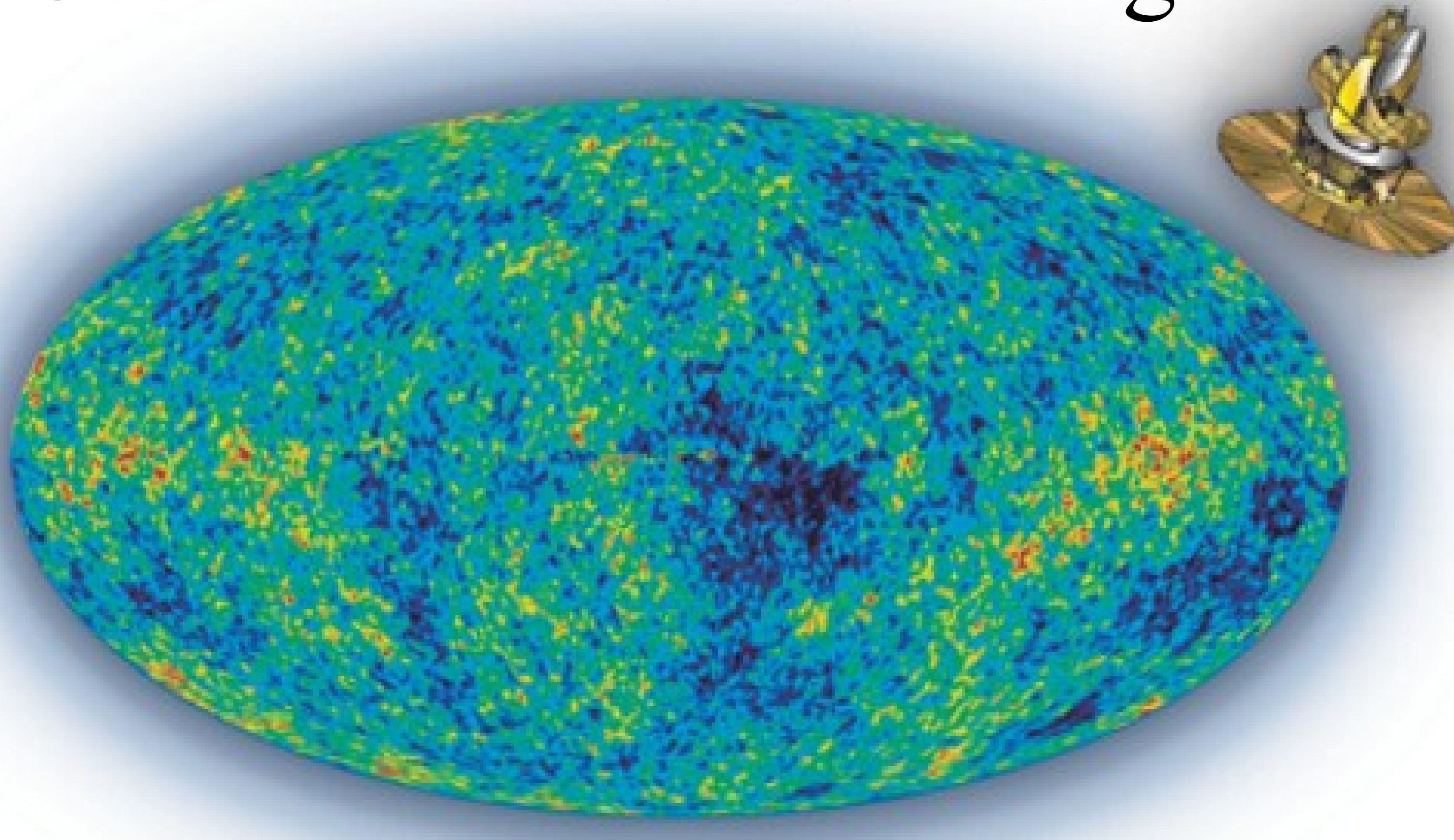
Really, really, what universe do we live in?

- Fluctuations in cosmic microwave background
  - Origin
  - Amplitude
  - Spectrum
  - Cosmic variance
- CMB observations and cosmological parameters
  - COBE, balloons
  - WMAP
  - Parameters
  - Cosmic harmony

Cosmic Microwave Background



Average temperature ~ 2.7 K.

After removal of dipole, $\Delta T/T \sim 10^{-5}$.

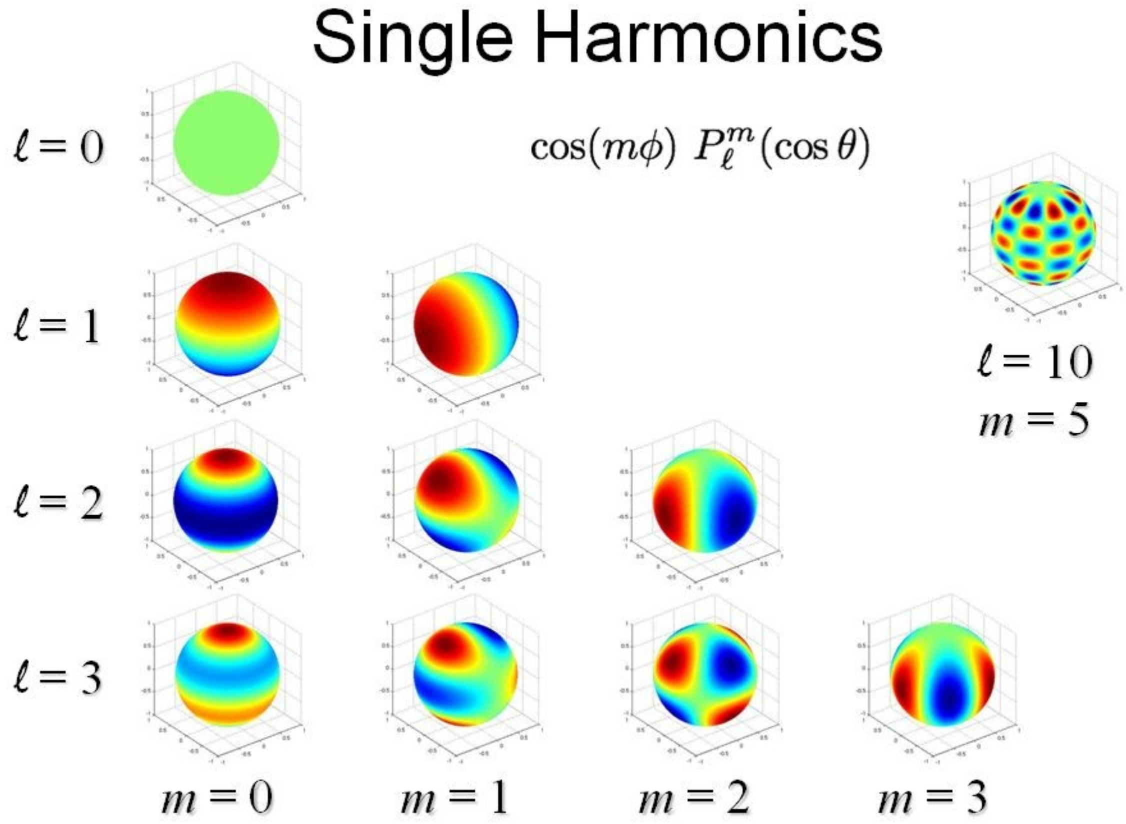
Fluctuations in CMB

- Caused by density perturbations at recombination
  - Need density fluctuations $\sim 10^{-3}$ at recombination to get galaxies today.
  - Observed $\Delta T/T \sim 10^{-5}$ suggests presence of dark matter.
- For an over dense region:
  - Enhanced baryon density causes high temperature
  - Stronger gravitational field means photons climbing out are redshifted (Sachs-Wolfe)
  - Due to gravitational redshift, photons in overdense regions are scattered early, when universe was hotter, negating part of gravitational effect (Sachs-Wolfe)
  - Matter falling into overdense region is redshifted
- Small length-scale fluctuations are damped because photons travel some distance before interacting (Silk damping).

Propagation effects

- Inverse-Compton scattering
  - Some CMB photons scatter on ionized intergalactic medium making an isotropic component
- Integrated Sachs-Wolfe effect
  - Photons propagate into then out of gravitational wells
  - Universe expands causing net frequency shift
- Gravitational deflection by density perturbations
  - Smears out fluctuations at small angular scales
- Sunyaev-Zeldovich effect
  - CMB photons scattered on hot gas in clusters

CMB power spectra



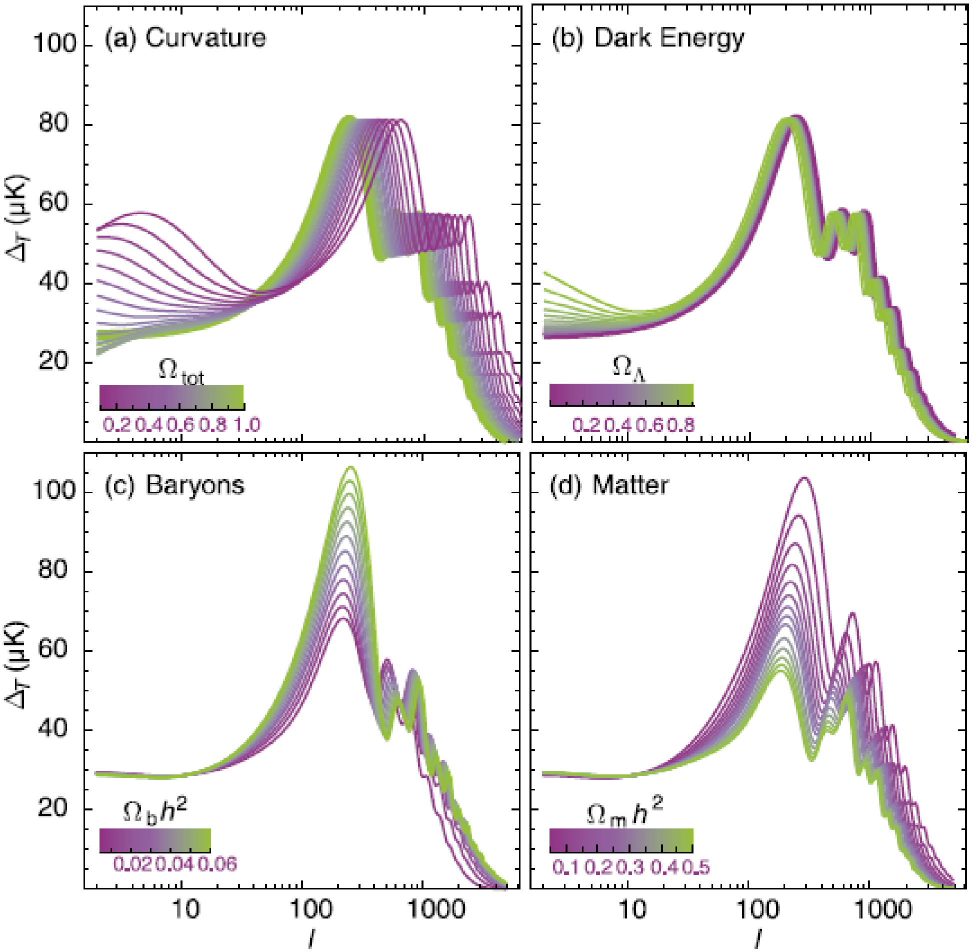
- Describe CMB in terms of correlation function and power spectrum.
- Need to do in terms of spherical harmonics, $l = 1$ dipole, $l = 2$ quadrapole, ...
- Angular scale $\theta \sim \pi/l = 180^\circ/l$.
- Specify power at each l as C_l
- Need to account for propagation and projection effects in chosen cosmological model. This is usually done numerically.

CMB power spectra

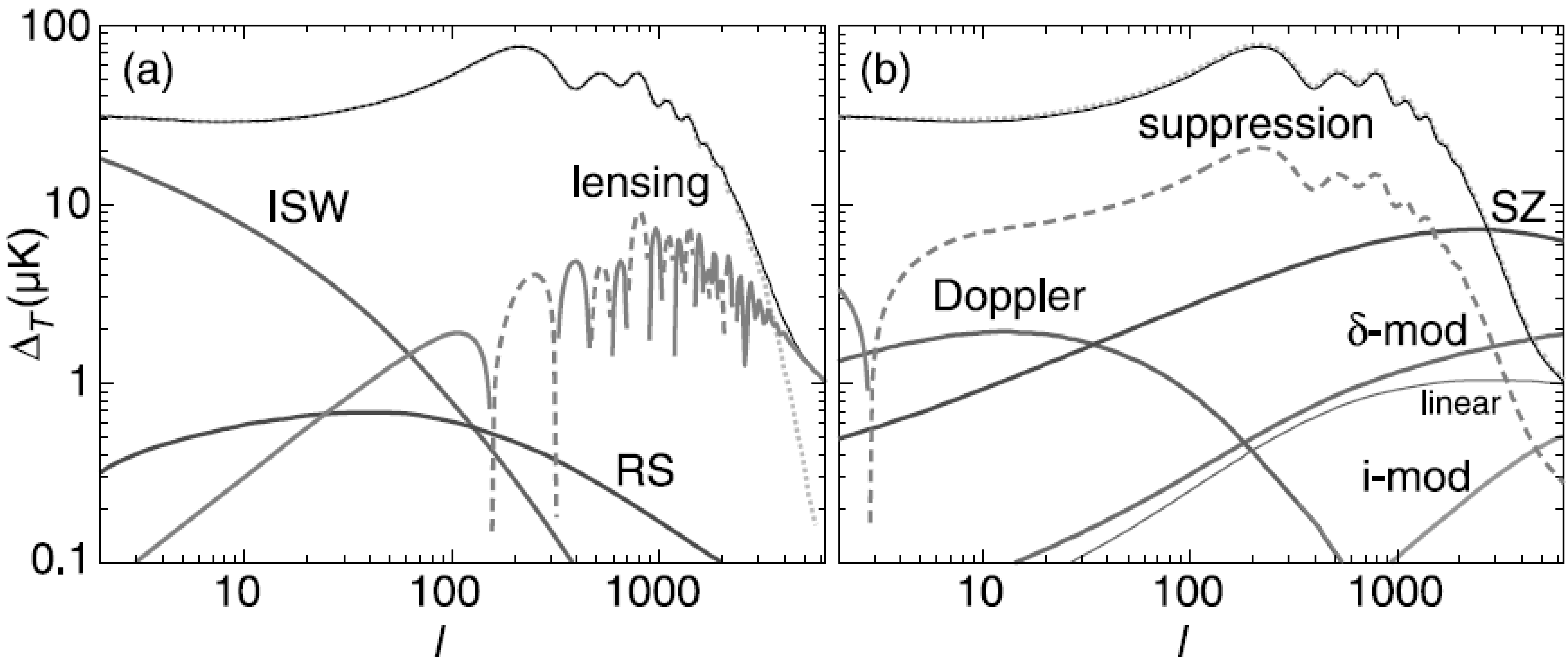
- Length (angular) scale is size of horizon at recombination
  - $\theta_H \sim 1.8°$ ($l \sim 100$) in flat universe with weak dependence on Ω_m
- On longer scales, $l << 100$, density fluctuations directly reflect primordial fluctuations
  - For Harrison-Zeldovich spectrum $P \sim k$, find $l(l+1)C_l \sim$ constant
- At small length scales, $l >> 100$, will have Silk damping. Also, recombination occurs over some range in redshift corresponding to some physical distance. For length scales shorter than the depth of recombination, any light of sight will average over many different physical volumes and average out fluctuations. Both these effects imply that the power on short length scales will be damped.
- Sound horizon
  - Perturbations in the the baryon-photon fluid propagate at the sound speed $c_s = c/\sqrt{3}$.
  - Fluctuations have a size $t_{rec} c_s = r_h(t_{rec})/\sqrt{3} \sim 1°$ or $l \sim 200$.
  - Find peaks at this scale and harmonics – "acoustic peaks".

CMB power spectra

- $\Delta T = T_0 \sqrt{l(l+1)C_l/2\pi}$
- Curvature – moves position of acoustic peaks. Also affects shape at low l. (a)
- Since we find a flat universe, panels b-d are for a flat universe.
- Ω_Λ small effect on position of acoustic peaks. Larger Sachs-Wolfe effect for larger Ω_Λ produces more power at low l.
- More baryons increase amplitude of first acoustic peak and decrease Silk damping since photons travel shorter distances.
- More (dark) matter increases amplitudes of acoustic peaks and shifts them slightly.

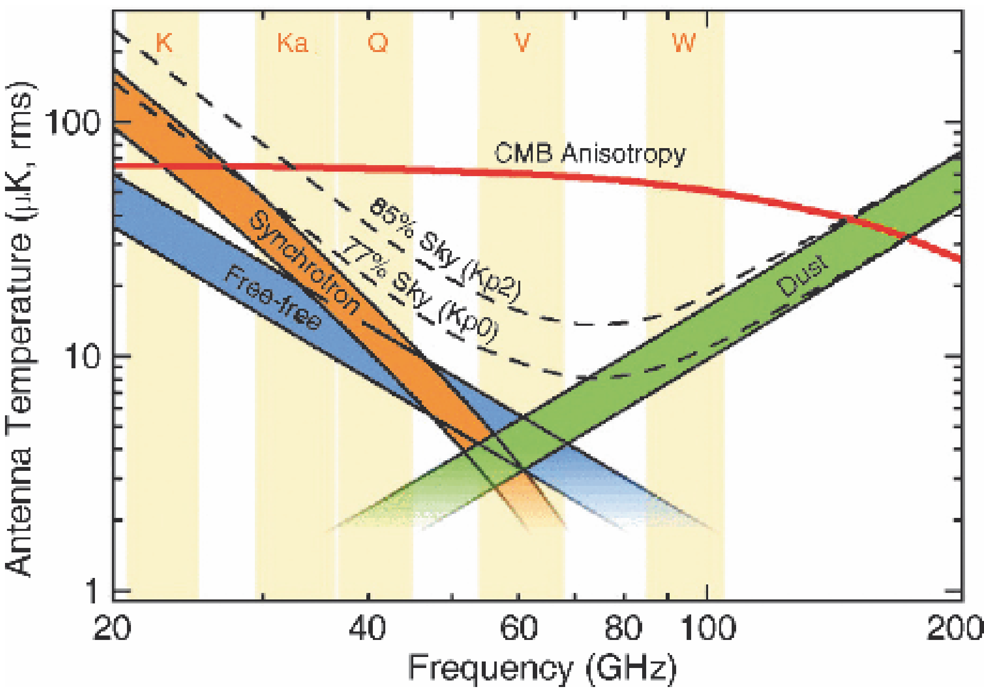


CMB power spectra



- Integrated Sachs-Wolfe is strong effect at low *l*.
- Sunyaev-Zeldovich and lensing are important at high *l*.
- Scattering of CMB photons on IGM reduces power by a factor e- where is the optical depth for scattering (labeled as suppression).

Backgrounds

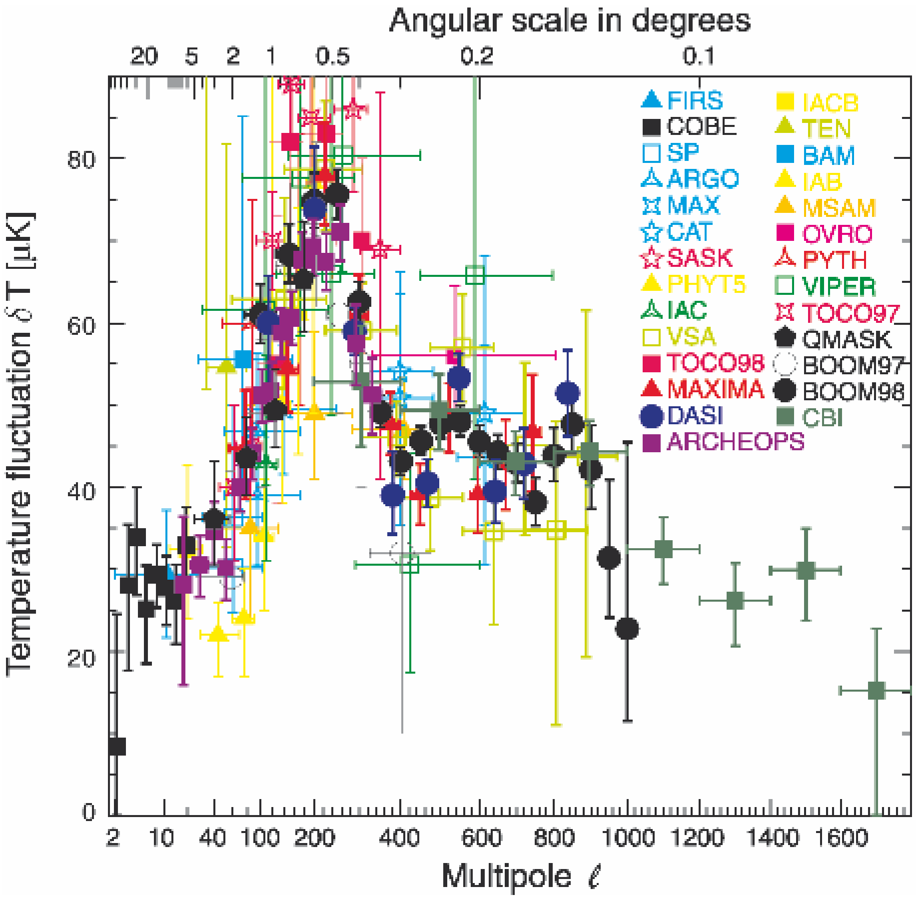


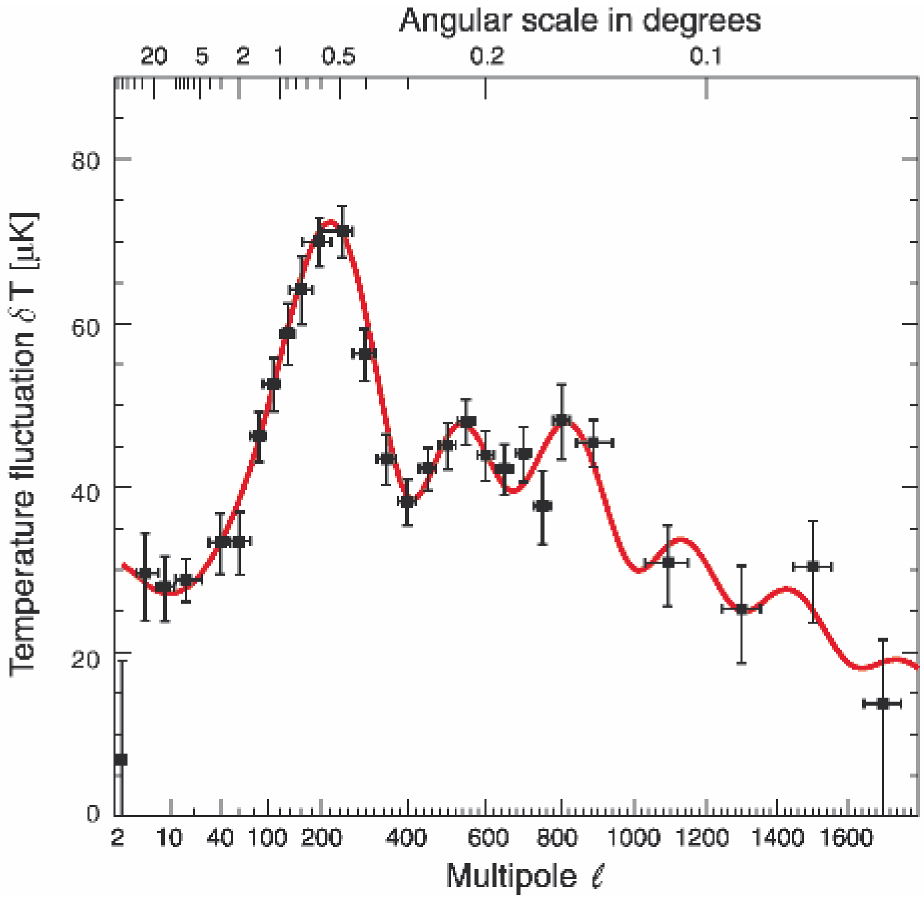
- Recent CMB measurements have been done from space or balloons to avoid atmospheric backgrounds.
- Galactic backgrounds:
  - Synchrotron radiation from cosmic ray electrons moving in Galactic magnetic field
  - Emission from warm dust
  - Bremsstrahlung from hot gas in the interstellar medium
- Spectra of various backgrounds are different from CMB spectrum, so do measurements at multiple frequencies to subtract these backgrounds.

CMB Measurements

- Discovery in 1965 by Penzias and Wilson
- First detection of fluctuations in 1992 with COBE satellite.
  - COBE had 7° angular resolution, $l < 20$, found flat power spectrum.
- In 2000, balloon experiments BOOMERANG and MAXIMA found first acoustic peak.
  - Measured $\Omega = 1.0 \pm 0.1$
  - Followed by many balloon measurements

CMB measurements





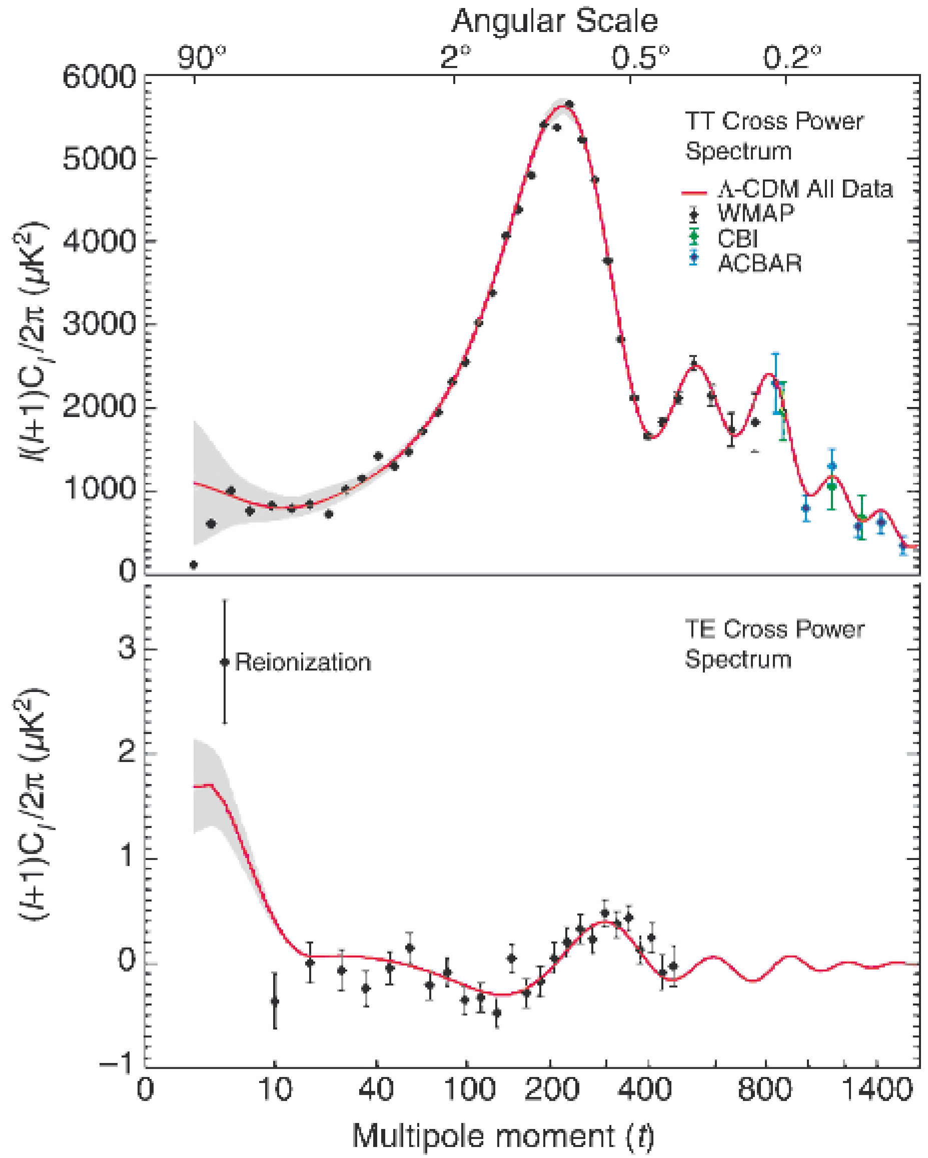
- Cosmological parameters can be determined from combined data set
- With assumption of a flat universe: $\Omega_\Lambda = 0.71 \pm 0.11$, $\Omega_b h^2 = 0.023 \pm 0.003$, primordial density fluctuation spectral index = 0.99±0.06, Hubble constant $h = 0.71 \pm 0.13$.

CMB Measurements

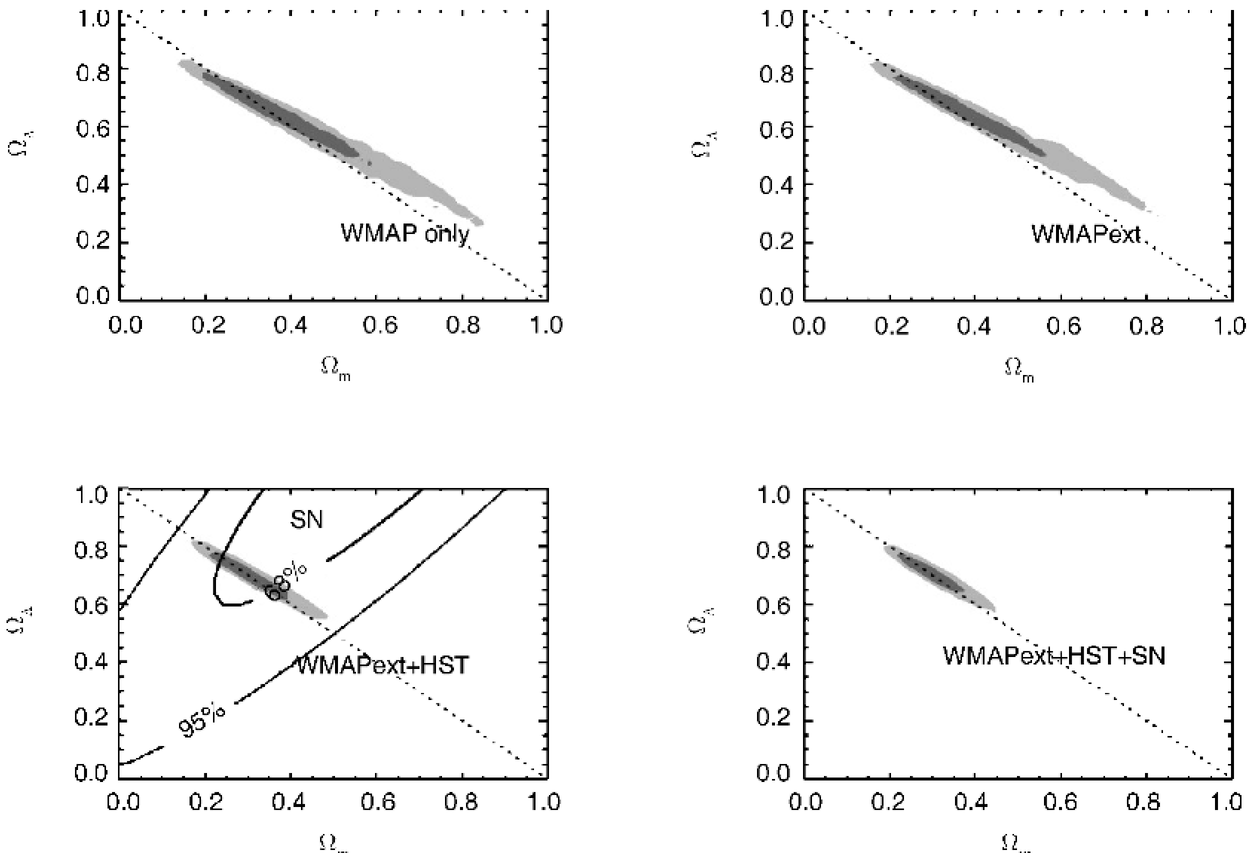
- In 2001, WMAP was launched and mapped the whole sky
  - Angular resolution of 0.3°
  - Measurements in 5 frequency bands
- Cosmic variance – Cosmological models predict the expectation value, the average value one would have if one ran the universe many times, for observables like the intensity of the CMB in a particular direction. There will be fluctuations in any particular universe, so the values we measure in our universe deviate from the expectation values. The deviations for CMB multipoles are $\Delta C_l = C_l / \sqrt{(2l+1)}$.
- Polarization of CMB – thermal radiation is unpolarized. However, scattered photons are polarized. Since the CMB viewed from any point in space is slightly anisotropic, this results in a net observed polarization.
  - TT = temperature-temperature correlations
  - TE = temperature-polarizations correlations

WMAP

- In 2003, WMAP released analysis of first year of data.
- Results were much more precise than combination of all previous CMB measurements. More accurate than cosmic variance for $l < 350$.
- Cosmological parameters found to be in good agreement with previous results, but more accurate.
- Quadrapole amplitude much lower then expected from model. May be due to issues with removal of foregrounds.
- Epoch of reionization found (from TE) to be unexpectedly early, z ~ 15.



Cosmological parameters



- Cosmological parameters from WMAP can be improved (and tested) by comparison with other types of measurements. (WMAPext = WMAP data + CMB measurements on smaller angular scales.)
- If individual measurements are consistent, then can use combined measurements to place constraints on cosmological parameters.

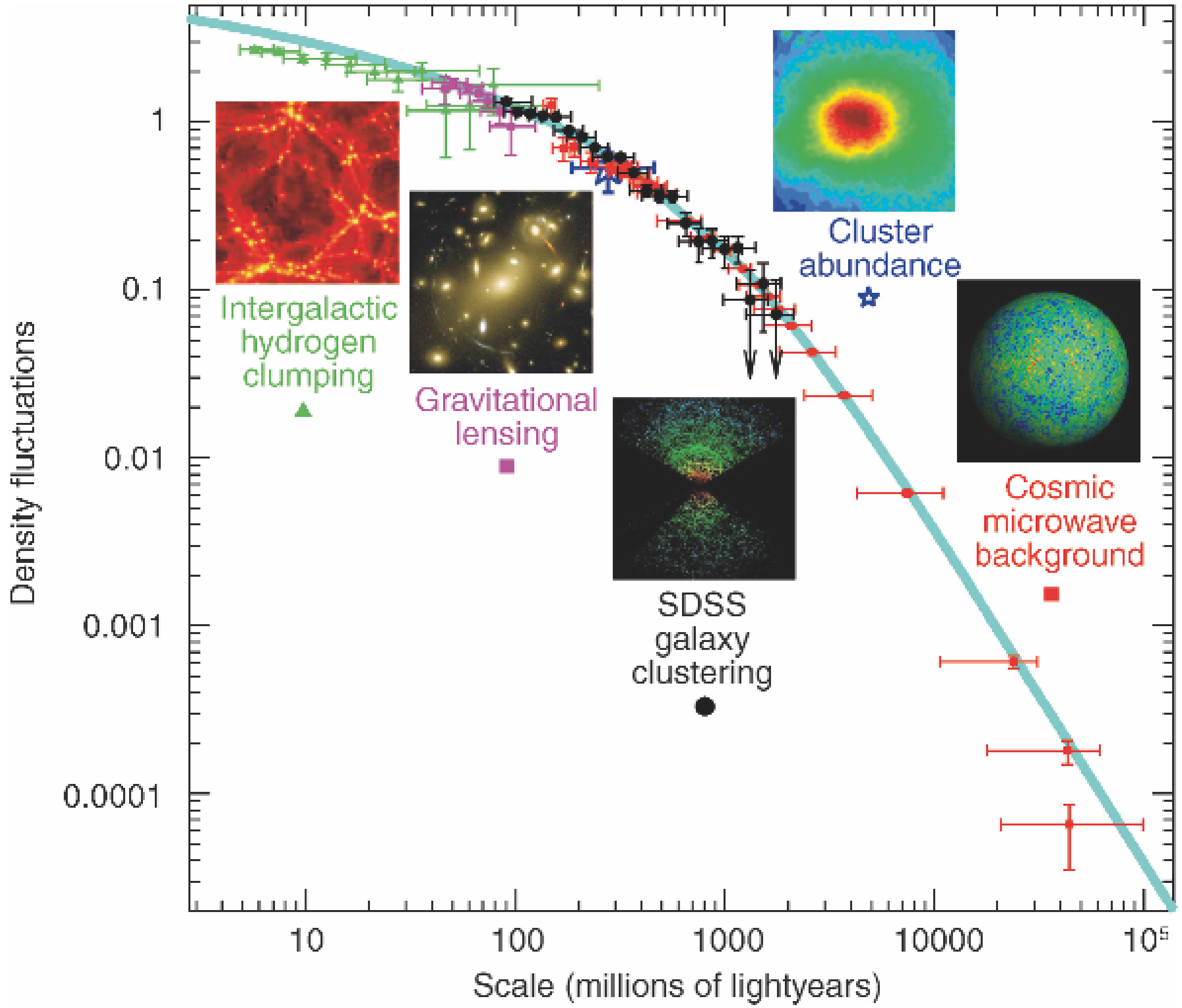
Cosmological parameters

	WMAP	WMAPext+2dFGRS+Lyα
h	0.72 ± 0.05	$0.71^{+0.04}_{-0.03}$
σ_8	0.9 ± 0.1	0.84 ± 0.04
$\sigma_8 \Omega_{\mathrm{m}}^{0.6}$	0.44 ± 0.10	$0.38^{+0.04}_{-0.05}$
Ω_{b}	0.047 ± 0.006	0.044 ± 0.004
Ω_{m}	0.29 ± 0.07	0.27 ± 0.04
t_0	13.4 ± 0.3 Gyr	13.7 ± 0.2 Gyr
z_{ion}	17 ± 5	17 ± 4
z_{rec}	1088^{+1}_{-2}	1089 ± 1
z_{eq}	3454^{+385}_{-392}	3233^{+194}_{-210}
n_{b}	$(2.7 \pm 0.1) \times 10^{-7}\ \mathrm{cm}^{-3}$	$(2.5 \pm 0.1) \times 10^{-7}\ \mathrm{cm}^{-3}$
η	$\left(6.5^{+0.4}_{-0.3}\right) \times 10^{-10}$	$\left(6.1^{+0.3}_{-0.2}\right) \times 10^{-10}$

- WMAP found Ω = 1.02 ± 0.0.2
- Other parameters are derived assuming a flat universe
- 2dFGRS = 2 degree field redshift survey
- Lyα = various Lyman α forest data

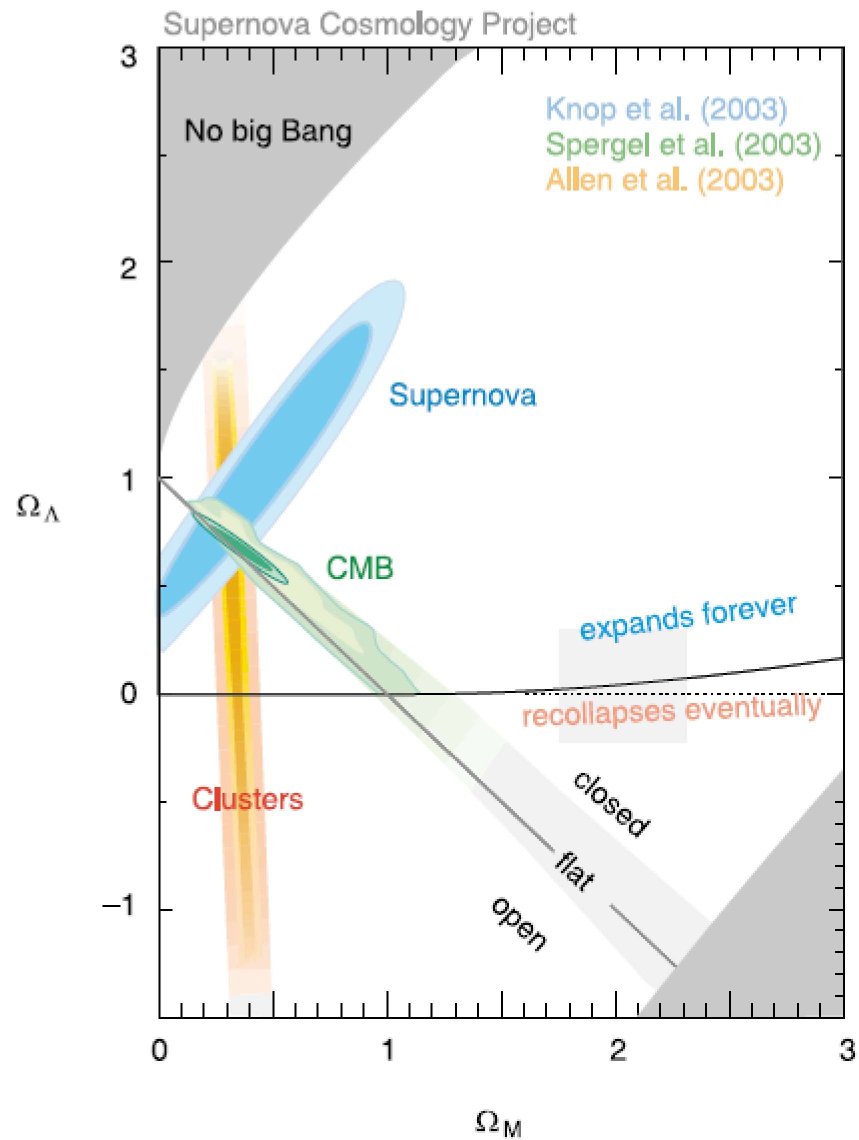
Power spectrum

- Power spectrum agrees well with model from ΛCMD model for scales larger than 10 Mpc.



Cosmic harmony

- Can test cosmological model by making multiple measurements of cosmological parameters using different techniques.
- Plot shows agreement between CMB, cluster, and supernovae data.



Cosmic harmony

- Hubble constant – HST Cepheids, CMB, SZ effect, lens time delays
- Baryon fraction – clusters, redshift surveys, CMB
- Baryon density – CMB, deuterium abundance + primordial nucleosynthesis
- Matter density – redshift surveys, CMB, evolution of cluster number density
- Vacuum energy – SN Ia, CMB + Sachs Wolfe
- Normalization of power spectrum – CMB, X-ray clusters, cosmic shear
- Age of the universe – CMB, age of oldest stars

For next class

- Read 91.-9.4.
- Project presentations on November 12 and 14. Should be full presentations with all results.