Quantum gravity

Planck mass $m = \sqrt{\frac{hc}{G}}$

Scale on which gravity and quantum mechanics are both important

In energy units 10^{19} GeV (proton mass about 1 GeV, Higgs 125 GeV, LHC 8,000 GeV)

Quantum gravity

Conventionally: means no hope (danger!) of making black holes or seeing effects of quantum gravity in the lab

- ideas that might make the Planck scale lower
- speculations about quantum gravity

Gravity is weak

Strength of gravity can be expressed as a ratio between the gravitational and electrostatic forces between particles: e.g. a proton and an electron

$$F_{grav} = \frac{G m_p m_e}{d^2} \qquad F_e = \frac{e^2}{4\pi\varepsilon_0 d^2}$$

Ratio: $4\pi\varepsilon_0 G \frac{m_p m_e}{e^2}$

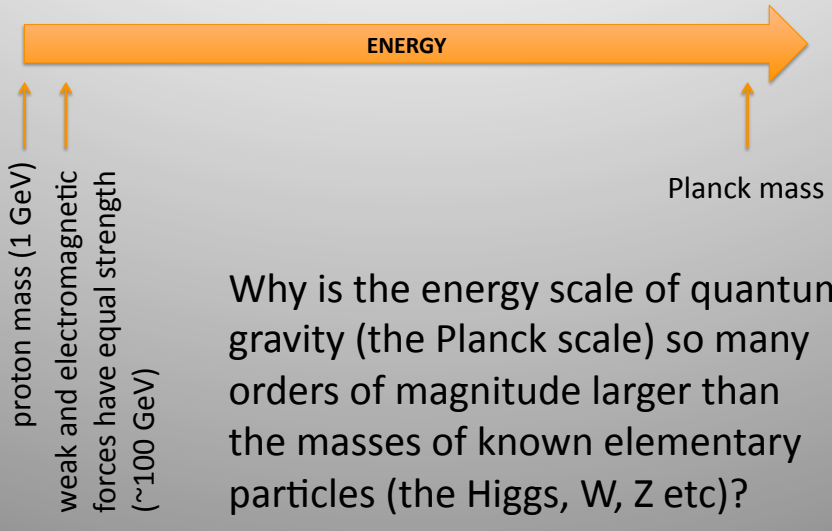
ε_0 is a constant and e is the electric charge of a proton / electron

Gravity is weak

$$4\pi\varepsilon_0 G \frac{m_p m_e}{e^2} \sim 4 \times 10^{-40}$$

Forces due ultimately to electromagnetism (magnets, muscles…) can routinely beat out the gravity of the entire Earth!

The Hierarchy Problem



Why is the energy scale of quantum gravity (the Planck scale) so many orders of magnitude larger than the masses of known elementary particles (the Higgs, W, Z etc)?

Extra Dimensions

Speculative solution: *it isn't*

Gravity *appears weak* because it (alone) is "spread out" through extra spatial dimensions, while other forces are confined to the usual 3 space dimensions

Extra Dimensions

Consequence: the actual Planck scale is much lower energy if the extra dimensions are "large"

Very energetic particle collisions in the lab might reach the Planck scale

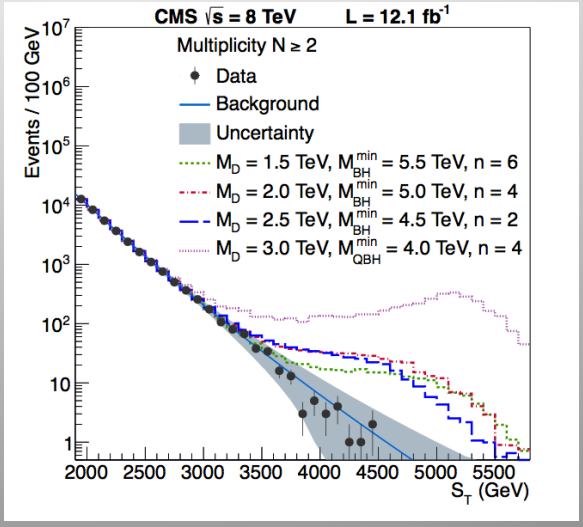
could make black holes!

Extra Dimensions

- any black hole made in the lab would evaporate by Hawking radiation instantly
- all quantum processes are reversible
- *if* high energy particle collisions made black holes, collisions of cosmic rays with neutron stars would make them… and we know neutron stars exist

LHC black holes

Search by CMS experiment at CERN for black holes in proton proton collisions at 8 TeV energy



LHC black holes

No signs of black holes

No support for the extra dimensions idea

BUT… no signs of other new physics that would provide explanation of the hierarchy problem either…

LHC upgrade / repair (8 TeV -> 14 TeV) underway

Fundamental forces

- electromagnetism
- weak nuclear force (radioactive decay)
- strong nuclear force (keeps quarks inside protons and neutrons)
- gravity

Very successful quantum theories of all these… except for gravity

Quantum gravity

No *experimental* need for quantum gravity:

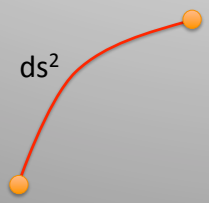
- no particle physics experiment involves gravity
- no gravitational experiment is inconsistent with general relativity

Quantum gravity

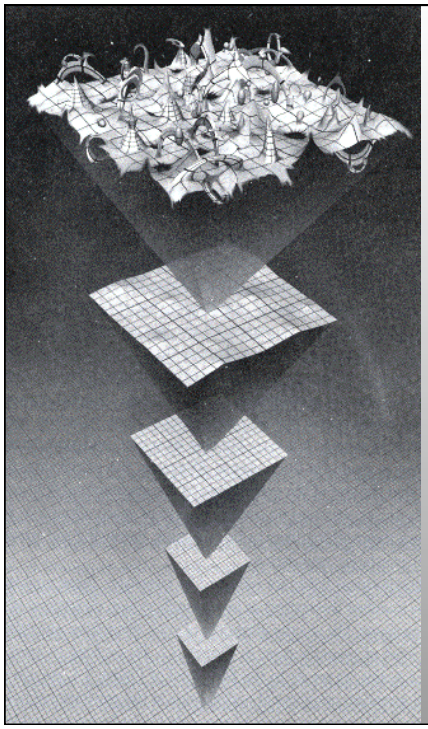
- what happens inside a black hole?
- what happens if two particles collide with enough energy to make a black hole?
- if gravity is purely classical, can devise thought experiments where we can evade the uncertainty principle of QM

Gravity cannot be converted into a quantum theory in the same way as the other forces

Physical principles that underlie quantum gravity are not yet known…



Basic quantity of GR is the *geometry* – the distance between points in space time measured by the metric



Perhaps spacetime itself is:

- "fuzzy"
- like a foam
- undefined

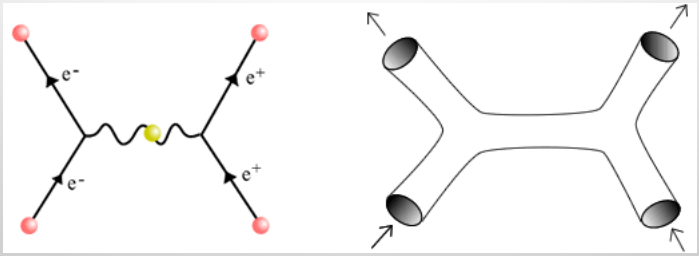
…on sufficiently small scales where quantum effects matter

Image: James Schombert

(Many) conceptual and technical problems

In GR *and* quantum mechanics, whether one event can *cause* another is precisely defined: **yes** if they are close enough together than a light signal could pass between them

If spacetime is itself uncertain, it may be uncertain whether two points can causally affect each other or not



String theory – fundamental objects are not point-like particles but extended strings

Candidate for a theory of quantum gravity that would also include *all* the known forces

Microscopic Origin
of the
Bekenstein-Hawking Entropy

ANDREW STROMINGER

Department of Physics
University of California
Santa Barbara, CA 93106-9530

and

CUMRUN VAFA

Lyman Laboratory of Physics
Harvard University
Cambridge, MA 02138

Abstract

The Bekenstein-Hawking area-entropy relation $S_{BH} = A/4$ is derived for a class of five-dimensional extremal black holes in string theory by counting the degeneracy of BPS soliton bound states.

1996: shown that the classical entropy of some types of black holes could be derived by "counting" the number of microscopic states in string theory

Status of quantum gravity…

Took Einstein many years to develop the physical insight of the equivalence principle into the final form of general relativity

Today, are we:

- missing some or all of the key ideas of quantum gravity?
- in possession of the right idea (string theory?) but unable to calculate the consequences?

"Therefore Simplicio, come either with arguments and demonstrations and bring us no more Texts and authorities, for our disputes are about the Sensible World, and not one of Paper."

Galileo