Elementary Particle Physics, Cosmology, and the Large Hadron Collider

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The Physics of Everything
Outline

Classical Mechanics: the world according to Isaac Newton

Quantum Mechanics: the world of atoms and their pieces

Particle Physics: breaking things apart as far as we can go

Relativity: space, time, and gravity

Cosmology: what's out there and where it came from

String Theory: the smallest pieces????

The Large Hadron Collider (LHC)

Classical Mechanics

Where Newton started

Before Newton the motions of planets and the motion of billiard balls had nothing in common

Astronomical observations by Galileo, Brahe, and Kepler quantified the motion of the planets.

Gravity was something experienced on Earth

Objects sat still or moved with respect to the whole universe

Classical Mechanics

Newtonian Mechanics

Newton is best known for his three laws of mechanics and the assertion that the laws apply **everywhere**

The laws

- An object at rest stays at rest and an object in uniform motion stays in uniform motion unless acted on by a net external force
- The acceleration of an object times its mass equals the net force applied to it. $F = m \times a$
- For every action there is an equal and opposite reaction

Newton's mechanics was amazingly successful

Classical Mechanics

Newtonian Mechanics

The first law has sweeping implications. It notes that motion and rest are relative. This is Newtonian Relativity.

Since Newton, a uniformly moving frame of reference has been called a Newtonian reference frame.

The laws of physics are the **same** in all Newtonian reference frames.

Unification has always been a prime goal in physics

- Galileo – earth and all the planets move by the same mechanisms
- Michael Faraday – electricity and magnetism are two aspects of the same electromagnetic field

Classical Mechanics

The end of physics

Newton unified the gravitation force we feel on earth with the force that keeps the planets near the sun

For two hundred years, no new physical laws were needed to describe mechanical systems and all systems were seen as mechanical.

- Electromagnetism was understood and described as a new force that obeyed Newton's laws
- Lots of discoveries increased our understanding of how heat and light work within Newton's laws

These were just elaborations on the variety of mechanical systems in the universe. All were built on Newton's mechanics. The universe was matter, forces, and Newton's laws.

Classical Mechanics

Not so quick with the shovel...

At the end of the 19th century, only a few oddities remained to be figured out

But researchers began to find new stuff in our universe

- Electromagnetic waves, J.C. Maxwell, 1864. Light was such a wave!
- Photoelectric effect, Heinrich Hertz, 1887
- X rays, Wilhelm Roentgen, 1895
- The electron, J.J. Thomson, 1896

All this stuff didn't exactly follow Newton's laws and the idea that matter was simple and solid

A new, improved mechanics was needed

Unification in Physics

Unification refers to the successes of physics in showing that all the world's complex features arise from combinations of simpler features

- The motion of planets and falling apples are governed by the same rules (gravity)
- Electric and magnetic effects are governed by a single set of equations (Maxwell's equations)
- All matter, and thus all atoms, are made of the same electrons, protons, and neutrons

The complexities are called emergent properties. They emerge when the simpler things are combined. For example, an automobile emerges from the assembly of chunks of metal and plastic.

Most physicists believe the universe is made of only one thing.

Quantum Mechanics

A whole new world

The world had been seen as made of particles—atoms, and fields—gravity and electromagnetism

The electromagnetic field carried waves, but matter on a very small scale seemed neither particles nor waves, it seemed something in between

In fact, electromagnetic waves seemed to be divided into packets, or quanta, or little particles.

Electrons, a component of ordinary, solid matter, acted like waves

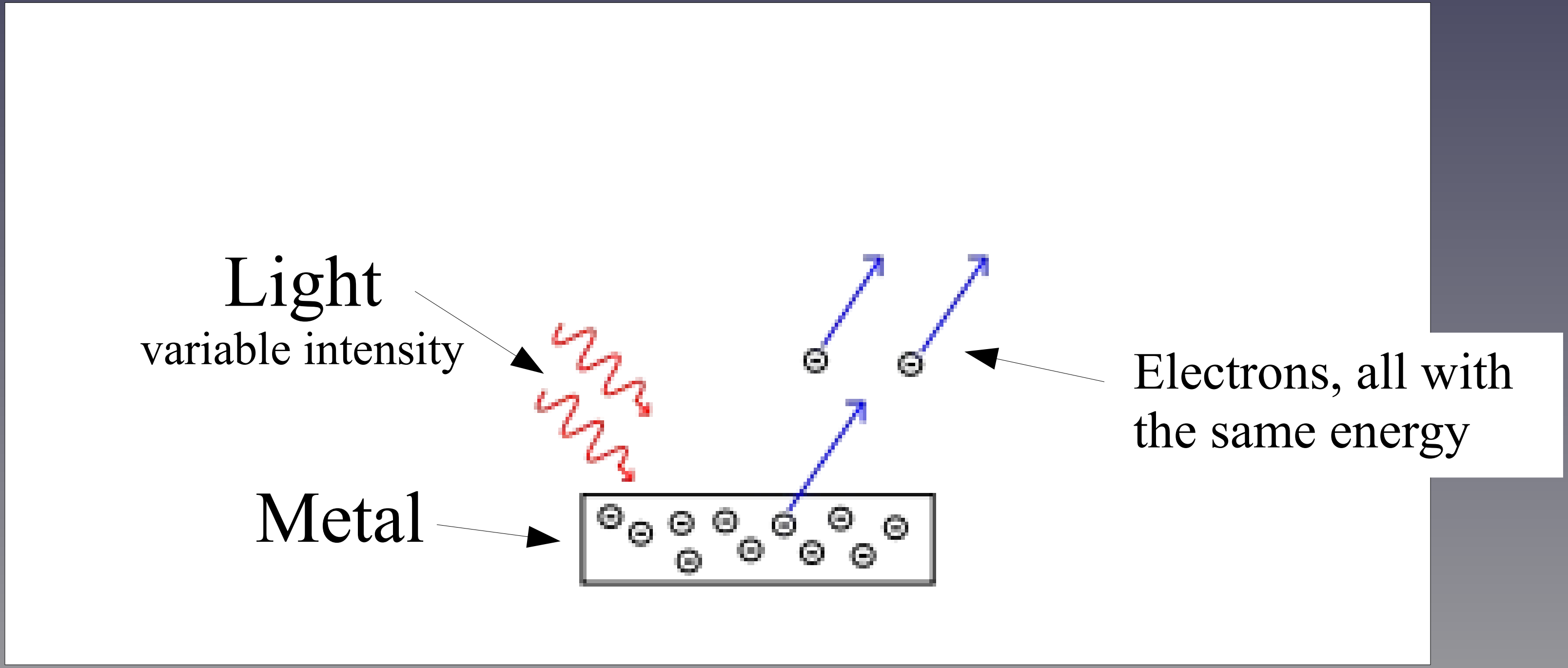
Quantum Mechanics

Particles and waves

Light was an electromagnetic wave (Maxwell)

But, light seemed to come only in packets, not continuous waves

The photoelectric effect (Heinrich Hertz, 1887)



Quantum Mechanics

Particles and waves

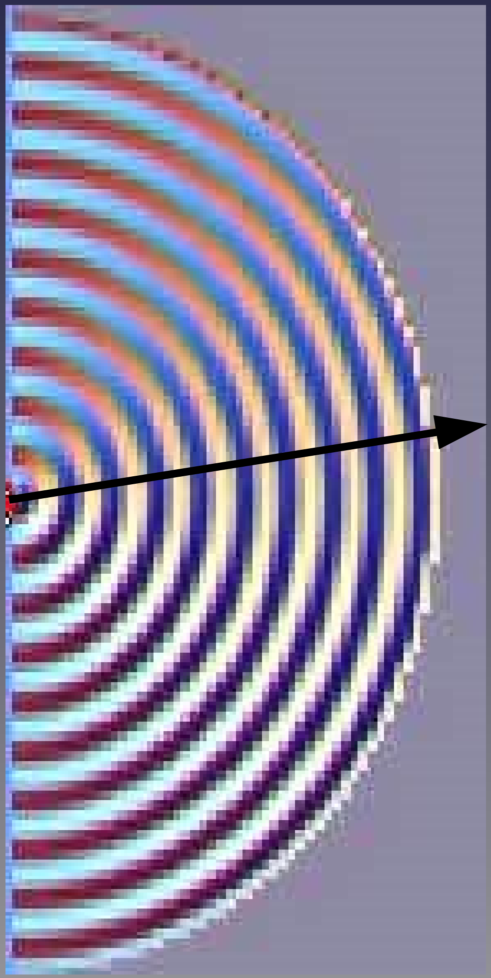
Drop a rock in a pond

Waves interfere (add together) either constructively or destructively

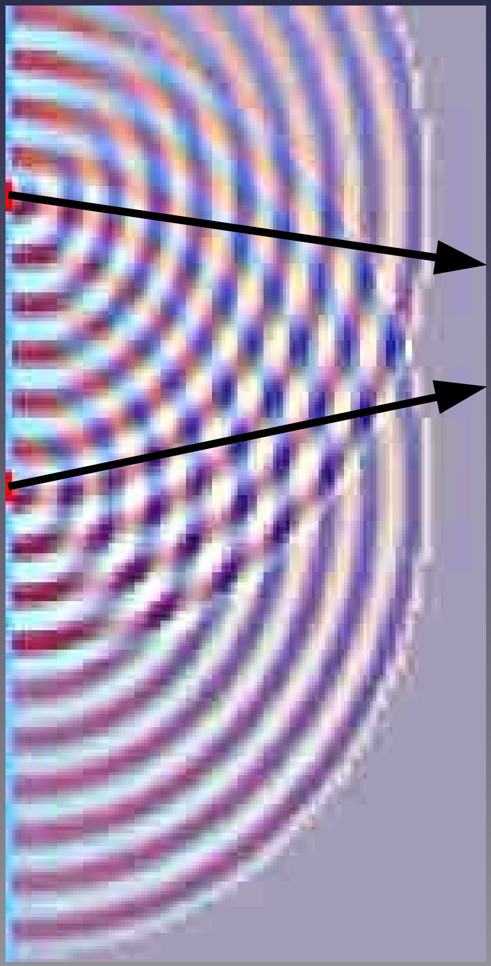
If both waves push the water up or down, it's constructive

One up, one down, they subtract—destructive interference

One rock



Two rocks



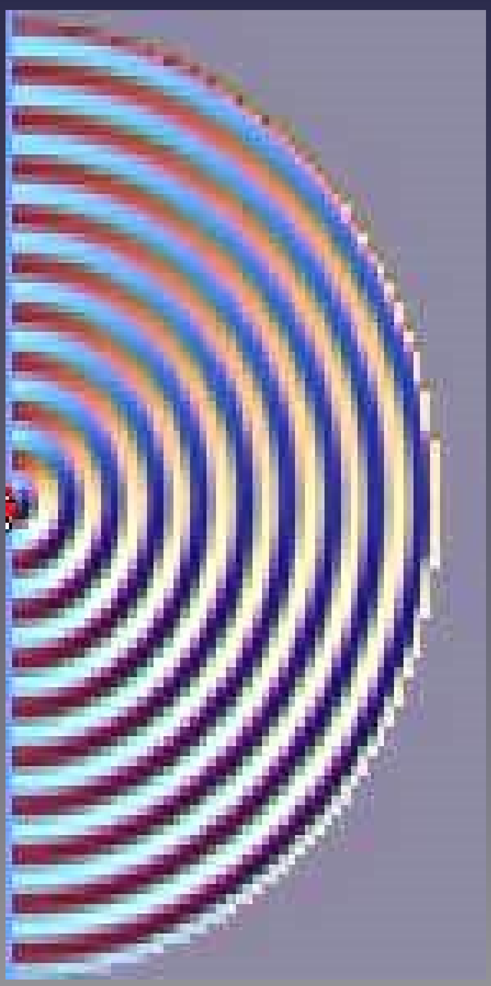
Quantum Mechanics

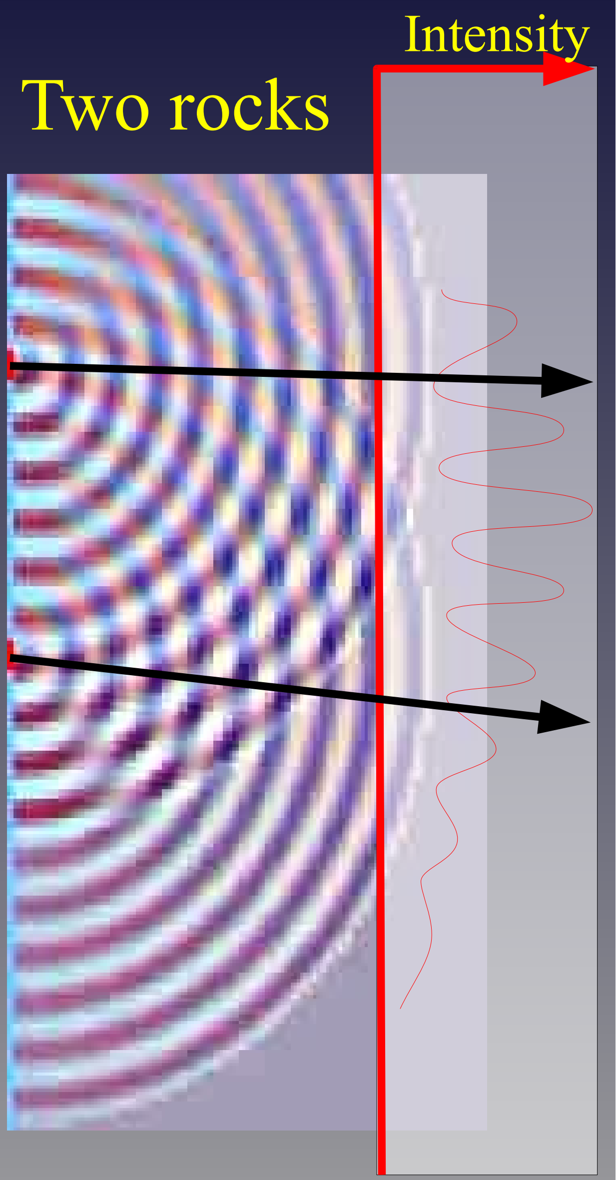
Particles and waves

The varying strength of the wave along a line is called its interference pattern or diffraction pattern

So, it was no surprise to find that light waves made interference patterns

Particles just hit one and only one place





Quantum Mechanics

Particles and waves

Light was an electromagnetic wave

Most puzzling, they found that light, electrons, and any small object acted as a wave and as a particle

The Double-Slit Experiment

Quantum Mechanics

Particles and waves

Not only did light behave as both a particle and a wave, electrons did too!

Particles building an interference pattern

Size matters! Any object that is small enough behaves as both a particle and a wave

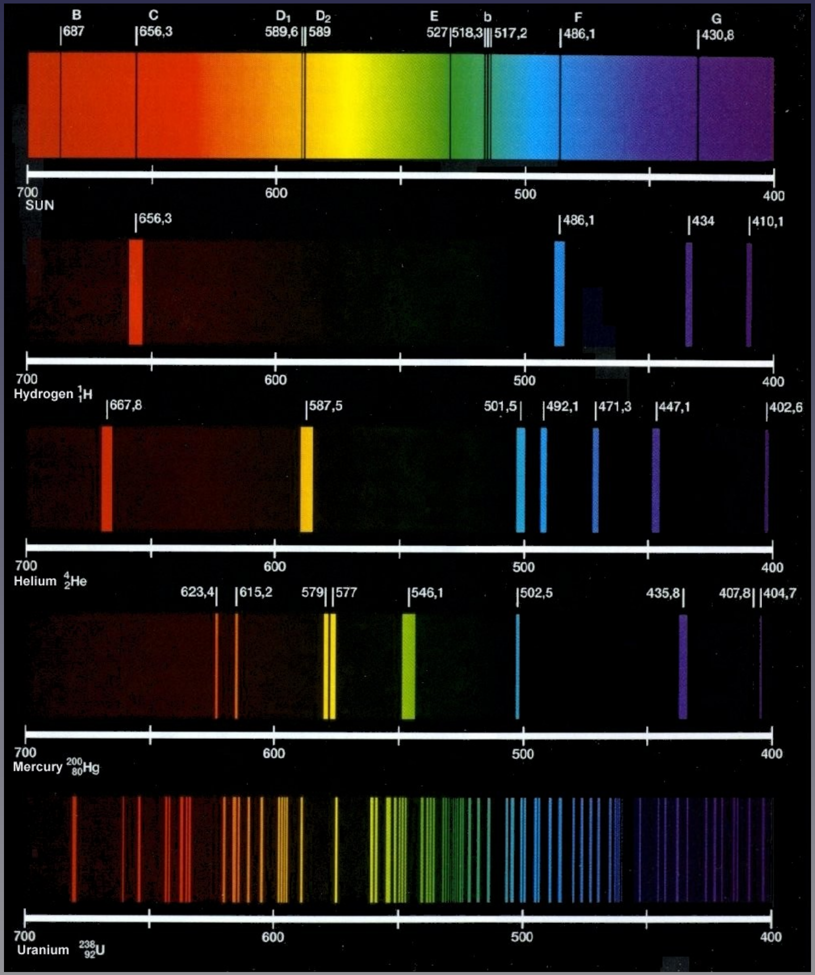
Quantum Mechanics

Making sense of the quantum world

At first, there was no comprehensive theory for the tiny wave/particles, but the wave properties of matter began to explain important things.

Most dramatically, the structure of atoms was explained

Perhaps the most puzzling data to be explained was the spectrum of light emitted by a particular kind of atom



Quantum Mechanics

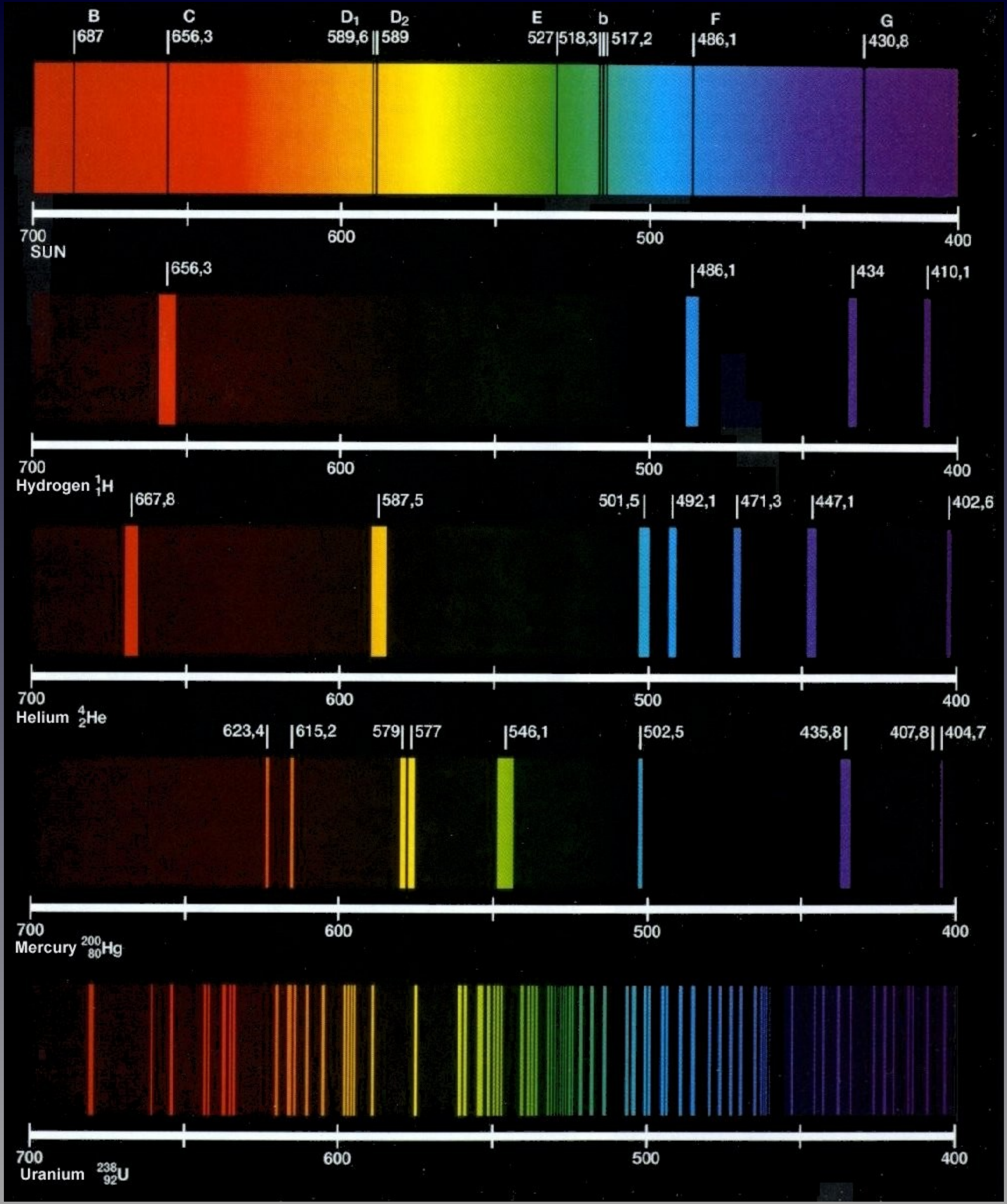
Explaining atomic spectra

Hydrogen

Helium

Mercury

Uranium

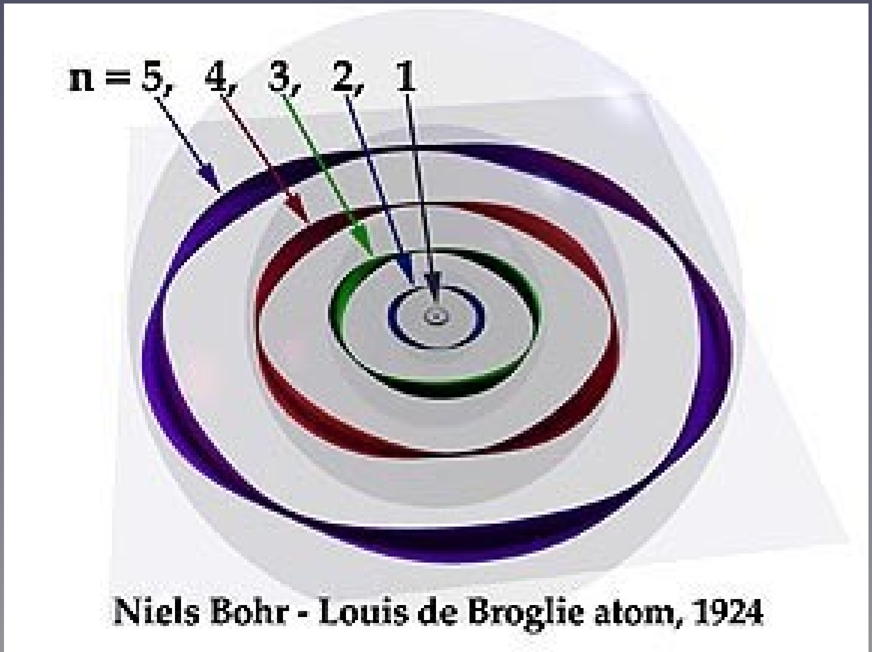


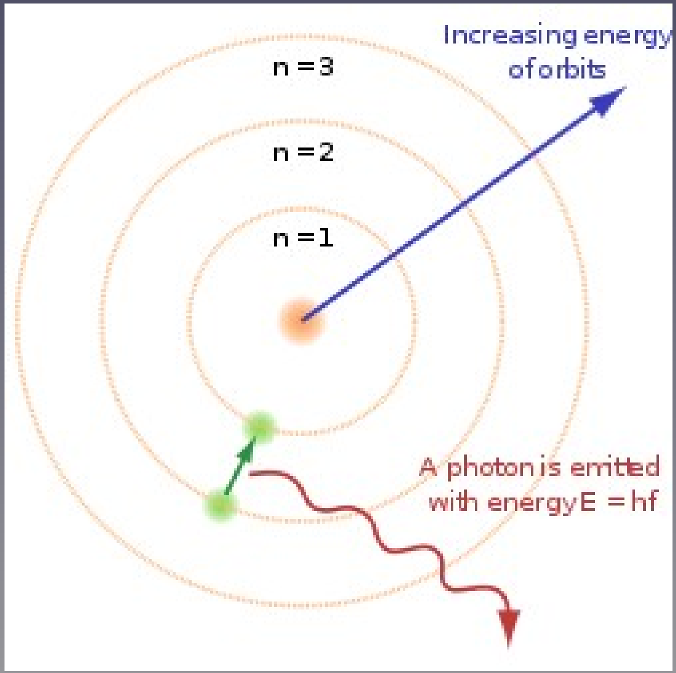
Quantum Mechanics

Making sense of the quantum world

The wave property of an electron meant its cycles had to fit exactly in one rotation around it's orbit

Each spectral line was generated by a jump from a higher orbit to a lower one





Quantum Mechanics

Wave Functions

Erwin Schrodinger found a new equation that described the mechanics of the microscopic wave/particle things just as Newton's did for large things.

Quantum mechanics describes tiny things by *wave functions*. They can only be described that way.

The wave function tells only the *probability* that the particle is at a particular place or is moving with a particular velocity.

Quantum mechanical objects behave as waves until they are observed or destroyed, then they behave as particles.

Quantum Mechanics

Wave Functions

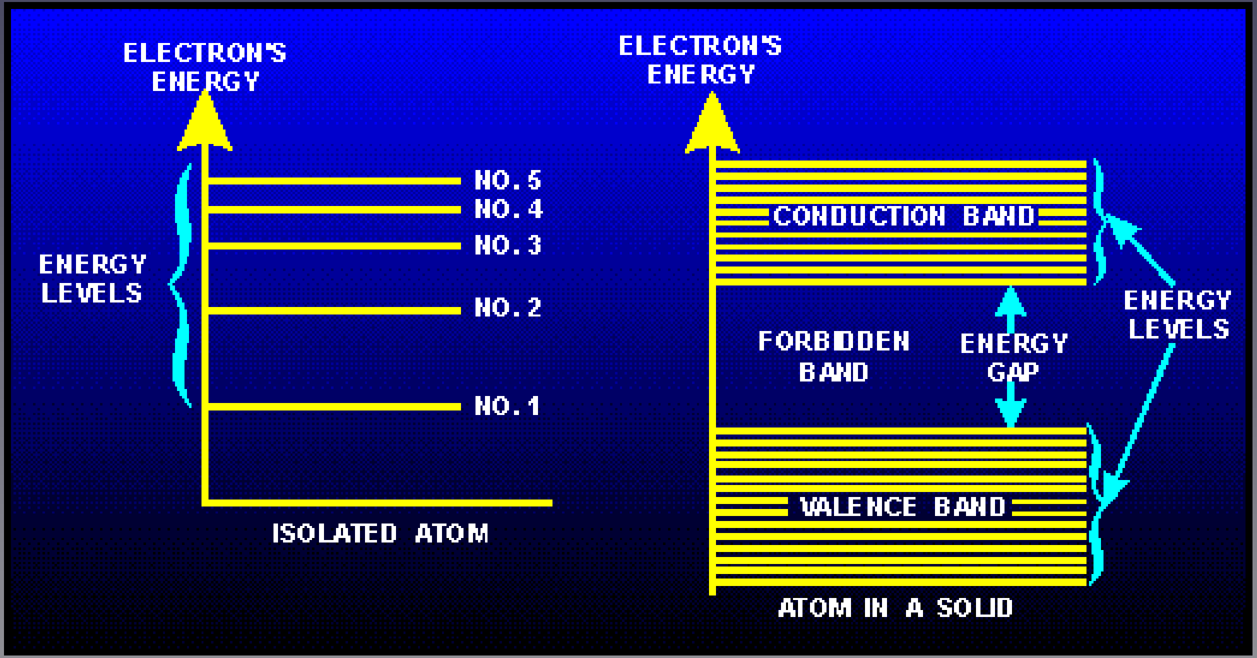
Schrodinger, the feline wave function

Quantum Mechanics

Successes

Quantum mechanics explained how electrons behave in solids

This has explained why metals conduct electricity, how transistors work, how solar panels work, and how to build lasers



Quantum Mechanics

How do we know it's true?

No one has or ever will see a wave function

Some aspects of quantum theory are still a mystery

Its proof lies in predicting the behavior of the atomic and subatomic scale universe

The acceptance of quantum theory is necessary for a scientist to use it and add to scientific understanding

At any moment, any scientist is free to propose an alternate theory or an improved theory and thus become a hero, so long as it explains the data better

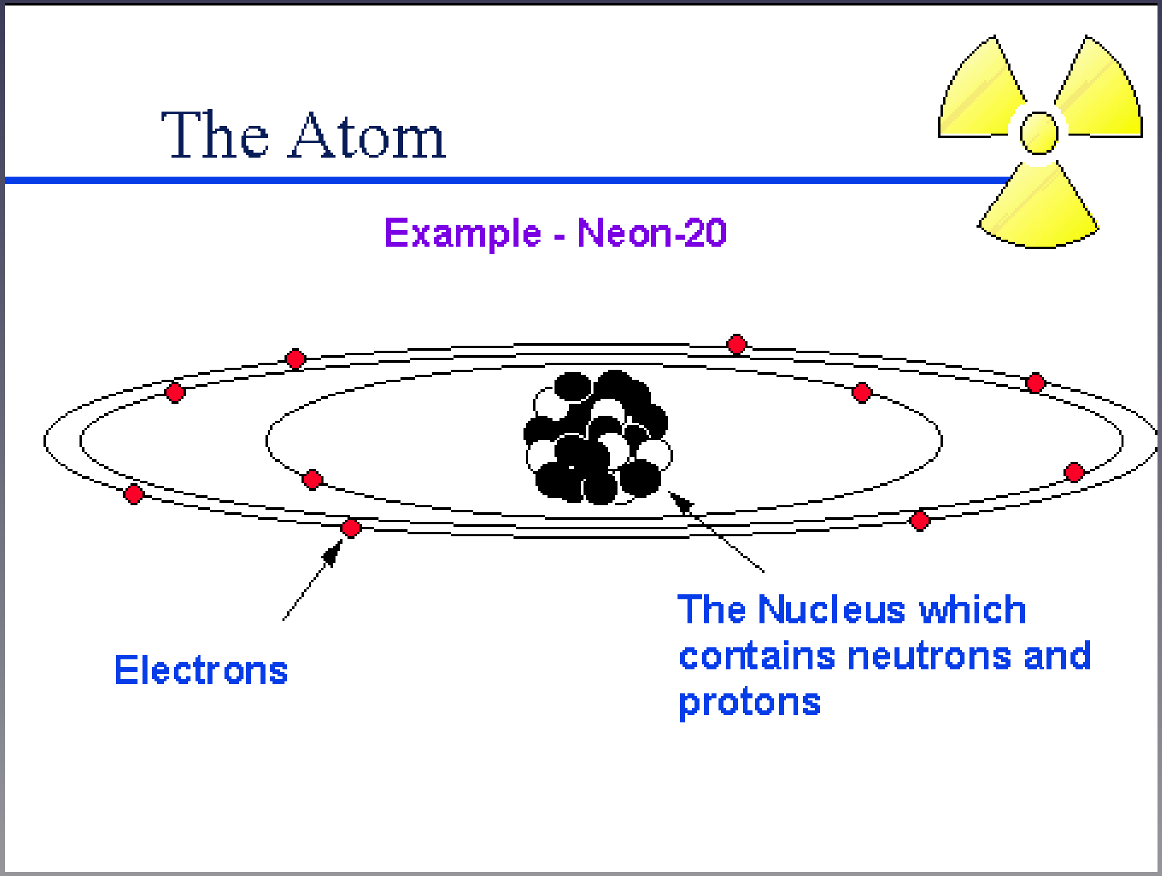
The quantum mechanics of small things is a scientific fact

Elementary Particle Physics

Physics with a sledge hammer

Atoms were originally supposed to be the smallest unit of matter

Then we found out that atoms are made of electrons and a nucleus

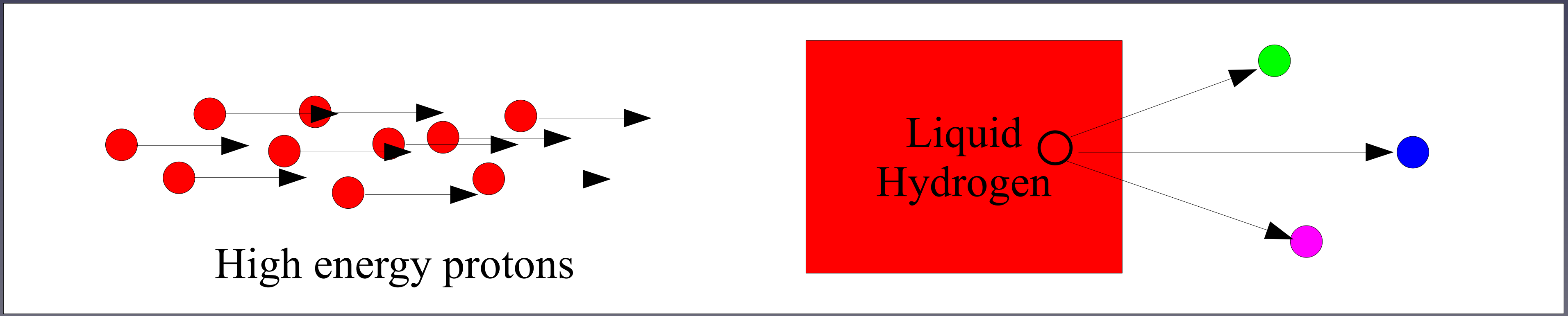


Elementary Particle Physics

Physics with a sledge hammer

Then we found out that each atomic nucleus is made of protons and neutrons

If you give protons lots of energy and ram them headon into each other, you get a shower of other particles



Are these particles elementary? In other words, can they be broken apart or not?

Just how many elementary particles are there?

Elementary Particle Physics

Physics with a sledge hammer

What we really want is

The Physics of Everything

We want a simple set of particles and rules for their behavior that describes everything in the universe

Complex, large-scale phenomena will all be emergent phenomena

Elementary Particle Physics

The Particle Zoo

As the energy of the beams increased, more and more particles were found

- Baryons (heavy):

  The nucleons: protons and neutrons

  Λ – Lambda, three types observed

  Ξ – Xi, eleven types observed

  Ω – Omega, three types observed

- Mesons: Pion, Kaon, Eta, B, D, Rho, J/Psi, Omega, Upsilon
- Leptons: Electron, Antielectron (Positron), Muon, Tauon, Neutrino

Life is getting more complicated, not simpler, not unified

Relativity

What is it?

Before we go on with Quantum Mechanics, we need to take a detour back through

Relativity

Relativity

What is it?

Newton stated a form of relativity, now known by his name, *Newtonian Relativity*

Actually stated by Galileo earlier, sometimes called *Galilean Invariance*

Newtonian Relativity

All that changes from one reference frame to the other is the velocity of the balls

Newton's laws describe the motion for both sets of observers. The laws are invariant to uniform motion

Relativity

Einstein's Special Relativity

In 1905, Einstein asked (and answered), "What kind of relativity do we have if the speed of light is invariant?"

- Newtonian relativity holds for objects moving much less than the speed of light
- Maxwell's equations for electromagnetism did not exactly mesh with Newton's laws if an object moved at nearly the speed of light.
- Measurements of the speed of light didn't seem to account for the motion of the earth

It was an amazing proposition and result, especially since Einstein was an amateur and since it was 1905.

As did Newton, he first considered only observers moving uniformly with respect to each other.

Special Relativity

Relativity

Einstein's Special Relativity

Einstein's special relativity fixed the problem with Maxwell's equations for electromagnetism and it explained why all measurements of the speed of light always gave the same number, but it predicted that when an object is moving...

- It get shorter in the direction of motion
- It gets heavier, and
- Time slows down

All these things have been observed!!!

Relativity

Einstein's Special Relativity

Special Relativity also reveals an equivalence of mass and energy

The energy of an object with mass, m, moving at velocity, v, is

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

When v approaches c, the energy approaches infinity

When v approaches 0, the energy does not go to zero. It goes to

$$E = mc^2$$

Relativity

Time travel

Since time slows down when one is moving with respect to another

Get in a spaceship and travel away from the earth at 0.99999999996 times the speed of light

A person watching from earth will see time pass quickly

You, in the spaceship will see time pass slower

1 day travel = 1,000 years on earth

10 days = 10,000 years on earth

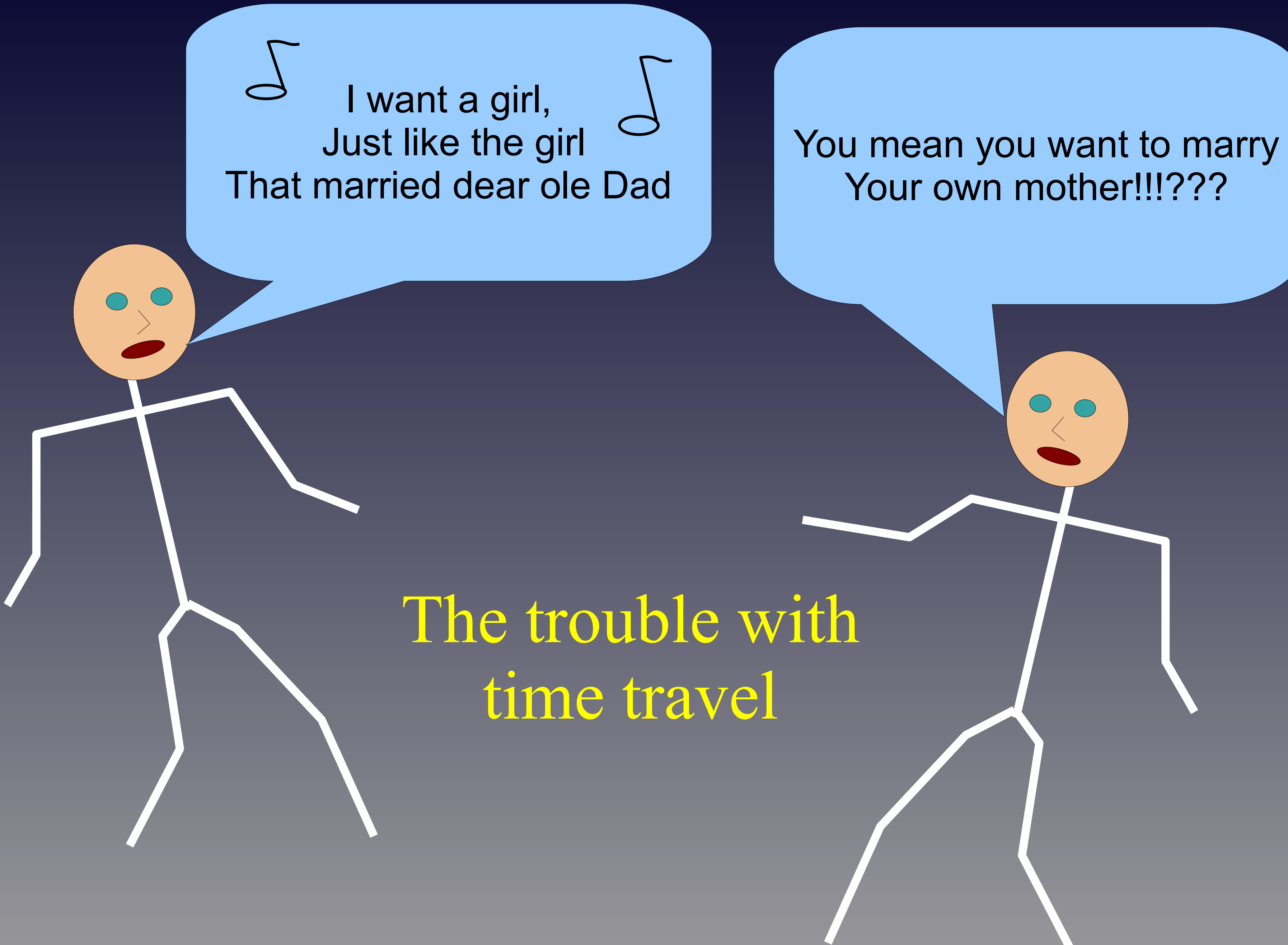
Hey, let's go!!!

Relativity

Time travel

- Since the mass of an object increases with its speed, the amount of energy required to go fast enough is just too great
- The acceleration would crush a human
- One can only go forward

Let's visit the good ole days!



The trouble with time travel

Relativity

General Relativity

But ole Albert was just getting started...

Special relativity came from just the idea that light travels at the same speed no matter how you measure it

Now Einstein considered that the effect of *gravity* is exactly the same as *acceleration*

This reasoning resulted in Einstein's theory of *General Relativity*

The Equivalence Principle

Relativity

General Relativity

General relativity predicts

- The passage of time is affected by gravity
- Even though light has no mass, it is affected by gravity

Neither time nor space are static

Enough mass in one place causes time and space to collapse to a point—a black hole

Relativity

Experiments

Two clocks were placed in commercial airliners going oppositely around the earth

A third clock remained in Washington, DC

The speed of the airplane slowed down the clocks

The reduced gravity at altitude speeded up the clocks by even more

When the clocks were brought back together, the time differences agreed with general relativity

Relativity

Experiments

The Global Positioning Satellite (GPS) network uses general relativity to correct its clocks

Without the correction, the GPS system would give errors that accumulate at about six miles per day

With the corrections, advanced systems can locate to less than 3 ft (1 meter)

Many other experiments show Einstein's relativity to be correct

Relativity

It's a fact!

No matter how strange Einstein's relativity seems, it has been verified so many times, in so many circumstances, by so many people, that it qualifies as a scientific fact.

Relativity

Black holes

Newton's Law of Gravity

$$F = \frac{G \times M_1 \times M_2}{R^2}$$

G is the universal gravitational constant $G = (6.67428 \pm 0.00067) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$.

F is the force between two masses

M_1 is the mass of one object

M_2 is the mass of the second object, and

R is the distance between the centers of the objects

Notice that F becomes infinite when R becomes zero!

Relativity

Black holes

When sufficient matter is compressed into a sufficiently small space so that nothing can escape the gravitational force, a black hole is formed.

The black hole has an event horizon, the surface of the region which nothing can escape from

A black hole can form from any amount of matter if it's compressed sufficiently

Relativity

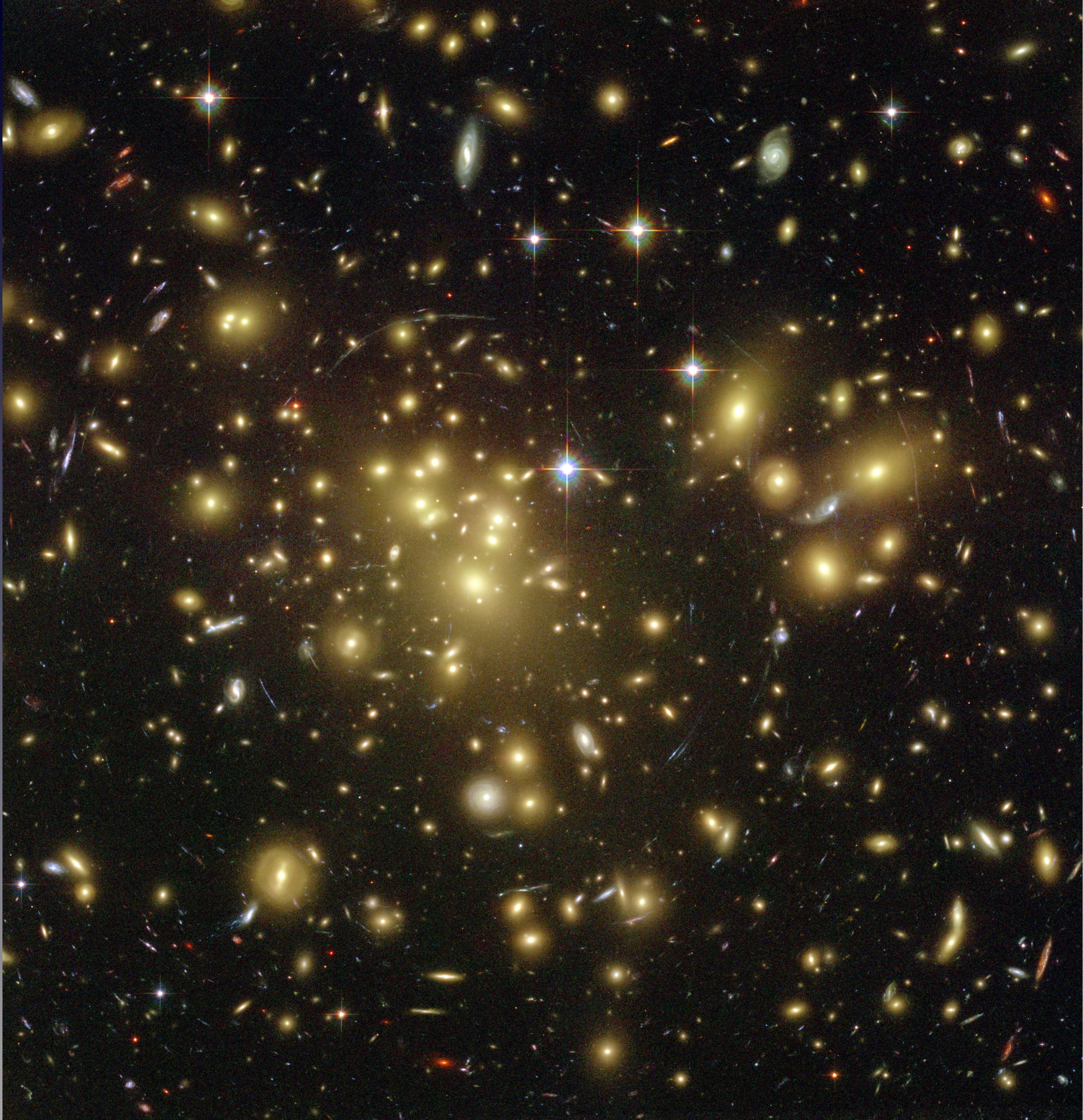
Black holes

Black holes are black. Thus, they can be seen only by their gravitational effects

Relativity

Black holes

Distant galaxies distorted by a cluster of nearer galaxies known as Abell 2218



Relativity

Space and Time

Space and time are not constant nor independent of what fills them

The presence of matter changes space and time

Movement and acceleration change space and time

Space and time seem to be observable fields like gravity and electromagnetism

Elementary Particle Physics

The Particle Zoo

Where were we?????

As the energy of the beams increased, more and more particles were found

- Baryons (heavy):
  - The nucleons: protons and neutrons
  - Λ – Lambda, three types observed
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Life is getting more complicated, not simpler, not unified

Elementary Particle Physics

The Particle Zoo

When the whole lot of particles that were produced in the high-energy collisions were categorized, they seemed to be composites; made of yet simpler particles

Beginning in the 1960s, and working until the middle-1970s, theorists converged on what we now call The Standard Model of particle physics

The standard model explains all matter as being made of a simpler set of elementary particles

It does not explain gravity

Elementary Particle Physics

The Particle Zoo

We need to explain:

- Gravity
- Electromagnetic force
- Weak nuclear force
- Strong nuclear force
- Matter
- Space and time

We have four kinds of forces (fields), matter and spacetime

Our task has gotten a bit more complicated since Newton, who had only gravity and matter

Elementary Particle Physics

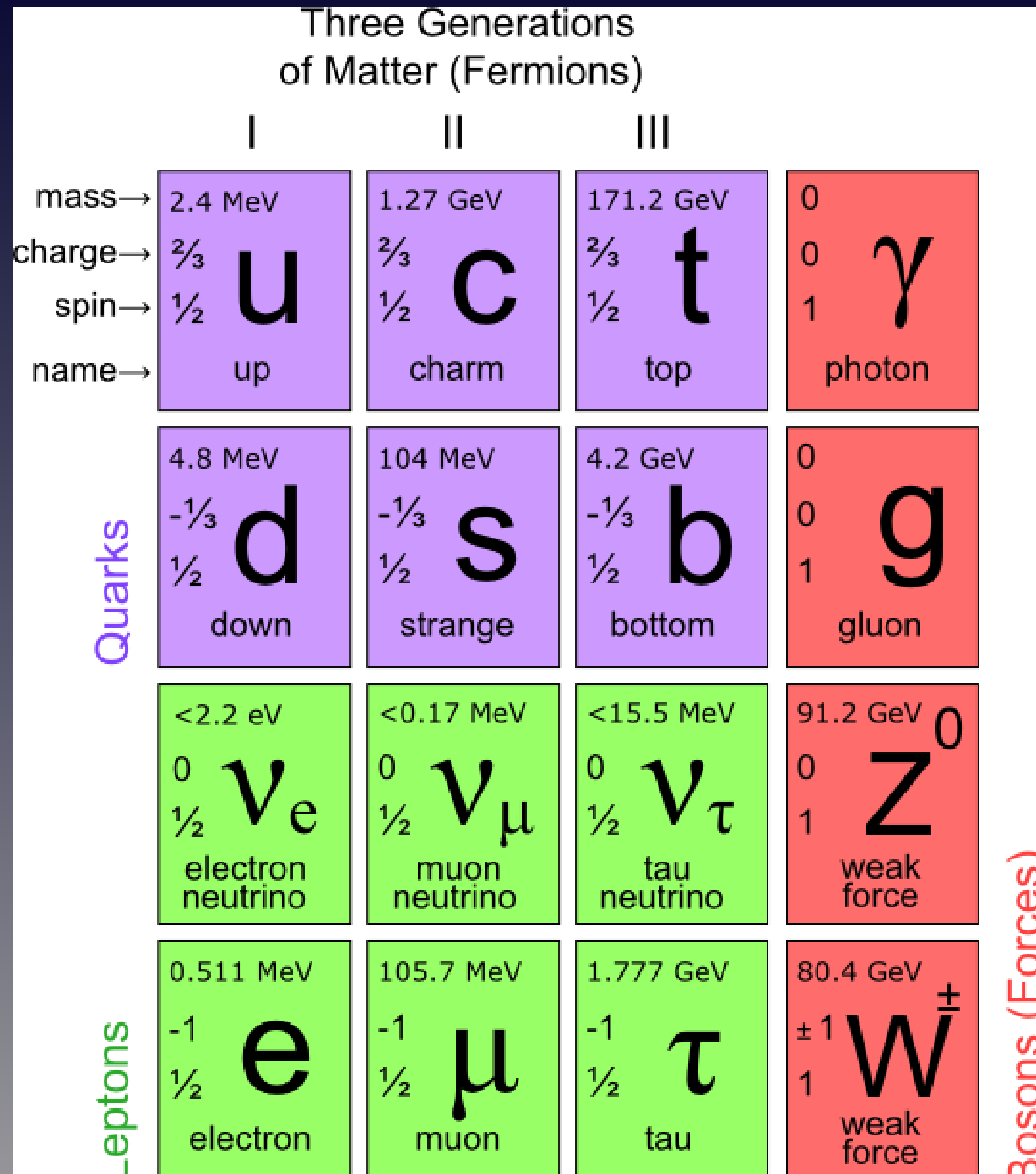
The Particle Zoo

A proton is made up of 2 up quarks and a down quark (the quark named by Murray Gell-Mann)

A neutron is made up of an up and two down quarks

The electron and photon are elementary particles

Thus all ordinary matter is made up of quarks and electrons



Elementary Particle Physics

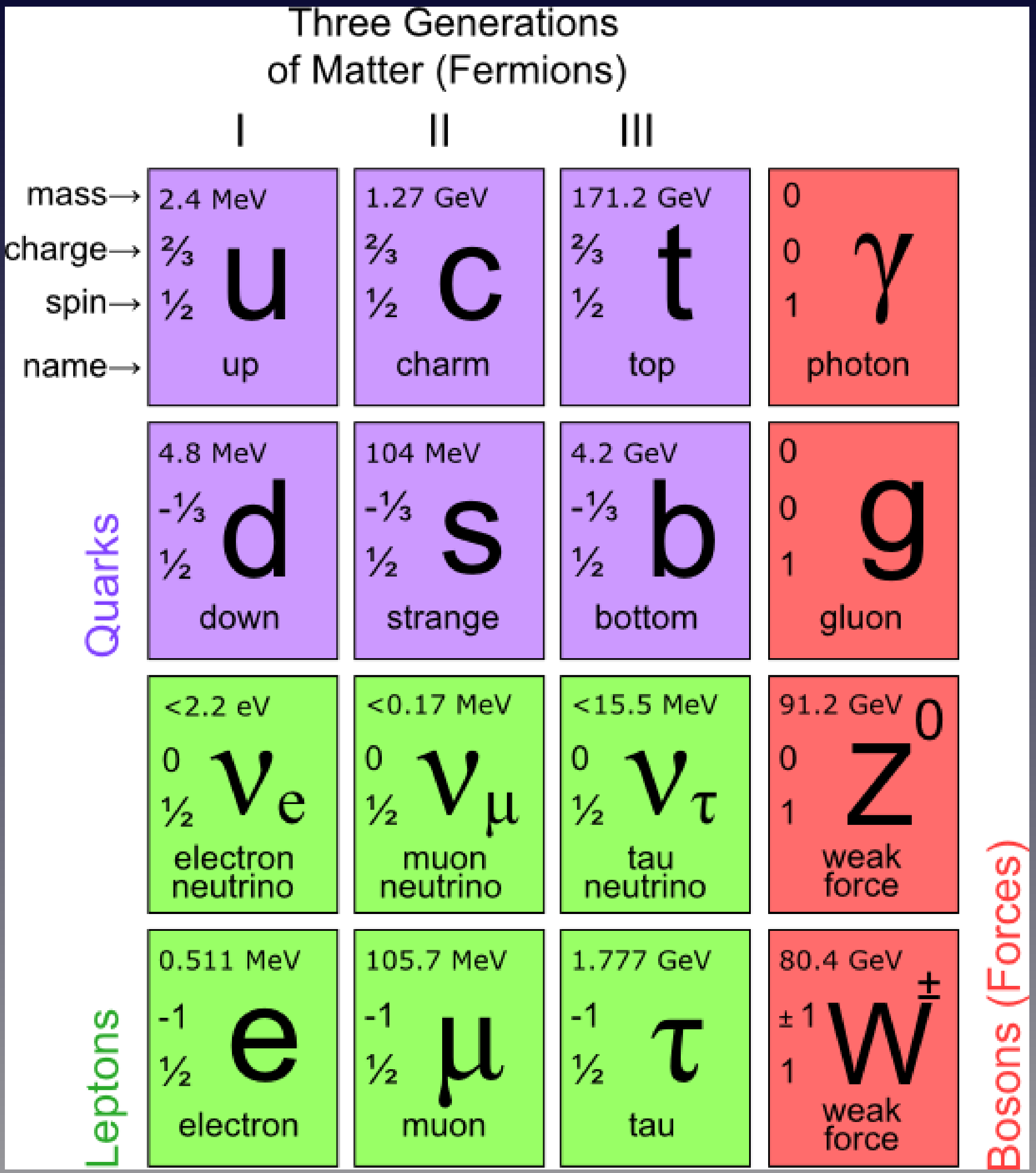
The Particle Zoo

The photon carries the electromagnetic force and forms the electromagnetic field

The gluon carries the strong nuclear force

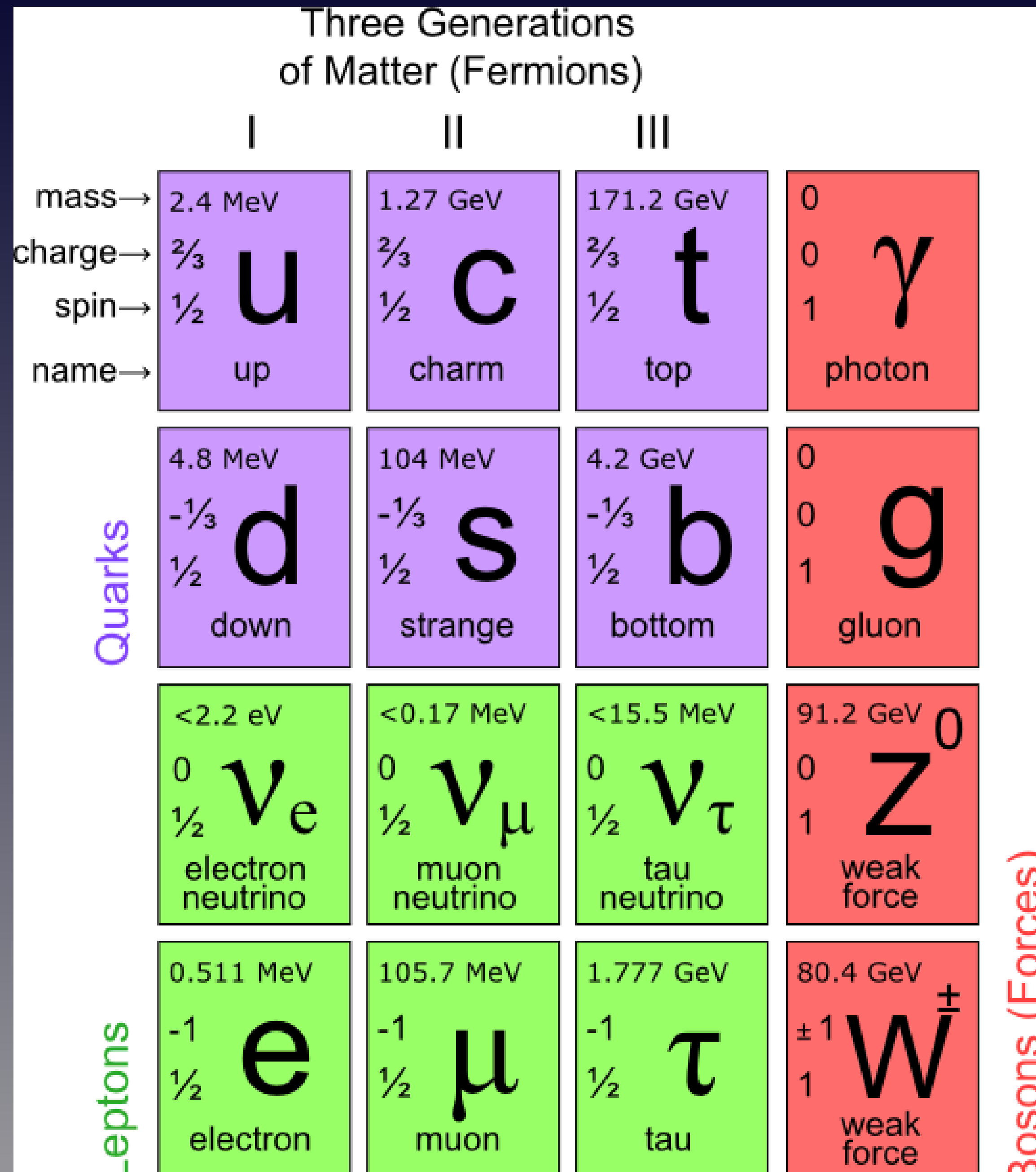
The Z and W particles carry the weak nuclear force

No gravity!



Elementary Particle Physics

The Particle Zoo



All the matter particles have spin 1/2; they are called Fermions

All the force particles have spin 1; they are called Bosons

The Standard Model predicts that all the particles have zero mass unless......

Elementary Particle Physics

The Particle Zoo

...unless there is one more field, the Higgs field

The Higgs field fills all space uniformly

The Higgs field interacts with the force-carrying bosons to give them energy, and thus mass

The Higgs boson arises from the Higgs field just as the other force-carrying particles arise from their fields

The Higgs boson is the only particle in the Standard Model that has not been observed.

Elementary Particle Physics

The end of physics

So, have we finally reached the end of physics?

Is that all there is?

Elementary Particle Physics

The end of physics

So, have we finally reached the end of physics?

Is that all there is?

But what are all the Standard Model particles made of?

Why are there so many of them? Why not just one?

Maybe we'll never find the Higgs particle

The Standard Model doesn't explain gravity

It's just like 1900 all over again. There are just a few loose ends that may point to a whole new part of reality.

How can we find out whether we've reached the end of physics?

Elementary Particle Physics

The end of physics

Maybe we're not smart enough to go any farther

Maybe there will always be another layer beneath what we find

Maybe we find that the Universe is made of one thing, but we don't know what that thing is made of

How can we find out whether we've reached the end of physics?