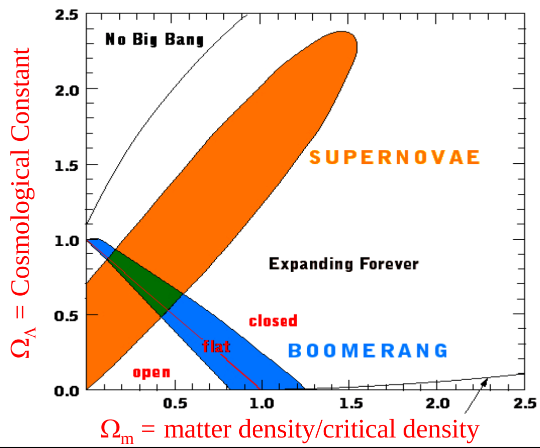
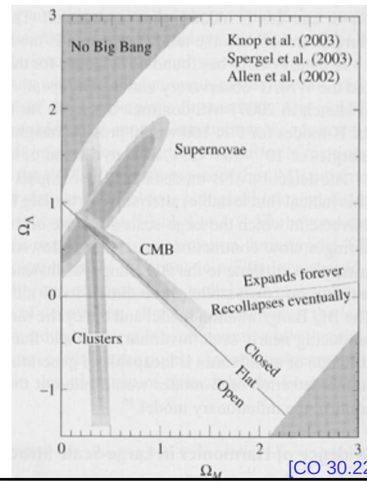
The "Concordance" Cosmology (or ΛCDM)

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



Another independent measure:
Rate of galaxy cluster evolution

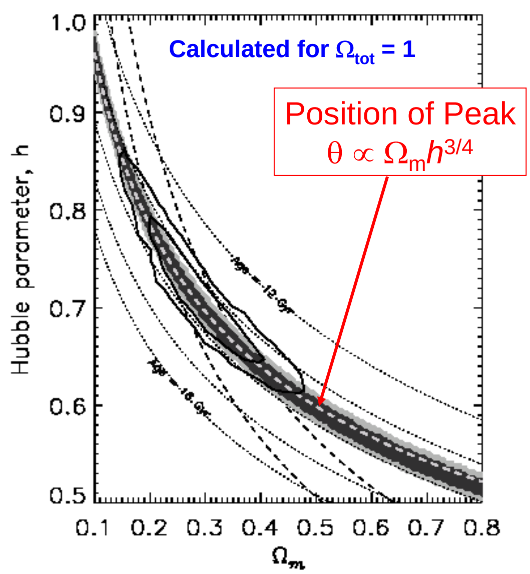


[CO 30.22]

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

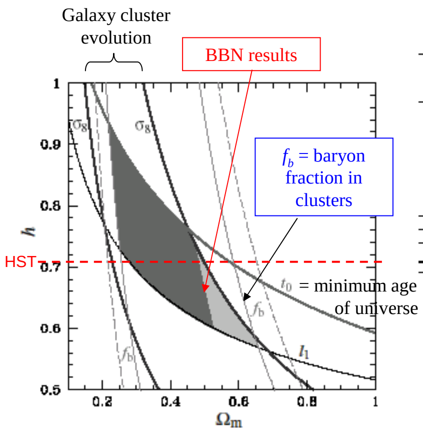
Height of peak

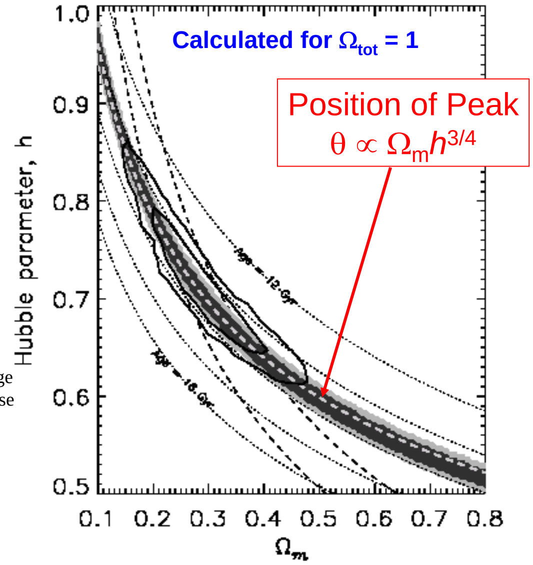
- Larger Ω_m ➔ all peaks have smaller amplitudes.
  - Through change in matter/radiation density ratio during radiation-dominated phase.
  - Through effect on when universe becomes matter dominated.



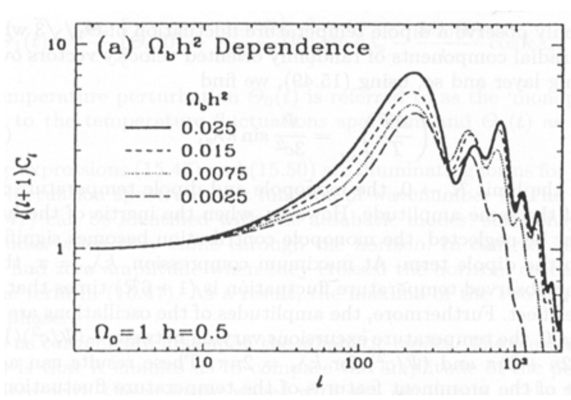
Position & height of first peak also depend on Ω_m, Ω_b, h

So use constraints from other measurements:

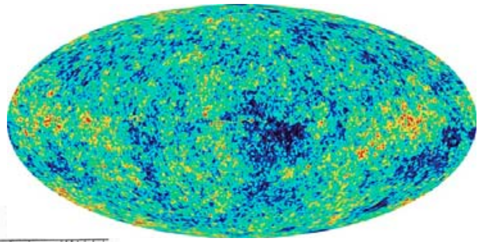


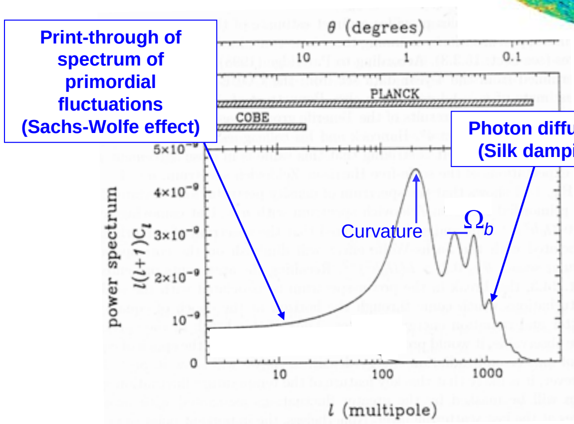


WMAP also measured second peak



- 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

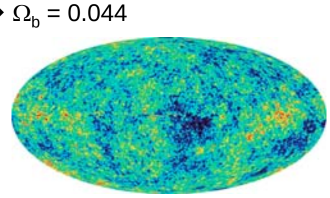
Results:

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

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)

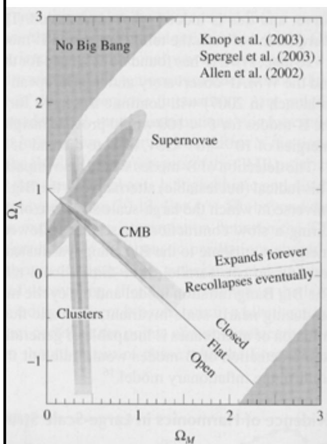
FIRST-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*)[1] OBSERVATIONS: INTERPRETATION OF THE TT AND TE ANGULAR POWER SPECTRUM PEAKS

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.

The Syllabus:

Nov 9,11,13	**The Structure of the Universe & Evolution of Galaxies** [27.3] Clusters of galaxies [28.4] Using quasars to probe the universe (gravitational lenses)
Nov 16,18,20	*What is dark matter?* [30.2] The origin of structure; WMAP measurements.
Nov 23,25	[26.1] Interaction of galaxies
Fri Nov 27	**Thanksgiving Holiday**
Nov 30, Dec 2,4	[26.2] The formation of galaxies
Dec 7,9,11	Quasars & Active galactic Nuclei (AGN) [28.2] Unified model of AGN … *(Skip [28.1], [28.3])* [18.2] Accretion Disk description pp. 661-666 [24.4] The Galactic Center

The agenda:

- Present-day structure.
- Evidence for Dark Matter.
  - Gravitational lenses.
- What is Dark Matter?
  - Hot vs. cold DM
- The growth of structure.
  - Initial fluctuations.
  - WMAP.
  - Bottom-up structure formation.

(turkey break)

- The Quasar Era.
- Evolution to modern-day galaxies.
- Chemical enrichment revisited.
- The first stars.

Final Exam: in BPS 1420, at 3PM Monday, Dec 14