Whatever Happened to Hot Dark Matter? *

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The lightest of the fundamental matter particles, neutrinos may play important roles in determining the structure of the universe. Neutrinos helped to control the expansion rate of the universe during the first few minutes, when the deuterium and most of the helium in the universe were formed, and neutrinos and photons each accounted for nearly half of the entire energy density of the universe during its first few thousand years, before cold dark matter became gravitationally dominant. The fact that neutrinos are so ubiquitous — with hundreds of them occupying every thimbleful of space today — means that they can have an impact upon how matter is distributed in the universe. Over the past two decades, the likelihood of this has risen and fallen as more and more data has become available from laboratory experiments and the latest telescopes. We now know from the Super-Kamiokande atmospheric neutrino data that neutrinos have mass. Current estimates are that the total neutrino mass could be comparable to that of the visible stars in the universe, or perhaps even larger.

Dark matter made of light neutrinos, with masses of a few eV, is called by cosmologists “hot dark matter” (HDM). (See Sidebar 1 for a summary of the various dark matter types and of the corresponding cosmological models.) By 1979, cosmologists had become convinced that most of the matter in the universe is completely invisible. This gravitationally dominant component of the universe was named “dark matter” by the astronomer Fritz Zwicky, who first described evidence for dark matter in the Coma cluster of galaxies in 1933: the galaxies were moving much too fast to be held together by the gravity of the visible stars there. This phenomenon was subsequently seen in other galaxy clusters, but since the nature of this dark matter was completely unknown it was often ignored. During the 1970s, it became clear that the motion of stars and gas in galaxies, and of satellite galaxies around them, required that dark matter must greatly outweigh ordinary matter in galaxies. The data gathered since then provides very strong evidence that most of the mass in the universe is dark matter.

Here’s the HDM story in a nutshell: For a few years in the late 1970s and early 1980s, hot dark matter looked like the best bet dark matter candidate. Such HDM models of cosmological structure formation led to a top-down formation scenario, in which superclusters of galaxies are the first objects to form, with galaxies and clusters forming through a process of fragmentation. Such models were abandoned by the mid-1980s when it was realized that if galaxies form sufficiently early to agree with observations, their distribution would be much more inhomogeneous than it is observed to be. Since 1984, the successful structure formation models have been those in which most of the mass in the universe is in the form of cold dark matter (CDM). But the HDM stock rose again a few years later, and

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for a while in the mid-1990s it appeared that a mixture of mostly CDM with 20-30% HDM gave a better fit to the observations than either pure HDM or pure CDM. This “cold + hot dark matter” (CHDM) theory could explain data on nearby galaxies and clusters only if the cosmological matter density $\Omega_m$ is large, either unity (a “critical density” universe) or close to it. And like all $\Omega_m = 1$ theories, CHDM predicted that clusters and galaxies would mostly form at low redshift. This turned out to disagree with observations, as clusters were discovered at higher and higher redshifts. Now increasing observational evidence favors $\Lambda$CDM — i.e., CDM with $\Omega_m \approx \frac{1}{3}$ and a cosmological constant $\Lambda$ or some other form of “dark energy” making up $\Omega_\Lambda \approx \frac{2}{3}$ so that $\Omega_{tot} = \Omega_m + \Omega_\Lambda = 1$ as implied by recent observations of the cosmic background radiation. The question now is how much room there is for HDM. At present, cosmology provides the best available upper limit on the neutrino masses.

It’s already clear from this brief summary that to describe the possible role of neutrinos as dark matter, I will have to say a few words about how structures such as galaxies formed as the universe expanded. The expansion itself is assumed to be described by our modern theory of gravity and spacetime, Einstein’s theory of general relativity (GR). Is this a good assumption? There are wonderfully precise tests of GR on the scales of binary pulsars and the solar system, and on much larger scales the masses of clusters of galaxies measured by gravitational lensing agree with the masses of the same clusters determined by the velocities of the galaxies and gas in them. On still larger scales, the accuracy of standard gravity theory is verified by the agreement between the observed flows of galaxies and the motions predicted by their observed distribution. The success of cosmological theory is the best test of GR on really large scales. For example, we now have three independent ways of estimating the age of the universe (see Sidebar 2: The Age of the Universe), and their agreement suggests that GR works on the largest scales.

In order for structure to form in the expanding universe, there must either have been some small fluctuations in density in the initial conditions, or else some mechanism to generate such fluctuations afterward. The only such fluctuation generation mechanisms that have been investigated are “cosmic defects” such as cosmic strings, and we now know that the pattern of fluctuations produced by such defects is inconsistent with the fluctuations in temperature observed on angular scales of a fraction of a degree in the cosmic microwave background (CMB) radiation. On the other hand, the sort of fluctuations predicted by the simplest cosmic inflation models — adiabatic fluctuations, in which all components of matter and energy fluctuate together — are in excellent agreement with the latest CMB results from the BOOMERANG and MAXIMA balloon flights and the DASI instrument at the South Pole, announced at the American Physical Society meeting in April 2001.

The evolution of adiabatic fluctuations is easy to understand if you just remember that gravity is the ultimate capitalist principle: the rich always get richer and the poor get poorer. What I mean by this is that, although the average density of the universe steadily decreases due to its expansion, the regions that start out with a little higher density than average expand a little slower than average and become relatively more dense, while those with lower density expand a little faster and become relatively less dense. When any
region has achieved a density about twice that of an average region of its size, it stops expanding and begins to collapse — typically first in one direction, forming a pancake-shaped structure, and then in the other two directions.

I can now explain the reason for the first hot dark matter boom about 1990. Improving upper limits on CMB anisotropies were ruling out the previously favored cosmological model with only ordinary matter. There was also evidence from an experiment in a Moscow laboratory that the electron neutrino mass is about 20-30 eV, which would correspond to $\Omega_m = 1$ if the Hubble parameter were $h \approx 0.5$, a value that was compatible with the data available then (see Sidebar 3: Neutrino Mass and Cosmological Density). In a cosmology in which most of the dark matter is light neutrinos, fluctuations on galaxy scales are erased by “free streaming” of the “hot” (i.e., relativistic) neutrinos in the early universe.

Since “free streaming” is the key property of HDM, it is worth explaining this in a little more detail. One year after the Big Bang, a region about one light-year across contained the amount of matter (both ordinary and dark matter) in a large galaxy like our own Milky Way. But the temperature then was about 100 million degrees, and correspondingly each particle had a thermal energy of $10^4$ eV. This is much higher than the rest energy $m(\nu)c^2$ of light neutrinos, which would therefore be moving at nearly the speed of light then. As a result of their rapid motion these neutrinos would spread out, and any fluctuations in the density of neutrinos on the mass scale of galaxies would soon have become smoothed out.

The first scales to collapse in a HDM universe would correspond to the mass inside the cosmic horizon when the temperature drops to a few eV and the neutrinos become nonrelativistic. This mass turns out to be of the order of $10^{16}$ times the mass of our sun (or about $10^4$ times the mass of our galaxy, including its dark halo). Evidence was just becoming available from the first large-scale galaxy surveys that the largest cosmic structures — “superclusters” — have masses of approximately the same size. This at first sight appeared to be a big success for the HDM scenario.

Superclusters of roughly pancake shape were found observationally to surround roughly spherical voids (regions where few galaxies are found), in agreement with the first cosmological computer simulations, which were run for the HDM model. In the HDM model superclusters are the first structures to form, since any smaller-scale fluctuations in the dominant hot dark matter were erased by free-streaming. Galaxies must then form by fragmentation of the superclusters. But it was already clear that galaxies are much older than superclusters, contrary to what the HDM scenario implies. And the apparent detection of electron neutrino mass by the Moscow experiment was soon contradicted by results from other laboratories.

The cold dark matter model was developed in 1982-84 (partly by the author of this article and his colleagues), just as the problems with the hot dark matter model were becoming clear. Proto-galaxies form first in a CDM cosmology, and galaxies and larger-scale objects form by aggregation of these smaller lumps — although the cross-talk between smaller and larger scales in the CDM theory naturally leads to galaxies in clusters forming earlier than those in lower density regions. In this and other respects, CDM appeared to
fit the observational evidence much better than HDM. The first great triumph of CDM was that it successfully predicted (to within a normalization uncertainty factor of about 2) the magnitude of the CMB temperature fluctuations, which were discovered in 1992 using the COBE satellite. But the simplest version of CDM, SCDM with $\Omega_m = 1$, had already begun to run into trouble.

Cosmological theories predict statistical properties of the universe — for example, the amplitude of fluctuations in the density of matter on different scales, described mathematically by the power spectrum. Sound or other fluctuation phenomena can be described the same way — for example, low frequencies might be loud (long-wavelength power). The simplest way of describing the problem with SCDM is to say that with a given amount of fluctuation power on the large scales probed by COBE (billions of light years), it has a little too much power on small scales relevant to the formation of individual galaxies and clusters (millions of light years and less). The fact that the SCDM theory could almost work across such a wide range of size scales suggested that it had a kernel of truth. The question then was whether some variant of SCDM might work better.

I personally first became worried that SCDM was in trouble when the large-scale flows of galaxies were first observed by my UCSC colleague Sandra Faber and her “Seven Samurai” group of collaborators. It had earlier been established that the local group is moving at a velocity of about 600 km/s with respect to the cosmic background radiation reference frame. But when the Seven Samurai and others found that bulk motions of galaxies with similar velocities across regions several tens of millions of light years across were the common pattern, it became clear that this was inconsistent with the expectations of the “biased” SCDM model that seemed to fit the properties of galaxies on smaller scales. So when the space shuttle Challenger exploded at launch in January 1986 and as a result Hubble Space Telescope could not be launched for several years, Jon Holtzman, then Faber’s graduate student, did a theoretical dissertation with me instead of the HST-based observational dissertation he and Faber had planned. Holtzman’s thesis, published in 1989, included detailed predictions for 96 variants of CDM. When we compared these predictions with the data available in 1992, it was clear that the best bets were $\Lambda$CDM and CHDM, each of which had less power on small scales than SCDM. Both of these variants had been proposed in 1984, when cold dark matter was still a new idea, but they were not worked out in detail until a few years later when the problems with SCDM began to surface.

Even if most of the dark matter is of the cold variety, a little hot dark matter can have dramatic effects on the small scales relevant to the formation and distribution of galaxies. In the early universe, the free streaming of fast-moving neutrinos washes out any inhomogeneities in their spatial distribution on the scales that will later become galaxies, just as in the HDM scenario. As a consequence, the growth rate of cold dark matter fluctuations is reduced on these scales, and at the relatively late times when galaxies form there is less fluctuation power in CHDM models on small scales. Since the main problem with $\Omega_m = 1$ cosmologies containing only cold dark matter plus the usual ordinary matter (baryonic) contribution $\Omega_b \approx 0.04$ is that the amplitude of the galaxy-scale inhomogeneities
is too large compared to those on larger scales, the presence of a little hot dark matter appeared to be possibly just what was needed.

And there was even a hint from an accelerator experiment that neutrino mass might be in the relevant range. The experiment was the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos, which saw a number of events that appear to be $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations followed by $\bar{\nu}_e + p \rightarrow n + e^+$, $n + p \rightarrow D + \gamma$, with coincident detection of $e^+$ and the 2.2 MeV neutron-capture $\gamma$-ray. Comparison of the LSND data with exclusion plots from other experiments allows two discrete values of $\Delta m^2_{\mu e}$, around 10.5 and 5.5 eV$^2$, or a range $2 \text{ eV}^2 > \Delta m^2_{\mu e} > 0.2 \text{ eV}^2$. The lower limit in turn implies a lower limit $m(\nu) > 0.5 \text{ eV}$, or $\Omega_\nu > 0.01$. This would imply that the contribution of hot dark matter to the cosmological density is greater than that of all the visible stars $\Omega_* \approx 0.004$. Such an important conclusion requires independent confirmation. The Karlsruhe Rutherford Medium Energy Neutrino (KARMEN) experiment results exclude a significant portion of the LSND parameter space, and the numbers quoted above take into account the current KARMEN limits. The Booster Neutrino Experiment (BOONE) at Fermilab should attain greater sensitivity.

By 1995, supercomputer technology and simulation techniques had advanced to the point where it was possible to do reasonably high resolution cosmological-scale dissipationless simulations (i.e., without the hydrodynamical complications of gas cooling, star formation, and feedback from stars and supernovae) including the random velocities of a hot dark matter component. (The HDM simulations five years earlier had actually been CDM simulations starting from a HDM power spectrum.) The results initially appeared very favorable to CHDM [1]. Indeed, as late as 1998 a comprehensive study of many CDM variants [2] found that a CHDM model with Hubble parameter $h = 0.5$ and density $\Omega_m = 1$ including $\Omega_\nu = 0.2$ was the best fit to the galaxy distribution in the nearby universe of any cosmological model. But cosmological data was steadily improving, and even by 1998 it had become clear that $h = 0.5$ and $\Omega_m = 1$ were increasingly inconsistent with several sorts of observations, and that instead $h \approx 0.7$ and $\Omega_m \approx 1/3$. For example, it was clear from the beginning that CHDM (and any other $\Omega_m = 1$ model with a power spectrum consistent with the observed galaxy distribution) predicts that galaxies and clusters form at relatively low redshift, but around 1998 increasing numbers of galaxies were discovered at redshifts beyond 3 and clusters began to be discovered at redshifts of 1 and beyond. And the fraction of baryons in clusters, together with the reasonable assumption that this fraction is representative of the universe as a whole, again gives $\Omega_m \approx 1/3$. That there is a large cosmological constant (or some other form of dark energy) with $\Omega_\Lambda \approx 2/3$ then follows from any two of the following three results: (1) $\Omega_m \approx 1/3$, (2) the CMB anisotropy data implying that $\Omega_m + \Omega_\Lambda = 1$, and (3) the high-redshift supernova data implying that $\Omega_\Lambda - \Omega_m \approx 0.4$.

The abundance of galaxies and clusters at high redshifts is in excellent agreement with the predictions of the $\Lambda$CDM model. However, the highest resolution simulations of $\Lambda$CDM that were possible in the mid-1990s gave a dark matter power spectrum that had more power on scales of a few million light years than the observed galaxy power spectrum on those scales, although they agreed on larger scales [3]. This was inconsistent with the
expectations that galaxies would be if anything more clustered (or “biased”) than the dark matter on these scales, not less clustered. However, when it became possible to do still higher resolution simulations that allowed the identification of the dark matter halos of individual galaxies, their power spectrum turned out to be in excellent agreement with that of the galaxies [4]. The galaxies were less clustered than the dark matter because galaxies merged or were destroyed in very dense regions because of interactions with each other and with the cluster center. This explained why the galaxy power spectrum is so much lower than the dark matter power spectrum on cluster scales, and it turned the former disagreement into a triumph for Λ CDM.

Thus ΛCDM is certainly the favored theory today. But we know from the atmospheric neutrino oscillations that there is enough neutrino mass to correspond to some hot dark matter, at least $\Omega_\nu \geq 10^{-3}$ (see Sidebar 3: Neutrino Mass and Cosmological Density). So the remaining question regarding neutrinos in cosmology is how much more room there is for hot dark matter in ΛCDM cosmologies. The answer is, perhaps ten times that much, but probably not 100 times. The reason there is any upper limit at all from cosmology is because the free-streaming of neutrinos in the early universe slows the growth of the remaining cold dark matter fluctuations on small scales, so to form the structure we see on the scale of galaxies there must be much more cold than hot dark matter. For the observationally favored range $0.2 \leq \Omega_m \leq 0.5$, the latest comprehensive analysis [5] gives a limit on the sum of the neutrino masses $m(\nu) \lesssim 2.4(\Omega_m/0.17 - 1)$ eV (95% C.L.), so for $\Omega_m < 0.5$, $m(\nu) \lesssim 5$ eV, and $\Omega_\nu \lesssim 0.1$. Astronomical observations that may soon lead to stronger upper limits on $m(\nu)$ — or perhaps a detection of neutrino mass — include data on the distribution of low-density clouds of hydrogen (the “Lyman-alpha forest”) at high redshifts $z \sim 3$, large-scale weak gravitational lensing data, and improved measurements of the cosmic background radiation temperature fluctuations on small angular scales. These types of data can be used to probe for the effects of any free-streaming of neutrinos in the early universe which as we saw can lead to less power on small scales, depending on the values of the neutrino masses.

The hot dark matter saga thus illustrates once again the fruitful marriage between particle physics and cosmology: while neutrino oscillation experiments can only tell us about the differences of the squared masses of neutrinos, cosmology can tell us about the masses themselves. In an earlier example of this connection, cosmological arguments based on Big Bang nucleosynthesis of light elements put a strict limit on the possible number of light neutrino species; this limit was eventually borne out high energy physics experiments on Z bosons at CERN and SLAC. The detailed studies of cosmological structures now going on or about to begin may eventually reveal something about neutrino mass itself.
Sidebar 1: Summary of Dark Matter Types and Associated Cosmological Models

| Dark Matter Type | Fraction of critical density | Comment |
|-----------------|------------------------------|---------|
| Baryonic DM     | $\Omega_b \approx 0.04$     | about 10x visible matter |
| Hot DM          | $\Omega_\nu \approx 0.001 - 0.1$ | light neutrinos |
| Cold DM         | $\Omega_c \approx 0.3$      | most dark matter in galaxy halos |

| Acronym | Cosmological Theory | Flourished |
|---------|---------------------|------------|
| HDM     | Hot DM cosmology with $\Omega_{tot} = 1$ | 1978-1984 |
| SCDM    | (standard) Cold DM with $\Omega_{tot} = 1$ | 1982-1992 |
| CHDM    | Cold + Hot DM with $\Omega_{cdm} \approx 0.7$ and $\Omega_\nu = 0.2 - 0.3$ | 1994-1998 |
| ACDM    | CDM with $\Omega_{cdm} \approx 1/3$ and cosmological constant $\Omega_\Lambda \approx 2/3$ | 1984- |

Sidebar 2: The Age of the Universe

In the mid-1990s there was a crisis in cosmology, because the age of the old globular cluster (GC) stars in the Milky Way, then estimated to be $t_{GC} = 16 \pm 3$ Gyr, was higher than the expansion age of the universe, which for an $\Omega_m = 1$ universe is $t_{expansion} = 9 \pm 2$ Gyr. Here I have assumed that the Hubble parameter has the value $H_0/(100 \text{ km/s/Mpc}) \equiv h = 0.72 \pm 0.07$, the final result from the Hubble Space Telescope project measuring $H_0$.

But when the data from the Hipparcos astrometric satellite became available in 1997, it showed that the distance to the GCs had been underestimated, which implied in turn that their ages had been overestimated. Correcting for this, and also using improved treatments of stellar evolution, the age of the oldest GCs is decreased to $t_{GC} = 13 \pm 3$ Gyr. The age of the universe is then $t_U \approx t_{GC} + \sim 1\text{Gyr}$ for GC formation $\approx 14 \pm 3$ Gyr.

Several lines of evidence now show that the universe does not have $\Omega_m = 1$ but rather $\Omega_m + \Omega_\Lambda = 1.0 \pm 0.1$ with $\Omega_m = 0.3 \pm 0.1$. Lowering $\Omega_m$ increases the expansion age, and a cosmological constant $\Omega_\Lambda > 0$ increases it still further, so now $t_{expansion} = 13 \pm 2$ Gyr. This is now in excellent agreement with the globular cluster age. The high-redshift supernova data alone give an expansion age $t_{SN} = 14.2 \pm 1.7$ Gyr.

Moreover, a new type of age measurement based on radioactive decay of Thorium-232 (half-life 14.1 Gyr) measured in a number of very old stars gives a completely independent age $t_{Th} = 14 \pm 3$ Gyr. A similar measurement, based on the first detection in a star of Uranium-238 (half-life 4.47 Gyr), is reported in the 12 Feb 2001 issue of Nature, giving $t_U = 12.5 \pm 3$ Gyr. Work in progress should soon improve the precision of this sort of measurement.

All the recent measurements of the age of the universe are thus in excellent agreement. It is reassuring that three completely different clocks — stellar evolution, expansion of the universe, and radioactive decay — agree so well.
Sidebar 3: Neutrino Mass and Cosmological Density

Cosmic rays hitting the top of the atmosphere all around the world produce “atmospheric neutrinos.” The atmospheric neutrino data from the Super-Kamiokande underground neutrino detector in Japan provide strong evidence of muon to tau neutrino oscillations, and therefore that these neutrinos have nonzero mass. This is now being confirmed by the K2K experiment, in which a muon neutrino beam from the KEK accelerator is directed toward Super-Kamiokande and the number of muon neutrinos detected is just as expected with the muon neutrinos oscillating to tau neutrinos at the atmospheric rate.

Oscillation experiments cannot measure neutrino masses directly, only the squared mass difference $\Delta m^2_{ij} \equiv |m_i^2 - m_j^2|$ between the oscillating species. The Super-Kamiokande atmospheric neutrino data imply that $5 \times 10^{-4} < \Delta m^2_{\tau\mu} < 6 \times 10^{-3}$ eV$^2$ (90% CL), with a central value $\Delta m^2_{\tau\mu} = 3 \times 10^{-3}$ eV$^2$. If the neutrinos have a hierarchical mass pattern $m(\nu_e) \ll m(\nu_\mu) \ll m(\nu_\tau)$ like the quarks and charged leptons, then this implies that $\Delta m^2_{\tau\mu} \approx m(\nu_\tau)^2$, so $m(\nu_\mu) \approx 5 \times 10^{-2}$ eV. These data imply a lower limit on the HDM (i.e., light neutrino) contribution to the cosmological density $\Omega_\nu > \sim 0.001$ — almost as much as that of all the stars in the disks of galaxies — and permit higher $\Omega_\nu$.

There is a connection between neutrino mass and the corresponding contribution to the cosmological density, because thermodynamics in the early universe determines the abundance of each of the three neutrino species (including both neutrinos and antineutrinos) to be about 112 per cubic centimeter. It follows that the density $\Omega_\nu \equiv \rho_\nu/\rho_c$ contributed by neutrinos, in units of critical density $\rho_c = 10.54 h^2$keV cm$^{-3}$, is $\Omega_\nu = m(\nu)/(93 h^2$eV), where $m(\nu)$ is the sum of the masses of all three neutrino species. Since $h^2 \approx 0.5$, $m(\nu_\tau) \approx 0.05$ eV corresponds to $\Omega_{\nu} \approx 10^{-3}$.

However, this is a lower limit, since in the opposite case where the oscillating species have nearly equal masses, the values of the masses themselves could be much larger. The only other laboratory approaches to measuring neutrino mass are (1) the attempt to detect neutrinoless double beta decay, which is sensitive to the value of a possible Majorana component of the electron neutrino mass, and (2) precise measurements of the endpoint of the tritium beta decay spectrum, which give an upper limit on the mass of the electron neutrino, given in the online 2001 Particle Data Book as 3 eV. Because of the small values of both squared mass differences $\Delta m^2_{e\mu} \lesssim 10^{-5}$ eV$^2$ from solar neutrino oscillations and $\Delta m^2_{\mu\tau} \lesssim 6 \times 10^{-4}$ eV$^2$ from atmospheric neutrino oscillations as discussed above, the tritium upper limit on $m(\nu_e)$ becomes an upper limit on all three neutrino species. But this is not a very stringent upper limit, corresponding to a maximum total neutrino mass $m(\nu) < 9$ eV. Perhaps surprisingly, cosmology already provides a stronger constraint on $m(\nu) \lesssim 5$ eV, from the effects of neutrinos on structure formation discussed in this article.
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Additional References

A technical article on the present subject with many references: “Hot Dark Matter in Cosmology,” by Joel R. Primack & Michael A. K. Gross, in Current Aspects of Neutrino Physics, ed. D. O. Caldwell (Berlin: Springer, 2001) pp. 287-308; also available on the web as astro-ph/0007165 and interactively as nedwww.ipac.caltech.edu/level5/Primack4/frames.html

The Neutrino Oscillation Industry webpage provides convenient links to current and future neutrino experiments: www.hep.anl.gov/ndk/hypertext/nuindustry.html

For reviews of the current status of cosmology see, e.g., “Cosmological Parameters 2000,” by Joel R. Primack, in Sources and Detection of Dark Matter in the Universe, Proc. 4th International Symposium (DM 2000), Marina del Rey, California, 20-23 Feb 2000, ed. D. Cline (Berlin: Springer, 2001), pp. 3-17, astro-ph/0007187; and “The Nature of Dark Matter,” by Joel R. Primack, to appear in Proceedings of International School of Space Science 2001, ed. Aldo Morselli (Frascati Physics Series), astro-ph/0112255.