

FINALLY IT IS POSSIBLE TO UNDERSTAND OUR UNIVERSE AND ITS IMPLICATIONS

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Abstract : It is proposed that existing theoretical frameworks, and existing and forthcoming data, arguably finally allow us to achieve a testable, final understanding of the string vacuum we live in, and its relation to ultimate questions.

Introduction

Today is possibly the most exciting time in physics, and in our quest to understand the underlying laws of nature that explain our physical world, in nearly a century. Arguably it is now finally possible to achieve a complete understanding of our universe and its underlying laws of nature within the next few years! In this essay I propose that such an understanding is not only possible, but realistically so, and soon.

To achieve an understanding of the laws that govern the physical universe there are several requirements. First, we must know the rules by which to calculate everything. These have actually been in place since about 1930 when Dirac and colleagues wrote down relativistic quantum field theories. Since then our understanding of relativistic quantum field theories has greatly improved, but the basic theory is unchanged, and there is no reason to think they are not the final rules. Second, one must know the particles (including dark matter ones) that make up everything we see and on which the forces act to give everything in our universe. The development of the Standard Model of particle physics has essentially told us that the basic particles that make up what we actually see are the quarks and leptons, and the forces are the familiar electroweak and strong forces, and gravity. Finally, some statements about initial conditions may be needed.

One can argue compellingly that the quarks and leptons are the ultimate constituents. For the quarks and leptons the first argument is the experimental one that probes for structure or excited states have reached nearly a million times the mass scales of the particles and no effects are observed. But such experimental arguments could turn out to fail as soon as the probe energies are increased. Two much stronger arguments combining experiment and theory exist. First, the Standard Model theory is a full relativistic quantum field theory that can be valid to the Planck scale, so the description of the quarks

and leptons can remain valid. Historically that was not the case, with descriptions of atoms and nuclei and protons relying on effective theories of limited validity. Second, in the supersymmetric extension of the Standard Model the extrapolations of the force strengths become equal at a unification scale somewhat below the Planck scale, thus allowing the forces to be interpreted as unified in a way that could emerge from an underlying theory. If the quarks and leptons were composite, for example, such unification and interpretation would be lost. Electrons may be viewed in string theory as strings of energy rather than as points in quantum field theory, but they are still electrons, and still elementary. Similarly, there is no evidence for forces in addition to the weak, strong, electromagnetic, and gravitational ones, and no theoretical need for them.

To illustrate, Newton's familiar 2nd law, $F=ma$, is a rule (like relativistic quantum field theory). By itself it is empty, until one specifies a force and the object (particle) on which the force acts. All three are necessary. To have a complete explanation of some motion the initial conditions are also needed. The situation is no different for ultimate explanations. With the successful confirmation of the Standard Model of particle physics for the particles and gauge forces, we have in place the ingredients to build on in order to understand the universe. We will address the dark matter below.

To avoid misunderstandings, it is essential to emphasize that this is an essay on what is ultimately *possible* in physics. I will describe in the following why we may be able to soon know the rules and the particles and the forces and additional features that leave no significant gaps in our understanding of the universe and its content, and (to move ahead of myself) the string vacuum we live in. This requires progress in both experimental information, and theory, which I will describe. Of course on this short time scale there may not be wide agreement that this goal has been achieved, but I will maintain that arguably it is indeed *realistically possible*.

The Theoretical Side

Before the advent of string theory, in the 1980s, achieving these goals would have not been possible. What is exciting about string theory is that it addresses in one consistent framework *all* the questions we want to address about understanding our universe. Of course at present not all of the questions are addressed in a particular string theory, let alone answered, but all of them are *addressed* in some string theory. A string theory is like a framework, or a Lagrangian, or a Hamiltonian in quantum theory. For an atom, there is a Hamiltonian, but the atom is normally in its ground state, so finding the ground state is crucial to testing the theory, and to understanding the behavior of the atom. Similarly we live in the vacuum of the string theory, the ground state, so the crucial thing is to identify our string vacuum.

This has increasingly been recognized by string theorists. Most string theorists still study string theories for their own sake, which is a necessary thing to do to improve our understanding. But many have been also or increasingly working on understanding the ground state. There have been seven international "string phenomenology" conferences that mainly focus on understanding the ground state, and recently in the U.S. the NSF has funded a network of top universities who participate in the "String Vacuum Project". A similar network was funded in Europe.

From a general string theory one constructs the vacuum by “compactifying” to four dimensions, breaking supersymmetry, and stabilizing “moduli”. The moduli are a number of scalar fields that do not have definite values or masses for their quanta in the string theory, but are stabilized at definite values in the vacuum. This in turn means that masses and coupling strengths take on definite values, and many testable predictions are possible.

This situation has led to much confusion about testing string theories and whether they are testable – they are. The situation is basically analogous to testing $F=ma$. Is $F=ma$ testable? Not as a general equation! One has to put in a definite force and mass and calculate the acceleration and measure it. Similarly one does not abstractly test the Schrodinger equation. One takes a definite Hamiltonian, and calculates predictions to test. In string theory one takes a definite theory and goes to the vacuum state, by compactifying and breaking supersymmetry and stabilizing moduli, and the tests involve all of these. Eventually it is likely that for a given string theory the compactification and the supersymmetry breaking and the stabilization of moduli are implied by the theory, but today we can proceed (in a “bottom-up” way) by trying different ways of compactifying, of breaking supersymmetry, etc. In this sense string theory is as testable as $F=ma$, the Schrodinger equation, etc.

Quantum theory, and relativistic quantum field theory, are testable in another way too. For example, one can test the superposition principle, or the spin and statistics connection, or the identity of all electrons, and these do not require being in the vacuum state or solving the equation of motion. We do not know yet if string theory has such tests, but it is reasonable to expect that once we understand our string vacuum we will be able to figure that out. This is not an idle statement such as “well, maybe we can do it”. If we have figured out what the string vacuum state is, and how moduli are stabilized, and made a number of testable predictions, then we should be able to learn if there are more general tests.

What do we want to understand about *our* string vacuum? We don’t need to calculate every mass, every parameter. A list many people would agree on includes: what corner of string theory are we in, what is(are) the inflaton(s), how is supersymmetry broken, how are moduli stabilized, how does the matter asymmetry originate, what is the dark matter, how is the electroweak symmetry broken, what is the origin of the fermion masses and their hierarchy, what is the origin of all CP violations, how is the strong CP problem solved, how are the forces unified, is the proton stable. The exciting thing that may allow us to be on the verge of great progress is that string theories address all these issues. Today people can construct single string models in which many of these can be addressed. I will briefly describe one example below. Constructing such string models was not possible even a decade or less ago.

Even if someone had guessed the correct underlying theory for our string vacuum, and even if we could work out one consistent construction that answered most or all of the questions we want to address in order to say we have understood our string vacuum, that construction would have to be tested. In addition, most people would not accept such an answer until more compelling experimental evidence for it existed. So let us turn to the experimental reasons why much more is testable today or soon than even recently.

The Crucial Data

After the Standard Model got established, and the W and Z bosons confirmed, in the mid 1980s, people's attention and resources turned to getting data on physics beyond the Standard Model. The SSC saga began in 1982, and ended in 1993. The only information it produced was insight into how modern societies viewed research on foundational questions, and the limits of the commitments to doing such research. The CERN collider LEP strongly tested the Standard Model, and taught us three major results about physics beyond the Standard Model. The first was that with precise values of the force strengths measured at LEP, and then extrapolated to high energies with standard relativistic quantum field theory, in a theory with superpartners for the Standard Model particles the coupling strengths of the forces became essentially equal at a high "unification" scale. Second, no observable differed significantly from its Standard Model prediction, as would be expected in any weakly coupled theory where the new particles only appeared in loops. Third, all the parameters of the Standard Model have been measured except the Higgs boson mass, so one can do a global one parameter fit of the LEP data to M_h , and one finds that the allowed Higgs boson mass is less than about twice the Z boson mass, as predicted in a general supersymmetric theory.

All these clues point to a supersymmetric extension of the Standard Model. In addition the Supersymmetric Standard Model provides a dark matter candidate and a framework in which the Higgs mechanism can be derived, generic ways to explain the matter asymmetry, and additional motivations. If the Supersymmetric Standard Model were an unbroken symmetry it would introduce no new parameters, and all predictions would be fully calculable. Of course very light superpartners have not been observed so the symmetry must be a broken one, which is common in nature. Understanding the way supersymmetry is broken will be a crucial issue for pointing toward the ultimate theory. That is likely to be the main contribution of the CERN Large Hadron Collider (LHC) which should start taking data in 2010 or perhaps somewhat earlier. In a theory with unbroken supersymmetry the electroweak symmetry is also unbroken, so quarks and gauge bosons do not get mass either. Understanding supersymmetry breaking is essential on the one hand for understanding the Higgs mechanism and the origins of quark and gauge boson masses, and on the other hand for understanding how our string theory vacuum arises, including how the moduli (and thus the force strengths and values of masses) are fixed at their values in the ground state of the theory. With the data from LHC these issues may fall into place, and in turn point to how they occur in the ultimate theory.

Supersymmetry may have already been discovered, by the PAMELA satellite experiment, which has reported an excess of positrons [1]. What they see is basically what would be seen if the superpartner of the W boson were the stable lightest superpartner (some people have argued that the observed antiproton flux is inconsistent with this interpretation, but this is now known to be an artifact of how they defined the antiproton background). This "wino" would then be the dark matter of the universe, and account for the observed relic density, about a quarter of the mass energy of the universe. The positrons arise from the occasional annihilation of dark matter particles throughout the galaxy. Thus today it is a defensible point of view that the lightest superpartner has been discovered, and also the dark matter.

Of course this must be confirmed and tested further. There are several ways that can occur. The first two are based on additional satellite experiments. The detector AMS-02, constructed by a group led by the Nobel Prize winner Samuel Ting, is expected to be installed on the space station by April 2010. It should have the capability to soon confirm the PAMELA data, and to extend it and test the supersymmetry and dark matter interpretations in several ways. Second, the Fermi satellite is taking data now that can test the supersymmetry and dark matter interpretations several ways, and particularly in an elegant way, using dwarf galaxies. These are small “galaxies” spread throughout our galaxy halo. Each might contain tens of visible stars, bound together (as is established from the motion of those few visible stars) by of order 10^7 solar mass equivalent mass of dark matter. Thus they are nearly pure sources of dark matter annihilation, background free! They have diameters of order a few hundred pc, at distances from 25 to several hundred kpc (we are 8 kpc from the galactic center), so they are basically point sources spread throughout the halo, perhaps a hundred or more of them. Gammas from them due to dark matter annihilation can be seen by Fermi, perhaps quite soon. In some cases there are also fairly intense isolated lines expected, as when two winos annihilate into $\gamma\gamma$ or γZ via a box diagram.

Third, many experiments have now begun to operate in data modes, after years of development, that will detect the scattering of a dark matter particle off quarks in nuclei in the laboratory (“direct” detection). The rates and recoil spectra depend on the composition of the dark matter particle and on the nuclei, so once these processes begin to be seen much can be learned from them to test the consistency of an emerging picture by varying the nuclei.

The LHC should also provide tests that the same dark matter candidate is being observed in the satellite experiments and at the collider. Pairs of the lightest superpartner will be present in every event at the LHC where superpartners are produced. Many characteristics of the events depend on the properties of the lightest superpartner, such as whether it is largely the W-boson partner, the photon partner, etc. Similarly, the same properties strongly affect its annihilation cross section in the galaxy, its branching ratio to positrons or gammas, etc. It will be essential to demonstrate that the same dark matter particle is being observed in all these ways, and the methods are known to study and check that.

All of this data is only available very recently, or soon. Without it we could not be confident that we were identifying and attaining a detailed description of our string vacuum. With it, we may be.

The dark matter data and the string theory connections also combine to imply a definite cosmological history [2]. The PAMELA satellite data suggest that the dark matter is dominantly composed of a wino lightest superpartner. This has a large annihilation cross section, and gives about the right relic density if the cosmological history is basically that of a generic string theory, with moduli dominating the energy density of the universe just after the end of inflation. The moduli decay into superpartners typically about a quarter of the time, and generate a large number of lightest superpartners. At the same time they generate lots of entropy that dilutes the relic density, and the resulting number is about right. The cosmological history is not in thermal equilibrium until nucleosynthesis. Dark matter candidates different from the wino have much smaller annihilation rates, and leave a much larger relic density,

overclosing the universe. The wino lightest superpartner suggested by the PAMELA data, the generic moduli of string theories, and a non-thermal cosmological history make a beautifully consistent picture, our wino string vacuum.

Some colleagues and I have been able to construct a string vacuum theory that does all the physics I have described here, and much more, simultaneously [3]. For our purposes here this demonstrates that the picture I am describing can today be realized in a concrete consistent testable model. We compactify 11 dimensional M-theory on a 7-dimensional manifold with G_2 holonomy, breaking supersymmetry generically in a hidden sector, stabilizing in a de Sitter vacuum all the moduli that appear in the gauge kinetic function, which include all those relevant for describing the ground state, generate a TeV scale without assuming it, find a wino lightest superpartner that is a very good dark matter candidate and can describe the PAMELA data, and is consistent with all existing data. More work is needed to fully embed the Standard Model matter rigorously, but a reasonable embedding of the Standard Model particles and their superpartners exists, including hierarchical masses and neutrino masses. In addition we have recently shown [4] that all the CP violating phases of the theory are contained in the Yukawa couplings (the soft-breaking terms are real), suggesting that the origin and implications of all CP violation can be understood in this theory. It allows baryogenesis to occur, possibly by large production of a baryon asymmetry as the moduli oscillate, with the needed amount remaining even after entropy production from the moduli decays. We are producing a full set of LHC tests that are feasible with the kinds of LHC data one can get in a year or two.

Perhaps other string constructions are on the verge of similar breadth and depth. The data will focus our attention on a class of them. Of course it could be that none would work, and we cannot prove yet that one will, but our goal here is to argue that it is possible one will, and the remarkable successes so far certainly allow us to defend that view. It is reasonable to be optimistic that within a few years we will have a consensus on a description of our string vacuum that is comparable to the consensus on the Standard Model before LEP.

What other issues are important for our ultimate understanding? There are several promising approaches to the strong CP problem in string constructions. Relevant axions exist for the axion solutions. Further study is needed in this area, and is underway. We need to be sure that our picture of the end of inflation is well tested. Fortunately considerable data will come soon in this area, from the Planck satellite and from several balloon experiments. Questions have been raised about the initial entropy of the universe and it will be important to check that is understood as this picture falls into place.

What about the cosmological constant problems? There are at least two – why is the naïve large quantum fluctuation estimate that is many orders of magnitude too large absent, and what accounts for the actual amount of dark energy we see today? From the viewpoint of understanding our string vacuum these are actually unlikely to be important issues. Most approaches to understanding them have little impact on understanding dark matter, the matter asymmetry, supersymmetry and supersymmetry breaking, electroweak symmetry breaking, fermion masses, CP violation, and so on.

Once we do understand our string vacuum and have a stringy quantitative description we will understand better whether there are enough populated string vacua for the anthropic approach to make sense, and whether each string vacuum can have its scalar potential tuned to give a small value at its minimum. The equation of state will be measured very precisely in the coming years, and will focus attention on the right class of solutions. For example, if the anthropic solution is correct it tells us very important physics about the multiverse but not about any aspect of our universe itself.

As understanding of string theory and of our string vacuum, and the inflation era, grow in the coming years we will have a much stronger foundation to discuss multiverse issues and the inevitability of the laws of nature. While we cannot yet be sure, it is certainly defensible that we already have the concepts and approaches and data in hand to address these questions scientifically. If the picture I am advocating is indeed basically correct, the pieces will fall into place without a need for superlarge facilities beyond those already under development and basically funded. It is not that there are no phenomena at higher than TeV scales, but that everything (neutrino mass scales, additional matter, etc) is so connected by having a theory that we can fill in the picture without Planck scale collisions. That is fortunate, because society is increasingly reluctant to fund facilities costing visible amounts of money, in spite of the obvious technological benefits that have and will emerge from carrying out such frontier research.

Could there be any limits to what we can understand? Before the mid-1980s we simply did not have the theoretical ideas and apparatus to address all the essential questions. Only now has the essential data begun to come, and it will take a few more years (assuming all goes well with the facilities) to finally have the data. There are no limits of the logical sort, such as Godel's incompleteness theorem. The physical universe is consistent. Physics does not prove its results as theorems, it tests them against the real world. One does not have to have an accelerator with Planck energies to test Planck scale physics, just as one did not have to directly observe the big bang to test its occurrence – there are always relics.

There is a useful way to describe scientific theories that may help make clear what I am arguing. We frequently speak of scientific theories as effective theories. For example, the Standard Model of particle physics is an effective theory of the particles and forces. One has to input certain parameters, in this case the masses of the quarks and leptons, and the symmetries, and the Higgs sector. Then one can calculate many results. The proton is then explained by the Standard Model in that it is an inevitable outcome and its properties are correctly predicted. In atomic physics one inputs the existence of protons and nuclei and electrons, and their masses and spins, and the electromagnetic force, and then one can calculate a great deal. I argue that we soon may have what is needed to explain our universe with no inputs, and test the resulting theory with the needed data, giving a theory that is no longer an effective theory, our wino string vacuum.

The effective theory way of thinking suggests another insight. The effective theories are relativistic quantum field theories, formulated in three space dimensions. Theories that can lead us to deeper understandings, such as string theories (which address determining the input parameters) are formulated with more space dimensions. It may be that the most important thing we have learned

recently is that underlying theories that can lead to a final understanding of our universe must be formulated in more than three space dimensions. String theories, with nine or ten space dimensions, are known to be able to determine what the fundamental particles and their quantum numbers are, and what fundamental forces emerge and how they are related to gravity. If indeed we can achieve the hoped-for ultimate understanding of the universe we argue for here, it may also teach us that we live in more than three space dimensions.

It will be incredibly exciting if humans can achieve a final understanding of our physical universe and its implications.

References

1. The arguments, and citations to the new data, are given in G. Kane, R. Lu, and S. Watson, PAMELA Satellite Data as a Signal of Non-Thermal Wino LSP Dark Matter, arXiv:0906.4765, to appear in Physics Letters B.
2. B. Acharya, P. Kumar, G. Kane, and S. Watson, A Non-Thermal WIMP Miracle, arXiv:0908.2430, to appear in Physical Review D.
3. B. Acharya, K. Bobkov, G. Kane, P. Kumar, and J. Shao, Explaining the Electroweak Scale and Stabilizing Moduli in M Theory, hep-th/0701034, Phys. Rev.D76:126010,2007; The G(2)-MSSM: An M Theory motivated model of Particle Physics, arXiv:0801.0478, Phys. Rev.D78:065038,2008; Non-thermal Dark Matter and the Moduli Problem in String Frameworks, arXiv:0804.0863, JHEP 0806:064,2008.
4. G. Kane, P. Kumar, and J. Shao, CP-violating Phases in M Theory and Implications for EDMs, arXiv:0905.2986, submitted for publication.