feature article

String theory and the real world

Gordon Kane

Although string theory is formulated in 10 or 11 dimensions, specific string theory solutions make unambiguous, testable predictions about our four-dimensional universe.

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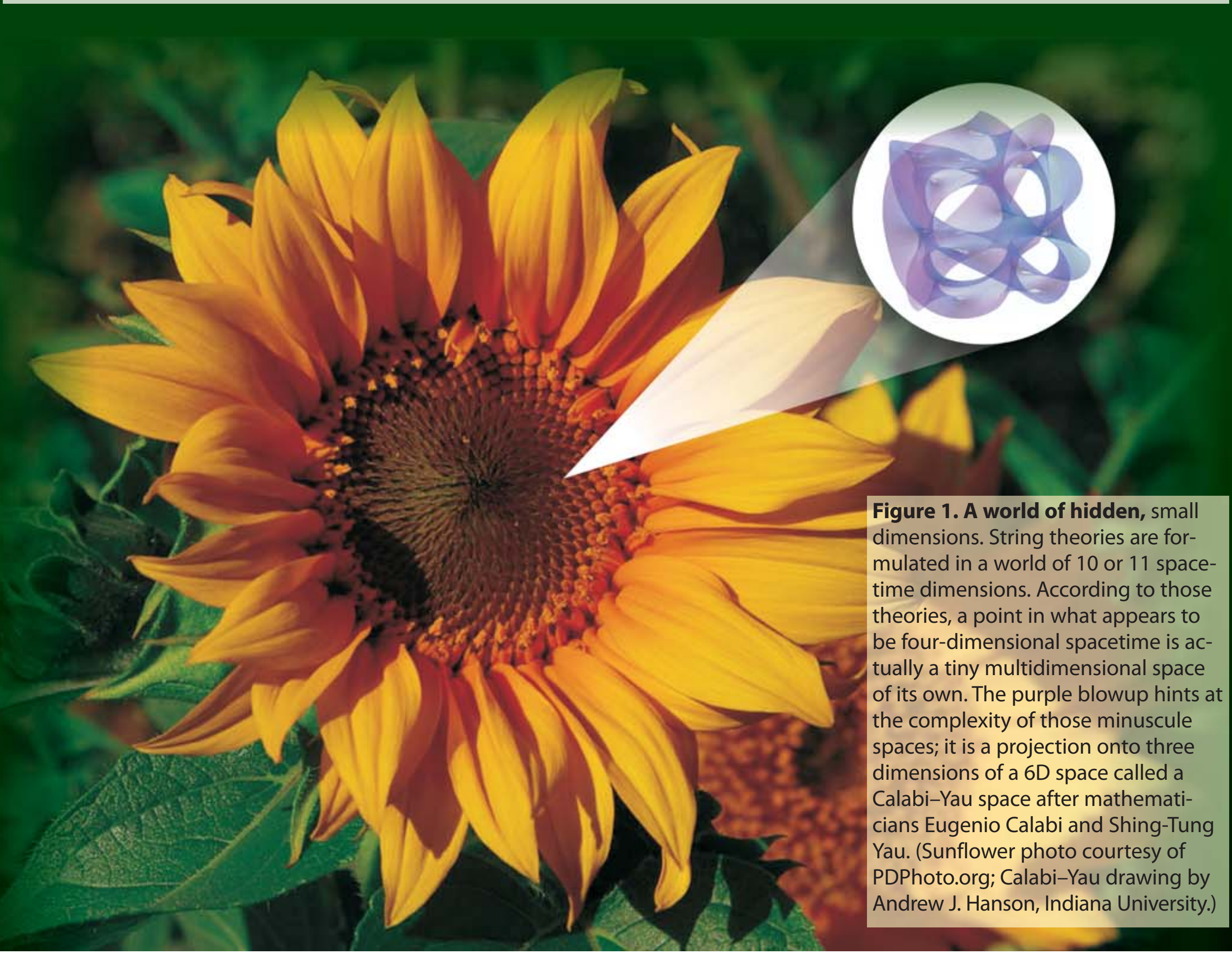

Figure 1. A world of hidden, small dimensions. String theories are formulated in a world of 10 or 11 spacetime dimensions. According to those theories, a point in what appears to be four-dimensional spacetime is actually a tiny multidimensional space of its own. The purple blowup hints at the complexity of those minuscule spaces; it is a projection onto three dimensions of a 6D space called a Calabi–Yau space after mathematicians Eugenio Calabi and Shing-Tung Yau. (Sunflower photo courtesy of PDPhoto.org; Calabi–Yau drawing by Andrew J. Hanson, Indiana University.)

We live in exciting times for particle physics. The Large Hadron Collider (LHC) at CERN has begun to collect data, and laboratory and satellite experiments are investigating the dark matter of the universe. Another, less appreciated fact increases the excitement. Physicists now have a coherent, consistent theoretical framework to address basic questions about particles, the interactions and forces between them, why they are what they are, and how numerous phenomena are related in a broader picture. That framework is "string theory." I put the term in scare quotes because there is not yet a final formulation of the theory. But the lack of a finished picture is not important for my purposes, so in this article I refer to the framework as string theory or M-theory. The perspective that string theory is the underlying framework to address many issues facing particle physics and cosmology is different from the more standard description of it as a

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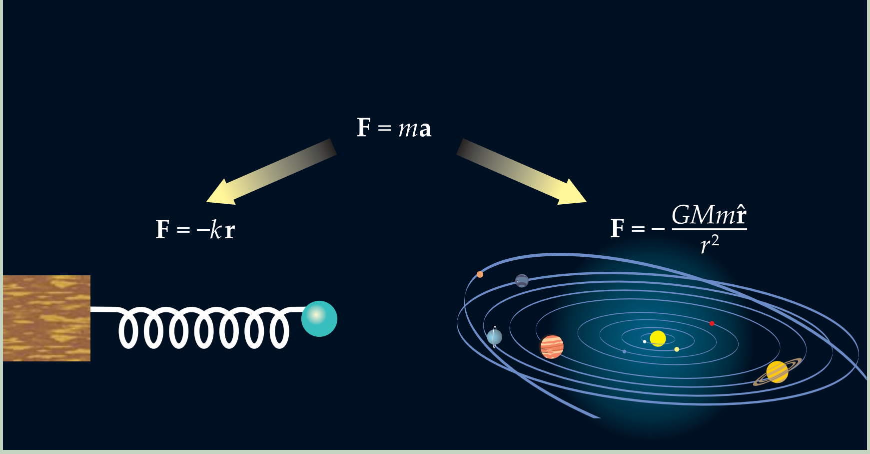

Figure 2. Testing a theory. What does it mean to test Newton's second law $\mathbf{F} = m\mathbf{a}$? Newton's law is a claim—that could have been wrong—about the actual relation between the force $\mathbf{F}$ on a particle with mass m and its acceleration $\mathbf{a}$. One tests it by calculating the acceleration with a presumed force and comparing it to the measured value. The test will fail if either Newton's law or the presumed force is wrong. Could $\mathbf{F} = m\mathbf{a}$ be tested more generally, without recourse to positing forces and looking at actual solutions? It seems not. The situation is similar with string theory. Properties of the real world test the overall string framework and, at the same time, "compactifications" analogous to the forces of Newtonian mechanics or the Hamiltonian of quantum mechanics.

consistent quantum theory of gravity. But it is a fruitful way to think about what string theory means.

String theory's long reach

I make a distinction between a theory's "explaining" something and the weaker claim of its "addressing" an issue. String theory and the standard model of particle physics both explain some facts, but string theory addresses much more than the standard model does. To understand the distinction, consider the proton. Quantum chromodynamics, a part of the standard model, is a theory of the strong interactions in which quarks interact via a force mediated by gluons. The QCD Lagrangian does not contain the proton explicitly. However, study of the QCD force reveals that bound states of quarks form. In particular, QCD requires the existence of a state that has all the properties—electric charge, spin, and so forth—of a proton. Moreover, physicists have used lattice gauge theory to calculate the mass of the proton to about 3% accuracy. So QCD explains the proton: If it had not been known, QCD would have predicted its existence and properties.

On the other hand, supersymmetric extensions of the standard model address but do not explain the dark matter of the universe. Supersymmetry is a hypothetical symmetry of nature in which the Lagrangian is symmetric under interchange of bosons (integer-spin particles) and fermions (with half-integer spin). Considerable indirect evidence suggests that supersymmetry is a symmetry of nature at the TeV energy scale. But it can't be exact at low energy because if it were, physicists would have seen a boson with the mass and charge of the electron. Thus supersymmetry is posited to be a broken symmetry with superpartners having masses different from those of the known particles. If that picture is correct, it is likely that some of the superpartners of the known particles will be observed at the LHC. The lightest of the superpartners is typically stable against decay into standard-model particles, and calculations confirm that it can have the right properties to be the dark matter of the universe. Thus the supersymmetric standard model addresses the problem of dark matter: If physicists did not know about dark matter, the model would suggest it and indicate how to look for it.

It is in the dark-matter sense that string theory provides a framework to address and relate many open questions in particle physics. We know that particles divide into three families exemplified by the electron, muon, and tau, but if we didn't know it, string theory would suggest that families exist and why. If we did not know about forces such as the strong and electroweak forces of the standard model, or the parity violation of the weak interactions, or supersymmetry, or inflation, or gravity, string theory would suggest them. Compelling answers to many of the key questions in particle physics have not yet been found, but we can now search for them systematically.

What is tested by a test?

Based on the presentation of string theory in some popular books, articles, and blogs, one might well be suspicious of taking purported string theory explanations seriously. Such sources often claim that string theory is not testable, and I agree that untestable explanations are not helpful. But I would also argue that string theory is testable in basically the same ways that other theories are and that string theory is ordinary science in terms of describing nature and testing its explanations. Almost 14 years ago I wrote an optimistic article in PHYSICS TODAY about testing string theory (February 1997, page 40). Since then, we have learned much about the subject, though much that is confusing or misleading has also been written.

To be sure, the majority of research into string theory is not focused on how the theory connects to the real world; rather, most physicists are exploring questions at a more theoretical level. Such formal work is necessary, because as noted above, we need a deeper understanding to fully formulate the theory. Even the many theorists who are interested in how string theory connects to the real world don't typically think much about what it means to test the theory. Fortunately, an increasingly active group of "string phenomenologists" are focusing on formulating a string-based description of the world and testing that understanding. They are already making testable predictions, and will increasingly do so.

String theory is formulated in 10 or 11 spacetime dimensions. The differences between the two versions are technical and have little effect on the questions discussed in this article. In the 10D case, the dimensions must be separated into the four spacetime dimensions that form the world of everyday experience and six small dimensions that typically form what is called a Calabi–Yau manifold, a space with well-studied mathematical properties (see figure 1). Those properties determine, in part, the physics that emerges from string theory, in particular the particle content and forces. The jargon for that separation of dimensions into large and small ones is compactification, an unfortunate word choice. In the 11D case, M-theory, the 7D space that remains small, called a G_2

manifold, has somewhat different mathematical properties from the Calabi–Yau space.

String theorists have found and studied a number of well-defined mathematical and physical steps to implement compactification and have developed well-known procedures for calculating many predictions of a compactified string theory. Because of the ways in which different phenomena are related to one another, tests of a compactified string theory can also reveal whether the underlying string theory is 10- or 11-dimensional.

The natural scales for the multidimensional world of string theory are quite unlike those that are useful in normal life. The natural length scale is the Planck scale, about 10^{-35} m, the length that one can form from Newton's gravitational constant, the speed of light, and Planck's constant. The associated time and energy scales are about 10^{-43} s and 10^{18} GeV, respectively. String theories can be formulated at lower energy scales—for example, the 10 000-GeV scale probed directly by the LHC—and physicists have studied testing string theories at those scales. I will not consider that possibility here, but rather will focus on the harder-to-test theories formulated near the Planck scale.

Some books and popular articles have claimed that because string theories are naturally formulated at such high energies or small distances, they cannot be tested. Obviously, collisions will never probe energy scales of 10^{18} GeV, some 14 orders of magnitude larger than that of the LHC. But equally obviously, one does not have to be somewhere to test what's going on there. Physicists have no doubt that a hot Big Bang occurred even though no one was there to witness it: We are convinced by the extensive evidence from relics such as the expanding universe, helium and other light-element abundances, and the cosmic microwave background radiation. You do not have to travel at the speed of light to test that it is the limiting speed. You do not have to have been present 65 million years ago to test that a major cause of dinosaur extinction was an asteroid impact.

To understand what it means to test string theories, it is crucial to recognize that a compactified string theory is analogous to a Hamiltonian (or Lagrangian; I won't carefully distinguish between the two) of a system. All areas of physics, including string theory, have general rules for deriving physics from a Hamiltonian, but one defines a particular theory only after specifying the Hamiltonian, or perhaps forces. Physical systems are described not by the Hamiltonian but by solutions to the equations calculated from it. In quantum theory, for example, to make predictions that test whether a given Hamiltonian for an atom is correct, one must find the ground state and calculate energy levels and transitions relative to it. Comparing the calculated values to reality serves to check the Hamiltonian and Schrödinger equation together. The situation is analogous for Newtonian mechanics, as illustrated in figure 2, or for string theory, in which the universe corresponds to a stable or metastable ground state or, in the jargon of the field, the vacuum. The key point is that solutions to the theory are the things tested. It's a point that is often ignored, even by experts, in popular discussions.

Testable predictions from string theory

To make contact with the real world, a 10D or 11D string theory must be compactified. String theories with stable or metastable ground states usually also have supersymmetry, so the compactification process must break that symmetry. Theorists have realized the procedure in a number of ways. Typically, the compactification leaves the ground state with recognizable remnants of supersymmetry—superpartners of the standard particles but with masses different from that of their partner. Sometimes it both is consistent with what we know about the world and leads to additional, testable predictions about dark matter, LHC discoveries, and more.

Indeed, anyone who has worked with compactified string theories knows they make a number of generic and detailed predictions that are not subject to qualitative changes from small input changes and can be falsified in a number of ways. Of course, a theory needs only to be falsifiable in one way to be testable. Some compactifications have generated wrong predictions. In those cases, we have successfully implemented a test, but the theory failed. I give specific examples of tests below; interested readers can find others in talks accessible from the website of the international String Phenomenology 2010 conference held in Paris this summer (http://stringpheno.cpht.polytechnique.fr) or from that of the String Vacuum Project (http://www.northeastern.edu/svp), a network of universities with theorists who focus on studying the ground states of string theories rather than the full higher-dimensional theory. It is simply wrong to say that string theory is not testable in basically the same way that $\mathbf{F} = m\mathbf{a}$ or the Schrödinger equation is testable.

One specific test of a compactified string theory involves neutrino masses. Theorists have devised many interesting models of neutrino masses, but they have not succeeded in writing down an underlying theory in which very light but

A problem, but not a concern

Physicists do not understand why the cosmological constant has the value that it has; naive dimensional-analysis computations give a result that is way too large. But that famous discrepancy should not change the arguments I have advanced in this article, nor should it get in the way of physicists finding the string ground state.

The cosmological constant is the value of an appropriate potential at its minimum, and in any particular string theory, it will scale with the product of the Planck mass and the mass of the gravitino, the supersymmetric partner of the massless graviton associated with the gravitational force. That result is not the one obtained by naive calculation, but still it gives too large a cosmological constant. In practice, one sets the minimum value of the potential at or near zero and calculates all observables. In reference 7, my collaborators and I followed a standard procedure and explicitly confirmed that for an M-theory compactified on a G_2 manifold, implementing the potential tuning leads to only small numerical changes in the observables. One always needs to check that the tuning doesn't have significant consequences, but it appears that the physics of dark matter, superpartner masses, families, and parity violation is not closely related to the potential minimum.

Solving the cosmological-constant problem does not seem likely to help physicists comprehend the rest of what needs to be understood, and not solving the problem does not seem likely to be a hindrance. Quantum chromodynamics has an analogous "strong *CP* problem." One would expect QCD to break the symmetry of nature under the combination of charge conjugation *C* and coordinate inversion, or parity *P*. To tame the expected symmetry breaking, one has to set a term in the QCD Lagrangian to be about 10 orders of magnitude smaller than its naive value. If that term were indeed equal to the naive value, every prediction of QCD would change. But for three decades, physicists have been ignoring the offending term and moving ahead without encountering any hint of a problem.

not massless neutrinos emerge in the sense that the proton emerges and is explained by QCD. Perhaps string theory could explain the light masses? A few years ago Joel Giedt (now at Rensselaer Polytechnic Institute), Paul Langacker (now at the Institute for Advanced Study), Brent Nelson (now at Northeastern University), and I realized that a particular compactified string theory had been studied so well by Mary K. Gaillard and her PhD students (including Giedt and Nelson) at the University of California, Berkeley that we could identify all the particles that could be neutrinos.[1] We showed that in no case could the theory generate light but not massless neutrinos. That work represents a clear example of a test of string theory. Although the particular compactification we studied did not yield the desired neutrino masses, different compactifications may allow for neutrino masses consistent with experiment and offer explanations of observed neutrino properties.

Sometimes when people talk about testing string theory, they are referring to tests that apply to the full 10D or 11D theory without compactification. Quantum mechanics admits a few ways to probe the general framework of the theory; most of those test the idea that the superposition principle applies to probability amplitudes. The general framework of quantum field theory has passed tests that confirmed the predicted connection between spin and statistics or that all quanta of a given kind—electrons, say—are identical. Perhaps string theory has such general tests even though no 4D universe is defined, but that is not yet clear.

Probably the ideal goal for those who want to examine string theory is to formulate testable properties that hold for all compactified string theories with metastable or stable vacua, regardless of the form of the compactification or other conditions such as supersymmetry breaking. Most knowledgeable physicists would agree that the gravitational force is one such property; its existence is a success for string theory. Some theorists have emphasized that compactified string theories should obey certain properties of general relativistic quantum field theories;[2] any putative theory that violates those principles cannot be right.

Naively, string theory predicts an energy of the universe, or cosmological constant, that is much greater than observed. That discrepancy is one of the outstanding puzzles of theoretical physics. Meanwhile, as I argue in the box on page 41, it is not expected to be an obstacle to exploring testable consequences of string theory.

A cosmological example

Earlier this year Bobby Acharya, Eric Kuflik, and I proposed a test that concerns the cosmological history of the universe, one that should be applicable to any compactified string theory.[3] Before explaining it, I need to describe two additional important features of compactified theories and supersymmetry breaking: moduli fields and gravitinos.

Moduli fields characterize the sizes, shapes, and metrics of the small manifolds—for example, the 6D Calabi–Yau manifolds in a 10D string theory. The moduli fields may be unfamiliar, but they are always present in compactified string theories, and the quantities they represent are physical. Once they take on definite values in the ground state—once they are stabilized—they determine many measurable observables such as interaction strengths and the masses of the gauge bosons that mediate the standard-model interactions. A modulus has quanta analogous to the photons associated with the electromagnetic field, and as usual, the fluctuations around the value of a modulus at the minimum of its potential energy determine the mass of the quantum. As theorists often do, I will sometimes use "moduli" to designate both the fields and the associated quanta.

The gravitino is the superpartner of the graviton, the massless quantum associated with the gravitational field. When supersymmetry is broken, the gravitino becomes massive. Its mass sets the scale for all the other superpartners and for the moduli.

String theories can have many moduli, with different stabilized values and masses. Nevertheless, string theories that could describe the world we live in generically have at least one modulus whose mass is on the order of the gravitino mass.[4] The result is so universal that my collaborators and I think, with further study, it will be promoted to a theorem. In any case, moduli quanta have interactions and decays with important cosmological implications.[5] Acharya, Kuflik, and I have generalized the argument of reference 4 and have extracted those implications in the context of compactified string theories.[3]

Moduli interact only gravitationally, so their behavior is essentially model independent. In particular, the lifetime of a modulus is approximately calculable in terms of its mass. If even one modulus were to decay after the beginning of nucleosynthesis, the decay products would alter the abundances of helium and other nuclei that are successfully described by the usual theory that does not include moduli. Thus the moduli and gravitino masses must be at least 30 TeV or so to guarantee that the decay occurs early enough.

The moduli decay when the universe has cooled to a temperature of order 0.01 GeV, and in doing so they introduce large amounts of additional particles. The dark-matter relic "density," as the term is commonly used in this context, is the ratio of dark-matter particles to all particles. So when the moduli decay adds to the number of particles, it decreases the relic density. On the other hand, the decay products of the moduli include candidate dark-matter particles, so the decays can still generate the observed dark-matter density.

The essential point is that in theories with decaying moduli, the universe has a nonthermal history. The conventional thermal history, in contrast, is one in which essentially the only thing the universe does after the Big Bang is cool adiabatically. No diluting particles are produced at any stage, and no dark-matter particles enter except from decay of related particles present immediately after the Big Bang; for example, superpartners present at the earliest instants of the cosmos quickly decay into the lightest superpartner. The new sources of particles and dark matter in the nonthermal picture lead to several testable predictions. Immediately after the inflationary epoch, the universe is matter dominated—by the moduli—not radiation dominated as in the usual model. The dark matter itself is not cold in the nonthermal case since it is created with significant kinetic energy from moduli decay. And it is not present until about 0.01 s after the Big Bang. Figure 3 shows a history of the universe with two landmarks indicated. First is the time when dark matter freezes out, that is, when it is cold enough and the universe has expanded enough that dark-matter particles are unlikely to encounter one another. Freeze-out fixes the amount of dark matter in the standard thermal picture. The second landmark shows when the later decay of moduli in compactified string theories dilutes the dark matter on the one hand and regenerates it on the other.

Nonthermal cosmic evolution is thus a general prediction for compactified string theories with broken supersymmetry and stabilized moduli. It apparently does not depend on the particular forms of the compactification, supersymmetry breaking, or stabilization. As theorists further study com-

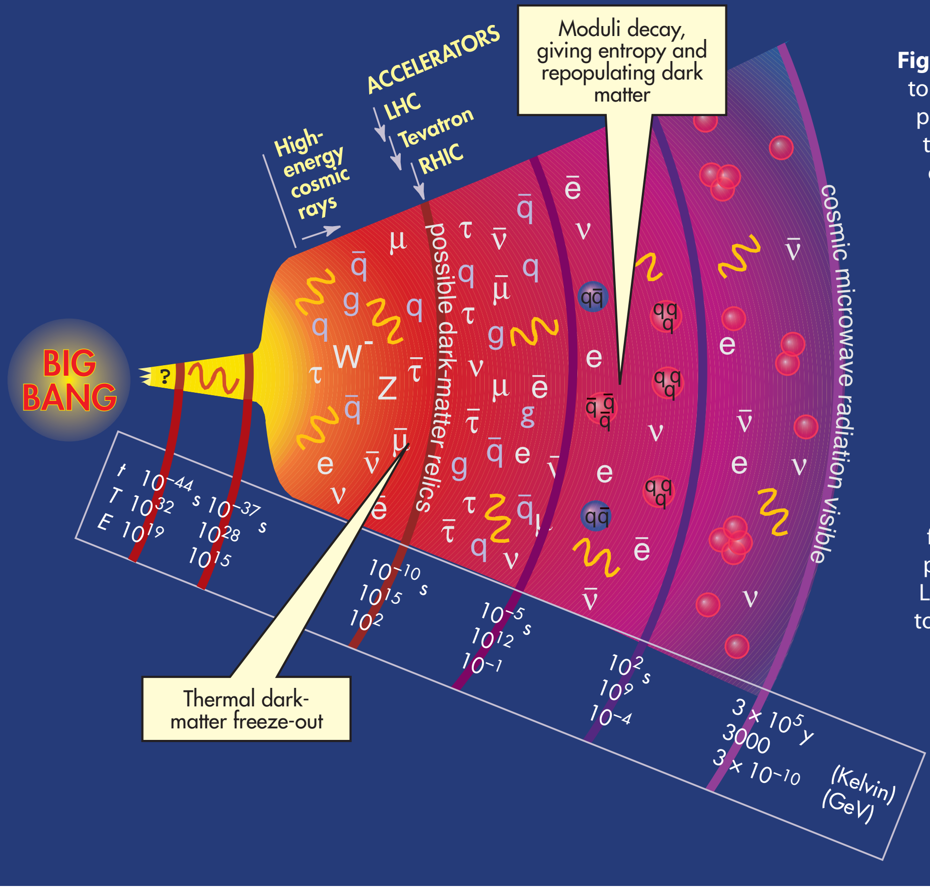

Figure 3. Revisionist history. This history of the early universe indicates particle types (including light nuclei) that were prevalent at various epochs. The three scales give time (t), temperature in kelvin (T), and temperature in GeV (E). The history is changed significantly if compactified string theories are correct: About 0.01 s after the Big Bang, so-called moduli fields of the theory decay, producing additional particles and dark matter. The plot also highlights the earlier freeze-out time of dark matter, that is, the time after which dark-matter particles no longer interact. (Adapted from a more extensive history prepared by the Particle Data Group, Lawrence Berkeley National Laboratory. Courtesy of the PDG.)

pactified string theories, they will presumably find additional examples of such tests.

A particularly interesting result of a moduli-based nonthermal cosmic evolution follows if all or most of the dark matter is the lightest superpartner. In that case, the dark-matter annihilation cross section must be rather large so that the lightest superpartners arising from moduli decay can annihilate down to a number small enough to be consistent with observation. Such a large annihilation cross section implies that the lightest superpartner is essentially the wino—the superpartner of the W boson. The winos annihilate into W bosons via a well-understood process that implies a galactic excess of positrons and antiprotons very much like those obtained by the PAMELA satellite-borne experiment.[6]

Can the landscape be navigated?

The string theory framework apparently allows an enormous number of solutions that could potentially describe the universe. Before theoretical physicists can claim to fully understand string theory, they must understand the existence and implications of the string theory landscape—that is, its many solutions. Some theorists have argued that the existence of so many solutions will prevent them from ever finding a theory that describes the vacuum and answers the important questions they want answered. But given the success already achieved with compactified string theories, I'm optimistic about obtaining a description of our string vacuum.

Historically, physicists have understood the natural universe through an interplay of experimentation and theory. String theory fits nicely into that tradition. With guidance from both theory and data, physicists are looking for a compactified string theory that incorporates the many phenomena they hope to understand—a string supersymmetric standard model.

Some of those who talk about testing string theory, and most critics of theory, are assuming the 10D or 11D approach and want somehow to test the theory without applying it to a world where tests exist. That is analogous to asking a Lagrangian to be falsifiable without applying it to any physical system. Is 10D string theory falsifiable? That is not the relevant question. What matters is that the predictions of the 10D theory for the 4D world are demonstrably testable and falsifiable. If no compactified string theory emerges that describes the real world, physicists will lose interest in string theory. But perhaps one or more will describe and explain what is observed and relate various phenomena that previously seemed independent. Such a powerful success of science would bring us close to an ultimate theory.

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