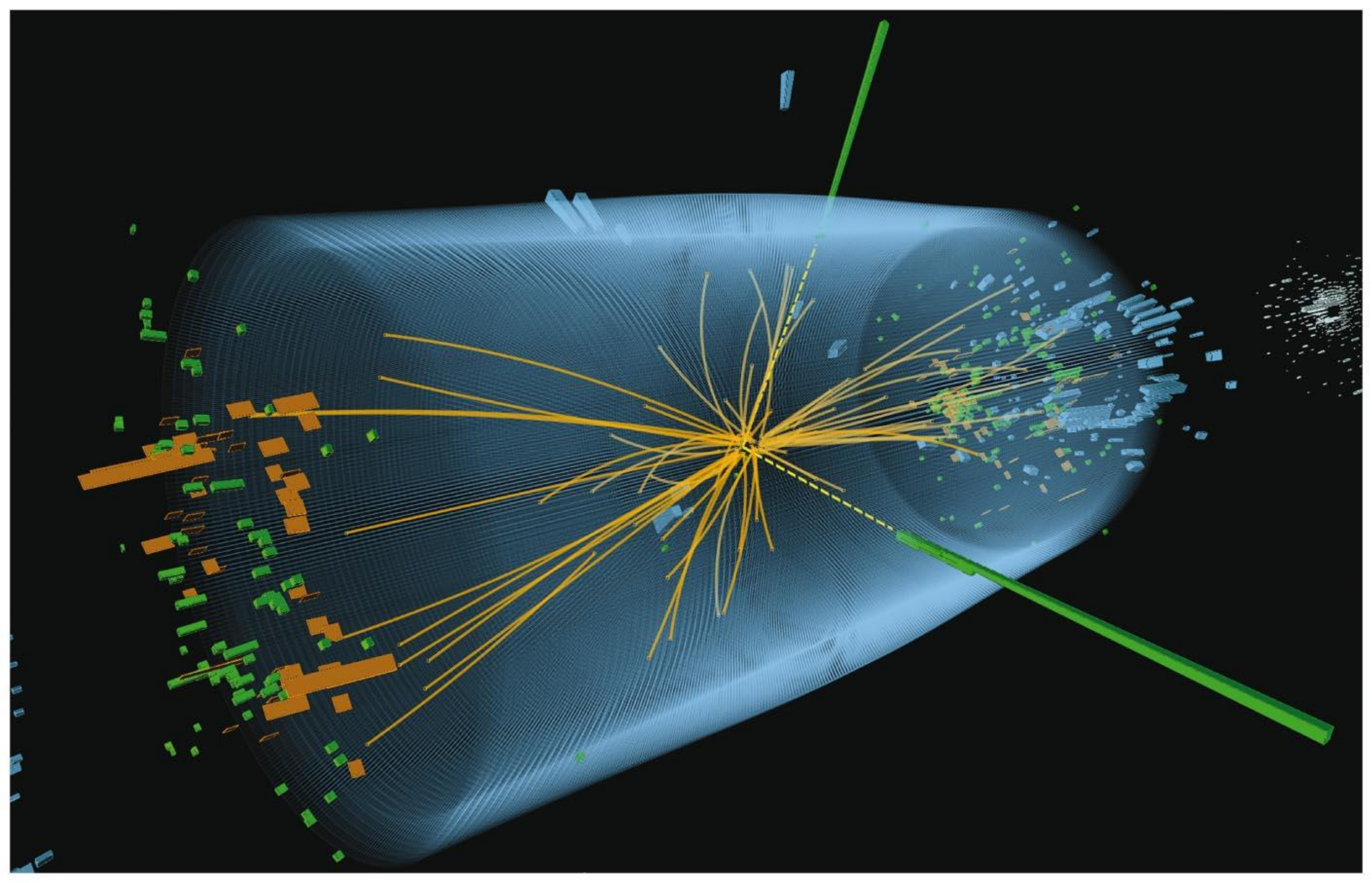
Building Blocks of the Universe



S4.1 The Quantum Revolution

- Our goals for learning:
  - **How has the quantum revolution changed our world?**

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 nature?
  - What are the fundamental forces in nature?

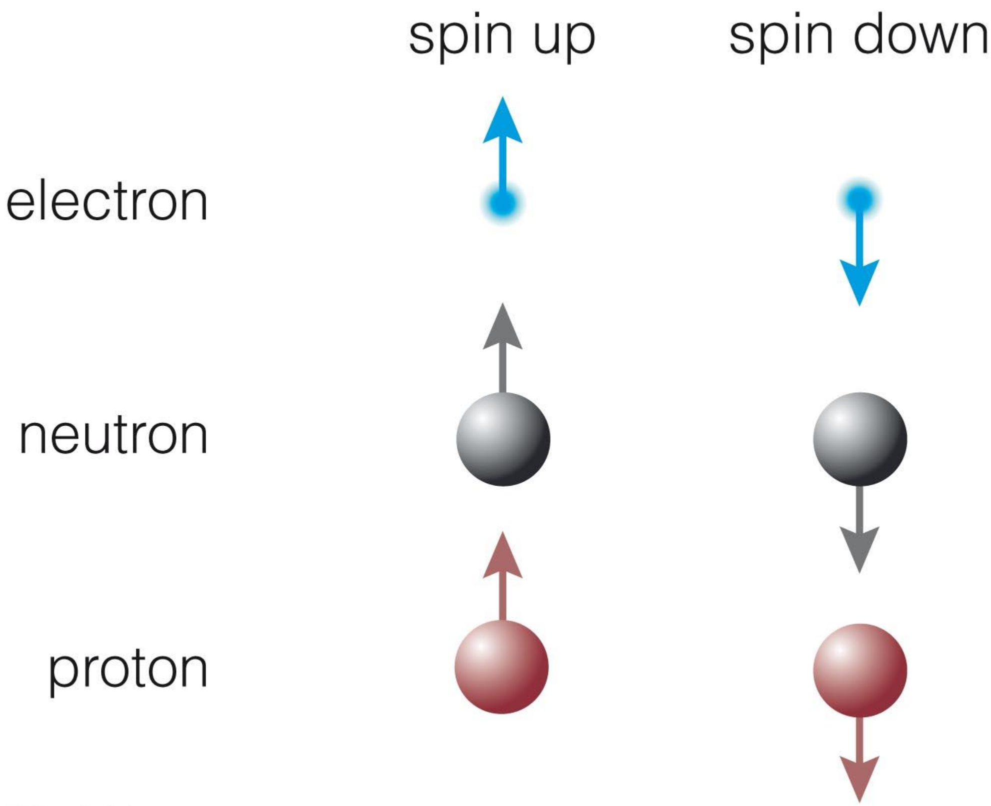
Particle Accelerators

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

Properties of Particles

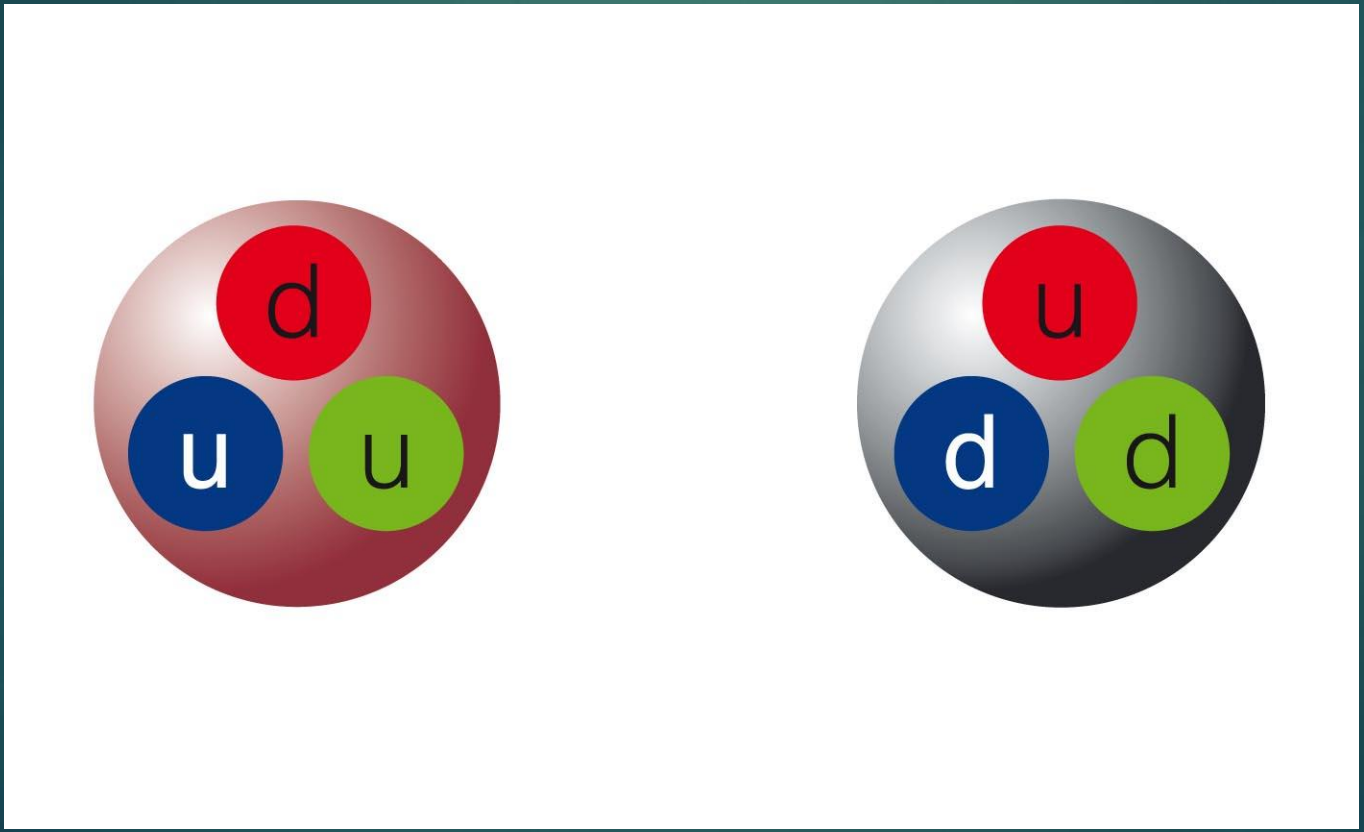
- Mass
- Charge (proton +1, electron –1)
- Spin
  - Each type of subatomic particle has a certain amount of angular momentum, as if it were spinning on its axis.

Orientation of Spin



- Particles can have spin in integer or half-integer multiples of $h/2\pi$.
- Particles with half-integer spin have two basic spin states: up and down.

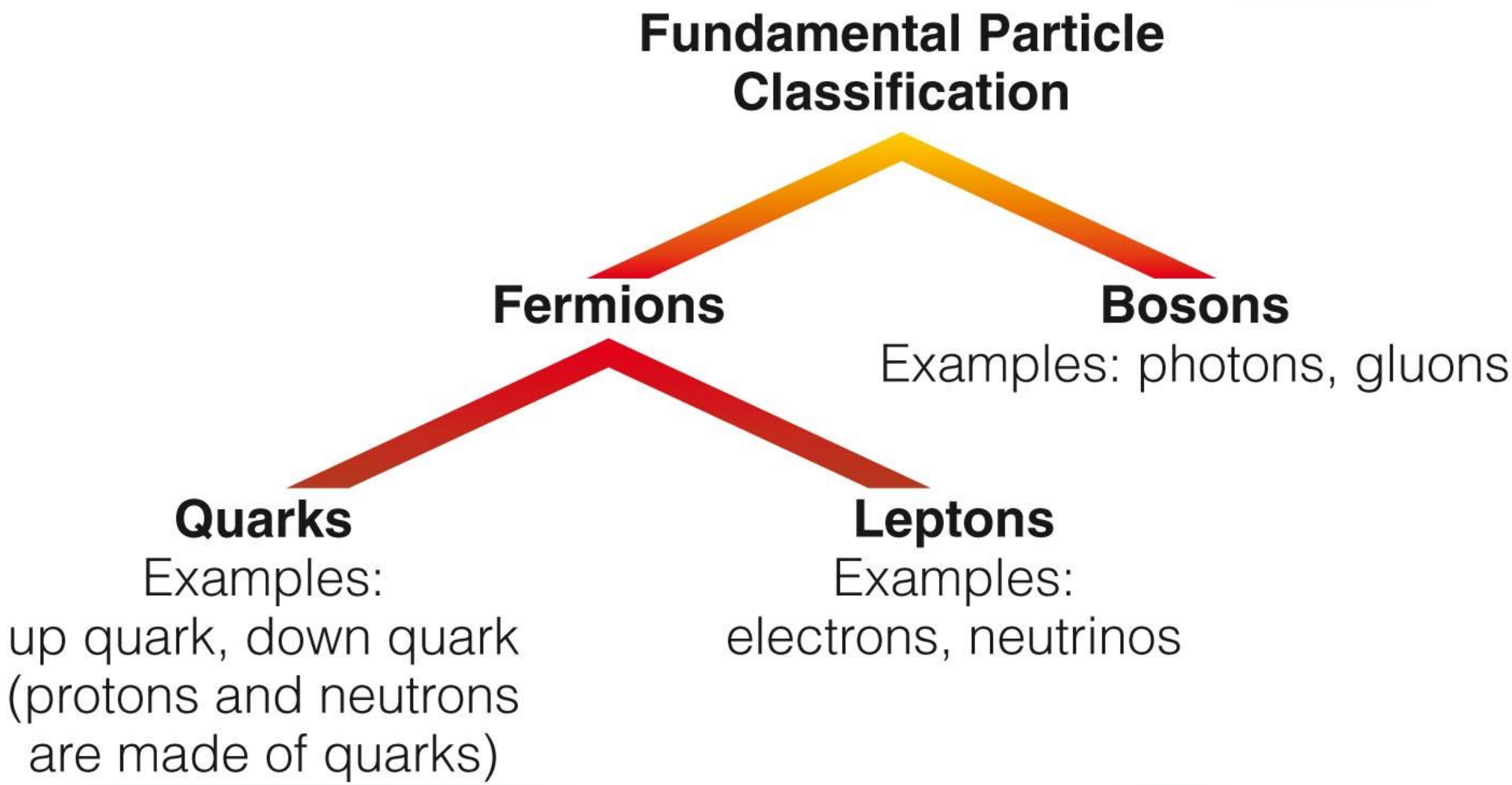
What are the fundamental building blocks of nature?



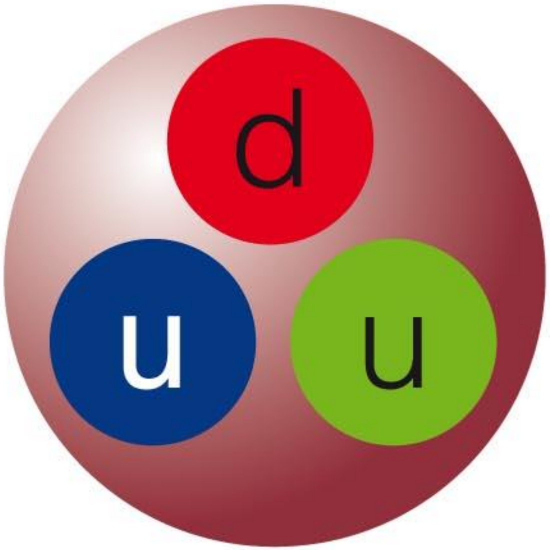
Fermions and Bosons

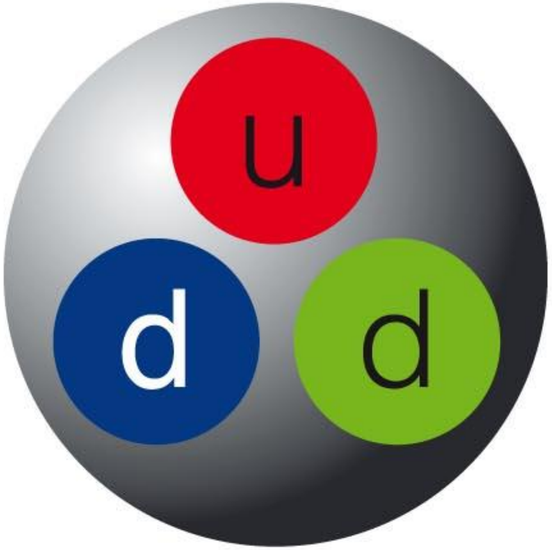
- Physicists classify particles into two basic types, depending on their spin (measured in units of $h/2\pi$).
- Fermions have half-integer spin (1/2, 3/2, 5/2,…).
  - Examples: electrons, protons, neutrons
- Bosons have integer spin (0, 1, 2,…).
  - Example: photons

Fundamental Particles



Quarks

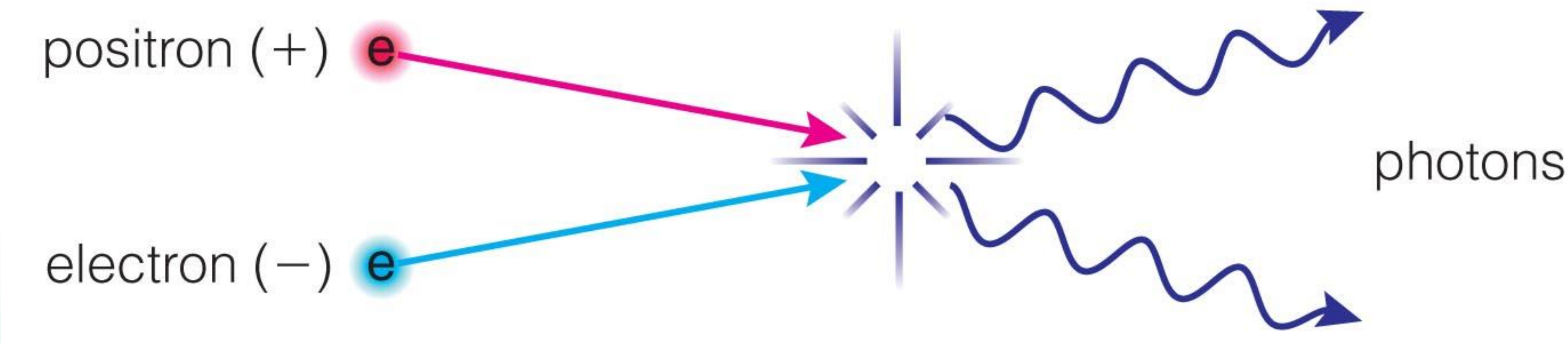




Quarks and Leptons

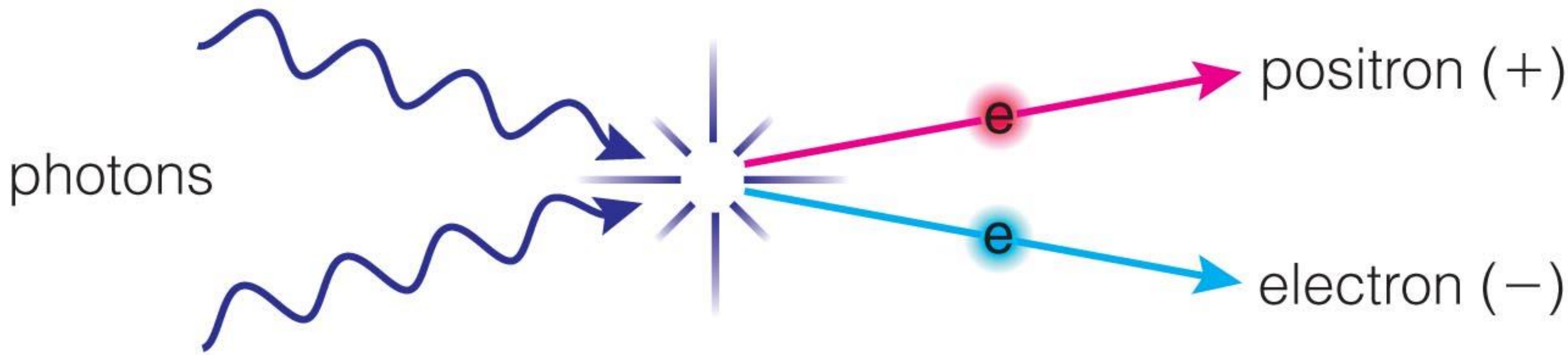
- Six types of quarks: up, down, strange, charm, top, and bottom
- Leptons are not made of quarks and also come in six types:
  - Electron, muon, tauon
  - Electron neutrino, mu neutrino, tau neutrino
- Neutrinos are very light and uncharged.

Matter and Antimatter



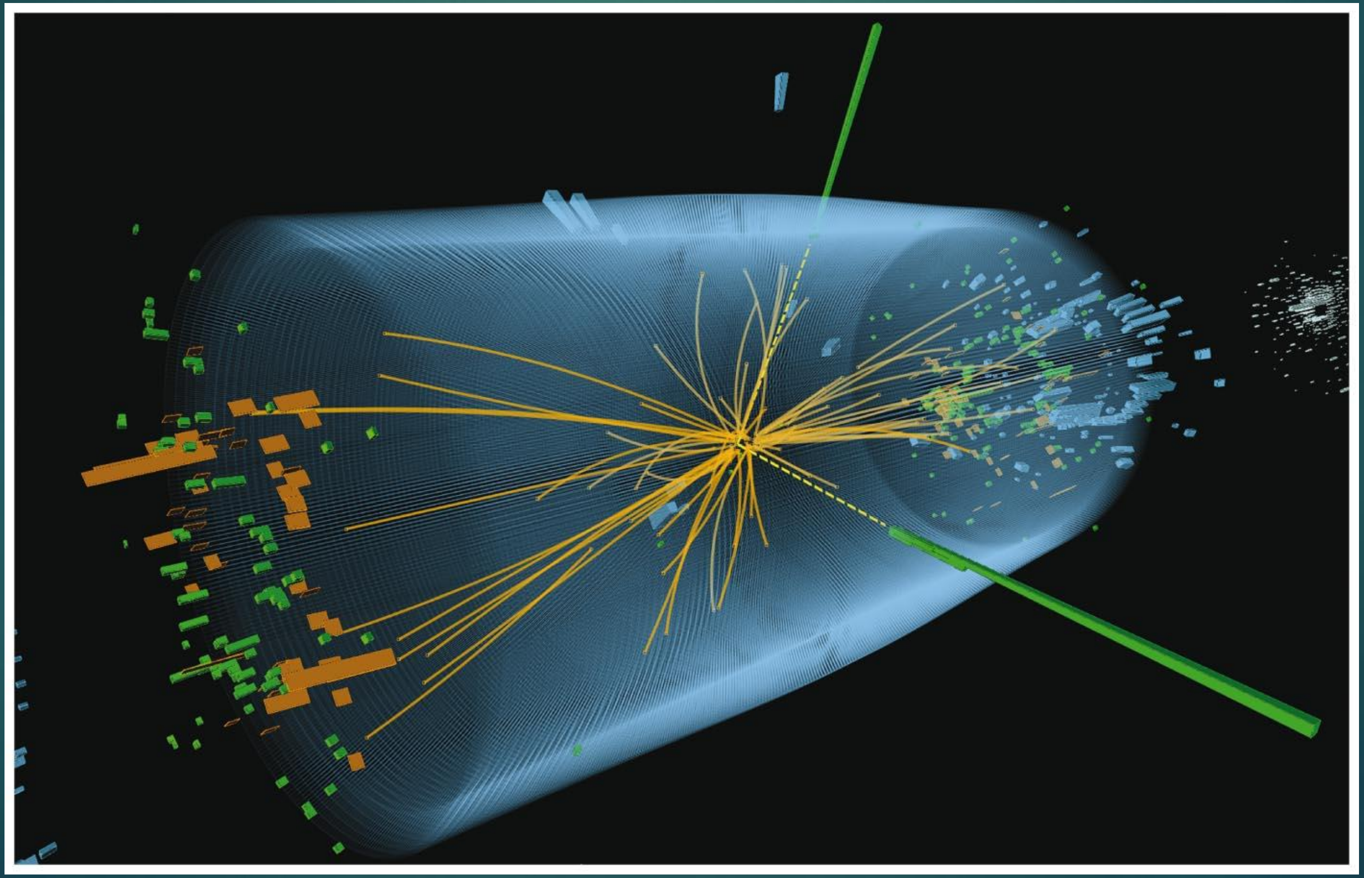
- Each particle has an antimatter counterpart.
- When a particle collides with its antimatter counterpart, they annihilate and become pure energy in accord with $E = mc^2$.

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 nature?**
  - Quarks (up, down, strange, charmed, top, bottom)
  - Leptons (electron, muon, tauon, neutrinos)
- **What are the fundamental forces in nature?**
  - Strong, electromagnetic, weak, gravity

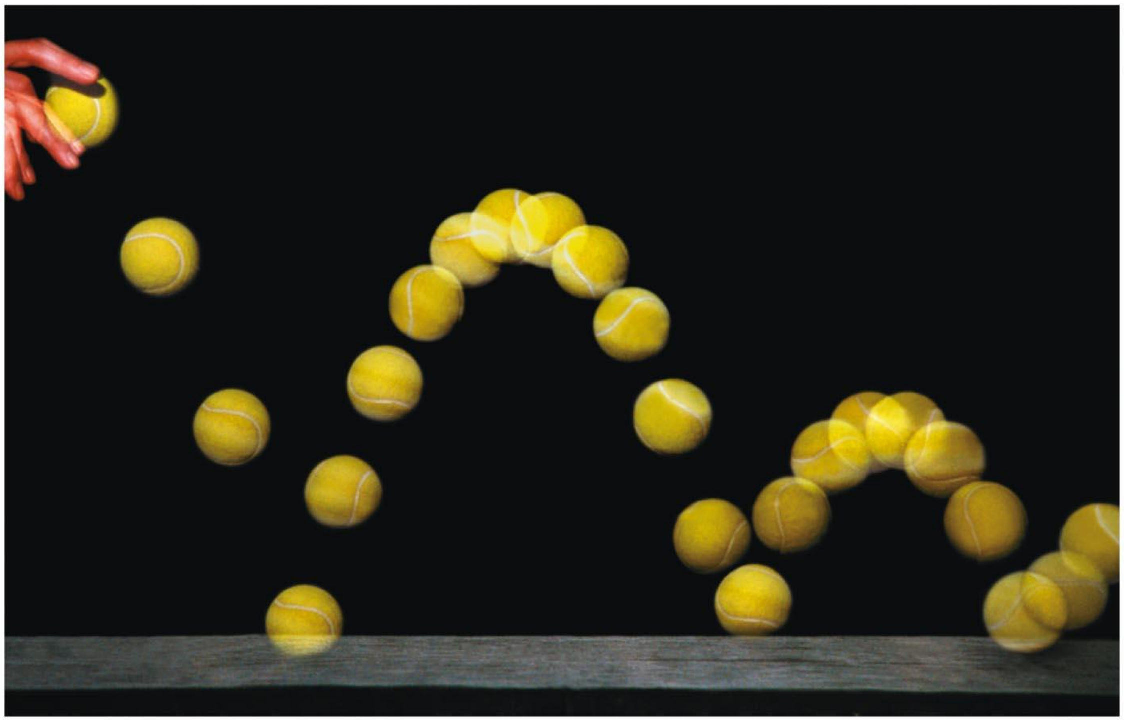
S4.3 Uncertainty and Exclusion in the Quantum Realm

- Our goals for learning:
  - What is the uncertainty principle?
  - What is the exclusion principle?

Uncertainty Principle

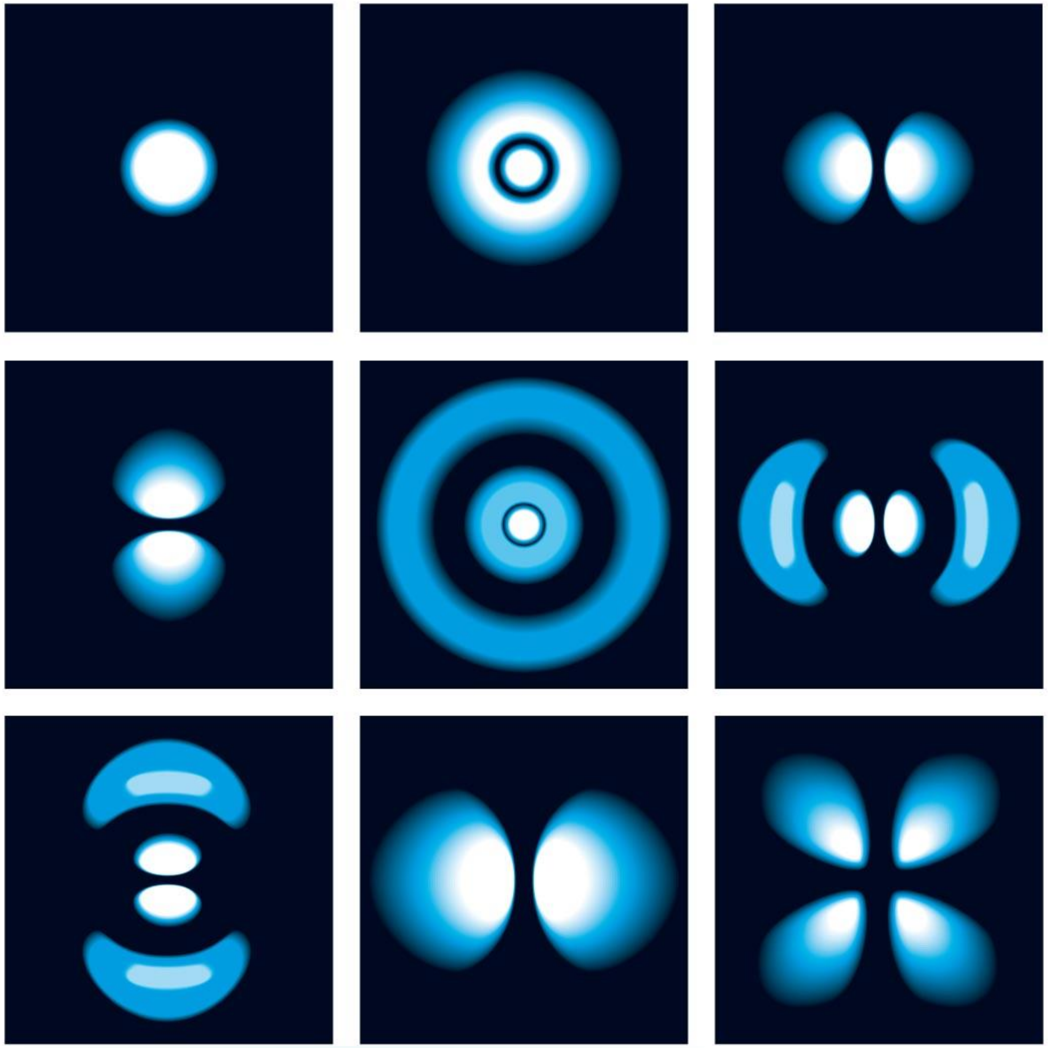
- The more we know about where a particle is located, the less we can know about its momentum, and conversely, the more we know about its momentum, the less we can know about its location.

Position of a Particle



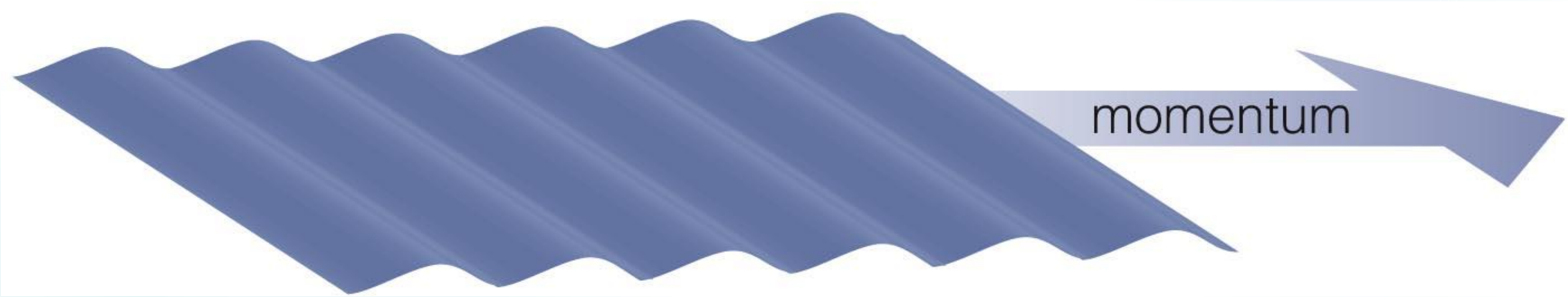
- In our everyday experience, a particle has a well-defined position at each moment in time.
- But in the quantum realm, particles do not have well-defined positions.

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.

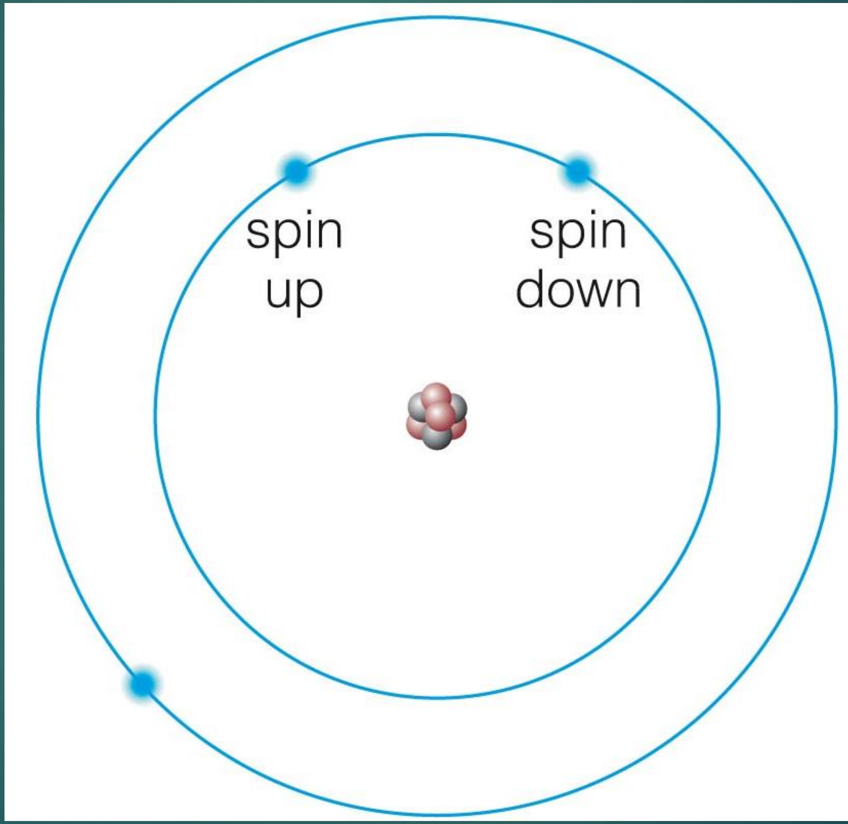
Location and Momentum

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?



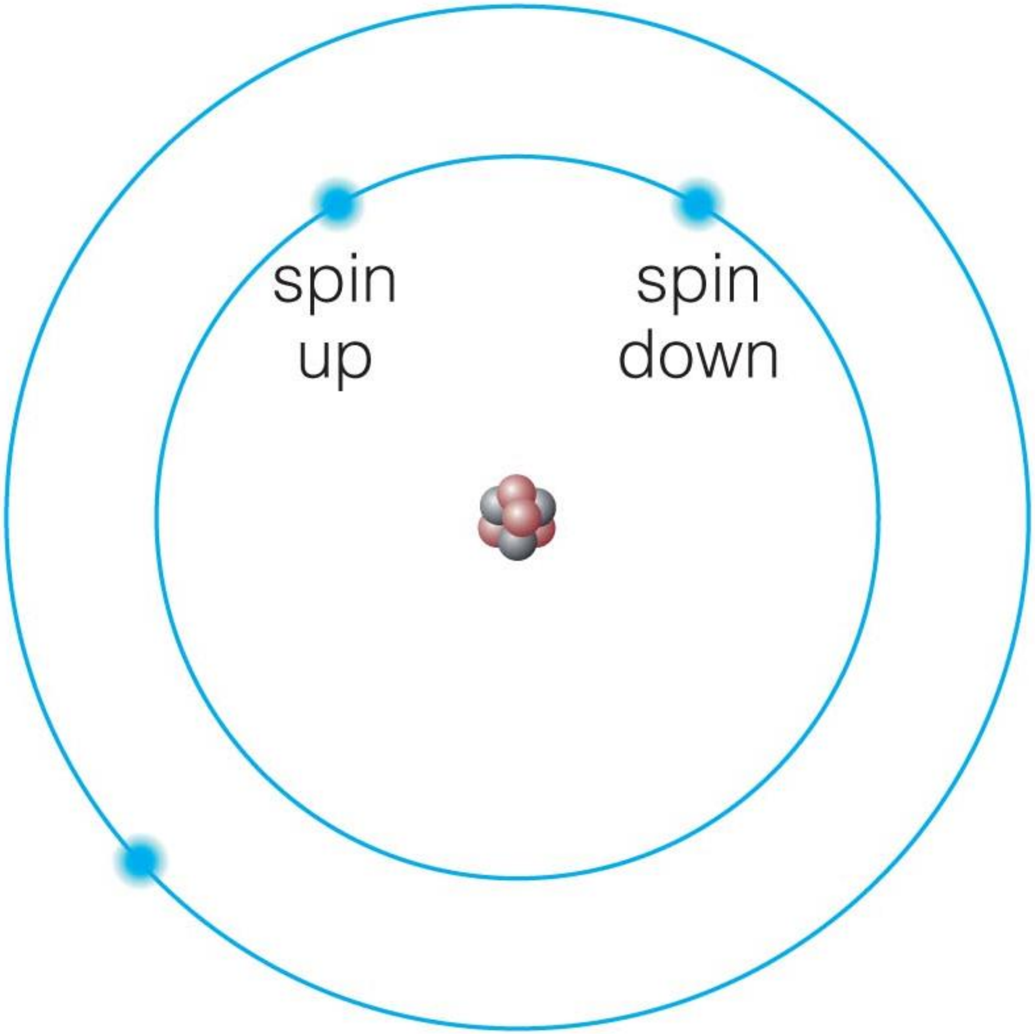
Quantum States

- 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.

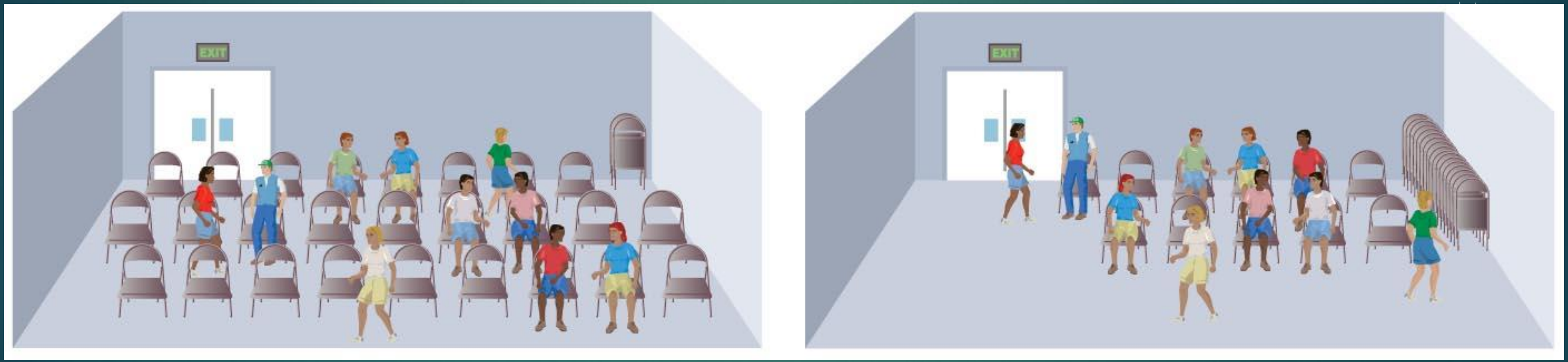
What have we learned?

- 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.**

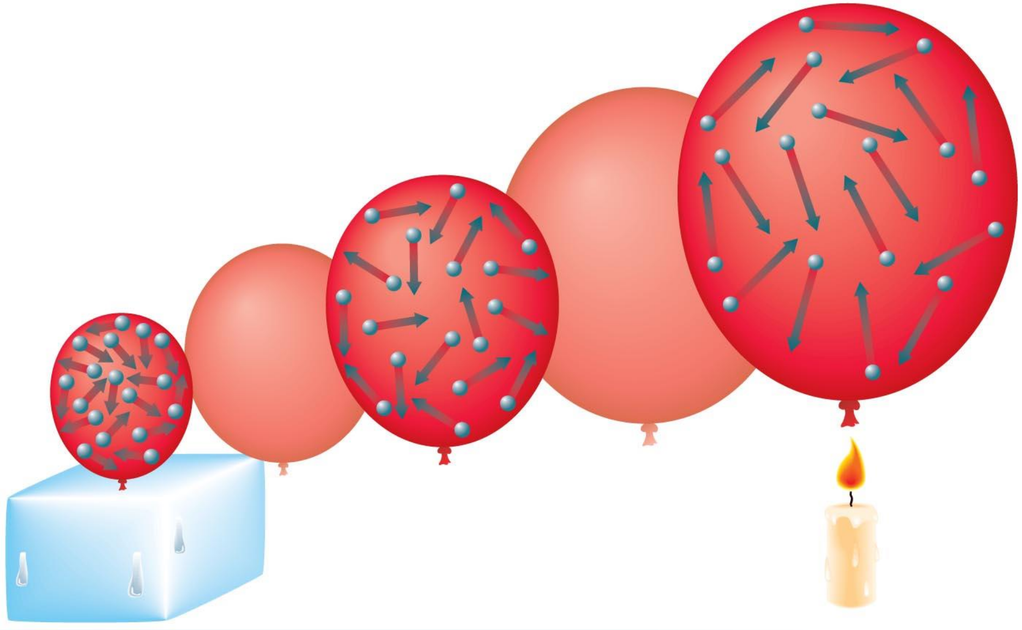
S4.4 The Quantum Revolution

- 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

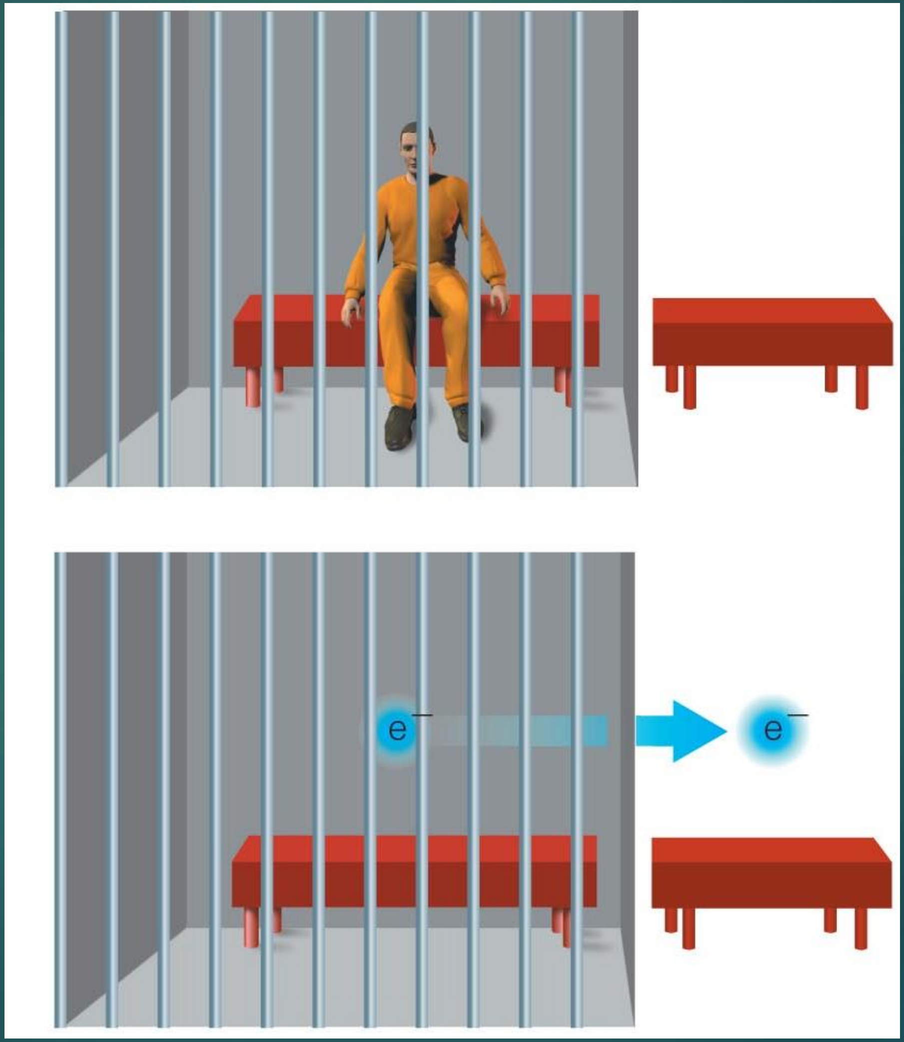
- When the number of quantum states (chairs) is nearly the same as the number of particles (people), it's hard to squeeze them into a smaller space.

Degeneracy Pressure in Stars

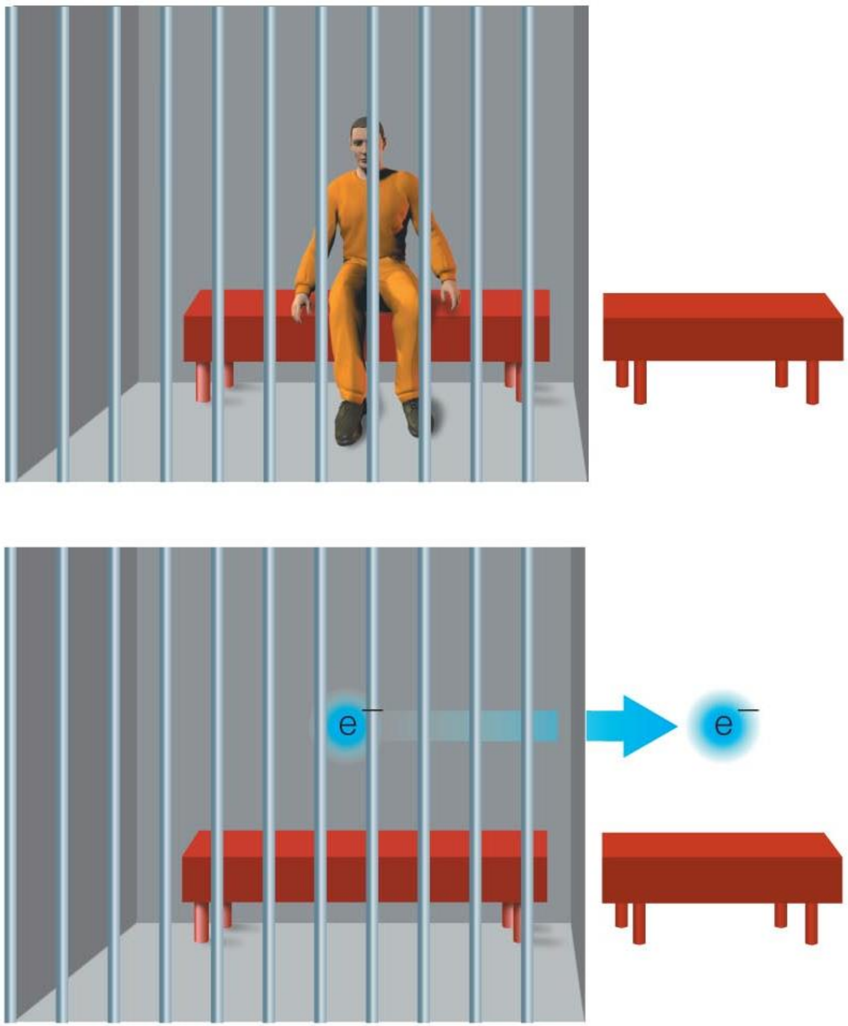
- *Electron degeneracy pressure* is what supports white dwarfs against gravity—quantum laws prevent their electrons from being squeezed into a smaller space.

- *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

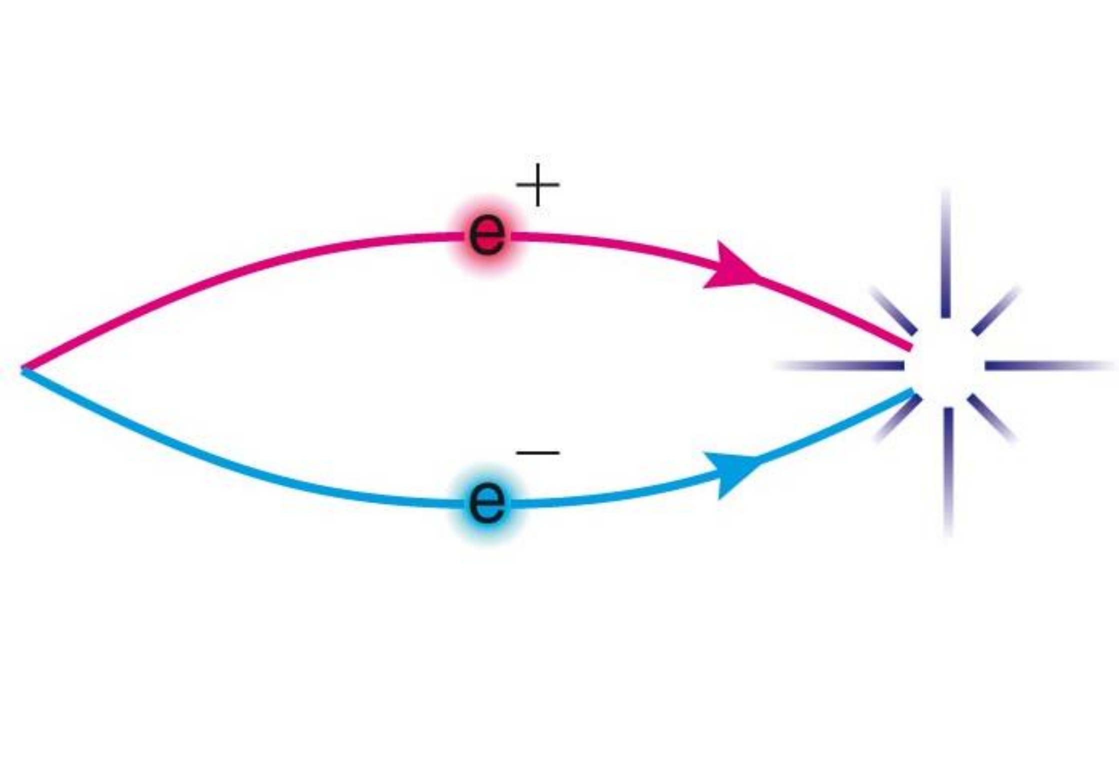


- A person in jail does not have enough energy to crash through the bars of a cell.
- Uncertainty principle allows subatomic particle to "tunnel" through barriers because of uncertainty in energy.

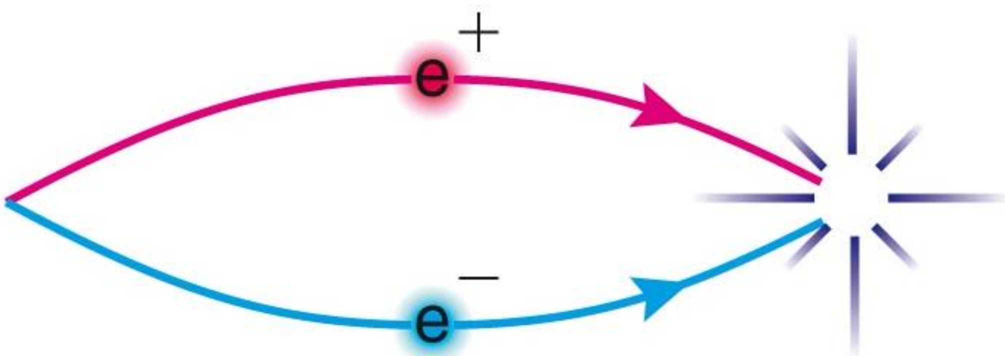
Quantum Tunneling and Life

- 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?

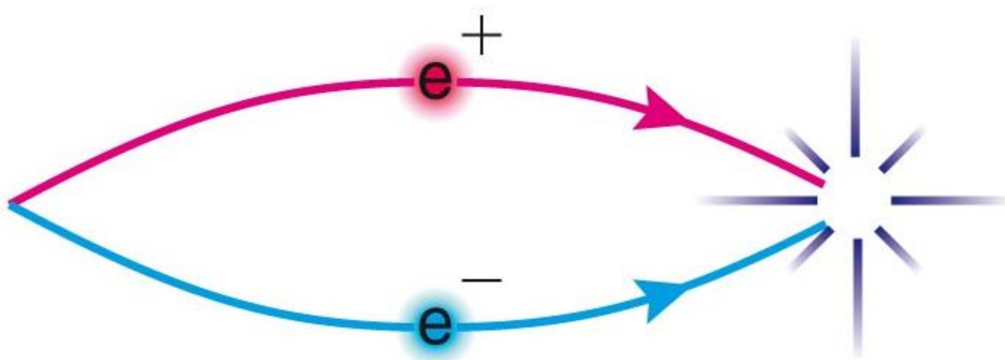


Virtual Particles



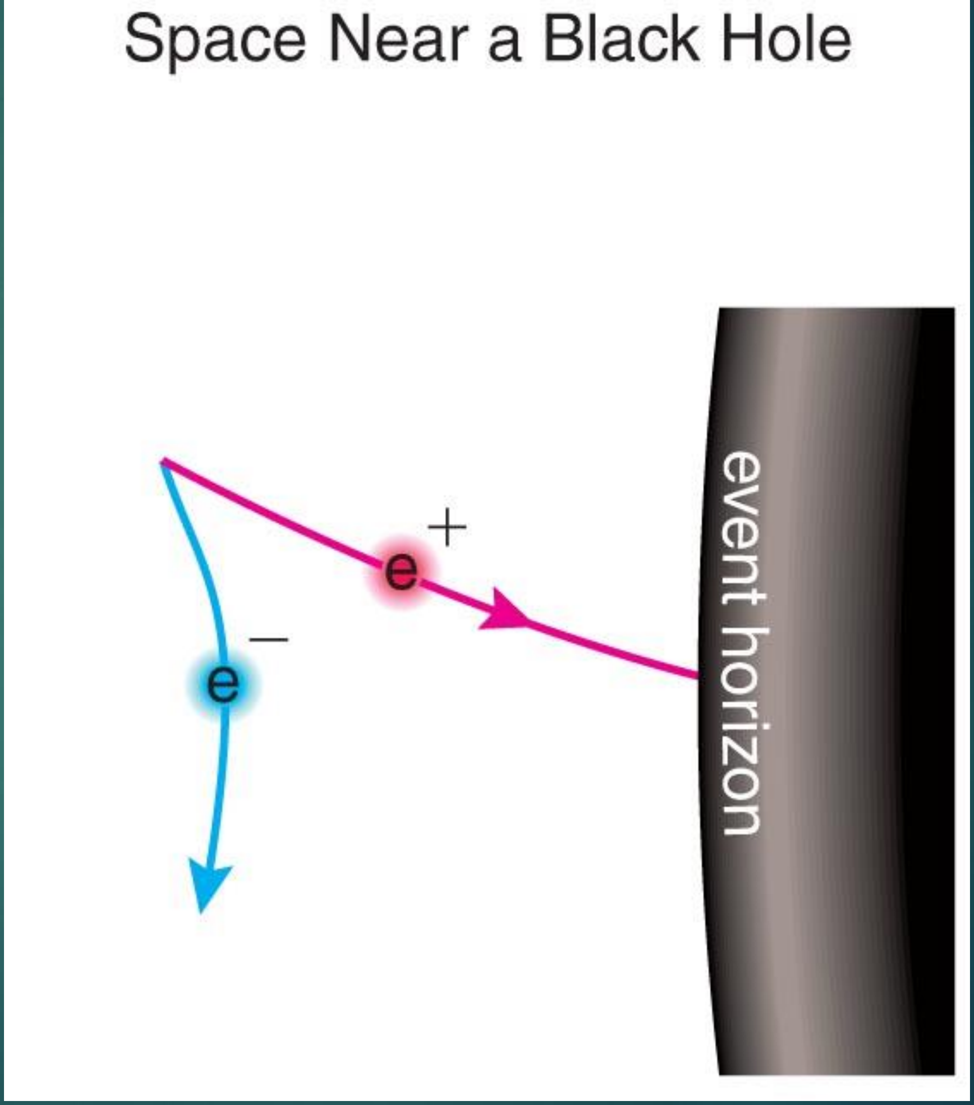
- Uncertainty principle (in energy and time) allows the production of matter-antimatter particle pairs.
- But particles must annihilate in an undetectably short period of time.

Vacuum Energy



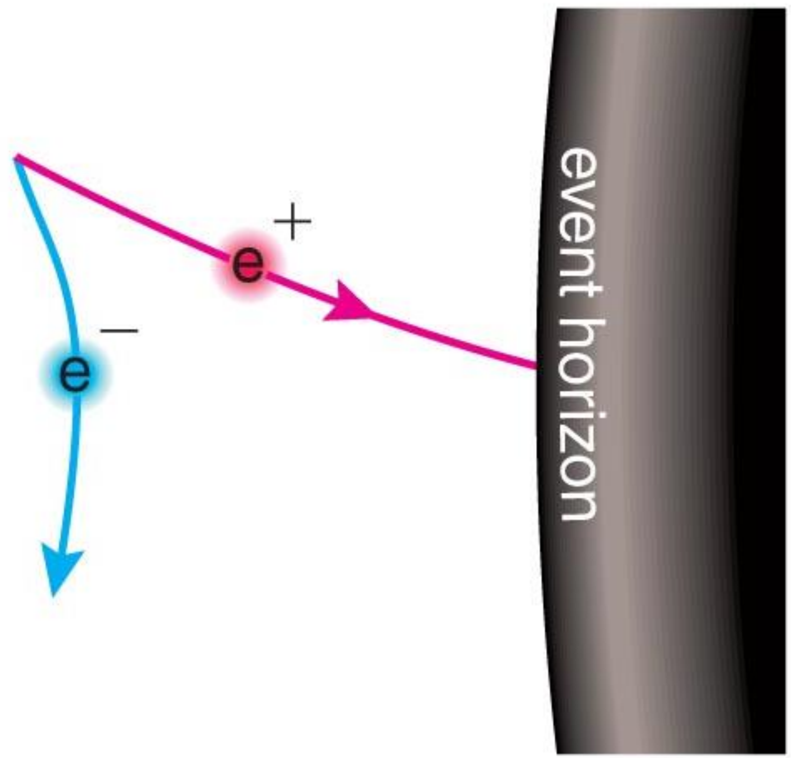
- According to quantum mechanics, empty space (a vacuum) is actually full of virtual particle pairs popping in and out of existence.
- The combined energy of these pairs is called the *vacuum energy*.

Do black holes last forever?



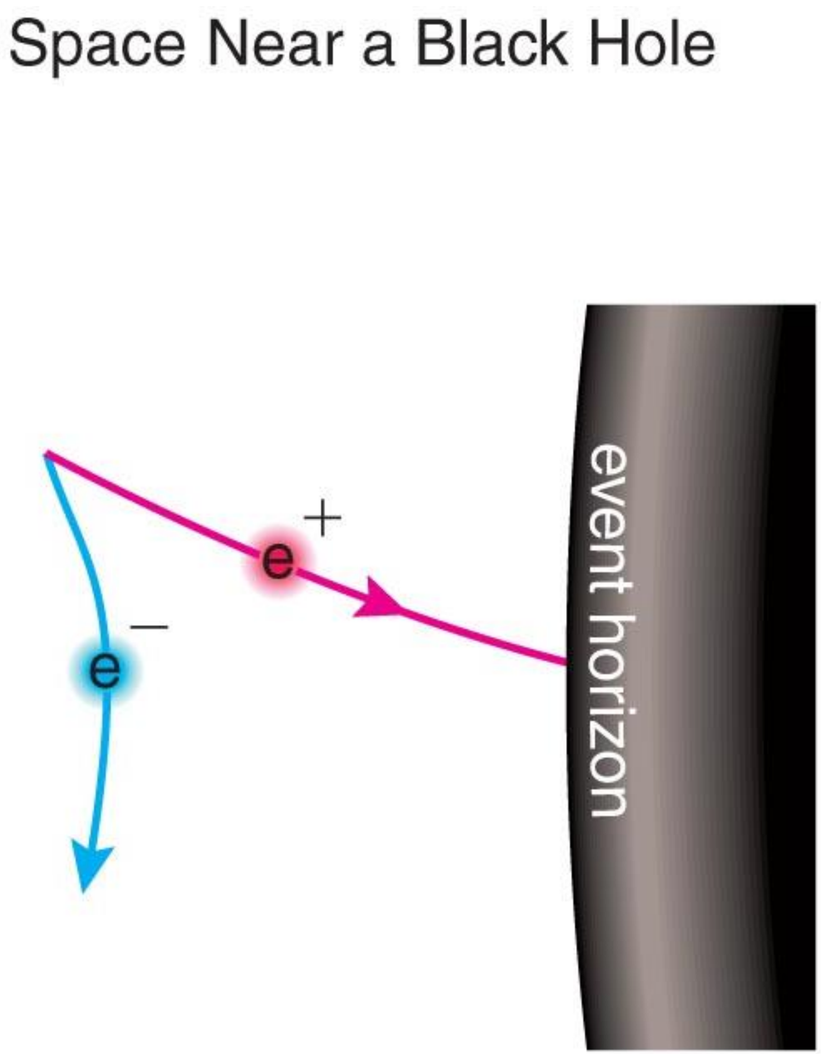
Virtual Particles near Black

Space Near a Black Hole



- 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."