hep-th/0107259
SCIPP-01/27

Dark Matter and Dark Energy: A Physicist's Perspective[1]

Michael Dine

Santa Cruz Institute for Particle Physics, Santa Cruz CA 95064

Abstract

For physicists, recent developments in astrophysics and cosmology present exciting challenges. We are conducting "experiments" in energy regimes some of which will be probed by accelerators in the near future, and others which are inevitably the subject of more speculative theoretical investigations. Dark matter is an area where we have hope of making discoveries both with accelerator experiments and dedicated searches. Inflation and dark energy lie in regimes where presently our only hope for a fundamental understanding lies in string theory.

[1]Physics summary talk of the conference *The Dark Universe: Matter, Energy and Gravity*, Space Telescope Institute, April 2001

1 Introduction

It is a truism that the development of astronomy, astrophysics, cosmology relies on our understanding of the relevant laws of physics. It is thus no surprise that my astronomy colleagues tend to know more classical mechanics, electricity and magnetism, atomic and nuclear physics than my colleagues in particle theory.

As we consider many of the questions which we now face in cosmology, we must confront the fact that we simply do not know the relevant laws of nature. The public often asks us "what came before the big bang." We usually think of this as requiring understanding of physics at the Planck scale. But at present we can't even come close. Ignorance sets in slightly above nucleosynthesis, and becomes severe by the time we reach the weak scale. Some of the questions which trouble us will be settled by experiment over the next decades; some require new theoretical developments. Needless to say, it is possible that much will remain obscure for a long time.

- GeV scales: QCD is by now a well tested theory, but the phase structure of QCD is not completely understood, and possible first order phase transitions, superconducting phases, strange matter, etc. could be relevant both to astrophysics and cosmology. These questions may be settled by improved lattice gauge calculations, and conceivably by developments at RHIC.

- $T = 100$ GeV-TeV: This is the regime of the weak phase transition. In order to understand this transition, we need experimental information on the Higgs particle, or whatever physics is responsible for the mass of the W and Z. This physics *might* be the origin of the matter-antimatter asymmetry[1]. This is physics which will be explored by the Large Hadron Collider at CERN and by a large electron-positron collider, hopefully to be built by an international consortium over the next decade.

- $T = 100$ Gev-TeV: One of the best-motivated candidates for the dark matter is the "LSP" (Lightest Supersymmetric Particle) expected if nature is supersymmetric. If the supersymmetry hypothesis is correct, we can expect to encounter this particle and its supersymmetric cousins at the Tevatron or LHC and the electron-positron collider. This physics could well be responsible for the matter-antimatter asymmetry.

- $T = 1$ Tev: There have been several suggestions over the past three years that the fundamental scale of physics might lie at the TeV scale[2, 3, 4]. In this case, the Planck scale would be so large – and gravity so weak – because there are some very large or highly warped extra dimensions of space. If this hypothesis is correct, there could well be dramatic new phenomena in cosmology just above the temperature of nucleosynthesis.

- $T = 10^{10}$ Gev? The axion is another well-motivated dark matter candidate. It is associated with a symmetry known as a Peccei-Quinn symmetry. 10^{10} GeV might be the scale at which this symmetry is broken. It also might be a scale associated with the dynamics responsible for supersymmetry breaking.
- $T = 10^{15}$ GeV? This could well be the scale of the physics responsible for inflation. Over the past few years, this scale has also emerged as a possible value for the fundamental scale of M theory[5]. The two might well be connected[6].
- $T > 10^{15}$ GeV? Perhaps physics at these scales holds the explanation of the value of the cosmological constant, and identification of the nature of the dark energy. Perhaps only here lies the physics which resolves the singularity of the big bang, and explains the initial conditions of the universe.

For particle physicists it is extremely exciting to think that there are

connections between events in accelerators and our understanding of the history of the universe. Perhaps as important, cosmology can serve as a testing grounds for ideas which are not so readily studied in more conventional experiments. We are probably not going to answer all of the questions which I have listed here soon. But it *is* remarkable that, as we will see, we have hopes of attacking all of them.

2 String or M Theory

I will take string theory as a theoretical umbrella in this talk. String theory is a natural framework to talk about all of the issues I have raised above. Indeed, for many of these questions, it is the only framework we have. First, string theory is our only consistent theory of gravity and quantum mechanics. Such a framework is essential if we are to address many of the questions which we face in cosmology. Equally important, string theory encompasses virtually every idea we have for dark matter and energy:

- Low energy supersymmetry, with symmetries like R parity which give rise to a stable, weakly interacting particle.

- Axions: As I will explain further below, string theory is the *only* theoretical context in which we can make sense of the axion hypothesis.
- Cosmological constant: String theory is the only theoretical framework in which we can, even in principle, calculate the cosmological constant. It has realizations all of the various proposed solutions: it has candidates for multiple vacua which might produce an anthropic solution, as mentioned in Vilenkin's talk; it can produce extremely light particles, which realize the other anthropic proposal which Vilenkin mentioned[7]; and it is "holographic" (to be explained below), so it might offer entirely

  new solutions.
- Quintessence: String theory is the only context in which we can sensibly discuss the sorts of extremely flat potentials necessary to realize the ideas of quintessence[8],[9].

What is also striking about string theory is that it will allow us to make rather definite statements about many of these ideas. We will see that within our current understanding of string theory, the two anthropic solutions which I mentioned above are implausible.[1] Physicists tend to view anthropic explanations of features of physical law with skepticism or worse. Personally, I have for many years thought we might have to contemplate an anthropic solution of the cosmological constant problem[10, 11, 12]. I realized at this meeting that astronomers are more receptive to these ideas than physicists. But what is significant here is that we can potentially use string theory to rule out some anthropic explanations on *scientific* rather than philosophical grounds.

While I will not stress the point here, by similar reasoning, the idea of quintessence similarly extremely difficult to realize in string theory[9].

2.1 String Theory: A Quick Introduction and Survey of Recent Developments

What is string theory? At the most simple level, it is just that: a theory of quantized strings. Such a theory is *automatically* a theory which is generally covariant with non-abelian gauge groups. Why? While there has been much progress in understanding these theories, we have at best only a glimpse as to the answer to this question.

[1] This statement requires some qualification; see [37].

More generally, string theory is a framework in which we might hope to address a variety of questions both in particle physics and cosmology. While it is often said to be a theory in ten dimensions, it has solutions with different numbers of dimensions, including four, and

- Standard model gauge interactions
- Repetitive generations (e.g. 3) of quarks and leptons
- Low energy supersymmetry
- Discrete symmetries (R-parity)
- Axions
- Light scalars with very flat potentials (inflatons? quintessence?)
- Exotic possibilities, such as large "compact" dimensions, with dramatic possible implications for particle physics, astrophysics and cosmology.

In the last few years, there have been a number of developments, which are usually grouped together under the heading of duality:

- What were once thought to be several independent string theories have been recognized to be states of one large theory (sometimes called M theory)[13]. Given that the difficulties of quantizing gravity seem so immense, the fact that all previously successful attempts are part of one structure suggests that, just as there is a unique theory of fundamental vector bosons interacting with matter, so there may truly be a unique theory of gravity.
- Many interesting dualities have been understood. For example, many string (and field) theories exhibit an exact electric-magnetic duality (see Jackson, chapter 6!)
- Many new theoretical tools have been developed, which have permitted the study of quantum aspects of black holes and other real phenomena of quantum gravity. For example, the Beckenstein-Hawking entropy has been understood through the counting of microscopic states[14].
- A striking new principle of quantum gravity has been discovered, known as the Holographic principle[15]: quantum theories of gravity have far fewer degrees of freedom than conventional quantum field theories, such as those of the Standard Model. The number grows like the surface area of the system rather than the volume. This is likely to

have profound consequences for the understanding of the question of the cosmological constant[16, 17, 18] and other issues in cosmology[19].

These developments have provided a number of new insights into longstanding problems. For example, we used to think that the basic scales in string theory would be of order the Planck scale. But with the new developments, we have recognized new possibilities.

- In the strong coupling limit, string theory is best described in terms of an eleven dimensional theory, with gravity propagating in all eleven dimensions, while gauge interactions are confined to ten dimensional walls[5]. There is some evidence that this limit is the best suited for describing the real world[20]. If this idea is correct, the fundamental scale of this theory, the eleven dimensional Planck mass, satisfies:

$$M_{11} \sim 10^{15}\mathrm{GeV} \tag{1}$$

  The eleventh dimension is curled up, along with the other (more conventional(!?)) six, with radii R_{11} and R given roughly by:

$$R_{11}M_{11} \sim 10-30 \qquad R^6 M_{11}^6 \sim 60 \tag{2}$$

  The values of G_N, and the unification of the gauge couplings, give support for this picture.

- Traditionally, in thinking about compactification, one imagined that any extra dimensions were extremely small, of order the Planck mass or unification scale. In recent years, it has been appreciated that extra dimensions might be far larger[3], or could be highly curved[4]. Either possibility, it has been suggested, might provide an alternative to supersymmetry as a solution to the hierarchy problem. (Prior to these developments, while large extra dimensions had occasionally been suggested, it had not been possible to make sense of them.) These new proposals involve walls or branes in a crucial way, much as in the eleven dimensional limit. The fundamental scale of physics lies at 1 TeV, or so; the smallness of Newton's constant is due to the large size of the extra dimensions, through the relation:

$$G_N = M_{fund}^8 V_{comp} \quad M_{fund} \approx \mathrm{TeV}. \tag{3}$$

The eleven dimensional picture predicts low energy supersymmetry, but also possesses scales of the sort needed to understand the features of inflation[6]. The large dimension idea predicts:

- Dramatic growth of cross sections for production of Kaluza-Klein modes (e.g. in the process $e^+ + e^- \rightarrow \gamma +$ missing energy).
- Cosmology: effects of Kaluza-Klein modes might be important just above nucleosynthesis. For example, some dimensions might be much smaller at early times.

2.2 What Makes String Theory Hard?

What makes string theory hard? Why don't we have all the answers? Part of the answer is simply that it is an ambitious theory. It's supposed to explain all the facts of the standard model, *with no parameters*. It is not reasonable to expect all of the answers to fall out so easily. But there are also some specific problems:

- While I said that there are states with desirable properties, there are in some sense too many states. For example, there are states with 11,10,9,8,...4,3 dimensions; states with or without supersymmetry; states with 1-100's of generations, and so on.
- The classical solutions possess continuous parameters. From the perspective of "low energy" physicists, these are associated with fields. These fields are called moduli. Examples include a field called the dilaton, whose expectation value determines the values of the gauge couplings;, and the radius. We will denote these by $g^{-2}(x^\mu)$ ("dilaton") and $R^2(x^\mu)$, respectively.
- Cosmology: Moduli are candidates for the inflaton, but they also lead to a set of cosmological difficulties.
- Cosmological constant (more later)

3 DARK MATTER

Particle physics has provided at least two plausible candidates for dark matter.

- The lightest supersymmetric particle (LSP): requiring that the proton lifetime be long in supersymmetric theories almost inevitably means that the LSP is stable. Supposing that supersymmetry is broken at a scale of order 1 TeV, automatically leads to a relic density for this particle of roughly the right order to be the dark matter[21].

In supersymmetric field theories, it is necessary to postulate discrete symmetries from nowhere to explain the stability of the proton; in string theory, such symmetries are ubiquitous[22]. We heard at this meeting descriptions of ongoing searches for these particles. While the hints from the DARMA experiment are controversial, the 2.6σ discrepancy in $(g-2)_\mu$ provides some cause for optimism that direct evidence for supersymmetry will soon be found[23]. Indeed, a number of physicists have argued for some time that if the supersymmetry hypothesis is correct, one is likely to see a discrepancy in $g-2$[24]. Over the next year, further data will be analyzed and the error bars will shrink significantly.

- Axions: The axion is associated with strong CP problem[25]. The axion idea predates the realization that string theory possesses axions by several years[26], but it is in string theory that the idea finds a natural home, and indeed it would inevitably would have been discovered there had it not been suggested earlier. In field theory, the Peccei-Quinn solution of the strong CP problem requires that one postulate that nature has a symmetry, which is broken only by tiny quantum effects in the strong interactions. This symmetry must hold so accurately that *extremely* tiny gravitational effects would spoil it, and it has sometimes been argued that this is implausible[27]. But in string theory, Peccei-Quinn symmetries of exactly the desired type automatically arise. Prior to the understanding of duality, the Peccei-Quinn scale in string theory was most naturally identified as M_p, so if the axions constituted the dark matter, they were undetectable. With the new understanding, many other possibilities have emerged[28].

4 The Problem of the Dark Energy

As we have heard at this meeting, the evidence for dark energy is mounting. As Professor Livio stressed in his summary, a year ago many astronomers would have doubted the existence of dark energy. Now most, if not totally convinced, are starting to believe it. As Professor Perlmutter remarked, it is particle physicists, especially theorists, who have been his biggest skeptics. As we will see, this is because the result is so surprising. But given that it now seems likely that the data – and its interpretation as dark energy – are correct, it is necessarily a profound clue to the nature of physics at some very different scale.

¿From the perspective of a particle theorist, the question is: what is the energy density of the vacuum, i.e. of the ground state of whatever is the underlying theory of nature. Obviously it is a tall order to compute this – we need to know the theory – but dimensional analysis suggests we are in trouble. Particle physicists like to describe the cosmological constant, Λ, as a quantity of dimensions of $[\text{mass}]^4$. So

$$\Lambda = M^4 \tag{4}$$

where M should be some characteristic mass scale in physics. Is $M = M_p$ (the Planck mass)? $M = M_Z$? $M = m_p$ (the proton mass)? Even in the last case, we would be off by 47 orders of magnitude! Could there be some principle which simply predicts zero? If so, what is the origin of the very tiny observed value?

In string theory, there is some good news with regards to this problem. At the classical level, all of the string vacua I have mentioned have vanishing cosmological constant. While technically easy to describe[22], this fact is in many ways mysterious. It is not a consequence of symmetries of space time. So this fact represents a striking failure of dimensional analysis, of just the sort we want!

However, even if $\Lambda = 0$ at the classical level of some theory, it is very hard to understand why quantum effects wouldn't generate a huge value for it. The quantum theories of the standard model describe approximately free fields, i.e they are collections of harmonic oscillators, one for each momentum, spin (and other quantum numbers). The ground state energy of such a theory is then, to lowest order in $\hbar$,

$$\Lambda = \sum (-1)^F \int \frac{d^3k}{(2\pi^3)} \sqrt{\vec{k}^2 + m^2}. \tag{5}$$

In general, this expression is very divergent. In our understanding of effective quantum field theories, so successful in describing the standard model, this means that Λ is just a parameter of the theory. This is why physicists (with a few exceptions) traditionally ignored this problem.

On the other hand, at some level, if this is the correct way to think about the vacuum energy, some physics must cut off this integral. What might this be? If nature were exactly supersymmetric, then the bosonic and fermionic contributions to Λ would cancel. If nature is approximately supersymmetric, the integral diverges quadratically, and assuming that physics at the Planck scale provides the cutoff,

$$\Lambda \sim M_{susy}^2 M_p^2 \approx (10^{10}\text{GeV})^4? \tag{6}$$

In string theory, there are no divergences. Since this is a theory of gravity, the calculation of the cosmological constant should be well defined. So this should be a good test of string theory. Does it pass? Is $\Lambda = 0$? 10^{-47}

Here we have the not so good news: We don't know the answer to this question. All of the string vacua we understand possess moduli at the classical level. These are the light fields with no potential which I referred to above. The expectation values of these fields determine the coupling constant of the string theory, and the masses of various states. Often we can compute a potential for these moduli, but the potential always tends to zero as the coupling tends to zero. Indeed, we have no examples where we can find a stable minimum of the potential in a completely controlled approximation, since, almost by definition, our approximations break down at such a point.

When one discusses moduli, with potentials which fall to zero at infinity, it is natural to consider quintessence. So far, I have spoken of the dark energy as a cosmological constant. As we have heard, many authors have considered the possibility that the dark energy represents some form of quintessence, which I will loosely refer to as the energy of some time-varying field. This is an interesting idea, if only as the equation of state for such a field provides a measure of the quality of future experiments to study the dark energy. It should be noted that, whatever the details of the underlying theory, the mass of the quintessence field today (the second derivative of its potential) can not be significantly smaller than the current horizon size. This is an extremely small number in particle physics units. In other words, not only must the actual value of the present energy density be extremely tiny but so must other quantities.

In string theory, however, it is hard to make sense of the quintessence idea, precisely for the reasons I gave above. The difficulty is that, in examples we can analyze, the scale of the potential is connected to the scale of supersymmetry breaking, which is much too large. So in some sense, one needs to fine tune not only the scale of the potential, but also its derivatives, with extreme precision[9]. (Since this

talk was presented, two papers have appeared noting that there are also serious conceptual issues with quintessence in string theory[29, 30].) Quintessence also does not provide a simple explanation of the "why now" puzzle: the question why the cosmological constant, now, is comparable to the energy density of dark matter. For example, in a simple model[31], this question is resolved by fine-tuning an additional parameter, at the percent or fraction of a percent level. This is not to say that observers should not focus their efforts on measuring w. At the very least, such measurements will give us further confidence that there is a large dark energy component.

Given that quintessence does not fit easily into our current understanding of string theory, let us return to the more conventional cosmological constant idea. If there are stable minima, they are in regions where we can't calculate. Do such stable states exist? Does the cosmological constant vanish, or is it very small for such states (as a consequence of some principle)? Might there be many such states so that we could implement an anthropic solution?

Here there is (reasonably) good news:

- String theory possesses features which allow us to discuss anthropic solutions of the cosmological constant of the type discussed by Vilenkin at this meeting. It has been argued that there might be a very

  dense set of vacuum states[32, 33]. There can be very flat potentials.

- String theory is *not* like field theory. There is good evidence that it does not possess nearly as many degrees of freedom as field theory. So perhaps the naive quantum estimate we described above is not correct. We might then hope that the classical cosmological constant vanishes, and that the quantum contributions are much smaller than naively expected.

It is interesting that both of theses ideas suggest that the cosmological constant is very small, but not zero.

5 The Anthropic Principle

To the "why now" question, a number of answers have been offered. Through the years, many authors have noted that an energy scale of order 1TeV is a natural scale to consider in physics, and that $G_N^2[\mathrm{TeV}]^8$ is within an order of magnitude of the observed dark energy (in the past, it was argued that it was within such a factor of the limit on the cosmological constant). This is quite impressive, until one remembers that we are indeed trying to explain a coincidence within a factor of two, and that the choice of TeV is very rough. E.g. if it happened that the correct scale was 3 TeV, we would be off by nearly 10^4!

Unfortunately, one can't help but look at the data and conclude that it is pointing us in the direction of some sort of anthropic explanation. Perhaps, if the cosmological constant were much different than observed, the conditions for life, even in its most rudimentary conceivable form, might not be satisfied? I observed at this meeting that astronomers are less afraid to contemplate such a prospect than physicists; they are aware of numerous coincidences in nature which may require such an explanation. In the company of many of my physics colleagues, mentioning the cosmological constant is viewed as barely better than advocating creationism. As Weinberg has remarked: A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you're against it, some people will think you're a little too interested.

This topic has been reviewed by Vilenkin at this meeting, and I will only add a few remarks. What I have in mind by the anthropic principle in this context is what Weinberg calls the "Weak anthropic principle." The idea is that the universe is vastly larger than what we see within our horizon. In different regions of the universe, the cosmological constant, and possibly other physical constants, take different values. Then just as people can only live on planets with water, atmospheres, etc. (or, just as fish can only live in water), galaxies/stars/planets/people can only exist in a tiny fraction of the full universe. From galaxy formation, it was originally argued that this hypothesis could not explain a cosmological constant as small as observed[10, 34]. More refined arguments give results which may be compatible with what we see[7].

As Vilenkin described, there have been a variety of proposals as to how the laws of nature might admit such variation of the parameters. One possibility is that the system has a huge (discrete) number of possible (metastable) ground states, and the distribution of the corresponding energies is nearly continuous[36, 32, 33]. This quasicontinuous distribution of states has been dubbed a "discretum"[32]. Note that the number of states must be enormous. If, for example, the typical scale of the energies is of order 1 TeV, then the number of states must be at least

of order 10^{61}. A second possibility is that the universe is permeated by an extremely light field, with Compton wavelength large compared to the present horizon. As a result this field is currently frozen, but during the inflationary era, it fluctuated over a range of values, large enough that in some regions it cancelled any preexisting cosmological constant.

One may not find this mode of explanation appealing, but in some sense it may not matter. Within string theory, one can argue that neither of these proposed explanations is very plausible. Consider, first, the possibility of a very light field, ϕ. The mass of this field has to be smaller than 10^{-50} GeV. There are mechanisms in string theory which could produce a particle this light. But these mechanisms all imply that the maximal value of the field is of order M_p. But in order to cancel off a cosmological constant of order $10^{12} GeV^4$, we need $\phi \sim 10^{40} M_p$ or so[35]!

In [36], it was argued that a peculiar type of axion, known as the "irrational axion," might give rise to a suitable discretum, but subsequent searches have failed to turn up any examples of the required phenomenon in string theory. Four form fluxes in string theory might provide the necessary "discretum" to understand the cosmological constant[32, 33]. Whether this works in detail requires resolving many difficult questions. For example, we need to understand the stability not of just one but of 10^{120} (or so)states. It also raises the specter that all quantities (the gauge coupling constants, the masses of the elementary particles....) would all be determined anthropically (or alternatively would be random numbers)[37]. It is hard to imagine that all of the standard model parameters are anthropic. Nor do they look like random numbers. So while this idea is the most difficult of the set to rule out, it does not see particularly promising.

In sum, the remarkable coincidence of the cosmological constant and the present dark matter density is very suggestive of an anthropic explanation. But an anthropic explanation, to be scientific, requires a sensible underlying theory, presumably in the context of a theory which is capable of making other predictions. So far, we don't have such a theory.

6 The Holographic Principle

't Hooft and Susskind argued, from considerations of black hole physics, that in a sensible theory of gravity, in a region of volume V and surface area A, the number of degrees of freedom must be proportional to A[15]. The most familiar piece of evidence for this is the Beckenstein-Hawking entropy formula:

$$S = \frac{G_N A}{4}. \tag{7}$$

Other features of black hole physics also support this. The fact that in some sense the information about what is going on in a large volume is encoded in degrees of freedom residing on the surface is the origin of the term holographic.

There is some evidence that string theory is holographic:

- Naive notions about numbers of degrees of freedom are not correct in string theory. For example, string ground states in smaller dimensions of space time have more degrees of freedom (suggesting that compactified theories are more "fundamental" than uncompactified ones).
- String perturbation theory has holographic features: the S matrix seems to be the crucial observable; C. Thorn argued long ago that the perturbation theory itself has one the

degrees of freedom of a theory in $d-1$ dimensions.

- Two non-perturbative formulations of string theory are known (the "Matrix Model" and the AdS-CFT correspondence). Both are explicitly holographic.

What might be the implications of this principle for the Cosmological Constant? These are not clear, but they seem likely to be dramatic, since in the cosmological constant expression, eqn. 5, one might

no longer have $V \int d^3k$, but instead a sum over far fewer degrees of freedom. Are there few enough? The problem is not sufficiently well understood to say at the present time[17].

This sort of reasoning has lead to even more radical conjectures. In string theory, there seem to be states with varying numbers of dimensions, and varying amounts of supersymmetry. Many states with unbroken supersymmetry can be argued to be exact solutions of the theory. Susskind has suggested that perhaps De Sitter space is not allowed in string theory. He offers no solid argument, but points to hints based on holography. Banks proposes that we think very differently about the question of supersymmetry breaking[16]. He argues that the number of states in De Sitter space is finite. Given that recent observations suggest that our universe is De Sitter. What determines the number of states? Banks proposes that this number is a *parameter*. The cosmological constant and the amount of supersymmetry breaking are determined by this parameter! This proposal explains why states with too much supersymmetry might not be viable (and it is the only proposal which does so). It requires that in holographic theories a different relation between Λ and the scale of supersymmetry breaking holds. There is some reason to believe this might be the case. It requires, however, a very surprising relation to hold between the cosmological constant and the scale of supersymmetry breaking.

Both ideas are highly speculative, and they are not (yet) supported by a substantial amount of evidence. But they are suggestive. Indeed, if nothing else, they indicate the sorts of radical rethinking of many of our basic ideas in physics which may be required to understand the dark energy.

7 Conclusions

Particle physicists are eager to know the answers to the questions:

- What is the dark matter?

- Is there really dark energy? What is its equation of state?

My experimental colleagues are very interested in dark matter searches, SNAP and ground based proposals to study Type Ia Supernovae. Theorists are hopeful that they have predicted the correct form of the dark matter; they are frantically trying to explain the dark energy. Both are sure to lead to important insights into fundamental law.

7.1 Acknowledgments

I would like to thank many of my colleagues for discussions, and for educating me about the issues raised here, especially Tom Banks, Nathan Seiberg and Leonard Susskind. I would like

to thank the organizers and participants in this conference for a very stimulating experience, and particularly to thank Mario Livio. This work was supported in part by the U.S. Department of energy.

References

[1] A.G. Cohen, D.B. Kaplan and A.E. Nelson, "Progress in Electroweak Baryogenesis," Ann.Rev.Nucl.Part.Sci. **43** (1993) 27, hep-ph/9302210

[2] Some precursors of these ideas can be found in V.A. Rubakov and M.E. Shaposhnikov, "Do We Live Inside A Domain Wall?," Phys. Lett. **125B**, 136 (1983); G. Dvali and M. Shifman, "Dynamical compactification as a mechanism of spontaneous supersymmetry breaking," Nucl. Phys. **B504**, 127 (1997), hep-th/9611213; G. Dvali and M. Shifman, "Domain walls in strongly coupled theories," Phys. Lett. **B396**, 64 (1997); (E)**B407**, 452,1997, hep-th/9612128.

[3] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, "The Hierarchy Problem and New Dimensions at a Millimeter," Phys. Rev. Lett. **B429** (1998) 263, hep-ph/9803315; . Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, "New dimensions at a millimeter to a Fermi and superstrings at a TeV," Phys. Lett. **B436**, 257 (1998) hep-ph/9804398. Some precursors of these ideas can be found in [2].

[4] L. Randall and R. Sundrum, "A Large Mass Hierarchy From a Small Extra Dimension," hep-ph/9905221; L. Randall and R. Sundrum, "An Alternative to Compactification," hep-th/9906064.

[5] P. Horava and E. Witten, "Eleven-Dimensional Supergravity on a Manifold With Boundary," Nucl.Phys. **B475** (1996) 94, hep-th/9603142; "Heterotic and Type I String Dynamics from Eleven-Dimensions," Nucl.Phys. **B460** (1996) 506, hep-th/9510209.

[6] T. Banks, "Remarks on M Theoretic Cosmology," hep-th/9906126.

[7] A. Vilenkin, these proceedings.

[8] P.J.E. Peebles and B. Ratra, Astrophysics J. **325** L17 (1988), and Phys. Rev. **D37** (3406) (1988); C. Wetterich, Nucl. Phys. **B302** (1988) 668.

[9] K. Choi, String or M Theory Axion as a Quintessence," Phys.Rev. **D62** (2000) 043509, hep-ph/9902292.

[10] S. Weinberg, Phys. Rev. Lett. **59** (1987) 2607.

[11] S. Weinberg, Rev.Mod.Phys. **61** (1989) 1.

[12] A. Vilenkin, Phys. Rev. Lett. **74** (1995) 846.

[13] E. Witten, "String Theory Dynamics in Various Dimensions," Nucl. Phys. **B443** (1995) 85, hep-th/9503124.

[14] A. Strominger and C. Vafa, "Microscopic Origin of the Beckenstein-Hawking Engropy," Phys.Lett. **B379** (1996) 99, hep-th/9601029.

[15] For a review, see D. Bigatti and L. Susskind, "TASI Lectures on the Holographic Principle," hep-th/0002044.

[16] T. Banks, "Cosmological breaking of Supersymmetry, or Little Lambda Goes Back to the Future II," hep-th/0007146.

[17] A.G. Cohen, D.B. Kaplan and A.E. Nelson, "Effective Field Theory, Black Holes and the Cosmological Constant," Phys.Rev.Lett. **82** (1999) 4971, hep-th/9803132.

[18] S. Thomas, "Holographic Vacuum Energy," hep-th/0010145.

[19] T. Banks and W. Fischler, to appear.

[20] E. Witten, "Strong Coupling Expansion of Calabi-Yau Compactification," Nucl.Phys. **B471** (1996) 135, hep-th/9602070

[21] The proceedings of this conference feature up to date reviews of both theoretical and experimental issues of dark matter and its detection.

[22] M. Green, J. Schwarz and E. Witten, "Superstring Theory," Cambridge University Press (1986) Cambridge.

[23] H.N. Brown et. al., "Precise Measurement of the Postive Muon Anomalous Magnetic Moment," Phys.Rev.Lett. **86** (2001) 2227, hep-ex/0102017.

[24] A. Czarnecki and W.J. Marciano, "The Muon Anomalous Magnetic Moment: A Harbinger for New Physics," Phys. REv. **D64** (2001) 013014, hep-ph/0102122.

[25] There are many reviews on the subject of axions. See, for example, M. S. Turner, Phys. Rept. **197** (1990) 67.

[26] E. Witten, "The Cosmological Constant from the Viewpoint of String Theory," hep-ph/0002297.

[27] M. Kamionkowski and J. March-Russell, "Planck Scale Physics and the Peccei-Quinn Mechanism," Phys.Lett. **B282** (1992) 137, hep-th/9202003

[28] T. Banks and M. Dine, "The Cosmology of String Theoretic Axions," Nucl.Phys.B505:445-460,1997 hep-th/9608197

[29] W. Fischler, A. Kashani-Poor, R. McNees and S. Paban, "The Acceleration of the Universe, A Challenge for String Theory," hep-th/0104181.

[30] S. Hellerman, N. Kalper and L. Susskind, "String Theory and Quintessence," hep-th/0104180.

[31] C. Skordis and A. Albrecht, "Planck Scale Quintessence and the Physics of Structure Formation," astro-ph/0012195.

[32] R. Bousso and J. Polchinski, "Quantization of Four Form Fluxes and Dynamical Neutralization of the Cosmological Constant," JHEP **0006** (2000), hep-th/0004134

[33] J.L. Feng, J. March-Russell, S. Sethi and F. Wilczek, Nucl.Phys. **B602** (2001) 307, hep-th/0005276.

[34] T. Banks, unpublished.

[35] T. Banks and M. Dine, "Dark Energy in Perturbative String Cosmology," hep-th/0106276.

[36] T. Banks, M. Dine and N. Seiberg, "Irrational Axions as a Solution of the Strong CP Problem in an Eternal Universe," Phys.Lett. **B273** (1991) 105, hep-th/9109040.

[37] T. Banks, M. Dine and L. Motl, "On Anthropic Solutions of the Cosmological Constant Problem," JHEP **0101** (2001) 031, hep-th/0007206.