Dark Side of the Universe

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Abstract. The dynamics on scales from dwarf galaxies to the entire universe is dominated by gravitating mass and energy that cannot be accounted for by ordinary matter. We review the astrophysical and cosmological evidence for dark matter and dark energy. While there is no obvious interpretation for dark energy, dark matter presumably consists of some new form of weakly interacting elementary particles. We discuss certain candidate particles and search strategies.

Keywords: Dark Matter, Dark Energy

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INTRODUCTION

The question of what makes up the gravitating mass of the universe is as old as extragalactic astronomy which began with the insight that nebulae such as M31 in Andromeda are actually galaxies like our own. Sometimes they form gravitationally bound clusters. From Doppler shifts of the spectra of the galaxies in the Coma cluster, Zwicky derived in 1933 their velocity dispersion and could thus estimate the cluster mass with the help of the virial theorem, concluding that there was far more gravitating than luminous matter [1]. It took until the 1970s and 1980s to become broadly acknowledged that on scales from dwarf galaxies to the entire universe, luminous matter (stars, hydrogen clouds, x-ray gas in clusters, etc.) cannot account for the observed dynamics.

Moreover, dark matter cannot consist of ordinary (“baryonic”) matter in some class of dark astrophysical objects such as compact stars. The amount of baryons is well measured to be about 4% of the cosmic critical density by the observed cosmic deuterium abundance in the context of big-bang nucleosynthesis and by the acoustic peaks in the angular power spectrum of the cosmic microwave background temperature fluctuations. So, most of the cosmic baryons are actually dark, yet most of the dark matter cannot consist of baryons.

In 1973 Cowsik and McClelland proposed that some of the dark matter might consist of neutrinos, the only known examples of weakly interacting particles [2]. Today we know that neutrinos indeed have small masses and provide some dark matter (no less than 0.1% of the cosmic critical density and no more than about 1–2%), but the bulk of dark matter must be something else. As far as we understand today, cosmology is demanding new weakly interacting particles beyond the particle-physics standard model. The experimental search for the proposed candidates is arguably the most important task on the path to answering the question first raised by Zwicky 75 years ago.

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Since 1998 the problem has become more mysterious still because yet another dark component became apparent in the global dynamics of the universe. The measured distance-redshift relation of thermonuclear supernovae (SNe Ia) as standard candles showed that the expansion of the universe is accelerating, in contrast to the deceleration expected if the dynamics is governed by matter or radiation, in whichever physical form. The new component (“dark energy”) acts like an ideal fluid with negative pressure, a behavior expected for the vacuum energy predicted by quantum field theory. However, a convincing physical interpretation of this dominating component is missing.

The “cosmic pizza plot” shown in Fig. 1 illustrates that most of the cosmic dynamical mass and energy components are dark. They lack an established physical interpretation and can not be accommodated by standard-model microscopic physics. One may well worry that we are completely missing some crucial insight about how our universe works. However, here we take the point of view that the dark elements of the universe provide us with opportunities to make new discoveries, for example in the form of new particles, that may well show up in the next round of dark matter searches or at the Large Hadron Collider that is about to take up operation at CERN. The dark universe is providing us with windows of opportunity for new and exciting discoveries!

In these brief notes I will present only some of the key ideas about the dark universe. Excellent and detailed recent reviews are provided by Gondolo (2003) [3], by Trodden and Carroll (2004) [4], and by Bertone, Hooper and Silk (2004) [5]. For the original ideas about particle dark matter and experimental search strategies see Primack, Seckel and Sadoulet (1988) [6], for supersymmetric dark matter Jungman, Kamionkowski and Griest (1995) [7]. An early review on dark energy is by Peebles and Ratra (2002) [8], a more recent one by Copeland, Sami and Tsujikawa (2006) [9]. A recent summary with references and resources is given by Ratra and Vogele in their “Resource letter on the beginning and evolution of the universe” (2007) [10]. A set of concise reviews on issues at the interface of particle physics with cosmology is found in the Review of Particle Physics [11]. And of course, there are numerous cosmology textbooks, each taking its own perspective on the dark universe [12, 13, 14, 15, 16, 17].

FIGURE 1. Cosmic pizza plot: Components of gravitating mass and energy.
EXPANDING UNIVERSE

Hubble Expansion and Robertson-Walker Metric

Two cosmological key observations were made in the early 1930s, the existence of large amounts of dark matter in galaxy clusters by Fritz Zwicky and the expansion of the universe by Edwin Hubble. Most of the luminous matter is concentrated in spiral galaxies such as the one shown in Fig. 2 that, as we will see, contain large amounts of dark matter. Moreover, the measured spectral Doppler shifts suggest that on average all other galaxies recede from us, with the more distant ones at larger velocities. Edwin Hubble formulated the relationship $v_{\text{recession}} = H_0 \times \text{distance}$ named after him where the present-day Hubble parameter is usually written in the form

$$H_0 = h \times 100 \text{ km s}^{-1} \text{ Mpc}^{-1}.$$  \hspace{1cm} (1)

Today we know that $h = 0.701 \pm 0.013$, but $h$ used to be very uncertain so that it is often kept as an explicit “fudge factor” that appears in many cosmological quantities. (Astronomical distances are usually measured in parsec (pc) where 1 pc = 3.26 light-years = $3.08 \times 10^{18}$ cm. Note that 1 pc is a typical distance between stars, 10 kpc is a typical scale for a galactic disk—the Sun is at 8.5 kpc from the center of the Milky Way—and the visible universe has a radius of about 3 Gpc.) If one extrapolates the Hubble expansion linearly into the past one finds that all galaxies must have begun their race about $H_0^{-1} = 14 \times 10^9$ years ago (“Hubble time”).

Hubble’s linear regression applies only for recession velocities safely below the speed of light. To interpret the cosmic expansion consistently we must transcend the Newtonian concept of space and time. If we assume homogeneity and isotropy on large scales,
the space-time geometry is fully described by the Robertson-Walker metric

$$ds^2 = dt^2 + a(t)^2 \left[ \frac{dr^2}{1 - k^2 r^2} + r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \right], \quad (2)$$

where $ds$ is the differential of the invariant distance, $r$, $\theta$ and $\varphi$ are co-moving spherical coordinates with an arbitrarily chosen origin, $t$ is the clock time of an observer that is co-moving with the cosmic expansion, and $a(t)$ is the time-dependent cosmic scale factor. The curvature parameter $k$ takes on the value 0 if space is Euclidean (flat), $k = +1$ if space is positively curved, and $k = -1$ for negative curvature. The time-dependent Hubble expansion parameter is defined as

$$H = \frac{\dot{a}}{a}, \quad (3)$$

$H_0$ denotes the present-time value (“Hubble constant”).

Within general relativity, the Hubble expansion is an expansion of the space between galaxies that remain locally at rest. For small distances we can interpret the same observations in terms of galaxies moving in a static space. Their spectral redshift is then interpreted as a Doppler effect (source and detector moving relative to each other). The general interpretation of the cosmic redshift is that the wavelength gets stretched along with the cosmic expansion. If the wavelength of a photon at emission is $\lambda_E$ and at absorption $\lambda_A$, then the corresponding ratios of cosmic scale factor is $a_E/a_A = \lambda_E/\lambda_A$. Every epoch of the universe can be characterized by its scale factor relative to the present epoch, or equivalently by the redshift $z + 1 = \lambda_0/\lambda$ of some radiation that was emitted at epoch $z$ with wavelength $\lambda$ and today has wavelength $\lambda_0$,

$$\frac{a}{a_0} = \frac{1}{1+z} \quad \text{or} \quad z = \frac{a_0}{a} - 1. \quad (4)$$

The cosmic expansion affects the distance between galaxies, but not the size of galaxies themselves, or of the solar system, people, atoms and so forth. All of these objects are dominated by forces that are much stronger than cosmic effects. Likewise, the galaxies in clusters, which are gravitationally bound, are not subject to the cosmic expansion. All astrophysical objects tend to have “peculiar velocities” relative to the cosmic expansion. These peculiar motions are determined by local dynamics.

For positive curvature ($k = +1$) space is closed in analogy to a sphere. For flat geometry or negative curvature space is infinite. However, for nontrivial topologies it is also possible that these spaces are finite. In particular, flat geometry allows for simple periodic boundary conditions, corresponding to a torus-like topology. Periodic boundary conditions are used in numerical simulations of structure formation.

In the context of the inflationary picture of the early universe, space was “stretched” by an early phase of exponential expansion, making it seem almost perfectly flat today. Possible topological effects would matter only at distances very much larger than a Hubble volume (the region of space that we can observe). One can speculate that other parts of the universe, not causally connected to ours, could have inflated differently and could even exhibit different physical laws, different dimensions of space, different properties of elementary particles, and so forth [13].

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Dynamics: Friedmann Equation

The maximally symmetric cosmological models considered here (homogeneous and isotropic) are fully described by their curvature parameter \( k \), topology, and the function \( a(t) \). It is determined by the effect of gravitating mass and energy. For our case the Einstein equations reduce to the Friedmann equation

\[
H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho - \frac{k}{a^2} + \frac{\Lambda}{3},
\]

where \( G_N \) is Newton’s constant, \( \rho \) the gravitating density of mass and energy, and \( \Lambda \) is Einstein’s cosmological constant.

If we assume flat geometry \((k = 0)\) and ignore \( \Lambda \), then the Friedmann equation establishes a unique relation between \( H \) and \( \rho \). Evaluated at the present epoch, this defines the “critical density”

\[
\rho_{\text{crit}} = \frac{3H_0^2}{8\pi G_N} = h^2 1.88 \times 10^{-29} \text{ g cm}^{-3} = h^2 10.5 \text{ keV cm}^{-3}.
\]

The contribution \( \rho_i \) of various mass or energy components is usually expressed by

\[
\Omega_i = \frac{\rho_i}{\rho_{\text{crit}}},
\]

Space is flat for \( \Omega_{\text{tot}} = 1 \), the curvature is negative for \( \Omega_{\text{tot}} < 1 \), and positive for \( \Omega_{\text{tot}} > 1 \).

One contribution to \( \rho \) is matter, including ordinary and dark matter. One can view it as an ideal fluid with density \( \rho \) and vanishing pressure \( p \) or on the microscopic level as particles that are essentially at rest relative to the cosmic expansion. The term “particle” could encompass an entire galaxy, but also a single dark matter particle. As the universe expands, matter trivially dilutes as \( a^{-3} \). In a matter-dominated universe, the scale factor evolves as \( a(t) \propto t^{1/2} \) (Table 1).

Another contribution is radiation (relativistic particles) where \( p = \rho/3 \). Here, \( \rho \propto a^{-4} \) where one factor \( a^{-3} \) comes from volume dilution, one factor \( a^{-1} \) from redshift by the expansion. All particles with mass eventually become nonrelativistic and then contribute to matter so that today the remaining radiation consists of photons, some gravitational waves, and perhaps the lightest neutrino. The relative importance of radiation decreases because of redshift so that radiation dominates at early times, matter at late times. Today \( \Omega_{\text{M}} \approx 0.27 \) whereas the cosmic microwave background contributes about \( \Omega_{\gamma} \approx 5 \times 10^{-5} \). Therefore, matter-radiation equality occurs at a redshift of about \( 3–5 \times 10^3 \), depending in detail on the neutrino masses.

In the absence of \( \Lambda \) and for \( k = +1 \), the universe recollapses. For \( k = -1 \) the curvature term eventually dominates because it scales as \( a^{-2} \). Therefore, at late times curvature dominates. In this “empty universe” the scale factor grows linearly with time and the Hubble parameter remains constant.

The cosmological constant is the most puzzling term. When Einstein derived the general theory of relativity, two parameters needed to be specified. One is Newton’s
TABLE 1. Evolution of the cosmic scale factor for generic terms on the r.h.s. of the Friedmann equation.

<table>
<thead>
<tr>
<th>Type</th>
<th>Equation of state</th>
<th>Behavior under cosmic expansion</th>
<th>Evolution of cosmic scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>$p = \rho / 3$</td>
<td>$p \propto a^{-4}$</td>
<td>$a(t) \propto t^{1/2}$</td>
</tr>
<tr>
<td>Matter</td>
<td>$p = 0$</td>
<td>$p \propto a^{-3}$</td>
<td>$a(t) \propto t^{2/3}$</td>
</tr>
<tr>
<td>Negative Curvature</td>
<td>$p = 0$</td>
<td>$p = 0$</td>
<td>$a(t) \propto t$</td>
</tr>
<tr>
<td>Vacuum energy</td>
<td>$p = -\rho$</td>
<td>$p = \Lambda / 8\pi G_N = \text{const.}$</td>
<td>$a(t) \propto \exp(\sqrt{\Lambda / 3} t)$</td>
</tr>
</tbody>
</table>

constant that is determined by experiments. The other is $\Lambda$ that has no impact on local physics. At that time the cosmic expansion was not yet observed and it seemed preposterous that the equations implied an expanding or contracting universe. A suitable $\Lambda$ allows the r.h.s. of the Friedmann equation to be finely balanced to give zero. Later Einstein reportedly called the cosmological term his “biggest blunder.”

On the contrary, Zeldovich realized that $\Lambda$ seems unavoidable in the framework of quantum field theory. Quantum fields are viewed as collections of harmonic oscillators, one for each wave number, each of which must have a zero-point energy of $\frac{1}{2}\hbar \omega$. As there are infinitely many modes, the zero-point energy (vacuum energy) of quantum fields seems infinite, or at least very large if there is an ultraviolet cutoff. This vacuum energy, being a property of “empty space,” must be invariant so that its energy-momentum tensor should be proportional to the metric, implying $p = -\rho$. As a consequence, $\rho$ does not dilute under cosmic expansion as behooves “empty space” that should be invariant under cosmic expansion. Therefore, vacuum energy behaves exactly like $\Lambda$ with $8\pi G_N \rho_{\text{vac}} \leftrightarrow \Lambda$. Since $\rho_{\text{vac}}$ does not dilute with cosmic expansion, it always dominates at late times and then leads to exponential expansion. The early-universe inflationary phase is thought to be driven precisely by such a term, which however disappears later when the underlying quantum fields decay, thereby reheating the universe.

In summary, the evolution $a(t)$ after the radiation epoch is dominated by matter, curvature, and $\Lambda$. A given model has three parameters: The Hubble constant $H_0$, the fraction of matter today $\Omega_M$, and the fraction of vacuum energy today $\Omega_\Lambda$. The curvature follows from whether $\Omega_{\text{tot}} = \Omega_M + \Omega_\Lambda$ is larger, smaller, or equal to 0. The best-fit parameters from observations to be discussed later are shown in Table 2.

TABLE 2. Best-fit parameters for a cosmic $\Lambda$CDM model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best-fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion rate</td>
<td>$H_0 = (70.1 \pm 1.3) \text{ km s}^{-1} \text{ Mpc}^{-1}$</td>
</tr>
<tr>
<td>Spatial curvature</td>
<td>$</td>
</tr>
<tr>
<td>Age</td>
<td>$t_0 = (13.73 \pm 0.12) \times 10^9 \text{ years}$</td>
</tr>
<tr>
<td>Vacuum energy</td>
<td>$\Omega_\Lambda = 0.721 \pm 0.015$</td>
</tr>
<tr>
<td>Cold dark matter (CDM)</td>
<td>$\Omega_{\text{CDM}} = 0.233 \pm 0.013$</td>
</tr>
<tr>
<td>Baryons</td>
<td>$\Omega_B = 0.0462 \pm 0.0015$</td>
</tr>
</tbody>
</table>
The evolution \( a(t) \) for such a three-parameter model is given by the inverse of the “look-back time”

\[
H_0 t = \int_1^a \frac{dx}{\sqrt{1 + (x^{-1} - 1) \Omega_M + (x^2 - 1) \Omega_\Lambda}},
\]

where the normalization \( a_0 = 1 \) was used. We take the present time to be \( t_0 = 0 \) and past times negative. The choice \( \Omega_\Lambda = 0 \) and \( \Omega_M = 1 \) corresponds to a flat, matter-dominated model where we show \( a(t) \) as the lower solid curve in Fig. 3. We also show, as a dashed line, the linear extrapolation of the Hubble law, corresponding to an empty universe with \( \Omega_M = \Omega_\Lambda = 0 \). By definition the dashed line is the tangent to the solid line at the present epoch. The matter-dominated evolution is decelerating: the expansion rate slows down. The time to the big bang is here \( \frac{2}{3} H_0^{-1} \). We show another flat example with \( \Omega_M + \Omega_\Lambda = 1 \) and \( \Omega_M = 0.2629 \), chosen such that the big bang occurs at exactly one Hubble time in the past. The universe first decelerates, then accelerates when the vacuum energy takes over. This model is very close to how our universe appears to be evolving.

**Accelerated Expansion**

In 1998 a revolution swept through cosmology in that accelerated expansion was discovered in the measured brightness-redshift relation of SNe Ia. These exploding stars can be used as cosmic standard candles and for a few weeks are so bright that they can be measured throughout the observable universe. Once automated searches had turned up enough of them, one could construct a Hubble diagram, displaying their redshift vs. their apparent brightness that translates into their distance. The latest “union compilation” of
307 SNe reaches to redshifts up to about 1.6 and thus traces a significant portion of the cosmic evolution [18]. Fitting the observations to a Robertson-Walker-Friedmann-Lemaître model of the universe, confidence contours in the parameter plane of $\Omega_M$ and $\Omega_\Lambda$ are shown in the left panel of Fig. 4. Together with other observations to be discussed later, one is restricted to a very small region consistent with a flat universe and the parameters shown in Table 2. However, the crucial point is that even the first useful SN data showed the need for a $\Lambda$ term because an expansion like the upper curve in Fig. 3 provided a much better fit than one corresponding to the lower curve. In other words, the SN data pointed to an accelerating rather than decelerating expansion.

The quick acceptance of this result was not only due to the SN data alone, but the new “concordance model” also relaxed a number of other tensions that had plagued the previous situation. For example, the expansion age could now easily accommodate the globular cluster ages that had always pointed to a relatively old universe. Moreover, a flat geometry had seemed natural for a long time, yet the dark matter inventory of the universe had always seemed too small to allow for $\Omega_{\text{tot}} = 1$.

![Figure 4](image-url)
Accelerated expansion alone does not prove that it is caused by a $\Lambda$ term. To consider hypothetical other equations of state (EoS), one may assume that the r.h.s. of the Friedmann equation is governed by an ideal fluid with pressure

$$p = w \rho .$$

(9)

All examples of Table 1 are of this form. If the EoS parameter obeys $w < -\frac{1}{3}$, the expansion is accelerated, otherwise decelerated. If $w < -1$ ("phantom energy"), the scale factor becomes infinite in a finite time ("big rip").

However, analyzing the data with $w$ a free parameter shows that it is quite close to the "boring" vacuum-energy value $w = -1$ (right panel of Fig. 4). The primary goal of future SN surveys with far better data is to find a deviation from $w = -1$ that would show a deviation from "simple" vacuum energy. For example, a slowly evolving scalar field permeating the universe ("quintessence") would typically produce different $w$ values. Moreover, the simple EoS considered here is but one parametrization of what could be a far more complicated function.

In summary, the SN Ia Hubble diagram and other data, when interpreted in the framework of Friedmann-Lemaître-Robertson-Walker cosmology, requires a "dark energy" component that, on present information, acts exactly like a cosmological constant. While it dominates the mass-energy inventory of the universe, it is very small by particle-physics standards where quantum field theory would naively point to a much larger value. For the time being, the observations are best fit with a simple $\Lambda$ as originally formulated by Einstein. If there is any positive $\Lambda$ it eventually dominates the expansion, but why is this happening "now," i.e., why do we live in an epoch when $\Omega_M$ and $\Omega_\Lambda$ are comparable? The apparent fine-tuning is even more striking if we note that the age of the best-fit universe is almost exactly $H_0^{-1}$, i.e., the upper solid curve in Fig. 3 begins almost exactly where the dashed curve begins. Be that as it may, a theoretical understanding of "dark energy" is largely lacking. For further reading see Peebles and Ratra [8] and Copeland, Sami and Tsujikawa [9].

**STRUCTURE FORMATION AND PRECISION COSMOLOGY**

**Matter distribution**

While the SN Ia Hubble diagram provides the most direct evidence for accelerated expansion and thus for something like dark energy, far more precise information on the overall model and its detailed parameters derive from other data (Fig. 4). The Hubble diagram uses information from the overall expansion, whereas a huge amount of additional information comes from deviations from perfect homogeneity. While the Friedmann models assume homogeneity on average (in practice on scales exceeding about 100 Mpc), on smaller scales the matter distribution is structured. The formation, evolution and observation of these structures leads to what is called "precision cosmology."

Even a sky map of the observed galaxies shows that they are not uniformly distributed, but a true revolution began in the mid 1980s when the first systematic redshift surveys were performed. Here one measures the redshifts of galaxies in a slice on the sky and
shows their redshift as a function of angular location. The redshift serves as a measure of distance through the overall Hubble flow. So one constructs a 3-dimensional map of the universe, the first one being the CfA slice shown in Fig. 5. The other blue images are from more recent surveys that reach to far larger redshifts and encompass far more galaxies. The distribution is indeed uniform on large scales, so the picture of overall homogeneity and isotropy appears justified. However, on small scales the galaxy distribution forms sheets and filaments as well as nodes and clusters. There are voids and large coherent structures called “walls.”

How did these structures form? The standard cosmological picture holds that the universe was almost perfectly homogeneous after the early phase of inflation, with tiny density fluctuations imprinted on it. What remains is the action of gravity. Regions of slight overdensity attract more matter, those of underdensity lose, so density contrasts enhance themselves by gravitational instability. Moreover, if the matter distribution is dominated by collisionless dark matter, the action of gravity is all that shapes the structures once an initial fluctuation spectrum has been specified. The red slices in Fig. 5 result from the largest-scale numerical simulations, showing a striking similarity between observed and simulated examples.
FIGURE 6. Power spectrum of cosmic density fluctuations measured by different probes on different scales. The solid line represents the best-fit cold dark matter (CDM) scenario including a cosmological constant $\Lambda$. (Figure from Ref. [21].)

Going beyond a visual comparison requires quantitative measures. The simplest is the power spectrum of density fluctuations. Assume a matter density $\rho(r)$ with an average $\bar{\rho}$. The field of density fluctuations is $\delta(r) = \rho(r)/\bar{\rho} - 1$, its spatial Fourier transform is $\delta(k)$ with $k$ the wave vector of a given mode. One expects the fluctuations to be a Gaussian random field, meaning that the $\delta(k)$ have no phase correlation. The random field is then fully characterized by $|\delta(k)|^2$, where no phase information is preserved, a quantity that is the power spectrum $P(k)$. With the additional assumption of isotropy, it only depends on $k = |k|$. $P(k)$ is identical with the two-point correlation function that is relatively straightforward to extract from redshift surveys.

In Fig. 6 we show observations on different scales overlaid with a best-fit theoretical curve. It assumes an initial power spectrum of the form

$$P(k) \propto k^n$$

(10)

where $n = 1$ is the classic Harrison-Zeldovich spectrum, but in general $n$ is a cosmic fit parameter, today found to be $n = 0.960 \pm 0.014$. In addition one allows for a $\Lambda$ term in the Friedmann equation and assumes that matter is mostly collisionless “cold dark matter” (CDM). These are particles so massive that they become nonrelativistic (“cold”) early enough to avoid washing out the initial fluctuations.
While the assumed initial spectrum is a power law and thus featureless, the observed spectrum has a distinct kink at intermediate scales. It can be understood from the way inhomogeneities grow. If space were not expanding, gravitational instabilities would grow exponentially. The cosmic expansion reduces the growth rate and one finds for a matter-dominated situation, where the scale factor grows as $a(t) \propto t^{2/3}$, that density contrasts grow linearly with scale factor: $|\delta(k)| \propto a$. On the other hand, when radiation dominates, the situation is more complicated. Small-scale modes do not grow at all or at most logarithmically, whereas large-scale modes grow as $|\delta(k)| \propto a^2 \propto t$. The distinction between “small” and “large” wavelengths is given by the horizon scale $H^{-1}$ which limits scales that are in causal contact with themselves in view of the limited distance traveled by any signal since the big bang. The universe began radiation dominated and later became matter dominated. In the earlier phase, the growth of small scale (large wave number) modes was suppressed. After matter domination, all modes grow together. Therefore, the kink in the present-day power spectrum is an imprint of the transition between radiation and matter domination in the early universe.

In a phase of exponential expansion caused by a $\Lambda$ term, structures do not grow at all. Therefore $\Lambda$ must be small enough to allow for the formation of galaxies, stars, and so forth. The observed $\Lambda$ is “typical” in the sense that a much larger value would have prevented structures from forming and observers from existing. Such anthropic arguments make only sense if we picture $\Lambda$ and/or other properties of our universe as numbers that could have been different and are not fixed by the laws of nature. We noted earlier that one way of looking at our universe is that it is but one realization of many possibilities that may actually exist in causally disconnected regions.

The agreement between this simple theory of structure formation and observations over a wide range of scales is stunning and one of the main pillars of support for the standard $\Lambda$CDM model. In the inflationary phase of the early universe, the metric was smoothed on large scales, providing for an almost flat geometry on our Hubble scale and far beyond. Another consequence is that fluctuations of the metric were imprinted. They are fundamentally quantum fluctuations stretched by inflation to macroscopic scales. One expects nearly scale-invariant Gaussian fluctuations and a spectral power-law index $n$ close to unity, but slightly smaller. This expectation is also borne out by observations.

### Cosmic Microwave Background (CMB)

The observation of the cosmic microwave background radiation by Penzias and Wilson in 1965 marked the true beginning of big-bang cosmology. This ubiquitous thermal radiation with a present-day temperature of 2.725 K proves that the universe was once hot. Photons decoupled from the cosmic plasma at a redshift of about 1100 when ordinary matter had “recombined” to form neutral atoms, a medium in which photons stream freely. From our perspective we are seeing a spherical shell of primordial matter around us where the photons originate, the “surface of last scattering.” A different observer elsewhere in the universe sees a different spherical shell around his own location, so the surface of last scattering is different for each observer.
Within tiny experimental errors, the CMB shows an exact blackbody spectrum. The temperature is almost perfectly uniform over the sky. This is surprising because the different regions, for example in opposite directions from us, were never in causal contact. An early inflationary phase explains the uniformity in that these regions were in causal contact until they were driven apart by the early exponential expansion.

Upon closer scrutiny one observes a small dipole in the temperature sky map on the level of $10^{-3}$. This shows our peculiar motion relative to the cosmic rest frame: we are seeing the same thermal radiation red-shifted in one direction and blue-shifted in the opposite direction. In other words, the CMB as a heat bath defines the cosmic reference frame where the universe is isotropic, i.e., the frame where the Robertson-Walker-Friedmann-Lemaître cosmology is formulated.

Upon even closer scrutiny, at the level of temperature differences of $10^{-5}$, one finds temperature fluctuations that must exist because the universe is not perfectly homogeneous. The remarkable feat of observing these tiny fluctuations was first achieved by the COBE satellite in 1992. The most detailed modern CMB temperature map from the WMAP satellite’s 5-year observations (2008) is shown in Fig. 7. What we are seeing are temperature fluctuations, corresponding to density fluctuations, of the small fraction of baryonic matter, whereas dark matter does not directly interact with photons.

This sky map provides little direct cosmological information. What is important once more are the statistical properties of the distribution. To this end one expands the sky map in spherical harmonics and displays the power spectrum as a function of multipole index $\ell$ as shown in Fig. 8. In contrast to the matter power spectrum discussed earlier, the multipole spectrum shows a distinct pattern of “acoustic peaks.” The density fluctuations in the primordial soup of baryonic matter and photons lead to oscillations of this plasma that is an “elastic medium,” in contrast to the collisionless dark matter. As in any elastic
medium, density fluctuations propagate as sound waves. Different modes oscillate with different frequencies, each reaching a different phase of oscillation since the big bang until the epoch of photon decoupling. The acoustic peaks in Fig. 8 are essentially a snapshot of the phases reached by the acoustic waves at photon decoupling.

The pattern of acoustic peaks has a lot of structure and therefore carries a lot of information about the parameters of the cosmological model. The sound waves in the early-universe plasma do not depend on the large-scale curvature of the universe that may exist today but was negligible at these early times. The sound waves provide an absolute length scale or “standard stick” that does not depend on the global cosmic parameters. On the other hand, upon propagating to us, we are seeing these scales as extending certain angles that do depend on the spatial curvature of the universe. In particular, the angular location of the first acoustic peak depends directly on the large-scale curvature of the universe. The measured result tells us with high precision that our universe is flat, the curvature radius exceeding about 30 Gpc, to be compared with a Hubble radius of about 3 Gpc. In the left panel of Fig. 4 we see the CMB best-fit region to be essentially aligned with the locus of flat models where $\Omega_M + \Omega_\Lambda = 1$. Moreover, it intersects with the SN Ia best-fit region for flat-universe parameters.

The measured curve of acoustic peaks carries so much information that it has been termed the “Cosmic Rosetta Stone.” Another crucial parameter is the cosmic baryon density that provides the inertia for the acoustic waves. Roughly speaking, it is the relative height of the first and second acoustic peaks that give us $\Omega_B$. The best-fit value in a common fit of all parameters is shown in Table 2 and tells us that most of the cosmic matter is dark. However, the density of luminous matter is only about a tenth of that, so actually most baryons are dark and presumably dispersed.

The baryon fraction also influences the relative abundances of light elements formed in the early universe, notably hydrogen, helium and deuterium. The tiny abundance of
this latter isotope is a sensitive probe of the baryon density. One measures its cosmic abundance in the absorption spectra of distant quasars in intergalactic hydrogen clouds where one can differentiate between hydrogen and deuterium absorption lines by the tiny isotope shift. The baryon abundance inferred by this method is perfectly consistent with the CMB value, but its uncertainties are much larger so that this classic measurement no longer plays a crucial role for cosmological parameter fitting. Of course, one measures the baryon abundance in vastly different cosmic epochs so that the good agreement provides gratifying evidence for the overall consistency of the standard picture.

The CMB is slightly polarized and these polarizations have been measured. The sky map of polarizations, in principle, allows one to distinguish between density fluctuations and tensor disturbances (gravitational waves). The next big prize in CMB physics is to find the spectrum of these subdominant tensor modes because their detection would be an important further confirmation of early-universe inflation that would excite tensor modes besides density fluctuations. The PLANCK satellite, to be launched shortly, may have a first chance of observing this fundamental effect.

Acoustic oscillations of the primordial plasma manifest themselves primarily in the temperature fluctuations of the CMB, but should also imprint themselves in the matter power spectrum as tiny modulations. These “baryon acoustic oscillations” (BAO) have recently been found by the Sloan digital sky survey (SDSS). The cosmological best-fit parameters implied by the BAOs are shown in Fig. 4, intersecting with the regions from other observations and thus allowing one to perform a common fit.

In summary, we get a consistent picture of the universe, accommodating all crucial observations, if we begin with a simple Friedmann cosmology and allow for dark ingredients in the form of cold dark matter (that clusters on small scales) and dark energy (that only influences the overall Hubble expansion). Together with a nearly scale-invariant spectrum of density fluctuations as predicted by inflation and the theory of gravitational instability, the observed density fluctuations on all scales and the global properties of the universe are all accounted for. The few adjustable parameters of the model are very well determined by a common fit to all relevant observables.

**DARK MATTER ON SMALL SCALES**

**Spiral Galaxies**

If the global dynamics of the universe and a consistent picture of structure formation require large amounts of cold dark matter, its presence should also be evident in smaller systems. It is here, of course, where dark matter was first discovered. Spiral galaxies provide perhaps the most direct evidence. They consist of a central bulge and a thin disk. One may use the Doppler shift of spectral lines to obtain the orbital velocity of the disk as a function of radius (“rotation curve”). If the mass is indeed concentrated in the bulge, then the orbital velocity of the disk should show the Keplerian $1/\sqrt{r}$ decrease familiar from the solar system (left panel of Fig. 9).

However, one always finds that the orbital velocity stays essentially flat as a function of radius, implying much more gravitating mass interior to a given radius than implied by the luminous matter. This behavior became established in the 1970s, at first by the
FIGURE 9. Left: “Rotation curve” of the solar system, showing the Keplerian $1/\sqrt{r}$ decrease of the planetary orbital velocities. Right: Rotation curve of the spiral galaxy NGC 6503 from radio observations of hydrogen in the disk [24]. The last measured point is at 12.8 disk scale-lengths. The dashed line is the rotation curve caused by the disk alone, the dot-dashed line from the dark matter halo alone.

optical observations of Vera Rubin. Spiral galaxies tend to have neutral hydrogen in the plane of their disks that reaches to much larger galactocentric radii than optical tracers. A typical case for such a rotation curve is shown in the right panel of Fig. 9. More than a thousand rotation curves have been studied and have allowed one to derive a “universal rotation curve” that depends only on a few empirical parameters [25].

Galaxy Clusters

Clusters of galaxies are the largest gravitationally bound systems in the universe. We know today several thousand clusters; they have typical radii of $1.5$ Mpc and typical masses of $5 \times 10^{14} M_\odot$. Zwicky first noted in 1933 that these systems appear to contain large amounts of dark matter. He used the virial theorem which tells us that in a gravitationally bound system in equilibrium $2\langle E_{\text{kin}} \rangle = -\langle E_{\text{grav}} \rangle$ where $\langle E_{\text{kin}} \rangle = \frac{1}{2} m \langle v^2 \rangle$ is the average kinetic energy of one of the bound objects of mass $m$ and $\langle E_{\text{grav}} \rangle = -mG\langle M/r \rangle$ is the average gravitational potential energy caused by the other bodies. Measuring $\langle v^2 \rangle$ from the Doppler shifts of the spectral lines and estimating the geometrical extent of the system gives one directly an estimate of its total mass $M$. As Zwicky stressed, this “virial mass” of the clusters far exceeds their luminous matter content, typically leading to a mass-to-light ratio of around 300.

With the beginning of x-ray astronomy it was recognized that clusters are powerful x-ray sources. They contain large amounts of hot gas, in virial equilibrium with the galaxies, that therefore is hot. The mass of this x-ray emitting matter far exceeds the luminous mass of the galaxies, yet is much less than the overall mass of the cluster. Besides the virial method, today detailed mass profiles can be measured using the gravitational light deflection of background galaxies. Galaxy clusters are so large that
over a Hubble time no significant mass exchange can have taken place with their environment so that their mass inventory should be typical for the universe. Indeed, one finds that the mass ratio of x-ray emitting gas to the total mass is similar to the ratio of $\Omega_B/(\Omega_B + \Omega_{CDM})$ implied by precision cosmological methods. Before the age of precision cosmology, this argument was turned around. The fraction of baryonic to total mass found in clusters together with the BBN-implied baryon density suggested that the total matter density could not be critical and that therefore it was very difficult to have a flat matter-dominated universe.

A spectacular case for dark matter in clusters was recently made by x-ray observations of the “bullet cluster” (Fig. 10). It consists of a small cluster (the “bullet”) that has collided with a large one and penetrated it, emerging on the other side. The blue false-color indication of the mass distribution is found to be very different from the red false-color x-ray image. The x-ray emitting gas was stripped from the two clusters as one moved through the other, whereas the galaxies and dark matter, being collisionless, moved right through. This image has been taken as one of the most direct proofs for the existence of dark matter and its nature as a gas of “collisionless stuff.”
WEAKLY INTERACTING PARTICLES

Neutrinos

If much of the gravitating matter in the universe is invisible and does not consist of baryons, then what could it be? Within the particle physics standard model, all stable matter consists of quarks of the first generation and electrons (Fig. 11). The simple periodic system of elementary particles leaves no room for weakly interacting dark matter except in the form of neutrinos. In spite of their weak interactions, neutrinos were in thermal equilibrium in the early universe until their interactions became too slow when the cosmic temperature fell below about 1 MeV. Since that time they streamed freely—we could see a neutrino sphere of last scattering if it were possible to detect neutrinos that today have energies as low as CMB photons.

The cosmic neutrino density is easy to predict if they were originally in thermal equilibrium. The only nontrivial point is that the disappearance of electrons and positrons at \( T \lesssim m_e = 0.511 \text{ MeV} \) heats the photon gas relative to neutrinos which are already decoupled. One finds the standard result that the number density of neutrinos plus antineutrinos of one family is \( n_\nu = \frac{3}{4\pi} n_\gamma \), the latter being the present-day density of CMB photons of 410 cm\(^{-3}\) so that \( n_\nu = 112 \text{ cm}^{-3} \). The density contribution of one flavor is simply \( \rho_\nu = \frac{3}{4\pi} n_\gamma m_\nu \). Comparing with the cosmic critical density of Eq. (6) reveals

\[
\Omega_\nu h^2 = \frac{\sum m_\nu}{94 \text{ eV}}. \tag{11}
\]

With current cosmological parameters neutrinos would be all of dark matter if \( \sum m_\nu \approx 11 \text{ eV} \). From oscillation experiments we know that the neutrino mass differences are negligible on this scale and from tritium beta decay experiments that the mass for a single flavor is below about 2.3 eV, so experimentally \( \sum m_\nu \lesssim 7 \text{ eV} \).

However, neutrinos can not be the bulk of dark matter. First, if neutrinos were to provide the dark matter in spiral galaxies, their mass would have to exceed about 20 eV or even 100 eV for dwarf galaxies. The phase space of neutrinos bound to a galaxy

\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Quarks} & \textbf{Leptons} \\
\hline
\textbf{Charge} & \textbf{Charge} & \textbf{Charge} & \textbf{Charge} & \textbf{Charge} \\
\textbf{+2/3} & \textbf{−1/3} & \textbf{−1} & \textbf{0} & \\
\hline
1. Family & Up \( u \) & Down \( d \) & Electron \( e \) & e-Neutrino \( \nu_e \) \\
\hline
2. Family & Charm \( c \) & Strange \( s \) & Muon \( \mu \) & \( \mu \)-Neutrino \( \nu_\mu \) \\
\hline
3. Family & Top \( t \) & Bottom \( b \) & Tau \( \tau \) & \( \tau \)-Neutrino \( \nu_\tau \) \\
\hline
\end{tabular}

\begin{tabular}{|c|}
\hline
Gravitation \\
\hline
Weak Interaction \\
\hline
Electromagnetic Interaction \\
\hline
Strong Interaction \\
\hline
\end{tabular}

\textbf{FIGURE 11.} Three families of standard-model particles and their interactions.
is limited so that essentially the Pauli exclusion principle prevents too many low-mass fermions to accumulate (“Tremaine-Gunn limit”).

From the perspective of structure formation, neutrinos form “hot dark matter” because they stay relativistic for a long time and their free streaming erases small-scale density fluctuations. Since neutrinos are some fraction of the total cosmic matter density, the matter power spectrum would be suppressed on small scales (large wave numbers). Indeed, $\sum m_\nu$ is an unavoidable cosmic fit parameter. On the present level of precision, cosmic data provide a best-fit value $\sum m_\nu = 0$ and an upper limit $\sum m_\nu \lesssim 0.6$ eV, implying $\Omega_\nu \lesssim 1.3\%$. The exact limit depends on the data sets used in the analysis. One problem is that the strongest limits come from the smallest scales where the matter power spectrum is in the nonlinear regime so that the data are more difficult to interpret. Whatever the exact limit, massive neutrinos can not provide the bulk of the dark matter. One may hope though that eventually precision cosmology will provide a measurement for $\sum m_\nu$ that can be compared with future experiments. Oscillation data imply $\sum m_\nu \gtrsim 50$ meV, a value that may be reachable by precision cosmology in the distant future.

Let us ignore oscillation experiments for the moment and assume that one of the neutrinos could have a large mass. When we show its contribution $\Omega_\nu$ to the cosmic matter inventory as a function of mass, we find the “Lee-Weinberg-curve” of Fig. 12. The low-mass branch of course reproduces the previous result that the number density is $3/11$ that of photons and thus the mass contribution grows linearly with $m_\nu$. Something new happens when the mass exceeds a few MeV, the temperature where neutrinos decouple from the thermal early-universe plasma. If $m_\nu \gg T$, their number density is suppressed by a Boltzmann factor $\exp(-m_\nu/T)$. In other words, as the cosmic $T$ falls, neutrinos annihilate and disappear without being replenished by inverse reactions. This continues until they become so dilute that they no longer meet often enough to annihilate and a relic population “freezes out.” Computing this “thermal relic population” is a straightforward exercise. For the given weak interaction strength of the standard model, $\Omega_\nu$ steeply decreases with $m_\nu$, providing the required dark matter density for $m_\nu \approx 10$ GeV. This would be safely in the regime of cold dark matter.

FIGURE 12. Cosmic neutrino mass density as a function of neutrino mass (Majorana case). The dashed line shows the required dark matter density.
Weakly Interacting Massive Particles (WIMPs)

The measured $Z^0$ decay width shows that there are exactly three neutrino families with masses up to $m_T/2 = 46$ GeV. Even if a fourth generation with a larger mass existed, the abundance would be too low to provide for dark matter. Still, a hypothetical massive particle with approximately weak interactions, a generic weakly interacting massive particle (WIMP) provides a good dark matter candidate because it naturally survives as a thermal relic in sufficient numbers after annihilation freeze-out. If the interaction strength were somewhat weaker, the particle would freeze out earlier and a greater number would survive (“survival of the weakest”). Typically one thinks of these particles as Majorana fermions, i.e., neutrino-like particles that are their own antiparticles, and thus can annihilate with themselves.

Supersymmetric extensions of the standard model motivate precisely such particles. One postulates that every bosonic degree of freedom is matched by a supersymmetric fermionic one and vice versa. Normal and supersymmetric particles differ by a quantum number called R-parity which may be conserved so that the lightest supersymmetric particle (LSP) would be stable. If the LSP is the lightest “neutralino,” i.e. the lightest mass eigenstate of a general superposition of the neutral spin-$\frac{1}{2}$ fermions photino, Zino, and Higgsino, then we have a perfect neutrino substitute. The interaction would be roughly, but not exactly, of weak strength. In detail the annihilation and scattering cross sections depend on specific assumptions and on the values of numerous parameters.

The main motivation for supersymmetry is the theoretical issue of stabilizing the electroweak scale of about 250 GeV against radiative corrections that would drive it up to the Planck mass of about $10^{19}$ GeV. For a typical gauge interaction strength, particles with masses around the electroweak scale have the right properties for cold dark matter (“WIMP miracle”). The Large Hadron Collider at CERN, taking up operation shortly, was designed to probe physics at this scale, notably to detect the Higgs particle and physics beyond the standard model that one may well expect at this scale such as supersymmetry. Therefore, if the ideas about the cosmological role of WIMPs are correct, the LHC may well discover these particles or indirect evidence for them.

Direct Search for WIMPs

In the mid-1980s it became clear that one can search for dark-matter WIMPs in the laboratory by a variety of methods. One always uses elastic WIMP collisions with the nuclei of a suitable target, for example a germanium crystal. Galactic WIMPs move with a typical virial velocity of around 300 km s$^{-1}$. If their mass is 10–100 GeV their energy transfer in such an elastic collision is of order 10 keV. Therefore, the task at hand is to identify such energy depositions in a macroscopic target sample. Three signatures can be used. (i) Scintillation light. (ii) Ionization, i.e., the liberation of free charges. (iii) Energy deposition as heat or phonons.

The direct search by such methods has turned into quite an industry. In Fig. 13 we show the three main techniques as a triangle, and list projects using them. The main problem with any such experiment is the extremely low expected signal rate. In
detail it depends on the assumed WIMP properties and target material, but a typical number is below 1 event kg$^{-1}$ day$^{-1}$, a counting-rate unit usually employed in this field. To reduce natural radioactive contaminations one must use extremely pure substances and to reduce cosmic-ray backgrounds requires underground locations, for example in deep mines (“underground physics”). Background can be suppressed by using two techniques simultaneously. In Fig. 13 the projects noted at a side of the triangle use the corresponding combination of techniques.

Most experiments have only reported limits on the interaction cross section of putative galactive WIMPs (Fig. 14). Intriguingly, the current experiments already bite deeply into the parameter space expected for supersymmetric particles and thus are in a position to actually detect supersymmetric dark matter if it exists.

One problem is how one would attribute a tentative signal unambiguously to galactic WIMPs rather than some unidentified radioactive background. One signature is the annual signal modulation which arises because the Earth moves around the Sun while the Sun orbits around the center of the galaxy. Therefore, the net speed of the Earth relative to the galactic dark matter halo varies. The DAMA experiment, using the NaI scintillation technique, has actually reported such a modulation for the past ten years [26]. Other experiments have now excluded this region when interpreted in terms of typical supersymmetric models. On the other hand, each detector uses a different material and their results do not directly compare. In fact, one way of identifying a WIMP is to see it with different detectors using different target materials. In this sense DAMA remains unconfirmed, but also is not strictly excluded as a dark matter signature. Ten years ago, the DAMA region in Fig. 14 was far below the sensitivity of any other experiment, whereas now it is vastly excluded if one compares the cross sections naively. This illustrates the enormous progress that has been made over the past decade.

FIGURE 13. Possible signals for WIMPs and experiments using them singly or in combination to suppress backgrounds.

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FIGURE 14. Experimental limits and foreseen sensitivities for WIMPs with spin-independent interactions. The theoretical benchmark is given by supersymmetric models.

The current level of sensitivity to scattering cross sections per nucleon is around $5 \times 10^{-44}$ cm$^2$. The goal is to reach roughly the $10^{-45} - 10^{-46}$ cm$^2$ level. On the path to this sensitivity there is a vast range of opportunity to find supersymmetric dark matter or other WIMPs.

Detecting WIMP Annihilation

In the WIMP paradigm it is usually assumed that these particles are self-conjugate spin-$\frac{1}{2}$ particles, i.e., they are their own antiparticles (Majorana fermions). Supersymmetric neutralinos have precisely this property. Therefore, one can perform the early-universe freeze-out calculation without having to worry about a possible asymmetry between WIMPs and anti-WIMPs. Of course, for ordinary matter it is precisely such an asymmetry which allows baryonic matter to exist; here the challenge is to explain how the universe developed this asymmetry (baryogenesis). One actually needs physics beyond the standard model to achieve the observed asymmetry. For WIMPs it is their very weak interaction that allows them to freeze out in sufficient numbers even without an asymmetry.

If WIMPs were produced and destroyed in the early universe by pair processes, the same goes on today, except with a much smaller rate. WIMPs froze out because they became too dilute to annihilate efficiently. However, whenever WIMPs concentrate in some
location one may hope for a potentially detectable annihilation signal. Since WIMPs are thought to be heavy, their properties being likely connected to the electroweak scale close to the TeV range, there is enough energy in an annihilation event to produce all sorts of final states, including protons and antiprotons, electrons and positrons, high-energy $\gamma$-rays and neutrino pairs. The efficiency of different channels depends on detailed models.

Dark matter particles are naturally concentrated in galaxies where a typical density is about $10^5$ times the cosmic average. The annihilation rate scales with the square of the particle density, so one gains 10 orders of magnitude relative to the cosmic average. Therefore, WIMP self-annihilation can lead to a contribution of cosmic-ray antiprotons, positrons and $\gamma$-rays, although the interpretation of possible signals depends on understanding the ordinary cosmic-ray background. The $\gamma$-ray excess observed by the EGRET satellite could be attributed to WIMP annihilation [27], although the accompanying antiproton flux seems too large. Once more one is confronted with the problem of how to unambiguously attribute a tentative signal to dark matter.

Therefore, “smoking-gun signatures” would be especially welcome that are difficult to ascribe to any other source. One example is WIMP annihilation into a single pair of $\gamma$-rays, producing a monochromatic line with energy corresponding to the WIMP mass. Hopes are high that the GLAST satellite, that was successfully launched on 11 June 2008, may detect such a signature. It explores a range of $\gamma$-ray energies in the few 100 GeV range that has not been explored yet.

In order to detect WIMPs in this way, one likely needs a significant “boost factor,” meaning that dark matter is distributed so inhomogeneously that $\langle n^2 \rangle \gg \langle n \rangle^2$. Cold dark matter simulations indeed find that WIMPs tend to cluster on smaller and smaller scales in an almost fractal-like fashion. This effect may be a problem for CDM cosmology because the baryonic matter distribution does not show such behavior even though one would expect baryons and thus stars (luminous matter) to build up in these small-scale sub-galactic structures.

Another smoking-gun signature could come from high-energy neutrinos emitted by the Sun where WIMPs would build up. As they stream through the Sun, they sometimes collide with nuclei and get gravitationally trapped, sinking to the solar center where they concentrate. Only final-state neutrinos could escape after annihilation. The high-energy neutrino telescopes IceCube that is built at the South Pole and ANTARES being built in the Mediterranean could eventually detect this flux. In terms of supersymmetric models, this method is complementary to direct laboratory searches. At present only limits exist that begin to bite into the supersymmetric parameter space.

If the dark matter indeed consists of WIMPs with properties as discussed here, the upcoming 5–10 years could prove crucial. With the LHC turning on, GLAST having been launched, IceCube reaching the cubic-kilometer size, and direct searches gearing up for larger size and greater sensitivity, one may hope that one or more methods will lead to a clear detection.
**AXIONS**

The search for WIMPs has strong synergy with other experimental activities, notably the LHC, neutrino and γ-ray astronomy, and the development of low-background detectors. Moreover, the supersymmetric motivation for neutralinos is compelling to many particle physicists. Still, we should not blind ourselves to the fact that the nature of dark matter is completely unknown and one should keep an open mind to other possibilities of which there exist many. However, few are both well-motivated and at the same time offer systematic opportunities to search for them. One alternative to supersymmetric particles that is both well motivated and searchable are axions. They form a particle dark-matter candidate sui generis in that they are very weakly interacting very low-mass bosons and yet a candidate for cold dark matter.

Axions are motivated by the Peccei-Quinn solution of the “strong CP problem.” The nontrivial vacuum structure of QCD produces CP violating effects that are represented by a parameter \(0 \leq \Theta \leq 2\pi\). The experimental limits on the neutron electric dipole moment (a CP-violating quantity) reveal \(\Theta < 10^{-10}\), although naively it should be of order unity. The Peccei-Quinn mechanism holds that \(\Theta\) should be re-interpreted as a physical field \(a(x)\) in the form \(\Theta \rightarrow a(x)/f_a\), where \(f_a\) is an energy scale, the Peccei-Quinn scale or axion decay constant. The CP-violating Lagrangian produces a potential which drives the axion field to the CP-conserving position corresponding to \(\Theta = 0\) (“dynamical symmetry restoration”).

The excitations of the new field are axions. Their properties are essentially fixed by the value of \(f_a\). Axions are closely related to neutral pions: they mix with each other with an amplitude of about \(f_\pi/f_a\) where \(f_\pi = 93\) MeV is the pion decay constant. The axion mass and interactions follow roughly by scaling the corresponding \(\pi^0\) properties with \(f_\pi/f_a\). The axion interactions are inversely proportional to \(f_a\) and thus can be arbitrarily small (“invisible axions”). Strong laboratory and stellar energy-loss limits suggest that axions, if they exist, must be very light \(m_a \lesssim 10^{-2}\) eV) and very weakly interacting (Fig. 15).

In concrete models the axion field is interpreted as the phase of a new Higgs field \(\Phi(x)\) after spontaneous breakdown of a new chiral U(1) symmetry, i.e., it is a Nambu-Goldstone boson. When the temperature in the early universe falls below \(f_a\), the symmetry breaks down and \(\Phi(x)\) finds a minimum somewhere in the rim of the Mexican hat, selecting one value for the axion field and thus for \(\Theta\). Later at a temperature \(T = \Lambda_{\text{QCD}} \approx 200\) MeV the QCD phase transition occurs, switching on the potential that drives the axion field to the CP-conserving minimum. In other words, at the QCD transition the Peccei-Quinn symmetry is explicitly broken, the Mexican hat tilts, and the axion field rolls towards the CP-conserving minimum.

In this way the initial “misalignment angle” \(\Theta_i\) sets the axion field into motion and thus excites coherent oscillations. They correspond to an axionic mass density of the present-day universe of about \([11]\)

\[
\Omega_a h^2 \approx 0.7 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \left( \frac{\Theta_i}{\pi} \right)^2.
\]

(12)

If inflation occurs before the PQ transition, the axion field will start with a different \(\Theta_i\) in each region which is causally connected at \(T \approx f_a\). Then one has to average over all
regions to obtain the present-day axion density and finds

\[ \Omega_a h^2 \approx 0.3 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \]  

(13)

Because axions are the Nambu-Goldstone mode of a spontaneously broken U(1) symmetry, cosmic axion strings form by the Kibble mechanism. This and other contributions from axion-field inhomogeneities are comparable to the homogeneous mode from misalignment, even though significant modification factors can occur. Therefore, the axion mass required for dark matter is rather uncertain as indicated in Fig. 15.

Axions produced by strings or the misalignment mechanism were never in thermal equilibrium. The field modes are highly occupied, forming a Bose-Einstein condensate. Axions are nonrelativistic almost from the start and thus form cold dark matter, in spite

**FIGURE 15.** Limits on the axion decay constant and axion mass from different sources.
of their small mass. If axion interactions were sufficiently strong ($f_a \lesssim 10^8 \text{GeV}$) they would have reached thermal equilibrium, leading to a thermal axion background in analogy to neutrinos. Axions, like neutrinos, contribute hot dark matter if their mass is in the eV range, but they are cold dark matter for much smaller masses, whereas WIMPs are cold dark matter for much larger masses. WIMPs are thermal relics whereas cold dark matter axions are nonthermal relics.

If axions are the galactic dark matter one can search for them in the laboratory. The detection principle is analogous to the Primakoff effect for neutral pions which can convert into photons in an external electromagnetic field due to their two-photon vertex (Fig. 16). Dark-matter axions would have a mass in the $\mu$eV–meV range. Their velocity dispersion is of order the galactic virial velocity of around $10^{-3}c$ so that their kinetic energy is exceedingly small relative to their rest mass. Noting that a frequency of 1 GHz corresponds to 4 $\mu$eV the Primakoff conversion produces microwaves. Because the galactic axions are nonrelativistic while the resulting photons are massless the conversion involves a huge momentum mismatch which can be overcome by looking for the appearance of excitations of a microwave cavity.

After several pilot experiments, a full scale axion search, the ADMX experiment in Livermore, has now begun and is expected to cover the search range indicated in Fig. 15, i.e., two decades in $f_a$ or $m_a$ in a well-motivated regime of parameters. The time scale for this search is about one decade. ADMX is the first axion search experiment that should definitely find axions if they are the dark matter and have masses in the search range.

**SUMMARY**

As astronomy and cosmology investigate the world at larger and larger scales, and as elementary particle physics probes the microscopic structure of the world and its forces at smaller and smaller scales, we realize that “inner space” and “outer space” are closely related and the two directions in many ways lead to similar questions.

The different components of the dark universe, and even the creation of the ordinary matter-antimatter asymmetry, cry out for physics beyond the standard model. Some of the open questions, notably the nature of dark matter, may boil down to the experimental challenge of detecting dark-matter particles in the laboratory. For the wide-spread hypothesis that supersymmetric particles are responsible, the next 5–10 years may become crucial with the LHC perhaps finding evidence for supersymmetry and with many direct and indirect search strategies reaching critical size. Likewise, the experimental search for axion dark matter, a completely different type of candidate, has finally reached the critical size to corner this hypothesis.
While the dark-matter problem may “simply” consist of the experimental challenge to detect very weakly interacting new particles, the dark-energy problem looks far more profound. The accelerated expansion of the universe is best fit, at current evidence, by a simple cosmological constant. If a nontrivial dynamical evolution were eventually discovered one would have a handle for a physical interpretation, perhaps in terms of new scalar fields. As long as dark energy is just a single measured number, nature does not provide us with much information about the underlying physics. So, if dark matter looks like an experimental challenge, dark energy looks like one for fundamental theory. Answers may depend on a profound understanding of a quantum theory of gravity, perhaps ultimately provided by string theory or some other novel approach.

The dark universe provides challenges to theory and experiment, but above all it provides us with windows of opportunity to test new ideas and to make exciting new discoveries. It may be the upcoming decade where light is shed on the dark universe.

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