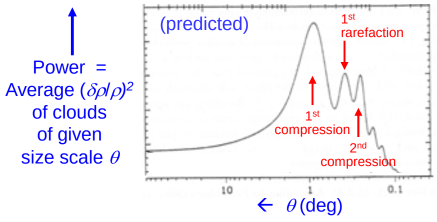
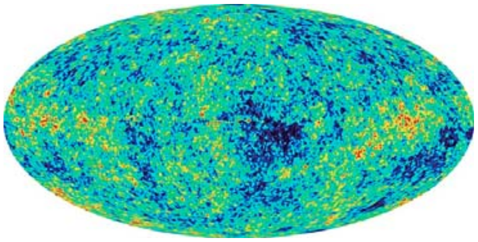
Analyzing the CMB Brightness Fluctuations





Fourier analyze WMAP image:

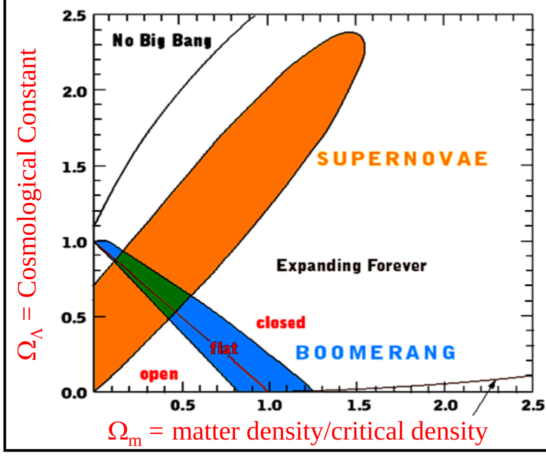
- Measures "*Power*" for each size scale θ.
- = *Power* for each mass scale *M.*

- All blobs of same mass *M* oscillate synchronously.
- Peaks are for mass scales that are either fully compressed or fully rarified.

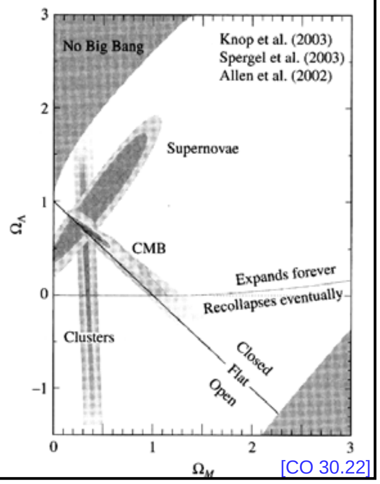
Position of first peak measures curvature
➔ universe is flat

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

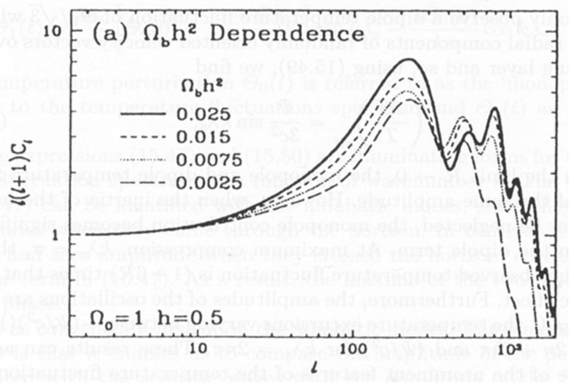


Another independent measure:
Rate of galaxy cluster evolution



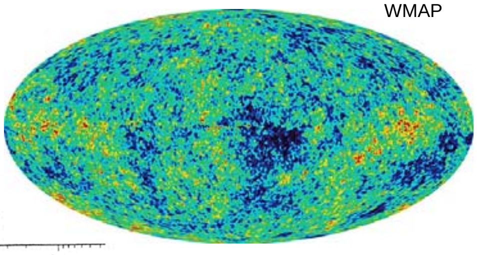
[CO 30.22]

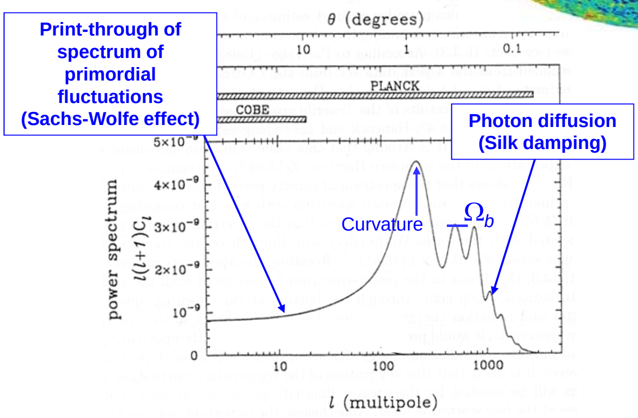
WMAP also measured second peak



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

WMAP



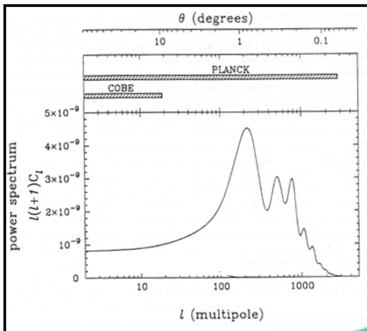


Print-through of spectrum of primordial fluctuations (Sachs-Wolfe effect)

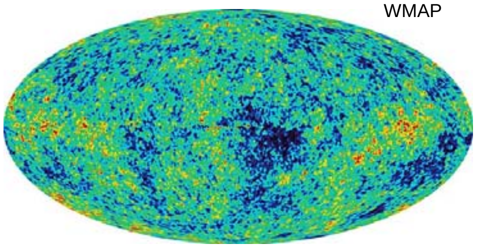
Photon diffusion (Silk damping)

Curvature

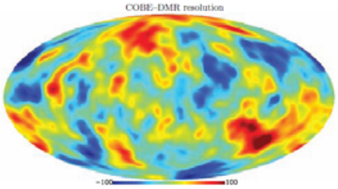
Ω_b



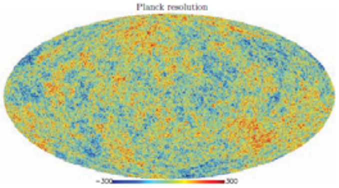
WMAP



COBE



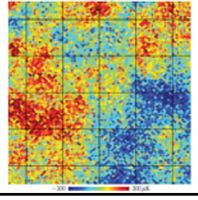
PLANCK



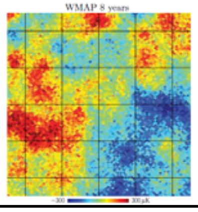
Planck

- ESA mission
- Launched May 2009
- Arr. L2 July 09

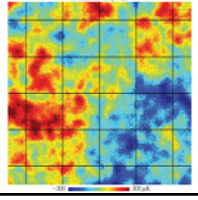
WMAP 2 yrs



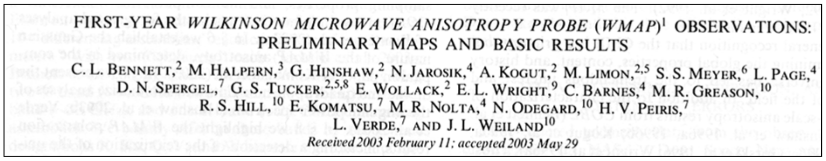
WMAP 8 yrs



PLANCK 1 yr



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

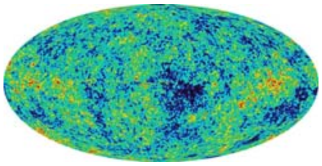
Results:

- 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: $\Omega_b h^2 = 0.0224 \pm 0.009 \rightarrow \Omega_b = 0.044$

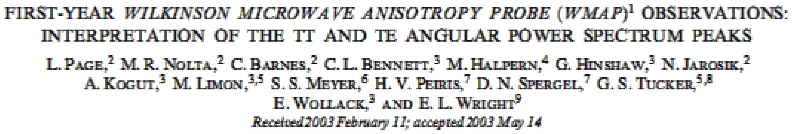
73% Dark Energy, 22% Dark Matter,
4.4% Baryonic Matter

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

➔ **INFLATION**



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



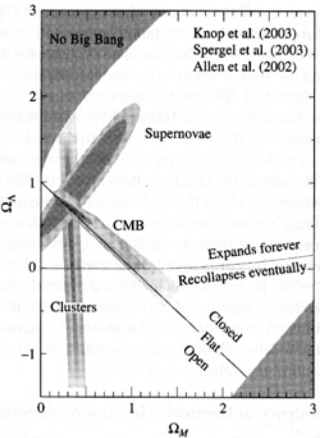
FIRST-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*)[1] OBSERVATIONS:
INTERPRETATION OF THE TT AND TE ANGULAR POWER SPECTRUM PEAKS

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

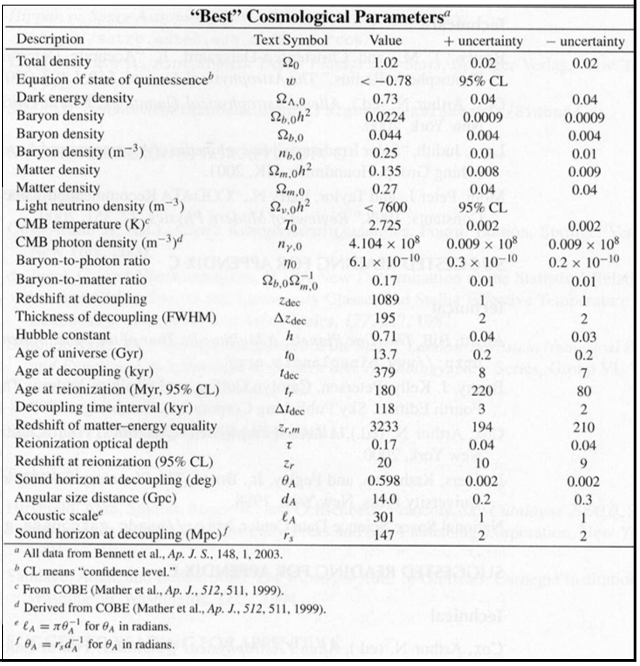
Power spectrum measures many things

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).

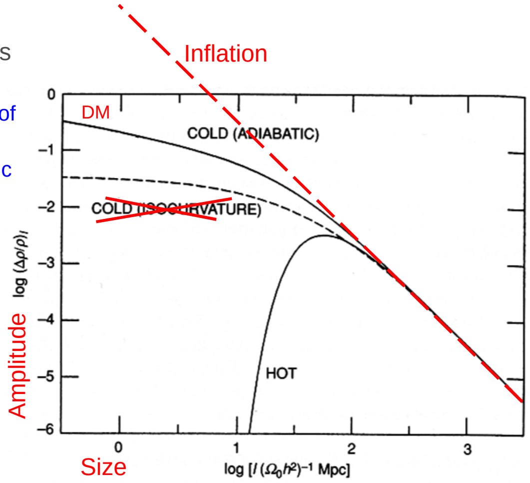
[d] Derived from COBE (Mather et al., *Ap. J.*, *512*, 511, 1999).

[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.

Hot vs. Cold Dark Matter Perturbations

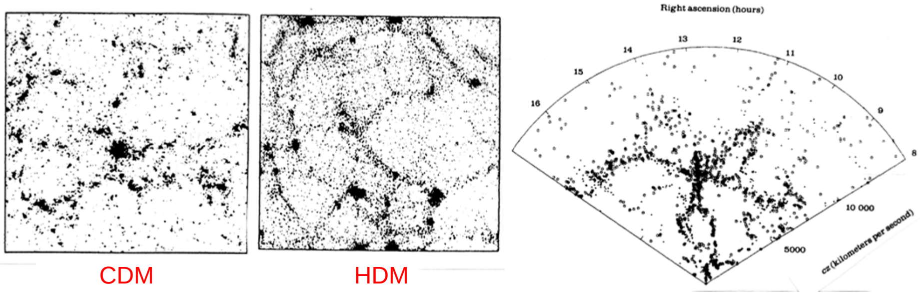
- Power spectrum of fluctuations
  - $P(k) \propto k^n$ where $P = |\delta\rho/\rho|^2$ and k = wave number = $2\pi/l$
- Inflation predicts $n = 1$
  - "scale invariant":
    - $\delta\rho/\rho$ always has same value when perturbation enters horizon.
  - Predicts $\delta\rho/\rho \propto M^{-2/3} \propto l^{-2}$
- HDM perturbations with wavelengths shorter than horizon are lost
  - relativistic particles free stream out of smaller condensations
  - until particles become non-relativistic at $T \sim 10^5$K
  - smallest condensations have $\sim 10^{13}$ M_{sun}
- CDM perturbations survive at all scales
  - some attenuation at shorter wavelengths
  - but most power still at shorter wavelength



N-body simulations ➔ CDM

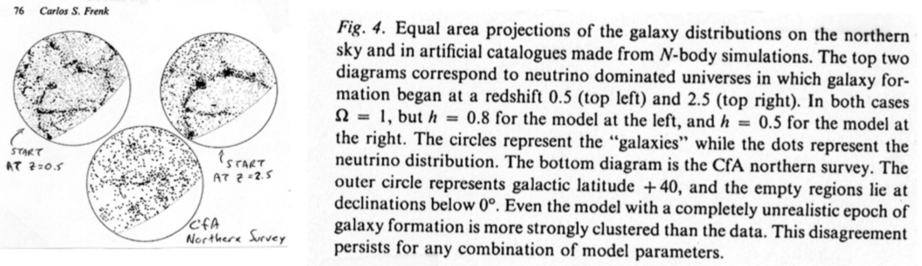
Standard CDM = SDCM, replaced by ΛCDM model

- Start with perturbation spectrum at time of decoupling
- Follow perturbations into highly non-linear regime.



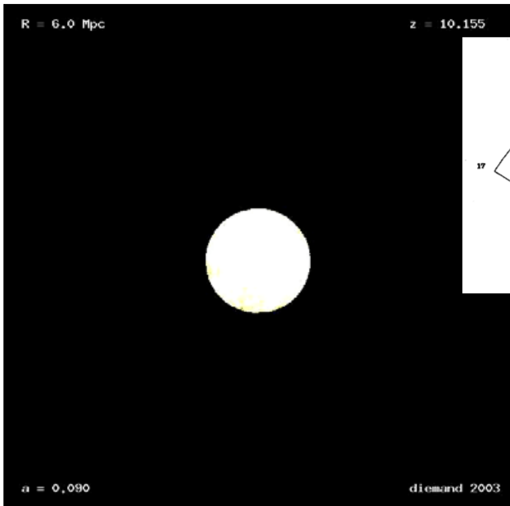
CDM HDM

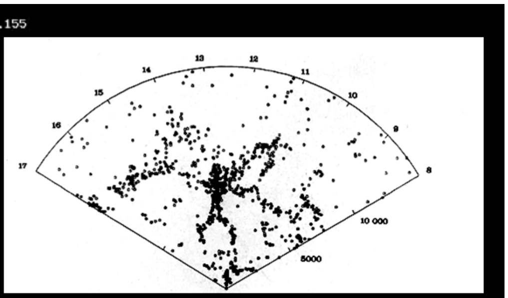
- HDM models become too highly clustered over observed lifetime of galaxies

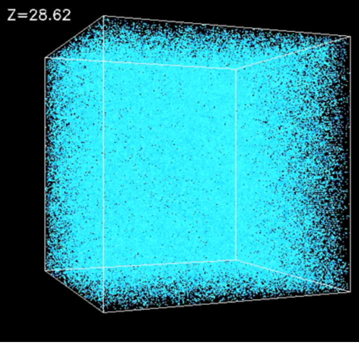


76 *Carlos S. Frenk*

Fig. 4. Equal area projections of the galaxy distributions on the northern sky and in artificial catalogues made from *N*-body simulations. The top two diagrams correspond to neutrino dominated universes in which galaxy formation began at a redshift 0.5 (top left) and 2.5 (top right). In both cases $\Omega = 1$, but $h = 0.8$ for the model at the left, and $h = 0.5$ for the model at the right. The circles represent the "galaxies" while the dots represent the neutrino distribution. The bottom diagram is the CfA northern survey. The outer circle represents galactic latitude +40, and the empty regions lie at declinations below 0°. Even the model with a completely unrealistic epoch of galaxy formation is more strongly clustered than the data. This disagreement persists for any combination of model parameters.



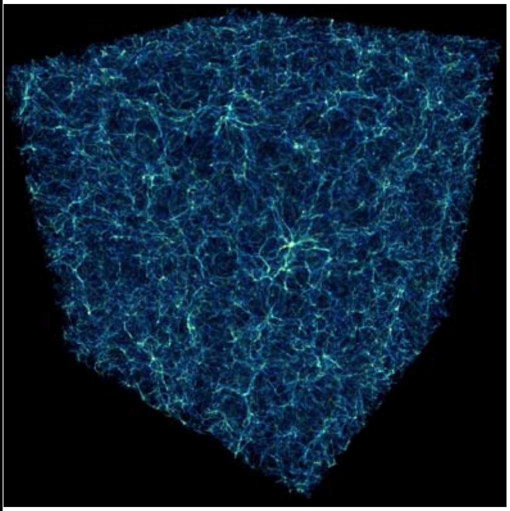




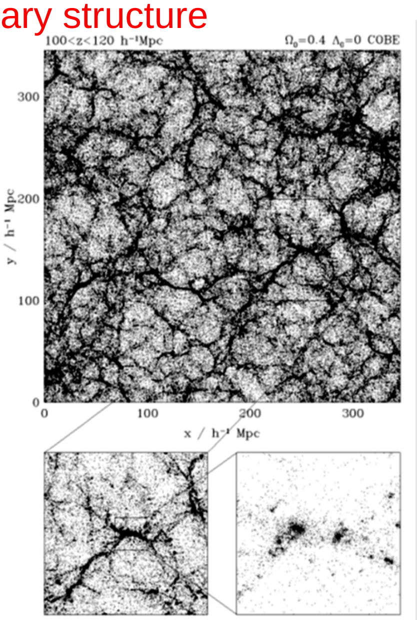
In “proper” coordinates

In
co-moving
coordinates

CDM structure-formation models reproduce observed filamentary structure



0.5 Gpc cube.
Simulation by MSU Prof. Brian O'Shea



From Cole et al (1997). See Weinberg et al. astro-ph/9708213

More CDM Simulations

(Frenk 1991, Physica Scripta T36, 70)

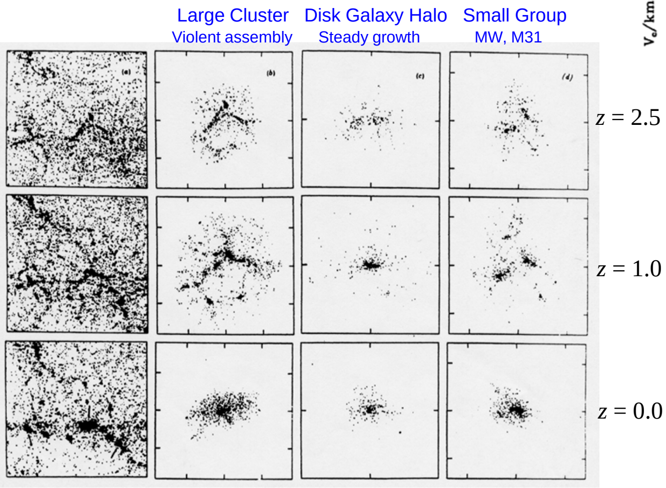
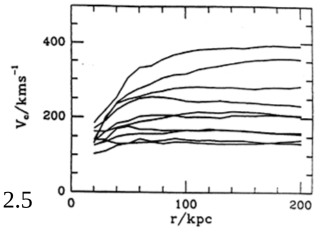


Fig. 8. **Evolution of a (14 Mpc)^3 volume of a flat CDM universe and of selected galactic halos that formed in it. Time increases** downwards in this figure. **Each row corresponds to a different redshift as follows: z = 2.5** (top), **z = 1 (middle) and z = 0 (bottom). The column labelled (a)** shows the simulation **as a whole, with positions plotted in comoving coordinates;** the region shown at the top of this panel **is thus 4 Mpc on a side.** The three clumps marked **with arrows at the bottom of (a) are shown in greater detail in** (b)–(d). **Physical, not comoving, coordinates are used in (b)–(d) and** tickmarks represent 1-Mpc **intervals. The three selected halos correspond to the two most** massive clumps **in the simulation and to a more isolated system.** (From Ref. [63].)



flat rotation curves reproduced

But now finding:

Galaxy dark matter halos do NOT have exactly the expected CDM density distribution (NFW profiles).

Bias

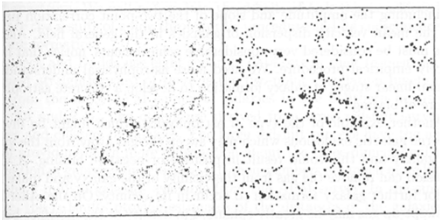
- CDM simulations ➔
  accurate predictions of CDM structure.

- Problems describing baryon response.
  - Observations ➔ preference for galaxies to form in denser regions.

$$\left(\frac{\delta\varrho}{\varrho}\right)_{\mathrm{B}} = b\left(\frac{\delta\varrho}{\varrho}\right)_{\mathrm{D}}$$ in CDM simulation ➔

$$b^2 = \frac{\sigma_8^2(\text{galaxies})}{\sigma_8^2(\text{mass})}$$ from observations,

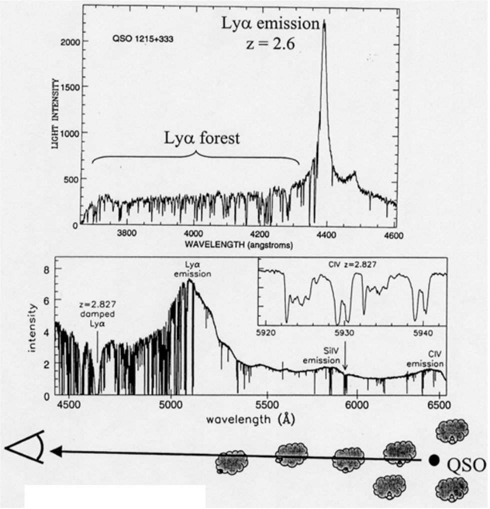
where σ_8 = variance of mass distr. in $8h^{-1}$ Mpc co-moving sphere.

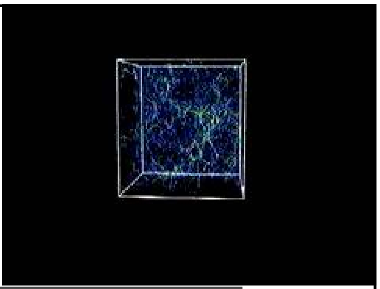


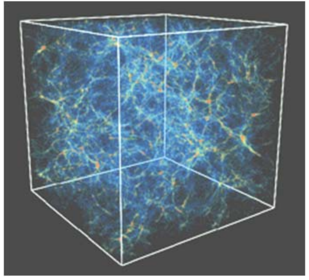
Dark matter Baryons (for b = 2.5)

- So arbitrary assumptions are needed to describe the observable galaxies.

The Lyα Forest



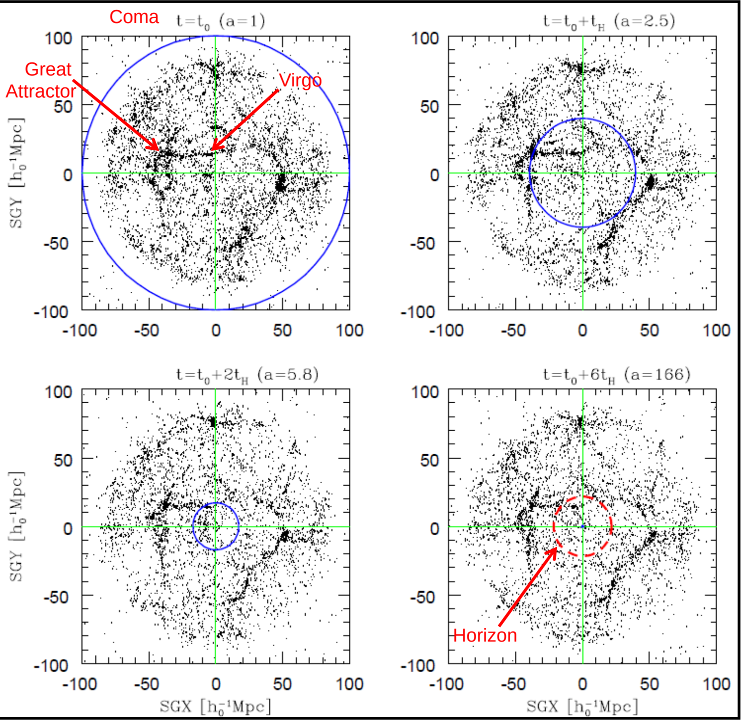




- It's the cosmic web.
- Contains most of the baryons at high redshift.
- Currently: ~1/2 baryons still in web, but heated to 10^6 K.

Warm-Hot Intergalactic Medium (WHIM) →

The next 60 billion years



The Syllabus:

Nov 8,10	**The Structure of the Universe & Evolution of Galaxies** [27.3] Clusters of galaxies [28.4] Using quasars to probe the universe (gravitational lenses) *What is dark matter?*
Nov 15,17	[30.2] The origin of structure; WMAP measurements.
Nov 22	[26.1] Interaction of galaxies
Thu Nov 24	**Thanksgiving Holiday**
Nov 29, Dec 1	[26.2] The formation of galaxies
Dec 6,8	Quasars & Active galactic Nuclei (AGN) [28.2] Unified model of AGN … *(Skip [28.1], [28.3])* [18.2] Accretion Disk 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 12:45PM Tuesday, Dec 13