From Quarks to Quantum Gravity

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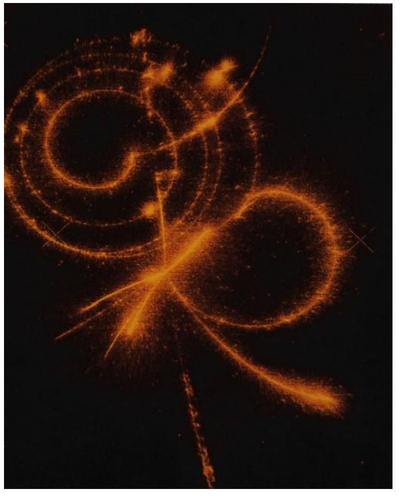
A History Lesson

- The 1950's and 1960's was a wonderfully confusing time to be a particle theorist



- In the early 1950's, thing's were looking rosy
  - Electron
  - Proton
  - Neutron
  - And a couple of others:
    - muon, pion, neutrino expected, and anti-particles

- By the mid-1960's the list had grown to hundreds of "elementary particles"
  - Kaons and vector rho mesons and Delta++ baryons and Omega's, Lambda's, Sigma's, Eta's, Nu's, Upsilon's,…

Looking for Patterns

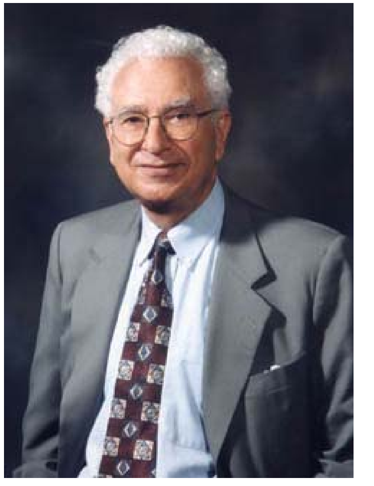
- It was hard to believe that all of these particles are “elementary”. People started looking for patterns among them.

- There were several startling features lurking within the masses and other properties of particles.

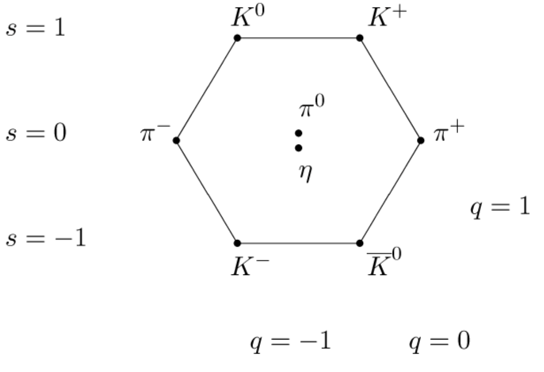
Quarks and the 8-Fold Way

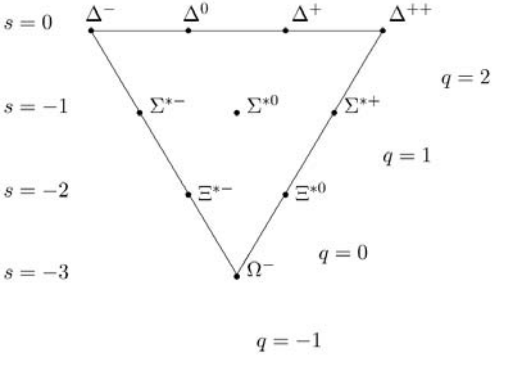
- Murray Gell-Mann conjectured that all these new particles were made up of 3 types of quarks, called “up”, “down” and “strange”

- All particles contain either three quarks, or a quark + anti-quark



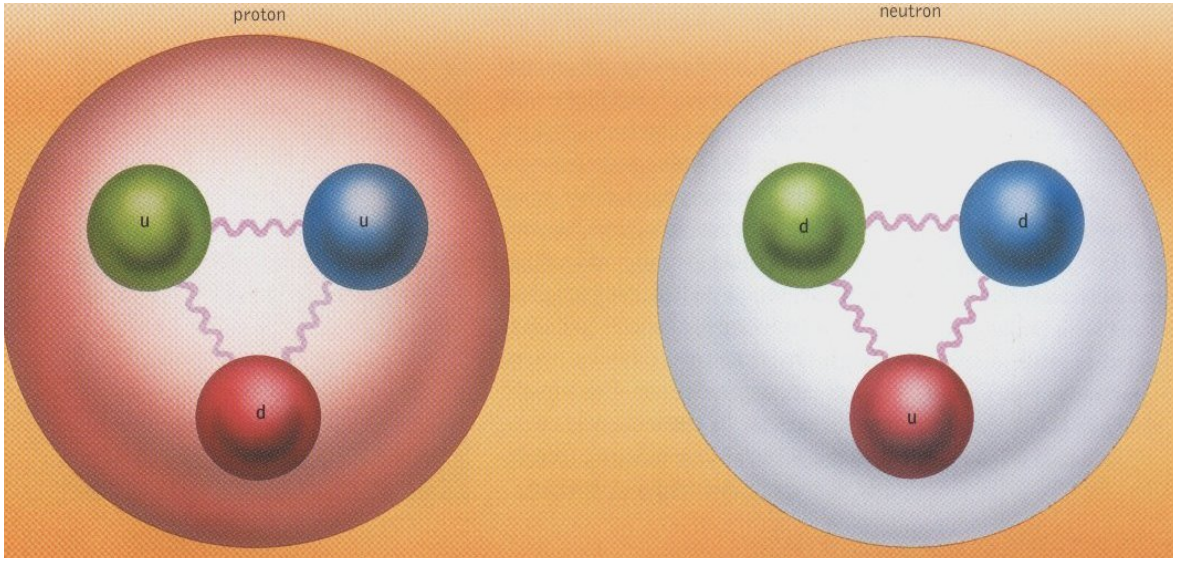
Murray Gell-Mann





Quarks

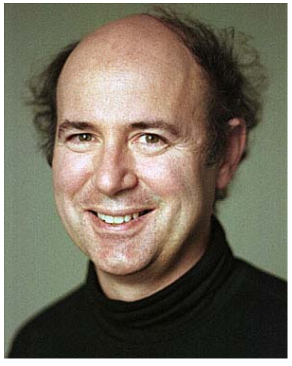
- In this classification, the electron is still an elementary particle
- However, the proton, neutron, and all the hundreds of new particles are composite.



Quantum Chromodynamics

- Gell-Mann’s idea is right. It’s now known that there are six types of quarks. (And we think that’s all of them!)
- We have a beautiful and simple theory of quarks, known as QCD

$$\mathcal{L} = -\frac{1}{4}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_i(i\gamma^\mu D_\mu - m_i)\psi_i$$



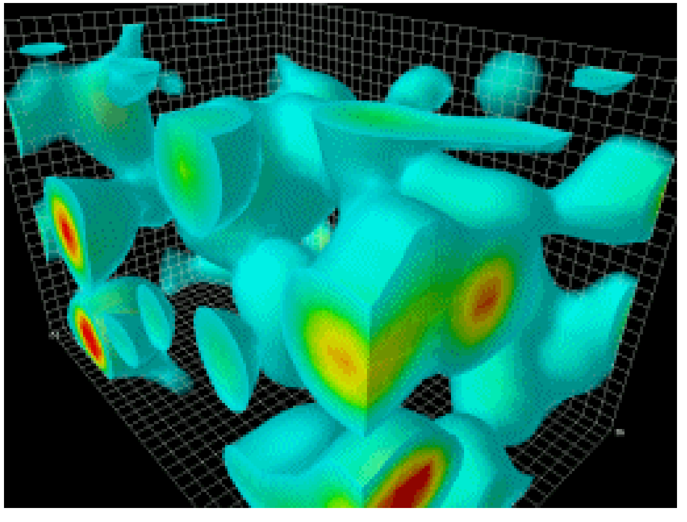
David Gross, Frank Wilczek + many others…. (not least Sidney Coleman)

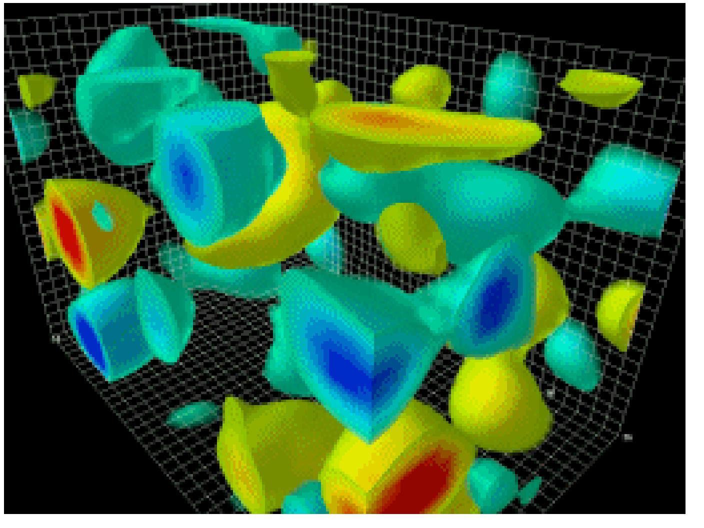
- But there’s a problem. QCD is hard. Really hard!!

QCD is Hard!

- Serious Supercomputers
- Clay Mathematics problem: $1 million

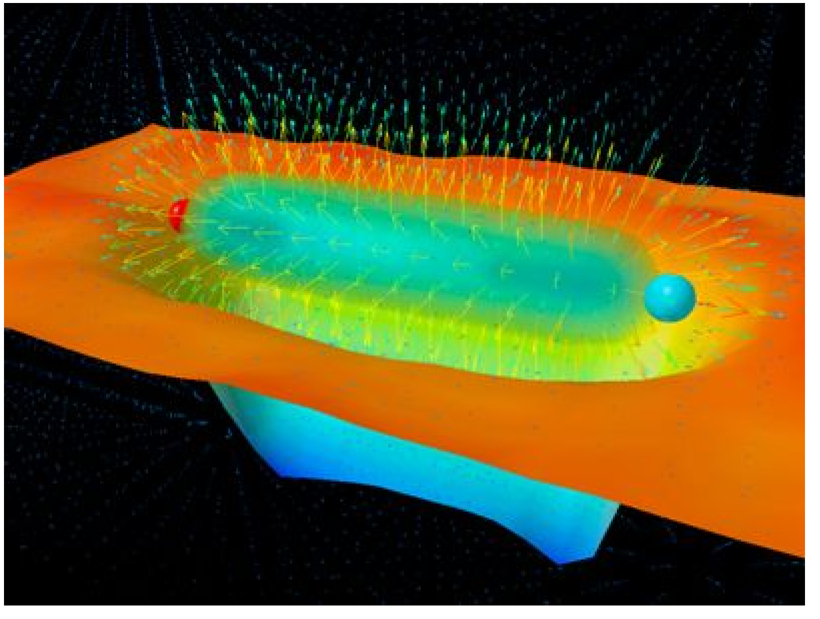
- Even the simplest question is immensely difficult: what does the vacuum look like?





Strings in QCD: Confinement

- The quarks can never escape the proton or neutron.
- If you try to pull a quark away, a long string forms pulling it back in. The force between two quarks is linear: $F \sim r$. This is called “confinement”

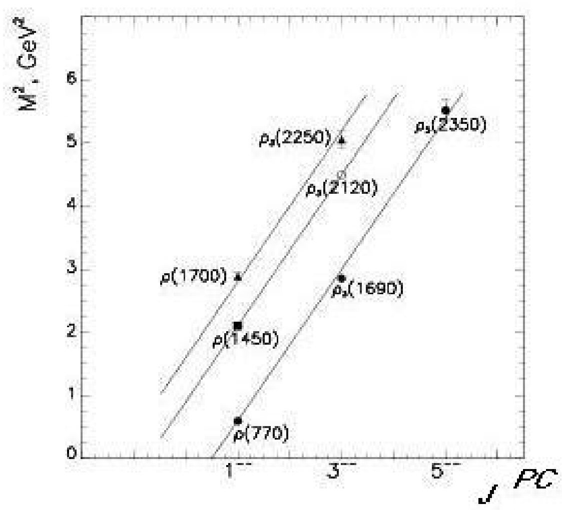


- To prove confinement, and the existence of strings, from the equations of QCD is one of the most important open problems in theoretical physics.

More Strings in QCD

- The existence of these strings in the real world, also shows up another way.
- The second pattern in the data of particles was found in the 1960’s and is called “Regge trajectories”

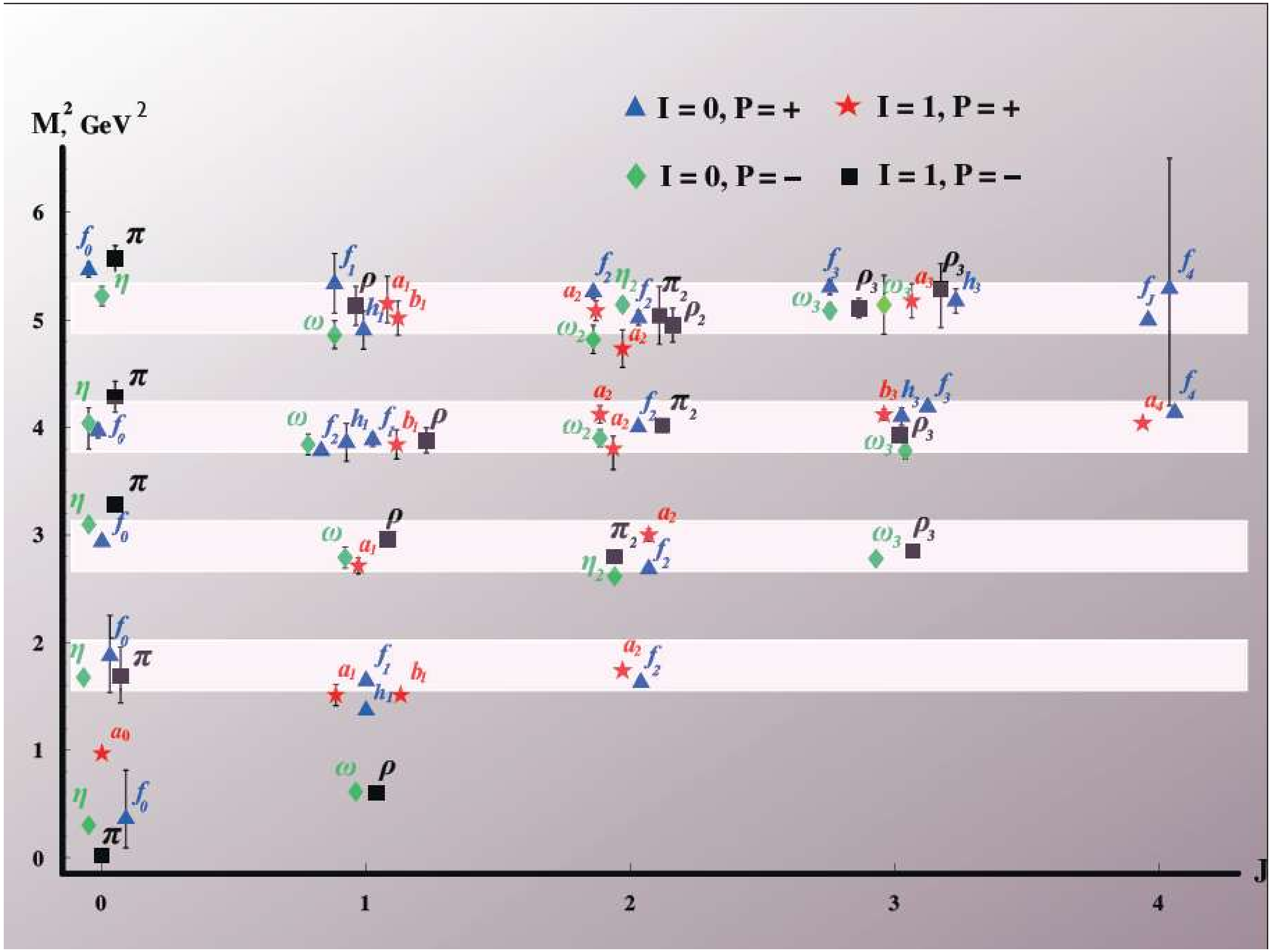
Mass squared



Angular momenum

- This is what you get if the particles are made of two quarks, attached by a long, spinning string. The attractive pull of the string is then balanced by the centrifugal force.

Regge Trajectories



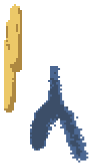
From Quarks to String Theory

- Much of the difficulty with QCD lies in the question of how these strings form and what their properties are.

- From 1968 to 1973, there was a great deal of effort in trying to understand if the right way to think about quarks was through strings.

- In 1973, QCD was discovered, and everyone stopped working on strings. Except for a small handful of people, including John Schwarz and Michael Green.

String Theory

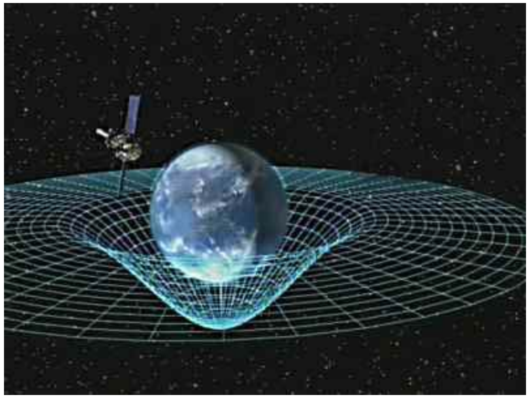


- Writing down a mathematically consistent theory of strings turned out to be very difficult.
- The final obstacle was surmounted in 1984 by Green and Schwarz. But by then, the theory didn't look anything like the theory of quarks!

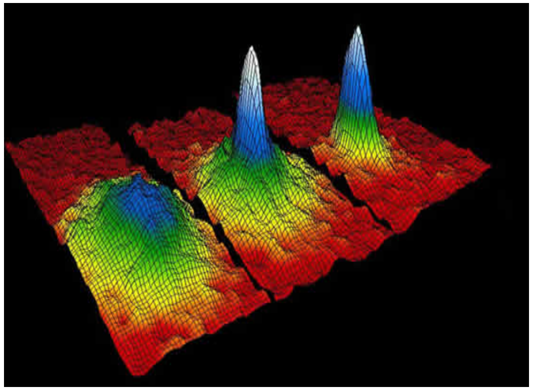
- String theory:
  - A theory of quantum gravity
  - Every elementary particle (electron, quarks, photons…) is made of a tiny, vibrating string
  - The strings are around 10^{-33}cm, instead of 10^{-13}cm of QCD
  - The theory lives in ten-dimensional spacetime
  - It is a candidate for the "theory of everything", unifying all the forces and gravity in a single framework.

Quantum Gravity

General Relativity



Quantum Theory



String Theory as Quantum Gravity?

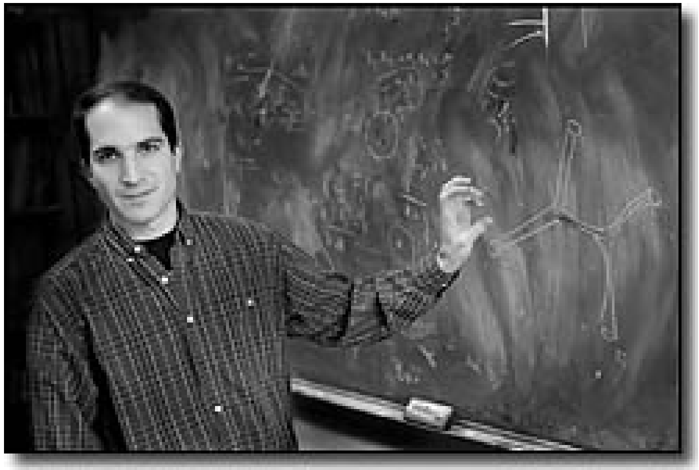
- We don't yet know the correct description of quantum gravity.
- Experimental tests of any theory will be very hard. (Big bang, black holes)
- String theory is a candidate theory
  - Lots of good points
  - Many problems
  - Controversial

In this talk, I don't want to ask whether string theory is right…………I want to ask whether it's useful!

A Puzzle

- String theory started as an attempt to describe quarks
- It ended up as an attempt to describe everything! What happened?
- QCD does have strings in it. So why on earth do strings seem to give a theory of gravity in ten dimensions that has little to do with QCD?! Something strange is afoot….

The Resolution

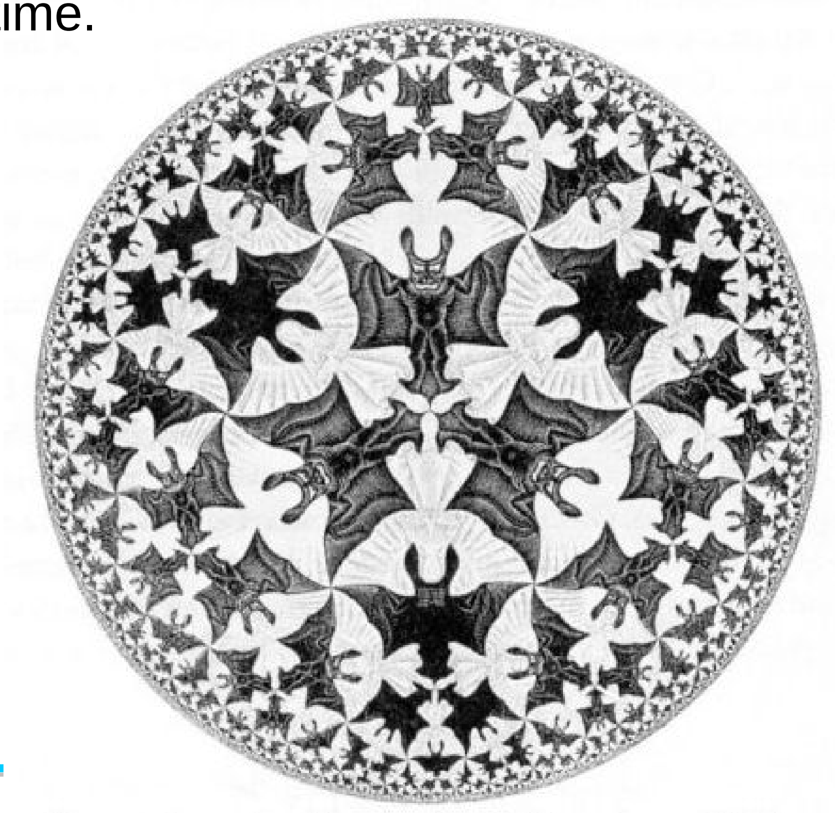


In the right circumstances, the theory of QCD (without gravity) is exactly the same as the theory of gravity in higher dimensions

- Maldacena Conjecture (1997)
- AdS/CFT Correspondence
- Gauge/Gravity Correspondence
- The Holographic Principle

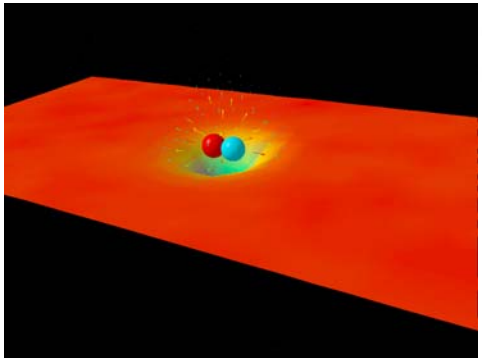
Higher Dimensions

- This curved space is called “Anti-de Sitter”
- You need to imagine this space having five dimensions
  - 4 space + 1 time….(I know…it’s hard!)
- The boundary of the space has four dimensions
  - 3 space + 1 time.

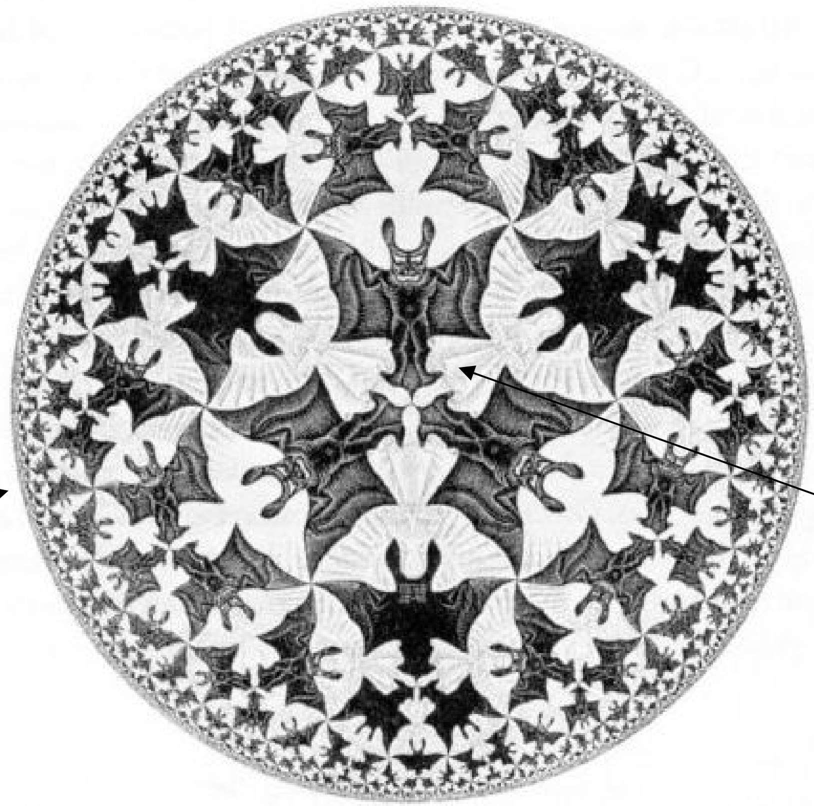


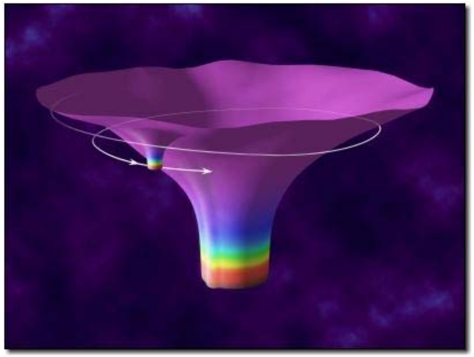
Higher Dimensions and Holograms

Quarks live only on the boundary. Their dynamics is governed by QCD (or similar theories).

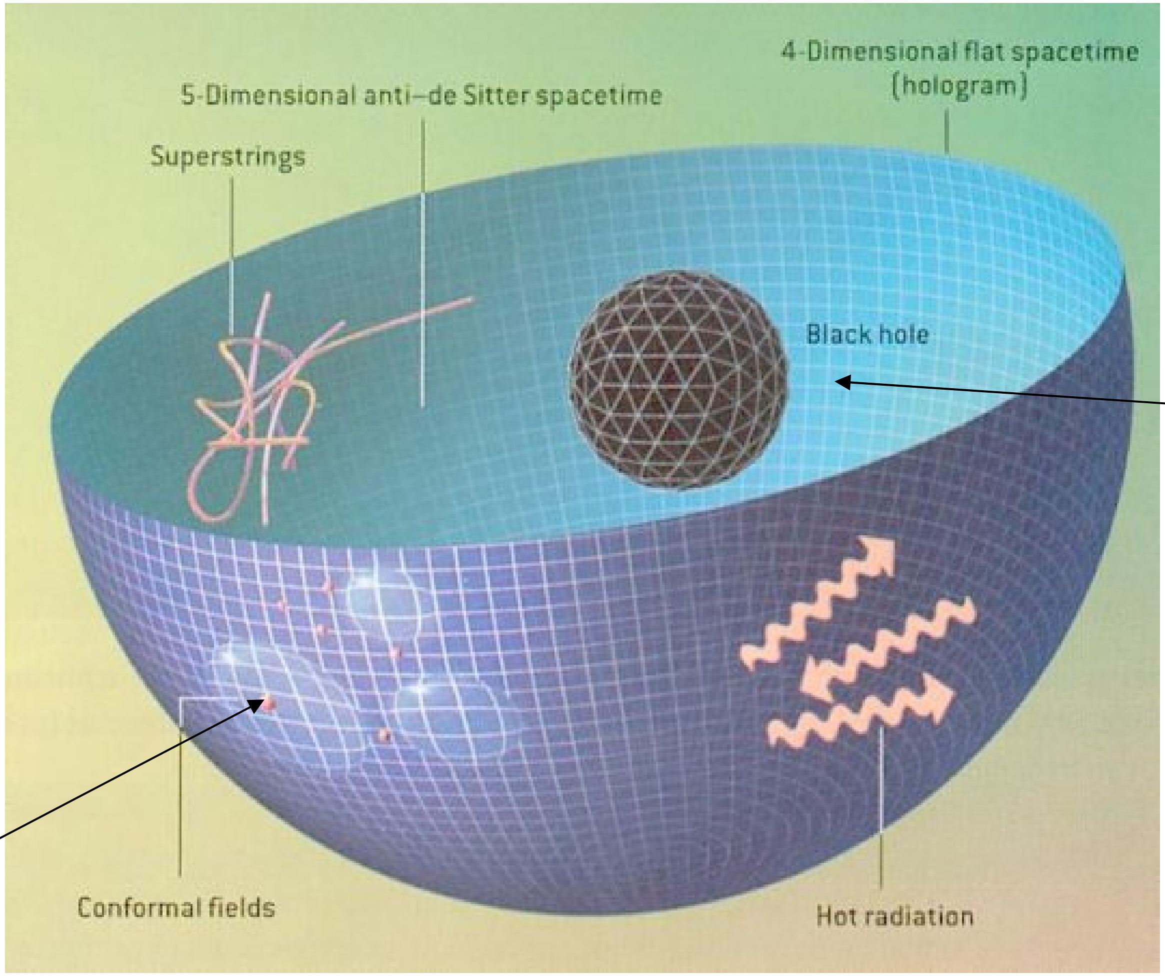


In the middle of the space lives Einstein's theory of gravity. It includes black holes, gravity waves, etc..





Higher Dimensions and Holograms

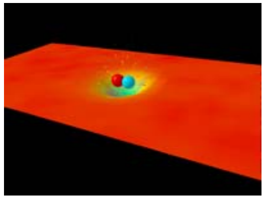


Gravity lives in the middle

Quarks live on the boundary

The Holographic Principle

- What happens to the quarks on the boundary is tied to what happens to black holes and other objects in the middle



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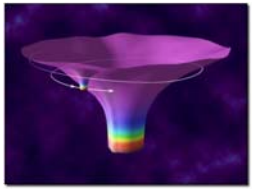


- You could either solve the theory of quarks, and figure out what the black holes are doing.
- Or you could solve the theory of black holes, and figure out what the quarks are doing.

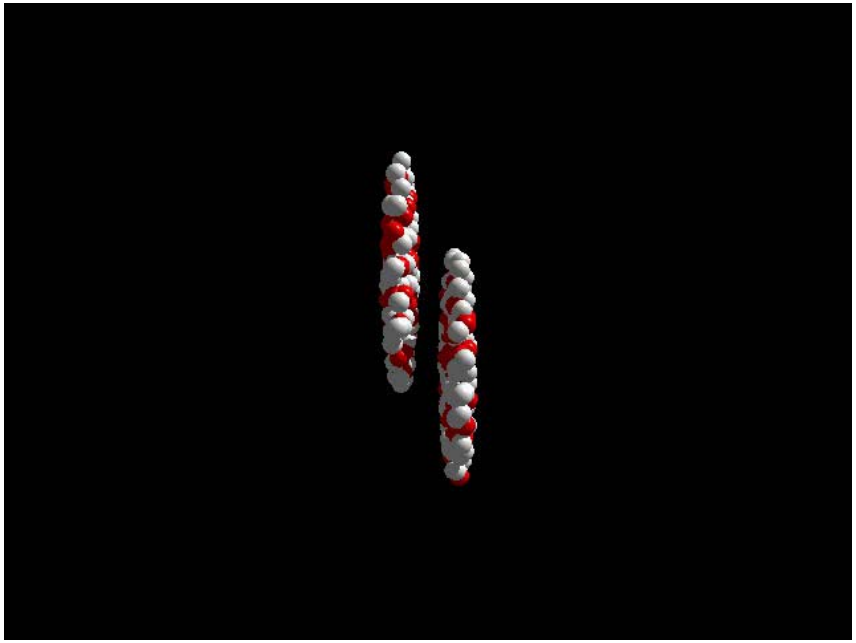
- Note: this is not a viable description of our world!! It is merely a useful tool to understand the theory of quarks.
  - No one knows how to make this amazing idea relevant for our universe

What can we do with it?

- The Maldacena conjecture brings the theory of strings and quarks full circle.
- It tells us that QCD is a theory of strings! It’s just that they live in higher dimensions. We can compute things in QCD by thinking about black holes in higher dimensions!
- That’s great….but what can we calculate?
    - Masses of particles (proton, pions, etc). Get in the right ball-park, but can’t trust the calculations. Within a finite number of years, computers will do a much better job
    - Properties of the Quark-Gluon Plasma

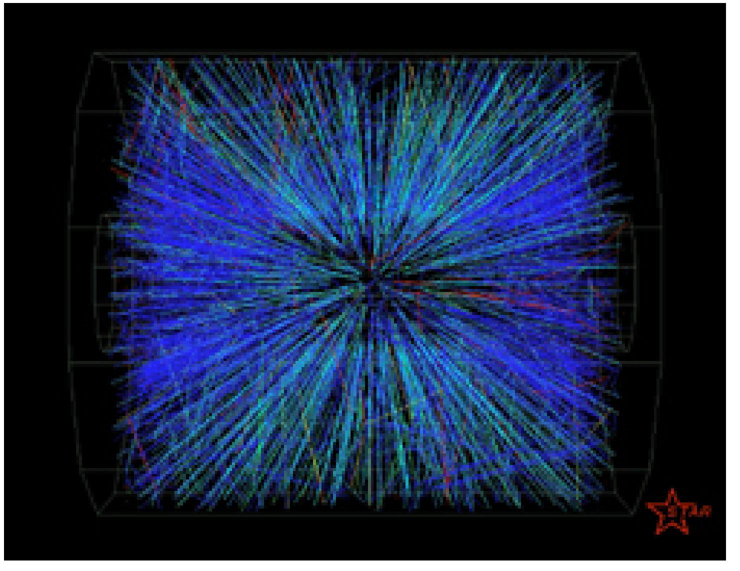
The Quark-Gluon Plasma

- The Relativistic Heavy Ion Collider smashes gold nuclei together.
- This creates conditions not seen in the universe since the Big Bang.
- For a brief microsecond, the quarks are liberated from their confined state.



The Quark-Gluon Plasma

- What comes out, depends on the properties of the quarks in the plasma

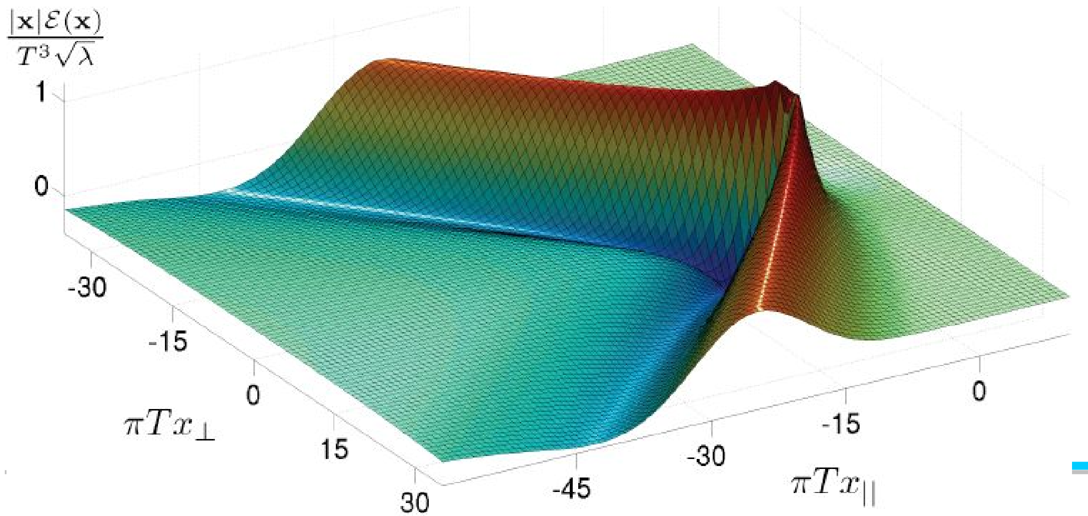


- This is something one should be able to compute from QCD. But (of course), it's hard!! The only known way to compute is by using black holes in higher dimensions!

Why String Theory is Useful!

- The quark-gluon plasma has some very strange properties
  - It is the most perfect fluid known. It has extremely low viscosity
  - It stops speeding bullets (well, quarks) dead in their tracks
- This was very unexpected.

- These properties can be computed using string theory, and black holes in higher dimensions. There is presently no other way to understand them



The wake of a quark ploughing through the plasma. (Or the wake of a particle moving past a black hole)

Summary

- We have a new and surprising way to understand the properties of quarks by looking at black holes in higher dimensions.

- This is one of the most exciting and active areas in theoretical physics.

- The BIG Question: What does this have to do with our world?
  - Are we really a hologram? Is the correct description of gravity in our universe in terms of some theory living on the boundary of the universe?