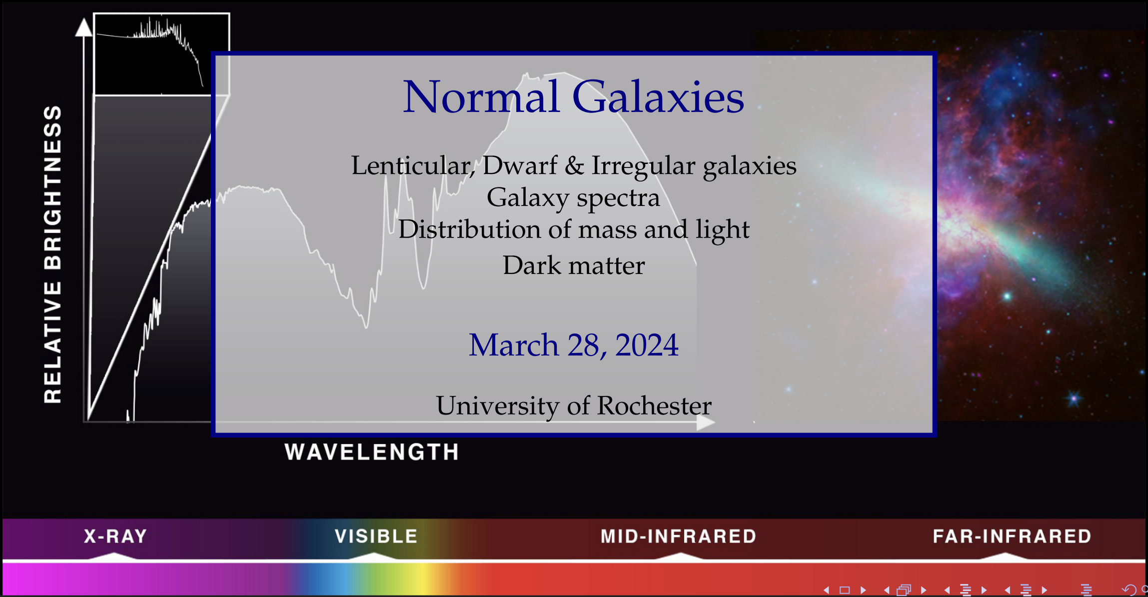


Normal Galaxies

Lenticular, Dwarf & Irregular galaxies
Galaxy spectra
Distribution of mass and light
Dark matter

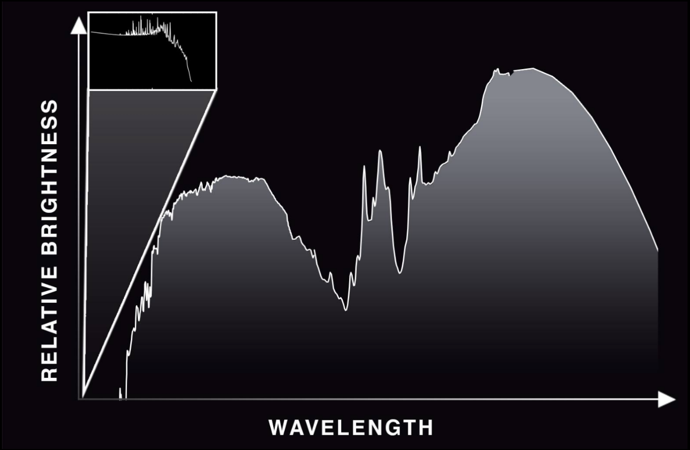
March 28, 2024

University of Rochester

Normal Galaxies

- Lenticular galaxies
- Irregular & dwarf galaxies
- Characteristics of galaxy spectra
- Distribution of mass and light in normal galaxies
- Dark matter in spiral galaxies

Reading: Kutner Ch. 17.3–17.4, Ryden Sec. 20.2

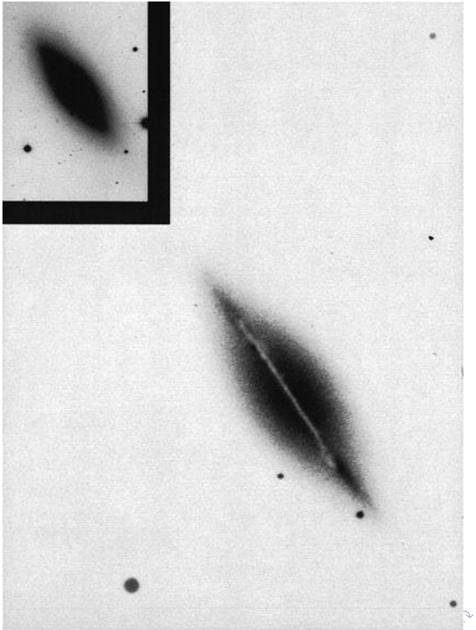


Spectral energy distribution (SED) of the starburst galaxy M82 (Viewspace.org).

Lenticular galaxies

Lenticular galaxies are Hubble types S0 or SB0.

- Like ellipticals, they have very little interstellar matter and very little star formation.
- Like spirals, they have disks in which rotation dominates the stellar velocity distribution.
- The central bulges tend to dominate the mass in lenticulars; no spiral structure is observed in the disks.
- Lenticulars are components of **polar ring galaxies**, an important class of “interacted” galaxies. More on that later.
- They got their name from their lens-like shape in photographs, as for NGC 5866 at right (Sandage & Bedke 1994).



NGC 5866, a S0 galaxy

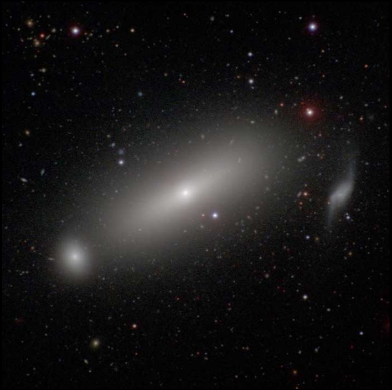
S0 galaxies tend not to look so obviously lens-like when observed with CCD cameras and presented with a non-photographic stretch.

The dust disk may in fact have some spiral structure. It is not easy to tell because of our edge-on view of the galaxy.

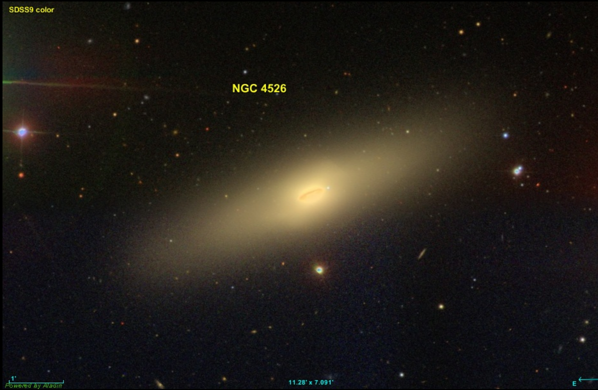
Image: HST image of NGC 5866, NASA/ESA.

The differences between E7 and S0

E7 (NGC 1332): smooth variation in brightness in all directions from the center. Round nucleus. Nothing disk-like at all.

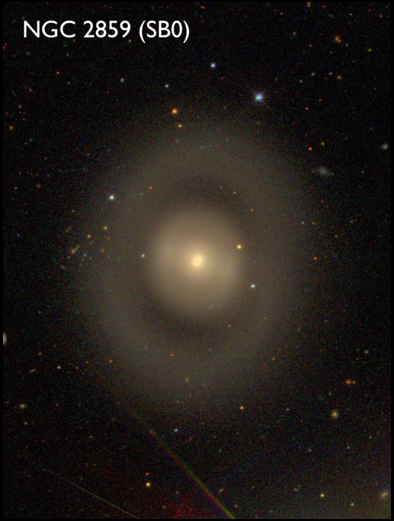


S0 (NGC 4526): definite bulge and extended disk; brighter disk 1 kpc diameter in nucleus. Both disks inclined at $i = 76^\circ$.



Lenticular galaxies viewed nearly face-on

Left: HST/WFC3 image (NASA/STScI). Right: *gri* image by D. Hogg and M. Blanton (SDSS).



Irregular galaxies

Usually set between the tines of the fork are the irregular galaxies, types Irr I and Irr II.

- These galaxies are supposed to be amorphous. They have a wide range of masses and luminosities, though they are small compared to typical spirals.
- They tend to be rich in ISM and have respectable star formation rates, though most have very small abundances of heavy elements.
- **Irr I**: hints of regular structure, e.g., the “bar” in the Large Magellanic Cloud.
- **Irr II**: no regular structure at all. However, note that the archetype Irr II, M82, looks amorphous just because of extinction. Underneath, it is a spiral galaxy!

Example of an Irr I

The Large Magellanic Cloud (LMC) is an Irr I.

The LMC is located 50 kpc from Earth and is easily visible to the naked eye from the Southern Hemisphere.

Photograph by Wei-Hao Wang, NRAO.

Archetype of Irr II

M82 (NGC 3034), the "Cigar" Galaxy, is the archetype Irr II.

Its rotation curve reveals that M82 is a nearly edge-on spiral with heavy foreground extinction.

BVI-Hα image from NASA, ESA, and the Hubble Heritage Team.

Dwarf galaxies

Due to technical limitations at the time, the Hubble sequence is only comprised of (and therefore only applies to) luminous galaxies with high surface brightness. This excludes dwarf galaxies, the most numerous galaxy type that exists.

Dwarf galaxies have low surface brightness and low luminosity. They also come in various shapes:

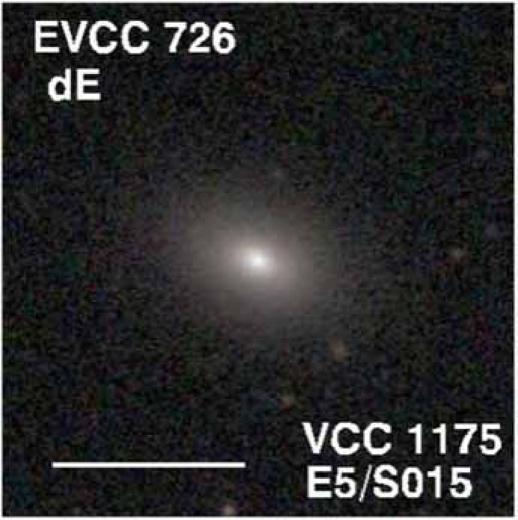
dE	Dwarf ellipticals ($L < 10^9 L_\odot$) are elliptical in shape and contain little gas or dust
dSph	Dwarf spheroidals ($L < 3 \times 10^7 L_\odot$) are extremely faint dwarf ellipticals with small ellipticity
dIrr	Dwarf irregulars have major ISM & star formation

There are very few dwarf spiral galaxies; the spiral structure is an apparent attribute of massive, luminous galaxies.

Example dE galaxy

Commonly found in galaxy clusters, dEs are thought to be primordial objects. Larger galaxies are believed to have formed as a result of the merging of many smaller dEs over time.

A dE member of the Virgo Cluster (The Extended Virgo Cluster Catalog, Kim et al. 2014)



Example dSph galaxy

Dwarf spheroidals are named after the constellation in which they are found. Because they are so faint, most that have been identified are satellites of the Milky Way. There are currently $\sim$25 dSph that have been identified.

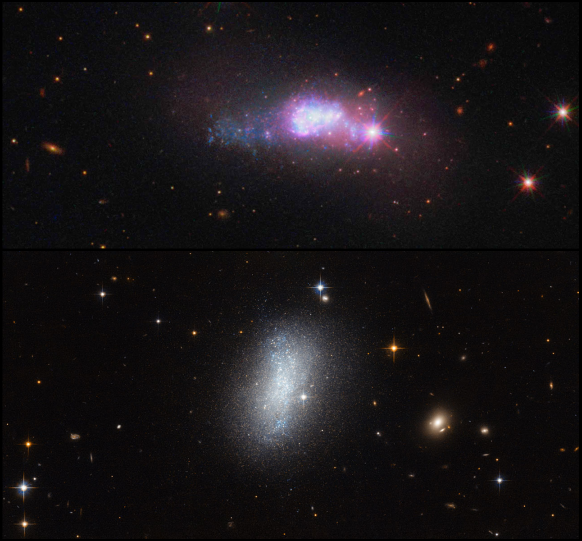
dSph are distinguished from globular clusters by the presence of a **dark matter halo**.

The Fornax dwarf galaxy, a dSph of the Milky Way (ESO/Digitized Sky Survey 2)

Example dIrr galaxy

About 90% of the dwarf galaxy population are characterized as dIrrs.

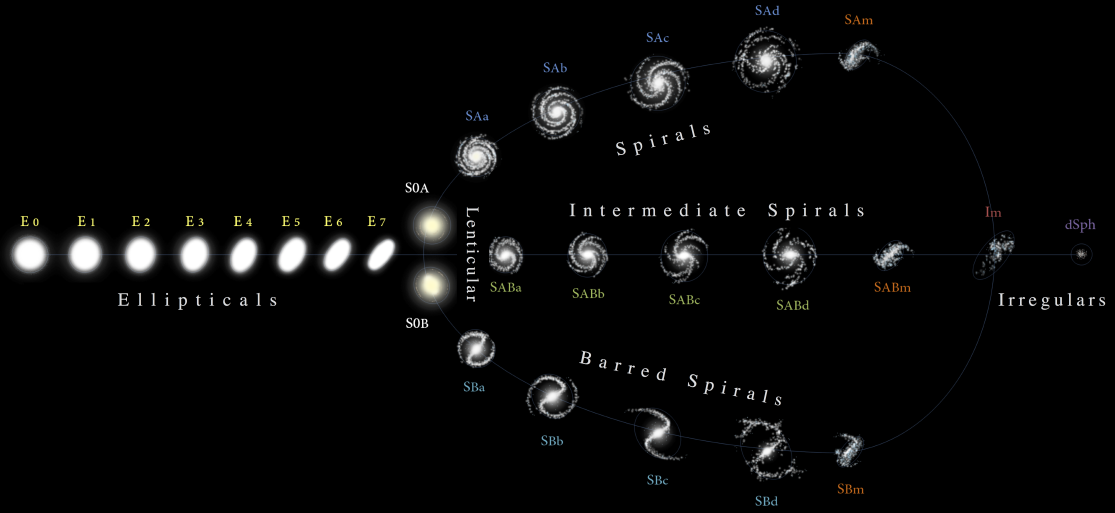
Similar to the dEs, dIrrs are also thought to be the predecessors of the more massive galaxies we see today. These objects typically have a significant amount of gas and a low metallicity, indicating that they are relatively young in their evolution.



Top: blue compact dIrr galaxy (ESA/Hubble & NASA)
Bottom: dIrr galaxy in the Local Group (ESA/Hubble & NASA)

Hubble – de Vaucouleurs sequence

Modified version of the original Hubble sequence commonly used today



Galaxy spectra: What else can a galaxy's light tell us?

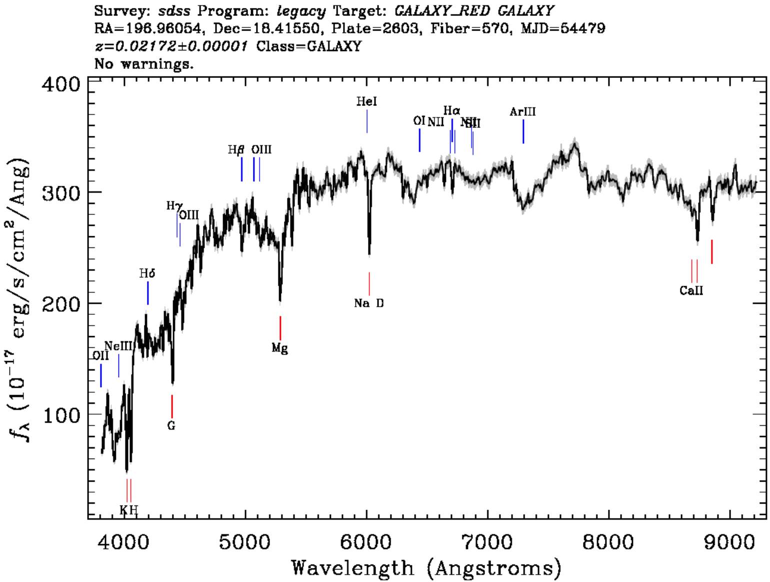
Most of a galaxy's visible light comes from one of two sources:

Stars which have absorption spectra

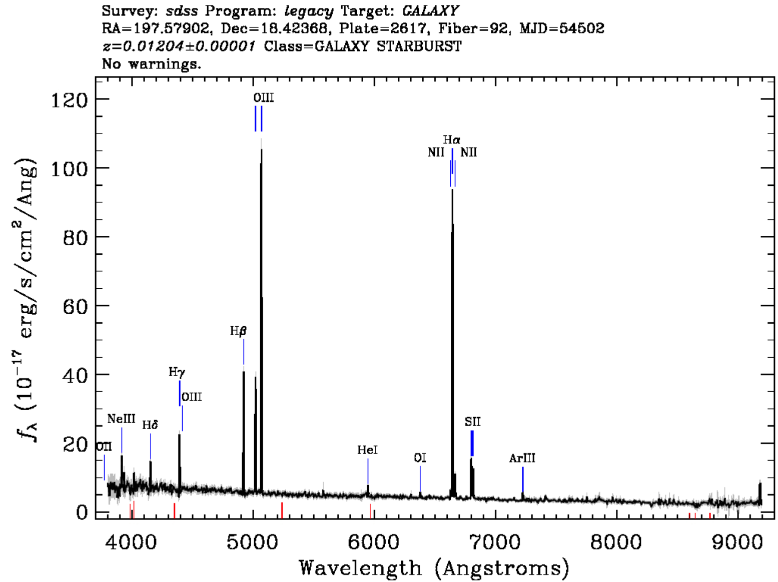
- Most of this light comes from the few very luminous stars, **not** from the huge number of dim M dwarfs.
- In galaxies with active star formation (spirals and irregulars), this light is dominated by the young, hot main sequence O and B stars. In quiescent galaxies (ellipticals and lenticulars), red giants dominate the light.
- The stellar light is the source of a galaxy's color.

Hot gas which produces an emission spectrum

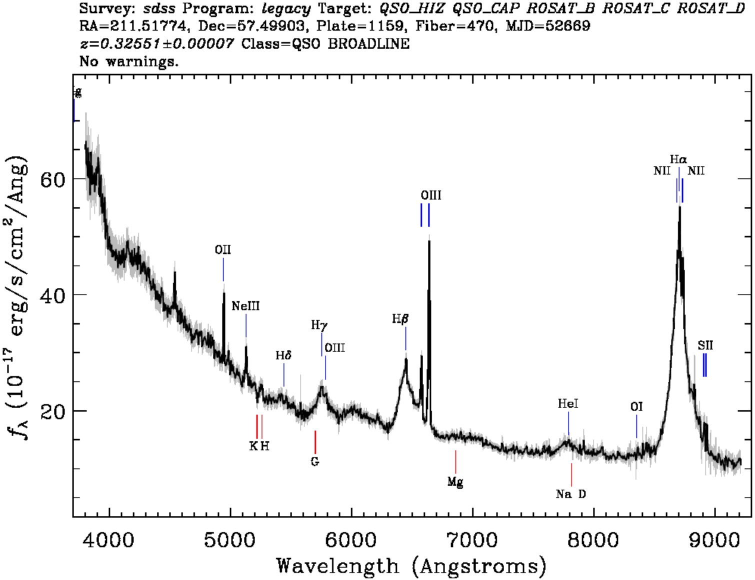
Spectrum of an elliptical galaxy



Spectrum of a spiral galaxy



Spectrum of an active galaxy



Survey: *sdss* Program: *legacy* Target: *QSO_HIZ QSO_CAP ROSAT_B ROSAT_C ROSAT_D*
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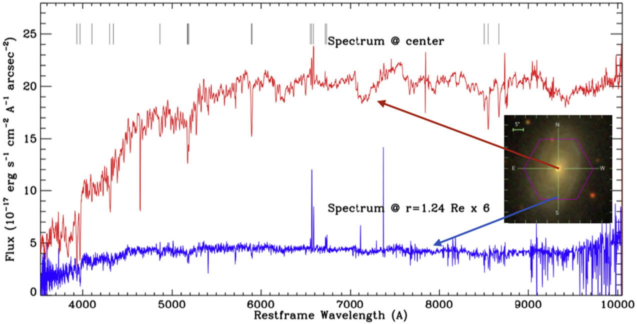
z=0.32551±0.00007 Class=QSO BROADLINE
No warnings.

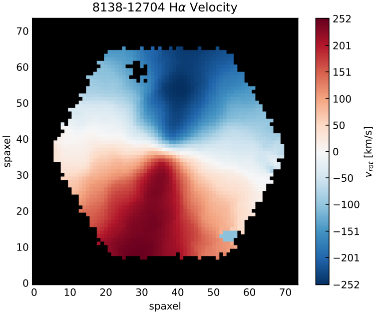
Gas kinematics from a spectrum

Using the observed wavelength of an emission line, we can measure the speed of a galaxy relative to ourselves.

- With only one spectrum of the galaxy, this gives us the galaxy's overall speed with respect to us: how fast it is moving with respect to us.

Because galaxies are typically extended, resolved objects, we can observe spectra across the surface of the galaxy. This allows us to measure the radial velocity as a function of position on the galaxy's surface.

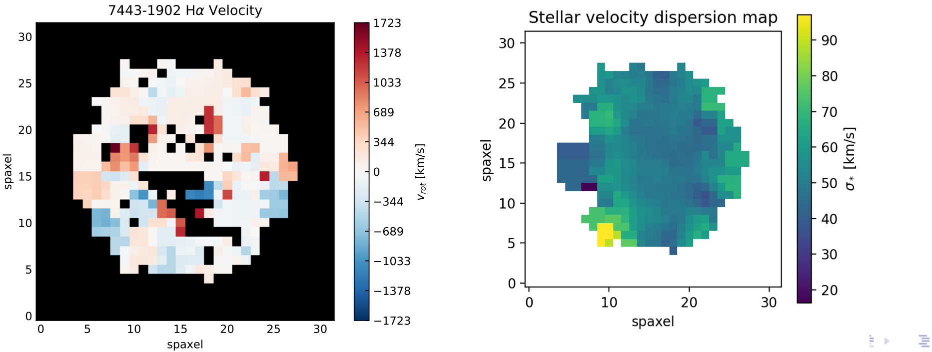




Stellar kinematics from a spectrum

Unlike spiral galaxies, elliptical galaxies do not show any significant organized rotational motion. However, the width of the absorption lines is much greater than what would be expected from the stellar temperatures.

Stars in an elliptical galaxy move in random orbits, causing a significant spread in the Doppler velocity. These galaxies are pressure supported.



Mass and light distribution in elliptical galaxies

Most **elliptical galaxies** are fit very well by this distribution of surface brightness (de Vaucouleurs 1948):

$$\mathcal{L}(r) = \mathcal{L}(0) \exp\left[-\left(\frac{r}{r_0}\right)^{1/4}\right]$$

where $\mathcal{L}$, the surface brightness, is the luminosity per unit area projected onto the plane of the sky, and r_0 is the core radius.

- This is an empirical relationship. Stellar-dynamical calculations often yield power-law expressions for $\mathcal{L}$ which resemble the de Vaucouleurs "law," but none give this exact result.
- Calculations are very sensitive to details of the stellar population, system age, and many other parameters.

Mass and light distribution in elliptical galaxies

- Mass, and the mass $M(r)$ contained within radius r, can be deduced from random motions and the virial theorem:

  $$M(r) = \frac{2r\overline{v^2}}{G} = \frac{6r\overline{v_r^2}}{G}$$

  where $\overline{v_r^2}$ is the mean square random component of radial velocity.
- From this we can determine the surface density $\mu(r)$. For example, if the galaxy is circularly symmetric in projection — i.e., it is an E0 galaxy — the surface density in an annulus of radius r is

  $$\mu(r) = \frac{m_{\text{ann}}}{A_{\text{ann}}} = \frac{1}{2\pi r\Delta r}\frac{d}{dr}M(r)\Delta r = \frac{1}{2\pi r}\frac{d}{dr}M(r)$$

Mass and light distribution in spiral galaxies

- The **bulges** of (unbarred) spiral galaxies usually fit the de Vaucouleurs law.
- **Disks** of spiral galaxies fit a simpler exponential:

$$\mathcal{L}(r) = \mathcal{L}(0)\exp\left(-\frac{r}{r_0}\right)$$

- The distribution of mass and surface density is easy to measure, as the motions in disks are dominated by rotation (whether of stars or of interstellar gas):

$$M(r) = \frac{v^2 r}{G} \qquad v \text{ is orbital speed at radius } r$$

$$\mu(r) = \frac{1}{2\pi r \Delta r}\frac{d}{dr}M(r)\Delta r = \frac{v^2}{2\pi G r} + \frac{v}{\pi G}\frac{dv}{dr}$$

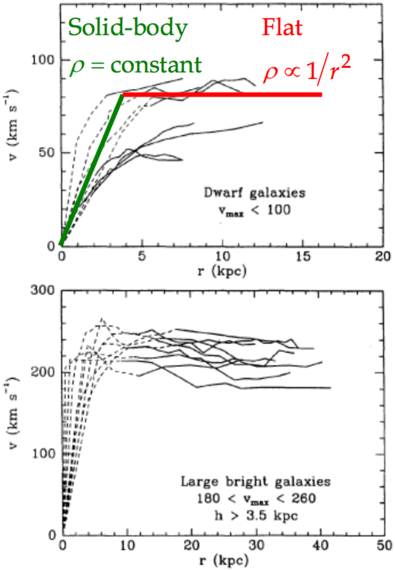
Spiral galaxies have flat rotation curves

It turns out that **all** spiral galaxies are like the Milky Way; $v(r)$ never becomes Keplerian at large distances from the center but stays flat as far as stars and gas can be detected (Rubin et al. 1980).

Thus, once outside the bulge,

$$\mu(r) = \frac{v^2}{2\pi G r} + \frac{v}{\pi G}\frac{dv}{dr} = \frac{v^2}{2\pi G r}$$

$$\frac{\mu}{\mathcal{L}} = \frac{v^2}{2\pi G \mathcal{L}(0)} \frac{e^{r/r_0}}{r}$$



$v(r)$ from a selection of dwarf galaxies and large bright galaxies (Casertano & van Gorkom 1991).

The galaxy rotation problem

Persuasive evidence for the galaxy rotation problem came from Vera Rubin and Kent Ford at Georgetown during the 1970s.

Possible solutions to the galaxy rotation problem:

1. Galaxies have dark matter halos.
2. Newtonian gravity is not correct on large scales (deviations from $1/r^2$).
3. Gravity is not the only force holding galaxies together.

Hypotheses 2 and 3 were taken seriously through the early 2000s, but we now favor the dark matter hypothesis.

Spiral galaxies have flat rotation curves

- Since e^{r/r_0} increases faster than r as a function of r, the mass-to-light ratio is very large in the outer parts of spiral galaxies.
- This $\mu/\mathcal{L}$ is much too large to explain with overabundant low-mass stars.
- Discounting the possibility that something is wrong with Newtonian gravity, this demands the presence of **dark matter**.
- A spherical halo of dark matter with $\rho \propto r^{-2}$ in each galaxy would correct the discrepancy.