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Early Universe Cosmology and Tests of Fundamental Physics: Report of the P4.8 Working Subgroup, Snowmass 2001

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Abstract

This is the report of the *Working Group on Early Universe Cosmology and Tests of Fundamental Physics*, group P4.8 of the of the Snowmass 2001 conference. Here we summarize the impressive array of advances that have taken place in this field, and identify opportunities for even greater progress in the future. Topics include Dark Energy, Cosmic Acceleration, Inflation, Phase Transitions, Baryogenesis, and String/M-theory Cosmology. The introductory section gives an executive summary with six key open questions on which we can expect to make significant progress.

I. INTRODUCTION

Although it is perhaps presumptious to judge the long-term significance of events without the remove of history, it is widely accepted that cosmology is now undergoing a renaissance. An impressive body of new data from a variety of observatories and experiments is arriving every year, and exciting theoretical ideas are being put to the test. A major driving force behind these dramatic developments has been the application of ideas from particle physics to the early Universe. These ideas have resulted in concrete proposals for the state and matter content of the Universe today, allowing the new data to take root in a rich context of fundamental physics. Thanks to this theoretical framework, the vast new datasets on the cosmic microwave background anisotropy and large-scale structure provide much more than brilliant cartography: they are addressing deep questions about the nature of matter, space, and time. In fact, the exciting opportunities presented by links to the early Universe and fundamental physics provided essential motivation for collecting the new data in the first place.

The excitement in this field was clearly evident in the sessions devoted to the early Universe and fundamental physics at Snowmass 2001. The high energy physics community can take pride in its key role in stimulating such advances in cosmology and celebrate the insights into fundamental physics that have already emerged from this activity. Here we outline the status of and recent advances in early Universe cosmology (interpreting this phrase quite broadly) and document the abundant opportunities for future progress. The combination of an impressive track record and great future opportunities makes a strong case for continuing the high energy physics community's role as a driving force in the field of cosmology. We can do this by exploiting the existing opportunities at the interface between particle physics and cosmology and by vigorously pursuing the fundamental questions that are central to particle physics. Advances on these frontiers are bound to create more opportunities to shape the future of cosmology and reap even greater rewards in the form of further insights into fundamental physics.

Over the next decade, the cosmological parameters determining the structure of the Universe will be determined to within a few percent. This era of precision cosmology will bring sharply into focus the issues of fundamental physics underlying the values of these parameters. The focus of our working subgroup was to survey and evaluate the status of early Universe cosmology, to consider how upcoming data, both astrophysical and collider-based, will shape our knowledge of the earliest times in the Universe, and to develop conclusions about the most promising avenues of research.

We have organized this report into six sections: dark matter; dark energy and the accelerating universe; inflation; cosmic phase transitions; baryogenesis; and cosmology and fundamental physics. Most of these topics are deeply intertwined with one another, so many specific issues turn up in more than one section. Before turning to these topics in depth, we briefly summarize their status with a series of open questions:

- **What is the Dark Matter?** While there is now compelling evidence that 30% of the critical density of the Universe is in the form of non-baryonic dark matter, and particle physics beyond the standard model provides attractive candidates, we have no direct evidence about its identity. Direct and indirect dark matter searches, including accelerator-based experiments, will be critical for helping unravel the identity of the dark matter.

- **What is the nature of the Dark Energy?** While there are now multiple lines of evidence indicating that 70% of the critical density of the Universe is in the form of a negative-pressure Dark Energy component, we have no firm clues as to its origin and nature. Theoretical studies operate in the shadow of the cosmological constant problem, the most embarrassing hierarchy problem in particle physics. Experiments to be carried out over the next decade should shed considerable light on the matter, by constraining the Dark Energy equation of state and determining whether it is consistent with vacuum energy or something else.

- **Did inflation occur in the early Universe?** Inflation provides the only well-studied paradigm for explaining the observed homogeneity and inhomogeneity in the Universe, but a consensus model has not been developed. In the near term, CMB anisotropy experiments will probe inflation via precision tests of cosmological parameters. In the longer term, polarization experiments hold out the prospect of perhaps observing the imprint of inflation-generated gravitational waves.

- **Are there observable relics from cosmic phase transitions?** Phase transitions may play a role in generating a variety of phenomena, from topological defects to baryogenesis to dark matter, magnetic fields, and ultra-high energy cosmic rays.

- **Why is there more matter than antimatter in the Universe?** While the necessary ingredients for successful baryognesis have been known for over 30 years, there is no consensus model for the actual mechanism. Recent attention has focused on baryogenesis at the electroweak scale, an idea which may be tested indirectly by accelerator experiments.

- **What roles do string theory, quantum gravity, and extra dimensions play in cosmology?** Perhaps subsantial ones, but current investigations have been mainly limited to toy models in the absence of a well-understood fundamental theory. Recent attention has focused on scenarios in which standard model particles are confined to a brane in a Universe with large extra dimensions.

II. DARK MATTER

Over the last thirty years, a mountain of evidence has accumulated indicating that the bulk of the matter in the Universe is *dark*. Observations of galaxies and galaxy clusters reveal substantially more mass associated with these systems than can be attributed to the luminous matter. The evidence includes flat spiral galaxy rotation curves, dynamical studies of satellite galaxies, galaxy-galaxy lensing, dynamical, X-ray, weak lensing, and Sunyaev Zel'dovich (SZ) studies of galaxy clusters, and the large-scale peculiar motions of galaxies. Taken together, these observations have consistently pointed to a matter density, expressed as a fraction of the critical density for a flat Universe, of $\Omega_m \simeq 0.15 - 0.3$. In addition, recent measurements of the cosmic microwave background (CMB) anisotropy, of the cosmic shear (large-scale weak lensing), of the galaxy and Lyman-alpha forest clustering power spectra, and of the galaxy cluster abundance have provided independent and consistent estimates of the cosmic mass density (in the context of additional assumptions about the formation of structure in the Universe and in combination with measurements of the Hubble parameter), yielding $\Omega_m \simeq 0.3$ (for recent reviews, see, e.g., [1, 2]).

The bulk of the dark matter in the Universe must be non-baryonic. Estimates of the cosmic baryon density, traditionally from big bang nucleosynthesis (e.g., [3]) and more recently from the CMB anisotropy [4–6], now yield $\Omega_b h^2 = 0.02$; combined with measurement of the Hubble parameter ($h = 0.72 \pm 0.07$ from the HST Key Project [7]), this implies $\Omega_b \simeq 0.04$, substantially below the total matter density. The case for non-baryonic dark matter has been strengthened by independent measurements of $\Omega_m/\Omega_b \simeq 7 - 9$, from the cluster baryon fraction (SZ and X-ray measurements) and from preliminary detection of baryonic wiggles in the large-scale power spectrum [8, 9]. In addition, the fact that $\Omega_b > \Omega_{Luminous} \simeq 0.007$ argues that a substantial fraction of the baryons in the Universe are also dark (perhaps in the form of compact objects or MACHOs).

Since the pattern of CMB anisotropy indicates that the spatial geometry of the universe is nearly flat, $\Omega_{tot} \simeq 1$ [4–6], the Universe must be dominated by a component—the so-called Dark Energy—which is smoothly distributed on at least the scale of clusters. In order for this component not to have disrupted the formation of structure, it should have come to dominate the energy density only at quite recent epochs, which implies that its effective pressure should be negative. This is consistent with observations of the apparent brightness of high-redshift SNe Ia, which indicate directly the presence of dark energy accelerating the Universe [10, 11]. A consistent cosmological model has thus emerged, in which $\Omega_m \simeq 0.3$ and $\Omega_{de} \simeq 0.7$.

While the observational evidence for dark matter and dark energy has been building, we still have no solid clues as to the identities of either of these two components. Nevertheless, their mere existence strongly points to physics beyond (perhaps way beyond) the standard model. Experiments aimed at trying to discover the nature of the dark matter and the dark energy are therefore critical for progress in both particle physics and cosmology. For the remainder of this section, we focus on recent developments in understanding the role of dark matter; the following section describes dark energy.

As has often been pointed out, the uncertainty in the mass of the (non-baryonic) dark matter constituent ranges over at least 70 orders of magnitude, from $\sim 10^{-5}$ eV (for axions) to $\sim 10^{63}$ eV (for planetary mass primordial black holes). Within this vast range, the theory of structure formation provides indirect evidence about some of the properties which the (bulk of the) dark matter must have (see below).

¿From the theoretical perspective, particle physics theories beyond the standard model do provide well-motivated candidates for non-baryonic dark matter. In supersymmetric models with conserved R-parity, the lightest supersymmetric partner (LSP) of ordinary fermions and bosons is stable. Such a particle is weakly interacting and has a mass of order the electroweak scale (hence the moniker WIMP, for weakly interacting massive particle); in combination, these properties imply that the LSP should have a relic cosmic density of order $\Omega_m \sim 1$ (within a few orders of magnitude) [12]. The axion, a stable pseudo-Nambu-Goldstone boson which emerges from models which address the strong CP problem via a global $U(1)$ (Peccei-Quinn) symmetry, is also constrained by astrophysical and cosmological arguments to have a density of order the critical density, if it exists.

The SUSY LSP and the axion are both plausible candidates for cold dark matter, with similar effects on the growth of large-scale structure, but their experimental signatures are quite different [13]. Direct searches for WIMPs in the halo of the Galaxy are now becoming mature—relying on the deposition of $\sim$ keV of recoil energy when a WIMP scatters from a nucleus in a detector. Several experiments have reported bounds on WIMP masses and cross-sections [14, 15], with one controversial report of a detection via the annual modulation signal [16]. The challenge for the next generation of direct detection experiments is to scale up the detector mass while continuing to beat down systematic backgrounds, in order to achieve sensitivity to much smaller event rates and thereby probe a large swath of SUSY parameter space. In addition, indirect WIMP searches, which rely on detection of high-energy gamma rays or charged particles from WIMP annihilation in the halo, or high-energy neutrinos from annihilations in the Earth or the Sun, will gain sensitivity with the coming round of large experiments such as GLAST, VERITAS, and ICECUBE. These direct and indirect WIMP searches should be considered complementary to searches for supersymmetry at colliders. Axion searches involve the resonant conversion of halo axions into microwave photons in the presence of a strong magnetic field; several experiments around the world are underway and are also planning upgrades which should enable them to probe the range of axion masses and couplings expected from theory [17, 18]. Both direct and indirect searches for particle dark matter are sensitive to some degree to the phase space distribution of dark matter particles in the Galaxy halo. Recent N-body simulations of cold dark matter have stimulated investigations of the expected clumpy nature of halo dark matter and its possible implications for experimental signatures [19–22].

In assessing dark matter candidates, we should continue to be cognizant of possible surprises and therefore keep an open mind: theory has provided a multitude of possible candidates beyond WIMPs and axions and could provide new ones. The experiments above are rightly aimed at what are currently considered the most plausible theoretical candidates, but some thought should go into constraining other possibilities.

Models of structure formation provide important clues about the nature of the dark matter, strongly suggesting that the bulk of it is (at most) weakly interacting and non-relativistic at late times (cold dark matter, CDM). Measurements of the CMB anisotropy on degree scales and larger indicate that the inflationary paradigm with nearly scale-invariant, adiabatic perturbations is a very strong candidate for the origin of structure. As noted above, in the context of this paradigm, measurements of galaxy and mass clustering from galaxy surveys point to a model with $\Omega_m \simeq 0.3$ in a dark matter component which can freely cluster on scales larger than of order a few kpc. On the other hand, as cosmological N-body simulations of structure formation have pushed to resolve smaller scales, they have uncovered potential discrepancies between CDM models, in which the dark matter is assumed cold (non-relativistic) and collisionless (weakly interacting with itself and with baryons and photons), and the observed properties of galaxy halos. In particular, CDM models predict dark matter halos with steep, 'cuspy' inner density profiles, $\rho(r) \sim r^{-n}$, with $n \simeq 1 - 1.5$, while rotation curves for dwarf and low surface brightness (LSB) galaxies indicate constant density cores (e.g., [23–28]). In addition, these simulations predict that the Local Group of galaxies should include substantially more dwarf satellite galaxies than are observed [29–31]: CDM halos appear to have too much surviving substructure.

The cusp and substructure problems (among others [32]) have prompted a number of authors to recently (re-)consider scenarios in which the fundamental properties of the dark matter are modified. In these alternatives, one no longer assumes that (all) the dark matter is both cold and collisionless: it has a new property which suppresses its small-scale clustering, thereby causing halos to be less cuspy and lumpy. Examples include dark matter which self-interacts [33–35], annihilates [36, 37], decays [38], has a non-negligible Compton wavelength (fuzzy dark matter) [39], or has a non-negligible velocity dispersion (warm dark matter) [40–42]. Another possibility is to stick with cold, collisionless dark matter but suppress the primordial power spectrum on small length scales [43, 44].

The degree to which these different alternatives solve the difficulties of 'oridinary' cold dark matter has been somewhat controversial [45–49]. From the theoretical standpoint, the proposed new dark matter properties are not particularly attractive. For example, warm dark matter requires a stable particle with a mass of order 1 keV, not particularly close to the electroweak or SUSY scale, which must decouple before a significant amount of entropy is transferred to the CMB, so that its cosmic abundance can be suppressed. For annihilating dark matter, one must suppress catastrophic annihilations in the early universe. For self-interacting dark matter, one must supply a new interaction with the requisite strength. The case for 'non-standard' dark matter properties would certainly be more appealing if they could be shown to arise naturally in the context of compelling extensions of the standard model of particle physics; while some work has been done along these lines (e.g., [41, 50]), this remains a challenge for model-builders.

It should also be noted that there may be more pedestrian 'astrophysical' explanations for these discrepancies, involving either the data or the fact that the simulations include only a limited physical description of the baryons. For example, new and reanalyzed data on the rotation curves of dwarf and LSB galaxies, with allowance made for beam-smearing effects, has led some authors to conclude that these systems do not discriminate strongly between constant density and cuspy inner halos [51–53]; however, another recent study has found that LSB rotation curves are definitely *not* well fit by cuspy cores [54]. It has also been suggested that the interactions of supermassive black holes (now known to be ubiquitous in the cores of galaxies) could destroy dark matter cusps when young galaxies merge [55]. In addition, the overabundance of galactic satellites may be reduced by reionization, which suppresses gas accretion and thus star formation in these low-mass clumps [56]. In this picture, the observed lack of halo substructure may be a property of the stellar baryons but not of the dark matter. Finally, it has been suggested that both the cusp and substructure problems could be resolved by the effects of galactic winds [57].

More data on the structure of halos and improved modeling of them is needed to ultimately resolve whether observed galaxy halos are consistent with 'ordinary' cold dark matter. Nevertheless, the study of alternative dark matter properties that the cusp and substructure problems stimulated remains of interest, because the issue can be turned around: we can use structure formation to constrain the properties of dark matter [58]. For example, for warm dark matter (WDM), the high phase space density of dwarf spheroidal galaxies implies a lower limit on the WDM particle mass, $m_X > 0.7$ keV [48]. The observed opacity distribution of the Lyman-alpha forest at redshift $z \sim 3$ leads to a similar lower mass limit [59]. Requiring that sufficiently massive black holes be able to form in time to power the observed highest redshift quasars at $z \sim 6$ and that high-redshift galaxies be able to reionize the Universe by that epoch also lead to qualitatively similar bounds [60]. On the other hand, if the WDM mass is much above 1 keV, it will only suppress power on mass scales well below $10^{10} M_\odot$ and therefore lead to structure on galaxy scales that is indistinguishable from CDM. Further data on halo structure, e.g., from strong gravitational lensing [61, 62] and from galaxy-galaxy lensing, and on halo clustering and abundances at high redshift will help constrain the nature of the dark matter. (For example, self-interacting dark matter models generally predict that galaxy halos are spherical instead of elliptical; in principle, the shapes of halos can be probed by lensing, by the dynamics of halo tracers in the Galaxy, by polar ring galaxies, and by X-rays from massive galaxies, among other methods.)

Large-scale structure can also place useful constraints on the masses of particles which contribute only a small fraction of the dark matter density—neutrinos. The atmospheric neutrino data from Super-Kamiokande and MACRO, interpreted as an effect of neutrino oscillations, indicate a neutrino mass squared difference of order $\delta m^2 \simeq (2-6) \times 10^{-3}$ eV^2, which implies a lower bound on the neutrino cosmic density of $\Omega_\nu > 0.0008$. On the other hand, the observed clustering of galaxies and the Lyman-α forest implies an upper bound on Ω_ν: since neutrinos are relativistic until late times, they free-stream out of perturbations on small scales, thereby damping small-scale power if they make an appreciable contribution to Ω_m. The current observations translate into the (roughly 2σ) upper limit $m_\nu < 3$ eV for the combined masses of light stable neutrinos [63, 64], comparable to current experimental limits on m_{ν_e} from tritium experiments. In the near future, neutrino masses as low as $m_\nu \sim 0.3$ eV can be probed by combining CMB experiments (MAP and Planck) with galaxy and Lyman-α forest power spectrum data from the Sloan Digital Sky Survey [65]. These improved constraints are again comparable to expected improvements in the experimental bounds on m_{ν_e}.

Partly motivated by the perceived problems of 'ordinary' cold dark matter noted above, there has been renewed attention paid to alternatives to dark matter: the mass discrepancies in galaxies normally ascribed to dark matter could instead be signalling the breakdown of Newtonian gravity (for a recent review, see, e.g., [32]). Until the dark matter is actually detected, this may remain a logical possibility. The most commonly discussed alternative, modified Newtonian dynamics (MOND) [66], may be expressed as a modification of the law of inertia below some fundamental acceleration scale; with an appropriate modification, the observed flat rotation curves of galaxies can be reproduced [67]. The degree to which MOND is consistent with the range of astrophysical data continues to be debated. Moreover, the fact that MOND is only a phenomenological prescription for describing dynamical systems, not a fundamental theory, has hampered attempts to apply it to cosmology [68], structure formation, and gravitational lensing [69].

While it is important to keep an open mind to dark matter alternatives, it is also necessary to subject them to observational tests and to hold them up to the lamp of theoretical plausibility. When MOND was first proposed, in the early 1980's, galaxy rotation curves offered the primary evidence for a mass discrepancy, and MOND was aimed at providing an alternative explanation for these observations. Although rotation curves still provide the strongest evidence for a mass discrepancy, ancillary circumstantial evidence for dark matter has built up substantially in the intervening years. As noted at the beginning of this Section, this newer evidence is of two kinds: (a) direct inference of mass discrepancies in galaxies and clusters using a variety of probes, and (b) consistency of the cold dark matter model with $\Omega_m \simeq 0.3$ with CMB, SNe Ia, large-scale structure, and weak lensing data. Although MOND cannot address most of these other observations without being embedded in a fundamental theory, as these new pieces of evidence mount up the possibility of explaining them all with something other than dark matter becomes less likely. On the theoretical side, while particle physics theory provides well-motivated candidates for cold dark matter, it has proved difficult to embed MOND in a more fundamental theory; part of this difficulty likely traces to the fact that it appears to violate cherished principles such as the equivalence principle, Lorentz invariance, and conservation of momentum [68]. Again, if it could be shown that dark matter alternatives arise naturally from new ideas in particle physics or gravitation, the case would be substantially more compelling (for some attempts, see, e.g., [70, 71]). Finally, it should be noted that modified gravity could in principle be falsified (along with self-interacting dark matter) by better data on the shapes of 'dark' halos or by confirmation of the existence of dark clumps (several of which have been inferred from weak lensing observations) [72].

III. DARK ENERGY AND THE ACCELERATING UNIVERSE

Recent observations of type Ia supernovae (SNe Ia) at high redshift indicate that the expansion of the Universe is accelerating [10, 11]: although concerns about systematic errors remain, these calibrated 'standard' candles appear fainter than would be expected if the expansion were slowing due to gravity. According to General Relativity, accelerated expansion requires a dominant component with effective negative pressure, $w = p/\rho < 0$. Such a negative-pressure component is now generically termed Dark Energy; a cosmological constant Λ, with $p_\Lambda = -\rho_\Lambda$, is the simplest but not the only possibility. As noted in the previous Section, recent results for the CMB anisotropy, which favor a nearly flat Universe, $\Omega_{total} = 1$, coupled with a variety of observations pointing unambiguously to low values for the matter density parameter, $\Omega_m = 0.3$, provide independent evidence for a dark energy component with $\Omega_{de} \simeq 0.7$. Such a cosmological model, with the additional assumptions that the dark matter is (mostly) cold and that the initial perturbations are adiabatic and nearly scale-invariant (as predicted by inflation), is in excellent agreement with CMB and large-scale structure data as well.

On the other hand, the history of dark energy—more specifically the cosmological constant—is not pretty: beginning with Einstein, it has been periodically invoked by cosmologists out of desperation rather than desire, to reconcile theory with observations, and then quickly discarded when improved data or interpretation showed it was not needed. Examples include the first 'age crisis' arising from Hubble's large value for the expansion rate (1929), the apparent clustering of QSOs at a particular redshift (1967), early cosmological tests which indicated a negative deceleration parameter (1974), and the second 'age crisis' of the mid-1990's arising from new evidence in favor of a high value for the Hubble parameter. Despite these false starts, it seems more likely that dark energy is finally here to stay, since we now have multiple lines of evidence pointing to it.

With or without dark energy, a consistent description of the vacuum presents particle physics with a major challenge: the cosmological constant problem (see, e.g., [73, 74]). The effective energy density of the vacuum—the cosmological constant—certainly satisfies $\Omega_\Lambda < 1$, which corresponds to a vacuum energy density $\rho_\Lambda = \Lambda/8\pi G < (0.003 \text{ eV})^4$. Within the context of quantum field theory, there is as yet no understanding of why the vacuum energy density arising from zero–point fluctuations is not of order the Planck scale, M_{Pl}^4, 120 orders of magnitude larger, or at least of order the supersymmetry breaking scale, $M_{SUSY}^4 \sim \text{TeV}^4$, about 50 orders of magnitude larger. Within the context of classical field theory, there is no understanding of why the vacuum energy density is not of the order of the scale of one of the vacuum condensates, such as M_{GUT}^4, M_{SUSY}^4, $M_W^4 \sin^4\theta_W/(4\pi\alpha)^2 \sim (175 \text{ GeV})^4$, or $f_\pi^4 \sim (100 \text{ MeV})^4$. The observational upper bound on the vacuum density appears to require cancellation between two (or more) large numbers to very high precision. Note that this is not an argument against the cosmological constant *per se*, merely a statement of the fact that we do not understand why Λ is as small as it is. Some theorists expect that whatever explains the smallness of the cosmological constant—e.g., some as yet undiscovered (or presently misunderstood) symmetry—may require it to be exactly zero, but as of yet no compelling mechanism has been proposed. This discrepancy is the most embarrassing hierarchy problem for modern particle physics theory. Moreover, the arguments above indicate that it is manifest even at low energies. It is therefore not obvious that its solution necessarily lies in unraveling physics at ultra-high energies, e.g., in string theory.

The cosmological constant problem predates the recent evidence for dark energy. However, dark energy raises a new puzzle, the so-called coincidence problem. If the dark energy satisfies $\Omega_{de} \simeq 0.7$, it implies that we are observing the Universe just at the special epoch when Ω_m is comparable to Ω_{de}, which might seem to beg for further explanation. We might rephrase these two problems as follows: (a) why is the vacuum energy density so much smaller than the fundamental scale(s) of physics? and (b) why does the dark energy density have the particular non-zero value that it does today? If the dark energy is in fact vacuum energy (i.e., a non-zero cosmological constant), then the answers to these two questions are very likely coupled; if the dark energy is not due to a pure cosmological constant, then these questions may be logically disconnected.

In recent years, a number of models in which the dark energy is dynamical, e.g., associated with a scalar field and not a fundamental cosmological constant, have been discussed (e.g., [75–88]). These models, sometimes known as "quintessence" models, start from the assumption that questions (a) and (b) above are logically disconnected. That is, they postulate that the fundamental vacuum energy of the universe is (very nearly) zero, owing to some as yet not understood mechanism, and that this new physical mechanism 'commutes' with other dynamical effects that lead to sources of energy density. This assumption implies that all such models do *not* address the cosmological constant problem. If this simple hypothesis is the case, then the *effective* vacuum energy at any epoch will be dominated by the fields with the largest potential energy which have not yet relaxed to their vacuum state. At late times, these fields must be very light.

Adopting this working hypothesis, we can immediately identify generic features which a classical model for the dark energy should have. Dark energy is most simply stored in the potential energy $V(\phi) = M^4 f(\phi)$ of a scalar field ϕ, where M sets the characteristic height of the potential. The working hypothesis sets $V(\phi_m) = 0$ at the minimum of the potential (although this assumption is not absolutely necessary); to generate a non-zero dark energy at the present epoch, ϕ must be displaced from the minimum ($\phi_i \neq \phi_m$ as an initial condition), and to exhibit negative pressure its kinetic energy must be small compared to its potential energy. This implies that the motion of the field is still relatively damped, $m_\phi = \sqrt{|V''(\phi_i)|} < 3H_0 = 5 \times 10^{-33} h$ eV. Second, for $\Omega_\phi \sim 1$ today, the potential energy density should be of order the critical density, $M^4 f(\phi) \sim 3H_0^2 M_{Pl}^2/8\pi$, or (for $f \sim 1$) $M \simeq 3 \times 10^{-3} h^{1/2}$ eV; the resulting value of the scalar field is typically $\phi \sim M_{Pl}$ or even larger. Thus, the characteristic height and curvature of the potential are strongly constrained for a classical model of the dark energy.

This argument raises an apparent difficulty for all "quintessence" models: why is the mass scale m_ϕ at least thirty orders of magnitude smaller than M and 60 orders of magnitude smaller than the characteristic field value $\phi \sim M_{Pl}$? In quantum field theory, such ultra-low-mass scalars are not *generically* natural: radiative corrections generate large mass renormalizations at each order of perturbation theory. To incorporate ultra-light scalars into particle physics, their small masses should be at least 'technically' natural, that is, protected by symmetries, such that when the small masses are set to zero, they cannot be generated in any order of perturbation theory, owing to the restrictive symmetry. While many phenomenological quintessence models have been proposed, with few exceptions [78, 80, 83, 88], model builders have ignored this important issue. In many quintessence models, particularly those with "runaway" potentials (e.g., exponentials, inverse power laws), this problem is compounded by the fact that the scalar field amplitude at late times satisfies $\phi \gg M_{Pl}$: the dark energy dynamics would be ruined by generically expected terms of the form ϕ^{4+n}/M_{Pl}^n unless they are highly suppressed. In addition, such 'eternal' quintessence models lead to horizons, which may create difficulties for (perturbative) string theory [89]. On the plus side, models in which the "quintessence" field is an axion with the requisite mass scales [78] may perhaps arise in perturbative string theory [83, 89], and the radion field in brane models with large extra dimensions may also have the requisite properties for dark energy [88].

Since the quintessence field must be so light, its Compton wavelength is comparable to the present Hubble radius or larger. As a result, depending on its couplings, it may mediate a new long-range force, a possibility constrained by equivalence principle experiments and astrophysical tests [90]. While quintessence models have been constructed which evade these bounds [88], these constraints remain an important consideration for theorists in bulding models. More sensitive equivalence principle experiments are warranted, as they will provide stronger constraints upon and (possibly) evidence for dark energy.

While "quintessence" models provide theoretical scenarios of varying plausibility for a dark energy component which differs from a cosmological constant ($w = p_\phi/\rho_\phi > -1$ if the field is rolling), the next major developments in this field will likely come from observations: progress in probing dark energy will be critical to pointing the way to theoretical understanding of it. The first challenge for the coming decade is to determine whether the dark energy equation of state parameter w is consistent with -1 (the vacuum) or not. The current constraints from SNe Ia observations (e.g., [91, 92]) are consistent with $w = -1$, but with large uncertainties. As the errors are reduced, will $w = -1$ be excluded or preferred? If the latter, i.e., dark energy consistent with vacuum energy, it will likely be difficult to make further theoretical progress without tackling the cosmological constant problem. If the former, i.e., dark energy inconsistent with vacuum energy, it would appear to point to a dynamical origin for this phenomenon. In that case, marshalling a variety of probes, including supernovae, weak lensing, cluster counting via SZ, Lyman-alpha forest clustering, and others (discussed elsewhere in these proceedings) to determine w and its possible evolution with redshift will be needed. Fortunately, it appears that the prospects for improved SNe observations and the maturation of complementary probes are quite good, and with them the prospects for determining the nature of the dark energy. As the discussion above indicates, these observations may in some sense be probing physics near the Planck scale.

IV. INFLATION: MODELS TESTS AND ALTERNATIVES

A Overview

The idea of cosmic inflation has played a central role in the development of cosmology over the last 20 years. Inflation offers an explanation for many features of the Universe that used to seem beyond the reach of scientific explanation, in particular its spatial flatness and homogeneity, and makes specific predictions for the seeds that formed galaxies and other structure. (For reviews see for example [93–95])

The emergence of the Cosmic Inflation idea has created many exciting opportunities. On the astronomical side, it has given us a "standard model" with specific values for the density of the Universe, Ω_{tot}, and the spectrum of deviations from perfect homogeneity, predictions that can now be confronted with astronomical data. The prospect of testing these predictions has been crucial to making the case for the host of new observational campaigns (such as the Sloan Digital Sky Survey and the MAP and PLANCK satellites) which are set to produce a flood of new data.

There are also key unresolved questions within the inflationary picture. Progress on these questions falls squarely in the domain of high energy physics and is likely to lead to additional opportunities for observational tests. One significant question is whether there is any real competition for cosmic inflation: are there alternative dynamical processes that could, like inflation, set up the Universe with the features we observe? If so, how can we tell which of the alternatives Nature might have actually chosen? Recent attempts to address these questions have stimulated considerable interest and have posed problems for fundamental physics that are exciting in their own right.

B The basic idea

Inflation is based on the idea that the Universe could have been dominated at very early times by an unusual type of matter with an equation of state $p = w\rho$, with $w < -1/3$. In most models, these conditions are achieved by a scalar field ϕ (the "inflaton") which enters into a state where the potential energy density $(V(\phi))$ dominates over other terms in the stress-energy tensor. Under these conditions, the inflaton has an equation of state with w close to -1, and the Universe enters a period of quasi-exponential expansion called inflation. In most models, the inflaton evolves classically down the potential V; these are called "slow roll" models.

During inflation, the spatial curvature becomes negligible, leading to a "flat" universe (with $\Omega_{tot} = 1$). Also, the quasi-exponential expansion pushes field modes from infinitesimal scales all the way to the size of the observed Universe and even well beyond that. Specific calculations allow us to follow the "zero point" quantum fluctuations in these modes out to cosmic scales and lead to concrete predictions for the primordial perturbations produced by a given inflationary scenario.

Cosmic Inflation has predictive power because details of the state of the Universe before inflation are hidden beyond the domain of realistic observations. The observable features of the Universe after inflation are specified by the dynamics of inflation and are insensitive to the initial conditions. To realize this picture, a minimum number (N_e) of e-foldings of the scale factor during inflation must be achieved (for example, $N_e \geq 60$ for inflation at the Grand Unification scale). After a sufficient period of inflation, energy must be transferred from the (dominant) inflaton field into ordinary matter via inflaton decay, causing the Universe to "reheat".

A crucial aspect of the inflationary scenario is that it radically changes the causal structure of the Universe as compared with the Standard Big Bang. It is only thanks to these changes that one can hope to explain the state of the Universe using causal processes. Thus, inflation is noted for "solving the horizon problem" (in the sense that it makes a Universe that appears homogeneous over the present Hubble scale much more probable, given a variety of initial conditions), in addition to explaining specific features of the observed Universe.

C Tests of Inflation

We first briefly discuss the classic tests of inflation and then continue with some more subtle issues. More extended discussion of many aspects of these tests can be found in the report of the P4.3 group on *CMB and Inflation*.

1 Density

Essentially all models of inflation involve a large amount of slow-roll inflationary expansion, much more than the minimum 60 e-foldings required. The curvature of the Universe today is completely negligible in these models, and thus we have the prediction $\Omega_{tot} = \bar{\rho}_{tot}/\rho_c \equiv 1$. However, we only measure $\bar{\rho}_{tot}$ and ρ_c in the part of the Universe we can observe. Fluctuations in the matter density on the scale of the present Hubble radius (part of the same spectrum of fluctuations that produced galaxies and other structure) give the distribution in the predicted Ω_{tot} a small width at the level of one part in 100,000 (much smaller than the current observational uncertainty).

The current observations on this front are consistent with the predictions from inflation. Data from the three most recent CMB experiments give $\Omega_{\rm tot} = 1.01 \pm .08, 0.97 \pm .10, 1.0 \pm .14$ (from DASI [96, 97], BOOMERANG [98], and MAXIMA [99] respectively). Combining all these experiments and others [100] results in $\Omega_{\rm tot} = 1.0^{+.06}_{-.05}$. This result is particularly impressive since the largest contribution to Ω_{tot} comes from the mysterious dark energy. Little is known about the nature of the dark matter and energy of the Universe (see sections II and III of this report). The one sure thing is that it all adds up to match the inflationary prediction. Future observations will determine Ω_{tot} to higher precision and offer an opportunity to either confirm or falsify the standard inflationary picture.

2 Coherence from inflation

As discussed at length by the P4.3 group, inflation gives the density fluctuations a special property called "coherence"[101]. This property is related to the dominance of very specific perturbation modes. One manifestation of coherence from inflation is a specific type of oscillation in the spectrum of CMB anisotropies. Each new round of CMB data has increased the observational evidence that these oscillations are really there. Already a class of competing models for the origin of cosmic structure, the cosmic defect models, have failed largely because they lacked sufficient coherence to match the data. Figure 1 illustrates this important result. Future observations will produce much more stringent tests of coherence and provide an opportunity to support or falsify the inflationary origin of cosmic structure.

3 Gravity waves from inflation

Perhaps the boldest prediction of the inflationary picture is the existence of a cosmic gravity wave background (CGB). There is no known alternative physical process that would predict anything comparable, so the detection of this background would be powerful evidence in favor of inflationary cosmology. As with the density perturbations, the gravity wave background is the

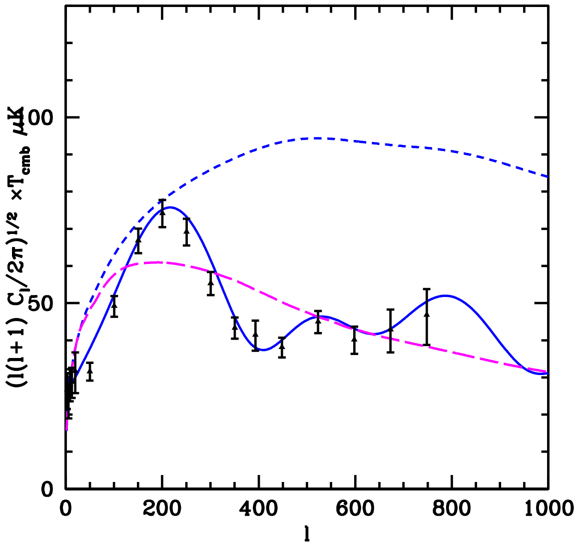

FIG. 1: Coherence in the CMB: Three models of the Cosmic Microwave Background anisotropies are shown with a compilation of the data. The two dashed curves represent defect models. The short-dashed curve is an exotic departure from the standard picture with the sole motivation of providing a better fit to the data, but even this curve fails to fit the oscillatory behavior. The inflation model (solid curve) with its coherence-related oscillations fits well. Details of this plot can be found in[102]

result of stretching the zero-point quantum fluctuations in quantum gravitational wave fields (tensor metric perturbations) to cosmic scales. Observation of the gravity wave background would provide strong evidence that the tensor modes of Einstein gravity are quantum mechanical, a very significant result given the problematic nature of quantum gravity. At the levels predicted by inflation, however, the CGB will be very hard to detect. Perhaps the best hope is through signatures in the polarization of the Cosmic Microwave Background, as discussed in the P4.3 report. It seems that a direct detection of the CGB will remain a challenge for future generations of cosmologists, but one with very exciting implications. (Extensive discussion of these and related issues can be found in the reports of the P4.6 group. A nice summary can be found in ref. [103])

4 The scalar spectral index

As examined at length in the P4.3 report, inflation predicts a "nearly scale invariant" spectrum of density perturbations (scalar metric perturbations). This corresponds to a "scalar spectral index" n_s for density perturbations of nearly unity. So far, the CMB observations are remarkably consistent with this value, and increasingly tight constraints on the spectral index can be expected in the near future. The precise nature of the deviations from scale-invariance depend on the model, but deviations of much more than 20% are outside the scope of the standard paradigm.

5 Further tests of inflation

As more data comes in, one can begin to take seriously the idea of making even more detailed tests of the inflationary machinery. After all, a model of inflation proposes a very specific origin for the perturbations that formed every observed object in the Universe. Interesting work has been done on the prospects of actually *reconstructing* the inflaton potential from cosmological data, and the possibility of other tests is currently an active subject of investigation. (Further discussion on reconstruction of the inflaton potential can be found in [103, 104])

6 Can one really *test inflation?*

A wide variety of models of the Universe have some kind of inflationary period. A standard paradigm has emerged, which encompasses the vast majority of existing models. That is the picture described so far in this section. There are a few intriguing alternative scenarios which incorporate a period of cosmic inflation but which look very different. For example, there are models in which our Universe exists inside a single bubble produced in a cosmic phase transition. A small amount of inflation is arranged to happen inside the bubble, and in such models $\Omega_{tot} \neq 1$ is possible.

So what does it mean to test inflation? The tests described above are tests of the standard paradigm of inflation. If all the tests come out positive, the standard picture will have passed some impressive milestones. If one or more tests are negative, the standard picture will have been falsified, and attention will shift to alternative ideas. Thus the field is poised to make dramatic progress. There is a standard paradigm which is clearly falsifiable by experiments that are well within reach.

Occasionally there are debates about whether testing the standard picture described above is truly testing *inflation*, because exotic alternatives exist. As always, what is tested by observations is determined by the nature of the observations, not by abstract philosophical debates. We urge the community to not let these debates of principle detract from the fact that there is very exciting progress to be made.

D Inflation and fundamental physics

The mechanism of cosmic inflation explores brand new territory, and there are many aspects of this idea that need to be better understood. In some cases simple assumptions have been made that need to be justified; in other cases potentially problematic issues have been ignored, for lack of any concrete way forward. In addition, a lot of details are still missing, because we still do not have a consensus model of physics on the energy scales at which inflation is supposed to have happened. All these issues are linked with fundamental questions in particle physics.

Small parameters: If a given inflationary model is sufficiently well specified, exact predictions can be made for the spectrum of cosmic perturbations that are produced. In most models, in order to achieve a suitable overall amplitude for the cosmic perturbations, a dimensionless parameter in the model must be set to a small value of order 10^{-12}. Although there are claims that in some cases the right amplitude comes out naturally[105, 106], this issue is far from settled. We hope that progress on a fundamental description of physics at high energies will yield a more solid foundation for the inflaton.

Re/Pre-heating: The decay of the inflaton into ordinary matter is a new territory in its own right. To have all the energy in the Universe tied up in the potential energy of a single coherent field and which then decays into ordinary matter is not yet a well-understood process.

Much of the analysis has been based on very simple arguments, although some intriguing coherence effects dubbed "pre-heating" have been investigated (for some recent discussions see [107, 108]. No doubt there is room for more progress to be made in this area, which could be crucial in determining which inflation models are really viable. There could be suprises (i.e., super-efficient or inefficient reheating) which would lead to very different inflationary scenarios.

The problem of negative pressure: Inflation depends on the inflaton achieving an equation of state with $p < -\rho/3$. While it is easy enough to construct a scalar field which has these properties under the right conditions, until recently it was thought that such states had never been observed in Nature. With the discovery of the cosmic acceleration (see Section III) there is evidence that somehow Nature is able to endow matter with a suitable equation of state, but we are still not sure how. In fact, there is even a threat hanging over inflation related to the cosmological constant problem (discussed in Section III), since the inflaton behaves very much like a cosmological constant during inflation. Whatever mechanism Nature chooses to remove the "vacuum energy" (which naively should exceed observational bounds by 120 orders of magnitude) could just as well kick in to prevent inflation from taking place at all. Alternatively it has been proposed that even ordinary gravity actually *has* a built-in mechanism that can cancel the vacuum energy with quantum corrections, but that these dynamical corrections happen slowly enough that it is still possible for a suitable period of inflation to take place[109, 110]. Whatever the outcome, it is intriguing that this problem is now linked with the observed cosmic acceleration, the understanding of which which there is hope for real progress based on observations.

"Trans-Planckian" modes and inflation: During inflation, quantum field modes are stretched from tiny scales (smaller than the Planck length) to cosmic scales. What do we really know about physics on trans-Planck scales? A simple "Bunch-Davies vacuum" provides the required input in the standard calculation, and it certainly serves the purpose. Interesting recent work [111] suggests that only extreme deviations from the assumed dispersion relation at these scales could change the predictions for large-scale structure. Ultimately we would like to see this subject on a much firmer footing, especially since the prediction of cosmic perturbations depends on what is input in the first place. (See the discussion in subsection VII D.)

Before Inflation: One of the impressive features of the inflationary picture is how a period of inflation transforms many different possible initial conditions into the kind of state we need to kick off the Standard Big Bang cosmology. It is tempting to think that with that kind of dynamics, we really do not need to think much about what might have happened before inflation. This may in the end turn out to be true, but this is currently an extremely poorly understood subject, and less pleasing results may emerge from a more sophisticated treatment. It is a challenge to treat quantitatively the "space of all pre-inflation states". It has even been argued that fundamental uncertainties to do with placing measures on pre-inflation states make predictions from inflation impossible[112], but few have found these arguments compelling (see for example ref. [113] for an alternative perspective). Recent work has also argued that one cannot have a past described purely by inflation[114], so we are stuck trying to come to grips with the issue of "pre-inflation". Another approach to this issue is to make a specific proposal for the "wavefunction of the Universe"[115–118] which at least in principle might address these questions.

E Alternatives to inflation

It is quite striking that we have a theory of initial conditions for the Universe, especially one that is testable and has met with some success. But the best way to measure the success of an idea is to have some real competition. So far the competition for inflation has been limited. (In the more narrow domain of the origin of perturbations, inflation has already vanquished a class of worthy competitors, the cosmic defect models[102].)

But competition does exist: one proposed alternative involves varying the speed of light (rather than the cosmic expansion) to resolve the horizon and other problems[119, 120], but this idea still has to find a compelling foundation in fundamental physics (interesting efforts in this direction are ongoing[121, 122]. Another idea is connected with holography (the notion that the degrees of freedom of a gravitating system are much fewer than basic field theory suggests). It has been proposed that these limitations actually force the early universe to be highly homogeneous[123, 124]. But this idea has yet to take a concete form with any real predictive power. There is also the "ekpyrotic" scenario[125], which creates the start of the Big Bang as a collision between two "branes" in a higher dimensional space. This picture takes a very different view of explaining initial conditions from inflation. Rather than creating a situation in which many different initial conditions evolve dynamically into what we need, the ekpyrotic Universe needs to set up extremely special initial conditions to start with. But regardless of one's opinion of this alternative approach, efforts to explore the ekpyrotic scenario have led to exciting investigations into the nature of colliding branes[126], work which may well elucidate interesting issues in brane physics.

V. PHASE TRANSITION AND THEIR RELICS

A Overview

Spontaneously broken symmetries play a key role in elementary particle physics. All the known fundamental forces of nature (except for gravity) can be described by renormalizable gauge theories, and the only viable mechanism for giving matter masses in these theories is spontaneous symmetry breaking. In almost all theories with spontaneous symmetry breaking the symmetry is restored at the high temperatures of the early Universe. This results in a cosmological phase transition as the Universe cools through the critical temperature at which the symmetry becomes broken [127–129].

Over much of its history, the evolution of the Universe appears to have been "adiabatic", with matter in local thermal equilibrium. However, phase transitions often involve very long timescale processes that can drop out of local equilibrium and lead to interesting effects. For example one can have domain formation, as local regions make different choices of symmetry breaking direction. Topological defects such as domain walls, magnetic monopoles, or cosmic strings form where domains meet. Complete equilibrium is only achieved when the domains grow (or "coarsen") until the Universe is covered by a single domain, but the coarsening process can take longer than the present age of the Universe to complete. Thus there can be out-of-equilibrium processes that continue right through to the present day. Topological defects typically have interior energy densities similar to the ambient energy density when they were first formed, even after the surrounding matter density has dropped by many orders of magnitude due to cosmic expansion. Thus defects can preserve a region with the high densities of the very early Universe to the present day, offering a unique window on ultra-high energy physics.

With or without the formation of long-lived defects, the out-of-equilibrium processes in cosmic phase transitions can lead to a wide variety of interesting effects. In some cases these effects introduce exciting new possibilities into the field of cosmology. In other cases the results of phase transitions are in clear conflict with observations, firmly ruling out any model that has that type of transition. The notorious "monopole problem" [130] ruled out almost all models of Grand Unification that were popular at that time. Guth's studies of the very same phase transitions led to his seminal paper on cosmic inflation[131].

Cosmic phase transitions could have had a variety of important roles, from creating baryon number, to producing high energy cosmic rays, "wimp-zillas", and a potentially observable background of gravitational radiation. For a time, they provided a viable competing picture for the origin of cosmic structure. In this section we review the current status and future opportunities.

B The many roles of cosmic phase transitions

Phase transitions and baryogenesis One of the insights we hope to gain from the application of particle physics to the early Universe is an explanation of the observed baryon asymmetry of the Universe. A crucial ingredient in any baryogenesis scenario is a period during which the relevant processes are out of equilibrium. Cosmic phase transitions provide an excellent opportunity to create out-of-equilibrium effects, and phase transitions are central to a wide variety of baryogenesis scenarios, from the GUT scale all the way down to the electroweak scale. Some scenarios involve topological defects, while others involve other out-of-equilibrium effects. A more extensive discussion of baryogenesis (including the connection with phase transitions) can be found in section VI.

Phase transitions and inflation As noted in subsection V A, phase transitions were crucial in creating the idea of cosmic inflation. They provided the first specific mechanism for how the Universe could enter an inflationary state, and also led to the monopole problem, which stimulated a fresh thinking about early Universe cosmology. Phase transitions continue to play a central role in the development of the inflationary scenario, and bubbles produced in a higher dimensional phase transition are at the core of a fascinating new alternative to inflation[132].

Cosmic Rays Cosmic rays are the most energetic particles observed, and they have energies almost a billion times greater than particles in the Tevatron. The origin of these particles remains a mystery. Defects formed in cosmic phase transitions carry energy densities set by the energy scale of the phase transition, which could be upwards of $10^{16} GeV$. Topologically stable defects would persist, to some degree at least, until the present day, and could perhaps produce ultra high energy cosmic rays. Thus cosmic rays could be providing us with a window on symmetry breaking at ultra-high energies. (Cosmic rays in general are discussed at length in the report of group P4.5.)

Gravity Waves Perhaps the most ambitious frontier of physics is the pursuit of gravity wave detection. Because the energy scales for cosmic defects can be extremely high, cosmic defects can be a significant source of observable gravitational waves. In fact, for topologically stable defects, the emission of gravity waves is often the only decay channel, and significant amounts of gravity waves are produced. (See the reports of the P4.3 and P4.6 groups for further discussion.)

Cosmic Magnetic Fields Magnetic fields of 10^{-6} Gauss are common within galaxies, and extragalactic magnetic fields are also present, although at lower strength. The origin of these fields, and especially of the small "seeds" that could be amplified by astrophysical processes, remains a mystery. One very interesting possibility is that primordial magnetic fields were generated in a cosmic phase transition[133, 134].

Exotic Objects Phase transitions produce dramatic out-of-equilibrium effects, and cosmic phase transitions can generate a wide range of exotic objects. Such objects could be a cosmological disaster (such as domain walls or monopoles), or they could help explain significant phenomena (for example, "WIMP-zillas", a candidate for the Dark Matter, could have formed in a cosmic phase transition[135]).

VI. BARYOGENESIS

All observations show that the universe is baryon-antibaryon asymmetric, and that there is negligible primordial antimatter in our observable universe [136]. To obtain a quantitative measure of this asymmetry we look to the standard cosmological model. One of the major successes of cosmology is an accurate prediction of the abundances of all the light elements; a calculation which requires a single input parameter, the *baryon to entropy ratio*

$$\eta \equiv \frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{s} \ , \tag{1}$$

where n_b is the number density of baryons, $n_{\bar{b}}$ is that of antibaryons, and s denotes the entropy density. If one compares calculations of elemental abundances with observations, then there is agreement between these numbers if

$$1.5 \times 10^{-10} < \eta < 7 \times 10^{-10} \ . \tag{2}$$

This number is an input parameter in the standard model of cosmology, and it is one of the goals of particle cosmologists to understand its origin from particle physics.

In 1968, Sakharov [137] identified the conditions necessary for a particle physics theory to generate any asymmetry between baryons and antibaryons. These are violations of the baryon number (B), the charge (C) and charge-parity (CP) symmetries, and a departure from thermal equilibrium. One can imagine (any many have) a great number of ways in which this combination of circumstances could be arranged in the context of particle physics in an expanding universe. However, it seems fair to devote most attention to those mechanisms which arise as a natural consequence of particle physics theories proposed for other compelling phenomenological reasons. In addition, those mechanisms amenable to experimental tests in the near future, particularly electroweak baryogenesis, deserve our immediate attention (for reviews see [138–143]).

Certainly, the original suggestion that grand unified theories (GUTs) may be responsible for the BAU is firmly in the first category, but probably not in the second. Grand unification is an attractive idea for understanding the origin of the standard model, the apparent meeting of the running $SU(3)$, $SU(2)$ and $U(1)$ couplings, and the quantization of charge. Further, baryon number is naturally violated in GUT models because quarks and leptons lie in the same representation of the grand unified gauge group, and C and CP may also naturally be violated. The required departure from thermal equilibrium must have an entirely cosmological origin, and in this case it occurs because the expansion rate of the universe at the GUT epoch is significantly faster than the rate of particle interactions. However, despite its attractive properties, there are an number of problems to be overcome by such models. While this is not the place to provide a detailed treatment of these, one is particularly relevant to our subsequent discussion.

The electroweak theory itself violates baryon number (and to an identical amount lepton number (L)) through an anomaly [144]. While this is irrelevant at zero temperature (since the relevant phenomenon is mediated by an instanton of large action, and hence has a close to vanishing rate), at temperatures around or above the electroweak scale such events are unsuppressed and copious [145]. One consequence of this is that if a GUT model does not produce a net baryon minus lepton number (B-L) asymmetry rather than just a baryon asymmetry, then anomalous electroweak interactions between the GUT and electroweak scales will erase the asymmetry. However, the presence of baryon number violation in the electroweak theory at finite temperature suggests that this theory itself may be capable of generating the BAU [146–156]. Of course, there are two other Sakharov conditions to be satisfied. In the standard model the condition of C violation is maximal and CP violation is present at a small level (as evidenced in the Kaon system). However, even if the level of CP violation were enough (which it is not) there is insufficient departure from thermal equilibrium at the electroweak scale, since the minimal electroweak phase transition is continuous for Higgs masses is the experimentally allowed range. This observation has led to the hope that the minimal supersymmetric standard model (MSSM) may allow for electroweak baryogenesis.

The behavior of the electroweak phase transition in the minimal supersymmetric standard model is dependent on the mass of the lightest Higgs particle, and the mass of the top squark. A variety of analytical [157–165] and lattice [166–169] computations have revealed that the phase transition can be sufficiently strongly first order in the presence of a top squark lighter than the top quark. In order to naturally suppress contributions to the ρ-parameter, and hence preserve a good agreement with precision electroweak measurements at LEP, the top squark should be mainly right handed. This can be achieved if the left handed stop soft supersymmetry breaking mass m_Q is much larger than M_Z.

The preservation of the baryon number asymmetry requires the order parameter $\langle\phi(T_c)\rangle/T_c$ to be larger than one. In order to obtain values of $\langle\phi(T_c)\rangle/T_c$ larger than one, the Higgs mass must take small values, close to the present experimental bound. Hence, small values of $\tan\beta$ are preferred. The larger the left handed stop mass, the closer to unity $\tan\beta$ must be. This implies that the left handed stop effects are likely to decouple at the critical temperature, and hence that m_Q mainly affects the baryon asymmetry through the resulting Higgs mass. A detailed analysis, including all dominant two-loop finite temperature corrections to the Higgs effective potential and the non-trivial effects arising from mixing in the stop sector, has been performed [164], and the region of parameter space for which MSSM electroweak baryogenesis can happen identified. Taking into account the experimental bounds as well as the requirement of avoiding dangerous color breaking minima, it was found that the lightest Higgs should be lighter than about 105 GeV, while the stop mass may be close to the present experimental bound and must be smaller than, or of order of, the top quark mass [164, 167]. This lower bound has been essentially confirmed by lattice simulations [169], providing a motivation for the search for Higgs and stop particles at the Tevatron and future colliders.

The popularity of this idea is tightly bound to its testability. The physics involved is all testable in principle at realistic colliders. Furthermore, the small extensions of the model involved to make baryogenesis successful can be found in supersymmetry, which is an independently attractive idea, although electroweak baryogenesis does not depend on supersymmetry. The most direct experimental way of testing this scenario is through the search for the lightest Higgs. In this sense, we are close to knowing whether electroweak processes were responsible for the BAU.

If the Higgs is found, the second test will come from the search for the lightest stop at the Tevatron collider. If both particles are found, the last crucial test will come from B physics, more specifically, in relation to the CP-violating effects.

Moreover, the selected parameter space leads to values of the branching ratio $\mathrm{BR}(b \to s\gamma)$

different from the Standard Model case. Although the exact value of this branching ratio depends strongly on the value of the μ and A_t parameters, the typical difference with respect to the Standard Model prediction is of the order of the present experimental sensitivity and hence in principle testable in the near future. Indeed, for the typical spectrum considered here, due to the light charged Higgs, the branching ratio $\mathrm{BR}(b \to s\gamma)$ is somewhat higher than in the SM case, unless negative values of $A_t\mu$ are present. The crucial nature of knowledge concerning CP violation in the B-sector for baryogenesis means that the results of the BaBar [170], BTeV [171] Belle [172] and LHCb [173] experiments, for example the BaBar measurement of $\sin(2\beta)$ [174] announced during the Snowmass meeting, will be particularly useful.

We now turn to a third baryogenesis scenario, that has received a lot of attention. This mechanism was introduced by Affleck and Dine (AD) [175] and involves the cosmological evolution of scalar fields carrying baryonic charge. These scenarios are most naturally implemented in the context of supersymmetric models (e.g. [176]). Consider a colorless, electrically neutral combination of quark and lepton fields. In a supersymmetric theory this object has a scalar superpartner, χ, composed of the corresponding squark $\tilde{q}$ and slepton $\tilde{l}$ fields.

Now, an important feature of supersymmetric field theories is the existence of "flat directions" in field space, on which the scalar potential vanishes. Consider the case where some component of the field χ lies along a flat direction. By this we mean that there exist directions in the superpotential along which the relevant components of χ can be considered as a free massless field. At the level of renormalizable terms, flat directions are generic, but supersymmetry breaking and nonrenormalizable operators lift the flat directions and sets the scale for their potential.

During inflation it is natural for the χ field to be displaced from the position $\langle\chi\rangle = 0$, establishing the initial conditions for the subsequent evolution of the field. An important role is played at this stage by baryon number violating operators in the potential $V(\chi)$, which determine the initial phase of the field. When the Hubble rate becomes of the order of the curvature of the potential, the condensate starts oscillating around its minimum. At this time, B-violating terms in the potential are of comparable importance to the mass term, thereby imparting a substantial baryon number to the condensate. After this time, the baryon number violating operators are negligible so that, when the baryonic charge of χ is transferred to fermions through decays, the net baryon number of the universe is preserved by the subsequent cosmological evolution.

The challenges faced by Affleck-Dine models are combinations of those faced by the GUT and electroweak ideas. In particular, it is typically necessary that $B - L$ be violated along the relevant directions and that there exist new physics at scales above the electroweak. If supersymmetry is not found, then it is hard to imagine how the appropriate flat directions can exist in the low energy models.

Of all models for baryogenesis, the electroweak scenario has received most attention. Electroweak baryogenesis is such an attractive idea because it is testable and uses physics that is already there for a good particle physics reason. If the model is successful, it is a triumph of the particle physics/cosmology union. If not, our primary attention should be focused on models with the same properties. It is possible that Affleck-Dine models may fit the bill, or that the discovery of neutrino masses is telling us something useful about the direction to go

VII. FUNDAMENTAL PHYSICS AND COSMOLOGY

Since the last Snowmass meeting, tremendous progress has been made in understanding the non-perturbative structure of string theory and the theory into which it has evolved - M-theory. These recent advances may be at last opening the door for a serious approach to analyzing the earliest times in the universe. Since the early universe is a hot, dense, highly energetic place and time, we expect a non-perturbative understanding of quantum effects in gravity to be essential to an analysis of cosmology in such an environment. For those who believe our basic framework for addressing these questions is in place, the recent explosion of interest in extra-dimensional physics should act as a cautionary tale. Solid tests of our cosmological model go back only as far as the epoch of primordial nucleosynthesis, at which the temperature of the universe was still only a few MeV. If we are to gain a quantitative understanding of earlier epochs, it will be necessary to develop a consistent approach to theoretical analyses of the early universe, and innovative new ideas for probing the nature of space and time at these early times. While most ideas in this field are wildly speculative at the present, we nevertheless present some interesting first steps here.

A Finite Temperature String / M-Theory and Cosmology

If we accept string / M-Theory as the correct theory of everything, then it must hold the key to the most fundamental problems in cosmology. Perhaps the most obvious modification to the standard equations of cosmology is that gravity is no longer described purely by general relativity. In particular, Einstein's theory is modified by the appearance of a dilaton field, related to the compactification of the theory, and by higher derivative terms in the action, at nonzero order in the string coupling constant. There have been a number of attempts to use these modifications to address the origin of the hot big bang phase of the universe, the issue of the initial singularity, and even the origin of the number of macroscopic dimensions we observe.

In the Brandenberger-Vafa scenario [177, 178], it is assumed that the fundamental physics respects a T-duality, interchanging large and small radii of a toroidal compactification. This has two particularly interesting implications for cosmology. First, since the small radius of the universe limit is equivalent to the large radius limit, there is no big-bang singularity in the usual general relativistic sense. Second, the dynamics of string winding modes constrains the number of dimensions that may become macroscopic. Imposing T-duality on the modified Einstein equations results in string winding around a particular direction preventing the expansion of that dimension. In the early universe, at high temperatures, it is argued that one should think of a gas of strings (and branes in an extended picture [179, 180]) and their modes. In more than three spatial dimensions, string winding modes cannot annihilate, and hence only as many as three dimensions may decompactify in this picture. Although there are a number of problems with this picture (such as the need for non-trivial one-cycles to wrap around, which do not exist in typical Calabi-Yau compactifications) this provides an interesting possiblity for explaining features of the universe that are inaccessible to our lower energy effective theories. In general, a careful analysis of the implications of finite temperature effects in string theory seems an interesting research avenue to be pursued.

B Extra Dimensions and Cosmology

The flurry of interest in extra dimensional physics [181–185] has led to a number of interesting proposals for modifying cosmology at early times. While one must be careful not to interfere with the successful predictions of the standard cosmology [186–188], the evolution of the universe at the earliest times must be very different in these models from that expected in the usual $3+1$ dimensional framework [189]. When confronted with a new model for the early universe, cosmologists typically ask themselves the following three fundamental questions: 1) Is there a new way to address the horizon and flatness problems in this picture? 2) Is there a way to understand the observed size of the cosmological constant in this picture? 3) Is there a new mechanism for generating the density and temperature fluctuations seen in large scale structure and the CMB? As far as the first point goes, there have been several suggestions. In ref [190, 191] it was suggested that if the universe is the direct product of a (3+1)-dimensional FRW space and a compact hyperbolic manifold [192], the decay of massive Kaluza-Klein modes leads to the injection of any initial bulk entropy into the observable (FRW) universe. This can act to smooth out any initial inhomogeneities in the distribution of matter and of 3-curvature sufficiently to account for the current homogeneity and flatness of the universe. In ref [193] it has been suggested that the true vacuum of the universe is a BPS state in heterotic M-theory. The fields describing our universe live on a brane in this space and the hot expanding phase that we know as the big bang arises due to an instanton effect [194] in which a new brane nucleates, travels across one of the extra dimensions and collides with our brane, depositing its energy there. The eternal nature of the cosmology and the special, flat nature of the BPS state lead to a flat and homogeneous FRW cosmology on our brane after the collision. While there may be existing fine-tunings in the above models, their feasibility and implications for cosmology are under investigation.

The cosmological constant problem remains unaddressed in the above scenarios. However, a particular scheme, the so-called self-tuning model [195, 196], has been proposed in the bane world context to address this issue. The cosmological constant problem arises in a simple sense because space-time is sensitive to the presence of vacuum energy. In the self-tuning picture, the effective theory of gravity on our brane is such that it does not respond to the presence of vacuum energy. This occurs because of a careful choice of coupling between the matter fields living on the brane and in the 5-dimensional bulk. As a result, whatever the value of the cosmological constant, or however it may change, the $3+1$-dimensional metric remains unaffected by it. However, there are a number of unresolved questions regarding the self-tuning models. First, there seems to be a singularity in these models, the possible resolution of which is yet to be understood [197–210]. Second, it seems quite difficult to reconcile the self-tuning picture with what is known about the cosmology of our universe. In particular, it seems necessary to modify the Friedmann equation on our brane [211–216] , which can lead to problems with big bang nucleosynthesis [217].

Finally, the issue of density and temperature perturbations is a highly quantitative challenge to any new theory of the early universe. The precision measurements of the temperature fluctuations in the CMB, and in particular the observation of the second (and perhaps third) acoustic peaks in the power spectrum now provide solid evidence for a scale-free adiabatic spectrum of initial fluctuations, consistent with that predicted by inflation. The question of whether any other mechanism could be responsible for these observations is a particularly pressing one for particle cosmology. Recently it was claimed that one of the scenarios mentioned above, the ekpyrotic scenario [193], may be able to generate the necessary perturbations. However, at present this is a hotly debated topic [126, 218–221], and the ultimate outcome is unclear. Certainly, if this claim is true, the ekpyrotic scenario will have earned further careful study.

C de-Sitter Space as a Solution to M-Theory

One interesting development to come out of the particle physics-cosmology interface is the role of de-Sitter space in M-theory. If inflationary theory is correct, then the universe must go through an accelerating (perhaps quasi-de-Sitter) phase at early times. However, the successes of the standard cosmology (not to mention our presence in the universe today) imply that this was a transient phase. However, the recent observations of type IA supernovae [222, 223] point to a second accelerating epoch, beginning at the present time. Taking this data at face value, there are two interesting possibilities: the acceleration could be caused by a small non-zero cosmological constant, or by some type of energy that redshifts sufficiently slowly as to cause acceleration, but that will eventually cease to act. Let us focus on the former possibility. If there exists a true cosmological constant in the universe, then the late-time space-time will approach de-Sitter space. This would seem to imply that de-Sitter space was a vacuum of the underlying theory. In the context of string theory this may be a problematic conclusion. Several authors [224, 225] have recently pointed out that de-Sitter space seems to be incompatible with string theory, at least at the level of perturbation theory. Other arguments, based on upper bound on entropy in de-Sitter space[226] also challenge the viablity of string theory (or any theory with infinite degrees fo freedom) in a universe with a real cosmological constant. If, as measurements of the equation of state of the dark energy are refined, and string (or M) theory matures and its non-perturbative structure is understood, this tension remains, this may be a a way for cosmology to constrain our fundamental theories.

D Transplanckian Physics and Cosmology

Quantum effects during inflation may be the origin of the temperature fluctuations observed today in the CMB. If so, then scales observed today in large scale structure originated at smaller than Planck scales at the beginning of inflation. Thus, cosmological observations may reveal the structure of physics at sub-Planckian distances. The problem arises because, since there are typically many more than 60 e-foldings in inflationary models, we must extrapolate the weakly-coupled field theories we understand into regimes in which the approximation is no longer valid in order to extract information about the fluctuations. Although we should not trust this procedure, there is at present no way to calculate the expected dispersion relation of fluctuation modes from first principles in any fundamental theory. To make progress, several authors [111, 227–234] have adopted a phenomenological approach, trying different modifications to the dispersion relation at small scales and studying the effects on the expected spectrum of fluctuations.

In general, it proves quite difficult to make short-scale modifications that lead to large effects in cosmological observables. However, this may prove to be a useful technique for testing fundamental physics. In particular, the effects of transPlanckian physics are expected to alter the ratio of the spectrum of scalar to tensor perturbations generated during inflation. In a large class of inflationary models the evolution is dominated by a single field. In that case this ratio is a fixed known number, and deviations from it must signal some departure from the standard picture. Whether the specific signals predicted from short-scale modifications of the dispersion relation can be isolated from other possible effects remains to be seen. Nevertheless, we consider any possible cosmological tests of our most fundamental theories an interesting avenue to pursue.

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