Is String Theory Testable?

Peter Woit

Columbia University

INFN Rome, March 8 2007
INFN Pisa, March 15 2007

Outline

Unusual talk, mixed feelings

- Focused on problems and failure not progress
- Would prefer to be discussing positive ideas about math and physics
- I am not an expert in this field, but have followed it closely for more than 20 years, with increasing concern

String theory is an incredibly complex subject, at least an order of magnitude more than QFT. It involves sophisticated mathematics, not well understood by most physicists.

Unusual background:

- Education and postdoc in particle theory, later career in math depts.
- Since March 2004, "Not Even Wrong" blog, often devoted to discussing these issues with string theorists
- Thanks to all who have argued with me about these issues, politely or not

What This Talk Is Not About

"String Theory" includes many areas I won't discuss, including:

AdS/QCD

- AdS/CFT duality may lead to a string theory dual to QCD. This idea is highly testable, should reproduce QCD calculations. Test of an equivalence of two theories, not an experimental test.
- Quark-gluon plasma in QCD may be sufficiently similar to that in N=4 Super Yang-Mills to allow AdS/CFT to be used to make qualitative predictions about phenomena in heavy-ion collisions, where accurate QCD predictions are not available.

Mathematics

String theory dualities imply remarkable predictions of unexpected isomorphisms between different mathematical objects. Revolutionary impact on some parts of algebraic geometry. Has opened up new, currently very active, mathematical areas ("Homological Mirror Symmetry").

String Theories of the Strong Interaction

Ideas about how to use string theory have evolved through various periods
Earliest string theories were intended to describe strongly interacting particles

Some History

- 1968 Veneziano amplitude, dual resonance model
- 1970 Quantization of a string (Nambu, Nielsen, Susskind)
- 1971 Supersymmetric strings to get fermions (Neveu-Schwarz, Ramond)
- 1973 Asymptotic freedom and QCD: strong interactions describable by QFT
- 1997 AdS/CFT (Maldacena)

String Theories as Unified Theories

New use for string theories: unified theories of gravity and particle physics

Some History

- 1974 Use to quantize gravity: spin-2 massless mode is graviton (Schwarz, Scherk, Yoneya)
- 1980 Superstrings: strings with space-time supersymmetry (Green, Schwarz)
- 1984 Anomaly cancellation (Green, Schwarz)
- 1984 Heterotic superstring
- 1985 Calabi-Yau compactifications, semi-realistic theories
- Late 80s: study of conformal field theory (CFT) to classify possible compactifications ("string backgrounds")

Unresolved problems: moduli and supersymmetry breaking

Second Superstring Revolution

D-branes

Early to mid-90s: Introduce new degrees of freedom ("D-branes"), fixed submanifolds strings can end on.

Equivalently: conformal boundary conditions for CFTs.

May carry "fluxes", higher dim. analogs of magnetic flux

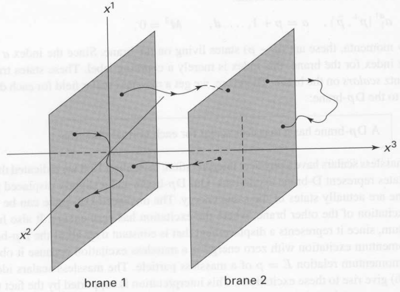


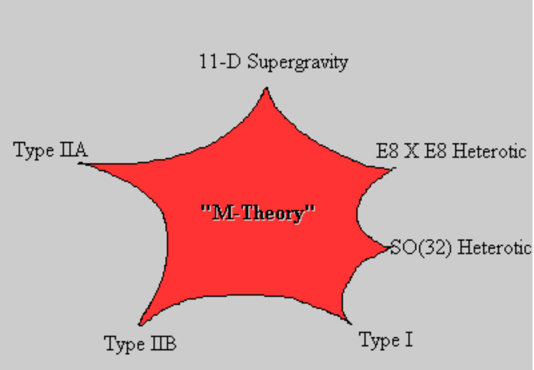
Figure 14.1 Two parallel D2-branes. Here x^1 and x^2 are longitudinal coordinates, and x^3 is a normal coordinate. The positions of brane one and brane two are specified by the coordinates $\bar{x}_1^3$ and $\bar{x}_2^3$, respectively. We show the four types of strings that this configuration supports.

Second Superstring Revolution

M-theory and Dualities

Branes part of discovery of dualities relating different string theories, supergravity.

M-theory conjecture (Witten 1995): there is just one string theory



Second Superstring Revolution

Successes and Problems

Successes

- Remarkable relations between different theories, dualities have huge mathematical implications
- New kinds of model-building "Brane-worlds"
- 1997: AdS/CFT Conjecture, revival of strings as theory of strong interactions, tool for studying strongly coupled gauge theories

Problems

- Still no nonperturbative theory (What is "M-theory"?)
- Doesn't help resolve problems getting viable theory (moduli, supersymmetry breaking)
- Huge number of new possible "string theory backgrounds" make things much worse. Many appear to be supersymmetric and consistent

Flux Compactifications and the Anthropic Landscape

Post-2000, various dynamical mechanisms found involving branes and fluxes that give different energies to different backgrounds ("Landscape")

Successes

- Moduli stabilization: can fix values of moduli fields parametrizing backgrounds at metastable minima
- At these minima, can break supersymmetry, get positive CC

Problems

- Essentially infinite number of minima, of sufficient complexity to give almost any physics
- Generically CC of Planck energy scale 10^{120} times too big

Anthropic Landscape (Susskind 2003): These two problems cancel. Any CC possible, including sufficiently small ones. Eternal inflation allows anthropic explanation for why we see such a small CC.

Fundamental Conceptual Problem

What is String (or M) Theory? (Only have perturbation theory in string coupling)

Conjectural framework

"All parameters dynamical, different values correspond to different states of the same theory"

Evidence

- Infinitesimal changes in background metric give different states
- Dualities relate different string theories

In practice "string theory" is largely perturbative strings in various self-consistent backgrounds.
Main conjecture for a non-perturbative theory: string/gauge duality, i.e. string theory defined holographically by gauge theory in lower dimension.

Heterotic String Models

First semi-realistic models (1985)

$E_8 \times E_8$ heterotic string on an $\mathbf{R}^4 \times CY^6$ background

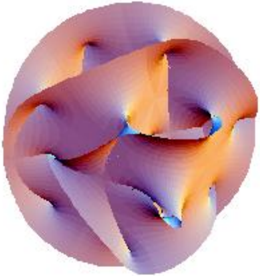
- CY^6 is a Calabi-Yau manifold (6d Kahler manifold with first Chern class zero)
- More general possibilities use different holomorphic bundles as additional structure on the CY^6 to get different gauge groups
- The number of generations is $\chi(CY^6)$, the Euler characteristic of the Calabi-Yau. Examples can be constructed with $\chi(CY^6) = 3$ (or just about anything)

Initial hope: small number of possible Calabi-Yaus, small number of consistent backgrounds

Heterotic String Models

Moduli

Calabi-Yaus come in at least of order 10^5 different topological types.
Finiteness of this is an open problem in algebraic geometry.
For each topological type, a "moduli space" of different possible Calabi-Yaus, of dimension determined by the Betti numbers (dimension of homology groups). Typically of order 100.
Example:



$z_1^5 + z_2^5 + z_3^5 + z_4^5 + z_5^5 = 0$ in $\mathbf{CP}^4$
This is one point in a moduli space of dimension 101 (vary coefficients to get rest)

Heterotic String Models

Moduli and Supersymmetry Breaking Problems

Moduli

By general philosophy, moduli parameters become dynamical fields, but then:

- If no potential, get massless fields. Huge number of new long-range forces, violating experimental bounds
- Get potentials that go to zero at large values, but if fields such as "dilaton" take on large values, need non-perturbative string theory.

Supersymmetry Breaking

No supersymmetry in observed spectrum, so need to break supersymmetry, at scale of 100 GeV or higher. Supersymmetry breaking provides contributions to the CC 10^{60} times larger than its observed value, must be somehow cancelled.

Intersecting Brane Models

Can get chiral N=1 supersymmetric models by taking configurations of intersecting D6-branes. Open strings can go from one brane to another. Standard Model-like examples.

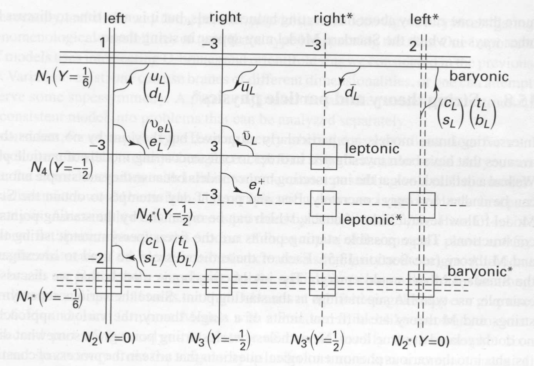
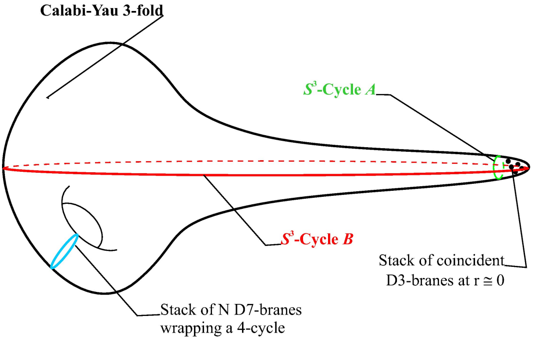


Figure 15.8 The brane configuration that leads to a Standard Model gauge group and matter content. There are $N_1 = 3$ baryonic branes, $N_2 = 2$ left branes, $N_3 = 1$ right branes and $N_4 = 1$ leptonic branes. The image D-branes created by the orientifolds are shown in dashed lines. Intersections framed by a square are mirrors of previously accounted intersections and do not give new particles.

KKLT Model

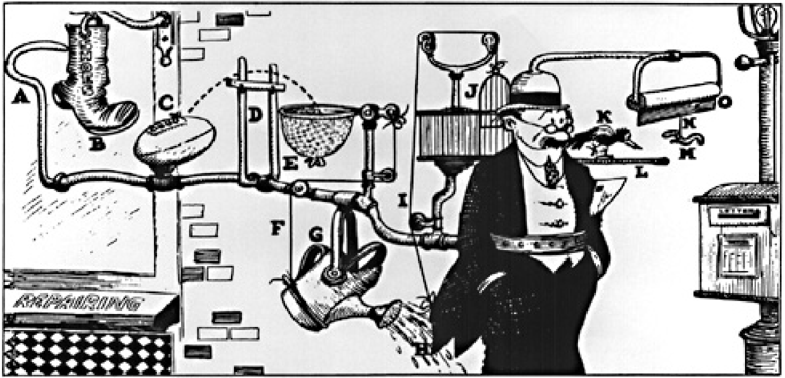
KKLT (2003): Use fluxes, branes, warped geometry, to get a background



that stabilizes all moduli

Leads to, for each Calabi-Yau, landscape with numbers like 10^{500} metastable minima

"Rube Goldberg constructions" (Susskind)



Keep You From Forgetting To Mail Your Wife's Letter RUBE GOLDBERG (tm) RGI 049

Rube Goldberg: *a comically involved, complicated invention, laboriously contrived to perform a simple operation*

Brane Inflation

Recent efforts to make connection to cosmology.

KKLMMT (2003)

Use KKLT construction, inflation comes from brane-antibrane annihilation in the warped geometry.

Very complex construction, relative position of branes is the inflaton field.

Does this framework add up to something testable?
We'll now examine various publicized claims of tests.

String Theory Predicts Gravity

Perhaps the most common claim for a prediction of string theory

Problems

- This is a "retrodiction", we know gravity exists. String theory is studied precisely because of the idea that a massless spin-2 particle in its spectrum would give gravity
- "String theory predicts gravity.... In 10 dimensions"
  Lisa Randall
  10-dimensional (super)gravity is quite different than 4-dimensional gravity

String Theory Predicts Supersymmetry

STRING THEORY IS TESTABLE, EVEN SUPERTESTABLE

Many believe that superstring theory, because of its extraordinarily tiny length scale and gargantuan energy scale, cannot be tested. That belief is a myth.

Gordon Kane

Suppose we could understand the laws of nature that govern the particles and their interactions, and in addition why the laws are as they are, and also how the universe evolved and perhaps even how it originated—an active research area today. That understanding—a theory—would be formulated not in terms of everyday units, but rather units built from constants such as the speed of light, Planck's constant and Newton's constant. From these constants one obtains the natural scales: the Planck length ($\sim 10^{-33}$ cm) and the Planck mass ($M_P \sim 10^{19}$ GeV/c^2). I will call this theory the primary theory, a name I like because it suggests that as we go through a hierarchy of effective theories, from macroscopic sizes to atoms to nuclei, we end at a primary one that is not related to another at a deeper level.

right-handed fermions are treated differently)—that is, why there is a muon and a tau so like the electron—will have passed a big test. It must also explain why matter comes as quarks and leptons but not as other possible forms such as leptoquarks. The theory will predict that there should or should not be additional kinds of matter that can be detected in collider experiments, such as particles to complete a representation of a larger group.

Similarly, the Standard Model of particle physics is based on certain symmetries under interchange of the particles: an SU(3) symmetry for interchanging quarks of different colors, an SU(2) symmetry for interchanging the up and down quarks and so on, and a U(1) symmetry for which the particles have different eigenvalues. Why those symmetries and no others?

Physics Today
February 1997

Problems

- Supersymmetry not observed in spectrum, must be broken. No prediction of supersymmetry-breaking scale or mechanism
  Landscape statistics $\Rightarrow$ Planck scale, not LHC
- Best understood string theories are supersymmetric

Science The New York Times ON THE WEB

April 4, 2000

Physicists Finally Find a Way to Test Superstring Theory

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- Join a Discussion on Superstrings and Beyond

By GEORGE JOHNSON

Keith Meyers/The New York Times

Dr. Lisa Randall speaking to Dr. Raman Sundrum, superstring theorists who portray the universe as one of many bubbles floating inside a four-dimensional megaverse.

F or a quarter of a century, superstring theory has promised that the universe could be understood more deeply than ever before, with all the forces unified into one, if it were seen in a startling new light -- as a kind of mathematical music played by an orchestra of

Space is 3d membrane embedded in warped higher dimensions

Problems

- Scales of other dimensions? LHC? Planck?
- Numbers, configurations of branes?
- Other physics on other branes?

An infinity of possible models
Effects not seen until unknown scale

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SLAC Physicists Develop Test For String Theory*

Joanne Hewett

Under Certain Conditions

String theory solves many of the questions wracking the minds of physicists, but it has one major flaw — there are currently no known methods to test it. SLAC scientists have found a way to test a particular version of this revolutionary theory. The test applies to a class of critical string theories which posit that there are 10 or 11 dimensions in our universe — no more, no less.

This past December, Joanne Hewett, Thomas Rizzo and student Ben Lillie published an article in *Physical Review Letters* which shows theoretically how to measure the number of dimensions that comprise the universe. By determining how many dimensions exist, Hewett, Lillie and Rizzo hope to either confirm or repudiate critical string theory under specific conditions.

Calculation of effects that depend on number of extra dimensions
String theory says 6

Problems

- Some dimensions too small to see at LHC energy?
- What about M-theory? (7 dimensions)

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Published: **15:54, January 26, 2006**

South Pole Neutrino Detector Could Yield Evidences of String Theory

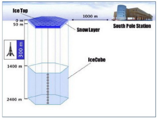


Diagram of IceCube. IceCube will occupy a volume of one cubic kilometer. Here we depict one of the 80 strings of opctical modules (number and size not to scale). IceTop located at the surface, comprises an array of sensors to detect air showers. It will be used to calibrate IceCube and to conduct research on high-energy cosmic rays. Author: Steve Yunck, Credit: NSF

Researchers at Northeastern University and the University of California, Irvine say that scientists might soon have evidence for extra dimensions and other exotic predictions of string theory. Early results from a neutrino detector at the South Pole, called AMANDA, show that ghostlike particles from space could serve as probes to a world beyond our familiar three dimensions, the research team says.
No more than a dozen high-energy neutrinos have been detected so far. However, the current detection rate and energy range indicate that AMANDA's larger successor, called IceCube, now under construction, could provide the first evidence for string theory and other theories that attempt to build upon our current understanding of the universe.

An article describing this work appears in the current issue of *Physical Review Letters*. The authors are: Luis Anchordoqui, associate research scientist in the Physics Department at Northeastern University; Haim Goldberg, professor in the Physics Department at Northeastern University; and Jonathan Feng, associate professor in the Department of Physics and Astronomy at University of California, Irvine.

High-energy neutrino cross-sections from AMANDA, IceCube experiments at South Pole
In some extra dimensional models, could be high due to e.g. black hole production

Problems

- Same as for LHC extra dimensional "predictions"
- AMANDA data consistent with Standard Model

Source: University Of California, Santa Barbara - Engineering
Date: June 14, 2004

Newly Devised Test May Confirm Strings As Fundamental Constituent Of Matter, Energy

Science Daily â€' Santa Barbara, Calif. -- According to string theory, all the different particles that constitute physical reality are made of the same thing--tiny looped strings whose different vibrations give rise to the different fundamental particles that make up everything we know. Whether this theory correctly portrays fundamental reality is one of the biggest questions facing physicists.

In the June on-line Journal of High Energy Physics (JHEP), three theoretical physicists propose the most viable test to date for determining whether string theory is on the right track. The effect that they describe and that could be discovered by LIGO (Laser Interferometer Gravitational-Wave Observatory), a facility for detecting gravitational waves that is just becoming operational, could provide support for string theory within two years.

When physicists look at fundamental particles--electrons, quarks, and photons--with the best magnifiers available (huge particle accelerators such as those at Fermi Lab in Illinois or CERN in Switzerland), the particles' structures appear point-like. In order to see directly whether that point-like structure is really a looped string, physicists would have to figure out how to magnify particles 15 orders of magnitude more than the 13 orders of magnitude afforded by today's best magnifying techniques--a feat unlikely to occur ever.

Cosmic superstrings, visible through

- Gravitational Lensing
- Gravitational Radiation LIGO, LISA

Problems

- Abundance?
- Properties? How to Distinguish from QFT cosmic strings?

"Could provide support for string theory within two years" (2004)

Science 29 September 2006:
Vol. 313. no. 5795, pp. 1880 - 1881
DOI: 10.1126/science.313.5795.1880b

NEWS FOCUS

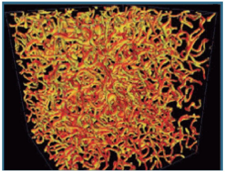
PASCOS 2006:

A Cosmic-Scale Test for String Theory?

Tom Siegfried

Theorists who think nature's ultimate building blocks are vibrating strands of energy called superstrings have always had a big problem converting skeptics. One reason: The strings are far too small to see. In fact, they are supposedly so small that no conceivable microscope (or particle accelerator) could ever render them visible. But some string theorists now believe they've found a way to make superstrings observable: supersize them.

Superstrings that were supertiny shortly after the big bang could have been stretched by the expansion of the universe to cosmic size today, Robert Myers of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada, noted at the meeting.[*] He described several ongoing investigations of the properties that such cosmic strings would have and how they might be detected.



Pumped up. Computer simulations show that cosmic inflation might have created networks of enormous "superstrings."

CREDIT: PAUL SHELLARD/UNIVERSITY OF CAMBRIDGE

Cosmic superstrings continue to be cited as a test of string theory.

Note: The picture with the article is a simulation of field theory cosmic strings, not superstrings.

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The first evidence for string theory?

18 December 2004
Marcus Chown

IF YOU consider them separately, these two observations are hardly going to set the scientific world on fire. But together they add up to a spectacular possibility. In a tiny region of sky, astronomers have seen a dozen galaxies that appear as a curious sequence of double images. They have also observed a quasar whose brightness oscillates in an unexpected way. What could cause these odd phenomena? The only explanation that covers both is pretty mind-bending: "superstrings" of pure energy that can stretch millions of light years across the universe. Is this the first experimental evidence for string theory?

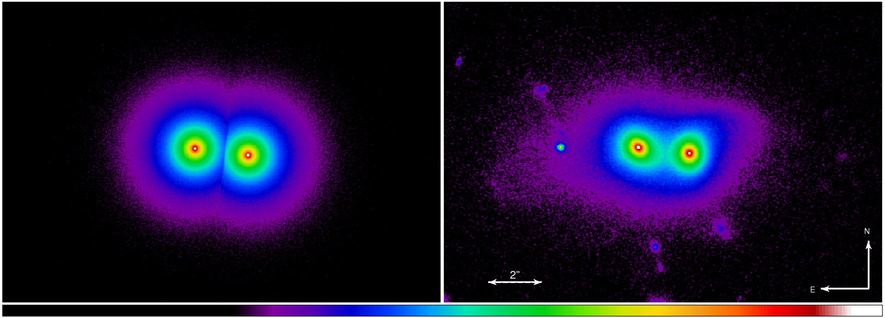
The theory is our best hope of understanding how the universe works at its most fundamental level. It suggests that the basic constituents of matter are impossibly narrow threads of concentrated energy. The various different ways these superstrings can vibrate correspond to different fundamental particles, such as the up-quark and the muon-neutrino. The idea is well on the way to becoming a "theory of everything", uniting the laws of physics to explain how all matter and energy behave.

Visible strings

One of the strangest features of string theory is that it requires many more dimensions than we can see: the only way the vibration modes of the superstrings can be sufficiently diverse to create all particles is if the superstrings vibrate in a space-time of 10 dimensions. Of course, we appear to live in a universe with only four dimensions - three of space and one of time - so string theorists have postulated that the extra dimensions are "rolled up" much smaller than the dimensions of an atom. However, until now no one had seen evidence to support string theory, and many scientists dismiss its ideas as untestable conjectures. But are they about to be proved wrong?

CSL-1

Two objects very near in sky, similar shape, spectrum.
Are they two different galaxies, or one galaxy lensed by a cosmic string?



One galaxy lensed by cosmic string

Image from Hubble Space Telescope

Conjecture falsified

EE Times: Latest News

Scientists devise test for string theory

R. Colin Johnson
EE Times
(02/06/2007 12:25 PM EST)

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REPRINTS

PORTLAND, Ore. — Researchers at the University of Wisconsin at Madison claim that they have found a way to determine the shape of the extra dimensions predicted by string theory.

String theory is a leading candidate in the search to identify a single principle that guides all other forces of nature in the universe—weak and strong nuclear forces as well as electromagnetic and gravitational forces. But until now no one had devised an experiment to test it.

The researchers suggest that they can confirm the unified theory from the effects seen as they peer back into time to observe the most distant astronomical objects, which existed "at the beginning" of the universe.

The postulation of these extra dimensions—up to 10 in all—explains why only the point-like tips of these particles are visible to humans: The rest of each particle could be spread through this multidimensional space. Their interactions in the other dimensions—akin to interference among vibrating "strings"—explains why quantum mechanics requires statistics to describe matter: their tips could be jumping about like the end of a whip.

Dependence of cosmological observables on details of brane-inflation models.
Especially the spectral index n_s.
WMAP3 result $n_s = .95 \pm .02$.

Problems

Complex models, few observables
Appears likely one can match any data by some model or other

New particle accelerator could rule out string theory
22:04 01 February 2007
NewScientist.com news service
David Shiga

String theory could be ruled out by experiments at the Large Hadron Collider (LHC), a particle accelerator scheduled to open by the end of 2007, a new study says. The finding offers a new approach for testing this potential "theory of everything", a goal that has so far proven elusive.

Enlarge image
The LHC will smash protons together and could test string theory (Illustration: LHC/FNAL)

According to string theory, particles like electrons and photons are actually tiny, vibrating strings. The beauty of the theory is that it accounts for all of the known forces – including gravity, which the standard model of physics does not. But its critics have complained that there is essentially no way to test it.

Strong evidence for string theory could come from the observation of short-lived, mini black holes at the LHC (see *Watching God play dice: The Large Hadron Collider*). But the chance of their appearing is extremely small, so a failure to see them would not be a death blow for the theory.

In 2006, string theorist Allan Adams of MIT in Cambridge, US, and others offered a more promising check. They showed that some particle collisions could reveal whether certain fundamental assumptions underlying string theory are wrong.

Now, another team has shown that the energies needed to reveal such effects are achievable at the LHC, which is being built in Geneva, Switzerland. The team was led by Jacques Distler of the University of Texas in Austin, US.

WW scattering amplitude bounds based on standard assumptions about QFT

- Unitarity
- Lorentz Invariance
- Analyticity

Remarkable claim that violation of bounds would falsify string theory.
Simpler interpretation: would falsify QFT, not string theory, actually providing an argument for string theory.
Violation of bounds seems very unlikely.

Can the String Theory Landscape Make Predictions?

Anthropic Principle

Ongoing Debate

Can the anthropic string theory landscape make predictions, even in principle?

By itself the Anthropic Principle is a tautology:

Life exists $\Rightarrow$ Universe has properties such that life can exist

Can't be falsified: will never observe universe to have a property incompatible with life.

Can turn into something more substantive by replacing "Life exists" by various observed properties of the universe that life seems to depend on:

Life exists $\Rightarrow$ galaxies exist with certain properties $\Rightarrow$ facts about physics

Still can't be falsified.

Can the String Theory Landscape Make Predictions?

Statistical Predictions

String theory landscape: our universe is a randomly chosen point in a space of 10^{500} or more possibilities

Predict probability density $P(x)$ for observing value x of observable O

$$P(x) = P_{prior}(x) P_{selection}(x)$$

$$P_{prior}(x)dx = \frac{\text{Number of universes with O between x and x+dx}}{\text{Total number of universes}}$$

$P_{selection}(x) =$ Fraction of universes with O taking value x that support life

- Conventional prediction: $P_{prior}(x) = \delta(x - x_0), \quad P_{selection}(x_0) \neq 0$
- Statistical prediction: value of x will be near maximum of $P(x)$, not far out in some tail

Serious Problems, Technical and Conceptual

Technical: Measure Problem

$P_{prior}(x)dx$ is typically of the form ∞/∞
Have to regularize to get finite values
Answer is regularization dependent

Often, just assume $P_{prior}(x)$ is constant on region where $P_{selection}(x)$ non-zero

Conceptual Problem

If $P_{prior}(x)$ constant, theory being tested is now much the same as the theory:
"We have no idea what is going on here, so all possible values of x are equally likely"

Prediction of Cosmological Constant (Weinberg, 1987)

Main claim of an anthropic landscape statistical prediction.

Weinberg (1987):

To have galaxy formation, CC cannot be too large, it should be some random value in the region that allows galaxy formation. In particular, it should not be zero. At the time only had upper bound on CC.

Observed value turns out to be non-zero, roughly 10% probability of being as small as it is.

Problem

Allowing not just CC to vary, but also other parameters (e.g. Q, the scale of density fluctuations), much larger CCs are anthropically allowed. Probability of CC being as small as observed more like .1%

Has the Anthropic Landscape Already Been Falsified?

Problem

Some observed quantities which vary widely over the string theory landscape, take values nowhere near the middle of the anthropic range, most dramatically:

- Proton lifetime: $> \; 10^{31} - 10^{33}$ years
  Anthropic range: $> \; 10^{11}$ years
- Strong CP violation

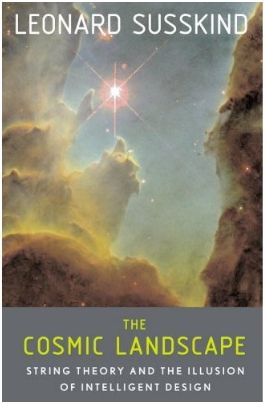
Computational Complexity Problems: Denef-Douglas

If the anthropic string theory landscape explanation of the small value of the cosmological constant is correct, likely to be impossible to predict other things about physics

Problem

- String theory backgrounds with anthropic CC values occur due to very delicate and unlikely cancellations of different contributions
- Calculating value of CC to necessary accuracy to see if this occurs difficult if not impossible for any particular string theory background (have to calculate to very high orders of perturbation theory)
- Even if could calculate for any particular background, need to do 10^{400} of these calculations to identify statistical sample of anthropic backgrounds

Can almost rigorously show this can't be done.



One prediction: Spatial curvature satisfies $\Omega \leq 1$, since universe comes from tunnelling
Expt: (WMAP+SDSS): $\Omega = 1.003 \pm .010$

Problem

hep-th/0610231 (R. Buniy, S. Hsu, A. Zee)
It has been claimed that the string landscape predicts an open universe, with negative curvature... We examine the robustness of this claim, which is of particular importance since it seems to be string theory's sole claim to falsifiability. We find that, due to subleading tunneling processes, the prediction is sensitive to unknown properties of the landscape. Under plausible assumptions, universes like ours are as likely to be closed as open.

Questions in Philosophy of Science

Falsifiability

Very unusually for high energy physics, claims made for string theory predictions raise questions of philosophy of science.

Roughly, science is characterized by gathering information about the world, then using this to make models that one then tests by experiments.

BUT: what does it mean to "test a theory by experiment"?

Simple answer (Popper):

To be scientific, a theory must be "falsifiable". It must make predictions such that if they are wrong the theory is wrong.

Problems With the Falsifiability Criterion

The use of the falsifiability criterion is not always so clear:

Subtleties

- Experimental results may be "theory-laden"
  Typically not a problem in HEP experiments, since the way we characterize observations is classical physics, far removed from what we are testing
- Predictions must be characteristic of theory.
  All theories are trivially falsifiable: all scientific theories predict angels will not emerge from the apparatus.
  A "test of a theory" must involve a prediction dependent on a distinctive aspect of the theory being tested.
- Theories have different degrees of rigidity. Typically, can evade falsifiability by making model more complicated

How Theories Fail

Theories are not always abandoned because they fail a specific test.

More often, they fail as they become more and more complicated in order to avoid contradiction with experiment.

Particular string theory models may be falsifiable, but variety of models is so great, no one has been able to come up with a viable test of the whole framework.

Difference between the QFT and string theory frameworks:

- Successful QFT is one of the simplest in the class of gauge theories
- Simplest string models disagree with experiment, have to go to complicated models to evade this

Why beauty is important in a theory;

Beautiful (or elegant) theories encode many non-trivial predictions in a simple structure. Highly rigid, and thus capable of being confronted with experiment

Is String Theory Testable?

Current Situation

Nothing like a conventional, falsifiable test exists. Simple string models disagree with experiment, and the class of those one is forced to examine to avoid this is too large to be predictive.

For this situation to change will require one of:

- Dramatic new observations that provide direct evidence: cosmic superstrings
- Dramatic new observations that provide indirect evidence: supersymmetry or branes at the LHC
- Dramatic new insights into nature of non-perturbative string theory

Will the LHC Save Us?

Possible LHC outcomes and my prejudices:

1. Extra dimensions or superpartners vindicate recent directions of research
   Unlikely since we should have already seen some evidence for these ideas
2. Completely unexpected results point to way beyond the Standard Model, most likely through insight into electroweak symmetry breaking
   This would be wonderful, and is certainly quite possible
3. The standard model continues to hold as we learn the Higgs mass and not much else, situation same as it is now
   This unfortunately is not unlikely, and would leave us in the same situation as now. Maybe we should think about how to deal with this, not wait for the LHC to save us...

Graphics from various places, including:

- Zwiebach, A First Course in String Theory
- Westphal, de Sitter String Vacua from Kahler Uplifting, Hamburg String Workshop 2007