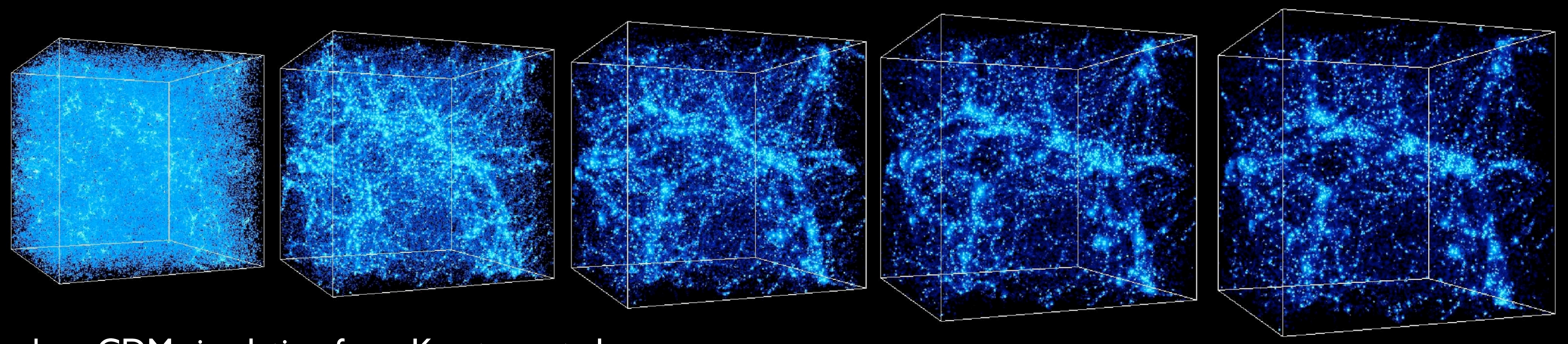
The Evolution of Large-Scale Structure in a Universe Dominated by Cold Dark Matter

Davis, Efstathiou, Frenk, & White (1985)



modern CDM simulation from Kravtsov et al.

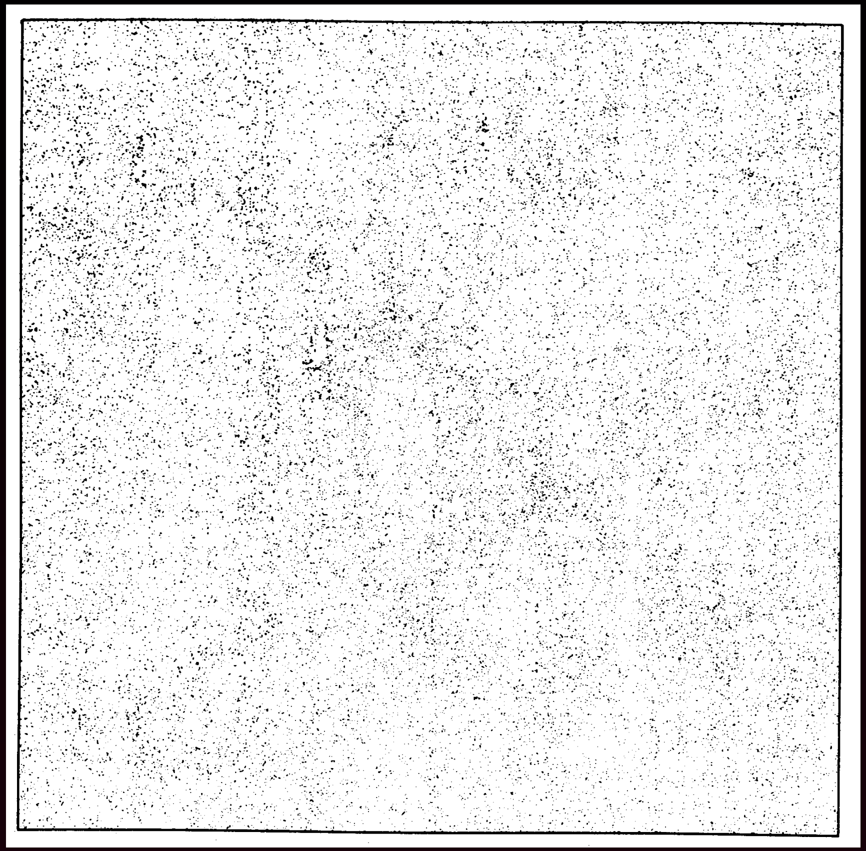
Cosmology on a Computer

- N-body code with only gravity
- particle-particle/particle-mesh (P^3M)
  - calculate nearby forces directly; $O(N^2)$
  - long range forces smoothed on mesh
- 32768 dark matter "particles"
  - $m \sim 10^{12}\,M_\odot$
  - box size ~ 100 Mpc "today"
- initial conditions from linear theory
- models with low/high Ω_M, one flat with Λ

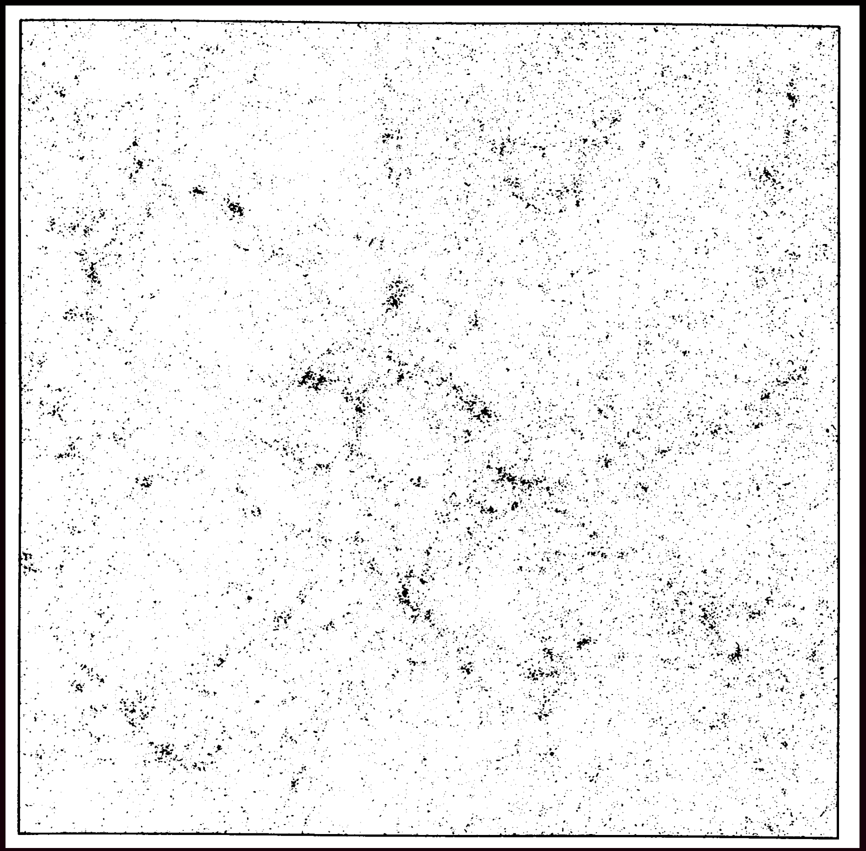
Figure 1: inital conditions

$\Omega_M = 1$ model evolution

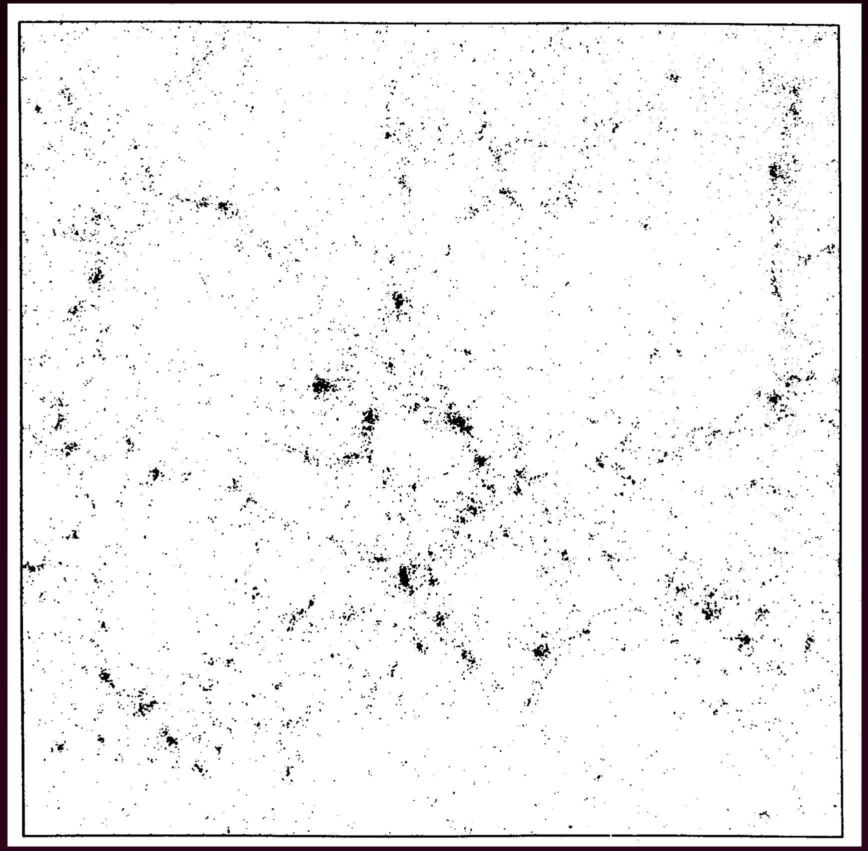
a = 1.0



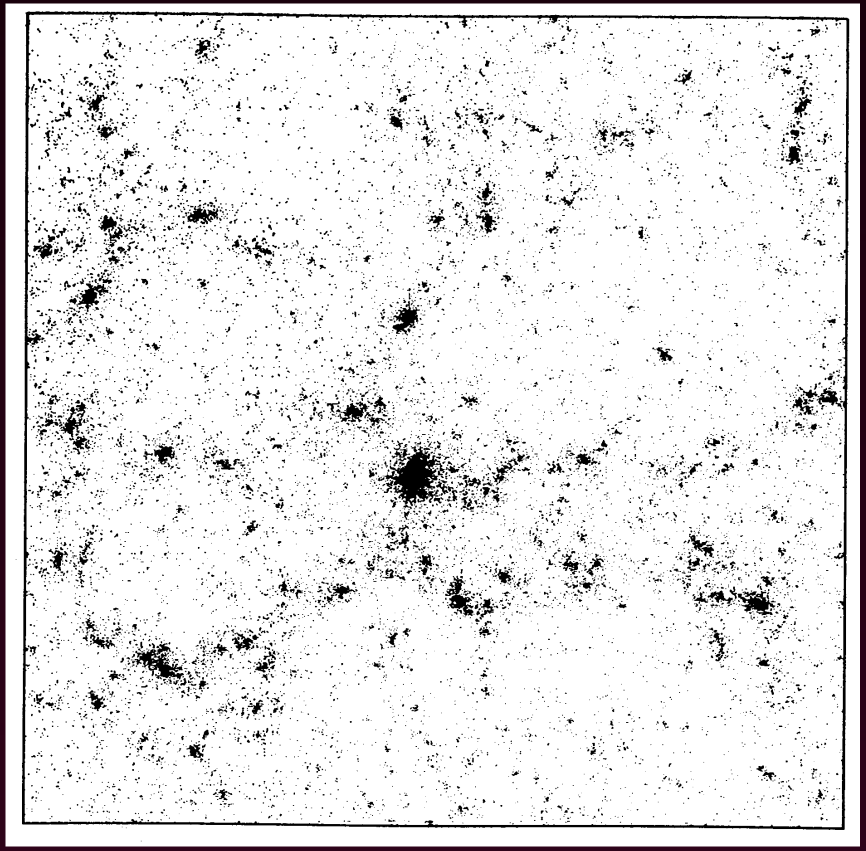
a = 1.8



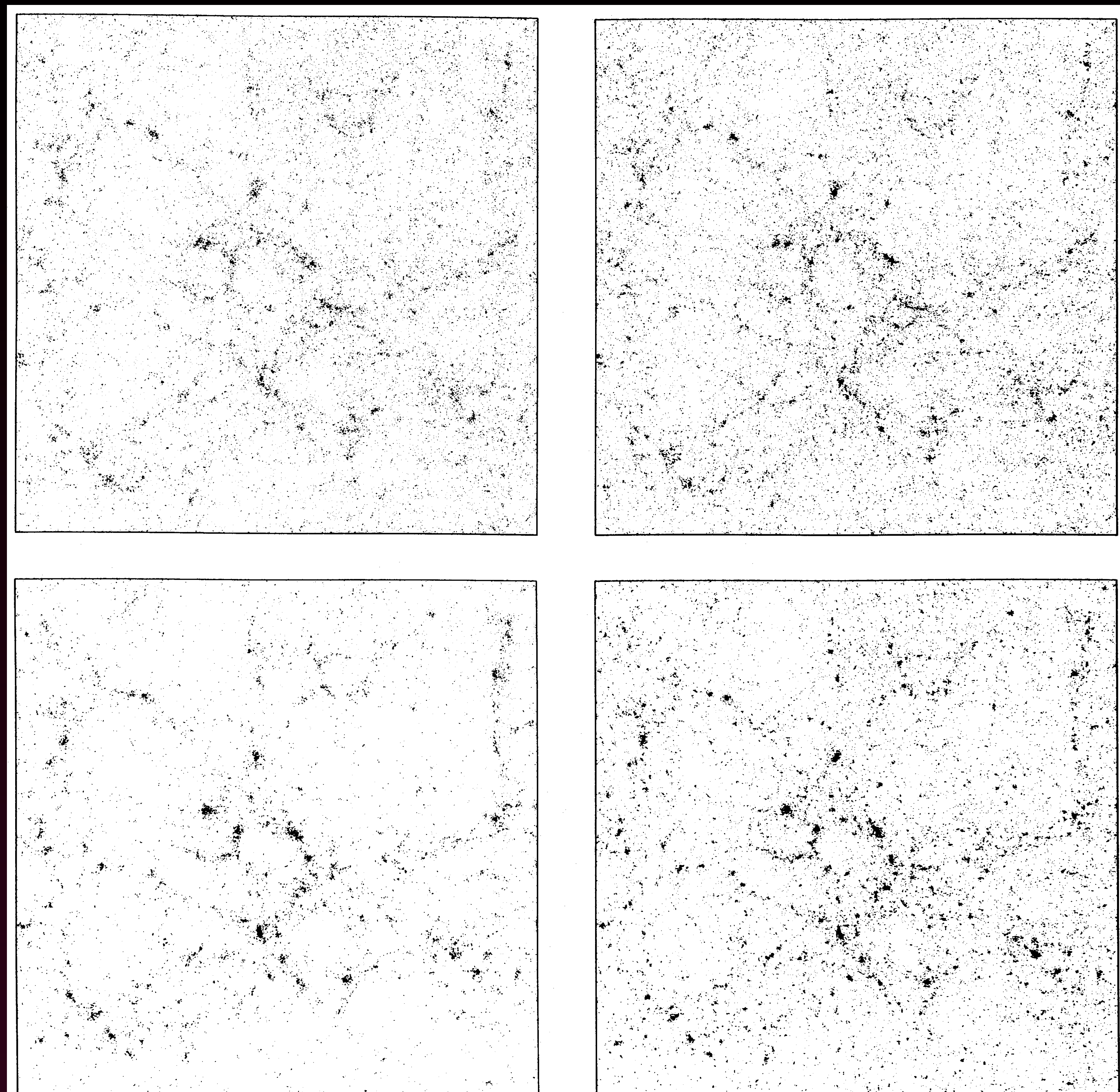
a = 2.4



a = 4.5



$\Omega_M = 1$ versus $\Omega_M < 1$



$a = 1.8$
$\Omega_M = 1$

$\rightarrow z = 0.3$

if $z = 0$

$a = 2.4$
$\Omega_M = 1$

$a = 3.2$
$\Omega_M = 0.2$

$\rightarrow z = 1.6$

if $z = 0$

$a = 8.4$
$\Omega_M = 0.09$

$\Omega_M = 1$ versus $\Omega_M < 1$ power spectrum

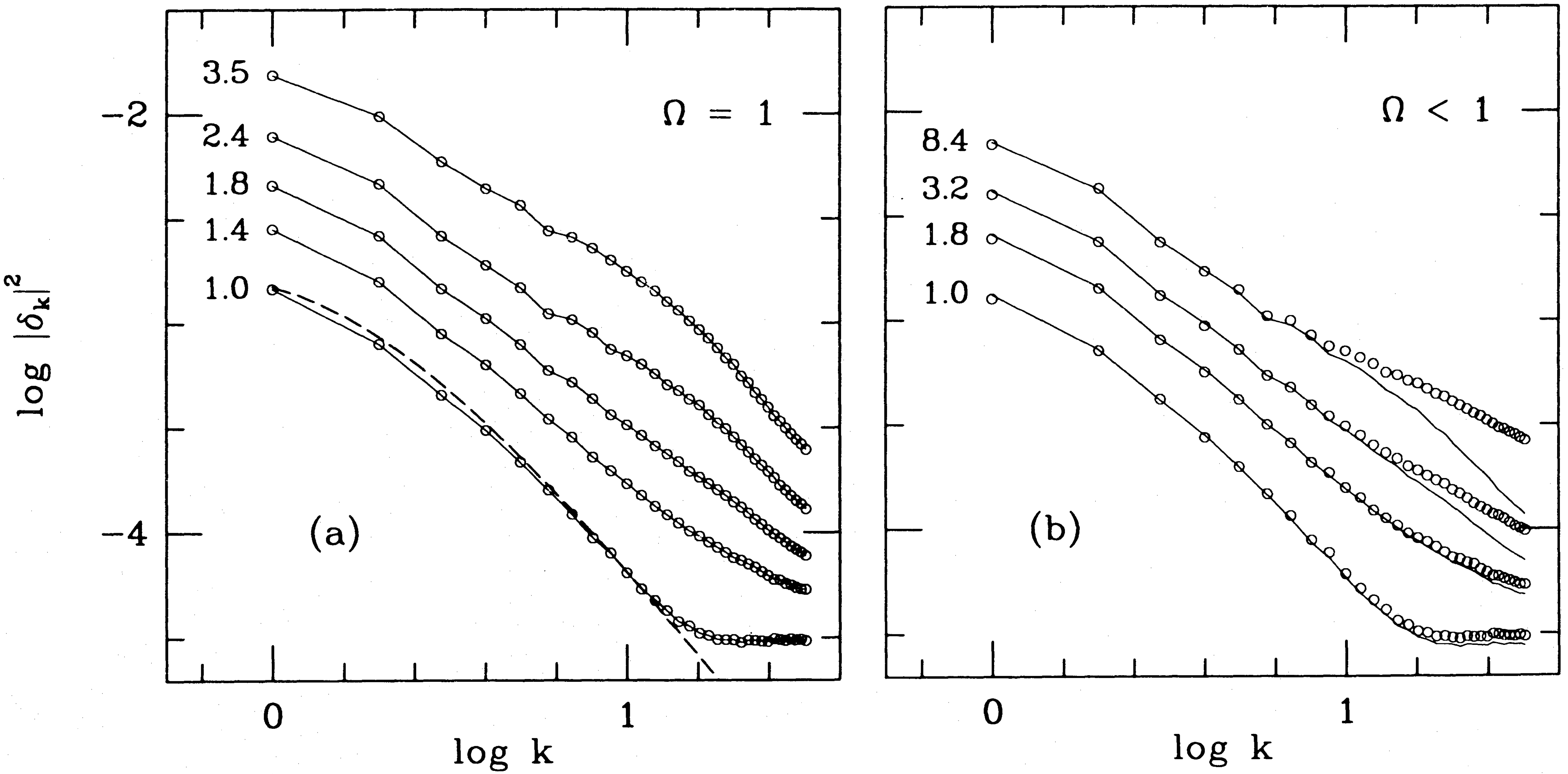


FIG. 2.—The evolution of the power spectrum for two ensembles of models, (*a*) EdS1–5 and (*b*) O1–4. The value of the expansion parameter *a* corresponding to each spectrum is given. The dashed line in (*a*) shows the theoretical spectrum (eq. [2]) used to generate the initial conditions. The solid lines in (*b*) repeat the results of (*a*) after multiplication by 0.9.

$\Omega_M = 1$ versus $\Omega_M < 1$
correlation function

see Peebles (1993)

$$dP = n\,dV \qquad dP = n^2(1+\xi(r))\,dV_1\,dV_2$$

observations show $\xi(r) = (r/r_0)^{-\gamma}$ with $r_0 \simeq 8$ Mpc, $\gamma = 1.8$

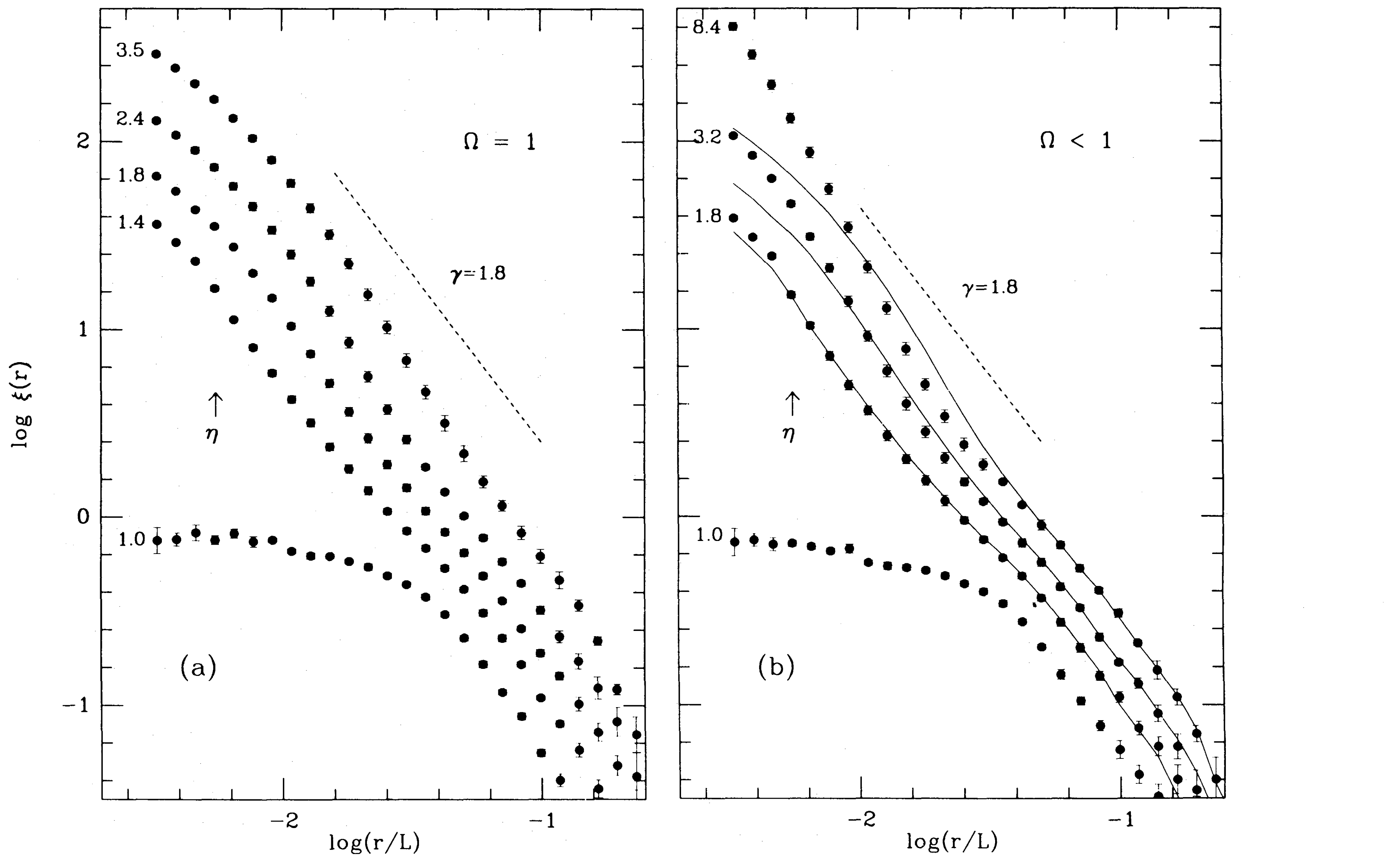


FIG. 4.—Two-point correlation functions $\xi(r)$ are shown for models (*a*) EdS1–5 and (*b*) O1–4, for various values of the expansion parameter *a*. The separation *r* is given in units of the side of the computational volume. The error bars give errors in the mean derived from the scatter within each ensemble. The dotted line is a power law with the index $\gamma = 1.8$, which fits the galaxy distribution. The solid lines in (*b*) repeat the results in (*a*) after multiplication by 0.9. An arrow in each panel marks the softening length of our simulations.

Confronting the Observations

simulation

data

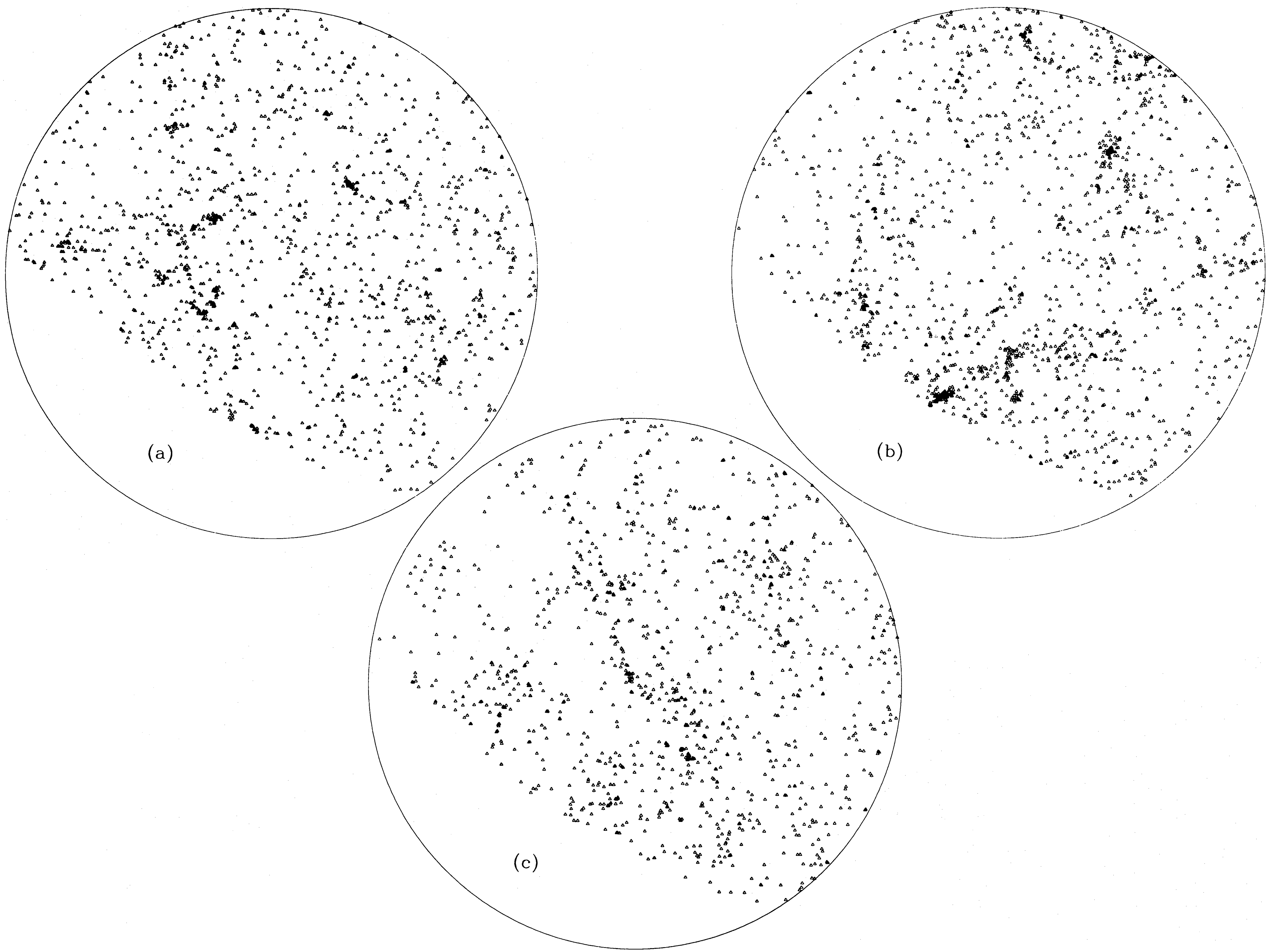


FIG. 12.—Redshift catalogs constructed from two open models (O2 and O3) are shown in (*a*) and (*b*) as projections onto the "sky." Particles were selected for inclusion in these catalogs in such a way as to mimic the northern CfA survey. The real data are shown in the same format in (*c*). These are equal area plots of the sky; the outer circle corresponds to Galactic latitude $+40°$, while the empty regions correspond to declinations below 0°. In constructing the catalog from O3 shown in (*b*), the "observer" was purposely sited near a prominent cluster.

Confronting the Observations

simulation

data

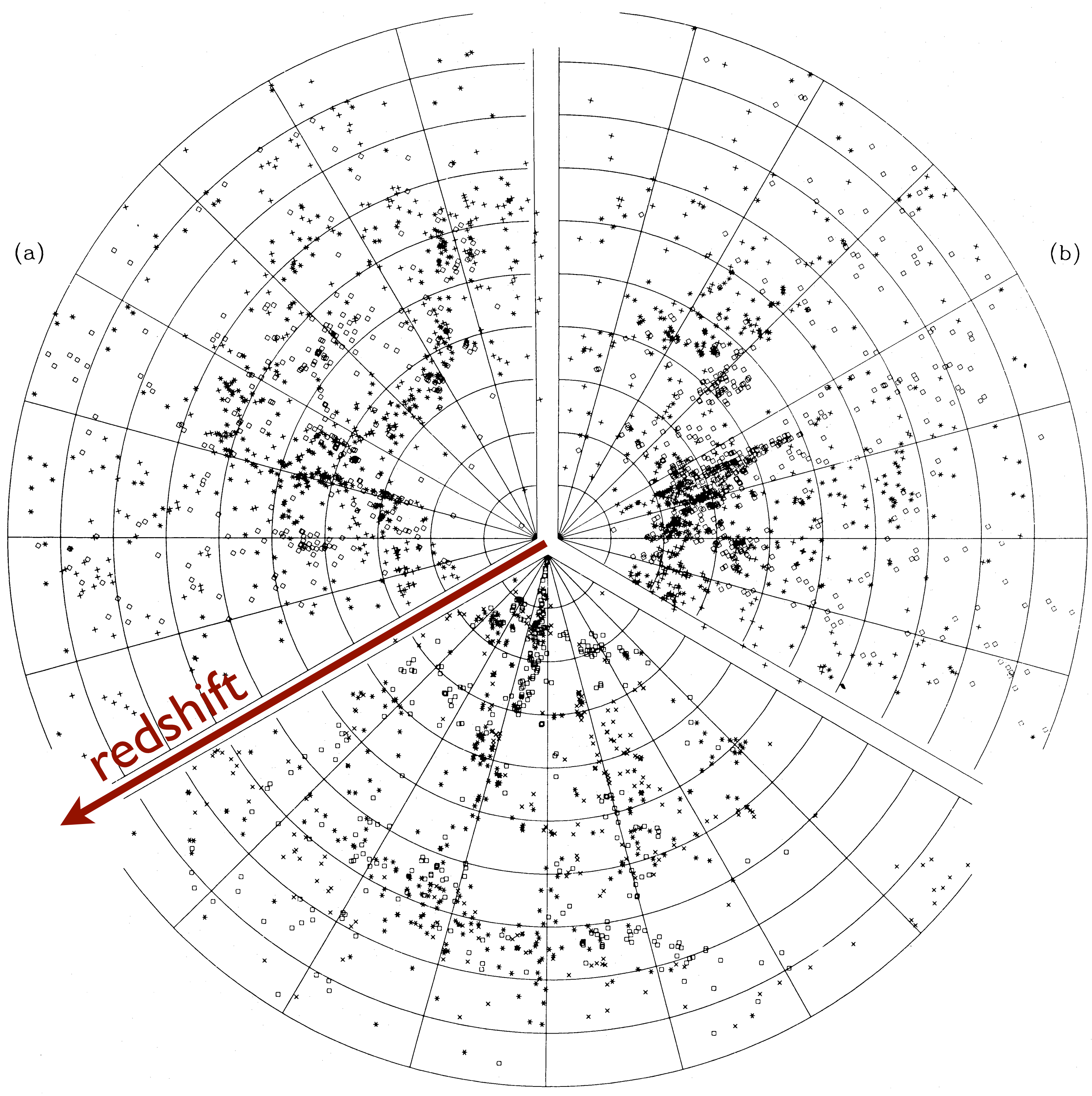


FIG. 13.—Wedge diagrams for the three catalogs illustrated in Fig. 12. The radial coordinate in these plots is recession velocity with successive circles corresponding to increments of 1000 km s^{-1}. The angular coordinate is right ascension with a line plotted for each hour. All "galaxies" in the declination range $0° < \delta < 45°$ are shown, with squares corresponding to $0° < \delta < 15°$, stars to $15° < \delta < 30°$, and crosses to $30° < \delta < 45°$. The three slices of this pie are labeled to correspond to Fig. 12. Note the large cluster in O3 and the Virgo Cluster in the CfA data.

Biased Galaxy Formation

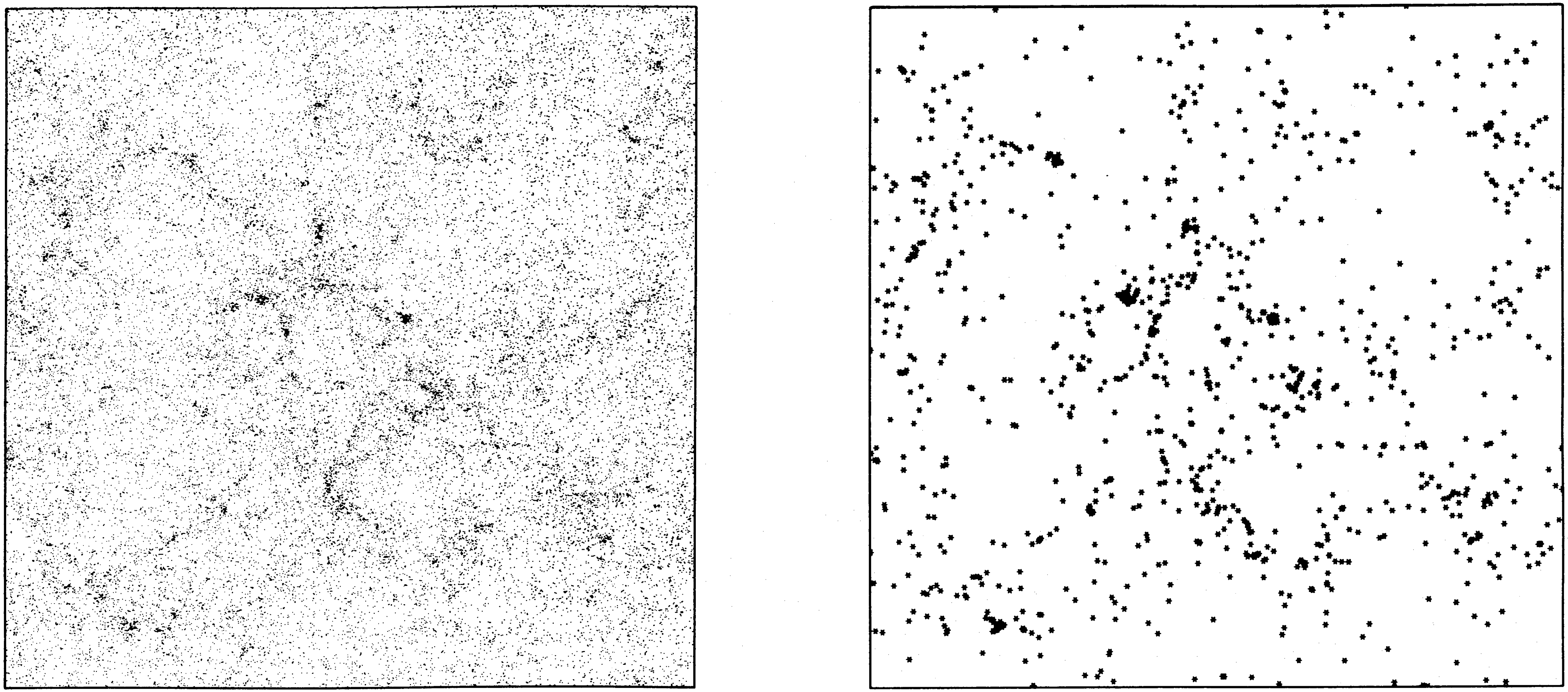


FIG. 16.—The projected distribution of all particles (*left*) and of the "galaxies" (*right*) in EdS1 at $a = 1.4$. The side of the box is $32.5h^{-1}$ Mpc. "Galaxies" are assumed to form only at the $2.5\,\sigma$ peaks of the linear density distribution.

→ increased clustering (galaxies relative to total mass, clusters relative to galaxies, etc.)

Conclusions

- CDM simulations do a reasonably good job of describing large-scale structure (e.g., power spectrum, correlation function, redshift surveys)

- Structure evolution is faster for high Ω_M, so given the structure we see today, we expect more structure at high redshift for lower Ω_M

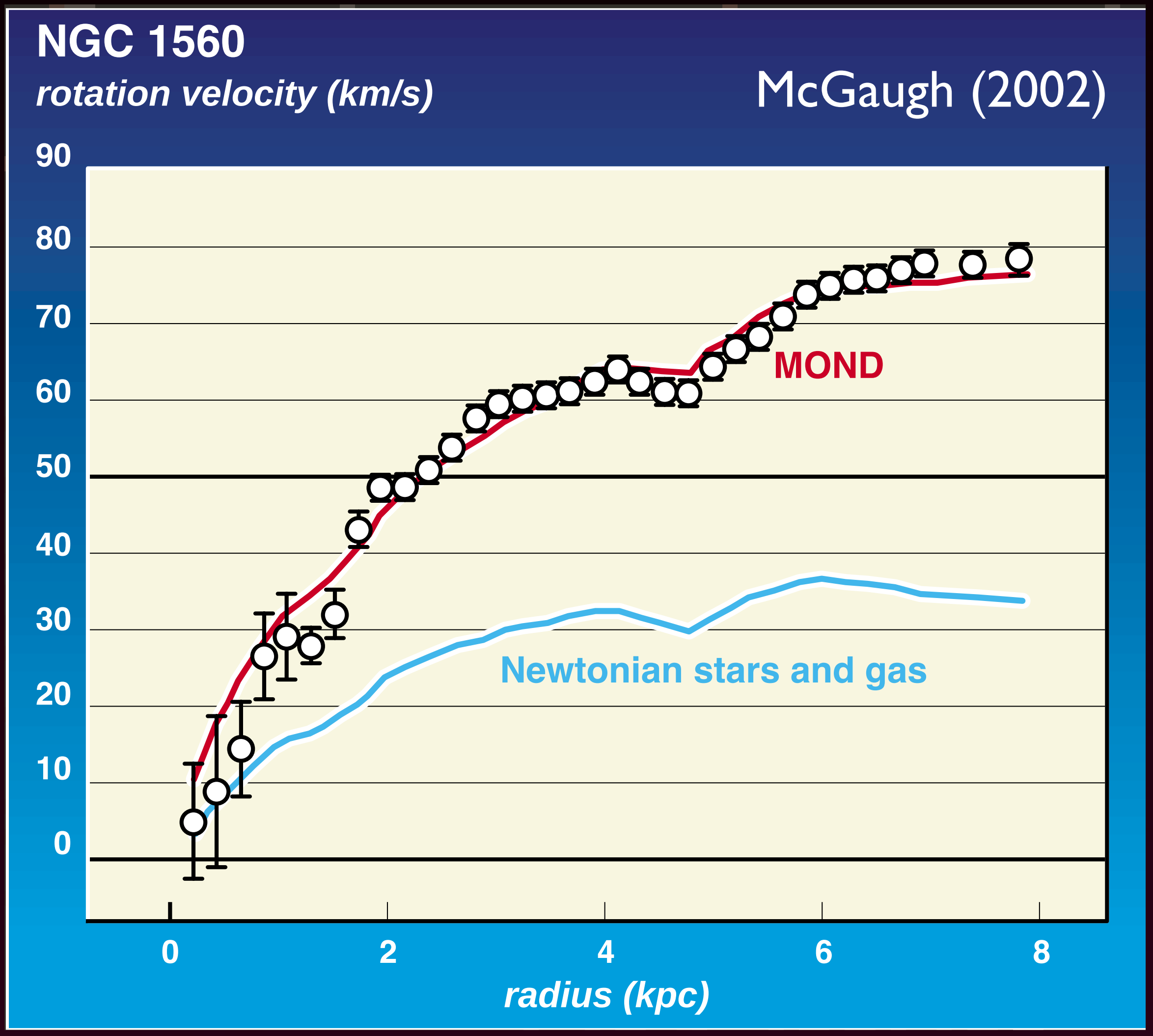
- Some problems matching observed velocity distributions and sizes of largest structures

- Biased galaxy formation has a large effect on matching epoch of simulation and "today" but could alleviate some of the discrepancies

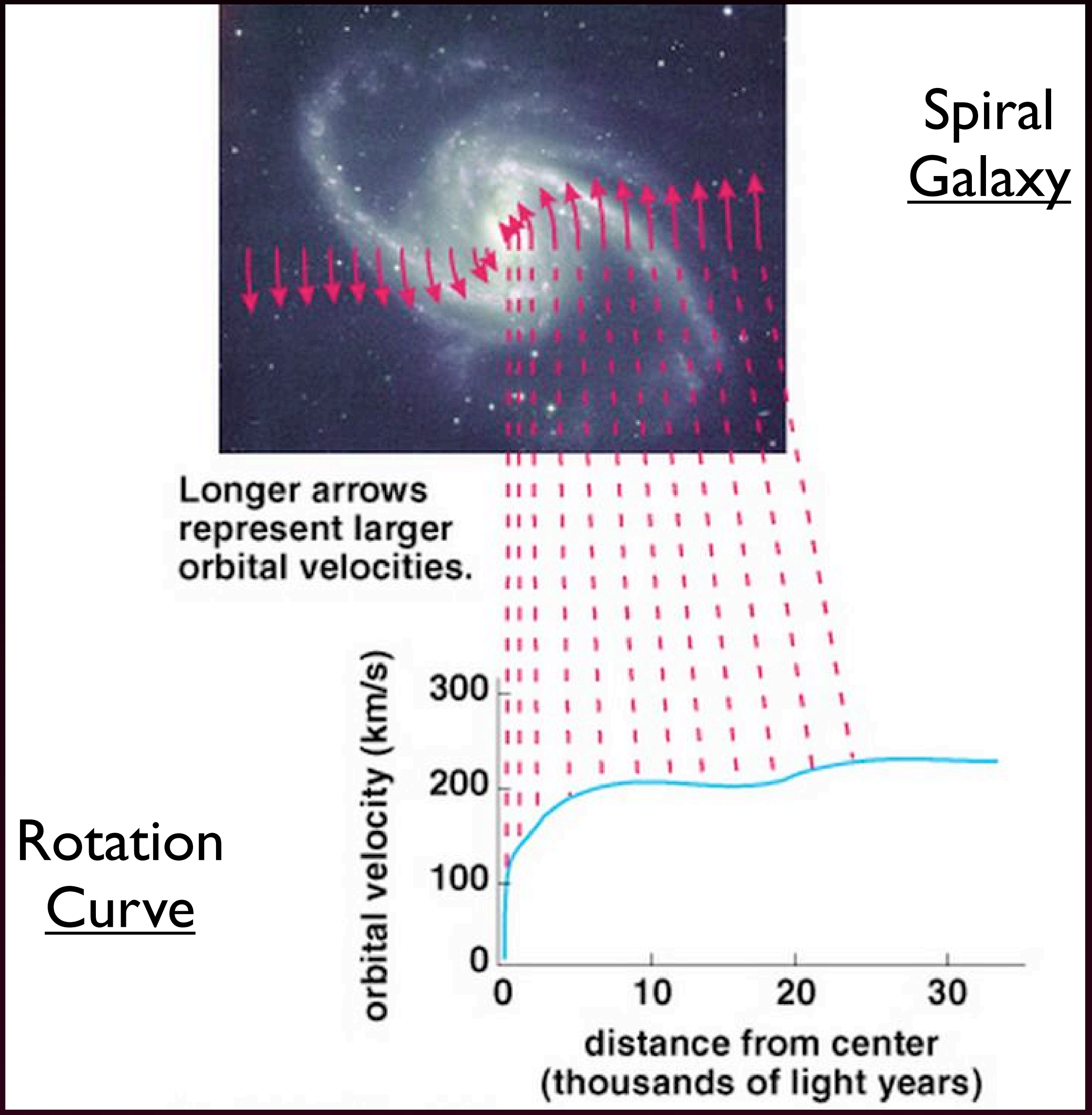
Modified Newtonian Dynamics as an Alternative to Dark Matter

Sanders & McGaugh (2002)

McGaugh (2007)



supplemented with information from The MOND Pages, maintained by Stacy McGaugh
http://www.astro.umd.edu/~ssm/mond/



Aside: Dark Matter or Modified Gravity?

BOTH!

- Case study: the solar system

- 1820s: observations of the orbit of Uranus show anomalies
  - could be accounted for with "dark matter": an unseen 8th planet
  - Neptune discovered in 1846 based on predictions of Le Verrier and Adams

- 1800s: observations of the orbit of Mercury show anomaly (perihelion advance, 0.42 arcsec/yr "extra")
  - "dark matter": hypothetical inner planet Vulcan
  - correct explanation: modified gravity! Einstein's General Relativity supersedes Newtonian gravity

analogy by Sean Carroll