

# Loop Quantum Gravity

The search for an atomic description  
of the universe

# Does space exist?

Beyond the smallest scale (the Planck length), space and the universe cease to exist in the normal sense.

# Why Do we need a TOE or GUT?

- **Goal** – describe all phenomena in terms of one theory valid at all levels of scale
- **Why** – Black Holes, Big Bang, effects on High Energy Particles can't be explained without
- **Hope** – GR and QM and String Theory should only be special cases of a complete theory

# General Relativity

Describes macroscopic reality well

- Universe is relational, continuous and deterministic; geometry of spacetime is warped by presence of massive objects
- Background independent - the relationships of matter and energy define a dynamic and evolving spacetime

## Problem

- When taken to quantum scale produces only infinities for the gravitational force (inverse square problem)

# Quantum Mechanics

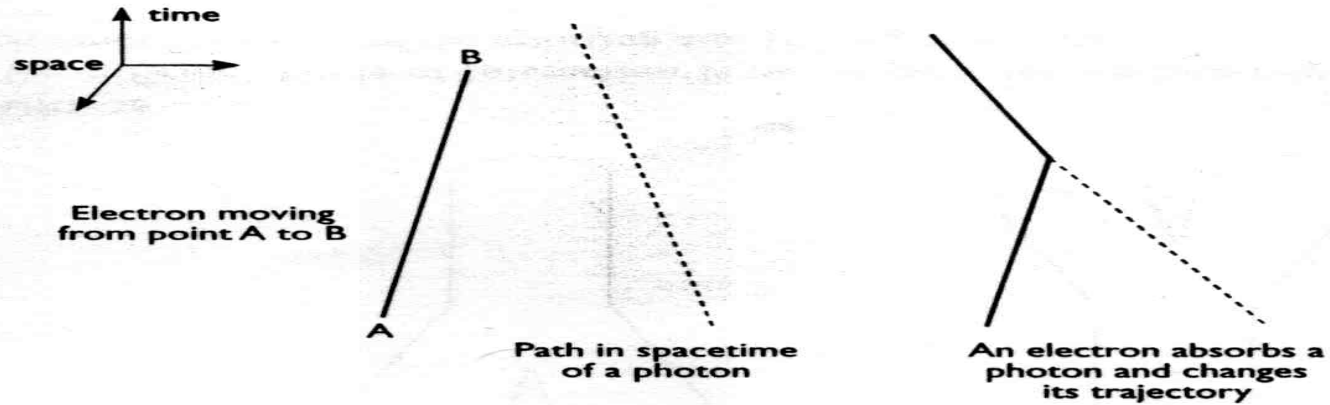
## **Describes sub-atomic phenomena**

- Probabilistic, lumpy and violently unpredictable
- Strong, Weak and EM forces are due to point particle interaction; gravity should be as well
- Fixed geometry background, there is a stage on which the drama of QM unfolds

## Problem

- Relativity equations don't translate, because of
  - uncertainty of quantum states (non-deterministic)
  - point particle assumption of the Standard Model

# Standard Model of Particle Interaction



**FIGURE 33**

The basic processes in the theory of electrons and photons (called quantum electrodynamics, or QED for short.) Electrons and photons can move freely in spacetime, or they can interact in events in which an electron absorbs or emits a photon.

Three Roads to Quantum Gravity. Smolin, p. 153



**Figure 6.6** In quantum field theory, a particle and its antiparticle can momentarily annihilate one another, producing a photon. Subsequently, this photon can give rise to another particle and antiparticle traveling along different trajectories.

The Elegant Universe. Green, 159

“Trying to do general relativity with the rules of quantum mechanics (or vice versa) would be like using the formula for the area of a circle to compute your chances of winning the lottery” (Bartusiak, 2)

“A proper theory of quantum gravity...should allow for space to evolve...in response to the forces or presence of mass.” (Bartusiak, 3)

# String Theory

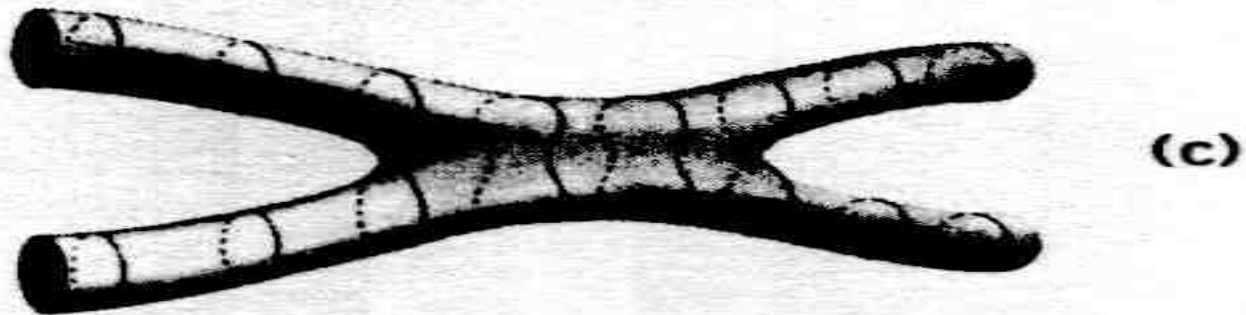
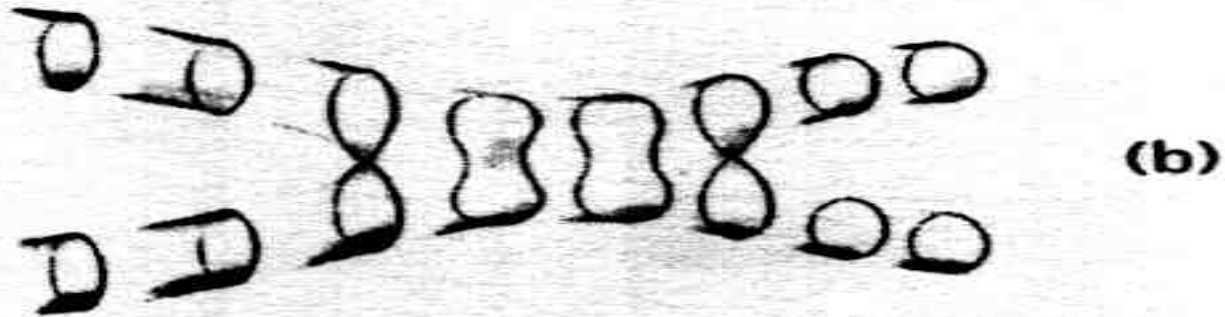
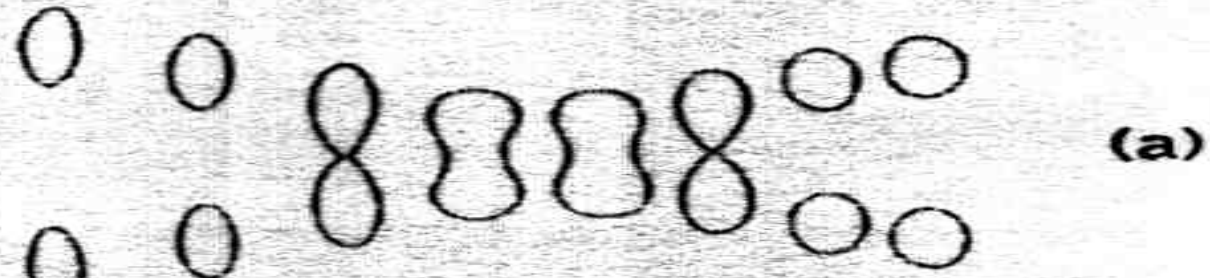
- Matter - strings of energy oscillating in different patterns and energy levels
- Forces – Strings joining and separating, no infinities because no point particles
- Larger than the Planck scale ( $10^{-33}$  cm)

## Problem

- Assumes fixed geometry background



# The String Theory of Particle Interaction



# String Theory Description of Gravity

“The graviton, the smallest bundle of gravitational force, is one particular pattern of string vibration... a gravitational field is composed of an enormous number of gravitons—that is, an enormous number of strings executing the gravitational vibrational pattern.

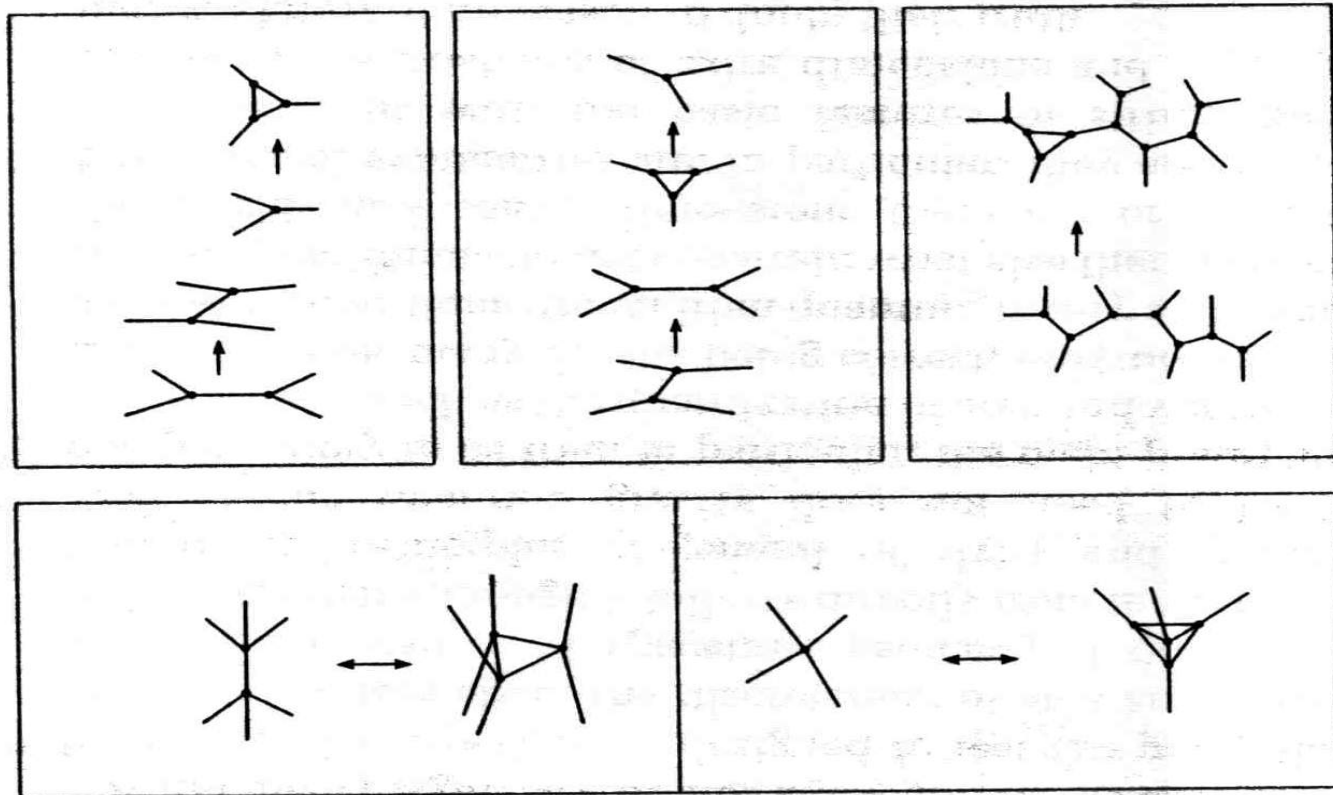
Gravitational fields, in turn, are encoded in the warping of the spacetime fabric [possibly spin networks of quantum loops]... our present formulation of string theory presupposes the existence of space and time within which strings (and the other ingredients found in M-theory) move about and vibrate.” (The Elegant Universe. Green, 378)

# Loop Quantum Gravity

- Derived from Einstein's equations
- Bridge between GR and QM - Ashtekar equations look like QM's EM equations with knot theory
- From GR – relational geometry – **Spin Networks**
- **Spacetime is not continuous**, but composed of loops spaced  $10^{-33}$  cm apart (Planck distance)
- Strings are waves in the fabric of loops
- Gravity is a wave/string disturbing the fabric

“To understand what we mean when we say that space is discrete, we must put our minds completely into the relational way of thinking, and really try to see and feel the world around us as nothing but a network of evolving relationships. These relationships are not among things situated in space – they are among the events that make up the history of the world. The relationships define the space, not the other way around.” (Smolin, 96)

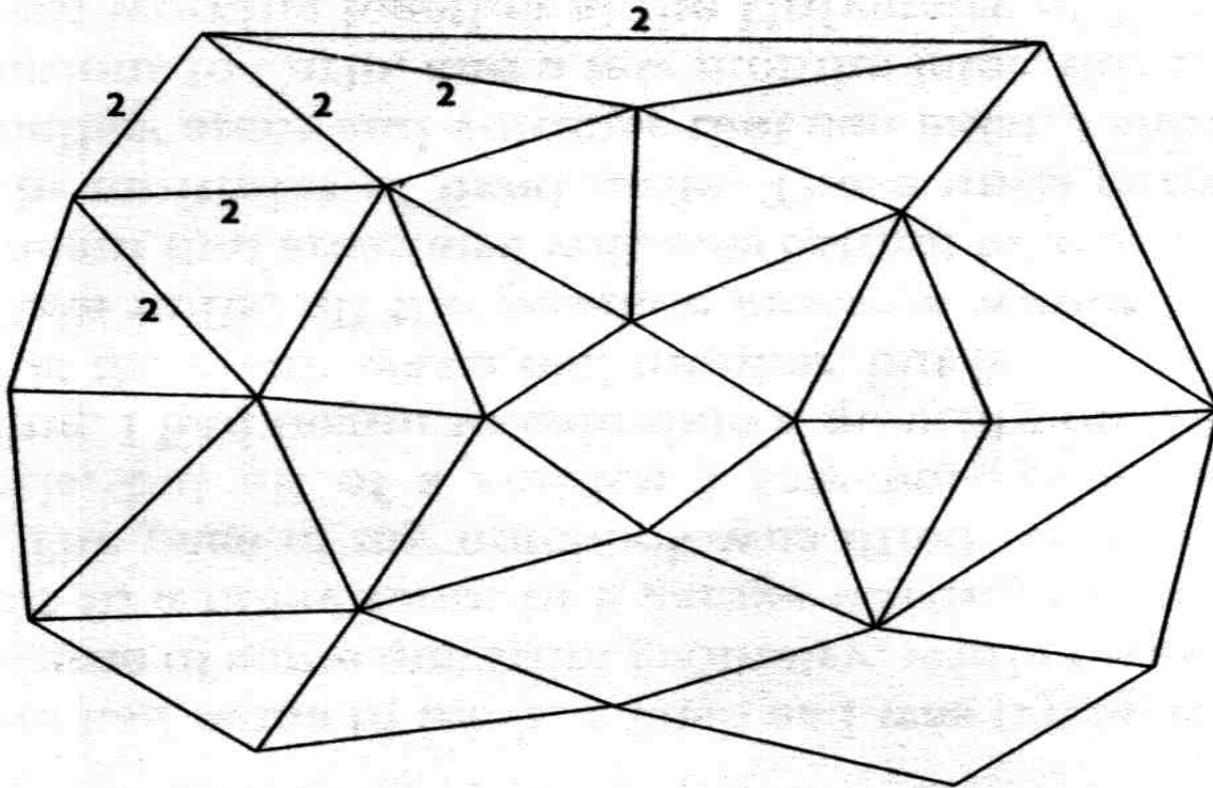
# If nothing changed would time exist?



**FIGURE 28**

Simple stages by which a spin network can evolve in time. Each one is a quantum transition of the geometry of space. These are the quantum theoretic analogues of the Einstein equations. [From F. Markopoulou, 'Dual formulation of spin network evolution', gr-qc/9704013. All the papers referenced here as gr-qc/xxxx are available at [xxx.lanl.gov](http://xxx.lanl.gov).]

# A crumpled world



**FIGURE 24**

A spin network, as invented by Roger Penrose, also represents a quantum state of the geometry of space. It consists of a graph, together with integers on the edges. By a few of the numbers are shown here.

# A Flat Version of Spacetime



# What Happened to Space?

The Space between loops is simply not defined because there is nothing there, not space, not time, not reality.

The universe is the relationships between quantum loops the collection creates spacetime. The individual loop has no meaning

Describe the chain mail at a point inside the rings! You can't!

The mail only exists in so much as the relationships of the different rings linked together gives it existence



# Problems with LQG

Spin networks at macroscopic scales have only a very few iterations with the flat geometry we observe the universe to have. Most are crumpled as in Figure 24

Some argue that strings are not merely disturbances in the quantum loop fabric but independent of it

# Implications

Discrete Universe. Was Einstein wrong?

“...on the smallest scales space and time may not have any well-defined structure. They may be more like a kind of ‘quantum foam.’” (Smolin in Waldrop, 5)

# Implications

- Discrete space implies
  - Point particles in the standard model are a bad description at the Planck length
  - Bifurcations in Chaos Theory do have a limit; the Planck length
- Black Holes are not infinitely dense
  - Bekenstein Bound
- Uncertainty – neither  $\Delta x$  nor  $\Delta p$  can be known to arbitrary accuracy

# Entropy of a Black Hole

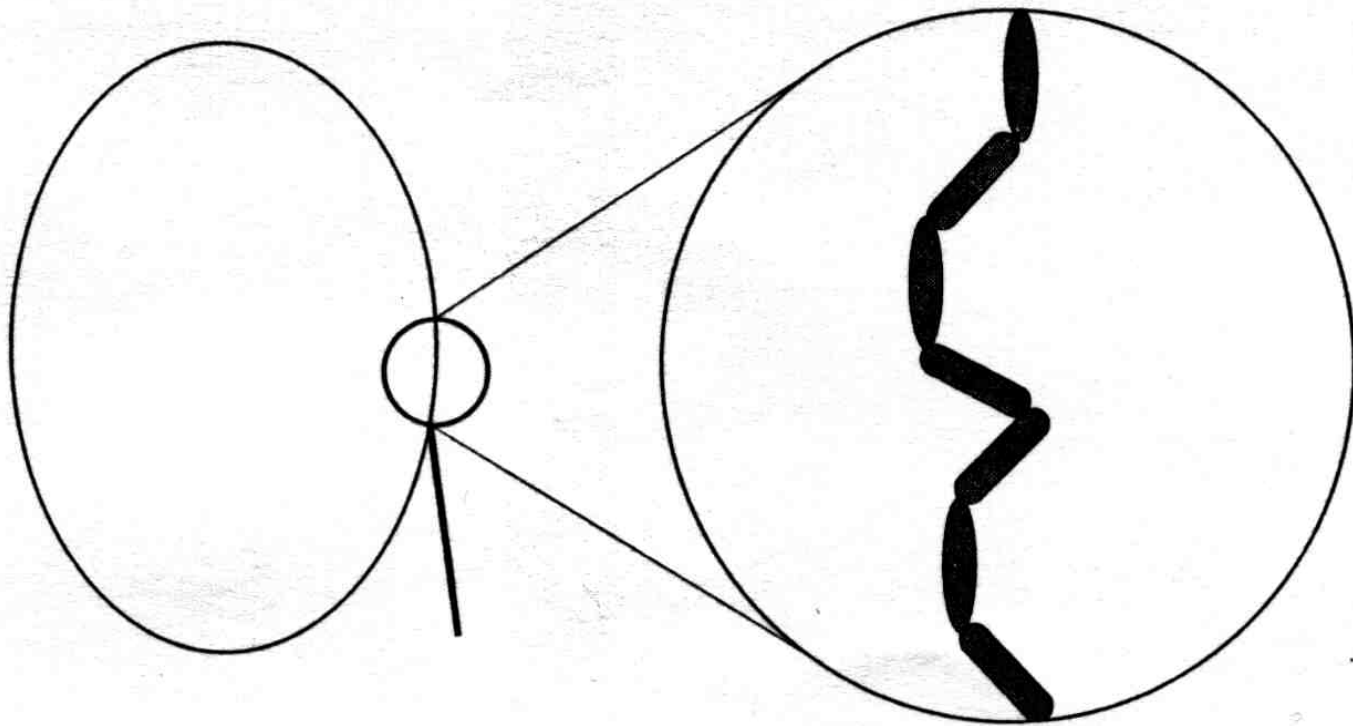
## Bekenstein's Law

With every horizon that forms a boundary separating an observer from a region which is hidden from them, there is associated an entropy which measures the amount of information which is hidden behind it. This entropy is always proportional to the area of the horizon. (Three Roads to Quantum Gravity. Smolin, 87)

$$S = \frac{1}{4} \left( \frac{A}{hG} \right)$$

A=area of horizon; G=gravitational constant

S is the **finite entropy** or number of bits of information hidden behind the horizon that describes the complete quantum state of the black hole. Energy increases the area of the horizon



**FIGURE 38**

A string seen through a Planck-scale magnifying glass is found to consist of discrete bits, rather like a wooden toy snake.

Each bit is the Planck length ( $10^{-33}$  cm)

(Three Roads to Quantum Gravity. Smolin, p. 165)

# Black Holes and Discrete Space

If spacetime were continuous then an infinite amount of information would be required to describe any volume of space, but according to Bekenstein this is not true.

Therefore spacetime may be discrete

# Implications for Uncertainty

Limitation on Uncertainty Principle.

- Can't know anything with arbitrary accuracy
- Limited to Planck length and time ( $10^{-33}$  cm or  $10^{-43}$  sec.)

$$\Delta x < (\hbar / \Delta p) + C \Delta p \quad (C \text{ is a Planck parameter})$$

- ♦ Uncertainty increases, because no phenomena can probe beyond the Planck length.

If that didn't fry your synapses try this!

“Listen, Shariputra, form is emptiness, emptiness is form; form does not differ from emptiness, emptiness does not differ from form. The same is true with feeling, perception, intention and consciousness...all dharmas are marked with emptiness; they are neither produced nor destroyed”

(The Prajnaparamita Heart Sutra)