

Duality and Emergence in String Theory

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STRING THEORY

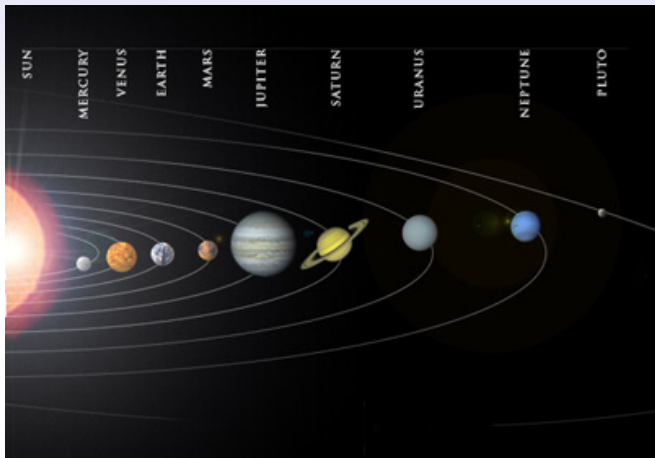


THEORETICAL PARTICLE PHYSICS



**PHYSICS :
THE HOW AND WHY OF
PHYSICAL PHENOMENA**

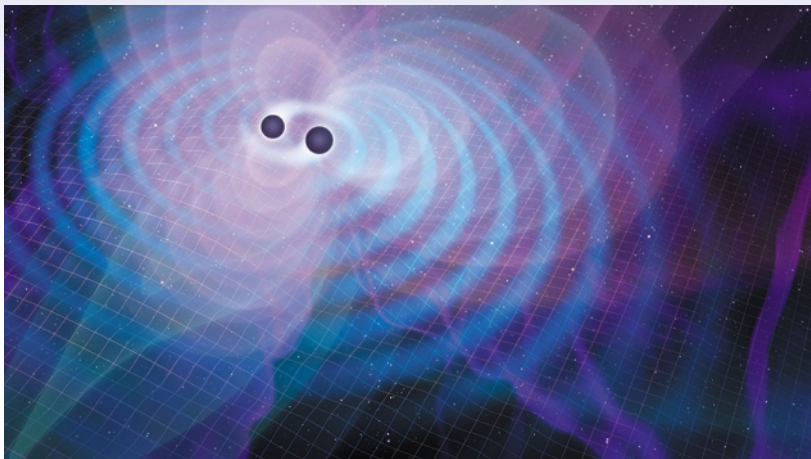
Planets of the solar system ...



.. have been orbiting the sun for over 4 billion years.

About 1.4 billion years ago, ...

Two extremely dense, massive objects called black holes



.. collided and merged.

Waves from this cosmic event ...



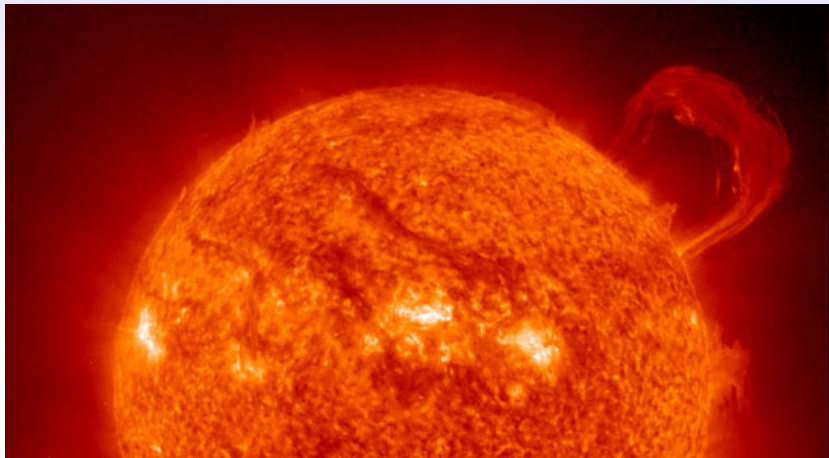
were measured on Earth in September 2015, at gravitational wave detectors based in the US.

A flash of lightning ...



carries an electrical current across a potential difference of over a 100 million volts.

The core of the sun



is a nuclear furnace with a temperature of over 15 million degrees Centigrade.

At an experiment in Geneva ...



sub-nuclear particles travelling at 99.9999990 percent of the speed of light (maximum physically possible, as discovered by Einstein) have been collided to discover a new fundamental particle (Higgs particle).

THREE things are common to all these
physical phenomena :

FORCES

PARTICLES

WAVES

Theoretical physics, in particular **Quantum Field Theory** (in the early 20th century) and **string theory** (since the late-20th/early-21st century), has delivered **many surprising insights** on the nature of these familiar, apparently mundane, concepts of force, particles and waves.

Insights which are raising new questions and driving current research in theoretical physics.

PHENOMENA → FORCES

Orbits of planets and collisions of black holes : **Force of gravity** .

Lightning : **Electromagnetic Force**.

Inside the sun, at the LHC collisions :
Strong and weak sub-nuclear forces.

THIS IS IT: FOUR FORCES

GRAVITY

ELECTROMAGNETIC

WEAK

STRONG

ELEMENTARY PARTICLE PHYSICS

EVERYTHING



18 FUNDAMENTAL PARTICLES

MATTER PARTICLES:

electrons, quarks (constituents of protons and neutrons), Higgs particle and neutrinos.

AND FORCE PARTICLES:

photon for electromagnetic force; gluons for strong; W , Z bosons for weak force; graviton for the force of gravity.

QUANTUM PHYSICS

POSITION AND SPEED OF ANY PARTICLE
CANNOT BE KNOWN WITH PERFECT
PRECISION.

THE UNCERTAINTY IS EXPRESSED IN **A
PROBABILITY WAVE.**

If you spot a grain of sand on the beach and look away, there is a minute probability it will be on the moon the next time you find it.

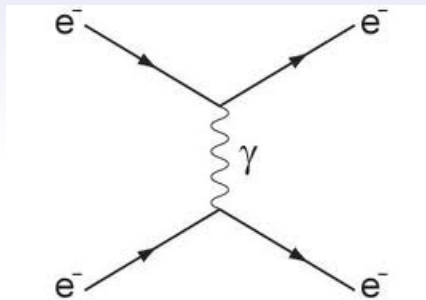
WAVE-PARTICLE DUALITY

IS DEVELOPED INTO A POWERFUL
MATHEMATICS OF

QUANTUM FIELD THEORY

QUANTUM FIELD THEORY (QFT)

Forces arise from exchange of force-particles



Quantum uncertainty : The interaction point can be anywhere in space and time. QFT ADDS all these possibilities.

THIS ADDITION OF INFINITE POSSIBILITIES

IS COMPLEX. IT **REQUIRES TAMING MANY INFINITIES** TO DELIVER FINITE MEASURABLE QUANTITIES, TO BE COMPARED TO EXPERIMENT. (- points colliding, velocities vanishing, energies diverging ...).

THE TAMING (RENORMALIZATION) CAN BE DONE FOR THREE OF THE FOUR FORCES.

QUANTUM GRAVITY REMAINED UNTAMED

STRING THEORY

REPLACES FUNDAMENTAL PARTICLES
WITH FUNDAMENTAL STRINGS.

MATTER AND FORCE PARTICLES ALL COME
FROM VIBRATIONS OF ONE STRING.

FUNDAMENTAL STRINGS

WOULD BE MUCH SMALLER THAN
ANYTHING MEASURED (approx $10^{-18}cm$) SO
FAR.

A REASONABLE CONJECTURE IS
 $10^{-30} \sim 10^{-33}cm$.

They are not composites of particles, like ordinary strings. They are 1-dimensional lumps of energy/mass.

VIBRATIONS OF STRING THEORY

lead to particles. Einstein's $E = mc^2$ says that mass is energy. The energy/mass of particles comes from the vibrational energy of fundamental strings.

These particles INCLUDE GRAVITONS
AS WELL AS, particles like PHOTONS,
GLUONS and WZ-bosons.

THE SIMPLEST STRING THEORIES

exist in TEN space-time dimensions,

whereas our universe which has 3 observed space and one time dimension.

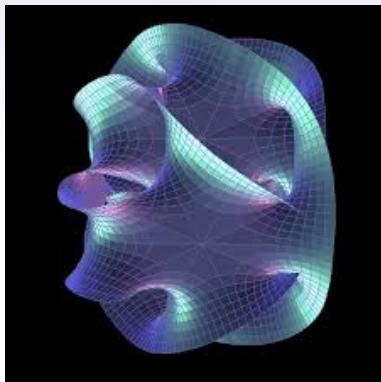
Points in a space (or space-time) can be specified by a sequence of numbers. In the world of our experience $(x, y, z) = (x_1, x_2, x_3)$, so three-dimensional. Or four if we describe locations and time (x_0, x_1, x_2, x_3) . The location of a string in the simplest string universes is given by a sequence (x_0, x_1, \dots, x_9) .

$$10-4 = 6$$

STRING THEORY allows 6 dimensions to be small. Leaving 4 large.

An object appear to be of lower dimension than it really is, e.g. an aeroplane (3D) can look like a point (zero-dimensional) from a distance. So the 6 hidden dimensions of string theory.

The shape of the six dimensions ..



determines the precise spectrum of particles we would observe at resolutions around 10^{-22} cm .

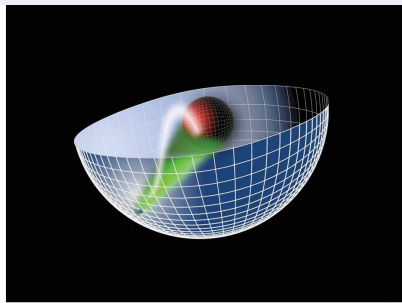
These ten dimensional string universes ..

are extremely interesting in their own right: They have revealed a new kind of duality between the forces.

Take one of these 10 dimensional string universes, which is called $AdS_5 \times S^5$. This contains strings, string excitations (e.g. gravitons), as well as additional extended objects (e.g. 3 + 1 dimensional objects called 3-branes).

Maldacena (1997) discovered that all the physical phenomena in this 10 dimensional universe can equivalently be computed in a different theory, called a dual theory ...

The dual theory ...



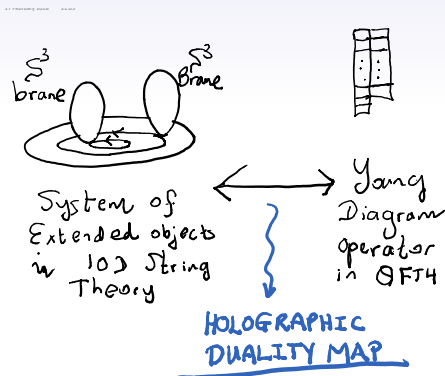
is a 4-dimensional quantum field theory, where the 4-dimensional world exists at the boundary of the 5-dimensional AdS5 space.

The QFT has **no graviton particles** - only particles like, quarks and gluons. The 3-color theory that describes the real world is replaced by N -color theory with N tending to infinity.

BUT a **mathematical map** between this 4D QFT and 10D QFT allows us to describe the gravitons of the 10D theory in terms of 4D quantum states. (Witten 1998 ; Gubser, Klebanov, Polyakov 1998).

3-branes of the 10D theory ...

can be described using maths of Young Diagrams



This map was given in : Corley, Jevicki, Ramgoolam (2001).

This holographic duality displays emergence ...

The physical phenomena described by the 4D quantum field theory (QFT4) include:

(a) **six extra (emergent) dimensions.**

(b) **(emergent) quantum gravity**, since there are no explicit gravitons in the 4D.

This QFT4 is sometimes called a hologram of the 10 D, and this relation between 4D QFT and 10D string theory is called HOLOGRAPHIC DUALITY.

$$10D \rightarrow 4D \rightarrow 2D ?$$

There are hints that this 4D theory could be dual to another theory in a yet smaller number of dimensions :

“CFT4 as SO(4,2) invariant TFT2,” de Mello Koch and Ramgoolam, Nuclear Physics B (2012).

Popular science article based on this:

<https://plus.maths.org/content/lower-dimension>

WAVE-PARTICLE DUALITY ...

lead to a new mathematical theory, Quantum field theory, which captured both wave and particle in **one mathematical object** called a quantum field.

$$\Phi^+(x) = \int \frac{d^3p}{2E_{\vec{p}}} a(\vec{p}) e^{-ipx}$$

Is **holographic duality** a hint of a new mathematical theory, where quantum gravity, strings, emergent dimensions of space-time and non-gravitational quantum fields combine into **novel mathematical objects** ?