Planning the Future of U.S. Particle Physics
Report of the 2013 Community Summer Study

Chapter 4: Cosmic Frontier

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Executive summary

Investigations at the Cosmic Frontier use the Universe as a laboratory to learn about particle physics. Our understanding of the Universe has been transformed in recent years. In particular, experiments at the Cosmic Frontier have demonstrated that only 5% of the contents of the Universe are well understood, with the rest composed of mysterious dark matter and dark energy. As a result, the Cosmic Frontier now plays a central role in the global particle physics program, providing overwhelming evidence for new particles and new interactions, as well as powerful, unique opportunities to address many of our most fascinating questions: What is dark matter? What is dark energy? Why is there more matter than antimatter? What are the properties of neutrinos? How did the Universe begin? What is the physics of the Universe at the highest energies?

To identify outstanding scientific opportunities for the coming 10 to 20 years, the Cosmic Frontier Working Group was organized into six subgroups: 1. WIMP Dark Matter Direct Detection, 2. WIMP Dark Matter Indirect Detection, 3. Non-WIMP Dark Matter, 4. Dark Matter Complementarity, 5. Dark Energy and CMB, and 6. Cosmic Particles and Fundamental Physics. In several cases, these subgroups were further divided into topical working groups. The work of these groups was carried out through teleconferences and meetings, including the Cosmic Frontier Workshop at SLAC, March 6–8, 2013 (http://www-conf.slac.stanford.edu/cosmic-frontier/2013), and the Community Summer Study 2013 meeting in Minnesota, July 29–August 6, 2013 (http://www.hep.umn.edu/css2013). More complete summaries and references than can be presented here may be found in the talks from these meetings, and the subgroup and topical group summaries [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15].

The ΛCDM standard model of cosmology provides the backdrop for much of Cosmic Frontier research. In this model, the Universe underwent a very early epoch of accelerated expansion (inflation), which was followed by eras in which the Universe was dominated successively by radiation, cold dark matter (CDM), and dark energy (Λ). At present, the known particles make up only 5% of the energy density of the Universe, with neutrinos contributing at least 0.1%. The rest is 25% dark matter and 70% dark energy. Remarkably, incisive measurements that explore all of the key components of the model are now within reach. The leaps in sensitivity of the new facilities bring us to a time with strong discovery potential in many areas. Further surprises are likely in this rapidly advancing area, with potentially far-reaching consequences.

Dark matter

The work of Snowmass highlighted the coming decade as one of particular promise for the goal of identifying dark matter. Evidence for particle dark matter has been building for 80 years through the study of galaxy clusters, galactic rotation curves, weak lensing, strong lensing, hot gas in galaxy clusters, galaxy cluster
collisions, supernovae, and the cosmic microwave background (CMB). However, all evidence so far is based on dark matter’s gravitational interactions, and its particle identity remains a deep mystery.

Among the many dark matter candidates, one well-known possibility is weakly-interacting massive particles (WIMPs) with masses in the 1 GeV to 100 TeV range. Particles with these masses are strongly motivated by particle physics, where they appear in many models designed to address the gauge hierarchy problem (the great discrepancy between the weak and Planck mass scales), and by cosmology, where they may obtain the correct relic density either through thermal freeze-out or through an asymmetry connecting their number density to that of baryons.

WIMP direct detection experiments search for the interactions of WIMPs with normal matter. WIMPs may scatter elastically off nuclei, producing recoil energies in the 1–100 keV range, which can be detected through phonons, ionization, scintillation, or other methods. There are daunting backgrounds, and so direct detection experiments must be placed deep underground. In the last several years, however, this field has seen a burgeoning of innovative approaches to discriminate signal from background, including experiments incorporating dual-phase media, self shielding, pulse shape discrimination, and threshold detectors.

The first two decades of direct detection experiments have yielded a diverse and successful program, resulting in “Moore’s Law”-type progress, with sensitivities doubling roughly every 18 months. In the coming decade, this rate of progress is expected to continue or even accelerate for both spin-independent and spin-dependent interactions. Upcoming second generation (G2) experiments will improve sensitivities by an order of magnitude, probing the Higgs-mediated cross sections expected for well-known supersymmetric and extra-dimensional candidates, and also extending the sensitivity to both ~ GeV low-mass WIMPs, where possible signals have been reported, and ~ TeV masses that are beyond the reach of colliders. Following these experiments, multi-ton-scale third generation (G3) experiments are expected to improve current sensitivities by up to three orders of magnitude and will either find dark matter or detect background events from solar, atmospheric, and diffuse supernovae neutrinos. Probing beyond this sensitivity will require either background subtraction or techniques such as directional detection or annual modulation. The Snowmass process produced a detailed census of present and proposed direct detection facilities, with uniform treatment of their capabilities and issues, along with a survey of promising technologies.

WIMPs may also be found through indirect detection, in which pairs of WIMPs annihilate, producing Standard Model particles, including gamma rays, neutrinos, electrons and positrons, protons and antiprotons, and deuterons and antideuterons. Detection of these particles may be used to constrain or infer dark matter properties. The expectation that WIMP annihilation in the early Universe determines the dark matter abundance sets a natural velocity-averaged annihilation cross section of \( \langle \sigma_{an} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \) for indirect detection experiments.

Gamma rays from dark matter annihilation may be detected by both space- and ground-based experiments. In space, the Fermi-LAT has recently demonstrated the promise of this approach, excluding the natural cross section \( \langle \sigma_{an} v \rangle \) for dark matter masses below 30 GeV, given certain halo profile and annihilation channel assumptions, and the reach is expected to be extended significantly with additional data. On the ground, VERITAS and other atmospheric Cherenkov telescopes have set significant limits by looking for gamma rays from dark matter-rich dwarf galaxies. Moving forward, the atmospheric Cherenkov telescope community has coalesced to build the Cherenkov Telescope Array (CTA), with sensitivity at the natural cross-section scale for dark matter masses from 100 GeV to 10 TeV, far beyond current or planned colliders, for conservative halo profiles and many of the possible annihilation channels. These projections require U.S. involvement in CTA, which will double the planned mid-sized telescope array and enable critical improvements in sensitivity and angular resolution.
Neutrinos also provide promising means for indirect detection of dark matter. High-energy neutrinos from the core of the Sun would be a smoking-gun signal of dark matter particle annihilation. The signal depends primarily on the spin-dependent WIMP-nucleon scattering cross section, which determines the capture rate. Current bounds from SuperK and IceCube already provide leading limits on this cross section, and the Precision IceCube Next Generation Upgrade (PINGU), an infill array upgrade to IceCube, will extend the sensitivity to lower masses. In the coming decade, IceCube and PINGU, along with Hyper-Kamiokande, will probe cross sections one to two orders of magnitude below current bounds, with sensitivities competitive with those of planned G2 direct detection experiments.

For antimatter, recent measurements of cosmic-ray positrons by the AMS-02 magnetic spectrometer confirm and improve with excellent precision earlier measurements by PAMELA and Fermi. The rising positron fraction could be indicative of positrons created in the decay or annihilation of dark matter. In the near future, AMS-02 will extend its determination of the positron fraction to energies close to 1 TeV, and add important information on cosmic-ray propagation. Given the possibility of astrophysical sources of primary positrons, however, it may be very difficult to definitively attribute the excess positrons to dark matter. Antideuterons provide a signal that is potentially more easily discriminated from astrophysical backgrounds. With a long-duration balloon flight, the General Antiparticle Spectrometer (GAPS) experiment could provide sensitivities comparable to AMS. Last, the production of positrons and electrons from dark matter annihilation also produces secondary radiation. Detection of signals with radio to X-ray frequencies has the potential to probe the WIMP parameter space.

The Snowmass process also evaluated the prospects for non-WIMP candidates, which could be some or all of the dark matter. The axion is particularly well-motivated, as it arises from the leading solution to the strong CP problem of the Standard Model. RF-cavity and solar searches for axions, such as ADMX and IAXO, will probe a large range of axion parameter space, including the cosmologically-favored region, and have strong discovery potential. Sterile neutrinos are also highly motivated by the observed non-zero masses of active neutrinos. In the mass range where sterile neutrinos are dark matter candidates, their radiative decays produce a monoenergetic photon, which may be detected with X-ray telescopes. Many other dark matter candidates were also surveyed, including asymmetric dark matter, primordial black holes, Q-balls, self-interacting dark matter, superheavy dark matter, and superWIMP dark matter.

How do the diverse strategies for identifying dark matter fit together? The Snowmass process produced a clear articulation of how the different approaches — including the direct and indirect detection experiments mentioned above, but also particle colliders and astrophysical probes — each provide unique and necessary information. This complementarity is discussed below and was examined in two theoretical frameworks. First, the discovery prospects were examined in complete supersymmetric models, with randomly selected parameters in the phenomenological MSSM framework. Second, the possibility that only the dark matter particle is kinematically accessible was considered using the framework of dark matter effective theories. In both cases, the complementarity of different approaches was evident at all levels, both to establish a compelling dark matter signal and, just as importantly, after discovery, to determine the detailed properties of the particle or particles that make up dark matter.

**Dark energy and CMB**

Cosmic surveys — optical imaging and spectroscopic surveys and detailed measurements of the CMB — precisely map the Universe on many different angular scales and over wide ranges of cosmic time. They provide unique information about cosmology and new physics, including inflation, dark matter, dark energy, and neutrino properties. These measurements are challenging, requiring advances in instrumentation and excellent control of systematic effects. Fortunately, these advances are now within reach, thanks to decades of investment and close collaborations between particle physicists and astrophysicists. The payoffs for this effort are large.
Measurements of the distance–redshift relation, first using supernovae and then additional complementary techniques, revealed the expansion history of the Universe, particularly over the past several billion years, and yielded the surprising discovery that the expansion rate has been increasing instead of decreasing. Now we must determine what is causing the cosmic acceleration. This “dark energy” must produce negative pressure to be responsible for the observed effect. One important clue is whether the negative pressure has been constant in time or is evolving. The stage III (the DES and HSC imaging surveys, and the PFS and eBOSS spectroscopic surveys) and stage IV (LSST imaging survey and DESI spectroscopic survey on mountaintops; Euclid and WFIRST-AFTA in space) dark energy facilities will constrain both the value and the evolution of the value with much higher precision, as recommended in previous community studies, but they will also do much more. We must also check whether our description of gravity is correct, and this is where measurements of the growth of structure, over a wide range of distance scales using both imaging and spectroscopic surveys, are needed. 

There are several alternatives to general relativity (GR) that can accurately describe the observed distance–redshift relation, but they also modify the behavior of gravity over different distance scales. The alternative models therefore predict structure growth rates that are different from those in the standard theory. Measuring the structure growth rate over many different distance scales will test GR and the alternative models. Deviation from expectation on just one of these scales will signal new physics. In other words, the upcoming dark energy facilities, particularly at stage IV, where systematic error management is built deeply into the design, will provide many precise tests and will characterize the behavior of dark energy in much richer ways than “just” the overall value and its evolution with time. We will know the strength of the effects in a two-dimensional parameter space of distance and cosmic time, as well as any deviations from expectations in the correlations among of them. Further surprises may await us.

Inflation is the leading paradigm for the dynamics of the very early Universe, and current observations of large-scale structure lend support to this intriguing idea. The most direct available probes of inflation come from CMB observations, and the overall agreement is remarkably good. However, it has not been possible to explore the underlying physics of inflation, until now: The coming generations of CMB experiments will have sufficient sensitivity to falsify large classes of models. The signal is a characteristic pattern with non-zero curl (called “B mode”) faintly imprinted on the polarization of the CMB fluctuations, due to gravitational waves produced during the epoch of inflation. The shape of the potential of the scalar field driving inflation directly affects the spectrum of gravitational waves and hence the strength of the imprint, $r$ (the ratio of tensor to scalar power), over characteristic angular scales on the sky. The current generation of experiments is sensitive to $r \sim 0.1$, but over the next 10 to 20 years, improvements of two orders of magnitude are possible by scaling the number of detectors by similar factors, from $\sim 10^3$ (current) to $\sim 10^5$ (generation III) to $\sim 5 \times 10^5$ (generation IV). This would require a change from the way things have been done in the past. Groups would merge into one coordinated effort, and national lab facility design, integration, computing, and management capabilities would be tapped.

Remarkably, future optical and CMB cosmic surveys, as well as future polar-ice neutrino projects (see below), will also provide precise information about neutrino properties, including the mass hierarchy, the number of light neutrinos, and the sum of the neutrino species masses. Combining this information with accelerator- and reactor-based neutrino experiments, as well as other experiments, such as those searching for neutrinoless double-beta decay, will accelerate our understanding of fundamental neutrino properties and enable us to understand the implications of apparent inconsistencies.

Snowmass provided an excellent opportunity to address common problems and to develop a common vision for the potential of cosmic surveys for particle physics. Highlights included advancing detailed strategies to distinguish dark energy from modified gravity; exploiting the complementarity of probes for determining the key cosmological parameters; understanding more deeply the strengths and ultimate limitations of the different techniques; and discussing the planned facilities, which are the result of intensive community
4.1 Direct detection of WIMP dark matter

Deciphering the nature of dark matter is one of the primary goals of particle physics for the next decade. Astronomical evidence of many types, including cosmic microwave background (CMB) measurements, cluster and galaxy rotation curves, lensing studies and spectacular observations of galaxy cluster collisions, all points
to the existence of CDM particles. Cosmological simulations based on the CDM model have been remarkably successful at predicting the actual structures we see in the Universe [10]. Alternative explanations involving modification of Einstein’s theory of GR have not been able to explain this large body of evidence across all length scales.

WIMPs are strong candidates to explain dark matter. They represent a class of dark matter particles that froze out of thermal equilibrium in the early Universe with a relic density that matches observation. This coincidence of scales — the relic density and the weak force interaction scale — provides a compelling rationale for WIMPs as particle dark matter. There are many particle physics theories that provide natural candidates for WIMPs, but they do not limit the search parameters very much, leaving a search region with a range of 1 GeV to 100 TeV in mass and $10^{-40}$ to $10^{-50}$ cm$^2$ in interaction cross sections with normal matter.

Direct detection experiments are designed to identify the interaction of WIMPs with normal matter. Since WIMPs should interact with normal matter by elastic scattering with nuclei [17], this requires detecting nuclear recoil energies in the 1–100 keV range. These low energies and cross sections represent an enormous experimental challenge, especially in the face of daunting backgrounds from electron recoil interactions and from neutrons that mimic the nuclear recoil signature of WIMPs. The unambiguous detection of signal above these backgrounds would confirm the existence of WIMPs in our galaxy and begin to unravel the mystery of their identity, especially with complementary information from production in colliders and signals from annihilation in our galaxy or in the Sun.

Direct detection experiments must be located in deep underground laboratories to avoid effects of cosmic-ray interactions that produce energetic neutrons that could mimic WIMPs. The experiments must also shield the detectors from the decay products of radioactivity in the environment and in the materials of the experiment itself. This is especially important for neutrons resulting from fission or $(\alpha,n)$ reactions, since a single scatter from a neutron produces a nuclear recoil that is indistinguishable from that produced by a WIMP. Luckily, some portion of the neutrons will scatter multiple times in the detector, and so neutron events can be identified and rejected on this basis. In most cases, the experiments also define an ultra-pure active “fiducial” volume that is shielded from radioactive decay products produced by impurities in the materials surrounding the detection material.

The basic methodology for direct detection experiments is to search for elastic scattering of a WIMP from a target nucleus. The rate of candidate nuclear recoils is converted into a cross section for WIMP-nucleon interactions following a standard prescription that includes the effects of nuclear physics and astrophysical properties [18]. Experiments can be sensitive to both nuclear spin-independent (SI) interactions and spin-dependent (SD) interactions. For the momentum exchange range of interest, the SI interaction is expected to be approximately coherent across the entire nucleus, so for a WIMP with equal coupling to protons and neutrons, the rate scales with the square of the atomic mass of the target nucleus. Current experiments are therefore more sensitive to SI dark matter than SD dark matter. Experimental results are usually presented as a plot of WIMP-nucleon cross section versus WIMP mass to allow comparison among experiments. Figure [4-1] shows the current SI landscape, with strict upper limits for higher mass WIMPs and some closed contours for lower mass WIMPs. The SD interaction is generally divided into proton and neutron couplings; the results to date are summarized in Figure [4-2]. Only direct detection can provide limits on neutron couplings, but solar neutrinos from WIMPs that annihilate in the Sun are stronger for proton coupling. Other types of interactions are possible, and it is important to run multiple experiments with different targets, both to cover the parameter space for discovery and to study the interaction type when signals are found.

Nuclear recoils from WIMP scattering result in a featureless energy spectrum, rising exponentially as the energy decreases. Experiments typically do not directly measure the nuclear recoil energy. Instead, the energy deposited by a particle interaction must be reconstructed from the experimental measurements as
4.1 Direct detection of WIMP dark matter

Figure 4-1. Constraints on spin-independent WIMP-nucleon cross sections as a function of WIMP mass as of Summer 2013 [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32].

either nuclear-recoil (keV_r) or electron-recoil (keV_{ee}). Conversion between the two energies is dependent on the target and experimental technique, and must be calibrated by each experiment. Typically, radioactive gamma sources or in-situ doped beta emitters are used to provide calibration for electron recoils, and neutron sources provide a source of nuclear recoil events. Since the nuclear recoil calibration is difficult at low energies, there is significant uncertainty in the low WIMP mass exclusion limits, sowing some controversy when comparing limits and discovery contours between targets.

A complete list of the current targets and technologies in use for direct detection of WIMPs can be found in the CF1 Summary [1]. One of the key features of modern experiments is the use of discrimination to select nuclear recoils and reject backgrounds that are dominated by electron recoils. Often the signal is split into two components that respond differently to nuclear and electron recoils. Noble liquids, such as argon and xenon, make use of ionization and scintillation light. Solid targets, such as silicon and germanium at cryogenic temperatures, use heat (or phonons) plus ionization. Crystals, such as CaWO_4, contrast phonons and scintillation light. Two components are not necessary if an experiment can achieve internal purities and excellent fiducial isolation, or can use pulse-shape discrimination (e.g., liquid argon), or is insensitive to electron recoil backgrounds (e.g., threshold detectors).

Another method to deal with backgrounds is to exploit the fact that the Earth is moving through the dark matter that surrounds our galaxy, yielding a “WIMP wind” that appears to come from the constellation Cygnus [38]. This should, in principle, create a small “annual modulation” in the detected WIMP rates, as well as a somewhat larger daily modulation. However, if such effects were detected in an experiment, there would still have to be a convincing demonstration that there are no such modulations in background sources. Since backgrounds are expected to be isotropic, detection of a signal with a preferred direction could provide a powerful additional discriminant against backgrounds. Directional detectors attempt to exploit this effect.
Figure 4-2. Spin-dependent WIMP-neutron (left) and WIMP-proton (right) cross section limits as functions of WIMP mass for direct detection experiments [33, 34, 28, 35, 36, 23, 22], as well as IceCube results (model-dependent) [37], as of Summer 2013.
by sensing the vector direction of nuclear recoils, and they are usually looking for a daily sidereal difference as the Earth rotates relative to the WIMP wind.

The first two decades of dark matter direct detection experiments have yielded a diverse and successful program, although not yet definitive evidence for WIMPs. Starting with just a few experiments using solid-state targets, the technologies used for these experiments have grown considerably. There has been a remarkable improvement in WIMP sensitivities, especially in the range where the WIMP mass is comparable to the atomic mass of the target nuclei. A selection of spin-independent results from the first two decades of these experiments, and projections for the coming decade, is shown in Figure 4-3 for a 50 GeV/c$^2$ WIMP mass. A “Moore’s law”-type improvement is particularly evident for such WIMP masses, with a sensitivity doubling time of roughly 18 months. Note that direct detection experiments have sensitivity to much larger WIMP masses as well, surpassing what is accessible at the LHC. More recently, there has also been rapid progress in sensitivity to WIMPs with masses at 10 GeV/c$^2$ and below.

Sensitivity projections are subject to uncertainties from many factors, including technical issues with the experiments, the appearance of unexpected backgrounds, and delays in funding. Despite these uncertainties, the history of the field gives us confidence that progress will continue unabated through the next decade. There is, however, an irreducible background caused by solar, atmospheric, and supernova neutrinos. The $^8$B component of the solar neutrinos provides the dominant neutrino coherent scattering rate at low recoil energies. The $^8$B spectrum can mimic a WIMP with a mass in the range of 5–10 GeV/c$^2$ (depending on the target) and a nucleon cross section of $\sim 5 \times 10^{-45}$ cm$^2$. For experiments targeted at larger WIMP masses,
the solar neutrinos give way to the more energetic atmospheric neutrinos and diffuse supernovae background. The flux of these neutrinos is much lower, and exposures with sensitivities to WIMP-nucleon cross sections of $\sim 1 \times 10^{-48} \text{ cm}^2$ are required to be sensitive to this neutrino component. Depending on the particular WIMP mass under consideration, these neutrino backgrounds can have a recoil spectrum that is very similar to an authentic WIMP signal. Given the Poisson fluctuations from the neutrino signal and their relatively large total flux uncertainties, this creates a challenge to improving the sensitivity of WIMP searches much beyond such cross sections [39]. Figure 4-4 shows not only the current landscape, but also the projected sensitivities of proposed experiments superimposed on the neutrino background, where coherent neutrino scattering will begin to limit WIMP sensitivity. This will eventually require either background subtraction or techniques such as directional or annual modulation to press beyond this background in the absence of a positive WIMP sighting.
4.2 Indirect detection of WIMP dark matter

If thermal decoupling is the mechanism that sets the abundance of WIMP dark matter in the early Universe, WIMPs generically are predicted to annihilate today as well, especially in regions of high dark matter density, producing Standard Model particles, including gamma rays, neutrinos, electrons, positrons, protons, antiprotons, deuterons, and antideuterons. Utilizing these Standard Model “messengers” to constrain or infer properties of the dark matter is the ultimate goal of indirect detection.

The dark matter annihilation signal depends both on particle physics properties, such as the annihilation cross section, and on the density distribution of dark matter. The latter can be determined either by N-body simulations of structure formation in the ΛCDM standard model of cosmology or by direct dynamical measurements that derive the enclosed mass (luminous and dark) by measuring the velocity dispersion of stars or molecular clouds. In the absence of baryons, CDM simulations indicate that dark matter halos are cuspy (with densities approximately scaling as $\rho \sim r^{-1}$ in their centers [16, 40, 41]), with a central concentration dependent on the mass of the halo and the halo formation time [12, 43]. Small halos tend to form earlier than big halos and also to be much more densely concentrated. However, the places where we have the highest dark matter annihilation rates (i.e., the centers of halos) are also the places where baryons settle and dominate the potential well for typical halos. There is not yet a consensus on how baryons affect dark matter halos [148, 149, 150, 151, 152]. Fortunately, even when one makes the most conservative assumptions about the halo profiles (e.g., cored profiles constrained by dynamics), indirect detection methods still constrain the viable WIMP parameter space.

4.2.1 Gamma-ray experiments

The ability to detect the dark matter signal from a given target depends critically on its dark matter density distribution and on $J$, the integral of the square of the dark matter density along the line of sight to the source. The ideal targets for dark matter annihilation searches are those that have both a large value of $J$ and relatively low astrophysical γ-ray foregrounds. These criteria have motivated a number of galactic and extragalactic targets including the galactic center (GC), dwarf spheroidal satellite galaxies of the Milky Way (dSphs), and galaxy clusters.

In and near the GC, the dark matter-induced γ-ray emission is expected to be so bright that one can obtain strong upper limits at the level of the target annihilation cross section $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3$ s$^{-1}$, even after excluding regions around the bright source at the GC and surrounding region. With the improved angular resolution of future γ-ray experiments, the astrophysical foregrounds will be more easily identified and separated from the diffuse annihilation signal, and if, e.g., the GC source is a point source, the dark matter sensitivity of future experiments could exceed the predictions presented here (see Figure 4-5).

The Milky Way is also known to host at least two dozen dSphs that are typically very dark-matter-dominated, with mass-to-light ratios of 100 to 1000, and are thought to have very small background emission of high energy γ-rays. About half of the dSphs were discovered in the Sloan Digital Sky Survey (SDSS). A large number of additional dSphs are believed to exist in the Milky Way halo [49, 50]. Big, deep, wide-field surveys like the Dark Energy Survey and, critically, LSST, should find more. In particular, these experiments should help to find additional nearby galaxies in the southern hemisphere, since SDSS did not explore this area. These objects are of particular importance to the future southern CTA experiment that is described below.

The Fermi-LAT data already exclude the target annihilation cross section for masses below 30 GeV, but only for the most optimistic phenomenological minimal supersymmetric standard model (pMSSM) models.
In the low-energy, background-dominated regime, the Fermi-LAT point source sensitivity increases roughly as the square root of the integration time. However, in the high-energy, limited-background regime (where many pMSSM models predict signals), the Fermi-LAT sensitivity increases more linearly with integration time. Thus, 10 years of data could provide a factor of $\sqrt{5}$ to 5 increase in sensitivity.

VERITAS has produced some of the best dark matter constraints at energies above a few hundred GeV through observations of one of the nearest, most dark-matter-dominated dwarf galaxies, Segue 1 [51]. This analysis was based on about 40 hours of data, but the current VERITAS program, augmented by recent upgrades, aims to observe dark matter targets for several hundred hours each season. This offers one of the strongest avenues available for WIMP dark matter detection and, in the absence of discovery, can provide severe constraints on many dark matter models.

For the next generation experiment, improving dark matter searches in the GC depends on stronger astrophysical background rejection through improved angular resolution. CTA [52] is a future ground-based γ-ray observatory that will have potentially game-changing sensitivity over the energy range from a few tens of GeV to a few hundreds of TeV. Doubling the size of the proposed southern CTA telescope, a device with the required resolution and good sensitivity to the GC and southern sources, will dramatically improve dark matter sensitivity. To achieve the best sensitivity over this wide energy range, CTA will include three distinct telescope sizes. Over this energy range, the point-source sensitivity of CTA will be at least one order of magnitude better than current generation imaging atmospheric Cherenkov telescopes (IACTs). CTA

![Figure 4-5. Constraints on the total annihilation cross section from γ-ray experiments, including the anticipated sensitivity of Fermi obtained by stacking 10 yrs of data on dSphs, and the sensitivity of the augmented CTA instrument, using an annulus about the GC.](chart.png)
will also have an angular resolution at least 2 to 3 times better. In the following sensitivity estimates, we consider an augmented version of the CTA array (ACTA) with a U.S. enhancement, which has twice as many medium-sized telescopes (∼60 in total) and triple the sensitivity.

Figure 4-6 shows the projected sensitivity of ACTA to a WIMP particle annihilating through three possible final states: $b\bar{b}$, $W^+W^-$, and $\tau^+\tau^-$. For an observation of the GC utilizing a $0.3^\circ$–$1.0^\circ$ annular search region, ACTA could exclude models with cross sections significantly below the target annihilation cross section. Overlaid in the figure are WIMP models generated in the pMSSM framework that satisfy all current experimental constraints from collider and direct detection searches. Approximately half of the models in this set could be excluded at the 95% confidence level in a 500-hour observation of the GC.

ACTA, with the critical U.S. enhancement, will provide a powerful new tool for searching for dark matter, covering parameter space not accessible to other techniques. ACTA will provide new information to help identify the particle nature of the dark matter and determine the halo profile. With support levels comparable to the complementary searches of the G2 direct detection experiments, the U.S. dark matter program would have the realistic prospect of both detecting dark matter in the lab and identifying it in the sky.

The HAWC detector will complement existing IACTs and the space-based $\gamma$-ray telescopes with its high-energy sensitivity and its large field-of-view. The instrument has peak sensitivity to annihilation photons from WIMP dark matter with masses between about 10 TeV and the unitarity limit $\sim$100 TeV. Such large...
masses can still satisfy all cosmological and particle physics constraints for a generic WIMP [53]. Much like Fermi, HAWC will survey the entire northern sky with sensitivity roughly comparable to existing IACTs and will search for annihilation from candidates that are not known a priori, such as galactic substructure. Furthermore, HAWC can search for sources of gamma rays that are extended by 10 degrees or more and can constrain even nearby sub-halos of dark matter.

4.2.2 Charged cosmic-ray/antimatter experiments

Dark matter may annihilate through a number of channels (e.g., \( t \bar{t}, b \bar{b}, W^+W^−, ZZ, \tau^+\tau^- \)) with similar branching ratios. These annihilation channels can eventually lead to cascades producing secondary particles, such as \( e^\pm, \gamma, \) and \( \nu \). Annihilation can also lead to the production of baryons, such as cosmic-ray protons and antiprotons and even deuterons and antideuterons.

Cosmic-ray electrons and positrons provide a unique astrophysical window into our local galaxy. To a good approximation, the magnetic fields in the galaxy randomize cosmic-ray directions. However, a small anisotropy may remain due to contributions from local sources, such as dark matter subhalos or nearby pulsars. The identification of a dark matter signal from cosmic rays thus requires the detection of a spectral feature that stands out against the background.

Recent measurement of cosmic-ray positrons by the AMS-02 magnetic spectrometer [54] confirms with excellent precision earlier measurements by PAMELA [55] and Fermi [56] showing a rising positron fraction, \( e^+/(e^+ + e^-) \), for energies between 10 and several 100 GeV [56, 55]. The most widely used models of propagation of cosmic rays in the galaxy [57] predict that secondary positrons would give a positron fraction falling well below the observed value. The rising positron fraction could be indicative of positrons created in the decay or annihilation of dark matter [58, 59]. Under this interpretation, the dark matter particles must have mass greater than 350 GeV. AMS-02 is capable of identifying cosmic-ray positrons with energies up to \( \sim 1 \) TeV. With several more years of data, AMS-02 should be able to extend its determination of the positron fraction to energies close to 1 TeV and add important information on cosmic-ray propagation. However, the possibility of astrophysical sources of primary positrons remains a source of great concern and makes it difficult to clearly attribute the excess positrons to dark matter annihilation [60, 61].

About a decade ago it was pointed out that antideuterons produced in WIMP-WIMP annihilations offered a potentially attractive signature for CDM [62]. The General Antiparticle Spectrometer (GAPS) detector [63] would consist of a detector that identifies antideuterons using a number of planes of Si(Li) solid state detectors and a surrounding time-of-flight system. A long-duration balloon flight of the proposed GAPs instrument could provide upper limits competitive with those obtained by AMS-02, and would provide two independent approaches to making this important measurement.

4.2.3 Neutrino measurements

Like their \( \gamma \)-ray counterparts, neutrino telescopes can potentially detect the products of WIMP annihilations pointing back to their origin in the GC, the galactic halo, from galaxy clusters, and from dSphs. Neutrino telescopes are also sensitive to WIMP annihilations in the core of the Earth or Sun, regions that are inaccessible to \( \gamma \)-ray telescopes. The WIMP source in the Sun has built up over solar time, averaging over the galactic dark matter distribution as those WIMPs that scattered elastically with solar nuclei and lost enough momentum became gravitationally trapped. Typically a sufficient density of WIMPs has accumulated in the
solar core that equilibrium now exists between WIMP capture and annihilation. Then, given a WIMP mass and decay branching ratios, one can unambiguously predict the signal for a neutrino telescope. The IceCube Collaboration continues to take data and has performed or is performing searches for neutrino signals from WIMPs in the center of the Earth [63], the solar core [37], the galactic halo [65] and center [66], galaxy clusters, and dSphs [67].

The PINGU detector is proposed as a new in-fill array for IceCube. PINGU will instrument an effective volume of several million metric tons for neutrinos with energy $E_{\nu} \sim 5$–15 GeV. The final geometry for the detector is still under study but will probably be comprised of 20 to 40 new strings with 60–100 modules per string. PINGU is focused on other physics goals but has sensitivity to neutrinos produced by WIMP annihilations. Together IceCube and PINGU will be able to probe a WIMP mass region that is of considerable interest, given intriguing results from other experiments that are consistent with a WIMP mass of a few GeV. In particular, WIMP properties motivated by DAMA’s annual modulation signal [68] and isospin-violating scenarios [69] motivated by DAMA and CoGeNT signals will be tested. The predicted sensitivities of Hyper-Kamiokande and PINGU are shown in Figure 4-6. Depending on the WIMP mass, IceCube or PINGU could detect a smoking-gun signal of dark matter (a high-energy neutrino signal from the Sun) as well as place competitive limits on the spin-dependent nuclear recoil cross section, compared with planned G2 direct detection experiments.

4.2.4 Astrophysical multiwavelength constraints

Pair annihilation of WIMPs will result in a conspicuous non-thermal population of energetic electrons and positrons from the decays of charged pions produced by the hadronization of strongly interacting final-state particles, as well as from the decays of gauge bosons, Higgs bosons, and charged leptons. This non-thermal $e^{\pm}$ population loses energy and produces secondary radiation through several processes, covering a wide range of the electromagnetic spectrum from the radio to the $\gamma$-ray band. Several recent studies have made it clear that searches in the radio [70] and X-ray frequencies [71] have the potential to reach sensitivities to the relevant WIMP parameter space that are comparable to, and in some instances broader than and complementary to, the sensitivities of $\gamma$-ray experiments. A detailed performance comparison depends critically on assumptions about propagation, energy losses, and the astrophysical environment where the secondary radiation is emitted [70]. An accurate definition of benchmarks is crucial for this field.

4.2.5 Indirect detection conclusions

The primary methods of indirect detection include $\gamma$-ray measurements of the center of our own galactic halo, in nearby dwarf galaxies and in clusters; observation of charged cosmic-ray antimatter; searches for high energy neutrinos from annihilation in the Sun; and astrophysical signatures, such as radio and hard X-ray emission. Just as the next generation of direct detection experiments is approaching the natural range for WIMP scattering cross sections, $\gamma$-ray experiments are reaching the sensitivity required to exclude the natural range of model predictions for WIMP annihilation cross sections. Given the close relation of the $\gamma$-ray production cross section to the total annihilation cross section, the bulk of the likely parameter space for SUSY WIMPs (or, in fact, any weakly interacting massive thermal relic) is focused in a relatively narrow band of cross sections compared to the nuclear recoil scattering cross section. Comparing direct and indirect detection, the dominant systematic uncertainty for direct detection from the nuclear recoil cross section might be even larger than the uncertainties in indirect searches from halo models. Even the conservative, cored halos give an observable signal for future $\gamma$-ray experiments.
A future experiment like CTA, with U.S. enhancement, could reach most of the parameter space in well-explored theoretical frameworks, such as the pMSSM, through observations of the GC for all but the most pessimistic assumptions about the halo profile or new astrophysical backgrounds. U.S. involvement in CTA is critical. This involvement would result in a doubling of the planned mid-sized telescope array with substantial improvements in sensitivity and angular resolution that are much more than an incremental improvement. Perhaps of equal importance, involvement of the U.S. HEP community would provide not only the technical expertise but also the scientific impetus to devote a large fraction of CTA’s observing time to dark matter targets.

New discoveries of nearby dwarf galaxies and new analysis techniques are likely to result in Fermi observations cutting into the pMSSM parameter space to energies up to tens of GeV. Above a few hundred GeV, VERITAS will come within an order of magnitude of the natural annihilation cross section for a combined dwarf analysis. IceCube searches for high-energy neutrinos from the Sun will continue to provide some of the most sensitive constraints on the spin-dependent scattering cross section and offer the potential for a smoking-gun discovery. The proposed PINGU extension to IceCube would provide sensitivity to WIMP masses favored by DAMA.

This is an exciting time for dark matter research, where direct detection experiments may see a hint of a signal, the LHC may find new physics, γ-ray measurements may identify the particle and measure its distribution in galactic halos, and neutrino measurements may provide a smoking-gun detection from the annihilation signal from the Sun. Without all of these avenues for research, the story would be incomplete.

4.3 Non-WIMP dark matter

In solving the mystery of dark matter, it is sensible to assume the properties of the dark matter particle candidate and predict its non-gravitational interactions before the particle can be identified. It is common to predict the properties of dark matter based on either compelling theoretical arguments or experimental and astrophysical hints. The relative significance of different arguments and hints cannot easily be evaluated objectively, which makes it difficult to rank dark matter candidates in importance. Although a combination of certain theoretical arguments, advanced direct search experimental techniques, and connection with collider experiments makes WIMPs attractive candidates, they are by no means the only appealing possibility.

Furthermore, there is no reason to believe that dark matter is comprised of only one type of particle. It is possible that the structure of the dark sector is as complex as that of the visible sector, or even more complex. A broad, extensive, and multifaceted approach to solving the mystery of dark matter is more likely to yield exciting discoveries than a focused pursuit of one dark matter candidate. At the same time, the enormous breadth of possibilities forces us to identify some directions as the most promising. Theoretical plausibility and experimental feasibility are commonly used in the community for this purpose.

The landscape of non-WIMP candidates is sketched in Figure 4-7. There are a large number of possibilities. To be directly detected, the dark matter needs to interact in some way with normal matter and radiation. Figure 4-8 shows the incredible range of interaction strengths and masses of the different candidates. Generally, the lighter the candidate, the more feeble its allowed interactions. Very heavy dark matter particles can have quite strong interactions. This wide range of coupling strengths and masses calls for an equally wide range of detector technologies. For the most feeble interactions of the axion, the detection technology is based on quantum-limited detection of radio photons. The rare interactions of the more massive candidates, such as Q-balls, produce distinctive signatures in large detectors. Finally, a number of candidates cannot be found in laboratory experiments in the foreseeable future, and so X-ray and gamma-ray telescopes, as well as gravitational lensing techniques, provide the best opportunities for their detection.
4.3 Non-WIMP dark matter

Figure 4-7. The landscape of dark matter candidates [from T. Tait].

Figure 4-8. The range of dark matter candidates’ masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates have an enormous range of possible masses and interaction cross sections.
The following non-WIMP dark matter candidates were highlighted in the course of Snowmass. This list is not a complete list of possible candidates, but it includes candidates for which there was substantial interest and identifiable experimental and theoretical research paths, and which were discussed in white paper contributions.

- **Asymmetric dark matter** is motivated by the fact that the abundances of ordinary matter and dark matter in the Universe are comparable \[72\] \[73\]. The two quantities can be similar and related if the two types of matter are produced simultaneously, or if they are generated from two separate but similar processes in the early Universe. Since the abundance of ordinary matter is controlled by the baryon asymmetry of the Universe, a similar asymmetry may be responsible for the observed dark matter abundance. In contrast with WIMPs, asymmetric dark matter candidates can have masses and interaction cross sections that are very different from the naive expectations motivated by the freezeout of a thermal relic.

- **Axions** arise from an elegant (and, arguably, the only viable) solution to the strong CP problem in the Standard Model \[74\] \[75\] \[76\] \[77\]. The vacuum of quantum chromodynamics (QCD) is characterized by a parameter $\theta_{\text{QCD}}$, which is independent of the phase $\theta_{\text{q}}$ in the quark mass matrix. It is a mystery why the sum of these two unrelated parameters, which controls CP violation in strong interactions, should vanish to an experimentally-measured precision of one part in ten billion. Peccei–Quinn theory explains this mystery and predicts a new light degree of freedom, the axion, which can also be dark matter. There are several promising experimental techniques to search for axions, and this program was viewed to have a strong discovery potential. A variant candidate is the axion-like-particle, a light particle with the axion’s quantum numbers, but having mass and couplings not linked by the Peccei-Quinn theory. Searches for such particles were discussed by both Cosmic Frontier and Intensity Frontier working groups.

- **Primordial black holes** can form in the early Universe \[78\] \[79\] \[80\], for example, from the same dynamics that govern cosmological inflation \[81\]. Although theoretical models invoke fine-tuning of parameters to explain the dark matter abundance, primordial black holes are a viable dark matter candidate that can be discovered using gravitational lensing observations \[82\].

- **Self-interacting dark matter** can explain some inconsistencies between the predictions of N-body simulations and observations \[83\] \[84\] \[85\] \[86\] \[87\].

- **Sterile neutrinos** are motivated by the fact that active neutrinos are massive, which is typically explained by introducing right-handed, gauge-singlet fermions \[88\] \[89\]. If one or more of these fermions is relatively light, as occurs in a number of different models \[90\] \[91\] \[92\] \[93\], the dark matter can consist of sterile neutrinos. In a part of the parameter space allowed for dark matter, the same sterile neutrinos can explain the observed pulsed velocities, since these sterile neutrinos would be emitted anisotropically from a cooling neutron star born in a supernova explosion \[94\] \[95\]. The most promising detection strategy is based on the radiative decays of sterile neutrinos, which can produce a line detectable by X-ray telescopes \[96\].

- **Superheavy dark matter** must have a low number density, which requires the use of very large detectors. Indirect detection of decay products can lead to discovery. Several candidates fall in this category, including quark nuggets \[97\] \[98\] and WIMPzillas \[99\].

- **Supersymmetric non-WIMP candidates** include SUSY Q-balls \[100\] \[101\] and products of their decays, as well as superWIMP dark matter \[102\] are well-motivated dark matter candidates in theories with supersymmetry. The search for these candidates is possible using direct and indirect techniques targeting specific properties of these candidates.

Among all these candidates, the axion deserves special mention. For a dark matter candidate, the QCD axion has the rare advantage of a fairly well-bounded parameter space. Although there are ways to evade...
the bounds, the axion-photon couplings $g_{a\gamma\gamma}$ over the range of benchmark models extend over an order of magnitude. The upper end of the QCD axion mass range is set at a few meV by the limit from SN1987A, and the lower end, limited by the requirement that axions not overclose the Universe, is set at around a $\mu$eV. A particularly promising approach to detect the QCD axion is via the RF-cavity technique \cite{103}. Although the expected conversion into RF power within the cavity is extraordinarily weak, experiments will shortly start taking data for a definitive search, which will either find the QCD dark matter axion with high confidence, or exclude it at high confidence. These experiments will sensitively explore the first two decades of allowed QCD axion mass, where the dark matter QCD axion is expected to be found. These searches have a large discovery potential over the next decade. There are axion and axion-like-particle alternatives to the QCD axion, and this opens a vast and largely unexplored search space. Much of this space, including the third decade of allowed QCD axion mass, could be explored by large next-generation detectors. For instance, the proposed solar-axion experiment IAXO would explore this space, including where there are astrophysical hints of new physics, yielding a good discovery potential. The axion might be found anywhere within the allowed parameter space, and there are arguments for both higher-mass axions (which would then be of the non-Peccei-Quinn type) or lower-mass axions (which could be QCD axions whose primordial abundance is explained by anthropic selection).

It may also be that the dark matter consists of several different particles. The range of possibilities is enormous. Aside from axions, proposals for special-purpose non-WIMP dark matter detectors and programs are less well-developed. However, existing experiments and astronomical instruments offer a number of serendipitous opportunities.

Once the axion or other dark matter particle is identified, it will mark a new beginning. For instance, one virtue of the RF-cavity experiments is that they measure the total energy of the axion — mass plus kinetic energy — and there may be fine structure to the signal due to the flows of dark matter in the halo. This contains a wealth of information about the history of the formation of our Milky Way galaxy and will mark the beginning of a new field of astronomy \cite{104}. On the other hand, if dark matter is made up of sterile neutrinos, the narrow spectral line from their decay could provide information about the redshift, allowing us to map out dark matter in the Universe and to use the redshift information for measuring the cosmological expansion \cite{89}. Much the same can be said about discovering any of the dark matter candidates: The identification of dark matter will be a revolutionary discovery that will open the door to a new chapter in our understanding of nature.

### 4.4 Dark matter complementarity

All current evidence for dark matter is derived solely through its gravitational interactions. The presence of dark matter has been quantified on length scales that range from the solar neighborhood to the horizon of the Universe. The history extends back to Jan Oort, who proposed using stars above the plane of the Milky Way as a way to minimize the influence of the stellar disk \cite{105}, and Fritz Zwicky who postulated dark matter in 1937 from the large measured velocity dispersion of galaxies in the Coma cluster \cite{106}. Subsequent progress in the 1970’s in measuring the rotation curves of nearby galaxies in both optical and radio frequencies \cite{107, 108} really brought the idea of dark matter home to many astronomers and physicists. The support for dark matter in the form of cold relic particles came about through revolutions in cosmology including galaxy correlations \cite{109, 110}, the CMB \cite{111, 112}, and measurements of hot gas in clusters \cite{113}. Visceral evidence for dark matter is provided by strong and weak lensing measurements \cite{114, 115}, including the famous Bullet Cluster \cite{116}. Together, these data provide overwhelming evidence that the energy in dark matter is roughly a quarter of the total energy in the visible Universe and about five times the energy in normal matter.
To understand dark matter, we need to answer some basic questions: (1) How many particle species make up the dark matter? (2) What are their masses and spins? (3) How do they couple to the Standard Model and other new (dark sector) particles? Our primary conclusion is that the broad range of possibilities for dark matter (more than one of which may be correct) argues strongly for multiple search strategies, including direct searches, indirect searches, collider searches, and astrophysical probes, to answer these basic questions.

The Dark Matter Complementarity working group highlighted the essential synergies of these different approaches. These approaches, as well as the complementarity of experiments within each approach, are discussed in greater depth above in Secs. 4.1, 4.2, and 4.3, and in the reports of the Cosmic Frontier dark matter working groups and the Energy Frontier new physics working group.

4.4.1 Dark matter candidates and the need for a multi-pronged search strategy

Several classes of particles are strong dark matter candidates. The most familiar dark matter candidates are WIMPs, discussed in Sections 4.1 and 4.2, which are produced in the hot early Universe and then annihilate in pairs. Those that survive to the present are known as “thermal relics” [117, 118, 119, 120]. Such particles are generically predicted in models of physics beyond the Standard Model, including models with supersymmetry [121, 122] or extra spatial dimensions [123, 124]. If these particles interact through the weak interactions of the Standard Model, the resulting thermal relic density is close to the observed dark matter density. This coincidence, known as the “WIMP miracle,” provides strong motivation for dark matter with masses up to about a TeV.

As discussed in Section 4.3, however, there are also many alternative scenarios. For example, in the case of asymmetric dark matter [125, 126, 127, 128, 129], there is a slight excess of dark particles over dark antiparticles in the early Universe. These annihilate until only the slight excess of dark particles remains. In many models, the dark matter asymmetry is related to the normal matter–antimatter asymmetry, and one expects the number of dark matter particles to be similar to the number of protons, implying a dark matter particle mass of $\sim 10$ GeV, assuming this particle is the dominant component of dark matter. Asymmetric or thermal relic dark matter may be in a so-called hidden sector, which has its own set of matter particles and forces, through which the dark matter interacts with other currently unknown particles.

The non-gravitational interactions of the above dark matter candidates may be with any of the known particles or, as noted above for hidden sector dark matter, with other currently unknown particles. A complete research program in dark matter therefore requires a diverse set of experiments that together probe all possible types of couplings, as shown in Figure 4-9. At a qualitative level, the complementarity may be illustrated by the following observations that follow from basic features of each approach.

- **Direct Detection.** Prime examples are the detection of WIMPs through scattering off nuclei and the detection of axions in RF cavities. The methods relying on scattering off nucleons are relatively insensitive to dark matter that couples to leptons only, or to WIMP-like dark matter with mass $\sim 1$ GeV or below, while they are powerful for dark matter that couples to charged particles or gluons.
- **Indirect Detection.** When pairs of dark matter particles annihilate, they produce high-energy particles in the cosmic rays. For example, antimatter from local annihilation events can be found by AMS-02, neutrinos from annihilations in the Sun can be detected at IceCube, and photons from annihilations at the GC or in other galaxies can be seen by $\gamma$-ray telescopes. Alternatively, dark matter may be metastable, and its decay may produce the same high-energy particles. These indirect detection experiments (together) are sensitive to the interactions with all Standard Model particles and probe the annihilation process.
Figure 4-9. Dark matter may have non-gravitational interactions with one or more of four categories of particles: nuclear matter, leptons, photons and other bosons, and other dark particles. These interactions may then be probed by four complementary approaches: direct detection, indirect detection, particle colliders, and astrophysical probes. The lines connect the experimental approaches with the categories of particles that they most stringently probe. The diagrams give example reactions of dark matter (DM) with Standard Model particles (SM) for each experimental approach. From Ref. [130].

suggested by the WIMP miracle. Experimental sensitivities are expected to improve greatly on several fronts in the coming decade but some modes require good understanding of astrophysical backgrounds. Further, the signals are typically subject to uncertainties in the spatial distribution of dark matter (which is often not directly constrained) and may be absent altogether whenever the dark matter annihilation is insignificant now, e.g., in the case of asymmetric dark matter or $P$-wave suppressed annihilation.

- **Particle Colliders.** Particle colliders, such as the Large Hadron Collider (LHC) and proposed future lepton colliders, produce dark matter particles that escape the detector, but are discovered as an excess of events with missing energy or momentum. LHC experiments are sensitive to the broad range of masses favored for WIMPs (especially if they couple to quarks and/or gluons), but are relatively insensitive to dark matter that interacts only with leptons. Collider experiments are also unable to distinguish missing momentum signals produced by a particle with lifetime $\sim 100$ ns from one with lifetime above $10^{17}$ s, as required for dark matter.

- **Astrophysical Probes.** The particle properties of dark matter are constrained through its impact on astrophysical observables. Dark matter distributions and substructure in galaxies are unique probes of the “warmth” of dark matter and hidden dark matter properties, such as its self-interaction strength, and they measure the effects of dark matter properties on structure formation in the Universe. Examples include the self-interaction of dark matter particles affecting central dark matter densities in galaxies (inferred from rotation velocity or velocity dispersion measures), the mass of the dark matter particle affecting dark matter substructure in galaxies (inferred from strong lensing data), and the annihilation of dark matter in the early Universe affecting CMB fluctuations. Astrophysical probes are typically unable to distinguish various forms of CDM from one another or make other precision measurements of the particle properties of dark matter.
4.4.2 Discovery complementarity

We illustrate the qualitative features outlined above in three ways. First, we consider a fairly model-independent setting by considering dark matter that interacts with Standard Model particles through four-particle contact operators. These interactions are expected to work well to describe theories in which the exchanged particle mass is considerably larger than the momentum transfer of the physical process of interest. To illustrate aspects of the complementarity of the different searches, we assume the dark matter is a spin-1/2 particle that couples in a generation-independent way to the Standard Model leptons (effective operators involving quarks or gluons were also considered in Ref. [130]). The relevant piece of the Lagrangian is \( M_\ell^{-2} \bar{\chi} \gamma^\mu \chi \sum_\ell \bar{\ell} \gamma^\mu \ell \), where \( M_\ell \) is the scale of the new physics. The complementarity of different experimental approaches in probing low masses (\( \leq 10 \text{ GeV} \)), moderate masses, and high masses (\( > 300 \text{ GeV} \)) is evident in the top left panel of Figure 4-10, which shows dark matter discovery prospects in the mass vs. annihilation cross section plane for current and future direct detection experiments [131], indirect detection experiments [132, 133], and particle colliders [134, 135] for dark matter coupling to leptons. A discovery in the yellow region of this plot (below the dot-dashed line) would indicate that the dark matter (if assumed to be a thermal relic) has other significant annihilation channels that are waiting to be discovered.

The interactions with quarks and gluons are here illustrated through a concrete example of a complete supersymmetric model. The dark matter candidate is the lightest neutralino \( \tilde{\chi}_1^0 \), which is its own antiparticle. Even within the general framework of supersymmetry, there are many different model scenarios, distinguished by a number of input parameters (\( \sim 20 \)). A model-independent approach to supersymmetry is to scan over all those input parameters and consider models that pass all existing experimental constraints and have a dark matter candidate that could explain at least a portion of the observed dark matter density [136]. Results from such model-independent scans with over 200,000 points are shown in the top right panel of Figure 4-10, where each dot represents one particular supersymmetric model and its color indicates whether the model is observable in future direct searches (green), indirect searches (blue), or in both (red). The models that escape both direct and indirect searches, but are discoverable with current LHC data, are shown in magenta. The top right panel of Figure 4-10 demonstrates that these three different dark matter probes combine to discover a large fraction of the supersymmetry models in this scan.

The bottom panel of Figure 4-10 is for an asymmetric dark matter candidate that is charged under a hidden sector broken U(1) that has kinetic mixing with the Standard Model photon. The broken U(1)’s fine-structure constant is taken to be \( 10^{-2} \) for illustration and the hidden sector gauge boson’s mass is in the 1–100 MeV range. Bounds from supernova cooling and beam dump experiments restrict the value of the kinetic mixing parameter to be below about \( \epsilon = 10^{-10} \). For this mixing parameter, the gauge boson also safely decays before big bang nucleosynthesis. The dark matter self-interaction cross section in the blue shaded region is large enough (0.2 to 20 barns/GeV) to affect dwarf galaxies on observable scales. The effect is to lower the densities (see, e.g., Ref. [137]) and create constant density cores (see, e.g., Refs. [138, 139]) in a manner that is preferred by observations. Also shown are bounds from Bullet Cluster observations and requirements that self-interactions not make galactic halos too round; consistency with observations excludes the parameter space above the indicated contours. Direct detection is sensitive to a large region of parameter space that is preferred by astrophysical observations as shown by the contour for XENON1T sensitivity. We see that astrophysical observables probe low masses, while direct detection experiments probe mid-range and high masses, illustrating the complementarity of these two approaches in this asymmetric dark matter framework. The same model also allows for symmetric dark matter that freezes out with the right relic density (like WIMPs), where the qualitative complementarity features are the same but with further implications for indirect searches.
4.4 Dark matter complementarity

![Diagram of dark matter discovery prospects](image)

**Figure 4-10.** Top left: Dark matter discovery prospects in the mass vs annihilation cross section plane in the effective operator framework for dark matter coupling to leptons [130]. Top right: A model-independent scan of the full parameter space in the minimal supersymmetric model (MSSM), presented in the mass vs. dark matter-nucleon spin-independent cross section plane [140]. Bottom: Prospects for direct detection of asymmetric dark matter that couples to quarks via gauge kinetic mixing with $\epsilon = 10^{-10}$, showing complementarity with astrophysics in the mass vs. dark matter-nucleon spin-independent cross section plane [141].
4.4.3 Post-discovery complementarity

As important as a broad program of complementary searches is to establishing a compelling signal for dark matter, for several reasons it becomes even more important after a signal has been reported.

First, as is well known, many tentative dark matter signals have already been reported. The potential identification of a quarter of the Universe will require extraordinary proof in the form of verification by other experiments. Second, each search strategy has its limitations, as noted earlier in Section 4.4.1. Last, the discovery of dark matter will usher in a rich and decades-long program of dark matter studies, requiring a multi-pronged approach.

Consider the following scenario: Direct search experiments see evidence for a 100 GeV WIMP, and missing energy searches at an upgraded LHC also see a consistent signal. However, further LHC and ILC studies constrain the neutralino’s predicted thermal relic density to be half of $\Omega_{DM}$, implying that it is not a thermal relic, or that it makes up only half of the dark matter. The puzzle is resolved when axion detectors discover a signal that is consistent with axions making up the rest of the dark matter. Progress in astrophysical theory, simulations, and observations eventually leads to a consistent picture with dark matter composed entirely of CDM and extends our understanding of the Universe back to 1 ns after the big bang. Direct and indirect detection rates are then used to constrain the local dark matter density, halo profiles, and substructure, establishing the new fields of neutralino and axion astronomy. We see from the above example that even for well-studied dark matter candidates, information from multiple approaches is required to fully understand the dark matter. This is even more true if the dark matter sector is richer than that imagined above.

A balanced program with components in each of the four approaches is required to cover the many well-motivated dark matter possibilities, and their interplay will likely be essential to realize the full potential of upcoming discoveries.

4.5 Dark energy and CMB

Maps of the Universe when it was 400,000 years old, from observations of the CMB and over the last ten billion years from galaxy surveys, point to a compelling cosmological model. This model requires a very early epoch of accelerated expansion, known as inflation, during which the seeds of structure were planted via quantum mechanical fluctuations. These seeds began to grow via gravitational instability during the epoch in which dark matter dominated the energy density of the Universe, transforming small perturbations laid down during inflation into nonlinear structures such as million-light-year-sized clusters, galaxies, stars, planets, and people. Over the past few billion years, we have entered a new phase, during which the expansion of the Universe is accelerating, presumably driven by yet another substance, dark energy.

Cosmologists have historically turned to fundamental physics to understand the early Universe, successfully explaining phenomena as diverse as the formation of the light elements, the process of electron-positron annihilation, and the production of cosmic neutrinos. However, the Standard Model of particle physics has no obvious candidates for inflation, dark matter, and dark energy. The amplitude of the perturbations suggests that the natural scale for inflation is at ultra-high energies\(^1\), so understanding the physics driving inflation could lead to information about the ultraviolet completions of our current theories. There are arguments that naturally link the dominant dark matter component to new physics hovering above the electroweak scale; the powerful experiments aiming to find this component have been discussed above in

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1Roughly, the measured amplitude of the density perturbations $\delta \rho/\rho \simeq 10^{-5} \sim (E_{inf}/m_{Planck})^2/\sqrt{\epsilon}$, where $\epsilon \simeq 0.01$ is a small parameter in slow roll inflation.
4.5 Dark energy and CMB

Sects. 4.1, 4.2, 4.3, and 4.4. Apart from the dominant component, neutrino oscillation experiments already inform us that neutrinos constitute a non-negligible fraction of the dark matter. One of the key points of this chapter is that experiments usually associated with dark energy and inflation are ideally suited to pin down the sum of the masses of the neutrinos and the cosmic existence of any additional (sterile) species.

The situation with dark energy is more complex. A cosmological constant ($\Lambda$) has effective pressure and energy density related by $p = -\rho$ (equation of state $w = -1$), consistent with preliminary measurements, but in supersymmetric theories, for example, the most natural scale for $\Lambda$ is at least 100 GeV. A cosmological constant with this value would produce a Universe accelerating so rapidly that the tips of our noses would be expanding away from our faces at a tenth the speed of light. If $\Lambda$ is responsible for the current epoch of acceleration, its value is many orders of magnitude smaller than this, but curiously just large enough that it began dominating the energy density of the Universe only recently. The mechanism driving the current accelerated expansion of the Universe remains a profound mystery.

The quest to understand dark energy, dark matter, and inflation is, then, driven by a fundamental tension between the extraordinary success of the model that explains our Universe and the failure of the Standard Model of particle physics to provide suitable candidates for the dark sector that is so essential to our current view of the Universe. Experiments on the Cosmic Frontier have demonstrated that the Standard Model is incomplete; the next generation of experiments can provide the clues that will help identify the new physics required.

4.5.1 Dark energy

Physicists have proposed a number of different mechanisms that could be responsible for the accelerated expansion of the Universe. None is compelling, but some of them have been predictive enough to fail, while others have led to a deeper understanding of field theory and gravity. Apart from the cosmological constant solution itself, all are predicated on the assumption that there is some (unknown) mechanism that sets $\Lambda$ to zero.

One possibility is that there is a previously undiscovered substance that contributes to the energy density of the Universe in such a way that the expansion accelerates. In the context of GR, acceleration (the positive second derivative of the scale factor $a$) is governed by Einstein’s equations, which reduce to

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left[ \rho + 3P \right],$$

where $G$ is Newton’s constant, $\rho$ the energy density, and $P$ the pressure. The substance that drives acceleration, therefore, must have negative pressure, or equation of state $w \equiv P/\rho < -1/3$. A nearly homogeneous scalar field whose potential energy dominates over its kinetic energy satisfies this requirement, leading to *quintessence* models with potentials designed to fit the data. In almost all viable models, however, the mass of the field must be less than the Hubble scale today, of order $10^{-33}$ eV. Embedding such a field in some extension of the Standard Model therefore is challenging, as one would expect the scalar mass to get loop corrections many orders of magnitude larger than this. This mass stability problem is an indication of just how hard the problem is: The mass that is protected is some 44 orders of magnitude smaller than the Higgs mass that lies at the center of the electroweak hierarchy problem. It seems clear that the new physics is an infrared phenomenon, as opposed to all prior hints of new physics, which have entered from the ultraviolet.

With no real guidance from theory, quintessence models are nevertheless appealing because they open up the parameter space: Most models have $w \neq -1$, and many have evolving equations of state so that $dw/da$
is also non-zero. This class of models therefore offers a clear, and arguably more appealing, alternative to the cosmological constant that would be favored if surveys find a deviation from $w = -1$. Although the quintessence field does not clump on scales smaller than its (very large) Compton wavelength, it should clump on the largest scales. This is yet another difference from the cosmological constant model. Finally, some models allow for episodic dark energy domination, so that the present accelerating era is not particularly special. Indeed, an early epoch of inflation is one such epoch, but there may have been others, for example, during phase transitions. Measuring the effects of dark energy in a series of redshift bins is therefore necessary to distinguish among the many possibilities. This is an area where the CMB, whose lensing maps are sensitive to structure from redshift $z = 10^3$ until today, can be profitably combined with galaxy surveys, whose lensing maps probe structure at a sequence of lower redshifts.

Quintessence models explicitly introduce an extra degree of freedom in the form of a new scalar field. An alternative is to modify Einstein’s theory of gravity so that it produces acceleration even in the absence of dark energy. Early attempts to modify gravity in this way (the “left-hand side of Einstein’s equations”) also implicitly introduced an extra degree of freedom, but in a different way than do quintessence models. Technically, these models differ from quintessence in that the coefficient of the Ricci scalar $R$ in the Jordan frame in the action depends on the new field. Different scalar-tensor models can therefore produce the variety of predictions found in quintessence models, but they extend the possibilities in a new direction: The non-canonical coupling to the Ricci scalar propagates to the equations that govern the evolution of perturbations. This leads to the general conclusion that modified gravity models typically predict that structure grows at a different rate (e.g., Ref. 144) than in models based on GR. Differentiating between modified gravity and GR-based dark energy therefore will require measurements of cosmological distances to pin down the background expansion, and then measurements of the growth of structure to distinguish between them.

Although there have been many proposals for how to modify gravity, the most interesting recent development traces back to an idea first proposed by Fierz and Pauli, that the graviton has non-zero mass. Qualitatively a massive graviton seems like an appropriate way to decrease the strength of the gravitational force on very large scales and hence to explain the acceleration of the Universe. In practice, the theory runs into two problems, both related to the fact that a massive spin-2 particle carries degrees of freedom beyond those of the massless graviton. These extra degrees of freedom typically lead to modifications of GR in the solar system, modifications that are excluded by the tight limits on post-Newtonian parameters. The second challenge for massive graviton models is to avoid Boulware-Deser ghosts, the instability of one of the extra degrees of freedom.

To satisfy the solar system constraints, the extra degrees of freedom need to be screened, i.e., heavily suppressed by limiting their range of interaction or effective coupling to matter in environments like the solar system. Any successful modified gravity model needs a screening mechanism. One possibility is Vainshtein screening, which arises due to non-linearities in the Fierz-Pauli potential. In general, these non-linear terms do not avoid the ghost problem, but recently the set of terms in the potential that are safe from ghosts has been identified. These Galileon models offer a potentially attractive way of addressing the acceleration of the Universe within a consistent framework. Beyond this theoretical breakthrough, the Vainshtein screening intrinsic to this model (and other proposed mechanisms) opens up yet another axis of tests: How and where do modified gravity theories transition to normal Newtonian gravity in the solar system? The full suite of methods to test modified gravity models is still under development.

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2 Redshift $z \equiv a^{-1} - 1$; high redshift corresponds to early cosmic time.

3 Theories can be written either in the Jordan frame, in which matter couples to the metric only through $\sqrt{-g} \mathcal{L}_m$, or in the Einstein frame, in which the gravitational part of the action remains Einstein-Hilbert and there are additional couplings of the new degrees of freedom to matter.
The modern view of the formation of structure in the Universe has been confronted with a growing array of precise tests, including both the temperature and polarization anisotropy spectrum of the CMB; light curves of distant supernovae; abundances of galaxy clusters; clustering of galaxies, quasars, and Lyman alpha systems; gravitational lensing; and cross-correlations between different pairs of these observations. The basic framework, with inflation, dark matter, and dark energy at its core, has been confirmed repeatedly over the past decade. We need to keep pushing: Either the basic picture will break or the agreement will become even more remarkable. Thinking in parameter space, the next decade will enable us to reduce the uncertainty in the equation of state \( w \) by a factor ten. Historically in physics, precision measurements of this sort have been pursued for these ends: Will the simple theory hold up or will it need to be replaced by something more profound? In the case of the cosmic acceleration, where there is no appealing fiducial model, the push for greater precision takes on an even greater importance.

Since scientists in the United States discovered evidence for cosmic acceleration over a decade ago, the U.S. has been the leader in the field of dark energy studies. The 2006 Dark Energy Task Force report \[149\] provided a systematic discussion of experimental approaches to dark energy and identified a sequence of “Stage III” and “Stage IV” dark energy experiments to build on those then in progress. Stage III surveys were designed to address systematic uncertainties, with the goal of statistics-limited constraints from four independent probes. Each of these probes will be developed over the ensuing decade to the point at which Stage IV surveys will enable sub-percent level consistency checks for all probes, some of which will have reached their cosmic variance limit, \( i.e. \), the limit imposed by the fact that we have only a single observable Universe to probe. This staged categorization was reiterated in the more recent Community Dark Energy Task Force Report \[150\], which particularly emphasized the importance of complementing planned imaging experiments with spectroscopic experiments. Figure 4-11 illustrates the timelines for several of the major dark energy experiments in which U.S. scientists are playing an important or leading role. Further details provided in a separate document \[8\].

Major gains beyond the current road map of dark energy projects will require advances on one of a number of fronts. One potential avenue is to develop new techniques or probes of cosmology and new physics that have not yet been developed. Data from many cosmological surveys have been used for tests not envisioned when those experiments were first designed, and we anticipate that that trend will continue \[15\]. Another path is to obtain complementary information that will enhance planned experiments. For example, a targeted program of spectroscopic redshift measurements can enhance the dark energy constraints from LSST compared to its baseline capabilities \[151\]. Finally, new instrumental capabilities could enable powerful new dark energy experiments to be conducted at reduced costs. Possible examples include methods that suppress flux from emission lines from the night sky, which are much brighter than distant galaxies at infrared wavelengths, or new detector technologies that would measure photon energy rather than just quantity. Modest investments in these avenues may yield large potential payoffs in the future.

The following sub-sections summarize the physical probes and measurements that address dark energy science. Each of these approaches is detailed further in a separate document \[10, 13, 15, 14\]. Taken together, these measurements and the projects that enable them constitute an all-out attack on the problem of cosmic acceleration. The program planned over the coming decade guarantees continuing U.S. leadership in this field.

### 4.5.1.1 Distances

The relationship between the redshift and distance of an object is one of the primary tests of the expansion history of the Universe, and therefore played a key role in the discovery of the accelerating Universe. The simple graph of the distance scale of the Universe as a function of redshift, indicating the evidence for cosmic
Figure 4-11. A timeline of Stage III and Stage IV dark energy experiments — photometric and spectroscopic — in which U.S. scientists are playing an important or leading role. Most of the projects are ground-based with either U.S. leadership (BOSS, DES, HETDEX, eBOSS, DESI, LSST) or active participation (HSC, PFS). The two space missions are Euclid, led by the ESA with a NASA-sponsored team of U.S. participants, and WFIRST, led by NASA.

Acceleration, has become an iconic plot in the physical sciences. The data for this plot so far come from measurements of Type Ia supernovae and baryon acoustic oscillations (BAO), and these will be the sources of streams of data in coming years. DES and LSST will provide an essentially limitless supply of supernova — thousands, then hundreds of thousands. The DES collaboration and LSST-DESC will coordinate the spectroscopic classification of a fraction of these objects. The challenge is to make sufficiently thorough measurements to mitigate systematic problems, especially those that depend on redshift. Detailed studies of nearby supernovae are beginning to provide clues for how to do this. Much would be gained if observations could be made from space, but a substantial gain will be also achieved if we make ground-based observations that avoid the atmospheric lines in the near infrared.

The subtle pattern of anisotropy in the CMB, just one part in $10^5$, is mapped at the two-dimensional boundary of a three-dimensional feature, the fluctuations in matter density throughout space. The counterpart of the oscillations in the CMB power spectrum is a peak in the correlation between the densities at points separated by 153 Mpc, measured relative to the scale size of the Universe, which is left behind by BAO in the early Universe. This very large meter stick can be observed as far out as redshifts $z = 1.6$ using galaxies as traces of matter density, and even out to $z = 3$ by observing correlations in the troughs of spectra from distant quasars [152]. The current Baryon Oscillation Spectroscopic Survey (BOSS) is likely to report a distance measurement soon with 1% accuracy. The eBOSS survey is designed to extend the reach of BAO measurements to higher redshifts. The Stage-IV BAO experiment, Dark Energy Spectroscopic Instrument (DESI), should provide more than 30 similarly accurate independent distance measurements.
Figure 4-12. Current and projected future uncertainties on cosmic distance as a function of redshift.
Figure 4-12 shows the current and projected future constraints on cosmic distances using these two techniques. If our basic understanding is correct, the supernova and BAO measurements should be in absolute agreement. The distance–versus–redshift curve of the Universe is fundamental, and exploring it with completely different techniques is essential. These stunning measurements will allow for percent-level determination of the equation of state and will be extremely sensitive to evolution of the dark energy at earlier times. By pinning down the distance–redshift relation, they will also allow for apples-to-apples comparisons of modified gravity versus dark energy models using the growth of structure.

4.5.1.2 Growth of structure

The quantity and quality of cosmic structure observations have greatly accelerated in recent years, and further leaps forward will be facilitated by imminent projects. These will enable us to map the evolution of dark and baryonic matter density fluctuations over cosmic history. The way that these fluctuations vary over space and time is sensitive to several pieces of fundamental physics: the primordial perturbations generated by GUT-scale physics, neutrino masses and interactions, the nature of dark matter, and dark energy. Here we focus on the last of these, and the ways that combining probes of growth with those of cosmic distances will pin down the mechanism driving the acceleration of the Universe.

If the acceleration is driven by dark energy, then distance measurements provide one set of constraints on $w$, but dark energy also affects how rapidly structure grows. Upcoming surveys are therefore designed to probe $w$ in two distinct ways: direct observations of the distance scale and the growth of structure, each complementing the other on both systematic errors and dark energy constraints. A consistent set of results will greatly increase the reliability of the final answer.

If cosmic acceleration is driven by modified gravity, then probes of structure become even more important. Generically, modified gravity models are able to reproduce any expansion history that can be attained in dark energy models, but at the cost of altering the growth of structure. How rapidly structure grows is quantified by the dimensionless growth function $D(a)$. Figure 4-13 illustrates how different models make predictions that differ from those of GR even though the distance–redshift relation in all these models is identical. The growth of structure then will be able to distinguish modified gravity from dark energy as an explanation for the cosmic acceleration.

Figure 4-13 projects constraints from a spectroscopic survey that measures the local velocities of galaxies by observing redshift space distortions. Similarly powerful constraints are projected from photometric surveys that are dedicated to measuring the shapes of galaxies and therefore are sensitive to the signal from weak gravitational lensing.

Achieving these powerful constraints will require both wide field imaging and spectroscopic redshift surveys, as depicted in Figure 4-11. The results will pin down far more than the equation of state to percent-level accuracy, although this in itself will be an important clue as to whether the cosmological constant or an alternative is driving the acceleration of the Universe. We will also learn whether the equation of state is varying with time and whether dark energy was relevant at high redshift. The surveys will probe cosmological perturbations as a function of both length and time, opening up dozens of possible failure modes for GR-based dark energy. If any of the possible deviations from GR predictions is reliably established, we will have a revolution on our hands.
**Figure 4-13.** Constraints on the growth of density fluctuations in the Universe with errors projected from DESI. The curves show the derivative of the logarithmic growth with respect to logarithmic scale factor — a quantity readily measured from the clustering of galaxies in redshift space — as a function of redshift. We show theory predictions for the standard \( \Lambda \)CDM model, as well as for two modified-gravity models, the Dvali-Gabadadze-Porratti (DGP) model [153], and the \( f(R) \) modification to Einstein action [154]. Because growth in the \( f(R) \) models is generically scale-dependent, we show predictions at wave numbers, \( k = 0.02 \) h Mpc\(^{-1}\) and \( k = 0.1 \) h Mpc\(^{-1}\). LSST projects to impose constraints of similar excellent quality on the growth function \( D(a) \).

### 4.5.1.3 Novel probes

Surveys enabling the twin probes of distances and structure can distinguish between modified gravity and dark energy on cosmological scales. It has become apparent over the last few years that non-cosmological tests can also play an important role in determining the mechanism driving the acceleration of the Universe. The basic idea is that gravity is known to reduce to GR on solar system scales, so any modified gravity model must have a screening mechanism, wherein the additional forces operative on large scales are suppressed in the solar system. Indeed, many of the models have screening built into them, so the solar system constraints can be naturally satisfied. The key issue is the nature of the transition from large (modified gravity) to small (GR) scales, and how that transition can be observed.

Most screening mechanisms utilize some measure of the mass distribution of halos, such as the density or the Newtonian potential, to recover GR well within the Milky Way. This leaves open the possibility that smaller halos, the outer parts of halos, or some components of the mass distribution, are unscreened and therefore experience enhanced forces. For a given mass distribution, unscreened halos will then have internal velocities and center-of-mass velocities larger than predicted by GR. Deviations from GR are typically at the ten percent level, with distinct variations between different mechanisms in the size of the effect and the way the transition to GR occurs. It is important to note that observable effects are typically larger on galaxy...
scales than on large (cosmological) scales or at high redshift. The comparison of dynamical and lensing masses provides a powerful test that is being implemented on a wide range of scales, from individual galaxies to large-scale cross-correlations (see Sections 4.5.1.2 and 4.5.1.4).

Although the Vainshtein screening mechanism mentioned earlier arises in some models, the chameleon mechanism, where the extra degree of freedom is suppressed in high density regions, is prevalent in others. Figure 4-14 shows a range of tests that have been implemented in one particular model, $f(R)$ gravity, with chameleon screening. The screening in this model, as in many others, depends on the value of a field in the region of interest. The $y$-axis in Figure 4-14 depicts the value of this field in Planck units divided by a coupling constant, while the $x$-axis shows that the model has been probed on scales ranging from the solar system all the way out to cosmological scales, with all tests to date verifying GR. In the next decade essentially the entire accessible parameter space of chameleon theories can be probed using the tests shown in the figure. Tests for the other important screening mechanism, Vainshtein screening, are at early stages with potential for rapid progress.

The program of testing gravity theories via these novel probes is in its infancy, but it is becoming increasingly clear that even modest investments in non-cosmological observations have enormous potential to contribute to the cosmic acceleration problem.
4.5.1.4 Cross-correlations

To extract the most information possible about dark energy from galaxy surveys and CMB experiments, scientists will be forced to combine probes. The multi-probe approach is not simply a matter of multiplying uncorrelated likelihoods. For example, gravitational lensing and large-scale structure are highly correlated probes, with the lensing signal enhanced behind over-dense regions and the density enhanced (due to magnification) behind regions with large lensing signals. The likelihoods are therefore not independent, and there is significant information contained in the cross-correlations. Beyond improvement in statistical power, these cross-correlations will enable us to isolate systematic uncertainties. The four principal probes — supernovae, clusters, lensing, and large-scale structure — are correlated with one another in ways that will need to be accounted for as we strive for percent-level accuracy in dark energy parameters.

The four probes enabled by optical surveys will be supplemented by data at other wavelengths. One of the most promising for the purposes of dark energy will come from the oldest probe, the CMB. To date, CMB experiments have supplemented galaxy surveys mainly by constraining parameters that would otherwise be degenerate with those that characterize dark energy. Since the CMB is sensitive to early Universe physics, it probes dark energy only through the geometric projection from the surface of last scattering. The photons from the last scattering surface, however, experience deflections due to gravitational lensing and to Compton scattering off free electrons. These deflections show up as secondary anisotropies, which often do carry information about dark energy.

Galaxy clusters are perhaps the quintessential example of the value of observing cosmic phenomena at different wavelengths. One of the key uses for clusters in dark energy studies is to compare their abundance above a given mass threshold as a function of redshift with theoretical predictions. The key uncertainty remains the mass determination, and it is in this regard that multi-wavelength studies become particularly important. By observing clusters in optical surveys, in the microwave frequencies via the Sunyaev-Zel’dovich effect that follows from Compton scattering off hot electrons in the clusters, and in the X-ray region when those same electrons emit radiation, we obtain many possible mass proxies. Taken together, they offer a powerful attack on the dominant systematic uncertainties in dark energy cluster studies. Figure 4.15 shows an example of these different views of a galaxy cluster.

4.5.2 Inflation

Cosmic inflation is the leading theory for the earliest history of the Universe and for the origin of structure in the Universe. Current observations of the large-scale distributions of dark matter and galaxies in the Universe and measurements of the CMB are in stunning agreement with the predictions of inflation. The next generations of experiments in observational cosmology are poised to explore the detailed phenomenology of the earliest moments of the Universe.

Although the landscape of possible models for inflation is large, the theoretical underpinnings are well understood, and we are able to make concrete predictions for observable quantities. One key prediction is the existence of a background of gravitational waves from inflation that produces a distinct signature in the polarization of the CMB (the $B$-modes in Figure 4.16). Under the so-called Lyth condition [162], all models in which the field driving inflation varies by an amount of order $m_{\text{Planck}}$ will produce gravitational wave (tensor) fluctuations that are at least 1% of the amplitude of density-fluctuation (scalar) power in the CMB ($r = 0.01$ in the figure). Definitive evidence as to the presence or absence of tensor modes with amplitudes at or above this level would therefore be a window on an infinite sequence of Planck-suppressed operators. Such scales require a quantum gravity treatment, and this will test string-theoretic mechanisms.
for large field inflation. If not detected, these observations at least decide between two broad classes of models, since they are sensitive to Planck-scale effects. This motivates the design of a next-generation CMB experiment with the sensitivity and systematics control to detect such a signal with at least 5σ significance, thus ensuring either a detection of inflationary gravitational waves or the ability to exclude large classes of inflation models.

There are several other ways to probe the physics of inflation. Inflation generically predicts small deviations from a scale-invariant spectrum, and current measurements confirm this prediction at the 5σ level. DESI projects to obtain a 15σ detection, thereby further reducing the range of allowed models. BOSS, eBOSS, and DESI will potentially constrain the running of the primordial spectrum (deviation from a pure power law) at the 0.2% level, a factor of five tighter than current constraints.

The non-gaussian distribution (non-gaussianity) of the primordial perturbations can take many forms. The search for one — so-called local non-gaussianity — is particularly important because single-field models of inflation generically predict negligible local non-gaussianity, so any detection will falsify a large class of models. Planck has placed strong upper limits on this and other forms of non-gaussianity consistent with these predictions. The upcoming surveys eBOSS, DESI, and LSST will constrain a variety of forms of primordial non-gaussianity on different spatial scales and be subject to different systematic uncertainties than the CMB. They will therefore pave the way for even more stringent bounds on inflationary models.

Figure 4-15. Map of a galaxy cluster using three probes: (i) Weak gravitational lensing (blue contours with labels showing the projected density κ); (ii) hot gas as measured by the Sunyaev-Zel’dovich distortion of the CMB (white contours with labels giving signal to noise); and (iii) galaxies as observed in three optical bands (background).
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Figure 4-16. Expected signal levels for the CMB Polarization E-mode (solid red), inflationary gravity-wave B-mode (solid blue), and lensing B-mode (solid green) signals. The gravitational wave B-mode signals are shown for tensor-to-scalar ratios of $r = 0.001$ (the Stage IV goal) and $r = 0.01$ (the boundary between small-field and large-field inflation models). The lensing B-mode signal is shown as a band encompassing the predicted signal for values of the sum of neutrino masses $0 \leq \sum m_\nu \leq 0.1 \text{eV}$. De-lensing by a factor of 4 in amplitude is shown schematically by the green arrow, with the residual signal at $\ell \leq 200$ (where the de-lensing is critical to the constraint on $r$) shown by the green, long-dashed line. The black, short-dashed line shows the level of current 95% upper limits on B-modes from WMAP, BICEP, QUIET and QUaD experiments. The brown, long-dashed lines show the expected polarized foreground contamination at 95 GHz for the cleanest 1% and 25% of the sky.

4.5.3 Neutrinos

One of the most remarkable aspects of physical cosmology is that the study of the largest physical structures in the Universe can reveal the properties of particles with the smallest known cross section, the neutrinos. At the simplest level, this cosmological sensitivity to neutrino properties is due to the fact that the neutrino cosmological number density is so large as to be second only to CMB photons. More specifically, the properties of neutrinos alter the effective energy density of cosmological radiation and therefore the amplitude, shape and evolution of matter perturbations, leading to changes in observables in the CMB anisotropies and in measures of large-scale structure.

The CMB and large-scale structure measured in galaxy surveys are sensitive to the sum of the neutrino masses and to $N_{\text{eff}}$, the number of species produced in the early Universe. These observations are therefore complementary to laboratory probes of neutrinos that measure mass differences and, potentially, CP violation. CMB experiments are sensitive enough to the neutrino energy density to exclude $N_{\text{eff}} = 0$ at more than 10$\sigma$; i.e., these experiments have already indirectly detected the cosmic neutrinos. Together with
A global fit to solar and atmospheric neutrino flavor oscillations in the standard 3-generation model determines two mass differences. A third parameter, which can be taken as either the sum of the masses or the lightest mass, is, therefore, unknown. Due to a sign ambiguity in one of the mass differences, there are two discrete possibilities, normal and inverted hierarchy, for the relationship between these two parameters. As indicated in Figure 4-17, upcoming CMB experiments and large-scale structure surveys will unambiguously detect the sum of the masses if the hierarchy is inverted and will likely do so at greater than 3σ significance, even if nature has chosen the normal hierarchy. Measures of the power spectrum from DESI, combined with Planck data, could improve the current constraint on $\sum m_\nu$ to 17 meV, and a Stage IV CMB survey combined with BAO measurements from DESI could achieve similar sensitivity [11]. Figure 4-17 highlights another aspect of the complementarity of laboratory experiments and cosmological probes: If the sum of the masses is found to be 0.15 eV by the cosmological probes, then it will take the lab experiments to determine whether the hierarchy is normal or inverted.

Short-baseline neutrino oscillation results hint at a richer neutrino sector than three active neutrinos participating in flavor oscillations, with one or more sterile flavors also participating [165, 166, 167, 168]. Future CMB experiments will achieve a 1σ error of $\Delta N_{\text{eff}} = 0.027$, which will complement future sterile neutrino
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searches and inform model building, since sterile neutrinos might be detected in the laboratory even though they were not produced in the early Universe and vice versa.

4.5.4 Dark energy and CMB conclusions

Cosmological surveys are sensitive to fundamental physics. To date, this has led to the discovery of the accelerating Universe, strong evidence for an epoch of early acceleration near the GUT scale, the indirect detection of the cosmic neutrino background, and the most compelling evidence for non-baryonic dark matter. However, surveys to date have measured only a fraction of all information available. If the Universe were contained in an area the size of the United States, galaxy maps so far would have surveyed the city of Birmingham, Alabama. CMB experiments have provided low-noise maps of the temperature down to angular scales of order a tenth of a degree. Strategic, valuable information remains unmined in higher-resolution temperature maps and the virtually uncharted polarization field. We have outlined the projections for how this extra information will constrain dark energy, neutrinos, and inflation, and these projections are extraordinary. But even they ignore the very real possibility that future experiments on the Cosmic Frontier will do just what their predecessors have done: Discover something fundamentally new!

The community has rallied behind previous reports [149, 169, 150] which are consistent with the current consensus to support the following key steps:

- **Remain a leader in dark energy research.** The U.S. played the leading role in discovering the acceleration of the Universe, as was recognized by the 2011 Nobel Prize. The acceleration remains a mystery, whose solution may usher in a revolution in either our theory of gravity or our understanding of particle physics. Different classes of theories make different predictions for the growth of structure, given a redshift-distance relation. A combination of spectroscopic and photometric surveys can determine both distances and structure growth, and so will help pinpoint the new physics driving the acceleration of the Universe. The current suite of surveys, Stage III, will be the first to implement the vision of multiple probes and small systematic uncertainties. This vision will be realized fully with the Stage IV surveys (LSST and DESI) when they reach the level where exquisite-precision dark energy constraints from different probes, in some cases approaching the cosmic variance limit, can be checked for consistency. Therefore, the community strongly supports continuing the program of Stage III and Stage IV dark energy experiments, and moving forward as quickly as possible with the construction of LSST and DESI.

- **Build a generation IV CMB polarization experiment.** CMB experiments can measure the sum of the neutrino masses and the energy scale of inflation, as well as constrain exotic physics such as early dark energy and extra neutrino species. After the current generation of small-scale experiments complete data-taking near the end of the decade, the community understands that the next generation experiment — one that can pin down neutrino masses and the scale of large field inflationary models — requires a nationwide coherent effort. Moving from thousands to hundreds of thousands of detector elements will require the involvement of the national laboratories working together with the university community.

- **Extend the reach.** With small additional investments, the dark energy program can be augmented in three important ways. A targeted spectroscopic campaign designed to optimize and calibrate methods of redshift estimation from imaging surveys can enhance their science returns beyond their nominal capabilities [12]. Second, a continued investment in instrumentation R&D will allow the community to do more science for less money and to be ready to capitalize on future discoveries. Finally, a suite of novel probes of gravity and dark energy can discover signatures of modified gravity and new physics in the dark sector. We have the opportunity to catalyze the next generation of tests by supporting work at
the interface of theory, simulation and data analysis, and making small enhancements to the dark energy survey program.

4.6 Cosmic particles and fundamental physics

Over the past decade we have witnessed a revolution in our understanding of the high-energy Universe. This includes several key discoveries.

- Supernova remnants have been shown to be a source of galactic cosmic rays [170].
- Very high energy neutrinos that are likely to be astrophysical in origin have been observed [171].
- The GZK suppression in the cosmic-ray flux above $3 \times 10^{19}$ eV has been observed [172, 173].
- The positron fraction of the cosmic rays has been measured up to 300 GeV, providing solid evidence for a high-energy primary source of positrons in the galaxy, either from dark matter annihilation or astrophysical processes [55, 54].
- Many sites of astrophysical particle acceleration have been directly observed, from supermassive black holes and merging neutron stars, to rapidly spinning neutron stars and supernova remnants in our galaxy [174].

These discoveries have been driven by the current generation of experiments: the IceCube neutrino detector at the South Pole, the Fermi gamma-ray observatory and the PAMELA and AMS experiments orbiting the Earth, the High Resolution Fly’s Eye and Pierre Auger Observatory ultra-high-energy cosmic ray experiments, and the HESS, VERITAS, MAGIC and Milagro experiments in very-high-energy gamma rays.

Looking forward, a new generation of instruments with greater sensitivity and higher resolution holds the promise of making large advances in our understanding of astrophysical processes and the fundamental physics studied with astrophysical accelerators. The goals for the coming decade are:

- Determine the origin of the highest energy particles in the Universe and understand the acceleration processes at work throughout the Universe.
- Measure particle cross sections at energies unattainable in Earth-bound accelerators.
- Measure the highest energy neutrinos that arise from interactions of the ultra-high-energy cosmic rays with the CMB.
- Measure the extragalactic background light at wavelengths between 1 and 100 $\mu$m to understand the star formation history of the Universe.
- Measure the mass hierarchy of the neutrinos.
- Search for physics beyond the Standard Model encoded in cosmic messengers as they cross the Universe.
- Understand the origins of the matter-antimatter asymmetry of the Universe.
- Probe the fundamental nature of spacetime.
In many of these areas, future progress will depend upon either the detailed understanding of particle acceleration in the Universe or the development of methods for controlling systematic errors introduced by our lack of understanding of these processes. High-resolution gamma ray measurements (spectral, angular, and temporal) of many objects and classes of objects are needed to find the source-invariant physics that is the signal for physics beyond the Standard Model. Such measurements, in conjunction with measurements at other wavelengths and with measurements of cosmic rays, neutrinos, and gravity waves, will enable us to understand Nature’s particle accelerators. We propose several recommendations to achieve these goals.

- **Significant U.S. participation in the CTA project** [175]. U.S. scientists developed the imaging atmospheric Cherenkov technique. Continued leadership in this area is possible with the development of novel telescope designs. A U.S. proposal to more than double the number of mid-scale telescopes would result in a sensitivity gain of 2 to 3, significantly improving the prospects for the indirect detection of dark matter, understanding particle acceleration processes, and searching for other signatures of physics beyond the Standard Model.

- **Simultaneous operation of Fermi, HAWC, and VERITAS.** Understanding particle acceleration and separating astrophysical processes from physics beyond the Standard Model requires observations over a broad energy range. The above three instruments will provide simultaneous coverage from 30 MeV to 100 TeV. HAWC and VERITAS will simultaneously view the same sky, enabling prompt follow-up observations of transient phenomena.

- **Construction of the PINGU neutrino detector** [176] at the South Pole. U.S. scientists have been leaders in the field of high-energy neutrino observations. PINGU, by densely instrumenting a portion of the IceCube Deep Core array, will lower the energy threshold for neutrinos to a few GeV. This will allow for a measurement of the neutrino mass hierarchy using atmospheric neutrinos.

- **Continued operation of the Auger and Telescope Array (TA) air shower arrays with upgrades** to enhance the determination of the composition and interactions of cosmic rays near the energy of the GZK suppression, and **flight of the JEM-EUSO mission** [177] to extend observations of the cosmic ray spectrum and anisotropy well beyond the GZK region.

- **Construction of a next-generation ultra-high-energy GZK neutrino detector** either to detect GZK neutrinos [178] and constrain the neutrino-nucleon cross section at these energies [179], or exclude all but the most unfavorable parts of the allowed parameter space.

### 4.6.1 Ultra-high-energy cosmic rays

HiRes [172], Auger [180], and TA [181] have established the existence of a suppression of the spectrum at the highest energies (above ~ $3 \times 10^{19}$ eV), as predicted by Greisen, Zatsepin, and Kuzmin (GZK) in 1966 [182, 183]. The GZK suppression is an example of the profound links between different regimes of physics, connecting the behavior of the highest-energy particles in the Universe to the CMB, and can be explained by the sub-GeV-scale physics of photo-pion production occurring in the extremely boosted relativistic frame of the cosmic ray. A similar phenomenon occurs for primary nuclei due to excitation of the giant dipole resonance, resulting in photo-disintegration. For iron nuclei, this occurs at about the same energy per particle as the photo-pion process does for protons.

The composition of cosmic rays and their interactions with air nuclei may be probed by studies of the depth of shower maximum, $X_{\text{max}}$ [184]. The mean value of $X_{\text{max}}$ rises linearly as a function of the logarithm of the cosmic ray’s energy, and depends on the nature of the primary particle, the depth of its first interaction,
and the multiplicity and inelasticity of the interactions as the shower evolves. Lower energy observations of $X_{\text{max}}$ indicate that the composition becomes lighter as the energy increases toward $\sim 10^{18.3}$ eV [185], which suggests that extragalactic cosmic rays are mainly protons. However, at higher energies the Auger Observatory’s high-quality, high-statistics sample exhibits the opposite trend, along with a decreasing spread in $X_{\text{max}}$ with increasing energy [180, 186]. Using current simulations and hadronic models tuned with LHC forward data, this implies the composition is becoming gradually heavier above $10^{18.5}$ eV. A trend toward heavier composition could reflect the apparent GZK suppression being in fact the endpoint of cosmic acceleration, in which there is a maximum magnetic rigidity for acceleration, resulting in heavy nuclei having the highest energy per particle.

Cosmic rays can be used to probe particle physics at energies far exceeding those available at the LHC. An alternative explanation for the observed behavior of $X_{\text{max}}$ is a change in particle interactions not captured in event generators tuned to LHC data. Auger measurements using three independent methods find that these models do not describe observed showers well. For example, the observed muon content of showers measured in hybrid events at Auger is a factor 1.3 to 1.6 larger than predicted [187]. TA also observes a calorimetric energy that is about 1.3 times higher than that inferred from their surface detector using these models. An example of a novel phenomenon that may explain these observations is the restoration of chiral symmetry in QCD [188].

A critical step in fully understanding the $X_{\text{max}}$ observations is to identify and correct the deficiencies in the beyond-LHC physics used in modeling showers. This requires continued operation of current hybrid detectors such as Auger and TA, with upgrades to enable improved multi-parameter studies of composition and interactions on a shower-by-shower basis. Enhancements of the surface detectors are particularly valuable because of the tenfold higher duty cycle than for fluorescence or hybrid operation.

Observations from space can extend studies of the spectrum and anisotropy beyond the GZK region with high statistics. Measurements at ground-based observatories hint that cosmic ray arrival directions may be correlated with the local distribution of matter [189, 190], but higher statistics trans-GZK observations are required to identify sources. In addition, answering the question of whether the spectrum flattens again above the GZK suppression or continues to fall will distinguish between the GZK and acceleration limit scenarios. The JEM-EUSO mission has an instantaneous collecting area of $\sim 40$ times that of existing ground-based detectors [177] and, taking duty cycle into account, will increase the collecting area above the GZK suppression energy by nearly an order of magnitude.

4.6.2 Neutrinos

IceCube has recently reported the detection of two neutrinos with energies above 1 PeV and 26 events above 30 TeV, with characteristics that point to an astrophysical origin [171]. These exciting results herald the beginning of the era of high-energy neutrino astronomy and initiate the study of ultra-long baseline high-energy neutrino oscillations. Neutrino data complement observations of cosmic rays and gamma rays due to the origin of neutrinos in the decays following high-energy hadronic interactions and their weak couplings. Several acute issues in particle physics and astrophysics can be addressed by neutrino experiments.

**GZK neutrinos.** GZK neutrinos are created in the weak decays of the mesons and neutrons produced in the interaction of ultra-high-energy cosmic rays with the CMB [178]. The production of these neutrinos takes place via well-known physics at high Lorentz boost, so robust predictions of the neutrino flux can be made. The flux depends on the composition of the primary cosmic rays (being lower for a heavier composition) and the evolution of the cosmic ray source density with redshift. Unlike many searches, there is a lower limit on the expected flux. Current detectors such as IceCube, Auger, RICE, and ANITA have begun to probe the...
highest predicted values of the neutrino flux. Next-generation experiments such as ARA, ARIANNA, and EVA can increase our sensitivity by about two orders of magnitude, and will either detect GZK neutrinos or exclude much of the parameter space. If GZK neutrinos are detected, the event rate as a function of zenith angle can be used to measure the neutrino-nucleon cross section and constrain models with enhanced neutrino interactions at high energy [191].

**Atmospheric neutrinos and the neutrino mass hierarchy.** PINGU is a proposed high-density infill of the IceCube detector with a reduced energy threshold of a few GeV, employing the rest of IceCube as an active veto. PINGU has sensitivity to atmospheric $\nu_\mu$ over a range of values of the length-to-energy ratio $L/E$ spanned by the variation in the distance to the production region as a function of zenith angle and the energy spectrum of atmospheric neutrinos. Preliminary studies of PINGU indicate that over these values of $L/E$, atmospheric $\nu_\mu$ oscillations can be used to determine the neutrino mass hierarchy with 3–5$\sigma$ significance, given two years of data with a 40-string detector [176].

**Supernova neutrinos.** The measurement of the time evolution of the neutrino energy and flavor spectrum from supernova bursts has the potential to revolutionize our understanding of neutrino properties, supernova physics, and measure or tightly constrain non-standard interactions. Collective oscillations of neutrinos leaving the neutron star surface imprint distinct signatures on the time evolution of the neutrino spectrum that depend on the neutrino mass hierarchy and the mixing angle $\theta_{13}$. Although the spectral distributions of anti-electron neutrinos for the normal and inverted mass hierarchies are not so distinct, the electron neutrino spectra are dramatically different [192]. Therefore, a large underground liquid argon detector, such as the Long Baseline Neutrino Experiment (LBNE) [193], which is predominantly sensitive to electron neutrinos, could determine the neutrino mass hierarchy if a supernova occurred within our Galaxy.

### 4.6.3 Gamma rays

High-energy gamma rays provide a unique view into the most extreme environments in the Universe, probing particle acceleration processes and the origin of the galactic and extragalactic cosmic rays. Active galactic nuclei (AGN), supermassive black holes emitting jets of highly relativistic particles along their rotation axis, have been shown to be sites of particle acceleration [174]. Outstanding issues in the acceleration processes include: the nature of the accelerated particles (hadronic or leptonic), the role of shock acceleration versus magnetic reconnection, and the formation and collimation of astrophysical jets [194]. Answers to these questions will come from higher resolution measurements in the GeV–TeV regime, multi-wavelength campaigns with radio, X-ray, and gamma-ray instruments, and multi-messenger observations with gamma rays, ultra-high energy cosmic rays, neutrinos, and potentially gravitational waves. Understanding these extreme environments and how they accelerate particles is of fundamental interest. In addition, these high-energy particle beams, visible from cosmologically interesting distances, allow us to probe fundamental physics at scales and in ways that are not possible in Earth-bound particle accelerators.

Recently, Fermi [170] and AGILE [195] measured the energy spectra of the supernova remnants W44 and IC44. The decrease in the gamma-ray flux below the pion mass in these sources is clear evidence for hadronic acceleration. This is the clearest evidence to date that some galactic cosmic rays are accelerated in supernova remnants. The detection of high-energy neutrinos from a cosmic accelerator would be a smoking-gun signature of hadronic acceleration. In the absence of multi-messenger signals, multi-wavelength energy spectra (X-ray to TeV) can test both leptonic models, where the high-energy emission is derived from inverse Compton scattering of the X-ray synchrotron emission, and hadronic models, where gamma rays result from pion decays or proton synchrotron radiation.
Backgrounds to dark matter searches. Understanding the origin of the galactic very high energy gamma rays is critical in the interpretation of some signatures of dark matter annihilation. The recent results from PAMELA [55] and AMS [54] of the increasing positron fraction with energy is a clear signal that the current model of secondary production and transport through the galaxy is not correct. There are three potential explanations for this signal: a new astrophysical source of positrons [196], modified propagation of cosmic rays or secondary production in the source [197], or dark matter annihilation [198]. An astrophysical source of positrons, pulsar wind nebula, is now known to also lead to an increasing positron fraction at high energies. Observations of the Geminga pulsar wind nebula in the TeV band by Milagro [199] have been used to normalize the flux of positrons in our local neighborhood from this source. The calculated positron fraction is an excellent match to the data [200]. Similarly, in searching for dark matter signatures from the GC or galaxy clusters, we must understand and measure the more standard astrophysical processes that may lead to signatures that are similar in nature to those expected from dark matter annihilation.

Extragalactic background light. The extragalactic background light (EBL) pervades the Universe. It is the sum of all the light generated by stars and the re-radiation of this light in the infrared band by dust [201], and it is therefore sensitive to the star formation history of the Universe. In addition to advancing our understanding of particle acceleration and astrophysical backgrounds for dark matter searches, the intense gamma-ray beams generated by AGN and gamma-ray bursts can be used to probe the intervening space and search for physics beyond the Standard Model. Future studies may measure the EBL, use the EBL to measure the intergalactic magnetic fields, and search for axion-like particles (ALPs). The production of electron-positron pairs from photon-photon scattering of the EBL with high-energy gamma rays leads to an energy-dependent attenuation length for high-energy gamma rays [202]. At the same time, cosmic rays, if they are accelerated by AGN, will interact with the EBL and the CMB along the line of sight and generate secondary gamma rays at relatively close distances to the observer [203]. This absorption, with the inclusion of secondary gamma rays, can be used to measure or constrain the EBL [201]. Lower limits on the EBL can be established from galaxy counts. An inconsistency between these lower limits and the measurements of the TeV spectra from AGN would be a signature of new physics. Such a discrepancy could be explained either by the secondary production of gamma rays from cosmic rays produced at AGN or by photon-ALP mixing mediated by the intergalactic magnetic fields.

Intergalactic magnetic fields. The origin of the galactic magnetic fields remains a mystery. Although astrophysical dynamos can efficiently amplify pre-existing magnetic fields, the generation of a magnetic field is difficult [204]. The strength of the magnetic fields in the voids between galaxy clusters should be similar to the primordial magnetic field. Measurements of AGN spectra and time delays in the GeV–TeV region have been used to set both lower and upper bounds on the strength of the intergalactic magnetic field [205]. Current bounds are model-dependent and span a large range of values for the magnetic field. Improved measurements of the EBL, the measurement of variability from distant AGN, improved determinations of the energy spectra, and understanding of the intrinsic AGN spectra are needed to significantly improve these limits.

Tests of Lorentz invariance violation. Experimentally probing Planck-scale physics, where quantum gravitational effects become large, is challenging. A unique signature of such effects would be the violation of Lorentz invariance — a natural, though not necessary, property of theories of quantum gravity [206]. Short, intense pulses of gamma rays from distant objects, such as gamma-ray bursts and active galaxies, provide a laboratory in which to search for small, energy-dependent differences in the speed of light. Current limits have reached the Planck scale if the energy dependence of the violation is linear [207], and $6.4 \times 10^{10}$ GeV if the violation is quadratic with energy. Future instruments could improve these limits by at least factors of 10 and 50, respectively, and significantly increase the sample size used to search for these effects.

TeV gamma-ray instruments. Ground-based TeV instruments fall into two classes: extensive air shower (EAS) arrays, capable of simultaneously viewing the entire overhead sky, and imaging atmospheric Cherenkov
4.6 Cosmic particles and fundamental physics

Telescopes (IACTs), pointing instruments with high sensitivity and resolution. Current IACTs are VERITAS, MAGIC, and HESS, while the HAWC (under construction) and Tibet arrays are the only operating EAS arrays. CTA, the next-generation experiment, will consist of a large array of IACTs with roughly an order of magnitude greater sensitivity than current instruments. It is expected to discover over 1000 sources in the TeV band [52]. The U.S. portion of the collaboration is proposing to more than double the number of mid-sized telescopes to over 50 using a novel optical design that will improve the sensitivity of CTA by a factor of 2-3 (a result of improved angular resolution of the new telescopes and an increase in the number of telescopes).

4.6.4 Baryogenesis

According to standard cosmology, the current preponderance of matter arises during the very early Universe from an asymmetry of about one part per hundred million between the densities of quarks and antiquarks. This asymmetry must have been created after inflation by a physical process known as baryogenesis. Baryogenesis requires extending the Standard Model of particle physics via some new physics that couples to Standard Model particles and is important during or after the end of inflation. Constraints on the inflation scale and on the reheat temperature at the end of inflation give an upper bound on the relevant energy scale for baryogenesis. The new physics must violate CP, as the CP violation in the Standard Model is insufficient [209]. There are a very large number of theoretical baryogenesis proposals.

**Leptogenesis.** Theoretically, baryon number violation at high temperatures is rapid in the Standard Model via nonperturbative electroweak processes known as sphalerons. Sphalerons conserve the difference between baryon and lepton numbers, leading to the idea of leptogenesis [210]. The decay of very heavy neutrinos in the early Universe could occur in a CP-violating way, creating a lepton asymmetry that the sphalerons convert into a baryon asymmetry. Whether and how leptogenesis could occur can be clarified by Intensity Frontier experiments that will probe CP violation and lepton number violation in neutrino physics [211]; Cosmic Frontier experiments, which may, for example, probe the high inflation scale required in most leptogenesis proposals; and Energy Frontier experiments [212], which may discover new particles, with important implications for leptogenesis.

**Affleck-Dine baryogenesis.** In supersymmetric theories, condensates of the scalar partners of quarks and leptons have relatively low energy density and are likely to be present at the end of inflation [213]. The subsequent evolution and decay of the condensates can produce the baryon asymmetry, and in some models, the dark matter [101, 214]. The dark matter could be macroscopic lumps of scalar quarks or leptons known as Q-balls, which have unusual detection signatures in Cosmic Frontier experiments [215]. A critical test of this theory is the search for supersymmetry, primarily via collider experiments. Instruments such as HAWC and IceCube will be sensitive to extremely low fluxes of Q-balls — over two orders of magnitude lower than current limits. Although the non-observation of Q-balls cannot exclude the Affleck-Dine mechanism, the observation of a Q-ball would have a profound impact on our understanding of the Universe.

**Electroweak baryogenesis.** New particles beyond the Standard Model that are coupled to the Higgs boson can provide a first-order phase transition for electroweak symmetry breaking, which proceeds via nucleation and expansion of bubbles of broken phase. CP-violating interactions of particles with the expanding bubble walls can lead to a CP-violating particle density in the symmetric phase, which can be converted by sphalerons into the baryon asymmetry [216]. The baryons then enter the bubbles of broken phase where the sphaleron rate is negligible. This scenario can be definitively tested by searches for new particles in high-energy colliders and nonvanishing electric dipole moments for the neutron and for atoms. Non-standard CP violation in \( D \)-
and $B$-meson physics may appear in some models. A non-standard Higgs boson self-coupling is a generic consequence. The first-order phase transition in the early Universe can show up via relic gravitational waves.

Other experiments that can shed light on baryogenesis include searches for baryon number violation. Neutron–antineutron oscillations violate the difference between baryon and lepton numbers, and most leptogenesis scenarios will not work if such processes are too rapid. Proton decay would provide evidence for grand unification, which would imply the existence of heavy particles whose decay could be responsible for baryogenesis, and which is a feature of some leptogenesis and supersymmetric models.

### 4.6.5 Fundamental nature of spacetime

Quantum effects of spacetime are predicted to originate at the Planck scale. In standard quantum field theory, their effects are strongly suppressed at experimentally accessible energies, so spacetime is predicted to behave almost classically, for practical purposes, in particle experiments. However, new quantum effects of geometry originating at the Planck scale from geometrical degrees of freedom not included in standard field theory may have effects on macroscopic scales [217] that could be measured by laser interferometers, such as the holometer [218]. In addition, cosmic particles of high energies can probe departures from Lorentz invariance, as discussed in Section 4.6.3 and the existence of extra dimensions on scales above the LHC.
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