# Quantum Gravity

Prof Nick Evans
University of Southampton

Gravity vs electric forces

QED but not QG

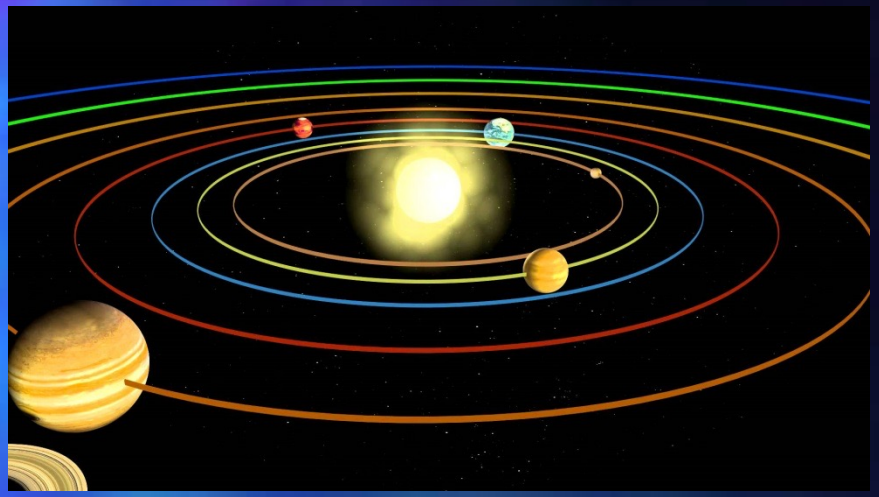
Gravity waves & Double copy

String theory

Braneworld & experiment

Holography

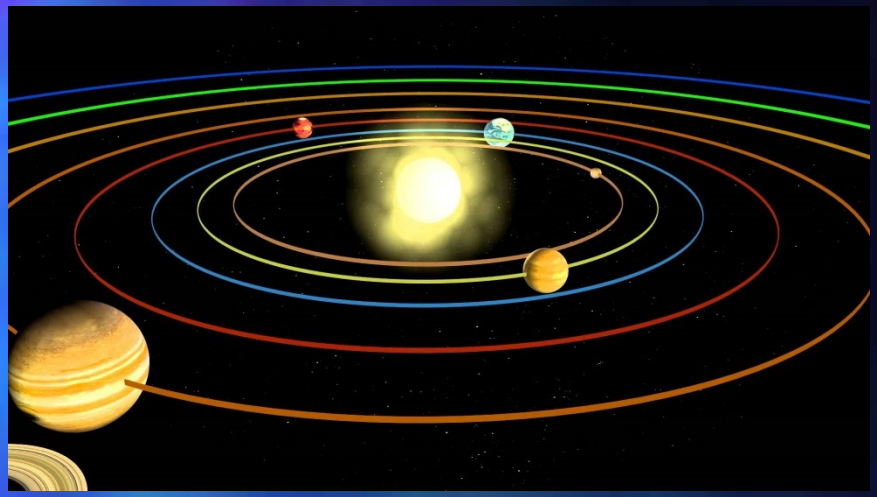
# Gravity



$$F = \frac{G\ M\ m}{r^2}$$

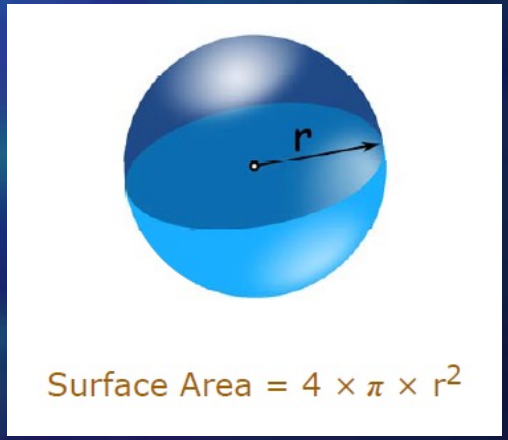
The force gets bigger as the two objects become heavier/ more bulky..

# Gravity



$$F = \frac{G\ M\ m}{r^2}$$

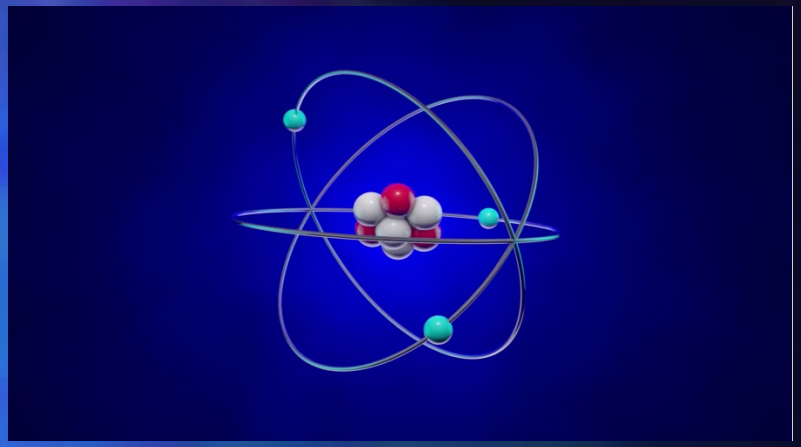
The force falls off as an inverse square of distance...



Quantum Gravity is a mess…

but what does that mean?

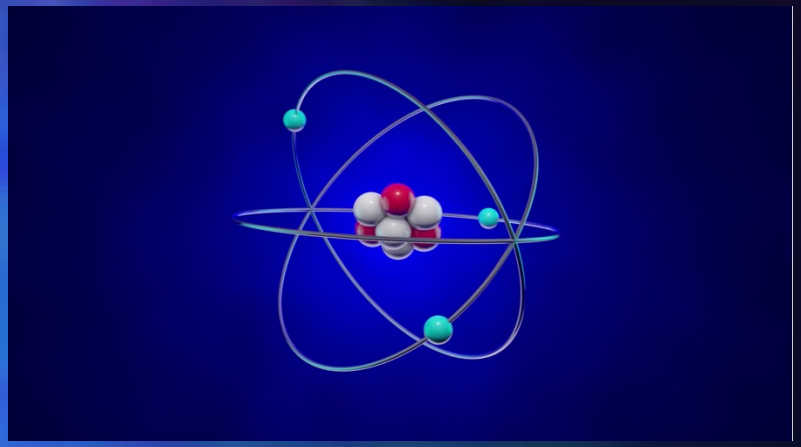
# Electric Forces



Electric forces (at first) look very similar to gravity…

$$F = \frac{G\ M\ m}{r^2}$$

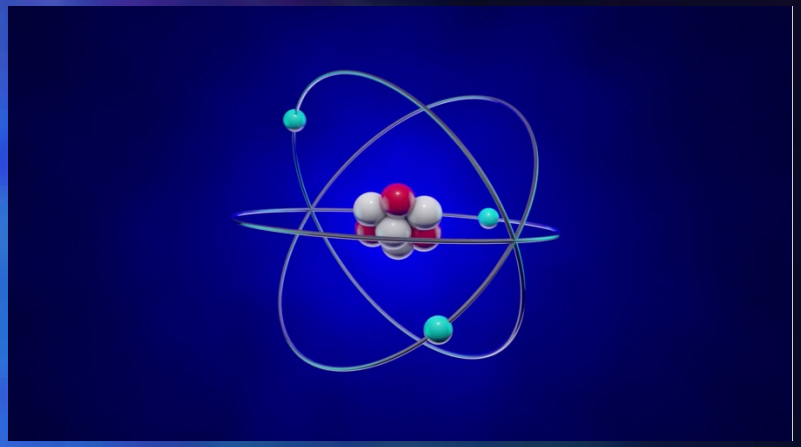
# Electric Forces



$$F = \frac{k\,Q\,q}{r^{2}}$$

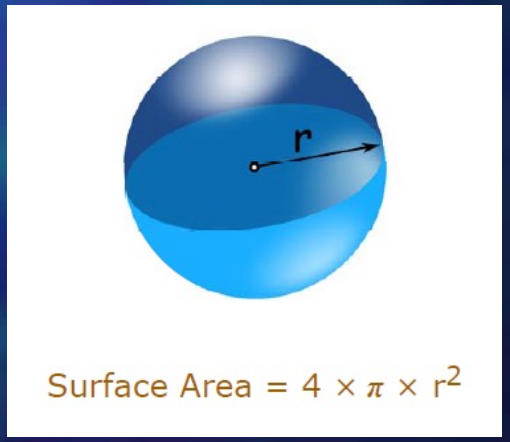
The force gets bigger as the two objects charges grow…

# Electric Forces



$$F = \frac{k\,Q\,q}{r^2}$$

The force falls off as an inverse square of distance...



Quantum Electrodynamics is very well understood…

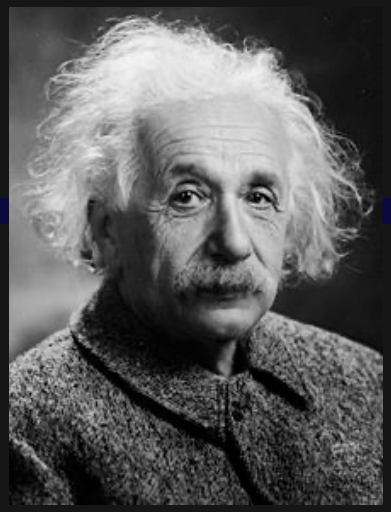
What is it?

Relativistic

Quantum

Electrodynamics

# Relativity



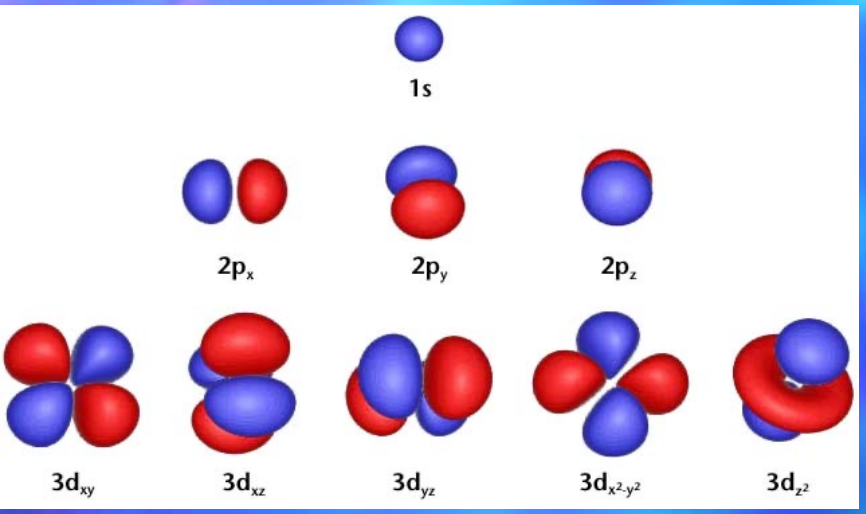
The speed of light is the same for any observer – it is the maximum speed attainable…

This means nothing can travel with light – nothing can reach v=c!

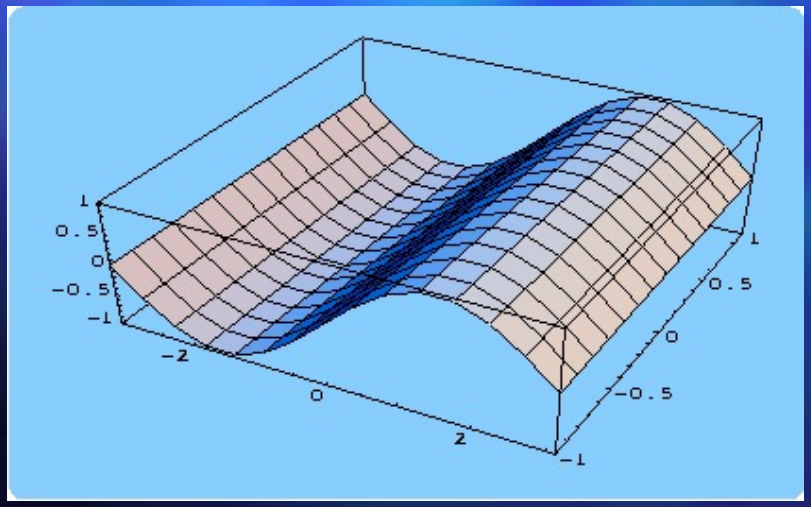
$$E = \sqrt{\frac{1}{1 - v^2/c^2}}\, mc^2$$

Rest mass = energy

# Quantum Physics



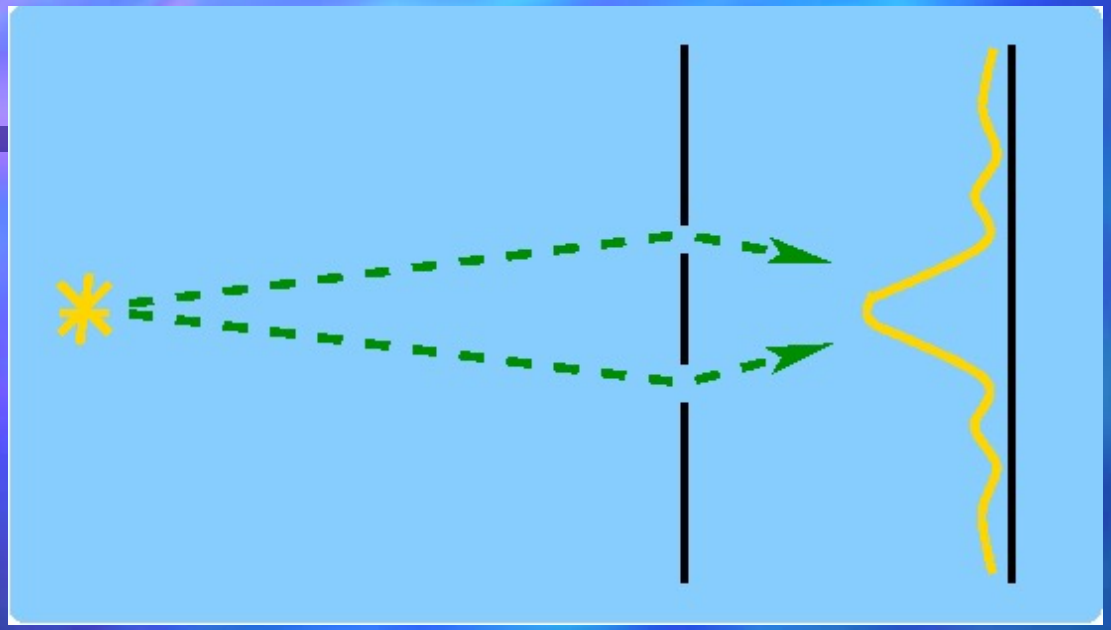

On atomic scales physics becomes fuzzy… electrons are not cricket balls following well defined trajectories…




There is a wave description… but..

energy comes in lumps – particles…

# Quantum Dynamics



The quantum in some sense travels by both paths….

There is an uncertainty in the position and momentum of the quantum

Heisenberg's Uncertainty Principle

$$\Delta x \, \Delta p > h$$

Or equally

$$\Delta t \, \Delta E > h$$

# The Quantum Vacuum

$$\Delta E \, \Delta t > h$$

The vacuum can borrow energy for short periods

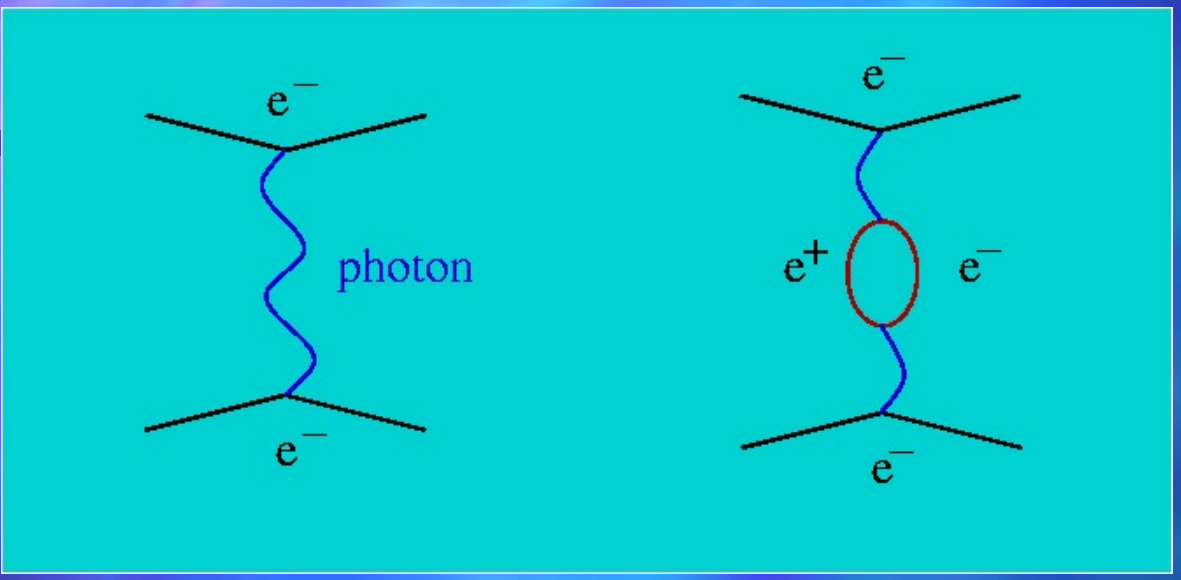
$$E = mc^2$$

The borrowed energy can be used to create particles

(You can't just create an electron because of charge conservation - but can create electron positron pair)

The quantum vacuum is a seething mass of particles appearing and disappearing constantly….

# How Can You Tell?




The “virtual” particle pairs interfere in electron scattering processes.

These are less than 1% effects…. But in the interaction between an electron and a magnetic field the predictions are tested to 12 decimal places… a huge success!!

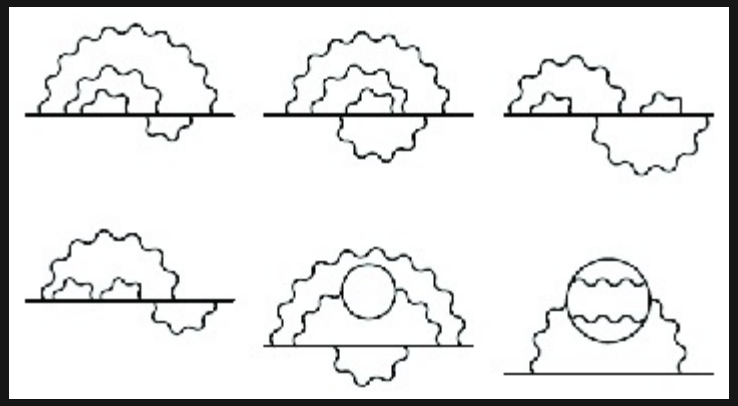
# So why not just repeat with Quantum Gravity?

$$F = \frac{G\,M\,m}{r^2}$$

Basically the same??

$$F = \frac{k\,Q\,q}{r^2}$$

Relativity: M ⟶ Energy…. very high energy particles become very strongly coupled



Multiple interactions become as important as one… and we can't compute… but also the large scale is communicated strongly to everything… no light particles remain…

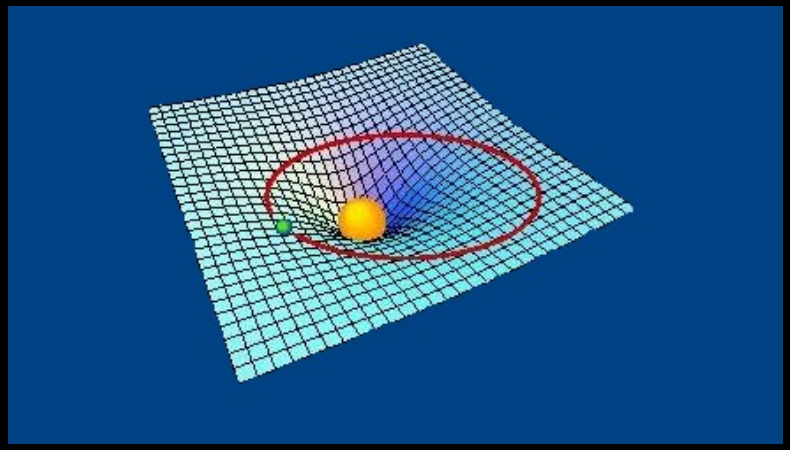
… and breath…

# General Relativity & Gravity Waves

Newton's gravity can't be the whole truth… instantaneous action at a distance is forbidden….

General Relativity describes gravity in a new way

Particles travel by the shortest path in a space curved by masses

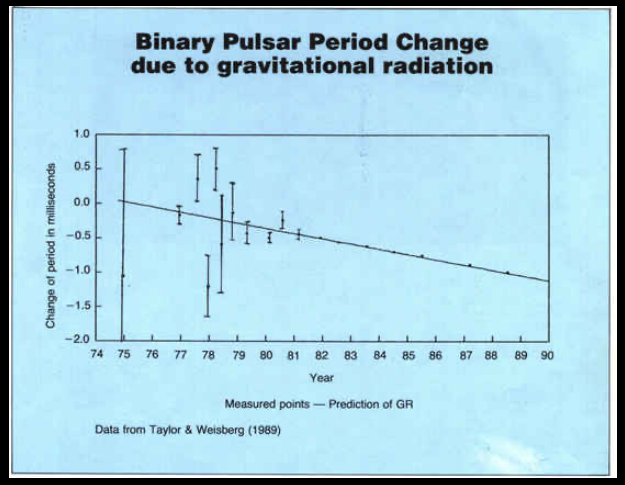


Space-time is like a rubber sheet that can be bent

Note: only the surface exists!

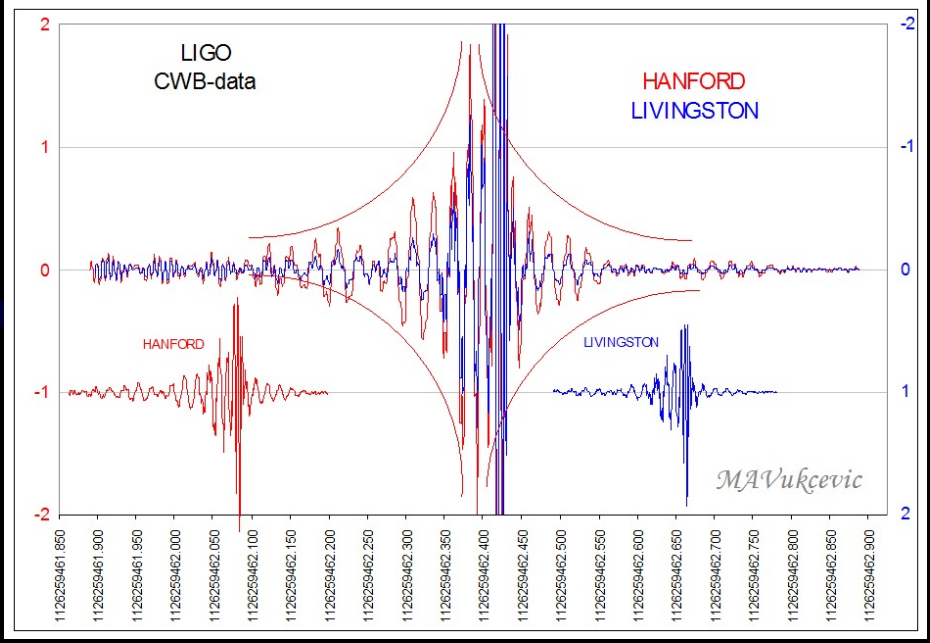
# Gravitational Waves

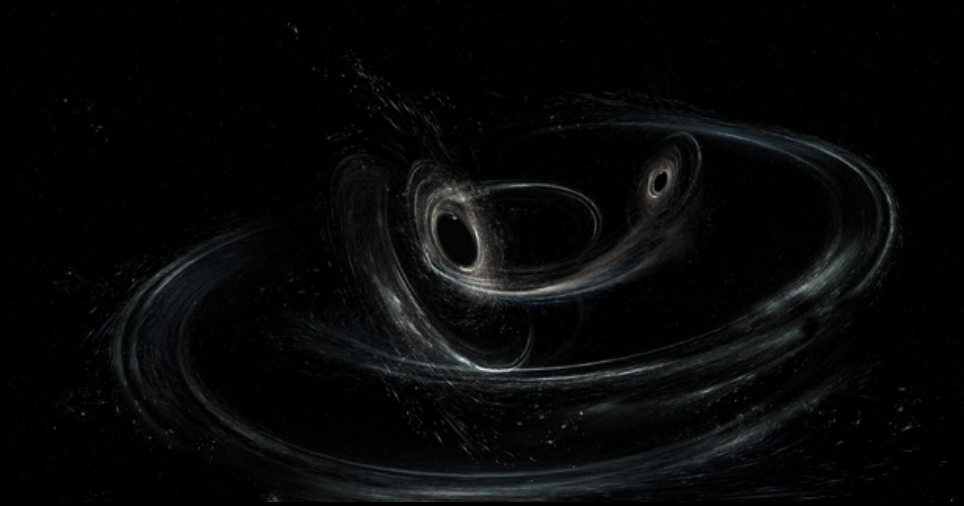
A very heavy mass, like a star, distorts the space time sheet if it oscillates or collides with something…


The energy loss from this emission has been seen for a pair of orbiting neutron stars

Searches are now on to see these very weak waves directly at LIGO



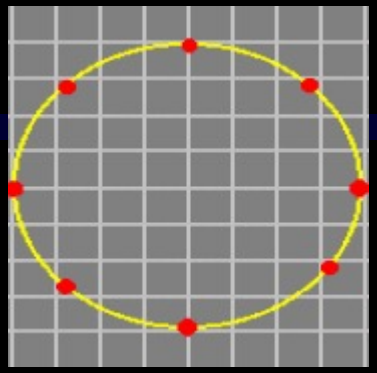
5/6 black hole events detected

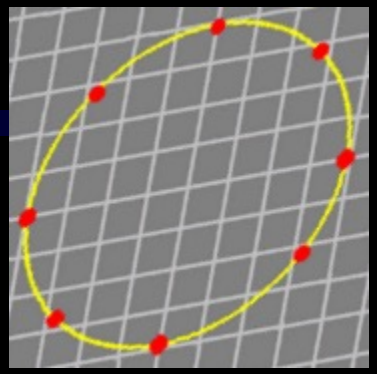
35 on 30 solar mass event
(23 on 13 solar mass event)
14 on 8 solar mass event
31 on 20 solar mass event
12 on 8 solar mass event
30 on 25 solar mass event

~1 billion light years away!

1 NS NS event

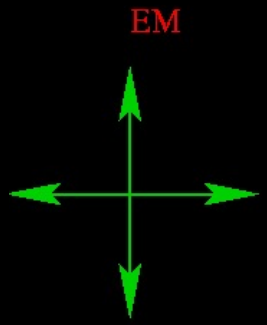
# Gravity Wave Polarizations





This is how distances change as the two “polarizations” of gravity waves pass through..

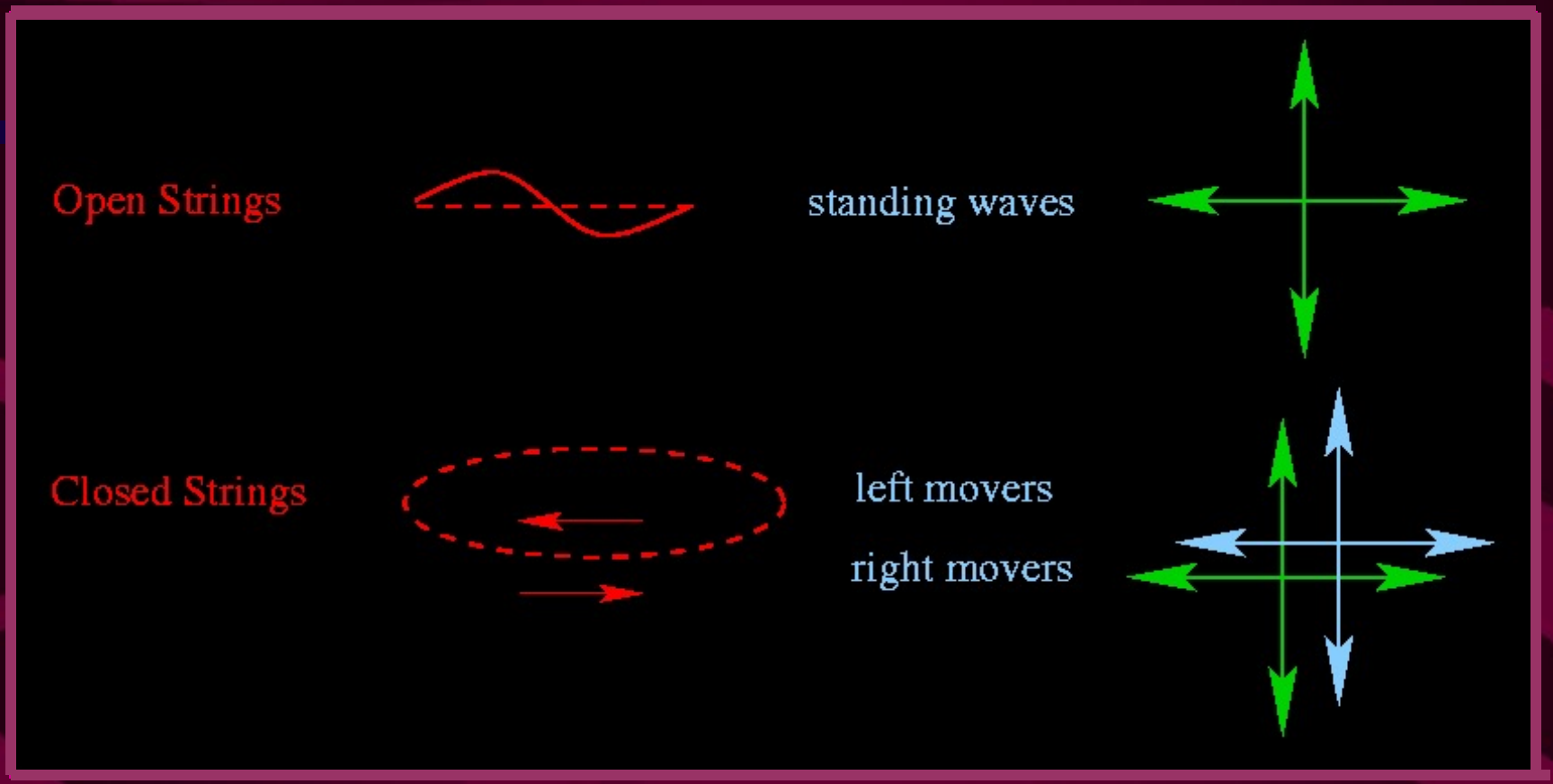
The displacements are like two electromagnetic wave polarizations superimposed…




Gravitons are like a double copy of a photon…

Could you make a theory of gravity by binding two photons together? Possibly but it is very unlikely the energies would cancel to leave an exactly  massless particle….

# String Theory




String theory unifies gravity and other forces

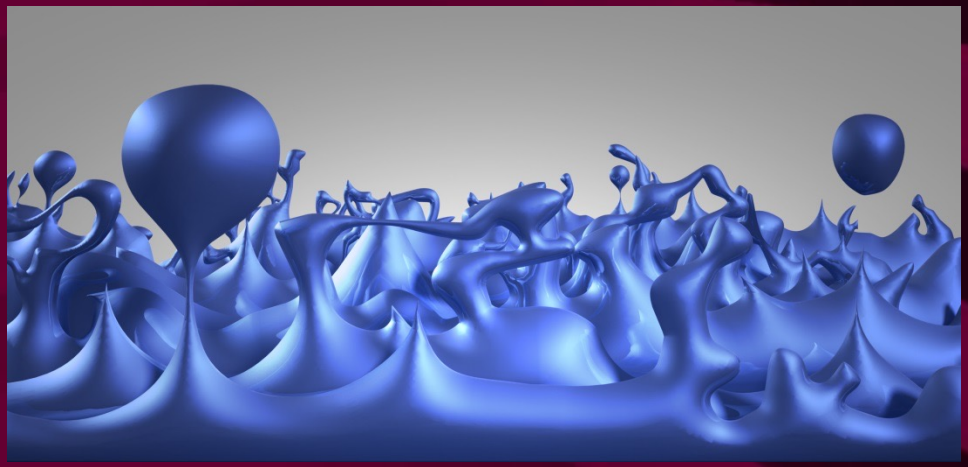
String theory is A quantum theory of gravity.. Is it THE quantum theory of gravity? - entering realm of speculation!

# Space-Time Emergence

Thinking of A graviton in a spacetime as a photon ball… or a string… is ok…. Somehow though the whole spacetime itself must be only present as a collection of a vast number of these objects…

Quantum spacetime must be

bitty, or frothy… or ????



This is a tough question even when you have a description of a string theory… we will return to this idea…

… and breath…

# Weird & Wonderful Gravity

# Extra Dimensions

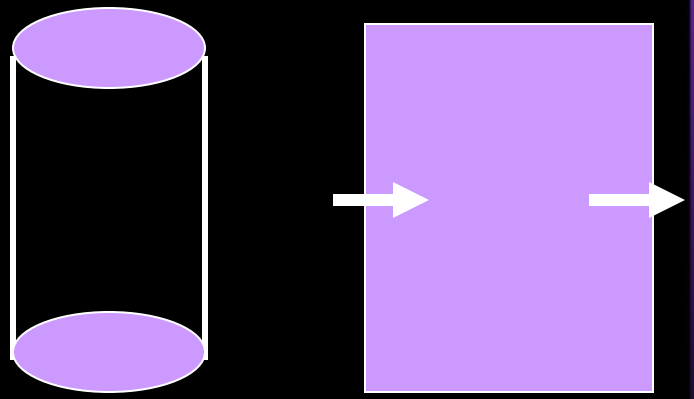
Surprisingly the mathematics of string theory only makes sense in 9 spatial dimensions and 1 time dimension!

A prediction…. But wrong!!

## Compactification

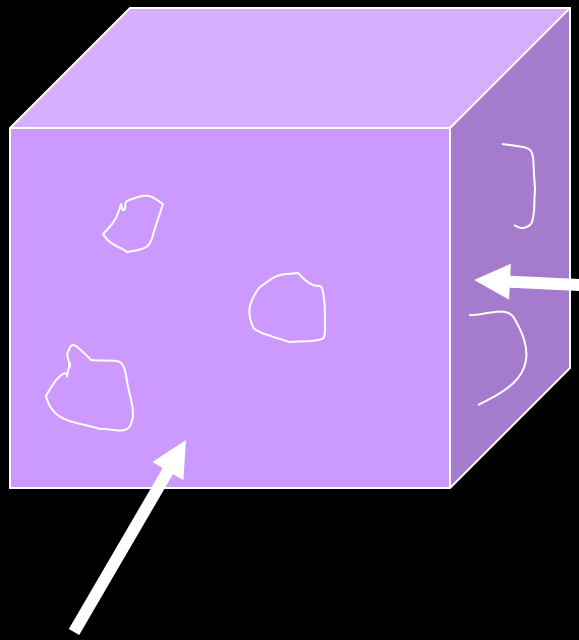
We can imagine a space where directions are curled up

We study A string in this space not ALL the strings that make the space…. Why are 6 dimensions compact… by what mechanism? UNKNOWN!



# Membranes

It turns out you can tie the ends of open strings to sub-surfaces in the space – in this way membranes emerge in the theory…



Electromagnetic particles live on a sub-space or "brane"

Gravitons live in a higher dimension "bulk"

"Existence proof" for such a world

# The Gravity Measurement Problem..

Remarkably gravitational interactions are completely unknown below 0.1 mm …

Particle physics works down to $10^{-18}$ m…

But doesn't include gravity…

Could gravity change at 0.1 mm?

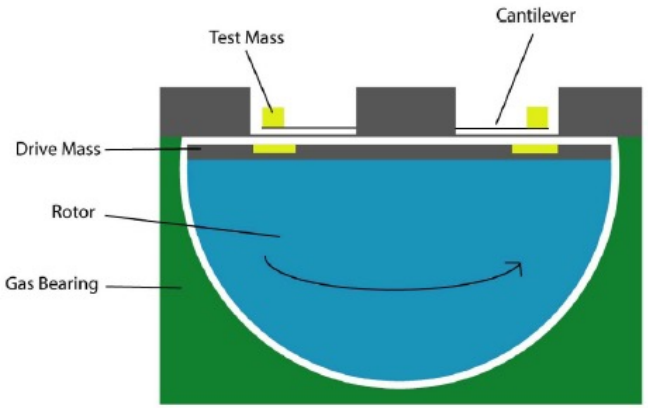
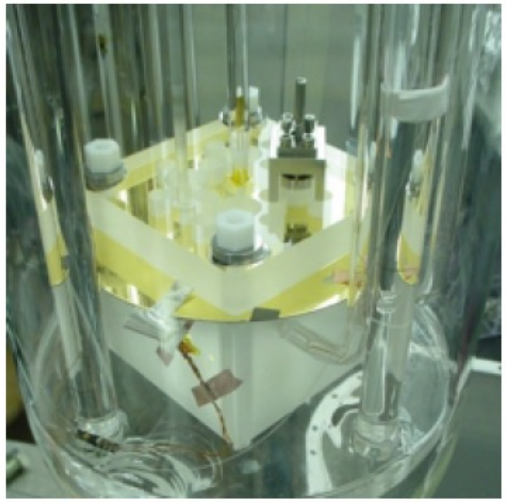
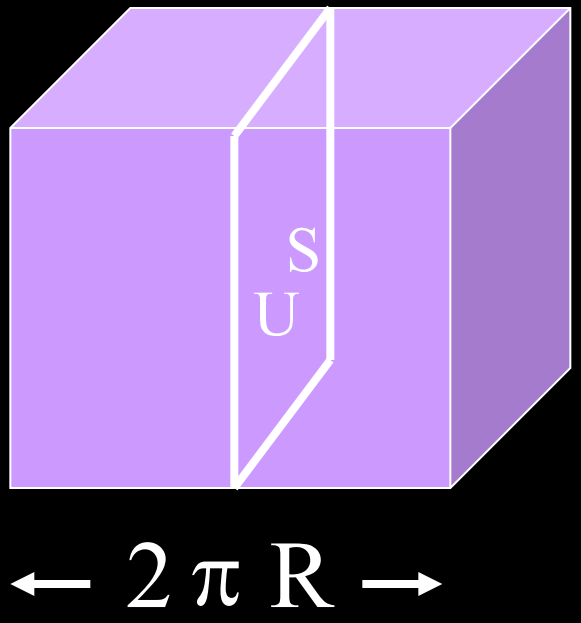



FIG. 1: (color online). A schematic side view (not to scale) of the heart of the experimental apparatus.



David M. Weld[1],* Jing Xia[1], Blas Cabrera[1], and Aharon Kapitulnik[1,2]
[1]*Department of Physics, Stanford University, Stanford, CA 94305 and*
[2]*Department of Applied Physics, Stanford University, Stanford, CA 94305*

# Could Our Universe Be A Brane?




The strength of gravity is determined by the number of spatial dimensions (gravitons spread out around mass)

$$F = \frac{G M m}{r^2}$$

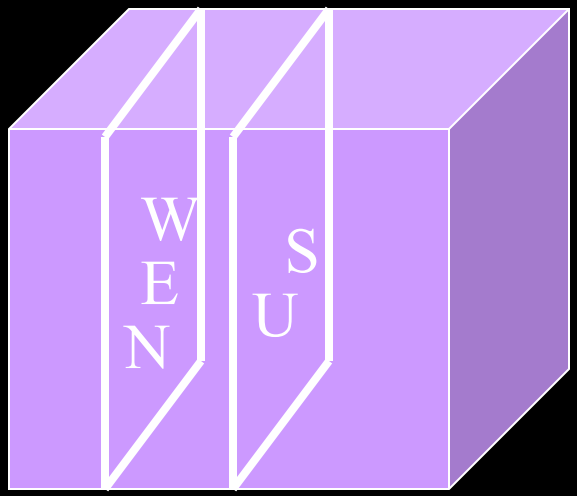
D=3+1

But…. we don't know anything about gravity on length scales below 0.1mm… R could = 0.1mm… and we wouldn't know it!

# Other Branes

Why should there be only one brane in the higher dimension spacetime?

There could be entire Universes only mm away!

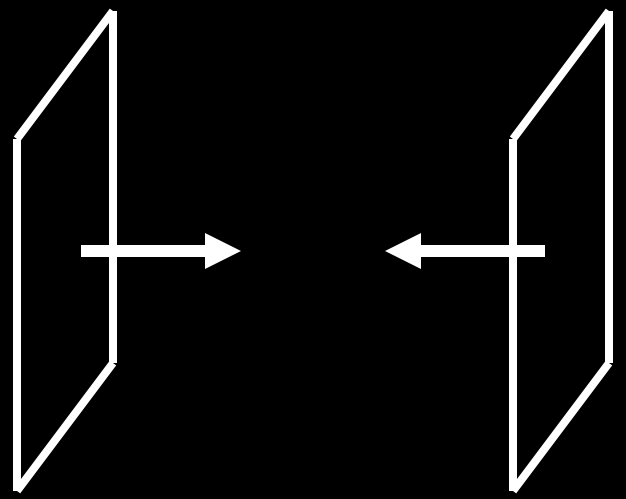



The matter on the other brane will only interact with our world gravitationally – it's dark matter….

Until we can produce high energy gravitons that are strongly interacting there's little way to directly probe this idea though

# Brane Collisions

There's no reason branes should be static in the extra dimensions…. So they could collide!



This would be catastrophic!

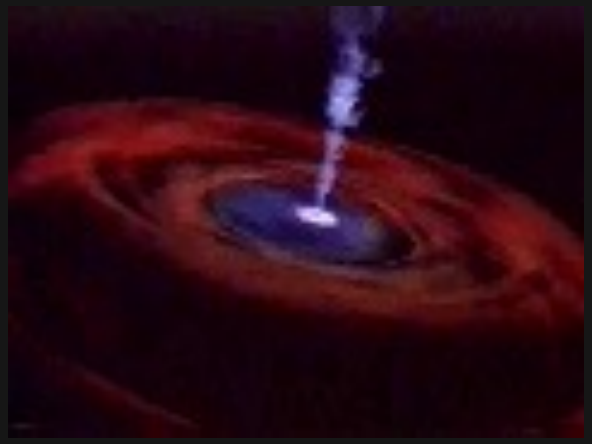
Huge amounts of energy would be dumped into our Universe….

Could that have triggered the currently observed expansion of the Universe??!!

… and breath…

# Holography

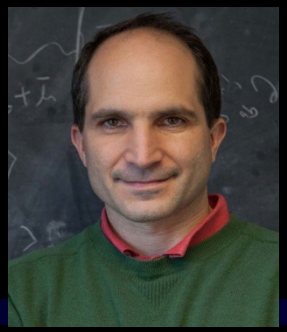
General Relativity predicts there should be objects whose gravitational attraction is enough to stop even light escaping – BLACK HOLES



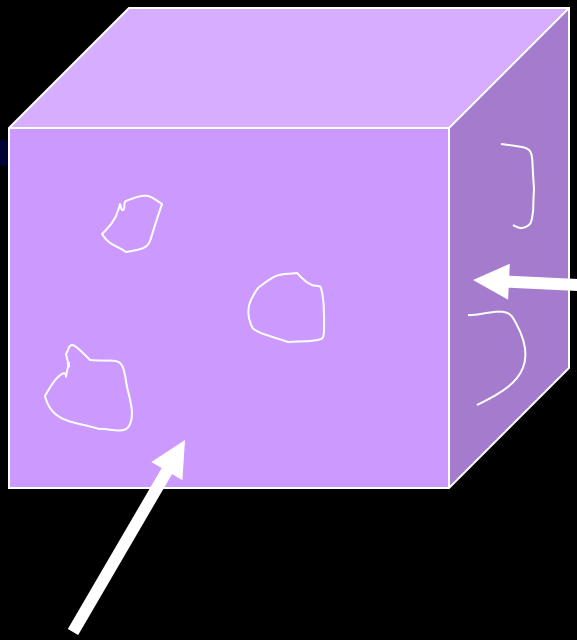
'tHooft argued that any information dropped into a black hole must be

- lost to our Universe
- spread over the surface

If the surface can contain all the information of the contents the real theory of the Universe must be 2 + 1 dimensional!



# Maldacena's Limit

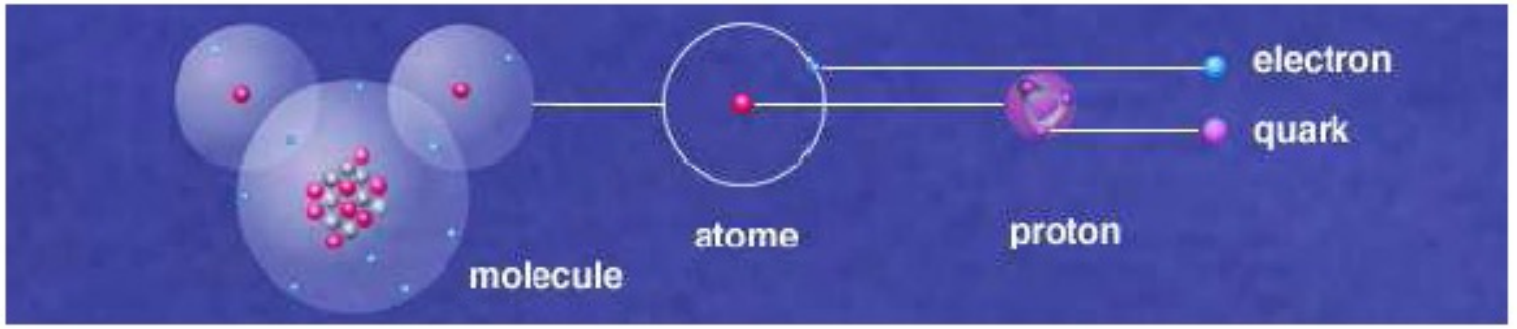


Electromagnetic particles live on a sub-space or "brane"

Gravitons live in a higher dimension "bulk"

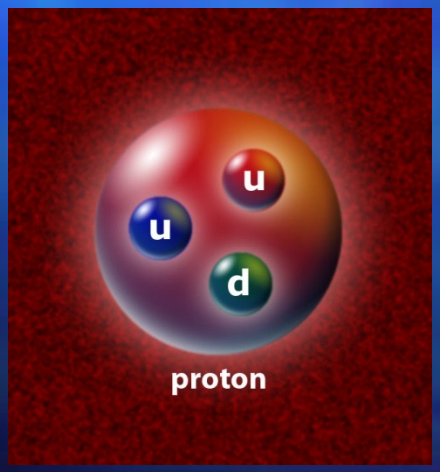
Juan proposed a limit in which the open and closed strings separate.. he then guessed that the surface theory was the holographic dual of the bulk gravity theory… 20 years on there is overwhelming evidence he's right….

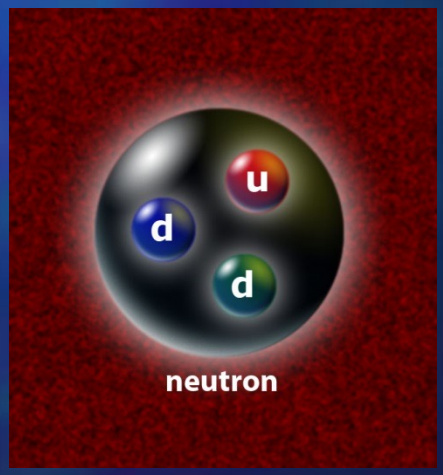
# Strong Nuclear Force is Holographic




Normal matter can be understood with just two types of quark.

- $u$ or up quark, charge $+2/3$
- $d$ or down quark, charge $-1/3$



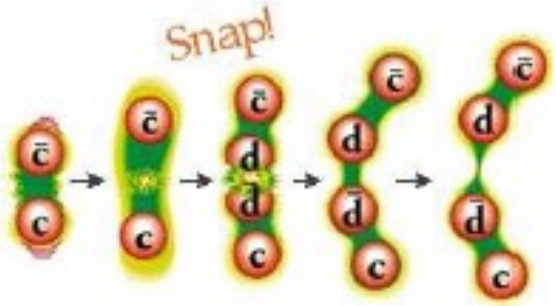
## Strong Force

Binds nucleons in the atomic nucleus.

Binds quarks into nucleons and other hadrons

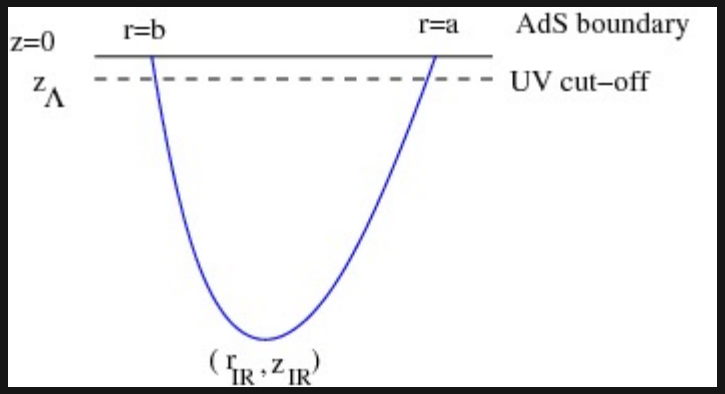
Quarks come in three colours. Exchange of coloured gluons between quarks is the mechanism of the strong force.


The strong force confines quarks inside hadrons. We never find isolated quarks experimentally. If you try to pull two quarks apart, so much energy is needed that it's favourable to create a new quark-antiquark pair instead: you end up with two hadrons rather than separated quarks.



# Strong Nuclear Force is Holographic

String theory grew out of attempt to describe confined quarks… but strings lived in 10d… now we know that is OK!!


The fuzziness of the spacetime is due to the thickness and minimum length of the QCD string…

This has kept me in papers for the last 20 years!

Holography does seem to be a key concept in quantum gravity…

# Overview

- Gravity talks, via quantum effects, to its strongly coupled high energy behaviour… so doesn't make sense…
- General Relativity teaches us the fundamental objects are spin 2 gravitons
- String Theory is an attempt to construct a sensible theory of these (and also includes electromagnetic forces)
- We are realizing it predicts wild possibilities eg extra dimensions
- Gravity is so weak though we can't experimentally access there ideas.
- Quantum gravity appears to have to be holographic – string theory is and this relinks it to gauge theories… progress?

Nick often puts too much in his talks… so some (masochists?) like to digest later…

So I'm self publishing talk write ups.. One so far (more to come)

Yours for £3 on Amazon!