Components of the Milky Way

Examples of Rotation Curves
Expected Versus Observed Rotation Curves for Our Galaxy

![Graph showing rotation speed versus distance from the Galactic center.](image)

21 cm Radiation as Tracer of Gas Clouds

The proton and electron in a hydrogen atom both have spin. They can be pointing in the same direction or in opposite directions. Spin in the same direction causes the electron to occupy a slightly higher energy state than spin in opposite directions.

About once every 10 million years, the electron will flip its spin and emit a radio photon at wavelength 21 cm.
The Correct Way to Think about Our Galaxy

Possible Dark-Matter Candidates

**Baryonic Dark Matter Candidates**
- neutron stars
- black holes
- black dwarf stars
- brown dwarf stars
- planets
- rocks

**Non-Baryonic Dark Matter Candidates**
- massive neutrino
- Weakly Interacting Massive Particles (WIMPS)
- cosmic strings
- modified gravity
Evidence Against Red Dwarfs as the Dark Matter

Gravitational Microlensing
Microlensing Targets

Large Magellanic Cloud  Small Magellanic Cloud

Microlensing Light Curves

Event 1

Days from 2 Jan 1992

HJD ~ 2450000
Microlensing Light Curves

Microlensing by a Binary System
Neutrinos as Nonbaryonic Dark Matter

About 100 neutrinos per cubic cm, throughout space.

Mass is about 0.05 eV = 1/10,000,000 mass of electron, although some uncertainty.

Neutrinos in the Universe have nearly as much mass as all of the stars!

Other Types of Nonbaryonic Dark Matter

XENON Dark Matter Detector
Large Hadron Collider at CERN

The LHC will search for supersymmetric and other new subatomic particles.

Dark Matter in M31 – Flat Rotation Curve
Dark Matter in Other Spiral Galaxies – Flat Rotation Curves

![Graph showing flat rotation curves for NGC 3198](image)

**Figure 26-25** The Rotation Curves of Four Spiral Galaxies. This graph shows the orbital speed of material in the disks of four spiral galaxies. Many galaxies have flat rotation curves, indicating the presence of extended halos of dark matter. (Adapted from V. Rubin and K. Ford)

Dark Matter in Elliptical Galaxies – Evidence from X-ray Gas

![Images of NGC 4697 optical and Chandra](image)
Dark Matter in Clusters of Galaxies

Fritz Zwicky

The Coma Cluster

Galaxy Motions in a Cluster of Galaxies

(a) Binary galaxy

(b) Galaxy cluster

The Coma Cluster
X-ray Evidence for Dark Matter in Clusters of Galaxies

Need enough gravity to keep the X-ray gas from “boiling off” into intergalactic space.

Gravitational Lensing Evidence for Dark Matter in Clusters of Galaxies

FIGURE 21.3B: A cluster’s powerful gravity bends light paths from background galaxies to Earth. If light can arrive from several different directions, we see multiple images of the same galaxy.
Gravitational Lensing in Abell 2218

Gravitational Lensing in 0024+1654
The Acceleration of the Universe

High-redshift supernovae are systematically fainter than expected based on extrapolation of low-redshift sources. Must be further away than expected. So need an effect to overcome the tendency of gravity to slow down the expansion.

Dark Energy in the Universe

Cosmic acceleration suggests presence of “dark energy” that drives space apart. This “dark energy” dominates the mass-energy density of the Universe! Supporting evidence comes from studies of the cosmic microwave background, clusters of galaxies, and large-scale structure.

What is this “dark energy”? Why is there the observed amount, not much more or much less?
Schematic of Cosmic History

The Future of the Universe

We cannot predict the fate of the Universe until we understand dark energy.