unequivocal evidence for a nonbaryonic, massive particle, and several candidates were proposed: massive neutrinos, axions, neutralinos, quark nuggets, and primordial black holes.

However, there may yet be further surprises in store. It turns out that the estimate of η depends sensitively on the primordial abundance of deuterium. Deuterium absorption lines were recently measured in primordial intergalactic clouds illuminated by a background quasar. The conclusion was that previous estimates for deuterium abundance were too high; consequently, the value of η almost doubled, and Ω_{BBNS} could now be as large as 0.1. This value is not far from the preferred value of the mass density ascribed to clusters ($\Omega_{cluster} \approx 0.3$).

Given the overall uncertainty of the various mass density measurements, it is dangerous to predict just how much of dark matter is nonbaryonic. However, this fraction is likely to be at least two-thirds of all dark matter ($\Omega_{BBNS} \sim 0.1$ and $\Omega_{cluster} \approx 0.3$), and it could be much higher if Ω eventually turns out to be unity. These results are summarized in Table I.

Table I. Comparison of Mass Densities

	Observation	Theory
$\Omega_{luminous}$	0.003	—
Ω_{galaxy}	0.02–0.1	—
$\Omega_{cluster}$	0.1–0.3	—
$\Omega_{baryonic}$	—	0.01–0.1 (BBNS)
Ω_{total}	0.1–1	1 (inflation)

The Big Bang: Structure Formation

One of the striking features of the Universe today—as opposed to the early Universe—is its inhomogeneity. Like islands and archipelagos in some vast ocean, matter floating in space has condensed into stars, planets, gas clouds, galaxies, and galactic clusters. Even the clusters seem to be organized into larger structures, creating great walls and sheets of galaxies that surround enormous bubbles or voids of lower density. Observations indicate that the Universe is "lumpy" on distance scales up to several tens of megaparsecs.

In earlier redshift surveys such as the CfA, there was strong inhomogeneity on the largest scales probed (~50 h^{-1} Mpc). (Although this distance is on the order of 300 million light-years, the survey probed but a tiny fraction of the observable Universe, which is estimated to be about 3000 h^{-1} Mpc across.) However, much deeper surveys such as Las Campanas (~600 h^{-1} Mpc) provide evidence that on very large distance scales, the size of structures saturate and no longer increase. The Universe is apparently homogeneous on scales greater than about 100 h^{-1} Mpc (see Figure 2).

A major triumph of the standard Big Bang model has been the progress made in understanding structure formation as a result of the gravitational Jeans instability. It turns out that the evolution of small perturbations of a uniform background density can be studied in much the same way as the stability properties of an ordinary plasma. The Jeans instability comes about because gravity always attracts: above a certain wavelength, called the Jeans length, density fluctuations are unstable and grow exponentially. In an expanding Universe, this exponential growth is modified and slows down to a weak power law.

An important aspect of the Jeans instability is that it does not saturate at some finite value from nonlinear feedback, but rather increases in strength as the gravitational collapse proceeds. It stops increasing only when the structures formed have enough internal energy—for example, gas pressure in stars and kinetic energy in the solar system—to be able to resist collapsing further.

Another subtlety that has to be taken into account is the growth of density perturbations in the presence of thermal radiation. In the early history of the Universe, when matter is in the form of an ionized plasma and the energy density in radiation is much greater than that of matter, there is a strong coupling between radiation and matter. The radiation field itself does not collapse, and it prevents matter from collapsing because of the strong coupling. Only perturbations on scales longer than the Jeans wavelength, given by

$$\lambda_J = v_s \sqrt{\frac{\pi}{\rho G}} ,$$

where v_s is the velocity of sound, continue to grow. Smaller-scale perturbations oscillate as damped acoustic waves. After recombination, the velocity of sound drops abruptly as the pressure support switches from radiation to neutral hydrogen. Consequently, density perturbations on much smaller scales can also begin to grow.

This picture of how initial density perturbations grow into structures is attractive, but it lacks a key ingredient: a source for the initial density perturbations that the Jeans instability would then amplify. The original Big Bang model does not have a physical mechanism to produce these perturbations. But the precise nature of the perturbation spectrum is very important, for it controls sensitively the types of