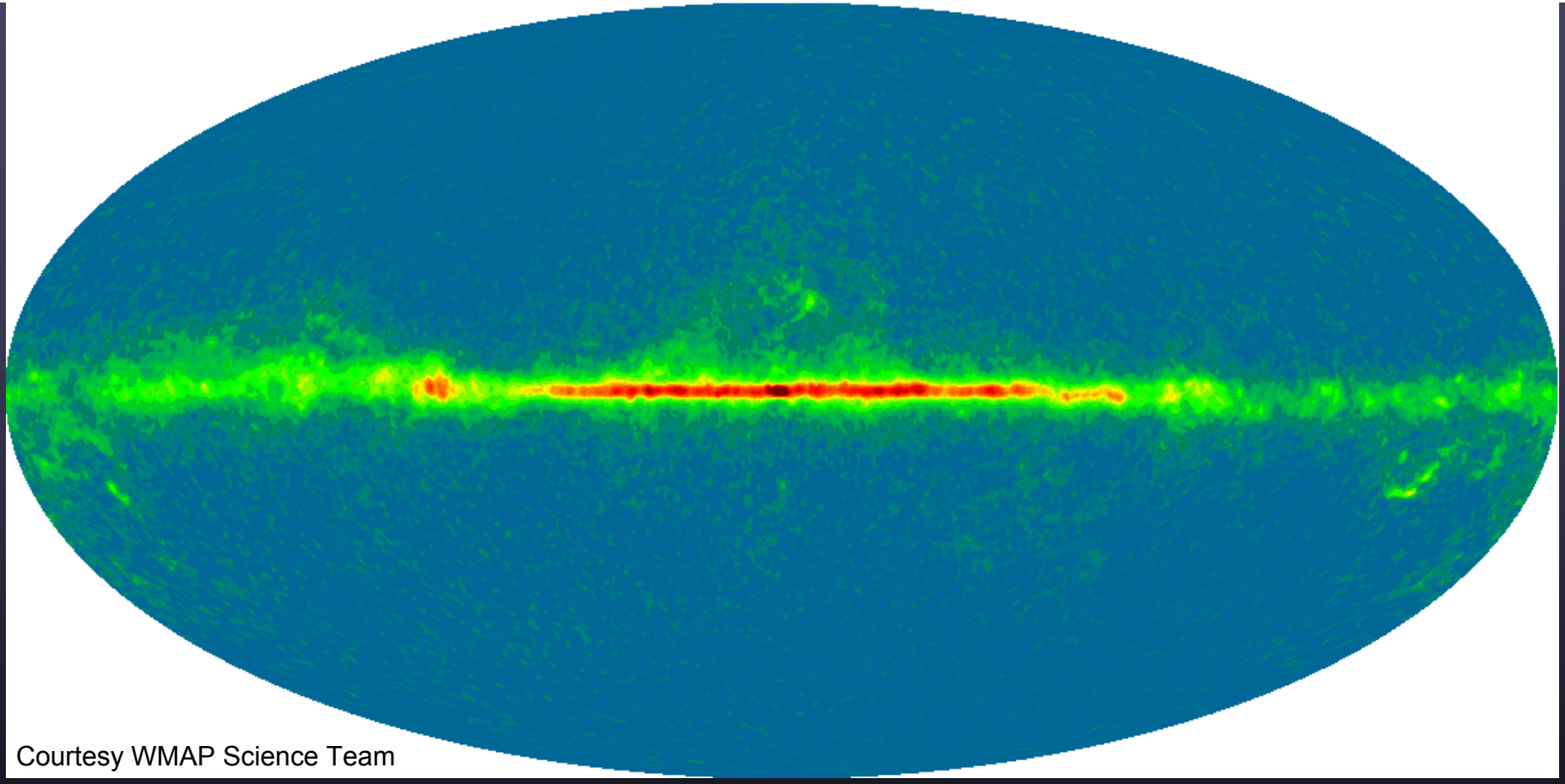
WMAP 3 – free-free



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

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

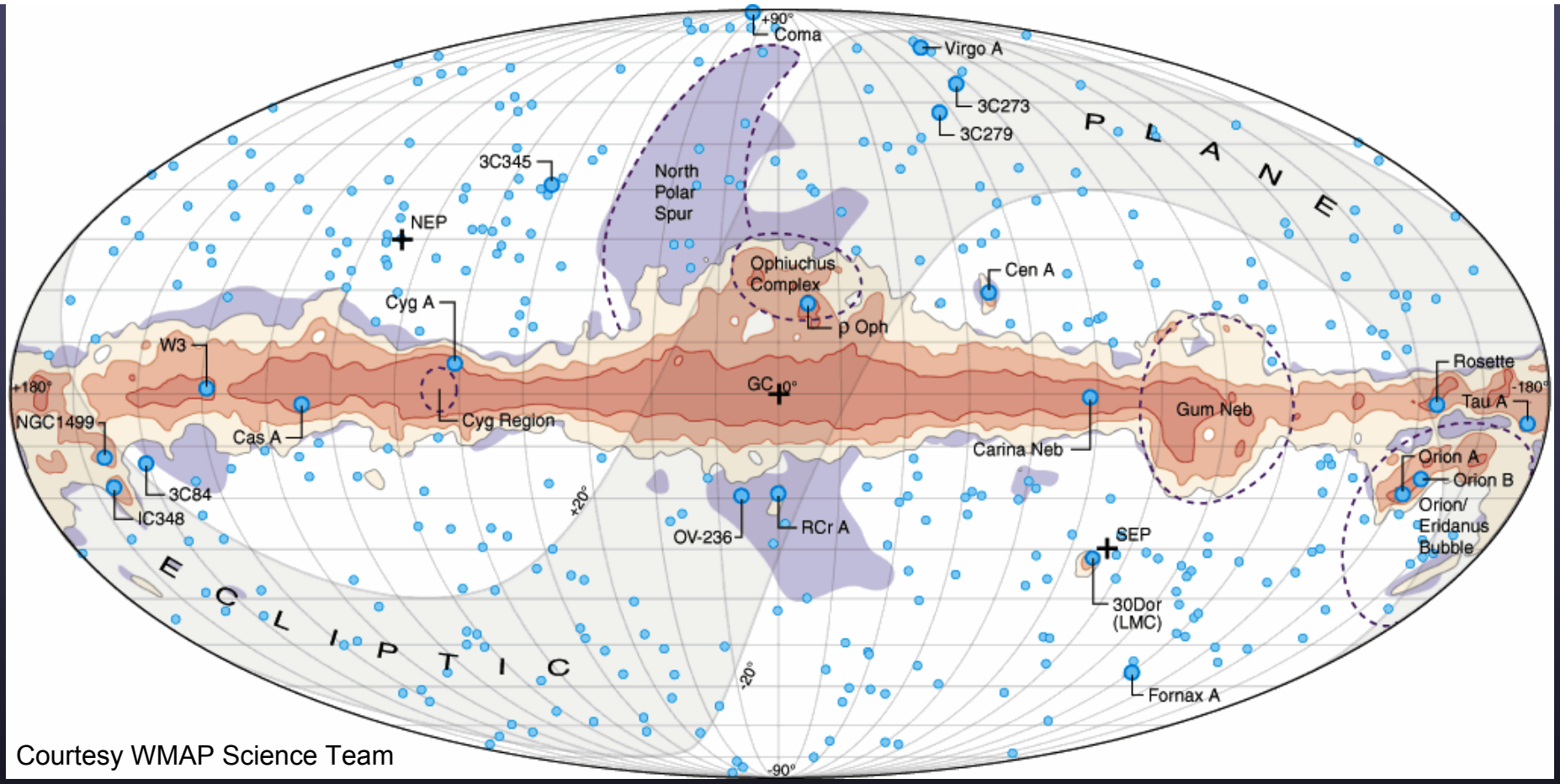
WMAP 3 - dust



WMAP 3-yr 94 GHz dust map (galaxy)

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

WMAP 3 galaxy



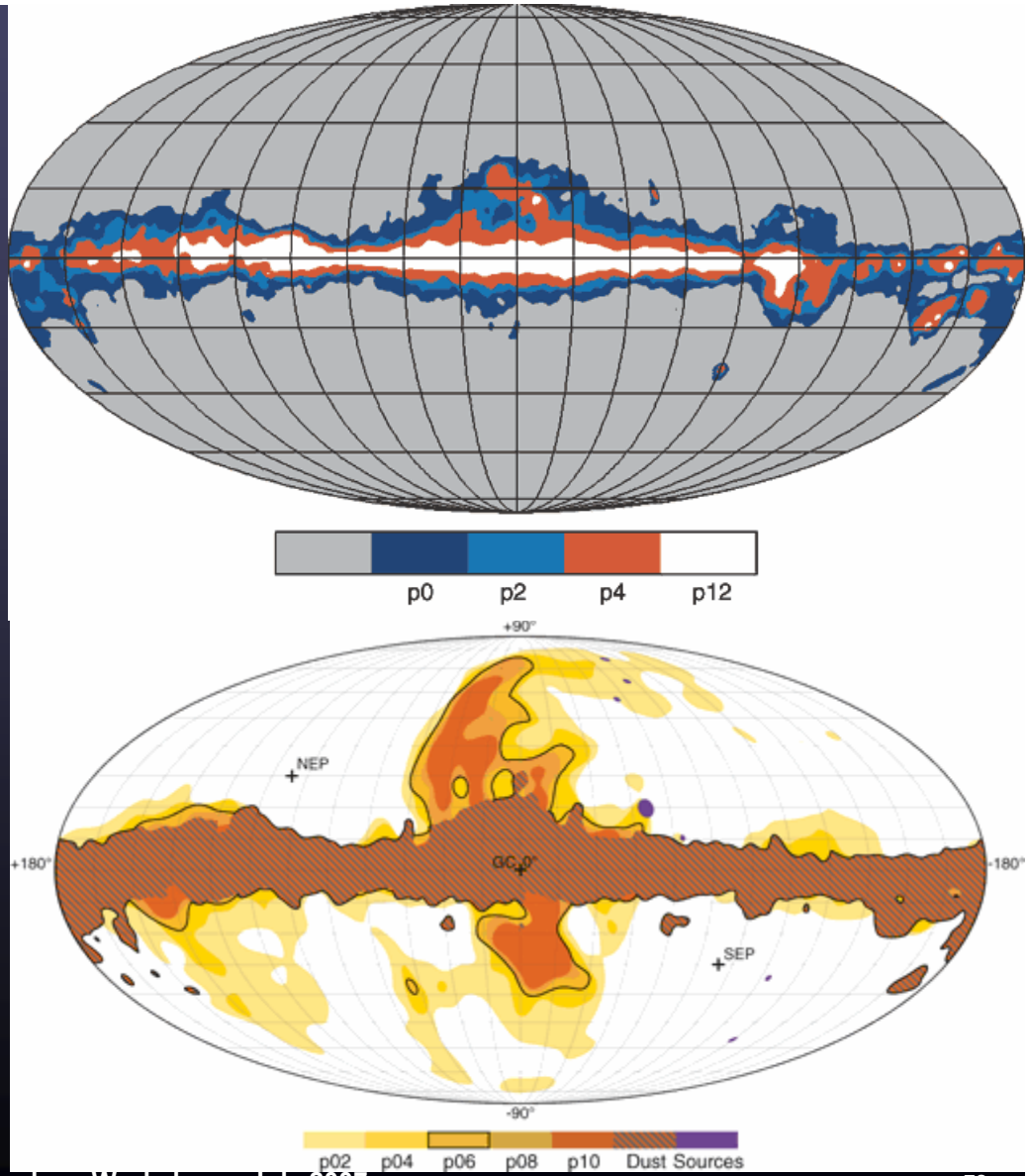
Courtesy WMAP Science Team

Galactic microwave map for orientation

Astronomers like foregrounds – they even name these things!

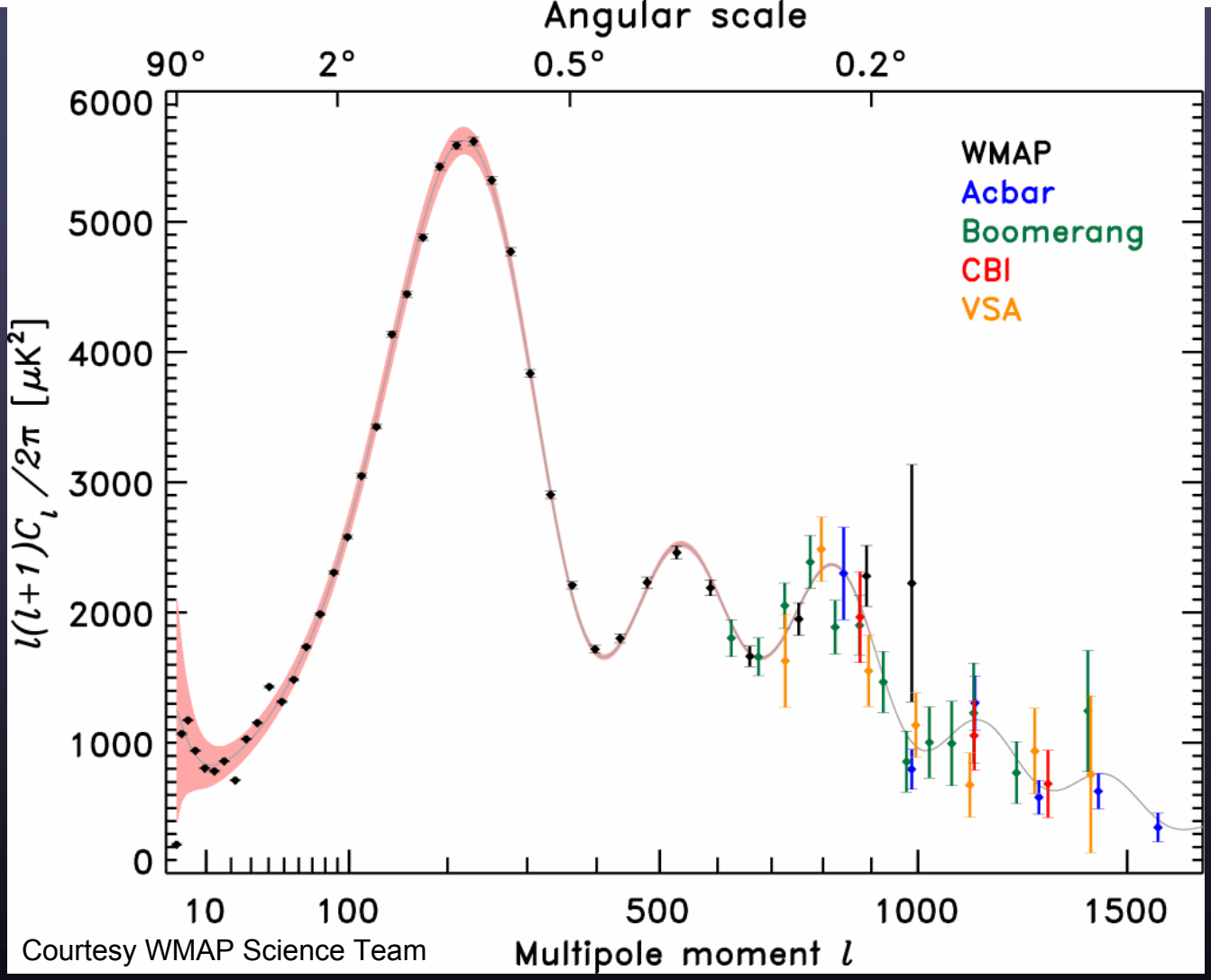
WMAP3 - masks

- To compute power spectrum and determine cosmological parameter constraints the WMAP team used galactic masks
  - *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*

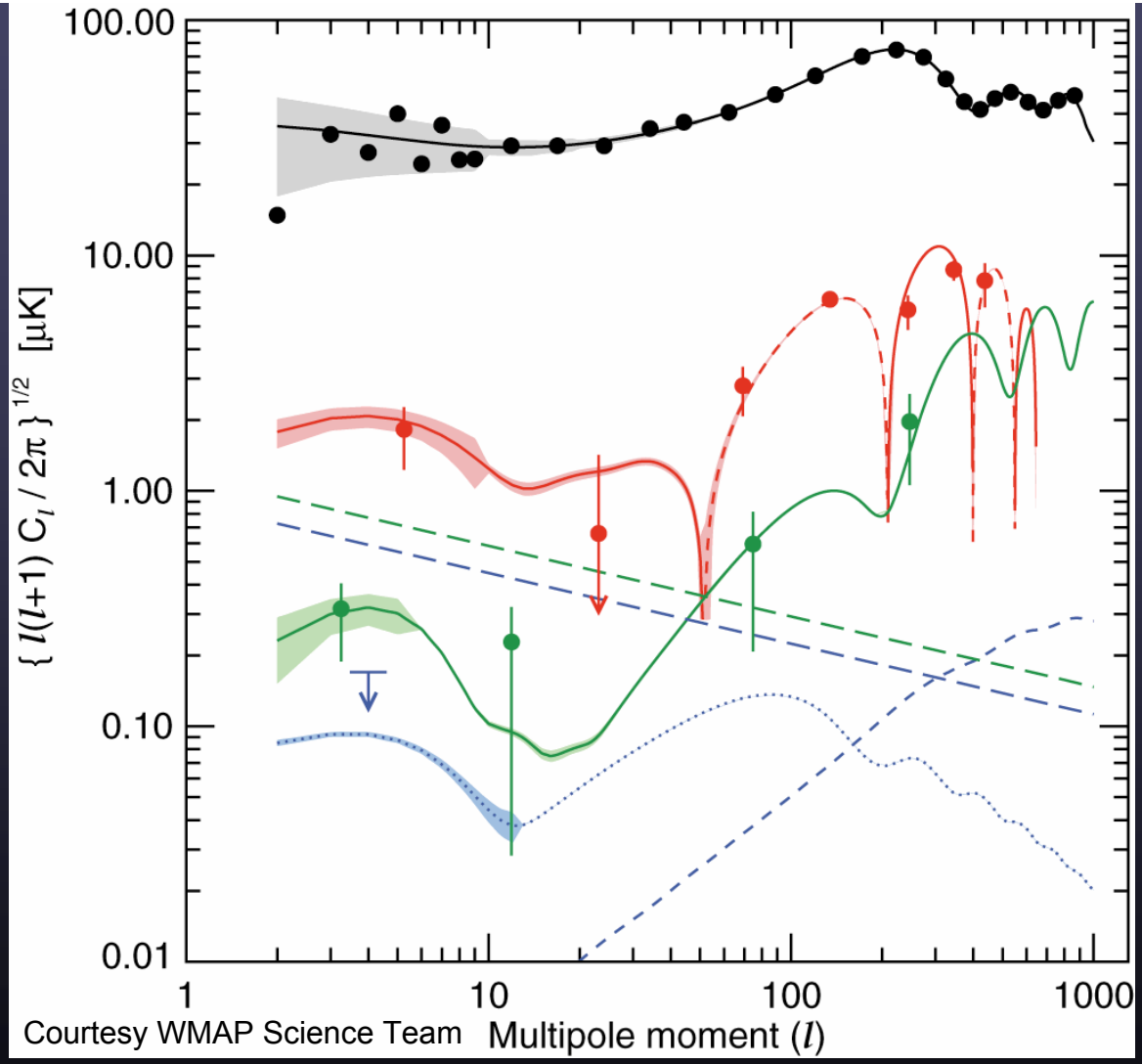
WMAP 3 – TT vs. the rest



Courtesy WMAP Science Team

WMAP+ 3yr TT power spectrum (Hinshaw et al. 2007)

WMAP 3 – TT/TE/EE spectrum



Courtesy WMAP Science Team

WMAP 3yr power spectra (Page et al. 2007)

WMAP 3 – Cosmological Parameters

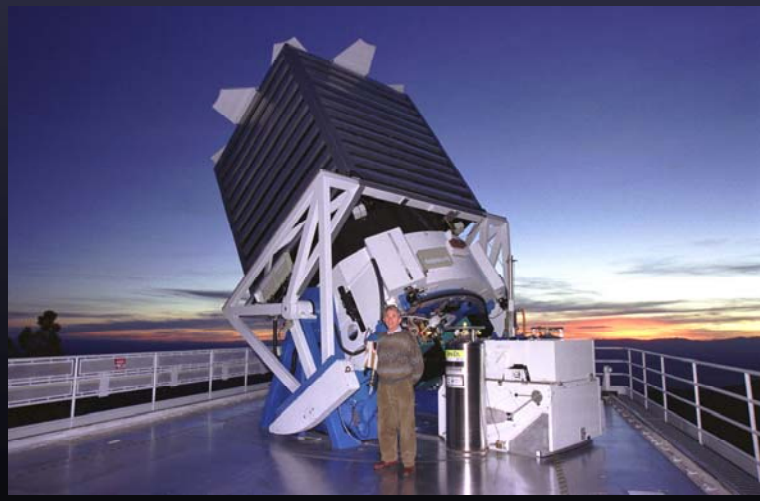
- Cosmological parameters (ΛCDM) from WMAP3 alone

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

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

WMAP+SDSS: Galaxies and ISW

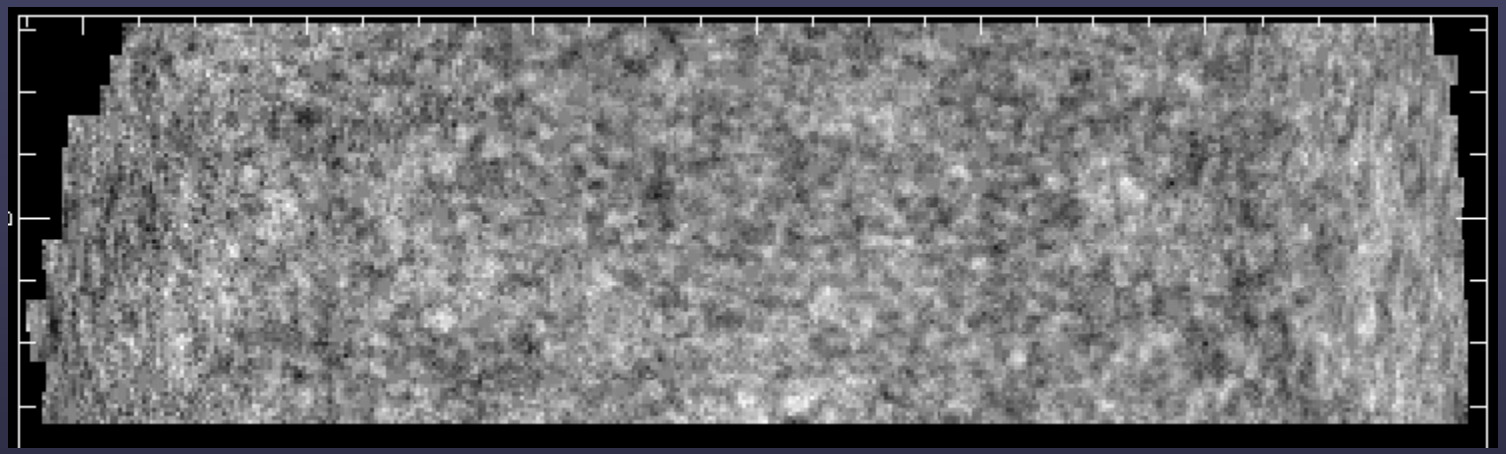
- The distribution of galaxies should reflect the distribution of potential wells in nearby Universe
  - Sloan Digital Sky Survey (SDSS)
- The decay of potential during epoch of Dark Energy domination (z>2) causes the Late ISW in the CMB
  - low-ℓ CMB anisotropies in WMAP
- Cross-correlate WMAP with SDSS



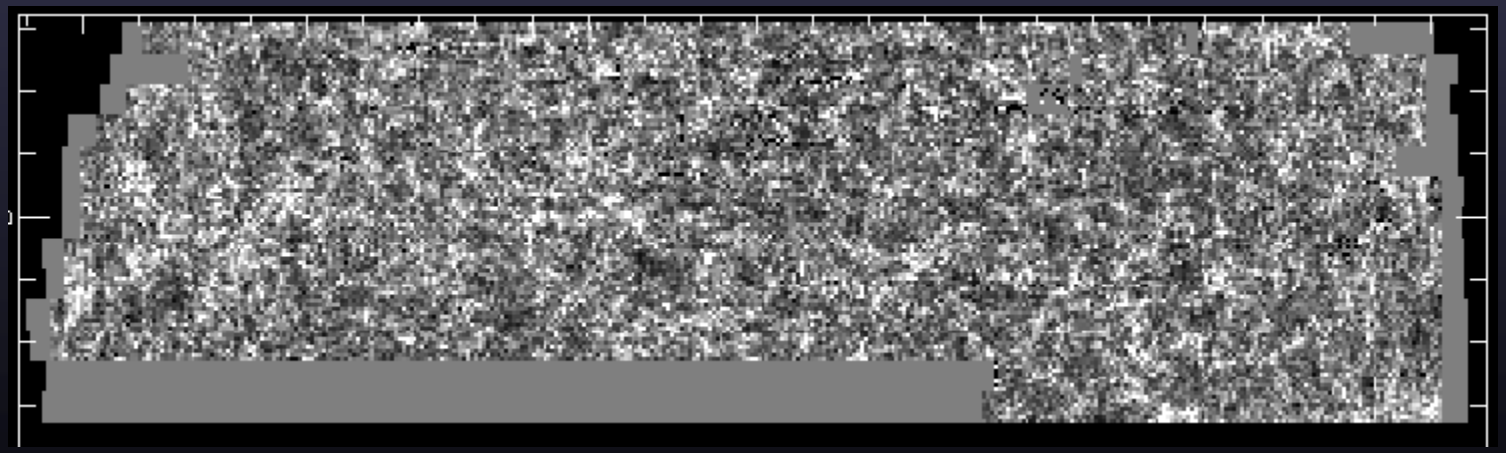
Courtesy SDSS collaboration

WMAP and SDSS

- cross-correlation should enhance ISW signal



WMAP W band temperatures across 50% of SDSS area



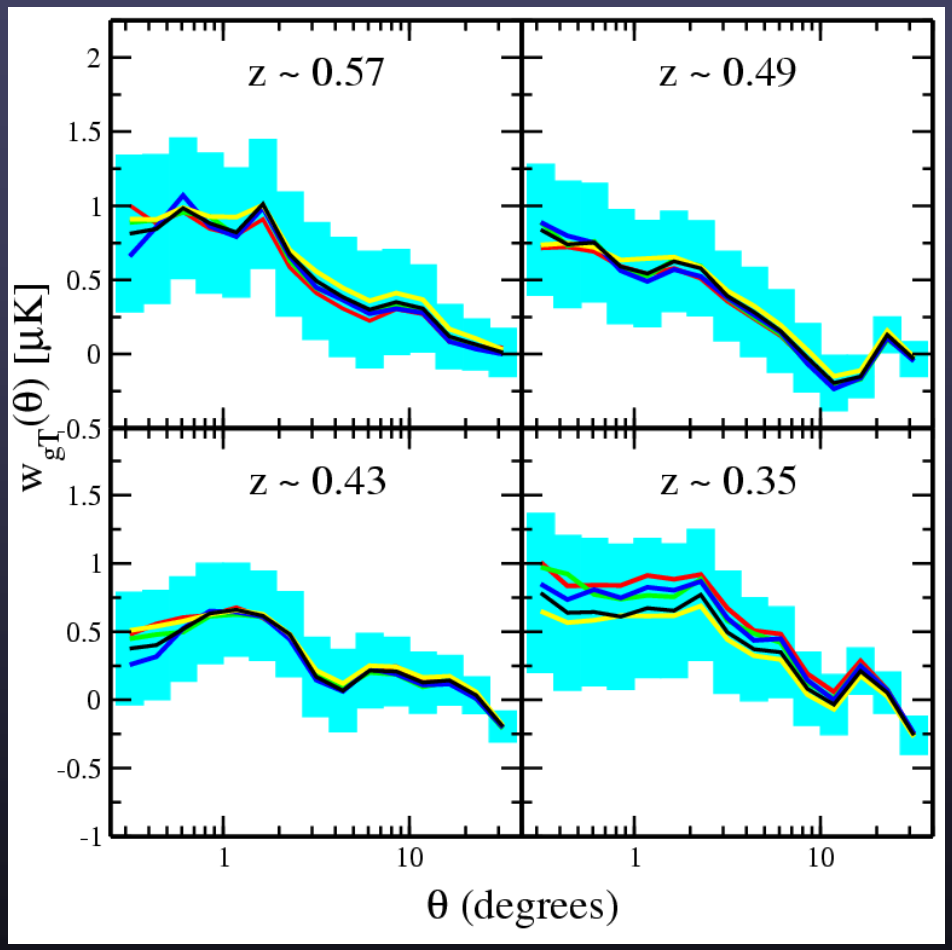
Density of Luminous Red Galaxies (LRGs) selected from the SDSS

Courtesy Bob Nichol

SDSS-WMAP correlation results

- LRG selection to z~0.8 (Eisenstein et al. 2001)
- 5300 sq degrees
- Achromatic (no contamination)
- Errors from 5000 CMB skies
- Compared to a null result
- >95% for all samples
- Low redshift sample contaminated by stars
- Individually >2s per redshift slice
- 4 redshift shells (not significant overlap)

- <u>Overall, signal detected at ~5σ</u>

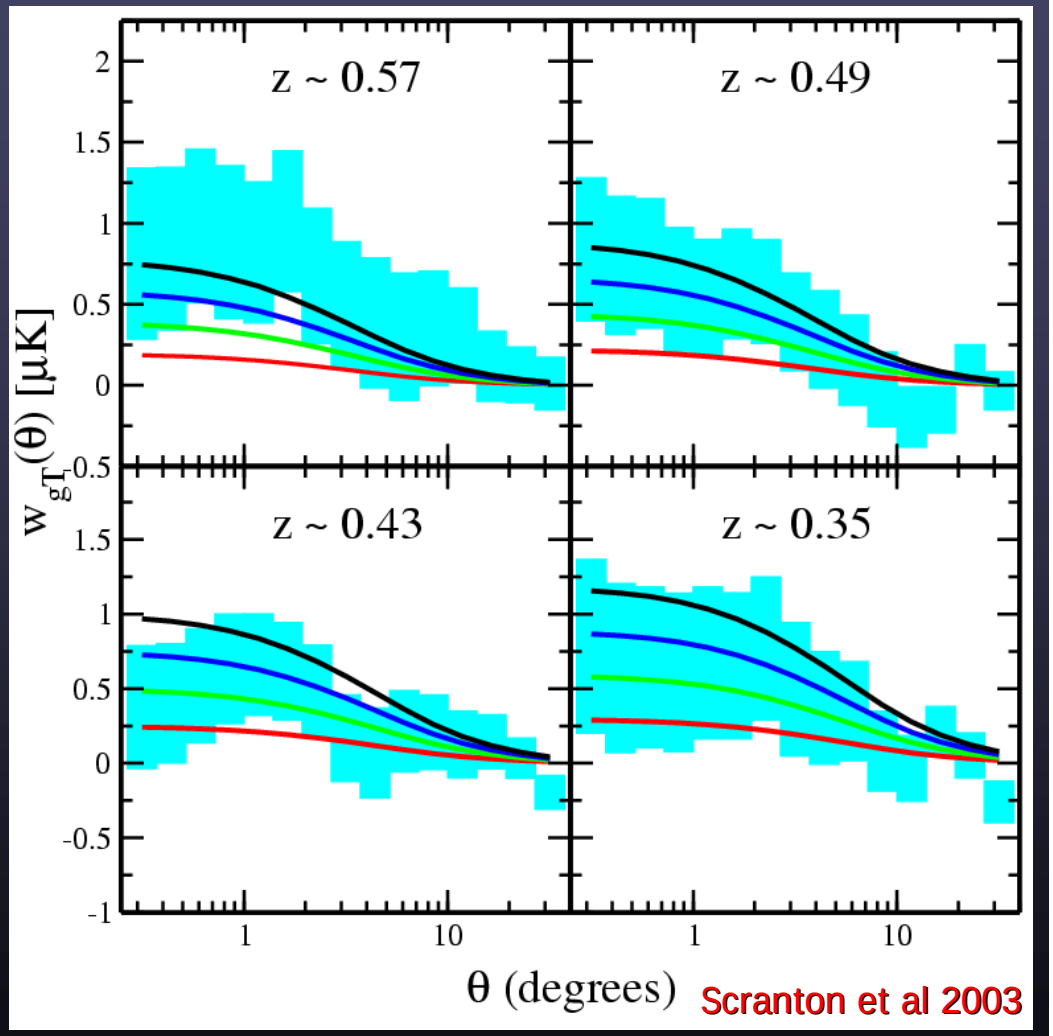


Scranton et al 2003

Courtesy Bob Nichol for SDSS team

ISW predictions

- Halo model. Biasing of b=1,2,3 & 4 for LRGs
- Plus SZ on small scales
- Data prefers DE model over null hypothesis at the >99% confidence for all combinations
- The measurement is very sensitive to n(z) assumed and Ω_m



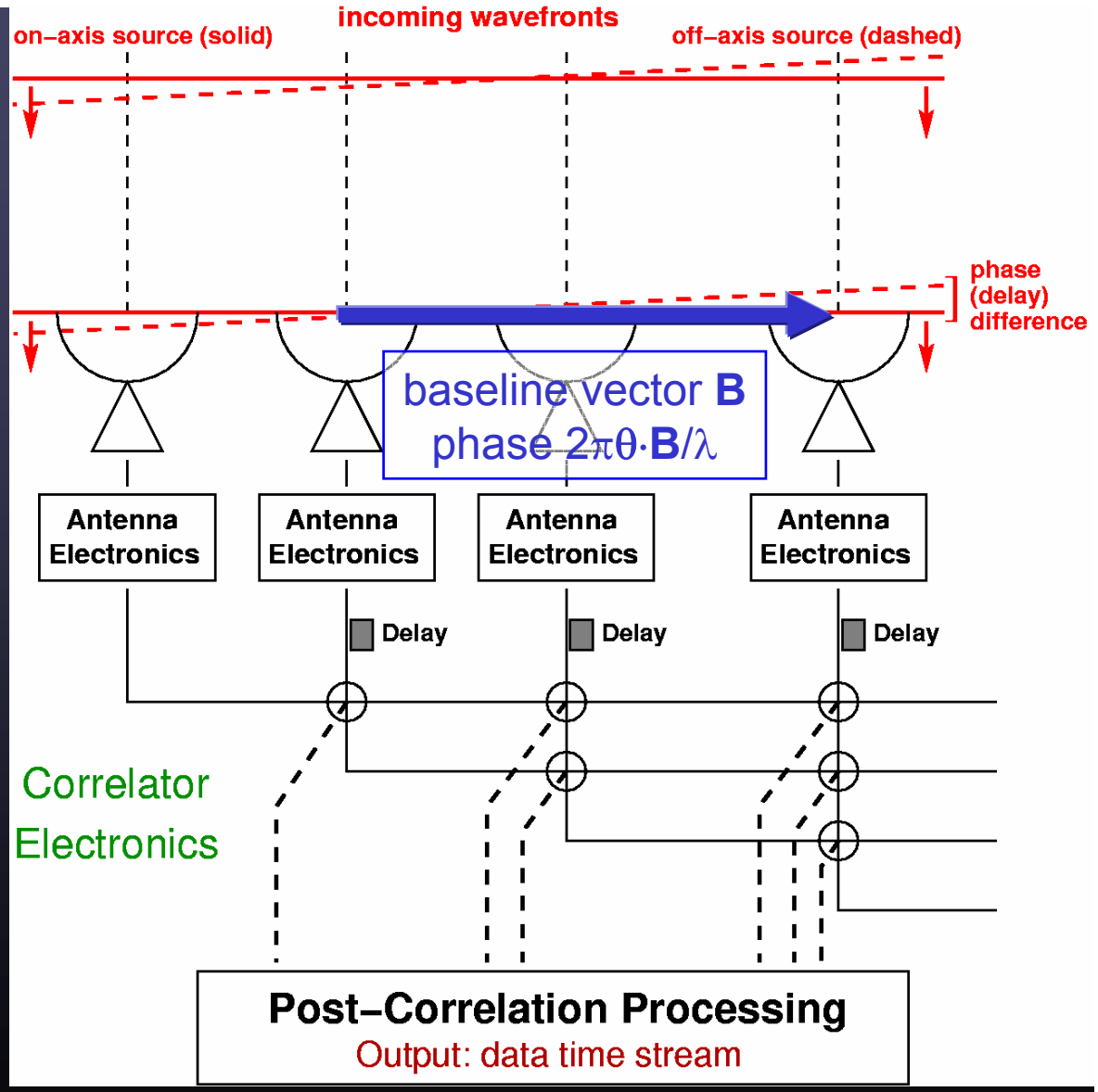
Scranton et al 2003

Courtesy Bob Nichol for SDSS team

CMB Interferometry: the CBI

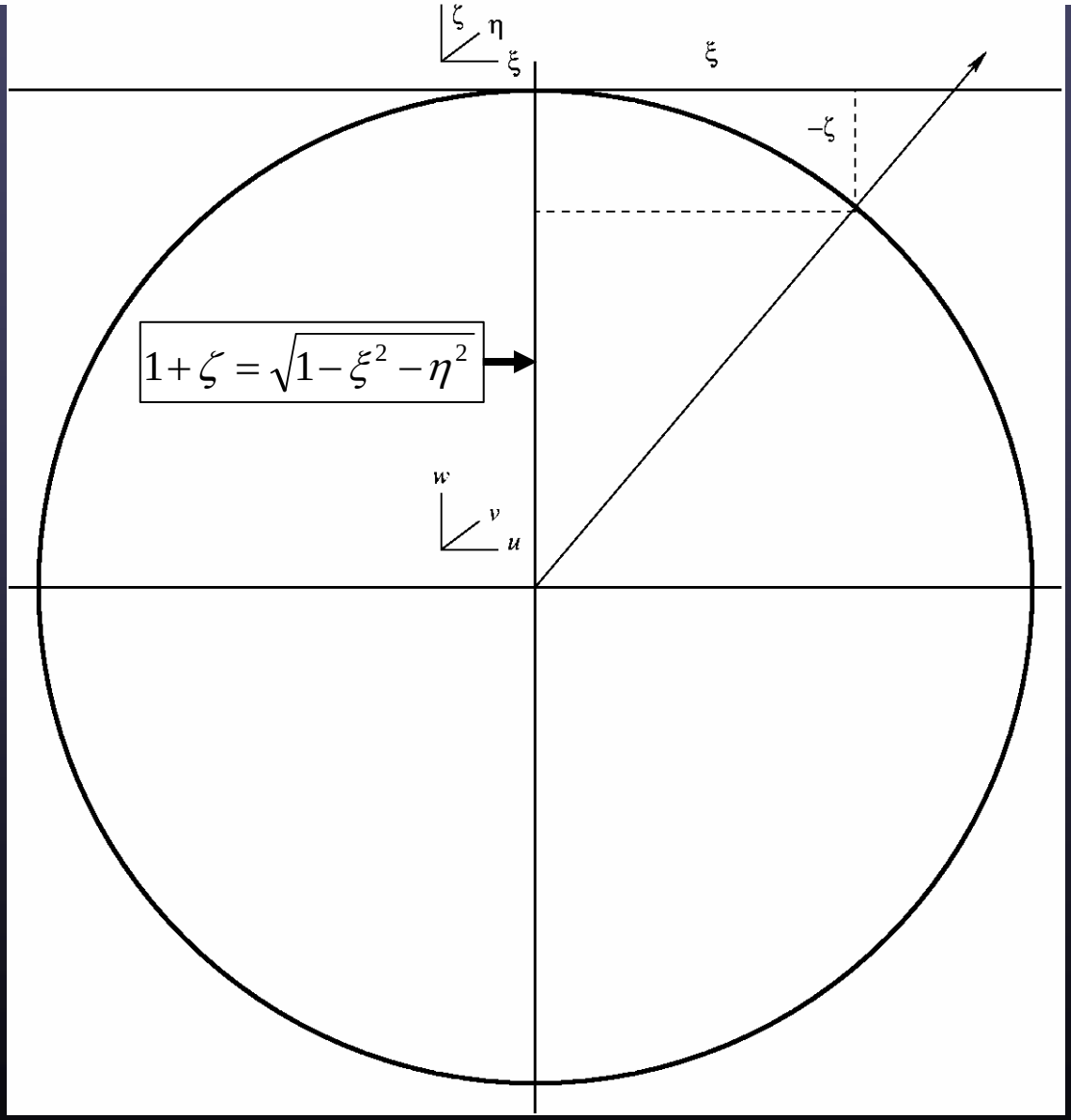
Radio Interferometer – schematic

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



Standard sky geometry

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



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

- An interferometer naturally measures the transform of the sky intensity in *uv*-space convolved with aperture
  - cross-correlation of aperture voltage patterns in uv-plane
  - its tranform on sky is the <u>primary beam</u> with FWHM ~ λ/D

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

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

- 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 $|\mathbf{u}| = \ell / 2\pi$

Statistics of the CMB revisited

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

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

- 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

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

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

  - T is real: uv-plane has Hermitian symmetry

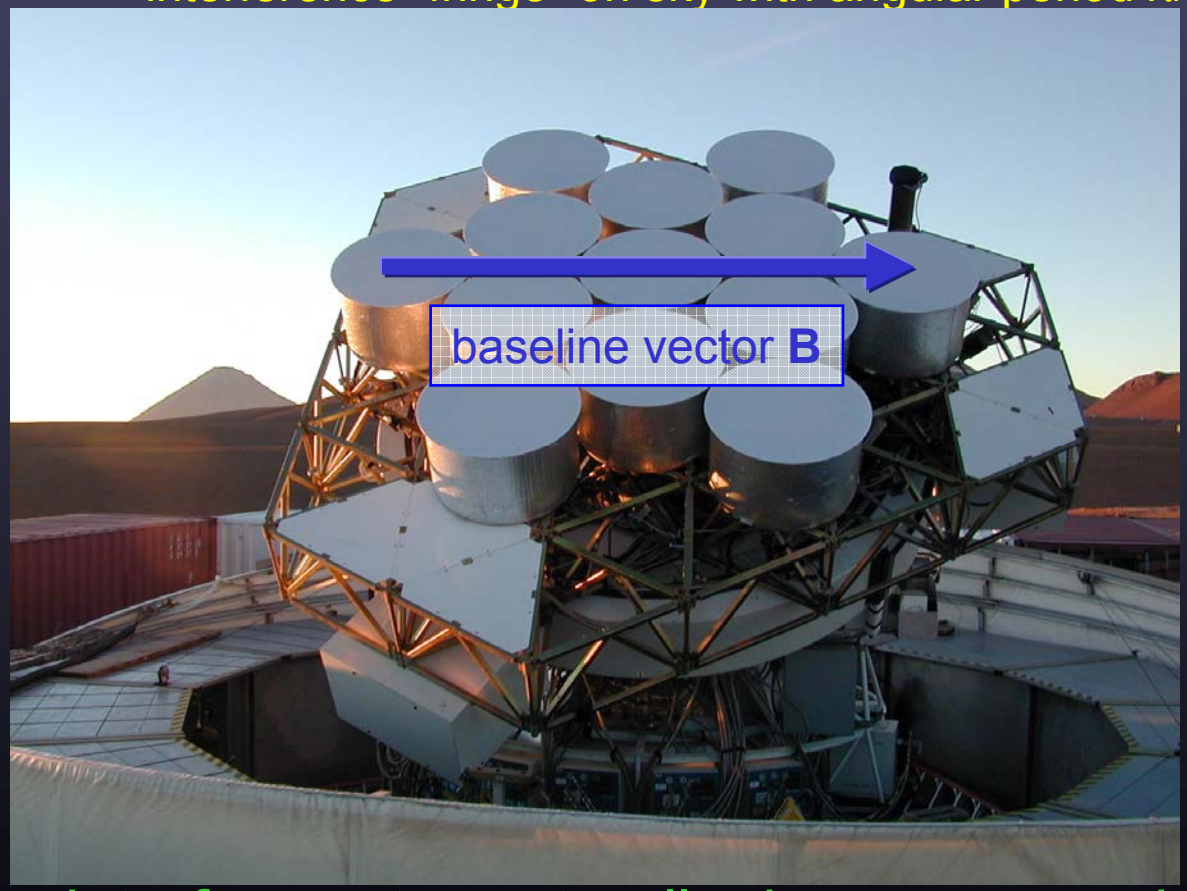
$$\tilde{T}(-\mathbf{u}) = \tilde{T}^*(\mathbf{u})$$

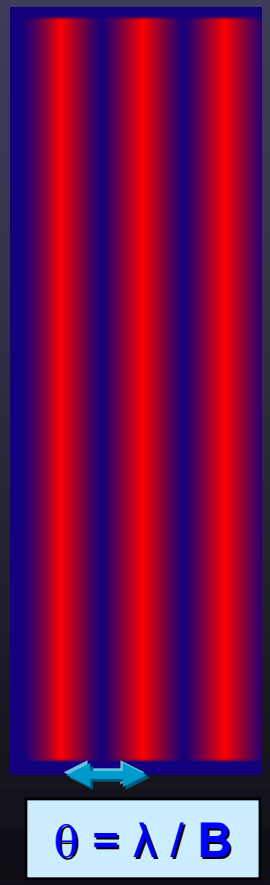
$$\left\langle \tilde{T}(\mathbf{u}) \tilde{T}(\mathbf{u}') \right\rangle = C_\ell \delta^2(\mathbf{u}+\mathbf{u}') \qquad \ell = 2\pi|\mathbf{u}|$$

<u>CMB is ideal for interferometry!</u>

Interferometer Baselines

- Baseline vector ***B*** in "aperture plane"
  - coherent signal applied to interferometer would produce plane-wave interference "fringe" on sky with angular period λ/B

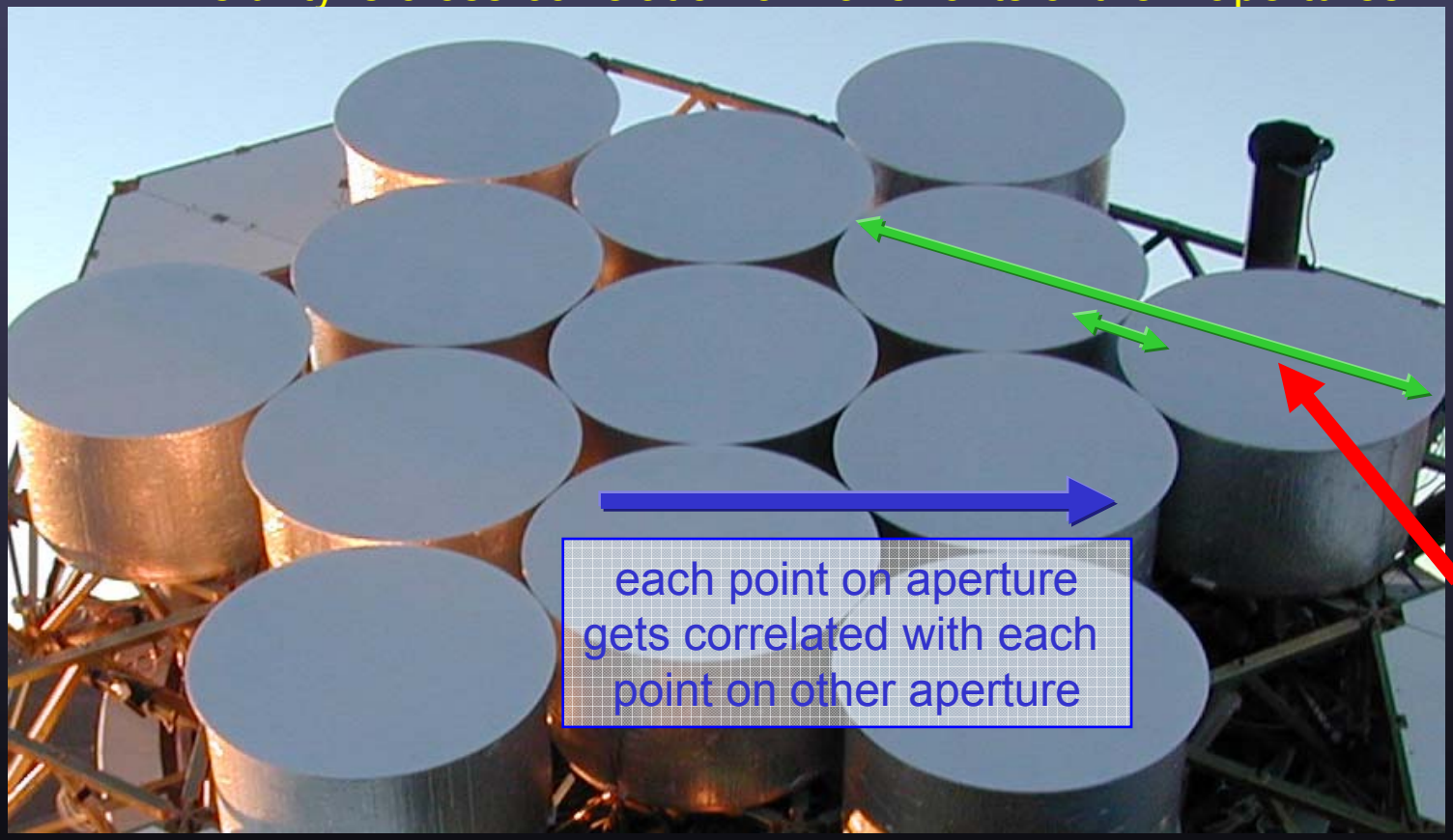




interferometer naturally decomposes sky into plane waves!

The Aperture Plane

- Correlate wavefronts in plane of apertures (Fourier transform of sky)
  - dish optics sum aperture plane at focus
  - visibility is cross-correlation of wavefronts of the 2 apertures



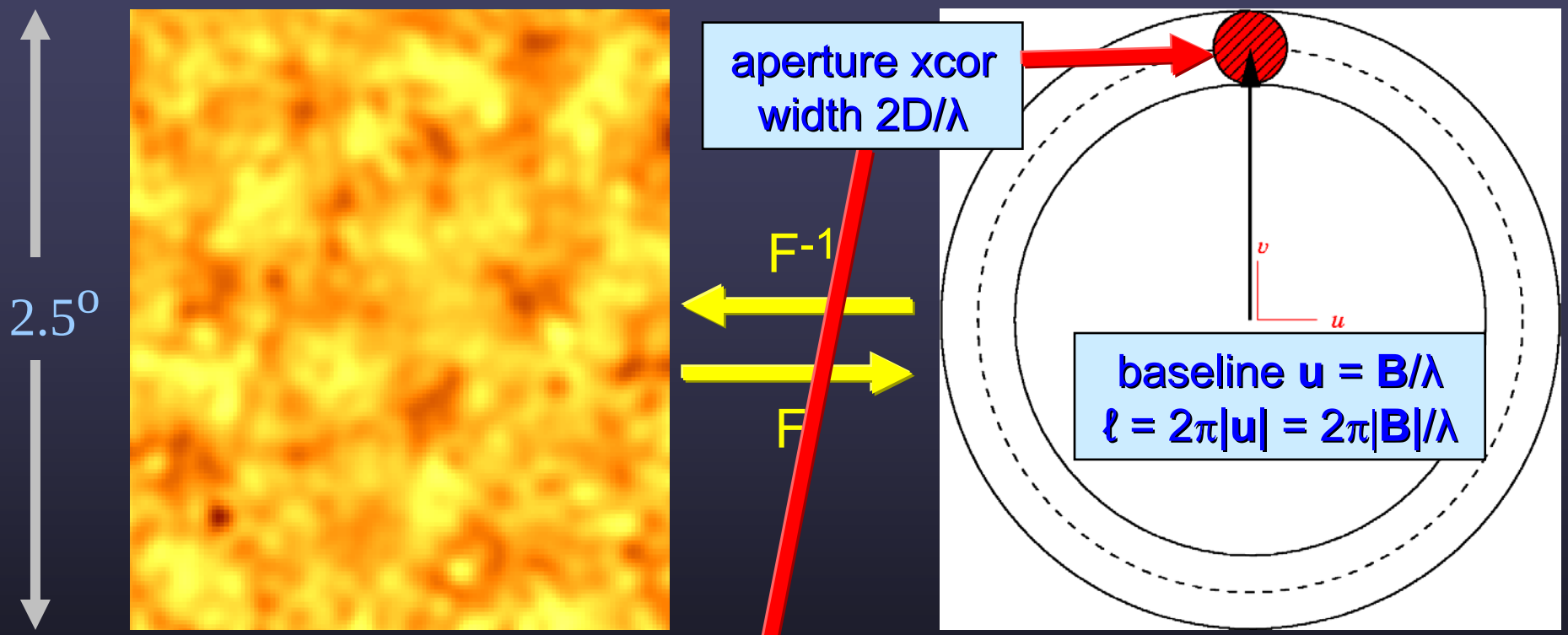
visibility contains range of baselines from closest to furthest parts of apertures

autocorrelations measure uv spacings inside D/λ

interferometer cannot measure "zero-spacing" w/o autocorrelations

From sky to uv-plane

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



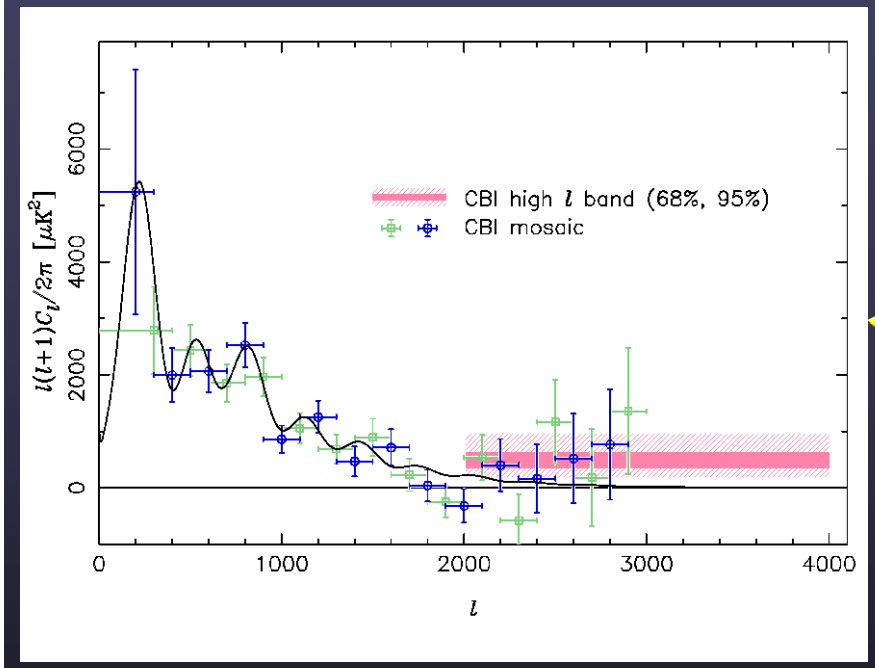
Sky Plane **x** = (x,y)

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

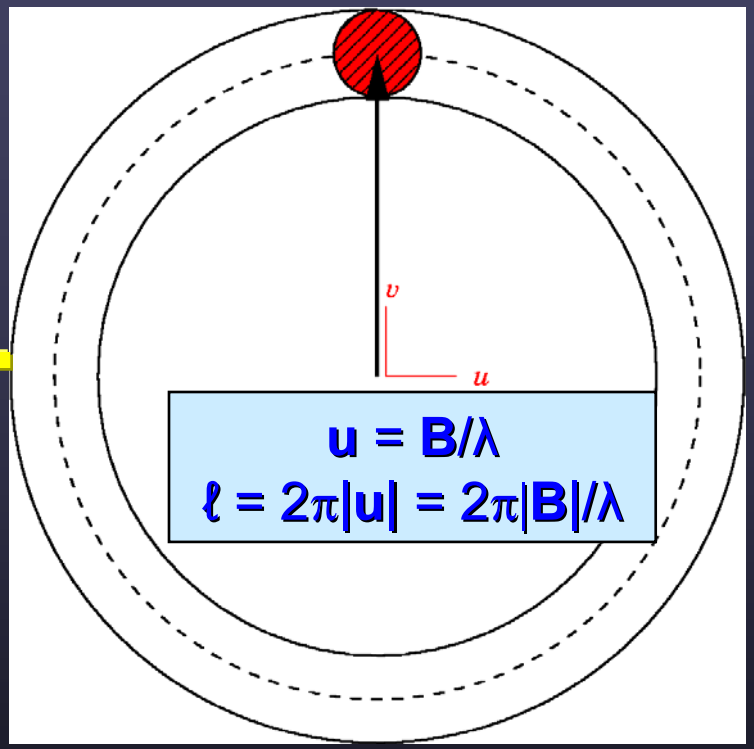
$$V(\mathbf{u}) = \int d^2\mathbf{v}\, \tilde{A}(\mathbf{u}-\mathbf{v})\, \tilde{I}(\mathbf{v})\, e^{2\pi i\, \mathbf{v}\cdot\mathbf{x}_p} + \mathrm{n}$$

From uv-plane to C_ℓ

The angular power spectrum is square of the Fourier Transform of CMB intensity



V^2



Power Spectrum C_ℓ

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

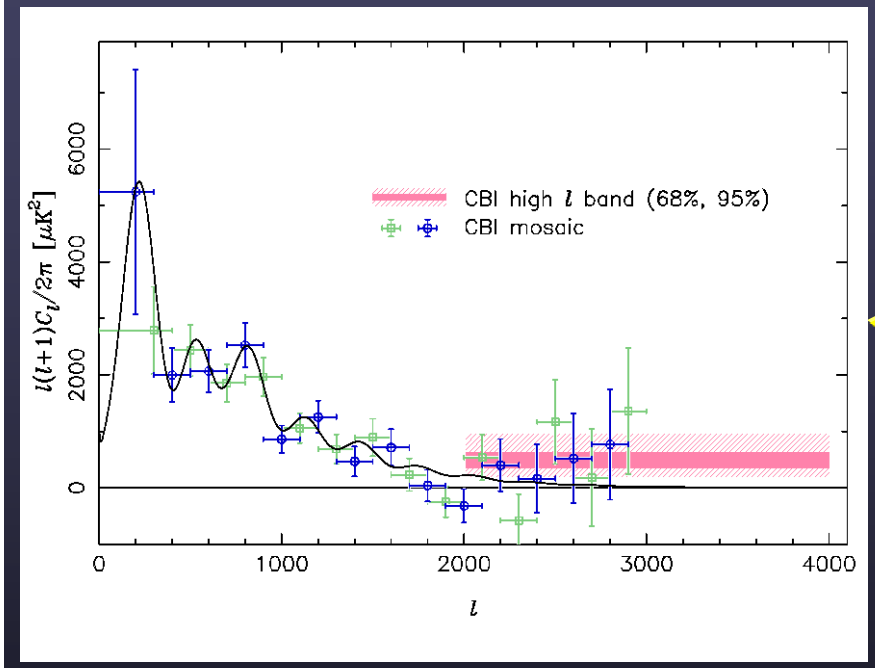
Fourier Plane $\mathbf{u} = (u,v)$

power spectrum easily extracted from interferometer visibilities!

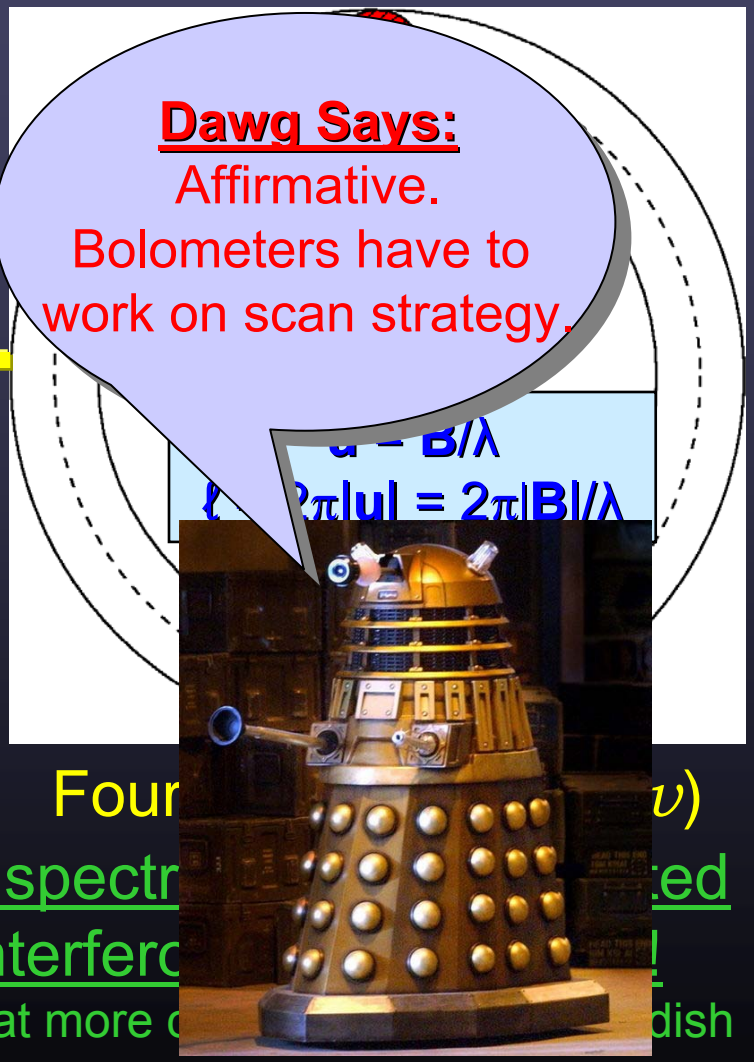
somewhat more complicated for single-dish

From uv-plane to C_ℓ

The angular power spectrum is square of the Fourier Transform of CMB intensity



V^2



Power Spectrum C_ℓ

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

Four … v)

power spectr … ted

from interferc … !

somewhat more c … dish

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°)

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

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

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

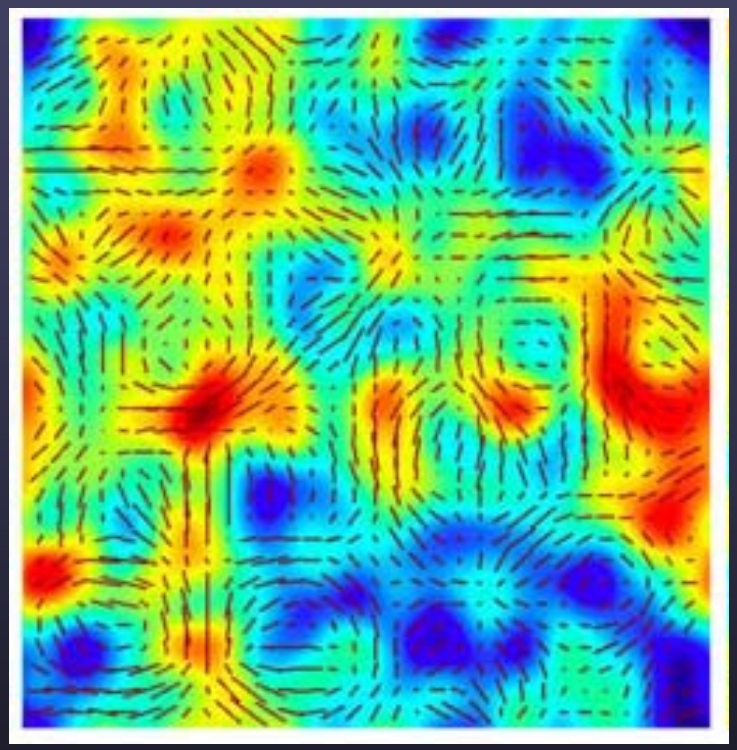
E : $\phi-\chi=0,\pi/2$
B : $\phi-\chi=\pm\pi/4$

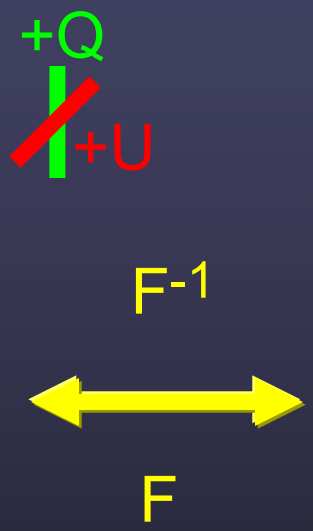
E and B measure alignment of plane-wave polarization with wave vector

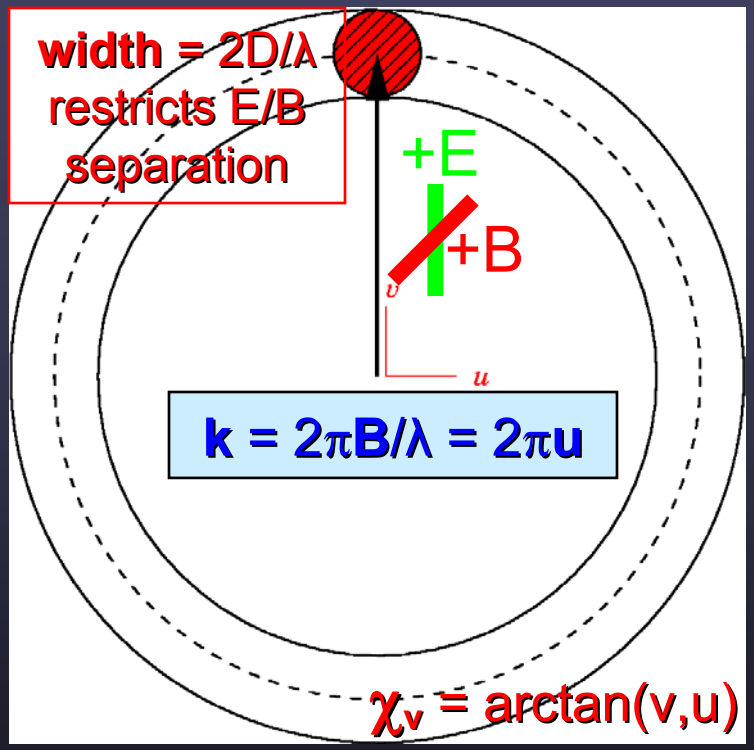
Q,U Cartesian vs. E,B polar coordinate frame in uv-plane

Polarization Interferometry : E & B

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







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

$$V^{RL}(\mathbf{u}) = \int d^2\mathbf{v}\, A(\mathbf{u}-\mathbf{v})[\tilde{E}(\mathbf{v}) + i\,\tilde{B}(\mathbf{v})]e^{i2(\phi-\chi)}e^{2\pi i\mathbf{v}\cdot\mathbf{x}_p}$$

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:

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

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

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

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

  - 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. $2\pi/l^2$)

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 :

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

Maximum Likelihood Estimate (MLE)

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

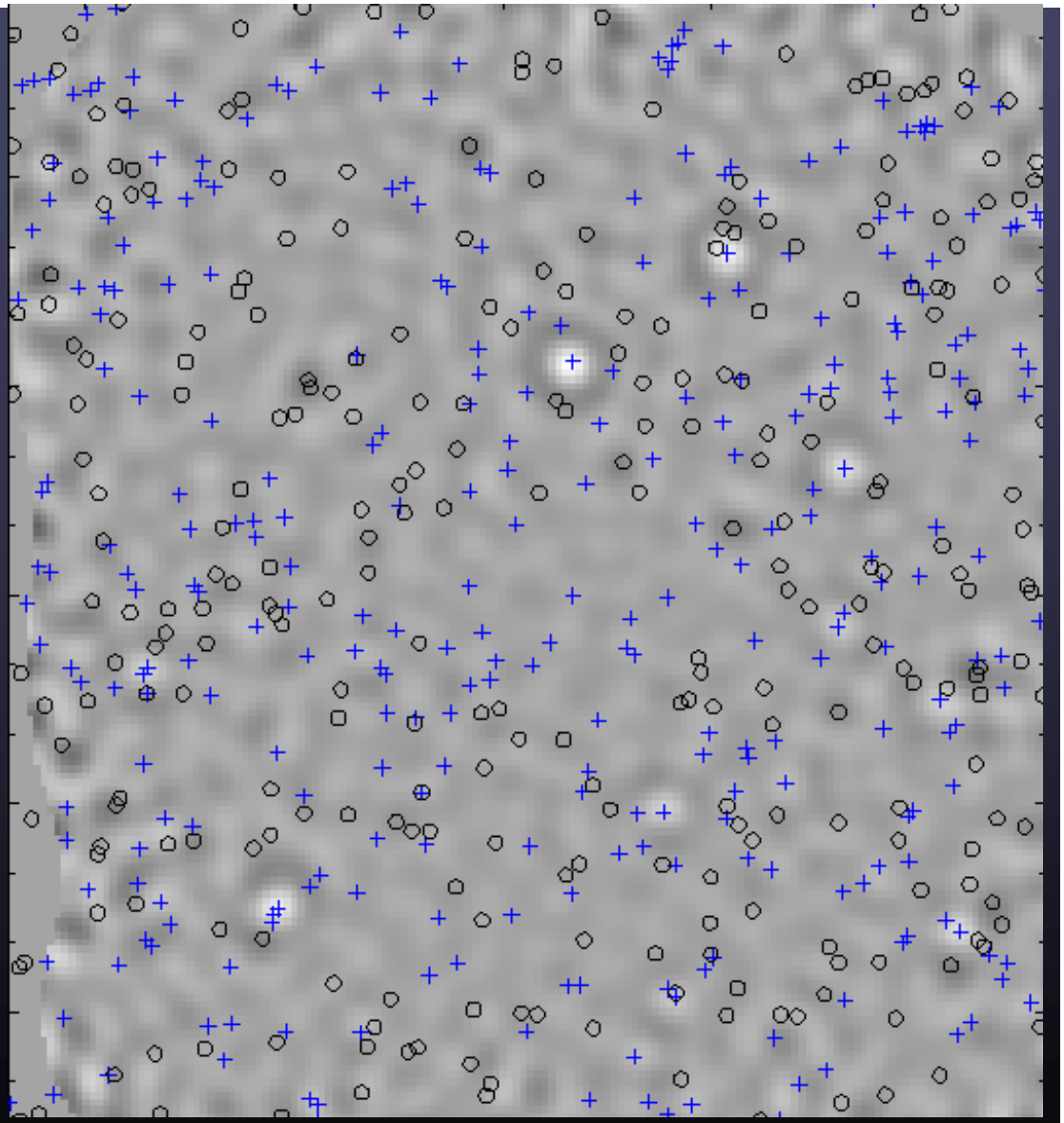
$$L\ (C_\ell \mid \mathbf{d}) = \frac{\exp\left[-\frac{1}{2}\mathbf{d}^T\left(\mathbf{S}(C_\ell)+\mathbf{N}\right)^{-1}\mathbf{d}\right]}{\left[(2\pi)^{N_d}\ \det\left(\mathbf{S}(C_\ell)+\mathbf{N}\right)\right]^{1/2}}$$

  - 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}

Myers et al. 2003, ApJ, 591, 575 (http://www.cita.utoronto.ca/~myers)

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

2nd order: D•P into I

2nd order: D²•I into I

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

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

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

1st order: D•I into P

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

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

3rd order: D²•P* into P

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

  - 1st Order: 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

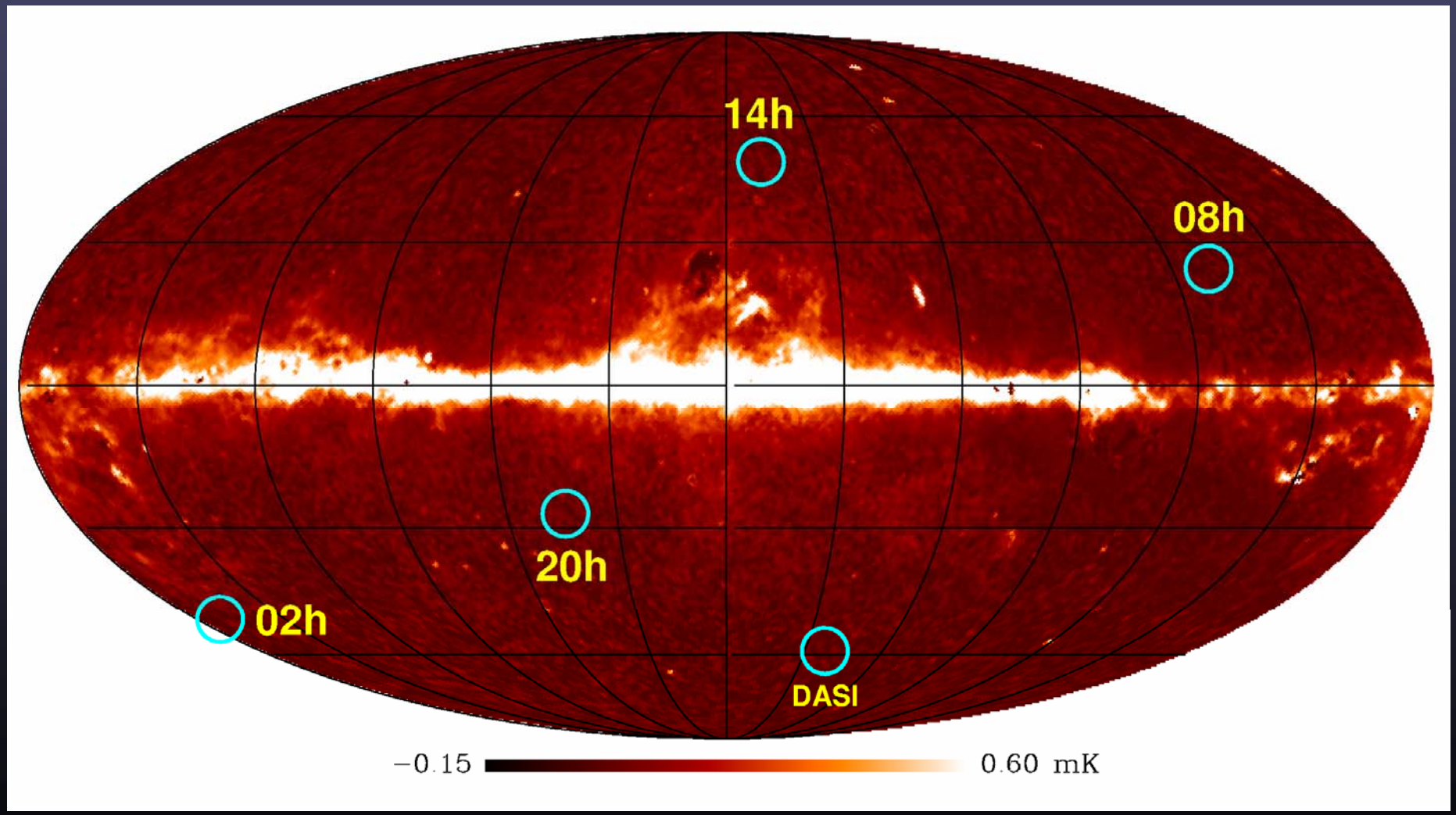
See the VLA!
Located on US 60
1 hour West of
Socorro (about 3
hours from Santa Fe

CMB Interferometer – the CBI

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

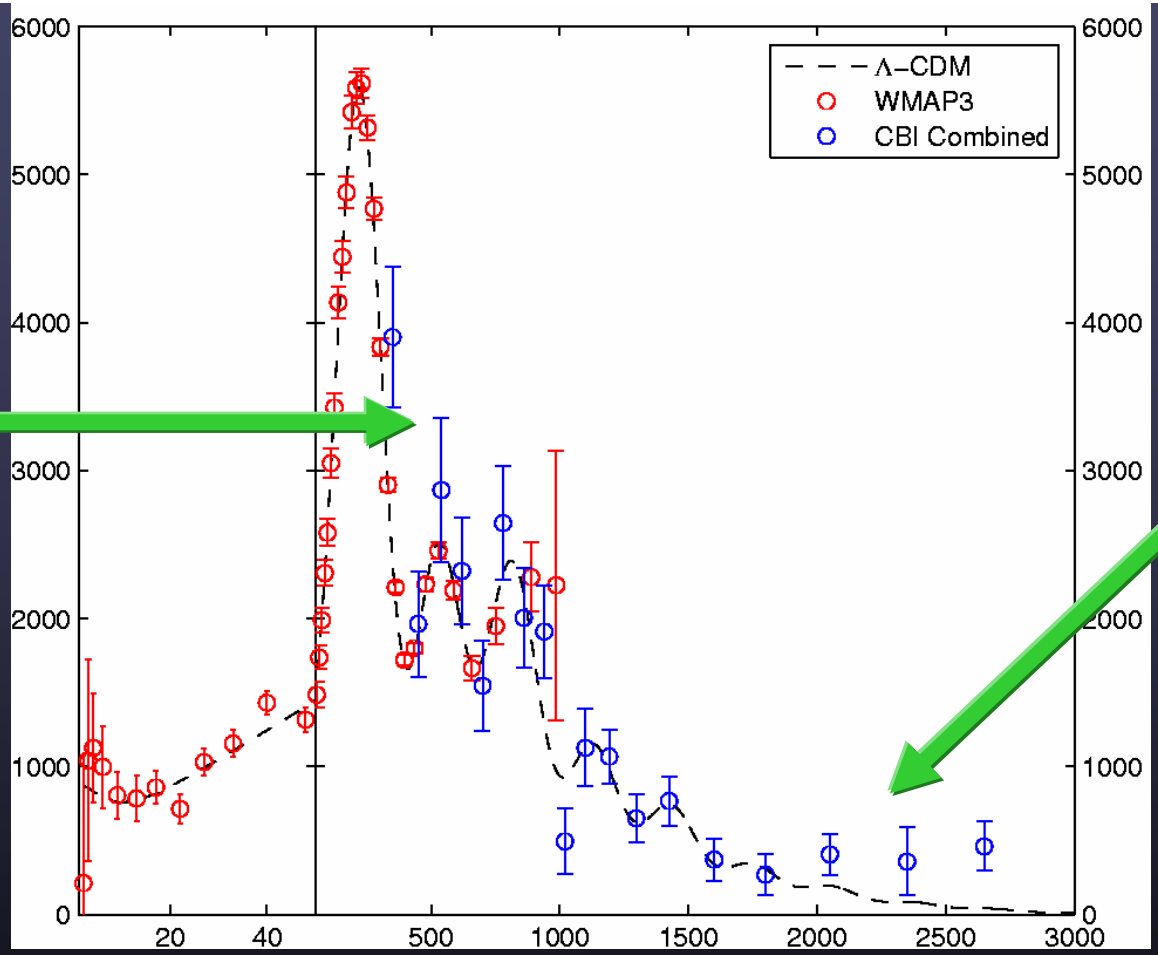
CBI & DASI Fields

galactic projection – image WMAP “synchrotron” (Bennett et al. 2003)



NEW: CBI 2000-2005 Temperature

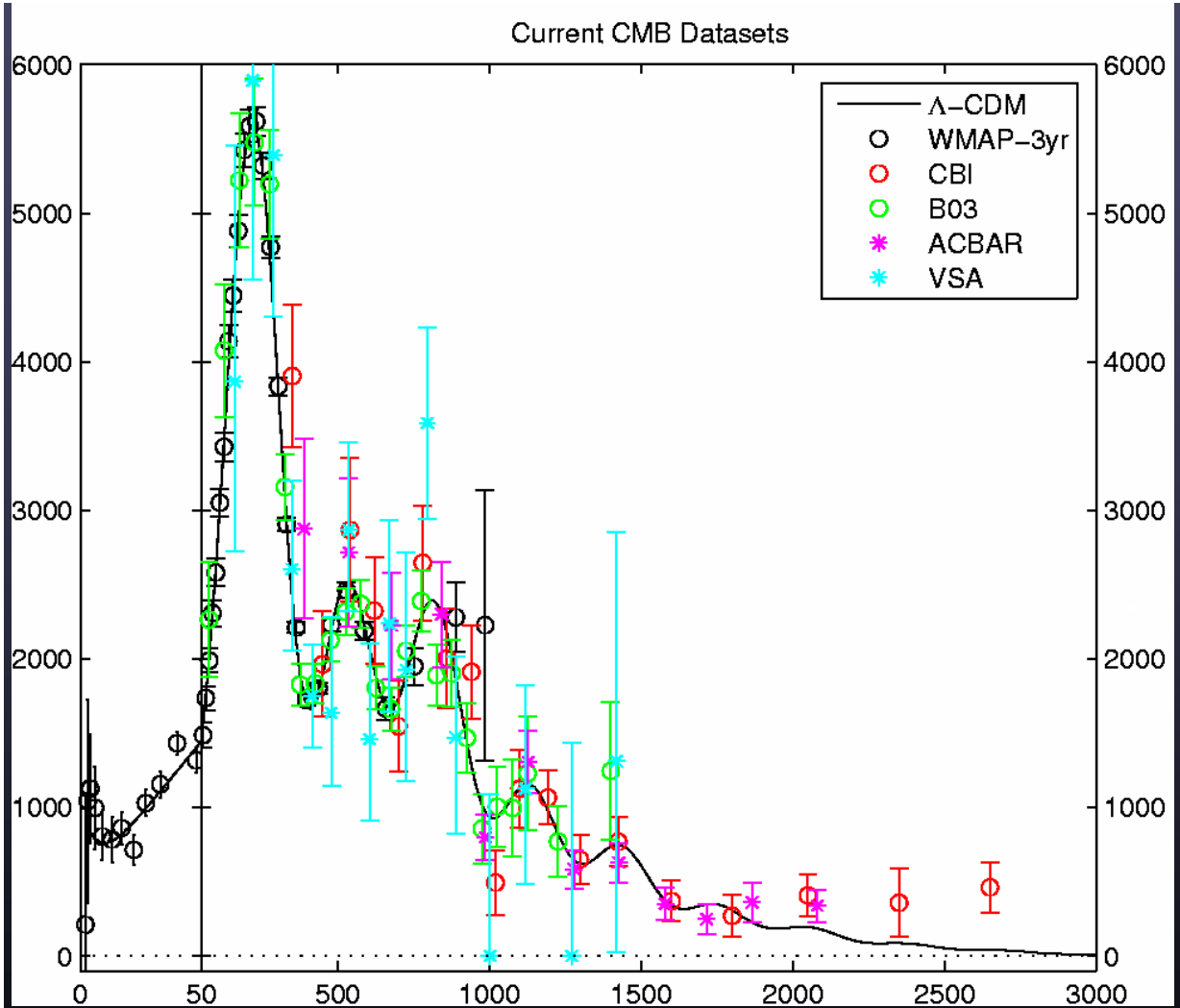
CBI shortest baseline:
B~88λ
(at 26.5GHz)
ℓ=2πB/λ
=555



High-ℓ excess
ℓ=2πB/λ>2000
B~300λ
~3σ over CMB

- Combined 2000-2001 and 2002-2005 data (NEW=unpublished!)
- matches WMAP3 at 2nd and 3rd peaks
- 5th acoustic peak (barely) visible, plus excess!

NEW: CBI 2000-2005 Temperature



Including new Boomerang (B03), plus VSA and ACBAR

CBI has measured CMB power spectrum to high ℓ

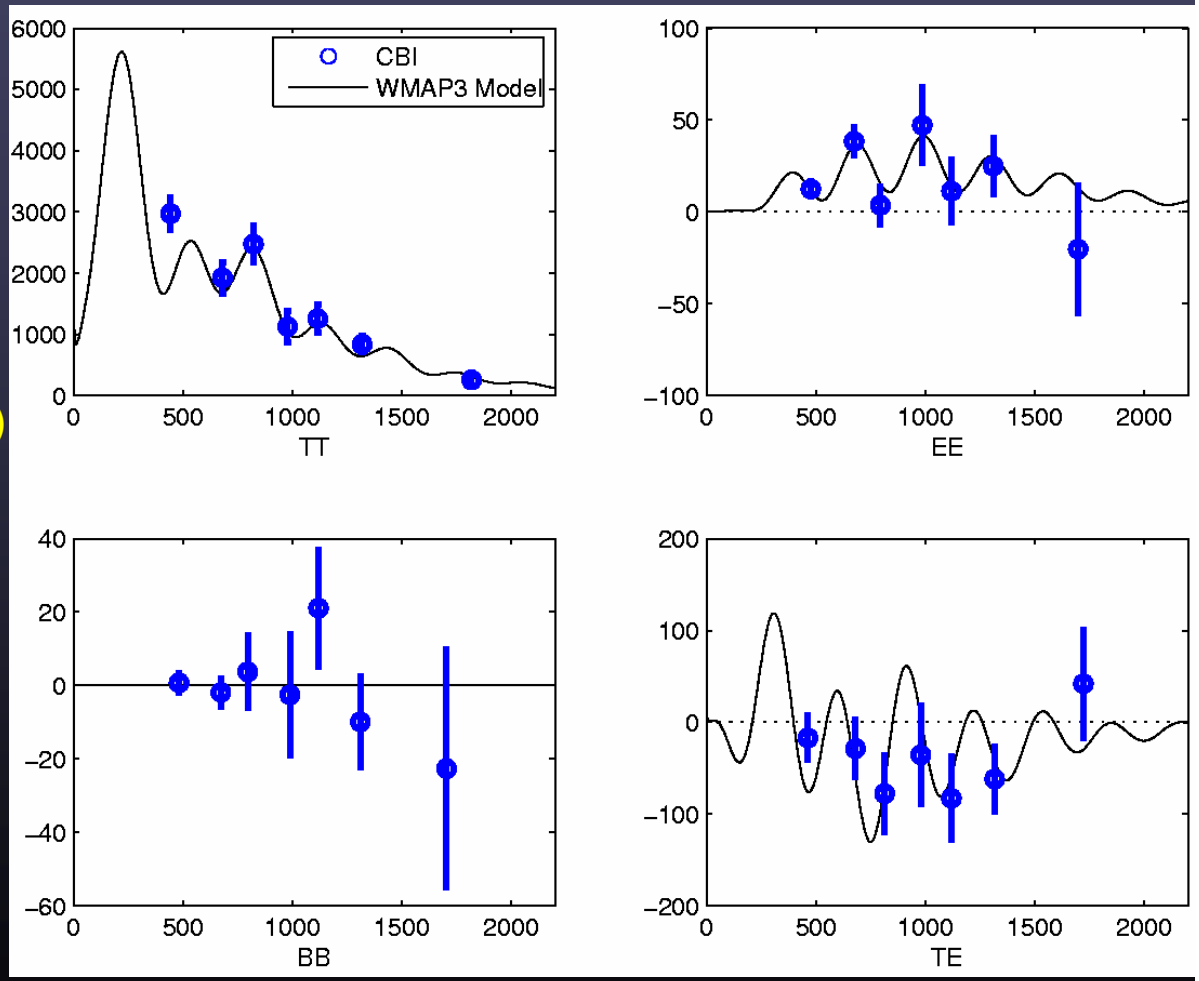
- past 6th peak
- well into damping tail
- consistent with Standard or Concordance Models
- agreement with WMAP3, ACBAR, Boomerang, DASI, VSA and Maxima at ℓ < 1000 is excellent

At 2000 < l <3500, CBI finds power ~ 3 sigma above the standard models

- Not consistent with any likely model of discrete source contamination
- Suggestive of secondary anisotropies, especially the SZ effect

CBI Polarization Power Spectra

- First reported in Paper 8: Readhead et al. 2004b, Science 306,836;
  - updated in Paper 9: Sievers et al. 2007 (ApJ, **660**, 976)
- All CBI Polarization data
  - 2002-2005
  - fixes bug that left 1st antenna (Rx0) out of Readhead et al. 2004b and Sievers et al. 2005! 18% more data! (no bias)
- Significances (shaped vs. zero, from likelihoods)
  - EE 12.0σ
  - TE 4.25σ
- Chi-squared χ^2 (~7 d.o.f.)
  - EE = 1.93 (vs. model)
  - BB = 2.5 (vs. zero)



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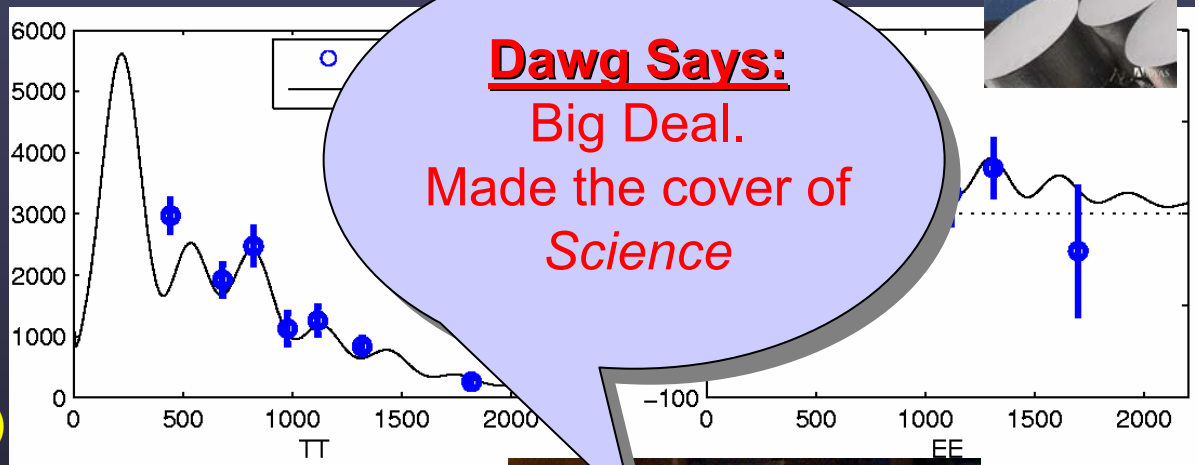
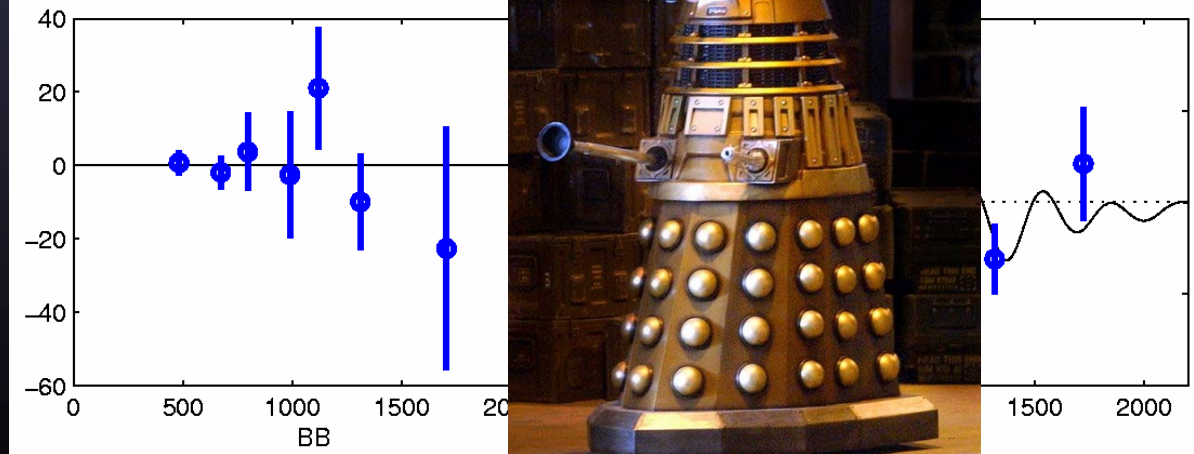
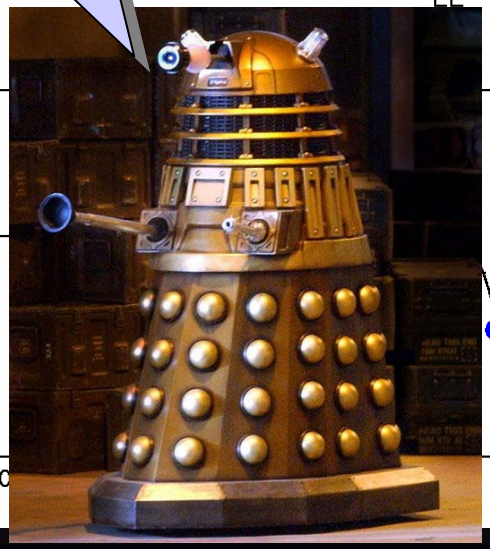


Dawg Says:
Big Deal.
Made the cover of
Science





NEW: EE detected at 12σ

- 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
  - fixes bug that left 1st antenna (Rx0) out of Readhead et al. 2004b and Sievers et al. 2005! 18% more data! (no bias)
- Significances (shaped vs. zero, from likelihoods)
  - EE 12.0σ
  - TE 4.25σ
- Chi-squared χ^2 (~7 d.o.f.)
  - EE = 1.93 (vs. model)
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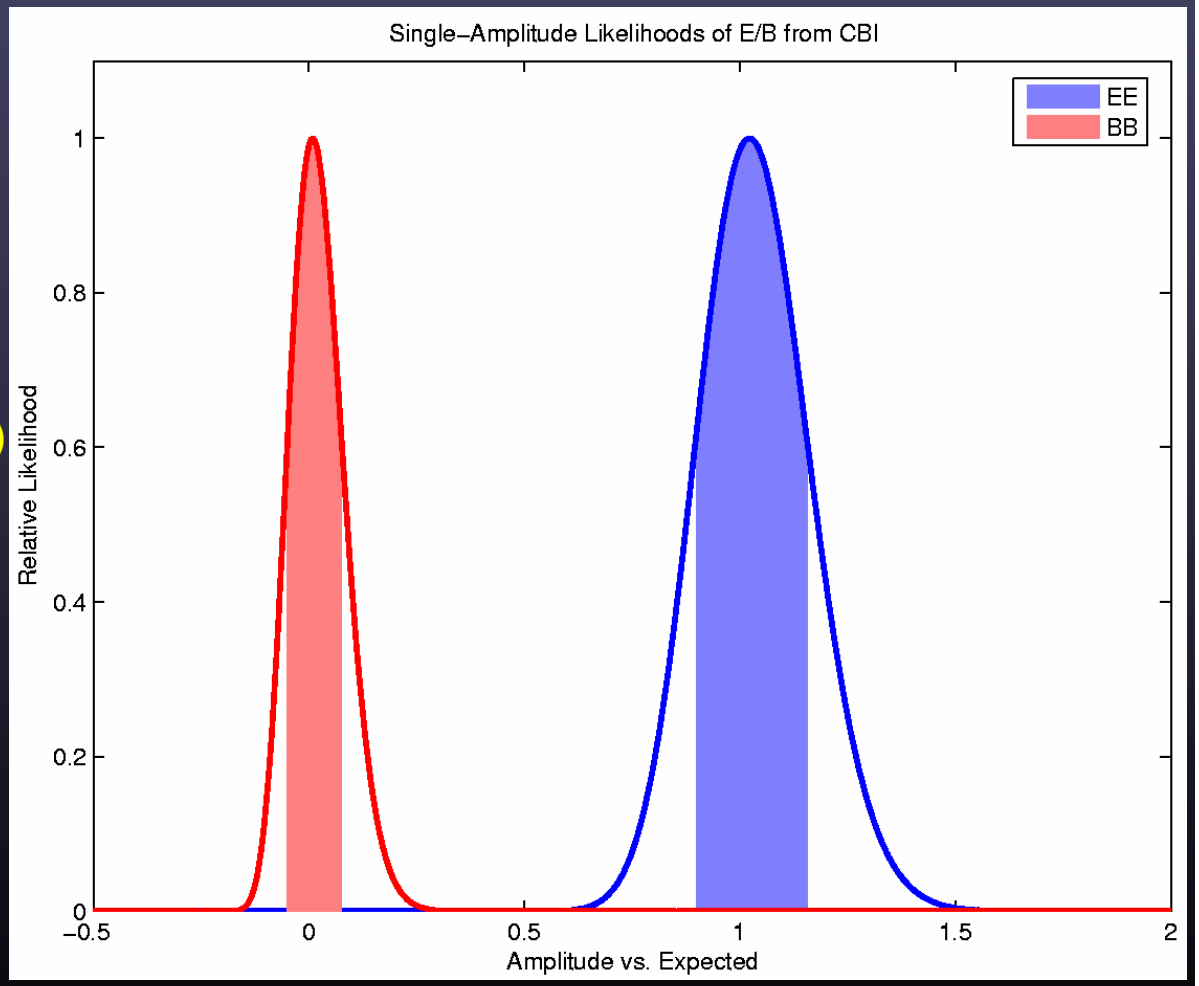
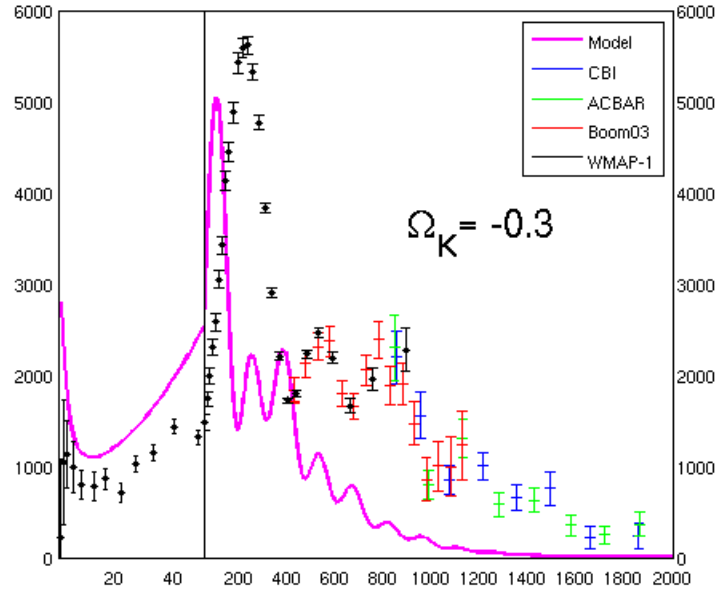


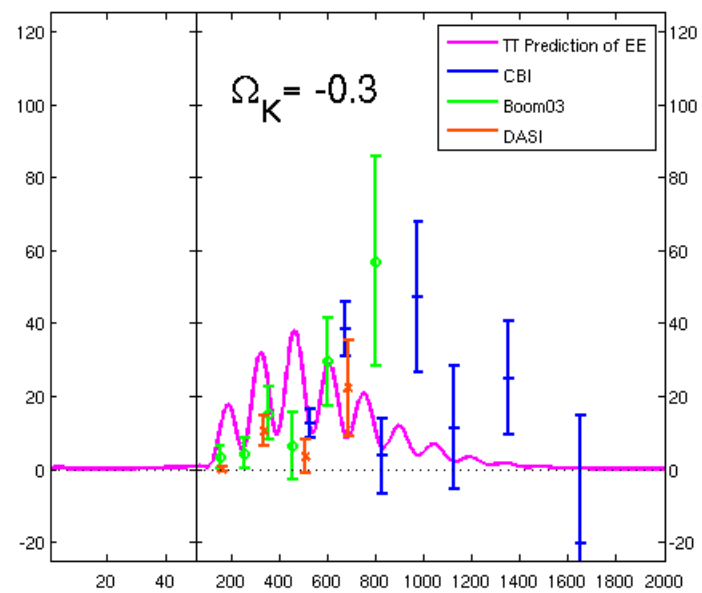
Polarization Peaks

- Predictable from TT oscillations
  - from velocity, EE 90° out-of-phase vs. TT [sin(ks) vs. cos(ks)]
- Primarily controlled by curvature
  - comoving distance to recombination
  - WMAP TT spectrum consistent with flat Universe (k=0)
  - check whether EE pattern is at predicted position

<u>EE spectrum shifted as expected</u>

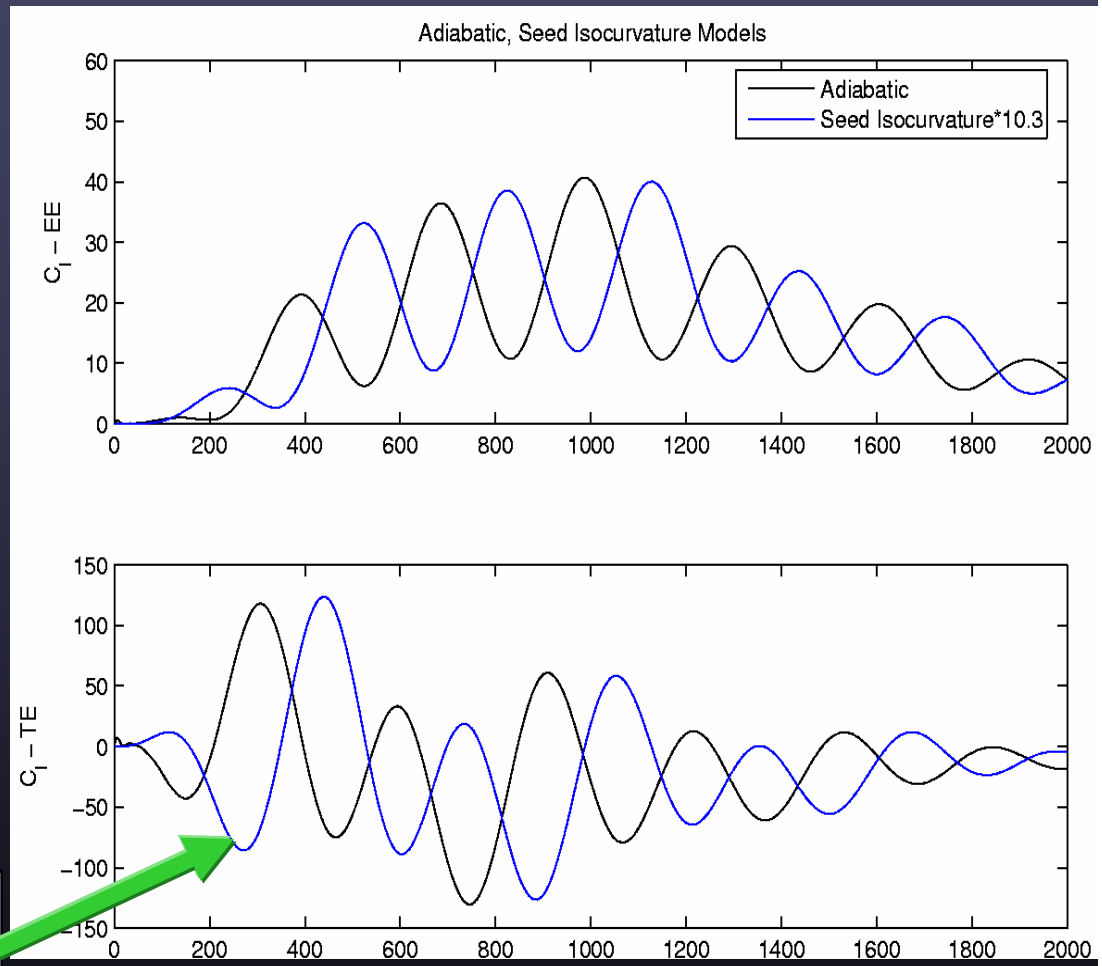
TT and EE match at same Ω_k





Isocurvature fluctuations?

- 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, no curvature fluctuations, acoustic peaks not shifted



isocurvature mode:
polarization peaks aligned w/TT

Constraining Isocurvature Modes

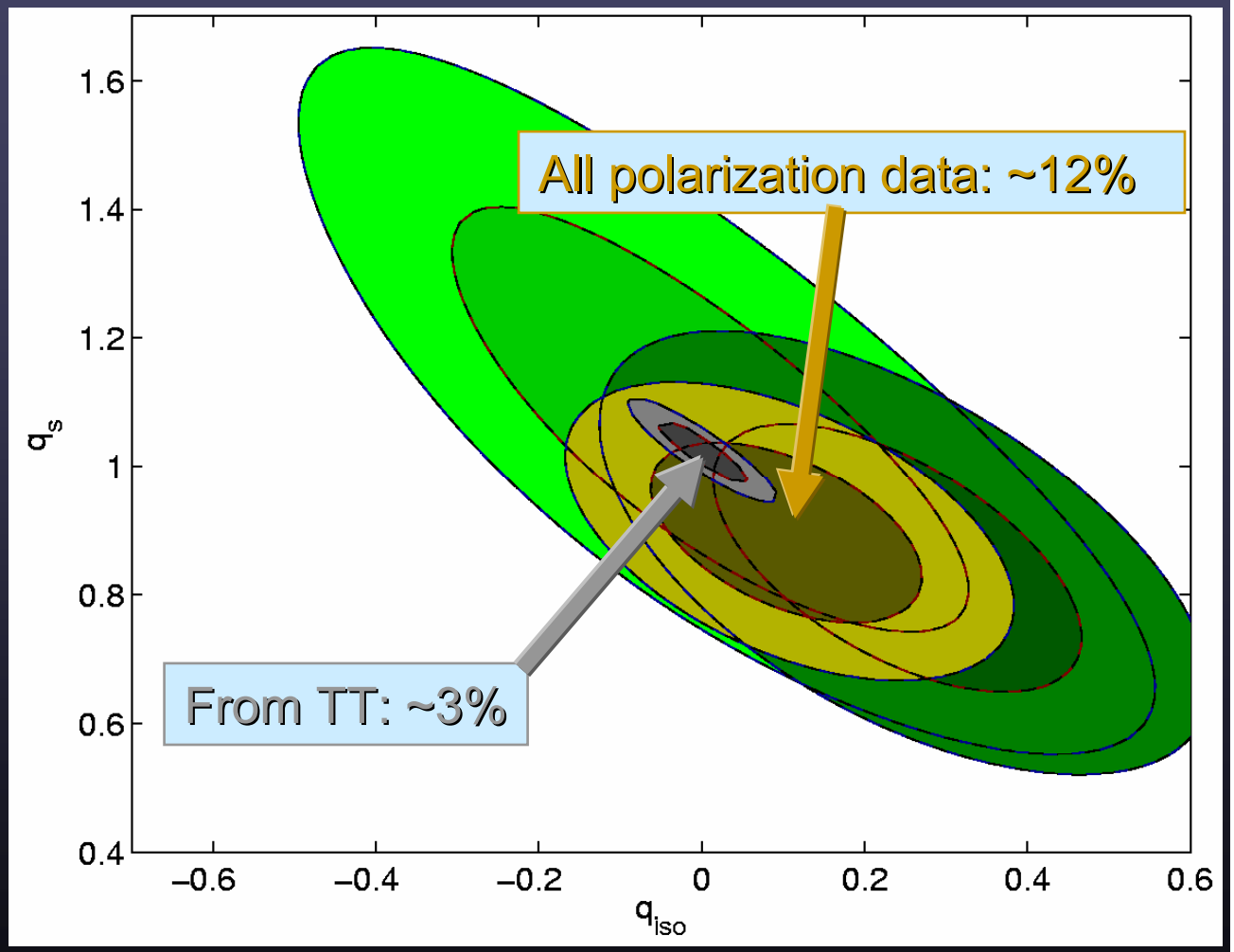
CBI Pol – green

All Pol – brown

CBI+B03 - grey

Note – strongest constraints from TT

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



E & B Mode Images

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

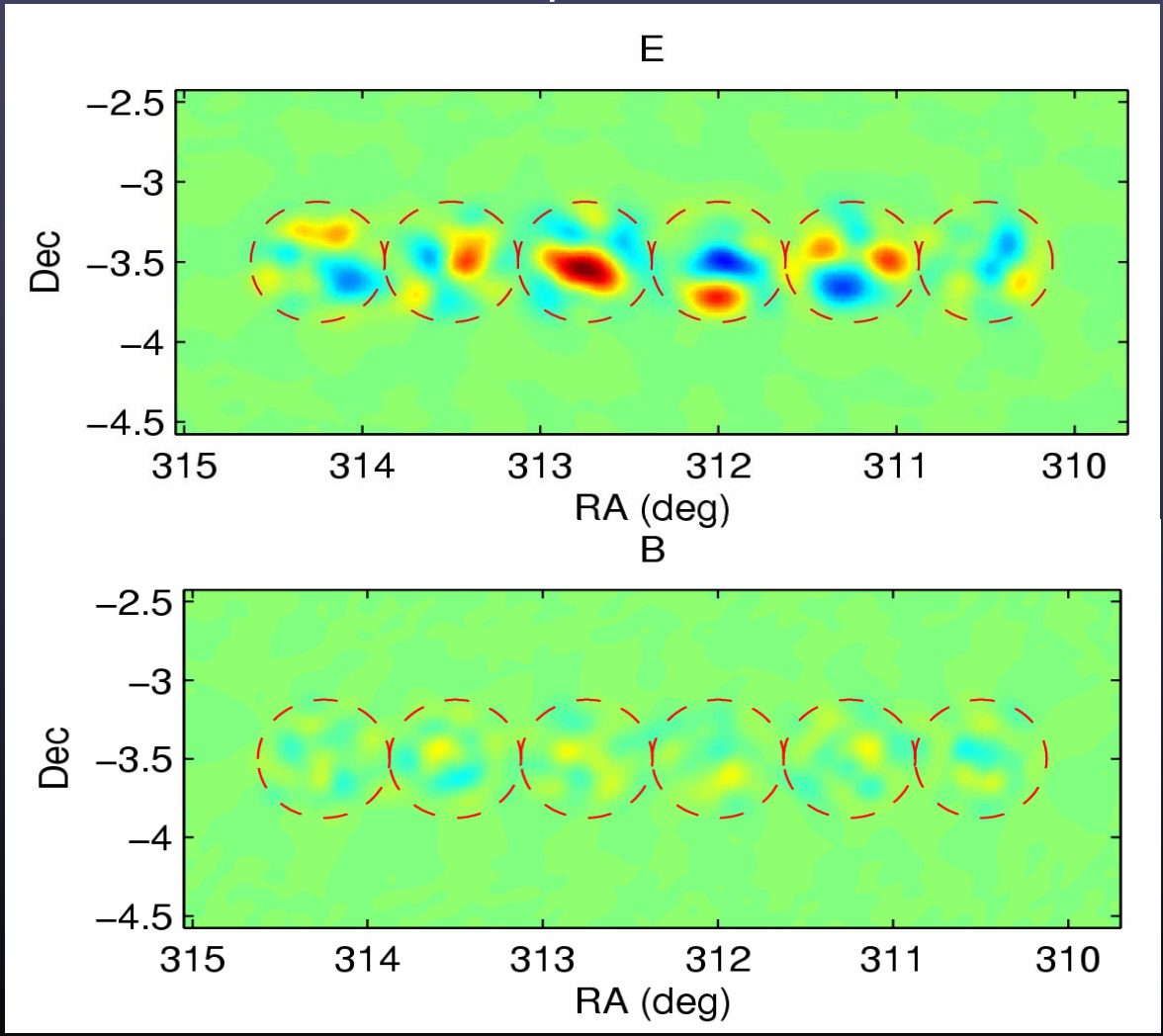
Variance of E in raw data 2.45 times B (ℓ<1000). B is consistent with noise.

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

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

Sievers et al. 2007

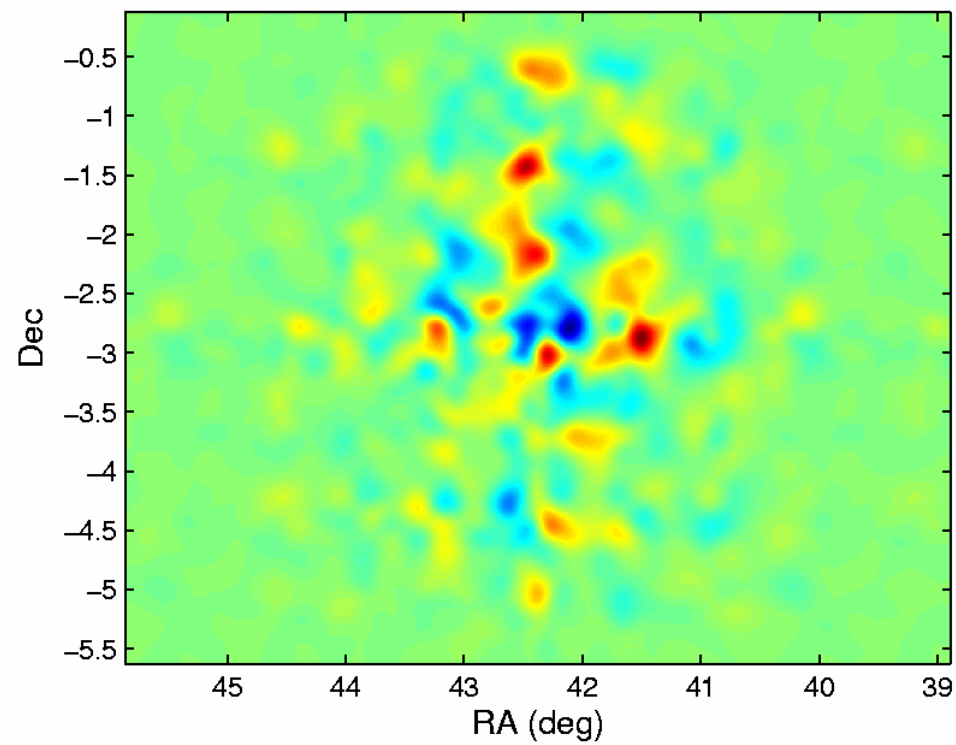
CBI 20h strip: gridded FT($E + i\,B$) transformed to

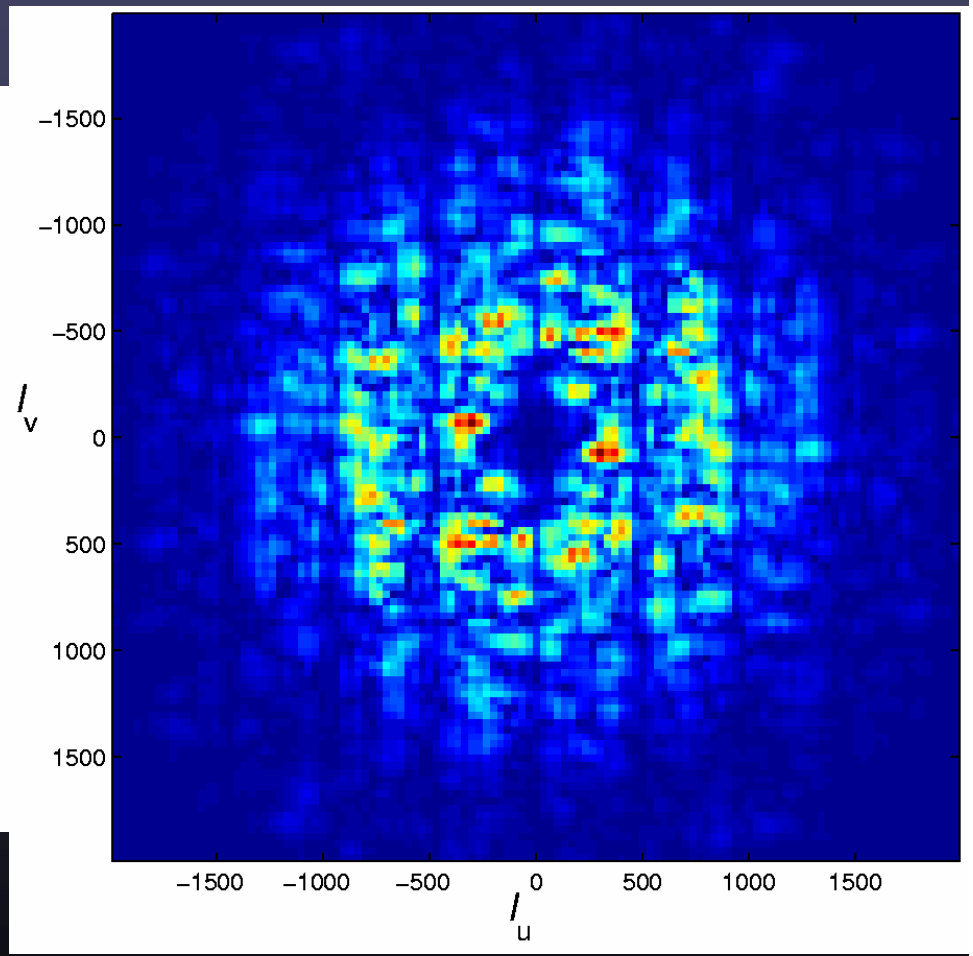


ℓ-space maps

- 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

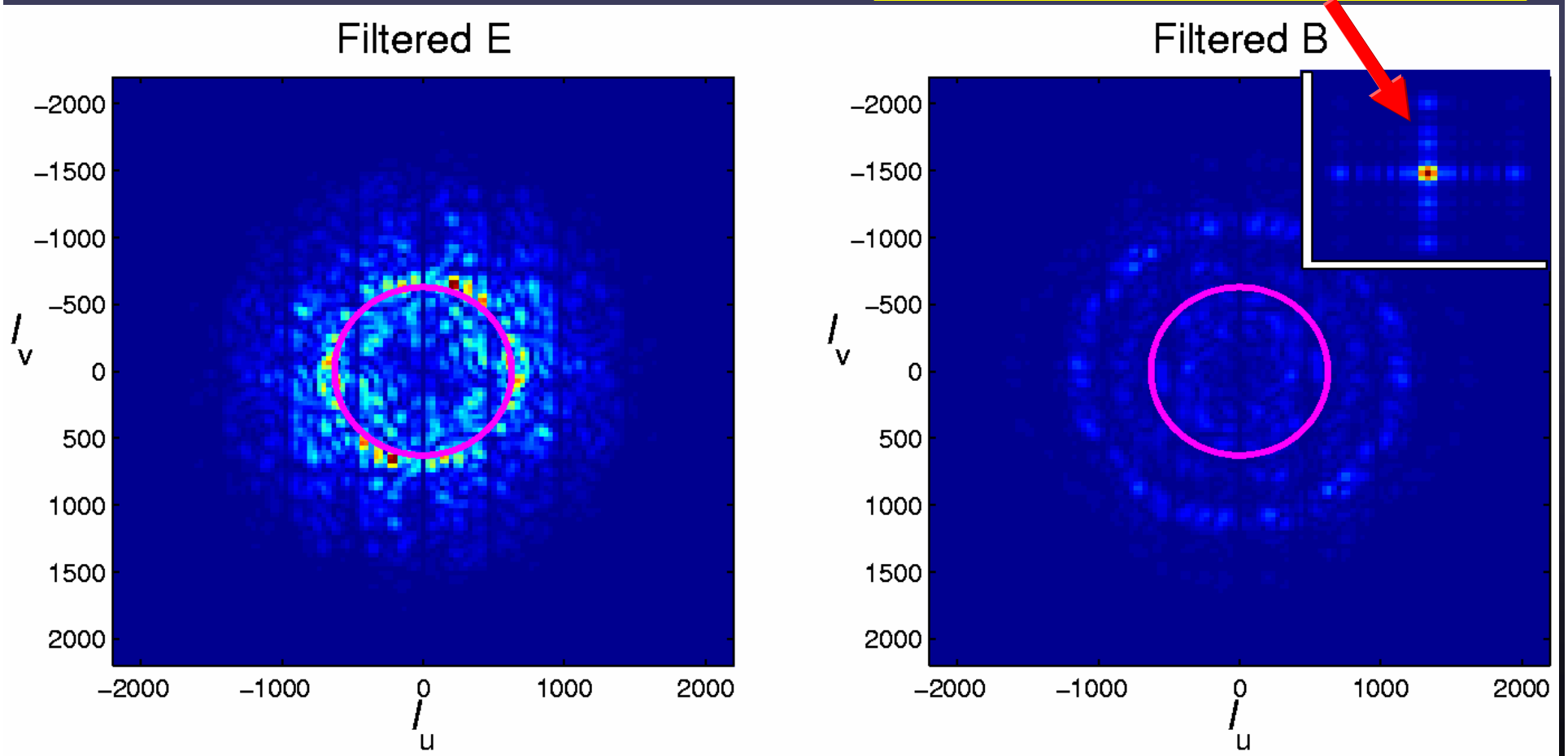
ℓ -space CLEAN deconvolved!

ℓ-space maps

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

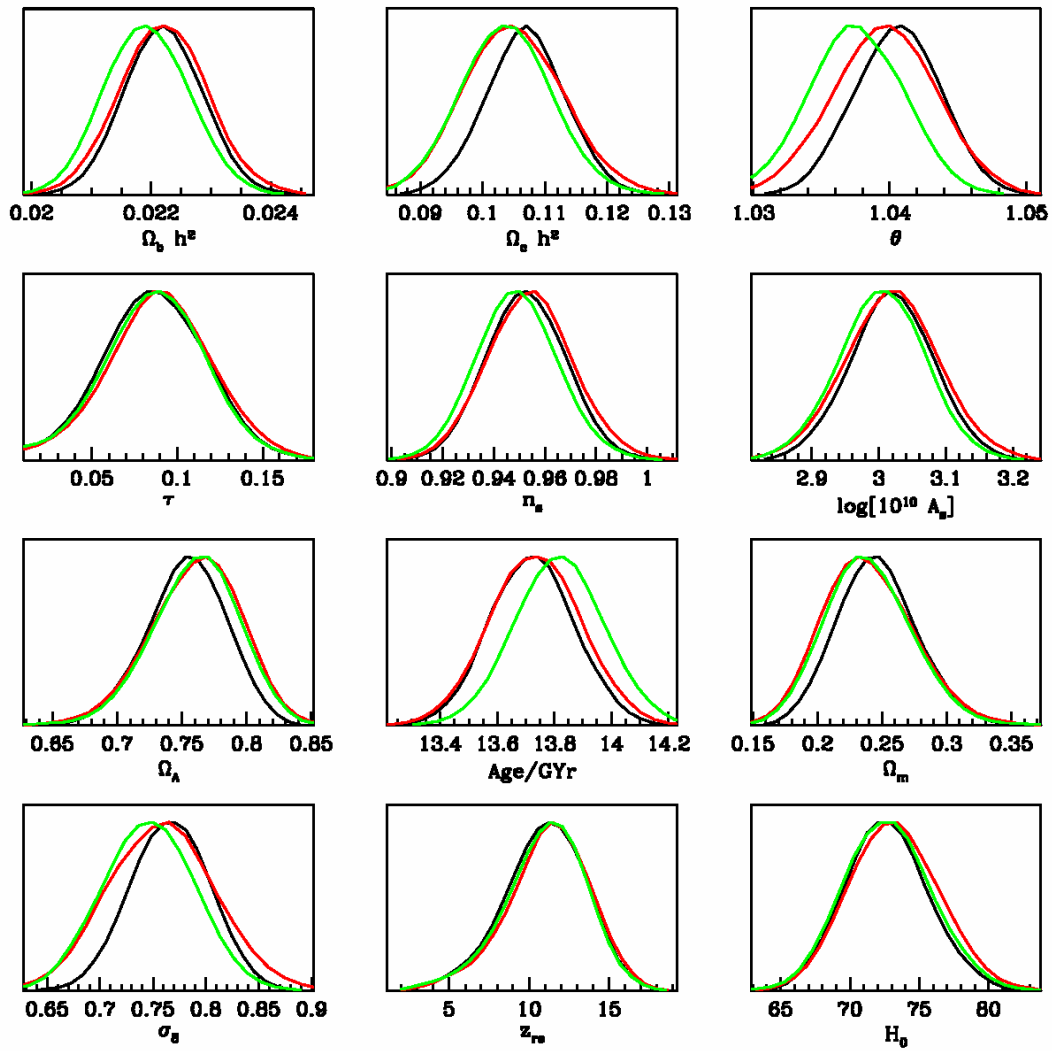
linear Wiener filtered reconstruction

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



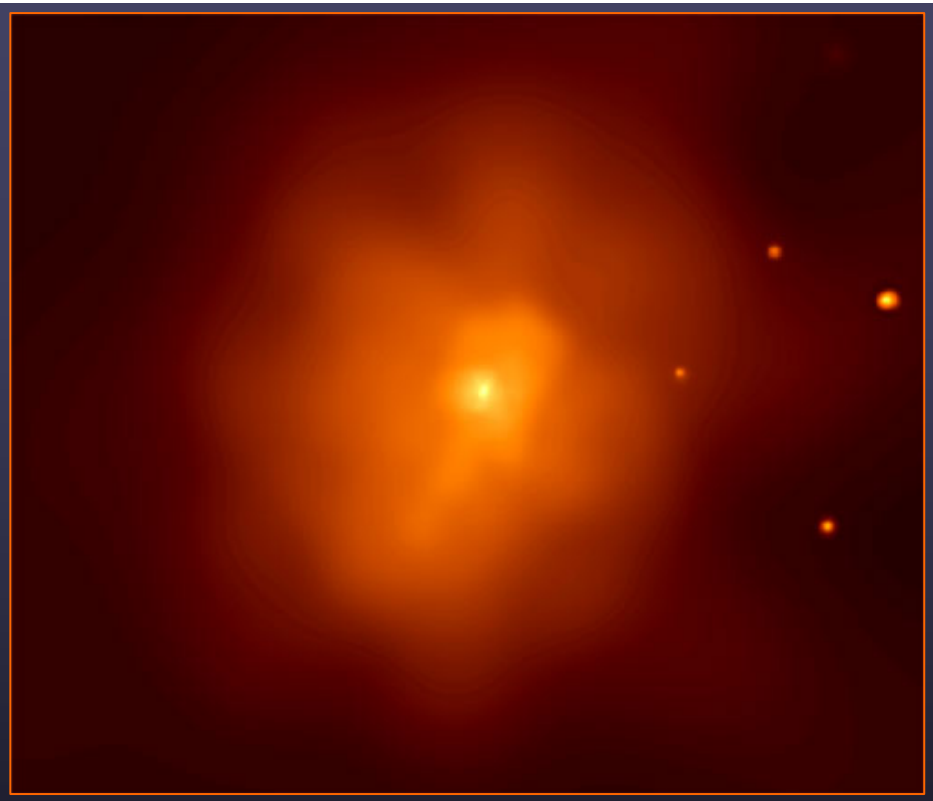
NEW: CBI01-05 + all parameters

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



Galaxy Clusters

HST optical image



Chandra x-ray observations

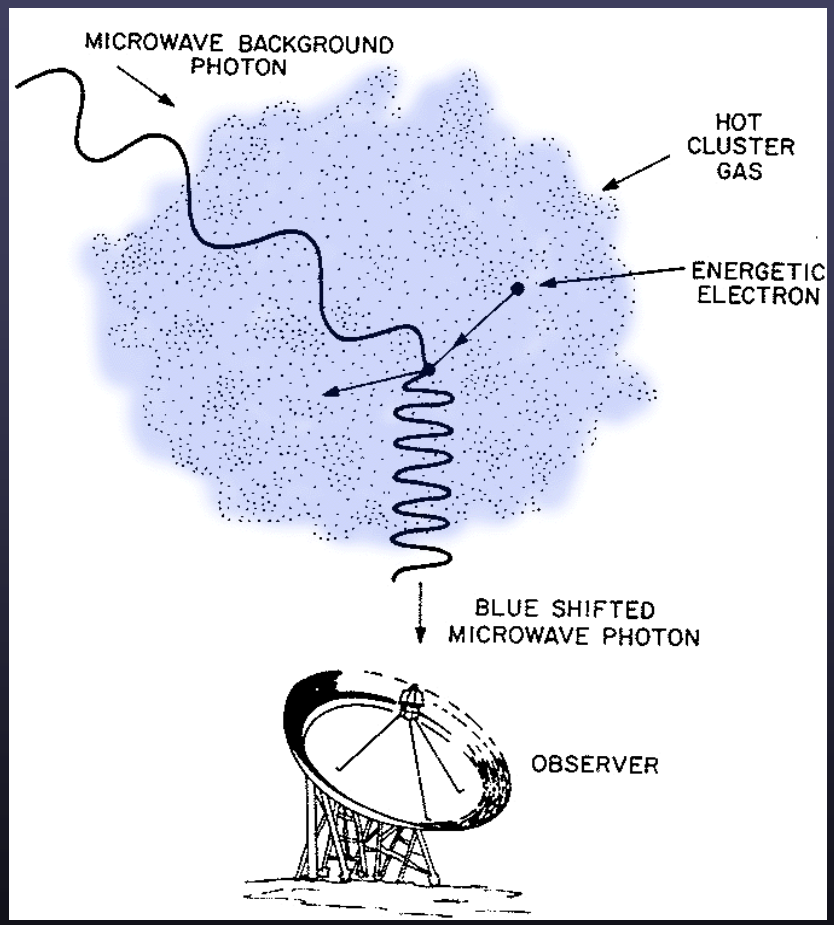
<u>The largest "objects" in the universe</u>

- their growth through cosmic time is sensitive to the evolution of Dark Energy/Matter
- consist mainly of dark matter and ionized gas (with a touch of galaxies)

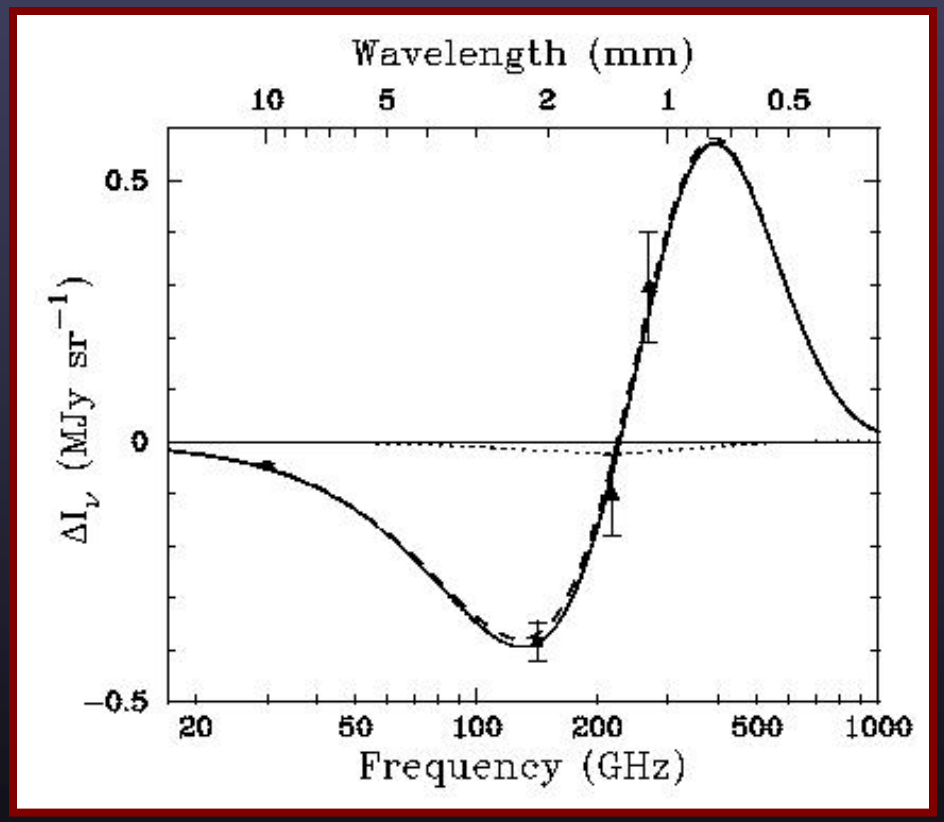
This slide stolen from J.Carlstrom – so sue me!

CMB & Galaxy Clusters

The Sunyaev-Zel'dovich Effect



Sunyaev & Zel'dovich 1970, 1972

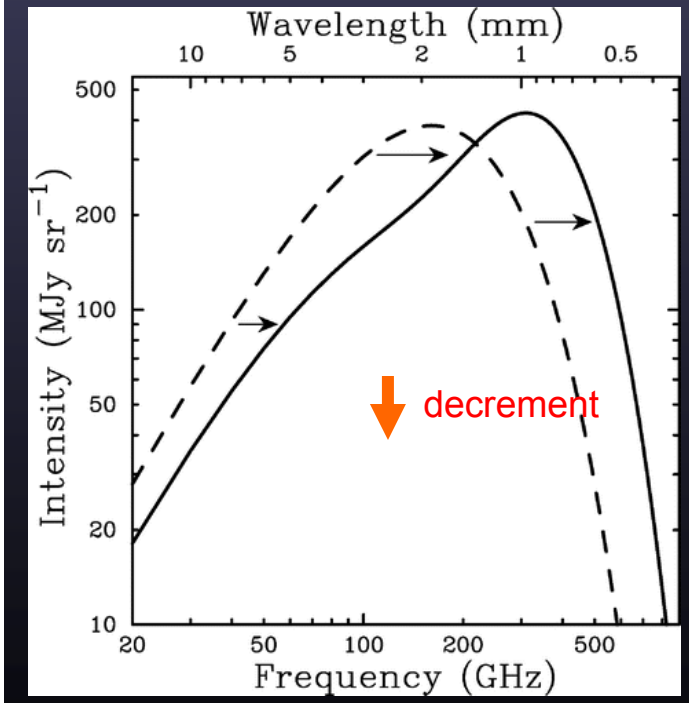


Adapted from L. Van Speybroeck

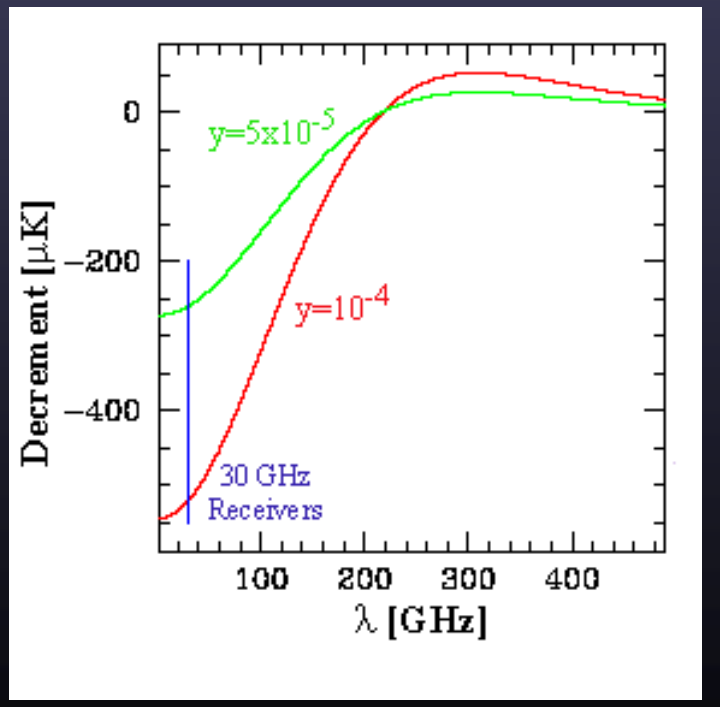
This slide stolen from J.Carlstrom – so sue me!

The SZE

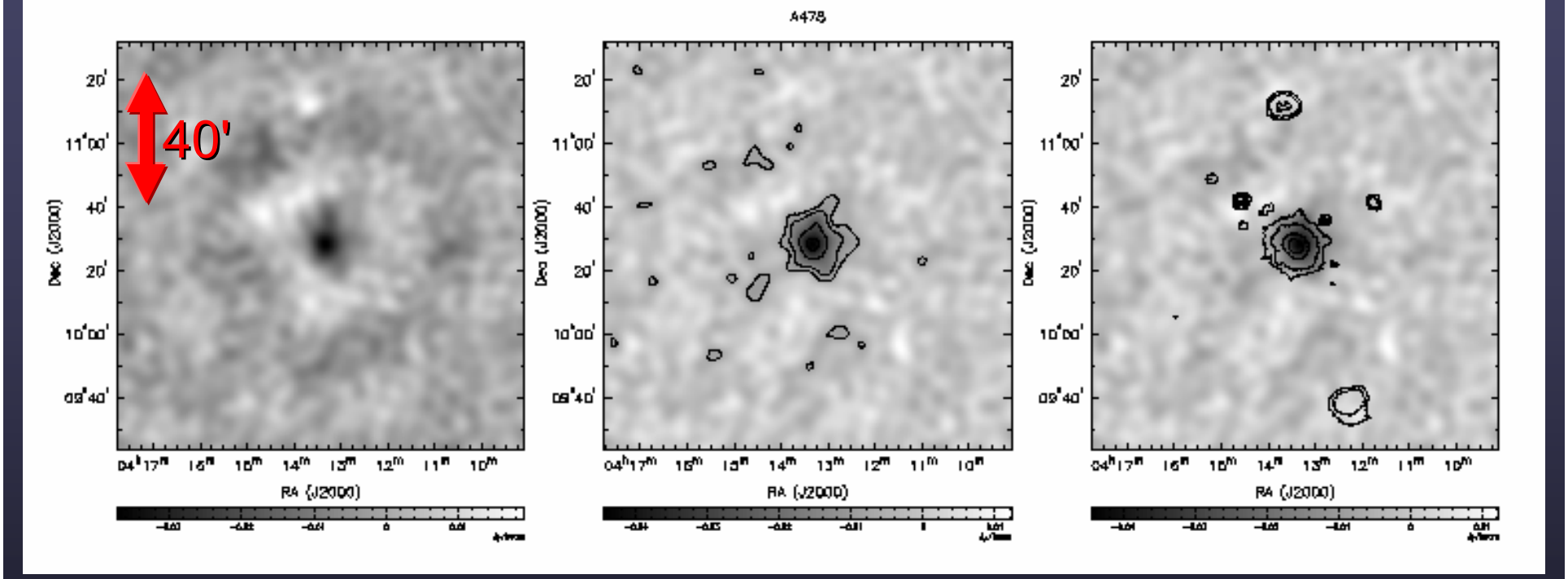
- The Sunyaev-Zeldovich Effect
  - Compton upscattering of CMB photons by keV electrons
  - decrement in I below CMB thermal peak (increment above)
  - negative extended sources (absorption against 3K CMB)
  - massive clusters mK, but shallow profile $\theta^{-1} \rightarrow -\exp(-v)$



$$\frac{\Delta T_{SZE}}{T_{CMB}} \propto \int n_e T_e dl$$



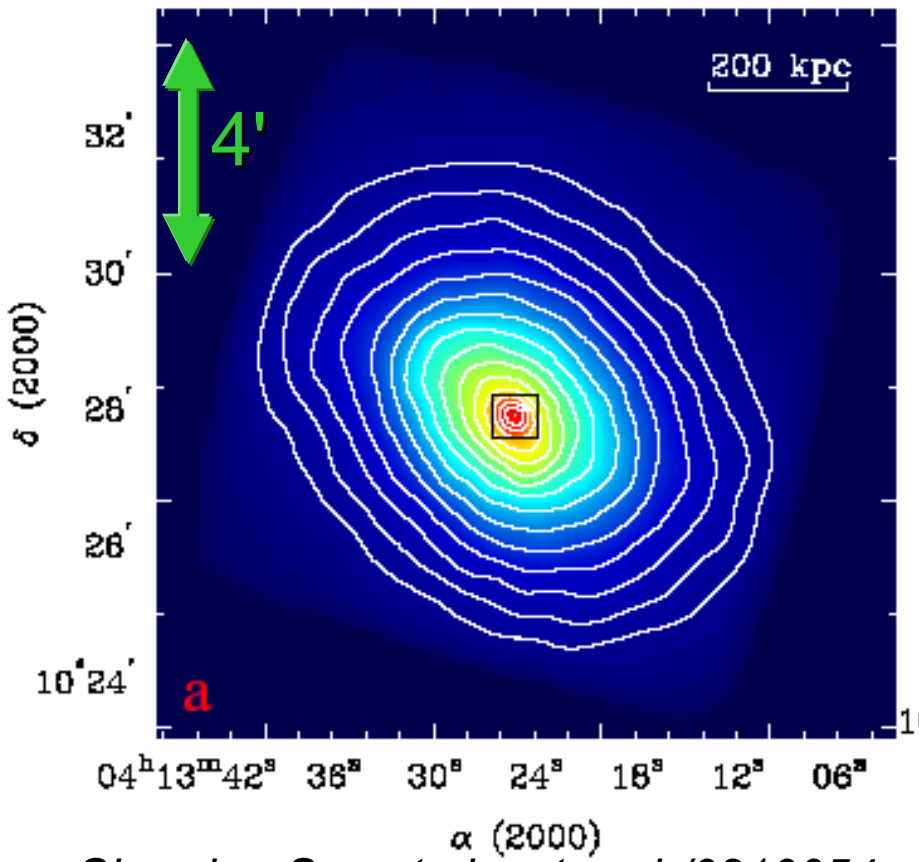
A478 – CBI SZE + ROSAT

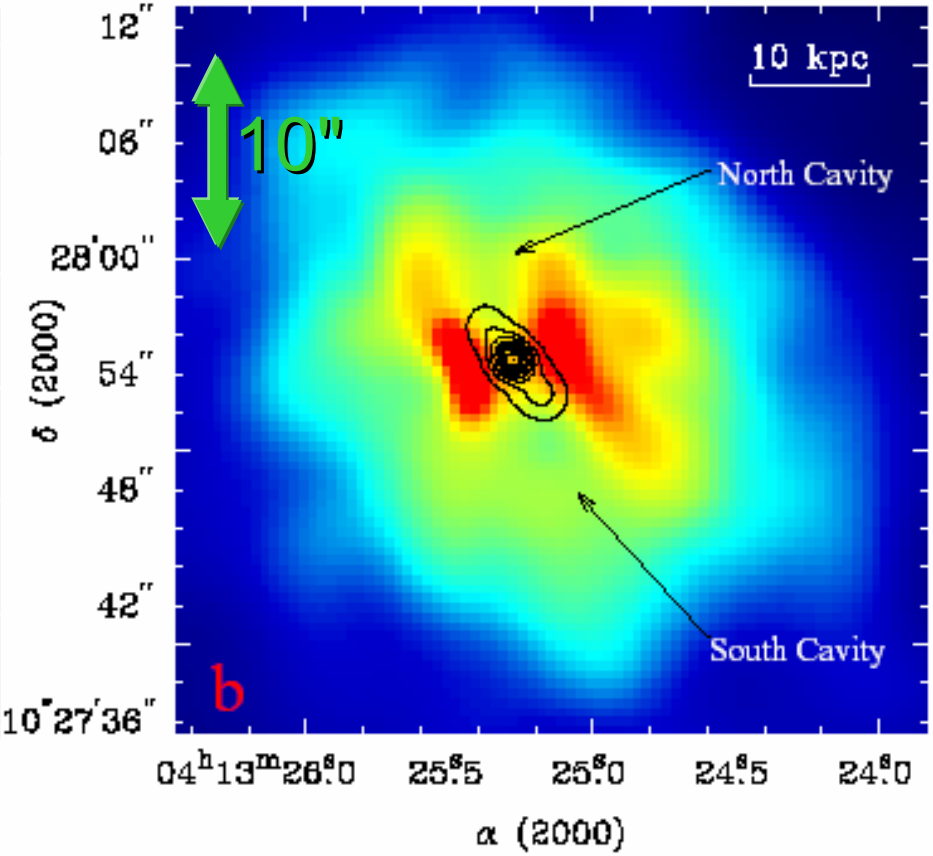


(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

- A478 – relaxed cooling flow cluster, X-ray cavities from AGN SZE measures IGM pressure → baryon surface density × kT

A478 – Chandra + VLA 1.4GHz





Chandra: Sun et al. astro-ph/0210054 *(inner region + 1.4 GHz radio)*

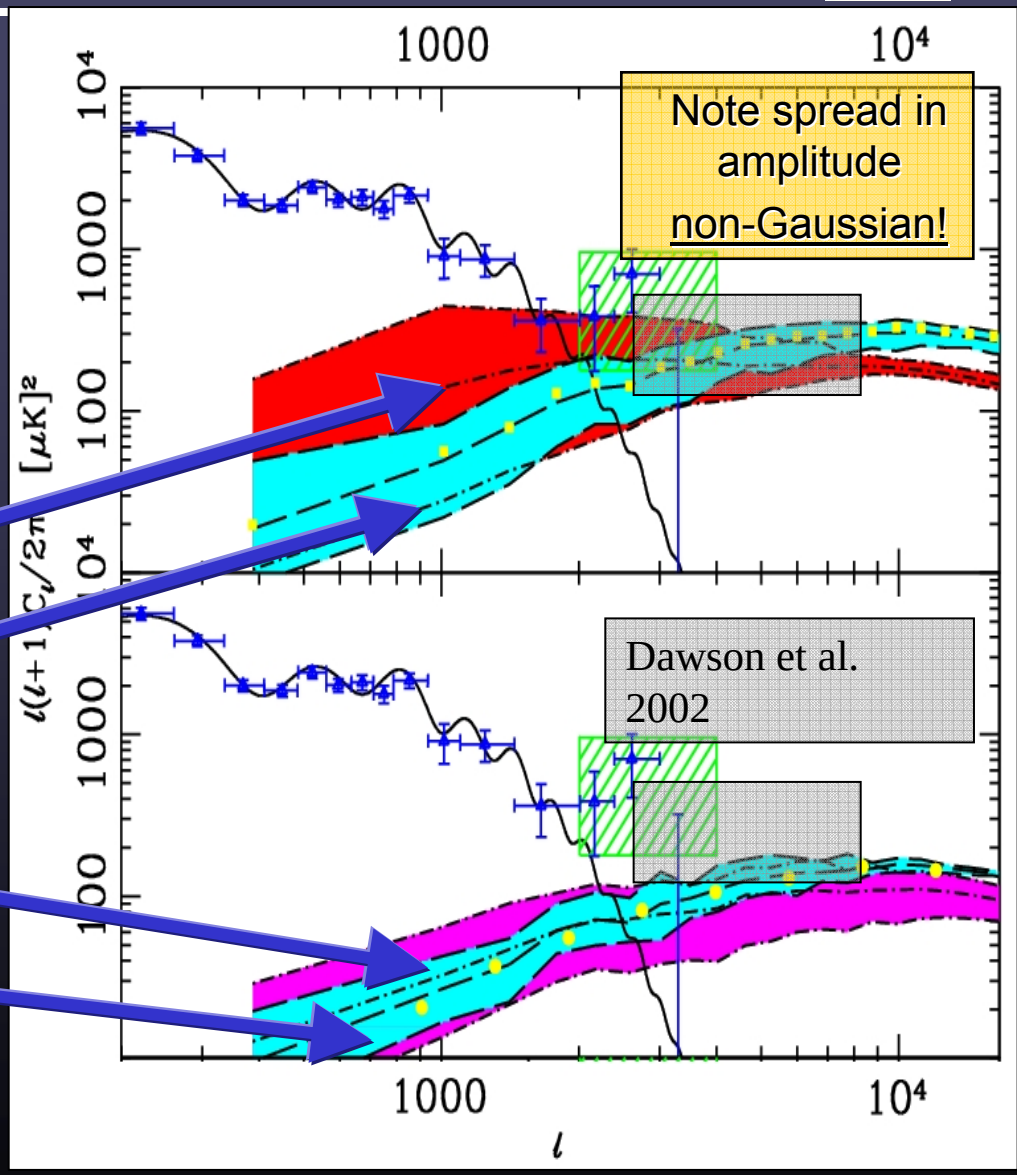
- A478 – relaxed cooling flow cluster, X-ray cavities from AGN
- Low resolution SZ measure pressure profile, look for substructure at high resolution!
- NEW: combined SZ+WeakLensing+Xray (Mahdavi et al. astro-ph/0703372)

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

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

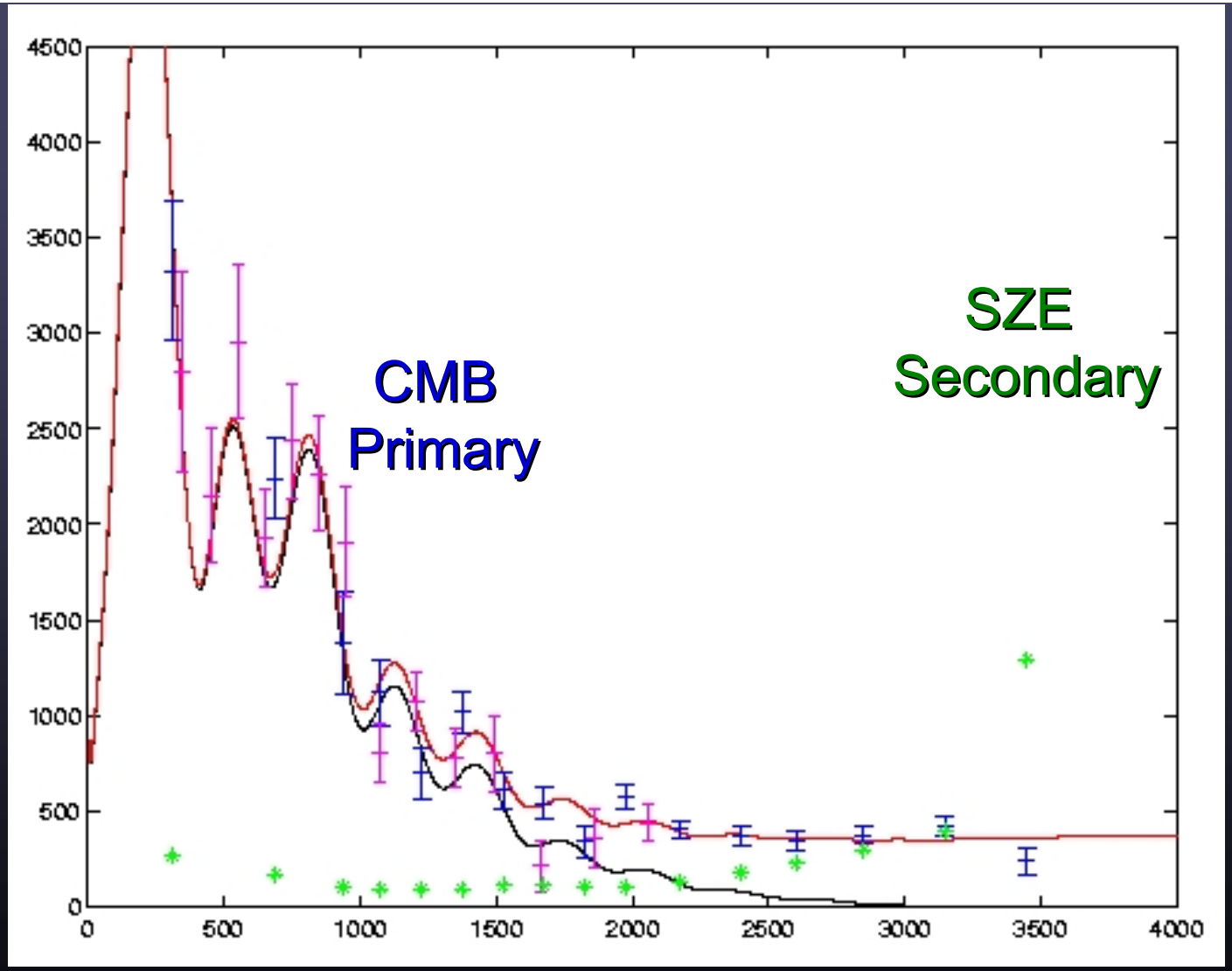


CBI2 Status – 2006 & 2007

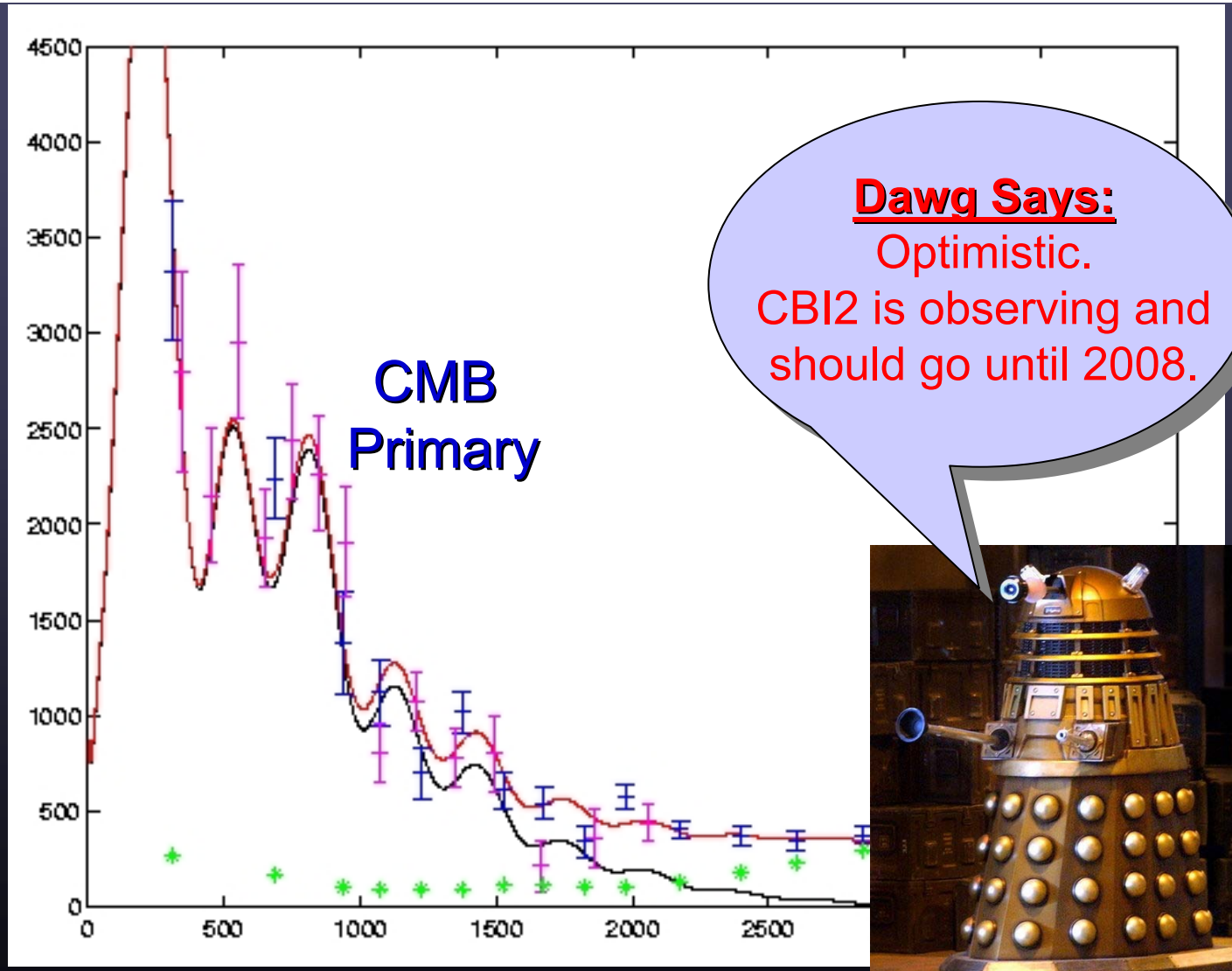
New antennas being installed

- photos: A.Taylor (Oxford)
- (below) driving up to the site
- (left) installation on the deck
- (lower right) 4 antennas in!
- (upper right) galaxy from San Pedro

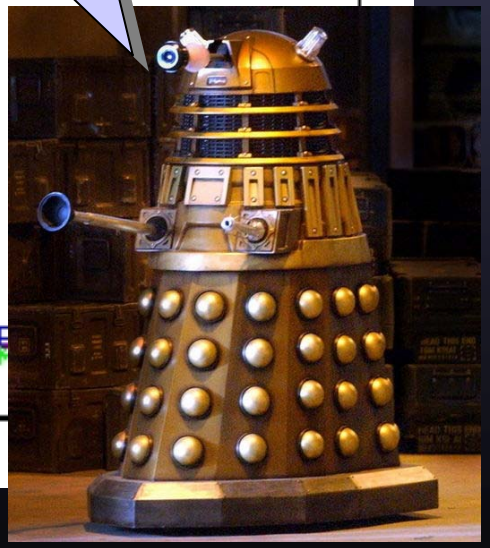
CBI2 Projection – 1 year



CBI2 Projection – 1 year



Dawg Says:
Optimistic.
CBI2 is observing and should go until 2008.



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 Polarization Checklist

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 ~ $(E_{inf}/10^{13}\ \mathrm{GeV})^4$

CMB Secondaries Checklist

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

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

CMB LSS Checklist

Structure predictions from inflation-inspired models:

- late-time non-linear structure formation (revisited)
  - gravitational lensing of CMB
  - √ – Sunyaev-Zeldovich effect from deep potential wells (clusters)
- growth of matter power spectrum
  - √ – primordial power-law above current sound horizon
  - √ – CMB acoustic peaks as baryon oscillations
- dark energy domination at late times
  - √ – correlation of galaxies with Late ISW in CMB
  - cluster counts (SZ) reflect LCDM growth and volume factors

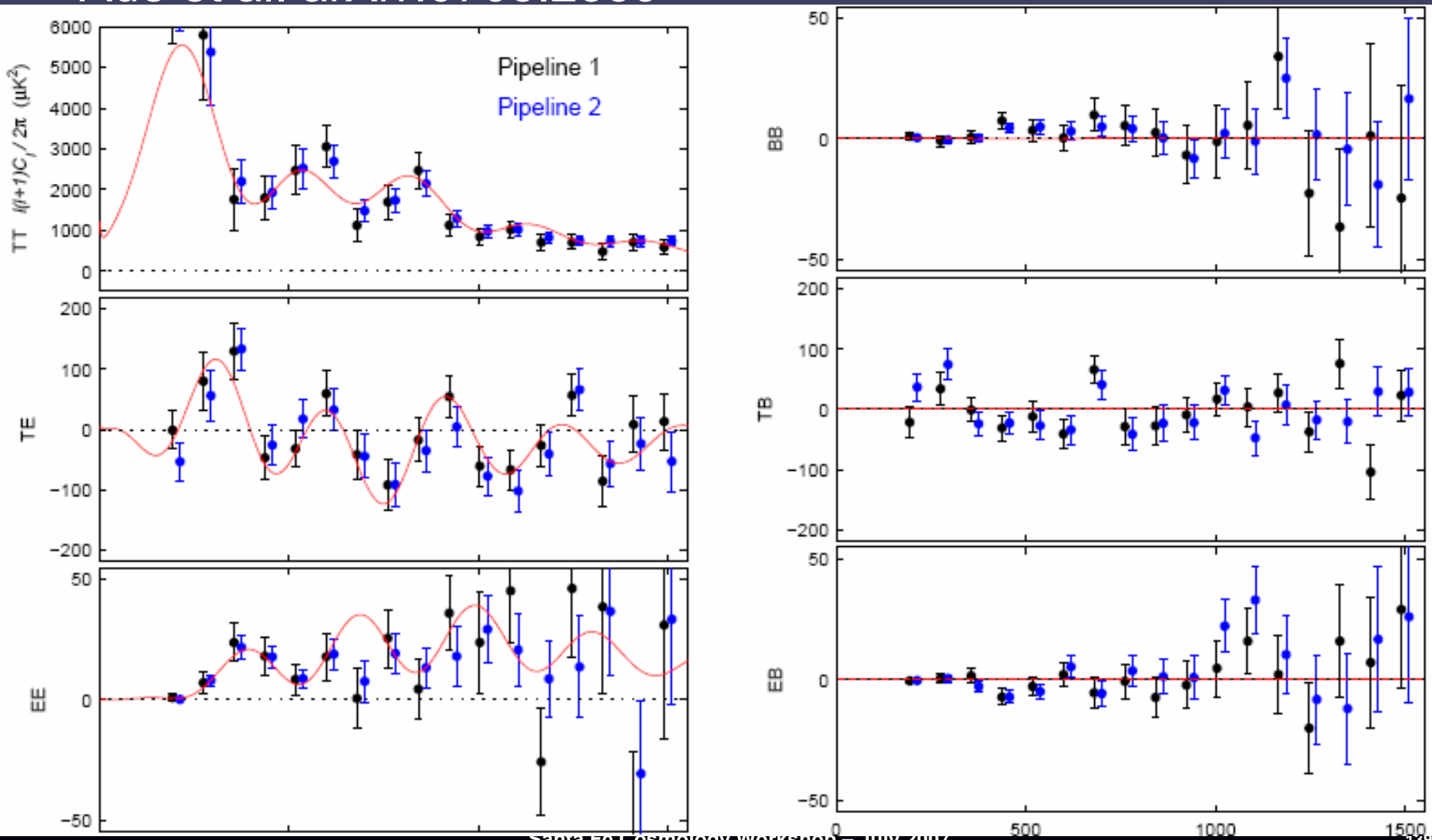
It does look like our current Universe is dominated in energy density by a Dark Energy (Lambda) component!

The Future is Now
QUaD, SZA, SPT, ACT, Mustang@GBT, ALMA

Many slides courtesy John Carlstrom

Recent Results: QUaD

- Ade et al. arXiv:0705.2359



Recent Results: QUaD

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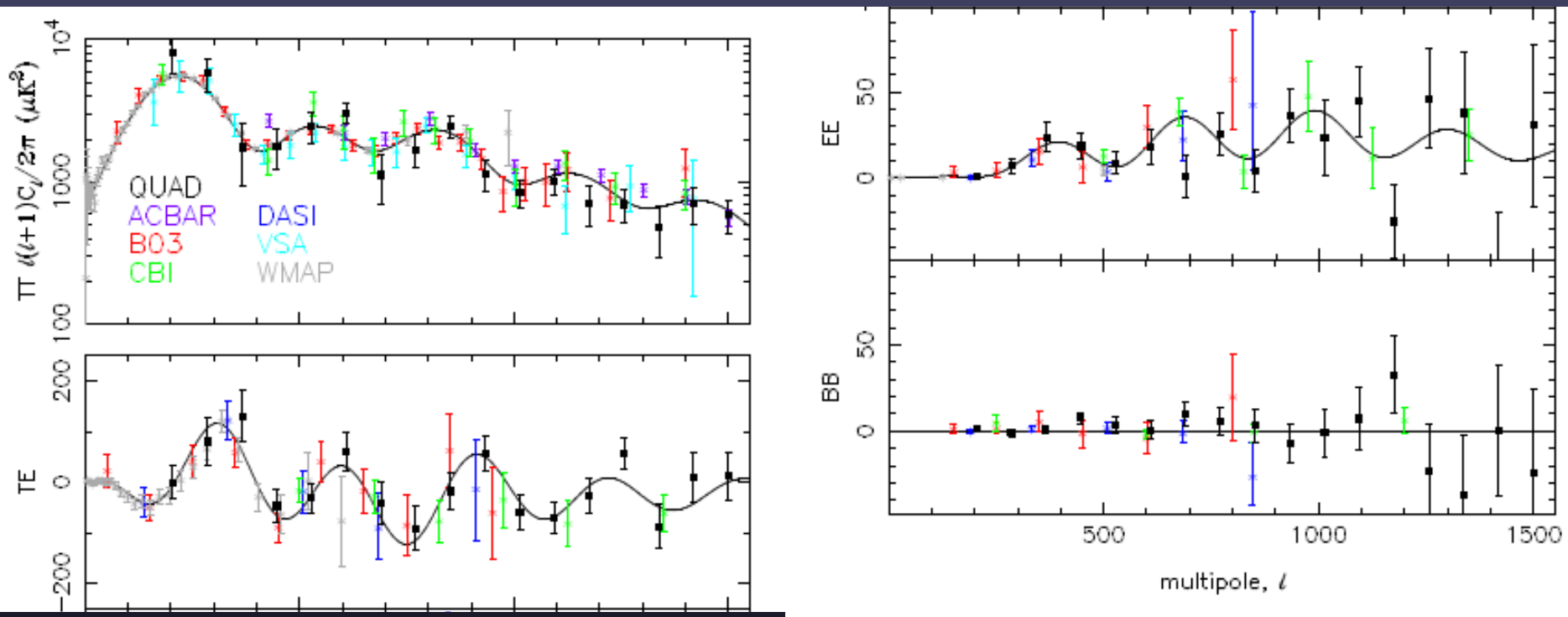
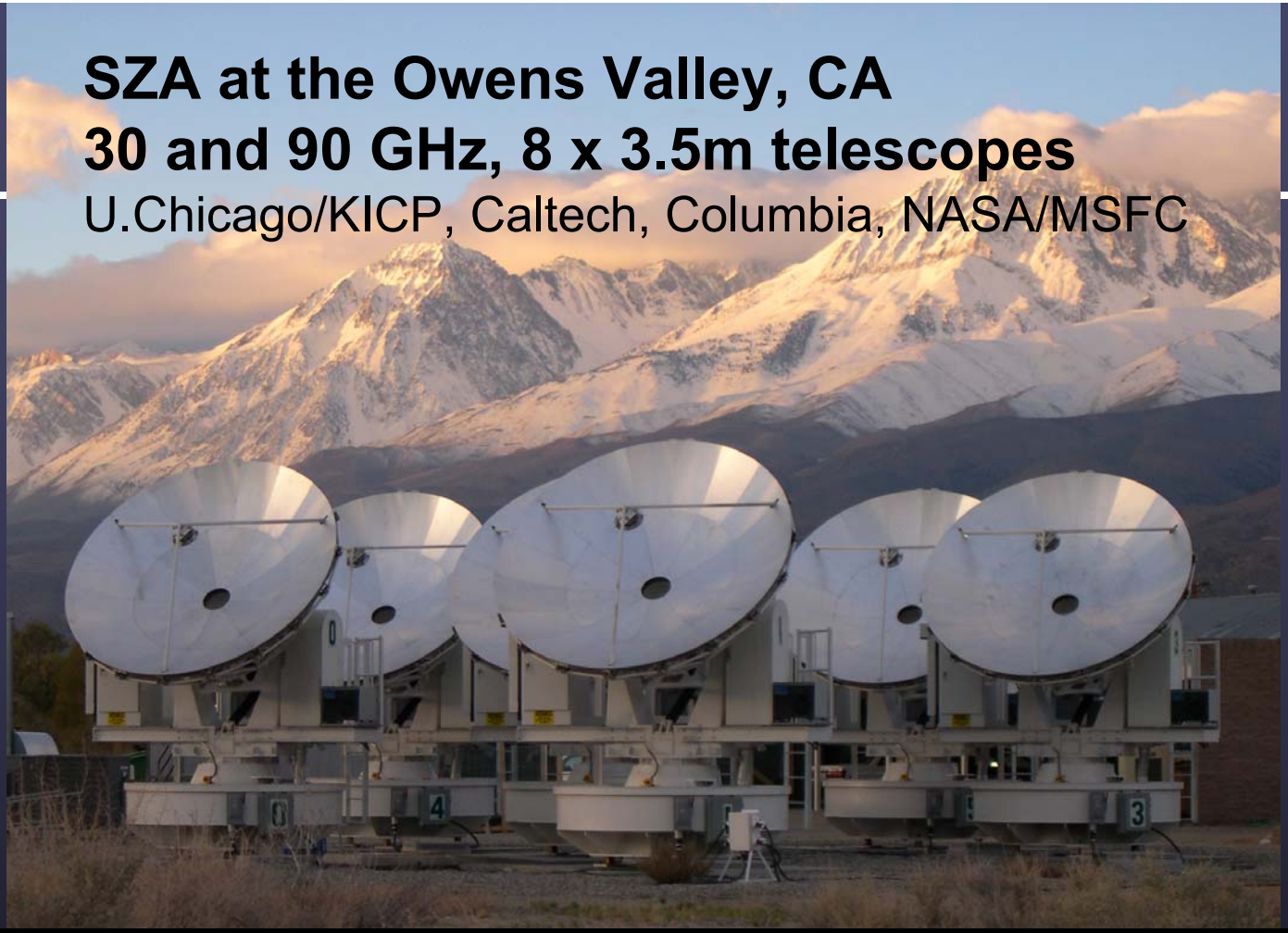


FIG. 3.— Comparison of preliminary QUaD first season power spectrum results to selected other published results to date. The experiments compared to are ACBAR (Kuo et al. 2006), BOOMERanG (Jones et al. 2006; Piacentini et al. 2006; Montroy et al. 2006), CBI (Sievers et al. 2005), DASI (Leitch et al. 2005), VSA (Dickinson et al. 2004) and WMAP (Hinshaw et al. 2006; Page et al. 2006). Note that the TT comparison is plotted with a log scale in the y-axis.

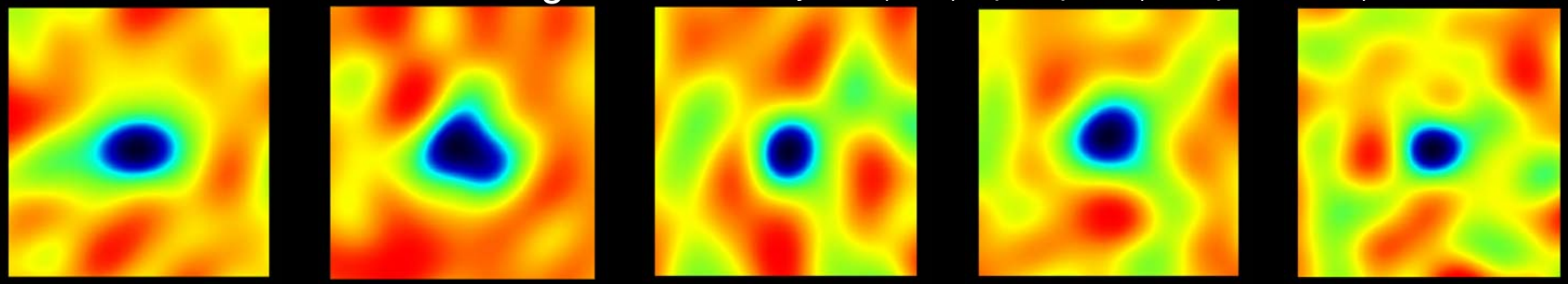
Note: CBI still has highest significance EE measurement

SZA at the Owens Valley, CA
30 and 90 GHz, 8 x 3.5m telescopes

U.Chicago/KICP, Caltech, Columbia, NASA/MSFC



First SZA images See Muchovej et. al (2006), ApJ in press (astro-ph:0610115)



z = 0.17 z = 0.17 z = 0.69 z = 0.89 z = 1.03

SZA Collaboration

UChicago: John Carlstrom, Clem Pryke, John Cartwright, Dan Marrone, Marcus Runyan, **Chris Greer, Ryan Hennessy, Michael Loh, Matthew Sharp**

Caltech/OVRO: Erik Leitch David Woody, David Hawkins, James Lamb

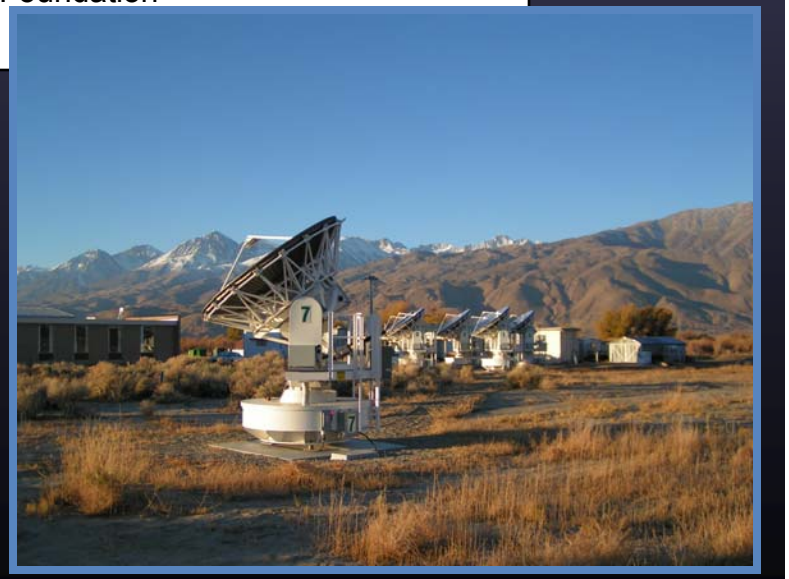
NASA/MSFC: Marshall Joy, Georgia Richards

Columbia: Amber Miller, **Tony Mroczkowski, Stephen Muchovej**

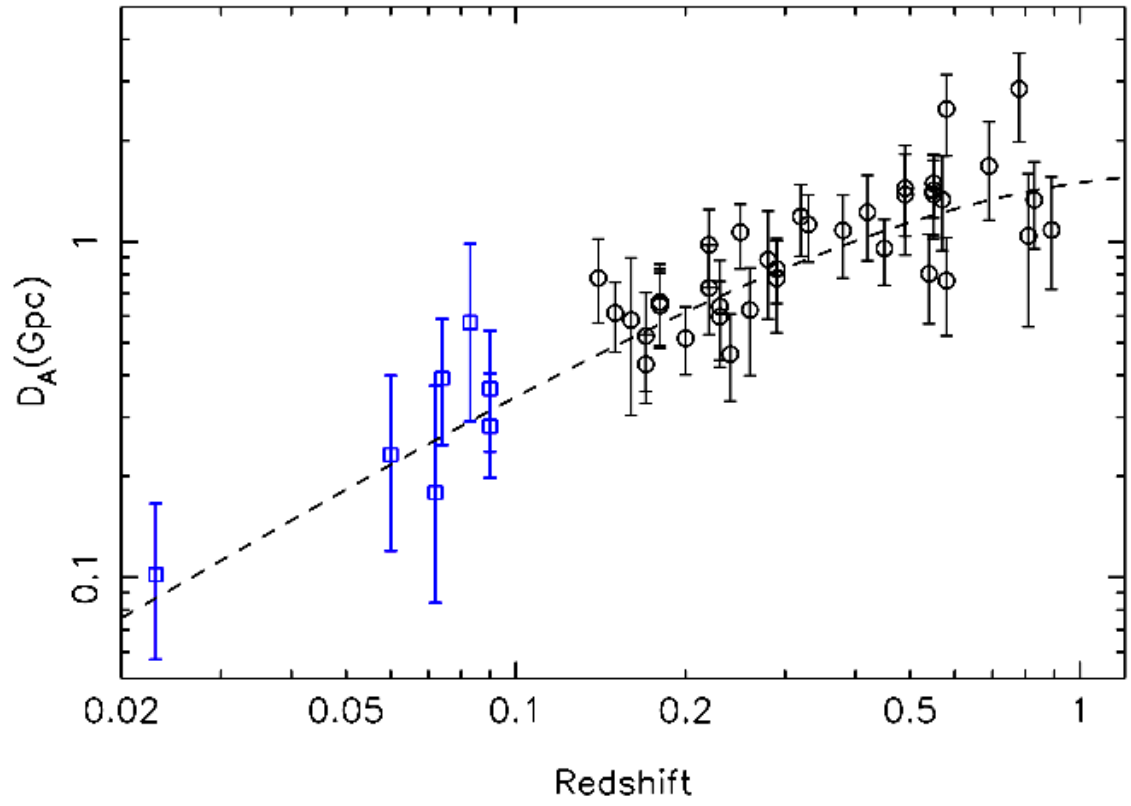
CARMA Collaboration: UCB, UMD, UIUC, Caltech

Graduate and undergraduate students heavily involved in all aspects of the project; six Ph.D. theses in the works.

Funding: NSF-ATI, NSF-KICP, McDonnell Foundation, U. Chicago, Packard Foundation



Hubble diagram from
OVRO/BIMA SZ & Chandra X-ray data



Distances, Ho

H_o=76.9 ±4 ±9 km s^{-1} Mpc^{-1}
(for ΛCDM)

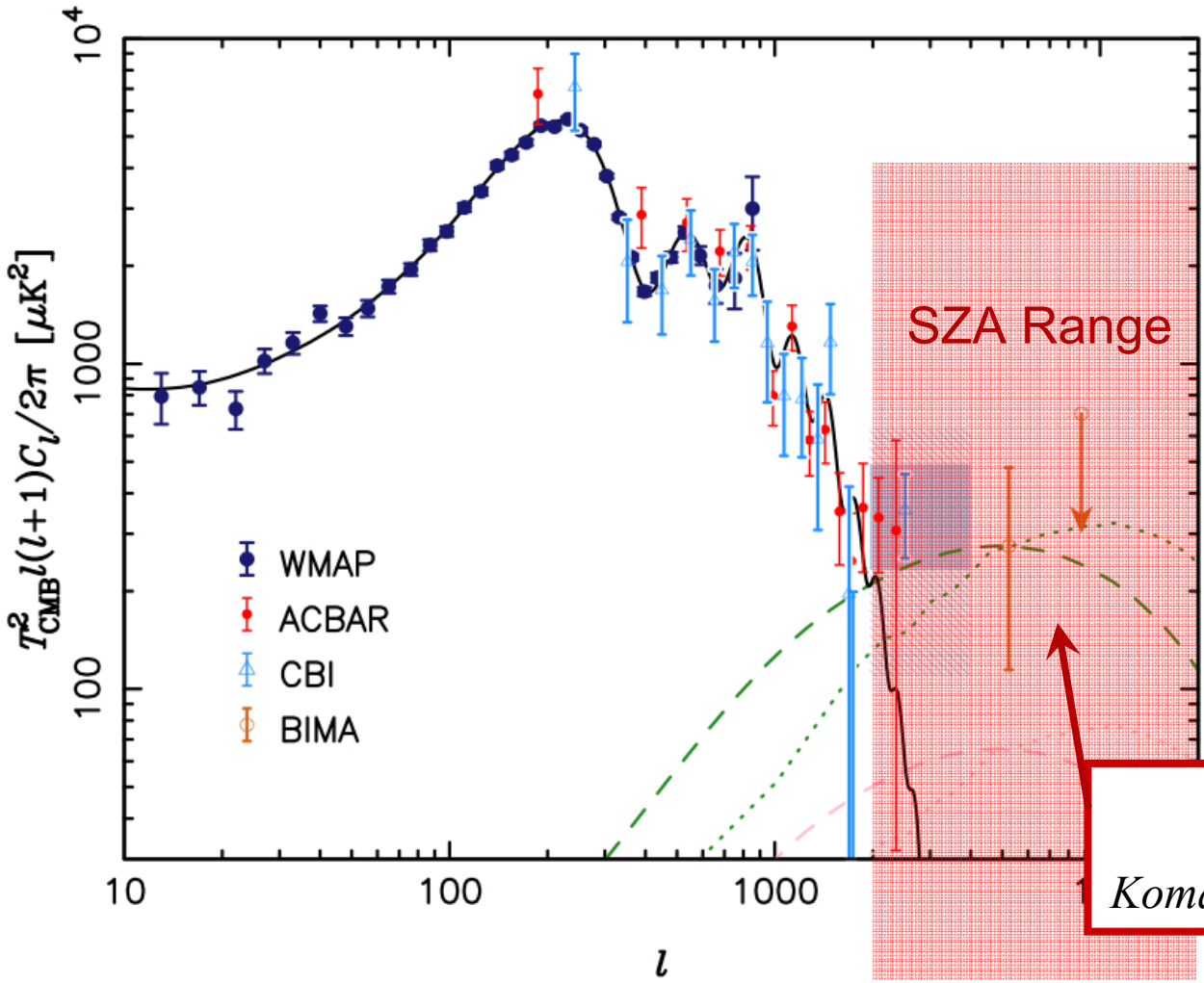
Massimilliano et al (BIMA/OVRO SZE team), 2006 ApJ 647, 25

Blue points: CBI, Udomprasert et al. 2004, not used in fit here.

SZA progress on high-l power spectrum

24 fields w/ total of 600 hrs of SZA data

Matthew Sharp Ph.D. thesis



Data passes all jack-knife tests!

Dealing with radio sources
- correlation w/ clusters.
- non-point-like sources

We have complete VLA coverage at 8 GHz.

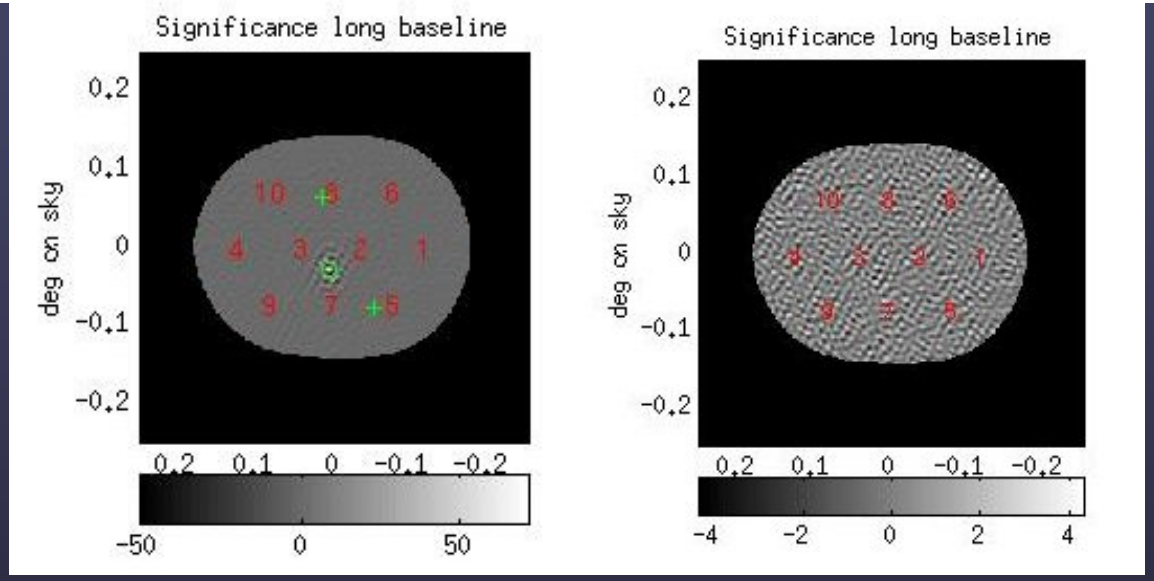
$$C_l(\mathrm{SZ}) \propto \sigma_8^{\,7}$$

Komatsu & Seljak astro-ph/0205468

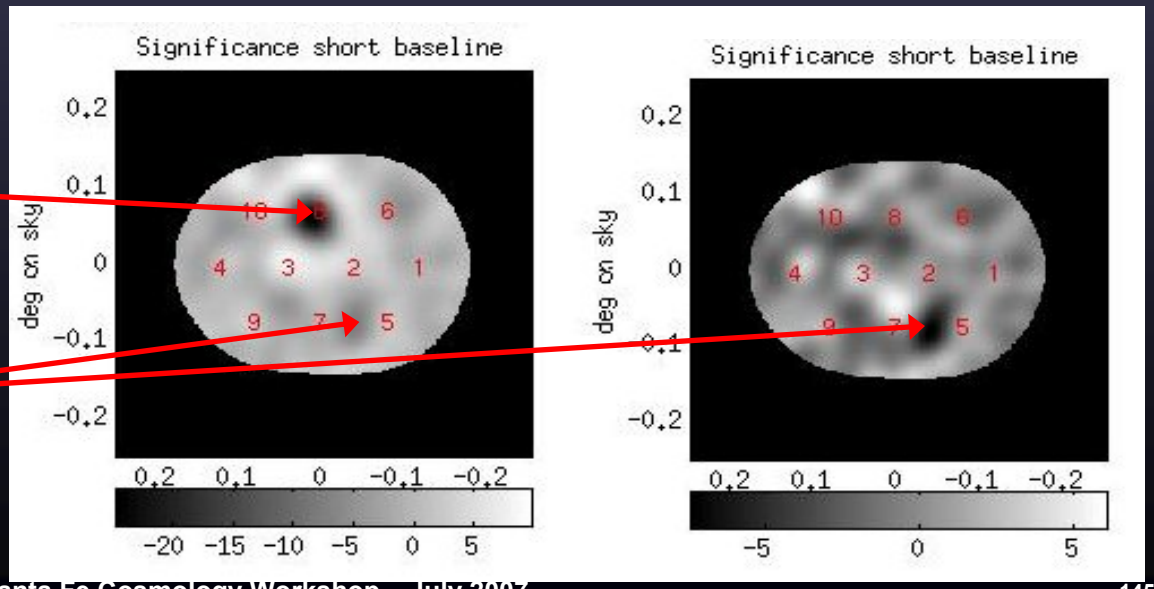
Readhead et al. ApJ. 609 (2004)

Test of SZA survey on Cl0016+0016

- 10 pointing SZA mosaic
- 4.8 arcminute separation
- Median rms 0.31mJy/beam
- Bright radio source at > 60 sigma



Two Clusters Detected

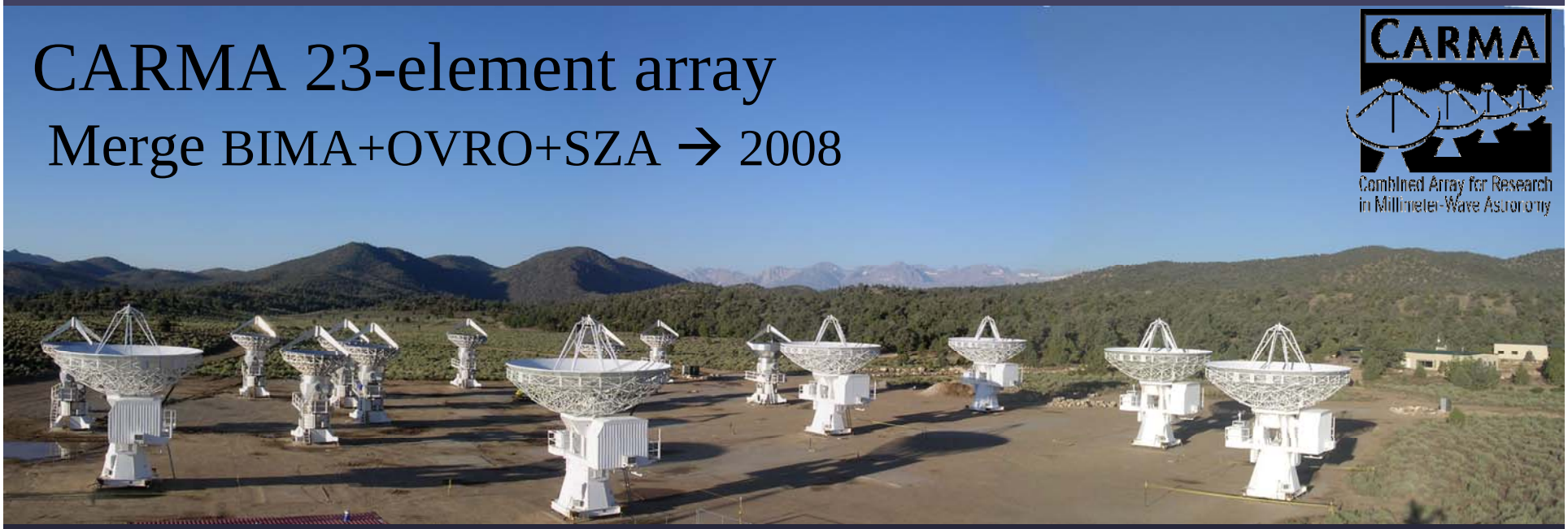


Cl0016+0016
M ~ 1.3 x 10^15 M_solar
(Hughes et al., 1995, ApJ448:L93)

RXJ0018.3+1618
M ~ 5 x 10^14 M_solar
(Hughes & Birkinshaw, 1998, ApJ 497:645)

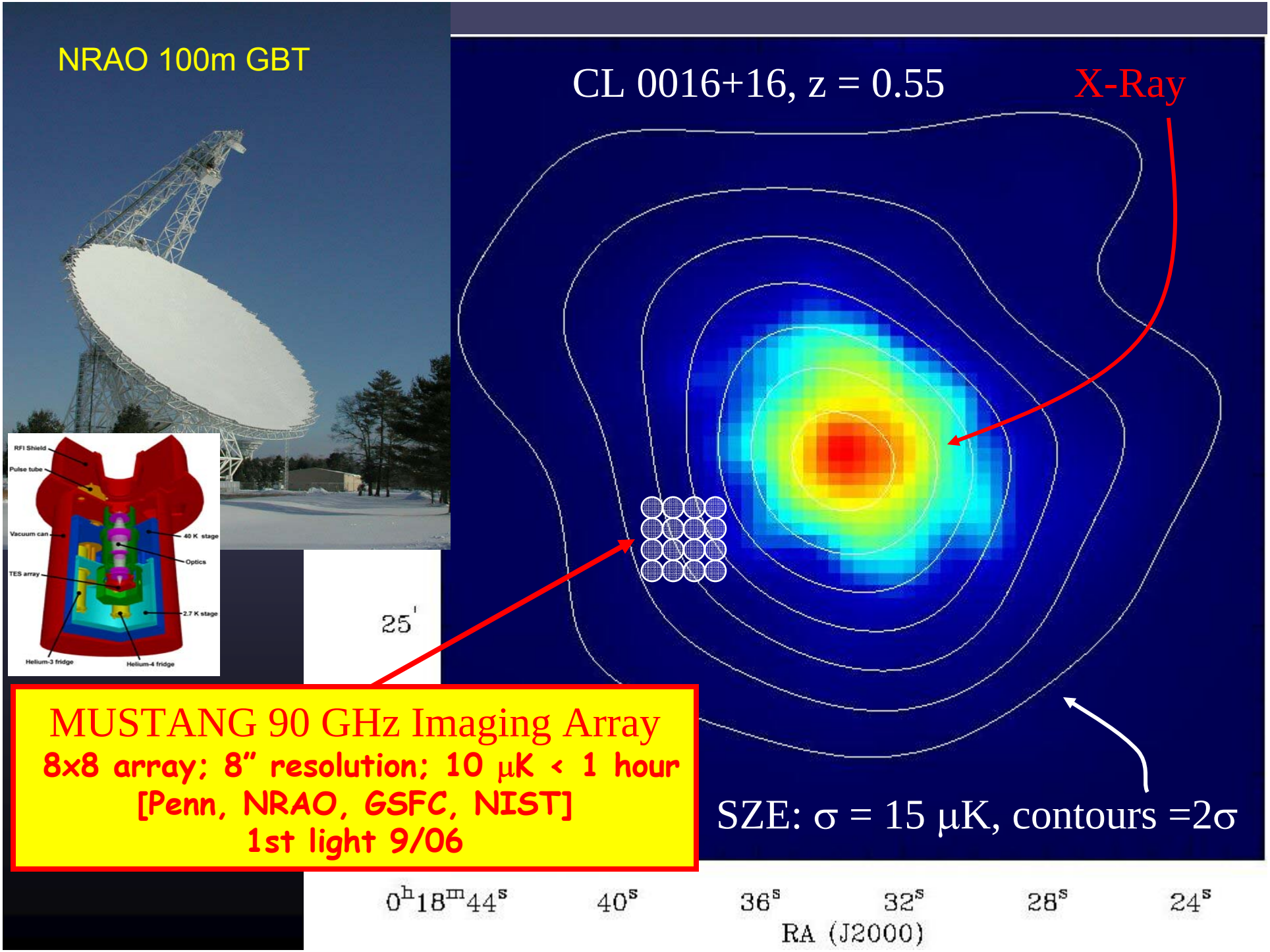
Loh et. al, in prep

SZA Future



- Currently finishing 6 sq deg SZ-survey (*S. Muchovej Ph.D Thesis*)
- SZA is not fast enough for a Dark Energy SZ-survey (need SPT)

FUTURE: Use SZA + CARMA for detailed SZ imaging



MUSTANG 90 GHz Imaging Array

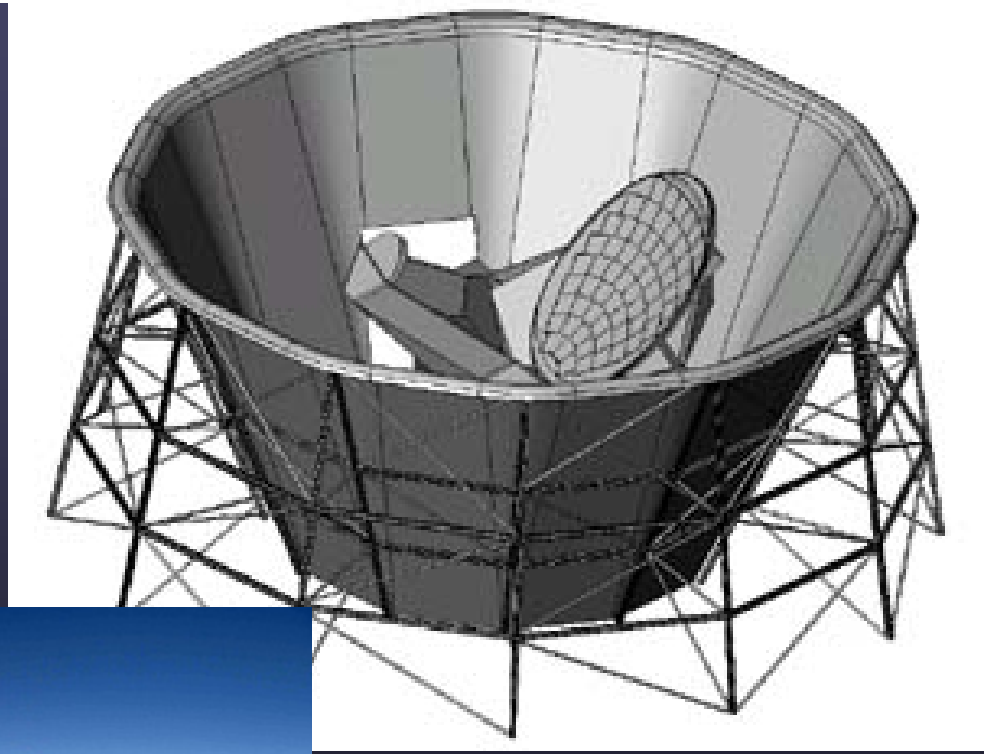
8x8 array; 8" resolution; 10 μK < 1 hour

[Penn, NRAO, GSFC, NIST]

1st light 9/06

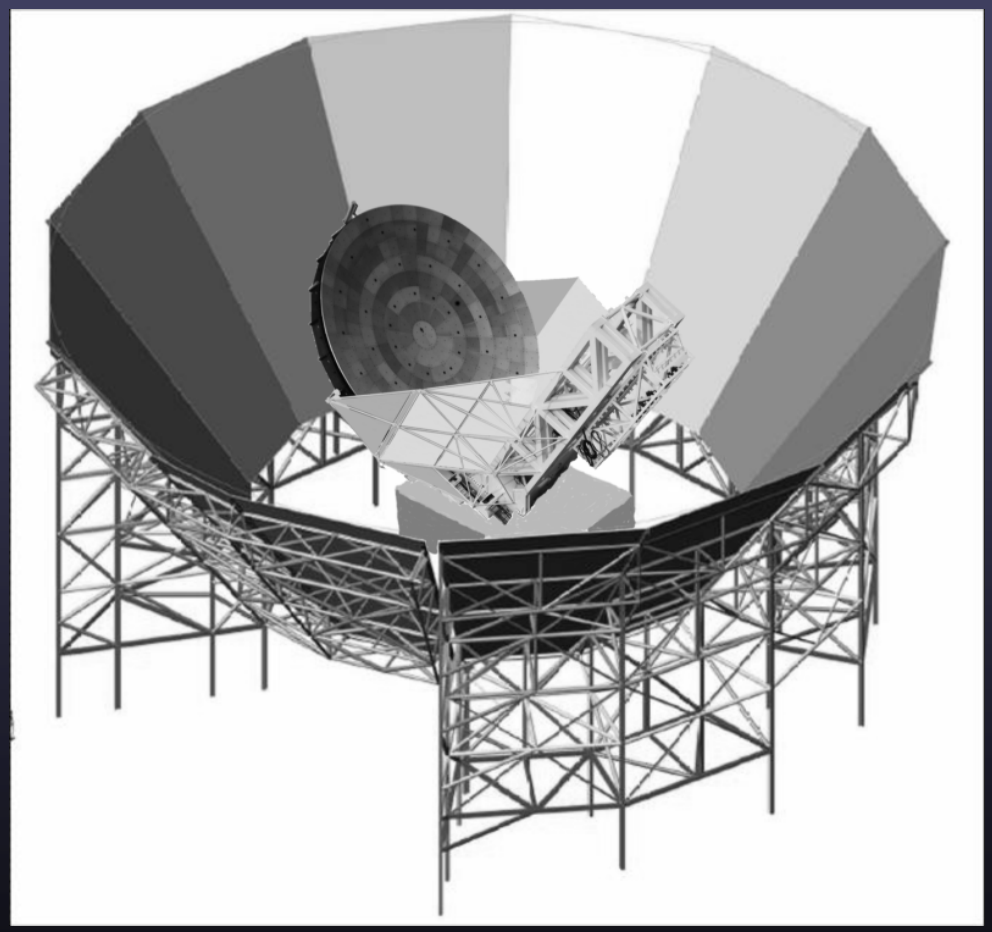
Atacama Cosmology Telescope (ACT)

- 6m off-axis dish with ground screen
- 1000 element bolometric arrays (similar tech to MUSTANG)
- Deploying near ALMA site
- 1st light achieved



Cardiff Columbia CUNY Drexel Haverford NASA/GSFC
Penn Princeton Rutgers Univ. de Catolica UMASS

10m South Pole Telescope (SPT) and 960 element bolometer array



Low noise, precision telescope

- 20 um rms surface over 10m
- 1 arcsecond pointing
- 1 arcmin resolution at 2 mm
- scan entire telescope
- 3 levels of shielding
  - 1 m radius on primary
  - inner moving shields
  - outer fixed shields

SZE and CMB Anisotropy

- up to 5 bands (start w/3) 90,150, 220, 270, 350 GHz
- **4000 sq deg SZE survey**
- deep CMB anisotropy fields
- deep CMB Polarization fields

First light achieved Feb 16, 2007

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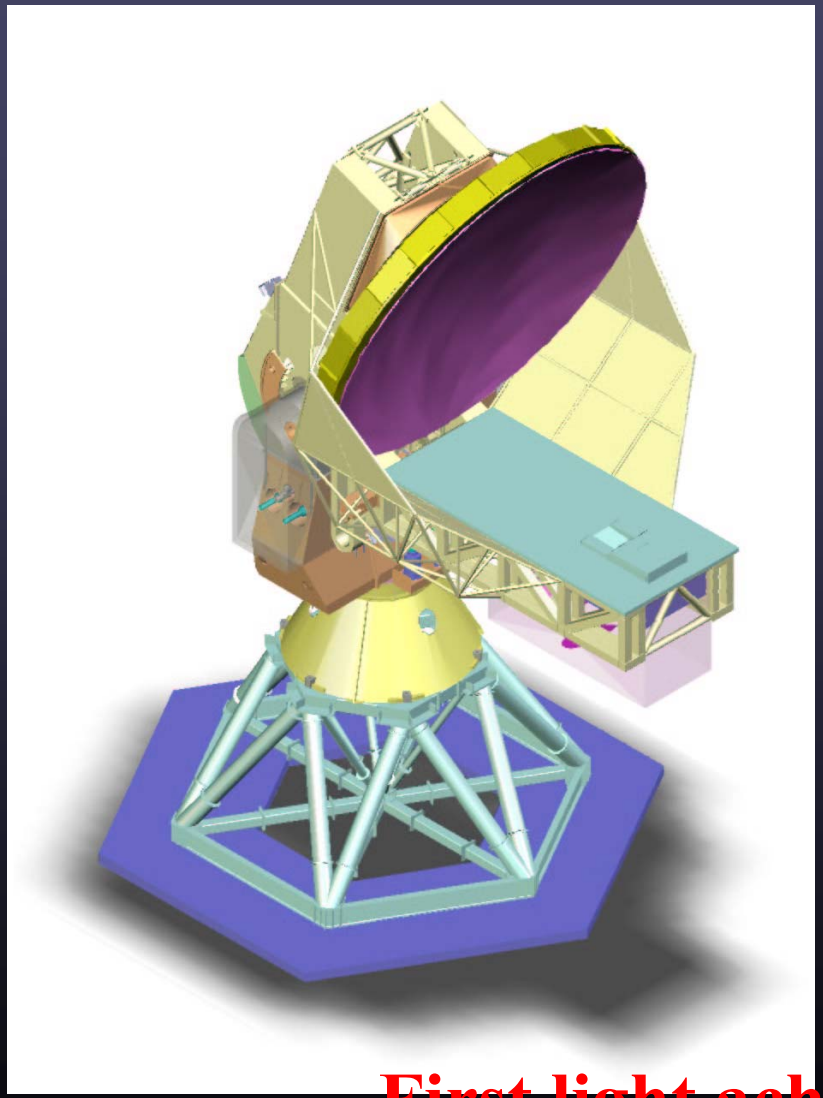

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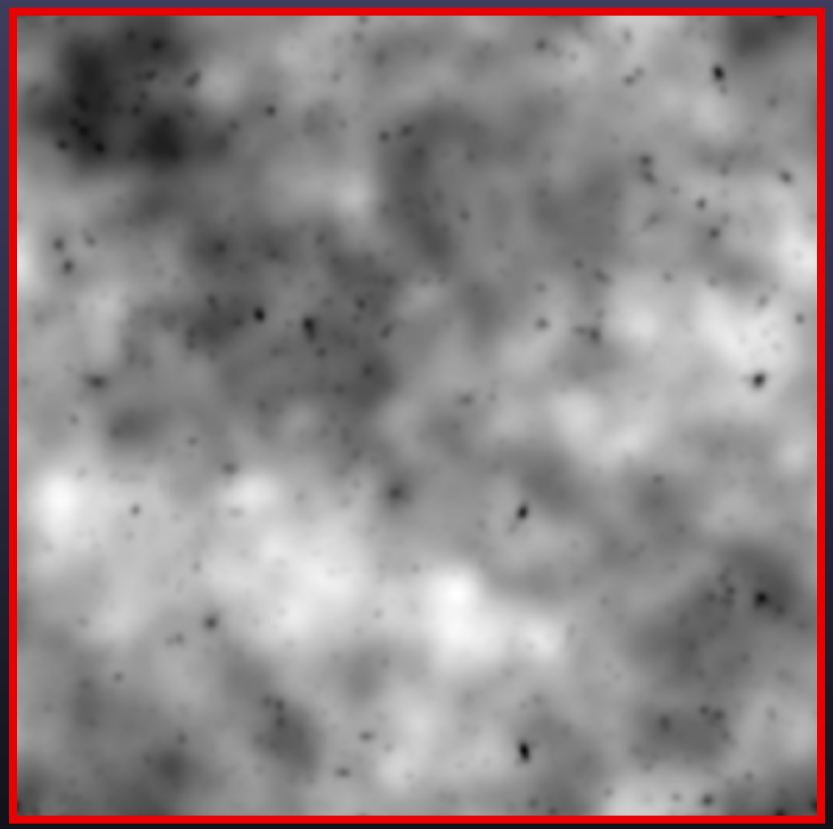
First light achieved Feb 16, 2007

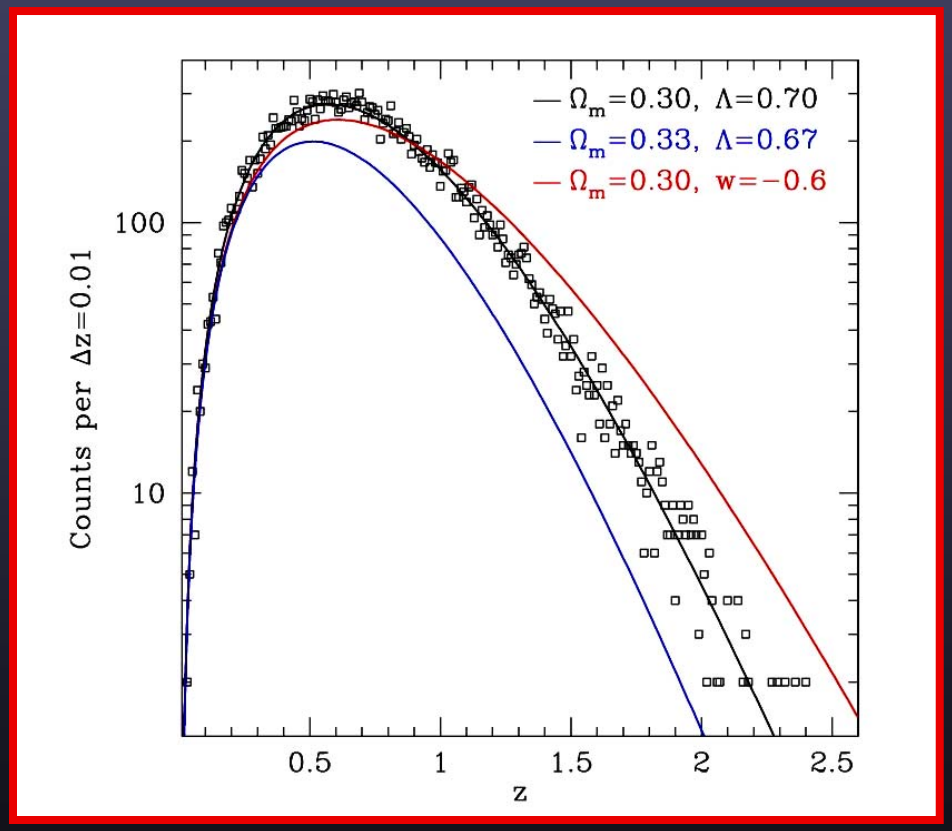
The SPT SZE Survey

Simulation of 10 sq degree patch of microwave sky



Simulations provided by M. White

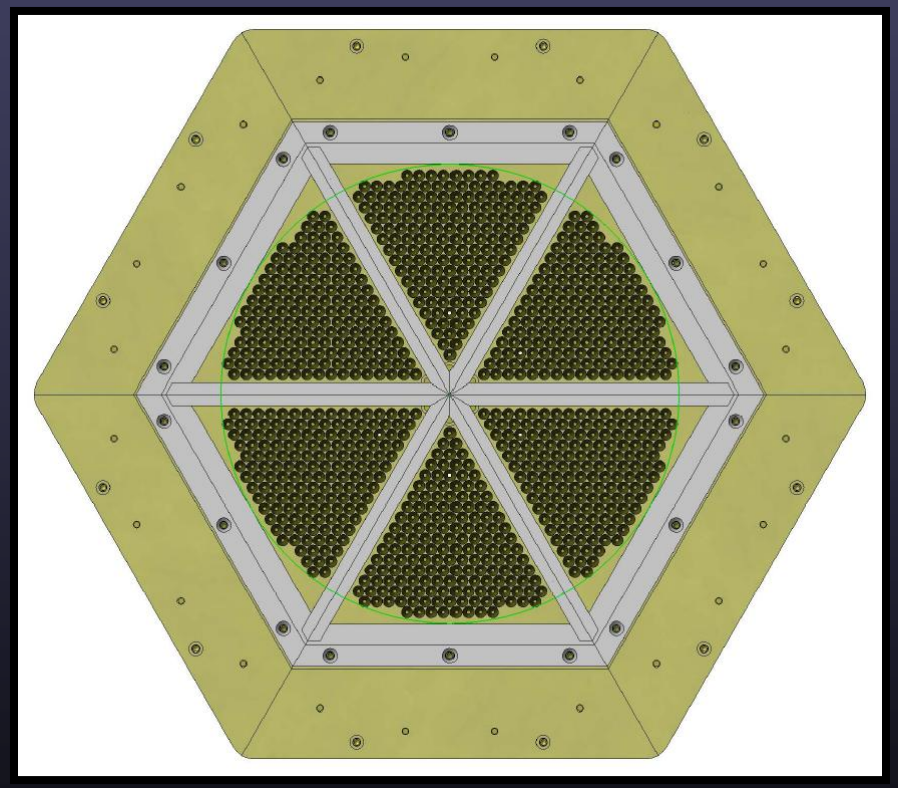
Cluster yields for SPT 4000 sq degree SZ-Survey



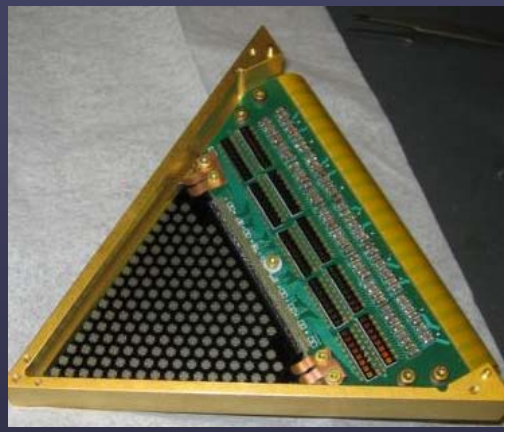
SPT detectors

- advanced bolometer camera:

180 mm; ~1 degree on sky



Built at UC Berkeley



- 160 possible channels on each wedge, 8x multiplex
- Transition Edge Sensor bolometers with Tc ~500mK

End of austral Summer 07/08

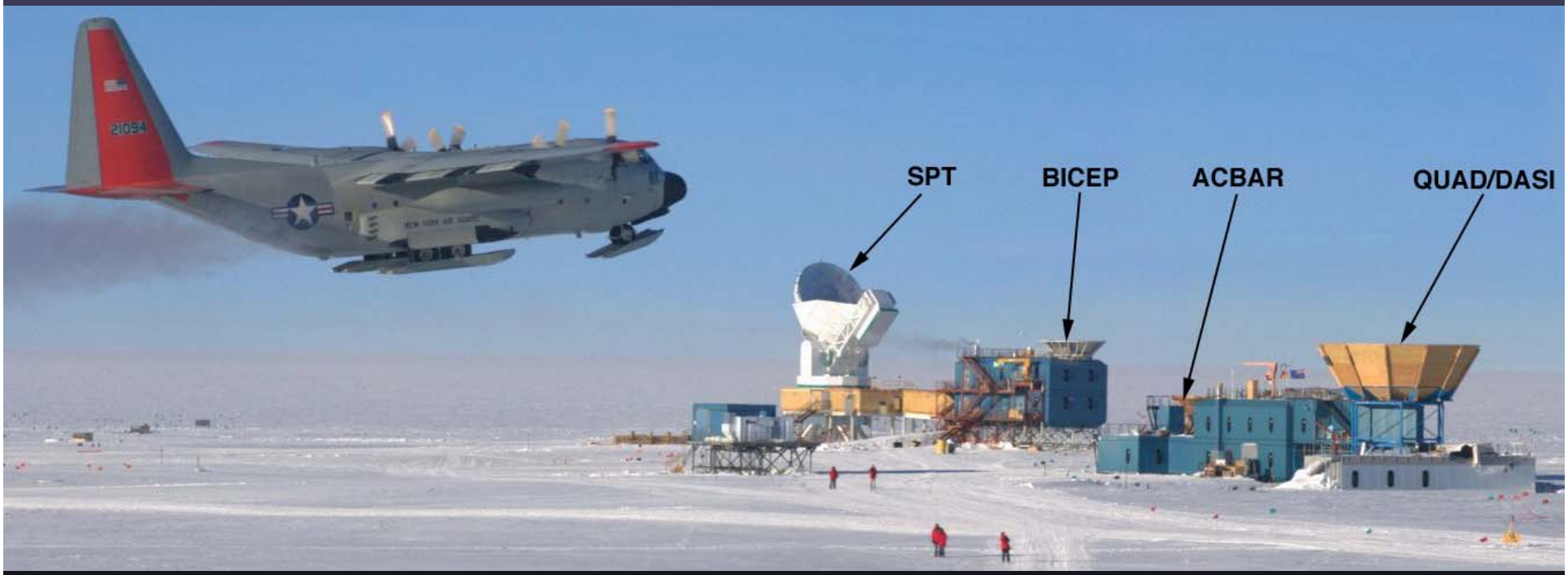
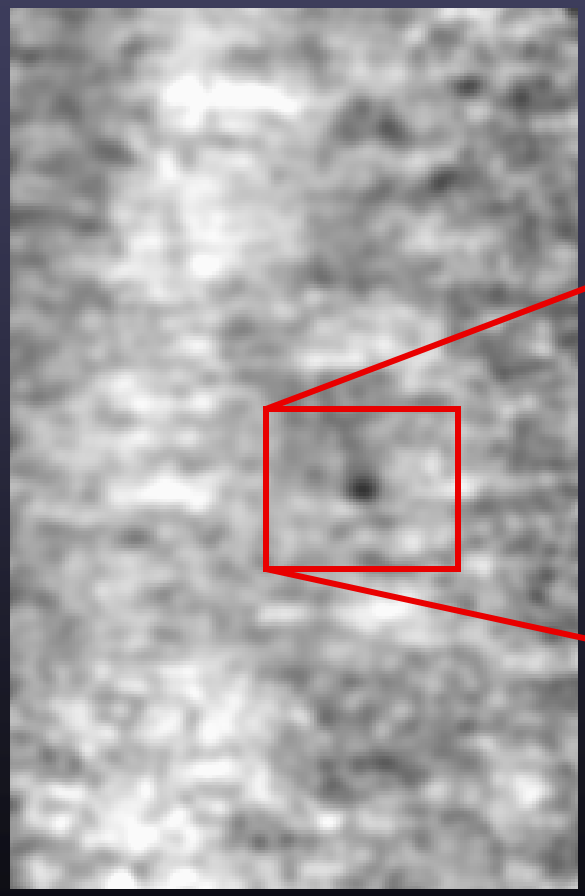


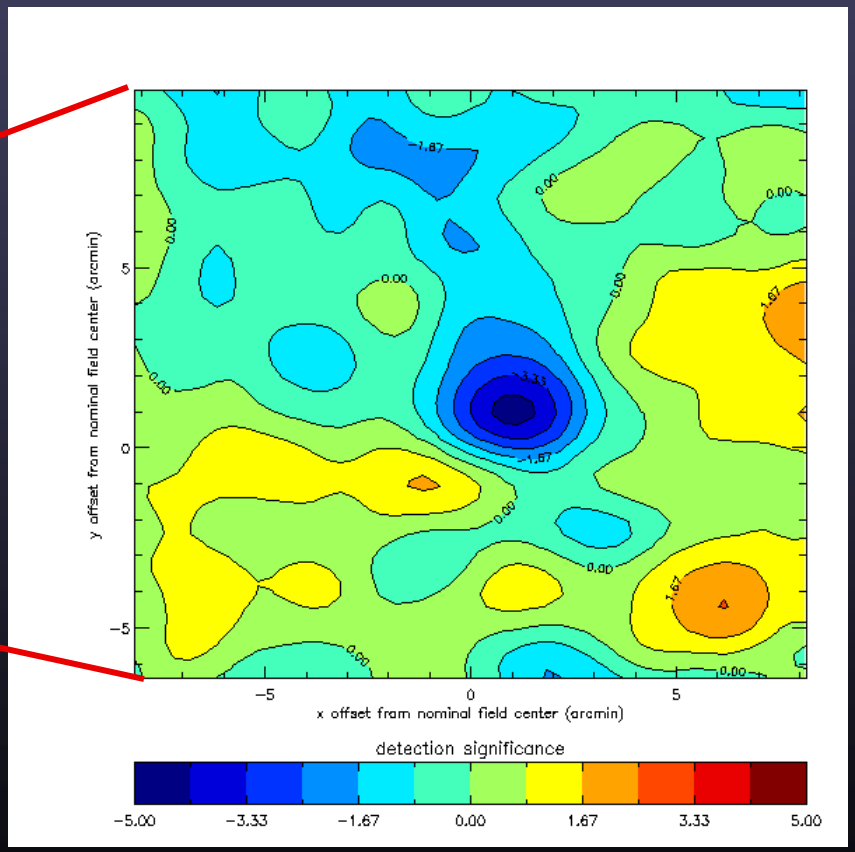
Photo Credit Steffen Richter

SPT's First SZ-effect Observations

First SZ cluster observed by SPT (AS1063)

(Combined 90 and 150 GHz detectors)





SPT Collaboration

Berkeley University of California

William Holzapfel
Adrian Lee
Martin White
Sherry Cho
Bradford Benson
Huan Tran
Martin Lueker
Jared Mehl
Tom Plagge
Dan Schwan
Erik Shirokoff

Cardiff University Prifysgol Caerdydd

Peter Ade

Case Case Western Reserve University

John Ruhl
Tom Montroy
Zak Staniszewski

Harvard-Smithsonian Center for Astrophysics

Antony Stark

Astronomy University of Illinois at Urbana-Champaign

Joe Mohr

Berkeley Lab

Helmuth Spieler

The University of Chicago

KICP Kavli Institute for Cosmological Physics at the University of Chicago

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Stephan Meyer
Clem Pryke
Wayne Hu
Andrey Kravtsov
Tom Crawford
Jeff McMahon
Clarence Chang
Kathryn Miknaitis

Joaquin Vieira
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Ryan Keisler
Lindsey Bleem
Jonathan Stricker

Colorado University of Colorado at Boulder

Nils Halverson

JPL

Erik Leitch

McGill

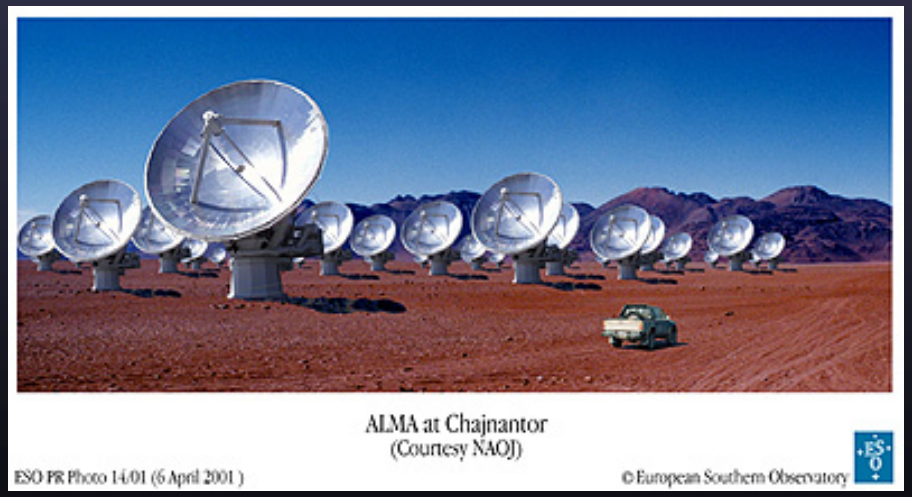
Matt Dobbs
Gil Holder
Trevor Lanting

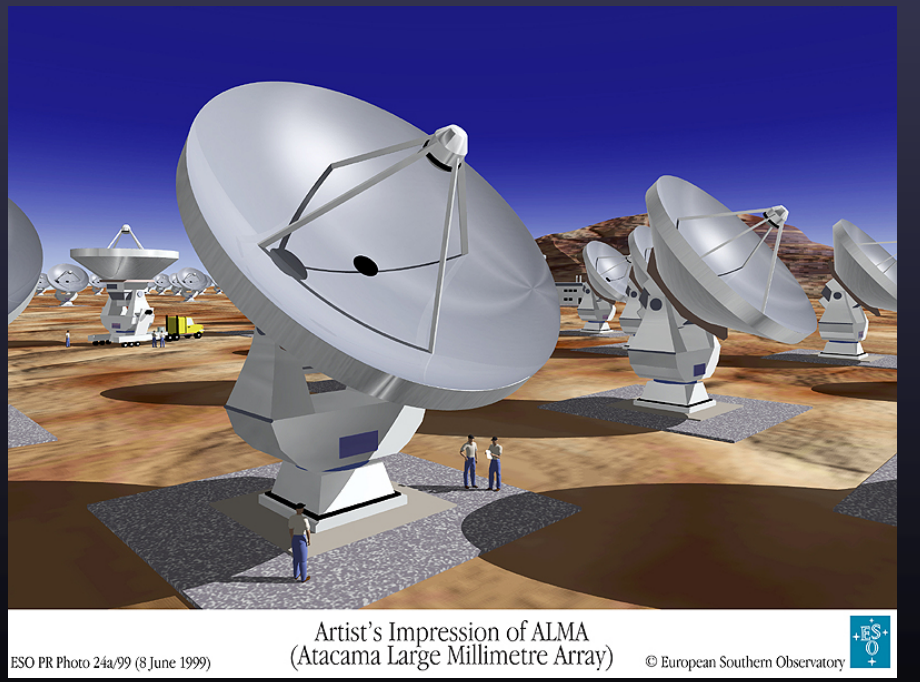
UC Davis University of California

Lloyd Knox
Jason Dick

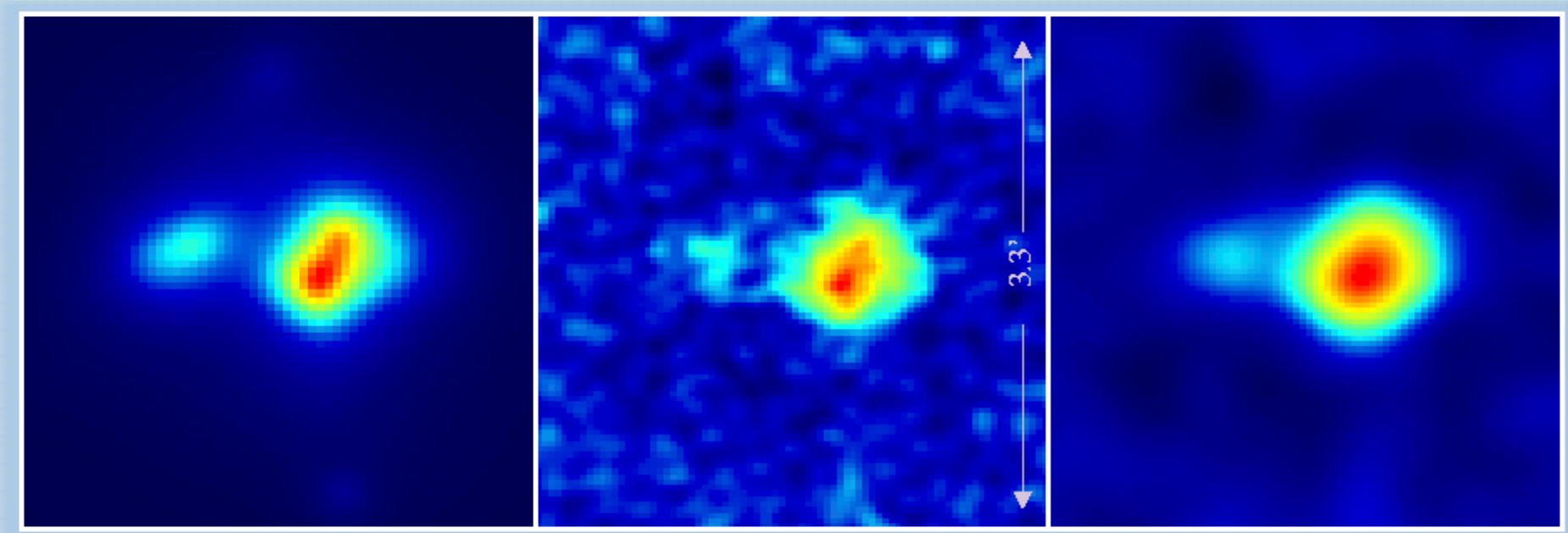
Atacama Large Millimeter Array

- 64 (probably 50) 12m antennas in main array
- sub-mm grade surfaces (good to THz)
- wide-band correlator (8 GHz bandwidth)
- from compact configuration (100-m) out to 17 km
- also ACA 10 x 7m (NAOJ)
- and 4 x 12m (NAOJ)





Imaging the SZE with ALMA Band 1



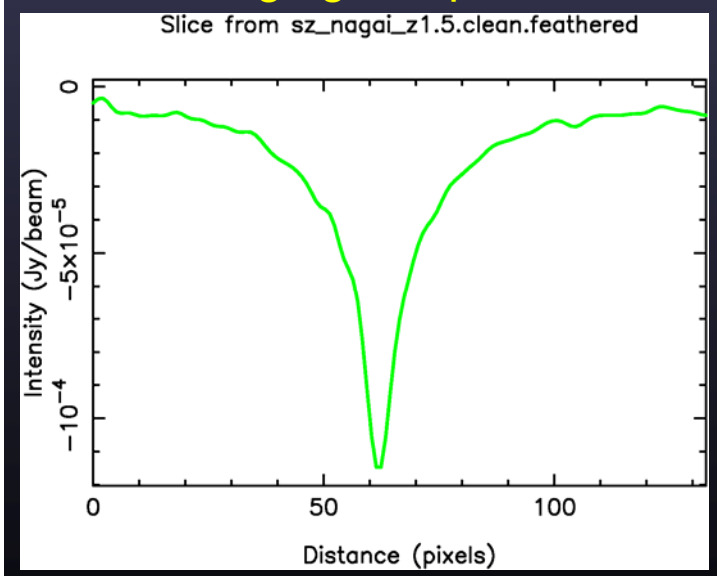
ALMA observes SZE

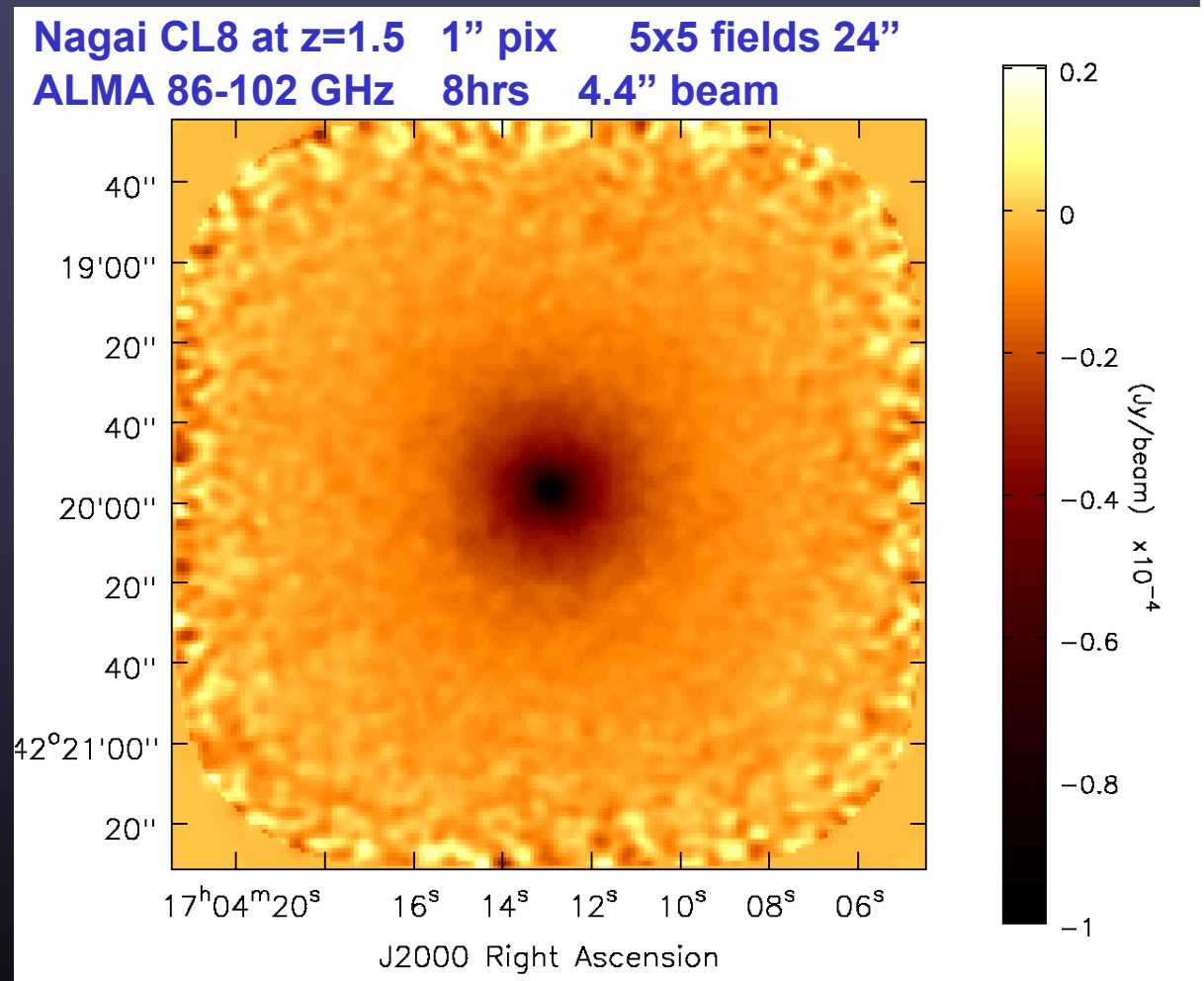
SZE simulation (left)	4 hours ALMA (center)	after 4kλ taper (right)
2.5×10^{14} Msun z=1	34 GHz in compact config.	equiv. 22" FWHM
~5σ SZA survey detection	1.5 μJy (14 μK) 9.7" beam	2.8 μJy (2.7 μK)

ALMA will provide images of high redshift clusters identified in surveys from other instruments like AMI, SZA, SPT, APEX-SZ, ACT

Preliminary results – ALMA sims

- Cluster simulations from Daisuke Nagai (Caltech)
  - 8.7 keV cluster at z=0
  - 2048^2 pix 7.5/h Mpc
  - placed at z=1.5
  - 50 ant ALMA compact
  - full simulated data and imaging in aips++

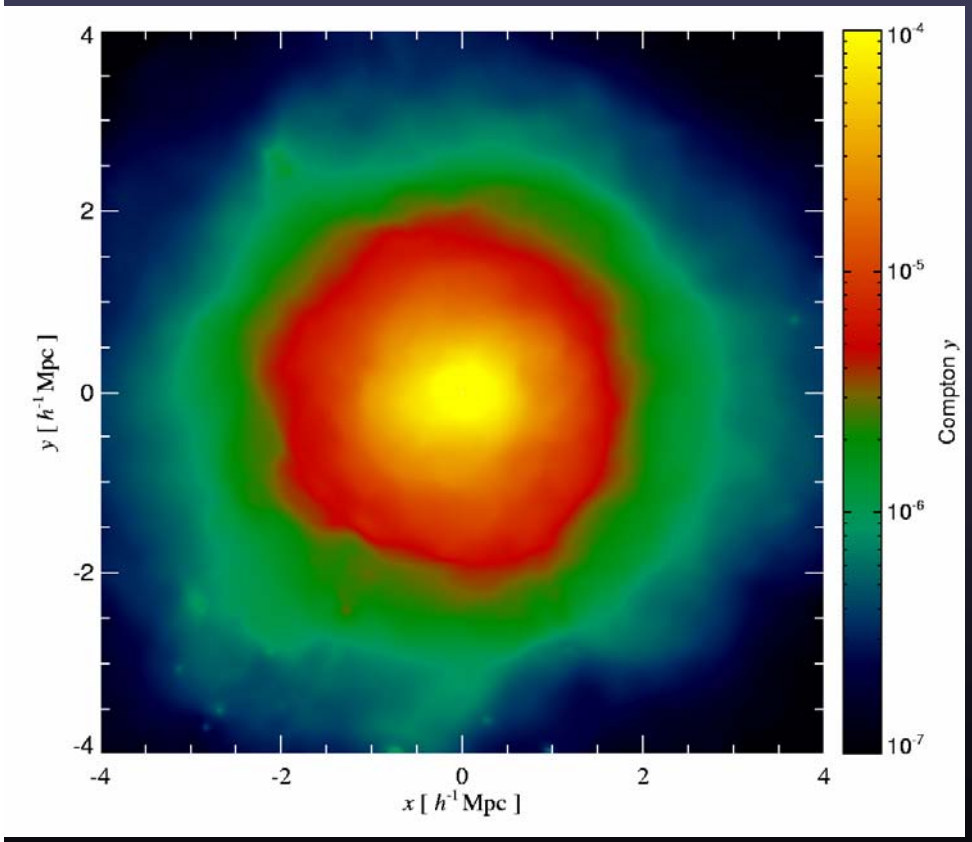


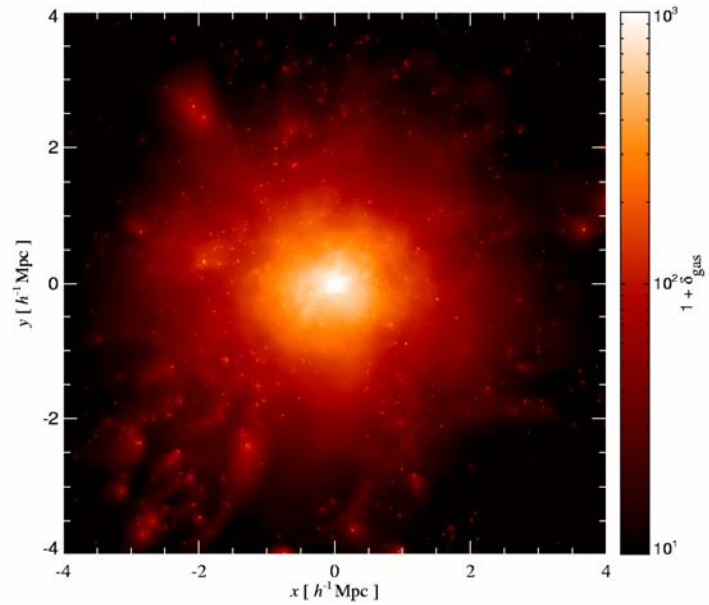


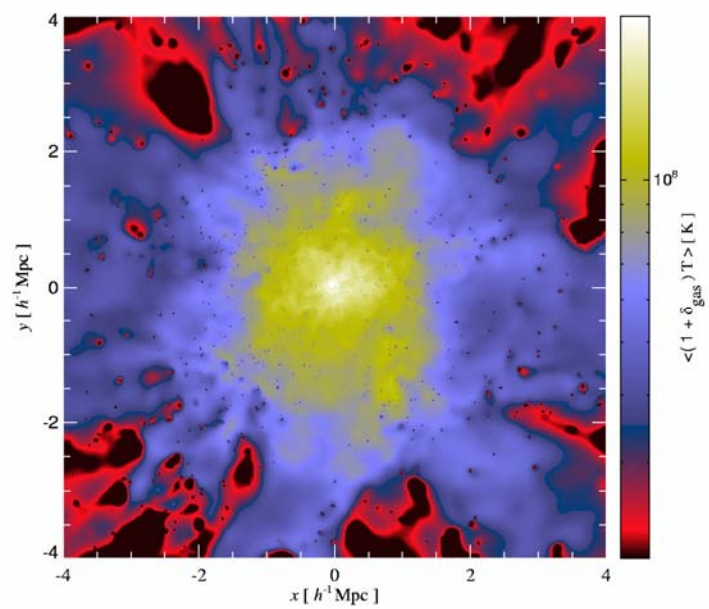
http://www.tapir.caltech.edu/~daisuke/Research/ARTcode/SZmockobs/szmockobs.html

Preliminary results – ALMA sims

- Cristoph Pfrommer (CITA)
  - Coma-like cluster
  - at z=0 : (below) Compton y; (upper right) density; (lower right) T



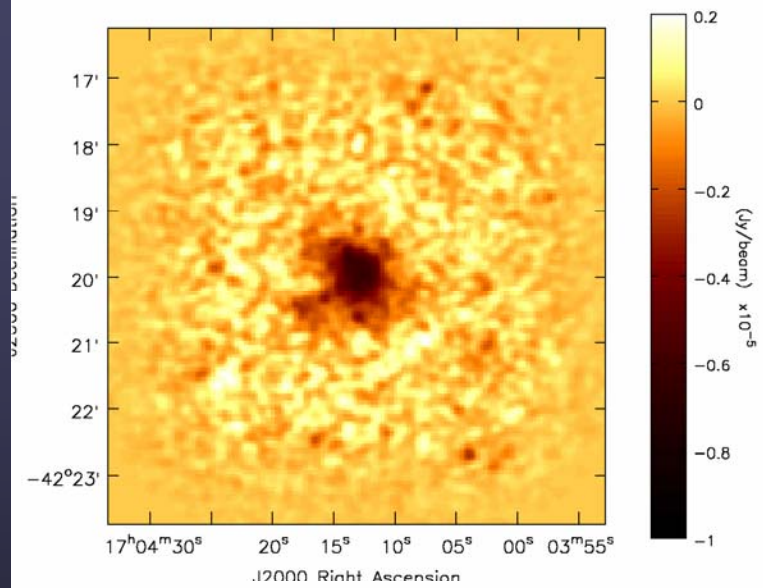


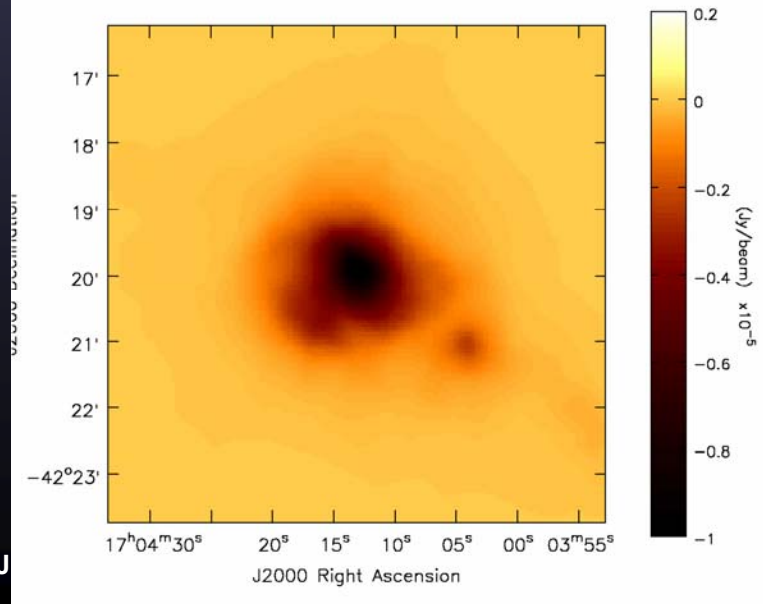


Preliminary results – ALMA sims

- Process with ALMA software
  - ALMA 30GHz ($\Delta\nu$=16 GHz)
  - main array only (50 ants)
  - 8 hours
  - 5x5 field mosaic at 60" spacing
  - cluster at z=1.5

  - (upper right) cleaned SZ image
  - (lower right) model image

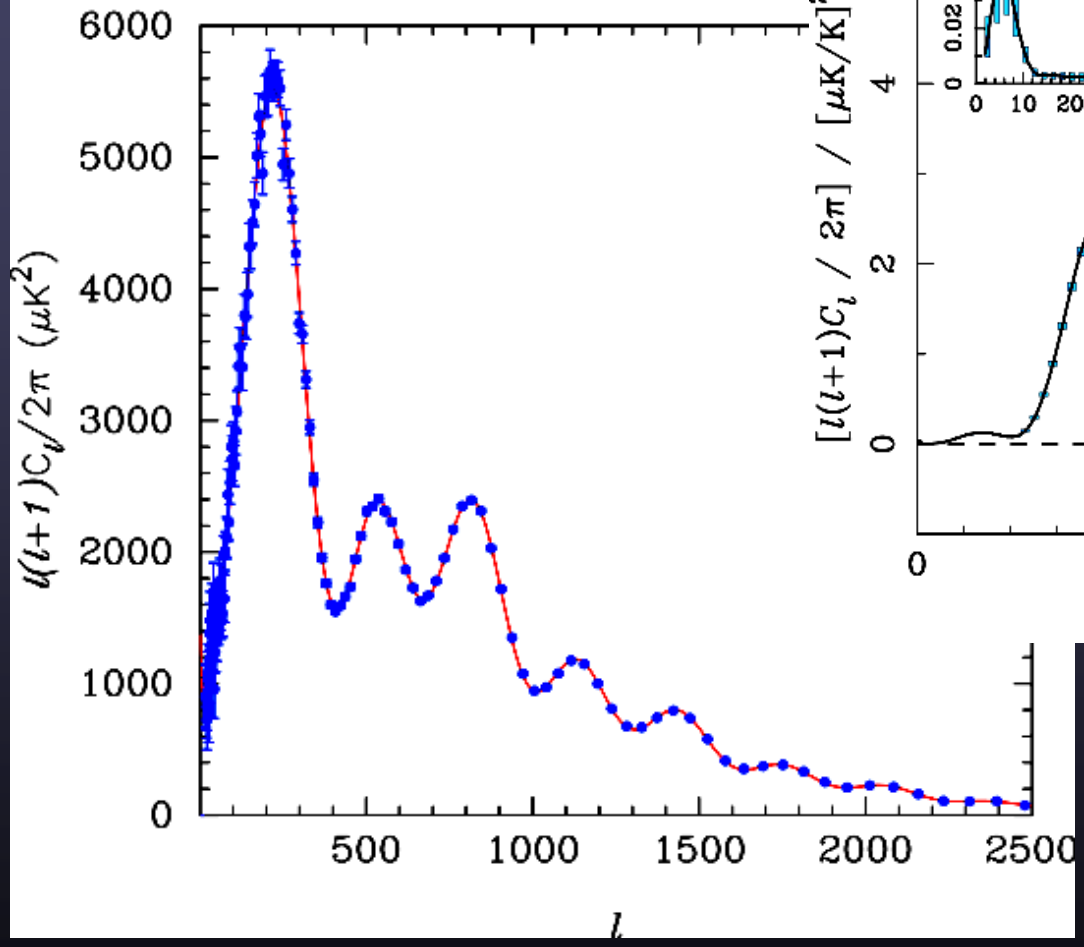


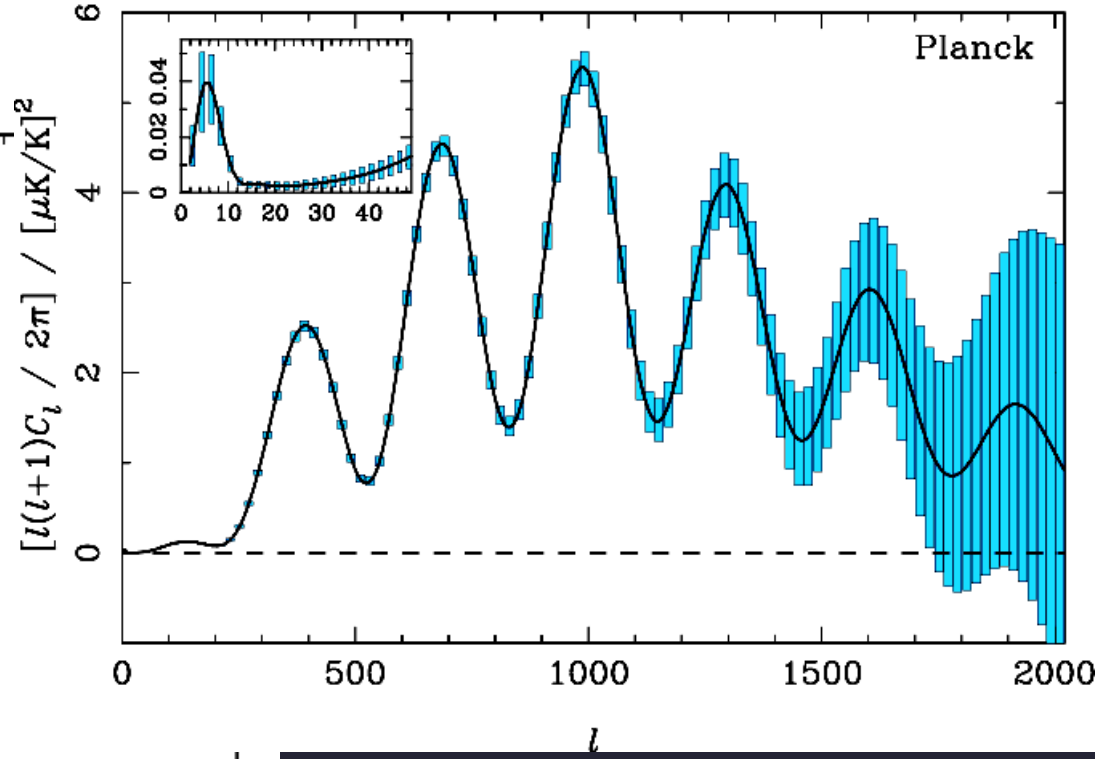


Need to fund Band 1 (30GHz) ALMA!

The Future is
somewhat later than now!

Next big thing: Planck!

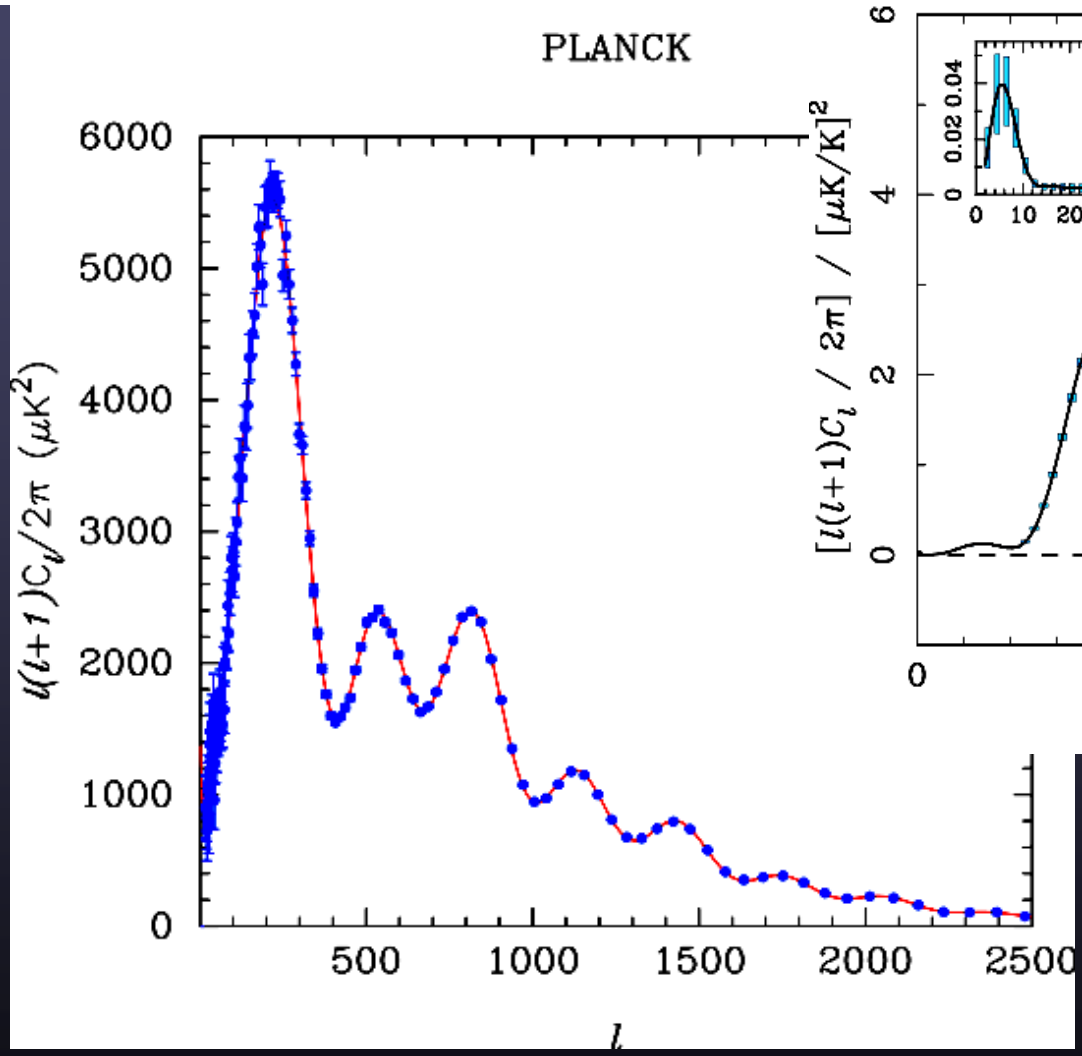


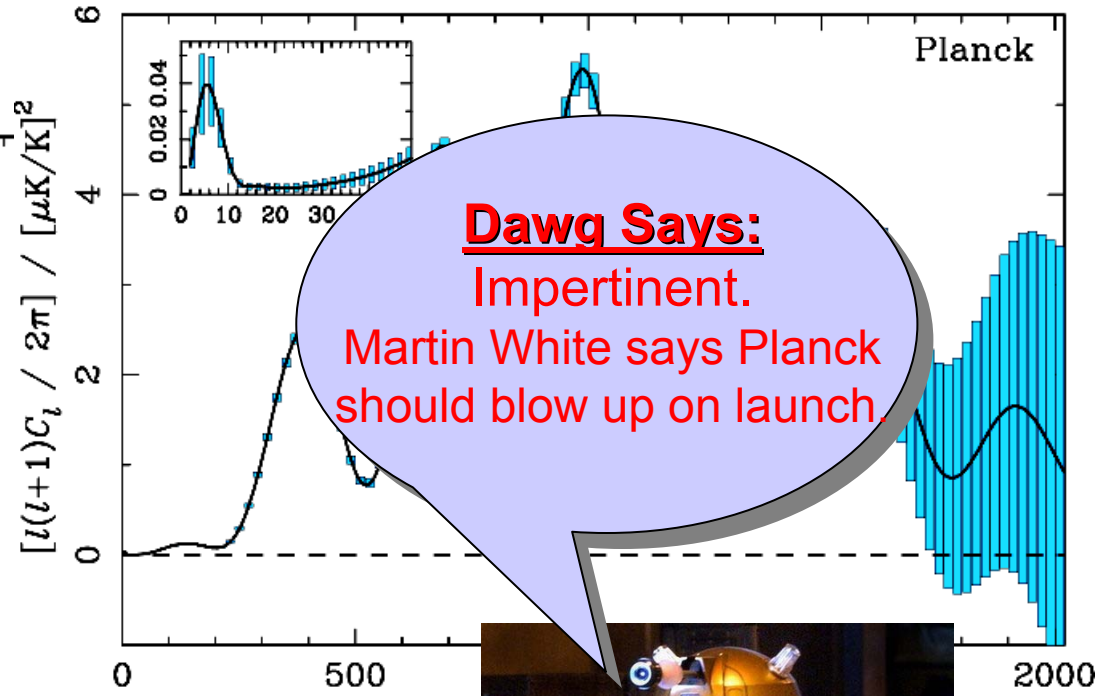


- Planck sensitivity, frequency & sky coverage critical:
  - TT: 3rd and higher peaks!
  - reach lensing BB modes
  - push towards tensor BB modes
  - determine foregrounds

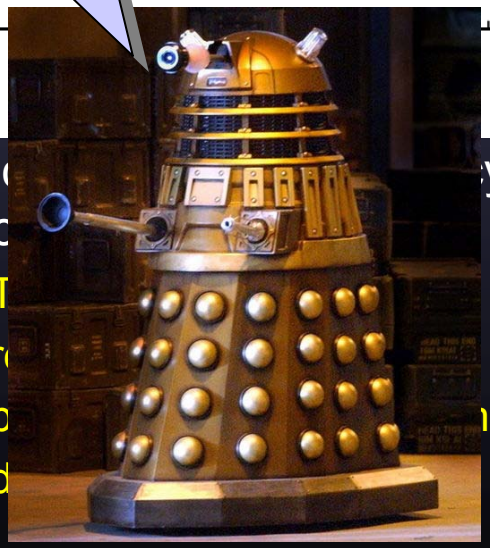
Figures courtesy Martin White

Next big thing: Planck!





Dawg Says:
Impertinent.
Martin White says Planck should blow up on launch.

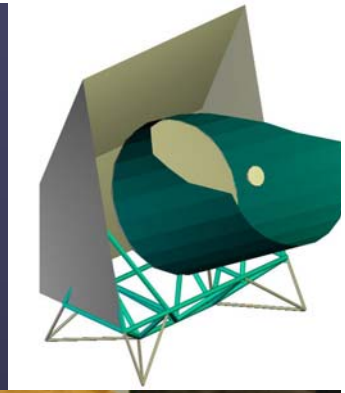


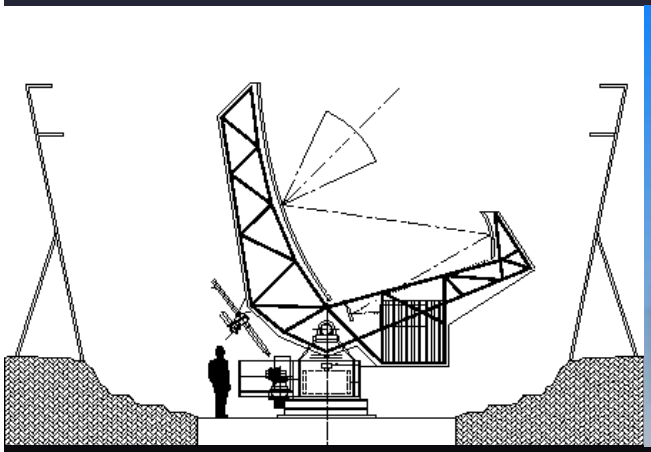
- Plan y &
  sky c
  - T
  - r
  - p odes
  - d

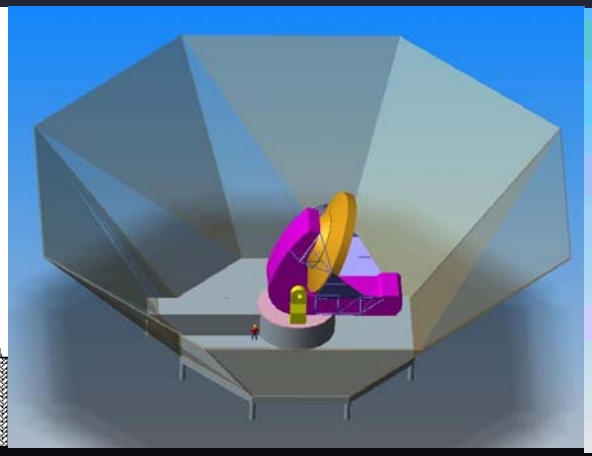
Figures courtesy Martin White

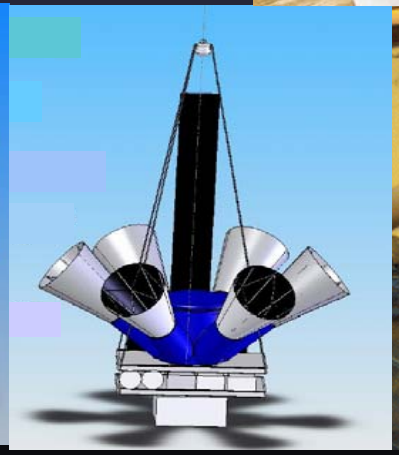
Current & Future "CMB" Experiments

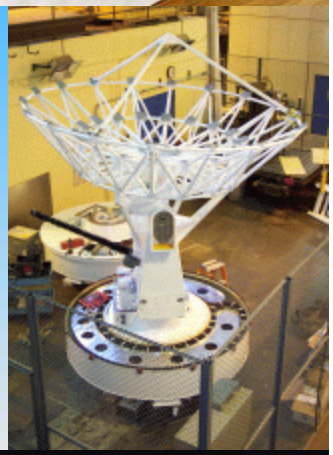
- Beyond Planck (a sampling):
  - ACT [6m] (Chile) – high-ℓ CMB
  - SZA [8x3.5m] (OVRO) – clusters, high-ℓ CMB
  - South Pole Telescope [8m] (SP) – cluster counts
  - QUaD [2.6m] (SP) – CMB polarization
  - QUIET [2m,7m] (Chile) – B-modes from ground
  - CCAT Atacama 25-meter (Chile) – FIR/sub-mm
  - SPIDER [2m] (Balloon) – B-modes from LDB





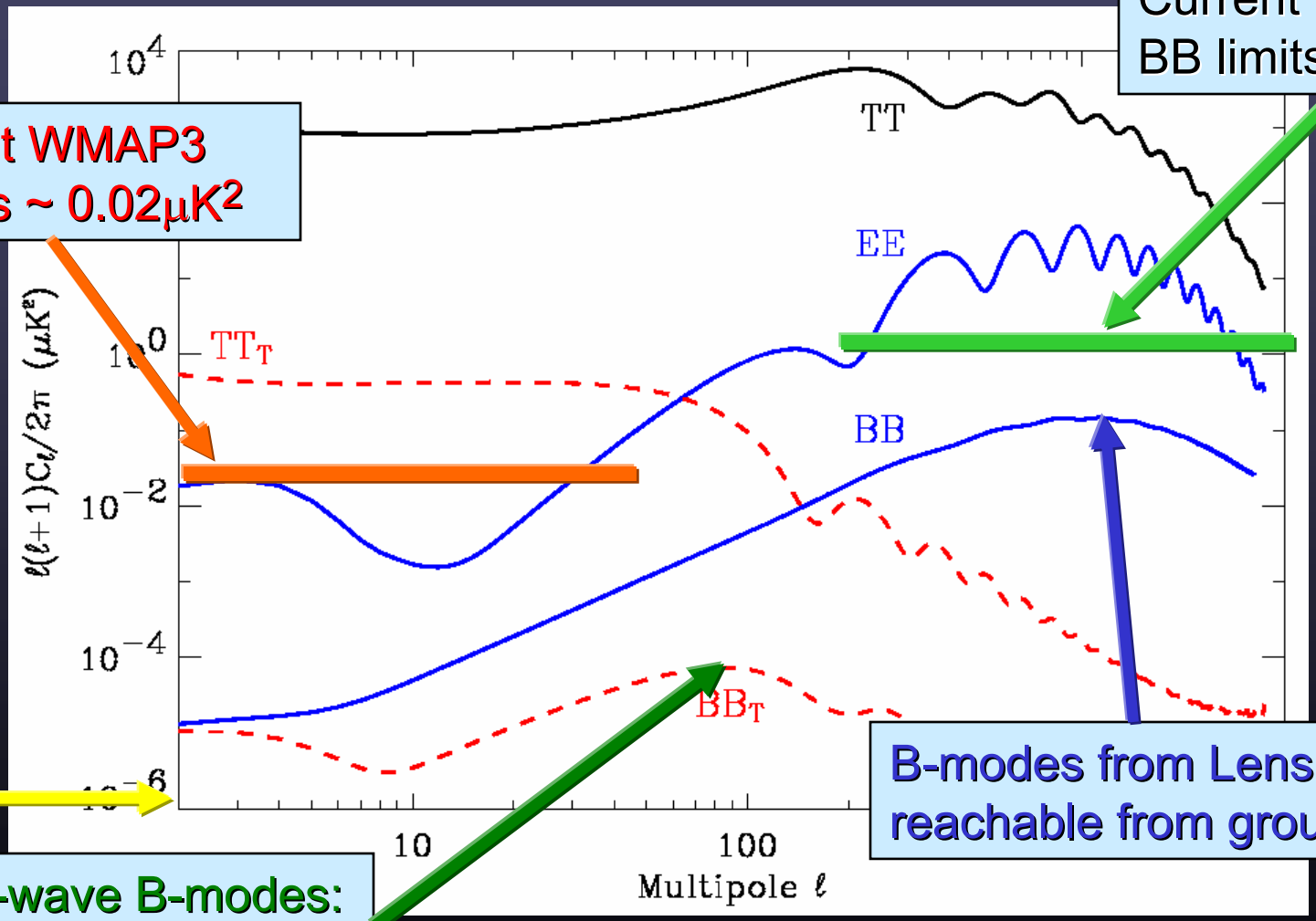






CMB Power Spectrum Goals

- EE and BB (lensing, inflation)



Current WMAP3
BB rms ~ 0.02μK²

Current CBI+DASI
BB limits ~ 1μK²

1 nK!

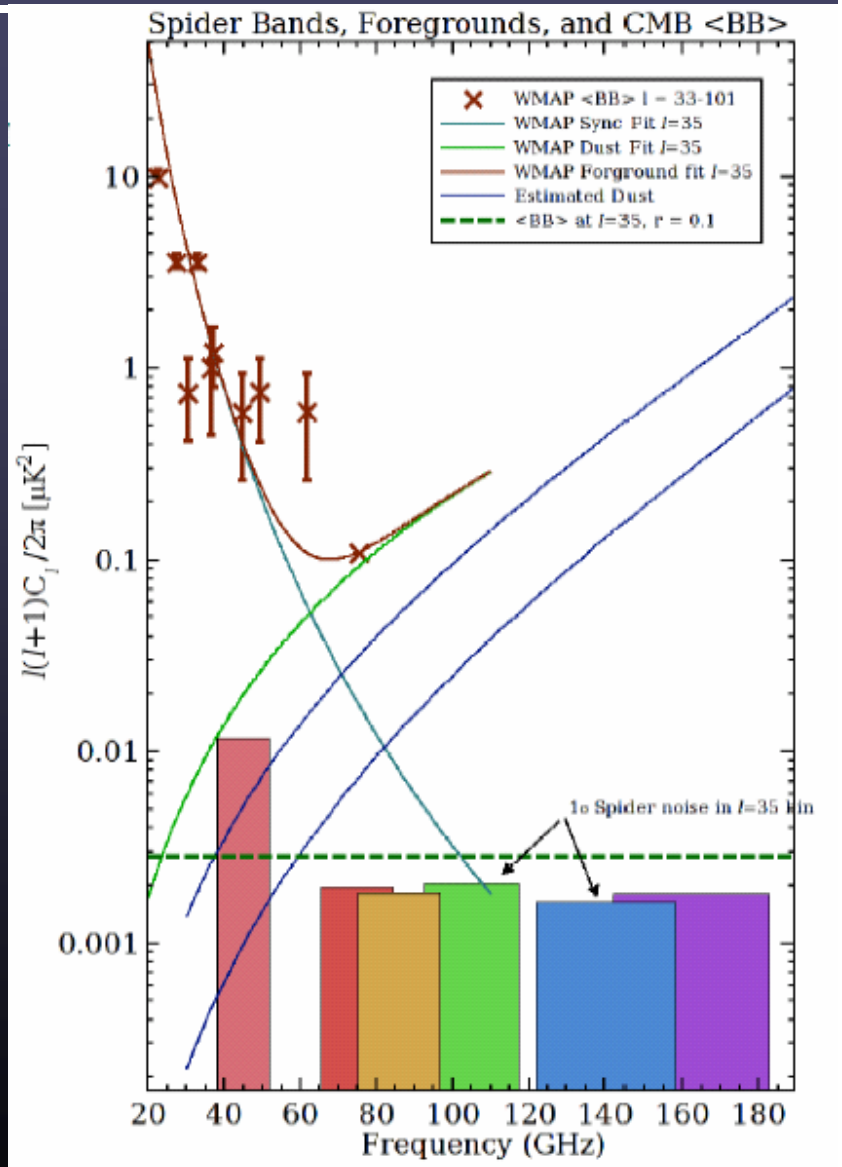
Gravity-wave B-modes:
for T/S=0.001

B-modes from Lensing:
reachable from ground.

The CMB Foreground Challenge

- Further progress in CMB astronomy will require the understanding and removal of foreground emission (solar system, galactic, extra-galactic) to unprecedented levels (10-100 nK)
  - Note – at 1cm in one square arcmin :
    1μK ~ 1μJy
- To image the CMB at these levels one images the entire Universe between *z*=0 and *z*=1000!

  = Whole Universe Imaging
- This is in full polarization…
- Frequencies from 20 GHz – 900 GHz!
- Looking at continuum, but beware of line contamination at these levels.



Plot from Barth Netterfield's talk at Irvine, March 2006
http://www.physics.uci.edu/CMB/

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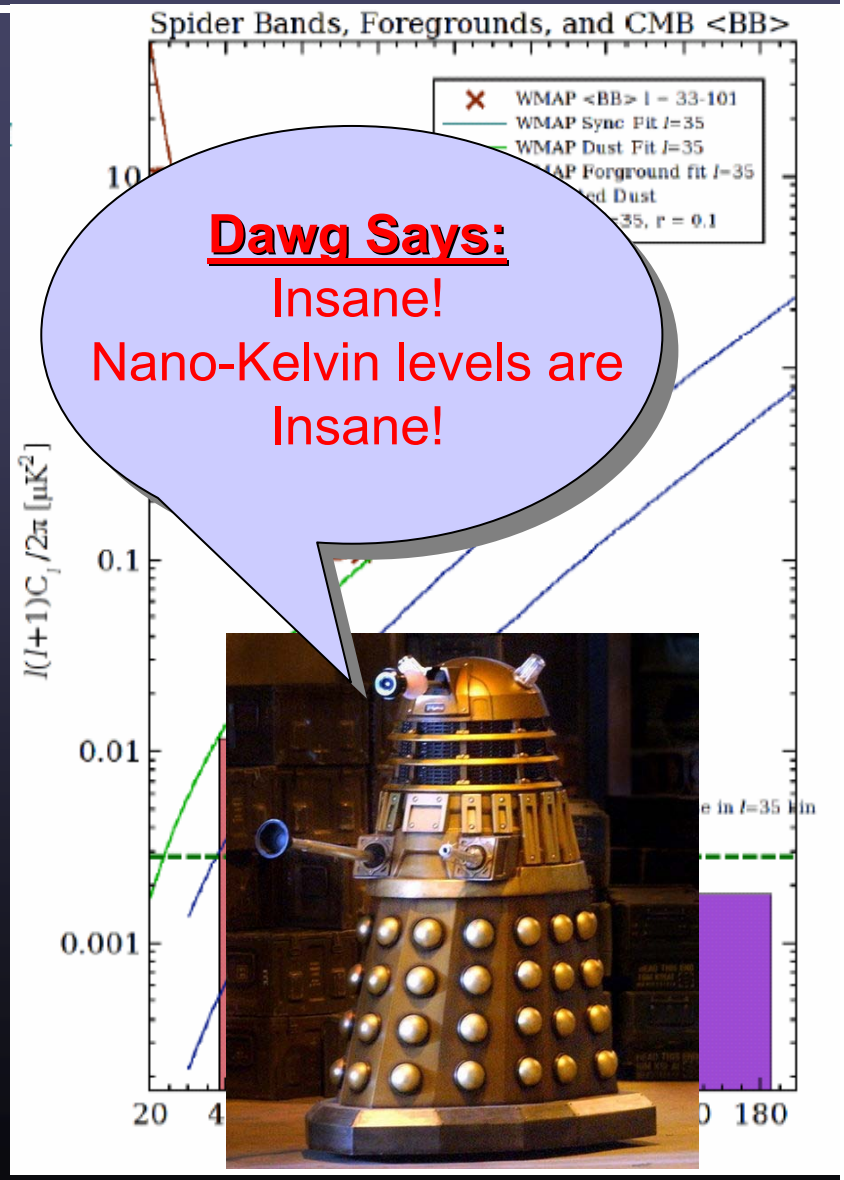

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Crazy? Toward a CMB Mega-Array?

- CBI, DASI, & VSA have demonstrated the utility of interferometry for CMB (particularly for polarization)
- sensitivity limited by number of elements
  - would need 100-1000 elements → 10^4 – 10^6 "pixels" (10-110x DASI)
  - could combine FPA and interferometer for multi-beaming
- would require massive wide-band correlators
  - development of "inexpensive" large-scale correlators
  - leverage R&D for other next generation big arrays (e.g. ATA,SKA)
- would be competing against bolometer & MMIC arrays
  - but systematics cleaner → complementary! for foregrounds?
- risky & expensive, but worth exploring…
  - detailed cost analysis: will NOT be a ~ $10M experiment
  - leverage off other next generation radio array development…

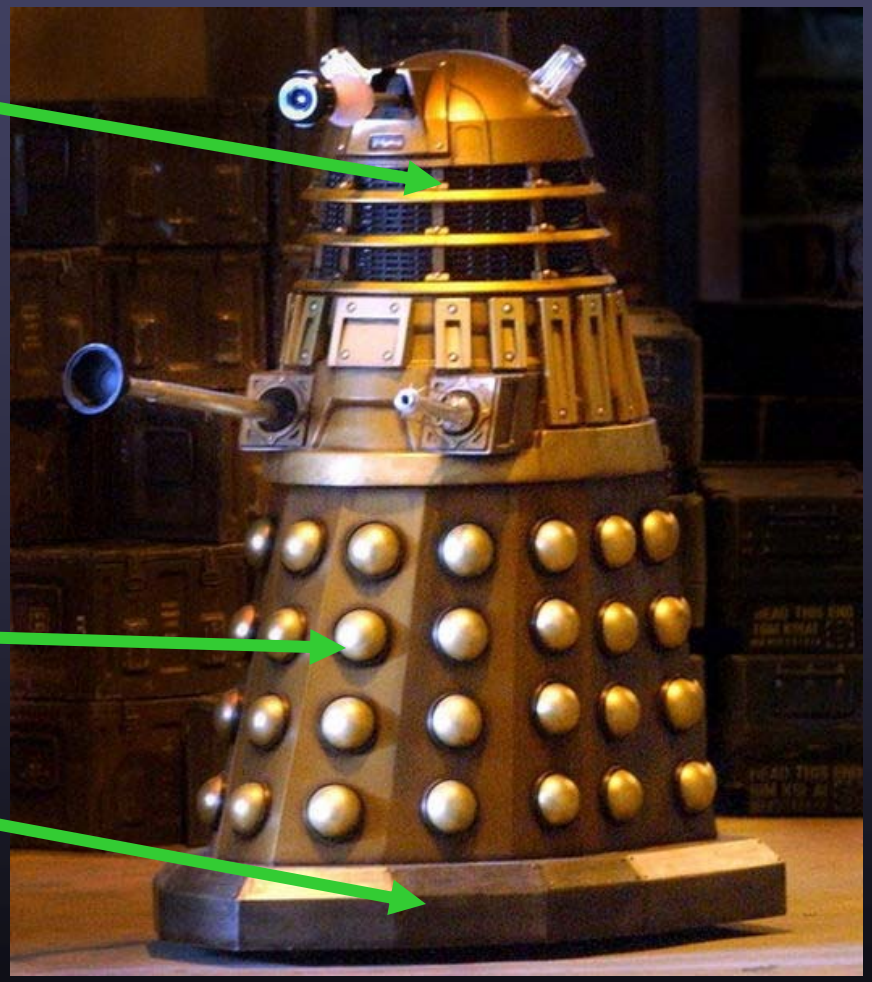
Join my Space Mission concept!

- DArk Lambda Explorer for Kosmogensis (DALEK)

correlator

interferometery arrays

propulsion unit



DALEK prototype “Dawg” in lab

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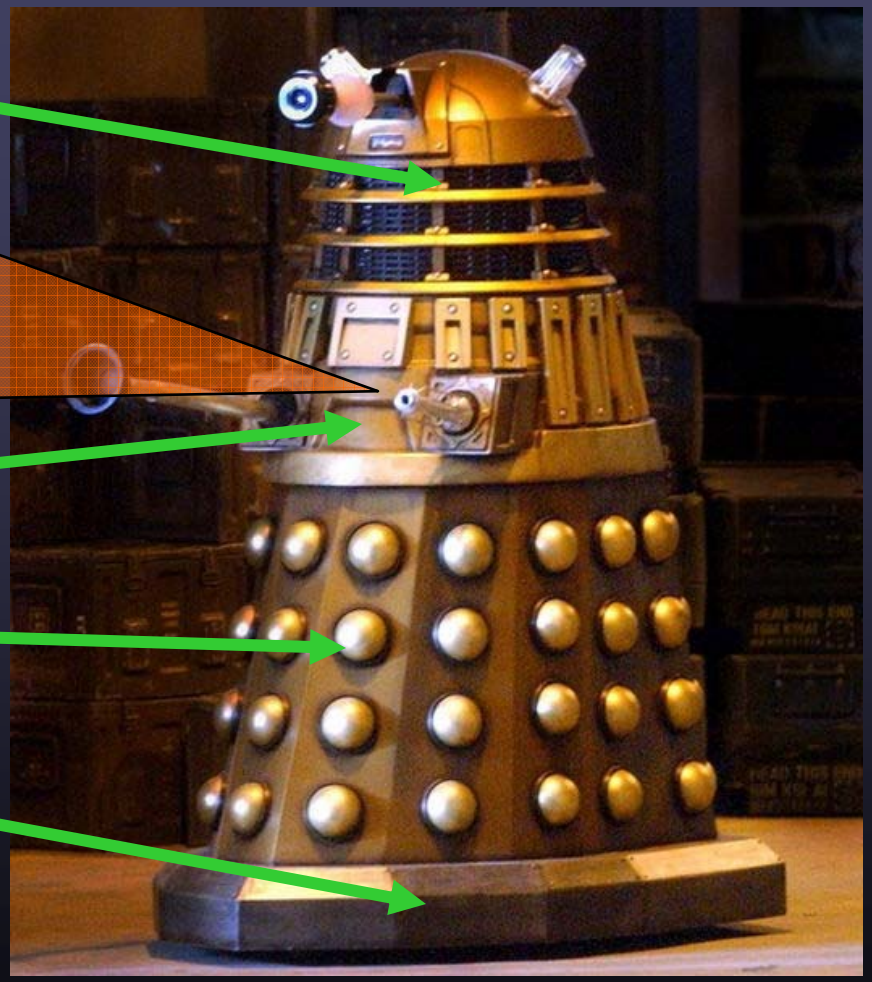

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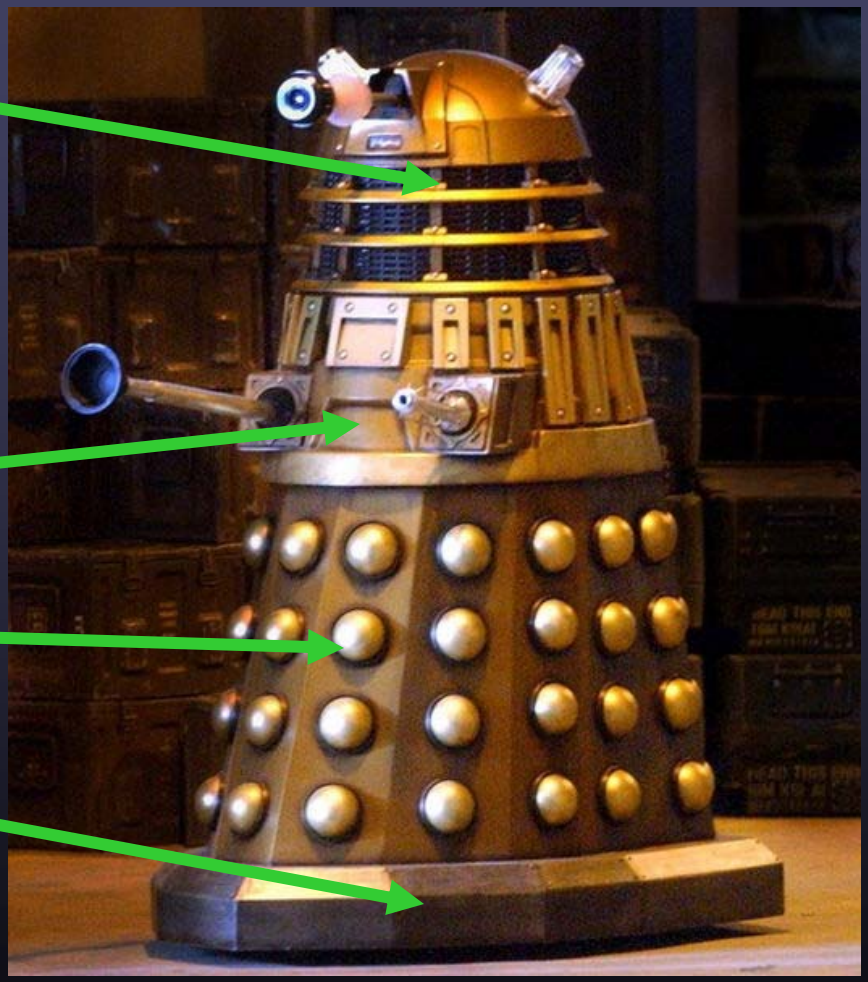

DALEK prototype “Dawg” in lab

People – The CBI Team

Caltech Team

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Steve Padin (formerly Project Scientist, now at University of Chicago)
Tim Pearson
Tony Readhead (Principal Investigator)
Martin Shepherd
Alison Farmer *
Russ Keeney *
Steve Miller *
Walter Schaal *
John Yamasaki *

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Caltech

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Joey Richards
Jonathan Sievers (PhD 2004; now at CITA, Toronto)
Pat Udomprasert (PhD 2004)

Universidad de Concepción

Ricardo Bustos
Rodrigo Reeves

Operations in Chile

Cristobal Achermann
Wilson Araya
Ricardo Bustos
José Cortes
Justina Cruz
Nolberto Oyarce
Rodrigo Reeves
Lorena Toro
Masao Uehara
Pablo Altamirano *
Tomislav Vucina *
José Nail *

* Former team members

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John Carlstrom (University of Chicago)
Simon Casassus (Universidad de Chile)
Carlo Contaldi (CITA)
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Richard Davis (Manchester)
Pedro Ferreira (Oxford)
Mike Jones (Oxford)
John Kovac (Caltech)
Paddy Leahy (Manchester)
Erik Leitch (JPL)
Brian Mason (National Radio Astronomy Observatory)
Jorge May (Universidad de Chile)
Karl Menten (MPIfR, Bonn)
Steven Myers (National Radio Astronomy Observatory)
Marian Pospieszalski (National Radio Astronomy Observatory)
Clem Pryke (University of Chicago)
Steve Rawlings (Oxford)
Angela Taylor (Oxford)
Sergio Torres (Universidad de Concepción)
Glenn White (Rutherford-Appleton Lab)
Peter Wilkinson (Manchester)
Anton Zensus (MPIfR, Bonn)

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Bill Holzapfel (University of California, Berkeley)
Marshall Joy (NASA's Marshall Space Flight Center)
Angel Otarola (European Southern Observatory)
Ue-Li Pen (CITA)
Dmitry Pogosyan (University of Alberta)
Simon Prunet (Institut d'Astrophysique de Paris)

- http://astro.caltech.edu/~tjp/CBI/
- http://www,aoc.nrao.edu/~smyers/cbi/
- Readhead et al. 2004, ApJ, 609, 498
- Readhead et al. 2004, Science 306, 836
- Sievers et al. 2005, astro-ph/0509203