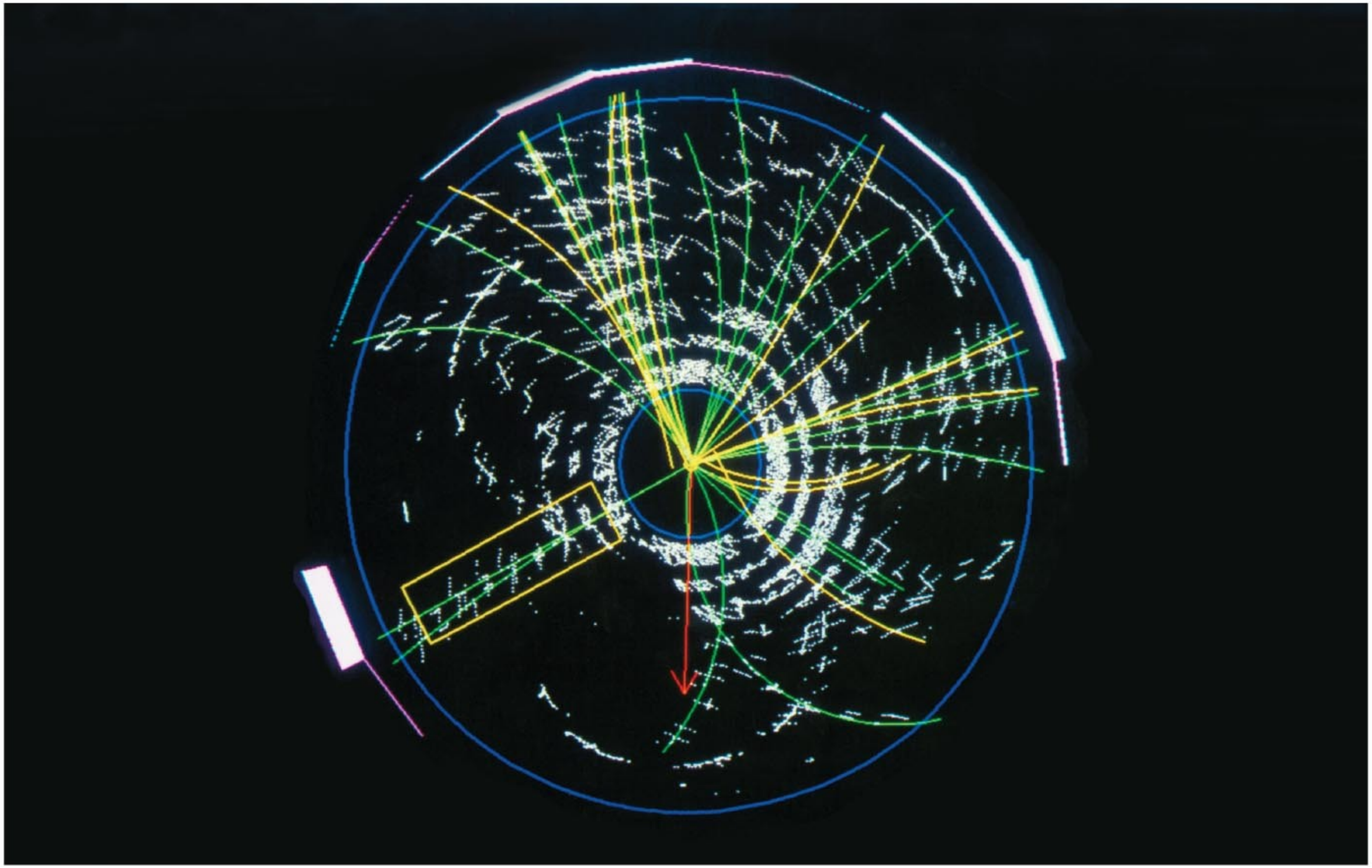
Chapter S4
Building Blocks of the Universe



S4.1 The Quantum Revolution

Our goals for learning:

- How has the quantum revolution changed our world?

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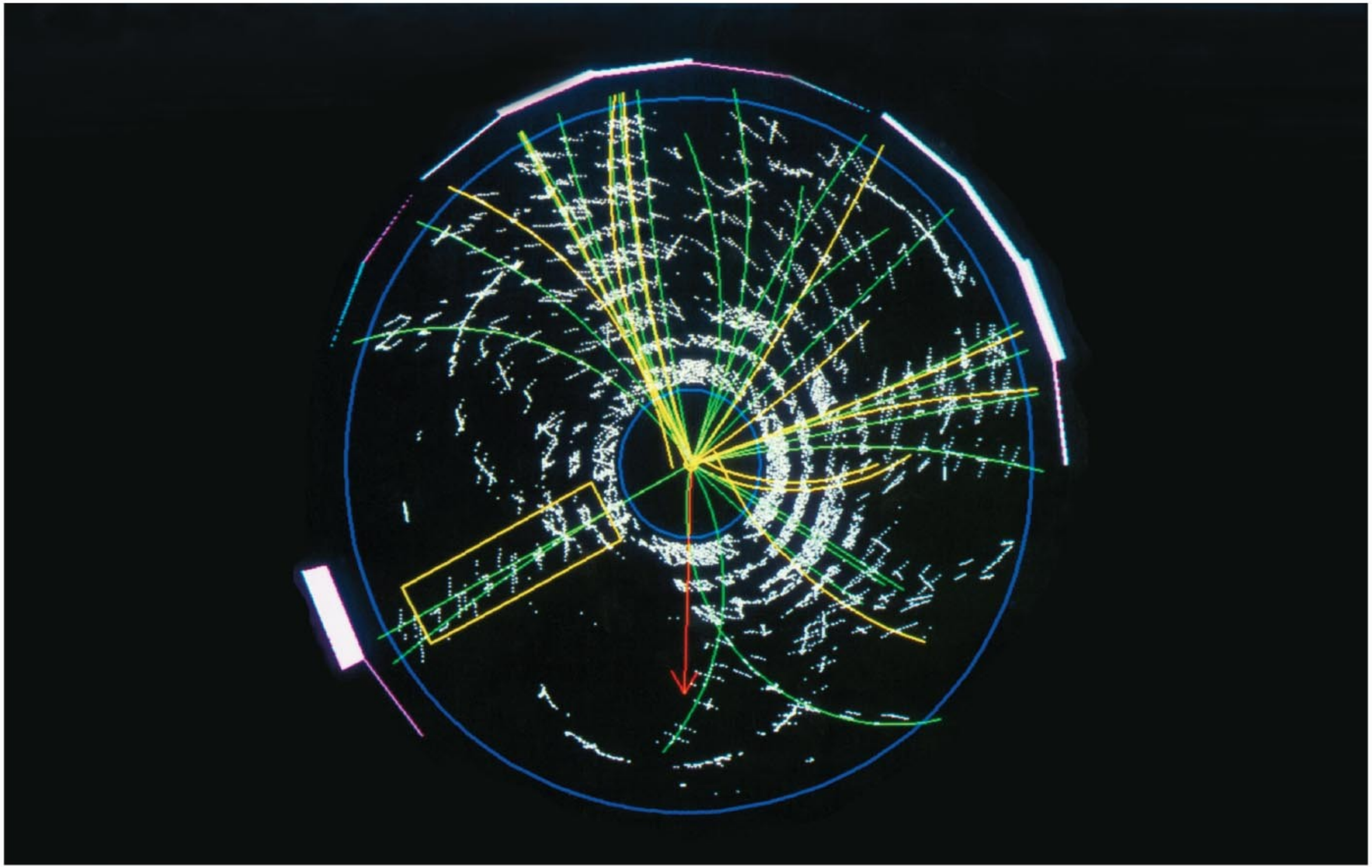


The Quantum Realm

- Light behaves like particles (photons).
- Atoms consist mostly of empty space.
- Electrons in atoms are restricted to particular energies.
- The science of this realm is known as *quantum mechanics*.

Surprising Quantum Ideas

- Protons and neutrons are not truly fundamental—they are made of *quarks*.
- Antimatter can annihilate matter and produce pure energy.
- Just four forces govern all interactions: gravity, electromagnetic, strong, and weak.
- Particles can behave like waves.
- Quantum laws have astronomical consequences.

Quantum Mechanics and Society

- Understanding of quantum laws made possible our high-tech society:
  - Radios and television
  - Cell phones
  - Computers
  - Internet

What have we learned?

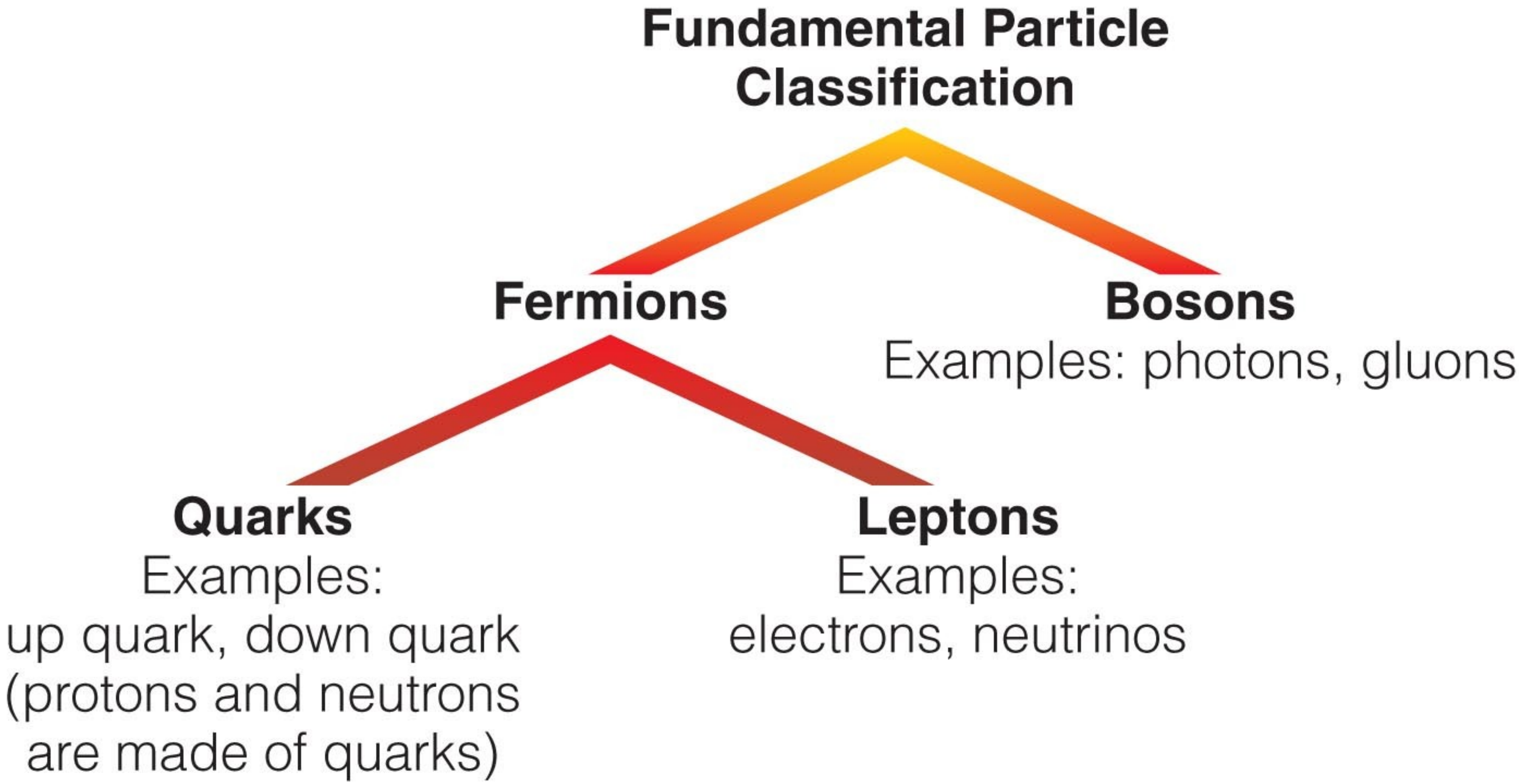
- How has the quantum revolution changed our world?
  - Quantum mechanics has revolutionized our understanding of particles and forces and made possible the development of modern electronic devices.

S4.2 Fundamental Particles and Forces

Our goals for learning:

- What are the basic properties of subatomic particles?
- What are the fundamental building blocks of matter?
- What are the fundamental forces in nature?

What are the basic properties of subatomic particles?



Particle Accelerators

- Much of our knowledge about the quantum realm comes from particle accelerators.
- Smashing together high-energy particles produces new particles.

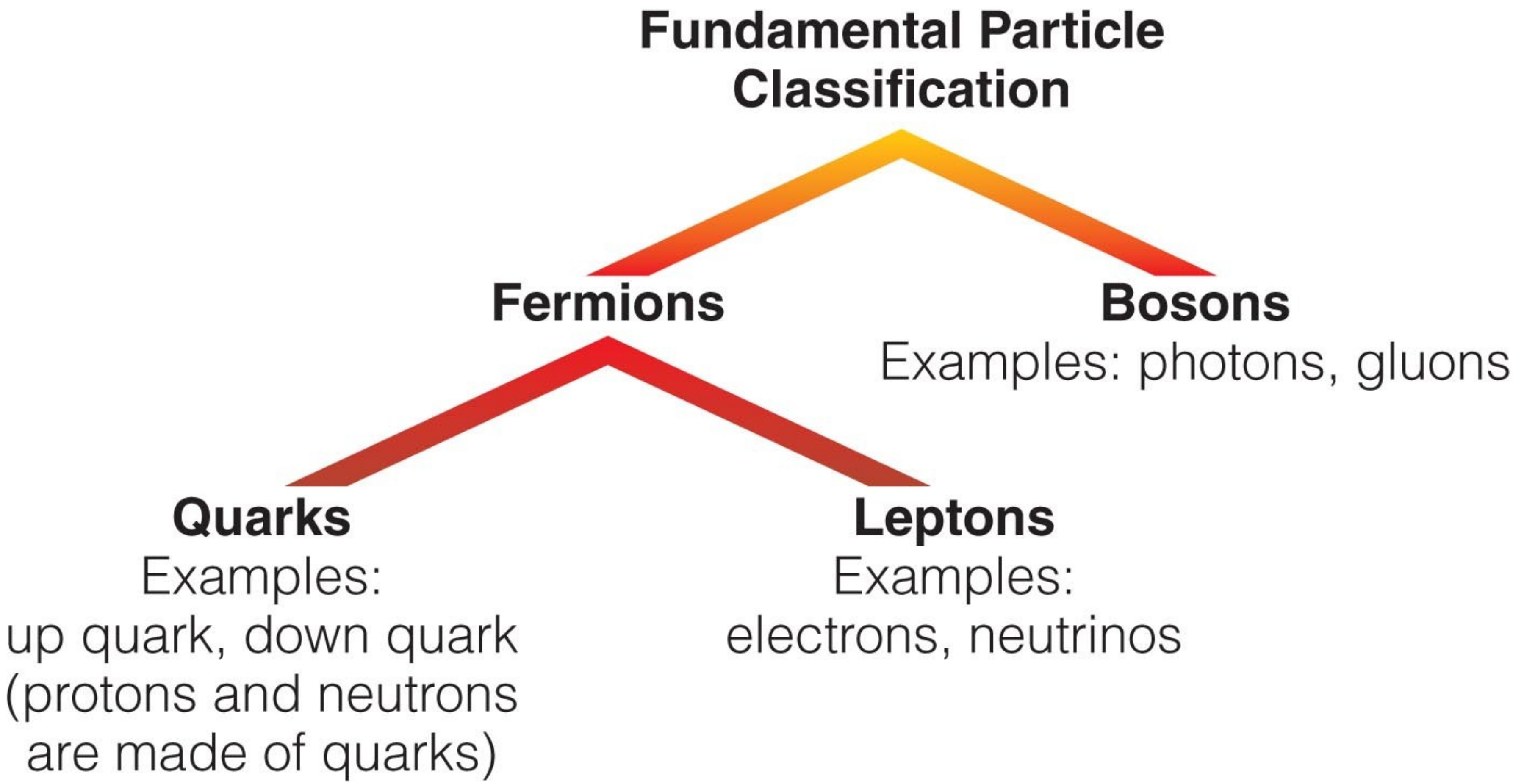
Properties of Particles

- Mass
- Charge (proton +1, electron –1)
- Spin
  - Each type of subatomic particle has a certain amount of angular momentum, as if it were spinning on its axis.

Fermions and Bosons

- Physicists classify particles into two basic types, depending on their spin (measured in units of $h/2\pi$).
- *Fermions* have half-integer spin (1/2, 3/2, 5/2,…).
  - Examples: electrons, protons, neutrons
- *Bosons* have integer spin (0, 1, 2,…).
  - Example: photons

Fundamental Particles



Matter particles are called FERMIONS

The spins are ½, 3/2, 5/2 …. in units
Of h/2pi

Leptons like electrons and neutrinos
Are leptons

Baryons are made of 3 quarks. Example:
Protons and neutrons. Baryons are made
Of up quark (charge 2/3) and down quark
(charge -1/3).
Proton = uud , charge = 4/3-1/3 = 1
Neutron = ddu , charge = -1/3-1/3+2/3 = 0

Force particles are called Bosons.

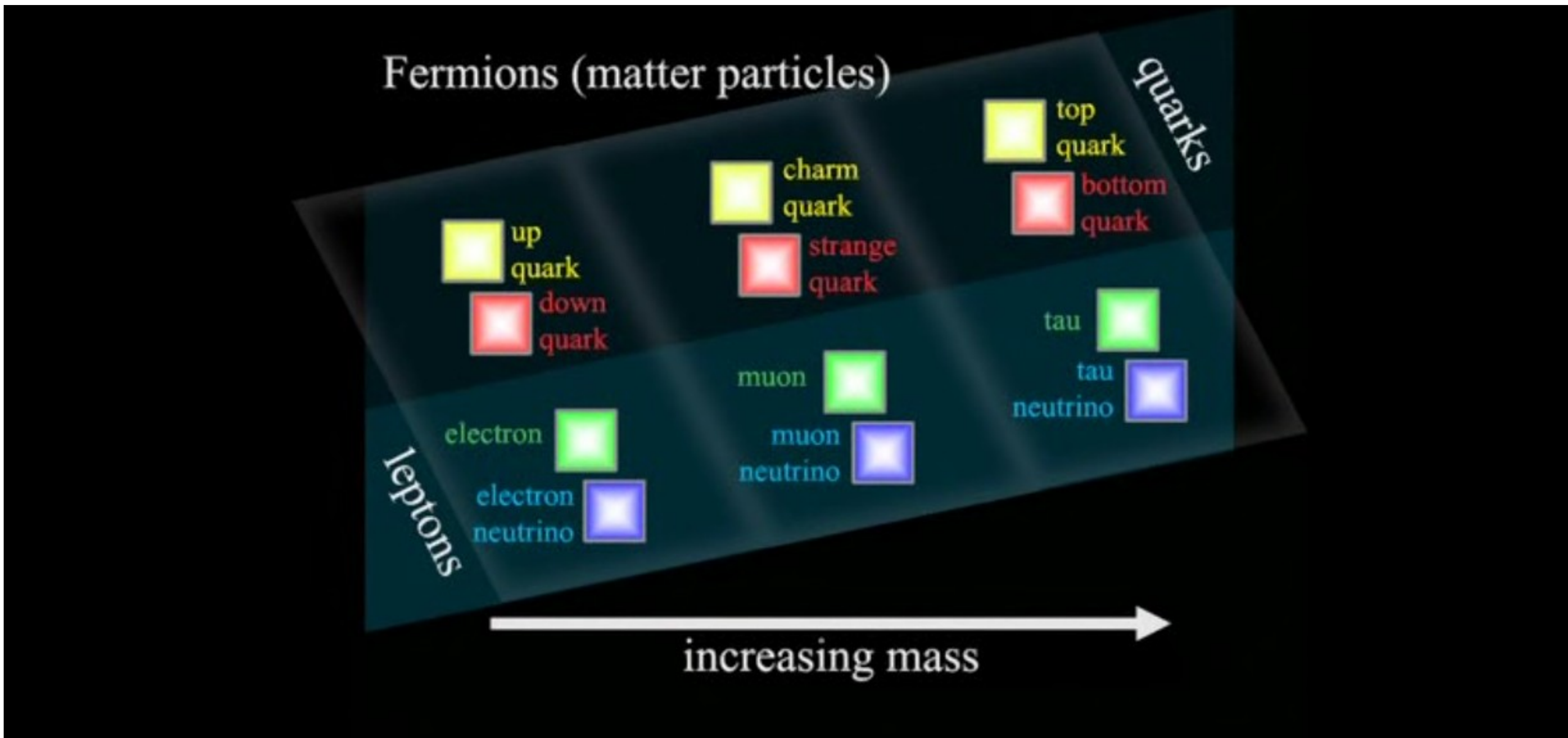
The spins are 1, 2, 3 …

Example: photons, gluons,
Gravitrons ….

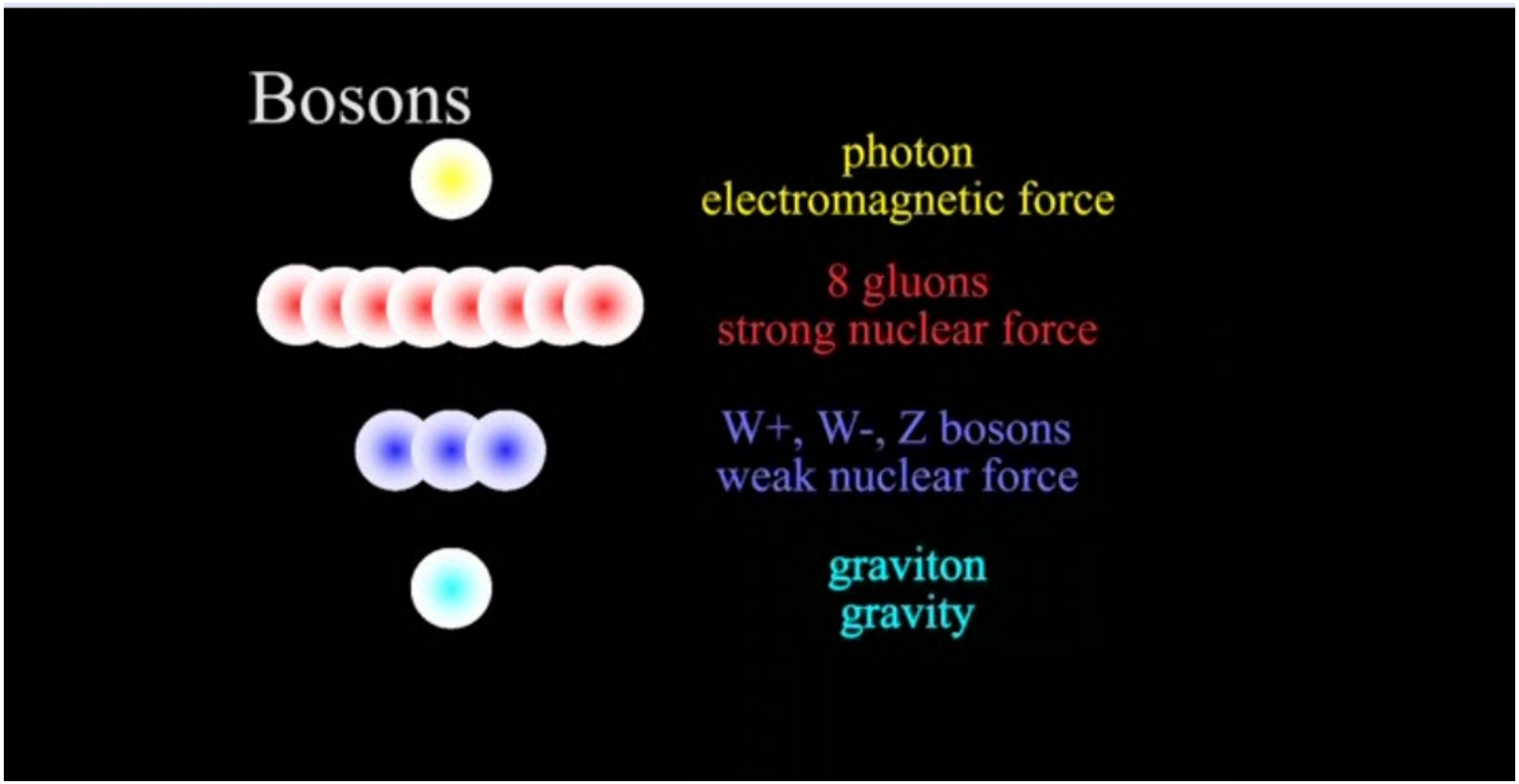
Hadrons are particles
Made of quarks :
Baryons have 3 quarks .
They are fermions.

Mesons are made of 2 quarks.
They are bosons. Like the
pion, the strong nuclear force carrier.

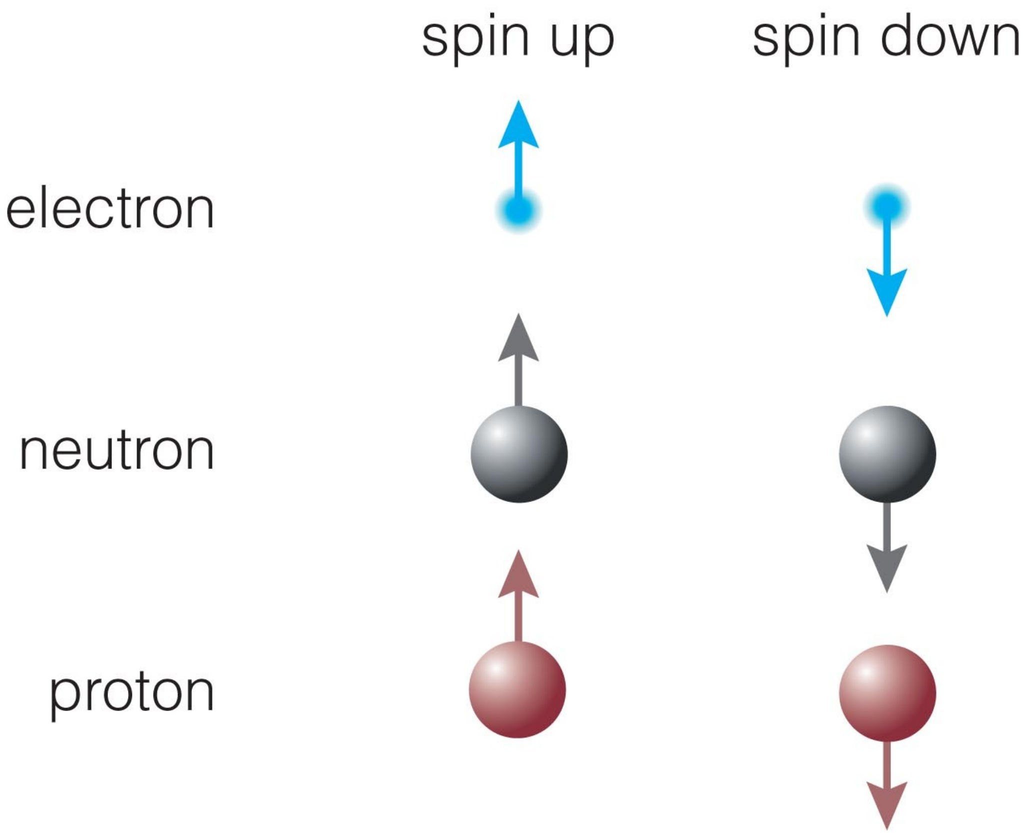
Protons and neutrons are made of up and down quarks but You have other quarks and other leptons.
+ each of the article has an anti particle too !
You also have the force particles.



Force particles.

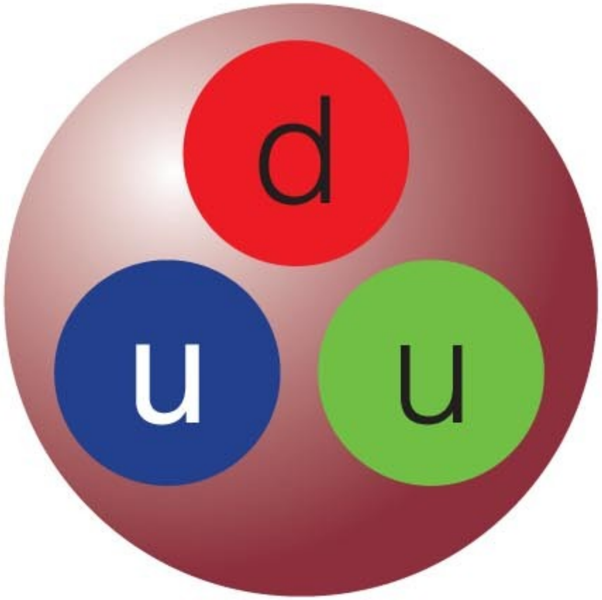


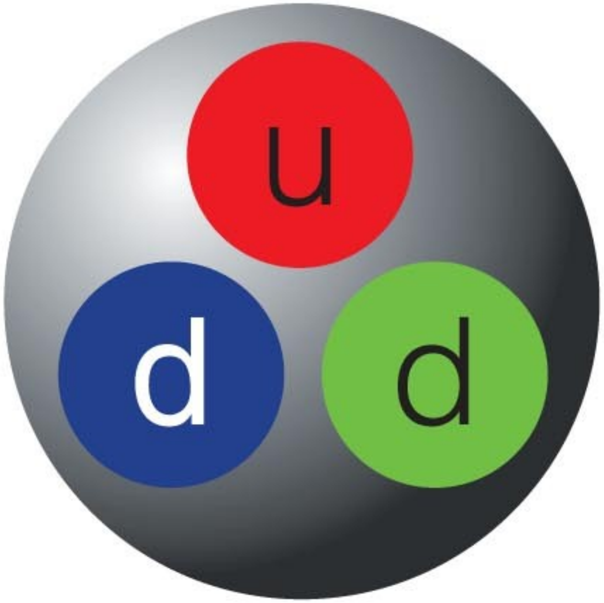
Orientation of Spin



- Fermions with spin of 1/2 have two basic spin states: up and down.

What are the fundamental building blocks of matter?





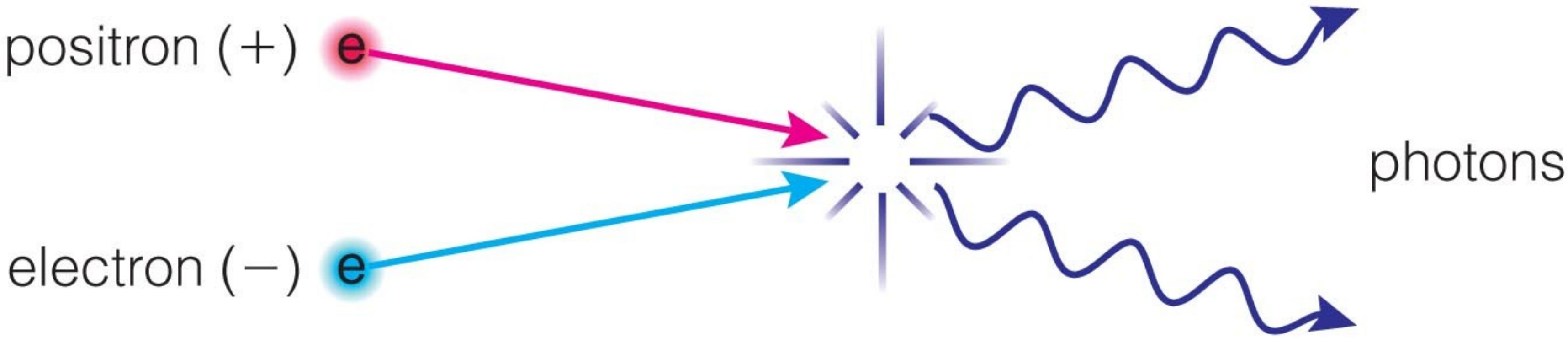
Quarks

- Protons and neutrons are made of quarks.
- *Up quark* (u) has charge +2/3.
- *Down quark* (d) has charge –1/3.

Quarks and Leptons

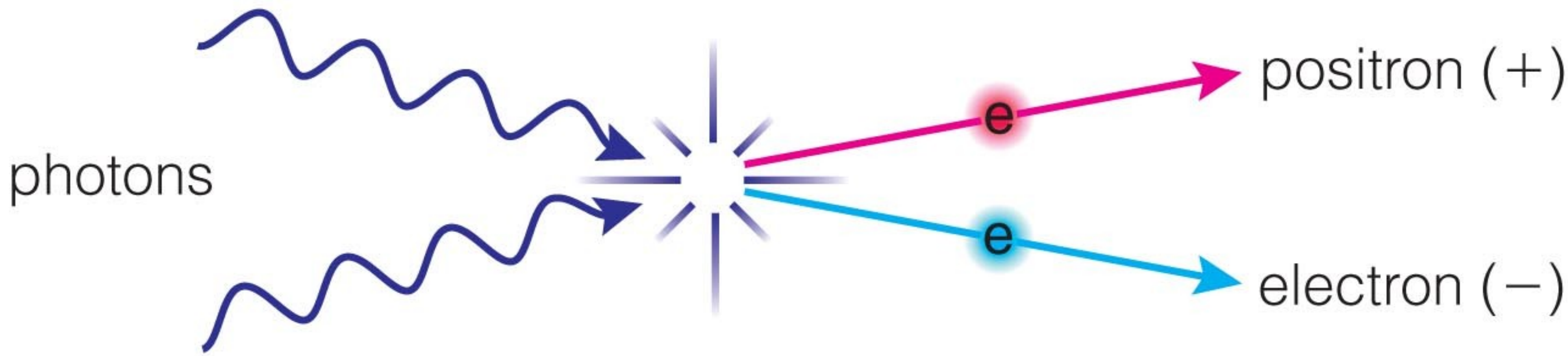
- Six types of quarks: up, down, strange, charmed, top, and bottom
- Leptons are not made of quarks and also come in six types:
  - Electron, muon, tauon
  - Electron neutrino, mu neutrino, tau neutrino
- Neutrinos are very light and uncharged.

Matter and Antimatter



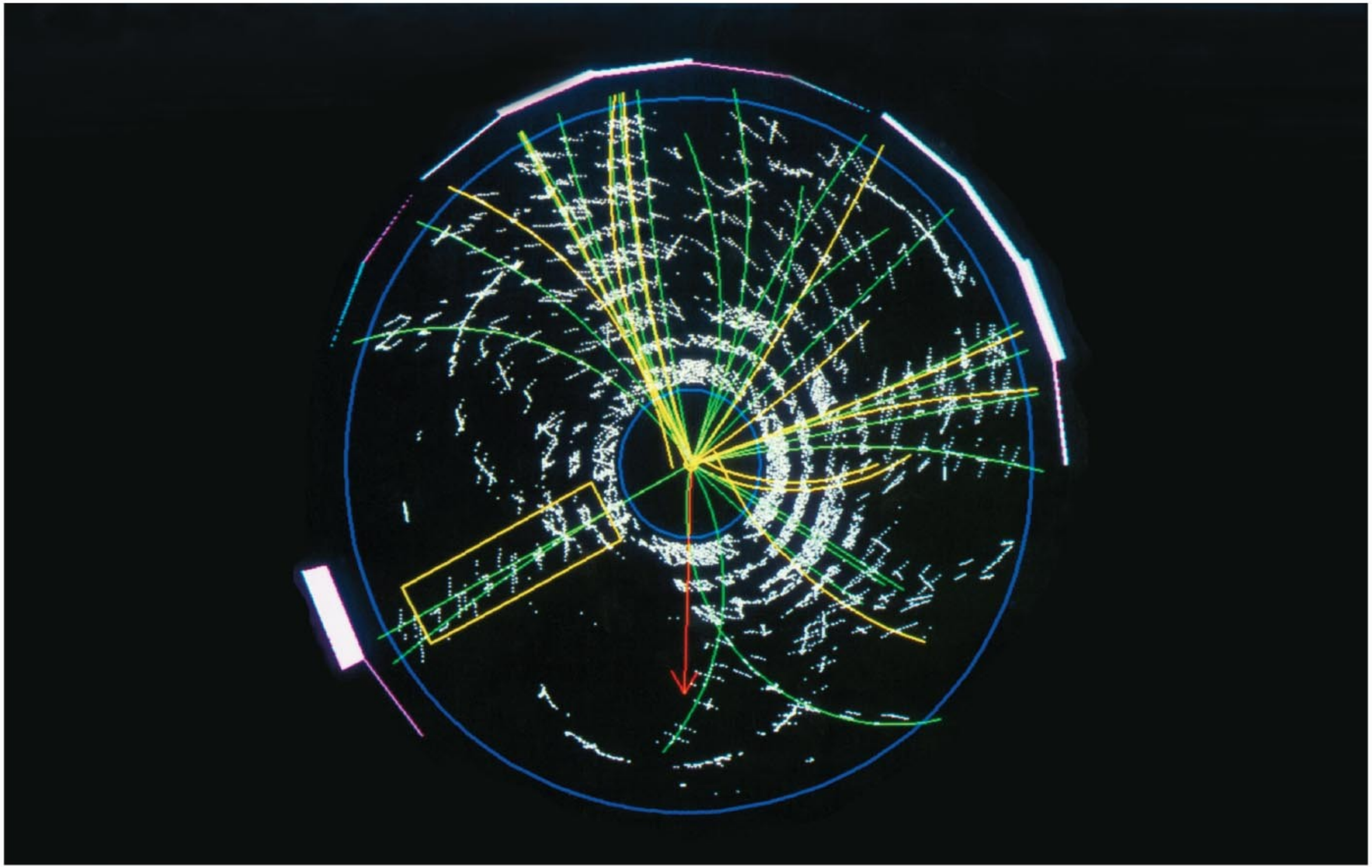
- Each particle has an antimatter counterpart.
- When a particle collides with its antimatter counterpart, they annihilate and become pure energy in accord with $E = mc^2$.

Matter and Antimatter



- Energy of two photons can combine to create a particle and its antimatter counterpart (pair production).

What are the fundamental forces in nature?



Four Forces

- Strong force (holds nuclei together)
  - Exchange particle: gluons
- Electromagnetic force (holds electrons in atoms)
  - Exchange particle: photons
- Weak force (mediates nuclear reactions)
  - Exchange particle: weak bosons
- Gravity (holds large-scale structures together)
  - Exchange particle: gravitons

Strength of Forces

- Inside nucleus:
  - Strong force is 100 times electromagnetic force.
  - Weak force is 10^{-5} times electromagnetic force.
  - Gravity is 10^{-43} times electromagnetic force.
- Outside nucleus:
  - Strong and weak forces are unimportant.

What have we learned?

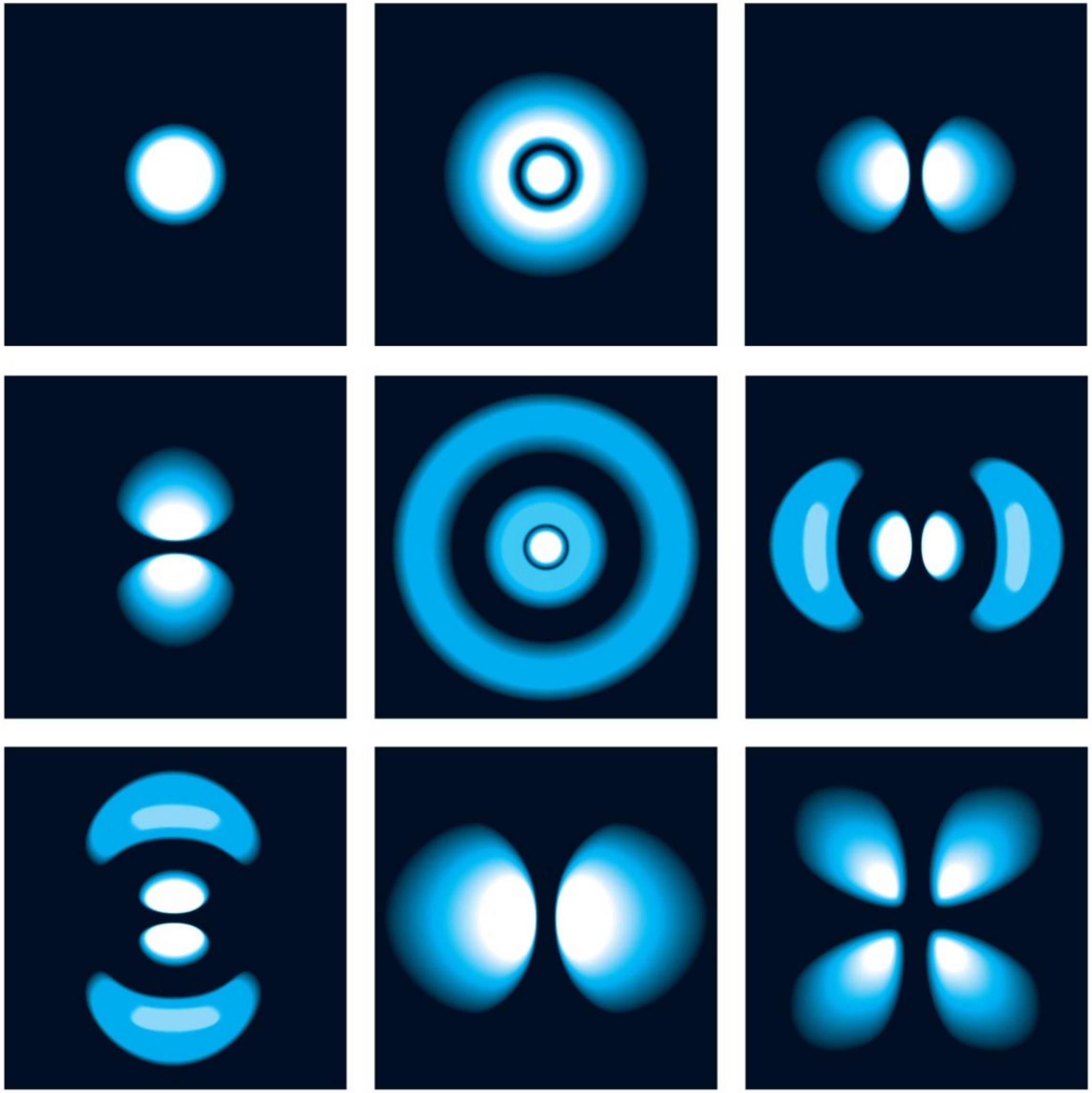
- What are the basic properties of subatomic particles?
  - Charge, mass, and spin
- What are the fundamental building blocks of matter?
  - Quarks (up, down, strange, charmed, top, bottom)
  - Leptons (electron, muon, tauon, neutrinos)
- What are the fundamental forces in nature?
  - Strong, electromagnetic, weak, gravity

S4.3 Uncertainty and Exclusion in the Quantum Realm

Our goals for learning:

- What is the uncertainty principle?
- What is the exclusion principle?

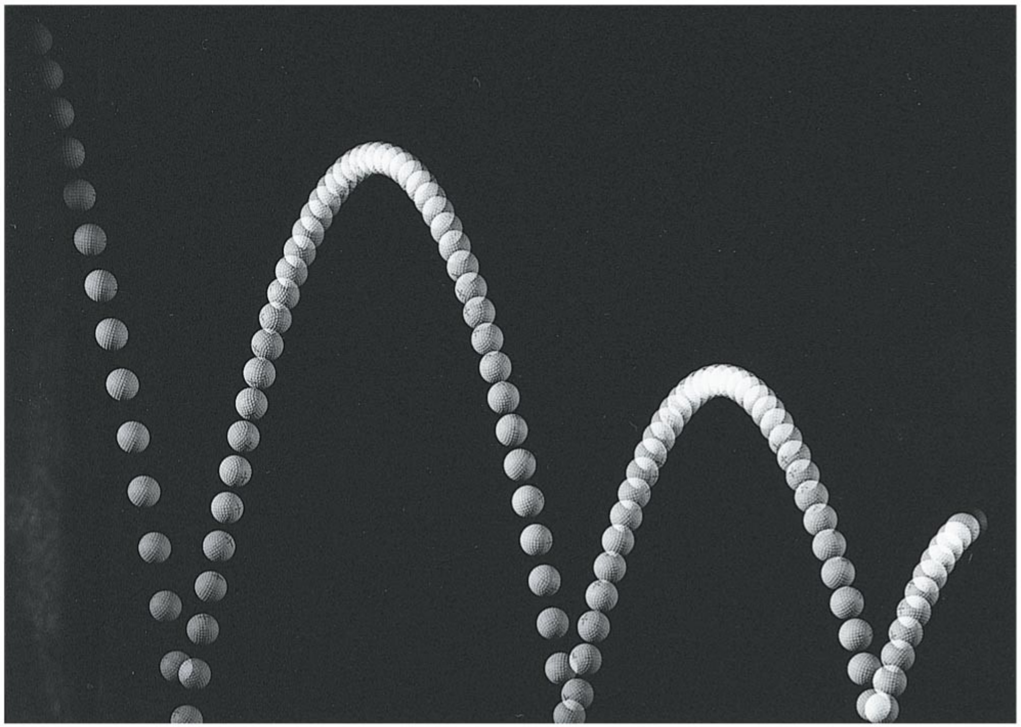
What is the uncertainty principle?



Uncertainty Principle

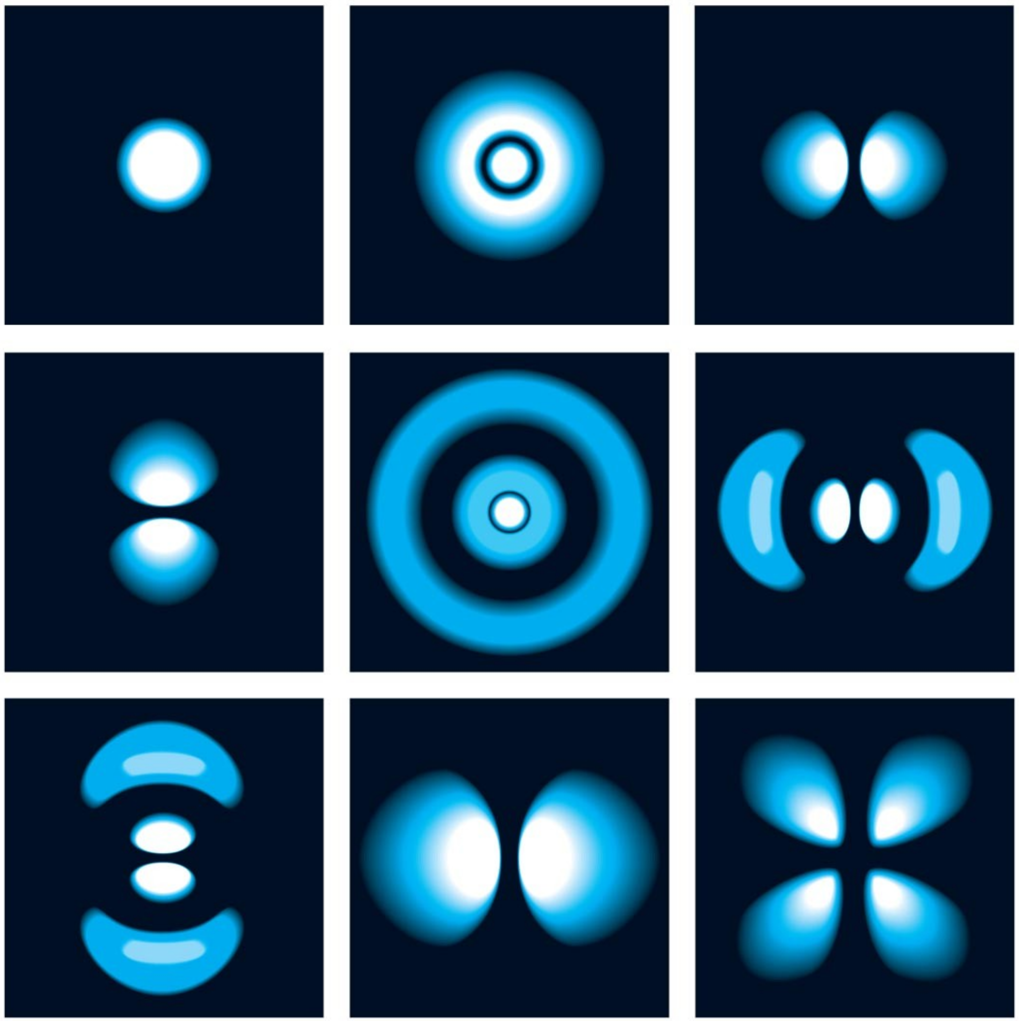
- The more we know about where a particle is located, the less we can know about its momentum, and conversely, the more we know about its momentum, the less we can know about its location.

Position of a Particle



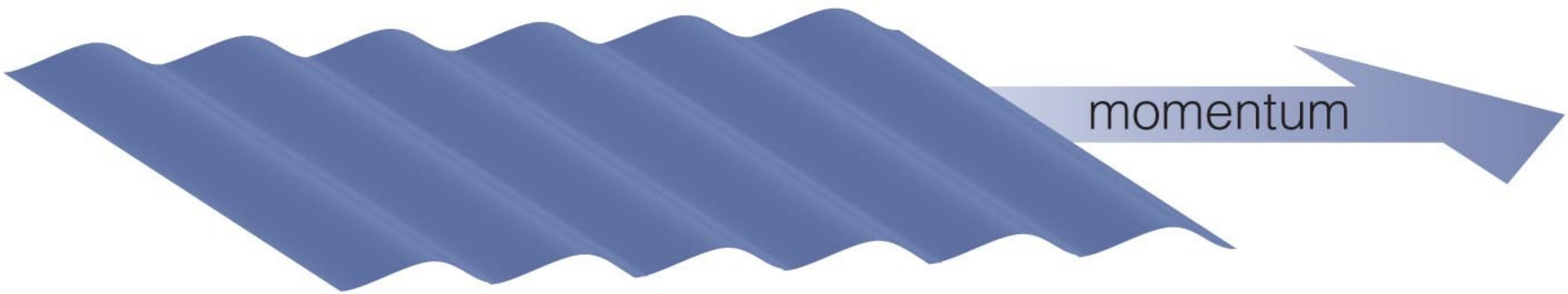
- In our everyday experience, a particle has a well-defined position at each moment in time.
- But in the quantum realm, particles do not have well-defined positions.

Electrons in Atoms



- In quantum mechanics, an electron in an atom does not orbit in the usual sense.
- We can know only the probability of finding an electron at a particular spot.

Electron Waves



- On atomic scales, an electron often behaves more like a wave with a well-defined momentum but a poorly defined position.

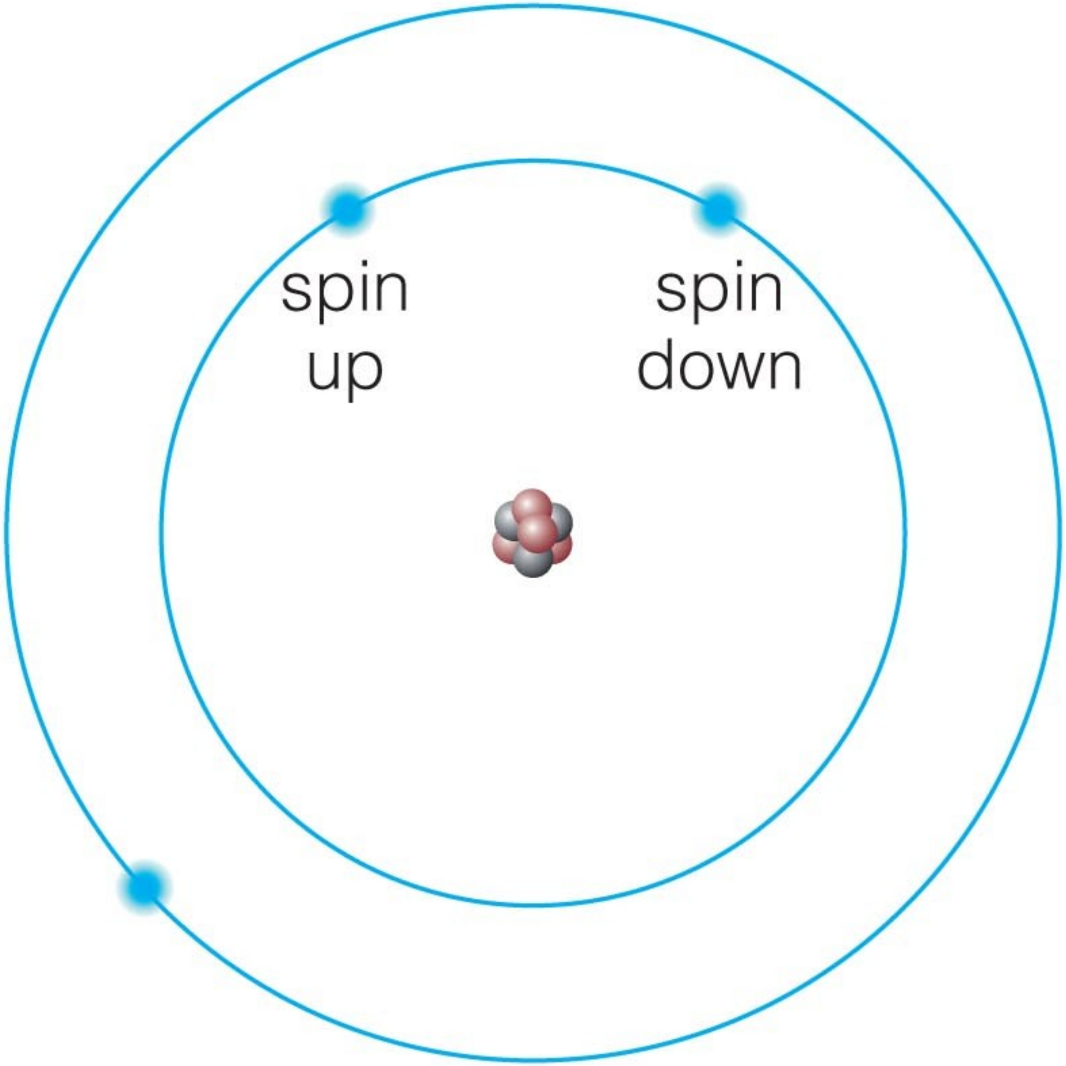
Location and Momentum

Uncertainty in location X Uncertainty in momentum = Planck's constant (*h*)

Energy and Time

Uncertainty in energy X Uncertainty in time = Planck's constant (h)

What is the exclusion principle?



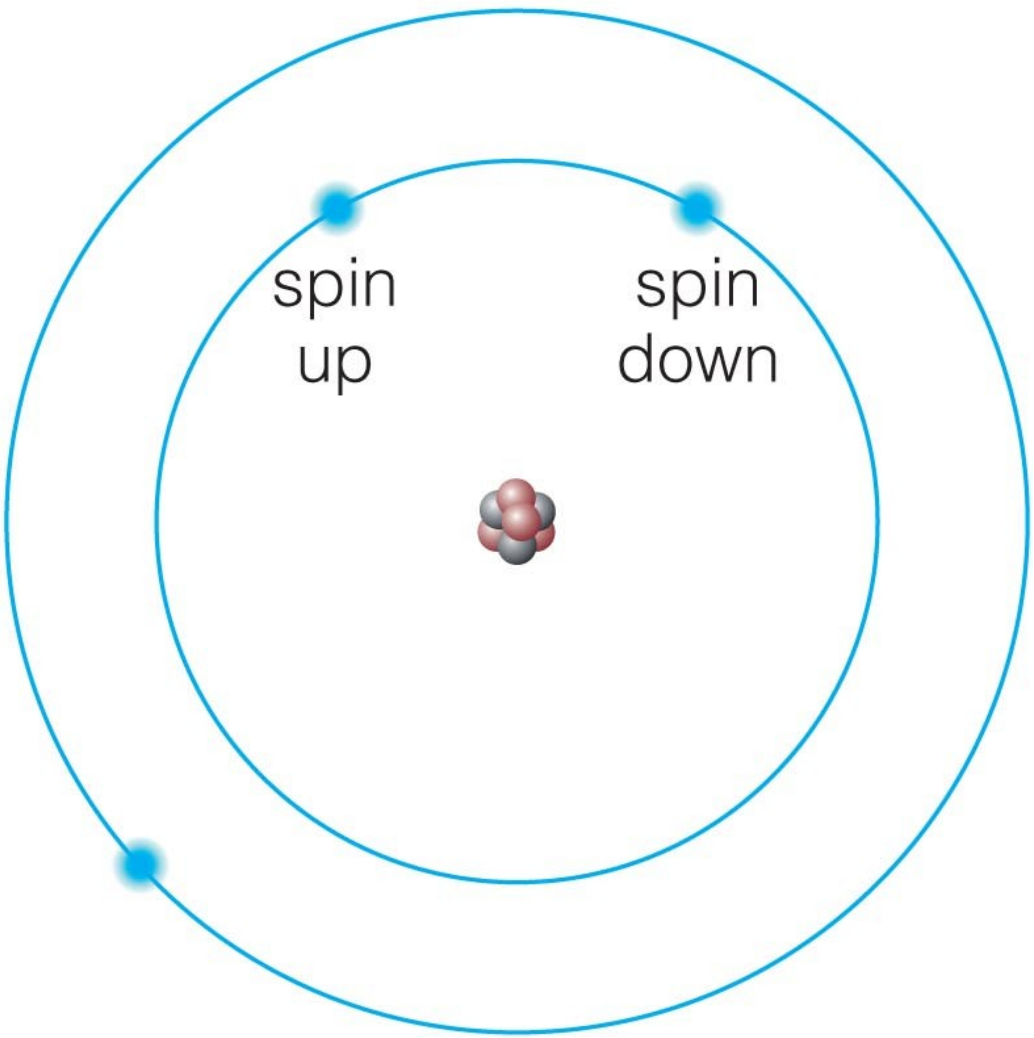
Quantum States

- The *quantum state* of a particle specifies its location, momentum, orbital angular momentum, and spin to the extent allowed by the uncertainty principle.

Exclusion Principle

- Two fermions of the same type cannot occupy the same quantum state at the same time.

Exclusion in Atoms



- Two electrons, one with spin up and the other with spin down, can occupy a single energy level.
- A third electron must go into another energy level.

What have we learned?

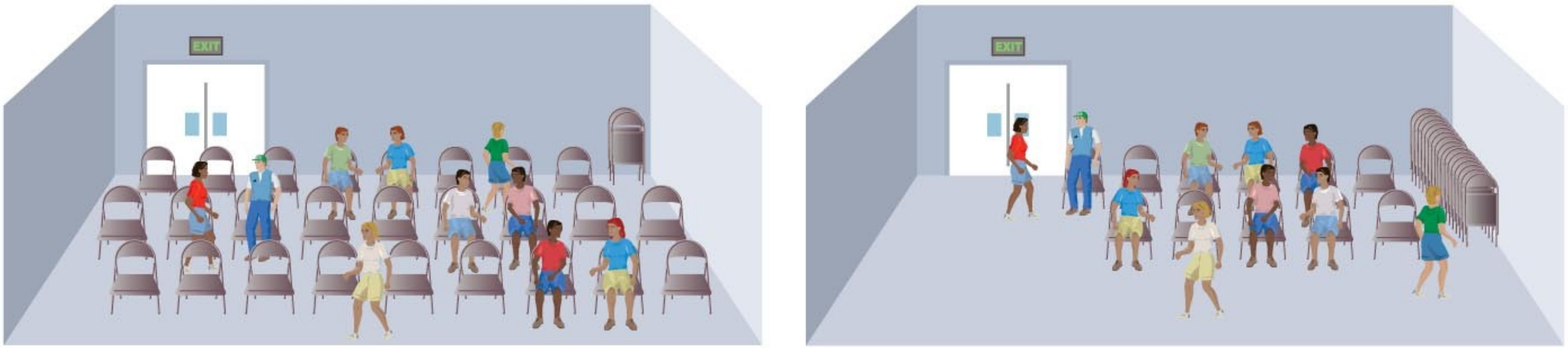
- What is the uncertainty principle?
  - We cannot simultaneously know the precise value of both a particle's position and its momentum.
  - We cannot simultaneously know the precise value of both a particle's energy and the time that it has that energy.
- What is the exclusion principle?
  - Two fermions cannot occupy the same quantum state at the same time.

S4.4 The Quantum Revolution

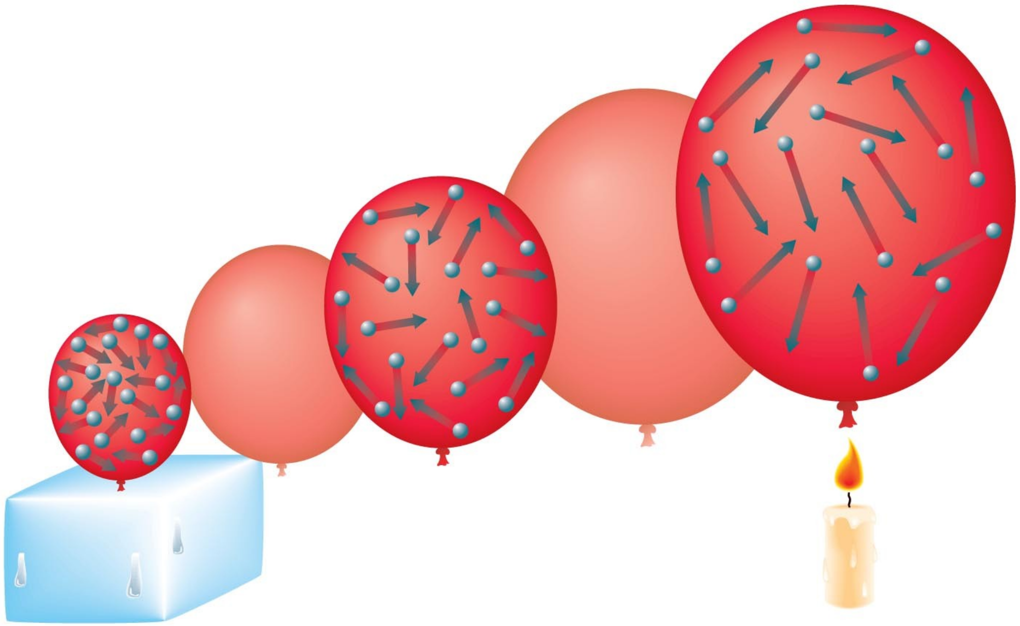
Our goals for learning:

- How do the quantum laws affect special types of stars?
- How is quantum tunneling crucial to life on Earth?
- How empty is empty space?
- Do black holes last forever?

How do the quantum laws affect special types of stars?



Thermal Pressure



- Molecules striking the walls of a balloon apply *thermal pressure* that depends on the temperature inside the balloon.
- Most stars are supported by thermal pressure.

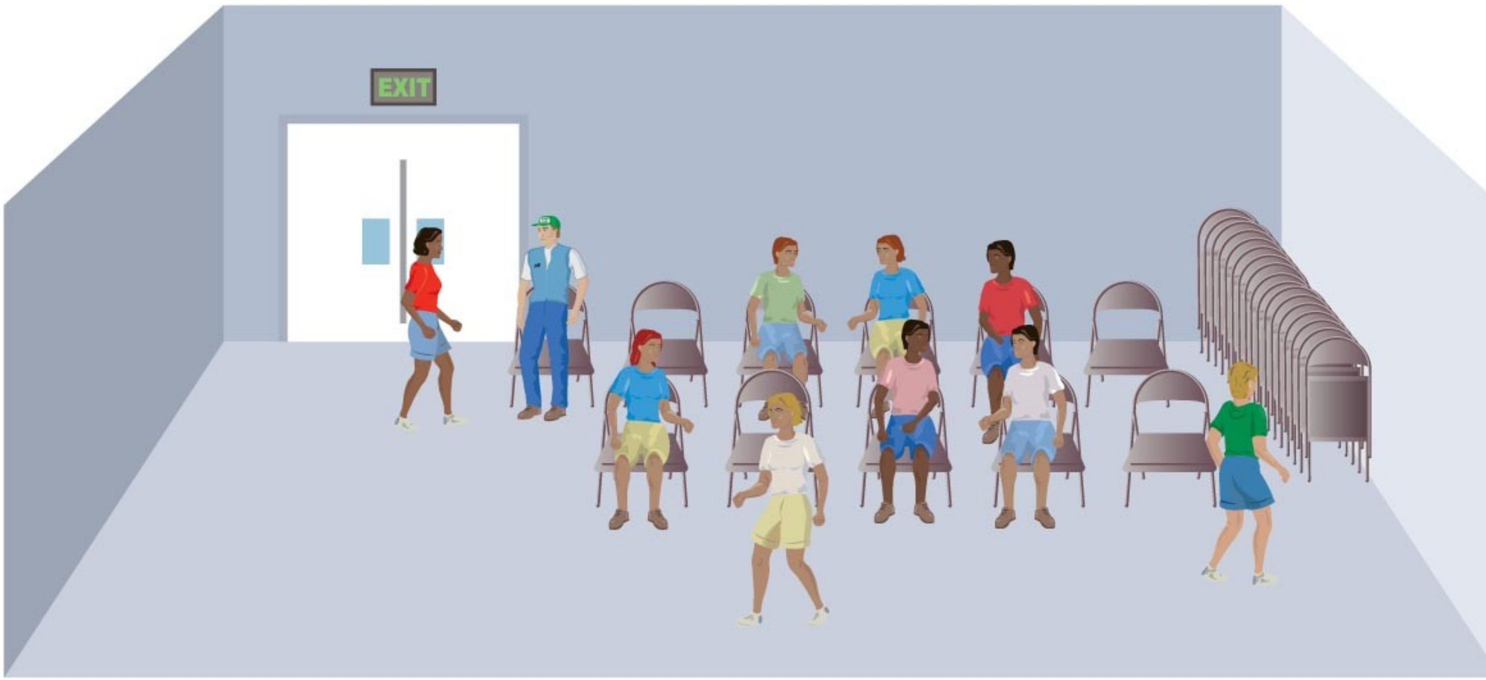
Degeneracy Pressure

- Laws of quantum mechanics create a different form of pressure known as *degeneracy pressure*.
- Squeezing matter restricts locations of its particles, increasing their uncertainty in momentum.
- But two particles cannot be in same quantum state (including momentum) at same time.
- There must be an effect that limits how much matter can be compressed—degeneracy pressure.

Auditorium Analogy for Degeneracy Pressure

- When the number of quantum states (chairs) is much greater than the number of particles (people), it's easy to squeeze them into a smaller space.

Auditorium Analogy for Degeneracy Pressure



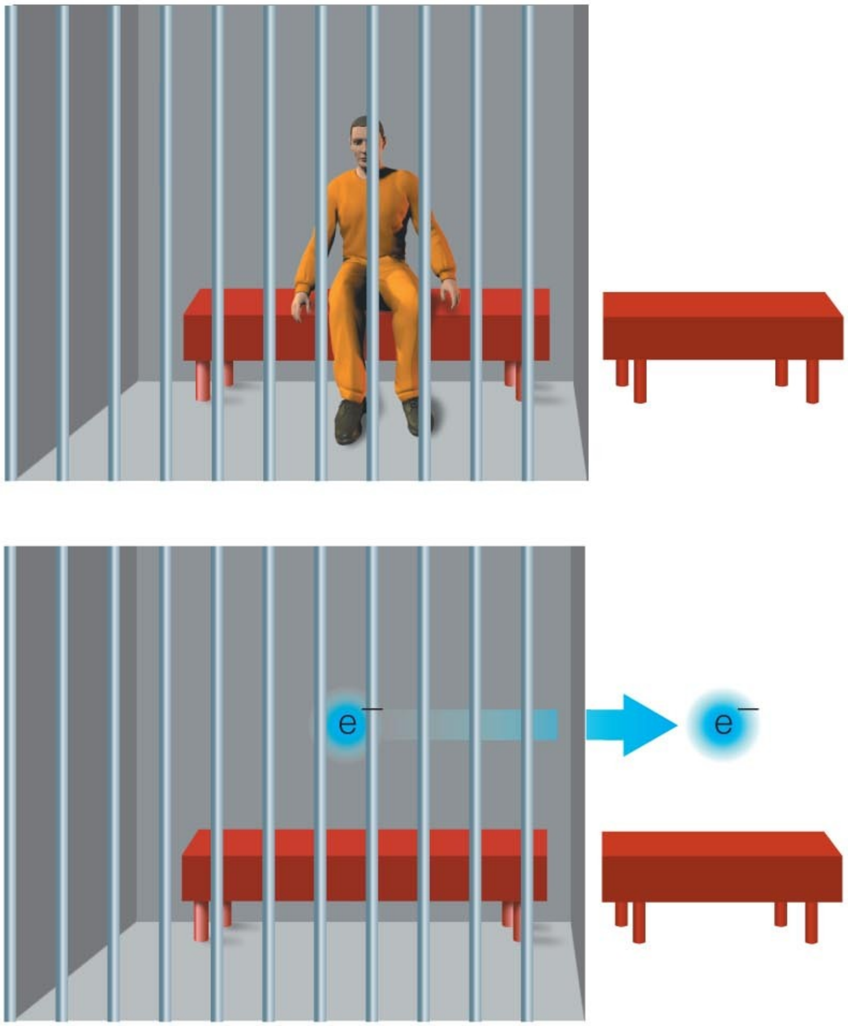
- When the number of quantum states (chairs) is nearly the same as the number of particles (people), it’s hard to squeeze them into a smaller space.

Degeneracy Pressure in Stars

- *Electron degeneracy pressure* is what supports white dwarfs against gravity—quantum laws prevent their electrons from being squeezed into a smaller space.

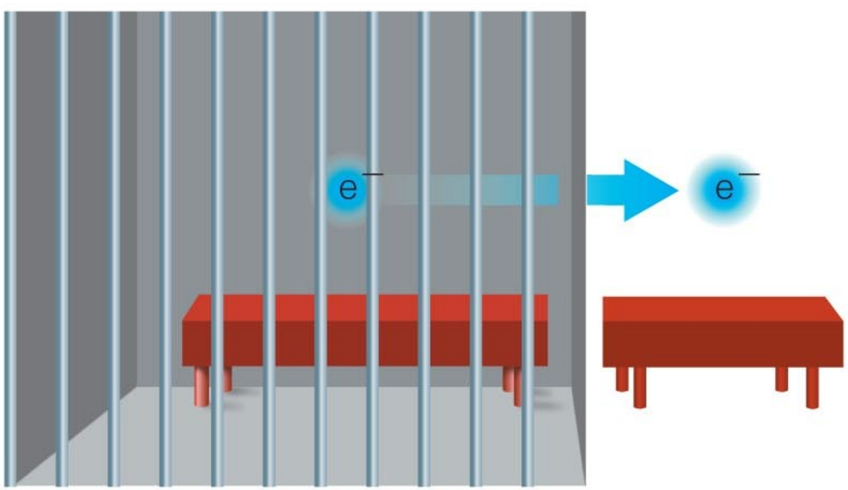
- *Neutron degeneracy pressure* is what supports neutron stars against gravity—quantum laws prevent their neutrons from being squeezed into a smaller space.

How is quantum tunneling crucial to life on Earth?



Quantum Tunneling

- A person in jail does not have enough energy to crash through the bars of a cell.



- Uncertainty principle allows subatomic particle to “tunnel” through barriers because of uncertainty in energy.

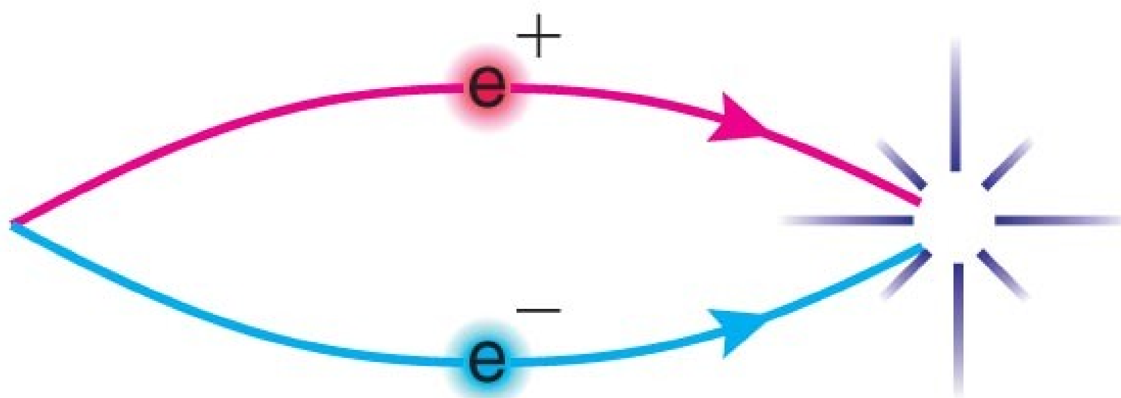
Quantum Tunneling and Life

- At the core of the Sun, protons do not have enough energy to get close enough to other protons for fusion (electromagnetic repulsion is too strong).

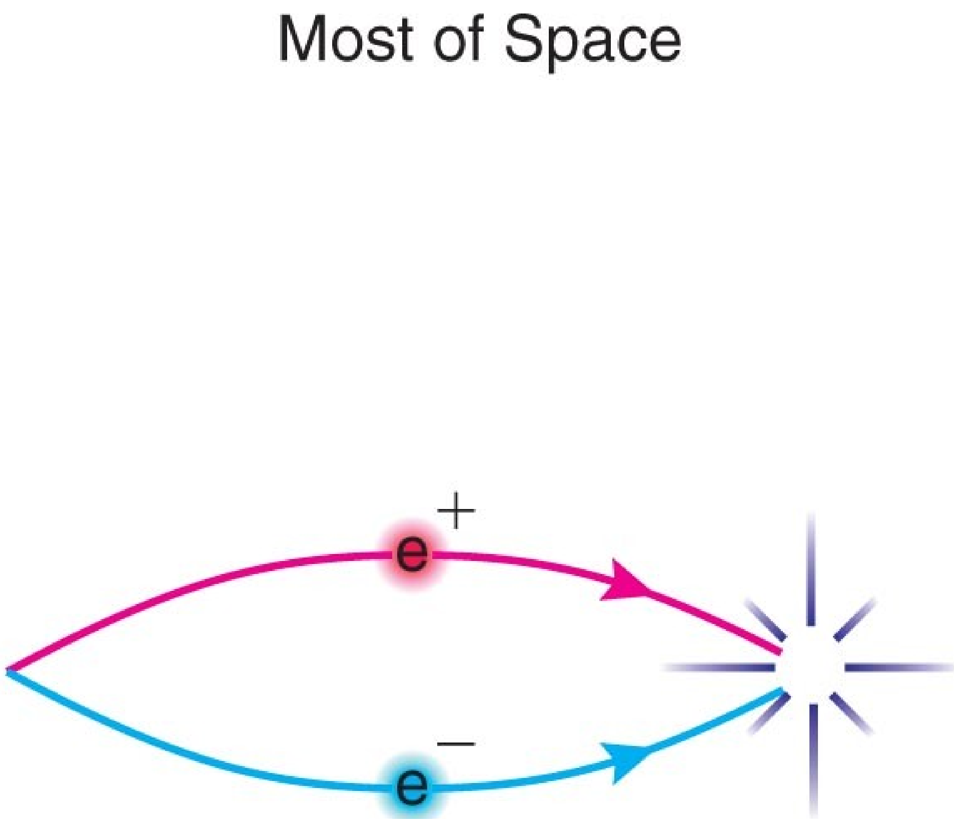
- Quantum tunneling saves the day by allowing protons to tunnel through the electromagnetic energy barrier.

How empty is empty space?

Most of Space

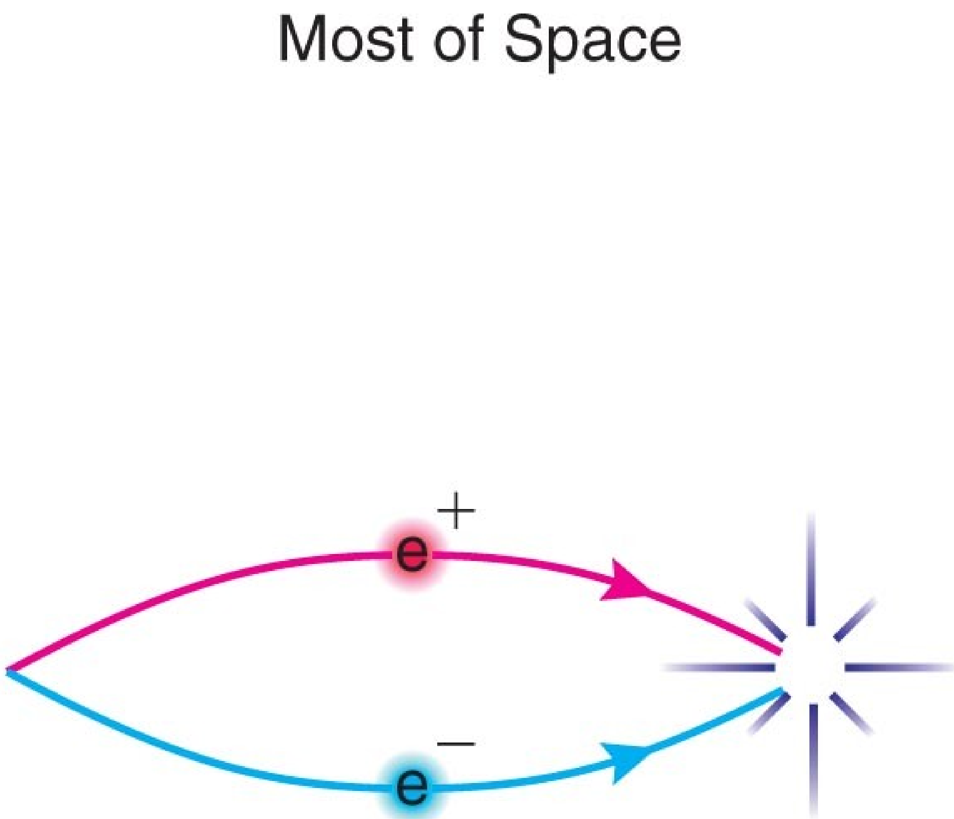


Virtual Particles



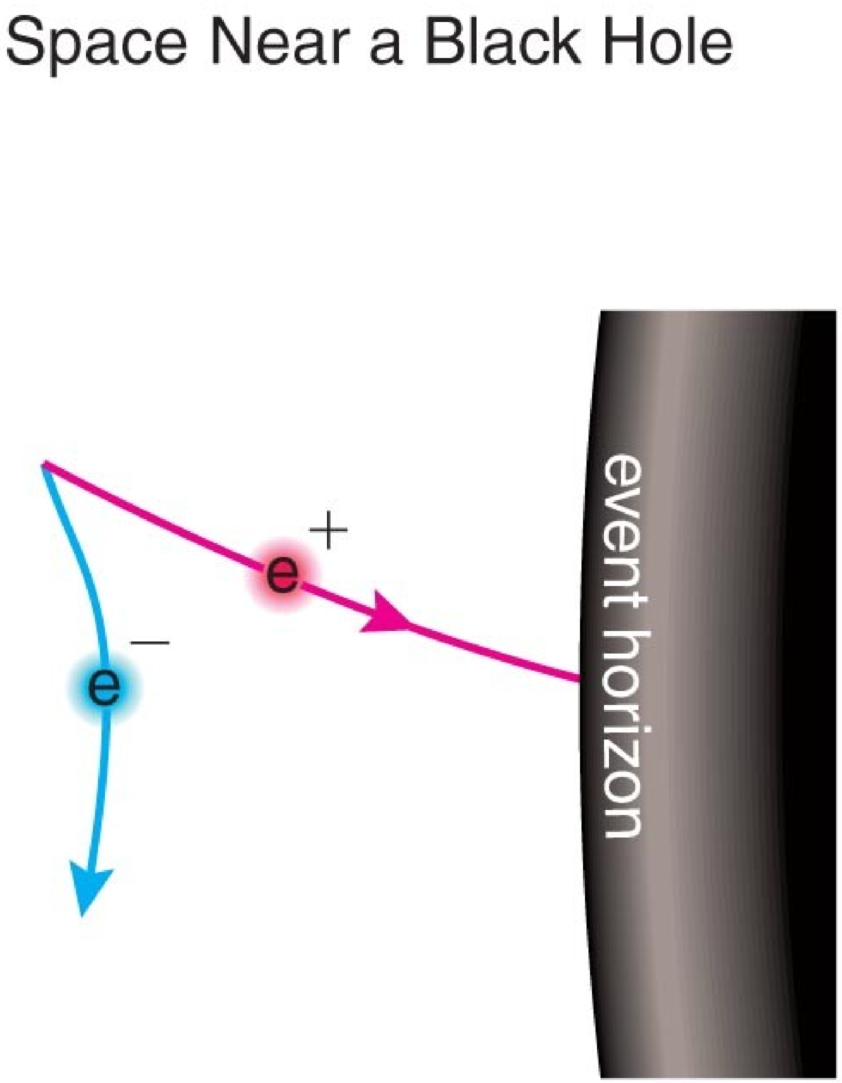
- Uncertainty principle (in energy and time) allows the production of matter-antimatter particle pairs.
- But particles must annihilate in an undetectably short period of time.

Vacuum Energy

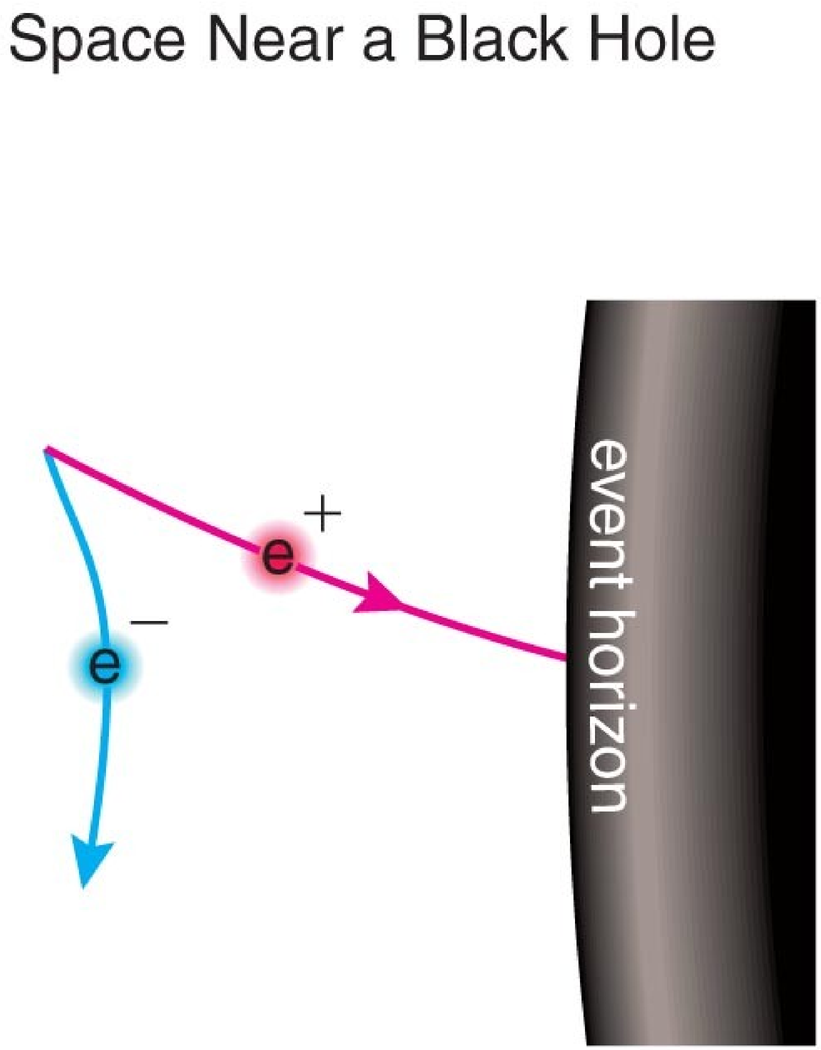


- According to quantum mechanics, empty space (a vacuum) is actually full of virtual particle pairs popping in and out of existence.
- The combined energy of these pairs is called the *vacuum energy*.

Do black holes last forever?



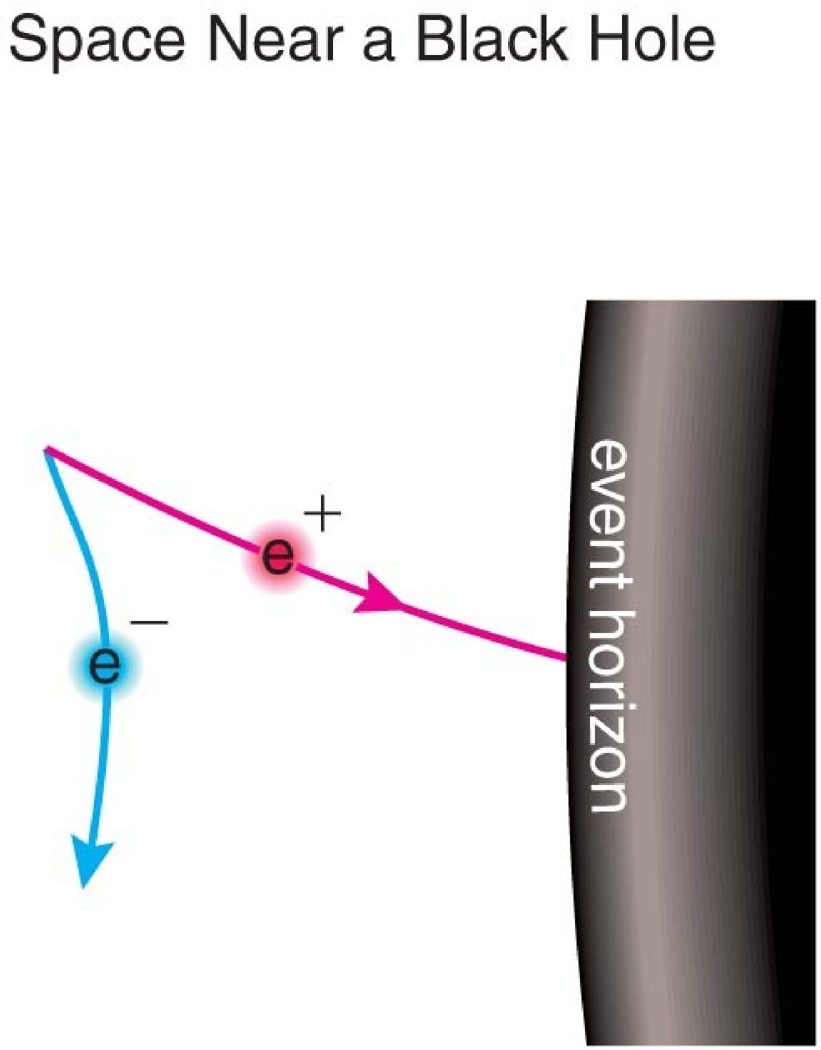
Virtual Particles near Black Holes



- Particles can be produced near black holes if one member of a virtual pair falls into the black hole.

- Energy to permanently create other particle comes out of black hole's mass.

Hawking Radiation



- Stephen Hawking predicted that this form of particle production would cause black holes to "evaporate" over extremely long time periods.

- Only photons and subatomic particles would be left.

What have we learned?

- How do the quantum laws affect special types of stars?
  - Quantum laws produce degeneracy pressure that supports white dwarfs and neutron stars.
- How is quantum tunneling crucial to life on Earth?
  - Uncertainty in energy allows for quantum tunneling through which fusion happens in Sun.

What have we learned?

- How empty is empty space?
  - According to quantum laws, virtual pairs of particles can pop into existence as long as they annihilate in an undetectably short time period.
  - Empty space should be filled with virtual particles whose combined energy is the vacuum energy.
- Do black holes last forever?
  - According to Stephen Hawking, production of virtual particles near a black hole will eventually cause it to “evaporate.”