Virgo cluster: nearest big galaxy cluster
The Hydra cluster

http://apod.nasa.gov/apod/ap120512.html
a galaxy is stripped of its gas as it orbits around its cluster
blue is X-ray emitting hot gas
Abell 2744: huge galaxy cluster, filled with X-ray emitting gas

The Hubble Deep Field (multi-week exposure: 1000s of galaxies)

http://apod.nasa.gov/apod/ap121014.html
We can use a version of Kepler’s third law \((M = rv^2/G)\) to weigh these galaxy clusters; and when we do we find that there’s a lot more mass there than what we’d assume from just the galaxies and the X-ray emitting gas.

We term this unseen additional mass, that has gravity but doesn’t emit or absorb light, *Dark Matter*.
Orbital speed as a function of distance from the Sun

$v$ goes like the square root of $r$
Andromeda

galactic center

location of Sun
Milky Way’s “rotation curve” : rotation speed vs. distance from the center
Andromeda has a flat rotation curve and dark matter, too

courtesy: Vera Rubin
\( M = \frac{rv^2}{G} \) implies for a constant \( v \) that \( M \), the mass enclosed, increases linearly with radius. There is a lot of mass near the edges of spiral galaxies than we’d expect just from the modest amount of starlight we see.

Dark Matter exists inside spiral galaxies, too, and it’s distributed much more evenly than the stars.
Cepheid variable in Andromeda

http://apod.nasa.gov/apod/ap110701.html
Cepheid Variable in M100
HST-WFPC2

dim    brighter     brightest
Period-luminosity relationship for Cepheid variables

Henrietta Leavitt (1920s-30s)

http://apod.nasa.gov/apod/ap000903.html

**Figure 20.12** Cepheid period-luminosity relation. The data show that all Cepheids of a particular period have very nearly the same luminosity. By measuring a Cepheid's period, we can therefore determine its luminosity and hence its distance. (Cepheids actually come in two types with two different period-luminosity relations. The relation here is for Cepheids with heavy-element content similar to that of our Sun, or Type I Cepheids.)
“White Dwarf Supernovae” are the most luminous standard candles.
The **Distance Ladder** - overlap of techniques is key

![Distance Ladder Diagram](image)

**Figure 20.16** Interactive Figure. Measurement of cosmic distances relies on a chain of interlocking techniques. The chain begins with radar ranging to determine distances within our solar system and proceeds through parallax and standard candle techniques. The use of these techniques allows us to calibrate Hubble's law, which we can then use to estimate distances to galaxies across the observable universe.
2df galaxy survey: each dot is a galaxy, we are at the center
Measuring the redshift of a galaxy (think back to the lab)

A particular galaxy originally emits this spectrum of light.

but the spectrum we observe from it is shifted by 5% to longer wavelengths, indicating that the galaxy is moving away from us at 5% of the speed of light.

**Figure 20.19** Redshifted galaxy spectrum.
Hubble’s original (1929) velocity-distance relationship
Hubble constant *determinations* over time
the expansion of the universe is like a uniform stretching

as space expands, the distances between things increases...including the wavelength of light
The Universe is 13.6 billion years old, and it appears that it will expand forever.

**Figure 20.21** White dwarf supernovae can be used as standard candles to establish Hubble’s law out to very large distances. The points on this figure show the apparent distances of white dwarf supernovae and the recession velocities of the galaxies in which they exploded. The fact that these points all fall close to a straight line demonstrates that these supernovae are good standard candles.