The Standard Model of particle physics does not include a natural mechanism to give mass to a neutrino. Neither does it provide a reason to exclude this possibility. Unlike photons and gravitons, which are constrained to be exactly massless because of gauge invariance, no such restriction applies to the neutrinos. Determining neutrino masses has been a long-standing experimental challenge that, despite concerted efforts, has proved rather difficult. To date, there is no direct evidence for neutrino mass, though upper limits of $m_{\nu_e} < 15$ electron volts ($eV$), $m_{\nu_x} < 170$ kilo-electron-volts (keV), and $m_{\nu_t} < 24$ million electron volts (MeV) have been placed. It is natural to speculate what the impact on physics would be if neutrinos were in fact massive. As far as our everyday world is concerned, there would be almost no effect at all: nuclei would still undergo beta decay, elements would still transmute, and stars would still boil inside and explode because of neutrino heating. Solar and atmospheric neutrinos would still be missing, although physicists would be fairly certain as to where they went.

Turning to the Universe, however, massive neutrinos could effect a radical transformation. Next to the ubiquitous photons that compose the cosmic microwave background radiation (the radiation field that permeates the Universe), neutrinos are the second-most-abundant particle species. Were they to have even a small mass, it would lead to profound consequences for the evolution of the Universe. In this article, we explore the possible impact that neutrinos with mass would have on three central issues in modern cosmology: the dynamics of the Universe, structure formation, and dark matter.

Cosmology is the science of the evolution and structure of the Universe. The concerns of cosmology include the birth of the Universe, its present age, and its ultimate fate. Some of the most pressing questions of current interest relate to the material make-up of the Universe: How much mass is present? What is it made of? How is mass distributed in space and how did it get there? A massive neutrino might well play a key role in the resolution of these puzzles.

According to the accepted theoretical paradigm in cosmology—the Big Bang—the Universe began as a hot, dense plasma that was isotropic and homogeneous to a very high degree. Fifteen billion or so years later, however, it is quite inhomogeneous (except on very large scales). Today the Universe is filled with galaxies that are arranged in clusters and sheets that surround vast pockets of space. Cosmologists attempting to understand structure formation must confront this puzzle: how did density fluctuations originate in the early Universe, and how did these small inhomogeneities lead to the distribution of mass that is currently observed?

Running parallel to the questions surrounding structure formation is the enigma of dark matter. After many years of observations, astronomers and cosmologists have been forced to a curious conclusion: the Universe appears to be dominated by an unseen form of matter whose precise nature is unknown.

For decades, it has been accepted that the luminous matter visible to the astronomer’s telescope—stars, dust, gas clouds, bright galaxies, even black holes—constitutes but a tiny fraction of the total mass of the Universe. The phrase “luminous matter” refers to any matter that emits, directly or indirectly, electromagnetic radiation (from radio waves to gamma rays) that can be detected on earth. It is in this sense that large black holes can be considered luminous, for they advertise their presence by x-rays that are emitted when material falls into the hole.

Dark matter is the unseen mass of the Universe. It is the antithesis of luminous matter, for it does not emit any detectable radiation, and its presence can be inferred only indirectly from the way it interacts with luminous matter. The three key questions relating to dark matter are what is it made of, how much is there, and how is it distributed?

Because it cannot be seen, we can only speculate as to what makes up dark matter. Many astronomers would argue that dark matter is simply stuff from the Universe’s graveyard: brown dwarfs, dead stars, sparse gas clouds that never coalesced, even entire galaxies with low surface brightness. If this belief is true, dark matter would be ordinary baryonic matter, i.e., matter composed of protons, neutrons, and electrons—that just fails to be detected.

Many theorists are convinced, however, that there is an exotic, nonbaryonic form of dark matter and that there is a lot more of it than ordinary matter. They hypothesize that the nonbaryonic dark matter is composed of particles that were created during the early, hot phase of the Universe but that still exist today. It is within this realm that the massive neutrino resides. While there are other plausible candidates for dark matter particles, such as axions and supersymmetric neutrinos, the neutrino is unique in that it is known to exist.

Because of improved observational capabilities, the last decade has seen a remarkable renaissance in astrophysics and cosmology. Telescopes such as the Keck and the Hubble Space Telescope, satellite experiments such as RELICT and the Cosmic Background Explorer (COBE), and large-scale redshift surveys such as CFA (conducted by the Harvard-Smithsonian Center for Astrophysics) and the Las Campanas Redshift Survey have changed the face of observational cosmology. As shown later on, the better quality of present-day data already allows us to rule out several plausible hypotheses concerning dark matter and structure formation.

In the coming decade, it is expected that data from new satellite missions that will measure the microwave background with unprecedented precision,
combined with new, high-statistics edshift surveys that will probe the age-scale structure of the Universe, will finally lead to a cohesive picture of the Universe on large-distance scales. Although the primary purpose of this riddle is to explain current theories about dark matter, structure formation, and the dynamics of the Universe, we do so with a word of caution. At present, the situation in cosmology is somewhat chaotic. Theorists are scrambling to keep pace with observational data, much of which is not simple to interpret and may contain significant systematic errors. Some of the observations discussed exist only in a very recent sense, and their validity may not survive over many years, but given the state of cosmology today, they are all we have to work with at the moment.

Dark Matter: A Historical Problem

Astronomers tend to be a cautious sort, and in 1915, when Robert A. Millikan (in 1948) and Urban- ean Joseph Le Verrier (independently in 1846) inferred the existence of the luminous Neptunian (through its gravitational effects on the orbit of Uranus), astronomers have appreciated that matter is often invisible to their telescopes. It was therefore only a minor prob-lem when Jacobus Kapteyn and James Ewan in 1922, and then Jan Oort a decade later, deduced that our galaxy, the Milky Way, might contain at least twice as much mass as could be accounted for by luminous matter alone. This missing mass would surely have been encountered. This is the moment of the Big Bang. If we run the clock forward from this moment (and use general relativity, quantum mechanics, electrodynamics, and thermodynamics to govern the interactions of matter, radiation, and geometry), we can construct a time line that orders the evolution of the Universe (see Figure 1).

The Big Bang: Dark Matter and the Dynamics of the Universe

One of the seminal discoveries in the history of science is Edwin Hubble’s observation in 1929 that galaxies are receding from each other at a velocity \( v \) that is proportional to their distance \( r \): 

\[ v = H_0 \cdot r. \]

The constant of proportionality, \( H_0 \) (known as the Hubble constant), is actually a function of time. It is a difficult parameter to measure, but most cosmologists agree that its current value is \( H_0 = 70 \text{ km/s/Mpc} \). The uncertainty in the value of \( H_0 \) is contained in the parameter \( \Omega \), defined as \( H_0 = 100 \Omega h \text{ km/s/Mpc} \). Hubble’s finding agreed with the velocity versus distance relationship predicted by Albert Einstein’s general theory of relativity. The expanding Universe was therefore taken to be strong evidence that general relativity correctly describes the dynamics of the Universe. Starting with present-day data, if the equations of general relativity are run backwards in time, the Universe becomes increasingly hotter and denser until the initial singularity, or a state of infinite density, is finally encountered. This is the moment of the Big Bang. If we run the clock forward from this moment (and use general relativity, radiation, and geometry), we can construct a time line that orders the evolution of the Universe (see Figure 1).

The Big Bang model holds that the Universe began in a state of infinite density and temperature, followed by rapid expansion and cooling. About \( 10^{-38} \text{ seconds} \) after its birth, quarks, leptons, and gauge bosons precipitated out much like ice crystals in a cooling pool of water. (Quarks and leptons are discussed in the primer, “The Oscillating Particle.”)

Figure 1. The Universe’s Time Line

The Big Bang model allows cosmologists to order events in the evolution of the Universe. This figure plots time on a logarithmic scale. Although cold dark matter begins to form structures within the first 100 years or so of the Universe’s history, those structures do not evolve into galaxies (or clusters of galaxies) until many millions of years later. The data implies that the velocity of x-ray-emitting gas increases the luminous mass by roughly a factor of 2, in addition to the mass still “missing,” but given the state of cosmology today, they are all we have to work with at the moment.

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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. Without very special initial conditions (or entirely new physics), only if the Universe started exquisitely close to the critical density could it have survived for such a long time. This is because the natural time scale in general relativity is the Planck time, which is only about $10^{-43}$ seconds. The fact that the Universe has existed for $10^{10}$ Planck times cannot be explained without very special initial conditions (or entirely new physics). Only if the Universe started exquisitely close to the critical density could it have survived for such a long time.

The theory of inflation, which has become an almost essential piece of today’s cosmology, was designed to deal with issues such as the flatness problem (also called the age problem). Inflation typically predicts deviations from the critical density on the order of only 1 part in $10^5$. Inflation also accounts for the “horizon” problem, which stems from the observation that the cosmic microwave background is remarkably isotropic across the entire sky. This is a puzzle, because points in the sky separated in angle by more than roughly a degree have not been in causal contact since the Big Bang. Inflation provides a resolution to both problems by postulating a phase of rapid expansion of the Universe driven by a matter field called the inflaton. During inflation, the scale factor of the Universe grows by a factor of roughly $10^{53}$. This growth occurs on a time scale as short as $10^{-35}$ seconds! In essence, inflation adds a long “history” to the Universe before the decoupling of radiation and matter, so that objects that appear to be causally connected in the microwave sky actually interacted in the past. Finally, through quantum fluctuations of the inflaton field, inflation provides the Big Bang with a natural mechanism to generate primordial density perturbations. This is an important point that will be discussed in the section on structure formation.

Whether $\Omega$ is unity or on the order of 0.3 depends on the estimate of the critical density [$\Omega_{\text{critical}} = 0.1$ to 0.3]—that is, the total number of baryons that were produced during the Big Bang. For many years, BBNs set a limit on the baryon density that was $\Omega_{\text{BBNS}} < 0.006$, a factor of 5 lower than the value predicted by inflation. This was viewed as 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 $\Omega$ 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 low; consequently, the value of $\Omega$ almost doubled, and $\Omega_{\text{BBNS}}$ could now be as large as 0.1. This value is not far from the preferred value of the mass density ascribed to clusters ($\Omega_{\text{cluster}} = 0.3$). 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 ($\Omega_{\text{dark}} = 0.1$ and $\Omega_{\text{cluster}} = 0.3$), and it could be much higher if the Jeans instability turns out to be unity. These results are summarized in Table I.

### Table I. Comparison of Mass Densities

<table>
<thead>
<tr>
<th>Theory</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_{\text{luminous}}$</td>
<td>0.003</td>
</tr>
<tr>
<td>$\Omega_{\text{dark}}$</td>
<td>0.02–0.1</td>
</tr>
<tr>
<td>$\Omega_{\text{cluster}}$</td>
<td>0.1–0.3</td>
</tr>
<tr>
<td>$\Omega_{\text{baryonic}}$</td>
<td>0.01–0.1</td>
</tr>
<tr>
<td>$\Omega_{\text{total}}$</td>
<td>0.1–1</td>
</tr>
</tbody>
</table>

In earlier redshift surveys such as the CfA, there was some evidence for nonbaryonic matter. These results are not confirmed by the Sloan Digital Sky Survey, which is a more sensitive test of the primordial large-scale density on the largest scales probed ($50 h^{-1}$ Mpc). (Although this distance is on the order of 300 million light-years, the survey probe but a tiny fraction of the observable Universe, which is estimated to be about 3000 $h^{-1}$ Mpc across.) This is because 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 larger than the Jeans wavelength, given by $\Lambda_J = \frac{\dot{v}_J}{\sqrt{\rho_c} G}$, are able to be able to resist collapse. This means that failures are infinite in space and that the radius $r$ of the expanding mass is $\frac{3h^2}{8\pi G} r^2$.

The critical, or closure, density provides a natural base line with which $\Omega$ compares observed mass densities. Defining a parameter $\Omega$ as the ratio of the density, $\rho$, to the critical density, $\rho_c = \frac{3H^2}{8\pi G}$, we have that at the critical density, $\Omega = 1$. The observed luminous, baryonic matter leads to

$$\Omega_{\text{luminous}} \approx \frac{\rho_{\text{luminous}}}{\rho_c} \approx 0.003,$$

where $0.3$ percent of the closure density, whereas measurements of low-redshift values for $\Omega_{\text{cluster}}$ within the range of 0.1 to 0.3. Most theorists, however, believe that the Universe is at or extremely close to the critical density (in spite of the apparent conflict with current observations). The basis for their belief is the fact that the Universe has existed for $10^{10}$ seconds, which is much higher if $\Omega = 0.1$ and $\Omega_{\text{cluster}} = 0.3$. The observed luminous, baryonic matter is

$$\Omega_{\text{baryons}} \approx \frac{\rho_{\text{baryons}}}{\rho_c} \approx 0.01–0.1,$$

where $\rho_{\text{baryons}}$ is the number of baryons per cubic meter. (We have assumed a value of $h = 65$ km/sec/Mpc.) The critical, or closure, density provides a natural base line with which $\Omega$ compares observed mass densities. Defining a parameter $\Omega$ as the ratio of the density, $\rho$, to the critical density, $\rho_c = \frac{3H^2}{8\pi G}$, we have that at the critical density, $\Omega = 1$. The observed luminous, baryonic matter leads to

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structures that form at later times. At present, the Universe has evolved numerous complex, scale-dependent structures, and the simplest primordial spectrum of density fluctuations that could potentially lead to what is observed today is the one put forth by Edward Harrison (in 1970) and Yakov Zeldovich (independently in 1972). The Harrison-Zeldovich spectrum was based on very general theoretical considerations and has been used as the initial density perturbation spectrum in most analytical studies and simulations that attempt to track the Big Bang. This spectrum implies that the amplitude of primordial fluctuations in the gravitational potential does not depend on the spatial scale and, for a critical-density matter-dominated Universe, is also independent of time.

Significantly, the Harrison-Zeldovich spectrum also emerges from inflation theory. Quantum fluctuations of the inflaton field that drives the inflationary expansion provide a natural source of density perturbations that follow a Harrison-Zeldovich spectrum. Thus, aside from solving the flatness and horizon problems, inflation builds into the Big Bang model a natural mechanism for generating initial density perturbations.

Given the observational constraints and a primordial density perturbation spectrum, the question is whether the Jeans instability successfully produces the large-scale structures that are observed today. One point to address is the normalization—that is, the absolute amplitude—of the primordial density fluctuations. Simply choosing a spectrum does not determine its absolute scale. The normalization needs to be determined by experiment, but how do we measure the size of density fluctuations that were present 15 billion years ago? Remarkably, a window to the past exists that allows us to do just that: measuring anisotropies in the CMBR temperature provides a virtual time-machine to determine the lumpiness of the very early Universe.

The discovery of the microwave background was a stunning confirmation of the Big Bang, but detection of a temperature anisotropy in the field, or deviation from a perfectly uniform temperature, could have an even greater impact. Photons that make up the microwave field have been traveling unimpeded since the time of recombination. Because of intrinsic fluctuations in the temperature and gravitational potential of the Universe at the time the photons decoupled from matter, there is a very small anisotropy in the CMBR temperature observed today.

The anisotropy over large-distance scales was measured with very high precision by the COBE satellite, launched in 1989 (see Figure 3). COBE’s angular resolution of 7 degrees corresponds to several hundred megaparsecs. (The COBE results, along with those of other experiments that probed the microwave background at higher angular resolution, set the normalization of the Harrison-Zeldovich spectrum (see Figure 4) and impose constraints on any proposed spectrum of initial density perturbations. One important consequence of the CMBR observations is that the observed large-scale structure of the Universe cannot have formed in the presence of ordinary baryonic matter alone.

In purely baryonic matter models, the growth of initial perturbations occurs only after recombination. As stated earlier, before that time, growth is suppressed by pressure that arises when radiation scatters from free electrons (Thomson scattering), resulting in the effective prevention of growth of perturbations on scales smaller than \( \sim 180 \text{h}^{-1} \text{Mpc} \). To produce the observed large-scale structures seen in Figure 2, the perturbations leave an anisotropy in the microwave background temperature of roughly 1 part in 10,000 on the scales probed by COBE. But the measured fluctuations were much smaller, deviating from pure uniformity by only 1 part in 100,000. The microwave background, therefore, contains the sufficient time for structure formation in a purely baryon-dominated Universe.

Figure 2. Result of the Las Campanas Redshift Survey
his map of over 23,000 galaxies extends to approximately 600 h^{-1} Mpc, or about one-fifth of the observable Universe. Galaxies brighter than 18th magnitude were counted in ares of the sky. Each slice spanned about 90 to 120 degrees and was con-

Figure 3. Temperature Fluctuations across the Microwave Sky
(a) The DMR experiment on the COBE satellite measured root-mean-squared (rms) temperature variations, \( \delta T / T \), in the CMBR to be on the order of 1 part in 10^7. (The theoretical spectrum does not determine its absolute scale.) The variations can be related to density fluctuations at the time of recombination that seeded the current large-scale structures seen in Figure 2. (The scale of the map shown in (a) is enormous. The largest structure of Figure 2 would easily fit within the smallest feature of the map.) (b) Data from 16 experiments that have measured the CMBR with varying degrees of angular resolution are shown in this figure of Angular multipole, \( l \), the anisotropy is

The Differential Microwave Radiometer (DMR) Map of CMBR Anisotropy

North Galactic Hemisphere
South Galactic Hemisphere

COBE
FIRS
TEN
SP
BAM
PYTH
MSAM
MAX
ARGO
SK
CAT
WI
OVRO
SLUSE
VLA
ATCA

Angular multipole, \( l \)

\( \delta T / T \) versus the angular multipole, \( l \), the anisotropy is

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Nonbaryonic dark matter, however, does not couple to photons and thus does not suffer from collisional damping. Density perturbations can begin to grow well before recombination, as soon as matter-radiation equality is reached. This allows the development of large density perturbations without isolating the density constraints implied by the scale invariance in the microwave background. Some form of non-baryonic dark matter, therefore, appears to be necessary to explain the formation of structure in the Universe.

Structure Formation and Dark Matter

Of all the proposed dark matter candidates, massive neutrinos have always been the most natural: neutrinos are known to exist, and they were produced in very large numbers during the Big Bang. (Roughly a billion neutrinos were created for every baryon.) Since the mean normalization, that is, the position of the spectrum in the vertical direction, the power spectrum that one compares with observations is a processed spectrum like the one shown in black. At low k, the spectrum is Harrison-Zeldovich, while the falloff at large k is model dependent. For any given model, the processed power spectrum is the Harrison-Zeldovich spectrum multiplied by a transfer function, T(k), which incorporates the contribution of all relevant physical processes.

Primordial Harrison-Zeldovich spectrum normalized to COBE data

Figure 4. The Harrison-Zeldovich Spectrum and a Processed Spectrum

Two theoretical, linear power spectra (best-fit mixed dark matter and standard cold dark matter) are shown superimposed on observational data. The black boxes are reconstructed in a model-dependent way from the measurements of the CMBR data shown in Figure 4 and are given here for mixed dark matter. (The box height reflects a 1-sigma confidence level. The boxes differ slightly near the peak of P(k) if a cold dark matter model is assumed.) Observations from matter surveys are shown in light gray. For k ≳ 0.3 h Mpc⁻¹, the data is measuring nonlinear structure, beyond which point it cannot be directly compared with the linear theoretical power spectra. The overproduction of small-scale structure by cold dark matter models is best seen in the region around k ≳ 10⁻² h Mpc⁻¹, where mixed dark matter is very successful.

Figure courtesy of G. Starkman and E. Silk, CMB Theory group, UC Berkeley.

Primordial Harrison-Zeldovich power spectrum (shown in red) is plotted against number, k, on a log-log scale. (Notice that k varies inversely with distance.) Data on COBE (rectangular box, derived from the CMBR data at large angular multiples) fixes the normalization, that is, the position of the spectrum in the vertical direction. The power spectrum that one compares with observations is a processed spectrum like the one shown in black. At low k, the spectrum is Harrison-Zeldovich, while the falloff at large k is model dependent. For any given model, the processed power spectrum is the Harrison-Zeldovich spectrum multiplied by a transfer function, T(k), which incorporates the contribution of all relevant physical processes.
temperatures to within a few percent. At 0. It is important to pin down their total and the Hubble constant.

Although we have presented an outlook on the Hubble constant, the corresponding amplitude in density fluctuations is several times too low to explain structure formation. In addition, the predicted small-angular-scale CMBR anisotropies are in conflict with present ground-based and balloon-borne observations.

Although we have presented an up-to-date summary of dark matter and its relationship to structure formation, it should be noted that the outcome of models of structure formation and CMBR anisotropy depends critically on the values of cosmological parameters such as \( \Omega_{\text{tot}} \) and the Hubble constant \( H_0 \). It is important to pin down their values to within a few percent. At present, the constraints on these parameters from CMBR anisotropy measurements are quite weak. But the future is full of promise. The constraints on \( \Omega_{\text{tot}} \) and \( H_0 \) are expected to improve dramatically with the next generation of satellite observations. The Microwave Anisotropy Probe (MAP) is scheduled to fly in 2001, followed several years later by the PLANCK satellite. In addition, deep, high-statistics redshift surveys of galaxies are expected to yield data within the next several years. The 2 Degree Field (2dF) and the Sloan Digital Sky Survey (SDSS) will go about the same distance as Las Campanas (roughly 600 km \(^2\) Mpc), but they will survey many more galaxies: a quarter of a million for 2dF and a million for SDSS, compared with roughly 25,000 for Las Campanas.

Analysis of the new CMBR data combined with the large-scale structure information from the redshift surveys will provide a very powerful discriminator between competing models of structure formation (see Figure 6). A value of \( \Omega_{\text{tot}} \approx 0.1 \) would be unfavorable for models incorporating light neutrinos and would be difficult to reconcile with inflation. (If the matter density is less than critical, that is, \( \Omega_{\text{tot}} < 1 \), it is still possible to save \( \Omega_{\text{tot}} \approx 0.1 \) by introducing a large cosmological constant, an alternative espoused by some theorists.) On the other hand, if standard inflation is vindicated and \( \Omega_{\text{matter}} \approx \Omega_{\text{tot}} \approx 1 \), a light neutrino might be just what the theory needs to satisfy the constraints imposed by structure formation. Even if this were the case, however, the neutrino would still not play a major role in dictating the dynamics of the Universe.

It is unlikely that the last word has been spoken on the cosmological consequences of a massive neutrino. Today, such a particle is not the favored dark matter candidate given our theories of initial conditions and structure formation. Just how good or bad these theories are will not be known until the next generation of CMBR observations yield results. Can the massive neutrino reign the dark matter center stage? The turn of the millennium may bring us the answer to that question.