Ordinary Matter vs Dark Matter

- Matter occupies 26% and dark energy occupies 74% of the energy of the universe at present.
- What do we mean by "matter"?
  - Ordinary Matter: atoms (baryons)
    - Atoms exist mostly in the form of gas
  - Extra-ordinary Matter: Dark Matter
    - Dark matter exists in the form of freely-moving particles
- Observations of deuterium abundance in the cold gas clouds as well as anisotropy of the cosmic microwave background suggest that the atoms contribute only to 4% of the energy of the universe. Therefore, dark matter must contribute to 22% of the energy of the universe.

What Is Dark Matter?

- We do not know the precise nature of dark matter particles, but we do know some of their properties.
- Dark matter interacts with the ordinary matter only weakly and gravitationally.
  - Why? We must have detected dark matter particles already otherwise.
  - Dark matter does not emit light or absorb light, which means that dark matter does not interact via the electro-magnetic force.
  - Dark matter does not have any charges.
- Dark matter particles should move slowly, much more slowly than the speed of light.
  - Why? Galaxies would not be formed otherwise.
  - Dark matter particles that move slowly are called "cold" dark matter.
  - Neutrinos are "hot" dark matter, as they move at nearly the speed of light.

Dark Matter Candidates

- It is most likely that dark matter particles are something that we have not seen in the laboratory yet. What could they be?
- Particles of "supersymmetry"?
  - All the particles may be divided into two classes: **bosons** and **fermions**, depending on their spins.
    - Bosons have integer spins: photons, pions, gravitons, …
    - Fermions have half-integer spins: electrons, neutrinos, quarks, …
  - Theory of "Supersymmetry" requires that each fermion have the corresponding boson, and vice versa. For example, photon's fermionic superpartner is called *photino*, and electron's bosonic superpartner is called *selectron*.
  - One of the popular supersymmetric dark matter candidates is *gravitino*, a fermionic superpartner of graviton.
- But, these are still theoretical possibilities…

How Do We Detect Dark Matter?

- **Very exciting possibility**: direct detection of super-particles may actually be possible in 2007-
  - LHC (Large Hadron Collider) @ CERN (Geneva)
  - Collide two proton beams to create lots of particles: LHC will reach the energy that is equivalent of 7×10^{16} K!!
  - Physicists are expecting to detect supersymmetric particles in LHC, finding evidence for Supersymmetry.
- What if they found nothing?
  - They would need to build a yet larger accelerator…

What Is Dark Energy?

- The present universe is accelerating, which implies that we have a positive cosmological constant in the universe. But, what is cosmological constant anyway?
  – Could it be something else? **Dark Energy.**
- We know very little about dark energy.
  – We may have two dark energy components.
    - Early dark energy which caused inflation in the very early universe.
    - Late dark energy which is causing the universe to accelerate now.
  – Dark energy influences visible or dark matter via gravity only.
  – Dark energy is very smooth: it cannot cluster.
  – Dark energy has a large, **negative** pressure.

Dark Energy Candidates

- Energy of vacuum (energy of empty space)
- Quintessense
- Modification to Einstein's General Theory of Gravity
- None of the above

How Do We Detect Dark Energy?

- There are no "particles" of dark energy
  – So, there is no way to detect dark energy directly.
- To constrain the nature of dark energy, one has to determine how exactly the expansion of the universe is accelerating. Therefore, the cosmological observations are the only methods that we can use to constrain dark energy properties.
  – Brightness-redshift relation (luminosity distance)
  – Size-redshift relation (angular diameter distance)
- The key parameter is *w*. (*w*=pressure/density)
  – Density of dark energy evolves as $1/R^{3(1+w)}$
  – w=-1: density does not change → cosmological constant
  – The current observational data: $w<-0.8$
- Determination of *w* is ***the*** most important subject in modern cosmology now.