NEW VIEWS OF COSMOLOGY AND THE MICROWORLD

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ABSTRACT

The past few years have seen several breakthroughs in particle astrophysics and cosmology. In several cases, new observations can only be explained with the introduction of new fundamental physics. In this talk I summarize some of these recent advances and describe several areas where progress may well be made in the future. More specifically, I focus on supersymmetric and axion dark matter, self-interacting dark matter, cosmic-microwave-background and large-scale-structure tests of inflation, and the dark-energy problem.

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1 Introduction

The aim of particle physics is to understand the fundamental laws of nature. The primary tools in this endeavor have been and continue to be accelerator experiments which provide controlled environments for precise experiments. However, this avenue may have limitations, especially considering that many of the most promising ideas for new physics beyond the standard model—e.g., grand unification and quantum gravity—can be tested only at energies many orders of magnitude greater than those accessible by current and planned accelerators.

We have recently seen an increased effort to develop cosmological and astrophysical tools to search for and/or constrain new physics beyond the standard model. These efforts do have precedents: Newton's law of universal gravitation was motivated by planetary orbits. Helium was first discovered in the solar spectrum. Positrons and muons were both discovered in cosmic-ray experiments. For several years before the advent of LEP, big-bang nucleosynthesis provided the only bound to the number of light neutrinos (e.g., Ref. 1). Cosmology for a long time provided by far the most stringent upper limits to stable-neutrino masses.

The promise of using astrophysics to study fundamental physics has also been realized more recently, most notably with the evidence for inflation from the cosmic microwave background (CMB), evidence for an accelerated cosmological expansion, and atmospheric and solar neutrinos.

At the Snowmass 2001 workshop on the future of high-energy physics, a working group (P4) was convened to identify opportunities for advances at the interface of particle physics, astrophysics, and cosmology.[2] This working group covered a broad range of topics, subdivided into eight topical groups: (1) dark matter and relic particles; (2) gamma rays and X-rays; (3) the CMB and inflation; (4) structure formation and cosmological parameters; (5) cosmic rays; (6) gravitational radiation; (7) neutrino astrophysics; and (8) the early Universe and tests of fundamental physics. Recent advances in these areas include the following:

(1) CMB measurements have now mapped the location of the first acoustic peak in the CMB power spectrum, which determines the geometry,[3] and found that the total energy density of the Universe (in units of the critical density) is $\Omega_{\rm tot} = 1.00^{+0.03}_{-0.02}$, providing for the very first time strong evidence that of the three possibilities (open, closed, or flat), the spatial geometry of the Universe is flat.[4–9] These CMB experiments moreover support the hypothesis that large-scale structure grew from primordial density

fluctuations that look much like those predicted by inflation.

(2) The discrepancy between a matter density $\Omega_m \simeq 0.3$ and $\Omega_{\rm tot} \simeq 1$ provides independent corroboration of the remarkable recent supernova evidence[10,11] that suggests that $\sim 70\%$ of the energy density of the Universe is in the form of some mysterious and theoretically unanticipated negative-pressure "dark energy".

(3) CMB data verify, through a completely independent avenue, the big-bang nucleosynthesis prediction that baryons make up only $\sim$5% of the critical density. When combined with dynamical and CMB evidence for a nonrelativistic-matter density of 30% of critical, we infer that 25% of the total density of the Universe must be in the form of nonbaryonic dark matter (the best bet being supersymmetric particles or axions).

(4) The sensitivities of experiments to directly detect supersymmetric and axion dark matter have been improved by several orders of magnitude and are now probing the cosmologically-relevant regions of parameter space.

(5) Neutrinos from astrophysical sources (atmospheric and solar neutrinos) have provided convincing evidence for neutrino oscillations and thus demonstrate that very concrete advances in fundamental physics can occur with astrophysical sources.

Here I summarize a few of the topics of the Snowmass P4 working group, focusing on several subjects that I find particularly interesting and providing updates in several cases where there has been progress during the past year.

2 Particle Dark Matter

Almost all astronomers will agree that most of the mass in the Universe is nonluminous. Dynamics of clusters of galaxies have long suggested a universal nonrelativistic-matter density $\Omega_m \simeq 0.1 - 0.3$ (in units of the critical density). It has also been appreciated for a long time that if there were no matter beyond the luminous matter we see, the duration of the epoch of structure formation would be very short, thereby requiring fluctuations in the CMB considerably larger than those observed.[12]

However, the most robust observational evidence for the existence of dark matter has always involved galactic dynamics. There is simply not enough luminous matter observed in spiral galaxies to account for their observed rotation curves (for example, that for NGC6503 shown in Fig. 1; from Ref. 13). These rotation curves imply the existence of a diffuse halo of dark matter that vastly outweighs and extends much further than the luminous component. Summing the contributions from all galaxies, we infer that dark matter associated with galaxies contributes $\Omega_{\rm halo} \gtrsim 0.1$. On the other hand, big-bang

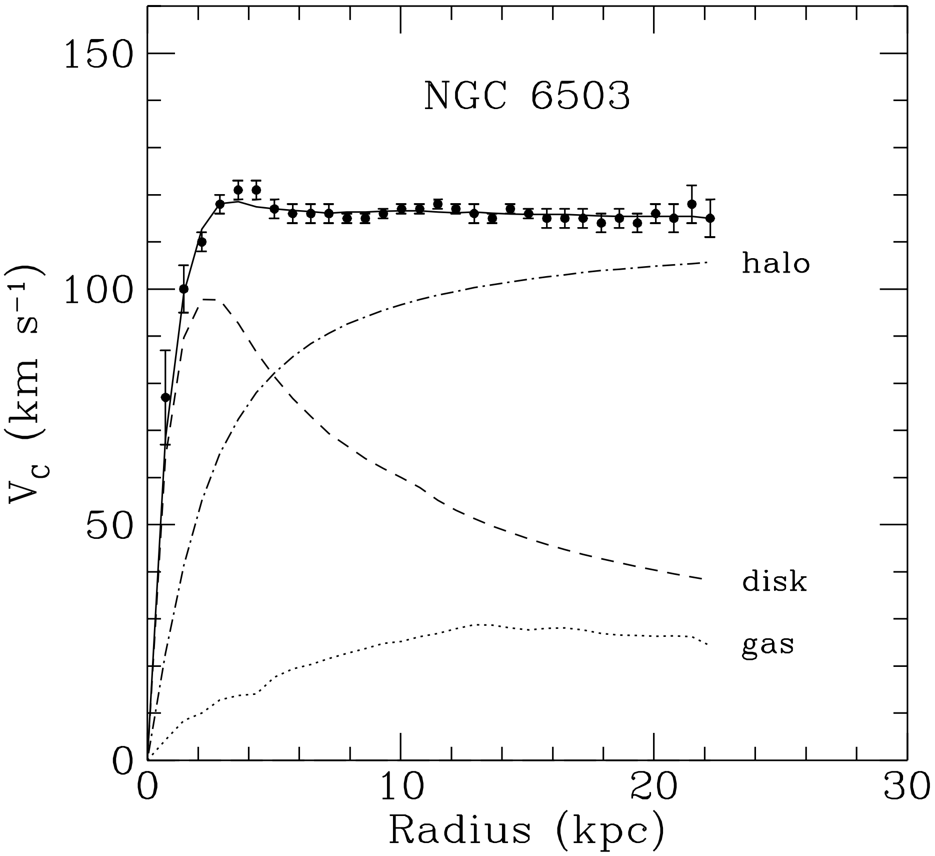

Fig. 1. Rotation curve for the spiral galaxy NGC6503. The points are the measured circular rotation velocities as a function of distance from the center of the galaxy. The dashed and dotted curves are the contribution to the rotational velocity due to the observed disk and gas, respectively, and the dot-dash curve is the contribution from the dark halo. From Ref. 13.

nucleosynthesis suggests a baryon density $\Omega_b \lesssim 0.1$ (Ref. 14). Thus, the bulk of the halo must be nonbaryonic. In the past few years, the existence of nonbaryonic dark matter has received independent and precise confirmation with new CMB results alluded to above. There is simply no good fit to the CMB power spectrum without nonbaryonic dark matter. The data require a nonbaryonic-dark-matter density $\Omega_{\rm dm} h^2 = 0.13 \pm 0.04$ (and h is the Hubble parameter in units of 100 km sec^{-1} Mpc^{-1}).

So, what could this dark matter be? A neutrino species of mass $\mathcal{O}(10\,{\rm eV})$ could provide the right dark-matter density, but N-body simulations of structure formation in a neutrino-dominated Universe do a poor job of reproducing the observed structure.[15] Furthermore, it is difficult to see (essentially the Pauli principle) how such a neutrino could make up the halo dark matter.[16] It appears likely then that some exotic particle dark matter 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,[17,18] and axions.[19]

2.1 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.

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 lepton-antilepton 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 for annihilation of χ's, $\Gamma = \langle\sigma v\rangle\, n_\chi$—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 curve) and actual (dashed

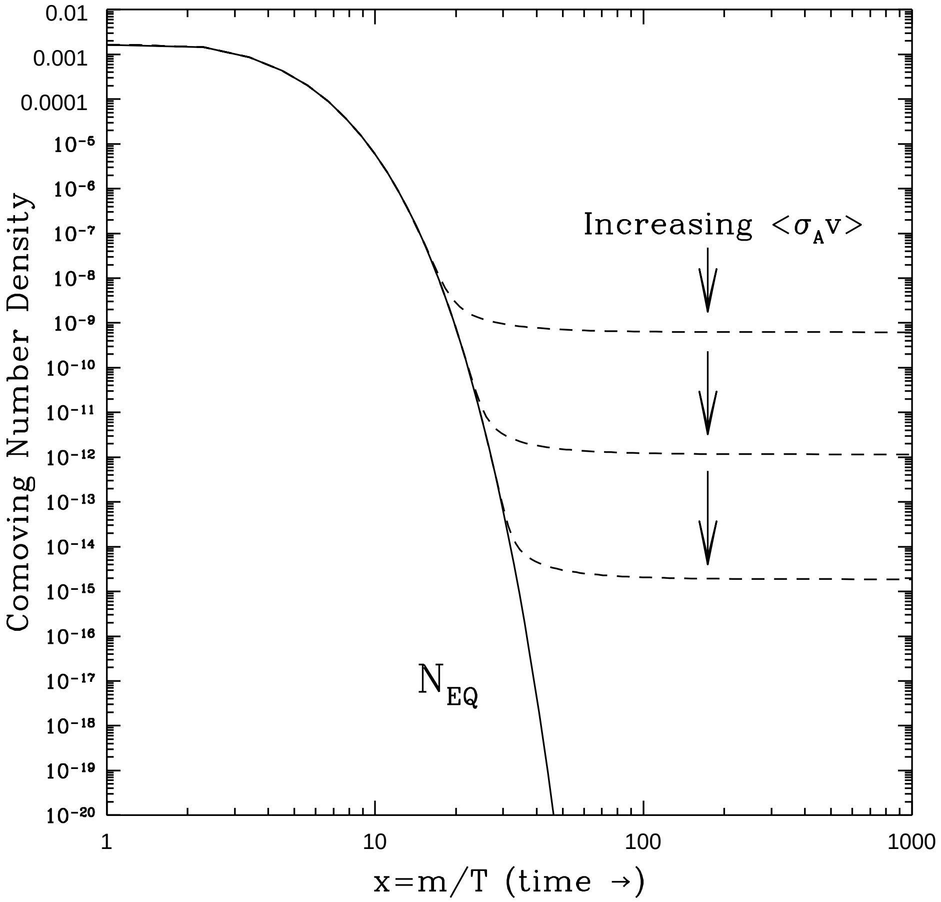

Fig. 2. Comoving number density of WIMPs in the early Universe. The dashed curves are the actual abundances for different annihilation cross sections, and the solid curve is the equilibrium abundance.

curve) abundances of WIMPs per comoving volume are plotted in Fig. 2 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 (in units of the critical density ρ_c),

$$\Omega_\chi = \frac{m_\chi n_\chi}{\rho_c h^2} \simeq \left(\frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{sec}^{-1}}{\langle \sigma_A v \rangle} \right) h^{-2}. \tag{1}$$

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. (1), the WIMP will have a cosmological abundance of order unity today if the annihilation cross section is roughly 10^{-9} GeV^{-2}. Curiously, this is the order of magnitude one would expect from a typical electroweak cross section,

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

where $\alpha \simeq \mathcal{O}(0.01)$ and $m_{\mathrm{weak}} \simeq \mathcal{O}(100\,\mathrm{GeV})$. The numerical constant in Eq. (1) needed to provide $\Omega_\chi \sim 1$ comes essentially from the age of the Universe. But why should the age of the Universe have anything to do with the age of the Universe? This unanticipated coincidence suggests that if a new, as yet undiscovered, stable massive particle with electroweak interactions exists, then it should have a relic density of order unity and is therefore a natural dark-matter candidate. This has been the argument driving the massive experimental effort to detect WIMPs.

The first WIMPs considered were massive Dirac or Majorana neutrinos with masses in the range of a few GeV to a few TeV. (Due to the Yukawa coupling which gives a neutrino its mass, the neutrino interactions become strong above a few TeV, and it no longer remains a suitable WIMP candidate.[20]) LEP 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),[21] and heavier Majorana neutrinos have been ruled out by indirect-detection experiments[22–27] (also described below) over much of their mass range. Therefore, Dirac neutrinos cannot comprise the halo dark matter;[28] 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).[17,18,29] SUSY was hypothesized in particle physics to cure the naturalness problem with fundamental Higgs bosons at the electroweak scale. Coupling-constant unification at the GUT scale seems to be improved with SUSY, and SUSY is 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 are sneutrinos, but these particles interact like neutrinos and have been ruled out over most of the available mass range.[30] 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 abundance is of order unity. In fact, with detailed calculations, one finds that the neutralino abundance in a very broad class of supersymmetric extensions of the standard model is near unity and can therefore account for the dark matter in our halo.[31]

This is illustrated in Fig. 3 where the cosmological abundance Ω_χ (times h^2) is plotted versus the neutralino mass m_χ. Each point represents one supersymmetric model, or equivalently, one choice of the MSSM parameters. Models with $\Omega_\chi h^2 \gtrsim 1$ are excluded if the Universe is at least 10 Gyr old, while those with $\Omega_\chi h^2 \lesssim 0.025$ are cosmologically consistent, but probably give too few neutralinos to account for the dark matter in galactic halos. The numerous models in which the neutralino abundance is between these two limits provide excellent dark-matter candidates.

2.2 Direct Detection of WIMPs

SUSY particles are now the primary targets of the next generation of accelerator experiments. 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.[32–34] 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 $\sigma \sim 10^{-38}\,\mathrm{cm}^2$.

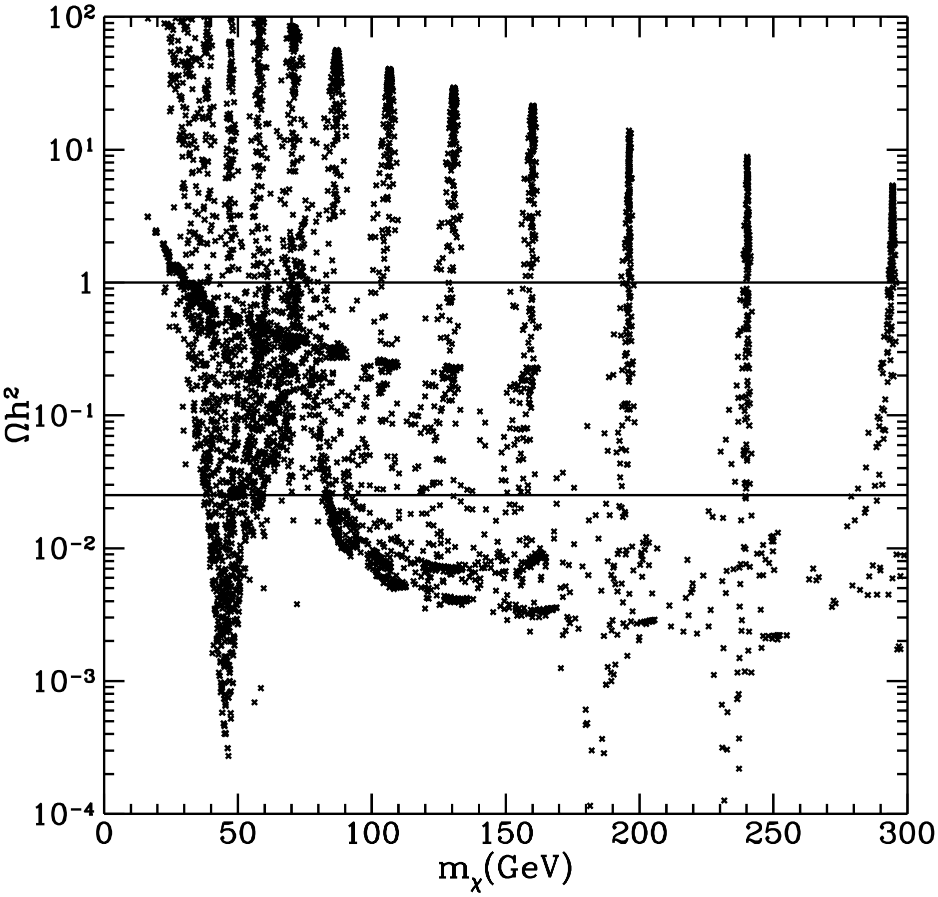

Fig. 3. Cosmological abundance of a WIMP versus the WIMP mass. Each point represents the result for a given choice of the MSSM parameters. The spikes arise simply as a consequence of our method of tiling the SUSY parameter space—they have no physical significance. From Ref. 17.

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 into 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. Therefore, rather than make a single precise prediction, theorists generally survey the available SUSY parameter space. Doing so, one finds event rates between 10^{-4} to 10 events kg^{-1} day^{-1} (Ref. 17), as shown in Fig. 55 of Ref. 17, although there may be models with rates that are a bit higher or lower.

2.3 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.[35] 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 which can escape from the center of the Sun and/or Earth and be detected in neutrino telescopes such as IMB, Baksan, Kamiokande, MACRO, or AMANDA. The energies of these 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).[36] 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 rock below the detector.

The annihilation rate of these WIMPs equals the rate for capture of these particles in the Sun, which can be calculated.[37] 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 m^{-2} yr^{-1} (Ref. 17), as shown in Fig. 57 of Ref. 17, 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 $\lesssim 0.02$ m^{-2} yr^{-1} (Ref. 22–25). Larger and more sensitive detectors such as super-Kamiokande[26] and AMANDA[27] are now operating, and others are being constructed.[38]

2.4 Recent Results

There has been some controversy and excitement among dark-matter experimentalists in recent years. The DAMA collaboration[39] has for several years seen an annual modulation in the event rate in their NaI detector, which they attribute to a WIMP. A WIMP can interact with nuclei either through a scalar interaction (where the WIMP-nucleus cross section scales with the nuclear mass), or through an axial-vector interaction (where the WIMP-nucleus cross section depends on something like the nuclear spin or magnetic moment). If the DAMA modulation is attributed to a WIMP with a scalar interaction with nuclei, then it implies a WIMP mass and WIMP-nucleon cross section in the region indicated in Fig. 4. For several years, null searches in the CDMS Ge detector[40] ruled out most of this region. This past year, new null results from EDELWEISS[41] and ZEPLIN[42] seem to have now ruled out the entire DAMA parameter space.

But what if the WIMP has an axial-vector interaction? Both Na and I have a spin carried primarily by an unpaired proton. Although ^{73}Ge also has a spin carried primarily by a proton, its isotopic abundance is only 7%. Thus, if the DAMA modulation is due to a WIMP with a spin-dependent interaction with protons, it would evade detection in CDMS[43] (and probably also in EDELWEISS; a careful analysis is now in progress[44]). In Ref. 43, however, we showed using the model-independent analysis of Refs. 45 that if the DAMA modulation were attributed to a WIMP-proton axial-vector interaction,

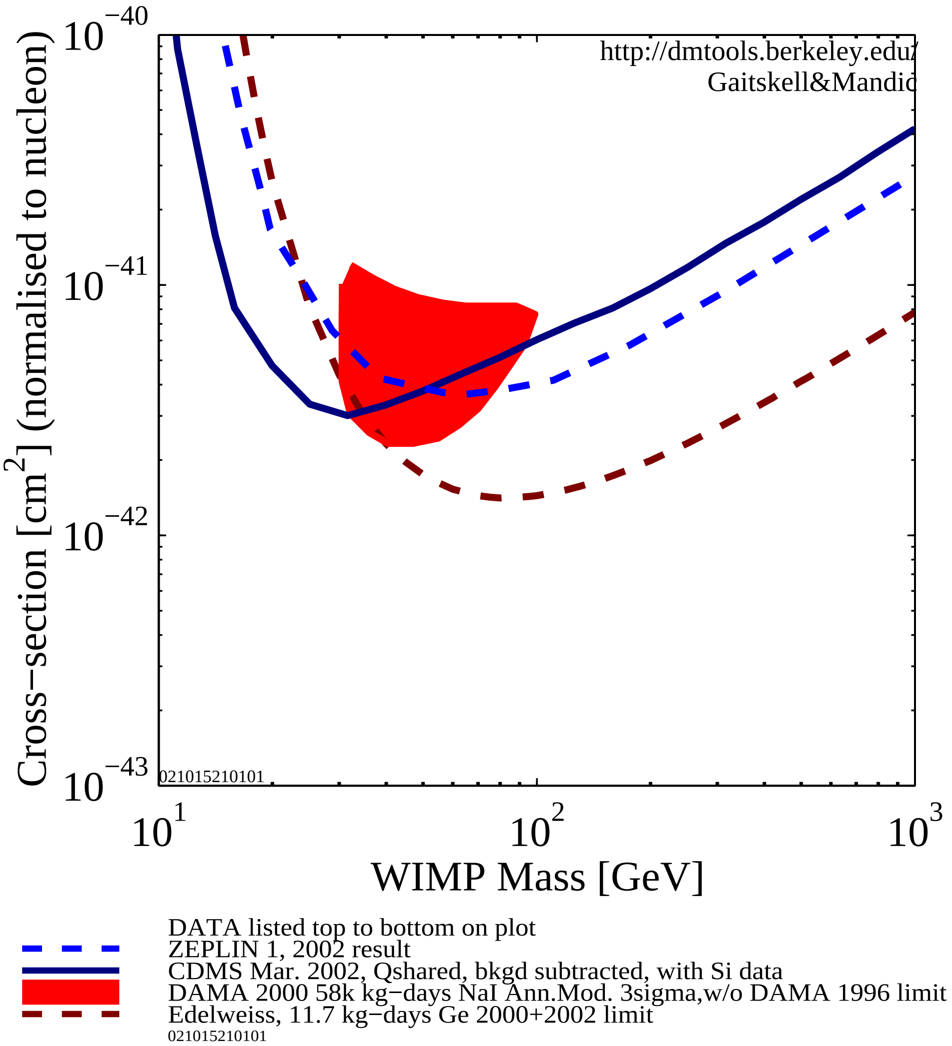

Fig. 4. The regions of the WIMP mass–cross-section parameter space for a WIMP with scalar interactions with nucleons. The shaded area is the parameter space inferred from the DAMA modulation, and the curves show upper limits from CDMS, EDELWEISS, and ZEPLIN. (From `http://dmtools.berkeley.edu`.)

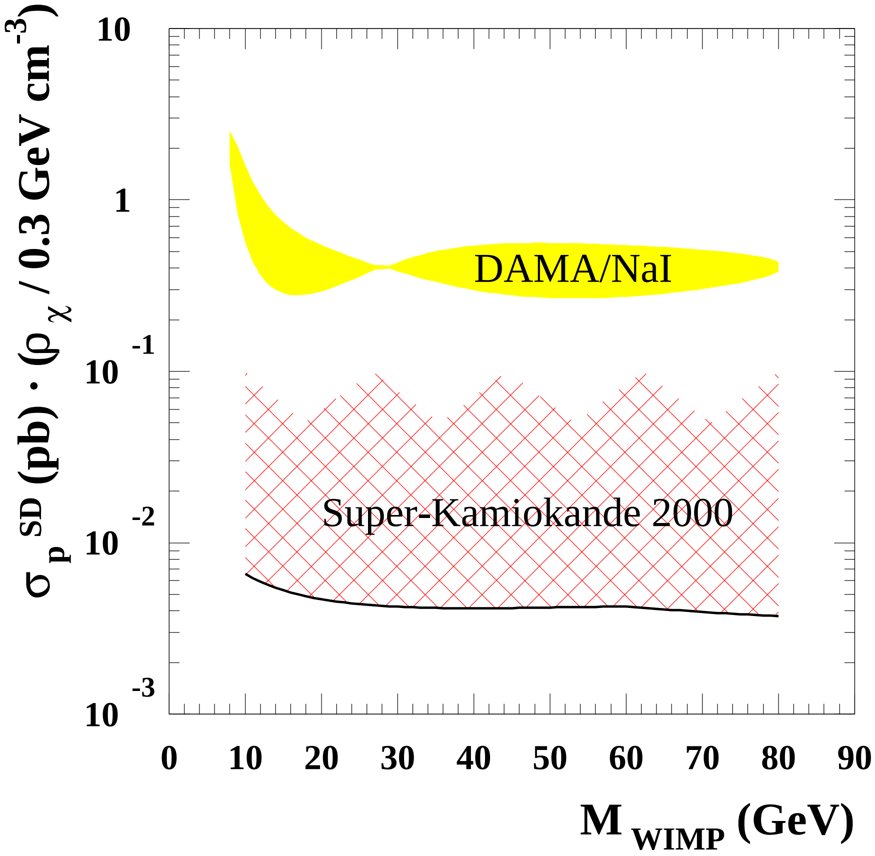

Fig. 5. The regions of the WIMP mass–cross-section parameter space for a WIMP with axial-vector interactions with protons. The shaded region shows the parameter space inferred if the DAMA modulation is attributed to a WIMP with only a spin-dependent interaction with protons. The lower curve is the upper limit from Super-Kamiokande. From Ref. 43.

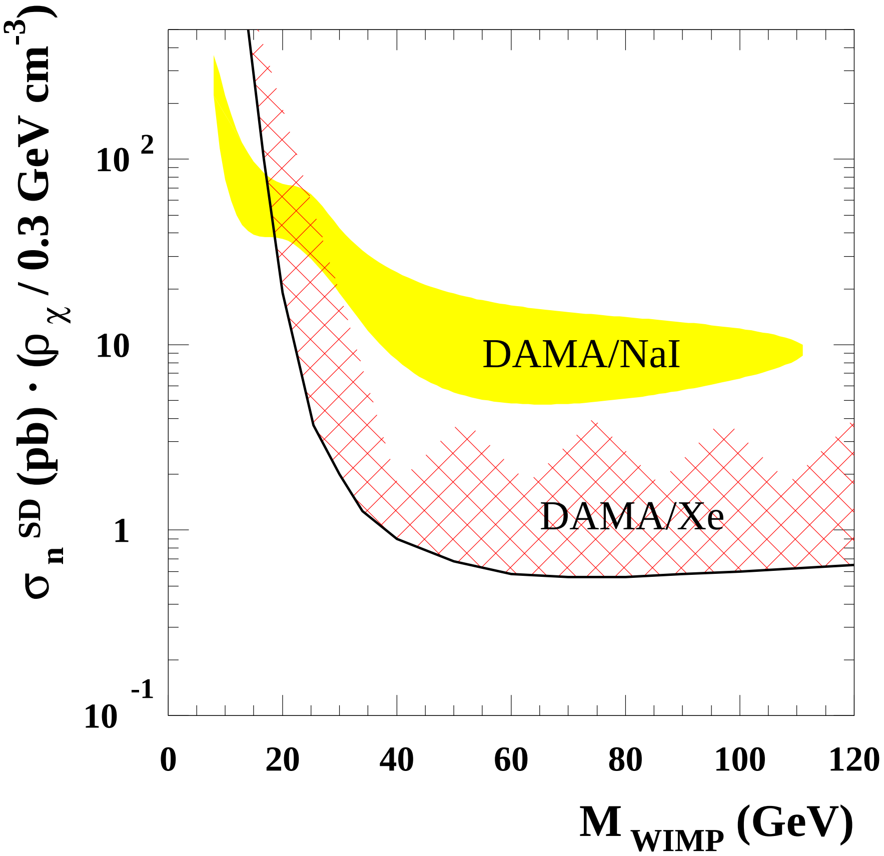

Fig. 6. The regions of the WIMP mass–cross-section parameter space for a WIMP with axial-vector interactions with neutrons. The shaded region shows the parameter space inferred if the DAMA modulation is attributed to a WIMP with only a spin-dependent interaction with neutrons. The lower curve is the upper limit from the DAMA Xe experiment. From Ref. 43.

then these WIMPs would accumulate efficiently in the Sun (which is made primarily of protons) and annihilate therein. The resulting flux of energetic neutrinos would have been well over an order of magnitude larger than the current upper bounds from Kamiokande, Baksan, and MACRO, as shown in Fig. 5. Alternatively, a small fraction of the nuclear spins in Na and I could be due to neutrons, and if so, the DAMA modulation could be explained by a WIMP with a spin-dependent interaction with neutrons. In this case, however, the WIMP-neutron interaction would have to be quite strong, and the WIMP would have already shown up in another of DAMA's detectors that is made of Xe, as shown in Fig. 6, and probably also in ZEPLIN (a detailed analysis is now in progress[44]).

2.5 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. As illustrated in Fig. 7,[46] WIMP annihilation might produce a cosmic-ray-positron excess at high energies.[46,47] 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.[48]

WIMP annihilation will produce an antiproton excess at low energies,[49] although Ref. 50 claims that 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.

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,[51,52] 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-

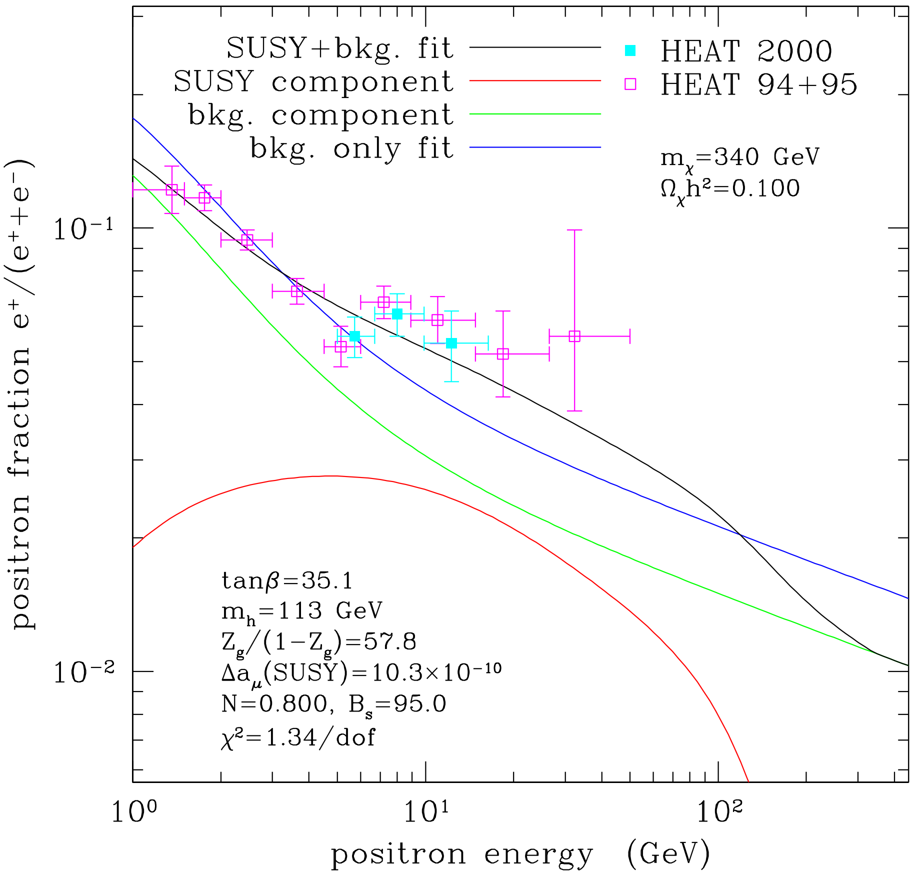

Fig. 7. The differential positron flux divided by the sum of the differential electron-plus-positron flux. Shown are the HEAT data as well as theoretical models of background and the background with a supersymmetric dark-matter annihilation signal added. From Ref. 46.

based experiments like STACEE or CELESTE or the GLAST satellite will seek this annihilation radiation.

It was recently argued[53] 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.[54]

2.6 Axions

The other leading dark-matter candidate is the axion.[19] The QCD Lagrangian may be written

$$\mathcal{L}_{QCD} = \mathcal{L}_{\rm pert} + \theta \frac{g^2}{32\pi^2} G\widetilde{G}, \qquad (3)$$

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 CP. 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,[55] which twenty-five years after it was proposed still seems to be the most promising solution. A global $U(1)_{PQ}$ symmetry broken at a scale f_{PQ}, and θ yields a dynamical field which is the Nambu-Goldstone mode of this symmetry. At temperatures below the QCD phase transition, nonperturbative quantum effects break explicitly the symmetry and drive $\theta \to 0$. The axion is the pseudo-Nambu-Goldstone boson of this near-global symmetry. Its mass is $m_a \simeq \,{\rm eV}\,(10^7\,{\rm GeV}/f_a)$, 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, stellar evolution, 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 may therefore 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}.

If $m_a \sim 10^{-4}$ eV, the magnitude of the explicit symmetry breaking is incredibly tiny compared with the PQ scale, so the global PQ symmetry, although broken, must be very close to exact. There are physical arguments involving, for example, the nonconservation of global charge in evaporation of a black hole produced by collapse of an initial state with nonzero global charge, that suggest that global symmetries should be violated to some extent in quantum gravity. In order for the PQ mechanism to work for $m_a \sim 10^{-4}$, the coupling of a generic global-symmetry-violating term from quantum-gravity effects must be extraordinarily small (e.g., $\lesssim 10^{-55}$).[56] 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.[57] Therefore, these arguments by no means "rule out" the axion solution. Rather, discovery of an axion would provide much needed clues to the nature of Planck-scale physics.

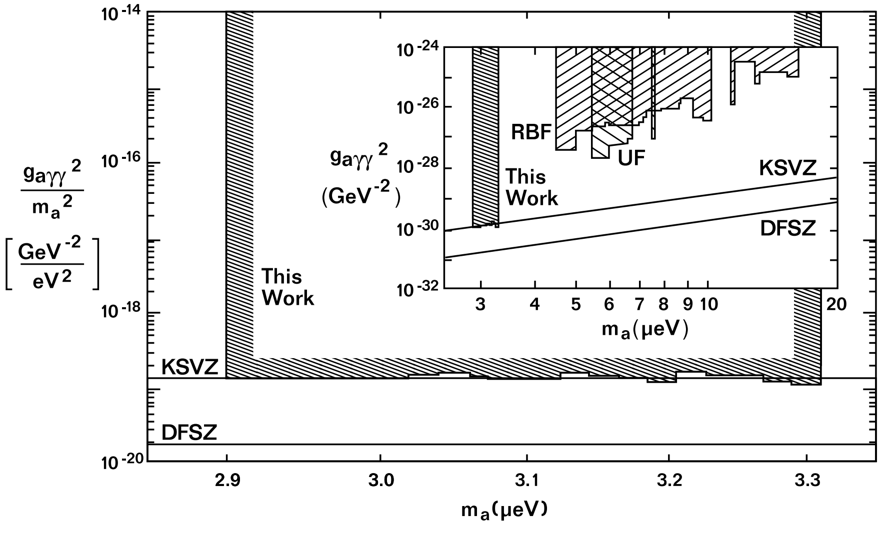

Fig. 8. Regions of axion mass-coupling parameter space currently being probed by an ongoing search at Livermore.[59]

There is a very weak coupling of an axion to photons through the anomaly. The axion can therefore decay to two photons, but the lifetime is $\tau_{a\rightarrow\gamma\gamma} \sim 10^{50}\,\mathrm{s}\,(m_a/10^{-5}\,\mathrm{eV})^{-5}$ 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.[58] Such an experiment is currently underway[59] and has already begun to probe part of the cosmologically interesting parameter space (see Fig. 8), and it should cover most of the interesting region parameter space in the next few years. A related experiment, which looks for excitations of Rydberg atoms, is also seeking dark-matter axions.[60] Although the sensitivity of this technique should be excellent, it can only cover a limited axion-mass range. The CERN Axion Solar Telescope (CAST) project[61] is searching for $m_a \simeq O(\mathrm{eV})$ axions by looking for resonant conversion of thermal axions from the Sun into x rays. This mass range is available only if there are loopholes in the stellar-evolution calculations that nominally exclude these masses.

2.7 Self-Interacting Dark Matter?

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,[62] while some dwarf-galaxy rotation curves indicate the existence of a density core in their centers.[63] This has prompted some theorists to consider self-interacting dark matter.[64] 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; in this way, the cusp can be smoothed into a core. In order for this mechanism to work, however, the elastic-scattering cross section must be $\sigma_{\mathrm{el}} \sim 10^{-(24-25)}(m_\chi/\mathrm{GeV})$ 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,[65] and if it is weaker, the heat transport is not sufficiently efficient 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. 66). 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.[67] 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.[68]

3 The Cosmic Microwave Background, Large-Scale Structure, and Inflation

3.1 Recent Progress in the CMB

In the past few years, the cosmic microwave background (CMB) has begun to provide perhaps the most exciting opportunity for learning about new physics at ultra-high-energy scales (for recent reviews, see, e.g., Refs. 69–71). We have already seen spectacular advances in measurements of temperature fluctuations in the CMB[4–8] that have led to major advances in our ability to characterize the largest-scale structure of the Universe, the origin of density perturbations, and the early Universe. In just the past few months we have seen the first detection of CMB polarization[72] and a spectacular measurement of fluctuations from 10-degree to sub-degree angular scales.[9] In the next few months we should see even more improvements from the MAP satellite,[73] and even more with the launch of the Planck satellite[74] in 2007.

The primary aim of these experiments has been to determine the CMB power spectrum, C_ℓ, as a function of multipole moment ℓ. Structure-formation theories predict a series of bumps in the power spectrum in the region $50 \lesssim \ell \lesssim 1000$, arising from oscillations in the baryon-photon fluid before CMB photons last scatter.[75] The rich structure in these peaks allows simultaneous determination of the geometry of the Universe,[3,76] the baryon density, Hubble constant, matter density, and cosmological constant, as well as the nature (e.g., adiabatic, isocurvature, or topological defects) and spectrum of primordial perturbations.[77]

Within the past two years, three independent experiments that use different techniques, observing strategies, and frequencies have each measured the power spectrum

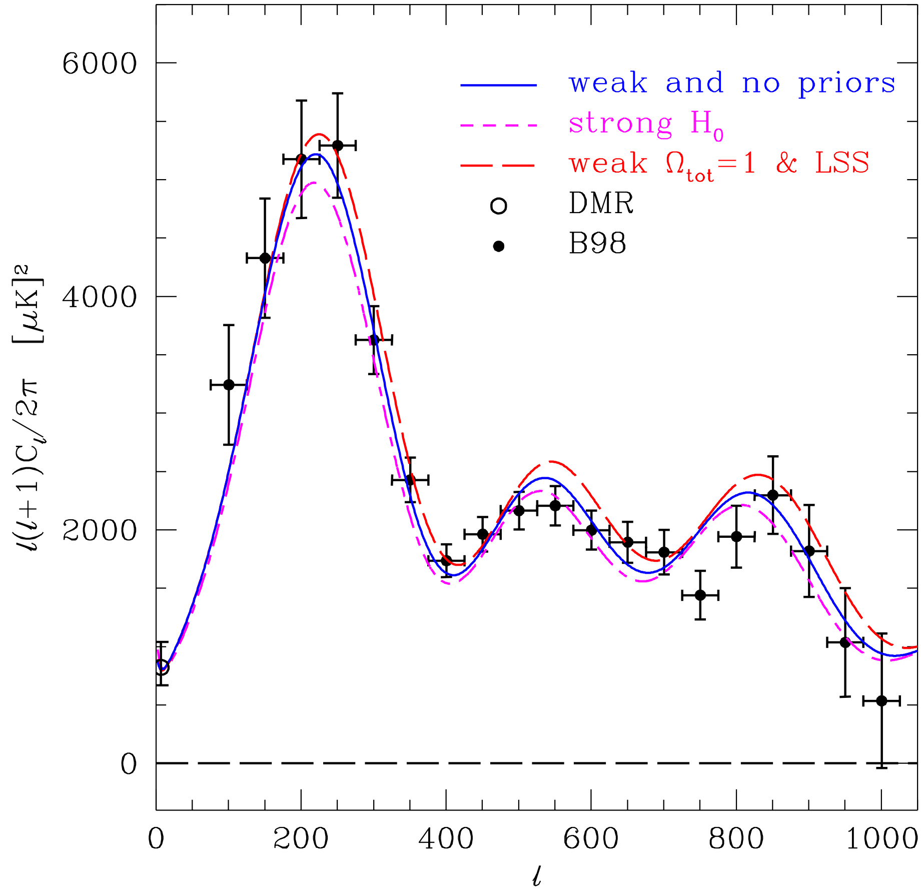

Fig. 9. The CMB power spectrum measured recently by BOOMERanG.[78] Similar results have been obtained also by DASI[7] and MAXIMA.[79]

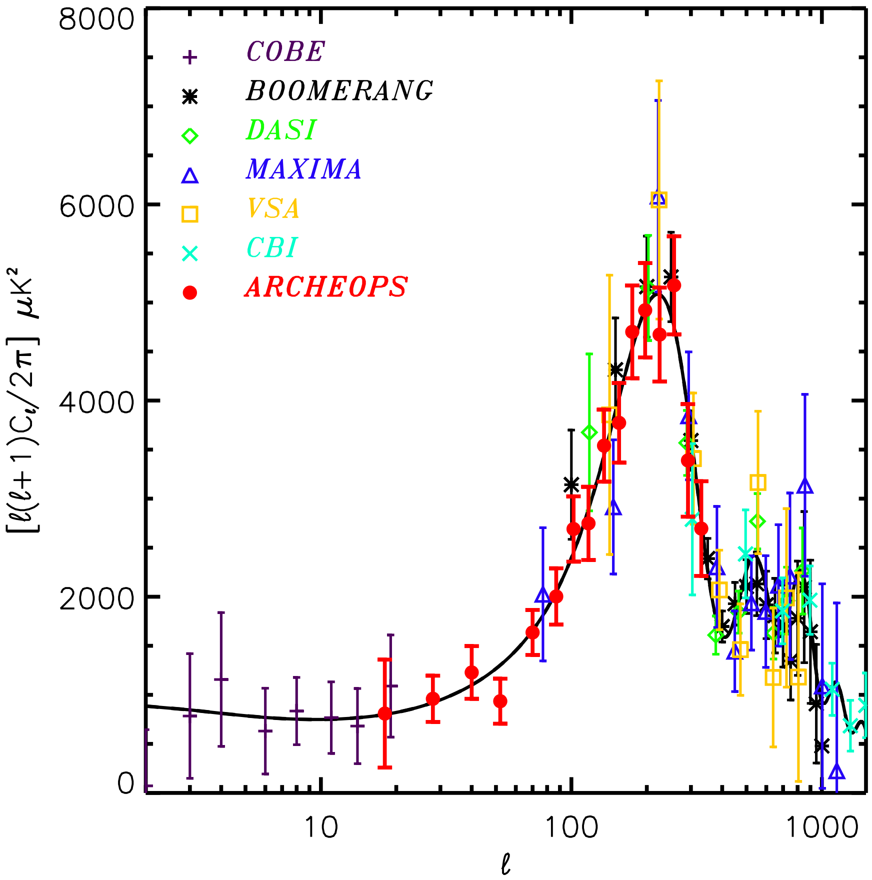

Fig. 10. The CMB power spectrum measured recently by ARCHEOPs, as well as by previous experiments. From Ref. 9.

in the range $50 \lesssim \ell \lesssim 1000$ (Refs. 78,79,72), and the existence of the second and third peaks has now been confirmed,[78] as shown in Fig. 9. These experiments represent a watershed event in cosmology, as they suggest for the first time that the Universe is flat and that structure grew from a nearly scale-invariant spectrum of primordial density perturbations. These two properties are robust predictions of inflation,[80,81] a period of accelerated expansion in the very early Universe driven by the vacuum energy associated with some new, yet undetermined, ultra-high-energy physics. The new results from ARCHEOPS,[9] shown in Fig. 10, overlap and also interpolate between the largest-angle measurements from COBE and the degree-scale experiments. The agreement with the earlier experiments is stunning.

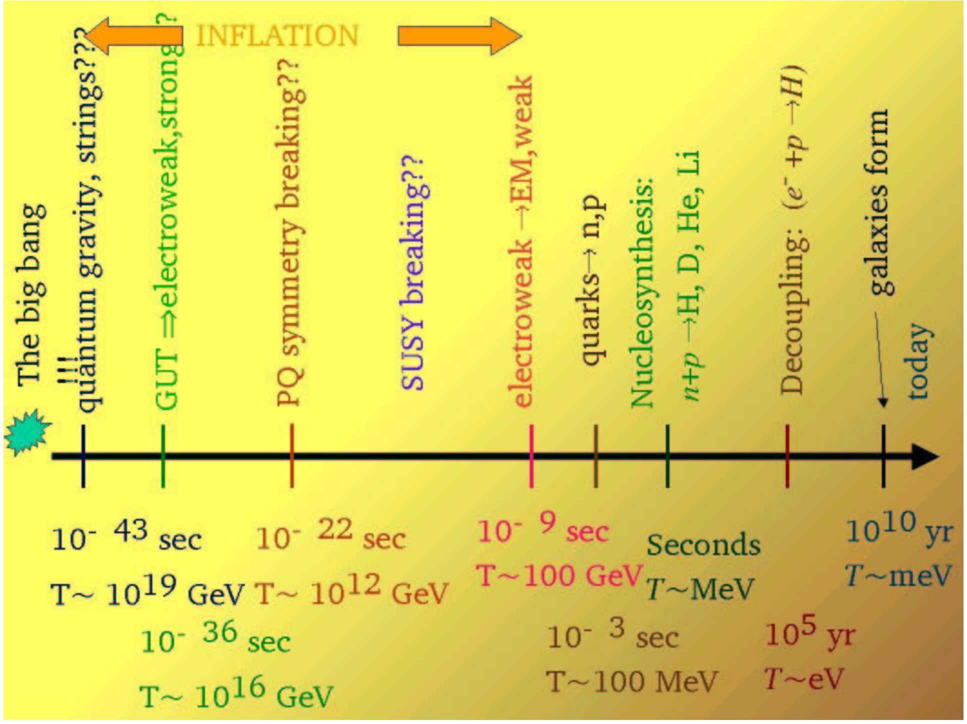

Fig. 11. Logarithmic history of the Universe.

Although these recent CMB tests suggest that we are on the right track with inflation, we still have no idea what new physics may have given rise to inflation. Plausible theoretical models place the energy scale of inflation anywhere from the Planck scale to the electroweak scale, and associate the inflaton (the scalar field responsible for inflation) with new fields that arise in string theory, GUTs, the Peccei-Quinn mechanism, supersymmetry breaking, and electroweak-scale physics, as shown in Fig. 11.

3.2 Inflation, Gravitational Waves, and CMB Polarization

Perhaps the most promising avenue toward further tests of inflation as well as determination of the energy scale of inflation is the gravitational-wave background. Inflation predicts that quantum fluctuations in the spacetime metric during inflation should give rise to a stochastic gravitational-wave background with a nearly-scale-invariant spectrum (defined to be the fourth root of the inflaton potential during inflation).[82] Inflation moreover predicts that the amplitude of this gravitational-wave background should be proportional to the square of the energy scale of inflation.

These gravitational waves will produce temperature fluctuations at large angles. Upper limits to the amplitude of large-angle temperature fluctuations already constrain the energy scale of inflation to be less than 3×10^{16} GeV. However, since density perturbations can also produce such temperature fluctuations, observed temperature fluctuations cannot alone be used to detect the gravitational-wave background.

Instead, progress can be made with the polarization of the CMB. Both gravitational waves and density perturbations will produce linear polarization in the CMB, and the two polarization patterns differ. More precisely, gravitational waves produce polarization with a distinctive curl pattern that cannot be mimicked by density perturbations (at linear order in perturbation theory; see below).[83,84] Moreover, inflation robustly predicts that the amplitude of this curl depends on the square of the energy scale of inflation.

Is this signal at all detectable? If the energy scale of inflation is much below the GUT scale, then the polarization signal will likely be too small to ever be detected. However, if inflation had something to do with GUTs—as many, if not most theorists believe—then the signal is conceivably detectable by a next-generation CMB experiment.[85] Although the MAP satellite, launched just last month, is unlikely to have sufficient sensitivity to detect the curl component from inflationary gravitational waves, the Planck satellite, a European Space Agency experiment to be launched in 2007, should have sufficient sensitivity to detect the CMB curl component as long as the energy scale of inflation is greater than roughly 5×10^{15} GeV. However, Planck will not be the end of the line. An experiment that integrates more deeply on a smaller region of sky can improve the sensitivity to the inflationary gravitational-wave background by almost two orders of magnitude.[86] Moreover, there are several very promising ideas being pursued now that could improve the detector sensitivity by more than an order of magnitude within the next decade. Putting these two factors together, it becomes likely that a CMB polarization experiment that probes inflationary energy scales to below 10^{15} GeV—and thus accesses the entire favored GUT parameter space—could be mounted on a ten-year timescale (if not sooner).

3.3 Cosmic Shear and the CMB

There is, however, another source of a curl component. Cosmic shear (CS)—weak gravitational lensing of the CMB due to large-scale structure along the line of sight—results in a fractional conversion of the gradient mode from density perturbations to the curl component.[87] 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.[88–90]

In addition to producing a curl component, CS also introduces distinct higher-order correlations in the CMB temperature pattern. 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.[91] 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. 89,90 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. Ultimately, if the energy scale is $E_{\rm infl} \lesssim 2 \times 10^{15}$ GeV, then there will be an irreducible cosmic-shear-induced curl, even with higher-order correlations. Thus, if the energy scale of inflation is below this value, the gravitational-wave background will not be detectable with the CMB polarization. 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.

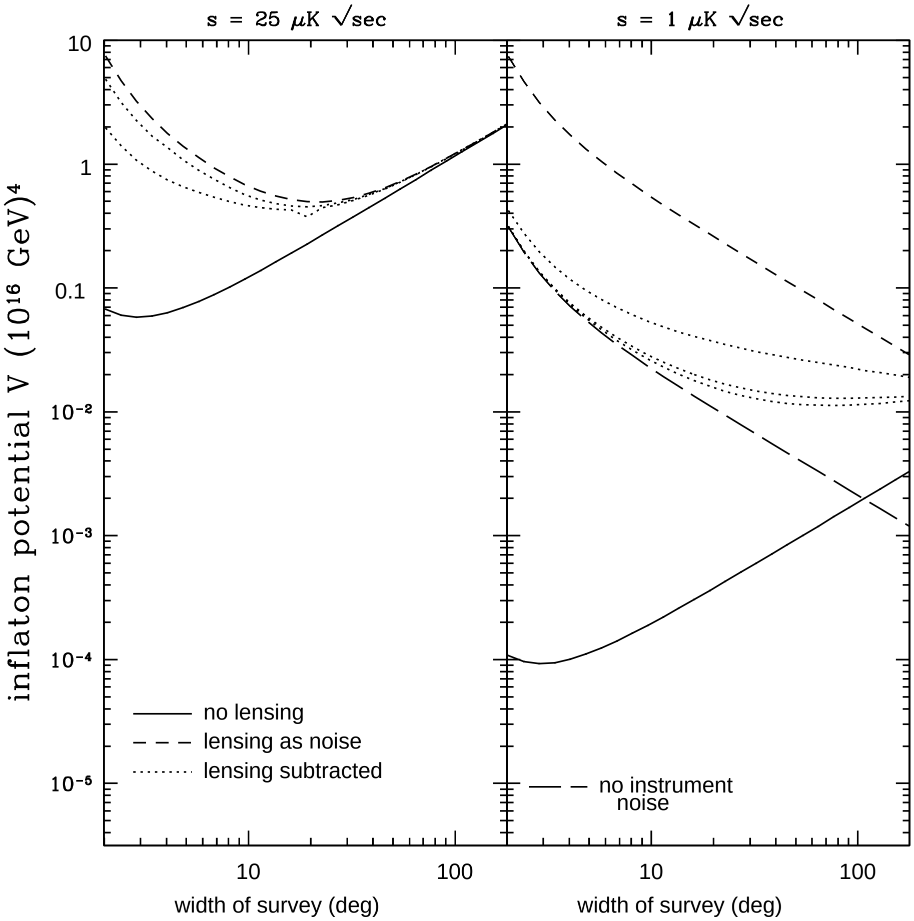

Fig. 12. Minimum inflation potential observable at 1σ as a function of survey width for a one-year experiment. The left panel shows an experiment with noise-equivalent temperature (NET, the detector sensitivity) $s = 25\,\mu\mathrm{K}\,\sqrt{\mathrm{sec}}$. The solid curve shows results that could be obtained if there were no cosmic shear. The long-dash curve shows the minimum detectable inflaton-potential height with the optimal detection strategy. See Ref. 89 for more details and a full description of the other curves.

3.4 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. See Ref. 92 for a brief review.

3.5 Structure Formation and Inflation

Large-scale galaxy surveys have become a reality, particularly with the advent of the Two-Degree Field[93] and Sloan Digital Sky Surveys.[94] We are now mapping the distribution of galaxies over huge volumes in the Universe. Moreover, just over two years ago, four independent groups reported detection of cosmic shear through the observation of ellipticity correlations in distant galaxies.[95] In the future, cosmic-shear measurements will map the distribution of matter (rather than just the luminous matter probed by galaxy surveys) over large volumes of space .

If the big bang is a cosmic accelerator, subtle correlations in the debris from the explosion can provide valuable information on inflation, just as subtle correlations in jets in accelerator experiments can provide information about the collisions that give rise to them. The primary aims of galaxy surveys and cosmic-shear maps are determination of the power spectrum $P(k)$ of the cosmological matter distribution as a function of wavenumber (inverse distance) k. These measurements are important for the study of inflation, as inflation relates the amplitude and shape of the power spectrum $P(k)$ to the inflaton potential $V(\phi)$ as a function of the value ϕ of the inflaton. Measurements of $P(k)$ with the CMB at the very largest scales, to intermediate scales with galaxy surveys, to the smallest scales with subgalactic structure[96] are now being pursued. Moreover, as discussed above, inflation predicts very precise relations between all of the higher-order correlation functions for the primordial mass distribution and its two-point correlation function, and these relations can also be tested with the observed distribution of mass in the Universe today. The growth of density perturbations via gravitational infall alters the precise structure of the correlation hierarchy from the primordial one. However, it does so in a calculable way so that the primordial distribution of density perturbations (Gaussian as predicted by inflation? or otherwise?) can be determined from the distribution observed in the Universe today.[97]

Information about the primordial distribution of matter can also be obtained by studying the abundances and properties of the rarest objects in the Universe: clusters of galaxies today and galaxies at high redshift (see, e.g., Ref. 98). Such objects form at rare ($\gtrsim 3\sigma$) high-density peaks in the primordial density field. Inflation predicts that the distribution of such peaks should be Gaussian. If the distribution is non-Gaussian—for example, skew-positive with an excess of high-density peaks—then the abundance of these objects can be considerably larger. In such skew-positive models, such objects would also form over a much wider range of redshifts and thus exhibit a broader range of properties (e.g., sizes, ages, luminosities, temperatures).[99]

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 over the past few years: roughly 70% of the energy density of the Universe is in the form of some mysterious negative-pressure "dark energy".[100] Supernova evidence for an accelerating Universe[10,11] has now been dramatically bolstered by the discrepancy between the total cosmological density $\Omega_{\rm tot} \simeq 1$ indicated by the CMB and dynamical measurements of the nonrelativistic-matter density $\Omega_m \simeq 0.3$.

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. For this dark energy to accelerate the expansion, its equation-of-state parameter $w \equiv p/\rho$ must satisfy $w < -1/3$, 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[101] or spintessence,[102] 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. (In fact, equations of state $w < -1$, which violate the dominant-energy condition in general relativity, have now been considered as well.[103])

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.

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.

The obvious first step to understand the nature of this dark energy is to determine whether it is a true cosmological constant, or whether its density evolves with time. 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 current best bet for determining the expansion history is with supernova searches, particularly those that can reach to 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 DMT[104] or WFHRI[105]) and space-based (e.g., SNAP[106]) supernova searches can be used to determine the expansion history. However, for redshifts $z \gtrsim 1$, the principal optical supernova emission (including the characteristic silicon absorption feature) gets shifted to the infrared which is obscured by the atmosphere. Thus, a space-based observatory appears to be advisable to reliably measure the expansion history in the crucial high-redshift regime.

Although supernovae provide perhaps the most direct probe of the expansion history, there are a number of other indirect probes as well. Rather than review them all, I simply discuss, as an example, one proposal made recently by N. Weinberg and me.[107,108] Wide-angle cosmic-shear surveys of blank regions of the sky have already begun, and much larger surveys will soon to be undertaken. Individual galaxy clusters should be detectable in these cosmic-shear maps, but it is possible that proto-clusters, massive overdensities that are still in the process of undergoing gravitational collapse, will also appear in these surveys. Unlike virialized clusters (i.e., those that have undergone gravitational collapse), which emit copious amounts of x-ray radiation, these nonvirialized clusters should be x-ray underluminous, or appear dark in x-ray bands. We showed that the abundance of both virialized and dark clusters that will be detected in a given cosmic-shear survey, as well as the ratio of the two, will depend on the equation-of-state parameter w, as shown in Fig. 13. At least 50 square degrees will need to be surveyed in order for this test to be carried out.

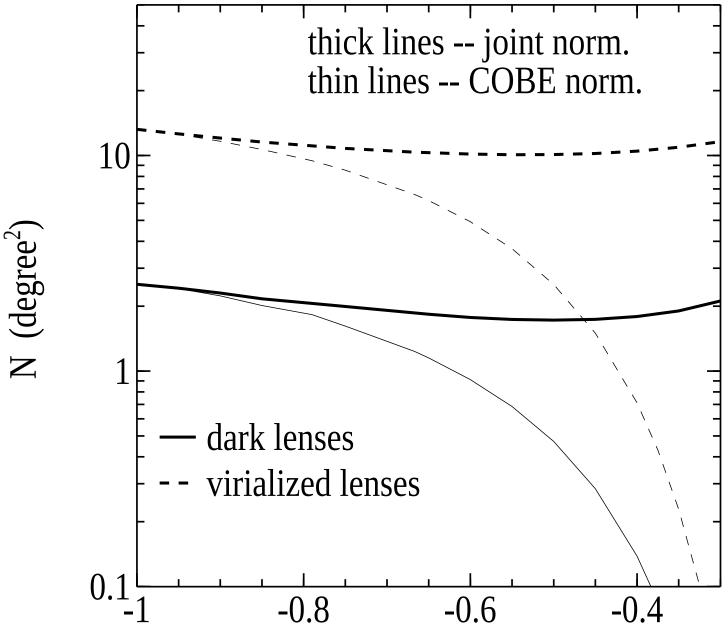

Fig. 13. The number per square degree of virialized (x-ray luminous) and dark(x-ray underluminous) clusters that should be detected in in a cosmic-shear survey. The solid and dashed curves are for power spectra normalized to COBE and to the cluster abundance. For each value of w, there is a unique normalization that fits both COBE and the cluster abundance. See Ref. 108 for more details.

Most discussions of observational probes of dark energy have involved the effects of quintessence on the expansion history. However, if a quintessence field exists, it may have some couplings to ordinary matter. If so, it could give rise to other observable.consequences. In particular, if the cosmological "constant" evolves with time (i.e., is quintessence), then there is a preferred frame in the Universe. Couplings of elementary particles to the quintessence field may thus give rise to small apparent violations of Lorentz and/or CPT symmetry (see, e.g., Ref. 109). A variety of accelerator and astrophysical experiments[109,110] can be done to search for such exotic signatures.

5 Summary and Conclusions

Particle astrophysics and cosmology now represent a very broad and active research front in non-accelerator probes of new physics beyond the standard model. Here I have reviewed dark-matter searches, the relation between observations of the cosmic microwave background, the current cosmological mass distribution, and the early Universe, and the dark-energy problem. There are a number of related topics that I did not discuss, such as neutrino astrophysics, the cosmology of extra large dimensions, cosmic rays, and the growing connections between gamma- and x-ray astrophysics and particle physics. At first, some degree of skepticism may be warranted when discussing astrophysics as a laboratory for advances in fundamental physics. On the other hand, there is no question that cosmology is now in the process of making incredible strides, and should continue to do so for the foreseeable future. Moreover, there are several precedents, including a very recent and very decisive one, for discovering new fundamental physics with astrophysical observations or sources. Whether these precedents will be followed in the future will ultimately only be determined with further vigorous cosmological experimentation.

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