DARK MATTER AND DARK ENERGY*

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This is a short review, aimed at a general audience, of several current subjects of research in cosmology. The topics discussed include the cosmic microwave background (CMB), with particular emphasis on its relevance for testing inflation; dark matter, with a brief review of astrophysical evidence and more emphasis on particle candidates; and cosmic acceleration and some of the ideas that have been put forward to explain it. A glossary of technical terms and acronyms is provided.

1. Introduction

Now is the time to be a cosmologist. We have obtained through remarkable technological advances and heroic and ingenious experimental efforts a direct and extraordinarily detailed picture of the early Universe and maps of the distribution of matter on the largest scales in the Universe today. We have, moreover, an elegant and precisely quantitative physical model for the origin and evolution of the Universe. However, the model invokes new physics, beyond the standard model plus general relativity, not just once, but at least thrice: (1) Inflation, the physical mechanism for making the early Universe look precisely as it does, posits some new ultra-high-energy physics; we don't know, however, what it is. (2) The growth of large-scale-structure and the dynamics of galaxies and galaxy clusters requires that we invoke the existence of collisionless particles or objects; we don't know what this stuff is. (3) The accelerated expansion of the Universe requires the introduction of a new term, of embarrassingly small value, in Einstein's equation, a modification of general relativity, and/or the introduction of some negative-pressure "dark energy," again, the nature of which remains a mystery.

In science, though, confusion and uncertainty are opportunity. There are well-defined but fundamental questions to be answered and data arriving to guide theory. Ongoing and forthcoming observations and experiments will in the next few years provide empirical information about the new physics responsible for inflation, the nature of the dark matter, and the puzzle of accelerated expansion. Future discov-

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eries may help us understand the new physics that unifies the strong, weak, and electromagnetic interactions, as well as gravity. There are also always the prospects for a major paradigm shift in physics, which may be required to unify gravity with quantum mechanics.

In this Chapter, I review the current status of our cosmological model as well as its shortcomings and the questions it leaves unanswered, and I discuss possible answers to these questions and possible avenues towards testing these answers. In particular, I focus on three subjects. In the next Section, I discuss the cosmic microwave background and inflation. Although the main subject of this review is dark matter and dark energy, the paradigm upon which many of our observations—including those that suggest dark matter and dark energy—are interpreted is a Universe with primordial perturbations remarkably like those predicted by inflation. Moreover, the most precise information we have now about the Universe and its contents is the cosmic microwave background, and so it behooves us to review this subject before considering dark matter and dark energy. I then move on in Section 3 to dark matter. I focus primarily on particle dark matter and discuss the prospects for detection of such dark matter, as well as some variations on the simplest particle models for dark matter. Section 4 reviews the cosmic-acceleration puzzle. I review the evidence and then discuss several possible solutions. Section 5 provides some closing remarks, and Section 6 contains a glossary (prepared in collaboration with Adrian Lee) of technical terms and acronyms used in this review and in the Chapter in this volume by Adrian Lee.

2. The Cosmic Microwave Background and Inflation

A confluence of theoretical developments and technological breakthroughs during the past decade have transformed the cosmic microwave background (CMB) into a precise tool for determining the contents, largest-scale structure, and origin of the Universe. Tiny (few parts in 10^5) angular variations in the temperature of the CMB were discovered in the early 1990s by the Differential Microwave Radiometer (DMR) aboard NASA's Cosmic Background Explorer (*COBE*) [1], and during the past few years, high–signal-to-noise high–angular-resolution ($\sim 0.2^\circ$) CMB temperature maps have been obtained [2]. These provide the very first snapshots of the Universe as it was roughly 380,000 years after the big bang, nearly 14 billion years ago, when electrons and light nuclei first combined to form neutral hydrogen and helium.

These new maps have provided several extraordinary breakthroughs. The most striking among these is fairly robust evidence that the Universe is flat and that large-scale structure (galaxies, clusters of galaxies, and even larger structures) grew via gravitational infall from a nearly scale-invariant spectrum of primordial density perturbations. Both of these observations hint strongly that the Universe began with inflation [3], a period of accelerated expansion in the very earliest Universe, driven by the vacuum energy associated with some new ultra-high-energy physics.

Even more recently, the polarization of the CMB has been detected [4] and begun to be mapped on small scales [5] and detected through its cross-correlation with the temperature [6,7]. The small-scale results are consistent with expectations based on models that fit the temperature results, and the results from three years of WMAP (Wilkinson Microwave Anisotropy Probe) indicate that reionization likely occurred at a redshift $z \sim 10$ [8].

As interesting as these results may be, the polarization may allow even more intriguing discoveries in the future. In particular, a cosmological gravitational-wave background from inflation is expected to produce a unique polarization pattern [9,10,11,12]. This "fingerprint" of inflation would allow us to see directly back to the inflationary epoch, 10^{-38} seconds after the big bang!

In the following, I summarize briefly recent progress and future prospects for CMB tests of inflation. For a more detailed review of the topics discussed here, see Refs. [13,14].

2.1. *Observation and Inflation*

Prior to the advent of these new CMB maps, the standard hot-big-bang theory rested on the cornerstones of the expansion of the Universe, the agreement between the observed light-element abundances and the predictions of big-bang nucleosynthesis (BBN), and the blackbody spectrum of the CMB. However, this standard model still left many questions unanswered.

The isotropy. The isotropy of the CMB posed the first conundrum for the standard big-bang theory. The CMB photons that we see last scattered from a spherical surface with a radius of about 10,000 Mpc (about 14 billion light-years), when the Universe was only about 380,000 years old, as shown in Fig. 1. When these photons last scattered, the size of a causally connected region of the Universe was roughly 380,000 light-years, and such a region subtends an angle of roughly one degree on the sky. Since there are 40,000 square degrees on the surface of the sky, *COBE* was thus looking at roughly 40,000 causally disconnected regions of the Universe. (Strictly speaking, *COBE*'s angular resolution was only 7 degrees, but the WMAP satellite [15], with a fraction-of-a-degree resolution saw temperature fluctuations of no more than $\sim 10^{-5}$.) If so, however, then why did each of these have the same temperature to one part in 10^5?

The most appealing explanation for the isotropy is inflation [3], a period of accelerated expansion in the very early Universe driven by the vacuum energy associated with some ultra-high-energy phase transition. Inflation simply postulates some new scalar field ϕ with a potential-energy density $V(\phi)$, which may look, for example, like either of the two forms shown in Fig. 2. Suppose that at some point in the early history of the Universe, the energy density is dominated by the potential-energy density of this scalar field. Then the Friedmann equation—the general-relativistic equation that relates the time t evolution of the scale factor $a(t)$ (which quantifies, roughly speaking, the mean spacing between galaxies) to the energy density ρ—becomes $H^2 \equiv (\dot{a}/a)^2 \simeq 8\pi G V/3$, where G is Newton's constant (and the dot denotes derivative with respect to time). If the scalar field is rolling

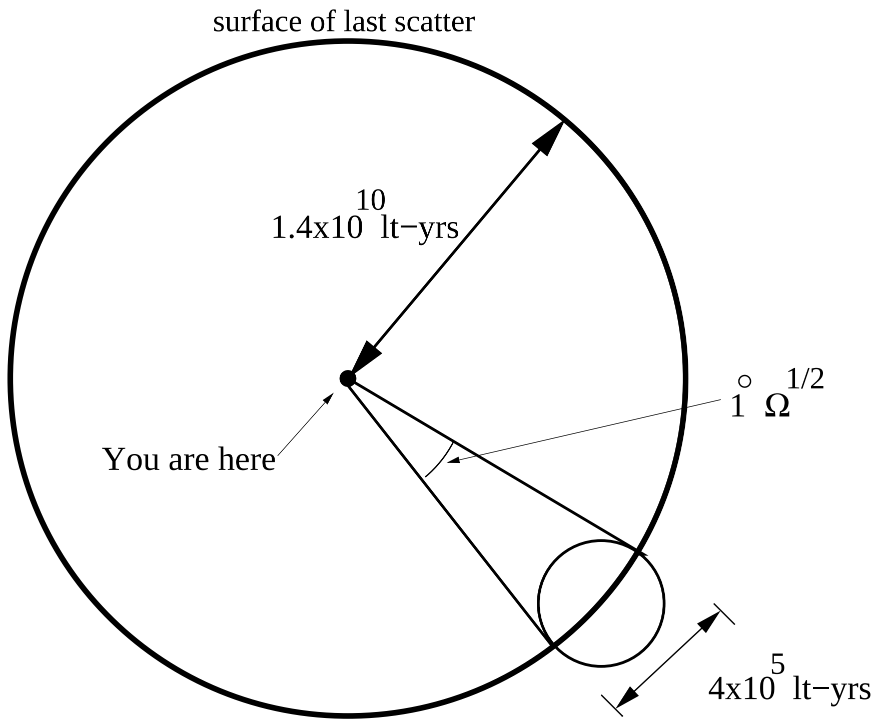

Figure 1: The CMB that we see last scattered on a spherical surface roughly 14 billion light years away. However, when these photons last scattered, the size of a causally connected region was closer to 380, 000 light years, which subtends an angle of roughly 1°.

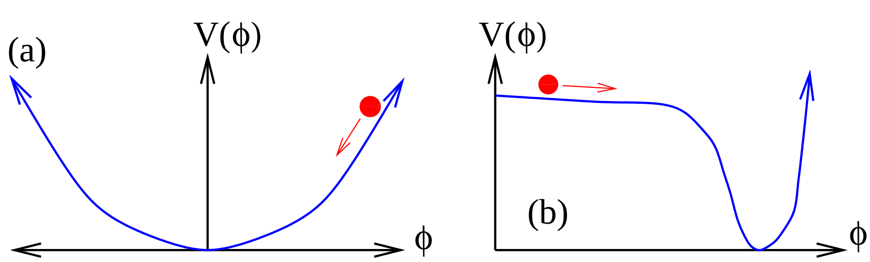

Figure 2: Two toy models for the inflationary potential.

slowly (down a potential, like one of those shown in Fig. 2), then V is approximately constant with time, and the scale factor grows exponentially, thus blowing up a tiny causally-connected region of the Universe into a volume large enough to encompass the entire observable Universe.

The geometry of the Universe. Hubble's discovery of the expansion of the Universe forced theorists to take the general-relativistic cosmological models of Einstein, de Sitter, Lemaitre, Friedmann, Robertson, and Walker seriously. These models showed that the Universe must be open, closed, or flat. A flat Universe is one in which the three spatial dimensions satisfy the laws of Euclidean geometry; in a closed Universe, the laws of geometry for the three spatial dimensions resemble those for a three-dimensional analogue of the surface of a sphere; and an open Universe is a three-dimensional analogue of the surface of a saddle. In a (flat,closed,open) Universe, the interior angles of a triangle sum to ($180°$,$> 180°$,$< 180°$), the circumference of a circle is (2π,$< 2\pi$,$> 2\pi$) times its radius, and (most importantly) the angular size of an object of physical size l observed at a distance d is ($\theta = l/d$,$\theta > l/d$,$\theta < l/d$). General relativity dictates that the geometry is related to $\Omega_{\rm tot} \equiv \rho_{\rm tot}/\rho_c$, the *total* density $\rho_{\rm tot}$ of the Universe in units of the critical density $\rho_c \equiv 3H_0^2/8\pi G$, where H_0 is the expansion rate today. A value of $\Omega_{\rm tot} > 1$, $\Omega_{\rm tot} = 1$, and $\Omega_{\rm tot} < 1$ corresponds respectively to a closed, flat, and open universe. For 70 years after Hubble's discovery, measurements of $\Omega_{\rm tot}$ were unable to achieve the precision required to determine the geometry.

However, the high-sensitivity high-angular-resolution maps of the CMB temperature that have now been obtained have allowed a direct test of the geometry [16]. These experiments have measured the temperature $T(\hat{\mathbf{n}})$ as a function of position $\hat{\mathbf{n}}$ on the sky. The coefficients in a spherical-harmonic expansion of $T(\hat{\mathbf{n}})$ are

$$a^{\rm T}_{(\ell m)} = \int d^2\hat{\mathbf{n}}\, T(\hat{\mathbf{n}})\, Y_{(\ell m)}(\hat{\mathbf{n}}), \tag{1}$$

and from them we can construct a power spectrum, $C_\ell = \left\langle |a_{lm}|^2 \right\rangle$, where the average is over all $2\ell + 1$ values of m.

Given a structure-formation theory (e.g., inflation) as well as the values of the cosmological parameters, it is straightforward to predict the CMB power spectrum. Such calculations take into account the evolution of density perturbations as governed by Einstein's equations as well as the motion and distributions of baryons, dark matter, neutrinos, and photons in these perturbations as governed by their fluid and Boltzmann equations. The solid curves in Fig. 3 show results of such calculations for inflationary density perturbations with a set of cosmological parameters consistent with current data: a flat ($\Omega_m + \Omega_\Lambda = 1$) model with $\{\Omega_m h^2, \Omega_b h^2, h, n_s, \tau\} = \{0.1277, 0.02229, 0.732, 0.958, 0.089\}$ [17]. Each panel shows the effect of independent variation of one of the cosmological parameters. The acoustic-peak structure, first predicted by Sunyaev and Zeldovich [18] and Peebles and Yu [19], is due to the propagation of density perturbations as acoustic waves in the primordial plasma. As illustrated, the height, width, and spacing of the

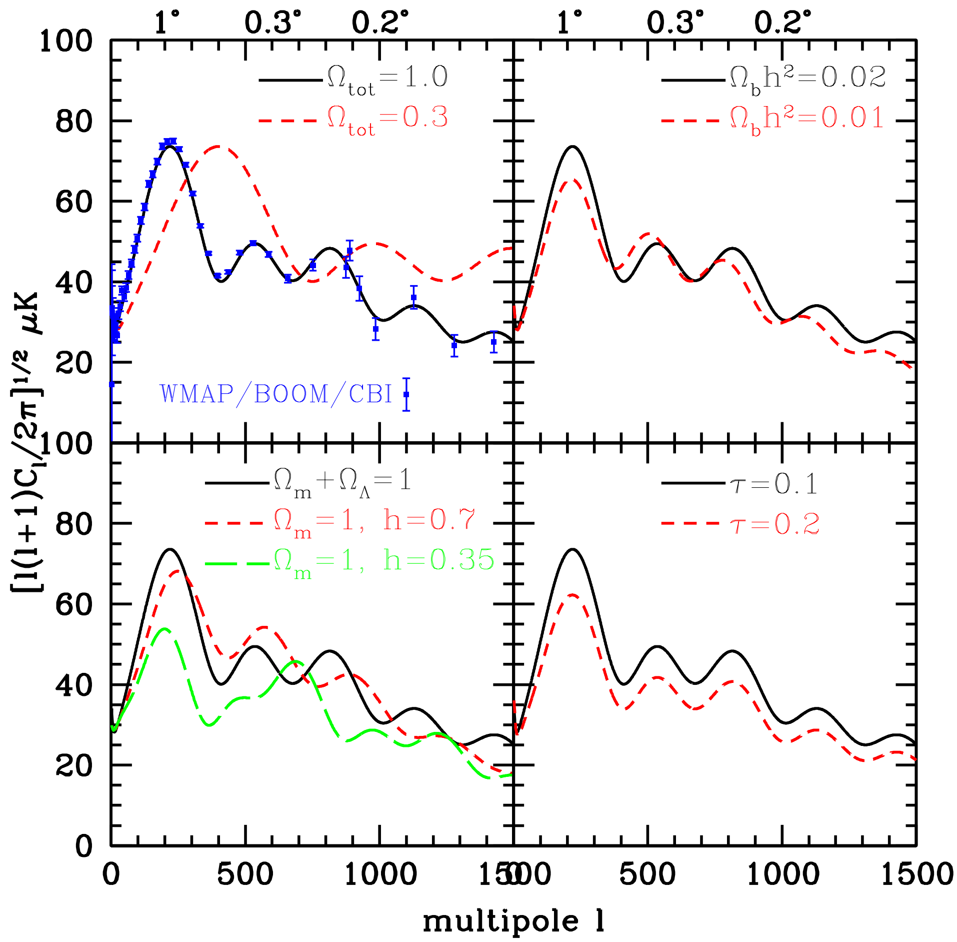

Figure 3: CMB power spectra. The solid curve in each panel show the current best-fit model, with $\{\Omega_m h^2, \Omega_b h^2, h, n_s, \tau\} = \{0.1277, 0.02229, 0.732, 0.958, 0.089\}$ [17]. To indicate the precision of current experiments, data points from WMAP (small ℓ), BOOMERanG (intermediate ℓ), and CBI (large ℓ) are shown. Each panel shows the effect of independent variation of a single cosmological parameter. The Planck satellite, to be launched in 2008, should have error bars from $\ell = 2$ to $\ell = 1500$ (and higher) that are no thicker than the thickness of the curve.

acoustic peaks in the angular spectrum depend on these (and other) cosmological parameters.

In particular, the location of the first peak is determined by the angle subtended by the acoustic horizon at the surface of last scatter. This is $\theta \simeq 1^\circ$ in a flat Universe, and it scales roughly as $\Omega_{\rm tot}^{1/2}$ in a non-flat Universe for the geometric reasons discussed above. Thus, the first peak should be located at $\ell \sim 220\Omega_{\rm tot}^{-1/2}$ [16,20]. As of 2000, balloon data already suggested $\Omega_{\rm tot} = 1.11 \pm 0.07^{+0.13}_{-0.12}$ (statistical and systematic errors), and WMAP now constrains $\Omega_{\rm tot} = 1.02 \pm 0.02$ [17].

Thus, a new question arises: i.e., why is the Universe flat? An answer to this also comes from inflation. If inflation is to last sufficiently long to explain the isotropy problem, then it must produce a flat Universe. This can be seen from the form of the Friedmann equation,

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G V}{3} - \frac{k}{a^2}, \tag{2}$$

during inflation. After inflation sets in, $a \propto e^{Ht}$, $V \sim$constant, and so the curvature term $k/a^2 \propto a^{-2Ht}$ decays exponentially.

The origin of large-scale structure. Another fundamental aim of modern cosmology is to understand the origin of galaxies, clusters of galaxies, and structures on even larger scales. The simplest and most plausible explanation—that these mass inhomogeneities grew from tiny density perturbations in the early Universe via gravitational instability—was confirmed by the tiny temperature fluctuations seen in *COBE* [1]. These temperature fluctuations are due to density perturbations at the surface of last scatter; photons from denser regions climb out of deeper potential wells and thus appear redder than those from underdense regions [21]. The observed temperature-fluctuation amplitude is in good agreement with the density-perturbation amplitude required to seed large-scale structure.

But this gives rise to yet another question: where did these primordial perturbations come from? Before *COBE*, there was no shortage of ideas: perturbations may have come from (just to list some names) inflation, late-time phase transitions, a loitering Universe, scalar-field ordering, topological defects (such as cosmic strings, domain walls, textures, or global monopoles), superconducting cosmic strings, a Peccei-Quinn symmetry-breaking transition, etc. However, after *COBE*, density perturbations like those produced by inflation [22] became the frontrunners; in particular, models with anything other than primordial adiabatic perturbations generically predict more large-angle temperature fluctuations than models with adiabatic perturbations [23]. Now, with the CMB maps obtained the last seven years, any alternatives to inflationary perturbations have become increasingly difficult to reconcile with the data, and the detailed acoustic-peak structure in the CMB power spectra are in beautiful agreement with inflationary models. The CMB shows that primordial perturbations were nearly scale invariant, and extend to distance scales that were larger than the horizon at the surface of last scatter. These superhorizon perturbations are another feather in inflation's cap.

2.2. *What is the New Physics Responsible for Inflaton?*

The agreement between inflation's predictions and the data obtained so far suggest that we may be on the right track with inflation, and this motivates us to consider new, more precise, tests and to think more deeply about the physics of inflation. Although the idea behind inflation is simple, we do not know what new physics is responsible for inflation. Another way to ask this question is when, in the early history of the Universe, did inflation occur? Since the temperature of the Universe increases monotonically as we go to earlier cosmological times, we may also ask at what temperature did inflation occur? To first get our bearings, we note that the Universe is today about 14 billion years old, and the temperature is 2.7 K, corresponding to a typical thermal energy of 10^{-3} eV, small compared even with molecular-transition energies. Stars and galaxies formed several billion years after the big bang. Electrons and protons first combined to form hydrogen atoms roughly 380,000 years after the big bang, at a temperature of roughly 3000 K, when the mean thermal energies of the CMB were comparable to the ionization energy for the hydrogen atom. CMB photons also decoupled from the primordial plasma at about this time (as the free electrons from which they scattered disappeared). Neutrons and protons were first assembled into light nuclei (D, ^{3}He, ^{4}He, ^{7}Li) a few seconds to minutes after the big bang, when the CMB thermal energies fell below an MeV, the binding energy per nucleon. Quarks presumably collected into hadrons at a temperature of roughly 100 MeV, although the details are still unclear.

To extrapolate further back in time, we need to understand the physics of elementary particles at higher energies. We now have a secure model that unifies the electromagnetic and weak interactions at energies ~ 100 GeV. This electroweak symmetry would have first been broken at a cosmological electroweak phase transition roughly 10^{-9} seconds after the big bang. Similarities between the mathematical structure of the strong and electroweak interactions have led particle theorists to postulate a grand unified theory (GUT) that would be first broken at an energy $\sim 10^{16}$ GeV, roughly 10^{-38} seconds after the big bang. String theories go even further and provide a mechanism for incorporating the strong, weak, and electromagnetic interactions into a quantum theory of gravity at the Planck scale, 10^{19} GeV. There are also other interesting ideas in particle theory, such as Peccei-Quinn symmetry (a new symmetry postulated in order to solve the strong-CP problem; see Section 1.3.9), which would be broken at $\sim 10^{12}$ GeV and supersymmetry (postulated in order to explain the hierarchy between the GUT scale and the electroweak scale), which must have also been broken at some point.

Inflation was originally conceived in association with grand unification, and many (although not all) theorists would still consider GUTs to provide the most natural home for inflation. However, the ingredients necessary for inflation may also be found in string theories, Peccei-Quinn symmetry breaking, supersymmetry breaking, or even at the electroweak scale. In recent years, a vast array of inflationary models with extra dimensions have been explored (see, e.g., Ref. [24]). Ref. [25] reviews particle-physics models of inflation.

2.3. *Inflation and CMB Polarization*

One way to determine the new physics responsible for inflation is to ask, what is the height V of the inflaton potential? or equivalently, what is the energy scale $E_{\rm infl}$, defined by $V = E_{\rm infl}^4$, of inflation? If inflation had something to do with grand unification, then we might expect $E_{\rm infl} \sim 10^{15-16}$ GeV; if it had to do with some lower-energy physics, then $E_{\rm infl}$ should be correspondingly lower (e.g., Peccei-Quinn symmetry breaking would suggest $E_{\rm infl} \sim 10^{12}$ GeV).

The energy scale of inflation can be determined with the gravitational-wave background. Through quantum-mechanical effects analogous to the production of Hawking radiation from black holes, inflation produces a stochastic cosmological background of gravitational waves [29]. It is well known that the temperature of the Hawking radiation emitted from a (non-charged and non-spinning) black hole is determined exclusively by the black-hole mass, as this determines the spacetime curvature around the black hole. Likewise, during inflation, the spacetime curvature is determined exclusively by the cosmological energy density, which is just the inflaton-potential height $V = E_{\rm infl}^4$ during inflation. Calculation shows that the amplitude of the gravitational-wave background is proportional to $(E_{\rm infl}/m_{\rm Pl})^2$, where $m_{\rm Pl} \simeq 10^{19}$ GeV is the Planck mass. Therefore, if we can detect this gravitational-wave background and determine its amplitude, we learn the energy scale of inflation and thus infer the new physics responsible for inflation. Fig. 4 shows the amplitude of the gravitational-wave background, as a function of frequency, from simple inflation models that produce a scale-invariant spectrum, one with a spectral index $n_t = 0$ (where n_t measures the relative amplitude of short- versus long-wavelength gravitational waves, and the subscript "t" stands for tensor perturbations, another term for gravitational waves) for several different $E_{\rm infl}$. More generally, inflation models usually predict $n_t < 0$, implying less power on smaller scales (or larger frequencies). The Figure also shows current constraints and future prospects for detection, as we now discuss.

Perhaps the most promising avenue toward detecting the inflationary-gravitational-wave (IGW) background is with the CMB, at ultra-low gravitational-wave frequencies, gravitational waves with wavelengths comparable to the observable Universe. Just as an electromagnetic wave is detected through observation of the motion its oscillating electromagnetic fields induce in test charges, a gravitational wave is detected through the motion that its oscillating gravitational field induces in test masses. More precisely, a gravitational plane wave will induce a quadrupolar oscillation in a ring of test masses located in a plane perpendicular to the wave's direction of propagation. Now suppose a long-wavelength gravitational wave is propagating through the Universe. Then the primordial plasma from which the CMB photons we observe last scatter can be used as a sphere of test masses. The gravitational wave will induce motions in this primordial plasma, as shown in Fig. 5. If photons last scatter from plasma that is moving away from or toward us, then the photons will appear red- or blue-shifted. Thus, that single gravitational wave will induce a temperature pattern on the CMB sky that looks like that shown in Fig. 6. Hence,

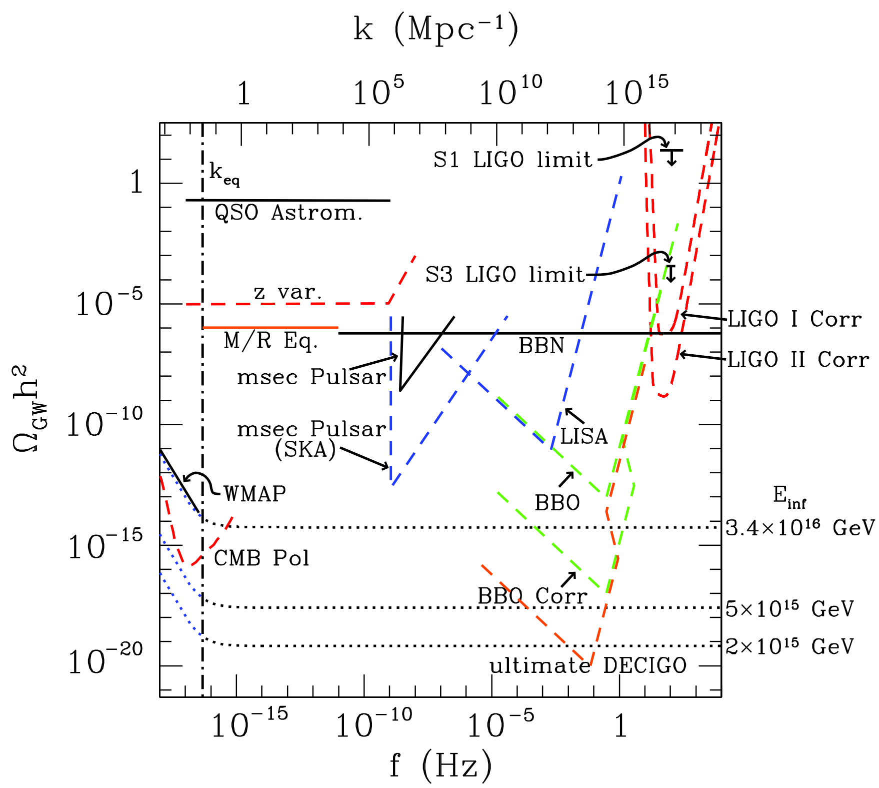

Figure 4: Current limits and projected sensitivities to a stochastic gravitational-wave background versus the gravitational-wave frequency. The solid curves all indicate current upper limits, while the various broken curves indicate projected sensitivities. The "M/R" line comes CMB constraints to the epoch of matter-radiation equality [26]. Curves corresponding to scale-invariant (i.e., $n_t = 0$) gravitational-wave backgrounds are shown (dotted curves), labeled by the associated inflationary energy scales. The amplitude of CMB temperature fluctuations currently constrains this value to be below 3.36×10^{16} GeV, but only at frequencies $f < 10^{-16}$ Hz. Future CMB measurements may be able to reach energy scales near 10^{15} GeV at these frequencies. The "QSO Astrom" curve is a limit from quasar astrometry, and the "z var" is a forecast for future redshift measurements. The S1 and S3 points are upper limits from the Laser Interferometric Gravitational Wave Observatory (LIGO) [27] and the other curves are forecasts for future LIGO sensitivities. The LISA curve shows forecasts for the future NASA/ESO Laser Interferometric Space Observatory and the BBO and DECIGO curves show forecasts for sensitivities for two space-based observatories now under study (the "Corr" designation is for a configuration in which the signals from two detectors or detector arrays are correlated against one another—e.g., for LIGO, if the signals from the Hanford and Louisiana sites are correlated). The two "pulsar" curves show current and future (from the Square Kilometer Array; SKA) sensitivities from pulsar timing. The WMAP and "CMB Pol" curves show the current upper limit from WMAP and the sensitivity forecast for CMBPol, a satellite mission now under study. From Ref. [28].

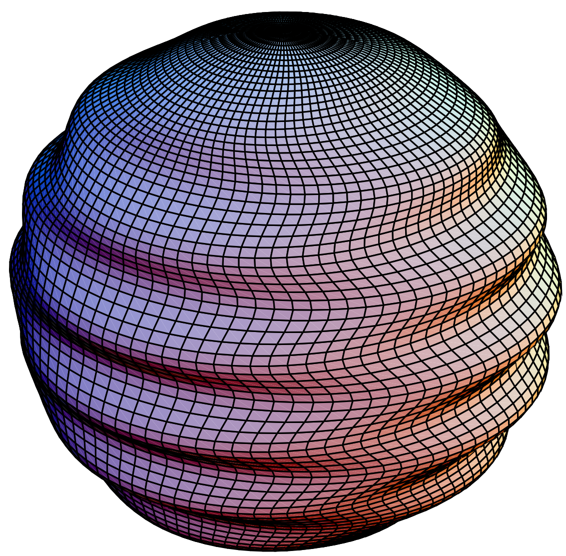

Figure 5: The shape of the surface of last scatter if a single gravitational wave propagates in the vertical direction through the Universe.

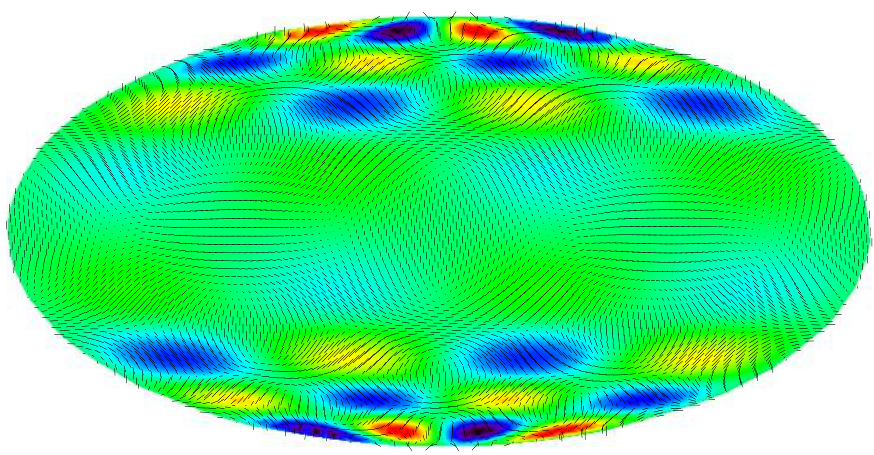

Figure 6: The CMB temperature and polarization pattern induced by a single gravitational wave. This is an equal-area representation of the full spherical surface of the sky. If this were a map of the Earth, North America, South America, Australia, and Eurasia would occupy, respectively, the upper-left, lower-left, lower-right, and upper-right quadrants. The orientation of the lines reflects that of the polarization, and the size is proportional to the polarization amplitude. The gray scale represents temperature fluctuations that span one part in 10^5. The quadrupolar variation of the temperature/polarization pattern can be seen as one travels along a curve of constant latitude, and the wavelike pattern can be seen as one moves along a constant longitude. From Ref. [30].

the WMAP limit to $\Omega_{\rm gw}h^2$ shown on the left-hand side of Fig. 4.

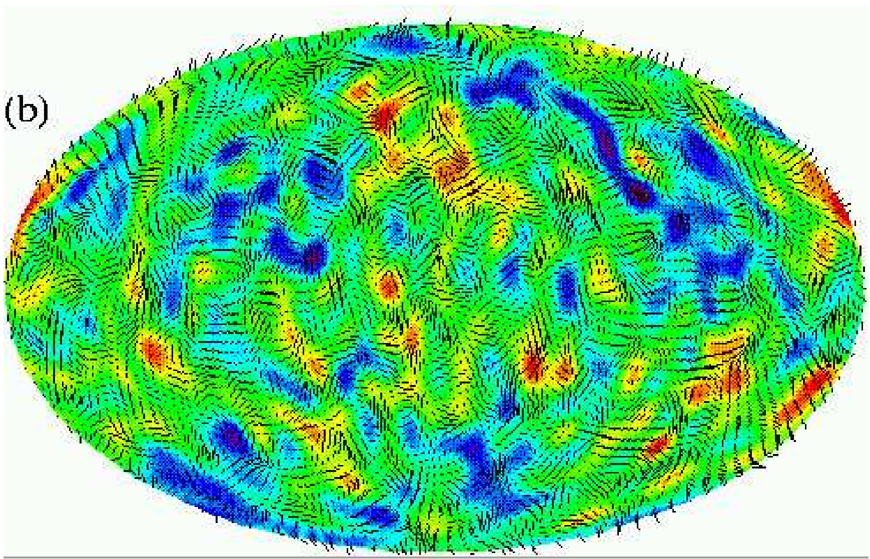

Figure 7: Simulated CMB temperature/polarization pattern induced by inflationary gravitational waves. From Ref. [30].

Inflation predicts a *stochastic* background of such gravitational waves, rather than a single gravitational wave, so the sky should look more like Fig. 7. However, a plausible spectrum of density perturbations could produce a temperature map that looks almost identical. More precisely, gravitational waves would produce temperature fluctuations only on large angular scales, so their presence would increase the power at $\ell \lesssim 50$ relative to the power in the peaks at $\ell \gtrsim 100$. However, re-scattering of some CMB photons from electrons that would have been reionized during the production of the first stars and quasars would reduce the power in the peaks relative to that at large angles, thus mimicking the effect of gravitational waves [31,32,33].

So how can we go further? Progress can be made with the polarization of the CMB. A small polarization will be produced in CMB photons because the flux of photons incident on the electrons from which they last scatter will be anisotropic (this is just polarization from right-angle scattering). Such a polarization will be induced for both density perturbations and gravitational waves, so the mere detection of the polarization does not alone indicate the presence of gravitational waves. However, the *pattern* of polarization induced on the CMB sky can be used to distinguish gravitational waves from density perturbations.

This can be quantified with a harmonic decomposition of the polarization field. The linear polarization of the CMB in a direction $\hat{\mathbf{n}}$ is specified by the Stokes

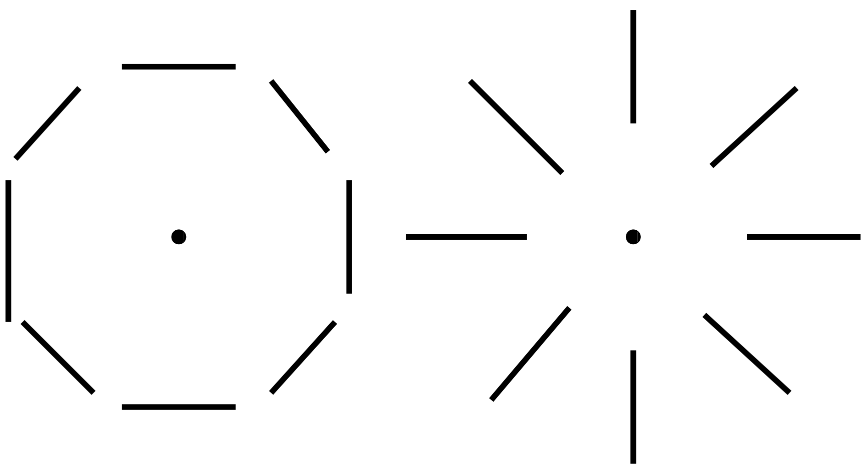

Figure 8: Polarization pattern with no curl.

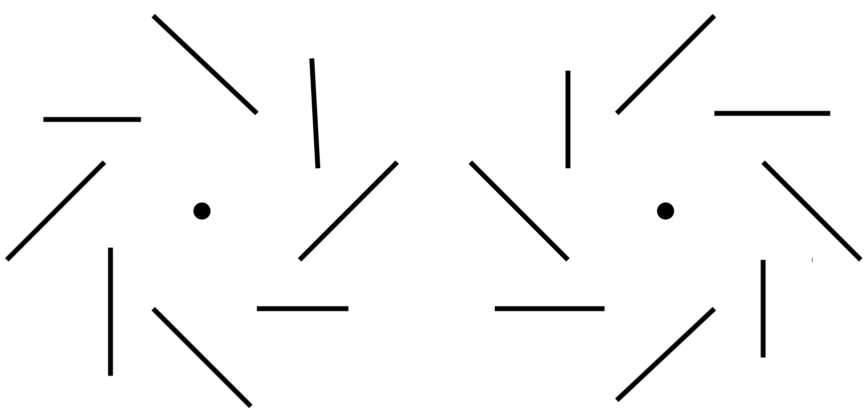

Figure 9: Polarization pattern with a curl.

parameters $Q(\hat{\mathbf{n}})$ and $U(\hat{\mathbf{n}})$, which are components of a polarization tensor,

$$\mathcal{P}_{ab}(\hat{\mathbf{n}}) = \frac{1}{2}\left(\begin{array}{cc} Q(\hat{\mathbf{n}}) & -U(\hat{\mathbf{n}})\sin\theta \\ -U(\hat{\mathbf{n}})\sin\theta & -Q(\hat{\mathbf{n}})\sin^2\theta \end{array} \right), \tag{3}$$

which can be thought of as a headless vector. This polarization tensor field can be decomposed into a curl and curl-free part in the same way as a vector field can be written in terms of the gradient of a scalar field plus the curl of some other vector field; Figs. 8 and 9 show examples of gradient and curl polarization patterns, respectively. Just as the temperature map can be expanded in terms of spherical harmonics, the polarization tensor can be expanded [9,10,11,12] (for a review, see, e.g., Refs. [34,35])

$$\frac{\mathcal{P}_{ab}(\hat{\mathbf{n}})}{T_0} = \sum_{lm} \left[a^{\rm G}_{(lm)} Y^{\rm G}_{(lm)ab}(\hat{\mathbf{n}}) + a^{\rm C}_{(lm)} Y^{\rm C}_{(lm)ab}(\hat{\mathbf{n}}) \right], \tag{4}$$

in terms of tensor spherical harmonics, $Y^{\rm G}_{(lm)ab}$ and $Y^{\rm C}_{(lm)ab}$, which form a complete orthonormal basis for the gradient (G) and curl (C) components of the polarization field (also referred to as "E" and "B" modes).

The two-point statistics of the combined temperature/polarization (T/P) map are specified completely by the six power spectra $C_\ell^{\rm XX'} = \left\langle a^{\rm X}_{lm} a^{\rm X'}_{lm} \right\rangle$, for $\rm X, X' = \{T, G, C\}$ (for temperature, gradient, and curl, respectively). Parity invariance demands that $C_\ell^{\rm TC} = C_\ell^{\rm GC} = 0$. Therefore, the statistics of the CMB temperature-polarization map are completely specified by the four sets of moments: $C_\ell^{\rm TT}$, $C_\ell^{\rm TG}$, $C_\ell^{\rm GG}$, and $C_\ell^{\rm CC}$.

Both density perturbations and gravitational waves will produce a gradient component in the polarization. However, only gravitational waves will produce a curl component [9,11]. Heuristically, since density perturbations produce scalar perturbations to the spacetime metric, they can have no handedness and can thus produce no curl. On the other hand, gravitational waves are propagating disturbances in the gravitational field analogous to electromagnetic waves. A gravitational wave can have right or left circular polarization, just like an electromagnetic wave. Gravitational waves can thus carry a handedness, so it is reasonable that they can produce a polarization pattern with a handedness, and in fact, they do. The curl component of the CMB polarization thus provides a unique signature of the gravitational-wave background.

Will we ever be able to detect the signature of gravitational radiation imprinted on the CMB? This depends ultimately on the height V of the inflaton potential. Roughly speaking, the raw instrumental sensitivity necessary to detect the curl component of the polarization from gravitational waves is [36,37],

$$s \lesssim (V^{1/4}/10^{15}\,{\rm GeV})^{-2}\, t_{\rm yr}^{1/2}\,\mu{\rm K}\,\sqrt{\rm sec}, \tag{5}$$

where s is the noise-equivalent temperature (NET), which provides a measure of the instantaneous sensitivity of the experiment, and $t_{\rm yr}$ is the duration of the experiment in years. A significant probe of the GUT parameter space, $V^{1/4} \sim 10^{15-16}$ GeV, will thus require an effective NET approaching 1 μK $\sqrt{\text{sec}}$.

2.4. *Slow-roll parameters and gravitational waves*

Once the inflationary potential $V(\phi)$ is specified, the *slow-roll parameters* are defined as

$$\epsilon = \frac{m_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2, \tag{6}$$

$$\eta = \frac{m_{\rm Pl}^2}{8\pi}\frac{V''}{V}, \tag{7}$$

where the prime denotes derivative with respect to ϕ. Slow-roll inflation generally requires $\epsilon, \eta \ll 1$. In slow-roll inflation, the scalar spectral index (the spectral index for primordial density perturbations) is $n_s = 1 - 6\epsilon + 2\eta$, and the density-perturbation amplitude determines $(V/\epsilon)^{1/4} = 6.6 \times 10^{16}$ GeV. Thus, V, and therefore the gravitational-wave amplitude, increases with ϵ. The commonly used tensor-to-scalar ratio $r = T/S$ (the ratio of the tensor to scalar contributions to the CMB quadrupole, where tensor here is another term for gravitational waves) is $r \sim 14\epsilon$.

There have been new developments in the measurement of inflationary observables with intriguing implications for the gravitational-wave background. When combined with other CMB experiments and large-scale structure, the BOOMERanG 2003 data suggested $n_s = 0.95 \pm 0.02$ [38]. Now, the WMAP three-year data, when marginalized over a six-dimensional parameter space, suggest $n_s = 0.95 \pm 0.015$, a 3σ departure from unity [17]. For a generic potential, one expects $\epsilon \sim \eta$. If so, and if $n_s = 0.95$, then $\epsilon \sim 0.01$, and if so, then $V^{1/4} \sim 2 \times 10^{16}$ GeV and $r \sim 0.1$—i.e., the amplitude of the gravitational-wave background is comparable to the "optimistic" estimates that are usually shown in experimental-CMB proposals! In other words, the gravitational-wave background should be within reach of next-generation experiments. Of course, $\epsilon \sim \eta$ is not guaranteed, and it is in fact possible to construct an inflaton potential that has $\eta \sim 0.01$ and $\epsilon \ll 0.01$. If so, then the gravitational-wave background will be small, even if $n_s = 0.95$. Still, it is perhaps not quite as easy to construct a model with $\epsilon \ll \eta$ as one might think. This would require $(V')^2 \ll V''$, a constraint that can be satisfied only over a narrow range of ϕ. As a specific example, consider the Higgs potential $V(\phi) = (\phi^2 - \mu^2)^2$. For values of ϕ very close to $\phi = 0$, it is indeed true that $\epsilon \ll \eta$. However, CMB scales exit the horizon roughly 60 e-folds before the end of inflation. This constraint demands, for this potential, that ϕ not be too close to the origin, and quantitatively, that $\epsilon \sim \eta$ leading to a fairly large gravitational-wave background [as illustrated in Fig. 11(c) below]. The bottom line is that although $n_s < 1$ does not "guarantee" a gravitational-wave background of detectable amplitude, detection of the gravitational-wave background is more promising than if n_s had turned out to be consistent with unity with small error bars.

2.5. *Cosmic shear and the CMB*

Although density perturbations produce, in linear theory, no curl, they can induce a curl component through cosmic shear (CS), gravitational lensing by density perturbations along the line of sight [39]. This additional source of curl must be understood if the CMB polarization is to be used to detect an inflationary gravitational-wave (IGW) background. The CS-induced curl thus introduces a noise from which IGWs must be distinguished. If the IGW amplitude (or $E_{\rm infl}$) is sufficiently large, the CS-induced curl will be no problem. However, as $E_{\rm infl}$ is reduced, the IGW signal becomes smaller and will at some point get lost in the CS-induced noise. If it is not corrected for, this confusion leads to a minimum detectable IGW amplitude [40,41,42].

In addition to producing a curl component, CS also introduces distinct higher-order correlations in the CMB temperature pattern [43]. Roughly speaking, lensing can stretch the image of the CMB on a small patch of sky and thus lead to something akin to anisotropic correlations on that patch of sky, even though the CMB pattern at the surface of last scatter had isotropic correlations. By mapping these effects, the CS can be mapped as a function of position on the sky [43]. The observed CMB polarization can then be corrected for these lensing deflections to reconstruct the intrinsic CMB polarization at the surface of last scatter (in which the only curl component would be that due to IGWs).

Refs. [41,42] show that if the gravitational-wave background is large enough to be accessible with the Planck satellite, then the cosmic-shear contribution to the curl component will not get in the way. However, to go beyond Planck, the cosmic-shear distortion to the CMB curl will need to be subtracted by mapping the cosmic-shear deflection with higher-order temperature-polarization correlations. According to the analyses of Refs. [41,42], which used quadratic estimators for the cosmic shear, there will be an irreducible cosmic-shear-induced curl, even with higher-order correlations, if the energy scale is $E_{\rm infl} \lesssim 2\times10^{15}$ GeV. However, maximum-likelihood techniques [44] have been developed for cosmic-shear reconstruction that allow a reduction in the CS-induced curl by close to two orders of magnitude below that achievable with quadratic estimators. Either way, the cosmic-shear distortions to the CMB will be of interest in their own right, as they probe the distribution of dark matter throughout the Universe as well as the growth of density perturbations at early times. These goals will be important for determining the matter power spectrum and thus for testing inflation and constraining the inflaton potential.

2.6. *CMB and Primordial Gaussianity*

Another prediction of inflation is that the distribution of mass in the primordial Universe should be a realization of a Gaussian random process. This means that the distribution of temperature perturbations in the CMB should be Gaussian and it moreover implies a precise relation between all of the higher-order temperature correlation functions and the two-point correlation function. These relations can be tested with future precise CMB temperature and polarization maps [45]. See Refs. [46,47] for reviews.

2.7. *Other implications of CMB results*

Although our focus has been elsewhere, the richness of the acoustic-peak structure—the locations and heights of the peaks as well as the troughs—allows the measurements to be used to simultaneously constrain a number of classical and inflationary cosmological parameters [31,48], in addition to the total density (determined by the location of the first peak). CMB maps have now provided an independent and precise new constraint to the baryon density (verifying the predictions of big-bang nucleosynthesis [49]), robust evidence for the existence of nonbaryonic dark matter, and an independent avenue—that confirms supernova evidence [50]—for inferring the existence of a cosmological constant. The CMB results (sometimes combined with large-scale-structure data) have resulted in a huge number of other new results and constraints. One example is the redshift $z \sim 10$ for the formation of the first stars [8]. As three other examples, I mention precise constraints to neutrino masses and degrees of freedom (see, e.g., Refs. [51,52]), a new constraint to the amplitude of a primordial gravitational-wave background that applies to a broad, hitherto unexplored, range of gravitational-wave frequencies [26], and new constraints to the mass-lifetime-abundance parameter space for decaying dark-matter particles [53]. In the next few years, the Planck satellite [54] will refine all of these measurements and constraints to even greater levels of precision.

2.8. *Direct detection of the gravitational-wave background?*

If the energy scale of inflation is high and the IGW spectrum close to scale-invariant, then there is some prospect for detecting primordial gravitational waves directly in gravitational-wave observatories (rather than indirectly through their effect on the CMB), a possibility that has been considered in Refs. [57]. Fig. 4 shows forecasts for sensitivities for the Big-Bang Observer (BBO) [58] and DECIGO (Decihertz Interferometer Gravitational Wave Observatory) [59], two future (i.e., after LISA—Laser Interferometric Space Antenna—a space-based gravitational-wave detector being considered now by NASA and ESA) space-based gravitational-wave detectors that are now under study. These are families of LISA-like detectors deployed in the solar system, with "BBO Corr" designating a more ambitious configuration in which signals from various detector arrays are correlated against one another. DECIGO is an even more ambitious concept. Ref. [28] considered several classes of inflationary potentials with parameters chosen to fit CMB constraints, shown in Fig. 10, to the tensor-to-scalar ratio r (or equivalently, IGW amplitude) and scalar spectral index n_s. The shaded regions show consistency of the parameters with assorted measurements, while the regions delineated by the lines indicate those regions of parameter space predicted by various classes of inflationary models. The names "chaotic," "hybrid," "power-law," and "symmetry-breaking" simply refer to

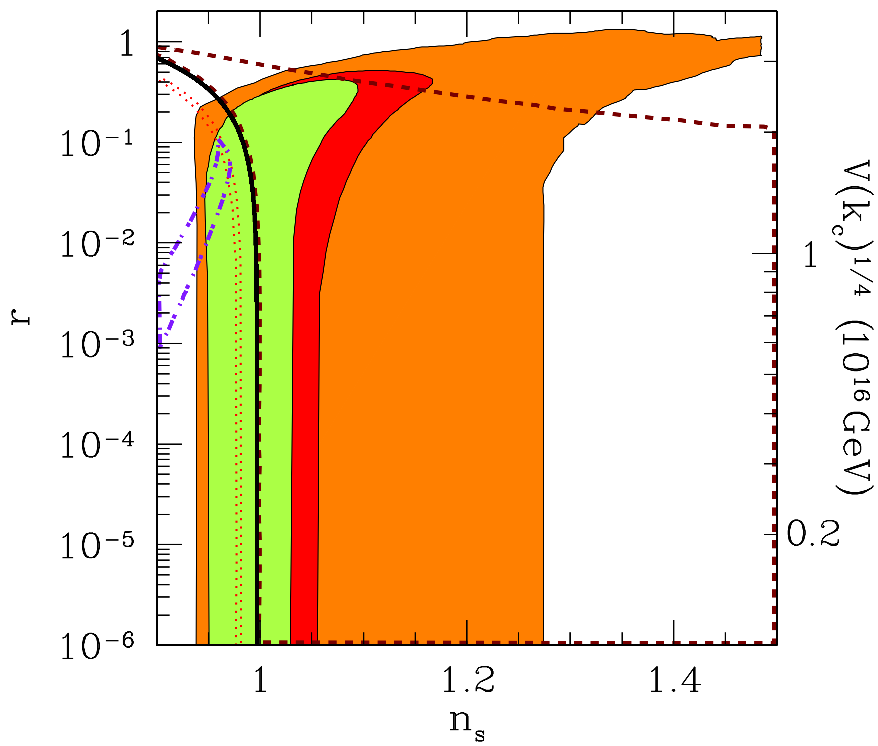

Figure 10: Regions in the n_s–r parameter space consistent with the CMB-only (medium gray) [55], CMB plus galaxy surveys (dark gray), and CMB plus galaxy surveys plus Lyman-alpha-forest constraints (light gray) [56]. Here, r is the tensor-to-scalar ratio, and n_s is the scalar spectral index at CMB scales. Plotted on top of these regions are the parameter spaces occupied by the four models of inflation we consider: power-law (solid line), chaotic (dotted), symmetry-breaking (dashed-dot), and hybrid (short-dashed). The parameter space for power-law inflation occupies the solid black curve; the parameter spaces for the other models occupy the interior of the delimited regions. The right axis shows the energy scale $[V(k_c)]^{1/4}$ of inflation. From Ref. [28]. (Note that this Figure has now been superseded by Fig. 14 in Ref. [17], which restricts further the parameter space, favoring a smaller value of n_s. We include this older parameter-space plot, as it corresponds with the regions shown below in Fig. 11, from the analysis in Ref. [28].)

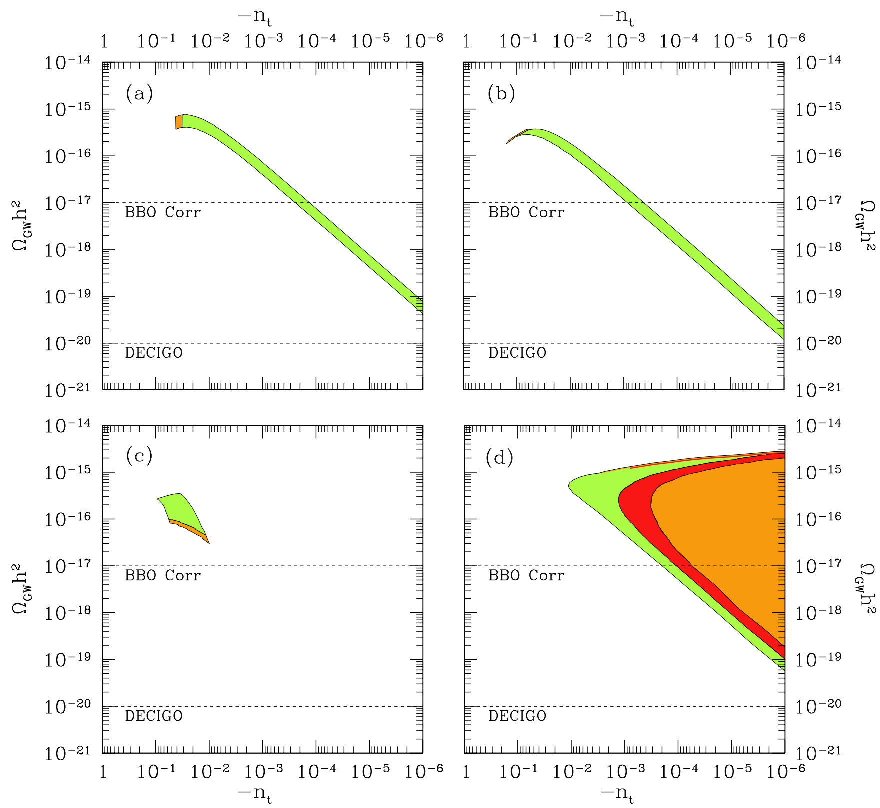

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Figure 11: Regions in the $\Omega_{\rm GW}h^2$–n_t parameter space for (a) power-law, (b) chaotic, (c) symmetry-breaking, and (d) hybrid inflation. The shaded regions map out the corresponding regions in Fig. 10. Here, the gravitational-wave density $\Omega_{\rm GW}h^2$ and spectral index n_t are both evaluated at DECIGO/BBO scales. Also shown are the sensitivity goals of BBO and DECIGO. From Ref. [28].

different functional forms for the inflaton potential; see Ref. [28] for details. The predicted gravitational-wave amplitudes for these four classes of inflationary models are then shown in Fig. 11 We see that inflationary models consistent with current data may indeed be detectable directly, but detectability depends on the inflationary model. It is also difficult to find inflationary gravitational-wave backgrounds that would be detectable directly, but not with CMB polarization. Given the huge difference in distance scales, detection of the gravitational-wave background both in the CMB and directly would provide a powerful lever arm for constraining the inflaton potential.

2.9. *The CMB polarization: additional remarks*

We have concentrated on CMB polarization as a probe of the inflationary gravitational-wave background. However, maps of the CMB polarization will address a plethora of cosmological questions. The small-angle temperature fluctuation is in fact due to peculiar velocities as well as density perturbations at the surface of last scatter, while the small-angle polarization is due only to the peculiar velocity [60]. Thus, only with a polarization map can primordial perturbations be reconstructed unambiguously. The polarization can further constrain the ionization history of the Universe [61], help determine the nature of primordial perturbations [62,63], detect primordial magnetic fields [64,65,66], map the distribution of mass at lower redshifts [39], and perhaps probe cosmological parity violation [68,69,70].

3. Dark Matter

Cosmologists have long noted—even well before the recent CMB results, the discrepancy between the baryon density $\Omega_b \simeq 0.05$ inferred from BBN and the nonrelativistic-matter density inferred from cluster masses, dynamical measurements, and large-scale structure, and the discrepancy between the baryon and total-matter densities in galaxy clusters (see, e.g., Ref. [71] for a review of these pre-CMB arguments). Today, though, we can simply point to the exquisite CMB results that suggest a nonbaryonic density $\Omega_{\rm cdm}h^2 = 0.105^{+0.007}_{-0.013}$ [48,17].

If neutrinos had a mass ~ 5 eV, then their density would be comparable to the dark-matter density. However, neutrino masses are now known, from laboratory experiments as well as large-scale-structure data to be $\lesssim$eV (see, e.g., Ref. [52]); even if neutrinos did have the right mass, it is difficult to see, essentially from the Pauli principle [72] how they could be the dark matter. It appears likely then, that some exotic new candidate is required.

For the past two decades, the two leading candidates from particle theory have been weakly-interacting massive particles (WIMPs), such as the lightest superpartner (LSP) in supersymmetric extensions of the standard model [71,73,74], and axions [75].

3.1. *Weakly-interacting Massive Particles*

Suppose that in addition to the known particles of the standard model, there exists a new stable weakly-interacting massive particle (WIMP), χ. At sufficiently early times after the big bang, when the temperatures are greater than the mass of the particle, $T \gg m_\chi$, the equilibrium number density of such particles is $n_\chi \propto T^3$, but for lower temperatures, $T \ll m_\chi$, the equilibrium abundance is exponentially suppressed, $n_\chi \propto e^{-m_\chi/T}$. If the expansion of the Universe were slow enough that thermal equilibrium were always maintained, the number of WIMPs today would be infinitesimal. However, the Universe is not static, so equilibrium thermodynamics is not the entire story.

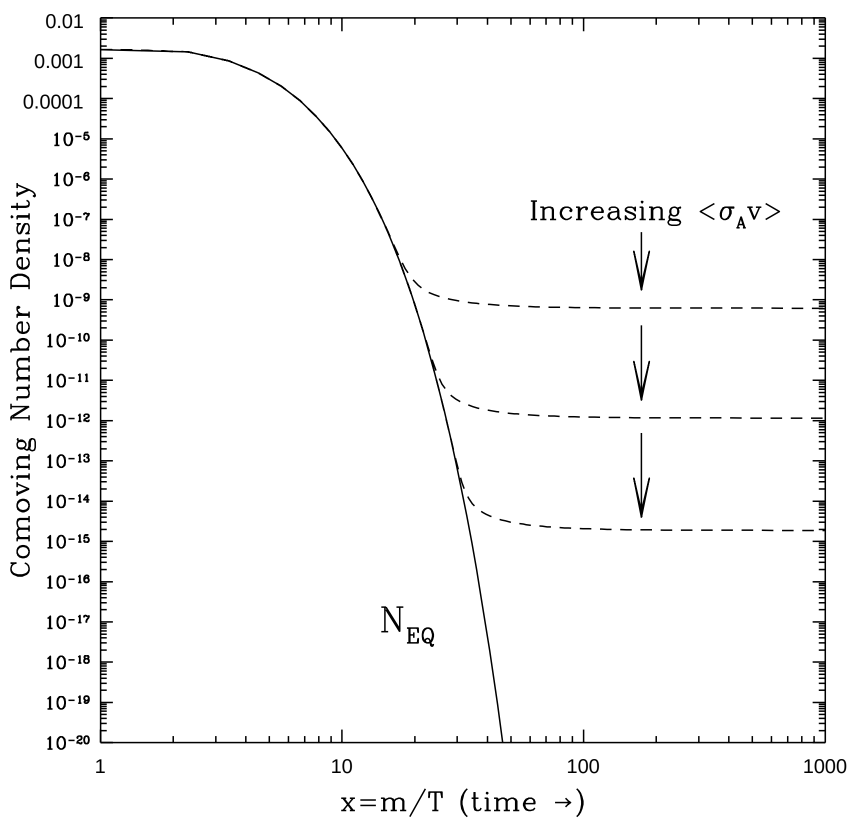

Figure 12: Comoving number density of WIMPs in the early Universe. The dashed curves are the actual abundances for different annihilation cross sections, and the solid curve is the equilibrium abundance. From Ref. [71].

At high temperatures ($T \gg m_\chi$), χ's are abundant and rapidly converting to lighter particles and *vice versa* ($\chi\bar{\chi} \leftrightarrow l\bar{l}$, where $l\bar{l}$ are quark-antiquark and leptonantilepton pairs, and if m_χ is greater than the mass of the gauge and/or Higgs bosons, $l\bar{l}$ could be gauge- and/or Higgs-boson pairs as well). Shortly after T drops below m_χ, the number density of χ's drops exponentially, and the rate $\Gamma = \langle \sigma v \rangle n_\chi$ for annihilation of WIMPs—where $\langle \sigma v \rangle$ is the thermally averaged total cross section σ for annihilation of $\chi\bar{\chi}$ into lighter particles times relative velocity v—drops below the expansion rate, $\Gamma \lesssim H$. At this point, the χ's cease to annihilate efficiently, they fall out of equilibrium, and a relic cosmological abundance remains. The equilibrium (solid line) and actual (dashed line) abundances of WIMPs per comoving volume are plotted in Fig. 12 as a function of $x \equiv m_\chi/T$ (which increases with increasing time). As the annihilation cross section is increased, the WIMPs stay in equilibrium longer, so we are left with a smaller relic abundance when they do finally freeze out. An approximate solution to the Boltzmann equation yields the cosmological WIMP abundance Ω_χ (in units of the critical density ρ_c),

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq 0.1 \left(\frac{3 \times 10^{-26}\, \mathrm{cm}^3\, \mathrm{sec}^{-1}}{\langle \sigma_A v \rangle} \right). \tag{8}$$

The result is to a first approximation independent of the WIMP mass and is fixed primarily by the annihilation cross section.

The WIMP velocities at freeze-out are typically some appreciable fraction of the speed of light. Therefore, from Eq. (8), the WIMP will have a cosmological abundance $\Omega_\chi h^2 \sim 0.1$ today if the annihilation cross section is roughly $3 \times 10^{-26}\, \mathrm{cm}^3\, \mathrm{sec}^{-1}$, or in particle-physics units (obtained using $\hbar c = 2 \times 10^{-14}$ GeV-fm), 10^{-8} GeV^{-2}. Curiously, this is the order of magnitude one would expect from a typical electroweak cross section,

$$\sigma_{\mathrm{weak}} \simeq \frac{\alpha^2}{m_{\mathrm{weak}}^2}, \tag{9}$$

where $\alpha \simeq \mathcal{O}(0.01)$ is the fine-structure constant, and $m_{\mathrm{weak}} \simeq \mathcal{O}(100\, \mathrm{GeV})$. The numerical constant in Eq. (8) needed to provide $\Omega_\chi h^2 \sim 0.1$ comes essentially from the expansion rate (which determines the critical density). But why should the expansion rate have anything to do with the electroweak scale? This remarkable coincidence suggests that if a new, as yet undiscovered, stable massive particle with electroweak interactions exists, then it should have a relic density suitable to account for the dark matter. This has been the argument driving the massive experimental effort to detect WIMPs.

The first WIMPs considered were massive Dirac neutrinos (particles which have antiparticles) or Majorana neutrinos (particles that are their own antiparticles) with masses in the range of a few GeV to a few TeV. (Due to the Yukawa coupling which gives a neutrino its mass, neutrino interactions become strong above a few TeV, and the neutrino no longer remains a suitable WIMP candidate [76].) The Large Electron-Positron (LEP) collider ruled out neutrino masses below half the Z^0 mass. Furthermore, heavier Dirac neutrinos have been ruled out as the primary component of the Galactic halo by direct-detection experiments (described below) [77], and heavier Majorana neutrinos have been ruled out by indirect-detection experiments [78,79,80,81,82,83] (also described below) over much of their mass range. Therefore, Dirac neutrinos cannot comprise the halo dark matter [84]; Majorana neutrinos can, but only over a small range of fairly large masses.

A much more promising WIMP candidate comes from electroweak-scale supersymmetry (SUSY) [71,73,74,85]. SUSY was hypothesized in particle physics to cure the naturalness problem with fundamental Higgs bosons at the electroweak scale; in the GUT theory, the parameter that controls the Higgs-boson mass must be extremely small, but it may be closer to unity (and thus, in the particle-theory parlance, more "natural") in supersymmetric theories. Unification of the strong and electroweak coupling constants at the GUT scale seems to be improved with SUSY, and SUSY seems to be an essential ingredient in theories that unify gravity with the other three fundamental forces.

The existence of a new symmetry, R-parity, in SUSY theories guarantees that the lightest supersymmetric particle (LSP) is stable. In the minimal supersymmetric extension of the standard model (MSSM), the LSP is usually the neutralino, a linear combination of the supersymmetric partners of the photon, Z^0, and Higgs bosons. Another possibility is the sneutrino, the supersymmetric partner of the neutrino, but these particles interact like neutrinos and have been ruled out over most of the available mass range [86]. Given a SUSY model, the cross section for neutralino annihilation to lighter particles, and thus the relic density, can be calculated. The mass scale of supersymmetry must be of order the weak scale to cure the naturalness problem, and the neutralino will have only electroweak interactions. Therefore, it is to be expected that the cosmological neutralino density is of order the dark-matter density, and this is borne out by detailed calculations in a very broad class of supersymmetric extensions of the standard model [87].

3.2. *Direct Detection of WIMPs*

SUSY particles are now among the primary targets for the Large Hadron Collider (LHC), which should begin science operations by the end of 2008. However, one can also try to detect neutralinos in the Galactic halo. In order to account for the dynamics of the Milky Way, the *local* dark-matter density must be $\rho_0 \simeq 0.4\,\mathrm{GeV/cm^3}$, and whatever particles or objects make up the dark-matter halo must be moving with a velocity dispersion of 270 km/sec.

Perhaps the most promising technique to detect WIMPs is detection of the $\mathcal{O}(30\,\mathrm{keV})$ nuclear recoil produced by elastic scattering of neutralinos from nuclei in low-background detectors [88,89,90]. A particle with mass $m_\chi \sim 100$ GeV and electroweak-scale interactions will have a cross section for elastic scattering from a nucleus which is $\sigma \sim 10^{-38}\,\mathrm{cm}^2$. If the local halo density is $\rho_0 \simeq 0.4$ GeV cm^{-3}, and the particles move with velocities $v \sim 300$ km sec^{-1}, then the rate for elastic scattering of these particles from, e.g., germanium, which has a mass $m_N \sim 70$ GeV, will be $R \sim \rho_0 \sigma v/m_\chi/m_N \sim 1$ event kg^{-1} yr^{-1}. If a 100-GeV WIMP moving at $v/c \sim 10^{-3}$ elastically scatters with a nucleus of similar mass, it will impart a recoil energy up to 100 keV to the nucleus. Therefore, if we have 1 kg of germanium, we expect to see roughly one nucleus per year spontaneously recoil with an energy of $\mathcal{O}(30\,\mathrm{keV})$.

More precise calculations of the detection rate include the proper neutralino-quark interaction, the QCD and nuclear physics that turn a neutralino-quark interaction to a neutralino-nucleus interaction, and a full integration over the WIMP velocity distribution. Even if all of these physical effects are included properly, there is still some uncertainty in the predicted event rates that arises from current limitations in our understanding of, e.g., squark, slepton, chargino, and neutralino masses and mixings. New contributions to the neutralino-nucleus cross section are still being found. For example, Ref. [91] found that there may be a hitherto neglected coupling of the neutralino to the virtual pions that hold nuclei together. Rather than make a single precise prediction, theorists thus generally survey the available SUSY parameter space. Doing so, one finds event rates between 10^{-4} to 10 events kg^{-1} day^{-1} [71], as shown in Fig. 55 of Ref. [71], although there may be models with rates that are a bit higher or lower.

3.3. *Energetic Neutrinos from WIMP annihilation*

Energetic neutrinos from WIMP annihilation in the Sun and/or Earth provide an alternative avenue for indirect detection of WIMPs [92]. If, upon passing through the Sun, a WIMP scatters elastically from a nucleus therein to a velocity less than the escape velocity, it will be gravitationally bound to the Sun. This leads to a significant enhancement in the density of WIMPs in the center of the Sun—or by a similar mechanism, the Earth. These WIMPs will annihilate to, e.g., c, b, and/or t quarks, and/or gauge and Higgs bosons. Among the decay products of these particles will be energetic muon neutrinos that can escape from the center of the Sun and/or Earth and be detected in neutrino telescopes such as the Irvine-Michigan-Brookhaven (IMB) [79], Baksan [80], Kamiokande [78,82], or MACRO [81] (underground neutrino observatories), or AMANDA [83] or IceCube (neutrino observatories built in deep Antarctic ice). The energies of the neutrino-induced muons will be typically 1/3 to 1/2 the neutralino mass (e.g., 10s to 100s of GeV), so they will be much more energetic than ordinary solar neutrinos (and therefore cannot be confused with them) [93]. The signature of such a neutrino would be the Cerenkov radiation emitted by an upward muon produced by a charged-current interaction between the neutrino and a nucleus in the material below the detector.

The annihilation rate of these WIMPs equals the rate for capture of these particles in the Sun [94]. The flux of neutrinos at the Earth depends also on the Earth-Sun distance, WIMP-annihilation branching ratios, and the decay branching ratios of the annihilation products. The flux of upward muons depends on the flux of neutrinos and the cross section for production of muons, which depends on the square of the neutrino energy.

As in the case of direct detection, the precise prediction involves numerous factors from particle and nuclear physics and astrophysics, and on the SUSY parameters. When all these factors are taken into account, predictions for the fluxes of such muons in SUSY models seem to fall for the most part between 10^{-6} and 1 event $\mathrm{m}^{-2}\ \mathrm{yr}^{-1}$ [71], as shown in Fig. 57 of Ref. [71], although the numbers may be a bit higher or lower in some models. Presently, IMB, Kamiokande Baksan, and MACRO constrain the flux of energetic neutrinos from the Sun to be $\lesssim 0.02\ \mathrm{m}^{-2}\ \mathrm{yr}^{-1}$ [78,79,80,81]. Larger and more sensitive detectors such as super-Kamiokande [82] and AMANDA [83] are now operating, and others are being constructed [95].

3.4. *Recent Results*

The experimental effort to detect WIMPs began nearly twenty years ago, and the theoretically favored regions of the SUSY parameter space are now beginning to be probed. An earlier claimed detection by the DAMA collaboration [96] has been shown to be in conflict with null searches from the EDELWEISS [97], ZEPLIN [98], and Cryogenic Dark Matter Search (CDMS) [99] experiments, if the WIMP couples to the mass of the nucleus, and it is conflict with CDMS [100] if it couples instead to nuclear spins. The putative DAMA signal also conflicts, under a fairly broad range of assumptions, with energetic-neutrino searches [101,102,103]. WIMPs have not yet been discovered, but only a small region of the parameter space has yet been probed. It will take another generation of experiments to probe the favored parameter space.

3.5. *WIMPs and exotic cosmic rays*

WIMPs might also be detected via observation of exotic cosmic-ray positrons, antiprotons, and gamma rays produced by WIMP annihilation in the Galactic halo. The difficulty with these techniques is discrimination between WIMP-induced cosmic rays and those from traditional astrophysical ("background") sources. However, WIMPs may produce distinctive cosmic-ray signatures. For example, WIMP annihilation might produce a cosmic-ray-positron excess at high energies [104,105]. There are now several balloon (e.g., BESS, CAPRICE, HEAT, IMAX, MASS, TS93) and satellite (AMS and PAMELA) experiments that have recently flown or are about to be flown to search for cosmic-ray antimatter. In fact, the HEAT experiment may already show some evidence for a positron excess at high energies [106].

WIMP annihilation will produce an antiproton excess at low energies [107], although Ref. [108] claims that more traditional astrophysical sources can mimic such an excess. They argue that the antiproton background at higher energies ($\gtrsim$few GeV) is better understood, and that a search for an excess of these higher-energy antiprotons would thus provide a better WIMP signature. Cosmic-ray antideuterons have also been considered as a signature of WIMP annihilation [109].

Direct WIMP annihilation to two photons can produce a gamma-ray line, which could not be mimicked by a traditional astrophysical source, at an energy equal to the WIMP mass. WIMPs could also annihilate directly to a photon and a Z^0 boson

[110,111], and these photons will be monoenergetic with an energy that differs from that of the photons from direct annihilation to two photons. Resolution of both lines and measurement of their relative strengths would shed light on the composition of the WIMP. Ground-based experiments like VERITAS, HESS, STACEE, CELESTE, or CACTUS or the GLAST satellite will seek this annihilation radiation. A recent (null) search was carried out for WIMP-annihilation lines in EGRET data [112].

It was recently argued [113] that there may be a very dense dark-matter spike, with a dark-matter density that scales with radius r as $\rho(r) \propto r^{-2.25}$ from the Galactic center, around the black hole at the Galactic center. If so, it would give rise to a huge flux of annihilation radiation. However, others have questioned whether this spike really arises [114].

While the Galactic center provides one source for gamma rays from WIMP annihilation, it has also been argued that other sources—in particular, the Draco dwarf galaxy—may have a sufficiently dense dark-matter core to provide an alternative target for WIMP-induced gamma rays [115]. A tentative excess of $\sim$ 100-GeV gamma rays from Draco [116]. was shown [117] shown to require WIMP-annihilation cross sections that are most likely too high to be explained by supersymmetric models, unless the central dark-matter halo of Draco has a very steep cusp.

3.6. *Non-minimal WIMPs?*

N-body simulations of structure formation with collisionless dark matter show dark-matter cusps, density profiles that fall as $\rho(r) \propto 1/r$ with radius r near the galactic center [118], while some dwarf-galaxy rotation curves indicate the existence of a density core in their centers [119]. This has prompted some theorists to consider self-interacting dark matter [120]. If dark-matter particles elastically scatter from each other in a galactic halo, then heat can be transported from the halo center to the outskirts, thereby smoothing the cusp into a core. In order for this mechanism to work, however, the elastic-scattering cross section must be $\sigma_{\rm el} \sim 10^{-(24-25)}(m_\chi/\mathrm{GeV})$ cm^2, roughly thirteen orders of magnitude larger than the cross section expected for WIMPs, and even further from that for axions. If the cross section is stronger, the halo will undergo core collapse [121], and if it is weaker, the heat transport is not efficient enough to remove the dwarf-galaxy dark-matter cusp.

The huge discrepancy between the magnitude of the required scattering cross section and that for WIMPs and axions has made self-interacting dark matter unappealing to most WIMP and axion theorists (but see, e.g., Refs. [122]). However, theoretical prejudices aside, self-interacting dark matter now seems untenable observationally. If dark matter is collisional, dark-matter cores should equilibrate and become round. Non-radial arcs in the gravitational-lensing system MS2137-23 require a non-spherical core and thus rule out the scattering cross sections required to produce dwarf-galaxy cores [123]. One possible loophole is that the scattering cross section is inversely proportional to the relative velocity of the scattering particles; this would lengthen the equilibration time in the core of the cluster MS2137-23.

This possibility has now been ruled out, however, by x-ray observations of the giant elliptical galaxy NGC 4636 which shows a very dense dark-matter cusp at very small radii [124].

There are (many!) other ways that non-minimal WIMPs could make themselves manifest cosmologically and astrophysically. As one example, Ref. [125] we considered the effects of WIMPs that are produced via decay of a charged particle with a lifetime of 3.5 years. If a WIMP spends the first 3.5 years of its existence as a charged particle, then during that time it couples to the baryon-photon plasma in the early Universe. If so, then pressure support from the plasma prevents the gravitational amplification of density perturbations in the WIMP fluid. Thus, the growth of modes that enter the horizon during the first 3.5 years—i.e., those on sub-Mpc comoving scales—is suppressed. This suppression can then explain the dearth of dwarf galaxies in the Local Group [126]. Although not generic, this charged-particle decay can occur in supersymmetric models [128], and there are ways, with 21-cm probes of the high-redshift Universe, that this mechanism may be distinguished from those [126] where the suppression is introduced by broken scale invariance during inflation.

3.7. *Kaluza-Klein modes and other possibilities*

Inspired by the presumed existence of extra spatial dimensions, it has become quite fashionable among particle theorists in recent years to consider the possibility that the Universe may contain large extra dimensions in which the graviton may travel, but which are inaccessible to standard-model fields. The array of models and phenomenology that has been derived from them is startling. However, there is a subclass of these theories, *universal extra dimensions* (see Ref. [127] for a recent review), in which standard-model fields are allowed to propagate on a toroidal compact extra dimension, usually taken to have a size $d \sim \mathrm{TeV}^{-1}$. The momenta in these extra dimensions are quantized in units of $\hbar/(2\pi d)$ and appear in our 3+1-dimensional space as a mass. What this means is that for every standard-model particle, there is a series of particles, "Kaluza-Klein" excitations (named after Kaluza and Klein, who first studied extra spatial dimensions), with the same quantum numbers and masses close to the inverse size of the extra dimension. The lightest of these KK modes is stable, due to conservation of momentum in the extra dimension. These particles can annihilate with particles with the opposite quantum numbers and opposite momenta in the extra dimension, with interaction strengths characteristic of the electroweak scale, and they may elastically scatter from ordinary particles, also with electroweak-strength interactions. Consequently, the dark-matter phenomenology of these particles parallels quite closely that of supersymmetric WIMPs.

Another avenue recently explored is to consider WIMPs in a model-independent way. In particular, there are obvious phenomenological questions one can ask, such as how dark is "dark"? I.e., how weak must the coupling of the photon be to the WIMP? One way to answer this question is to postulate that the WIMP has a tiny electromagnetic charge, a millicharge, and then constrain the value of the charge as a function of its mass [129]. Another possibility is to suppose the dark-matter particle is neutral, but couples to the photon through an electric or magnetic dipole [130].

3.8. *Kinetic decoupling of WIMPs and small-scale structure*

When we speak of freeze-out of WIMPs in the early Universe, we usually refer to the freezing out of WIMP annihilation and thus the departure of WIMPs from *chemical* equilibrium. This, however, does *not* signal the end of WIMP interactions. *Elastic* scattering of WIMPs from light standard-model particles in the primordial plasma keep WIMPs in *kinetic* equilibrium until later times (lower temperatures) [131,132,133]. The temperature $T_{\rm kd}$ of *kinetic* decoupling sets the distance scale at which linear density perturbations in the dark-matter distribution get washed out—the small-scale cutoff in the matter power spectrum. In turn, this small-scale cutoff sets the mass $M_c \simeq 33.3\,(T_{\rm kd}/10\ {\rm MeV})^{-3}\ M_\oplus$ [134] (where $M_\oplus$ is the Earth mass) of the smallest protohalos that form when these very small scales go nonlinear at a redshift $z \sim 70$. There may be implications of this small-scale cutoff for direct [135] and indirect [136] detection.

Early work assumed that the cross sections for WIMPs to scatter from light particles (e.g., photons and neutrinos) would be energy independent, leading to suppression of power out to fairly large (e.g., galactic) scales. However, in supersymmetric models, at least, the relevant elastic-scattering cross sections drop precipitously with temperature, resulting in much higher $T_{\rm kd}$ and much smaller suppression scales [132]. This estimate has been used to derive $T_{\rm kd}$ and infer that the minimum protohalo mass is $M_c \sim M_\oplus$ [133,134,135].

Ref. [137] calculated the kinetic-decoupling temperature $T_{\rm kd}$ of supersymmetric and UED dark matter concluding that $T_{\rm kd}$ may range all the way from tens of MeV to several GeV implying a range $M_c \sim 10^{-6}\ M_\oplus$ to $M_c \sim 10^2\ M_\oplus$.

3.9. *Axions*

The other leading dark-matter candidate is the axion [75]. The QCD Lagrangian may be written

$$\mathcal{L}_{QCD} = \mathcal{L}_{\rm pert} + \theta \frac{g^2}{32\pi^2} G\widetilde{G}, \tag{10}$$

where the first term is the perturbative Lagrangian responsible for the numerous phenomenological successes of QCD. However, the second term (where G is the gluon field-strength tensor and $\widetilde{G}$ is its dual), which is a consequence of nonperturbative effects, violates charge-parity (CP) symmetry. From constraints to the neutron electric-dipole moment, $d_n \lesssim 10^{-25}$ e cm, it can be inferred that $\theta \lesssim 10^{-10}$. But why is θ so small? This is the strong-CP problem.

The axion arises in the Peccei-Quinn (PQ) solution to the strong-CP problem [138]. A global $U(1)_{PQ}$ symmetry is broken at a scale f_a, and θ becomes a dynamical field with a flat potential. At temperatures below the QCD phase transition, nonperturbative quantum effects break explicitly the symmetry and produce a non-flat potential that is minimized at $\theta \to 0$. The axion is the pseudo-Nambu-Goldstone boson of this near-global symmetry, the particle associated with excitations about the minimum at $\theta = 0$. The axion mass is $m_a \simeq \mathrm{eV}\,(10^7\,\mathrm{GeV}/f_a)$, and its coupling to ordinary matter is $\propto f_a^{-1}$.

The Peccei-Quinn solution works equally well for any value of f_a. However, a variety of astrophysical observations and laboratory experiments constrain the axion mass to be $m_a \sim 10^{-4}$ eV. Smaller masses would lead to an unacceptably large cosmological abundance. Larger masses are ruled out by a combination of constraints from supernova 1987A, globular clusters, laboratory experiments, and a search for two-photon decays of relic axions.

Curiously enough, if the axion mass is in the relatively small viable range, the relic density is $\Omega_a \sim 1$, and so the axion may account for the halo dark matter. Such axions would be produced with zero momentum by a misalignment mechanism in the early Universe and therefore act as cold dark matter. During the process of galaxy formation, these axions would fall into the Galactic potential well and would therefore be present in our halo with a velocity dispersion near 270 km sec^{-1}.

It has been noted that quantum gravity is generically expected to violate global symmetries, and unless these Planck-scale effects can be suppressed by a huge factor, the Peccei-Quinn mechanism may be invalidated [139]. Of course, we have at this point no predictive theory of quantum gravity, and several mechanisms for forbidding these global-symmetry violating terms have been proposed [140]. Therefore, discovery of an axion might provide much needed clues to the nature of Planck-scale physics.

There is a very weak coupling of an axion to photons through the triangle anomaly, a coupling mediated by the exchange of virtual quarks and leptons. The axion can therefore decay to two photons, but the lifetime is $\tau_{a\to\gamma\gamma} \sim 10^{50}\,\mathrm{s}\,(m_a/10^{-5}\,\mathrm{eV})^{-5}$ which is huge compared to the lifetime of the Universe and therefore unobservable. However, the $a\gamma\gamma$ term in the Lagrangian is $\mathcal{L}_{a\gamma\gamma} \propto a\vec{E}\cdot\vec{B}$ where $\vec{E}$ and $\vec{B}$ are the electric and magnetic field strengths. Therefore, if one immerses a resonant cavity in a strong magnetic field, Galactic axions that pass through the detector may be converted to fundamental excitations of the cavity, and these may be observable [141]. Such an experiment is currently underway [142] and has already begun to probe part of the cosmologically interesting parameter space (see the Figure in Ref. [143]), and it should cover most of the interesting region parameter space in the next few years.

Axions, or other light pseudoscalar particles, may show up astrophysically or experimentally in other ways. For example, the PVLAS Collaboration [144] reported the observation of an anomalously large rotation of the linear polarization of a laser when passed through a strong magnetic field. Such a rotation is expected in quantum electrodynamics, but the magnitude they reported was in excess of this expectation. One possible explanation is a coupling of the pseudoscalar $F\tilde{F}$ of electromagnetism to a low-mass axion-like pseudoscalar field. The region of the mass-coupling parameter space implied by this experiment violates limits for axions from astrophysical constraints, but there may be nonminimal models that can accommodate those constraints. Ref. [145] reviews the theoretical interpretation and shows how the PVLAS results may be tested with x-ray re-appearance experiments.

4. Dark Energy

In addition to confirming the predictions of big-bang nucleosynthesis and the existence of dark matter, the measurement of classical cosmological parameters has resulted in a startling discovery: roughly 70% of the energy density of the Universe is in the form of some mysterious negative-pressure dark energy [146]. The original supernova evidence for an accelerating Universe [50] has now been dramatically bolstered by CMB measurements, which indicate a vacuum-energy contribution $\Omega_\Lambda \simeq 0.7$ to the critical density.

As momentous as these results are for cosmology, they may be even more remarkable from the vantage point of particle physics, as they indicate the existence of new physics beyond the standard model plus general relativity. Either gravity behaves very peculiarly on the very largest scales, and/or there is some form of negative-pressure "dark energy" that contributes 70% of the energy density of the Universe. As shown below, if this dark energy is to accelerate the expansion, its equation-of-state parameter $w \equiv p/\rho$ must be $w < -1/3$, where p and ρ are the dark-energy pressure and energy density, respectively. The simplest guess for this dark energy is the spatially uniform time-independent cosmological constant, for which $w = -1$. Another possibility is quintessence [147] or spintessence [148], a cosmic scalar field that is displaced from the minimum of its potential. Negative pressure is achieved when the kinetic energy of the rolling field is less than the potential energy, so that $-1 \leq w < -1/3$ is possible.

The dark energy was a complete surprise and remains a complete mystery to theorists, a stumbling block that, if confirmed, must be understood before a consistent unified theory can be formulated. This dark energy may be a direct remnant of string theory, and if so, it provides an exciting new window to physics at the Planck scale.

Although it is the simplest possibility, a cosmological constant with this value is strange, as quantum gravity would predict its value to be 10^{120} times the observed value, or perhaps zero in the presence of some symmetry. One of the appealing features of dynamical models for dark energy is that they may be compatible with a true vacuum energy which is precisely zero, to which the Universe will ultimately evolve.

4.1. *Basic considerations*

The first law of thermodynamics (conservation of energy) tells us that if the Universe is filled with a substance of pressure $p = w\rho$, where ρ is the energy density and w the equation-of-state parameter, then the change in the energy $dE = d(\rho a^3)$

in a comoving volume (where a is the scale factor) is equal to the work $dW = -pd(a^3)$ done by the substance. Some algebraic rearrangement yields $(d\rho/\rho) = -3(1+w)(da/a)$ from which it follows that the energy density of the substance scales as $\rho \propto a^{-3(1+w)}$. For example, nonrelativistic matter has $w = 0$ and $\rho \propto a^{-3}$, while radiation has $w = 1/3$ and $\rho \propto a^{-4}$. And if $w = -1$, we get a cosmological constant, $\rho \propto$constant. Now in order to get cosmic acceleration, we require superluminal expansion; that is, that the scale factor a grow more rapidly than t. If the Universe is filled with a substance with equation of state $p = w\rho$, then the Friedmann equation is $H \propto (\dot{a}/a) \propto a^{-3(1+w)}$, from which it follows that $a \propto t^{-2/3(1+w)}$. We thus infer that we must have $w < -1/3$ for cosmic acceleration.

A negative pressure may at first be counterintuitive, but intuition is rapidly established when we realize that a negative pressure is nothing but tension—i.e., something that pulls, like a rubber band, rather than pushes, like the molecules in a gas. Still, one may then wonder how it is that something that pulls can lead to (effectively) repulsive gravity. The answer is simple. In Newtonian mechanics, it is the mass density ρ that acts as a source for the gravitational potential ϕ through the Poisson equation $\nabla^2\phi = 4\pi G\rho$. In general relativity, it is energy-momentum that sources the gravitational field. Thus, in a molecular gas, pressure, which is due to molecular momenta, can also source the gravitational field. Roughly speaking, the Newtonian Poisson equation gets replaced by $\nabla^2\phi = 4\pi G(\rho + 3p)$. Thus, if $p < -\rho/3$, gravity becomes repulsive rather than attractive.

4.2. *Observational probes*

The obvious first step to understand the nature of this dark energy is to determine whether it is a true cosmological constant ($w = -1$), or whether its energy density evolves with time ($w \neq -1$). This can be answered by determining the expansion rate of the Universe as a function of redshift. In principle, this can be accomplished with a variety of cosmological observations (e.g., quasar-lensing statistics, cluster abundances and properties, the Lyman-alpha forest, galaxy and cosmic-shear surveys, etc.). However, the currently leading contenders in this race are supernovae, particularly those that can reach beyond redshifts $z \gtrsim 1$. Here, better systematic-error reduction, better theoretical understanding of supernovae and evolution effects, and greater statistics, are all required. Both ground-based (e.g., the LSST [149]) and space-based (e.g., SNAP/JDEM [150]) supernova searches can be used to determine the expansion history. However, for redshifts $z \gtrsim 1$, the principal optical supernova emission (as well as the characteristic silicon absorption feature) gets shifted to the infrared which is obscured by the atmosphere. Thus, a space-based observatory appears to be desirable to reliably measure the expansion history in the crucial high-redshift regime.

In recent years, baryon acoustic oscillations have become increasingly attractive as a possibility for determining the expansion history. The acoustic oscillations seen in the CMB power spectrum are due to oscillations in the photon-baryon fluid at the surface of last scatter. The dark matter is decoupled and does not participate in these oscillations. However, since baryons contribute a non-negligible fraction of the nonrelativistic-matter density, oscillations in the baryon-photon fluid get imprinted as small oscillations in the matter power spectrum at late times [151]. Quite remarkably, these oscillations have now been detected in galaxy surveys [152]. The physical distance scale at which these oscillations occur is well understood from linear perturbation theory, and they thus provide a standard ruler. The effects of cosmological geometry can therefore be inferred by comparing their observed angular size to that expected from their distance. If this can be done at a variety of redshifts, including high redshifts $z \gtrsim 1$, then these acoustic oscillations provide a way to measure the expansion history [153]. There are now a number of competing proposals and efforts to carry out galaxy surveys at high redshifts to make these measurements.

The other two leading candidates for expansion-history probes are cluster surveys and cosmic-shear (weak gravitational lensing) surveys, but there are many others that have been proposed. For example, the abundance of proto-clusters, massive overdensities that have yet to virialize and become x-ray clusters, has been suggested as a dark-energy probe [154]. Another suggestion is to measure to relative ages of cluster ellipticals as a function of redshift [155].

4.3. *Supernova data*

The supernova statistics have been building steadily since the initial 1998 results. Two years ago, it was announced that supernova data at high redshift were able to see the transition between cosmic acceleration and cosmic deceleration expected at earlier times [156]. More precisely, the measurements of the luminosity-distance–redshift relation (the relation between the distances inferred by the apparent brightness of "standard candles," sources of fixed luminosity) had become sufficiently precise to measure the cosmic jerk j_0, the cubic correction to the expansion law, in addition to the usual deceleration parameter q_0, the quadratic correction. Ref. [157] pointed out that this measurement provides the first classical (i.e., non-CMB) cosmological probe of the geometry of the Universe. The point is that the spatial curvature in Friedmann-Robertson-Walker (FRW) models does not enter until the cubic term in the expressions for the angular-diameter distance (the distance inferred by the observed angular size of an object of known physical size) and luminosity distance. Assuming, then, that the dark energy is a cosmological constant allows us to use these results to constrain the curvature scale, as shown in Fig. 13.

4.4. *Quintessence*

The simplest paradigm for cosmic acceleration is quintessence. The idea is somewhat similar to inflation. In such scenarios, one postulates a scalar field $\phi(t, \vec{x})$ with a potential-energy density $V(\phi)$, such that the scalar field is rolling sufficiently slowly down its potential to lead to an accelerated expansion. The equation of

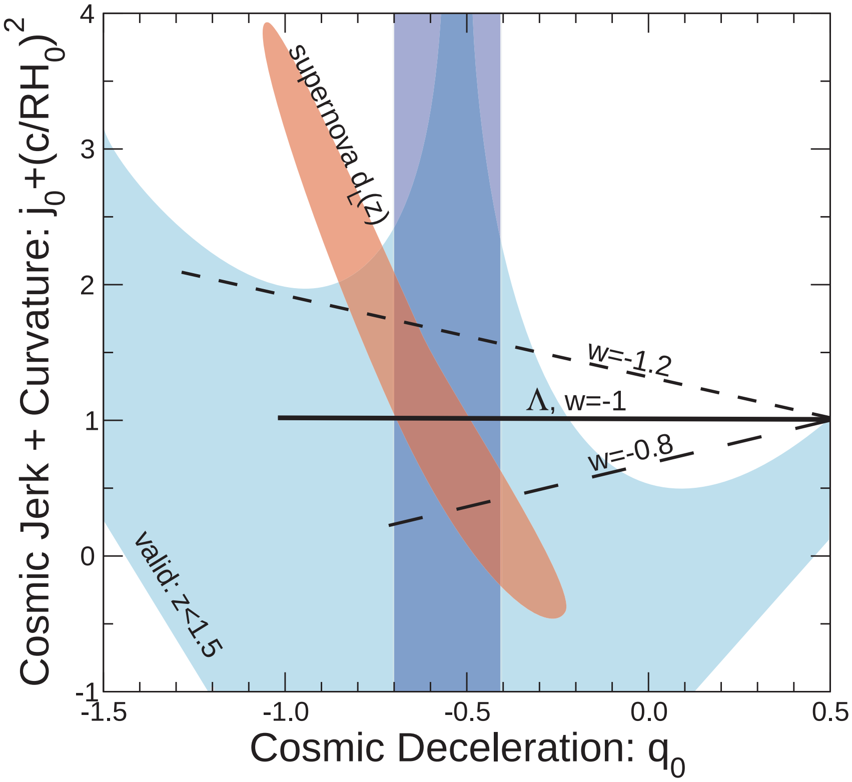

Figure 13: Current constraints to the $[q_0,\, j_0 + (H_0 R)^{-2}]$ plane, where R is the universal radius of curvature. The dark shaded region is the 95% confidence-level constraint from recent high-redshift supernova measurements [156]. The light-shaded region shows the domain of validity of the cubic redshift expansion; more precisely, outside these regions, there would be a unit magnitude error at $z = 1.5$ introduced by the quartic term. The solid curve indicates a family of flat cosmological-constant models with decreasing matter density from right to left, terminating at $q_0 = -1$ when $\Omega_m = 0$. The short-dash curve shows the same for flat models with quintessence with $w = -1.2$, and the long-dash curve shows the same for $w = -0.8$. The vertical band shows the range of values for a spatially-curved model with $\Omega_m + \Omega_\Lambda = 1$ and matter density spanning the range $0.2 < \Omega_m < 0.4$. From Ref. [157].

motion for the homogeneous component of the field is $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$, where the dot denotes derivative with respect to time, and H is the expansion rate. Here, the expansion serves as a friction term that prevents the scalar field from rolling directly to its minimum. The pressure in the field is $p = (1/2)\dot{\phi}^2 - V(\phi)$, and the energy density is $\rho = (1/2)\dot{\phi}^2 + V(\phi)$. Thus, if the field rolls slowly enough, then $w < -1/3$ and cosmic acceleration can proceed.

Quintessence models can be designed to provide the correct energy density today, but the right answer usually has to be put in by hand. As with the cosmological constant, the "why now" problem—i.e., why does the vacuum energy show up billions of years after the big bang, rather than much earlier or later?—is not really answered. There may be "tracker models," [158] though, that go some way toward addressing this problem. It turns out that if the quintessence potential is $V(\phi) \propto e^{-\phi/\phi_0}$, then during matter or radiation domination, the field rolls down the potential in such a way that the kinetic-plus-potential energy density scales with the expansion in the same way as the dominant component, matter or radiation. Thus, the scalar-field energy density in such models is not required to be infinitesimal compared with the dominant energy component over many decades in scale factor.

Another class of alternatives includes spintessence [148], in which one postulates a complex scalar field with a $U(1)$ symmetry. The field is then postulated to be spinning in the $U(1)$ symmetric potential, and it is the centrifugal-force barrier (or the conserved global charge), rather than expansion friction, that prevents the field from rolling directly to its minimum. Depending on the form of the potential $V(|\phi|)$, spintessence can act as dark matter or as dark energy. There is, however, generically an instability to production of Q-balls (balls of spinning scalar field) for spintessence potentials that produce cosmic acceleration, and finding workable spintessence models for acceleration has proved to be difficult.

The astronomical observations aimed at probing dark energy aim, to a first approximation, to determine the expansion history of the Universe. A few may probe the possible effects of quintessence or other models on the growth of perturbations, particularly on large scales. However, might there be other ways to determine the physics of dark energy? If the dark energy is quintessence, rather than a cosmological constant, then there may be observable consequences in the interactions of elementary particles if they have some coupling to the quintessence field. In particular, if the cosmological constant is time evolving (i.e., is quintessence), then there is a preferred frame in the Universe. If elementary particles couple weakly to the quintessence field, they may exhibit small apparent violations of Lorentz and/or CPT symmetry (see, e.g., Ref. [67]). A variety of accelerator and astrophysical experiments [67,68,69] can be done to search for such exotic signatures.

Quintessence models are simple and fairly predictive, once the potential $V(\phi)$ is specified. Although they must all be considered toy models, they are handy as working phenomenological models, or placeholders for a more fundamental theory.

4.5. *Alternative gravity*

Quintessence postulates the existence of some new form of "dark energy," a scalar-field configuration, with negative pressure that then drives the accelerated expansion in accord with general relativity. Another possibility is that there is no new exotic substance, but that the laws of gravity are modified on large distance scales. One simple example is $1/R$ gravity [159]. The usual Einstein-Hilbert Lagrangian is simply proportional to the Ricci scalar R, which measures the scalar curvature of space. When this action is minimized, it leads to Einstein's equation. In the absence of matter, the isotropic homogeneous spacetime that minimizes the action is Minkowski space; i.e., a spacetime with $R = 0$. If, however, we postulate an additional term, μ^4/R, where μ is a (very small) mass scale, in the action, then the isotropic homogeneous spacetime that minimizes the action is $R = \mu^2$ [159]; i.e., de Sitter space. Thus, an empty Universe has an accelerated expansion, and a sufficiently low-density Universe, like our own, is headed toward a de Sitter spacetime. Unfortunately, though, this model is phenomenologically untenable [160]. Theories in which the action is a function $f(R)$ of the Ricci scalar can be mapped onto scalar-tensor theories. The additional term in the action brings to life the scalar degree of freedom in the metric, leading to a change in the spacetime metric surrounding a massive object. Thus, the deflection of light by the Sun is altered in a way that is (very) inconsistent with current limits.

An alternative approach comes from large extra dimensions. In DGP (for Dvali-Gabadadze-Porrati) gravity [161,162], spacetime is five-dimensional, but energy-momentum is located on a four-dimensional brane. The action for gravity is

$$S_{(5)} = -\frac{M^3}{16\pi}\int d^5x\sqrt{-g}R - \frac{M_P^2}{16\pi}\int d^4x\sqrt{-g^{(4)}}R^{(4)}, \tag{11}$$

where M is the five-dimensional Planck scale, M_P the observed four-dimensional Planck scale, g and R the bulk metric and scalar curvature, and $g^{(4)}$ and $R^{(4)}$ those on the brane. On the brane, the gravitational potential due to a point mass m is $V \sim -G_{\rm brane}m/r$ at $r \ll r_0$, and $V \sim -G_{\rm bulk}m/r^2$ at $r \gg r_0$, where $G_{\rm bulk} = M^{-3}$ and $G_{\rm brane} = M_P^{-2}$ are five- and four-dimensional Newton's constants, respectively, and $r_0 = M_P^2/2M^3$ is a cutoff scale that separates the ordinary short-distance behavior from the new long-distance behavior. Thus, gravity is weaker at large distances. The theory admits accelerating FRW solutions [163] that have $w_{\rm eff}(z) = -1/(1+\Omega_m)$ and imply a crossover scale $r_0 \sim H_0^{-1}$. Although it was originally believed that the model would violate solar-system tests, in much the same way that $1/R$ gravity does, the short-distance phenomenology of the model is a bit more subtle [164]. The model leads to a perihelion advance (in addition to the usual general-relativistic one) for planetary orbits of $\Delta\phi \sim 5(r^3/2r_0^2 r_g)^{1/2}$ with radius r, where $r_g = Gm$. For values consistent with those required to explain cosmic acceleration, the perihelion advance is consistent with measurements, although, interestingly enough, possibly detectable with future experiments. As a classical theory of gravity, DGP theory thus provides a theoretically sophisticated arena for calculation and an interesting

Table 1: The history and future of the Universe with $w = -3/2$ phantom energy.

Time	Event
$\sim 10^{-43}$ s	Planck era
$\sim 10^{-36}$ s	Inflation
First Three Minutes	Light Elements Formed
$\sim 10^{5}$ yr	Atoms Formed
~ 1 Gyr	First Galaxies Formed
~ 14 Gyr	*Today*
$t_{\rm rip} - 1$ Gyr	Erase Galaxy Clusters
$t_{\rm rip} - 60$ Myr	Destroy Milky Way
$t_{\rm rip} - 3$ months	Unbind Solar System
$t_{\rm rip} - 30$ minutes	Earth Explodes
$t_{\rm rip} - 10^{-19}$ s	Dissociate Atoms
$t_{\rm rip} = 35$ Gyrs	Big Rip

connection between the cosmic acceleration and local tests of gravity.

Finally, it was suggested recently [165] that cosmic acceleration could be understood simply as a consequence of cosmological inhomogeneities in general relativity, with*out* the introduction of dark energy or alternative gravity. This proposal received a flurry of attention, but was then shown to be unworkable [166].

4.6. *Big Rip*

Prior to the advent of the data that indicated its existence, hardly any theorist would have really believed in his/her heart that there was a cosmological constant or some other sort of negative-pressure dark energy. The simplest phenomenological models (i.e., the simplest single-field quintessence models), as well as various energy conditions (an assortment of hypotheses about the stress-energy properties allowed for matter), suggest $w \geq -1$. However, current data are consistent with $w < -1$; for example, the latest WMAP data [17] indicate $w = -0.97^{+0.07}_{-0.09}$, centered near $w = -1$ but consistent with $w < -1$.

It is thus interesting to ask, what happens if dark energy is phantom energy [167]? i.e., what if it has an equation-of-state parameter $w < -1$? In this case, the dark-energy density *increases* with time, and if w remains less than -1, then it can be shown that the Universe ends in a "big rip," [168,169] a singularity in which the Universe is stretched to infinite scale factor in finite time, ripping everything in the Universe apart as it does so (see Table 1). To illustrate, let's imagine that the value of w was $w = -1.5$. In that case, the Universe, currently about 14 billions year old, will stretch to infinite size in about 20 billion years (with the constraints to w from WMAP, the onset of the big rip will occur later). About a billion years before that, galaxy clusters will be stripped apart, and about 60 million years before, the Milky Way will become dissociated. Three months before the Big Rip, the Solar System will be ripped apart, and then the Earth, about half an hour before the end of time. The final fraction of a second will see atoms dissociated and ultimately, nuclei.

Although phantom energy is indeed somewhat fantastic, there have been a number of exotic theoretical models for phantom energy, based, e.g., on scalar-field models with higher-derivative terms [167,170], or perhaps on supergravity or higher-derivative gravity theories. There have also been models for $w < -1$ based on theories with higher dimensions [174], strings [175], or the AdS/CFT (for anti-de-Sitter space and conformal field theory) correspondence [169].

5. Conclusions

Cosmology is in an exciting period. What were until recently wild theoretical speculations about the very earliest Universe must now be considered very serious models. Experiments that were just until a few years ago "futuristic" have now been completed, with spectacular success. We have gone from being an area in which the standard was order-of-magnitude estimates to a precision science with elegant experiments with controlled errors. The results of the experiments have confirmed what was long surmised—e.g., that most of the matter in the Universe is nonbaryonic—and provided new surprises, such as the accelerated expansion of the Universe.

In this brief review, I have discussed what we have learned from CMB experiments, and then moved on to discuss the candidates we have for dark matter and some of the ideas that have been discussed for dark energy. It must be realized that the CMB, inflation, dark matter, and dark energy now occupy the attention of a very significant fraction of the research enterprises of both physics and astronomy. There are thus an extraordinary wealth of ideas as well as a plethora of detailed theoretical calculations that I have not touched upon. The interested reader can use the reference list here as an introduction to peruse the broader literature.

Where will cosmology go next? We cannot say for sure. One obvious target is the CMB polarization due to inflationary gravitational waves, which, as discussed above, may now—with new CMB evidence for a scalar spectral index $n_s < 1$—be likely to be observable by next-generation experiments. Then there are dark-matter searches, which have been developing steadily in sensitivity over the past few decades. Again, a "definitive" experiment is hard to specify precisely, but experiments have been steadily improving in sensitivity. It is conceivable that within the next decade or two, we will probe most of the favored supersymmetric parameter space. Dark energy is here perhaps the dark horse. We are, theoretically, at a loss for really attractive explanations for the dark energy. The primary observational question being addressed is whether it is a true cosmological constant, or whether its density evolves with time. However, this will be an experimental challenge. And what happens if it turns out to be consistent with a cosmological constant?

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6. Glossary of Technical Terms and Acronyms[‡]

ACBAR (Arcminute Cosmology Bolometer Array Receiver). A bolometer-based CMB temperature experiment that characterized the damping tail of CMB temperature fluctuations. It had a 16-element array and 4 arc-minute resolution at 150 GHz (`http://cosmology.berkeley.edu/group/swlh/acbar/`).

Acoustic peaks. Wiggles in the CMB temperature and polarization power spectra that arise from acoustic oscillations in the primordial baryon-photon fluid.

Adiabatic perturbations. Primordial density perturbations in which the spatial distribution of matter is the same for all particle species (photons, baryons, neutrinos, and dark matter). Such perturbations are produced by the simplest inflation models.

AdS/CFT (Anti-de Sitter space/conformal field theory) correspondence. A conjectured equivalence between string theory in one space and a conformal gauge theory on the boundary of that space.

AMANDA. An astrophysical-neutrino observatory in deep Antarctic ice (`http://amanda.uci.edu`).

AMS (Alpha Magnetic Spectrometer). A NASA space-based cosmic-ray-antimatter experiment (`http://ams.cern.ch`).

APEX-SZ (Atacama Pathfinder EXperiment-Sunyaev-Zel'dovich). A bolometer-based experiment designed to search for galaxy clusters via the Sunyaev-Zel'dovich effect. The 12-meter diameter APEX telescope gives one arc-minute resolution at 150 GHz (`http://bolo.berkeley.edu/apexsz/`).

Axion. A scalar particle that arises in the Peccei-Quinn solution to the strong-CP problem. If the axion has a mass near 10^{-5} eV, then it could make up the dark matter.

Baksan experiment. A Russian underground astrophysical-neutrino telescope (`http://www.inr.ac.ru/INR/Baksan.html`).

BICEP (Background Imaging of Cosmic Extragalactic Polarization). A bolometer-based CMB polarization experiment sited at the South Pole. It uses a small refractive telescope to achieve 0.6 degree resolution at 150 GHz (`http://www.astro.caltech.edu/~lgg/bicep_front.htm`).

Baryons. In cosmology, this term refers to ordinary matter composed of neutrons, protons, and electrons.

BBN (Big-bang nucleosynthesis). The theory of the assembly of light nuclei from protons and neutrons a few seconds to minutes after the big bang.

BBO (Big Bang Observer). A mission concept, currently under study, for a post-LISA space-based gravitational-wave observatory designed primarily to seek inflationary gravitational waves (`http://universe.nasa.gov/program/bbo.html`).

[‡] Prepared in collaboration with Adrian Lee.

BESS (Balloon-borne Experiment with a Superconducting Spectrometer). A Japanese-US collaborative series of balloon-borne experiments to measure antimatter in cosmic rays (`http://www.universe.nasa.gov/astroparticles/programs/bess/`).
Big rip. A possible end fate for the Universe in which the Universe expands to infinite size in finite time, ripping everything apart as it does so.
Boltzmann equations. Equations for the evolution of the momentum distributions for various particle species (e.g., baryons, photons, neutrinos, and dark-matter particles).
BOOMERanG. A balloon-borne CMB-fluctuation experiment that reported in 2000 the first measurement of acoustic-peak structure in the CMB. It used a bolometer array and had 10 arc-minute resolution at 150 GHz (`http://cmb.phys.cwru.edu/boomerang`).
Brane or ***p*-brane**. A p-dimensional subspace of some higher-dimensional subspace. As an example, in some string theories, there may be many extra dimensions, but standard-model fields are restricted to lie in a 4-dimensional volume that is our $3+1$-dimensional spacetime.
CACTUS. A heliostat array for > 40 GeV gamma-ray astronomy (`http://ucdcms.ucdavis.edu/solar2`).
CAPRICE (Cosmic AntiParticle Ring Imaging Cherenkov Experiment). A 1994 balloon-borne cosmic-ray-antimatter experiment (`http://www.roma2.infn.it/research/comm2/caprice`).
CBI (Cosmic Background Imager). An interferometric CMB telescope designed to measure the smallest-angular-scale structure of the CMB (`http://www.astro.caltech.edu/~tjp/CBI`).
CAPMAP (Cosmic Anisotropy Polarization MAPper). A CMB polarization experiment using the Lucent Technologies 7-meter diameter telescope at Crawford Hill NJ and coherent detectors (`http://quiet.uchicago.edu/capmap/`).
CDMS (Cryogenic Dark Matter Search). A U.S. experiment designed to look for WIMPs (`http://cdms.berkeley.edu`).
CELESTE. A heliostat array for ~ 100 GeV gamma-ray astronomy.
CMB (Cosmic microwave background). A 2.7 K gas of thermal radiation that permeates the Universe, a relic of the big bang.
CMBPOL. A mission concept, currently under study, for a post-Planck CMB satellite experiment designed primarily to search for inflationary gravitational waves.
COBE (Cosmic Background Explorer). A NASA satellite flown from 1990–1993 with several experiments designed to measure the properties of the CMB. John Mather and George Smoot, two of the leaders of COBE, were awarded the 2006 Nobel prize for physics for COBE (`http://lambda.gsfc.nasa.gov/product/cobe`).
Cosmic jerk. A parameter that quantifies the time variation of the cosmic acceleration.

Cosmic shear (CS). Gravitational lensing of distant cosmological sources by cosmological density perturbations along the line to those sources.

Cosmological constant (Λ). An extra term in the Einstein equation that quantifies the gravitating mass density of the vacuum.

Critical density. The cosmological density required for a flat Universe. If the density is higher than the critical density, then the Universe is closed, and if it is smaller, then it is open.

DAMA. An Italian experiment designed to look for WIMPs (`http://people.roma2.infn.it/~dama/web/home.html`).

Dark energy (DE). A form of negative-pressure matter that fills the entire Universe. It is postulated to account for the accelerated cosmological expansion.

Dark matter (DM). The nonluminous matter required to account for the dynamics of galaxies and clusters of galaxies. The preponderance of the evidence suggests that dark matter is not made of baryons, and it thus often referred to as "nonbaryonic dark matter." The nature of dark matter remains a mystery.

DASI (Degree Angular Scale Interferometer). An interferometric CMB experiment sited at the South Pole that characterized the acoustic peaks in the CMB power spectrum and first detected the E-mode polarization in the CMB (`http://astro.uchicago.edu/dasi/`).

DECIGO (Deci-hertz Interferometer Gravitational Wave Observatory). A mission concept, currently under study in Japan, for an even more ambitious version of BBO.

DGP (Dvali-Gabadadze-Porrati) gravity. A theory for gravity, that may explain cosmic acceleration, based on the introduction of one extra spatial dimension.

Dirac neutrino. A type of neutrino that has an antiparticle.

DMR (Differential Microwave Radiometer). An experiment on COBE that measured temperature fluctuations in the CMB (`http://lambda.gsfc.nasa.gov/product/cobe`).

EDELWEISS. A French experiment designed to look for WIMPs (`http://edelweiss.in2p3.fr`).

EGRET (Energetic Gamma Ray Experiment Telescope). A high-energy gamma-ray experiment flown aboard NASA's Compton Gamma-Ray Observatory in the early 1990s (`http://cossc.gsfc.nasa.gov/docs/cgro/cossc/EGRET.html`).

Einstein's equations. The equations of general relativity.

Electroweak (EW) phase transition. The phase transition at a temperature ~ 100 GeV that breaks the electroweak symmetry at low energies to distinct electromagnetic and weak interactions.

Friedmann equation. The general-relativistic equation that relates the cosmic expansion rate to the cosmological energy density.

Friedman-Robertson-Walker (FRW) spacetime. The spacetime that describes a homogeneous isotropic Universe.

Galaxy clusters. Gravitationally bound systems of hundreds to thousands of galaxies.

General relativity (GR). Einstein's theory that combines gravity with relativity.

GLAST (Gamma Ray Large Area Space Telescope). A NASA telescope, to be launched within a year, for high-energy gamma-ray astronomy (`http://www-glast.stanford.edu`).

Grand-unified theories (GUTs). Gauge theories that unify that electroweak and strong interactions at an energy $\sim 10^{16}$ GeV.

Gravitational lensing. The general-relativistic bending of light by mass concentrations.

Gravitational waves (GWs). Propagating disturbances, which arise in general relativity, in the gravitational field, analogous to electromagnetic waves (which are propagating disturbances in the electromagnetic field).

Hawking radiation. Radiation emitted, as a result of quantum-mechanical processes, from a black hole.

HEAT (High Energy Antimatter Telescope). A balloon-borne cosmic-ray-antimatter telescope from the 1990s.

HESS (High Energy Stereoscopic System). A ground-based air Cerenkov telescope for GeV–TeV gamma-ray astronomy (`http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html`).

Hubble constant. The constant of proportionality between the recessional velocity of galaxies and their distance. The Hubble constant is also the expansion rate. When used in this context, the term is a misnomer, as the expansion rate varies with time.

IceCube. An astrophysical-neutrino observatory (a successor to AMANDA) now being built at the South Pole (`http://icecube.wisc.edu`).

IMAX (Isotopie Matter Antimatter Telescope). A 1992 balloon-borne cosmic-ray-antimatter telescope (`http://www.srl.caltech.edu/imax.html`).

Inflation. A period of accelerated expansion in the early Universe postulated to account for the isotropy and homogeneity of the Universe.

Inflationary gravitational waves (IGWs). A cosmological background of gravitational waves produced via quantum processes during inflation.

IMB (Irvine-Michigan-Brookhaven) experiment. A U.S. underground detector designed originally to look for proton decay, but used ultimately (from 1979–1989) as an astrophysical-neutrino detector (`http://www-personal.umich.edu/~jcv/imb/imb.html`).

JDEM (Joint Dark Energy Mission). A space mission in NASA's roadmap that aims to study the cosmic acceleration (`http://universe.nasa.gov/program/probes/jdem.html`).

Kaluza-Klein (KK) modes. Excitations of a fundamental field in extra dimensions in a theory with extra dimensions. These modes appear as massive particles in our 3+1-dimensional spacetime.

Kamiokande and Super-Kamiokande. A Japanese underground astrophysical-neutrino telescope (and proton-decay experiment) and its successor (`http://www-sk.icrr.u-tokyo.ac.jp/sk/index.html`).
Large extra dimensions. A currently popular idea in particle theory that the Universe may contain more spatial dimensions than the three that we see, and that the additional dimensions may be large enough to have observable consequences.
Large-scale structure (LSS). The spatial distribution of galaxies and clusters of galaxies in the Universe.
Laser Interferometric Space Antenna (LISA). A satellite experiment planned by NASA and ESA to detect gravitational waves from astrophysical sources (`http://lisa.nasa.gov`).
LEP (Large Electron-Positron) Collider. The electron-positron collider at CERN (European Center for Nuclear Research) which from 1989 to 2000 tested with exquisite precision the Standard Model.
LHC (Large Hadron Collider). The successor the LEP at CERN, the LHC will be (starting November 2007) a proton-proton collider, and the world's most powerful particle accelerator.
LSP (Lightest superpartner). The lightest supersymmetric particle (and a candidate WIMP) in supersymmetric extensions of the Standard Model.
LIGO (Laser Interferometric Gravitational-Wave Observatory). An NSF experiment, currently operating, designed to detect gravitational waves from astrophysical sources (`http://www.ligo.caltech.edu`).
Local Group. The group of galaxies that the Milky Way belongs to.
LSST (Large Synoptic Survey Telescope). A proposed wide-field survey telescope (`http://www.lsst.org/lsst_home.shtml`).
Lyman-alpha forest or **Ly-α forest**. The series of absorption features, in the spectra of distant quasars, due to clouds of neutral hydrogen along the line of sight.
Majorana neutrino. A type of neutrino that is its own antiparticle.
MACRO (Monopoles and Cosmic Ray Observatory). An underground astrophysical-neutrino telescope (and proton-decay experiment) that ran at the Gran Sasso Laboratory in Italy from 1988 to 2000.
MASS (Matter Antimatter Superconducting Spectrometer). A 1989–1991 balloon-borne cosmic-ray-antimatter telescope (`http://people.roma2.infn.it/~aldo//mass.html`).
MAT/TOCO (Mobile Anisotropy Telescope on Cerro TOCO). A CMB experiment using coherent detectors that gave early results on the location of the first acoustic peak in the CMB angular power spectrum (`http://www.physics.princeton.edu/cosmology/mat/`).
MAXIMA (Millimeter Anisotropy eXperiment Imaging Array). A balloon-borne experiment that reported in 2000 measurements of temperature fluctuations on degree angular scales. It had a 16 element bolometer array operated at 100 mK and 10 arc-minute beams at 150 GHz (`http://cosmology.berkeley.edu/group/cmb`).

MAXIPOL. A balloon-borne CMB polarization experiment based on the MAXIMA experiment
(`http://groups.physics.umn.edu/cosmology/maxipol/`).
Naturalness problem. In grand-unified theories without supersymmetry, the parameter that controls the EW symmetry-breaking scale must be tuned to be extremely small.
NET (Noise-equivalent temperature). A quantity that describes the sensitivity (in units of μK$\sim\sqrt{\text{sec}}$) of a detector in a CMB experiment.
Neutralino. The superpartner of the photon and Z^0 and Higgs bosons, and an excellent WIMP candidate in supersymmetric extensions of the standard model.
PAMELA. A space-based cosmic-ray-antimatter experiment flown in 2006
(`http://wizard.roma2.infn.it/pamela`).
Peccei-Quinn mechanism. A mechanism, involving the introduction of a new scalar field, that solves the strong-CP problem.
Phantom energy. An exotic form of dark energy that is characterized by an equation-of-state parameter $w < -1$.
Planck satellite. A collaborative NASA/ESA satellite experiment aimed to measure temperature fluctuations in the CMB with even more precision and sensitivity than WMAP
(`http://www.rssd.esa.int/Planck`).
Planck-scale physics. A colloquial term that refers to quantum gravity or string theory.
POLARBeaR (POLARization of the Background Radiation). A planned bolometer-based CMB polarization experiment to be sited in Chile
(`http://bolo.berkeley.edu/polarbear/index.html`).
Primordial density perturbations or sometimes just **primordial perturbations.** The small-amplitude primordial density inhomogeneities (which may have arisen during inflation) that were amplified via gravitational instability into the large-scale structure we see today.
Pseudo-Nambu-Goldstone boson. A nearly massless scalar particle that arises in a theory with an explicitly broken global symmetry.
PVLAS. A laser experiment designed to look for the vacuum magnetic birefringence predicted in quantum electrodynamics
(`http://www.ts.infn.it/physics/experiments/pvlas/pvlas.html`).
Q-balls. Extended objects, composed of a a spinning scalar field, that appear in scalar field theories with a $U(1)$ symmetry (i.e., a cylindrical symmetry in the internal space).
QCD (Quantum chromodynamics). The theory of the strong interactions that confine quarks inside protons and neutrons.
QuaD (Q and U Extra-galactic Sub-Millimetre Telescope and DASI). A bolometer-based CMB polarization experiment at the South Pole. It has 4 arcminute resolution at 150 GHz
(`http://www.stanford.edu/∼schurch/quad.html`).

Quantum gravity. A term that refers to a theory—still to be determined but widely believed to be string theory—that unifies quantum mechanics and gravity.

Quark-hadron phase transition or **QCD phase transition**. The transition at temperature ~ 100 MeV at which quarks are first bound into protons and neutrons.

Quintessence. A mechanism postulated to explain cosmic acceleration by the displacement of a scalar field (the quintessence field) from the minimum of its potential.

Recombination. The formation of atomic hydrogen and helium at a redshift $z \simeq 1100$.

Redshift (z). The recessional velocity of a galaxy divided by the speed of light. The redshift is used as a proxy for distance or time after the big bang, with higher redshift indicating larger distances and earlier times.

SKA (Square-Kilometer Array). A large radio-telescope array planned by NSF (`http://www.skatelescope.org`).

SNAP (Supernova Acceleration Probe). A proposed space-based telescope dedicated to measuring the cosmic expansion history (`http://snap.lbl.gov`).

SPIDER. A balloon-borne bolometer-based CMB polarization experiment with six refractive telescopes
(`http://www.astro.caltech.edu/~lgg/spider_front.htm`).

Spintessence. A variant of quintessence in which the scalar field is taken to be complex with a $U(1)$ symmetry.

SPUD (Small Polarimeter Upgrade for Dasi). A proposed CMB experiment to be attached to the DASI mount at the South Pole.

STACEE (Solar Tower Atmospheric Cerenkov Effect Experiment). A ground-based air Cerenkov telescope designed to detect gamma rays in the ~ 100 GeV range (`http://www.astro.ucla.edu/~stacee`).

Standard Model (SM). The theory of strong, weak, and electromagnetic interactions.

String theory. A theory that postulates that all elementary particles are excitations of fundamental strings. The aim of such theories is to unify the strong and electroweak interactions with gravity at the **Plank scale**, an energy scale $\sim 10^{19}$ GeV.

Strong-CP problem. Although the strong interactions are observed to be parity conserving, there is nothing in QCD that demands that parity be conserved.

Supersymmetry (SUSY). A symmetry between fermions and bosons postulated primarily to solve the naturalness problem. It is an essential ingredient in many theories for new physics beyond the Standard Model.

Triangle anomaly. A coupling, mediated by the exchange of virtual fermions, between a scalar particle and two photons. This coupling is responsible for neutral-pion decay to two photons.

TS93. A 1993 balloon-borne cosmic-ray-antimatter telescope
(`http://people.roma2.infn.it/~aldo//ts93.html`).

Universal extra dimensions (UED). A class of theories for new physics at the electroweak scale in which the Universe has extra large dimensions in which standard-model fields propagate.

Vacuum energy. The energy of free space.

VERITAS (Very Energetic Radiation Imaging Telescope Arrays System). A ground-based air Cerenkov telescope for GeV–TeV gamma-ray astronomy (`http://veritas.sao.arizona.edu`).

VSA (Very Small Array). A ground-based CMB interferometer that is sited in the Canary Islands. It is sensitive to a wide range of angular scales with a best resolution of 10 arc-minute (`http://www.mrao.cam.ac.uk/telescopes/vsa/index.html`).

WIMP (Weakly-interacting massive particle). A dark-matter candidate particle that has electroweak interactions with ordinary matter. Examples include massive neutrinos, supersymmetric particles, or particles in models with universal extra dimensions.

WMAP (Wilkinson Microwave Anisotropy Probe). A NASA satellite launched in 2001 to measure, with better sensitivity and angular resolution than DMR, the temperature fluctuations in the CMB (`http://map.gsfc.nasa.gov`).

ZEPLIN An experiment designed to look for WIMPs.

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