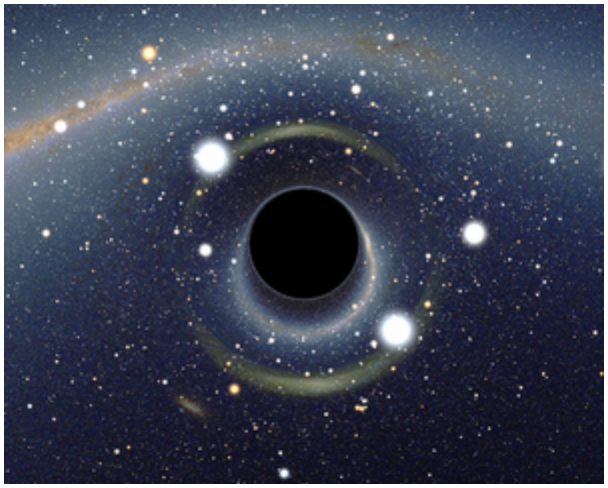
Implications

(iii) black holes



The roles of space and time reverse inside the *Schwarzschild radius* of a black hole.

$$r_{\mathrm{sh}} = \frac{2GM}{c^2} \approx 2.95 \, \frac{M}{M_{\mathrm{Sun}}} \ \mathrm{km},$$

To a distant observer, clocks near a black hole appear to tick more slowly than those further away from the black hole. Due to this effect, known as gravitational time dilation, an object falling into a black hole appears to slow down as it approaches the event horizon, taking an infinite time to reach it.

Implications

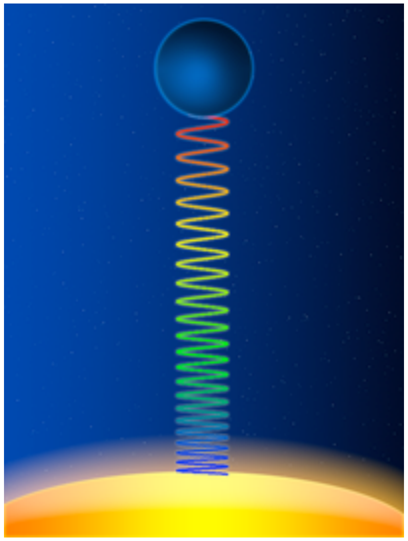
(iv) gravitational time dilation

clocks run slow near masses

One particular set of observations is related to eminently useful practical applications, namely to satellite navigation systems such as the Global Positioning System that are used both for precise positioning and timekeeping. Such systems rely on two sets of atomic clocks: clocks aboard satellites orbiting the Earth, and reference clocks stationed on the Earth's surface. General relativity predicts that these two sets of clocks should tick at slightly different rates, due to their different motions (an effect already predicted by special relativity) and their different positions within the Earth's gravitational field. In order to ensure the system's accuracy, the satellite clocks are either slowed down by a relativistic factor, or that same factor is made part of the evaluation algorithm

Implications

(v) gravitational red shift



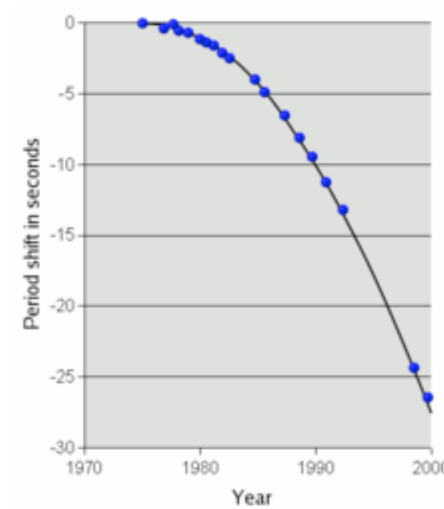
Light climbing against a gravitational potential ("up") is *red shifted,* meaning it is shifted to lower frequency.

Einstein predicted the gravitational redshift of light from the equivalence principle in 1907, but it is very difficult to measure. Although it was measured by Walter Sydney Adams in 1925, it was only conclusively tested when the Pound–Rebka experiment in 1959 measured the relative redshift of two sources situated at the top and bottom of Harvard University's Jefferson tower using an extremely sensitive phenomenon called the Mössbauer effect. The result was in excellent agreement with general relativity. This was one of the first precision experiments testing general relativity

Implications

(vi) gravitational waves

Coulomb's law -> EM waves
Newton's law -> gravitational waves



The first observation of a decrease in orbital period due to the emission of gravitational waves was made by Hulse and Taylor, using the binary pulsar PSR1913+16 they had discovered in 1974.

[noon, March 17, 2014: the discovery of gravitational waves from the Big Bang was announced.]

Implications

(vi) gravitational waves

Coulomb's law -> EM waves
Newton's law -> gravitational waves

LIGO
Laser Interferometer
Gravitational
Wave Observatory

Quiz

fast moving clocks run fast

(a) true
(b) false

clocks in a strong gravitational field run fast

(a) true
(b) false

if you are moving fast, your wrist watch runs slow

(a) true
(b) false

the Fizeau water experiment and the Michelson-Morley experiment are explained by SR

(a) true
(b) false

energy curves spacetime

(a) true
(b) false

Quiz

black holes have been observed

(a) true
(b) false

gravitational time dilation has been observed

(a) true
(b) false

gravitational waves have been directly observed

(a) true
(b) false

Review

special relativity:

joins space and time

Einstein

corrects Galilean invariance

time dilation

length contraction

speed of light is constant in all frames

general relativity:

equivalence principle

gravity is like a fictitious force

gravity is curvature of spacetime

light bends, red shift, gravitational time shift, black holes

Some Loose Ends

The Void and the Continuum

The story so far:

the ancient Greeks had two views on this

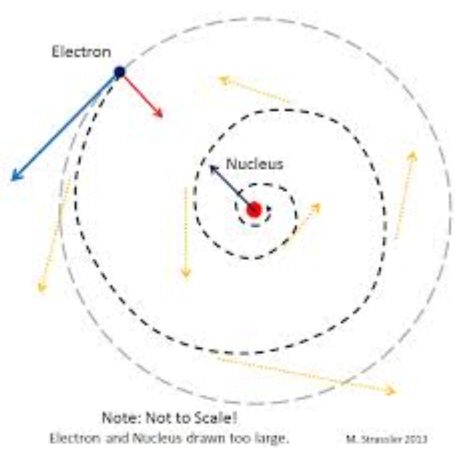
(i) matter is irreducible at some small distance, this forces there to be nothing between the atoms. They argued that this is the only way in which motion can happen.

(ii) there is always something, no matter how small the distance, because "saying there is nothing is saying there is a thing".

The Void and the Continuum

The discovery of atoms in the late 1800’s and the proof of their existence in the early 1900’s seemed to settle the issue in favor of the void.

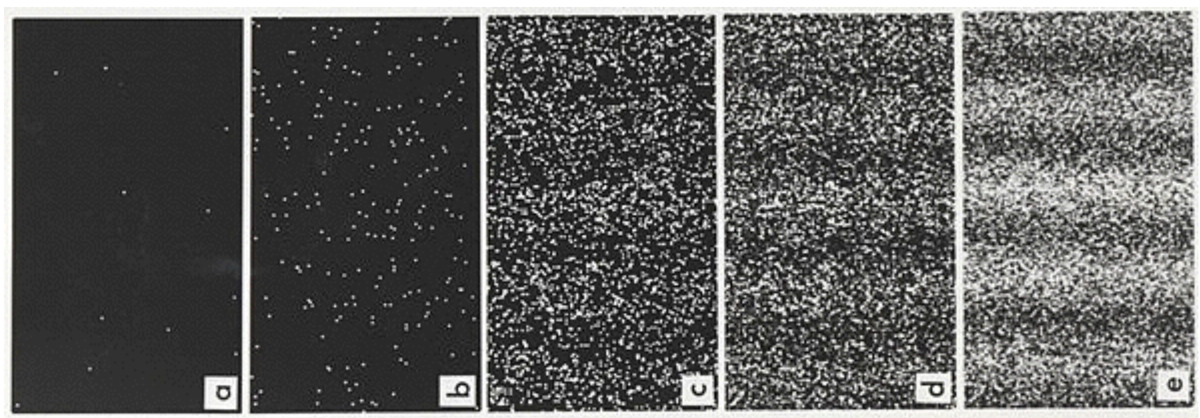
However, atoms can only be understood with *quantum theory*. The problem is that electrons circling a nucleus will lose energy by emitting electromagnetic waves and spiral into the nucleus.



This is resolved in the quantum theory by only permitting electrons to inhabit certain orbits, so it takes a fixed amount of energy to drop inward (and there is a smallest orbit). This gives atoms a rigidity that prevents atoms from decaying away and prevents matter from collapsing on itself.

The Void and the Continuum

Quantum mechanics says that particles sometime behave as waves (this is called *wave-particle duality*).



Electrons passing through a foil with two slits.

The Void and the Continuum

If quantum particles can act wave-like, can quantum (EM) waves act particle-like?

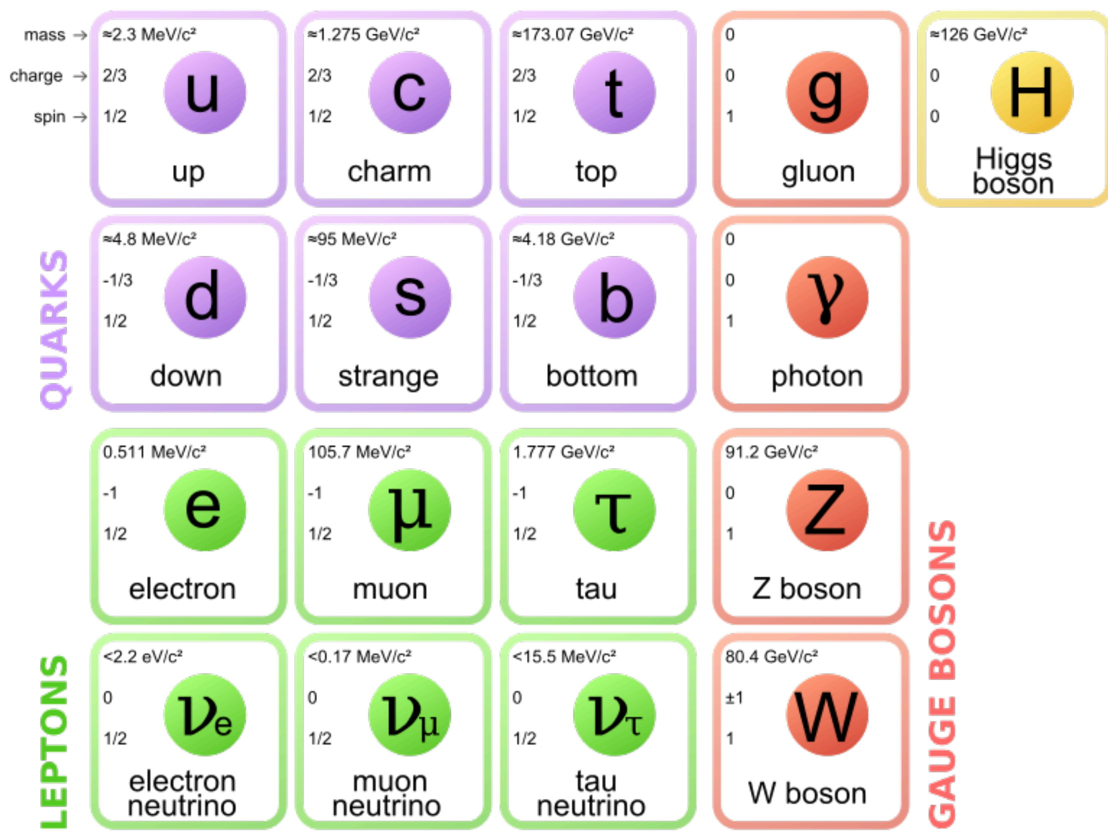
Yes! We call the particles of light, *photons*.

Thus the world consists of particle-waves and wave-particles. Both of these are described by *quantum fields*.

There is *one* quantum field that describes all the electrons in the world, another for all the photons in the world, and so on.

This field is everywhere and has physical effects. Thus the Greeks were right and wrong at the same time. There is a void, but it is not empty — it is filled with quantum fields. The most famous such field was discovered July 4, 2013, and is called the *Higgs field*.

The Void and the Continuum



The graviton and these are all the fields (that we know about) that make up the universe. We are only familiar with the first generation (up, down, electron, electron neutrino) in everyday life.

The gauge bosons are the particles (quanta) associated with forces.

The Higgs field supplies mass to other fields.

The Void and the Continuum

The issue was resolved around 1940:

Quantum fields are everywhere and have physical effects. Thus the Greeks were right and wrong at the same time. There is a void, but it is not empty — it is filled with quantum fields. The most famous such field was discovered July 4, 2013, and is called the *Higgs field*.