String Theory: Then and Now

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Saturday 21st May 2016

Mornings of Theoretical Physics

The World in 1968


L'OSSERVATORE ROMANO

EDITORIAL AND MANAGEMENT OFFICES VATICAN CITY

Price: 60 lire

WEEKLY EDITION IN ENGLISH

UNICUIQUE SUUM NON PRAEVALEBUNT

FIRST YEAR

N. 19 — August 8, 1968

Annual Subscription: Italy Lit. 3,000 — Abroad - Air Mail: European Countries $ 7 U.S. - Outside of Europe $ 15 U.S.

ENCYCLICAL LETTER «HUMANAE VITAE»

ENCYCLICAL LETTER OF HIS HOLINESS

POPE PAUL VI

ON THE REGULATION OF BIRTH

To the Venerable Patriarchs Archbishops and Bishops and other Local Ordinaries in peace and communion with the Apostolic See to Priests, the Faithful and to all men of good will

Particle Physics in 1968

- Quantum electrodynamics is established as the correct theory describing the electromagnetic interactions
- The strong and weak interactions are a mystery
- The weak interactions have a phenomenological description with Fermi theory, which is known to break down at high energies (around 100 Giga-electronVolt)
- In strong interaction experiments, a zoo of particles is known, but the underlying logic is mysterious…$p, n, \pi^0, \pi^\pm, K^0, K^\pm, \rho, \eta, \Lambda, \Omega, \Sigma$ …

"If I could remember the names of all these particles, I'd be a botanist"

Enrico Fermi

Open Problems in 1968

- How to understand the strong interactions?

  1. What is the organising principle of the strong interactions?

  2. How can one make calculable predictions for them?

  3. There are many approaches – Regge theory, the analytic S-matrix, bootstrap methods, total nuclear democracy, quantum field theory – which is the key that turns the lock?

The first ever paper on string theory

IL NUOVO CIMENTO Vol. LVII A, N. 1 1° Settembre 1968

Construction of a Crossing-Simmetric, Regge-Behaved Amplitude for Linearly Rising Trajectories.

G. Veneziano (*)
CERN - Geneva

(ricevuto il 29 Luglio 1968)

Crossing has been the first ingredient used to make Regge theory a predictive concept in high-energy physics. However, a complete and satisfactory way of imposing crossing and crossed-channel unitarity is still lacking. We can look at the recent investigations on the properties of Reggeization at $t=0$ as giving a first encouraging set of results along this line of thinking (1). A technically different approach, based on superconvergence, has been also recently investigated (2), and the possibility of a self-consistent determination of the physical parameters, through the use of sum rules, has been stressed.

In this note we propose a quite simple expression for the relativistic scattering amplitude, that obeys the requirements of Regge asymptotics and crossing symmetry in the case of linearly rising trajectories. Its explicit form is suggested by the work of

The first ever paper on string theory…

- …. Does not mention strings ANYWHERE in the paper!

- Veneziano proposes a formula to describe the scattering of strongly interacting particles

$$\frac{\Gamma(-1+\frac{1}{2}(k_1+k_2)^2)\Gamma(-1+\frac{1}{2}(k_2+k_3)^2)}{\Gamma(-2+\frac{1}{2}((k_1+k_2)^2+(k_2+k_3)^2))}$$

- This formula is now called the *Veneziano amplitude.*

‘Dual Resonance Models’: 1968 - 1973

- Veneziano’s paper triggered a burst of work on what would be called *Dual Resonance Models*
- The aim was to understand Veneziano’s formula, generalise it to other processes, and make predictions for strong interaction physics

  Joel Shapiro:

  This paper arrived at [the lab in] Berkeley in the summer of 1968….and I returned to find the place in a whirlwind of interest. Everyone had stopped what they were doing, and were asking if this idea could be extended.

‘Dual Resonance Models’: 1968 - 1973

- In this period another surprising result was found by Claud Lovelace:

  The dual resonance models were only consistent in twenty-six dimensions

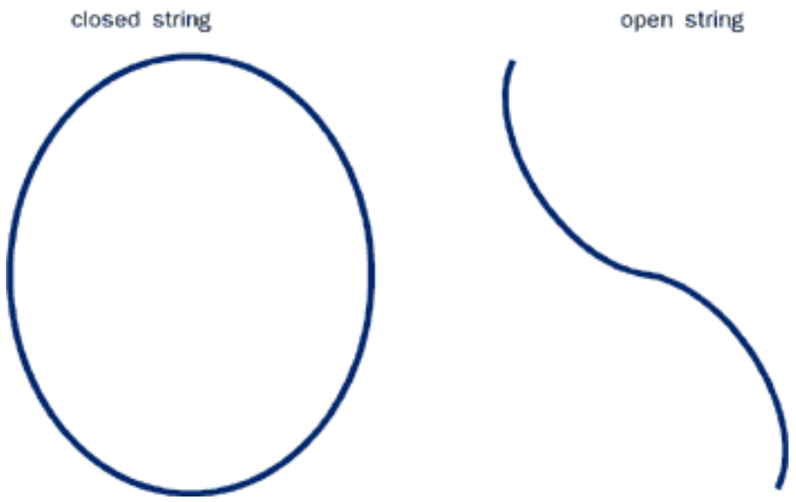
- Reaction:

  I was the only professor not being promoted despite the many citations of my papers. However, the jeers of the physics establishment did have one good consequence. When my discovery turned out to be correct....they remembered that I had said it first. One has to be very brave to suggest that spacetime has 26 dimensions.

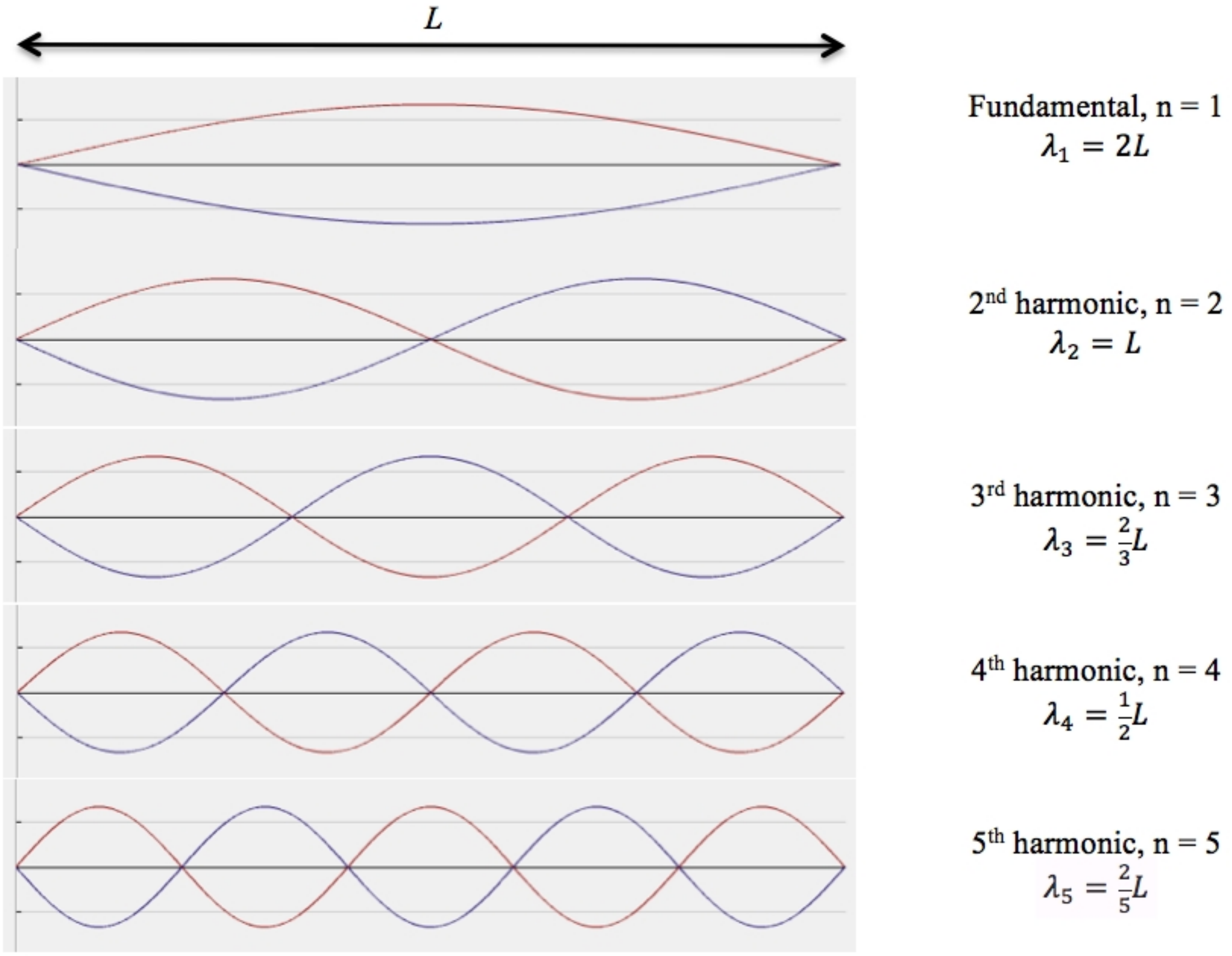
The Naming of String Theory

- ‘String theory’ starts as Yoichiro Nambu and others realise in 1971 that the Veneziano amplitude arises from a theory of quantum mechanical, relativistic strings
- What do strings do?

1. They oscillate in many different modes
2. If you pluck them, they vibrate
3. Two kinds of string: open and closed

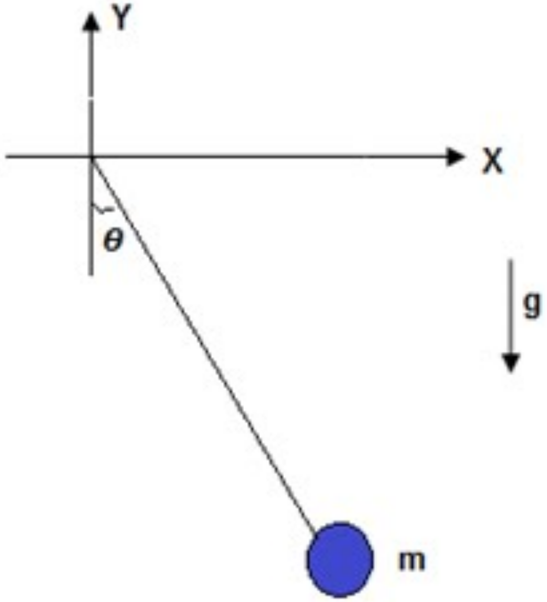


Strings oscillate at their harmonics



Strings and Harmonic Oscillators

- A string corresponds to an *infinite number* of harmonic oscillators.



“The career of a young theoretical physicist consists in treating the harmonic oscillator in ever-increasing levels of abstraction.” Sidney Coleman

The Simple Harmonic Oscillator

- The simple harmonic oscillator is the most important system in physics
- The kinetic energy is $\frac{1}{2}mv^2$ and the potential energy $\frac{1}{2}m\,\omega^2 x^2$
- The classical equations of motion are

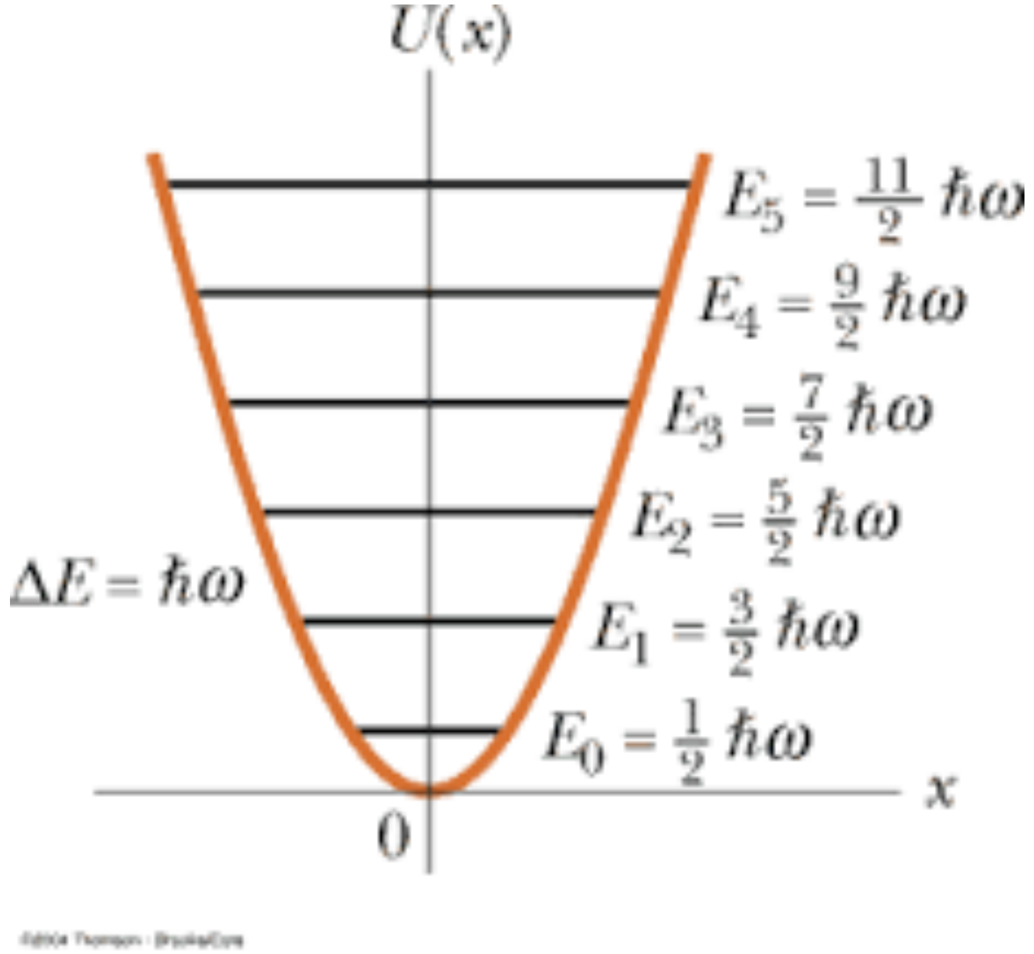
$$m\ddot{x} = -m\omega^2 x$$

with an oscillating solution

$$x = A\cos(\omega\, t + \ \phi)$$

The world is quantum.

For a *quantum harmonic oscillator,* we should instead use discrete energy levels.



The Quantum Harmonic Oscillator

- The spectrum of the quantum harmonic oscillator is

$$E_0 = \frac{1}{2}\hbar\omega$$

$$E_1 = (1+ \frac{1}{2})\hbar\omega$$

$$E_2 = (2+ \frac{1}{2})\hbar\omega$$

$$E_3 = \left(3 + \frac{1}{2}\right)\hbar\omega$$

- The *n*th state of the harmonic oscillator is labelled |n>

Strings and Harmonic Oscillators

- A string can oscillate in *every direction transverse to its length*
- The frequency of each harmonic is an integer multiple of the fundamental frequency

$$\omega_n = n\,\omega_0$$

- *Every harmonic corresponds to a individual quantum harmonic oscillator*
- Allowed states of the string correspond to the particles present in the Veneziano amplitude.

Strings and Harmonic Oscillators

- The quantum state of a string is labelled by the excitation mode for each harmonic oscillator
- A string in *D* space-time dimensions has (*D-2)* directions it can oscillate in
- In each direction, there is a first harmonic, second harmonic, third harmonic….
- The quantum state of a string along x-direction is labelled as

$$|n_1^y, n_2^y, n_3^y, \ldots., n_1^z, n_2^z, n_3^z, \ldots.. n_1^{z'}, n_2^{z'}, n_3^{z'}, \ldots.. >$$

String theory: 1968 - 1973

- In this period, ‘string theory’ is a candidate theory for the strong interactions

- It was also not called ‘string theory’, but *Dual Resonance Models*

- The aim is to associate the excited states of vibrating strings with the hadrons of the strong interactions.

$$|\, Vibrating\ strings > \equiv |Strong\ interaction\ hadrons > ?$$

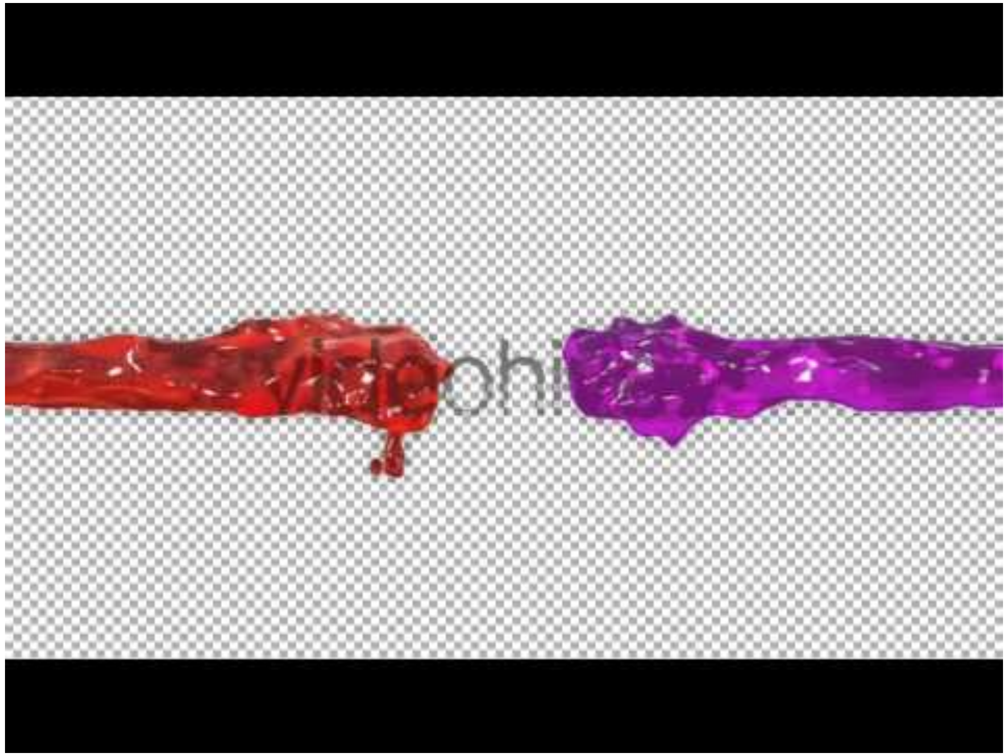
$$Hadron\ Interactions \equiv String\ Interactions\ ?$$

- What are the characteristic predictions of string interactions?

Strings are extended objects

They have *soft* scattering

They scatter like jelly and not like snooker balls – they do not scatter at large angles



What happens in 1973?

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.[1] In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically ap-

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

What happens in 1973?

- Gross, Politzer and Wilczek establish Quantum Chromodynamics as the theory of the strong nuclear force
- Just like the electromagnetic and weak forces, the strong force is *also* described by a quantum field theory
- The predictions of Quantum Chromodynamics are confirmed and re-confirmed in multiple experiments
- Quark and gluons scatter like snooker balls and not like jelly

- String theory as a theory of the strong interactions is dead.

What happens in 1973?

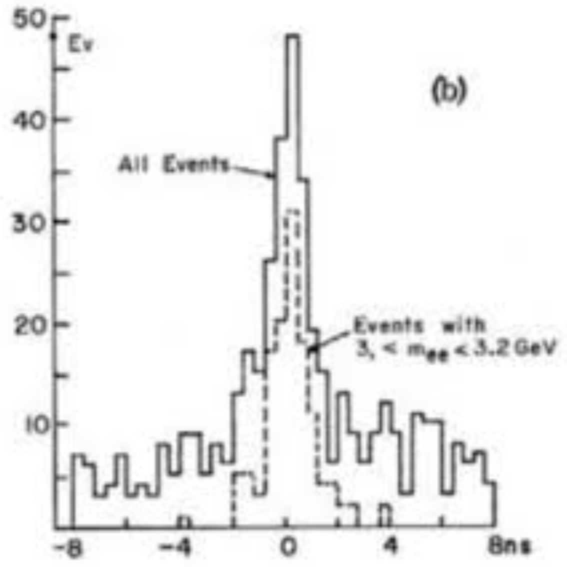
- Joel Scherk and John Schwarz propose a re-interpretation of string theory.
- One of the oscillatory modes of closed strings has the same properties of the *graviton* - the hypothesised quantum carrier of the gravitational force.
- $String\ Interactions\ \equiv Quantum\ Gravitational\ Interactions$?
- Very few people care!

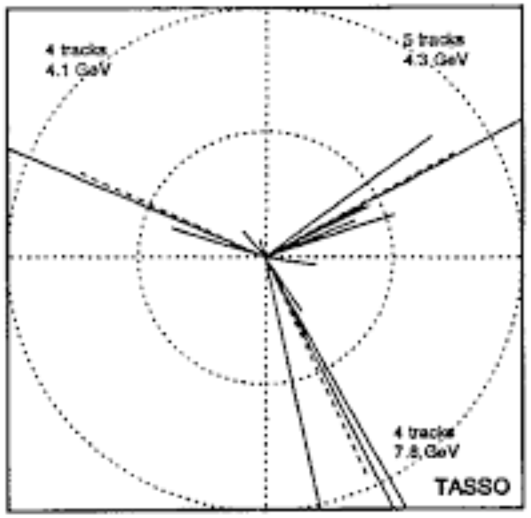
Particle Physics 1973 - 1984

- The golden age of quantum field theory

- New particles discovered

  1. Charm quark in 1974
  2. Tau lepton in 1975
  3. Bottom quark in 1977
  4. Gluon in 1978





- Jets discovered
- Predictions of Standard Model confirmed and reconfirmed….

String theory 1973 - 1984

- Some people think string theory may lead to a quantum theory of the gravitational force…..

  ….almost no-one is interested.

- String theory is a minor topic on the periphery of what is respectable

- A few people continue to work on it, but most have their attention elsewhere

String theory: 1973 - 1984

- John Schwarz:

  We felt that string theory was too beautiful to be just a mathematical curiosity. It ought to have some physical relevance. We had frequently been struck by the fact that string theories exhibit unanticipated miraculous properties…they have a very deep mathematical structure that is not understood. By digging deeper one could reasonably expect to find more surprises and then learn new lessons.

- A series of technical advances improves understanding

- The ‘superstring’, which requires ten space-time dimensions, solves consistency issues with the bosonic string (26 spacetime dimensions)

String Theory in 1984

- ’The First Superstring Revolution’
- A calculation by Michael Green and John Schwarz shows that string theory solves a problem in standard ’supergravity’ approaches to quantising the gravitational force.
- The result reaches Edward Witten in Princeton – who was by now one of the most influential physicists in the world
- He adopts string theory – and everyone else follows.
- The failed theory of the strong interactions becomes the number one most fashionable topic in particle physics

String Theory from 1984

- This is a period of triumphalism

- String theory is viewed as a consistent theory of ten-dimensional quantum gravity

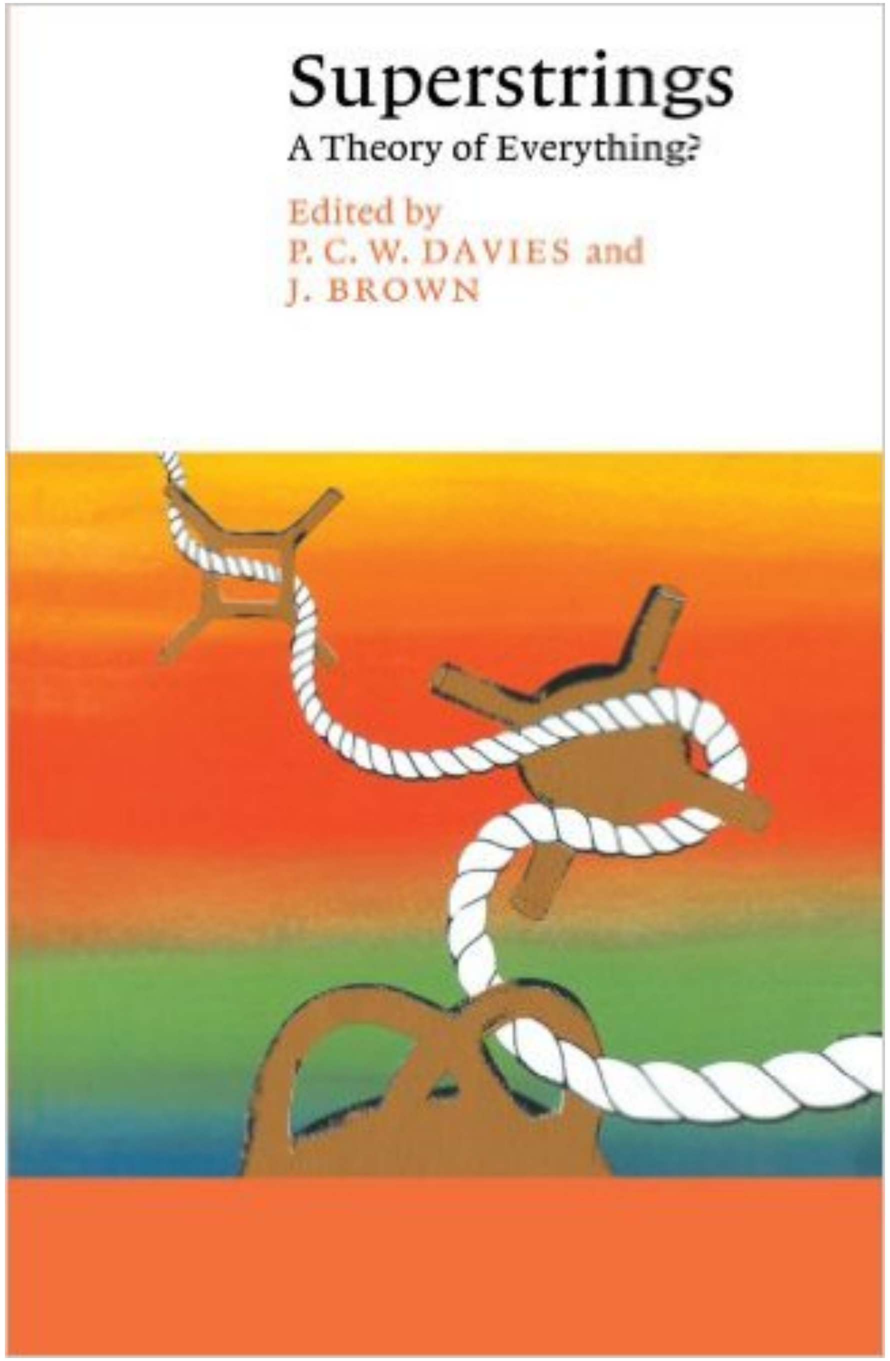
- Reduction of this theory to four dimensions will give the Standard Model of particle physics and explain the value of its constants (the details were still to be filled in, but it was thought these would not take very long….)

The Age of Excitement

- *'We study candidate vacuum configurations in.....superstring theory that have unbroken N=1 supersymmetry in four dimensions. This condition permits only a few possibilities, all of which have vanishing cosmological constant.'*

  from the paper *Vacuum Configurations for Superstrings* in spring 1985.

- Today, there are at least 473 800 776 similar possibilities known!



(1988)

”…. a remarkable new theory has captured the imagination of physicists. Known as… superstring theory, it promises to proved a unified description of all forces, all the fundamental particles of matter, and space and time – in short, a Theory of Everything. “

1995: ‘The Second Superstring Revolution’

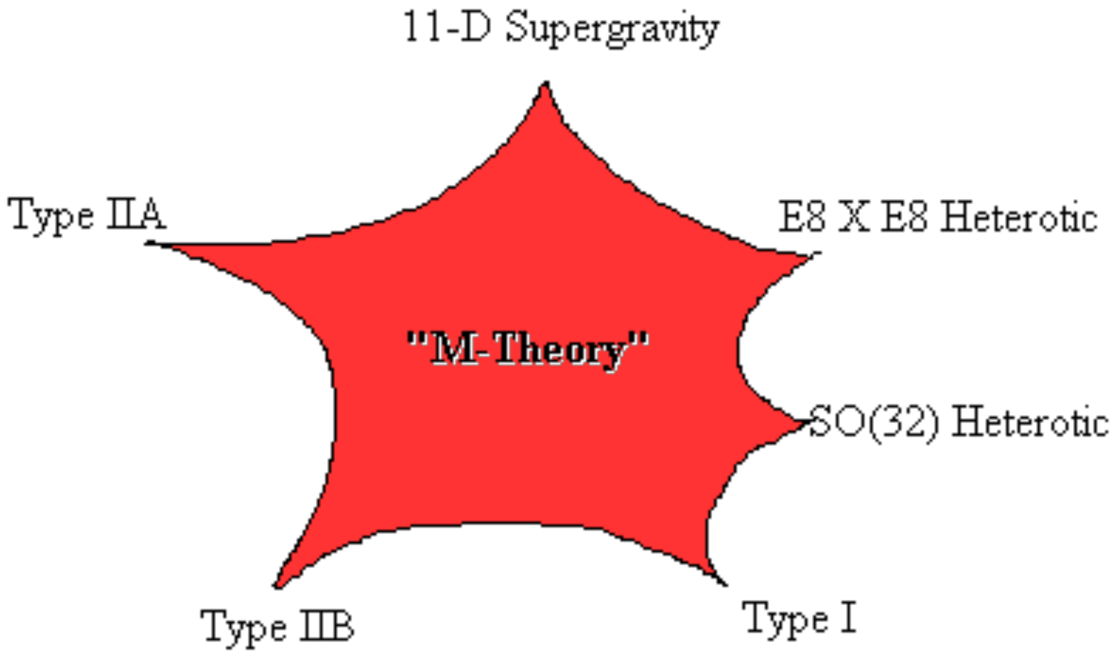
- Traditionally, this starts with a talk by Edward Witten at the Strings 1995 conference in Santa Barbara

  Witten integrates his and others’ insights into a new picture of the subject
- String theory is a limit of ‘M-Theory’, a mysterious 11-dimensional theory known from its boundaries.
- Away from the boundaries, M-theory is not a theory of strings
- What does ‘M’ stand for: ‘magic’, ‘mother’, ‘mystery’, ‘membrane’?

1995: ‘The Second Superstring Revolution’

All different types of string theory are viewed as different limits of a single over-arching theory

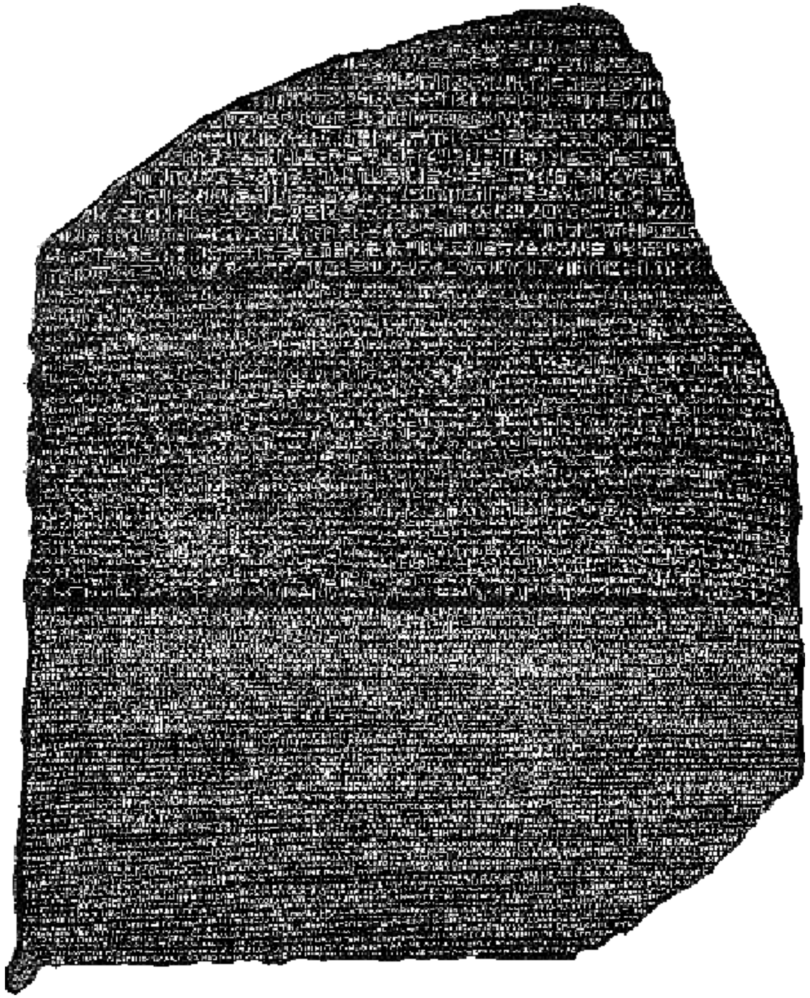
This over-arching theory is dubbed “M-Theory”



1997 : AdS/CFT

- In November 1997 the Argentinian physicist Juan Maldacena proposes a correspondence between certain string theories and certain quantum field theories
- Certain string theories are *identical* to certain quantum field theories
- Calculations in one are entirely equivalent to calculations in the other
- Result is both deep and useful! (cf Andrei Starinets' talk)

1997: AdS/CFT



Different words, different languages….the same text.

The same is true with AdS/CFT

The same physics can be described EITHER with string theory OR with quantum field theory

Different symbols and different equations can describe the same physics

AdS/CFT

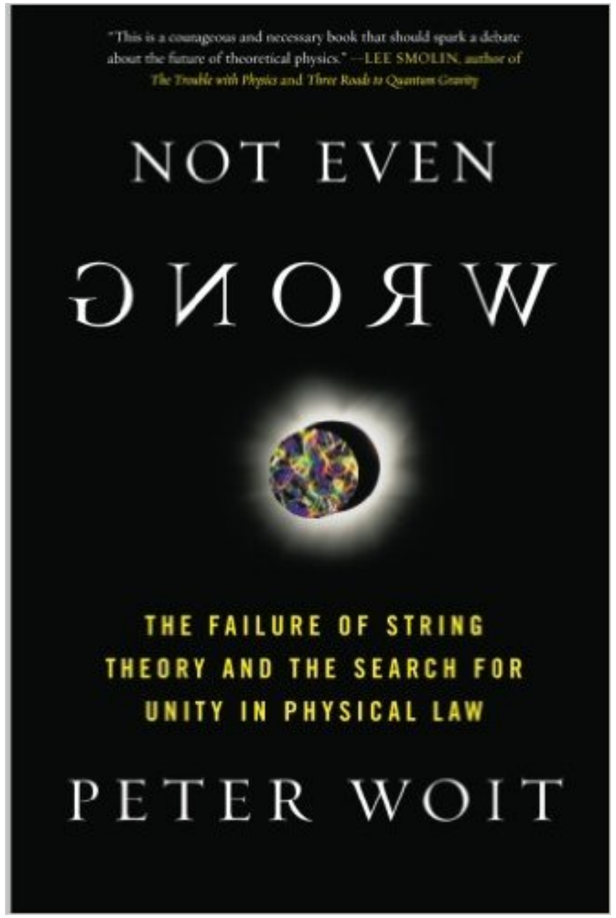
- The original paper on AdS/CFT is now the most cited paper *ever* in theoretical particle physics

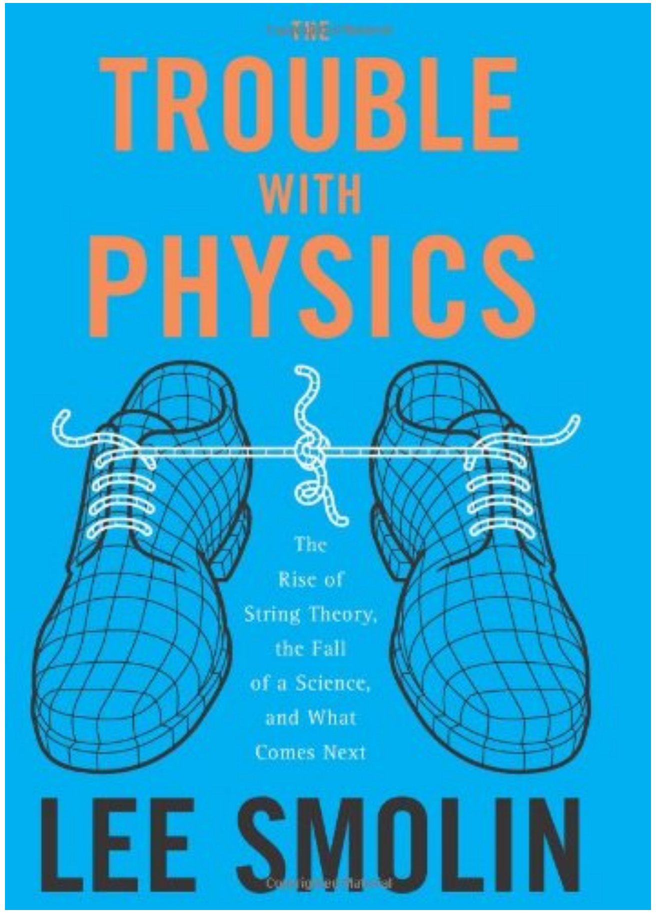
  (even more than the foundational papers of the Standard Model…..)

- It is the start of a period where string theory is used as much for its applications to other areas as for a fundamental theory of physics

- String theory and its method are used as tools in many areas of mathematics and quantum field theory

String Theory: The Backlash





‘String theory’ in 2016

- First, it is not (mostly) about strings.

  1. Most ‘string theorists’ do not work on the theory of quantised, relativistic strings

- Second, it is not (mostly) about quantum gravity

  2. Only a small fraction of ‘string theorists’ work on understanding the quantum aspects of the gravitational force

‘String Theory’ in 2016

- ‘String Theory’ today involves research on many different topics for many different reasons:

  Quantum gravity, particle physics, cosmology, mathematics, quantum field theory
- It involves different communities who use different tools and care about different things
- The ideas involved come from the theory of quantised relativistic strings - but the connection may be loose

String Theory: Fifty Years On

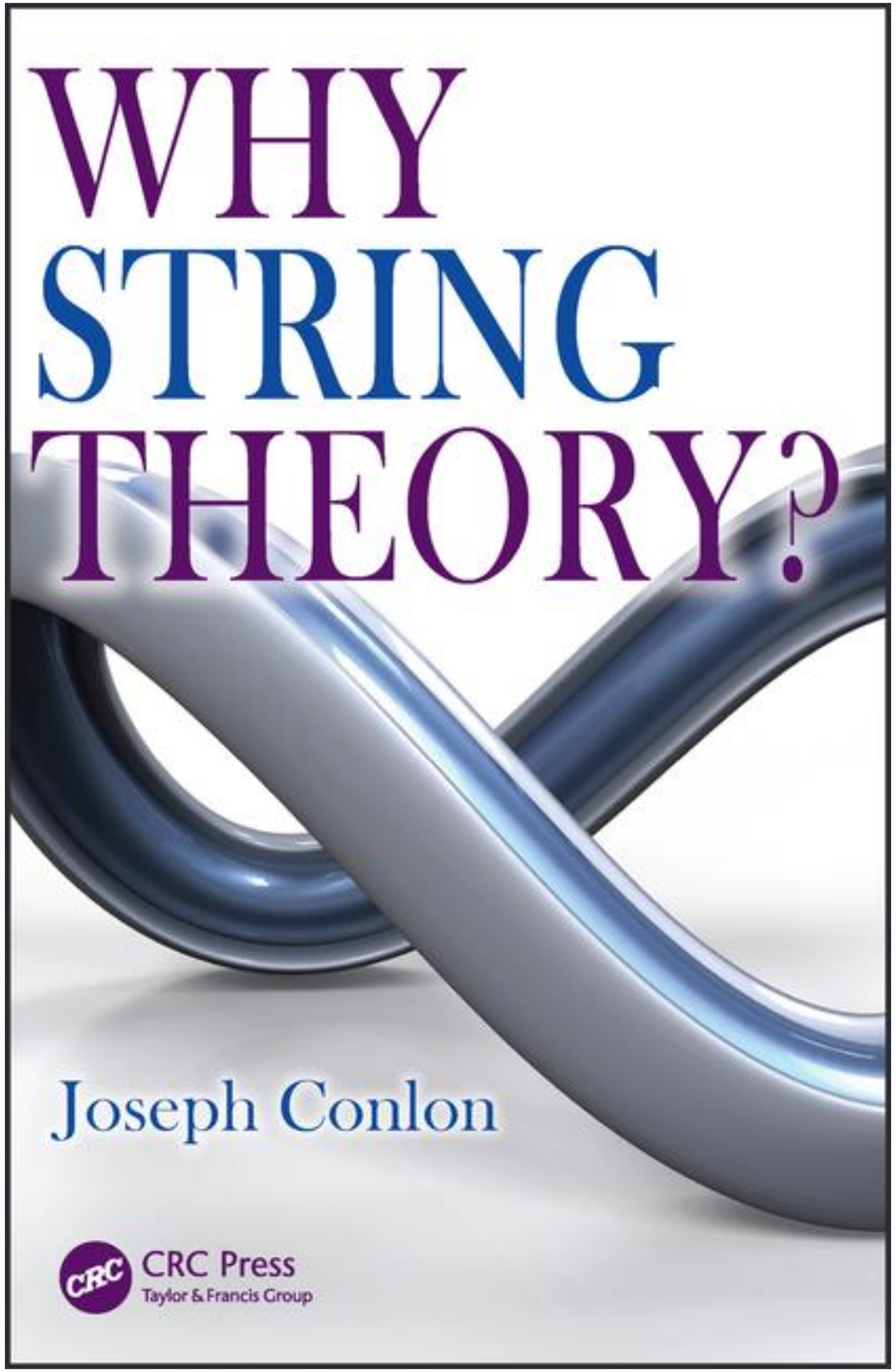
- Michael Green (2014):

  “As time goes by and String Theory evolves, it is more and more apparent that it is not just a

  ‘Theory of String-like Elementary Particles’

  but it is a

  ‘Magnificent theoretical framework that interrelates a very wide range of topics in physics and mathematics.’


WHY
STRING
THEORY?
Joseph Conlon
CRC Press
Taylor & Francis Group