1. **Gravity**  
\[ \text{force} \sim \frac{\text{mass}}{(\text{separation})^2} \]

The dependence on \((\text{separation})^2\) can be understood intuitively. The area on surfaces of shells about the mass depend on \((\text{radius})^2\) of the shell. The effect of the force is diluted over the surface of the shell with this dependence.

The gravitational force is weaker by far than the other forces but it is the only one that accumulates on larger scales. Hence it becomes the dominant force on large scales.

The force of gravity involves the exchange of `gravitons`, whose individual influence is so small that they have not yet been detected. In principle, they can be. **NOW DETECTED!**

2. **Electromagnetic force**  
\[ \text{force} \sim \frac{\text{charge}}{(\text{separation})^2} \]

The dependence on \((\text{separation})^2\) is the same as with gravity and for the same reason.

The strength of the electromagnetic force is much greater than that of gravity in the sense that two charged particles at atomic separations have a great influence on each other through the electromagnetic interaction but have negligible gravitational influence on each other. There can be both attraction (opposite charges) and repulsion (same charges). Since opposite charges attract, there is a tendency for a collection of particles to be neutral. For this reason, the force tends to cancel out on large scales and gravity comes to dominate.

Energy exchanges with the electromagnetic force are with the photon. Examples were given in the `Basic Concepts` lectures (e.g., energy level transitions in atoms and molecules, ionization and recombination, black body radiation, etc.)
3. Strong force

The attractive force that binds nuclei. This force must be strong enough, on small scales, to dominate the repulsion of the electromagnetic force felt between nucleons of the same charge. This force falls off faster than $d^2$ so becomes unimportant on large scales.

The equivalent to charge is a property called ‘color’ for the strong force. However charge is just +/- while there are three ‘colors’ and three ‘anti-colors’. Hence the exchange possibilities are more complicated.

Energy is exchanged through mediation of the ‘gluon’ particle which, unlike the photon and graviton, have mass.

4. Weak Force

This is also a nuclear-range force and acts through a property called ‘spin’. Energy is exchanged through transfer of ‘W’ and ‘Z’ particles. This force is at play in transitions which involve interactions with neutrinos.
**Pair Production and the Heisenberg Uncertainty Principle**

* The **Heisenberg uncertainty principle** is a fundamental concept of physics at the atomic level, described by quantum mechanics. It asserts that we can never know both where a particle is located and how fast it is moving to better than a certain precision:

\[
(\text{uncertainty in position}) \times (\text{uncertainty in mass} \times \text{velocity}) > \text{constant}
\]

An alternative formulation is:

\[
(\text{uncertainty in energy}) \times (\text{uncertainty in time}) > \text{constant}
\]

* **Einstein’s equivalency between mass and energy:** \( E = mc^2 \)

Accordingly, it is possible to convert energy \( \leftrightarrow \) matter

[With the atomic (fission) or hydrogen (fusion) bomb, nuclear transitions result in a loss of mass with a corresponding release of energy.]

* **Pair production and annihilation.** Following from the mass-energy equivalency, it is possible for photons to convert into particle-antiparticle pairs. Alternatively, a particle can encounter an antiparticle and annihilate into a packet of energy.

The pair production can happen spontaneously but requires that the photon have at least enough energy to equal the sum of the rest masses of the particles. For example, the energy equivalent rest mass of an electron is 0.5 Million electron volts (MeV). An electron - positron pair can be spontaneously produced from a gamma-ray photon that is common at temperatures above 10 billion \( (10^{10}) \) degrees K.
Virtual Particles

Virtual particles and antiparticles can be created even though there does not seem to be photons available with sufficient energy. This virtual particle production is governed by the uncertainty principle. They must disappear through annihilation on a commensurate timescale:
\[ \Delta E \Delta t \sim \text{constant} \]

If the particles have rest mass \( \Delta E \) then they must be annihilated before \( \Delta t \).

In bizarre situations, the particles may not annihilate, like near a black hole. One of the particle-antiparticle pair might fall into the black hole before the annihilation and the other might escape. The escaping particle carries away part of the mass of the black hole. Small black holes could evaporate this way (the timescale for the evaporation of a large black hole is much longer than the age of the Universe so it is an inconsequential process.) Called ‘Hawking radiation’.

Planck Mass.

As we extrapolate back to higher energies and earlier times, we can push back so close to the beginning that the product: \( \text{(age of the Universe)} \times \text{(mass/energy within the horizon)} \)
fails the uncertainty principle of quantum mechanics.

The mass within the horizon is equivalent to the Schwarzschild radius which defines a black hole:
\[ \text{radius} = \frac{2GM}{c^2} \]

Planck mass = \( 10^{-5} \) grams = \( 10^{19} \) GeV equivalent rest mass energy
Planck length = \( 10^{-33} \) cm
Planck time = \( 10^{-43} \) seconds (age of Universe when it has the Planck density)
Today there is interplay between 4 distinct forces.

At very high energies (experienced in the Universe when it was very young) there is a merging of forces.

At $T = 10^3$ GeV ($t = 10^{-12}$ sec) there was unification of the electromagnetic and weak forces (confirmed by accelerator experiments).

At $T = 10^{15}$ GeV ($t = 10^{-36}$ sec) grand unified theory expects unification of the strong force with electro-weak (GUT).

It is speculated that at $T = 10^{19}$ GeV ($t = 10^{-44}$ sec) there would be unification of gravity with GUT.
Phase Transitions and Symmetry Breaking

Familiar examples:

H₂O can exist as a solid, liquid, or gas depending on the temperature.

In the highest energy state (as a gas) the H₂O is in a state of symmetry because the molecules are randomly oriented with respect to each other.

In the lowest energy state (as ice) the molecules are in defined lattices; this restriction in positions is technically a loss of symmetry.

The intermediate energy state (as water) is also a case of broken symmetry because of restrictions on positions.

An iron bar acts as a magnet below the “Curie temperature” but not above.

At lower temperatures the atoms align to create North and South magnetic poles but at higher temperatures the atoms are randomly oriented. The high energy state of randomness is one of symmetry. Below the Curie temperature the atoms choose an orientation and symmetry is broken.
Phase Transitions and Symmetry Breaking

High energy phase transitions:

**Electroweak symmetry breaking: \( t \approx 10^{-10} \text{s}, T \approx 10^{15} \text{K}, 100 \text{ GeV} \)**

Higher temperatures are above the threshold temperatures for the Z, W and Higgs particles; so these particles are part of the caldron of particles and photons of the Big Bang. The Z and W particles, the carriers of the weak force, are not given mass by interactions with the Higgs field so are “massless” like photons. The weak force is indistinguishable from the electromagnetic force; the two then referred to as the electroweak force.

At lower temperatures the symmetry between photons and Z, W particles is broken as the Z and W acquire mass from the Higgs field.

**GUT symmetry breaking: \( t \approx 10^{-39} \text{s}, T \approx 10^{29} \text{K}, 10^{16} \text{ GeV} \)**

Gluons are indistinguishable from photons and the strong force is merged. At this temperature, hypothetical X particles are abundant in the Big Bang caldron. Suppose X particles and their anti-particles decay at different rates so the number of (baryons – anti-baryons) is not conserved at zero. The consequence is baryogenesis (more baryons than anti-baryons).
Fermions: obey Pauli exclusion principle (two fermions cannot occupy the same quantum state). Spin $\frac{1}{2}$ integral. Protons and neutrons are examples of fermion composite particles (eg: proton made of 2 up and 1 down quarks and neutron made of 1 u and 2 d quarks).

Bosons: can occupy the same quantum state. Spin integral. Most bosons are composite (eg: mesons). Only elementary bosons are 4 gauge bosons ($\gamma$, g, Z, W$^{\pm}$) with spin 1 and the Higgs boson with spin 0.
### Particle Zoo

**Fermions**
- **Leptons** (spin = 1/2)
  - Neutrino
  - Electron
  - Muon
  - Tau

- **Quarks** (spin = 1/2)
  - Up
  - Down
  - Charm
  - Strange
  - Top
  - Bottom

**Mesons q̅q**
- There are about 140 types of mesons.

**The Family of Elementary Particles**
- Particles that obey the Pauli exclusion principle
  - **Fermions** (matter particles)
  - Leptons:
    - Electron
    - Muon
    - Tau
  - Quarks:
    - Up
    - Down
    - Charm
    - Strange
    - Top
    - Bottom

- **Mesons**
  - Pion
  - Kaon
  - Rho
  - B-zero
  - Eta-c

**Particles that do not obey the Pauli exclusion principle**
- **Bosons** (gauge particles: force carriers)
  - Photons
  - W^+ / W^-
  - Z^0
  - Graviton

**Hadrons**
- Particles composed of three quarks
  - Baryons:
    - Proton
    - Sigma (Σ^+, Σ^0, Σ^-)
    - Xi (Ξ^0, Ξ^-)
    - Omega
    - Lambda
  - Mesons:
    - K, K^0, K^+
    - Pion (π^+, π^0, π^-)
    - /psi
    - B (B^+, B^0, B^-)
    - D (D^+, D^0, D^-)

**Quarks interact with bosons to form hadrons**
Higgs Field and Particle

Higgs particle is the quantum of the Higgs field just as the photon is the quantum of the electromagnetic field. Particles that interact with the Higgs field cannot travel at the speed of light. The degree that they interact, and hence are slowed, defines their mass.

Protons and neutrons are examples of composite particles whose rest mass is only partially given by the Higgs interaction, but mostly from the kinetic energy of the quarks and energy of the gluon field binding the quarks.

Higgs particle now convincingly observed with Large Hadron Collider with mass 125 GeV
Dark Matter: 
Beyond the Standard Model

Most explanations for Dark Matter invoke particles that are not anticipated by the standard model. The generic candidate is a **WIMP** (Weakly Interacting Massive Particle), usually entertained as a stable particle with mass near 100 GeV (similar to Higgs and W,Z) and interacting via the weak force.

**Supersymmetry** is a theory that entertains that every particle in the standard model has a supersymmetric partner that is heavier and with opposite spin. Most of these particles (like most standard particles) have short lifetimes. The Dark Matter might be the lightest stable superpartner.

The **Neutralino** is favored. Spin ½ fermion partners of neutral gauge (Z, γ) and Higgs bosons.

Other supersymmetric candidates:
- chargino (charged fermion superpartners of charged gauge and Higgs bosons);
- gravitino (superpartner of graviton, potentially low mass and hence warm DM);
- sneutrinos (scalar partners of neutrinos, but probably too massive).
**Dark Matter: Other Ideas**

**Extra dimensions**: in string theory there are dimensions that are only manifested on subatomic scales. The Dark Matter could be the lightest Kaluza-Klein particle, a particle curled in the 4th dimension.

**Axions**: used to explain why the strong interaction displays CP symmetry; would explain why neutron doesn’t have a large electric dipole. Mass only ~1eV or less but created by a non-thermal process so slow moving, hence can cluster.

**Mirror Matter**: Ordinary matter in a mirror world that only communicates through gravity – 2 branes in higher dimensional space.

**WIMPzillas**: particles created by gravitational interactions at the end of inflation; mass scales $10^{13}$ GeV.

**Branons**: string theory fluctuations, both thermal and non-thermal.

**Q-balls**: non-topological solitons in supersymmetry; possible self-interactions.

**Sterile Neutrinos**: don’t interact electroweakly – mix with active neutrinos.

**Primordial Black Holes**: collapse during a phase transition; eg. Quark – Hadron transition at $T\sim 100\text{MeV}$, $M_{\text{horizon}} \sim 1$ solar mass.
String Theory
(speculative)

Particles considered to be strings instead of point-like.

Strings have high tension => vibrate near speed of light.
Mass, spin, charge and color depend on vibration pattern
Particles are differentiated by vibration patterns.
One pattern matches the graviton, unifying gravity with other forces.

String theory requires the existence of 6 extra dimensions which must be compactified to the Planck length.
The size and shape of extra dimensions determine the properties of particles and vacuum energy densities – the string theory landscape.

Quantum tunneling can occur between separate bubble states.
A negative energy bubble nucleating in our universe would cause it to collapse to a Big Crunch.