Cosmology from WMAP

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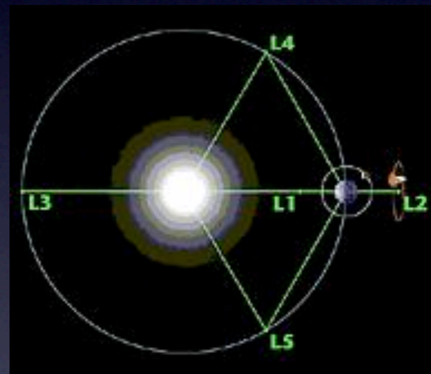
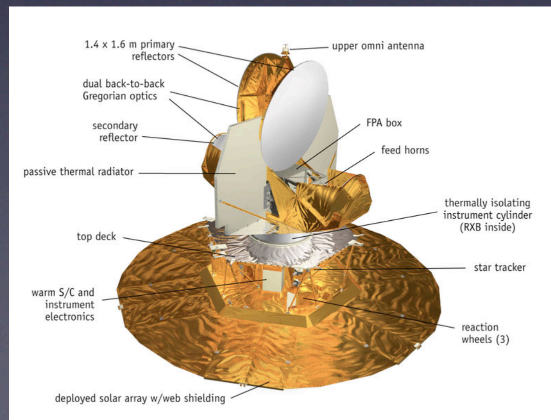
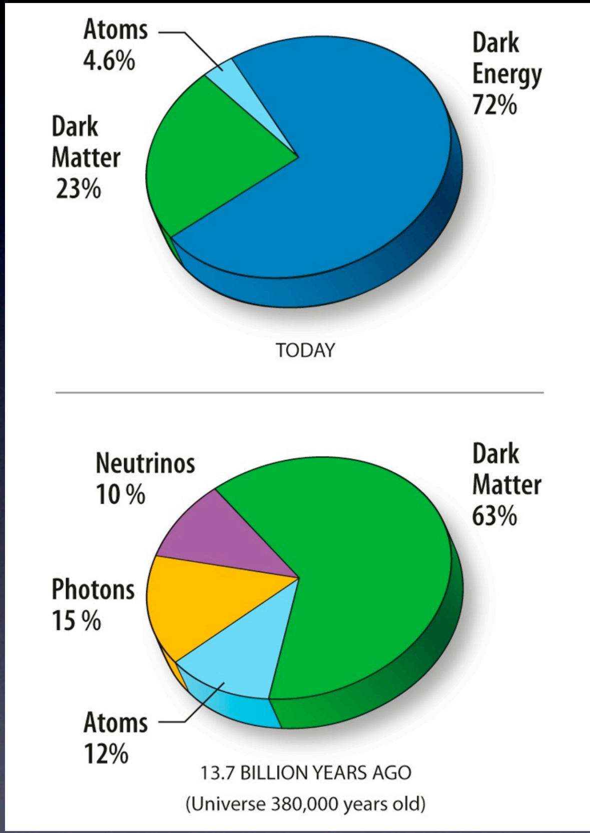


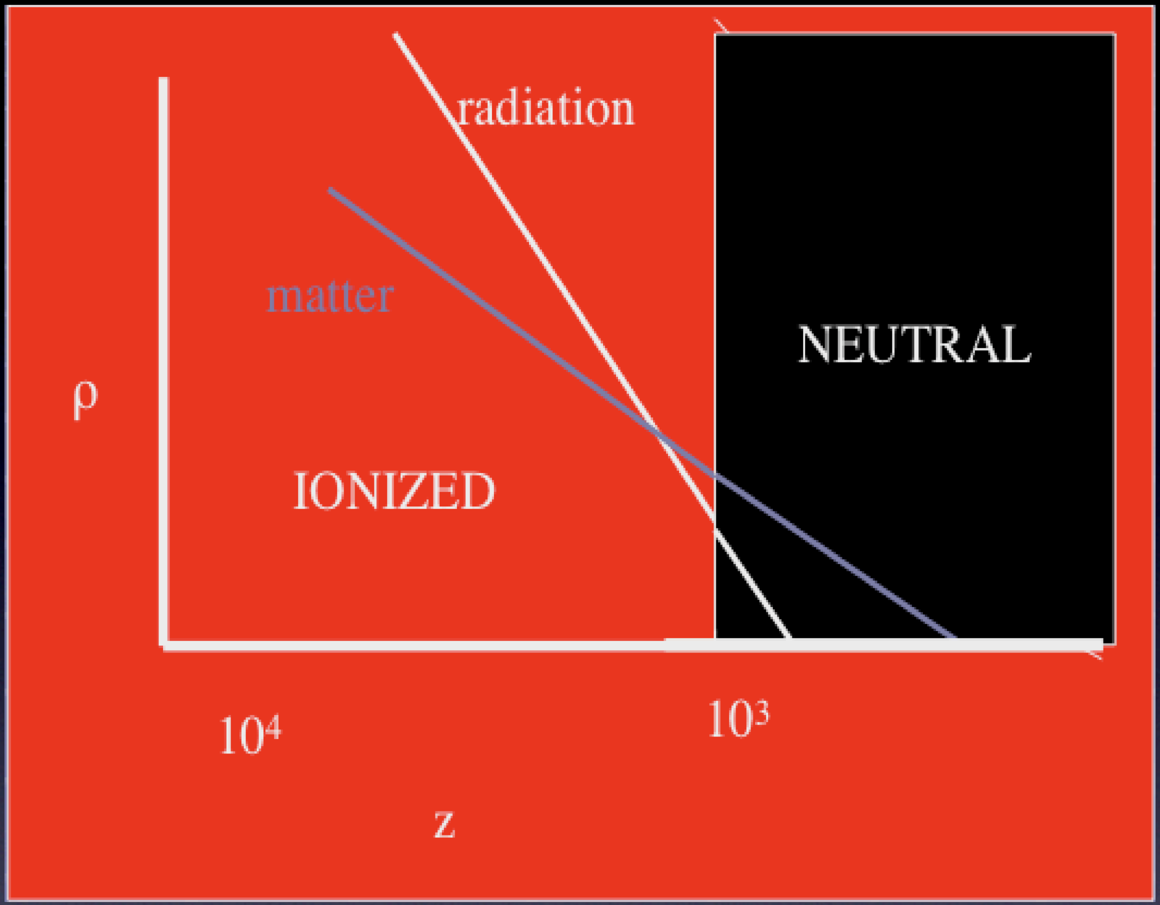


In summary...

- The LCDM cosmological model is still doing well
- Model is consistent with virtually all other astronomical observations

- Main improvements with five-year WMAP data are large-scale CMB polarization and 'third peak' temperature (~0.2 deg scales)
- Tells us more about contents of universe, inflation, reionization
- Improved non-WMAP distance measurements (from galaxy positions plus supernovae) help place strong combined constraints on wider range of models





Universe starts out hot, dense and filled with radiation.

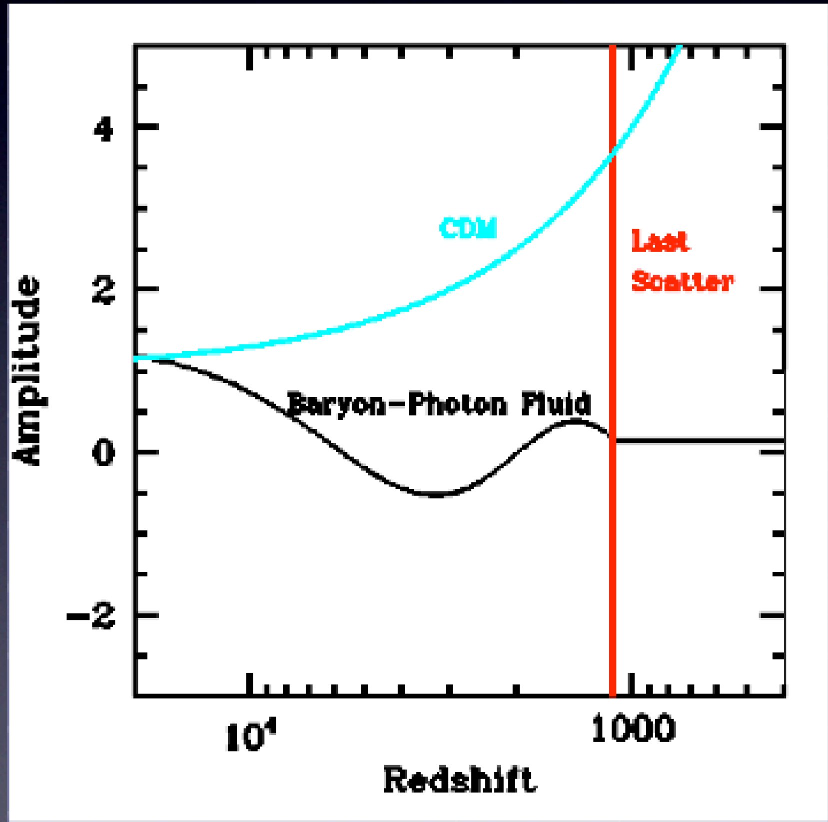
As the universe expands, it cools.
During the first minutes, light elements form
After 400,000 years, atoms form
After ~100,000,000 years, stars start to form
After ~1 Billion years, galaxies and quasars

CMB as probe of fluctuations

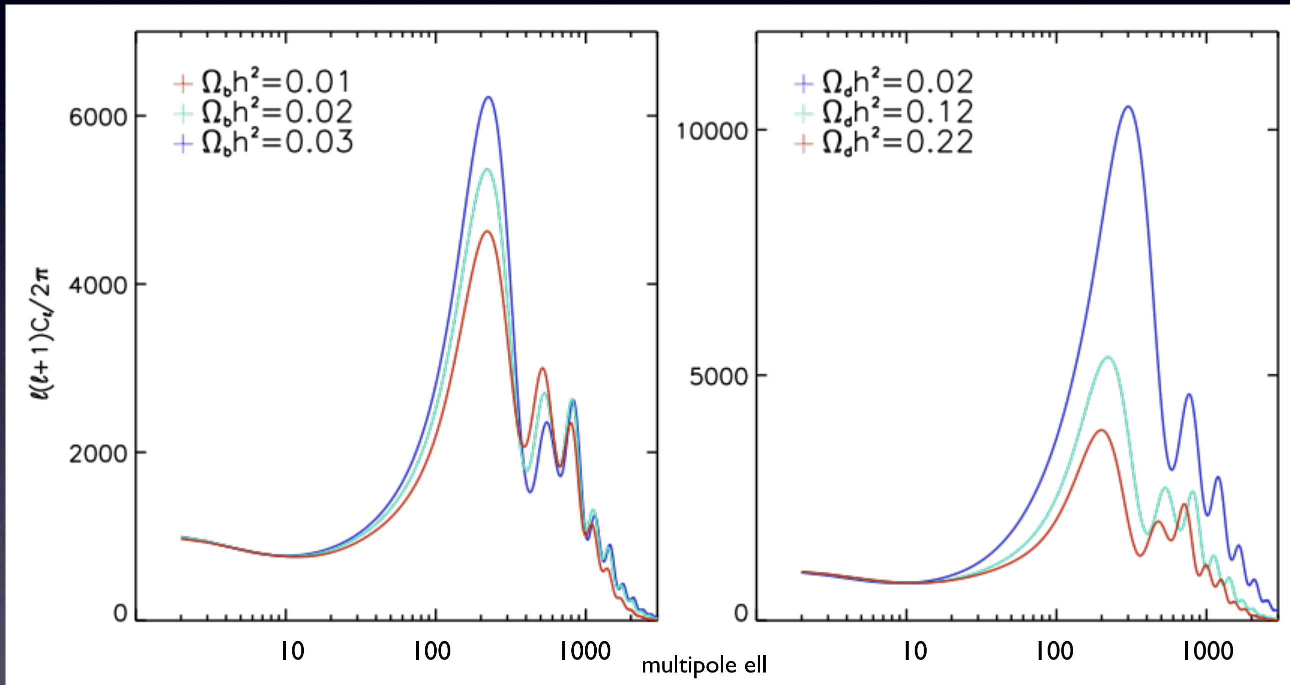
Linear theory
Basic elements have been
understood for 30 years
(Peebles, Sunyaev & Zeldovich)
Numerical codes agree to better
than 0.1% *(Seljak et al 2003)*

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

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



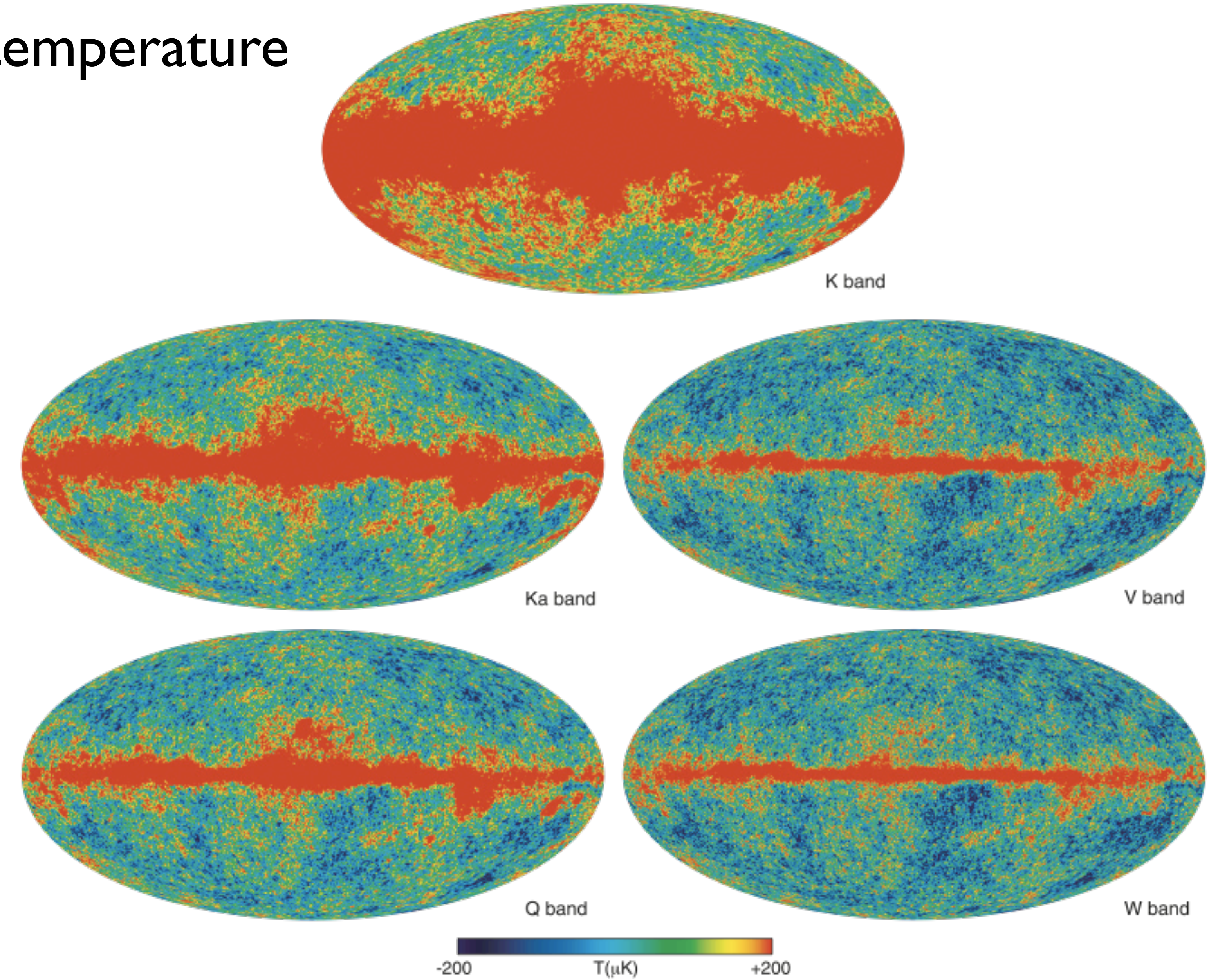
How we constrain parameters



Baryon density

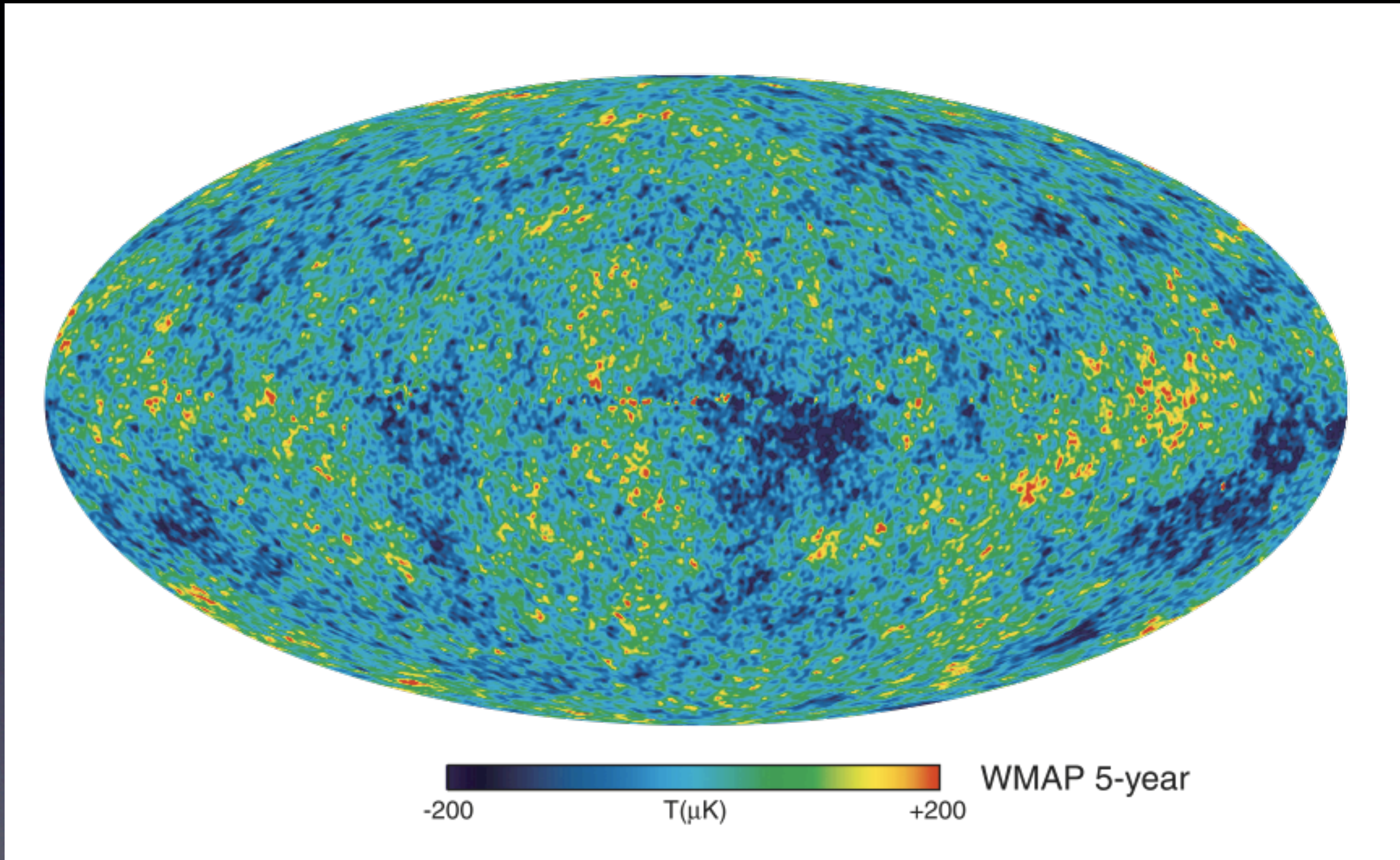
CDM density

5yr temperature



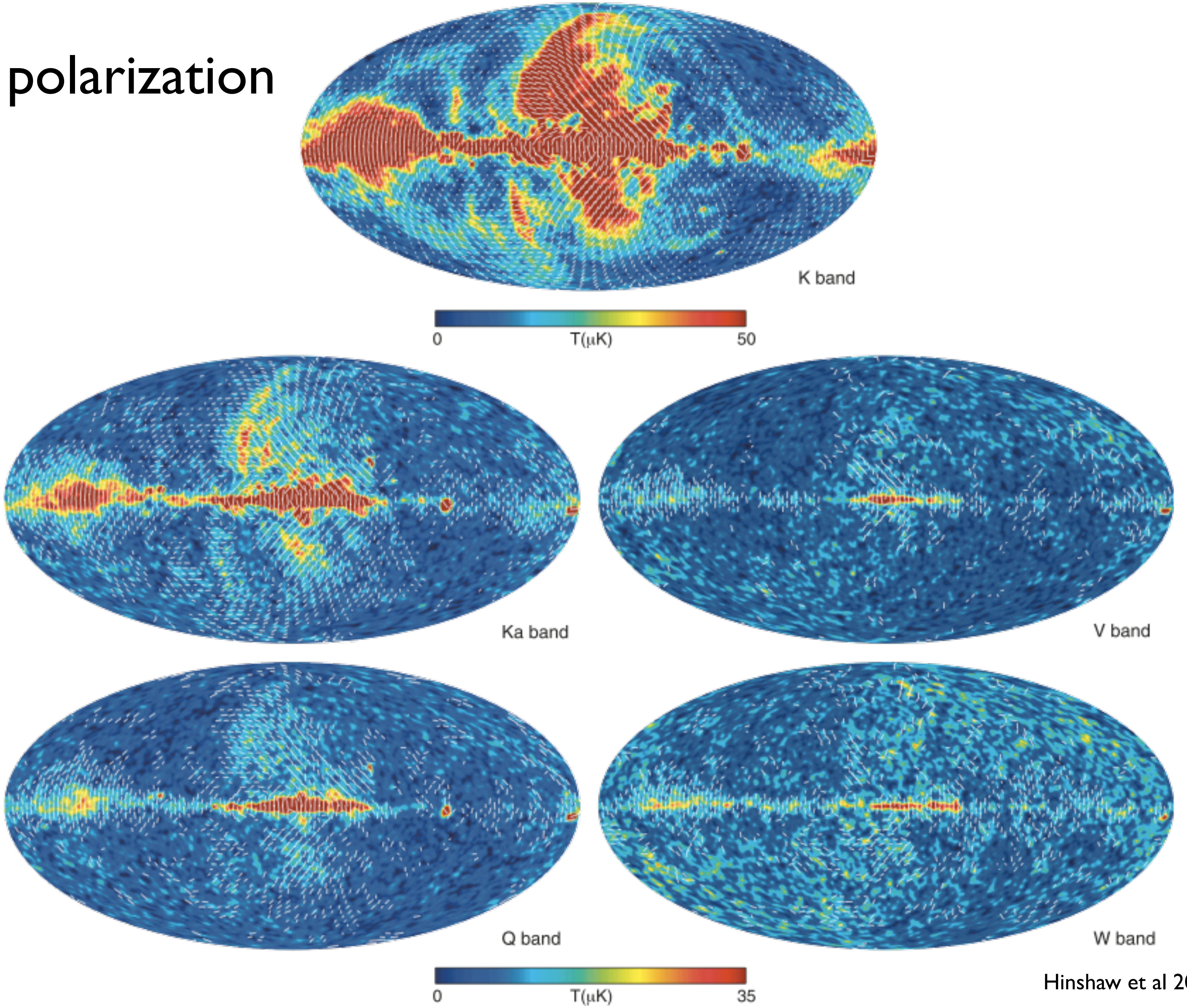
Hinshaw et al 2008

WMAP 5-yr data



Hinshaw et al 2008

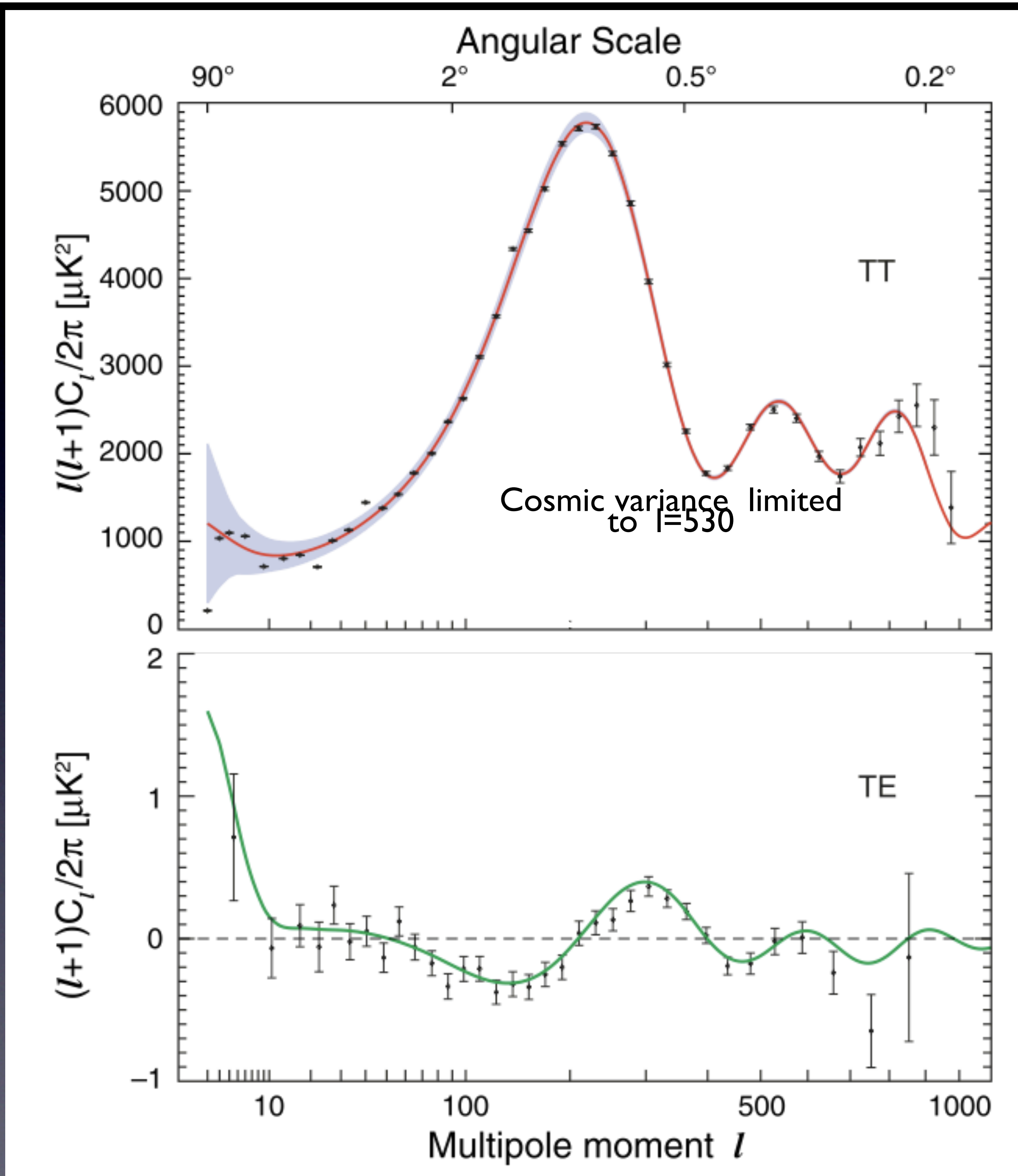
5yr polarization



Hinshaw et al 2008

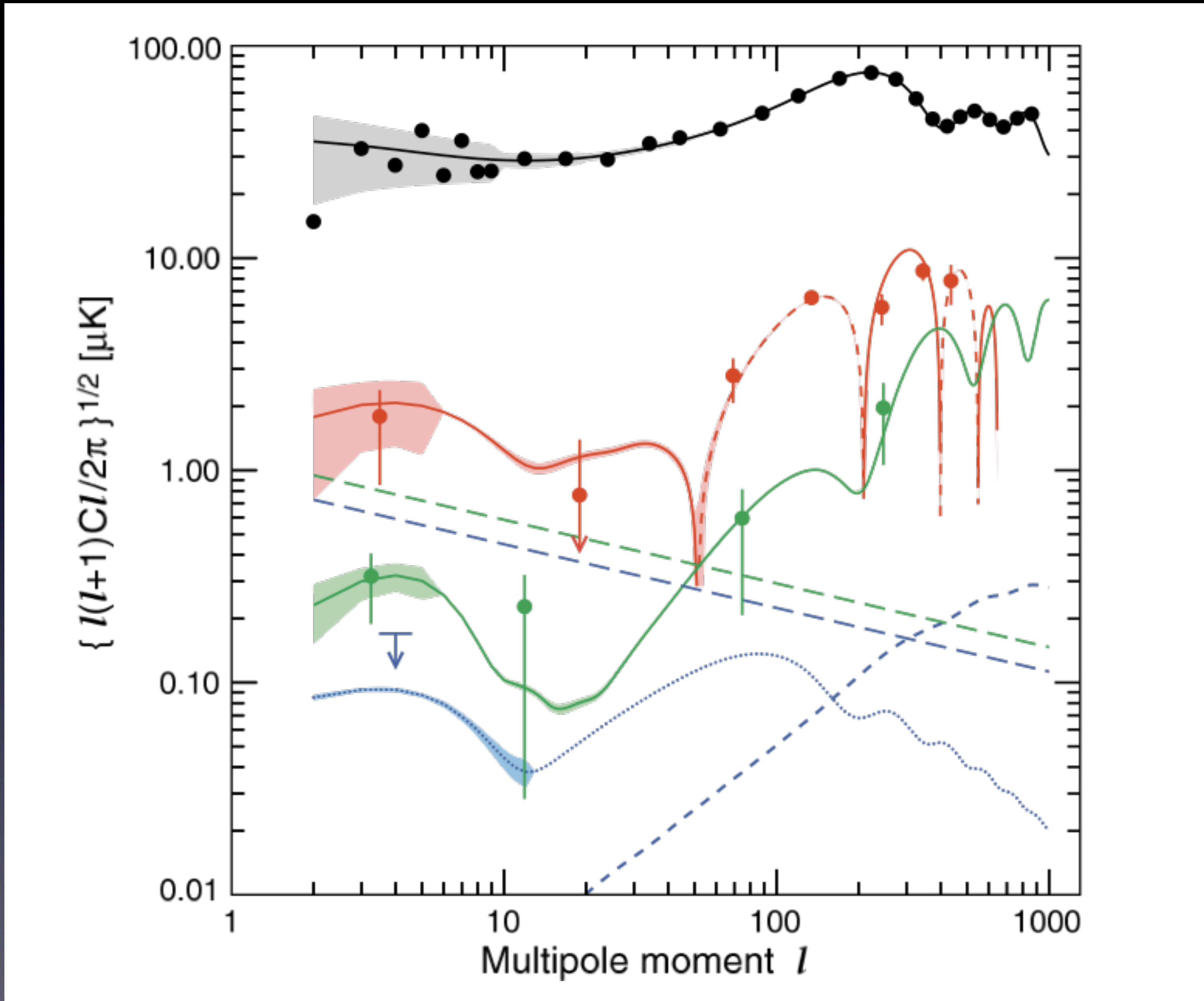
Improved Data and Analysis

- Improved Beam Model
  - 5 yrs of Jupiter observations, combined with physical optics modeling, reduce the beam uncertainty by a factor of 2 to 4 (Hill et al 2008).
- Improved Calibration
  - Improved algorithm for the calibration from the CMB dipole reduces error from 0.5% to 0.2%
- More Polarization Data for Cosmology
  - We now confidently use the CMB polarization data in three bands (33-61 GHz)



Much improved measurement of the 3rd peak!

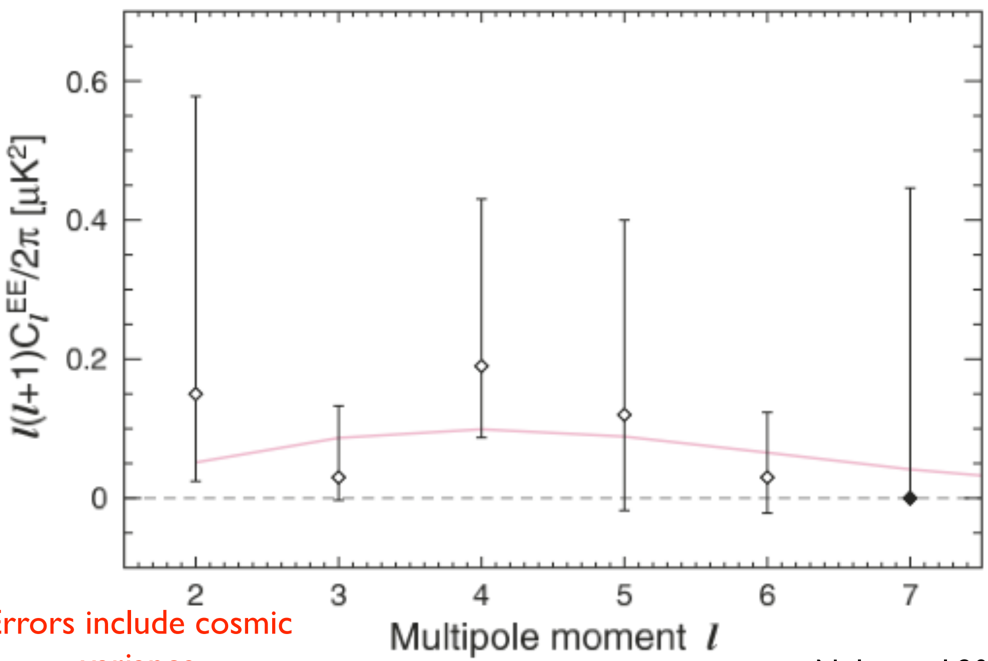
Hinshaw et al 2008



100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment l
{ l(l+1)Cl/2π }^1/2 [μK]

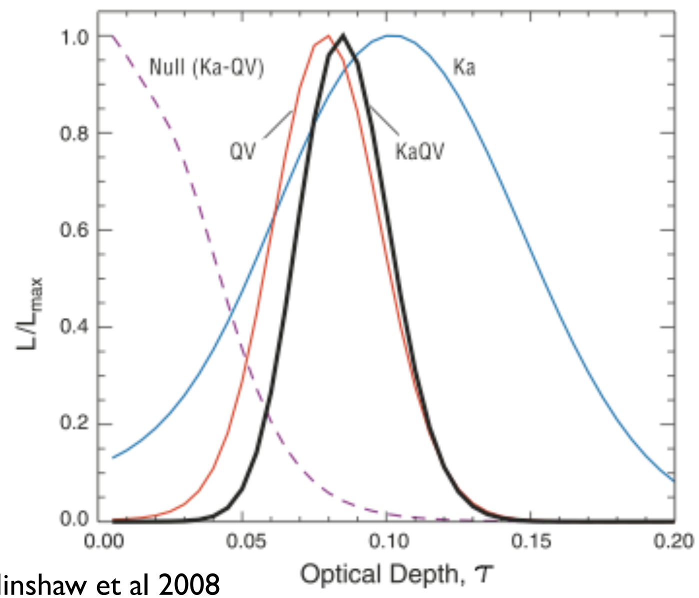
E-mode polarization

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



Errors include cosmic variance

Nolta et al 2008

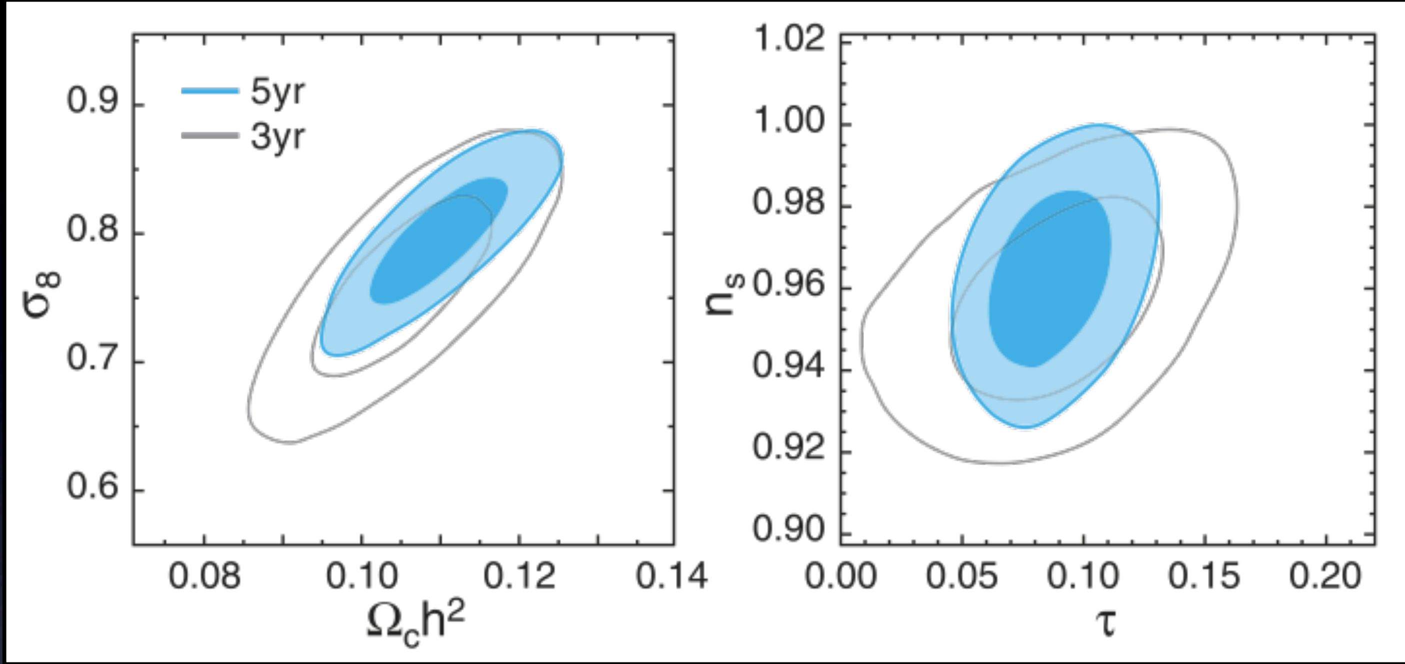


Hinshaw et al 2008

Optical Depth to reionization:

- Tau(5yr) = 0.087 +/- 0.017
- Tau(3yr) = 0.089 +/- 0.030 (Page et al.; QV only)

Λ CDM Cosmological Model

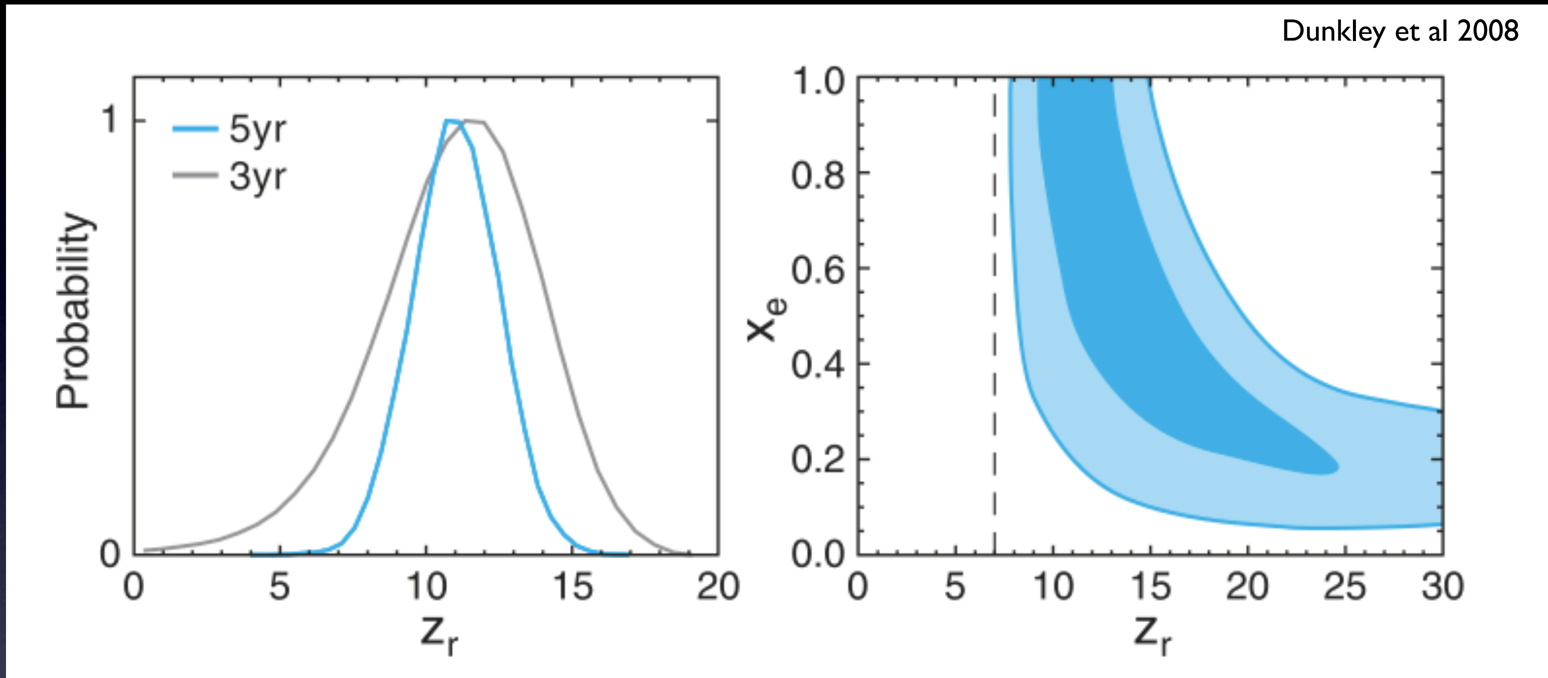


Dunkley et al 2008

- 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
$\Delta^2_\mathcal{R}$	$(2.35 \pm 0.13) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$
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	$73.2^{+3.1}_{-3.2}$	$71.9^{+2.6}_{-2.7}$
$z_{\rm reion}$	11.0 ± 2.6	11.0 ± 1.4
t_0	13.73 ± 0.16	13.69 ± 0.13

Reionization of the universe

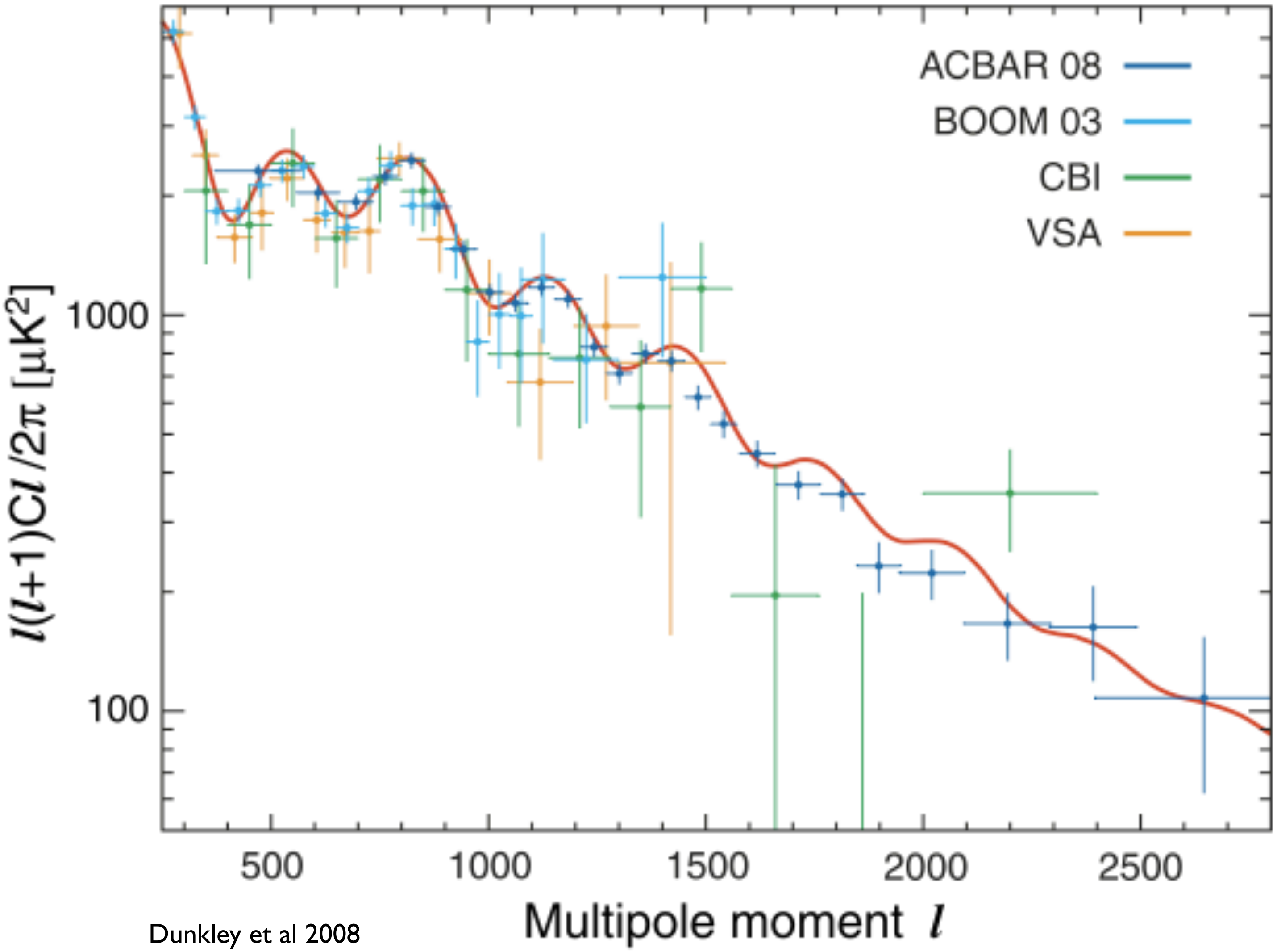


- Measure z=11.0 +-1.4 for sudden reionization (~400 million years)
- Quasar observations indicate some neutral fraction at z~6-6.5
- Indicates that a longer process is preferred by observations

More data will allow different histories to be better constrained

Model is consistent with other observations

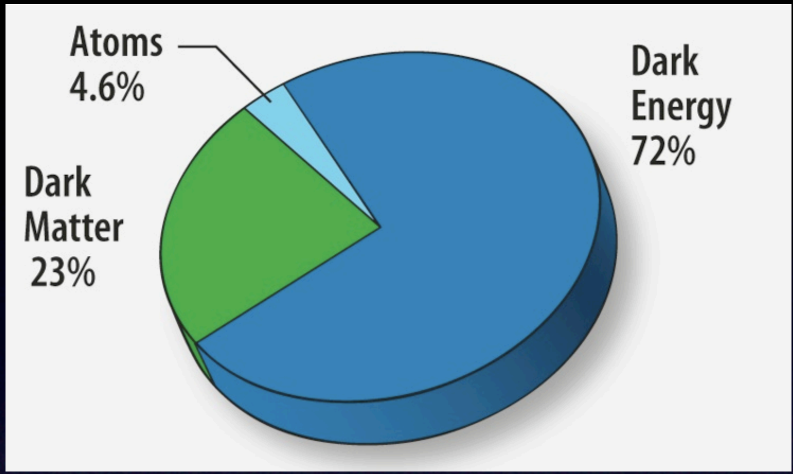
- Small-scale CMB
- Baryon Acoustic Oscillations in galaxies
- Type Ia Supernovae
- Galaxy power spectra
- Weak lensing
- Big Bang Nucleosynthesis
- Hubble constant
- Strong lensing
- Galaxy clusters
- Lyman-alpha forest
- Integrated Sachs Wolfe
- Galaxy peculiar velocities



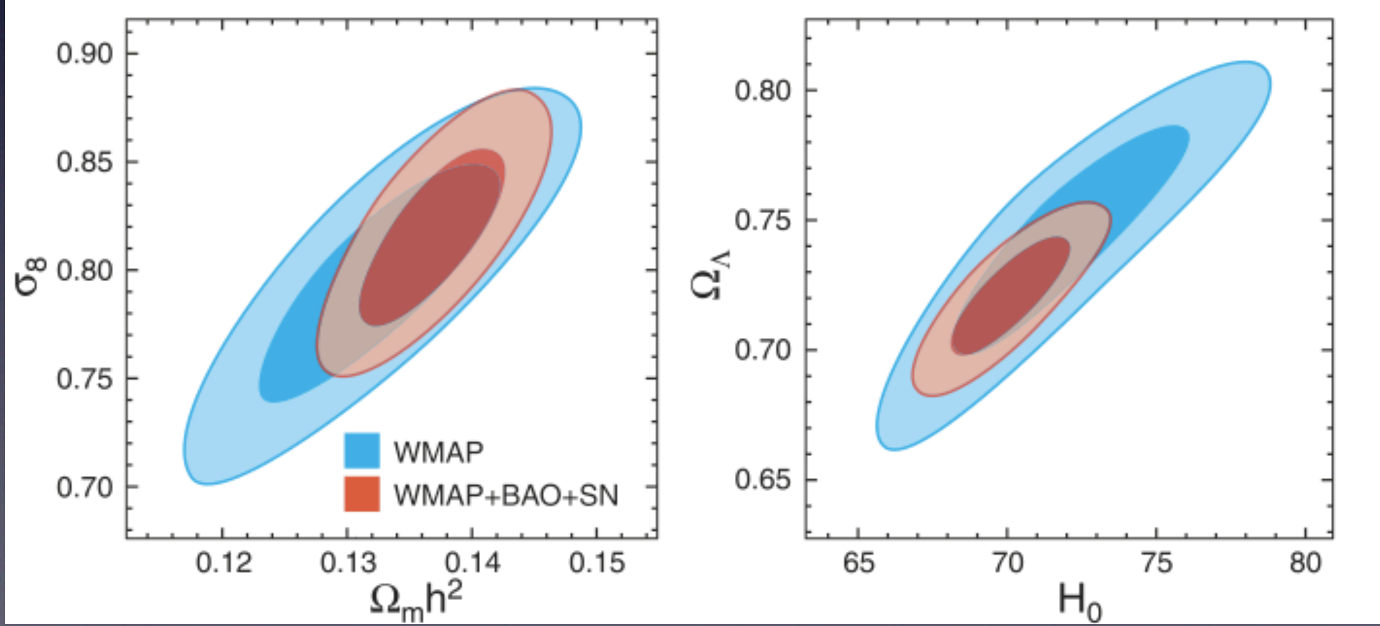
Dunkley et al 2008

We can improve limits by adding extra information:

• Luminosity distances from Type Ia supernovae
• Angular diameter distances from galactic baryon acoustic oscillations (BAO), measured by Sloan Digital Sky Survey and 2dFGRS



Komatsu et al 2008



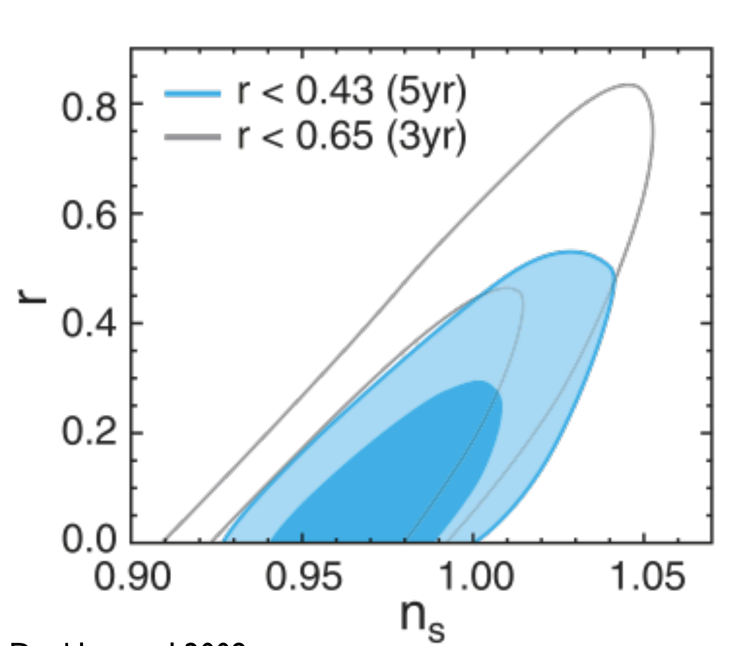
Testing inflation

The WMAP data is consistent with these classical inflationary predictions:

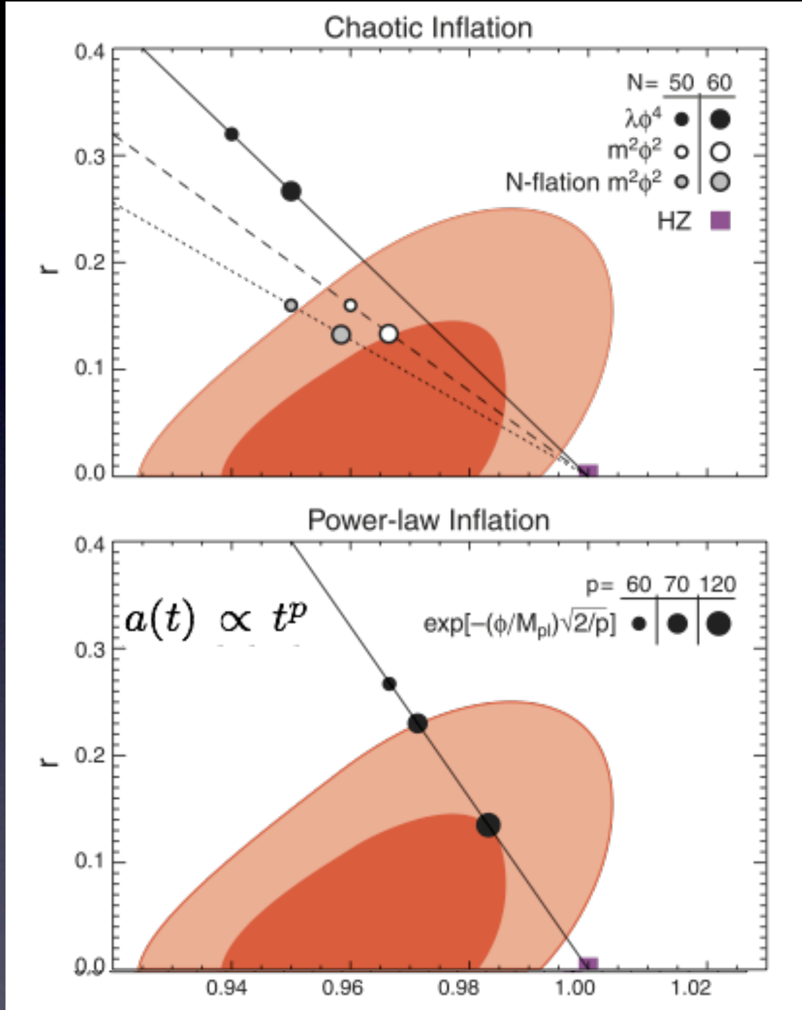
- The observable universe is flat
- The primordial fluctuations are adiabatic
- The primordial fluctuations are Gaussian
- The power spectrum is nearly scale invariant

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 BB r < 20)



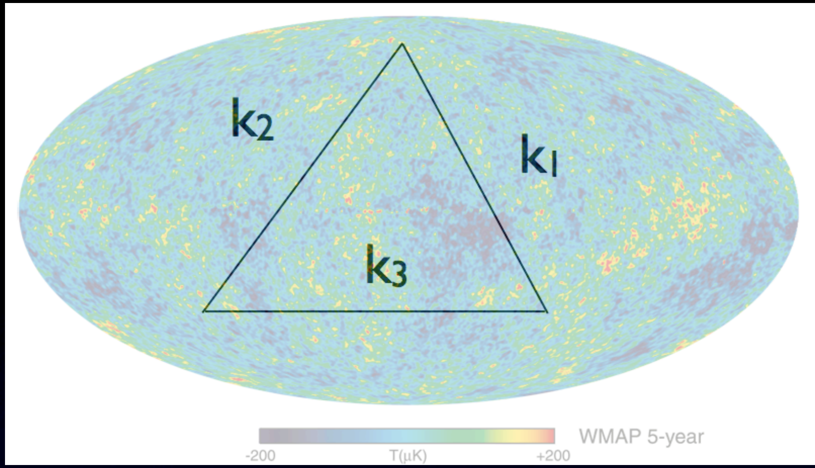
Dunkley et al 2008



Komatsu et al 2008

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

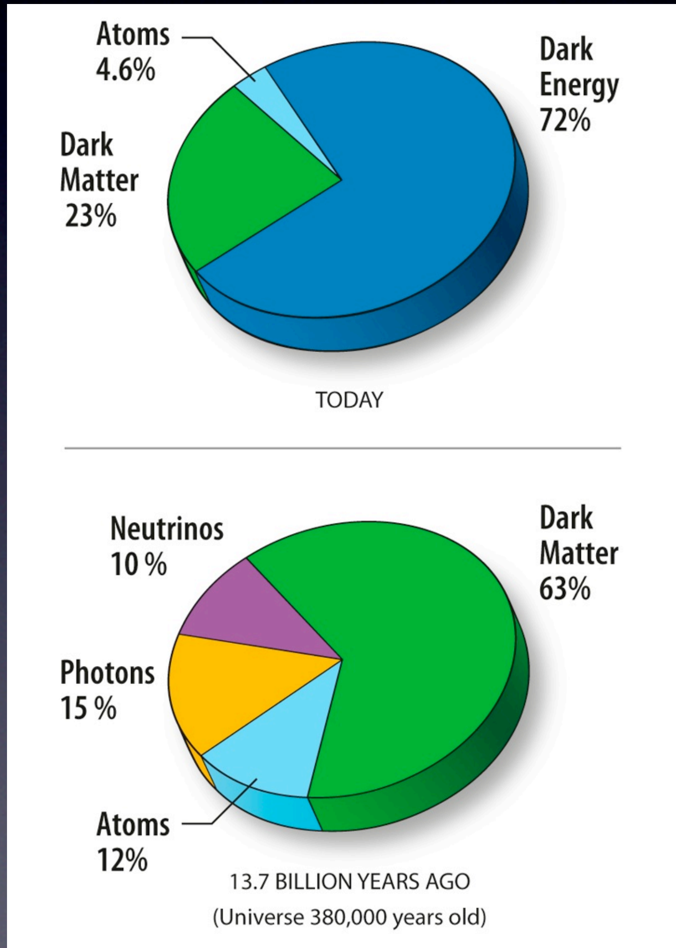
Non-Gaussianity?



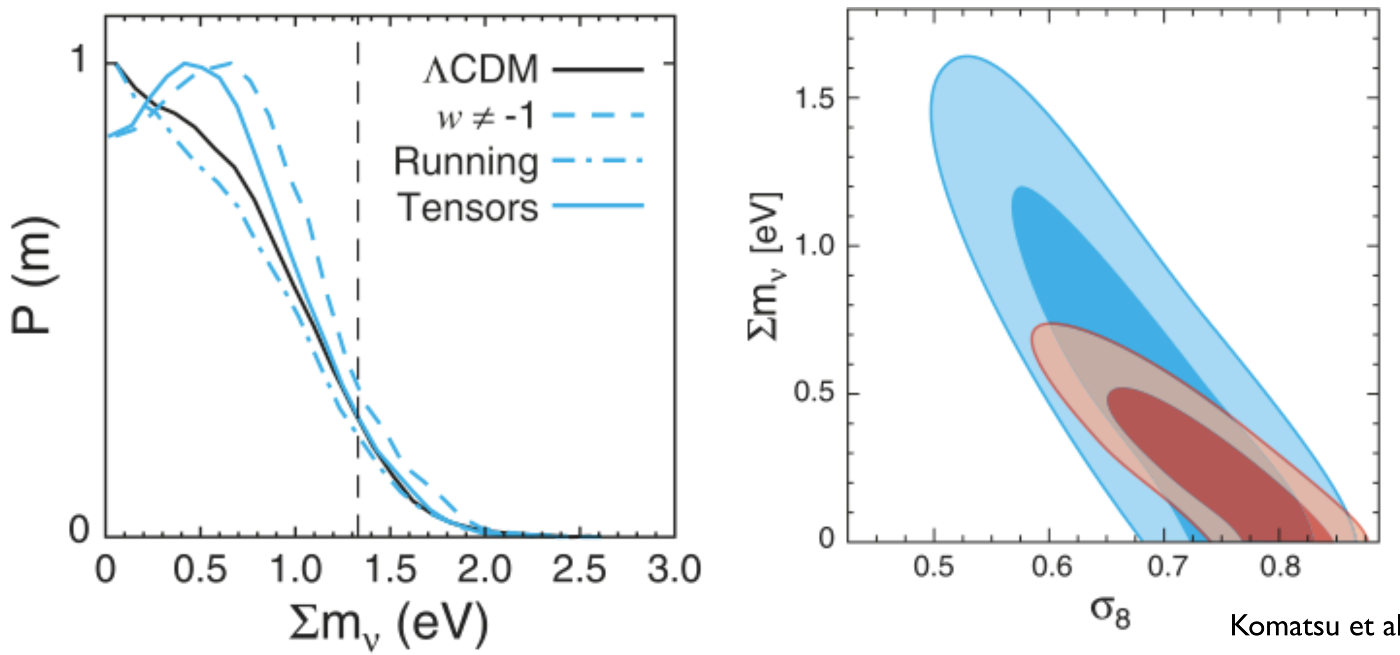
- Can look for non-Gaussianity by looking for non-zero bispectrum = 3 point function
- Define 'f_NL' using curvature fluctuations: Φ(x)=Φgauss(x) +f_NL[Φgauss(x)]2
- -9 < f_NL(local) < 111 (95% CL) (Komatsu et al 2008)
- -151 < f_NL(equilateral) < 253 (95% CL) (Komatsu et al 2008)
- The primordial curvature perturbations are Gaussian to 0.1% level
- Use the new Galaxy mask (KQ75) and correct for point-source contamination.

Contents of the universe

- Constrained baryon density, CDM density
- Constrained total geometry
  -0.02 < Ω_k < 0.01 (95% CL)
- What can we say about dark energy?
  (6-7% errors on constant w)
- What can we say about neutrinos?



Neutrino mass limits



Komatsu et al 2008

$$\sum m_\nu = 94\Omega_\nu h^2 eV$$

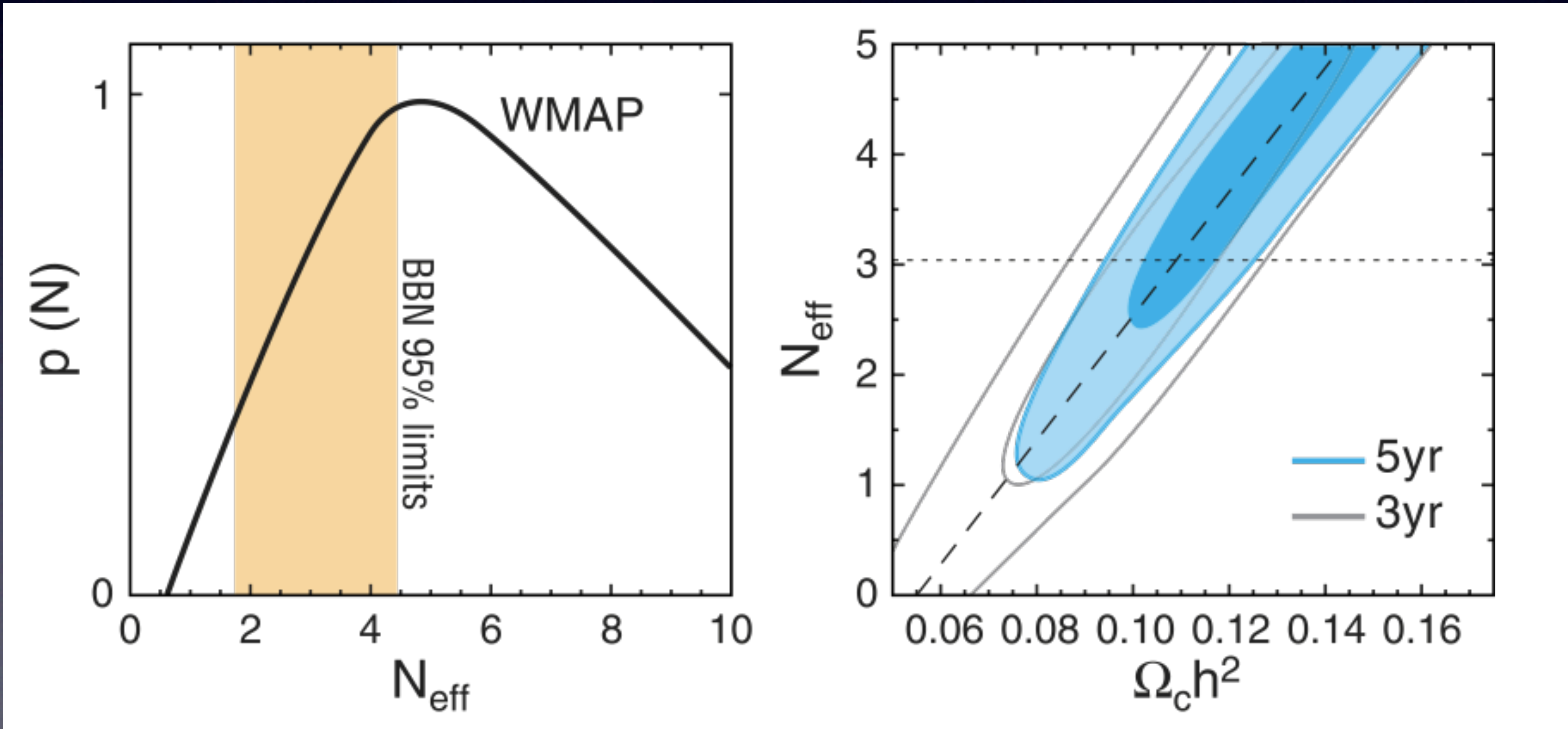
$$\sum m_\nu < 1.3eV$$ WMAP alone

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

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



Summary

- 'Simple' LCDM cosmological model fits WMAP 5-year data, and is now better constrained
- Fits array of other observations
- Consistent with simple inflationary predictions placing stronger limits on deviations
- Evidence for relativistic species (assumed neutrinos)
- Better view of the reionization of the universe
- WMAP due to observe 9 years until 2010