21st-century Physics

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Overview

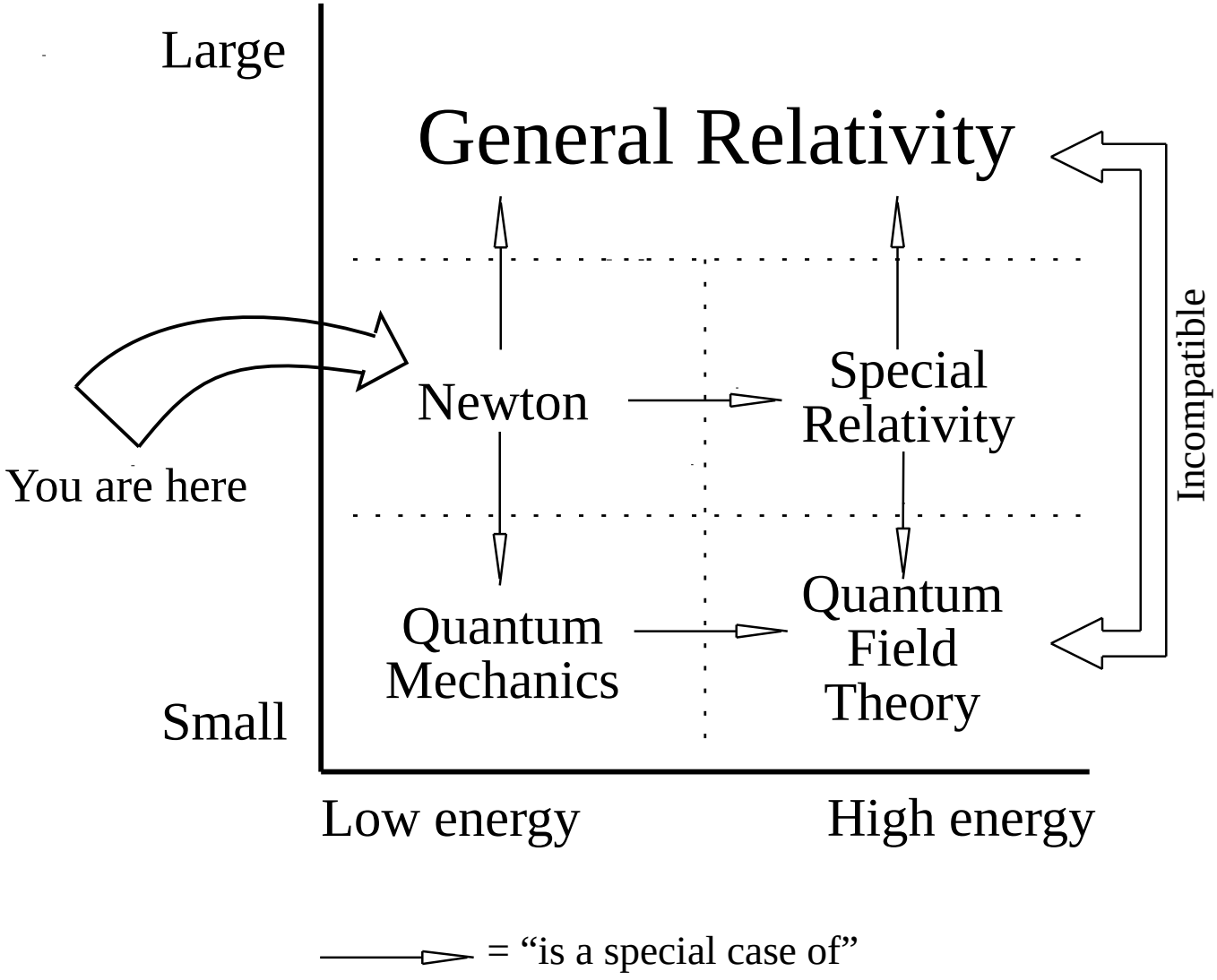
- Orientation
- Classical gravity
- Quantum mechanics and particle physics
- Quantum gravity: what's the problem?
- Superstrings
- Loop quantum gravity
- Experimental support

Orientation

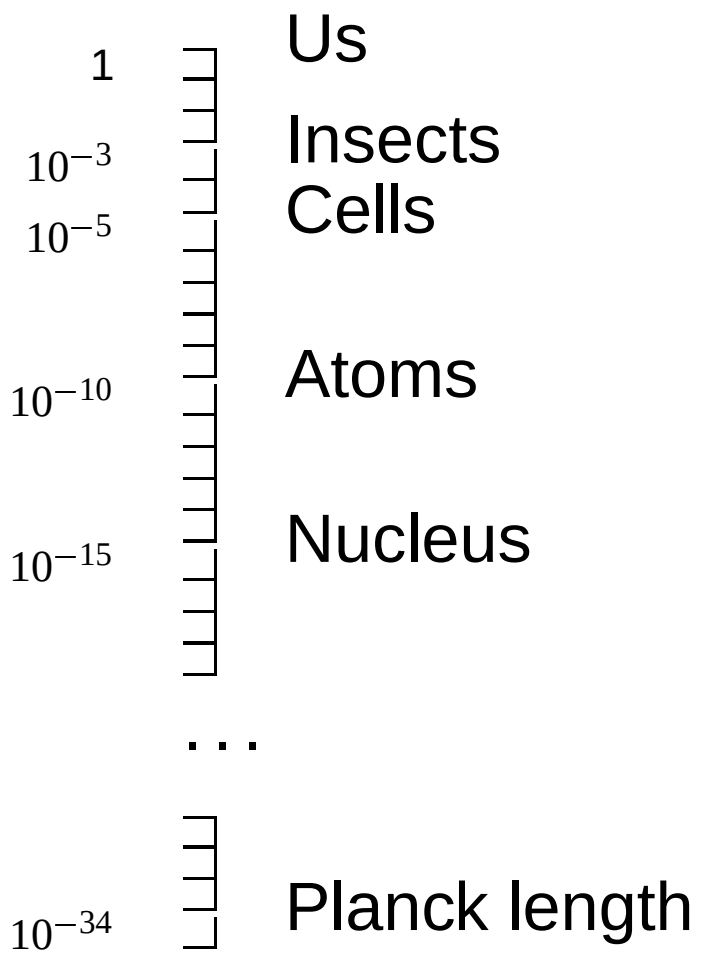
Contents

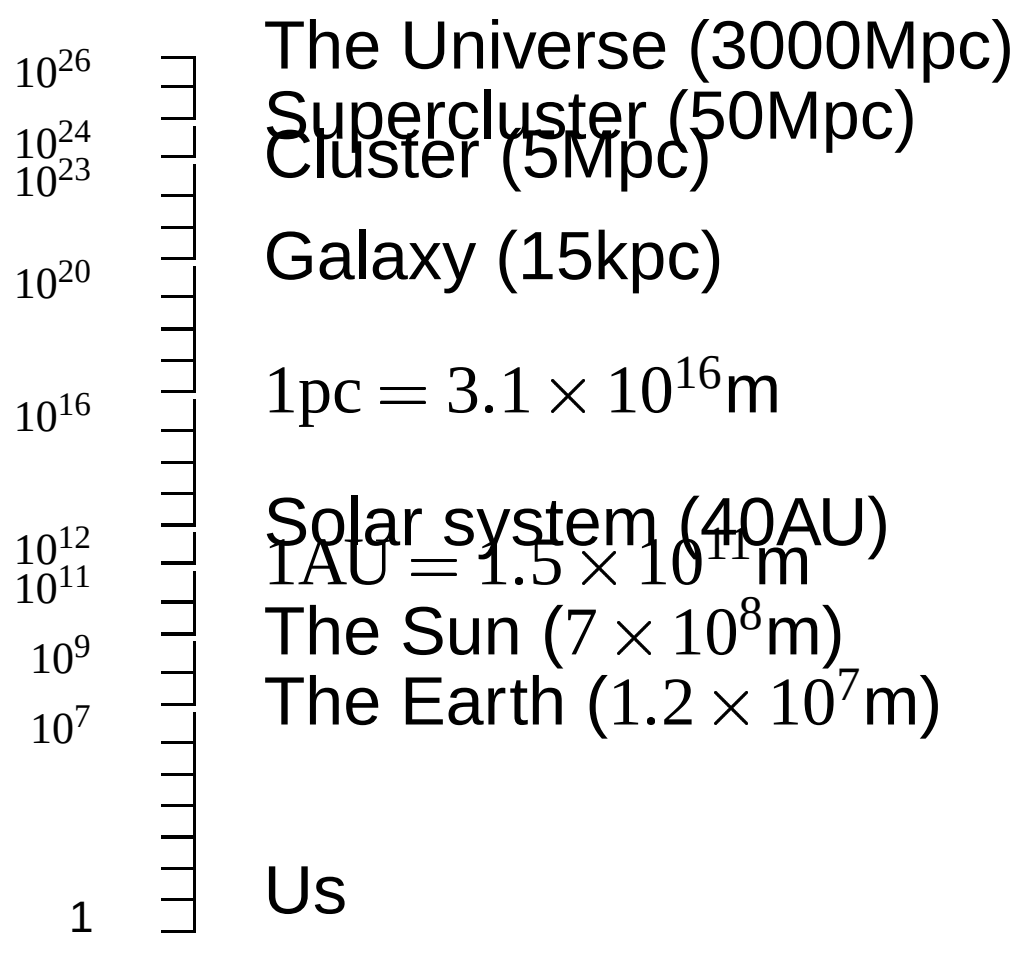
- The plan
- More

The plan


Large
General Relativity
Incompatible
You are here
Newton
Special Relativity
Quantum Mechanics
Quantum Field Theory
Small
Low energy
High energy
= “is a special case of”

More


1
Us
10^{-3}
Insects
10^{-5}
Cells
10^{-10}
Atoms
10^{-15}
Nucleus
...
10^{-34}
Planck length

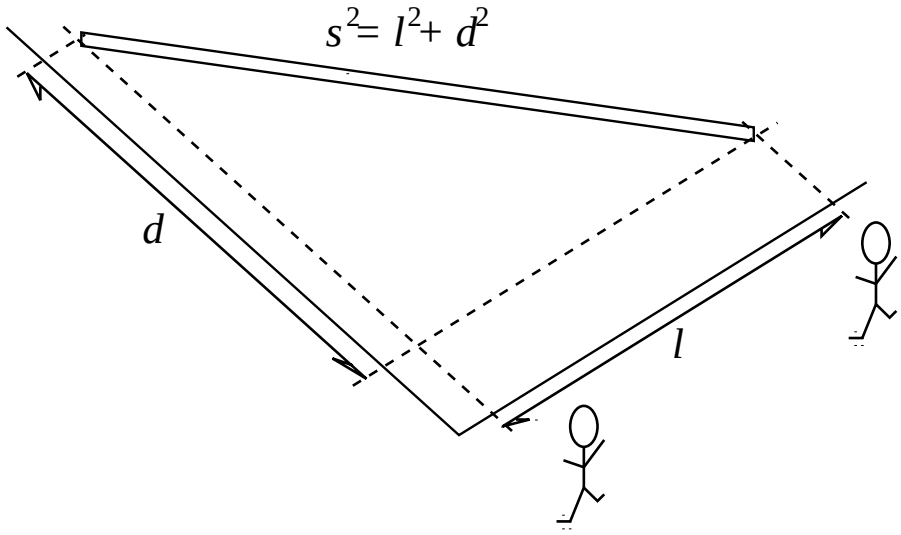

10^{26}
The Universe (3000Mpc)
10^{24}
Supercluster (50Mpc)
10^{23}
Cluster (5Mpc)
10^{20}
Galaxy (15kpc)
10^{16}
$1\text{pc} = 3.1 \times 10^{16}\text{m}$
10^{12}
Solar system (40AU)
10^{11}
$1\text{AU} = 1.5 \times 10^{11}\text{m}$
10^{9}
The Sun (7×10^{8}m)
10^{7}
The Earth (1.2×10^{7}m)
1
Us

Classical gravity

Contents

- Special relativity and geometry
- Geometry: the equivalence principle
- Geometry: falling lifts
- Geometry: Simplicity

Special relativity and geometry



— For distances, $s^2 = l^2 + d^2$

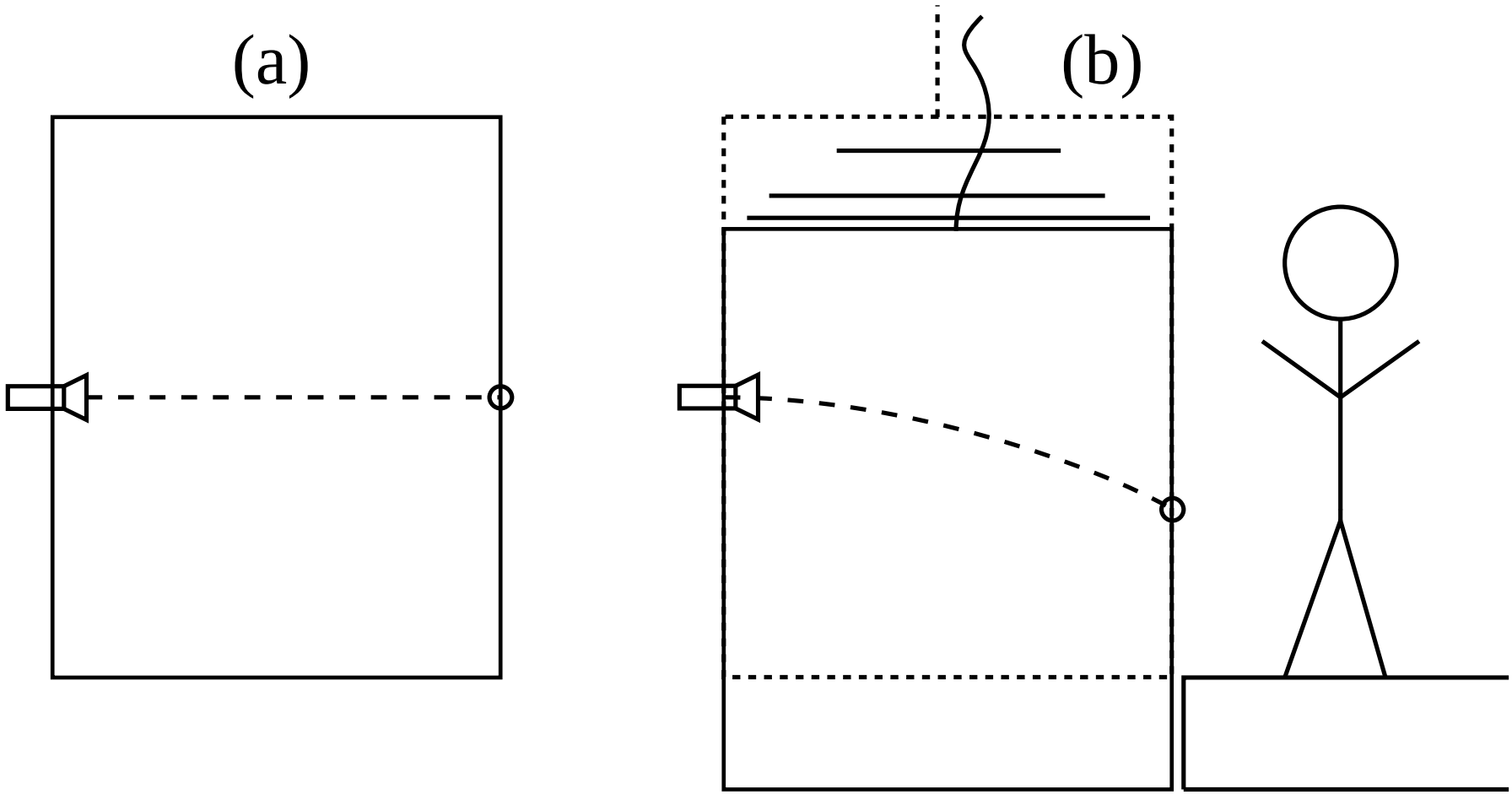
— Two bangers go off, separated by a distance l in space and a ‘distance’ t in time. Differently moving observers see *different* l and t, but. . .

— . . . $s^2 = (ct)^2 - l^2$

Geometry: the equivalence principle

- Physical systems in a gravitational field behave the same as they do in an accelerated frame (in a small laboratory)
- The behaviour of a free particle in an accelerated frame is independent of the composition of the particle. The equivalence principle tells us that the same must be true of a particle in a gravitational field. Linked to. . .
- . . . all objects fall at the same rate, independent of their mass.

Geometry: falling lifts



Gravity is geometry.

Geometry: Simplicity

— Einstein's equations: $G_{\mu\nu} = -\kappa T_{\mu\nu}$

— Bekenstein-Hawking equation: $S = A k_B c^3 / 4\hbar G$

Quantum mechanics and particle physics

Contents

- Quantum mechanics
- Fundamental particles
- The Particle Zoo: groups
- The Particle Zoo: forces
- Unification

Quantum mechanics

— *The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds. I. The first involves the question, How could the earth move through an elastic solid, such as essentially is the luminiferous ether? II. The second is the Maxwell-Boltzmann doctrine regarding the partition of energy.* – William Thomson, Lord Kelvin, 1901.

— The second point is concerned with thermodynamics and black-body radiation.

— Led to quantum mechanics.

Fundamental particles

This started off nice and simple:

- Inside atoms there were *protons*, *neutrons* and *electrons*
- . . . then came neutrinos
- . . . then came cloud chambers
- The current Particle Data Group summary of particle properties is 184 pages.

The Particle Zoo: groups

leptons For example, the electron, muon and neutrino. These particles have very small masses, and seem to be truly fundamental.

hadrons For example, the proton, neutron and pion. These are split into two groups, the *baryons* and the *mesons*, and have substantially larger masses than the leptons. These particles feel the 'strong nuclear force' described below.

'gauge bosons' The photon, the W and Z particles and the gluon (see below). These are the particles which carry the fundamental forces.

The Particle Zoo: forces

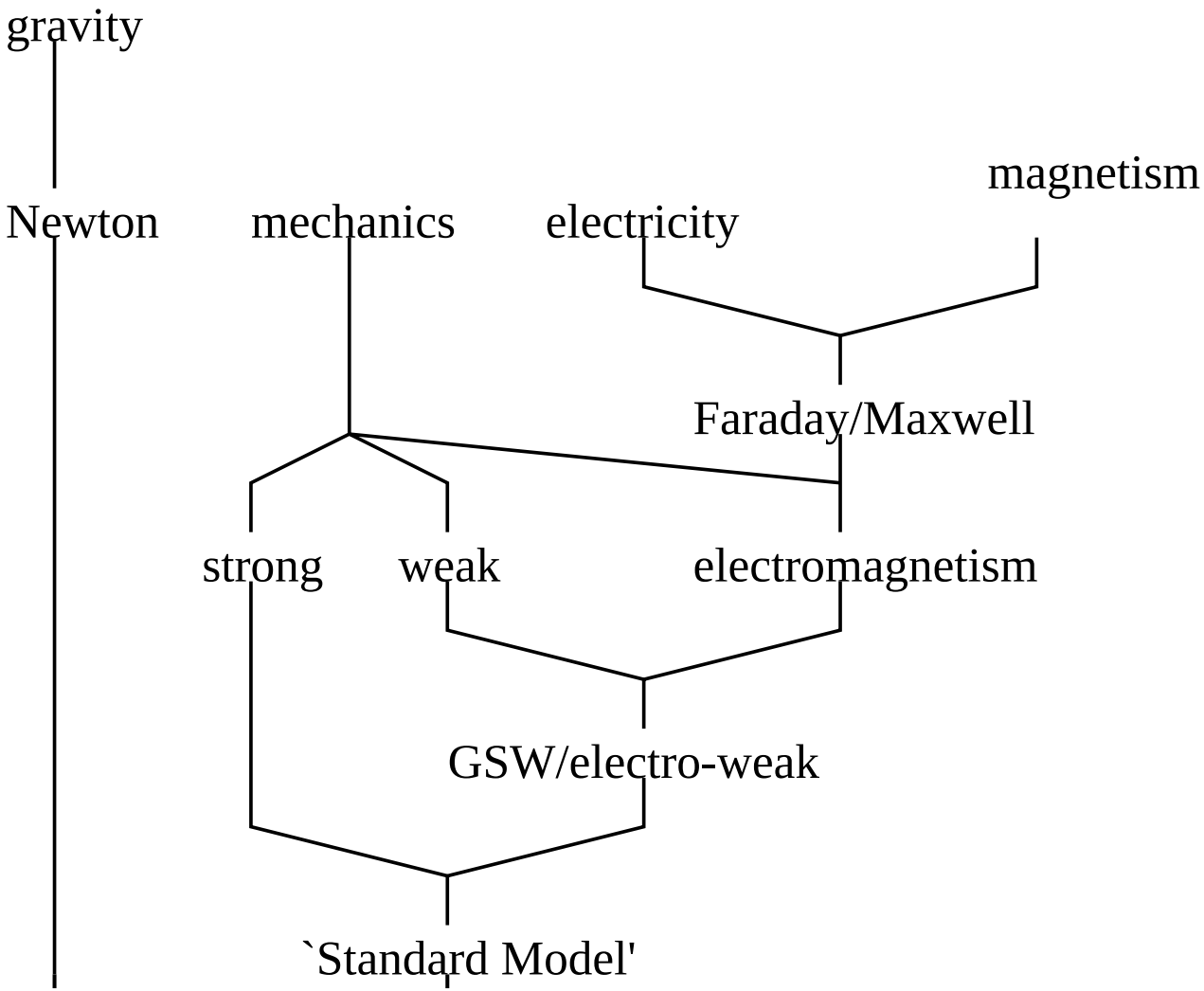
Gravity In this picture, gravity is the stage on which all of the rest of physics takes place, and in consequence *everything* feels its effects, even the massless photon. 'Space tells matter how to move; matter tells space how to curve.'

Electromagnetism This is the force that drives motors, comprises radio waves, keeps the electrons circling the nucleus, and stops us falling through the floor.

Weak nuclear force Responsible for radioactive decay, when a neutron decays into a proton, and electron, and a neutrino.

Strong nuclear force The strong nuclear force is the force that keeps nuclei firmly in one piece against the huge electrostatic repulsive force.

Unification



Quantum gravity: what's the problem?

Contents

- Contradictions
- Scales

Contradictions

- Classical gravity works!
- The Standard Model works!
- But they flatly contradict each other, and the unifications that worked for the Standard Model won't work with gravity.

Scales

— Particle physics experiments work at up to TeV scale, or 10^{12}eV, on length scales of an atom (10^{-10}m), or a nucleus (10^{-15}m) or a little smaller.

— Gravity works on scales of 10^{3}m to 10^{10} parsecs, or 10^{26}m.

— The ‘unification scale’ is where the various Standard Model theories converge: Planck energy: $\hbar c^5/G = 10^{28}$eV

— Planck length: $\sqrt{\hbar G/c^3} = 10^{-35}$m; time, $\sqrt{\hbar G/c^5} = 10^{-44}$s; mass, $\sqrt{\hbar c/G} = 10^{-7}$kg

— . . . not directly accessible by experiment, but they *do* involve G!

Superstrings

Contents

- Strings
- Dimensions
- Black holes
- Too many theories

Strings

- Comes from particle physics, and is a modification of standard quantum mechanics.
- It is a response to the perplexing observation that the ‘fundamental’ particles do have a lot of properties: spin, parity, colour, charge, hypercharge.
- Surely the Planck scale is where the internal machinery lives.
- Instead of point particles (zero dimensions) being the fundamental objects, have strings (one dimension) instead – immediately gives much richer structure.
- But it only makes sense in 10 dimensions.
- Strings can’t interact with particles, so either all matter (particles and photons) is stringy, or none of it is.

Dimensions

- Compactification: like a hosepipe
- Kaluza-Klein
- Reduce number of observable dimensions, but still have dynamics in all 10. Explains ‘internal’ properties.

Black holes

— Hawking radiation: black holes evaporate, and return their energy to the universe

— And they have an *entropy*: Bekenstein-Hawking equation, $S = Ak_b c^3/4\hbar G$

— A black hole constructed from D-branes has precisely this entropy!

Too many theories

— The problem is that there are too many possibilities – something like 10^{100} possible vacua, and no *a priori* way of distinguishing between them

— ‘Pocket universes’; anthropic arguments?

Loop quantum gravity

Contents

- A different approach
- Spin networks
- Successes

A different approach

- Superstring theory assumes a simple background space – a flat stage – and has exotic objects moving around in it
- Loop quantum gravity talks of quantising space itself, completing (?) the transition from Newton's space, to Einstein's, and beyond

Spin networks

- We intuit that in space we can move from one point, continuously, to any other point
- Replace this with a network of nodes and links: space consists of the collection of nodes, and we can only move from one node to another to which it connected by a link
- Natural quantisation of space, into volumes around each node (around the size of the Planck length) and areas corresponding to each link, forming the boundaries of a cell

Successes

- Has also derived the Bekenstein-Hawking equation (once a free parameter has been fixed)
- ‘Spinfoam’ is the history of a spin network, and allows you to calculate ‘sum over histories’

Experimental support

Not quite yet. . .