Title: Cosmology from WMAP

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Abstract:

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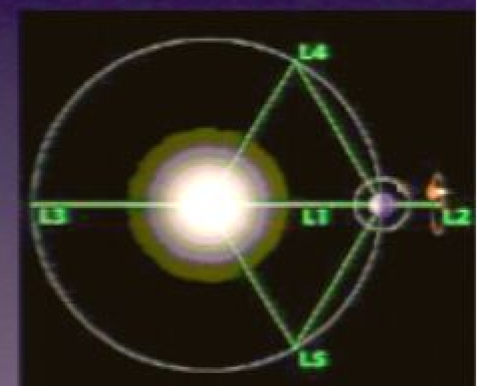
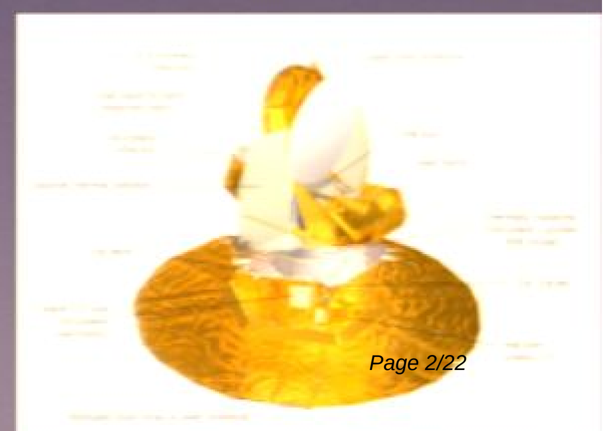
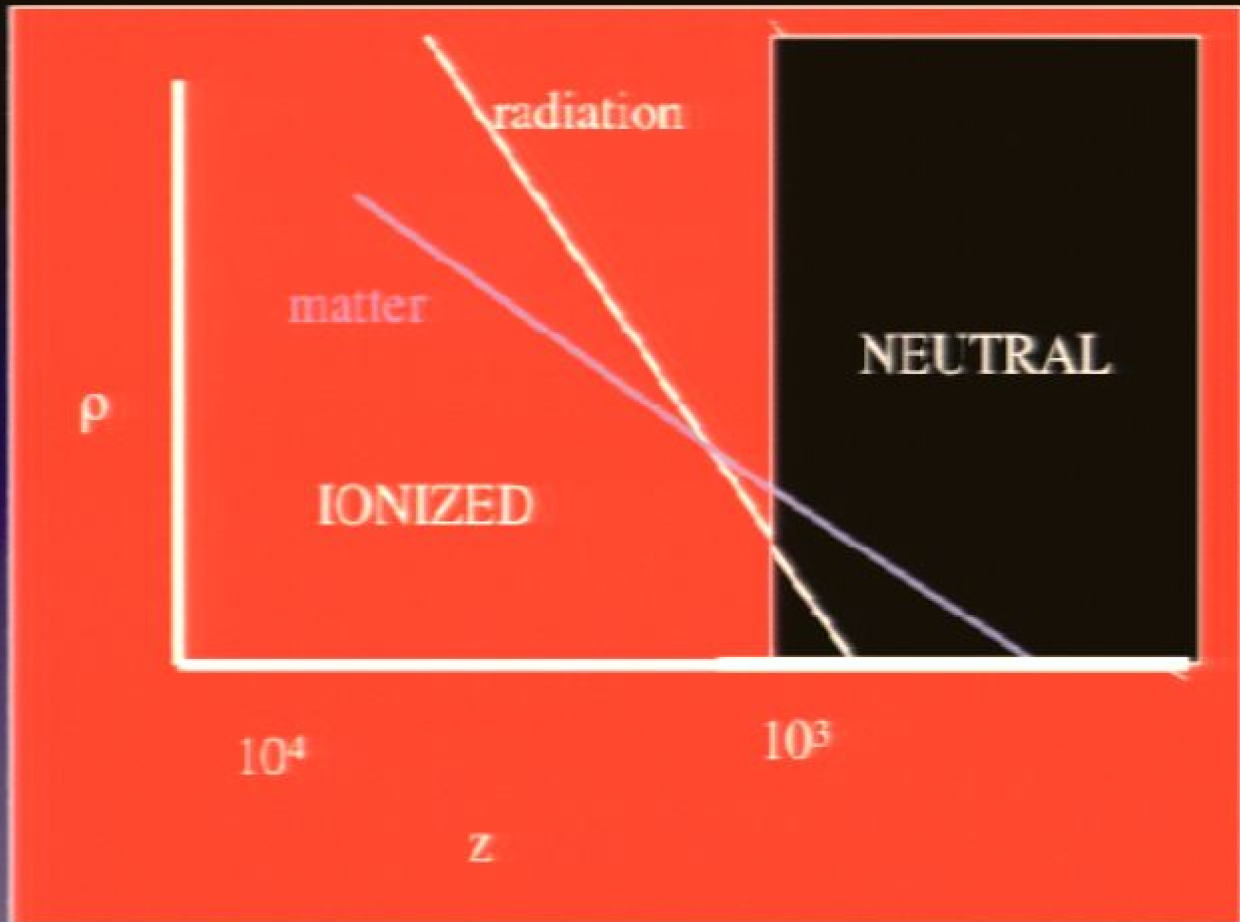




WMAP 5-yr papers

- Hinshaw et al., "Data Processing, Sky Maps, and Basic Results"
- Hill et al., "Beam Maps and Window Functions"
- Gold et al., "Galactic Foreground Emission"
- Wright et al., "Source Catalogue"
- Nolta et al., "Angular Power Spectra"
- Dunkley et al., "Likelihoods and Parameters from the WMAP data"
- Komatsu et al., "Cosmological Interpretation"

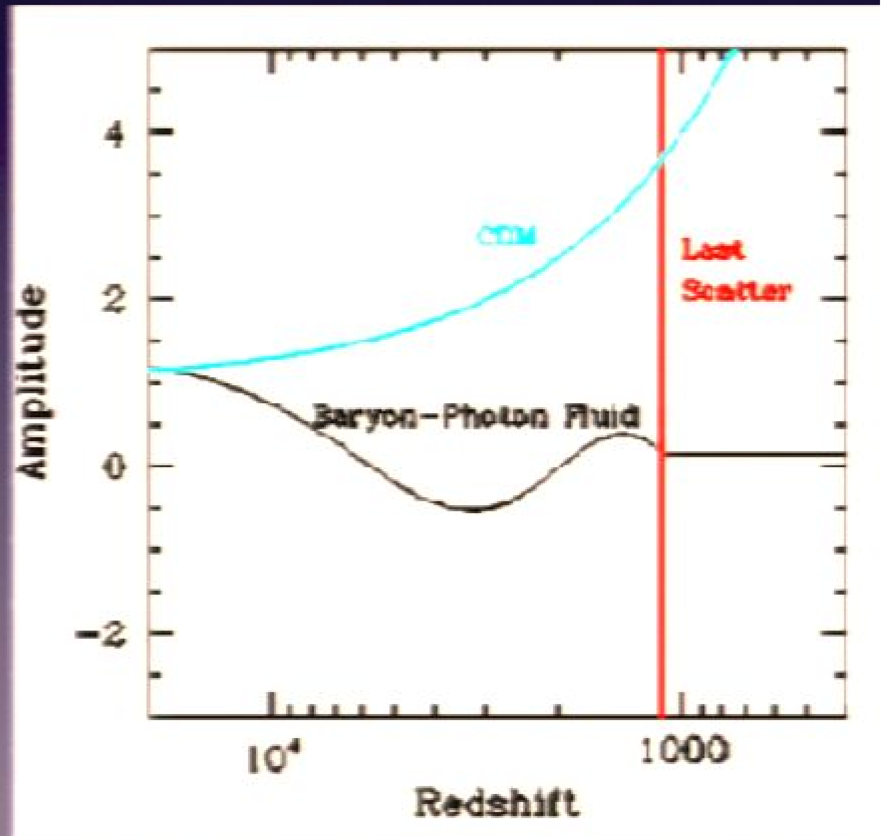


Universe starts out hot, dense and filled with radiation.

As the universe expands, it cools.
- During the first minutes, light elements form
- After 400,000 years, atoms form
- After ~100,000,000 years, stars start to form
- After ~1 Billion years, galaxies and quasars

CMB as probe of fluctuations

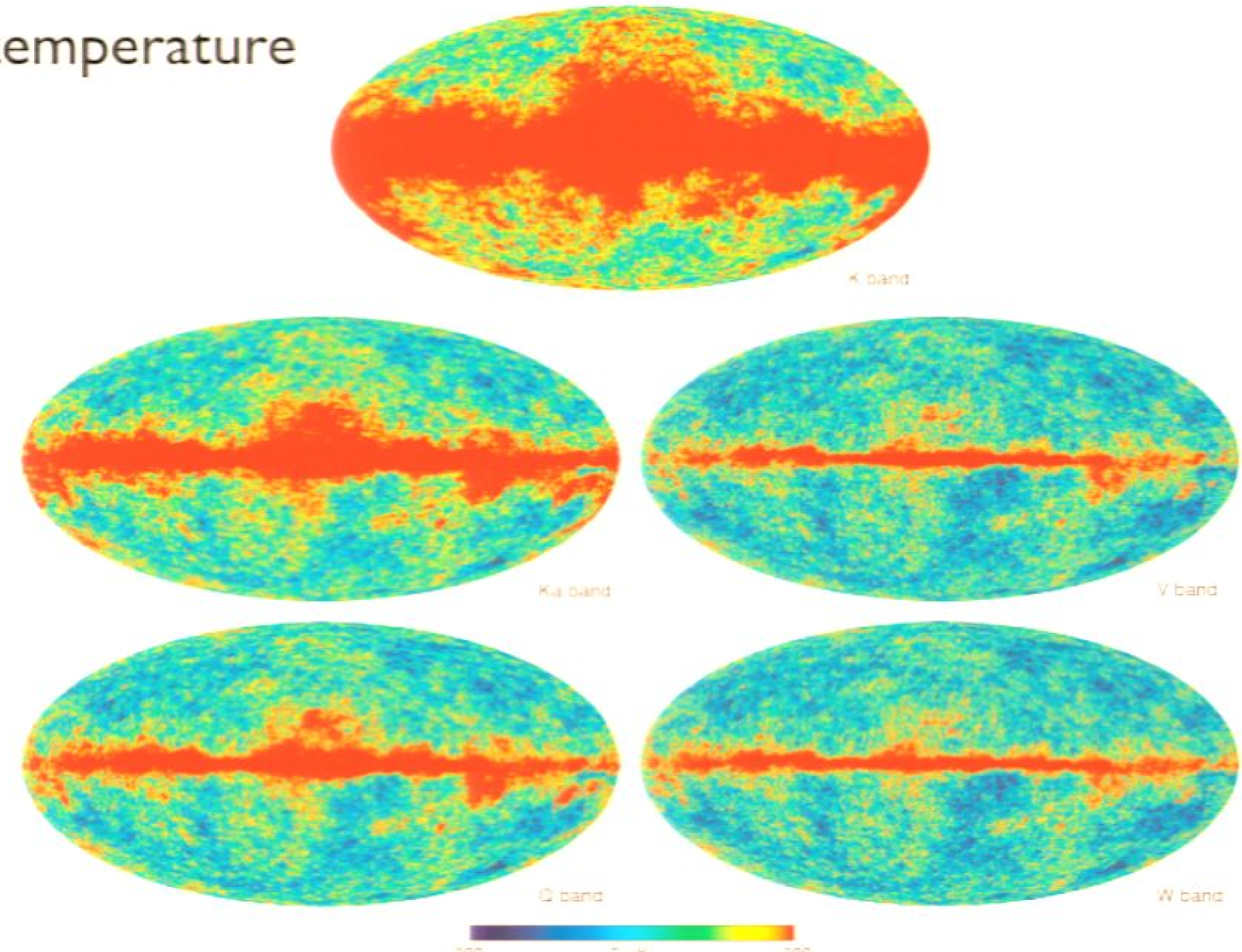
Linear theory
Basic elements have been understood for 30 years (Peebles, Sunyaev & Zeldovich)
Numerical codes agree to better than 0.1% *(Seljak et al 2003)*



$$T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

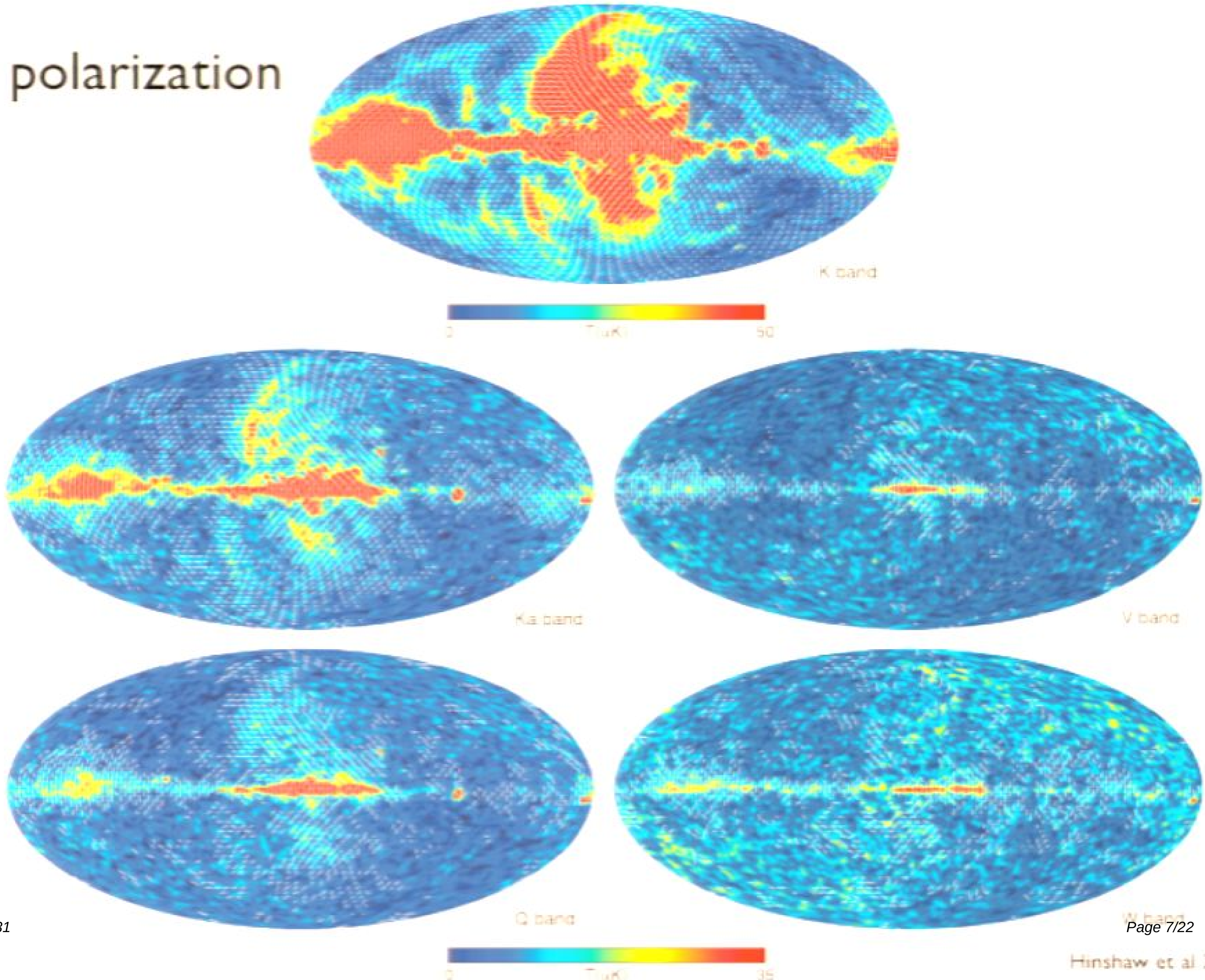
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

5yr temperature



Hinshaw et al 2008

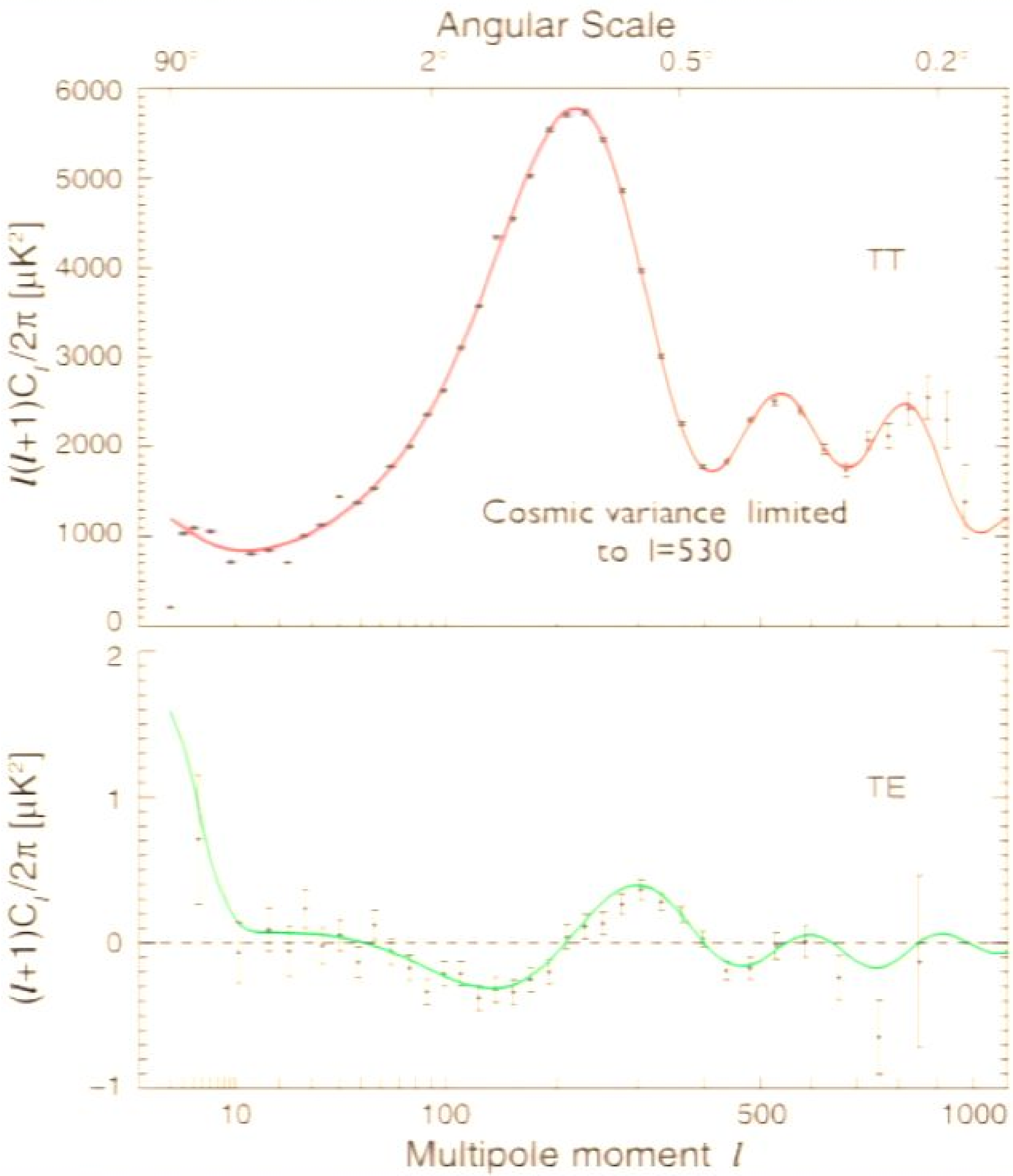
5yr polarization



Hinshaw et al 2008

Improvements in analysis

- More Polarization Data for Cosmology
  - We now use the polarization data in three bands
- Improved Beam Model
  - 5 yrs of Jupiter observations, combined with optics modeling, reduce the beam uncertainty by a factor of ~2 (Hill et al 2008). 5-year power spectrum is ~2.5% larger at $l>200$
- Also: improved calibration from the CMB dipole, improved Galactic mask, faster likelihood code

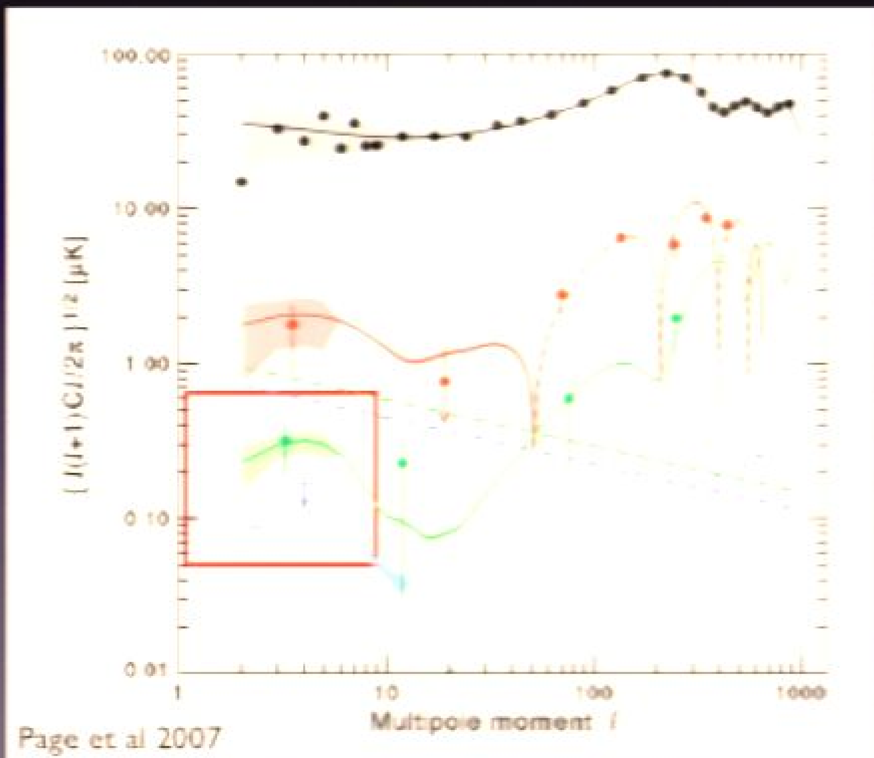


Much improved measurement of the 3rd peak

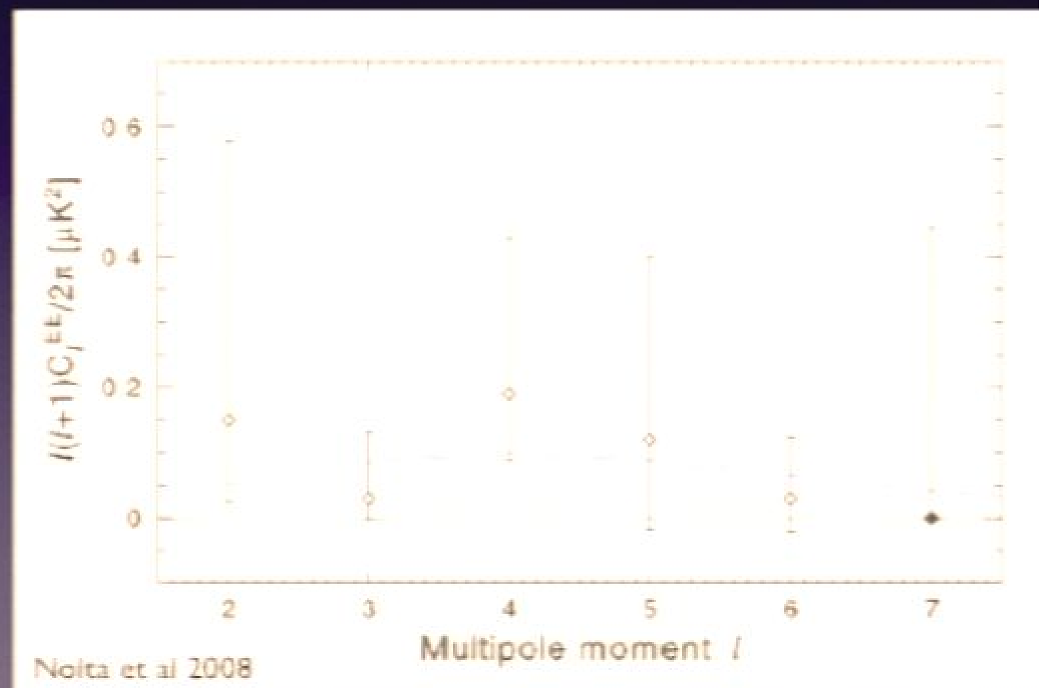
Hinshaw et al 2008

E-mode polarization

Generated at large scales by CMB quadrupole scattering off electrons from reionized universe



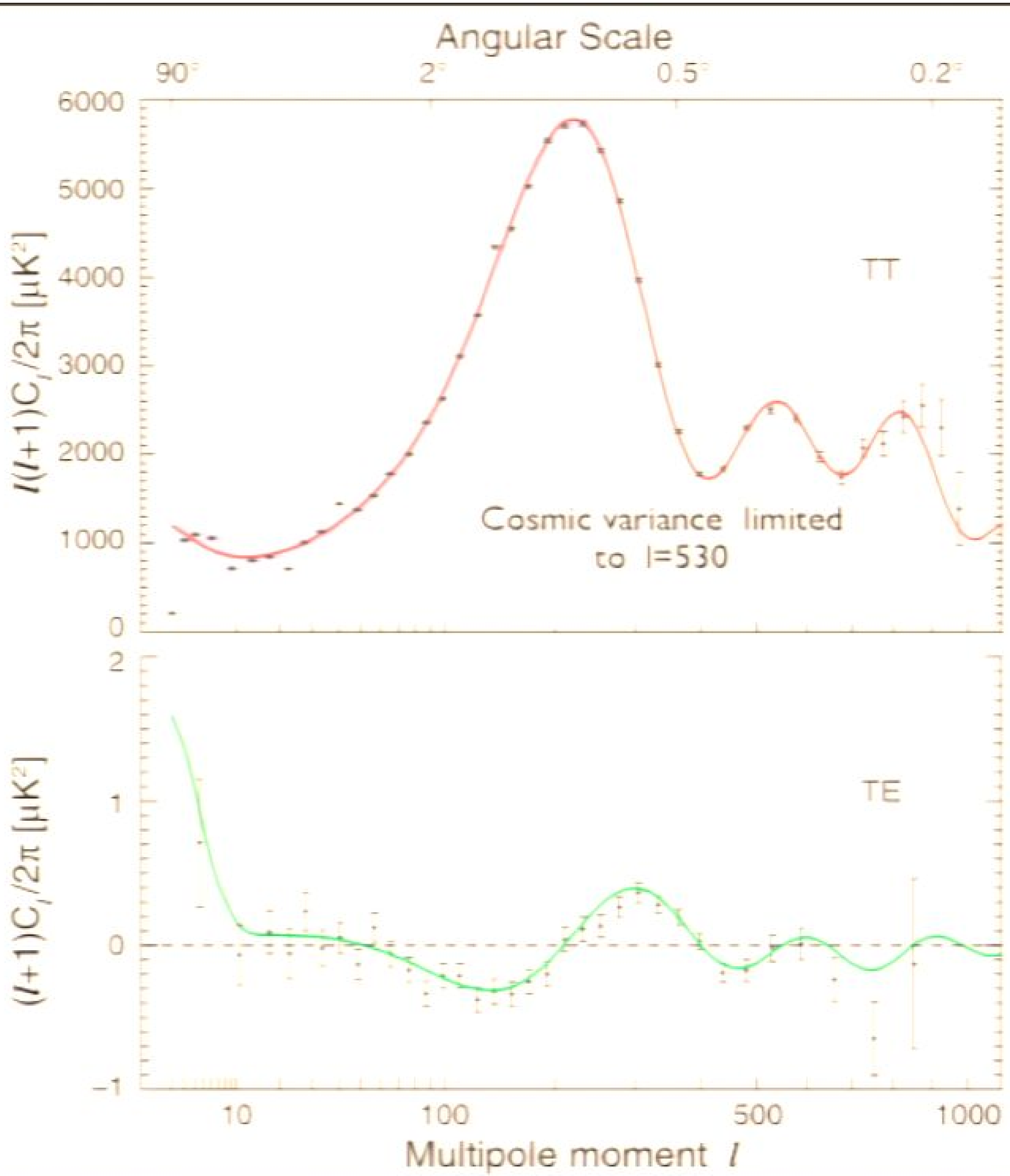
Page et al 2007



Nolta et al 2008

Optical Depth to reionization:

- Tau(5yr) = 0.087 +/- 0.017 (Dunkley et al. 2008)
- Tau(3yr) = 0.089 +/- 0.030 (Page et al. 2007)



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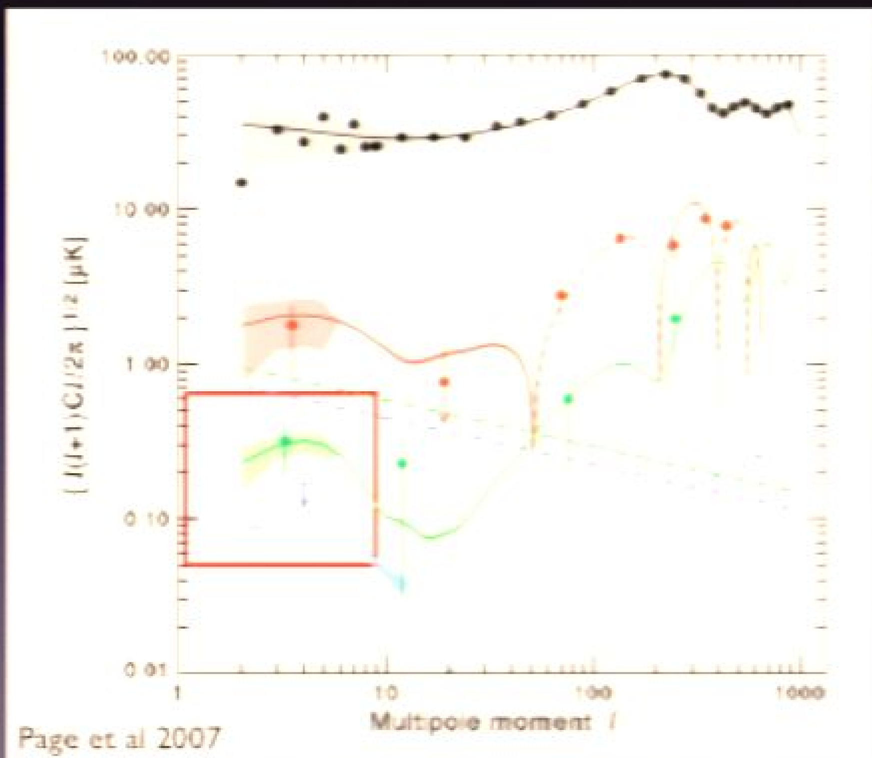

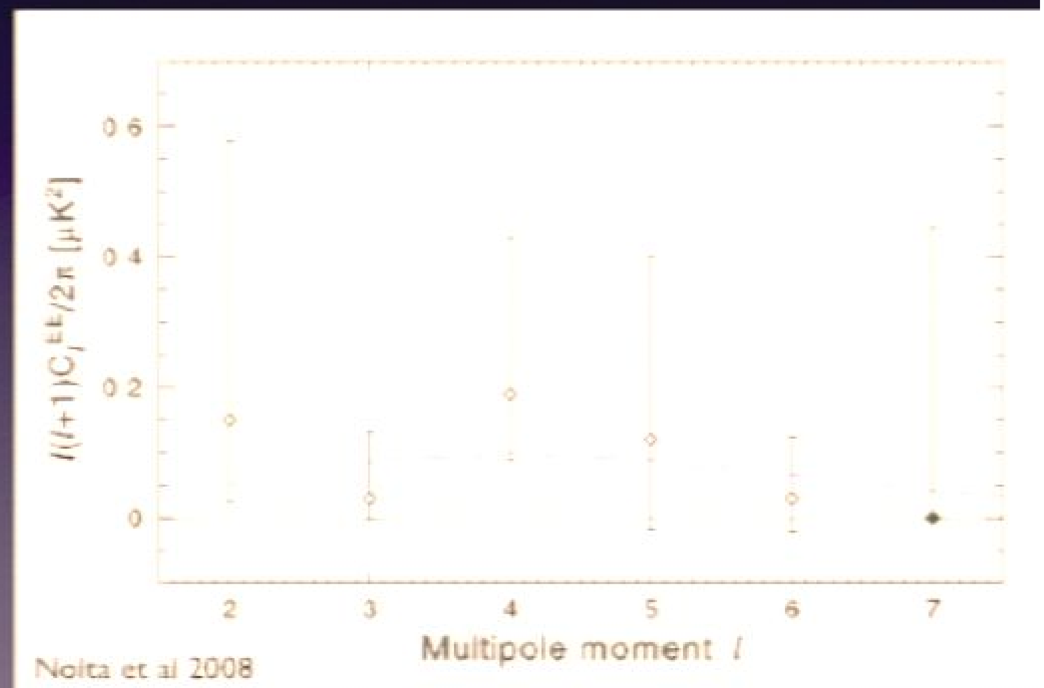

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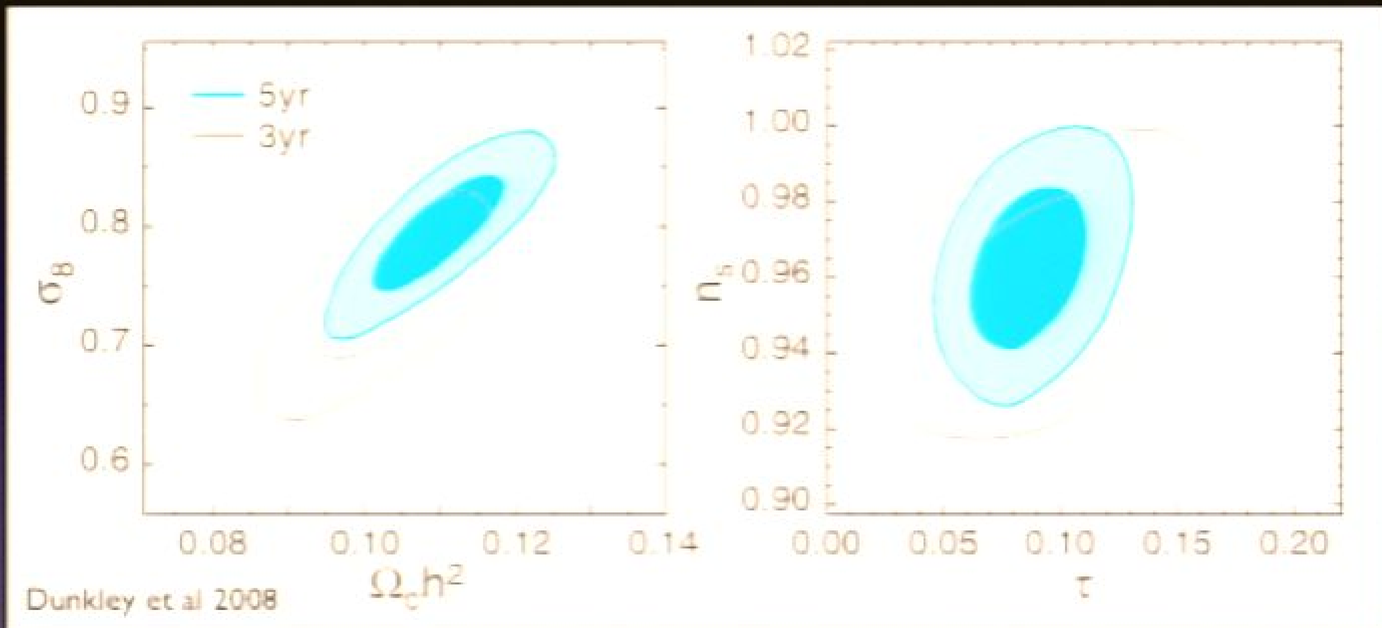
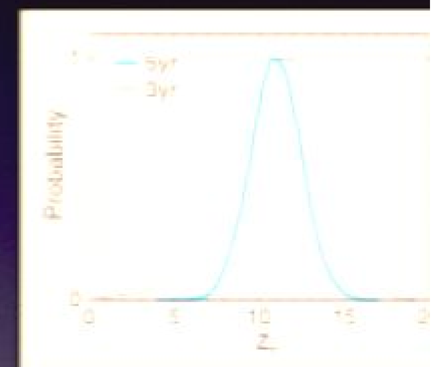
LCDM Cosmological Model



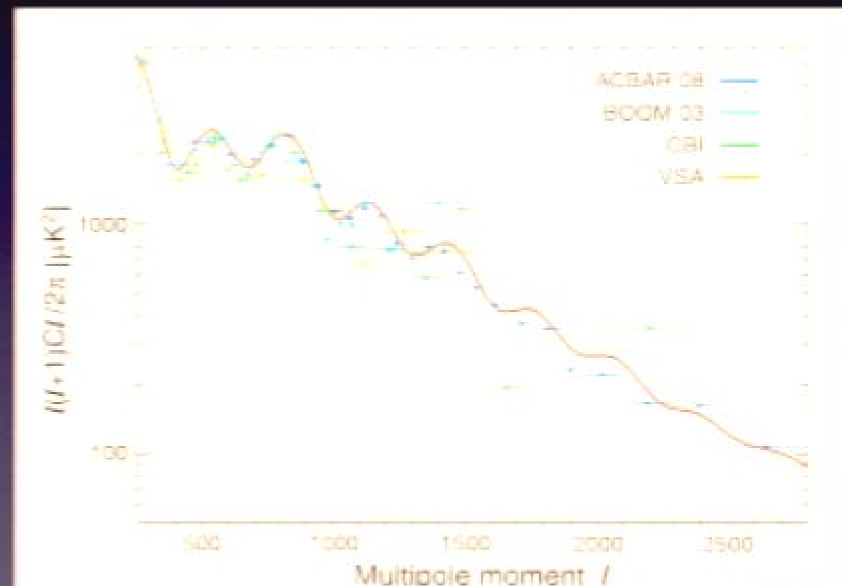


- Flat universe filled with baryons, CDM, cosmological constant, neutrinos, photons.
- Gaussian, adiabatic, nearly scale-invariant fluctuations

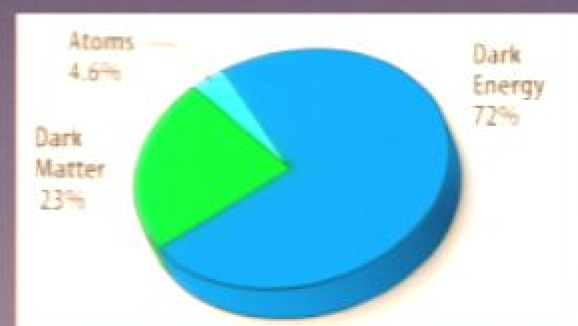
Parameter	3 Year Mean	5 Year Mean
$100\Omega_b h^2$	2.229 ± 0.073	2.273 ± 0.062
$\Omega_c h^2$	0.1054 ± 0.0078	0.1099 ± 0.0062
Ω_Λ	0.759 ± 0.034	0.742 ± 0.030
n_s	0.958 ± 0.016	$0.963^{+0.014}_{-0.015}$
τ	0.089 ± 0.030	0.087 ± 0.017
Δ^2_R	$(2.35 \pm 0.13) \times 10^{-9}$ [illegible]	$(2.41 \pm 0.11) \times 10^{-9}$ [illegible]
σ_8	0.761 ± 0.049	0.796 ± 0.036
Ω_m	0.241 ± 0.034	0.258 ± 0.030
$\Omega_m h^2$	0.128 ± 0.008	0.1326 ± 0.0063
H_0	73.2 [illegible]	71.9 [illegible]
z_{reion}	11.0 ± 2.6	11.0 ± 1.4
[illegible]	13.73 ± 0.16	13.69 ± 0.13

Model is consistent with other observations

- Small-scale CMB
- Baryon Acoustic Oscillations
- Type Ia Supernovae
- Galaxy power spectra
- Weak and strong lensing
- Big Bang Nucleosynthesis
- Hubble constant
- Galaxy clusters
- Lyman-alpha forest
- Integrated Sachs Wolfe



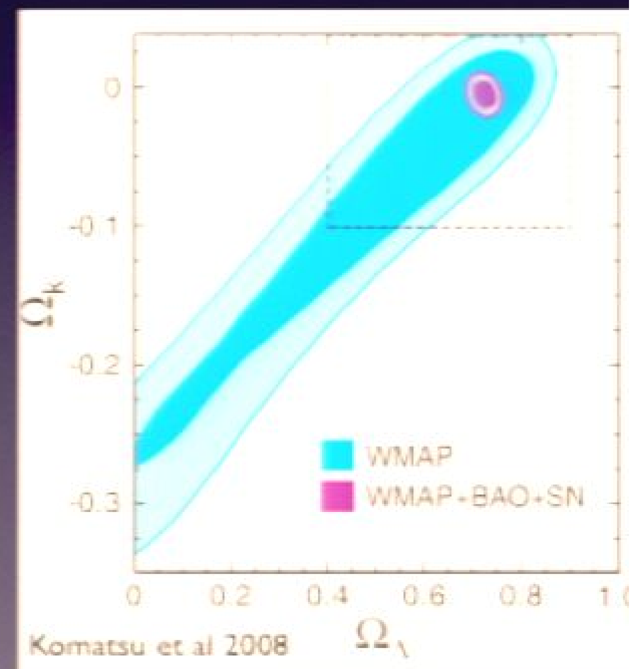
Dunkley et al 2008



Testing inflation

The WMAP data is consistent with these classical inflationary predictions:

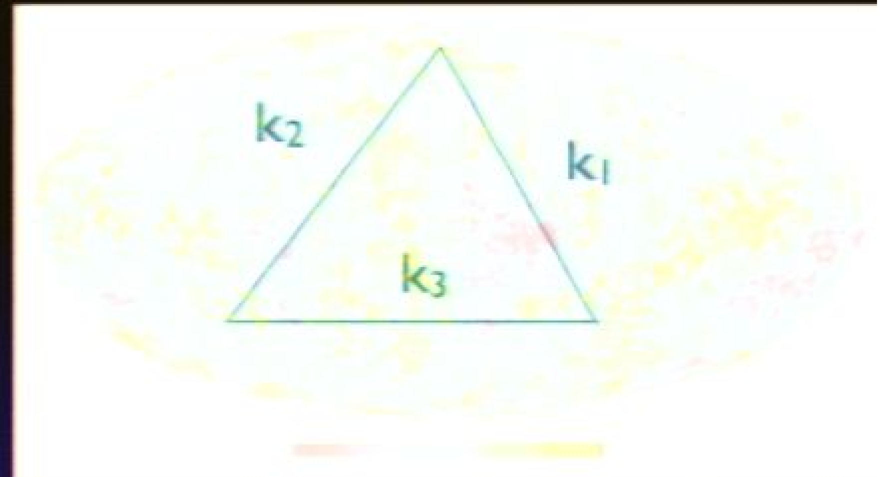
- The observable universe is flat
- The primordial fluctuations are adiabatic
- The primordial fluctuations are Gaussian
- The power spectrum is nearly scale invariant



With WMAP plus BAO and SN
-0.018 < Ω_k < 0.007 (95% CL

Curvature radius: R>23/h Gpc

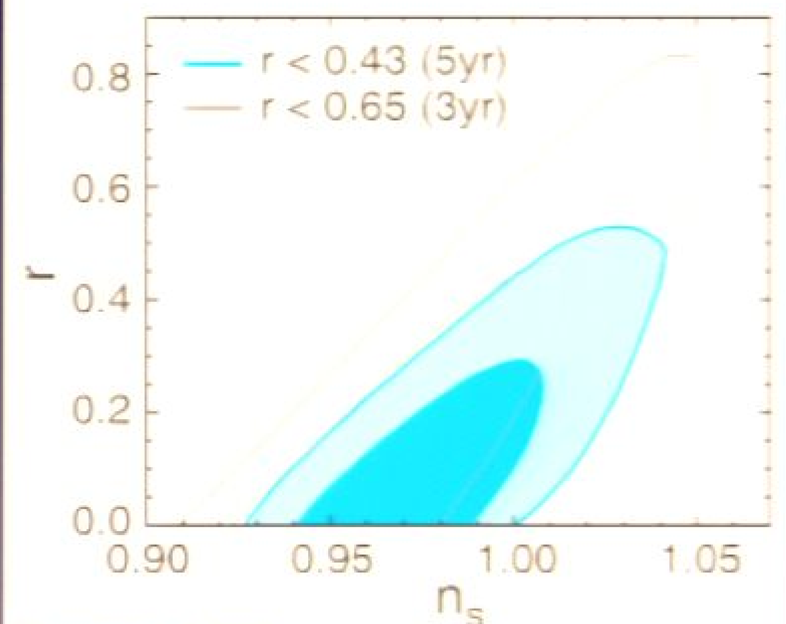
Non-Gaussianity?



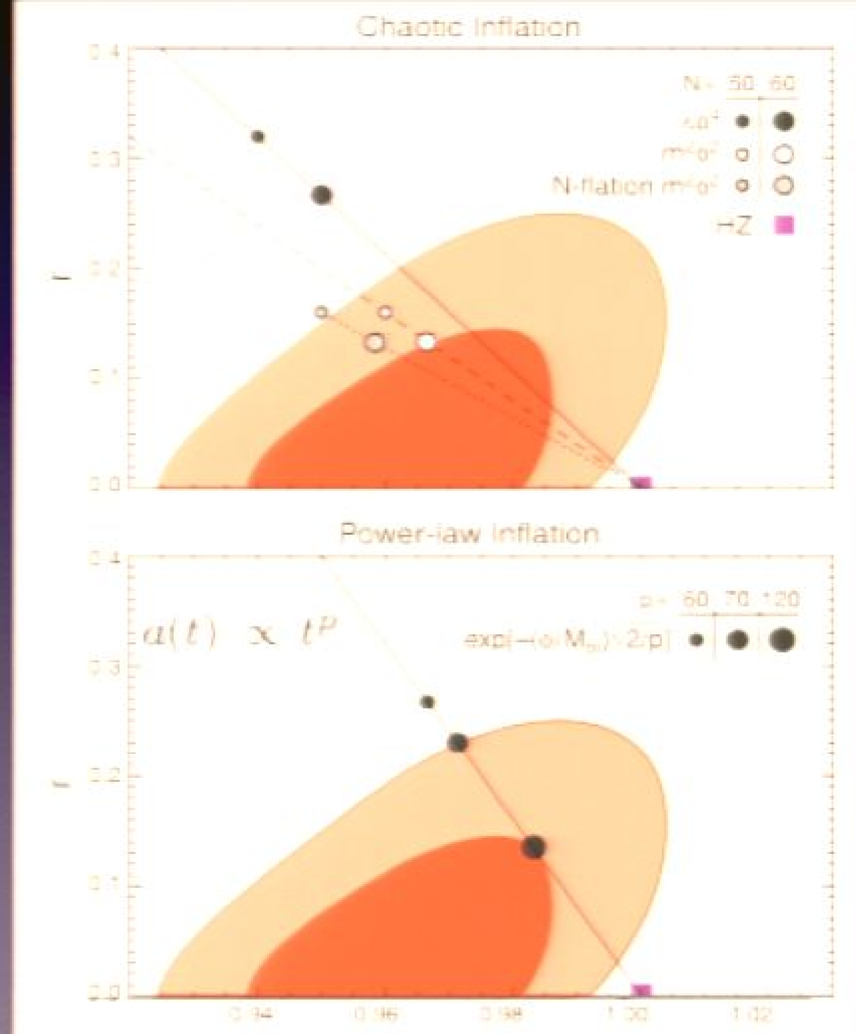
- Can look for non-Gaussianity by looking for non-zero bispectrum = 3 point function $\langle\Phi(k_1)\Phi(k_2)\Phi(k_3)\rangle = f_{NL}(2\pi)^2\delta^3(k_1+k_2+k_3)b(k_1,k_2,k_3)$
- $\Phi(k)$ is the Fourier transform of the curvature perturbation
- $-9 < f\_NL(local) < 111$ (95% CL) (Komatsu et al 2008)
- $-151 < f\_NL(equilateral) < 253$ (95% CL) (Komatsu et al 2008)
- The primordial curvature perturbations are Gaussian to 0.1% level
- Use the new Galaxy mask (KQ75) and correct for point-source contamination.

Limits on gravitational waves

Use WMAP to constrain tensor-to-scalar ratio: tensors produce B-mode polarization, but also a large-scale temperature signal.
(Currently low-l BBL r < 20)



Dunkley et al 2008



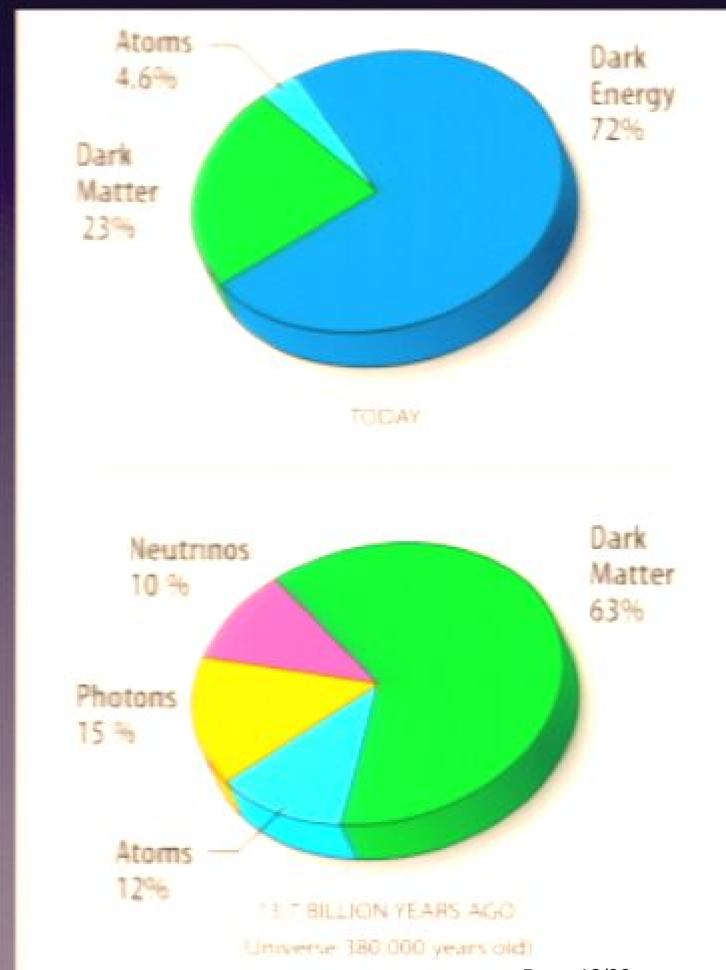
Komatsu et al 2008

- With all data: r < 0.20 (95% CL)

Contents of the universe

- Constrained baryon density, CDM density
- Constrained total geometry (2% errors on total curvature)
- What can we say about dark energy? (6-7% errors on constant w)
- What can we say about neutrinos?

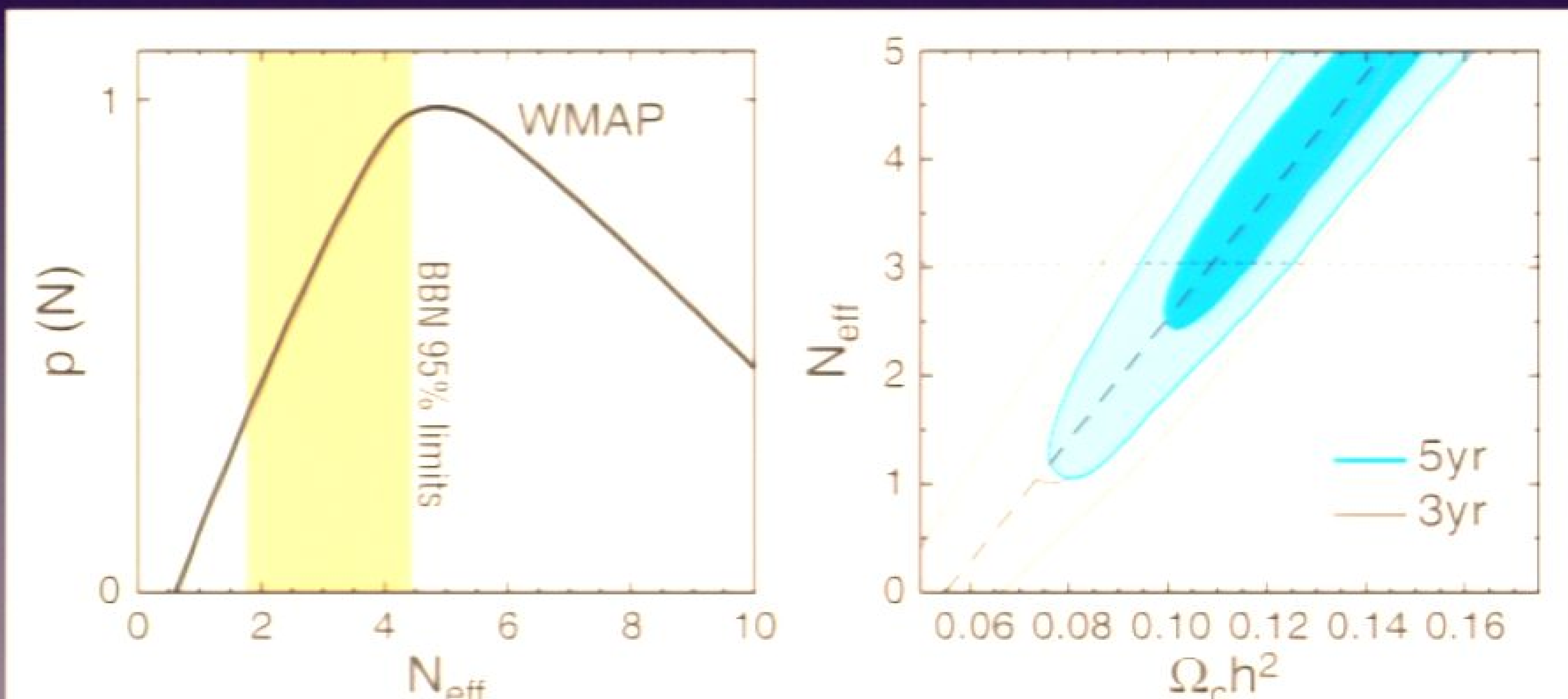
WMAP only	$\sum m_\nu < 1.3eV$
WMAP+BAO+SN	$\sum m_\nu < 0.61eV$



Evidence for relativistic species

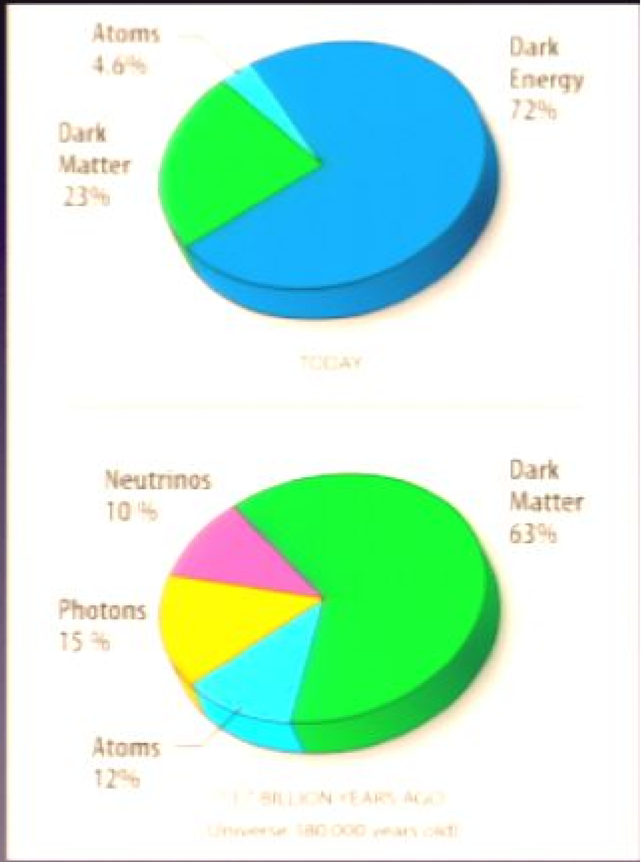
$$\rho_\nu = \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$

Relativistic species, e.g. neutrinos, that don't couple to photons/ baryons, affect expansion rate and acoustic oscillations



In summary...

- The LCDM cosmological model is still doing well, and is consistent with virtually all other astronomical observations
- Improvements with five-year WMAP: large-scale CMB polarization and third peak in temperature (~0.2 deg scales)
- Tells us more about contents of universe (hint of neutrinos), inflation/early universe (r<0.2, f_NL =0 within 2 sigma), reionization (likely extended)
- Improved non-WMAP distance measurements (from galaxy positions plus supernovae) help place strong constraints on wider range of models (e.g. w, curvature)



Komatsu et al. (2008

Main Result (Local)

Band	Mask	l_{max}	f_{NL}^{local}	Δf_{NL}^{local}	b_{src}
V+W	*KQ85*	400	50 ± 29	1 ± 2	0.26 ± 1.5
V+W	*KQ85*	500	61 ± 26	2.5 ± 1.5	0.05 ± 0.50
V+W	*KQ85*	600	68 ± 31	3 ± 2	0.53 ± 0.28
V+W	*KQ85*	700	67 ± 31	3.5 ± 2	0.34 ± 0.20
V+W	*Kp0*	500	61 ± 26	2.5 ± 1.5	
V+W	*KQ75p1*[a]	500	53 ± 28	4 ± 2	
V+W	*KQ75*	400	47 ± 32	3 ± 2	-0.50 ± 1.7
V+W	*KQ75*	500	55 ± 30	4 ± 2	0.15 ± 0.51
V+W	*KQ75*	600	61 ± 36	4 ± 2	0.53 ± 0.30
V+W	*KQ75*	700	58 ± 36	5 ± 2	0.38 ± 0.21

- The results are not sensitive to the maximum multipoles used in the analysis, l_{max}.