Is String Theory Testable?

Peter Woit

Columbia University

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Outline

1. Introduction and Excuses
2. Development of String Theory
3. Various Popular Models
4. Some Advertised Tests
5. Predictions of the Anthropic Landscape
6. What Does It Mean To Test a Theory?
7. Conclusion
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").
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.
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.
Various Popular Models

Heterotic String Models

First semi-realistic models (1985)

$E_8 \times E_8$ heterotic string on an $\mathbb{R}^4 \times CY^6$ 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
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:

$$z_1^5 + z_2^5 + z_3^5 + z_4^5 + z_5^5 = 0 \text{ in } \mathbb{CP}^4$$

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.

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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 (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)
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.
Some Advertised 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 is Testable, Even SuperTestable

String theory is testable, because of its extraordinarily tiny length scale and gargantuan energy scale, cannot be tested. That belief is a myth.

Gordon Kane

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
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
Some Advertised Tests

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)

*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.
Some Advertised Tests

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
Some Advertised Tests

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)
Some Advertised Tests

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.
Some Advertised Tests

CSL-1

Two objects very near in sky, similar shape, spectrum.

Are they two different galaxies, or one galaxy lensed by a cosmic string?

Peter Woit (Columbia University)
Some Advertised Tests

One galaxy lensed by cosmic string

Image from Hubble Space Telescope

Conjecture falsified
Some Advertised Tests

Dependence of cosmological observables on details of brane-inflation models.
Especially the spectral index $n_s$. WMAP3 result $n_s = 0.95 \pm 0.02$.

Problems

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

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.

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 Collid). 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 $O$.

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

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

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

- **Conventional prediction**: $P_{\text{prior}}(x) = \delta(x - x_0)$, $P_{\text{selection}}(x_0) \neq 0$
- **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

\[ P_{\text{prior}}(x) dx \text{ is typically of the form } \infty/\infty \]

Have to regularize to get finite values
Answer is regularization dependent

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

Conceptual Problem

If \( P_{\text{prior}}(x) \) 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”
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%
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
Predictions of the Anthropic Landscape

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): $\Omega = 1.003 \pm 0.010$

Problem

hep-th/0610231 (R. Bunyi, 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.
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
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
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