

Particle Astrophysics and Cosmology: Cosmic Laboratories for New Physics (Summary of the Snowmass 2001 P4 Working Group)

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The past few years have seen dramatic breakthroughs and spectacular and puzzling discoveries in astrophysics and cosmology. In many cases, the new observations can only be explained with the introduction of new fundamental physics. Here we summarize some of these recent advances. We then describe several problem in astrophysics and cosmology, ripe for major advances, whose resolution will likely require new physics.

I. OVERVIEW

The goal of the Snowmass 2001 P4 working group was to identify opportunities for advances at the interface of particle physics, astrophysics, and cosmology. Since the previous Snowmass meeting (Snowmass96 [1]), there have been spectacular advances in cosmology and particle astrophysics. These include, but are not limited to, cosmic microwave background (CMB) evidence favoring inflation, supernova and CMB evidence for negative-pressure dark energy, and results from solar- and atmospheric-neutrino experiments. Taken together, these results demonstrate that astro/cosmo/particle physics is an integral component of the particle-physics research enterprise.

The P4 Working Group covered a very broad range of topics, subdivided into eight topical groups:

1. Dark matter and relic particles
2. Gamma rays and X-rays
3. Cosmic microwave background and inflation
4. Structure formation and cosmological parameters
5. Cosmic rays
6. Gravitational radiation
7. Neutrino astrophysics
8. Early Universe and tests of fundamental physics

There is intense experimental and theoretical activity in all of these areas. Every major breakthrough listed below has been made since Snowmass96, and the prospects for the next decade and beyond are even brighter. It is not possible to describe here all the work discussed during the P4 sessions at Snowmass. Instead, we

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emphasize the overarching themes that these areas represent and their relevance to the purpose of Snowmass 2001.

There have been spectacular observational breakthroughs:

- Recent CMB measurements provide evidence that the total energy density of the Universe, Ω_{tot} , is close to unity. For the first time, we may know the geometry of the Universe. Observations support the hypothesis that large-scale structure grew from primordial density fluctuations, in agreement with predictions from inflation. This provides the scientific connection between the large-scale structure of the Universe and elementary particle physics, and is indicative of new physics at higher energy scales.
- The discrepancy between a matter density $\Omega_m \simeq 0.3$ and $\Omega_{\text{tot}} \simeq 1$ provides independent corroboration of the remarkable recent supernova-survey evidence for some form of “dark energy”. If confirmed, this suggests that $\sim 70\%$ of the energy density of the Universe is of a previously unknown and mysterious type. The existence of the dark energy was not even suspected by most physicists at the time of Snowmass96.
- The CMB data verify that 25% of the density of the Universe must be in the form of nonbaryonic dark matter—as suggested earlier by dynamical measurements of the matter density and big-bang-nucleosynthesis predictions of the baryon density—implying physics beyond the standard model. This strengthens the case for some form of particle dark matter (e.g., supersymmetric particles or axions) in our Galactic halo.
- At the same time that the case for nonbaryonic dark matter continues to strengthen, prospects for detecting dark-matter particles over the next decade, using both direct and indirect methods, are promising. A fleet of experiments with complementary sensitivities and systematics are probing deeper into theoretically well-motivated regimes of particle-physics parameter space.
- Underground observations of solar neutrinos and cosmic-ray-induced atmospheric neutrinos, indicating the existence of neutrino oscillations, have provided evidence that neutrinos are not massless. This is the first direct experimental confirmation that the standard model is incomplete.
- The most massive black holes are central to TeV-class astrophysical accelerator systems that have been observed to radiate immense power in gamma rays. Unprecedented leaps in sensitivity will be made by the next generation of both ground-based and space-based gamma-ray instruments, opening up large discovery spaces. Together, these gamma-ray measurements also provide a unique probe of the era of galaxy formation, and will provide the first significant information about the high-energy behavior of gamma-ray bursts.
- The evidence for the highest-energy cosmic-ray events ($E > 10^{20}$ eV) poses significant challenges to our theoretical understanding. Observations under way, and new detectors under construction and in planning, both on the ground and in space, will shed new light on this highest-energy mystery. These experiments, as well as high-energy neutrino telescopes, will allow us to exploit the highest-energy particles for particle physics.
- Soon, the Universe will be viewed not only with photons, but also with high-energy charged particles, high-energy neutrinos, and gravitational waves. These observations will test strong-field general relativity and open vast new windows on the highest-energy astrophysical phenomena and the early Universe.

Interest in astro/cosmo/particle physics has grown remarkably since Snowmass96. Of the five P working groups at Snowmass 2001, the subscription to P4 was second only to that of P1, Electroweak Symmetry Breaking, and the overlap with all of HEP was obvious in P4 joint sessions with other groups. Interest in the Snowmass-wide teach-in on astro/cosmo/particle physics was very strong.

In summary, there is vigorous and fast-growing activity in astro/cosmo/particle physics, and the intellectual overlap between the particle-physics community and others—especially the high-energy astrophysics and cosmology communities—has grown into full and healthy partnerships, greatly accelerating progress. These partnerships provide enormous opportunities as well as new challenges.

II. INTRODUCTION

The aim of particle physics is to understand the fundamental laws of nature. The primary tools in particle physics have been, and continue to be, accelerator experiments, as they provide controlled environments for addressing precise questions. However, such experiments have limitations, especially when we consider that

many of the most promising ideas for new particle physics—e.g., grand unification and quantum gravity—can be tested only at energies many orders of magnitude greater than those accessible by current and planned accelerators.

During the past few decades, it has become increasingly apparent that the study of cosmology and astrophysics can provide hints or constraints to new physics beyond the standard model. In just the past few years, the promise of these endeavors has begun to be realized experimentally, most notably with new results from the CMB, evidence for an accelerated cosmological expansion, and with evidence of neutrino masses and mixing that comes from experiments with neutrinos from astrophysical sources.

For Snowmass 2001, we convened a working group aimed to discuss how cosmology and astrophysics can be used in the future to search for new physics beyond the standard model. We organized our activities into eight topical subgroups, each convened by three to six sub-group convenors. These groups and the convenors were:

- Dark matter and relic particles (S. Asztalos, P. Gondolo, W. Kinney, and R. Schnee)
- Gamma rays and X-rays (J. Buckley, T. Burnett, and G. Sinnis)
- The CMB and inflation (S. Church, A. Jaffe, and L. Knox)
- Structure formation and cosmological parameters (R. Caldwell, S. Deustua, P. Garnavich, L. Hui, T. McKay, and A. Refregier)
- Cosmic rays (J. Beatty, J. Mitchell, P. Sokolsky, and S. Swordy)
- Gravitational radiation (P. Bender, C. Hogan, S. Hughes, and S. Marka)
- Neutrino astrophysics (B. Balantekin, S. Barwick, J. Engel, G. Fuller, and T. Haines)
- The early Universe and tests of fundamental physics (A. Albrecht, J. Frieman, and M. Trodden)

P4 working group plenary talks and parallel sessions took place throughout all three weeks of the workshop, often in coordination with the activities of the E6 working group. The P4 sessions attracted the participation of well over 200 scientists from particle physics and astrophysics.

In this article, we briefly summarize the activities of the P4 working group with an aim of listing science questions for particle physics that may be addressed with astrophysical and cosmological experiments and observations. More detailed discussions of all of these topics, as well as more comprehensive lists of references, will be provided by the individual topical sub-group reports.

III. DARK MATTER AND RELIC PARTICLES

Since the mystery of dark matter first appeared in the thirties due to observations of galaxy clusters by Zwicky, the evidence has steadily mounted and today strongly suggests the possibility of a solution rooted in new fundamental particle physics [2]. Dark matter refers to matter that is inferred only through its gravitational effects, and which neither emits nor absorbs electromagnetic radiation. These effects are observed on a wide range of distance scales—from individual galaxies to superclusters to mass flows on the largest observable scales. Direct observation of dark matter and the determination of its nature is one of the most important challenges to be met in cosmology today. Moreover, it is likely that this determination will yield new information in particle physics, since there is strong evidence that the dark matter is not composed of baryons, but rather is in some exotic form.

At the time of Snowmass96, much of the evidence for nonbaryonic dark matter was already in place. The most reliable measurements of the universal mass density come from galaxy clusters, the largest observed equilibrium structures. Using a variety of methods (gravitational lensing, virial analysis, X-rays from intracluster gas), it is found that the matter density is significantly greater than can be accounted for by the baryon density allowed by big-bang nucleosynthesis (BBN) and the measured primordial abundance of deuterium and other light elements (e.g., [3, 4, 5]). As discussed elsewhere in this document, cosmological evidence accumulated since Snowmass96 provides independent confirmation of this picture. Observations of distant supernovae and the cosmic background radiation together suggest a flat Universe in which 30% of the energy density is due to nonrelativistic matter and only 4% due to baryons, consistent with the measurements from clusters and BBN, respectively.

Particle physics offers two different hypotheses for the dark matter—WIMPs and axions—either of which would constitute a major discovery of physics beyond the standard model. First, weakly-interactive massive particles, or WIMPs, would be produced in thermal equilibrium with the hot plasma of the early Universe.

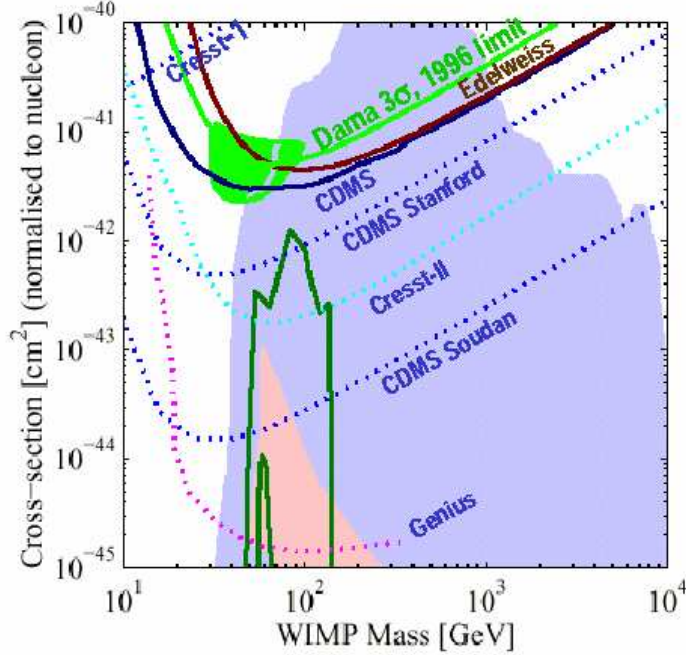


FIG. 1: Regions of the WIMP mass–cross-section parameter space accessible with various detectors. The solid lines indicate upper limits (90% C.L.) achieved to date, along with the 3-sigma contour for the DAMA experiment. The CDMS limit is the dark solid line. The projected limits for future experiments are shown as dashed lines. The large shaded areas show regions of parameter space allowed by different supersymmetric models; see <http://dmtools.berkeley.edu> for further details and a complete list of references.

WIMPs with masses in the 10–1000 GeV/ c^2 range and weak-scale cross sections would have fallen out of equilibrium in sufficient number to have a relic density today comparable to the critical density. The leading and best studied candidate in this generic class of particles is the lightest superpartner (LSP) from supersymmetry, which is expected to be the neutralino [2]. Experimental approaches to detecting dark matter were discussed in great detail in the E6 sessions. There are direct laboratory searches for nuclear recoils produced by WIMP–nuclear interactions; searches for energetic neutrinos from annihilation of WIMPs that have accumulated in the Sun and/or Earth; and searches for exotic cosmic-ray antiprotons and positrons and gamma rays produced by WIMP annihilation in the Galactic halo. We note here that a broad range of experiments, including many new technological developments, are steadily improving the sensitivity for detecting WIMPs in the galactic halo, both through direct WIMP–nuclear scattering experiments and through indirect searches. Current searches are already exploring the parameter space of supersymmetric WIMPs, with prospects for a factor of a hundred improvement in the coming five years [6, 7, 8].

The two most sensitive experiments to date appear to be inconsistent. The DAMA collaboration [7] measures an annual modulation in the event rate in a large array of NaI scintillators, which is expected for WIMPs due to the differential speed of the Earth about the galactic center as it orbits the sun. However, the results are controversial within the dark-matter community, since the possibility of a systematic effect has not been ruled out. Also, the CDMS experiment [6], using a smaller array of more sensitive lower-background detectors, does not observe the expected event rate that should occur if the WIMP inferred by DAMA has scalar interactions with nuclei, while null searches for energetic neutrinos from the Sun conflicts with DAMA if the WIMP has spin-dependent interactions with nuclei [9]. The signal and limits from these experiments are shown in Figure 1 (for scalar interactions), along with a number of previous and proposed experiments. While it is clear that a positive result would be a landmark discovery in both astrophysics and particle physics, it is also clear that complementary studies in the more controlled setting of accelerator-based experiments will be crucial in unraveling the relevant physics.

In addition to a review of progress in the field of direct and indirect WIMP detection, there were cross-cutting sessions devoted to the connections between halo WIMP searches and SUSY searches at accelerators [10], as well

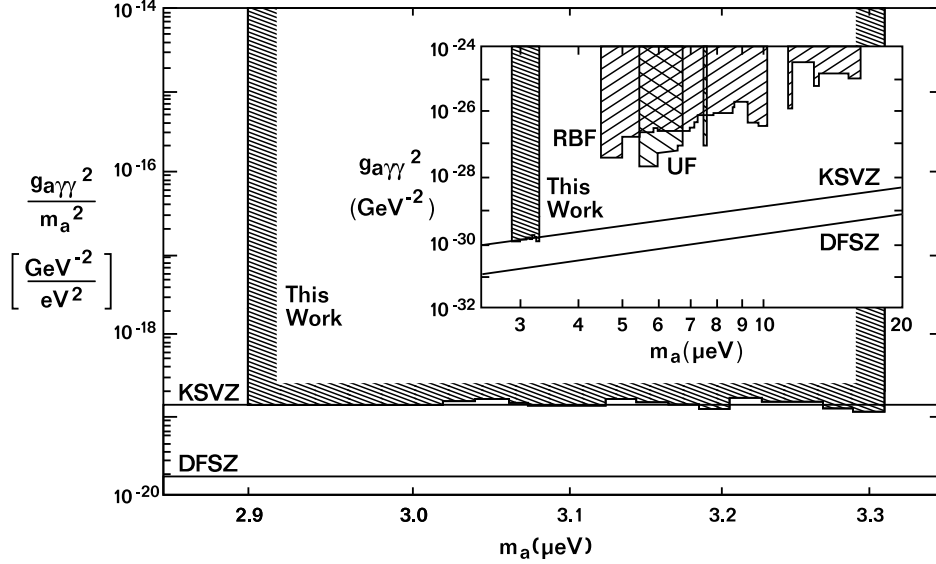


FIG. 2: Regions of axion mass-coupling parameter space currently being probed by an ongoing search at Livermore [17].

as current ideas of galaxy formation that predict steep dark-matter spikes around the black hole at the Galactic center [11, 12]. These spikes lead to predictions for higher-than-observed rates of gamma-ray annihilation products. There were also discussions about possible discrepancies between observations and theoretical models that predict halo cusps [13] and substructure [14, 15] that have lead some researchers to consider other particle dark-matter candidates, such as warm or self-interacting dark matter [16]. These were very active sessions and reflect the exciting ongoing work at the interplay between these areas of research. In particular, the resolution of the cuspy-halo and spike questions are quite likely to tell us something about particle physics and galaxy formation [11, 12].

The second important candidate for particle dark matter is the axion, the pseudo-Nambu-Goldstone boson resulting from the spontaneous breakdown of Peccei-Quinn symmetry, a hypothetical symmetry which has been postulated to explain the lack of CP violation in the strong interaction [18]. Axions would be produced as a Bose condensate during the QCD phase transition, or through the decay of axionic strings or domain walls. The best method conceived to detect axions is to exploit their pseudoscalar coupling to two photons. By threading a high-Q RF cavity with a strong magnetic field, axions would interact with the B-field photons and produce final-state photons with energy nearly equal to the axion mass. The allowed mass range for the axion can be studied by sweeping the resonant frequency of the cavity. When the cavity is tuned to the frequency that matches the axion mass, the cavity will resonate with excess power. The experimental challenge of sufficiently low cavity/amplifier noise has been met and realistic “KSVZ” axion models corresponding to $2.9 < m_a < 3.3 \mu\text{eV}$ have now been tested and ruled out (Fig. 2). Work is ongoing to extend the mass range and lower the noise floor so that nearly two decades of mass can be probed at the weaker coupling of the “DFSZ” model. The two decades of axion mass that have not yet been ruled out by experiments or astrophysical observations are precisely in the range that could explain the dark matter. It is reasonable to expect that in less than a decade, axions as dark matter could be detected or definitively ruled out. Moreover, the RF cavity experiments arguably stand the best chance of any approach for discovering axions at all.

IV. GAMMA-RAY ASTROPHYSICS

A. Introduction

Measurements of the fluxes of celestial gamma rays provide a variety of important information about the Universe. Gamma rays are emitted by particle jets from nature’s largest accelerators and they otherwise do

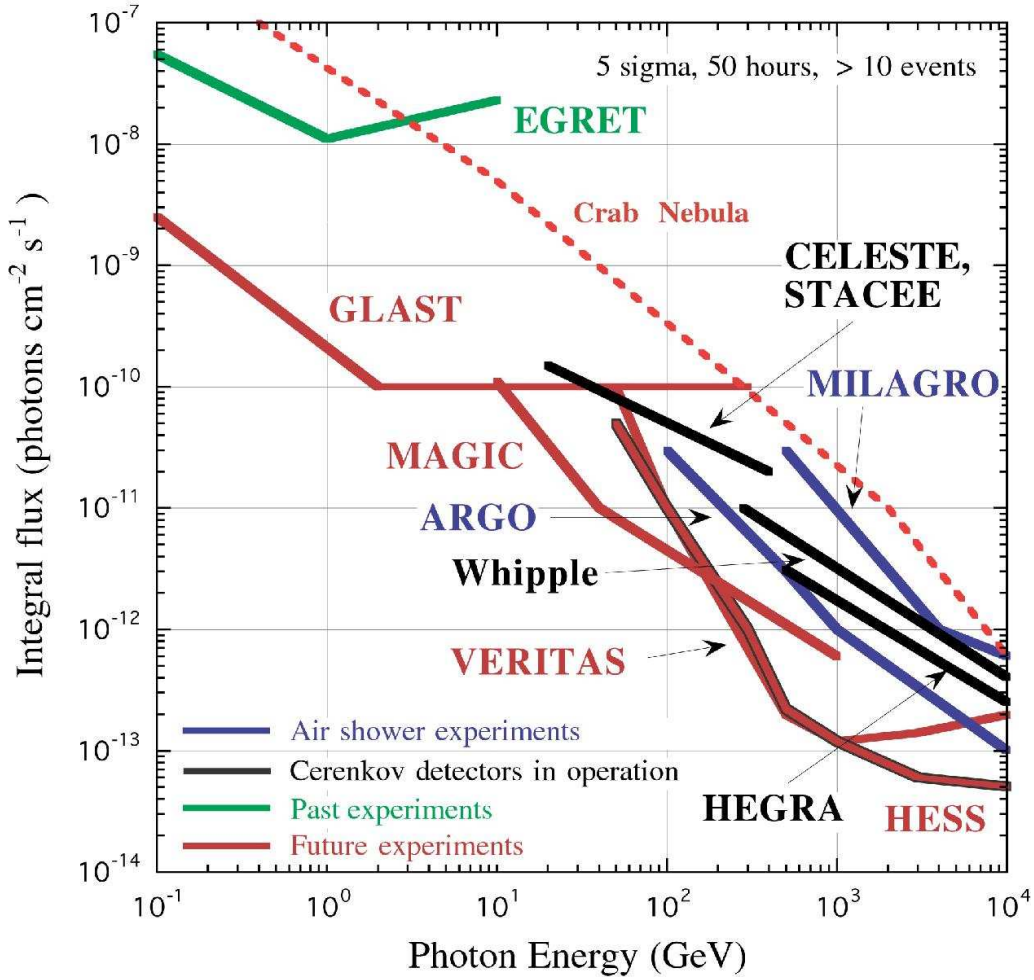


FIG. 3: Sensitivities and frequency ranges for current and planned gamma-ray experiments [19].

not interact much at their source, offering a direct view inside. Similarly, the Universe is mainly transparent to gamma rays below 10 GeV, so they probe cosmological volumes, and the energy-dependent attenuation of the flux above 10 GeV provides important information about those volumes. Conversely, gamma rays interact readily in detectors, with a clear signature; and they are neutral, so there are no complications due to magnetic fields (galactic-flux calculations do not have trapping-time uncertainties, the photons point directly back to their sources, etc.). In general, gamma-ray emission identifies sites of extreme particle acceleration and/or decays of very massive states. The gamma-ray energy regime is one of the least well-measured portions of the electromagnetic spectrum, and the measurements that have already been done have confirmed the expectation of surprise when a new domain is opened for exploration. At Snowmass, we reviewed recent results, surveyed the next generation of experiments and their capabilities, and explored the physics opportunities provided by the upcoming experiments. Sessions included talks and discussions on areas of shared interest with other sub-fields, notably dark matter, X-rays, cosmic rays, and neutrinos.

B. Experiments

Although gamma rays with energies below 10 GeV have no difficulty reaching us from the edge of the visible Universe, they interact in the upper atmosphere and never reach the ground. Space-based measurements are required. For significantly higher-energy gamma rays, sufficient information from the air showers initiated by the primary photon reaches the ground and can be measured with ground-based apparatus. Space-based detectors use the pair-conversion technique for direction information and separation from the large cosmic-ray backgrounds. There are two basic types of ground-based detectors: air-shower Cerenkov telescope (ACT) detectors, and air-shower particle detectors. Since the flux of celestial gamma rays is falling rapidly with

increasing energy (typically as E^{-2} or faster), larger collecting area is required for meaningful statistics at higher energy. Large-area space-based detectors are a challenge. One of the main goals of the present and next round of experiments, therefore, is to push the high-energy frontier of space-based instruments upward and the low-energy threshold of ground-based instruments downward, to provide a significant overlap in coverage. A one-decade or more energy overlap will provide important opportunities for systematic error comparisons and essential information about both the gamma-ray sources themselves and the energy-dependent flux attenuation in this particularly interesting region. The importance of future experiments with sensitivity comparable to that of VERITAS for $E > 100$ GeV, but with a much wider field of view (FOV), was also discussed at Snowmass.

The experimental situation is summarized in Figure 3. The vertical axis is the point-source sensitivity integrating over photons with energy greater than E_0 , given on the horizontal axis. The two space-based experiments are toward the upper left, and the ground-based experiments are toward the lower right. The ground-based experiments have a much better sensitivity in photons $\text{cm}^{-2}\text{s}^{-1}$, but astrophysics dictates that they must. The red dashed line gives the Crab flux integrated above E_0 , showing the rapid decrease in flux with increasing energy. The sensitivity to physical sources is, in some sense, therefore given by the perpendicular distance from the flux line. Viewed in that way, the sensitivities of the ground-based and space-based experiments in each generation are quite well matched.

Ground-based and space-based detectors have capabilities that are complementary. Ground-based air Cerenkov detectors typically have good angular resolution, low duty cycle, huge collecting area, small FOV, and good energy resolution. Ground-based air-shower particle detectors have relatively poor energy resolution, but much larger duty cycle and FOV. Space-based detectors have good angular resolution, excellent duty cycle, relatively small collecting area, excellent FOV, and good energy resolution with relatively small systematic uncertainties. Since the gamma-ray sky is extremely variable, and spans more than seven orders of magnitude in energy, it is important to operate these detectors together.

Gamma-ray experiments draw the interest of both particle physicists and high-energy astrophysicists. An important feature of this field is that, instead of having separate collaborations of particle physicists and astrophysicists that periodically share their results, the communities are already intertwined within the collaborations. The designs of the instruments and the effectiveness of the collaborations have benefitted greatly from this deepening cooperation.

C. Abridged overview of physics topics

The flux of $E > 10$ GeV photons is attenuated due to pair creation by the diffuse field of UV-optical-IR extragalactic background light (EBL). The EBL is produced mainly by starburst activity, so a measurement of the EBL gives important information about the era of galaxy formation. Different models [20, 21, 22] predict distinctly different EBL densities. Figure 4 shows the opacity as a function of energy for curves of constant redshift for one model. Using known gamma-ray point sources, the TeV gamma-ray experiments study the EBL in a relatively local volume of space, while the 1–100 GeV experiments study the EBL density over cosmological distances. This is a major motivation for intermediate experiments such as STACEE [23] and CELESTE [24].

The gamma-ray sky includes an apparently diffuse, isotropic flux ($\approx 1.5 \times 10^{-5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ for $E > 100$ MeV [25]) that is presumably extragalactic. The origin of this flux is a mystery. Is it really isotropic, produced at an early epoch in intergalactic space, or an integrated flux from a large number of yet-unresolved point sources? GLAST [26, 27], with a large effective area (for a space experiment) and much-improved angular resolution, will have the capability to resolve a large fraction of the flux, if it is indeed composed of point sources. This constitutes a ‘no lose’ theorem: either the diffuse flux will be resolved into thousands of new point sources (compared with the total catalog of 271 sources from EGRET [28]) to be studied both in detail in their own right and for use in EBL probes, or a truly diffuse flux of gamma rays from the early Universe will have been discovered.

There is an excellent candidate for those point sources: active galactic nuclei (AGN), which produce vast amounts of power (some flares are believed to reach 10^{45} ergs/sec) from a very compact volume. The prevailing idea [29, 30, 31] is that AGN are powered by accretion onto supermassive black holes ($10^6 - 10^{10}$ solar masses). Models of AGN include multi-TeV, highly collimated particle jets with extremely variable gamma-ray emission. Due to the huge collecting area, the next-generation ACTs such as VERITAS [32] will have the remarkable capability to resolve sub-15-minute variability of these objects, providing important information about the characteristic sizes of the gamma-ray emitting regions. Constraining models of AGN high-energy emission requires observations across all wavelengths, so once again use of the combined capabilities of all the experiments is essential.

Gamma-ray bursts (GRBs) are the most powerful known explosions in the Universe, and their origin continues to be a mystery. While the behavior of bursts at lower energies is now being studied in greater detail, even

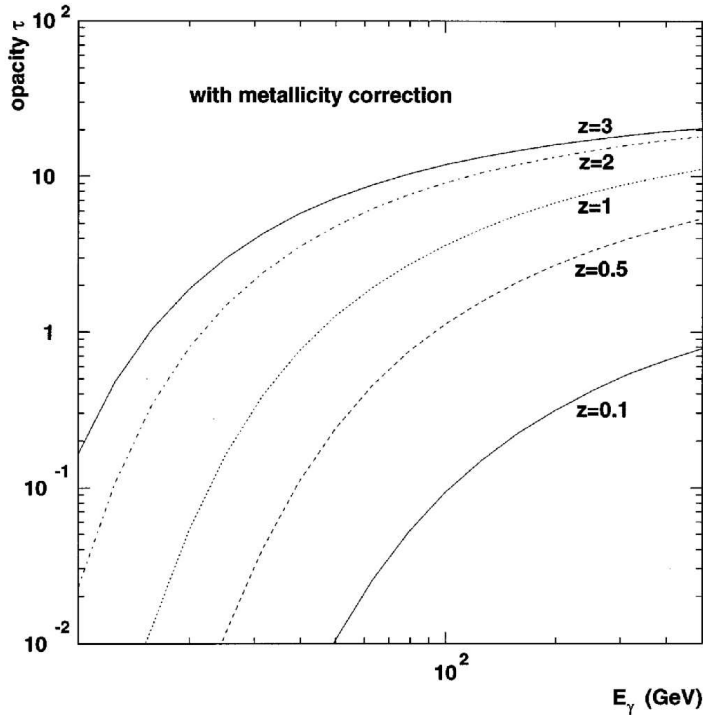


FIG. 4: Opacity for the extragalactic background light as a function of photon energy for curves of constant redshift [20].

less is known about the behavior of bursts at the highest energies. This situation should improve dramatically over the coming decade: if the bursts are close enough, or bright enough, their cutoff energies may finally be observed by the ACTs. The air-shower experiments such as Milagro [33] and ARGO [34], with their large FOV and excellent duty cycle, may serve as alert triggers. There is already evidence that Milagrito, the Milagro prototype, has observed TeV emission from one burst [35]. The GLAST observatory should see hundreds of bursts, covering the energy range 10 keV to 300 GeV and also providing worldwide burst alerts.

Bursts at cosmological distances may also allow novel searches for a small velocity dispersion of photons, since the vast distance provides a huge lever arm. Models [36] that anticipate a full theory of quantum gravity suggest such dispersion. Due to the broad energy coverage, these measurements can be made within a single gamma-ray experiment. The signature would be an arrival-time ordering of events with energy. However, the intrinsic emission characteristics of bursts must be understood. The arrival-time differences should increase with redshift for a true dispersion, providing an additional observational handle. Evolution effects would then have to be ruled out if such a signal were observed.

If the galactic dark matter is a halo of WIMPs, annihilations of these particles could produce a detectable flux of gamma rays. This possibility is especially intriguing since one signature would be mono-energetic ‘lines’, set by the WIMP mass, at somewhere between 10’s and 100’s of GeV. One of the open questions is the distribution of WIMPs, particularly near the galactic center, since the annihilation rate is proportional to the square of the density. The degree to which the density spikes has a critical impact on other exclusion limits and on the size of the potential gamma-ray signal [11, 12].

Additional topics include pulsars, supernova remnants and the origin of the cosmic rays (at least for $E < 10^{14}$ eV), the unidentified sources from EGRET, emission from galactic clusters, primordial-black-hole evaporation, decays of topological defects and other massive relics from the big bang, and signatures of large extra dimensions [37].

Finally, we note that this list only contains the phenomena we already know, or that we have already imagined. It is reasonable to expect that the next decade of astrophysical gamma-ray observations will be punctuated with surprising discoveries.

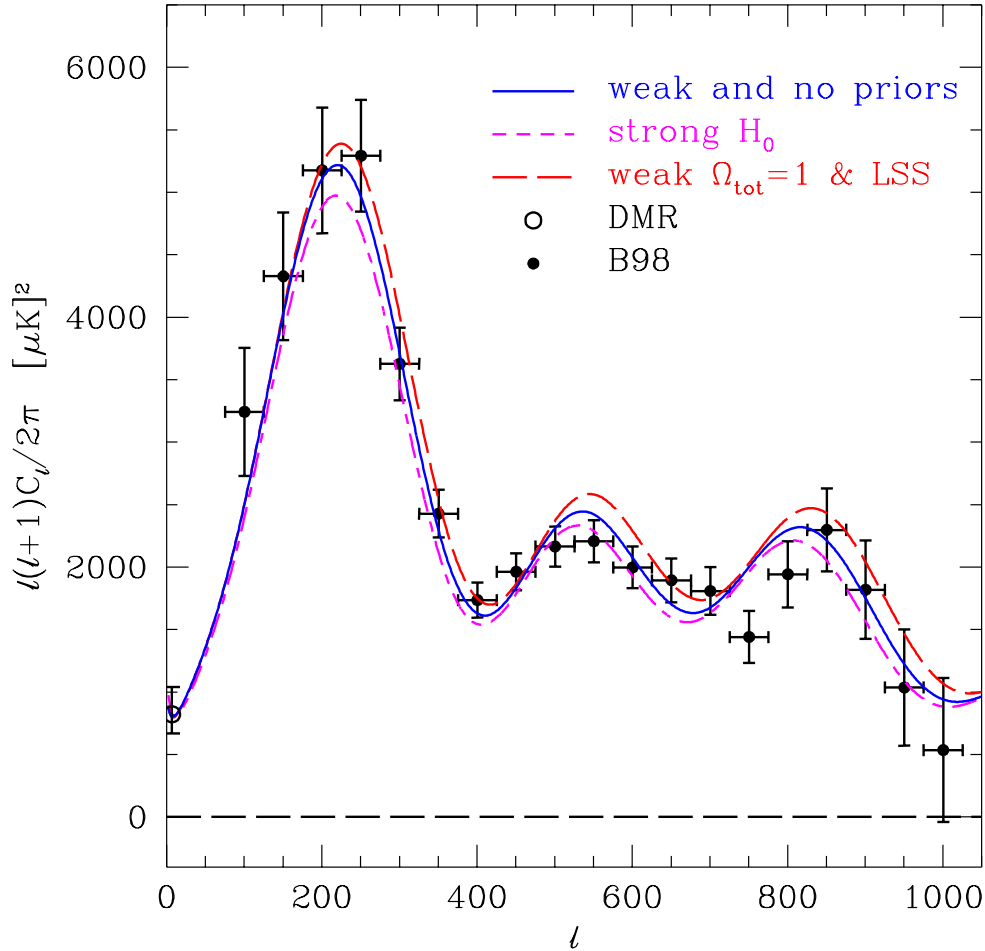


FIG. 5: The CMB power spectrum measured recently by BOOMERanG [46]. Similar results have been obtained also by DASI [47] and MAXIMA [48].

V. THE COSMIC MICROWAVE BACKGROUND AND INFLATION

A. Recent Progress in the CMB

In forthcoming years, the cosmic microwave background (CMB) will provide one of the most exciting opportunities for learning about new physics at ultra-high-energy scales (for recent reviews, see, e.g., [38, 39], as well as the report of the P4.3 working group [40]). The past two years have already seen spectacular advances in measurements of temperature fluctuations in the CMB that have led to major advances in our ability to characterize the largest-scale structure of the Universe, the origin of density perturbations, and the early Universe. In the next year we should see enormous improvements with the recently launched MAP satellite, and then even more precise data with the launch of Planck [41] in 2007.

The primary aim of these experiments has been to determine the CMB power spectrum, C_ℓ , as a function of multipole moment ℓ . Structure-formation theories predict a series of bumps in the power spectrum in the region $50 \lesssim \ell \lesssim 1000$, arising as consequences of oscillations in the baryon-photon fluid before CMB photons last scatter [42, 43]. The rich structure in these peaks allows simultaneous determination of the geometry of the Universe [44], the baryon density, Hubble constant h , matter density, and cosmological constant, as well as the nature (e.g., adiabatic, isocurvature, or topological defects) and spectrum of primordial perturbations [45].

Within the past two years, three independent experiments that use different techniques, observing strategies, and frequencies have each measured the power spectrum in the range $50 \lesssim \ell \lesssim 1000$ with sufficient precision to see clearly a first and second peak in the CMB power spectrum, as well as hints of a third [46, 47, 48], as shown

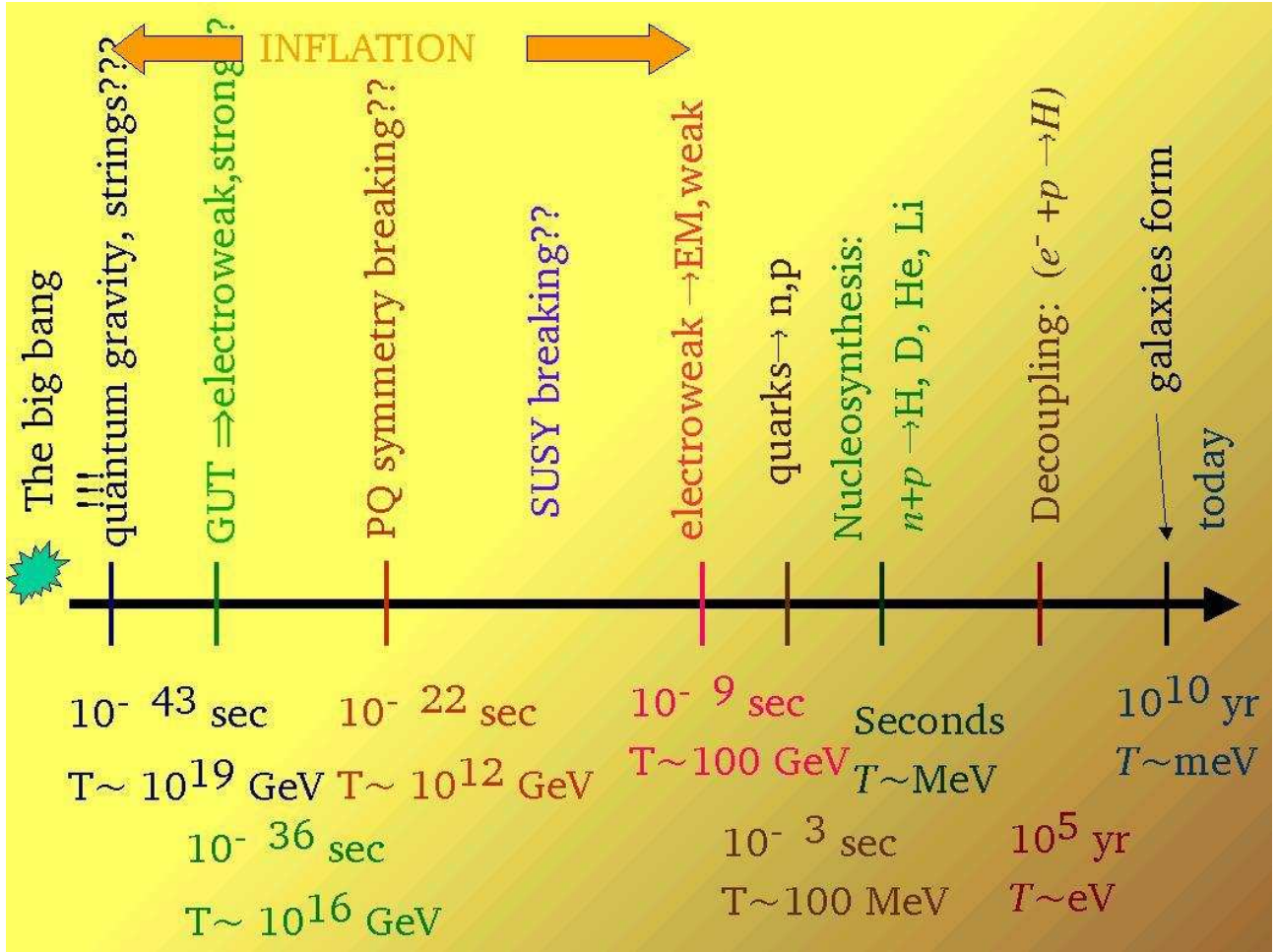


FIG. 6: Logarithmic history of the Universe. Inflation may have taken place at any time from the Planck time until the time of electroweak-symmetry breaking. Given the CMB confirmation of the inflationary predictions of a flat Universe and primordial adiabatic perturbations, an obvious goal of early-Universe cosmology should be to determine the time, or equivalently, the energy scale of inflation (defined more precisely to be the fourth root of the vacuum-energy density during inflation). This can be accomplished by searching for the unique CMB polarization pattern produced by the inflationary gravitational-wave background, the amplitude of which scales on the inflationary energy scale.

in Figure 5. These experiments represent a watershed event in cosmology, as they suggest for the first time that the Universe is flat and that structure grew from a nearly scale-invariant spectrum of primordial density perturbations. These two properties are robust predictions of inflation, a period of accelerated expansion in the very early Universe driven by vacuum energy associated with ultra-high-energy physics.

Although these recent CMB tests suggest that we are on the right track with inflation, we still have no idea what new physics may have given rise to inflation. Plausible theoretical models place the energy scale of inflation anywhere from the Planck scale to the electroweak scale, and associate the inflaton (the scalar field responsible for inflation) with new fields that arise in string theory, GUTs, the Peccei-Quinn mechanism, supersymmetry breaking, and electroweak-scale physics, as shown in Figure 6.

B. Inflation, Gravitational Waves, and CMB Polarization

Perhaps the most promising avenue toward further tests of inflation as well as determination of the energy scale of inflation is the gravitational-wave background. Inflation predicts that quantum fluctuations in the spacetime metric during inflation should give rise to a stochastic gravitational-wave background with a nearly-scale-invariant spectrum [49]. Inflation moreover predicts that the amplitude of this gravitational-wave background should be proportional to the square of the energy scale of inflation.

These gravitational waves will produce temperature fluctuations at large angles. Upper limits to the amplitude

of large-angle temperature fluctuations already constrain the energy scale of inflation to be less than 2×10^{16} GeV. However, since density perturbations can also produce such temperature fluctuations, temperature fluctuations cannot alone be used to detect the gravitational-wave background.

Instead, progress can be made with the polarization of the CMB. Both gravitational waves and density perturbations will produce linear polarization in the CMB, and the polarization patterns produced by each differ. More precisely, gravitational waves produce a polarization pattern with a distinctive curl pattern that cannot be mimicked by density perturbations (at linear order in perturbation theory; see below) [50, 51]. Moreover, inflation robustly predicts that the amplitude of this polarization curl depends on the square of the energy scale of inflation.

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

C. Cosmic shear and the CMB

There are several interesting astrophysics questions that must be addressed on the way to this inflationary goal. First of all, cosmic shear—weak gravitational lensing by density perturbations along the line of sight—can produce a curl component in the polarization. This cosmic-shear curl component might be subtracted (and the curl component from inflationary gravitational waves isolated) by measuring higher-order correlations in CMB temperature maps [52], and so precise CMB temperature maps must be made in tandem with the polarization maps. The information from these CMB cosmic-shear maps will be of interest in their own right, as they probe the distribution of dark matter throughout the Universe as well as the growth of density perturbations at early times. These goals will be important for determining the matter power spectrum and thus for testing inflation and constraining the inflaton potential, as discussed further in the Section on structure formation below.

D. CMB and Primordial Gaussianity

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

E. The Sunyaev-Zeldovich Effect and Cosmological Parameters

A further goal of CMB studies is precise measurement of the Sunyaev-Zeldovich effect (see, e.g., Ref. [53] and references therein), the scattering of CMB photons from the hot gas in galaxy clusters. Measurements of the Sunyaev-Zeldovich effect may soon provide entirely new and unique avenues for classical cosmological tests—e.g., measurements of the matter density and of the expansion history (as discussed in connection with dark energy below), as well as for studying the growth of large-scale structure (as discussed in connection with inflation below). A particularly intriguing advantage of the Sunyaev-Zeldovich effect is that the signal from a given cluster does not depend on the distance to the cluster. This allows for the possibility of detecting clusters at much higher redshifts than may be detected with X-ray or other observations. Also, the amplitude of the Sunyaev-Zeldovich effect is linear in the electron density, and thus provides a more faithful tracer of the underlying cluster mass than the X-rays, which depend on the more uncertain square of the electron density.

VI. COSMOLOGICAL PARAMETERS AND STRUCTURE FORMATION

A. Dark energy

A long-standing aim of cosmology has been the determination of the contents of the Universe, characterized by their fractional contribution Ω to the critical density. These components include, for example, the baryon density Ω_b and the cold-dark-matter density Ω_{cdm} . During the past few years, there has been a convergence in measurements of these parameters from a variety of independent techniques. The new CMB measurements discussed above find a baryon density $\Omega_b h^2 \simeq 0.02$, in very good agreement with the baryon density expected from big-bang nucleosynthesis (using the recently determined quasar deuterium abundance [4]). And as discussed above, the CMB power spectrum is best fit by a dark-matter density $\Omega_m \simeq 0.3$, in agreement with a number of dynamical determinations of the matter density.

In addition to confirming the predictions of big-bang nucleosynthesis and the existence of dark matter, the measurement of classical cosmological parameters has resulted in a startling discovery over the past few years: roughly 70% of the energy density of the Universe is in the form of some mysterious negative-pressure dark energy [54]. Supernova evidence for an accelerating Universe [55, 56] has now been dramatically bolstered by the discrepancy between the total cosmological density $\Omega_{\text{tot}} \simeq 1$ indicated by the CMB and dynamical measurements of the nonrelativistic-matter density $\Omega_m \simeq 0.3$. New and independent evidence is provided by higher peaks in the CMB power spectrum that also suggest $\Omega_m \simeq 0.3$, again leaving 70% of the density of the Universe unaccounted for.

As momentous as these results are for cosmology, they may be even more remarkable from the vantage point of particle physics, as they indicate the existence of new physics beyond the standard model plus general relativity. Either gravity behaves very peculiarly on the very largest scales, or there is some form of negative-pressure “dark energy” that contributes 70% of the energy density of the Universe. For this dark energy to accelerate the expansion, its equation-of-state parameter $w \equiv p/\rho$ must satisfy $w < -1/3$, where p and ρ are the dark-energy pressure and energy density, respectively. The simplest guess for this dark energy is the spatially uniform, time-independent cosmological constant, for which $w = -1$. Another possibility is quintessence [57, 58, 59, 60] or spintessence [61], a cosmic scalar field that is displaced from the minimum of its potential. Negative pressure is achieved when the kinetic energy of the rolling field is less than the potential energy, so that $-1 \leq w < -1/3$ is possible.

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

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

The obvious first step to understand the nature of this dark energy is to determine whether it is a true cosmological constant, or whether its density evolves with time. This can be answered by determining the expansion rate of the Universe as a function of redshift. In principle this can be accomplished with a variety of cosmological observations (e.g., quasar-lensing statistics, cluster abundances and properties, the Lyman-alpha forest, galaxy and cosmic-shear surveys, etc.). However, the current best bet for determining the expansion history is with supernova searches, particularly those that can reach beyond to redshifts $z \gtrsim 1$. Here, better systematic-error reduction, better theoretical understanding of supernovae and evolution effects, and greater statistics, are all required. Both ground-based (e.g., the DMT [62] or WFHRI [63]) and space-based (e.g., SNAP [64]) supernova searches can be used to determine the expansion history. However, for redshifts $z \gtrsim 1$, the principal optical supernova emission (including the characteristic silicon absorption feature) gets shifted to the infrared which is obscured by the atmosphere. Thus, a space-based observatory appears to be required to reliably measure the expansion history in the crucial high-redshift regime.

If the dark energy is quintessence, rather than a cosmological constant, then there may be observable consequences in the interactions of elementary particles if they have some coupling to the quintessence field. In particular, if the cosmological constant is time evolving (i.e., is quintessence), then there is a preferred frame in the Universe. If elementary particles couple weakly to the quintessence field, they may exhibit small apparent violations of Lorentz and/or CPT symmetry (see, e.g., [65]). A variety of accelerator and astrophysical experiments can be done to search for such exotic signatures.

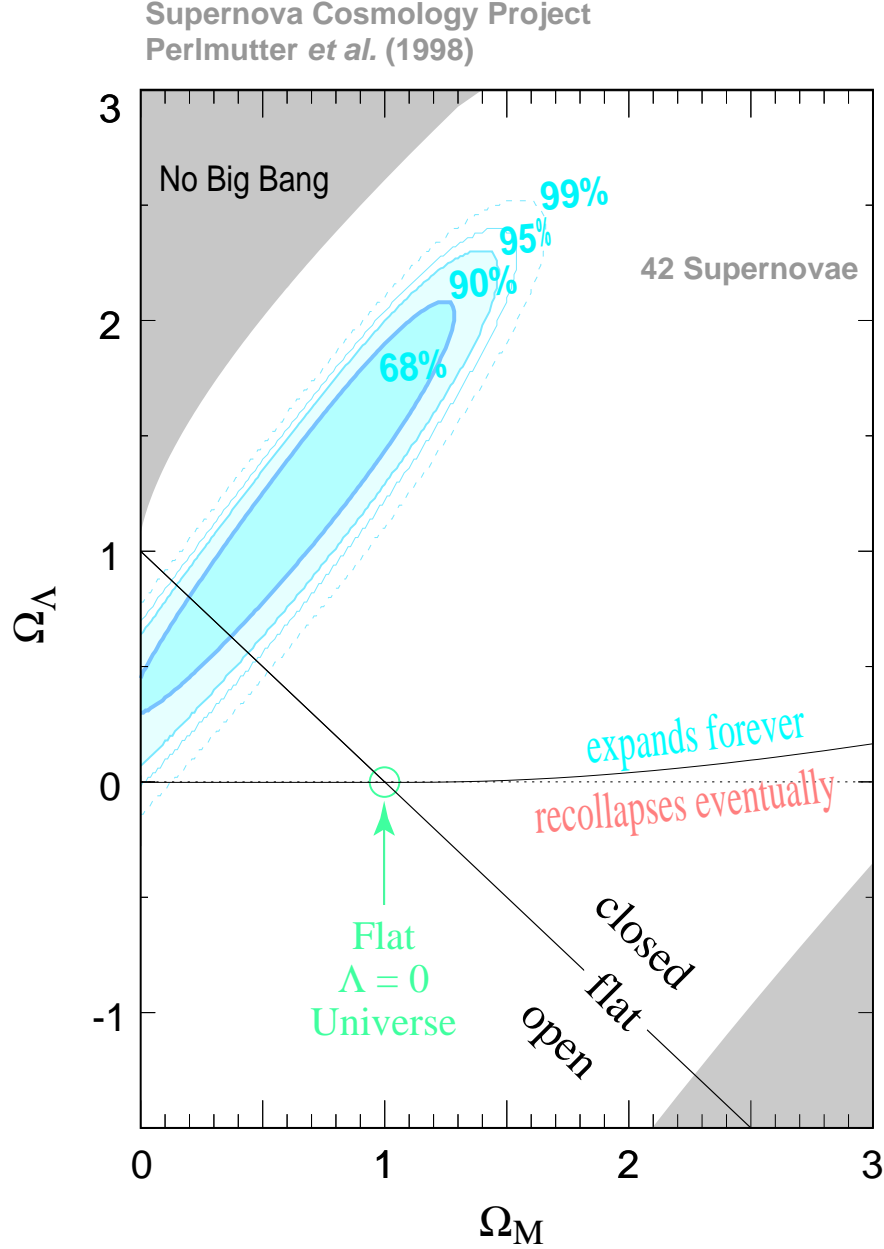


FIG. 7: Regions in the $\Omega_m - \Omega_\Lambda$ parameter space consistent with supernova searches and the CMB (which now constrain $\Omega_m + \Omega_\Lambda \simeq 1$).

B. Structure formation

Since the Snowmass96 meeting, large-scale galaxy surveys have become a reality, particularly with the advent of the Two-Degree Field [66] and Sloan Digital Sky Surveys [67]. We are now mapping the distribution of galaxies over huge volumes in the Universe. Moreover, just last year, four independent groups reported detection of “cosmic shear,” correlations in the distortions to the shapes of distant galaxies induced by weak gravitational lensing due to large-scale mass inhomogeneities [68, 69, 70, 71]. In the future, cosmic-shear measurements will map the distribution of matter (rather than just the luminous matter probed by galaxy surveys) over large volumes of space (interestingly, the telescope requirements for cosmic-shear maps match those for supernova searches). Figure 8 illustrates how a cosmic-shear experiment might map the mass density projected along the line of sight.

If the big bang is a cosmic accelerator, subtle correlations in the debris from the explosion can provide valuable

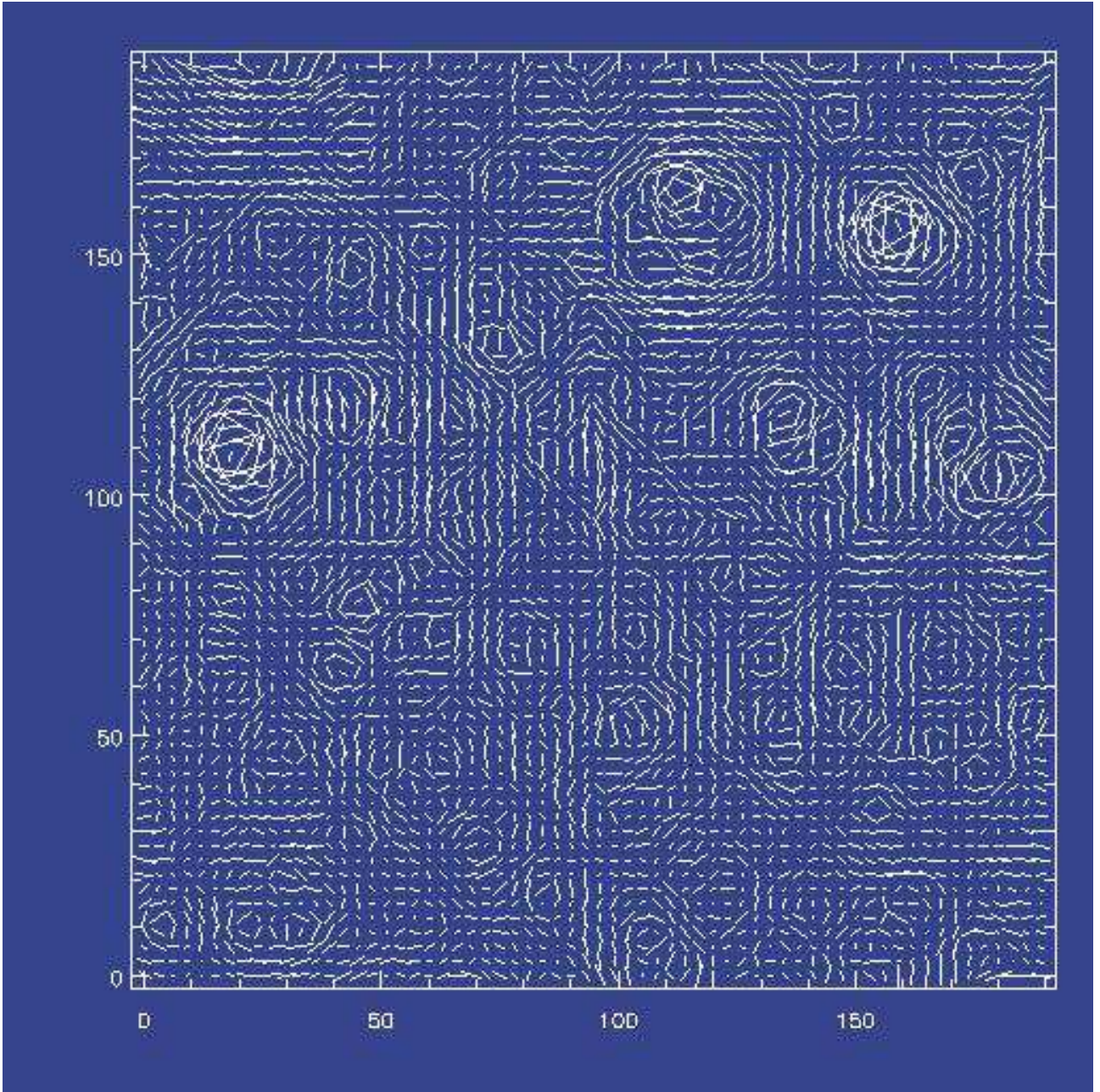


FIG. 8: A simulation of a cosmic-shear map that could be reconstructed from the alignments of the shapes of numerous distant background galaxies. The projected mass density can be inferred from such a map.

information on inflation, just as subtle correlations in jets in accelerator experiments can provide information about the collisions that give rise to them. The primary aims of galaxy surveys and cosmic-shear maps are determination of the power spectrum $P(k)$ of matter in the Universe as well as higher-order correlation functions for the mass distribution. These measurements are important for the study of inflation, as inflation relates the amplitude and shape of the power spectrum $P(k)$ to the inflaton potential $V(\phi)$ [72]. Moreover, as discussed above, inflation predicts very precise relations between all of the higher-order correlation functions for the primordial mass distribution and its two-point correlation function, and these relations can also be tested with the observed distribution of mass in the Universe today. The growth of density perturbations via gravitational infall alters the precise structure of the correlation hierarchy from the primordial one. However, it does so in a calculable way so that the primordial distribution of density perturbations (Gaussian as predicted by inflation? or otherwise?) can be determined from the distribution observed in the Universe today [73].

Information about the primordial distribution of matter can also be obtained by studying the abundances

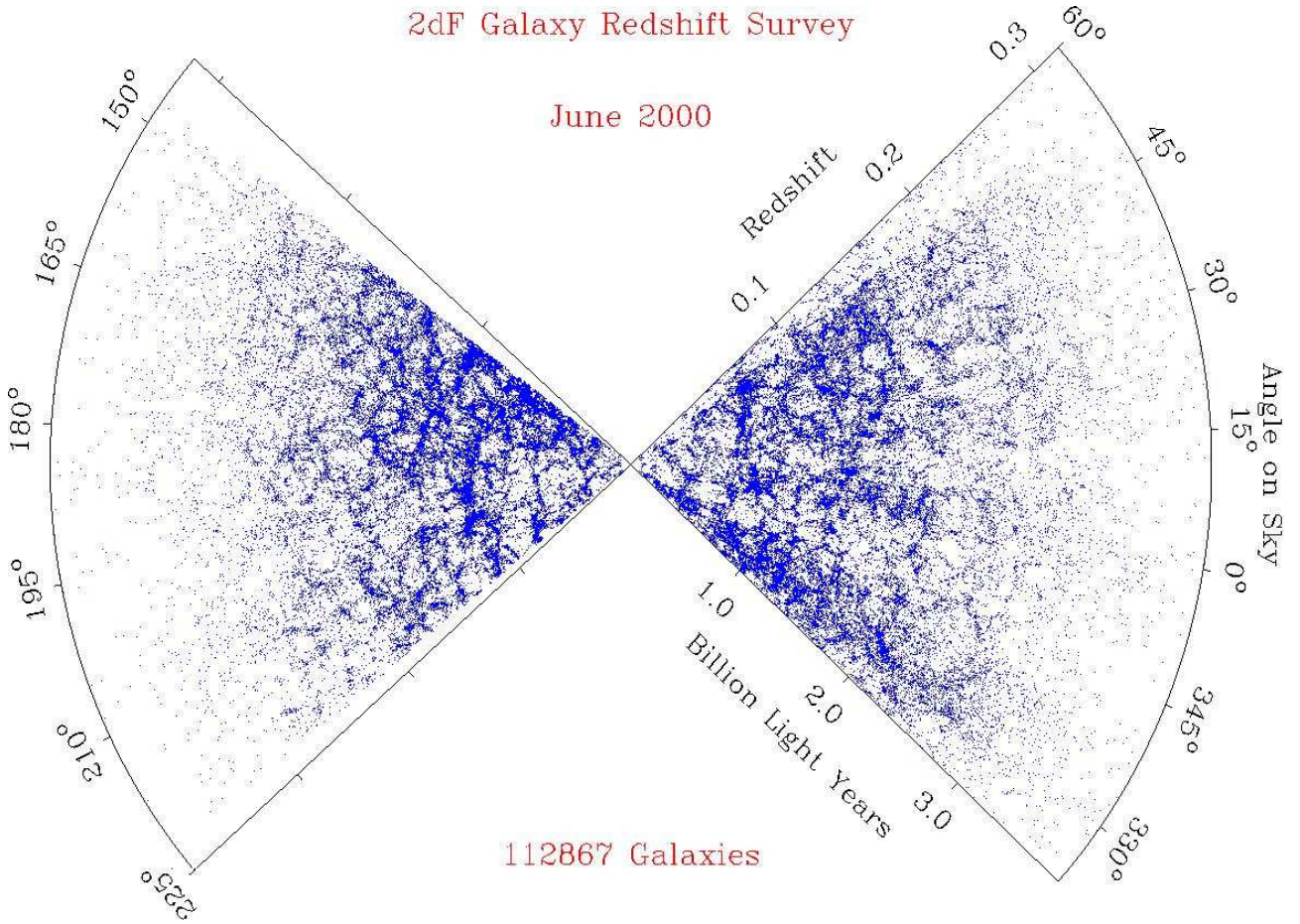


FIG. 9: Galaxy distribution as mapped by preliminary results from the 2dF survey. According to inflation, the galaxy distribution can be used to infer parameters of the inflaton potential.

and properties of the rarest objects in the Universe: clusters of galaxies today and galaxies at high redshift (see, e.g., [74]). Such objects form at rare ($\gtrsim 3\sigma$) high-density peaks in the primordial density field. Inflation predicts that the distribution of such peaks should be Gaussian. If the distribution is non-Gaussian—for example, skew-positive with an excess of high-density peaks—then the abundance of these objects can be considerably larger. In such skew-positive models, such objects would also form over a much wider range of redshifts and thus exhibit a broader range of properties (e.g., sizes, ages, luminosities, temperatures).

VII. COSMIC RAYS

There are strong historical connections between particle physics and cosmic-ray physics. Over time, as artificial accelerators reached high energies and intensities, the emphasis of cosmic-ray research has shifted away from using cosmic rays as natural particle beams toward their use as cosmic messengers.

The cosmic-ray spectrum is shown in Figure 10. Some of the questions today are (1) What is the origin of cosmic rays? This remains an unsolved mystery, though there are good candidates for at least a portion of the energy spectrum. (2) What are the processes involved in the propagation of cosmic rays from their source(s) to us? (3) What produces the features seen in figure 10? In particular, what produces the ‘knee’ and the ‘ankle’?

There are also some other questions of perhaps more direct interest to particle physics. (4) Is there cosmic-ray antimatter from exotic sources in the Universe? For example, topological defects or supermassive relics (such as those that might account for ultra-high-energy cosmic rays; see below) might produce particles and antiparticles in equal numbers leading to cosmic-ray antiprotons or positrons. Although theory says that it is highly unlikely that large regions of the Universe consist of antimatter, even a single anti-nucleus (e.g., anti-carbon) would demonstrate the existence of large antimatter regions. Finally, in some supersymmetric models, annihilation WIMPs in the Galactic halo could produce detectable fluxes of cosmic-ray antiprotons and/or positrons. The

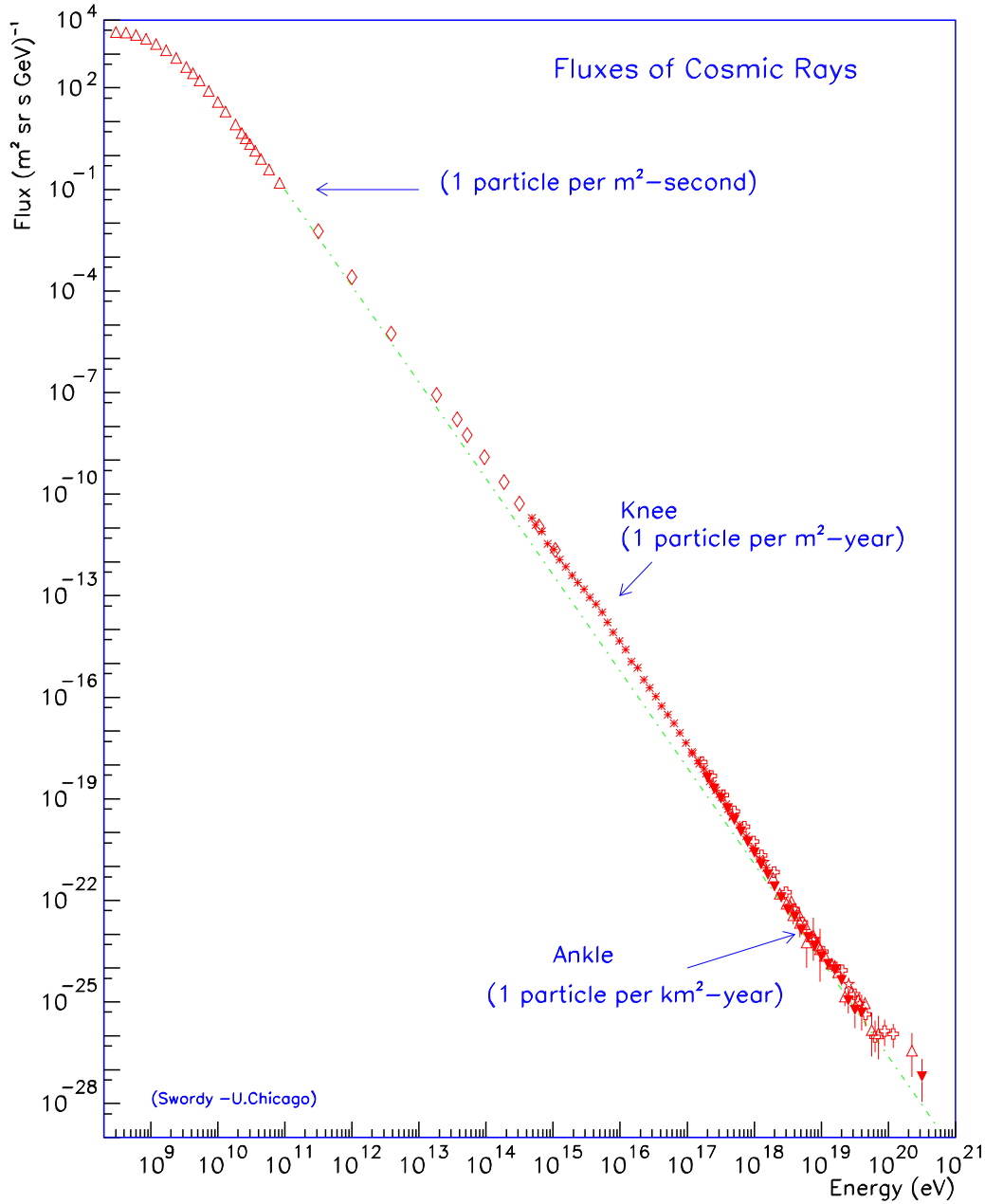


FIG. 10: Cosmic-ray spectrum.

AMS experiment [75], which had a successful engineering flight on the shuttle in 1998, is manifested for the space station in 2005 to help answer these questions. The PAMELA experiment [76, 77], which will be in operation in early 2003, will measure the antiproton and positron fluxes in polar orbit.

Over the past decade, balloon measurements have provided a wealth of new information to help address questions about cosmic rays from traditional astrophysical sources as well as about exotic cosmic rays. In particular, there have been searches for antiparticles (BESS, CAPRICE, HEAT, IMAX, MASS, TS93), studies of isotopic composition and clock isotopes (ISOMAX, SMILI), heavy-element composition (TIGER), element spectra (BESS, CAPRICE, HEAT and IMAX 100 GeV/nucleon; ISOMAX to almost 1 TeV/nucleon; ATIC H and He to > 10 TeV; TRACER O to Fe to 100 TeV total energy), and high-energy spectra (JACEE, RUNJOB).

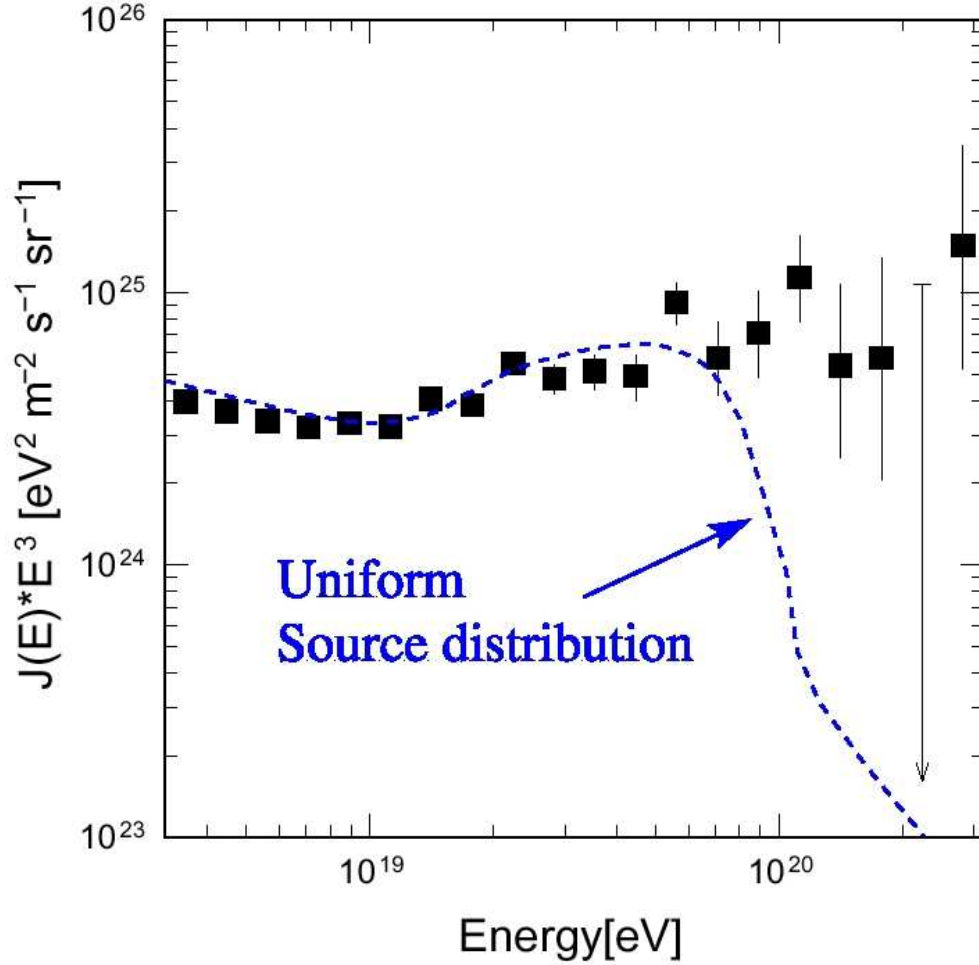


FIG. 11: Spectrum of ultra-high-energy cosmic rays measured by AGASA [78].

A. Ultra-high-energy cosmic rays

Of particular interest is the origin and nature of the ultra-high-energy cosmic rays (UHECRs), those with energies greater than 3×10^{19} eV, the Greisen-Zatsepin-Kuzmin (GZK) threshold [79, 80]. Such cosmic rays, if they are protons, should be attenuated by photopion production from scattering of CMB photons and thus have a mean-free path of ~ 30 Mpc. Thus, if the sources of these UHECRs are uniformly distributed cosmological sources, we would expect to see a drop in the flux at energies higher than the GZK cutoff, as indicated by the curve in Figure 11. However, observations from both AGASA [81] (shown in Figure 11) and HiRes [82] (see Figure 11) indicate no such drop; in fact there may even be an increase in the flux above the GZK threshold (although there is still some concern about possible inconsistency between AGASA and HiRes)! Another problem is that these cosmic rays (whose trajectories should be bent negligibly by magnetic fields) do not seem to come from any obvious accelerators within 30 Mpc. In fact, there seem to be no obvious accelerators anywhere within 30 Mpc of the Milky Way, so even if their trajectories were bent, there are still no obvious sources. Moreover, none of these UHECRs point back to any obvious sources even at larger distances.

There is no single convincing explanation for this mystery, although there are a number of very intriguing ideas. For example (1) The apparent excess is due to experimental error and/or statistical fluctuations. (2) The primary particles are heavier nuclei, which might be able to travel farther. (3) The sources are nearby astrophysical sources (e.g., intergalactic shocks or Centaurus A). Although some of them may have some appeal, all of these traditional-astrophysics explanations have troubles. (4) The UHECRs require new physics; e.g., decays of supermassive cosmological relics or topological defects; some new non-interacting particles; production of protons from interactions of ultra-high-energy neutrinos with the 1.9 K cosmological neutrino background. The answer could be some combination of these solutions, or it could be something else entirely.

This problem has been the focus of much theoretical [83] and experimental activity, and major advances can

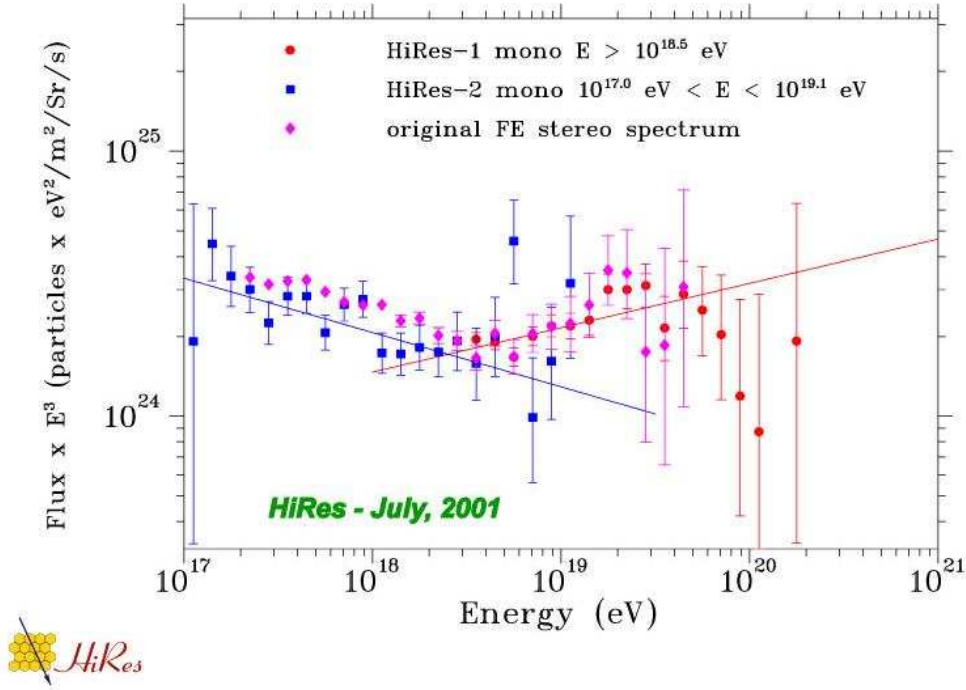


FIG. 12: Spectrum of ultra-high-energy cosmic rays from new HiRes data and from early Fly's Eye data.

Experiment	Technique	Effective Aperture [$1000 \times km^2 sr$]	Status
AGASA [81]	Ground Array	~ 0.2	running
HiRes [82]	Fluorescence	~ 1	running
Auger [84]	Ground Array + Fluor.	7 ($\rightarrow \times 2$)	building (proposed)
Telescope Array [85]	Fluorescence	8	under study
OWL [86]	Fluorescence	~ 300	under study

TABLE I: Summary of experiments addressing the mystery of the highest energy cosmic rays.

be expected over the next decade. A summary of the experimental capabilities is given in Table I. Extrapolating the number of events above 10^{20} eV, one would expect ~ 10 per year from HiRes, ~ 100 per year from Auger [84] and the telescope array [85], and thousands per year from OWL [86], assuming also that the spectrum extends beyond 10^{21} eV. There is also EUSO [87], an ESA mission under study for the space station, and there may be other novel ideas (e.g., CHICOS [88]) being developed. Note that the table is simplistic, and only approximates important effects of duty cycle, energy thresholds, resolution, and systematics.

VIII. GRAVITATIONAL RADIATION

Almost all current knowledge of the Universe outside the Solar System derives from observations of electromagnetic radiation (with some input from neutrinos and cosmic rays). The advent of gravitational-wave observatories promises to open a new window on the astrophysical Universe, likely to lead to a greatly improved understanding of mysterious phenomena as well as discoveries as yet completely unanticipated. A careful survey of gravitational-wave astrophysics is available in the P4.6 summary report [89].

Gravitational radiation is generated by bulk motions of large masses. The resulting waves induce small tidal forces on any object they pass by; in interferometric detectors, the most promising current designs, these tidal forces are detected by measuring the differential displacement of widely-separated test masses. The primary problem facing the prospective gravitational-wave astronomer is the extreme weakness of the gravitational force.

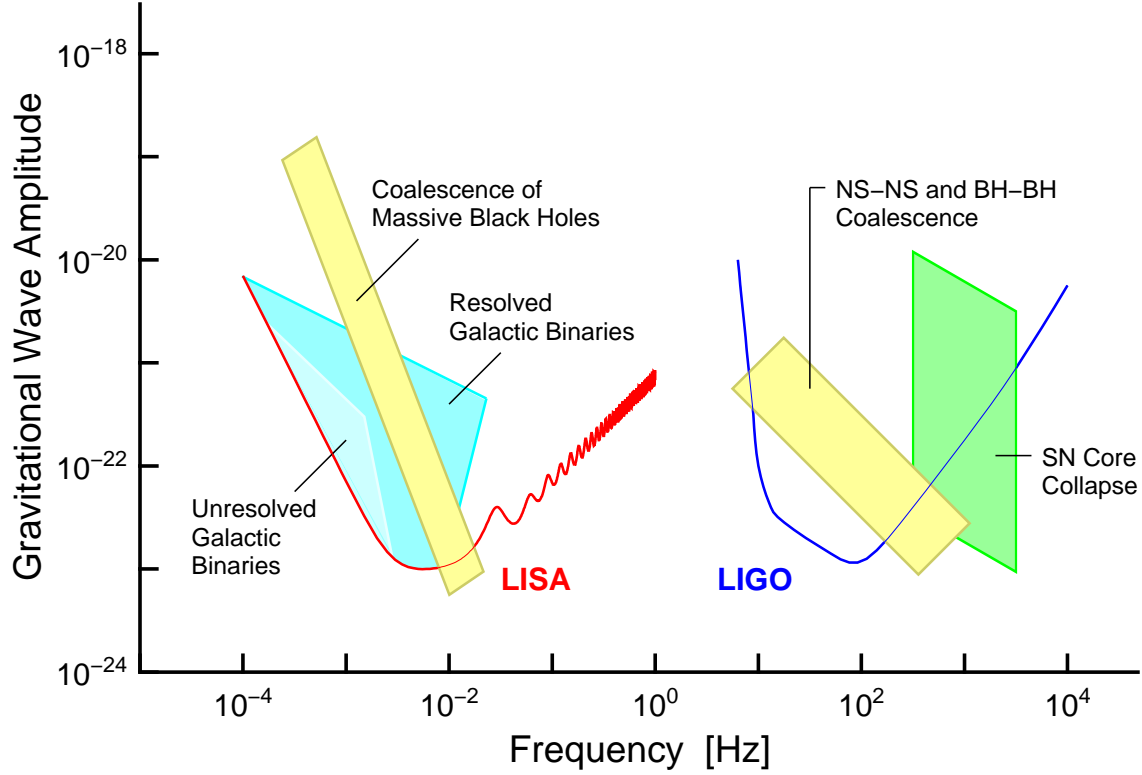


FIG. 13: Sensitivities as a function of frequency for typical ground-based (LIGO) and space-based (LISA) gravitational-wave observatories [90].

For a typical source — e.g., a coalescing binary neutron star at a distance of several hundred Mpc — the strain $h = \delta L/L$ (where L is the distance between the test masses) is of order 10^{-21} or less. The requisite precision for ground-based detectors is achieved by means of multiple-pass interferometry: laser light is first passed through a beam splitter into the orthogonal Fabry-Perot cavity arms of a Michelson interferometer, where it makes numerous round trips before being recombined once more, in such a way that almost all of the light goes back toward the laser in the absence of a gravitational wave. A passing wave disturbs the mirrored test masses, changing the interference pattern and scattering more light into a photodiode. Due to the quadrupole nature of the gravitational waves, the phase shifts in the orthogonal arms have opposite signs, which can be effectively detected by interferometric means. Recycling of the light going back toward the laser is used to improve the sensitivity. Dealing with the various noise sources is one of the greatest challenges of gravitational-wave astronomy; for ground-based detectors, detections of coherent signals at multiple locations will provide strong evidence for the reality of a passing gravitational wave.

A. Ground-based detectors and their sources

A number of ground-based gravitational-wave observatories are currently under construction or being commissioned. In the United States, these include the two LIGO observatories at Hanford, Washington and Livingston, Louisiana [91]. Both sites feature two perpendicular arms of 4 km each; the Hanford site also includes a pair of 2 km arms sharing the same tunnels as the 4 km arms. European facilities include the 3 km interferometer Virgo, in Pisa, Italy [92], and the 600 meter interferometer GEO600 in Hanover, Germany [93], both under construction. Japan has a working detector, the 300 meter TAMA300 observatory near Tokyo [94].

An important distinction between gravitational and electromagnetic astronomy is the natural all-sky coverage that gravitational waves provide. Determining accurate positional information about a source of gravitational waves is difficult, and requires information to be gathered from at least three widely-spaced sites. A Southern-hemisphere detector (such as the ACIGA observatory, being studied in Australia [95]) would greatly supplement the abilities of the existing sites.

Both LIGO observatories have completed their major facility construction; the 2 km Hanford and 4 km

Livingston interferometers have been installed (and the 4 km Hanford interferometer is well under way) and are in the process of collecting engineering data, working toward the beginning of the first science runs. These facilities have been purposefully designed to allow for significant future improvements; major detector upgrades are proposed for 2006.

The limiting noise sources for ground-based detectors depend on the frequency of the gravitational wave being observed. Below about 100 Hz the dominant source is seismic noise, and above 100 Hz it comes from photon shot noise due to fluctuations in the input laser beam; there is also a small region in the vicinity of 100 Hz in which thermal noise in the suspension system for the test masses dominates. The “filter” of observable frequencies runs roughly from 100 to 1000 Hz for current interferometers, extendable down to 10 Hz in future upgrades.

In this frequency range, the most promising sources of gravitational radiation are inspiraling compact binaries, in which both objects are either black holes or neutron stars [96]. For first-generation interferometers, it is quite possible that no visible sources will be found, although a black-hole/black-hole binary of 10 solar masses each at 100 Mpc will be on the edge of detectability. Future upgrades will increase sensitivity to new kinds of sources, including rotating neutron stars [97], collapsing stellar cores [98], and stochastic backgrounds [99]. (The displacement due to a gravitational wave falls off only as $1/r$, so that a small increase in sensitivity yields a large increase in the volume — second-generation detectors should probe a volume 1000 times bigger than that of first-generation detectors.) These instruments will also feature the ability to tune the detectors to maximize sensitivity in promising frequency ranges.

B. Space-based detectors and their sources

The only known way to escape low-frequency noise sources on Earth is to construct detectors in space. The proposed Laser Interferometer Space Antenna (LISA) would consist of three satellites, separated by 5 million km, orbiting the Sun at approximately 20 degrees behind the Earth’s position. A collaboration between NASA and the European Space Agency, LISA is planned to be launched in 2011 [90, 100].

The strain sensitivity of LISA is actually comparable to that of LIGO, although the frequency ranges are quite different, with LISA being most sensitive to frequencies around 10^{-2} Hz. In this vicinity, one of the most important sources will be compact binaries in our galaxy, which actually will provide a noise background at low frequencies. Other anticipated astrophysical sources involve massive (of order $10^6 M_\odot$) black holes in other galaxies. LISA will be sensitive to a variety of processes, including the growth and formation of such objects, radiation from smaller compact objects orbiting around them, and from the coalescence of two massive black holes.

From the point of view of particle physics, perhaps the most intriguing potential for LISA is the chance to observe a gravitational-wave background from a phase transition in the early Universe. If the electroweak phase transition is strongly first-order (which is disfavored by current models, but seems to be required in scenarios of electroweak baryogenesis), the resulting gravitational radiation has a frequency today of $10^{-4} - 10^{-3}$ Hz, accessible to LISA [101, 102]. Thus, space-based gravitational-wave detectors could provide crucial information about the electroweak sector.

C. Testing general relativity

Gravitational-wave observatories offer a direct view into the behavior of gravity under extreme conditions, especially near the event horizon of a black hole. Almost all current tests of general relativity are carried out in the weak-field regime, the binary pulsar being the unique exception; consequently, observations of gravitational radiation will provide new tests of classical gravity. These tests will come both from observing the behavior of coalescing black holes, and from small black holes orbiting supermassive ones. This last test is especially promising, as it provides a way to map out the curvature of spacetime using objects which can be successfully theoretically modeled [103]. Additionally, we will be testing for the first time the propagation of gravitational waves across cosmological distances; comparing this propagation with that of electromagnetic radiation (does gravity “travel at the speed of light”?) will constrain models of extra dimensions as well as alternative theories of gravity [104].

IX. NEUTRINO ASTROPHYSICS

A. Atmospheric and solar neutrinos

Neutrino astrophysics has recently had a tremendous impact on our knowledge of neutrino masses and mixing angles. Recent experiments with atmospheric and solar neutrinos have started delivering on the promise of using astrophysical sources to address fundamental particle properties. Since Snowmass96, the Super-Kamiokande experiment, with its zenith-angle measurement of the atmospheric neutrino signal, has produced the clearest evidence to date for a non-trivial neutrino sector [105]. By extending the reach of earlier water Cerenkov experiments to detection of multi-GeV neutrinos, the SuperK collaboration has used the angular dependence of muon and electron neutrinos produced in the atmosphere to obtain a clear signature of muon neutrinos oscillating into tau neutrinos [106] (Fig. 14); the data are so precise that there is even evidence that discriminates between oscillation to tau and to sterile neutrinos. This year the SNO collaboration, by combining the charged-current breakup of the deuteron with elastic scattering on electrons, provided the first measurement of the electron neutrino component of the solar-neutrino flux [107]. They found that the solar-neutrino flux is composed of roughly one-third electron neutrinos and two-thirds other active flavors. By measuring the total solar-neutrino flux they also confirmed the prediction of the Standard Solar Model.

What we can infer from the combined SuperK and SNO measurements is somewhat surprising: it appears that neutrino mixing angles are rather large, unlike the mixing among quarks. In addition these experiments provide rather strong constraints for the mixing between first and second generations, as well as the mixing between second and third generations. At this time the amount of mixing between the first and third generations (i.e. the test of unitarity of the neutrino mixing matrix) and the possible existence of sterile neutrinos that may mix with the active flavors remain as open questions. When combined with results from a variety of laboratory searches for neutrino masses and mixings, strong constraints to vast regions of mass-mixing parameter space can be derived (as discussed further in the P2 sessions on flavor physics). Further experiments on atmospheric and solar neutrinos, as well as from other astrophysical sources such as supernovae and extragalactic sources, will all help to constrain the properties of the neutrinos [108].

B. Neutrinos elsewhere in the Universe

Although solar and atmospheric neutrinos have taken center stage in neutrino astrophysics recently, neutrinos make important appearances in a variety of other areas in cosmology and astrophysics. For many years, concordance between the observed abundances of light elements and those predicted by BBN provided the most stringent constraints to the number of light neutrinos. Nucleosynthesis and shock reheating in supernovae also depend on the properties of neutrinos, and can provide constraints to neutrino masses and mixings. The CMB and structure formation may also constrain neutrino properties.

We are also now in the midst of rapid progress in the study of high-energy astrophysical neutrinos, from the several GeV to PeV range [109]. Ocean water or Antarctic ice can provide huge volumes for neutrino telescopes that detect the Cerenkov radiation from upward muon induced by energetic neutrinos that interact in the rock below the detector. Just in the past two years, the AMANDA [110] experiment, which operates at the South Pole, has begun to see a large number of events ($\sim 1/day$). The IceCube [111] experiment, will soon expand on this success, eventually aiming toward a km^3 detector. Any source that accelerates high-energy particles should produce high-energy neutrinos, as high-energy protons (such as those in Galactic cosmic rays or from extragalactic UHECRs) will interact with photons or other protons and to produce pions that then decay to neutrinos. Thus, possible sources of high-energy neutrinos (in addition to the numerous atmospheric neutrinos) include active galactic nuclei and gamma-ray bursts. Such neutrino telescopes should also have some sensitivity (at the ~ 100 GeV range) to WIMP annihilation from the Sun or Earth. In addition, there could be even more interesting surprises since the energy range above a TeV is just started to be explored. In particular, cosmic-ray protons above an energy of 10^{20} eV (the “GZK cutoff”) interact with CMB photons leading to photoproduction, *e.g.* at the Δ resonances. The resulting neutrino decay products are therefore a useful probe of the extragalactic processes that would have produced UHECRs.

X. THE EARLY UNIVERSE AND TESTS OF FUNDAMENTAL PHYSICS

Perhaps the most obvious connection between particle physics and cosmology arises in the study of the early Universe, which both requires particle physics for a complete description, and constrains new ideas by requiring

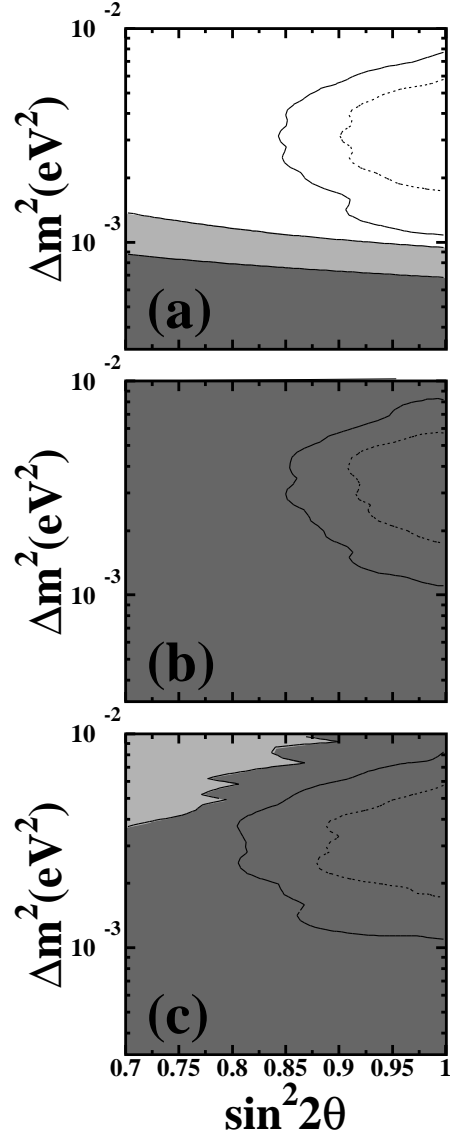


FIG. 14: Regions of the mass-mixing parameter space for mixing into τ and sterile neutrinos constrained by atmospheric-neutrino results from super-Kamiokande. These results demonstrate that astrophysical particle sources (in this case, cosmic-ray spallation products) can provide precise and unique constraints to particle properties.

that they give rise to a sensible cosmology. Here we give a brief overview of this connection; more details can be found in the P4.8 summary report [112].

A. The Universe as a particle-physics laboratory

The big-bang model is a framework which, when combined with the standard model of particle physics, leads to definite predictions for quantities such as the relic abundances of various particle species. Comparing these predictions with observations provides crucial information about the strengths and weaknesses of the standard model. A canonical example is the asymmetry of baryons over antibaryons, which Sakharov pointed out can only arise in an initially symmetric Universe if there are appreciable violations of baryon number, C and CP

symmetries, and thermal equilibrium. Although in principle all of these ingredients are to be found in the minimal standard model, in practice only nonminimal extensions can lead to a quantitatively acceptable baryon number [113]. Thus, the predominance of matter over antimatter in the Universe is a strong indication of the need for new particle physics.

Another such indication is the existence of nonbaryonic dark matter. Both primordial nucleosynthesis [114] and CMB anisotropies [46, 115] are consistent with a density parameter in baryons $\Omega_b = 0.04 \pm 0.01$, while dynamical measurements of the matter density yield $\Omega_m = 0.3 \pm 0.1$, necessitating nonbaryonic matter. There are no reasonable candidates for nonbaryonic dark matter in the minimal standard model. Massive neutrinos, which are easily accommodated in minor extensions of the standard model, can contribute to the dark matter, but their masses are likely to be sufficiently low that they act as hot dark matter, which is ruled out by studies of large-scale structure and the CMB. Instead we must turn to more exotic possibilities, such as axions or neutralinos (stable superpartners to ordinary neutral particles) [116]. Direct searches in terrestrial laboratories for such particles represent a promising strategy for learning about particle physics in a way that complements traditional high-energy accelerators; this is discussed in more detail in Section III.

We have also discussed in Section VI the discovery of dark energy, a slowly-varying smooth component constituting about 70% of the critical density. The simplest candidate for the dark energy is a cosmological constant Λ , or vacuum energy, which arises naturally when quantum field theory is combined with general relativity [54]. Unfortunately the necessary value of the vacuum energy density is $\rho_\Lambda \approx 10^{-120} M_{\text{Planck}}^4$, far below its natural value. This problem is further exacerbated in supersymmetric theories, where the numerical discrepancy is not as bad (sixty orders of magnitude if supersymmetry is broken at the weak scale, rather than 120 orders of magnitude), but the reliability of the estimate is much greater (the vacuum energy is calculable in a given supersymmetric field theory, rather than simply being an arbitrary parameter). In addition, vacuum energy scales rapidly with respect to matter, $\rho_\Lambda/\rho_M \propto a^3$, where a is the cosmic scale factor. Since a has changed enormously since the early Universe (by a factor of order 10^3 since recombination, and 10^9 since nucleosynthesis), it is very hard to understand why the vacuum and matter densities are comparable today. Attempting to solve this puzzle has led to numerous proposals for dynamical dark-energy candidates; to date, none has provided a compelling solution to this naturalness problem. An even more dramatic possibility would be to modify Einstein's general relativity on cosmological scales; but again, no attractive possibilities have been proposed.

B. Inflation

The idea that the Universe underwent a period of quasi-exponential expansion at early times solves a number of cosmological problems, including the absence of noticeable spatial curvature, the absence of a significant density of magnetic monopoles from the breaking of a grand-unified symmetry at high scales, and the apparent violation of causality in the large-scale homogeneity and isotropy of the Universe [117]. One of the drawbacks of the inflationary scenario is that it seems to inevitably require fine-tuning in the construction of a particle-physics model responsible for the inflation [118]; indeed, despite a great deal of effort, the search for believable models has not been a great success. As particle physics learns more about what lies beyond the standard model, it may become possible to construct a sensible picture of the inflationary era.

Soon after inflation was proposed, it was realized that inflation could produce a spectrum of nearly scale-free adiabatic perturbations. It is just such perturbations which seem to be indicated by modern measurements of CMB anisotropy, as discussed in section V. Future measurements of CMB polarization will enable us to disentangle the effects of cosmological parameters from those of features in the primordial spectrum, and detection of tensor perturbations (gravitational waves) will directly probe a prediction of inflation. However, it is important to recognize that exotic models of the inflationary phase (including multiple fields, non-standard kinetic terms, a time-dependent gravitational constant, and so on) can yield perturbations (both scalar and tensor) with properties that differ in important ways from those of standard inflation. Since our knowledge of the physics underlying inflation is so primitive, we should not be surprised to detect deviations from the models we consider to be the most simple and generic; it will be the duty of theorists to continue to refine these predictions as the experiments continue to improve.

C. Planck-scale physics

A complete understanding of the early Universe will eventually entail an understanding of quantum gravity and physics at the Planck scale; conversely, cosmology provides a unique window onto Planckian physics. The leading candidate for reconciling quantum mechanics and general relativity is string theory. String theory

predicts a number of intriguing features for cosmologists, including supersymmetry, extended objects (branes), and extra dimensions; however, our current understanding of the theory is insufficiently developed to enable us to say anything definite about the early Universe, or cosmological backgrounds more generally. Nevertheless, a number of attempts have been made in this direction; proposals include the idea that the dynamics of string gases in compactified geometries can explain why three spatial dimensions are large [119], that the expanding Universe in which we live was preceded by a contracting phase at early times [120], and that the hot big bang arose from the collision of initially cold and nearly featureless three-dimensional branes [121]. While all of these are speculative and beyond the reach of experimental tests at this time, it is important to continue to push ideas in this direction, in hopes of reconciling long standing puzzles of early-Universe cosmology.

Another approach to exploring quantum gravity is to be more independent of any specific theory, and to analyze possible effects of generic departures from low-energy physics at the Planck scale. A recently popular effort in this direction involves the study of modified dispersion relations for massless particles, including new terms that are suppressed by the Planck energy. While such terms are clearly negligible in the laboratory, cosmology offers at least two ways they can be studied: in gradual effects on the propagation of light as it travels over cosmological distances [36], and in the distortion of modes whose wavelengths were shorter than the Planck length at early times, and were subsequently boosted by inflation to give the density perturbations that have grown into large-scale structure in the current Universe [122, 123]. These two examples serve to illustrate how cosmological observations may be lead to direct experimental data that bears on the physics of quantum gravity.

D. Extra dimensions and tests of general relativity

Much of our speculation about the early Universe relies on an extrapolation of low-energy physics to the scale of grand unification or quantum gravity. While such an extrapolation is perfectly reasonable, it is not foolproof, and we should be open to the possibility of dramatically different scenarios. One example is provided by brane-world pictures, in which standard-model fields are confined to a three-dimensional brane embedded in a larger space. There are two interesting versions of this idea: multiple flat (or slightly-curved) dimensions of size 1 mm or less (Arkani-Hamed, Dimopoulos and Dvali, or ADD [37]), and a single highly curved extra dimension of arbitrary size (Randall and Sundrum, or RS [124]).

Both possibilities come with cosmological implications. In the RS model, the conventional Friedmann equation of cosmology can be altered at high densities, leading to constraints from achieving “normalcy” by big-bang nucleosynthesis. Modifications of the RS idea have been put forward in pursuit of a solution to the cosmological-constant problem. The ADD scenario predicts a plethora of new light particles, on which cosmology and astrophysics provide stringent bounds. At the same time, the dynamics of the extra dimensions can play an important role in processes such as inflation and baryogenesis.

These scenarios can lead in principle to deviations from conventional gravity on short (but macroscopic) length scales. This has led to renewed interest in laboratory tests of Newtonian gravity. In particular, the ADD scenario with n extra dimensions predicts a changeover from a $1/r^2$ force law to a $1/r^{2+n}$ law at distances smaller than the size of the extra dimensions; recent searches for this effect have limited this size to less than 0.1 mm [125], and future experiments will continue to improve this limit.

The possibilities of extra dimensions and new light scalar fields are strongly suggested by string theory, and bring home the importance of a wide-ranging program to search for deviations from general relativity. Light scalar fields will generically couple to ordinary matter with Planck-suppressed interactions, which can lead to fifth-force effects and apparent violations of the Equivalence Principle. Laboratory experiments have placed stringent bounds on such phenomena, and proposed satellite and radar-ranging tests would bring a significant improvement. Coupled with observations from gravitational-wave observatories, observations of binary pulsars, and new satellite and laboratory tests, these experiments promise a new era of precision knowledge of the behavior of gravity.

XI. SUMMARY AND CONCLUSIONS

Particle astrophysics and cosmology present a number of exciting theoretical and experimental challenges along a broad front. There are a variety of mysterious astrophysical and cosmological phenomena that almost certainly will require new physics to be understood. Here we have surveyed much of the activity in this field, focusing in particular on areas with recent breakthroughs, and presented a broad overview of some of the most exciting questions that may be addressed experimentally in the foreseeable future. More detailed discussions of all of the topics we have covered can be found in the topical subgroup reports in this Snowmass proceedings.

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