String Theory for Philosophers

J. Harvey, March 31, 2011

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A presentation of string theory to philosophers exists in a milieu characterized by

1) A skeptical attitude on the part of many philosophers and physicists towards the attitudes of the other camp as exemplified by the following quotes taken from Michael Redhead's book ``From Physics to Metaphysics."

One must admit that many physicists would dismiss the sort of question that philosophers of physics tackle as irrelevant to what they see themselves doing, viz. producing simple, unified, empirically adequate theories about the world.

It may not comes as a surprise to learn that philosophers generally regard physicists as naive people, who do physics in an uncritical way, rather like a child riding a bicycle, quite innocent of the subtleties of rigid-body dynamics!

Or as Feynman wrote, ``Philosophers say a great deal about what is absolutely necessary for science, and it is always, so far as one can see, rather naive, and probably wrong.

2) A general preference among many philosophers of science for alternate approaches to quantum gravity. D. Rickles in his review ``Interpreting Quantum Gravity" writes

Rovelli is a physicist who has contributed to numerous philosophical collections—the passage above is from such a collection—in a bid to bolster philosophers' enthusiasm for his approach to quantum gravity—the approach known variously as *loop quantum gravity*, *loop gravity*, or the *loop representation* (it is arguably the only strong competitor to string theory, and my personal view is that it is in fact far superior).[4] John Baez—a mathematical physicist who has done important work

[4]The other founders of this approach (e.g. Abhay Ashtekar, Lee Smolin, and others) also demonstrate a heightened sense of philosophical awareness. Like Rovelli, Lee Smolin shows an openness to philosophical issues, and likewise contributes to philosophers' events and books.

Yet among physicists and mathematicians there is a clear preference for string theory. Why the discrepancy?

Loop quantum gravity has its roots in general relativity, a field whose major figures (Einstein, Wheeler) have been more open to insights from philosophy than have particle theorists

Loop quantum gravity emphasizes the role of philosophical foundations such as background independence.

String theory is much more technically demanding than loop quantum gravity and thus less accessible to most philosophers.

In my opinion the ideas and structures that have come out of string theory are deeper, richer and in the long run will teach us more about the fundamental structure of reality.

Topics I will discuss

- The historical origins of string theory in the strong interactions
- Dualities in String Theory
- Gauge/String Duality
- Background Independence
- Emergent spacetime

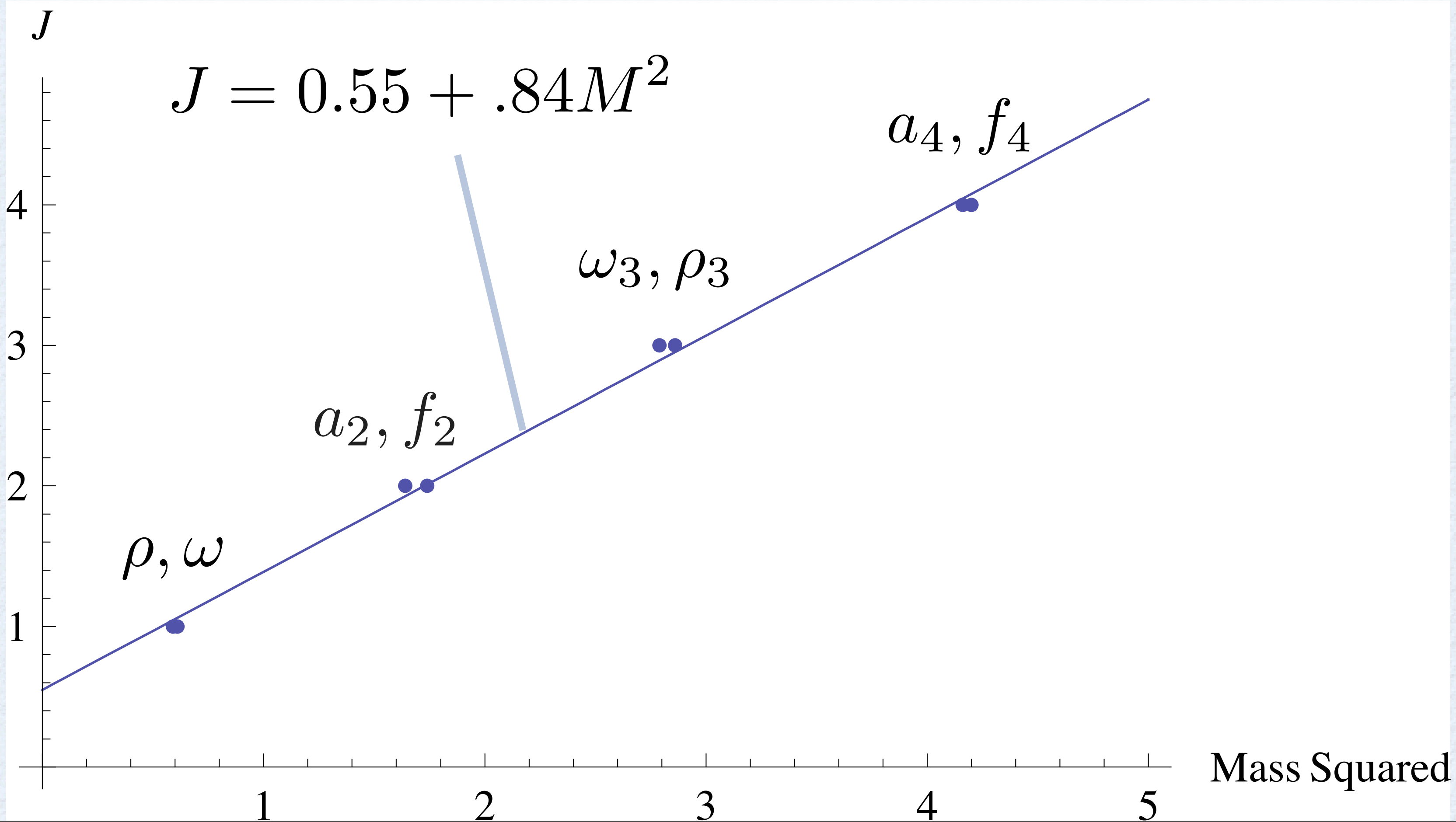
Topics I will not discuss

- The Landscape, the multiverse and the anthropic principle
- Loop quantum gravity and other approaches to quantum gravity

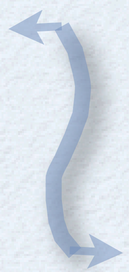
The historical origins of string theory

In the 60's it was noticed that mesons with fixed quantum numbers lie on straight lines in a plot of angular momentum vs. mass squared.

Chew-Frautschi Plot and Regge Theory

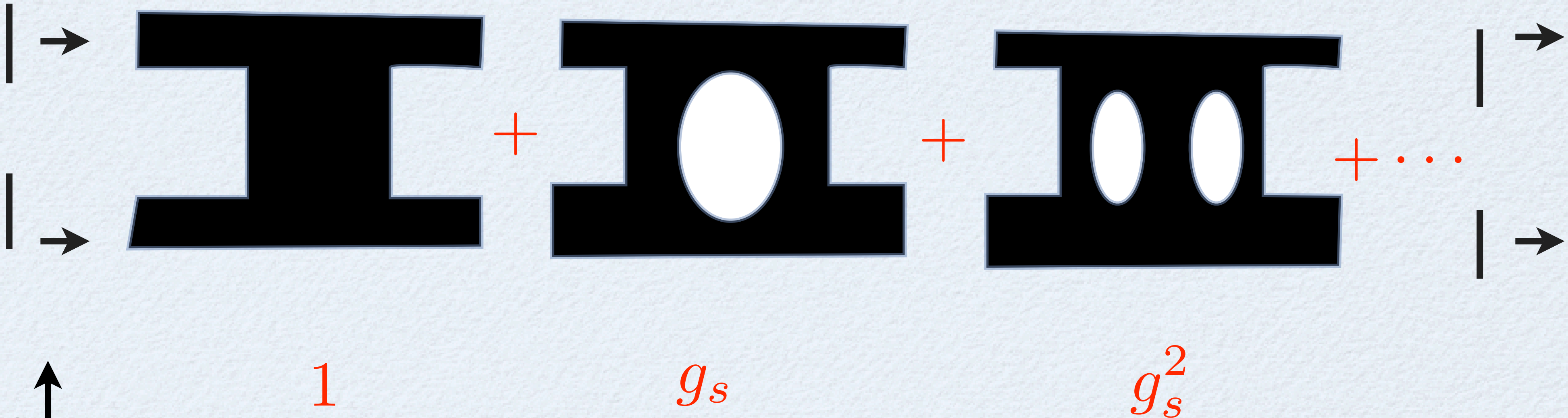


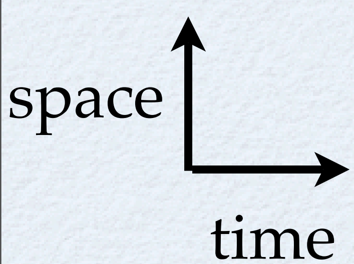
After much work it was discovered that this is the spectrum of quantized, relativistic rotating strings:



$$M^2 = J$$

And a perturbative expansion involving the topology of the world-sheet was developed to describe scattering of strings.





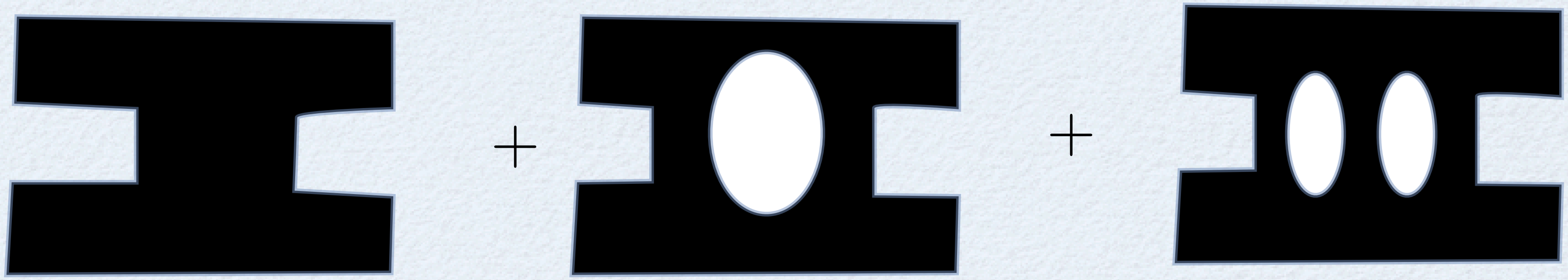
These early glimmering of a stringy formulation of the strong interaction were made more precise in the work of 't Hooft who connected the topological expansion in string theory to the $1/N_c$ expansion in QCD.

QED $\alpha = e^2/4\pi \simeq 1/137$

QCD Let quarks have N_c colors, expand in $1/N_c$. Keep $g_{YM}^2 N_c$ fixed. Of course in the real world $N_c = 3$

This simple idea is quite brilliant because it introduces a small parameter where none was apparent, and the expansion in $1/N_c$ has many features of the observed strong interactions.

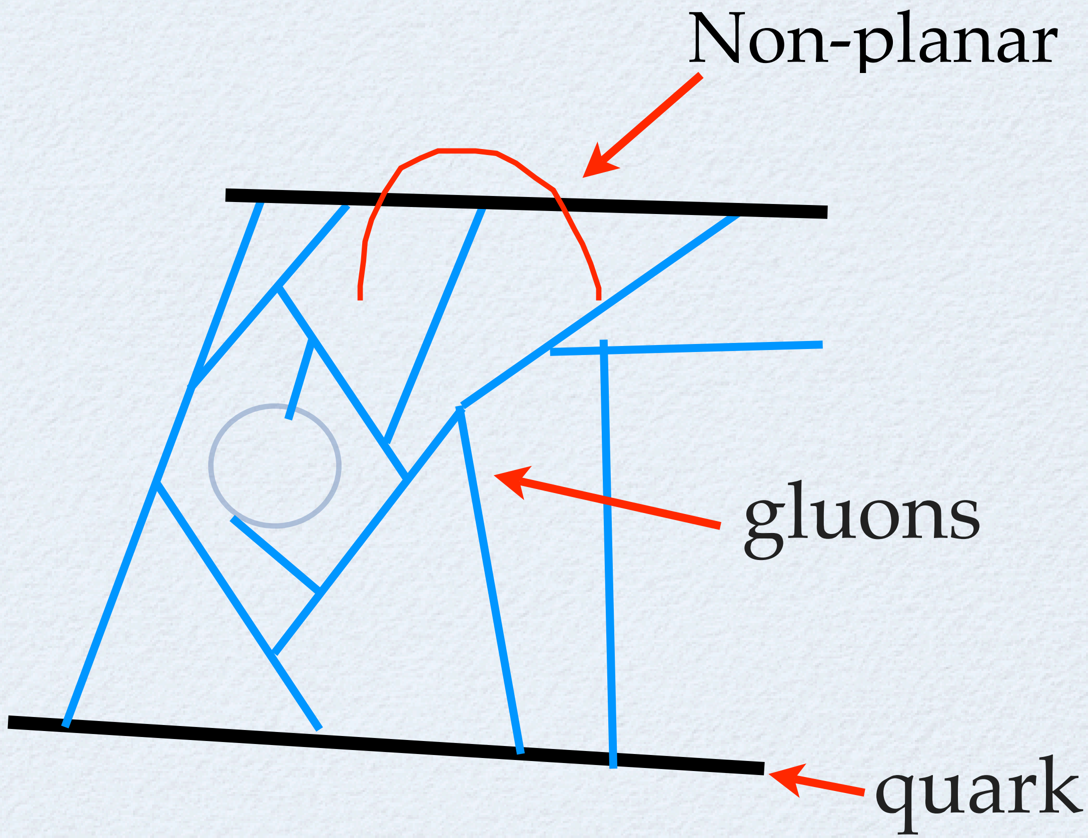
The topological expansion in string theory



is related to the expansion in QCD in the number of quark colors $1/N_c$

Open strings:
HOLES

Closed strings:
HANDLES



The framework needed to turn this observation into a well defined calculational framework were developed in the late 1990's. This involves the subject of gauge/gravity duality which I will turn to later.

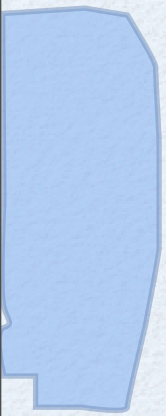
The purpose of this short history is to make you aware that there is a part of string theory which involves the full mathematical formalism of string theory, but which is not being applied to unified theories including quantum gravity, but rather to the study of the strong interactions. It involves an interplay between theory and experiment. It is simply another tool (along with perturbative calculations and lattice gauge theory) for studying phenomena involving the strong interactions, but one that would not have been developed without the full formalism of string theory involving extra dimensions, D-branes and black holes.

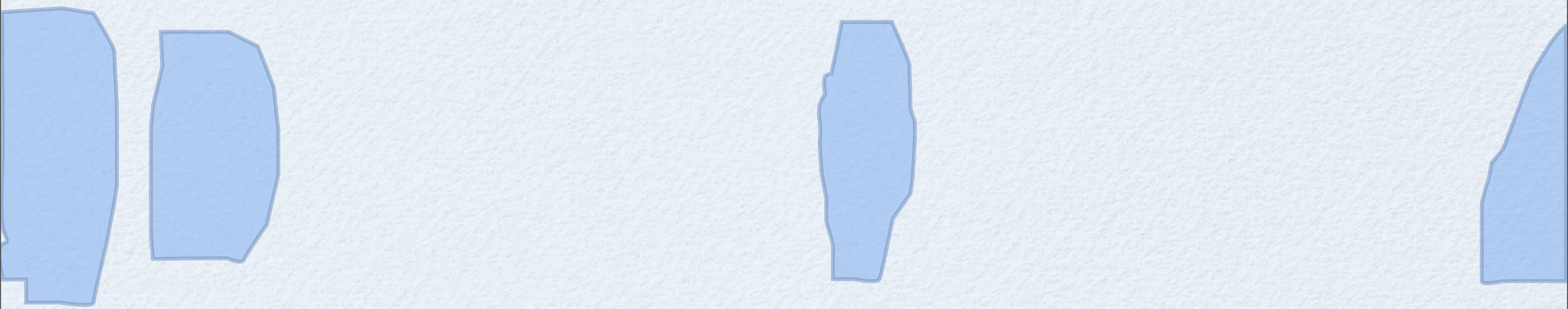
Dualities in String Theory

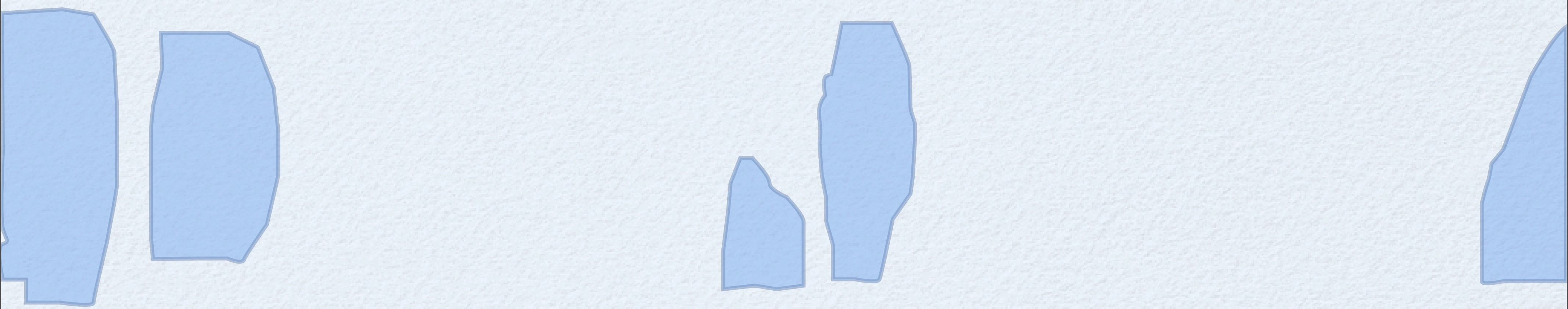
Dual:

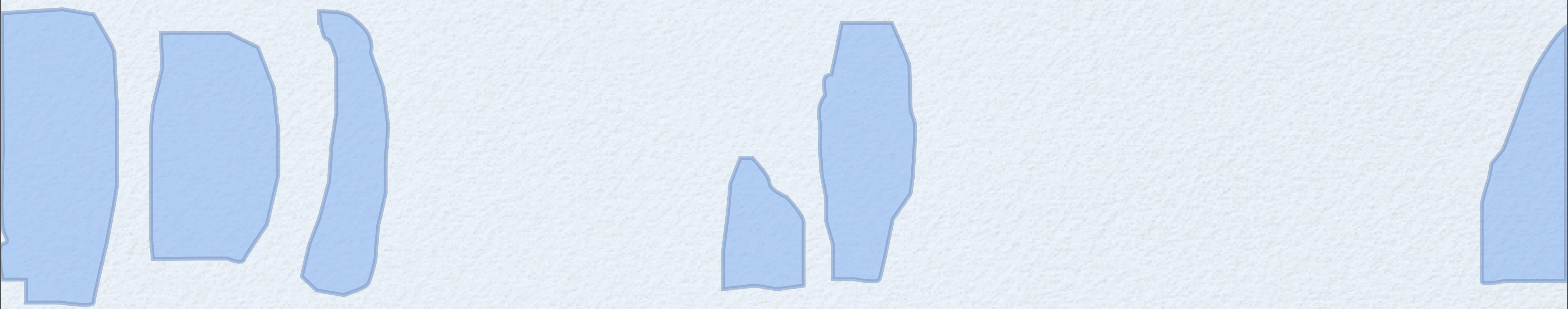
``Having a double character or nature”

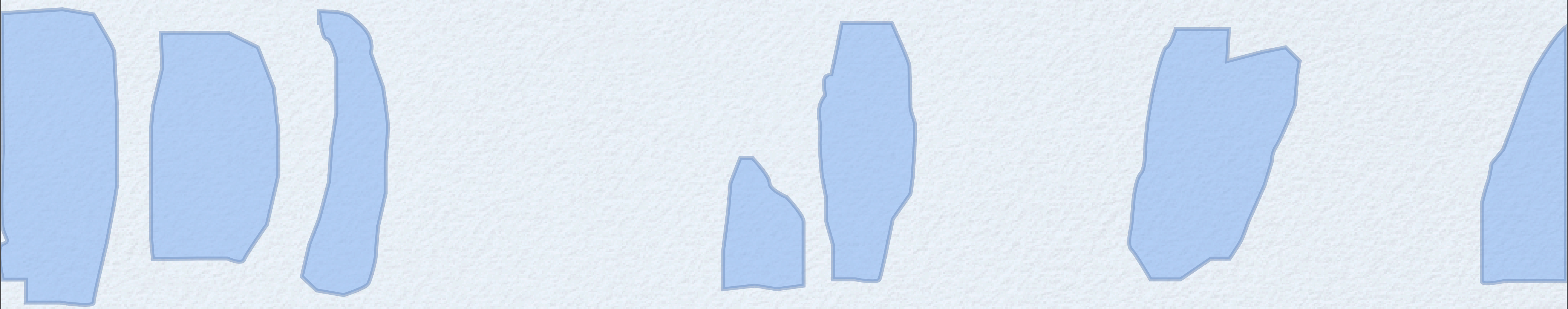
The presence and remarkable power of dualities is one of the hallmarks of string theory. I will illustrate some of these dualities starting with some of the simplest examples and then discuss some of the lessons that can be drawn from these dualities.

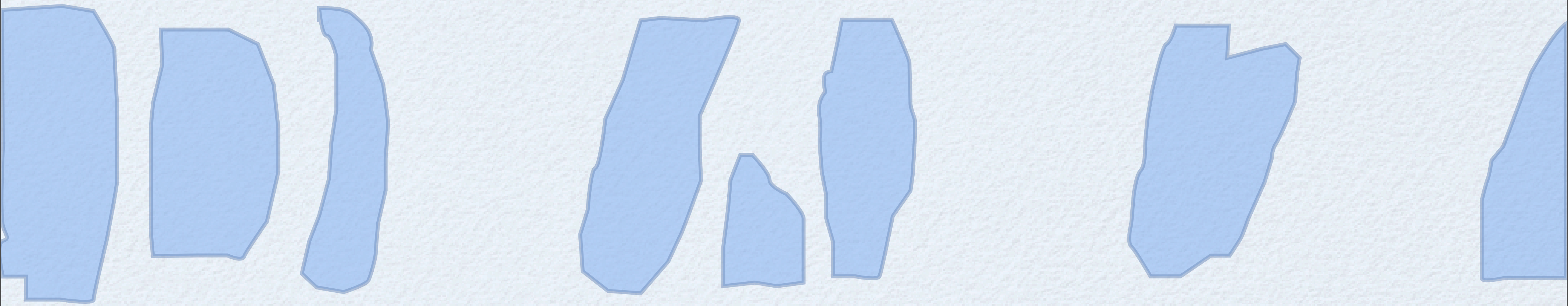


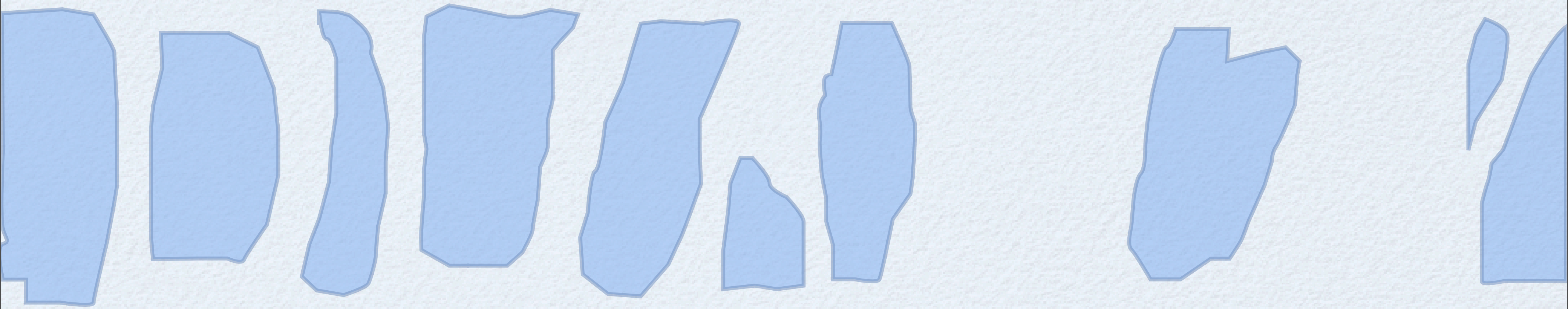


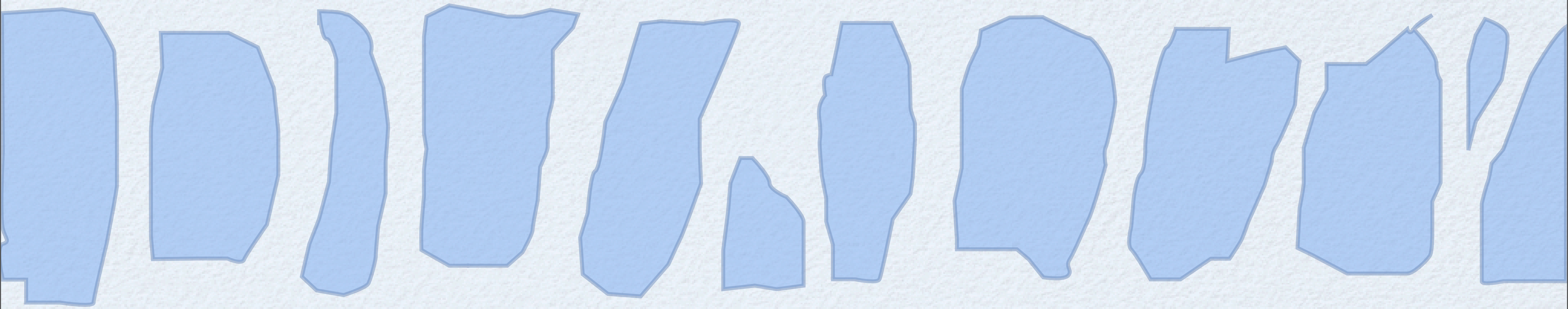


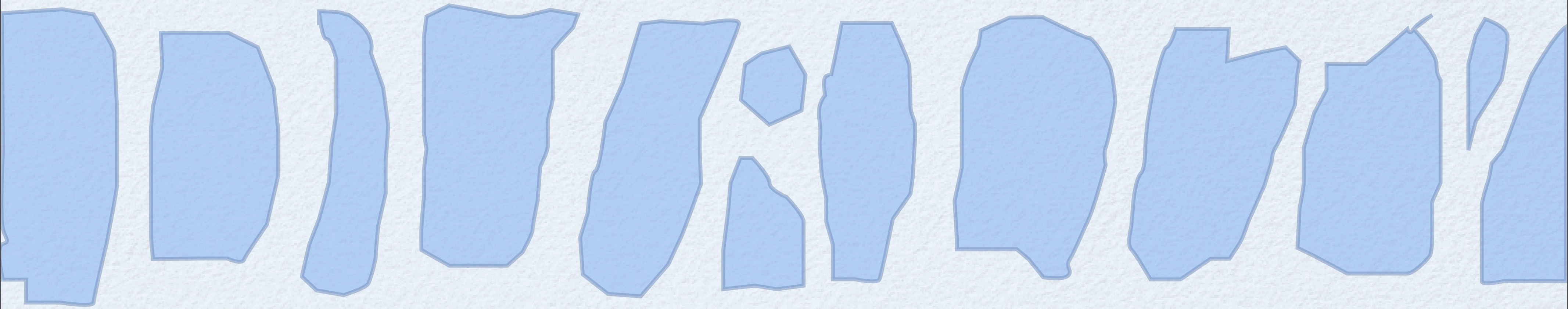


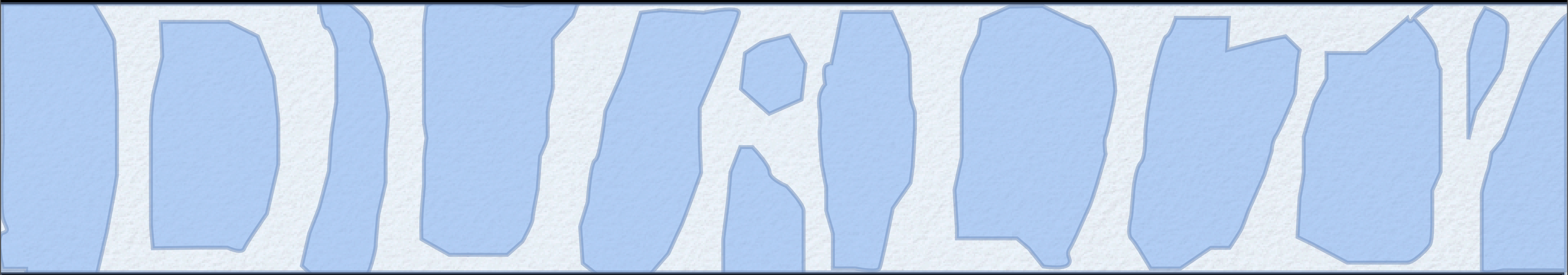


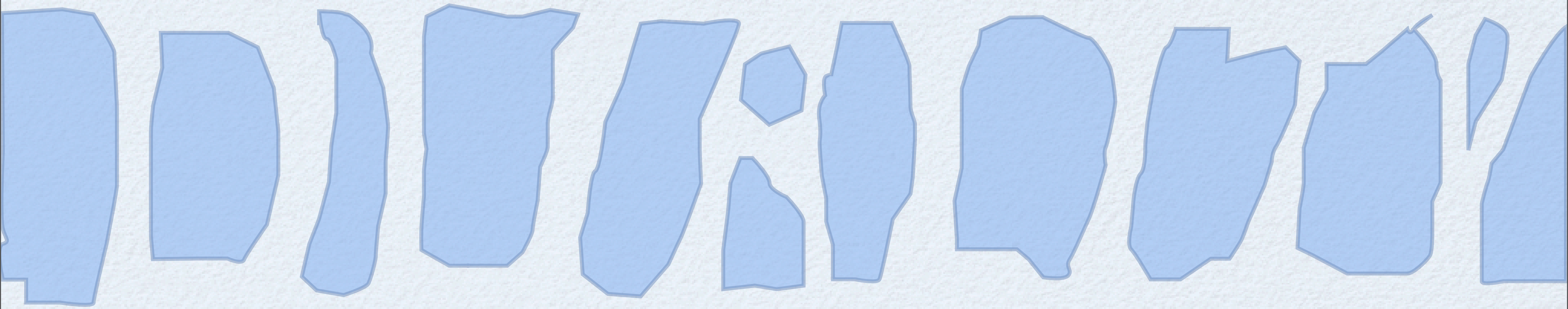




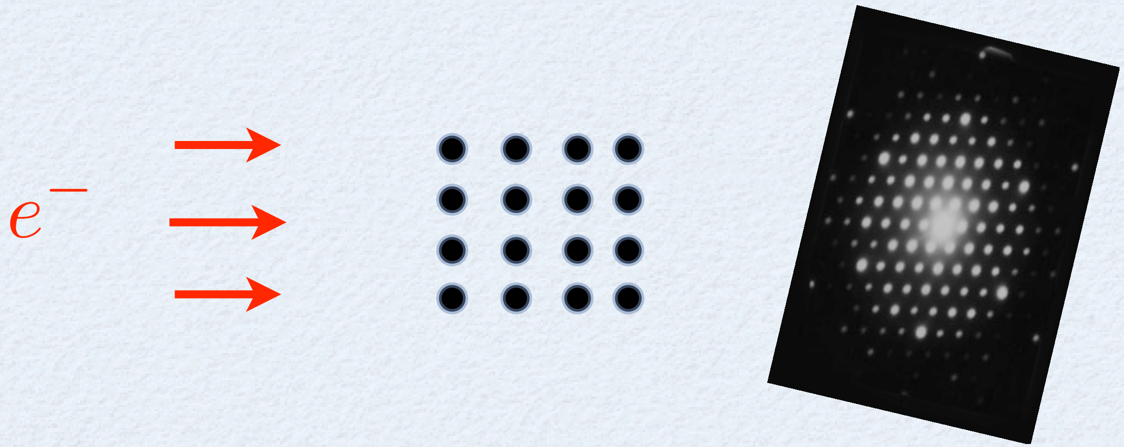








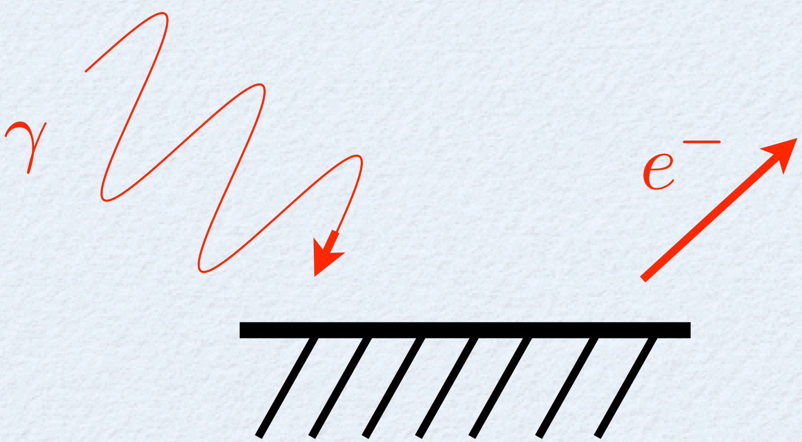
We learn in Quantum Mechanics that particles can act like waves



Electron diffraction
with wavelength

$$\lambda_e = h/p_e$$

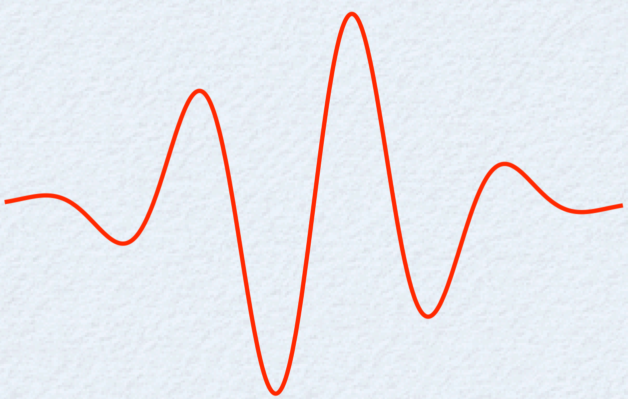
and waves can act like particles

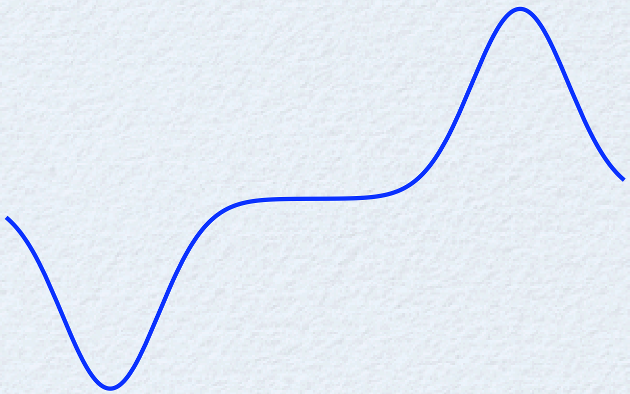


The photoelectric effect
occurs when the
quantized photon energy
is large enough

$$h\nu > W$$

The mathematical representation of this wave-particle duality is via the Fourier transform:

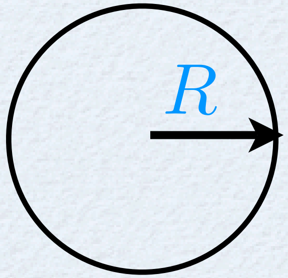




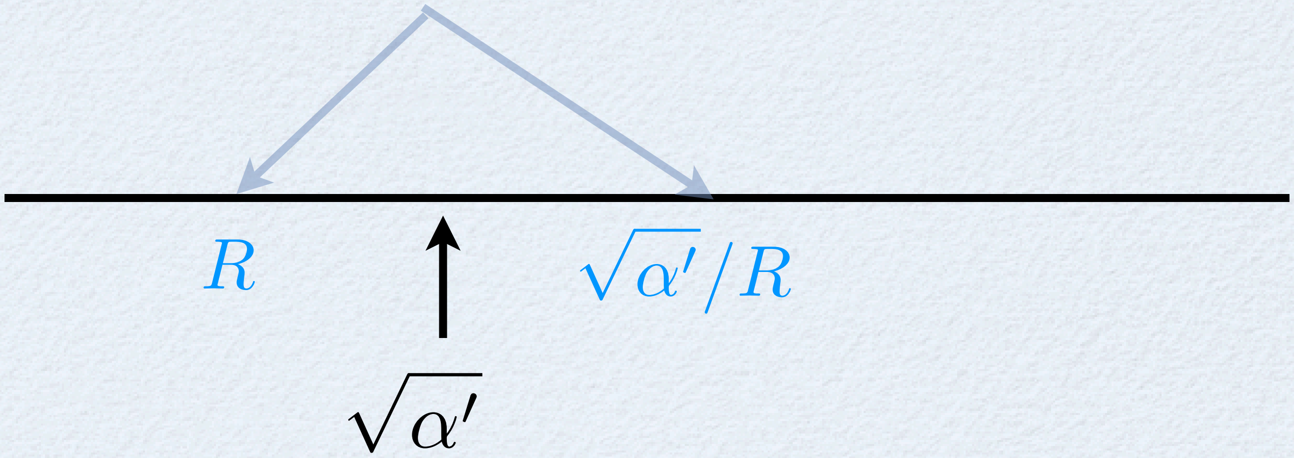
$$f(x) = \int \frac{dk}{2\pi} e^{ikx} \tilde{f}(k)$$

$$\tilde{f}(k) = \int dx \; e^{-ikx} f(x)$$

These give dual points of view: position x or momentum $p = \hbar k$. The fact that both points of view can not both be exact is summarized by the uncertainty principle $\Delta p \Delta x \geq \hbar/2$.



String theory on a circle exhibits T-duality

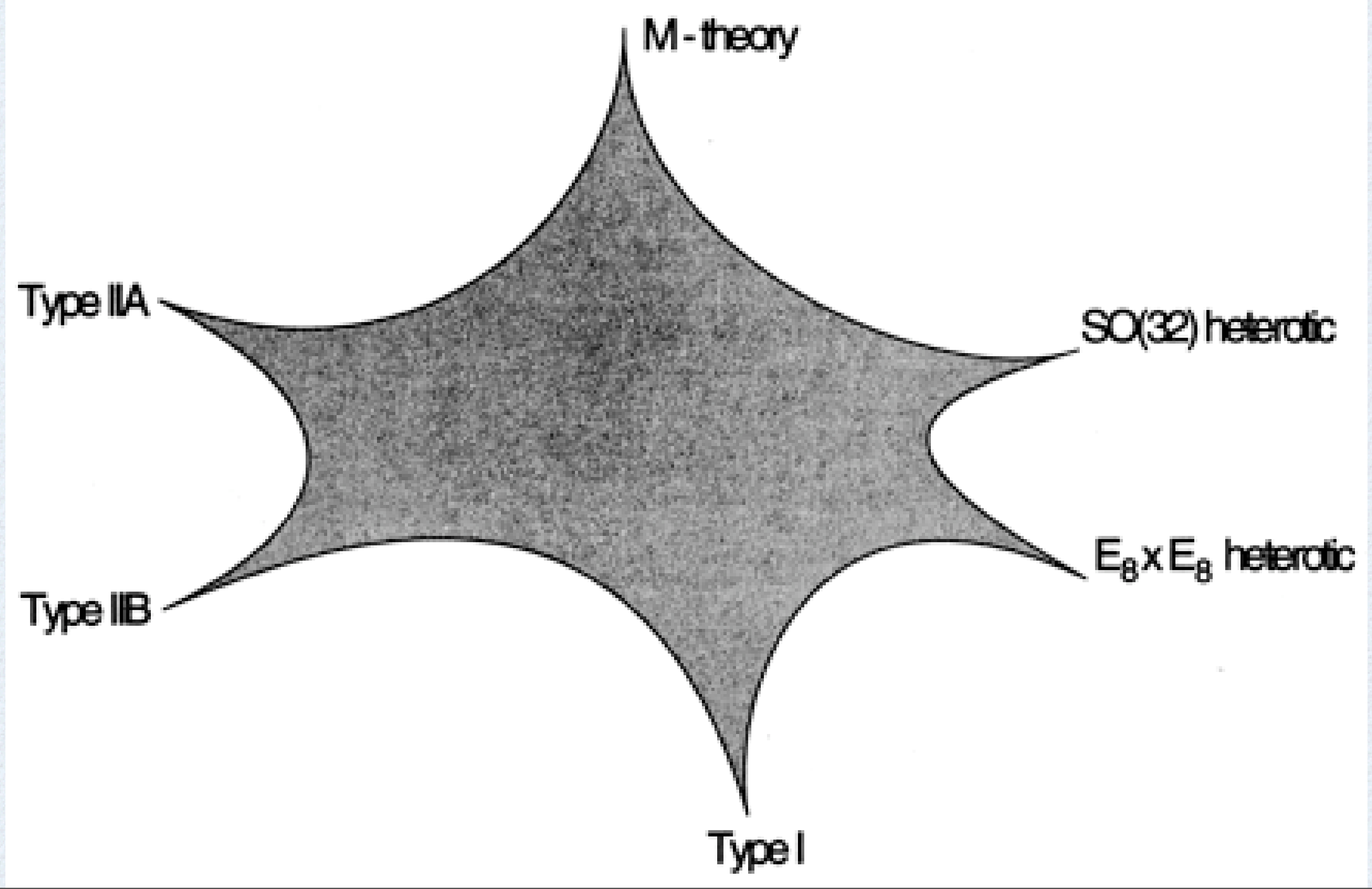


It maps modes of the string with momentum (which are heavy when R is small) to modes of the string with winding (which are heavy when R is large)

It has a generalization to more complicated Calabi-Yau spaces which appear in more ``realistic" versions of string theory where it is known as mirror symmetry and has deep and surprising implications for the mathematical field of enumerative geometry.

This has several interesting implications. One is that our notion of classical background geometry is too naive. There are identifications, redundancies or gauge symmetries relating what are classically very different spaces. A second is a novel resolution of the puzzle of why there isn't an infinite hierarchy of structure as we go to smaller and smaller scales. In string theory very small scales are equivalent to very large scales.

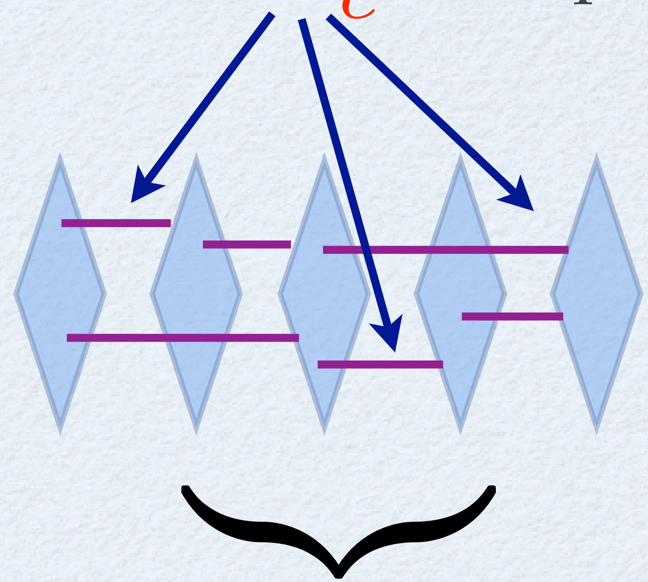
Other dualities discovered in the 1990's relate string theories on different spaces with different values of the coupling constant. These results suggest that there are strong coupling limits of string theory which have a qualitatively different structure known as M theory.



Gauge/String Duality

The understanding of these dualities involved the discovery of D-branes as solutions to string theory. D-branes are extended objects on which open strings can end, and whose dynamics are described by $SU(N_c)$ Yang-Mills theory.

At large N_c one finds a decoupled set of states near coincident D-branes with two different descriptions.



$SU(N_c)$ Yang-Mills with N=4 SUSY

IIB string theory on $AdS_5 \times S^5$

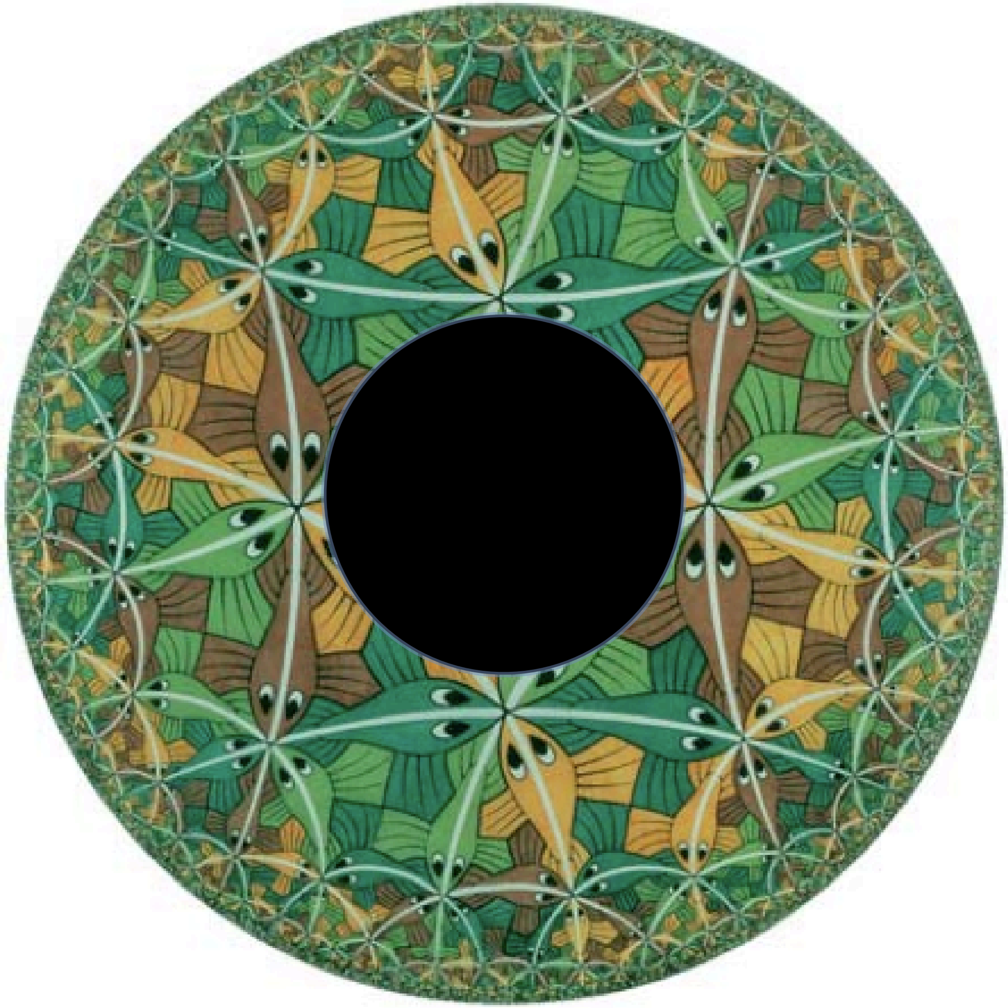
$$\frac{R^2}{\ell_s^2} \sim \sqrt{g_{YM}^2 N_c}$$

This AdS/CFT correspondence was proposed by Maldacena and extended by Gubser, Klebanov,Polyakov and Witten into a well defined scheme for computing quantities in strong coupling, large N_c Super Yang-Mills theory in terms of classical computations in a dual, gravitational theory (the low-energy limit of string theory).

How is this possible?

- The large N_c limit IS a classical limit in which correlation functions factorize: $\langle AB \rangle = \langle A \rangle \langle B \rangle + O(1/N_c)$
- Gravitational theories in asymptotically AdS spaces are not well defined without a specification of boundary conditions.
- Black Hole entropy ~ Area suggests gravitational theories have fewer degrees of freedom than field theories.

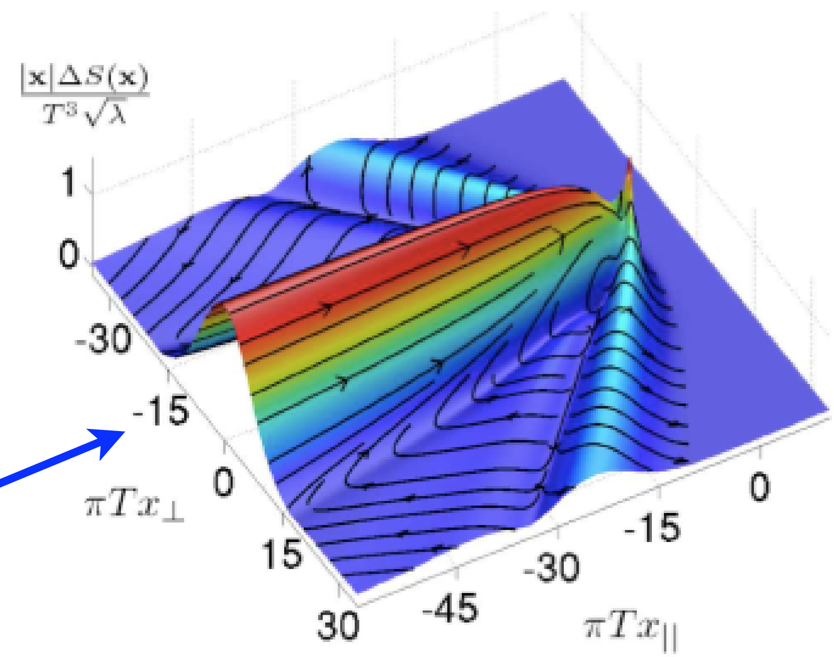
To study QCD at finite temperature add a Black Hole to AdS. The temperature is the Hawking temperature!



RHIC Physics:

Viscosity/entropy of quark-gluon plasma

Drag/energy loss



Energy flux of a quark moving through the quark/gluon plasma (Chesler&Yaffe)

Background Independence

What is background independence?

How much background independence should we expect or want?

How much background independence do we find in current formulations of string theory?

In many physical systems it makes sense to divide the system into a macroscopic part and small, fluctuating part. Some examples:

- In the description of gravitational waves in General Relativity one writes the metric as $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ and expands to second order in $h_{\mu\nu}$.
- In the Higgs mechanism which breaks the electroweak symmetry of the Standard Model, or in the study of superconductivity, one writes the Higgs field (Cooper pair wave function) as constant, classical part plus a fluctuation $\phi_H(x) = \phi_c + \delta\phi(x)$.

The classical part is the background. When quantum mechanics is taken into account the quantized fluctuations manifest themselves as particle-like excitations above the background (e.g. the graviton and the Higgs boson)

Of course if the fluctuating part becomes very large this separation is no longer useful and other techniques must be used. The background is not forever fixed and unchanging as in the Newtonian view of space and time, rather one simply treats the changes as small because that is often a good approximation. In some cases we don't fully understand the theory when the fluctuations become large. This is true of General Relativity since large fluctuations form black holes with singular spacetimes that cannot be fully described by Einstein gravity.

Background independence is the demand that the theory not require a specification of the background in advance, but rather it should emerge as a solution to equations of motion which make no reference to any preferred background, as in General Relativity.

String theory as formulated in the mid 80's involves this kind of separation into background and fluctuations, but the equations which determine the allowed backgrounds are those of Einstein gravity with additional fields at large distances, and the fluctuations include fluctuations of the background geometry. If this is background dependence it is a much weaker form of it than claimed by some critics of string theory. Of course with no classical background at all it is hard to interpret what the theory means, a problem which has not been resolved by loop quantum gravity which has the problem of demonstrating that any kind of classical spacetime emerges from the theory.

The AdS/CFT correspondence sheds some additional light on this issue. It gives a formulation of string theory not just on Anti de Sitter spacetime, but on any spacetime which has the same behavior as AdS at its boundary. It is independent of the bulk background, but not of the boundary background.

The dynamics of gravity, the possible observable quantities, and the required boundary conditions are dramatically different in Minkowski space than in spaces asymptotic to AdS. For example, in AdS light rays can reach the boundary and return to an observer, thus requiring boundary data to specify the time evolution of physical quantities. In Minkowski space on the other hand one only needs data on an initial time slice.

A formalism which is independent of the choice of boundary behavior may or may not exist. It is not clear what problem would arise if it did not exist since no finite energy excitation can change the boundary behavior of such spacetimes. In philosophical discussions of background independence in any theory of quantum gravity care should be made to distinguish independence of the bulk background from independence of the boundary background since these play different physics roles in the theory.

Emergent spacetime

The AdS/CFT correspondence provides us with an example of a theory with different classical limits, and each classical limit has different emergent structures. One limit has gauge theory and gauge symmetry in a four-dimensional space time, the other has gravitational theory and diffeomorphism invariance in a five-dimensional spacetime. Other examples of the phenomenon of emergent spacetime and emergent gauge symmetries include the Matrix formulation of 11d supergravity and dual descriptions of various supersymmetric theories where different gauge theories govern different limits of the underlying theory.

One reason this is possible is that gauge symmetries are not real symmetries, they are redundancies in our description of the physics, apparently required by locality. Of course we do not yet know if our spacetime is emergent, but these ideas suggest that it is. Neither string theory nor loop quantum gravity has yet given a convincing explanation of what structure it may emerge from.

Comments on the peculiar position occupied by string theory

I have not discussed string theory as a unified theory encompassing both the Standard Model of the weak, electromagnetic and strong interactions and quantum gravity. In part because I assume this idea is familiar from other sources and in part because this leads into ideas of the landscape and multiverse about which I have a generally skeptical attitude and little wisdom to impart. This part of string theory has of course not been confirmed by empirical observation, nor is it likely to be in the near future. It critics have called it pathological science, religion, a cult, and so on.

String theory also has remarkable ties to many areas of modern mathematics including algebraic geometry, enumerative geometry, Lie algebra theory and its extensions, finite group theory, modular functions and the Langlands program. Yet its methods and goals are usually not those of mathematics. In particular there is little emphasis on mathematical proof which is to mathematics what empirical confirmation is to science. Yet it works. I asked about the influence of string theory on mathematics on the math Q&A site Math Overflow and got the following response:

Dear Jeff, string theory has had a colossal influence on the renewal of enumerative geometry, a two century old branch of algebraic geometry inextricably linked to intersection theory. Here is a telling anecdote.

Ellingsrud and Strømme, two renowned specialists in Hilbert Scheme theory, had calculated the number of rational cubic curves on a general quintic threefold by arguments based on their paper

On the Chow ring of a geometric quotient, Annals of Math. 130 (1987) 159–187

Their result differed from that predicted by string theory. Of course everybody thought the mathematicians were right, but actually there had been a programming error in their calculations and the correct result was that of the physicists (which Ellingsrud and Strømme confirmed after fixing their bug).

This was the beginning of a long list of results predicted by string theorists and subsequently proved by mathematicians, a celebrated example being Kontsevich's formula.....

–Georges Elencwajg

It is certainly an odd state of affairs when a ``pathological science" finds and corrects the errors of leading mathematicians.

I do not suggest that we abandon the demand for empirical tests of string theory, but neither do I see any reason why the time required for these tests must fit neatly into the current lifespan of a scientific career. Quantum Field Theory and General Relativity were subject to early experimental confirmation, but these tests only involved very limited aspects of the theory. Other, more involved parts of the theory have required 50+ years of investigation both to be understood and to be tested.

In any event, a rich set of ideas has emerged from string theory, some of which I presume might be of interest to philosophers of science. It has connected very different areas of physics and has application to more established areas of physics which are subject to experimental tests. It provides an example of a theory of quantum gravity which allows one to obtain physically sensible, finite answers and has predicted many nontrivial mathematical results. It also occupies a unique place in the history of science.