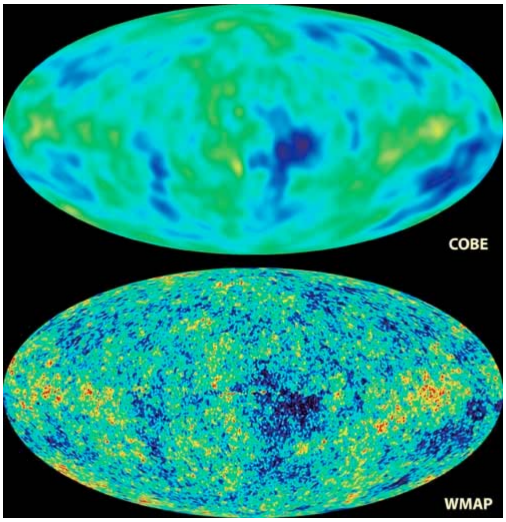
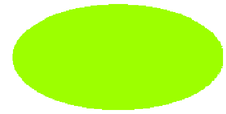
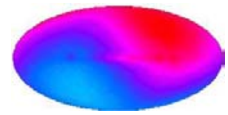
Cosmic Microwave Background Anisotropies = structure in the CMB

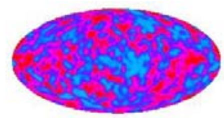




Blue = 0°K
Red = 4°K

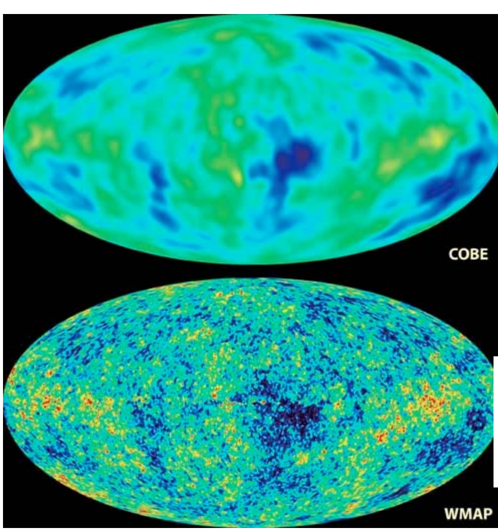


Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy
~ 1 part in 300



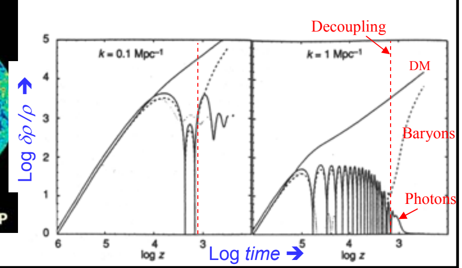
After removing dipole
Red – blue = 0.0002°K
~ 1 part in 10^5

Cosmic Microwave Background Anisotropies = structure in the CMB



Structure = snapshot of oscillations

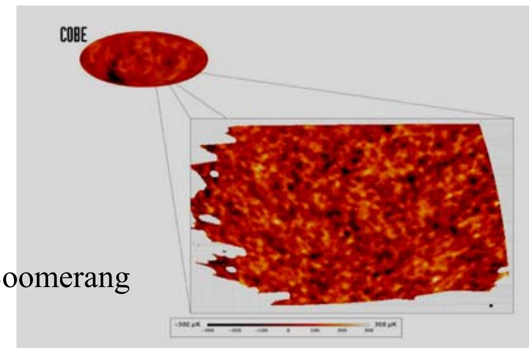
$M < M_J$:
$\delta\rho/\rho = exp(-ir - i\omega t)$ → Oscillations



Structure in the CMB

Boomerang balloon flight.

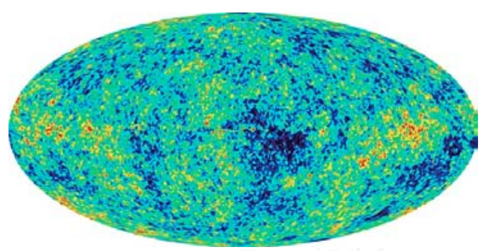
Mapped Cosmic Background Radiation with far higher angular resolution than previously available.



Boomerang

Launch near Mt. Erebus in Antarctica

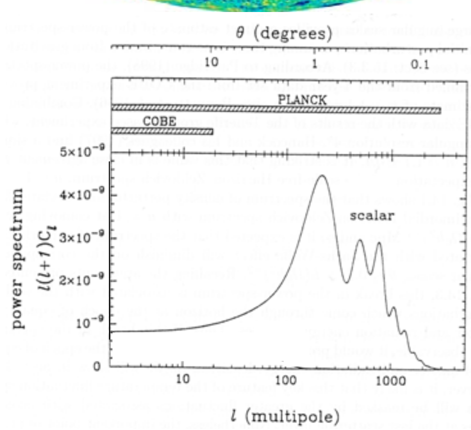
What is measured?

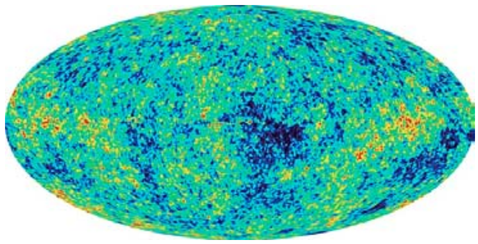


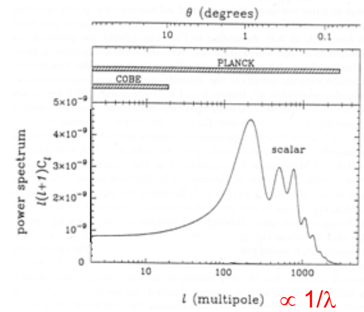
Basically,

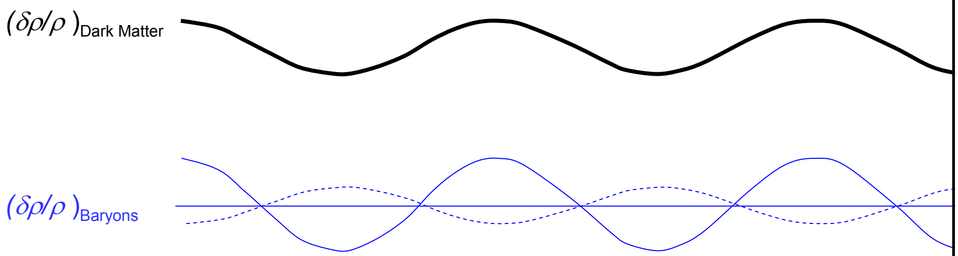
Power spectrum of $\Delta T/T$ vs. $l = \pi/\theta$

(think of Fourier transforming the sky in angular coordinates)









Baryons: Shorter spatial wavelengths oscillate with higher time frequency

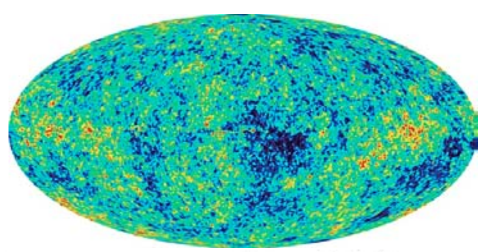
What is measured?

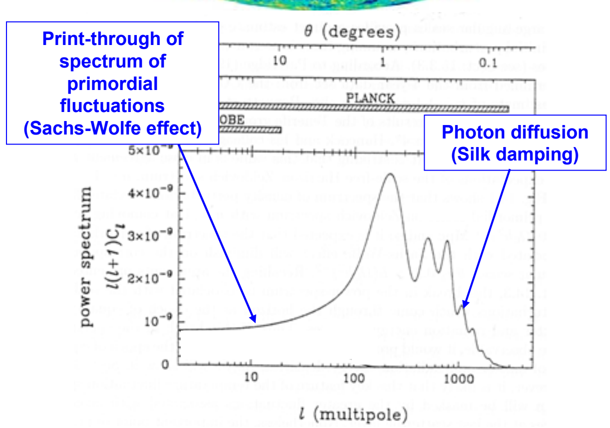
Basically,

Power spectum of $\Delta T/T$

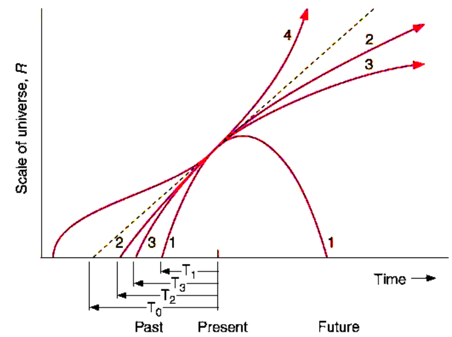
vs. $l = \pi/\theta$

(think of Fourier transforming the sky in angular coordinates)





Position of 1st peak:



- Density fluctuations print through CMB fluctuations.

  $\delta\rho/\rho = 3\delta T/T$ [CO 30.30]

- Measures angular size of pulsations which permeated universe just before decoupling of CMB.
- Linear size of largest structure

  = (speed of sound) x (age of universe at that time).

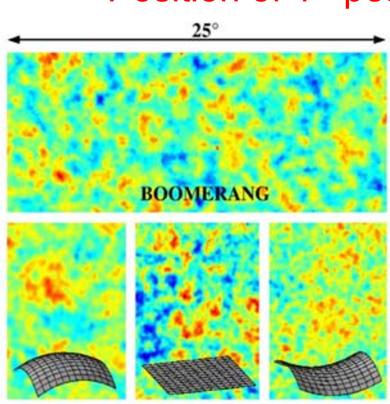
- (Linear size) / (Angular size) = angular size distance.
- Ang. Size Distance depends on geometry = Ω_{tot}
  - $d = (2c / H_o\Omega_o)$ for large z.

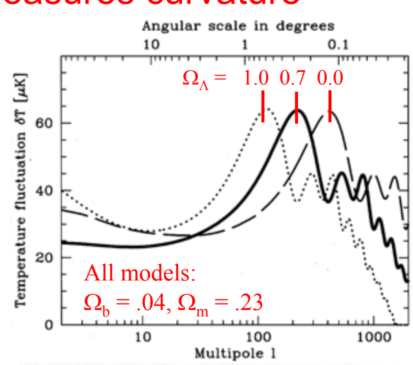
Sonic Horizon Distance

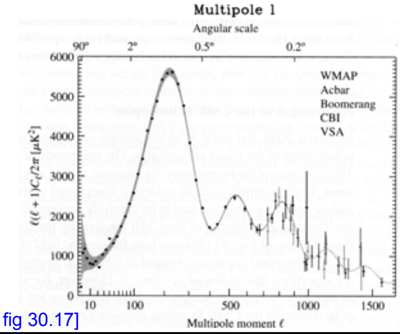
$d_s(t) = ct\sqrt{3}$

= linear size of perturbation

Position of 1st peak measures curvature







[CO fig 30.17]

First peak:

Size of "acoustic horizon"

$r = v_s\,(t_{Decoupling} - t_{Horizon})$

$\theta = r/\chi(d)$

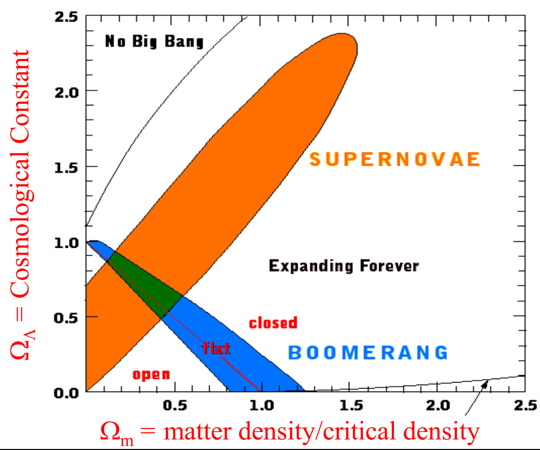
$\chi = sin(d), d, sinh(d)$

$l_{peak} = 220/\Omega_{tot}^{1/2}$

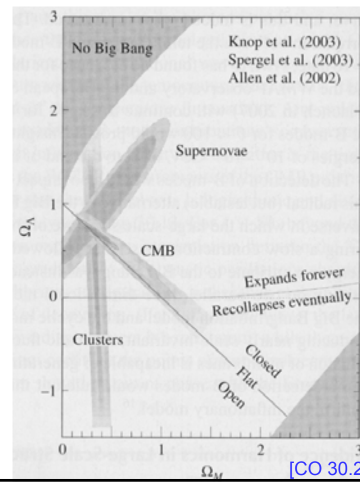
Measured l_{peak} ➔ $\Omega_{tot} = 1.02 \pm .02$

The "Concordance" Cosmology (or ΛCDM)

- Type Ia Supernovae as "standard candles"
  - ➔ accelerating expansion
  - ➔ $q_o = \Omega_m/2 - \Omega_\Lambda$
- CBR anisotropy ➔ $\Omega_{total} = \Omega_m + \Omega_\Lambda$
- Can solve for Ω_m , Ω_Λ



Another independent measure:
Rate of galaxy cluster evolution

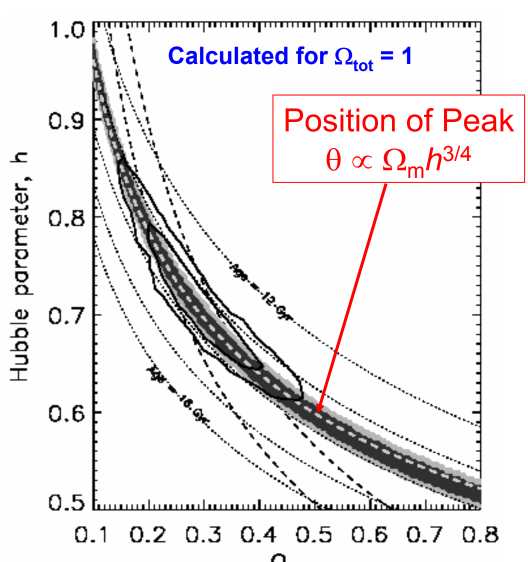


[CO 30.22]

Position & height of first peak also depend on Ω_m, Ω_b, h

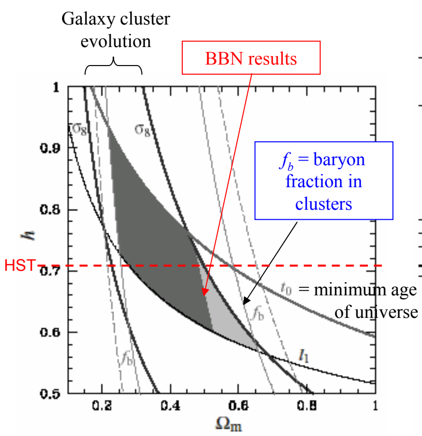
Height of peak

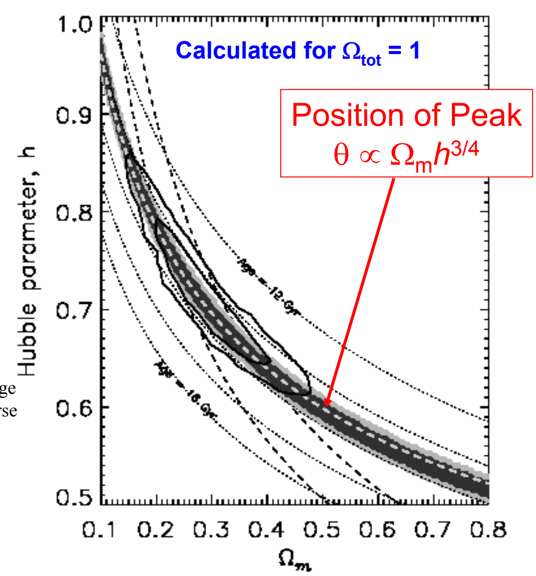
- Larger Ω_m ➔ all peaks have smaller amplitudes.
  - Through change in matter/radiation density ratio during radiation-dominated phase.
  - Through effect on when universe becomes matter dominated.



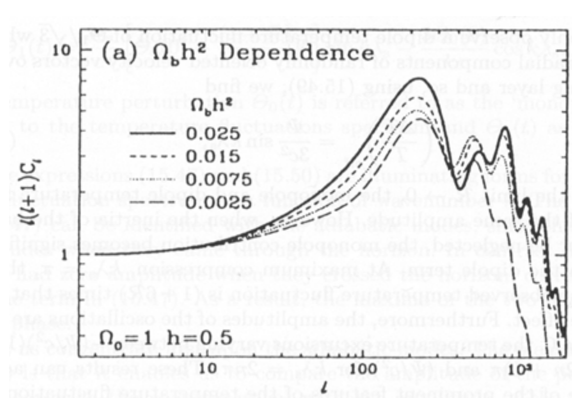
Position & height of first peak also depend on Ω_m, Ω_b, h

So use constraints from other measurements:





WMAP also measured second peak



- Due to rarefaction of an acoustic wave.
- Larger Ω_b ➔ smaller amplitude of second peak.
  - greater inertial mass in oscillating plasma.

Astrophysical Journal Supplement 148, pg. 1 (September 2003)

FIRST-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*)[1] OBSERVATIONS: PRELIMINARY MAPS AND BASIC RESULTS

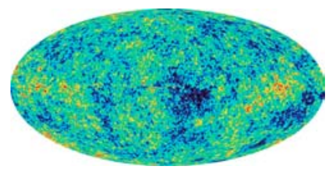
C. L. Bennett,[2] M. Halpern,[3] G. Hinshaw,[2] N. Jarosik,[4] A. Kogut,[2] M. Limon,[2,5] S. S. Meyer,[6] L. Page,[4] D. N. Spergel,[7] G. S. Tucker,[2,5,8] E. Wollack,[2] E. L. Wright,[9] C. Barnes,[4] M. R. Greason,[10] R. S. Hill,[10] E. Komatsu,[7] M. R. Nolta,[4] N. Odegard,[10] H. V. Peiris,[7] L. Verde,[7] and J. L. Weiland[10]

Received 2003 February 11; accepted 2003 May 29

Results:

- Total density: $\Omega_o = \Omega_{tot} = 1.02 \pm 0.02$
- Age of Universe: $t_o = 13.7 \pm 0.2$ Gyr
- Matter density: $\Omega_m h^2 = 0.135$ $+0.008/-0.009$ ➔ $\Omega_m = 0.27$
- Baryon density: $\Omega_b h^2 = 0.0224 \pm 0.009$ ➔ $\Omega_b = 0.044$

73% Dark Energy, 22% Dark Matter,
4.4% Baryonic Matter



Flat Universe with density fluctuations $P(k) \sim k^n$, $n \sim 1$

➔ **INFLATION**

Astrophysical Journal Supplement 148, pg. 233 (September 2003)

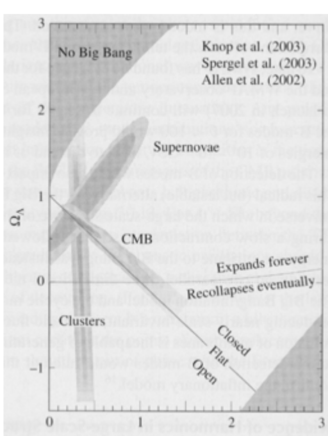
FIRST-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*)[1] OBSERVATIONS: INTERPRETATION OF THE TT AND TE ANGULAR POWER SPECTRUM PEAKS

L. Page,[2] M. R. Nolta,[2] C. Barnes,[2] C. L. Bennett,[3] M. Halpern,[4] G. Hinshaw,[3] N. Jarosik,[2] A. Kogut,[3] M. Limon,[3,5] S. S. Meyer,[6] H. V. Peiris,[7] D. N. Spergel,[7] G. S. Tucker,[5,8] E. Wollack,[3] and E. L. Wright[9]

Received 2003 February 11; accepted 2003 May 14

Power spectrum measures many things

- But still needs to be combined with other measurements.



[CO 30.22]

APPENDIX

N WMAP Data

"Best" Cosmological Parameters[a]				
Description	Text Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_0	1.02	0.02	0.02
Equation of state of quintessence[b]	w	< -0.78	95% CL	
Dark energy density	$\Omega_{\Lambda,0}$	0.73	0.04	0.04
Baryon density	$\Omega_{b,0}h^2$	0.0224	0.0009	0.0009
Baryon density	$\Omega_{b,0}$	0.044	0.004	0.004
Baryon density (m^{-3})	$n_{b,0}$	0.25	0.01	0.01
Matter density	$\Omega_{m,0}h^2$	0.135	0.008	0.009
Matter density	$\Omega_{m,0}$	0.27	0.04	0.04
Light neutrino density (m^{-3})	$\Omega_{\nu,0}h^2$	< 7600	95% CL	
CMB temperature (K)[c]	T_0	2.725	0.002	0.002
CMB photon density (m^{-3})[d]	$n_{\gamma,0}$	4.104×10^8	0.009×10^8	0.009×10^8
Baryon-to-photon ratio	η_0	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_{b,0}\Omega_{m,0}^{-1}$	0.17	0.01	0.01
Redshift at decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL)	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter–energy equality	$z_{r,m}$	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift at reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (deg)	θ_A	0.598	0.002	0.002
Angular size distance (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[e]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[f]	r_s	147	2	2

[a] All data from Bennett et al., *Ap. J. S.*, 148, 1, 2003.
[b] CL means "confidence level."
[c] From COBE (Mather et al., *Ap. J.*, *512*, 511, 1999).
[d] Derived from COBE (Mather et al., *Ap. J.*, *512*, 511, 1999).
[e] $\ell_A = \pi\theta_A^{-1}$ for θ_A in radians.
[f] $\theta_A = r_s d_A^{-1}$ for θ_A in radians.