Chapter 16
Dark Matter, Dark Energy, & the Fate of the Universe
Some say the world will end in fire,
Some say in ice.
From what I’ve tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

-- Robert Frost
Unseen ("Dark") Influences in the Cosmos

**Dark Matter**
- An undetected form of mass that emits little or no light but whose existence we infer from its gravitational influence.
- Evidence for its existence dates from the 1930s and is very solid.

**Dark Energy**
- An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate.
- Evidence for its existence was found only ~8 years ago, and it is much less well-understood.

*Although these have similar sounding names, they refer to two very different things, which have been identified by very different means.*
Contents of Universe (by Mass)

• **“Normal” Matter:** ~ 4.4%
  - Normal matter inside stars: ~ 0.6%
  - Normal matter outside stars: ~ 3.8%

• **Dark Matter:** ~ 25%
  - We have some good candidates for this.

• **Dark Energy** ~ 71%
  - This is a big mystery.
Observational Evidence for Dark Matter

• Any non-luminous component of the Universe can only be detected indirectly, by its gravitational influence on the luminous (light-emitting) components.

• Many lines of evidence
  – Orbits of stars in galaxies.
  – Motions of galaxies in galaxy clusters.
  – Hot gas in galaxy clusters.
  – Gravitational lensing.
Measuring masses using gravity

• We can measure an object’s mass from the orbital period & avg distance of bodies in orbit around it.
  – Ex: Find mass of Jupiter based on its moons’ orbits.

• This comes from Newton’s form of Kepler’s Third Law, which can be rewritten as:

\[ M_{\text{enc}} = \frac{v \times r^2}{G} \]

  \( v = \text{orbital velocity} \)
  \( r = \text{average orbital separation} \)
  \( M_{\text{enc}} = \text{mass enclosed by orbit} \)
  \( G = \text{gravitational constant} \)

• So by measuring the orbital velocity & separation, we can determine the total mass enclosed by the orbit.
How do we measure the mass of the Galaxy?

- Measuring the Sun’s orbital motion (radius and velocity) gives us the mass inside Sun’s orbit: \(~1.0 \times 10^{11} M_{\text{sun}}\).
- Note that we cannot measure the mass outside of the Sun’s orbit in this fashion.
Measuring masses of spiral galaxies

- Use the 21-cm emission line of hydrogen gas clouds to trace orbital motions. *(Can also use stellar motions, but gas clouds are found to larger distances.)*

- Measure the galaxy’s rotation curve to determine the total mass as a function of separation from the center.
Rotation curve = a plot of velocity versus orbital radius.

Ex: Merry go-round. Who has the largest orbital velocity?

A, B, or C?
Rotation curve of merry-go-round rises with radius.
Rotation curve = a plot of velocity versus orbital radius.

Solar system’s rotation curve declines because the Sun has almost all the mass.
Rotation curves measure the mass distribution

**Solar System**

Rotation curve declines with distance because the Sun has nearly all the mass.

**Milky Way**

Rotation curve stays flat with distance, meaning the mass is more spread out.
Rotation curves measure the mass distribution

The stars in the Milky Way go out to ~50,000 light-yrs.

If the stars represented all the mass in the galaxy, then the rotation curve would decline at large separations. But it doesn’t!

Most of the Milky Way’s mass seems to be dark matter!!

*Rotation curve stays flat with distance, meaning the mass is more spread out.*
The true mass distribution of galaxies

The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.

The total mass in dark matter is about 10x more than in stars!!
Spiral galaxies all tend to have flat rotation curves indicating large amounts of dark matter.
We can measure the velocities of galaxies in a cluster from their Doppler shifts.

The mass we find from galaxy motions in a cluster is about 50 times larger than the mass in stars!

98% of the mass is not visible in this image!
Clusters contain large amounts of very hot Xray emitting gas.

**Temperature of this hot gas** measures the cluster’s mass, b/c gas has to be held in the cluster by gravity.

- 85% dark matter
- 13% hot gas
- 2% stars
Measuring mass in galaxy clusters: Method 3

Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster’s mass.
A gravitational lens distorts our view of things behind it.
Gravitational lenses (and dark matter) are ubiquitous
All three methods of measuring cluster mass indicate similar amounts of dark matter.

So what is this stuff?
**Does dark matter really exist?**

1. Dark matter really exists, and we are observing the effects of its gravitational attraction.

   **OR**

2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter.

   *Because gravity is so well tested, most astronomers prefer option #1.*
What is dark matter?

**MACHOS** or **WIMPS**

**M**assive **C**ompact **H**alo **O**bjects

Dead or failed stars in the halos of galaxies (brown dwarfs, white dwarfs, small black holes)

**W**eakly **I**nteracting **M**assive **P**article **S**

Mysterious neutrino-like particles.
MACHOs occasionally make other stars appear brighter through gravitational lensing. 

... but not enough lensing events to explain dark matter.
What might dark matter be made of?

1. Ordinary Dark Matter (MACHOs)
   Massive Compact Halo Objects:
   dead or failed stars in halos of galaxies

2. Extraordinary Dark Matter (WIMPs)
   Weakly Interacting Massive Particles:
   mysterious neutrino-like particles

This is our best bet for the nature of dark matter.
Why worry about dark matter?
(there’s none in the Solar System, it’s all on large scales)

Because the fate of the Universe depends on it!
Recap: Evidence for dark matter

- Orbital motion of stars in galaxies (e.g. rotation curves of spiral galaxies)

- Multiple signs in galaxy clusters
  - Galaxy motions
  - Hot intracluster gas
  - Gravitational lensing
Recap: The Nature of Dark Matter

• We infer that dark matter exists from its gravitational influence.

• Some of dark matter could be ordinary matter (MACHOS), but there does not appear to be enough to explain it all.

• Most dark matter is probably extraordinary matter consisting of undiscovered particles (WIMPs).
Why worry about dark matter? (there's none in the Solar System, it's all on large scales) Because the fate of the Universe depends on it!
Is the universe expanding fast enough to escape its own gravitational pull? (Does it have enough kinetic energy?)

Critical density of material needed is 10^{-29} \text{ g/cm}^3 (about a few H atoms in your closet). Visible matter is only \sim 0.5\% of this.
Fate of universe depends on amount of dark matter.
Fate of universe depends on amount of dark matter

- Lots of dark matter
- Not enough dark matter

Fate of universe depends on amount of dark matter
Fate of universe depends on amount of dark matter.

- Lots of dark matter: recollapsing universe
- Critical density of matter: critical universe
- Not enough dark matter: coasting universe

Diagram shows the future, present, and past of the universe with different densities of dark matter leading to different outcomes.
Amount of dark matter is ~25% of the critical density, suggesting fate is eternal expansion.

Fate of universe depends on amount of dark matter.
In fact, recent observations suggest that the expansion of the universe is speeding up! Accelerating universe!!

Dark Energy ??
Brightness of distant white-dwarf supernovae tell us how much universe has expanded since they exploded.

The data show that the rate of expansion is increasing - the Universe is accelerating!!

Measuring the expansion of the Universe over its history
Accelerating universe is best fit to supernova data
Estimated age of the Universe depends on the assumed amount of dark matter and dark energy.
We know almost nothing about 96% of the Universe!!!