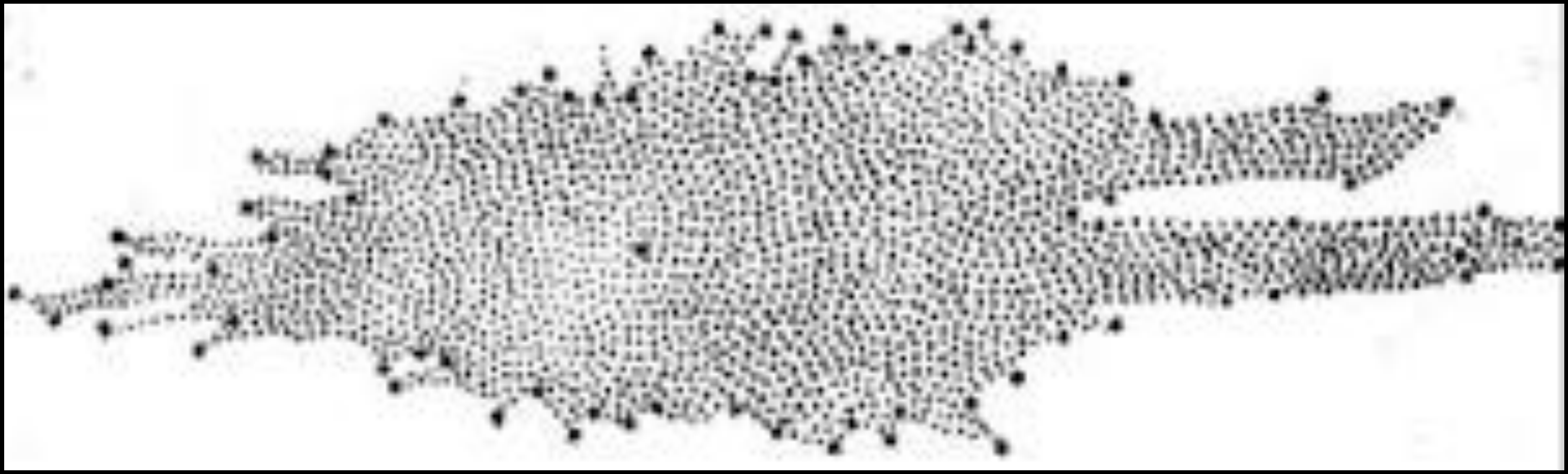
Milky Way (Galaxy)

Lecture 17-18, ASTB23

- History of Galaxy research
- Milky Way
- Classification of galaxies, Hubble sequence

GALAXIES

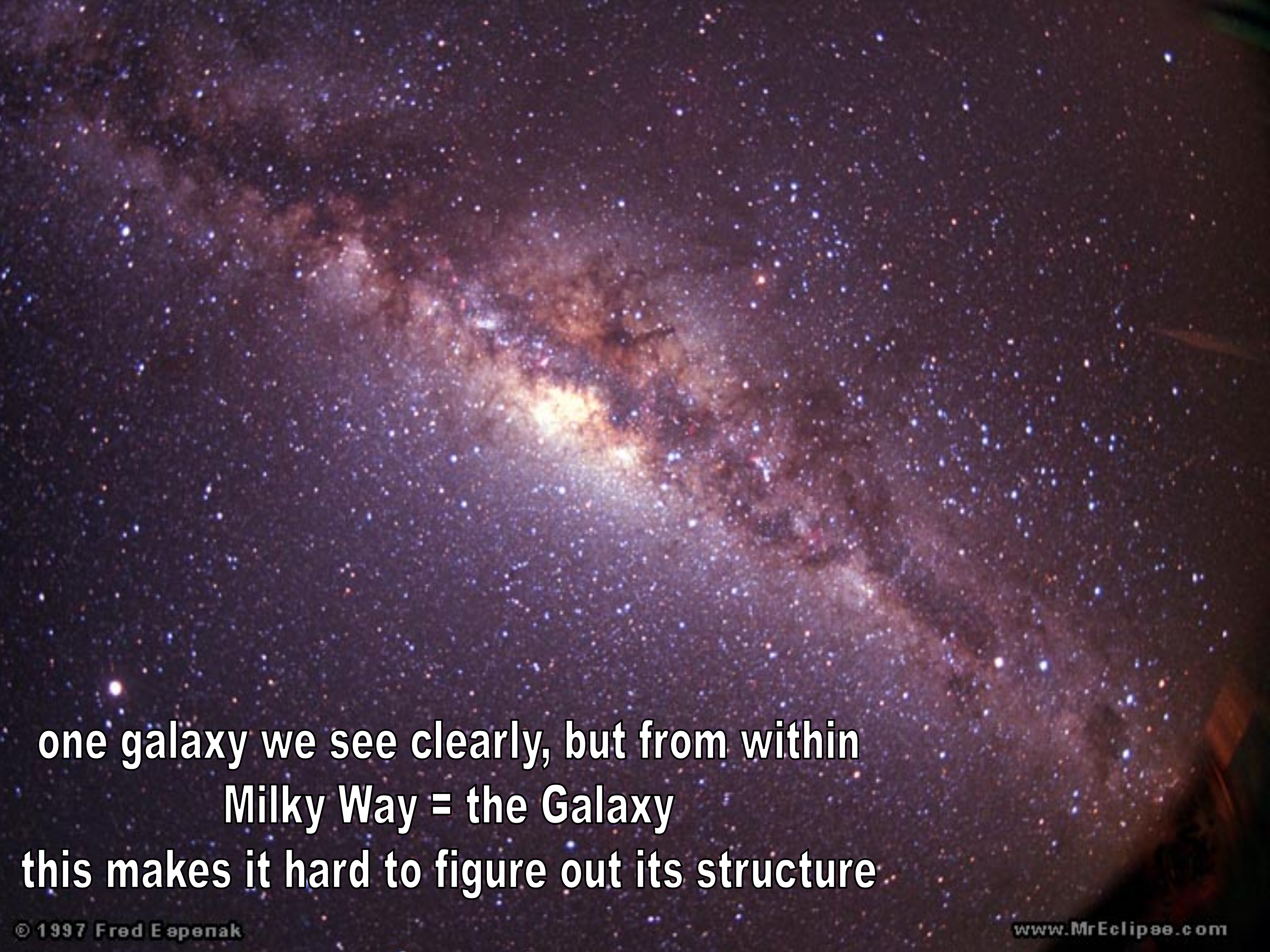


- History of the Milky Way: Galileo, Hershel, Kapteyn et al.
- The idea of spiral nebulae as island universes (Kant)
- The Great Debate of 1920: Curtis vs. Shapley

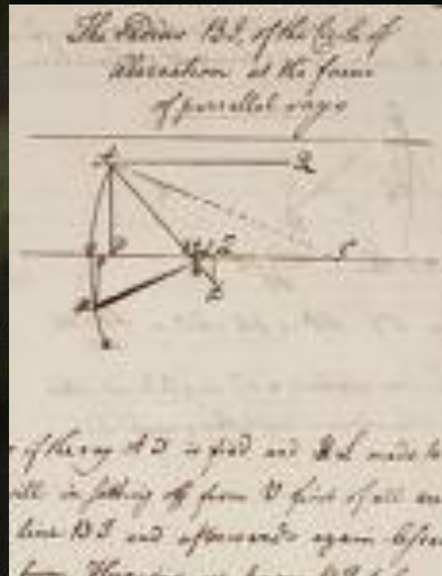
Charles Messier (1730-1817) was a comet hunter.

His 1771 catalogue listing fuzzy nebular objects which are NOT comets later proved a treasure trove of interesting nebulae and galaxies

(most M objects from M1 to M103 are in the northern sky, because Messier observed from France).


one galaxy we see clearly, but from within
Milky Way = the Galaxy
this makes it hard to figure out its structure
© 1997 Fred Espenak
www.MrEclipse.com

this is a spiral galaxy other than our own: M81
(an early telescopic observation on the left,
a modern mosaic of multiple bandpasses – different filters,
different wavelengths)



20ft focal length reflector, magnif. x157

[Frederik] William Herschel (1738-1822)

1773 - aged 35, reads a book on astronomy

1774 - starts making mirrors, telescopes & observe

1781 - discovers a “comet” (in fact, Uranus)

1782 - appointed as Court Astronomer, drops music as a profession

1783 - finds his first galaxy

1785 - finds his 1000th new object

1802 - a total of 2500 nebulae & clusters discovered

Discovery of the Milky Way

Historical Models of the Milky Way Galaxy

As can be seen by even a casual observation of the dark night sky, an almost continuous band of light appears to circle Earth, inclined about 60° with respect to the celestial equator (see Fig. 24.1). It was Galileo who first realized that this Milky Way is a vast collection of individual stars. In the mid-1700s, in order to explain its circular distribution across the heavens, Immanuel Kant (1724–1804) and Thomas Wright (1711–1786) proposed that the Galaxy must be a stellar disk and that our Solar System is merely one component within that disk. Then, in the 1780s, William Herschel (1738–1822) produced a map of the Milky Way based crudely on counting the numbers of stars that he could observe in 683 regions of the sky (see Fig. 24.2). In his analysis of the data, Herschel assumed that (a) all stars

FIGURE 24.1 A mosaic of the Milky Way showing the presence of dust lanes. (Courtesy of The Observatories of the Carnegie Institution of Washington.)

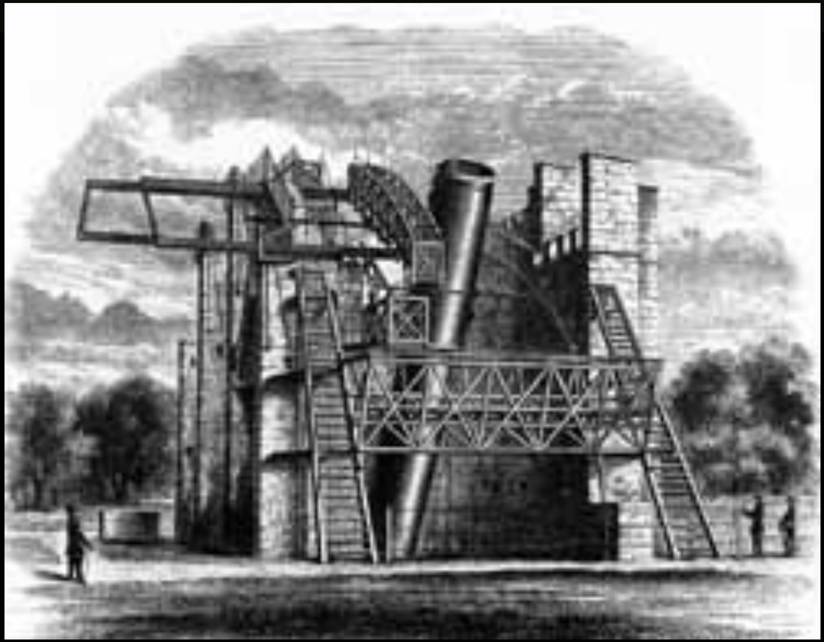
Galaxy, 19th century

Herschel assumed that stars are about the same luminosity (intrinsic brightness), and that there is no obscuring medium between us and the stars.

He concluded that we are near the center of the Galaxy, which is a flattened disk of stars (flattening ratio 1:5)

The development of the observations called for better telescopes

English-Irish nobleman Lord Rosse (W. Parsons, 1800-1867) and his Leviathan telescope (6’=72 in=1.8m aperture)

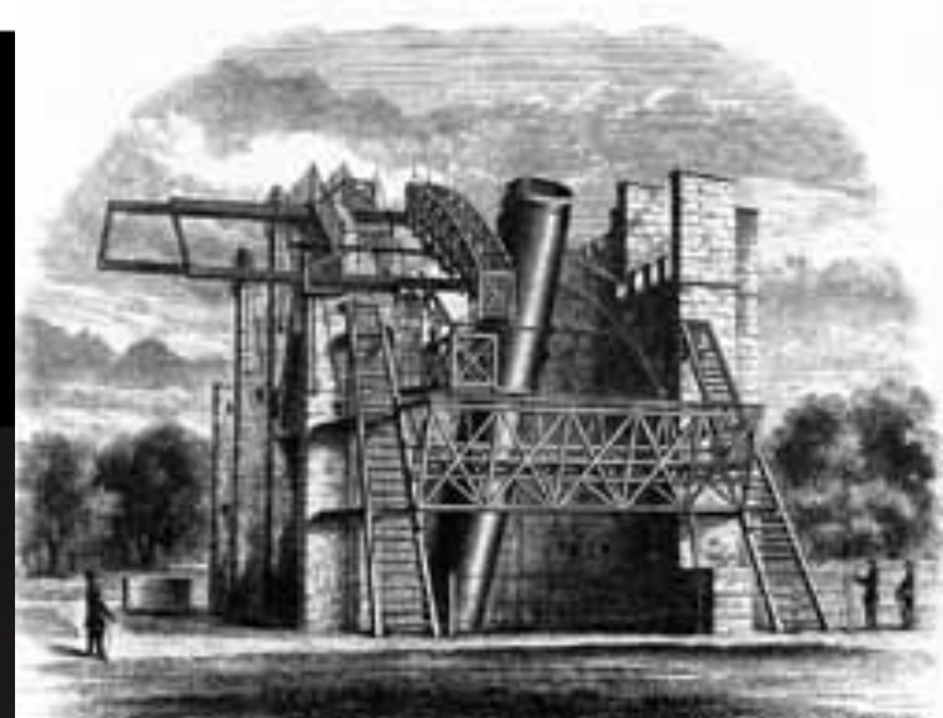


(1.8m, 1845)

galaxy M51
then
and
now

(HST, 2.4m, 1990)

But...



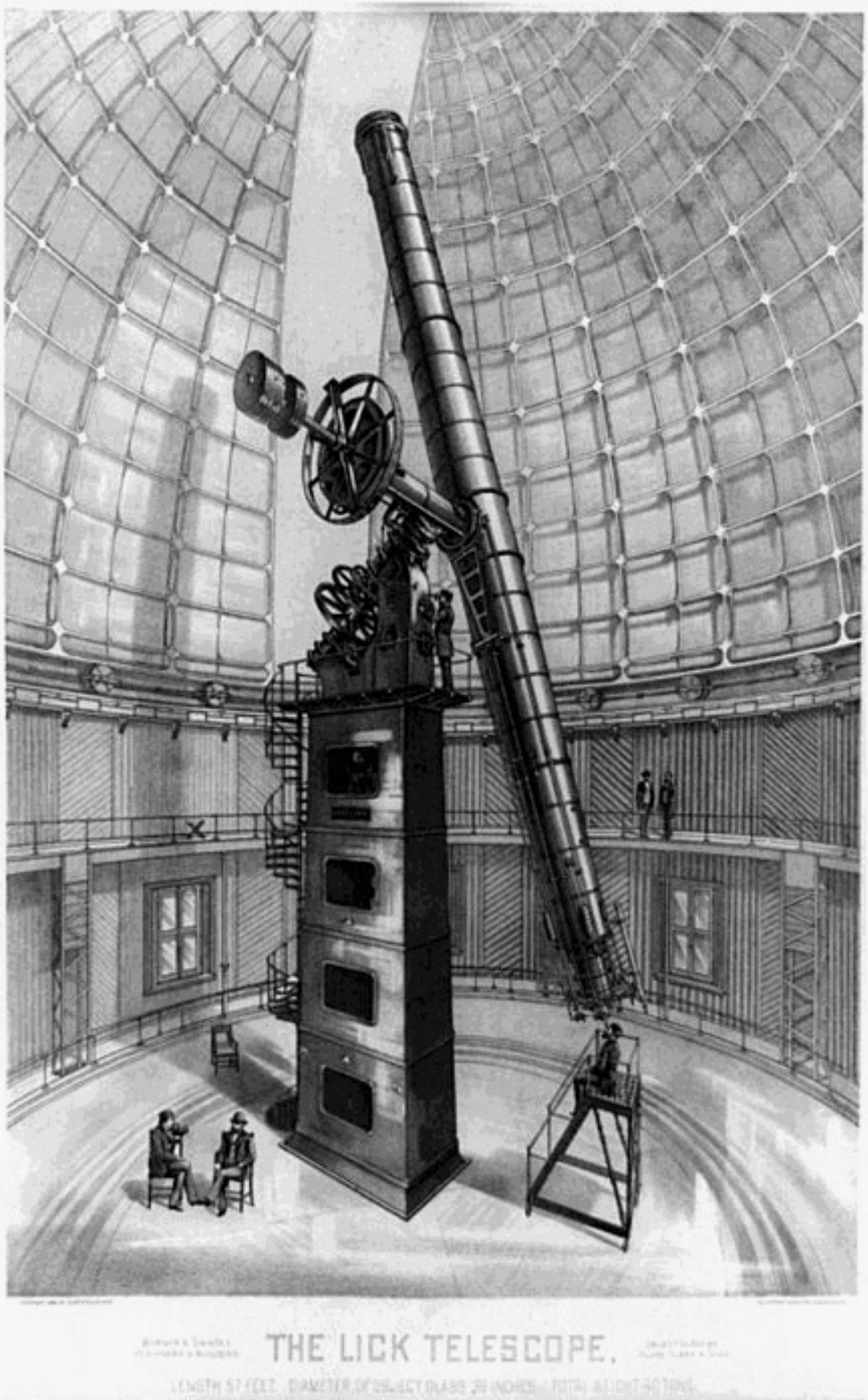
Through the 18/19th-century telescopes, spiral galaxies looked a lot like blurry, perhaps gaseous objects.

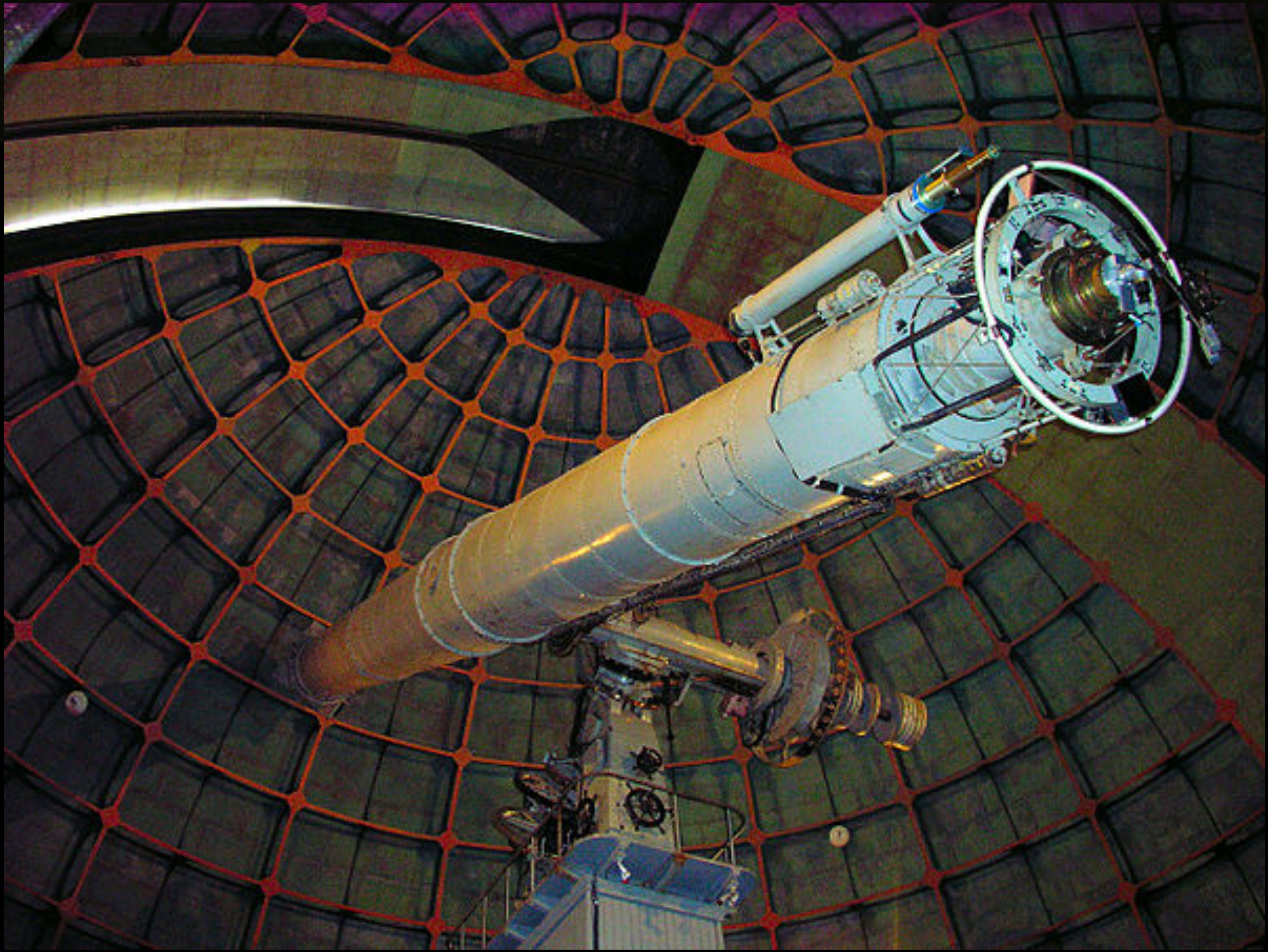
Hence the idea that they’ re much smaller parts of the Milky Way.

Telescopes, 19th century

James Lick (1796-1876),
born in Pennsylvania as a son of a carpenter.
Piano builder, moved to Argentina, then
Chile and Peru.

With some cash and 276 kg of chocolate to sell in 1848 Lick moved to a small village of Yerba Buena, Mexico, renamed San Francisco, Mexico, by the 246 Mormon settlers from the US. He correctly anticipated the annexation of California by the U.S & became a land owner. After the 1849 Gold Rush the wealthiest man in California, and an eccentric patron of sciences.
Lick Observatory was built near San Jose, on Mt. Hamilton. The mountain overlooks what's now known as Silicon Valley. The road was completed by the time Lick died in 1876, but the telescope was not yet ready. His body was interred under the column of the James Lick telescope.


THE LICK TELESCOPE.



Lick observatory's largest achromatic lens built by Alvan Clarke
36 inch = 91 cm diameter

Galaxy, 19th/20th century

Herschel assumed that stars are all about the same luminosity (intrinsic brightness), and that there is no obscuring medium between us and the stars. *(That was incorrect, as it turns out)*
He concluded that we are near the center of the Galaxy, which is a flattened disk of stars (flattening ratio 1:5)

Dutch astronomer Jacobus Kapteyn (1851-1922) confirmed the star counts of Herschel under the same assumptions. He was aware of the fact that there MIGHT be extinction of light between us and the stars, but could NOT find any quantitative proof of it. He added a more precise scale to his heliocentric Universe (which other's called Kapteyn's universe):
stellar numbers fall to less than 1% of the density we see near the sun at 30,000 ly (8,500 pc) along the plane of the Galaxy, and 5,000 ly (1700 pc) in the perpendicular direction
1 pc = 1 parsec = 3.26 light-years (a convenient distance unit used by galactic astronomers and cosmologists).

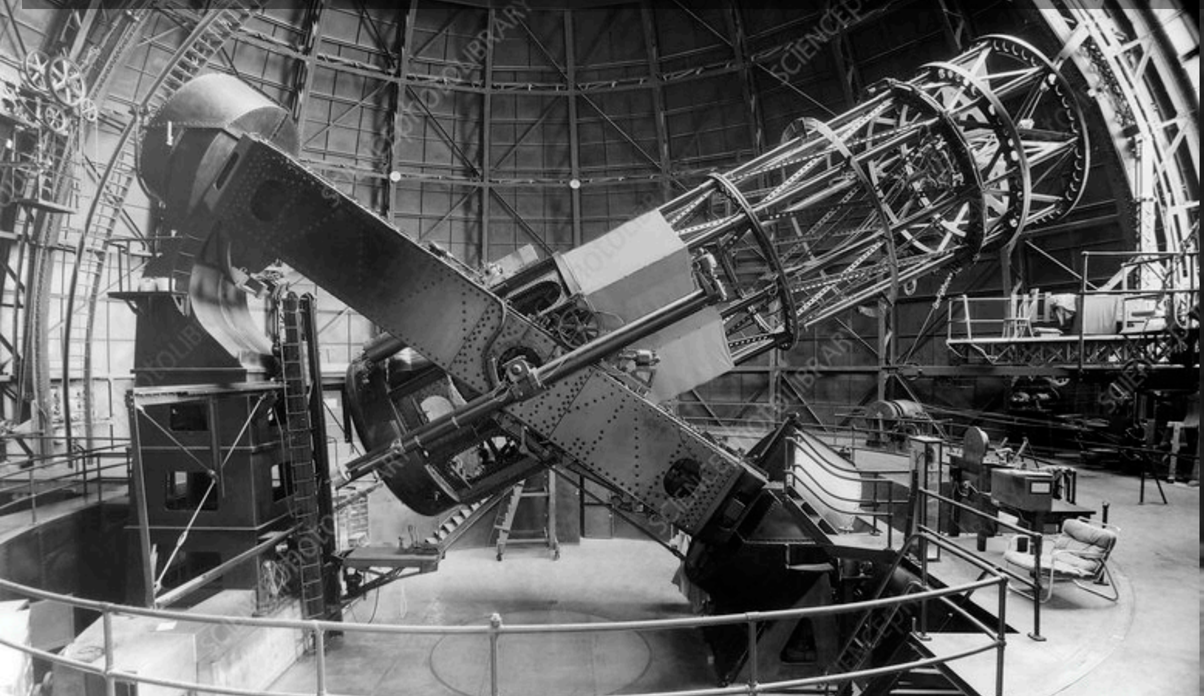
This model had 1:6 flattening

Observatories & the largest telescopes in early 20th century world

The greatest astronomical entrepreneur of the 20th century was astronomer George Ellery Hale, seen below on the right with philanthropist Andrew Carnegie. Hale founded *The Astrophysical Journal,* built the institution with the largest refractor – Yerkes Observatory near Chicago and, after visiting California decided to move there & build an observatory near Pasadena (just north of Los Angeles) - **the Mount Wilson observatory (1904).**

He first built a 60-in telescope in 1908. That year, he invited J. Kapteyn to collaborate on a 100-in mirror telescope (2.4 m diameter, named Hooker telescope, built 1917).

https://www.mtwilson.edu/building-the-100-inch-telescope



The questions about ...

- the nature of Herschel's nebular objects (gaseous or stellar)
- distance to them
- size of the Galaxy
- location of the sun in the Galaxy

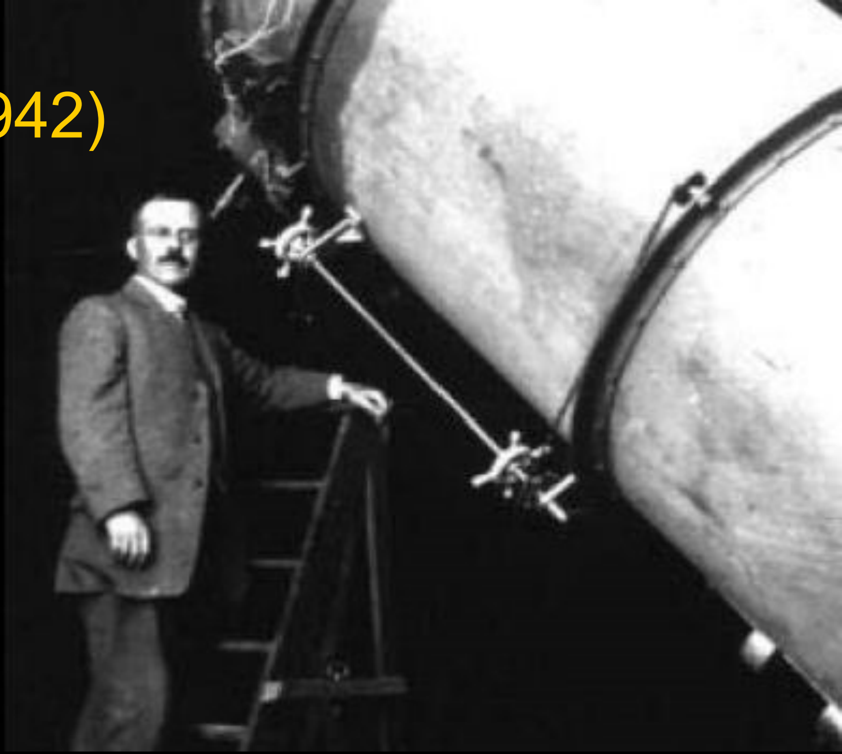
..were very interesting but difficult. Different lines of evidence were gathered by the great telescopes, including the Californian Hooker telescope on Mt. Wilson (near Pasadena) and the Lick Telescope (near San Jose). The results were sometimes contradictory.

Techniques at the beginning of the 20th century included:

- ◆ Doppler effect measurements of radial velocity of objects
- ◆ Photographic plates to discover variable stars or record changes in appearance such as rotation of nebulae

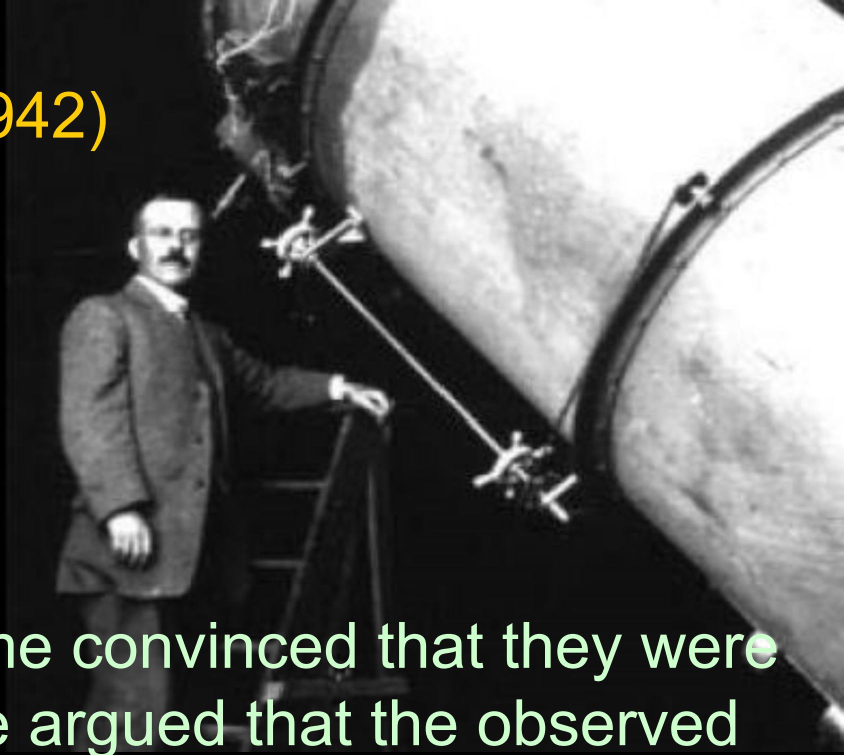
The stage was set for a great scientific confrontation in 1920.

Heber D. Curtis (1872-1942)



American astronomer.
After a Ph.D. in astronomy in Virginia, he joined the staff of the Lick Observatory. His position was named Astronomer, it included instrument building and observation.

Heber D. Curtis (1872-1942)

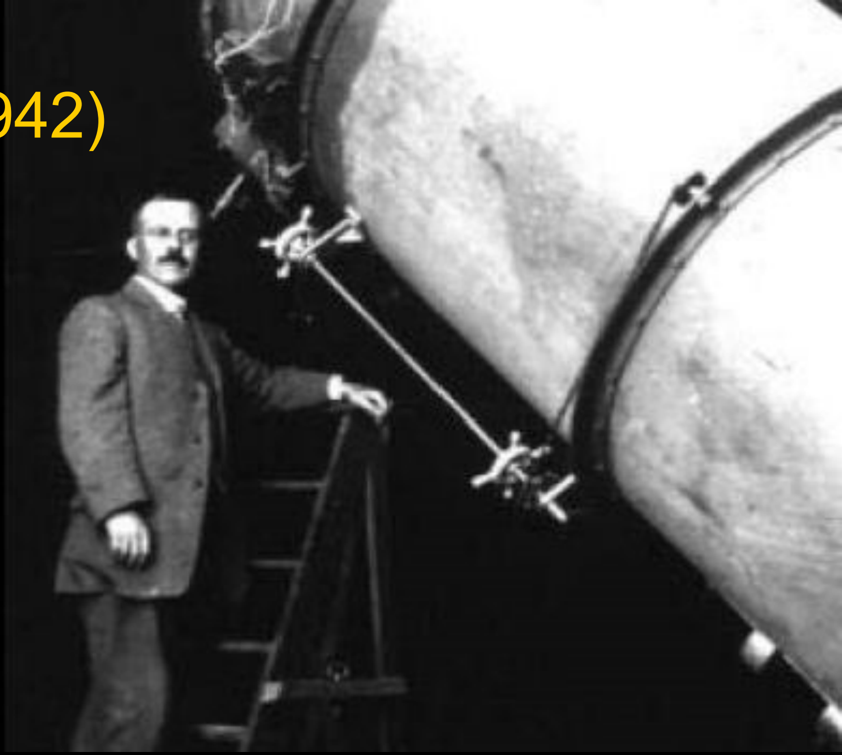


Investigating spiral nebulae he became convinced that they were independent star systems. In 1917 he argued that the observed brightness of stars undergoing outbursts (novae, supernovae) in the spiral nebulae proves they are very much further than the outer limits of our Galaxy. Therefore, they are island universes.

Curtis derived a large distance to Andromeda galaxy (M31) equal to ~0.5 million light-years (0.5 Mly), causing some controversy.

(color-coded ideas are today considered correct)

Heber D. Curtis (1872-1942)



Curtis believed in a small size of our Galaxy
as well as the nearly central location of the sun in it,
somewhat similarly to Kapteyn.

(red shows things known to be incorrect today)

Harlow Shapley (1885-1972)

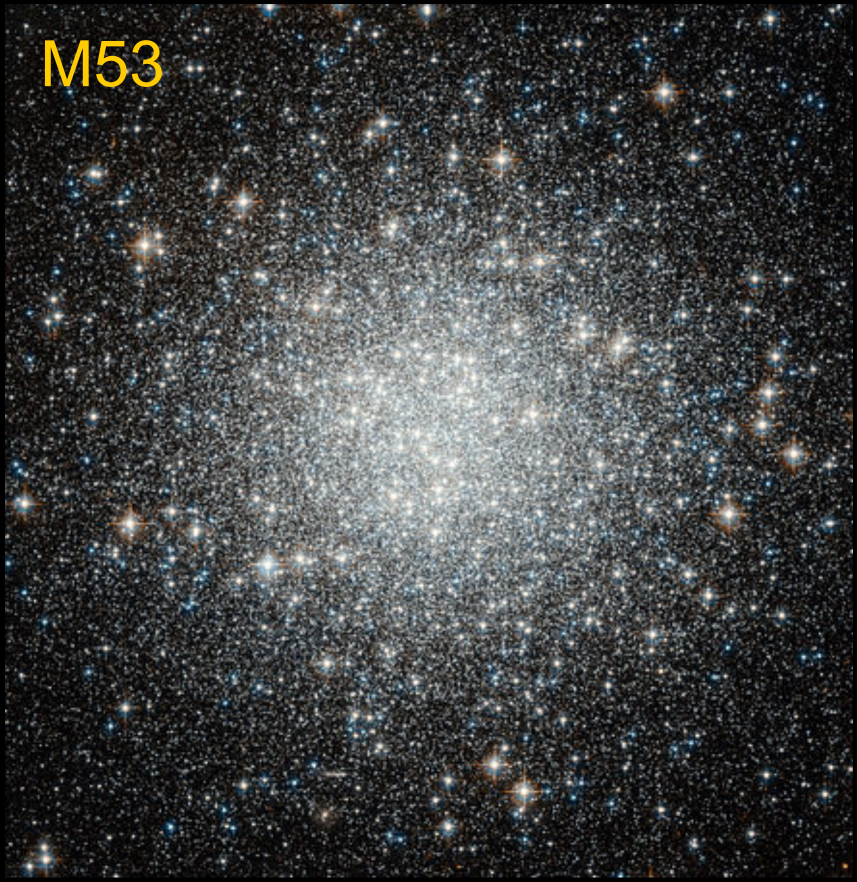
(the Mt. Wilson astronomer hired by G. E. Hale)

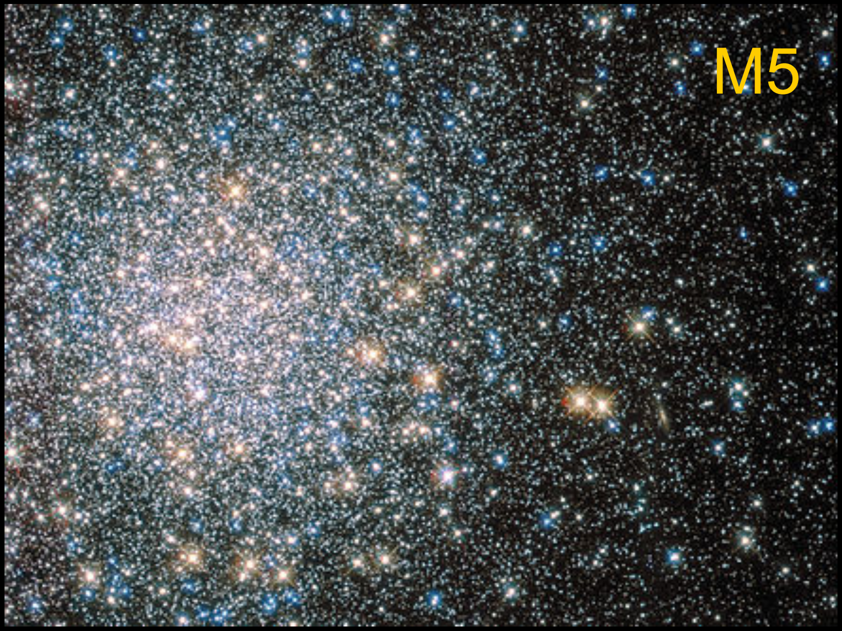
American astronomer. He decided to pick up the *first subject he came across in the course directory*. Rejecting Archaeology, which he later explained he couldn't pronounce, Shapley chose the next subject, Astronomy.

Graduate student at Princeton University, NJ – applied the newly discovered method of finding distances (Cepheid variables, explained later) to find the distances to globular clusters.

Globular clusters consist of stars orbiting a common center of mass.

Sizes up to a few parsecs (~10 light-years).
Number of stars: many 1000s to millions.
# of clusters in Galaxy: ~150
# of clusters in Andromeda: ~500





Harlow Shapley (1885-1972)

Shapley gathered evidence against the central location of the sun in the Galaxy. He found that globular clusters have their own density peak at a location of order 30,000 lyr (10 kpc) from us. He concluded that the center of the globular cluster distribution is the center of the Galaxy, and we with our sun are on the periphery.

This was a second Copernican revolution.

Harlow Shapley (1885-1972)

Shapley measured a very large size of the Galaxy, ~100 kpc or 300 kly, and correctly concluded that the Galaxy is much larger than the Kapteyn universe.

Shapley overestimated the distances, because he assumed that variable stars found in his globular clusters, are of Cepheid variety. (In reality, this led to some erros; they are RR Lyrae variable stars, not Cepheides – see below)

He thought that spiral nebulae live inside our Galaxy.

Harlow Shapley (1885-1972)

'No one trusts a model except the man who wrote it.
Everyone trusts an observation, except the man who made it.'
(H. Shapley)

Shapley cited Van Maanen's observations, which suggested that spiral galaxy M101 turns around its axis fast enough to be detectable after several years (0.02 degrees per year).

(that would endow parts of this galaxy with speed > speed of light if it is a distant universe)

Eventually, the careful observer Van Maanen admitted an error – spiral galaxies rotate by an amount which to this day remains undetectable (except via Doppler effect).

Who won the Great Debate?

Shapley's actual talk and argument given during the Great Debate was completely different from the published paper. Hi talk was elementary to avoid controversy, because he was then a candidate to become Director of Harvard College Observatory. With the weak performance by Shapley, the audience felt that Curtis won the debate. Curtis was indeed a good debater.

But today, many people take a view that Curtis' win on the nature of spiral nebulae (galaxies) does not match the Shapley's "second Copernican revolution".

Shapley displaced the sun (and humanity) from the center of the Universe.

extra notes on the Debate from Carroll and Ostlie

was based on the
catalog, the NGC includes many entries that are either gaseous nebulae or stellar clusters located within the Milky Way. However, the true nature of other objects in the catalog remained in question.[3]

It was in 1845 that William Parsons, the third Earl of Rosse (1800–1867), built what was then the largest telescope in the world. Located in Ireland and nicknamed the "Leviathan," the 72-in (1.8-m) instrument was able to resolve, for the first time, the spiral structure in some nebulae. Their pinwheel appearance strongly suggested that these *spiral nebulae* may be rotating. This suspicion was eventually verified by Vesto M. Slipher (1875–1969) in 1912 when he detected Doppler-shifted spectral lines in a number of these objects.

The Great Shapley–Curtis Debate

The argument over the nature of the nebulae centered on their distances from us and the relative size of the Galaxy. Many astronomers believed that the spiral nebulae resided within the confines of the Milky Way, and others favored the view that they were really Kant's island universes. On April 26, 1920, at the National Academy of Sciences in Washington, D.C., Harlow Shapley of the Mount Wilson Observatory and Heber D. Curtis (1872–1932) of the Lick Observatory met to argue the merits of each point of view. In what has become known as the *Great Debate* in astronomy, Shapley supported the idea that the nebulae are members of our Galaxy. Curtis, on the other hand, was a proponent of the extragalactic interpretation of the data, believing that the nebulae were physically much like the Milky Way, but separated from it.

One of Shapley's strongest points was based on the apparent magnitudes of novae observed in M31. He argued that if the disk of Andromeda were as large as the Milky Way (approximately 100 kpc in diameter by his own recent estimates), then its angular size in the sky ($\sim 3^\circ \times 1^\circ$) would imply a distance to the nebula that was so large as to make the luminosities of the novae in M31

extra notes on the Debate from Carroll and Ostlie

members of our

interpretation of the data, believing that the nebulae were physically much like the Milky Way, but separated from it.

One of Shapley's strongest points was based on the apparent magnitudes of novae observed in M31. He argued that if the disk of Andromeda were as large as the Milky Way (approximately 100 kpc in diameter by his own recent estimates), then its angular size in the sky ($\sim 3° \times 1°$) would imply a distance to the nebula that was so large as to make the luminosities of the novae in M31 much greater than those found in the Milky Way.

His second major point was based on data of Adrian van Maanen (1884–1946), a well-respected observer, whose proper-motion measurements of M101 seemed to suggest an angular rotation rate of $0.02'' \text{ yr}^{-1}$. If M101 had a diameter similar to Shapley's estimate for the Milky Way, then points near its outer edge would have rotational speeds far in excess of those observed within the Milky Way.

In defense of the extragalactic hypothesis, Curtis argued that the novae observed in spiral nebulae must be at least 150 kpc away from us in order to have intrinsic brightnesses comparable to those in the Milky Way. At this distance, M31 would be similar in size to Kapteyn's much smaller estimate of the diameter of the Galaxy, rather than to Shapley's estimate (recall the discussion in Section 24.1). He also argued that the large radial velocities measured for many spiral nebulae seemed to indicate that they could not remain gravitationally bound within a Kapteyn-model Milky Way. Furthermore, assuming that the transverse velocities of the nebulae are similar in value to their radial velocities, then if the nebulae were close enough to be located within the Milky Way it should be possible to

[3]It is worth pointing out that most of the members in the Messier catalog are contained within the NGC; for instance, M31 is also designated as NGC 224.

of the details of this method shortly. In his original study, Kapteyn used over 200 selected regions of the sky.

During the years between 1915 and 1919, shortly before Kapteyn's model was published, Harlow Shapley (1885–1972) estimated the distances to 93 globular clusters using RR Lyrae and W Virginis variable stars (Section 14.1). Since these stars are easily identified in the clusters through their periodic variations in luminosity, it is a relatively simple matter to use their absolute magnitudes (obtained from a period–luminosity relation such as Eq. 14.1) to estimate their distances from the Sun. The distances to the variable stars correspond to the distances to the clusters in which they reside.

In analyzing his data, Shapley recognized that the globular clusters are not distributed uniformly throughout space but are found preferentially in a region of the sky that is centered in the constellation of Sagittarius, at a distance that he determined to be 15 kpc from the Sun. Furthermore, he estimated that the most distant clusters are more than 70 kpc from the Sun, over 55 kpc beyond the center. As a result, by assuming that the extent of the globular clusters was the same as the rest of the Galaxy, Shapley believed that the diameter of the Galaxy was on the order of 100 kpc, close to ten times the value proposed by Kapteyn. Shapley's picture of the Galaxy also differed from Kapteyn's in another important way: Kapteyn's model located the Sun relatively near the center of the distribution of stars, whereas Shapley's Galactic center was much farther away.

We know today that both Kapteyn and Shapley were in error; Kapteyn's universe was too small and the Sun was too near the center, and Shapley's Galactic model was too large. Surprisingly, both models erred in part for the same reason: the failure to include in their distance estimates the effects of interstellar extinction due to dust and gas. Kapteyn's selected regions were largely within the Galactic disk where extinction effects are most severe; as a result, he was unable to see the most distant portions of the Milky Way, causing

extra notes on the Debate from Carroll and Ostlie

large. Surprisin[g]... their distance es[timates]...

selected regions were largely within the Galactic disk where extinction effects are most severe; as a result, he was unable to see the most distant portions of the Milky Way, causing him to underestimate its size. The problem is analogous to someone on Earth trying to see the surrounding land while standing in a dense fog with limited visibility. Shapley, on the other hand, chose to study objects that are generally found well above and below the plane of the Milky Way and that are inherently bright, making them visible from great distances. It is in directions perpendicular to the disk that interstellar extinction is least important, although it cannot be neglected entirely. Unfortunately, errors in the calibration of the period–luminosity relation used by Shapley led to overestimates of the distances to the clusters. The calibration errors were traced to the effects of interstellar extinction (see Section 27.1).

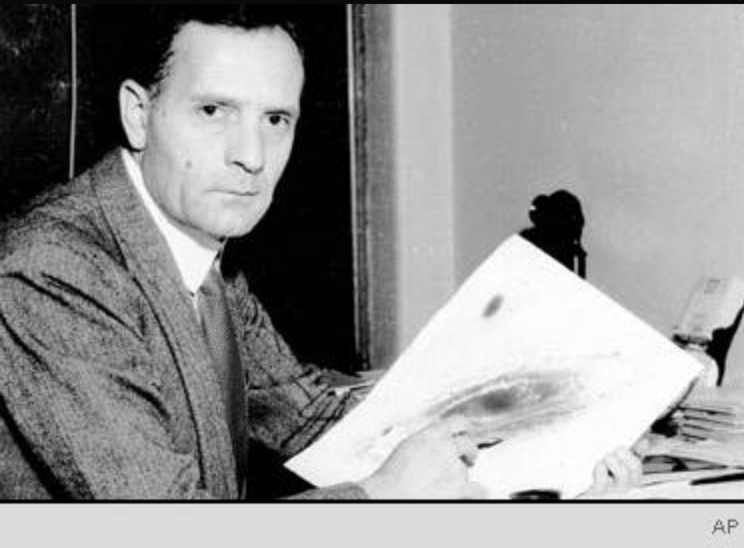
Interestingly, Kapteyn was aware of the errors that interstellar extinction could introduce, but he was unable to find any quantitative evidence for the effect, even though researchers suspected that dust might be responsible for the dark bands seen running across the Milky Way (see Fig. 24.1). Further evidence for strong extinction could also be found in Shapley's own data; no globular clusters were visible within a region between approximately $\pm 10°$ of the Galactic plane, called the **zone of avoidance**. Shapley suggested that globular clusters were apparently absent in the zone of avoidance because strong gravitational tidal forces disrupted the objects in that region. In reality, interstellar extinction is so severe within the zone of avoidance that the very bright clusters are simply undetectable. Clearly the problems encountered by Kapteyn and Shapley in deducing the structure of our Galaxy point out the difficulty of determining its general morphology from a nearly fixed location within the

The Great Debate was organized by National Academy but took place in the Museum of Natural History in Washington D.C., on April 26, 1920

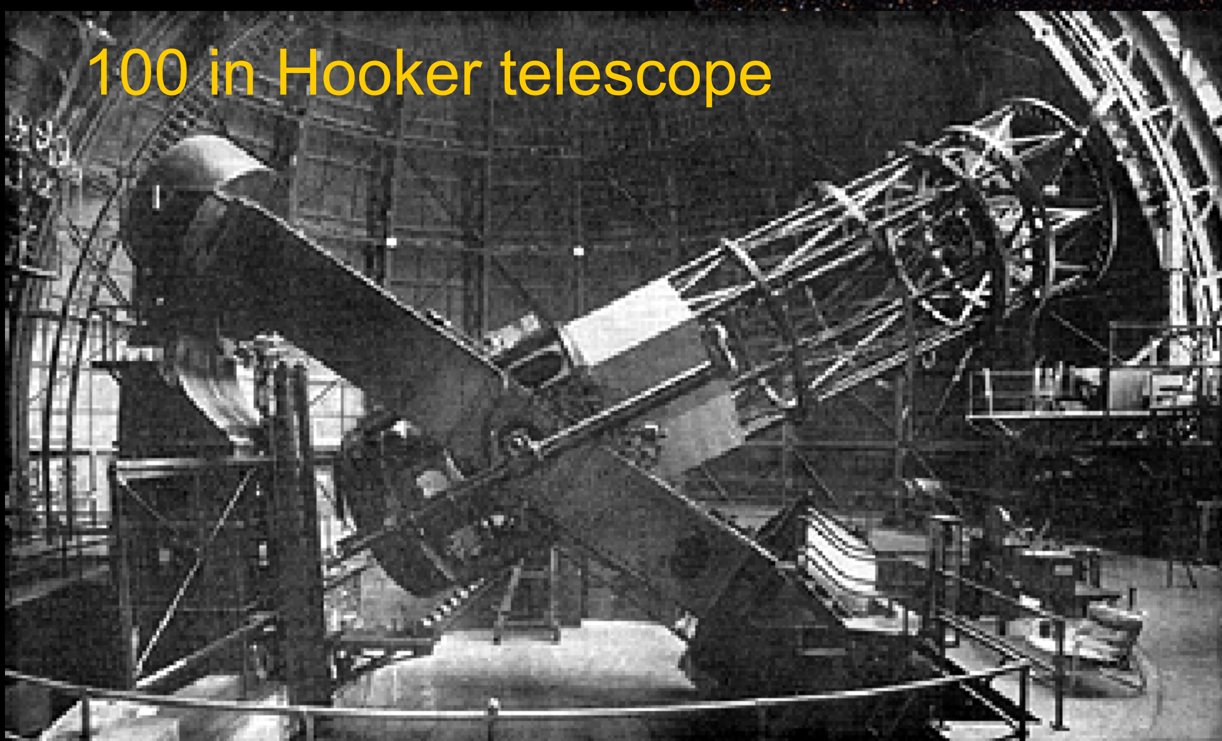
Harlow Shapley vs. Heber Curtis

http://apod.nasa.gov/debate/debate20.html

https://www.youtube.com/watch?v=TEHHFLxmazI



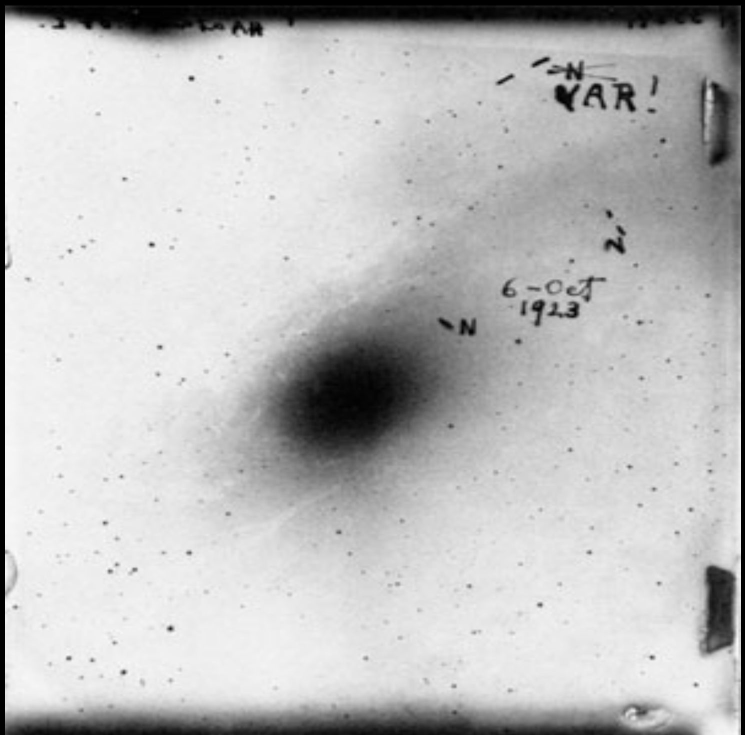
Astronmer Edwin Hubble in 1931



Most important issues left unresolved after Great Debate were successfully resolved by the greatest modern observer

Edwin P. Hubble (1889-1953)

"I hope to find something we had not expected"



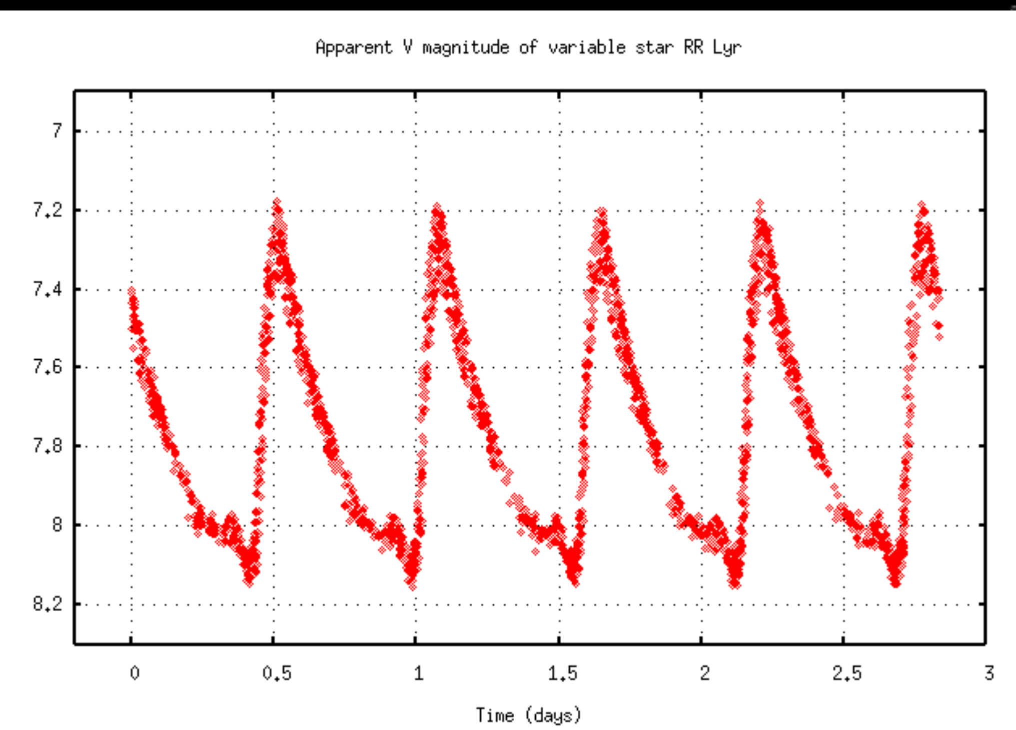
In 1923, Hubble found the first Cepheid variable star in M31, and established the distance to it, proving that it is a large galaxy of the same kind as the Milky Way.

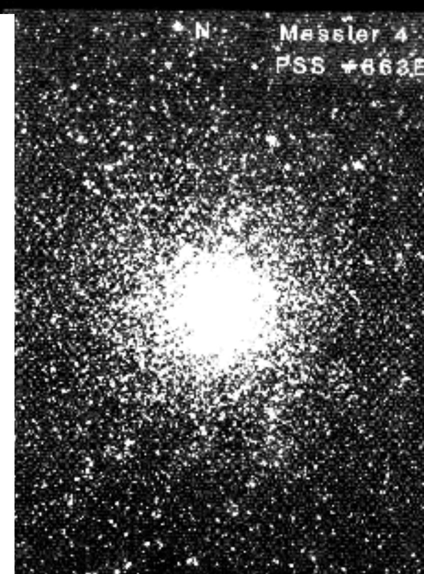
This proved what Heber Curtis was earlier claiming based on less precise "standard candles", novae/supernovae.

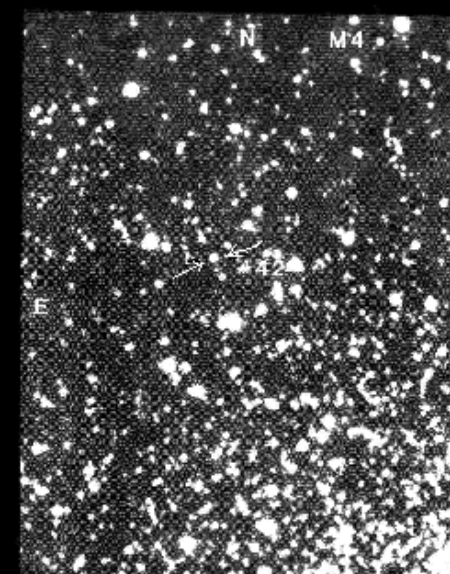
Distance measurement: RR Lyr variables

Another class of variable stars are **RR Lyrae variables** (named after the prototype pop II star RR Lyrae or RR Lyr).

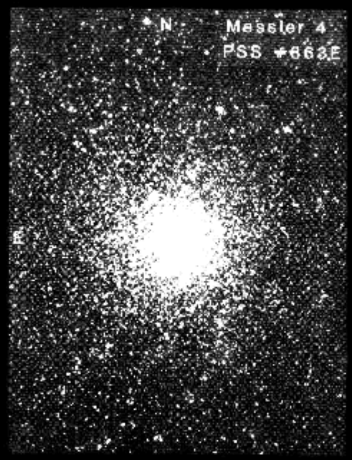
Discovered by Williamina Fleming at Harvard in 1901. RR Lyrae stars are evolved old, low mass stars found in globular clusters.

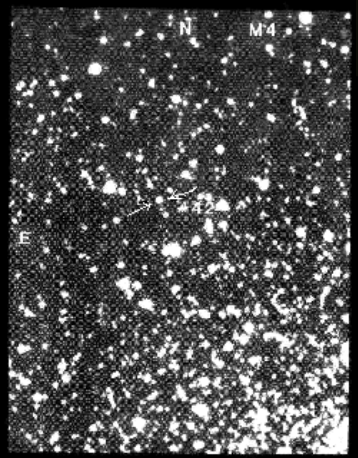


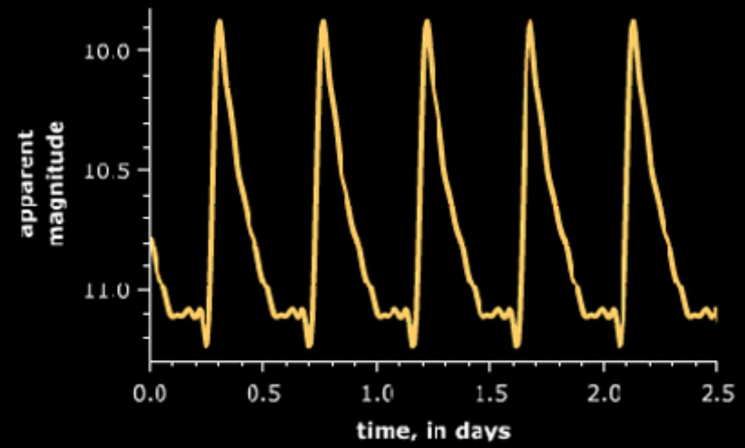




Distance measurement: RR Lyr variables







Lower-mass stars, and therefore generally more numerous than Cepheid variables. A single globular cluster may have dozens of them. Periods of RR Lyrae stars are typically 0.3 to 1 day, making it possible to see one or more periods (cycles) in a single night of observations.

The period-absolute magnitude (or alternatively P vs. L) relations have been known but initially somewhat incorrectly calibrated. E.g, RR Lyrae stars' AVERAGE absolute magnitude is +0.6, which corresponds to 49 L_sun.

The RR Lyr variables can be seen and used as standard candles out to distances up to about **0.74 Mpc** (M31 is 0.78 Mpc away) – not far enough in some cases!

A “nova star” flaring up dramatically in Andromeda nebula, after examination of photographic plates by other astronomers, turned out to be a Cepheid star.

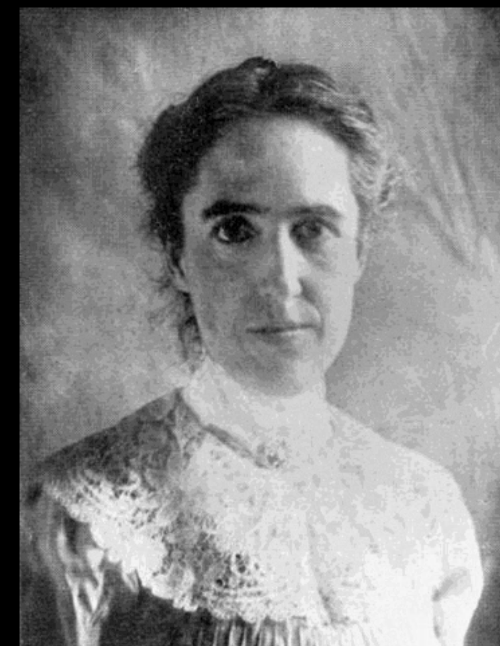
Hubble used it to measure the distance to M31 galaxy.

The **Cepheid variables** are evolved massive stars that lie within the crowded spiral arms of a galaxy. There are few of them in each galaxy. Cepheid variables have periods 1-100 days, as opposed to < 1 day among RR Lyr variables. But they are more luminous!

Let’s see how they were discovered & used as “standard candles”...

Henrietta Swan Leavitt (1868-1921)

from 1893 worked at Harvard Observatory as a computer, to measure and catalog the brightness of stars as they appeared in the observatory's photographic plate collection.



Harvard computers a.k.a. "Pickering's Harem" in 1913
after Edward Charles Pickering (Harvard U.)

Leavitt noted thousands of variable stars in images of Large and Small Magellanic Clouds (nearby irregularly shaped galaxies visible from the Southern hemisphere).

She noticed the period-luminosity,

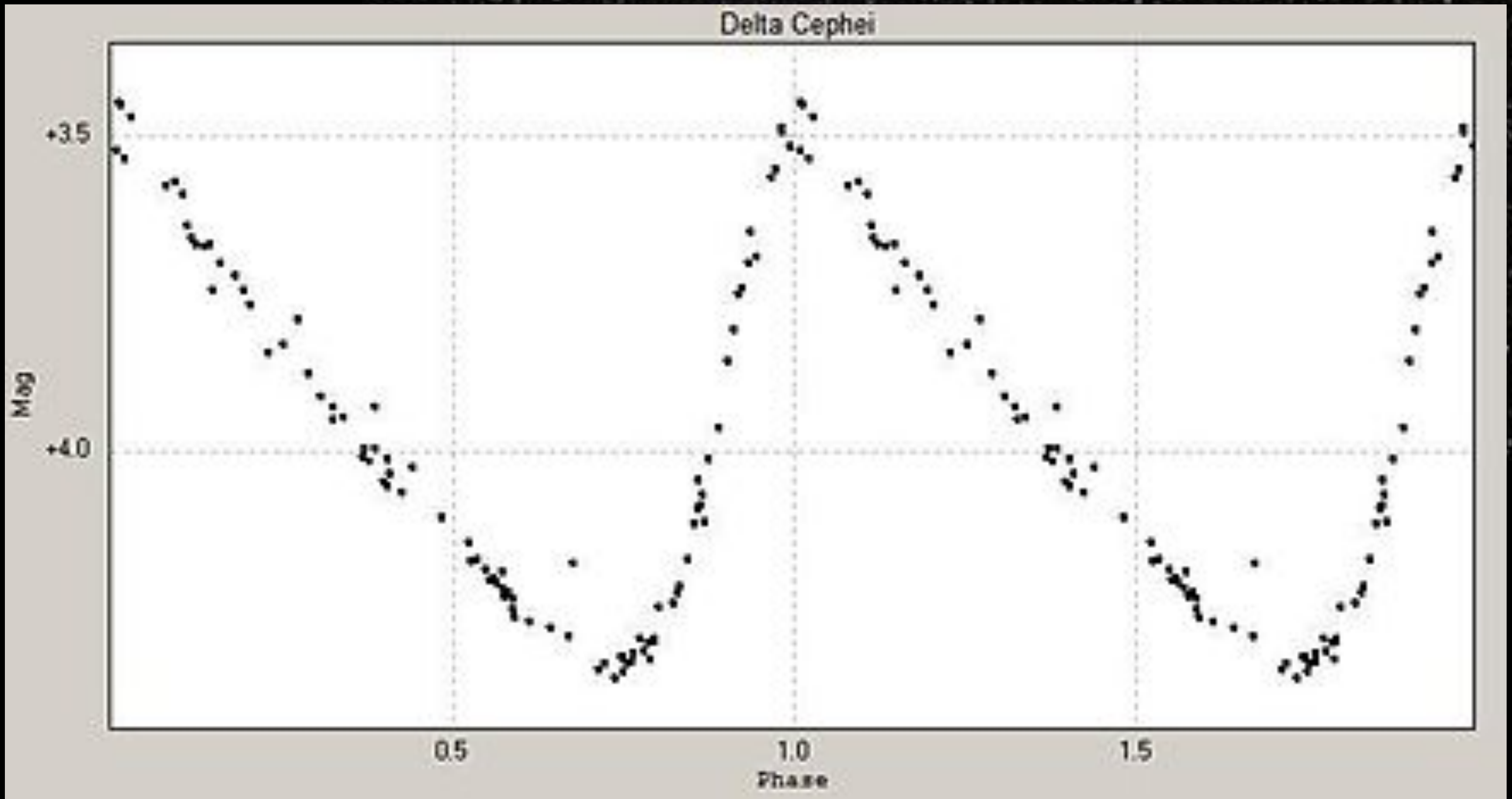
or P vs. L relationship.

In 1908 she published her results in the *Annals of the Astronomical Observatory of Harvard College,* noting that a few of the variables showed a pattern: brighter ones appeared to have longer periods. After further study, she confirmed in 1912 that

"Since the variables are probably at nearly the same distance from the Earth, their periods are apparently associated with their actual emission of light, as determined by their mass, density, and surface brightness."

Large Magellanic Cloud (LMC)

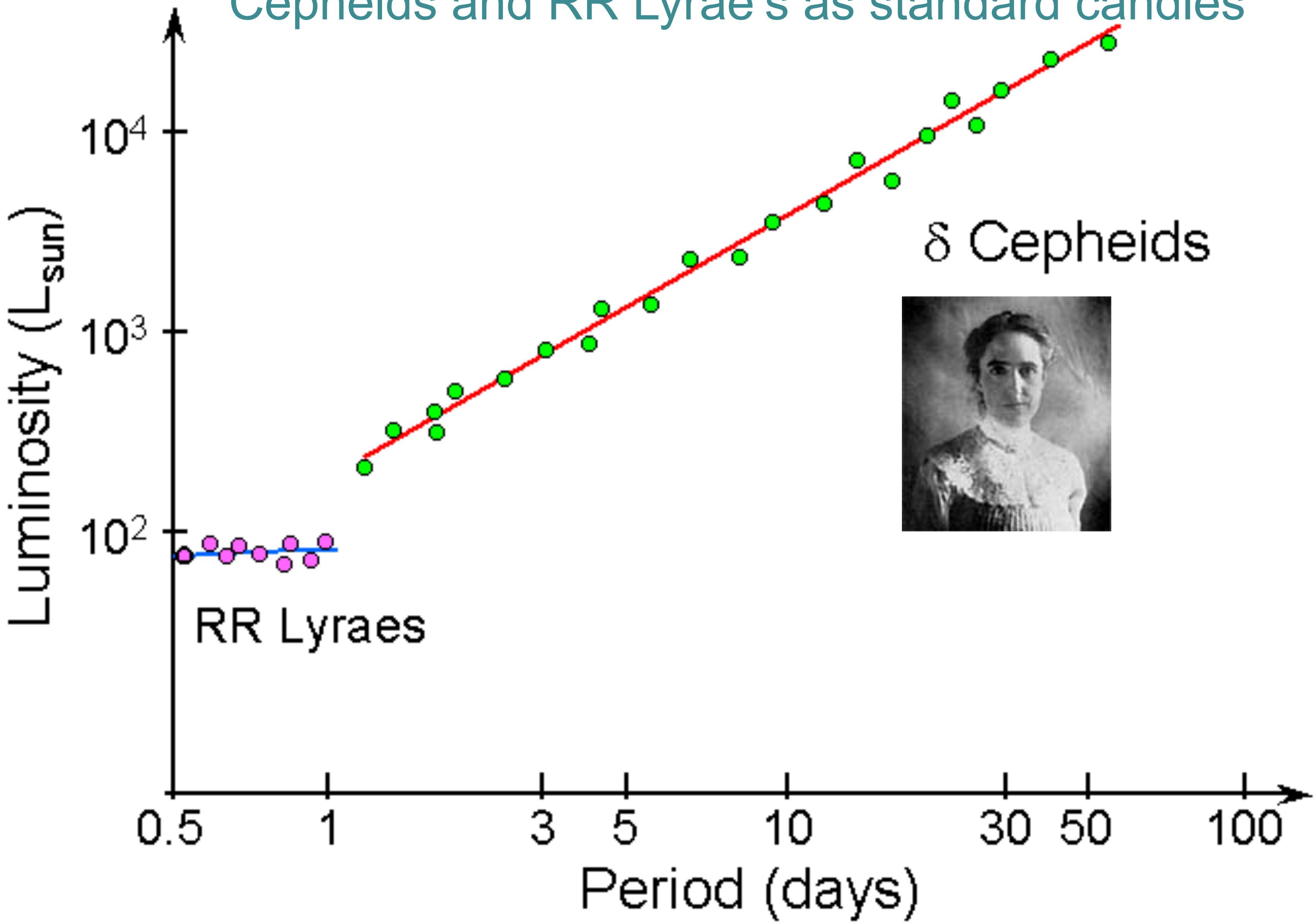
Since Delta Cephei and other Cepheid stars are very bright, they can now be seen and used out to distance of 40 Mpc ~ 130 Mly



1pc=3.26 ly

Period-Luminosity Relationship

Cepheids and RR Lyrae’s as standard candles



Distance measurement using Cepheids, or δ Cep variables.

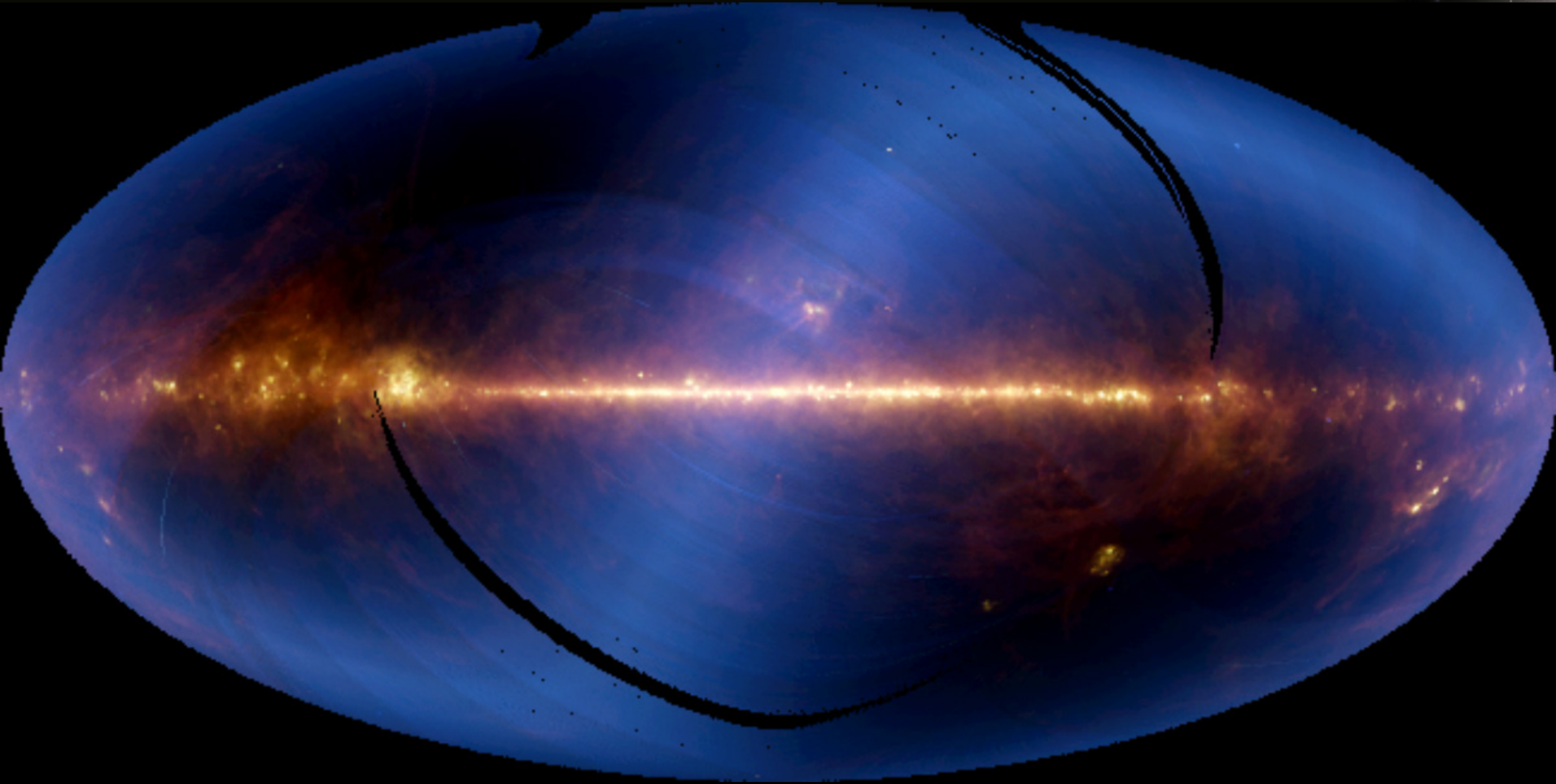
Hubble could place M31 with it’s “VAR!” star a million light-years away - far outside the Milky Way, and thus itself a galaxy containing billions of stars. He thus proved the “island universes” idea.

German astronomer Walter Baade working in the same Mt. Wilson Observatory later discovered that there are two types of Cepheid variables and showed that E. Hubble, treating all Cepheids as one class of stars, underestimated the size and age of the Universe by a factor of about 2.

More importantly, Baade’s observations benefitting from WW2 blackouts of L.A. established that the Milky Way’s stars divide into 2 distinct populations of different age, kinematics, and metallicity (heavy element contents).


© Anglo-Australian Observatory

IRAS (IR Astronomical Satellite) all sky survey in the infrared



It is easiest to see through Galactic dust clouds in wavelengths of electromagnetic waves which are longer than the mean size of dust grains, say, λ >10 microns (micrometers)

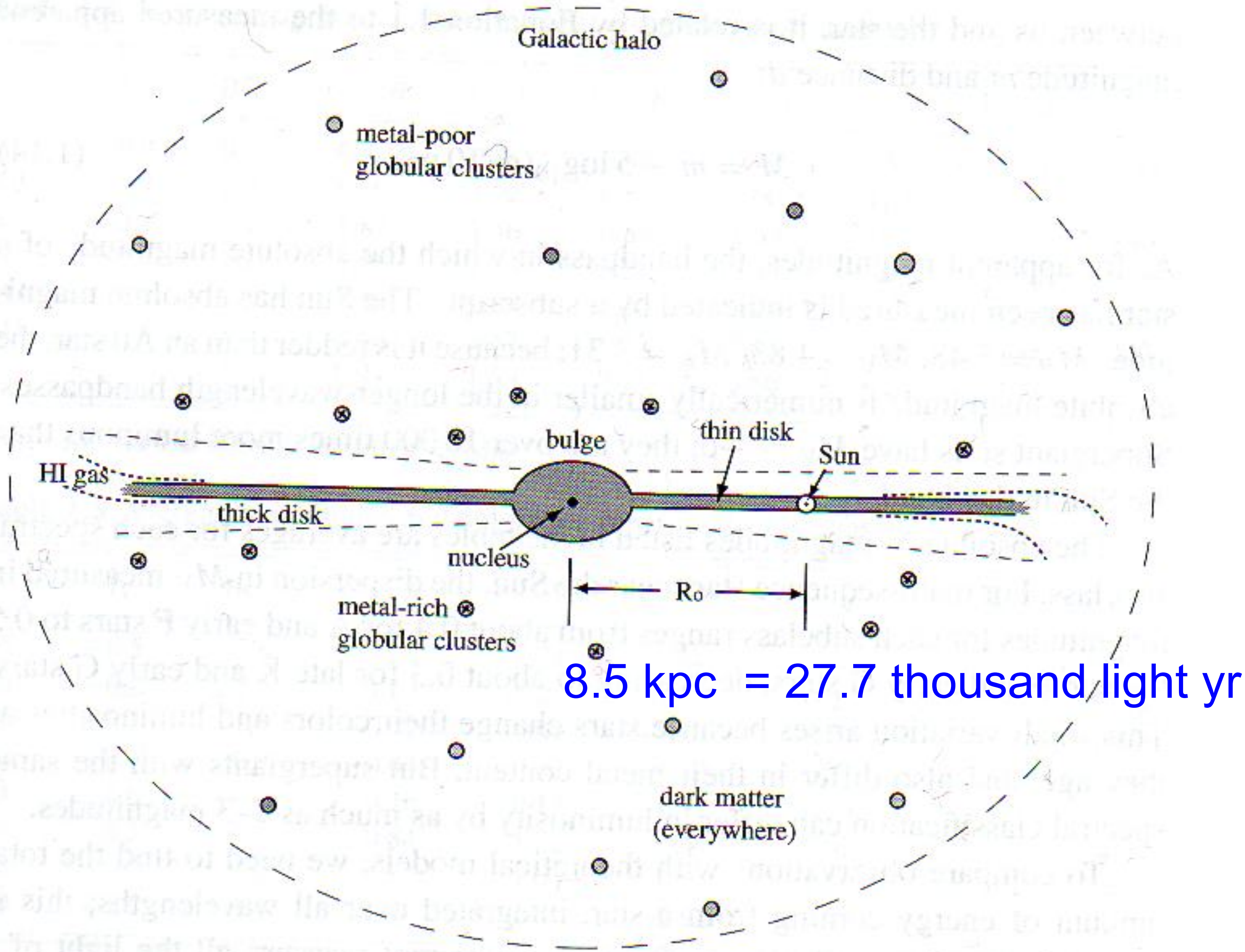


Figure 1.8 A schematic side view of the Milky Way.

Stellar populations:
age, morphology,
kinematics, metallicity
all correlated

population II (pop II) =
old,
fast & isotropic motions (shape,kinem.),
low Z

population I (pop I) =

younger, in a disk,
high Z

8.5 kpc = 27.7 thousand light yr

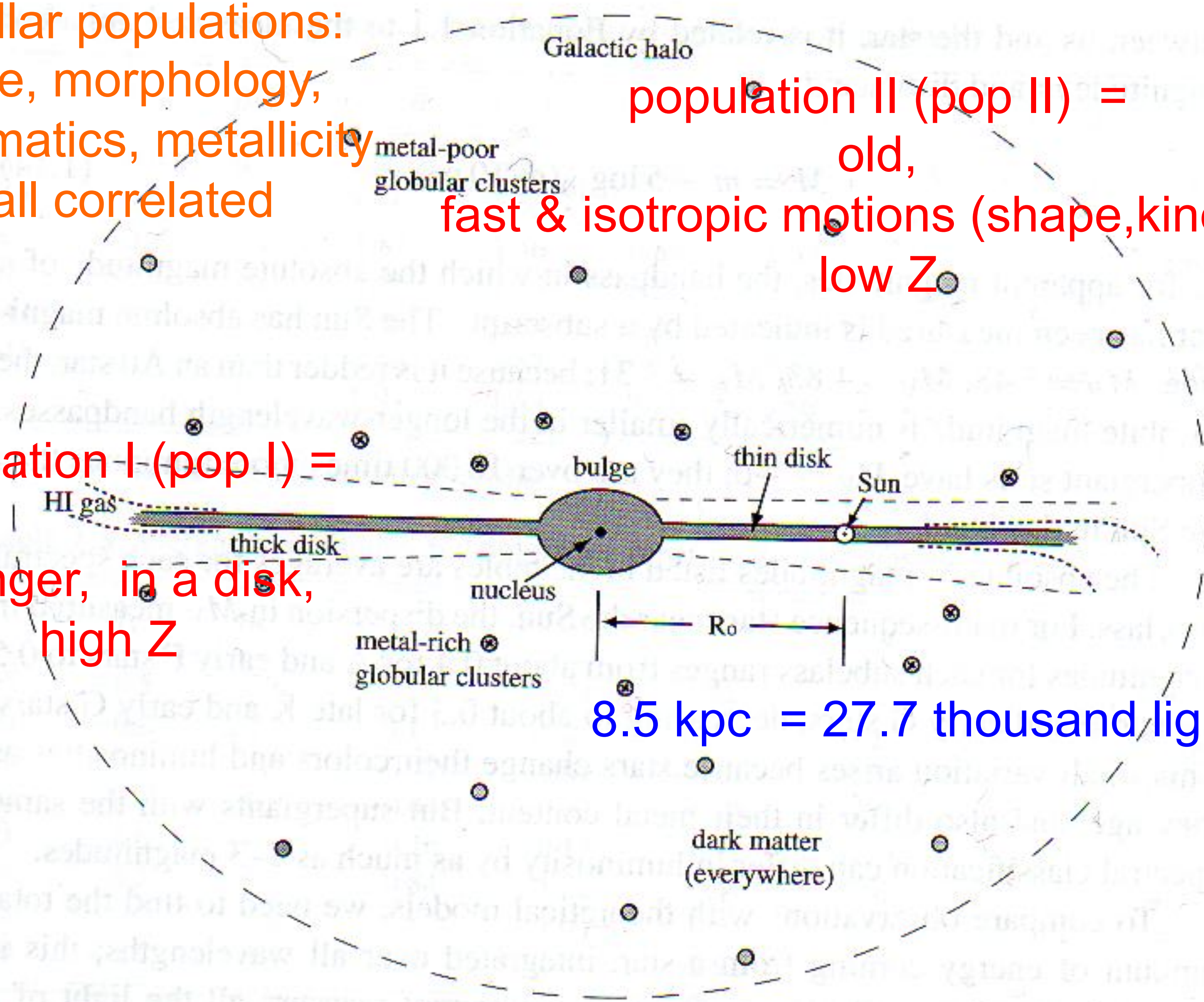


Figure 1.8 A schematic side view of the Milky Way.

1.2 Our Milky Way

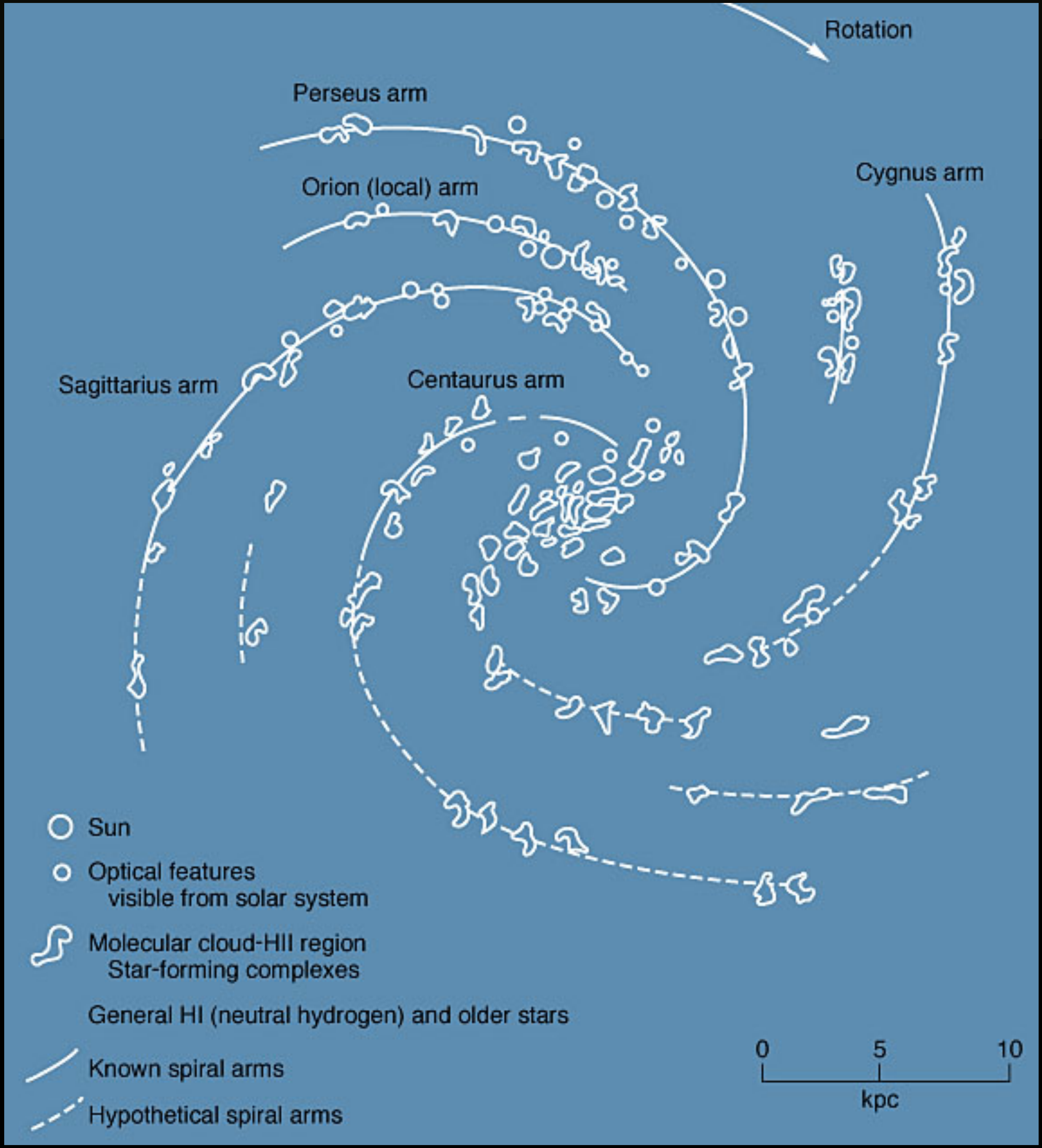
We are resident in the Milky Way, which is also called the Galaxy (with a capital G). Here, we have a close-up view of the stellar and gaseous content of a typical large spiral galaxy. This section gives a brief sketch of our Galaxy, and how we observe the gas and dust that lie between the stars. We also define some of the coordinate systems by which astronomers locate objects on the sky and within the Milky Way.

An external observer might see the Milky Way looking something like what is drawn in Figure 1.8. The Sun lies some way from the center, in the stellar disk that is the Milky Way's most prominent feature. As its name implies, the disk is thin and roughly circular; when we look out on a dark night, the disk stars appear as a luminous band stretching across the heavens. Dark patches in this band mark concentrations of dust and dense gas. In the Southern sky, the bright central regions are seen as a bulge extending above and below the disk. At the center of the bulge is a dense *nucleus* of stars; this harbors a radio source, and possibly a black hole with $\mathcal{M} \sim 10^6 \mathcal{M}_\odot$.

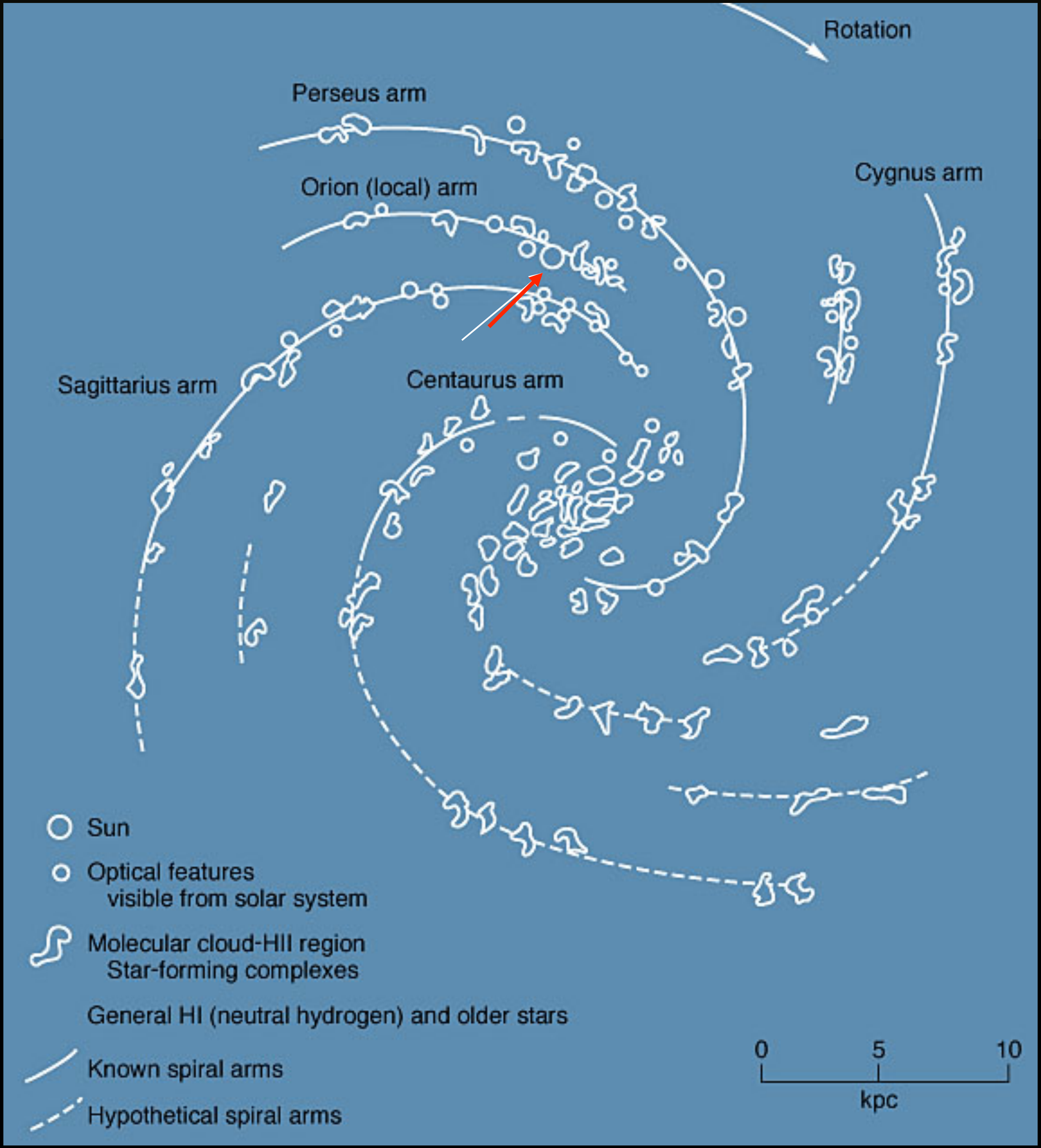
To measure distances within the Galaxy we use *parsecs*, which are defined in Section 2.1; one parsec (pc) is about 3.26 light-years or about 3×10^{13} km, and a kiloparsec (kpc) is 1000 pc. The Milky Way's central bulge is a few kiloparsecs in radius, while the stellar disk stretches out to at least 15 kpc, with the Sun about 8 kpc from the center. The density n of stars in the disk drops by about a factor of e as we move out in radius R by one *scale length* h_R, so that $n(R) \propto e^{-R/h_R}$. Estimates for h_R lie in the range 2–4 kpc.

The *thin disk* contains 95% of the disk stars, and all of the young massive stars. Its *scale height*, the distance we must move in the direction perpendicular to the disk to see the density fall by a factor of e, is 300–400 pc. The rest of the stars form the *thick disk*, which has a larger scale height of about 1000–1500 pc. We will see in Chapter 2 that the stars of the thick disk were made earlier in the Galaxy's history than those of the thin disk, and they are poorer in heavy elements. The gas and dust of the disk lie in a thinner layer than the stars. Near the Sun's position, most of the neutral hydrogen gas lies within 100 pc of the midplane, with the thickness of this layer increasing approximately in proportion to the Galactocentric radius.

Both the Milky Way's disk and its bulge are rotating. Stars in the disk orbit the Galactic center at about 200 km s^{-1}, so the Sun takes roughly 250 Myr to complete its orbit. Disk stars follow nearly circular orbits, with small additional random motions amounting to a few tens of kilometers per second. Bulge stars have larger random velocities. We will see in Chapter 3 that this means they must orbit the center with a lower average speed, of about 100 km s^{-1}. Stars and globular clusters of the *metal-poor halo* do not have any organized rotation around the center of the galaxy. Like comets in the Solar system, their orbits follow random directions, and they are often *eccentric*, so that the stars spend most of their time in the outer reaches of the Galaxy but plunge deeply inward at pericenter.



Can you find the sun?



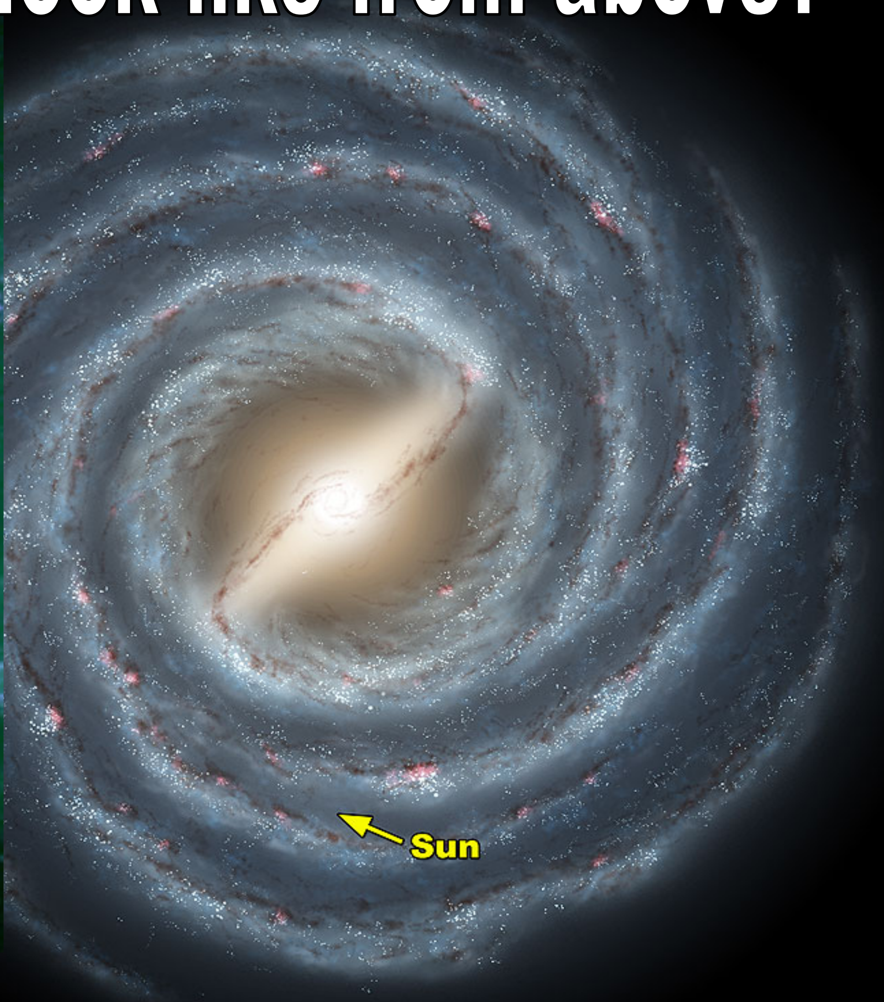
yeah, that isn't easy.

Shapley realized that the sun is not in any privileged position

How does our Galaxy look like from above?

Earlier ideas

the spirals are density waves
or “traffic jams”



Recent findings:

a bar (made of stars)

in the outer reaches of the Galaxy but plunge deeply inward at pericenter.

In all, the luminosity of the disk is about $15–20 \times 10^9 L_\odot$, and the mass in stars is around $60 \times 10^9 \mathcal{M}_\odot$. For the bulge $L \approx 5 \times 10^9 L_\odot$, while the mass of stars is about $20 \times 10^9 \mathcal{M}_\odot$. The halo stars form only a small fraction of the Galaxy's mass, accounting for no more than about $10^9 \mathcal{M}_\odot$.

$V^2 = GM(r)/r$

When we measure the orbital speeds of gas, stars, and star clusters at large distances from the center of the Milky Way, and use Equation 3.20 to find the mass required to keep them in those orbits, we find that the total mass of the Galaxy must be more than just that present in the stars and gas. In particular, most of the Galaxy's mass appears to lie beyond 10 kpc from the center, where there are relatively few stars. We call this the *dark matter* and usually assume, without a compelling reason, that it lies in a roughly spherical *dark halo*. The nature of the unseen material making up the dark halo of our Galaxy and others is one of the main fields of research in astronomy today.

1.2.1 Gas in the Milky Way

In the neighborhood of the Sun, we find about one star in every 10 pc^3. The diameter of a solar-type star is only about 10^{-7} pc, so most of interstellar space is empty of stars; but it is filled with gas and dust. This dilute material makes itself apparent both by absorbing radiation from starlight that travels through it and by its own

From BT

Table 1-1. Inventory of the solar neighborhood

Component	Volume density ($M_\odot\,pc^{-3}$)	Surface density ($M_\odot\,pc^{-2}$)	Luminosity density ($L_\odot\,pc^{-3}$)	Surface brightness ($L_\odot\,pc^{-2}$)
Visible stars	0.044	26.4	0.067	15
Stellar remnants	0.028	18.2	0	0
Gas	0.042	5.3	0	0
Other matter	0.07	25	0	0
Total	0.18	75	0.067	15

NOTES: Volume densities are taken from §4.2.1(b). Surface densities are computed from volume densities following Bahcall and Soneira (1980). Luminosity density is measured in the *V* band and is taken from Table 4-5 of MB. Surface brightness is taken from Bahcall and Soneira (1980) and de Vaucouleurs and Pence (1978). Volume and luminosity densities are measured in the galactic plane.

From Ch.1 BT

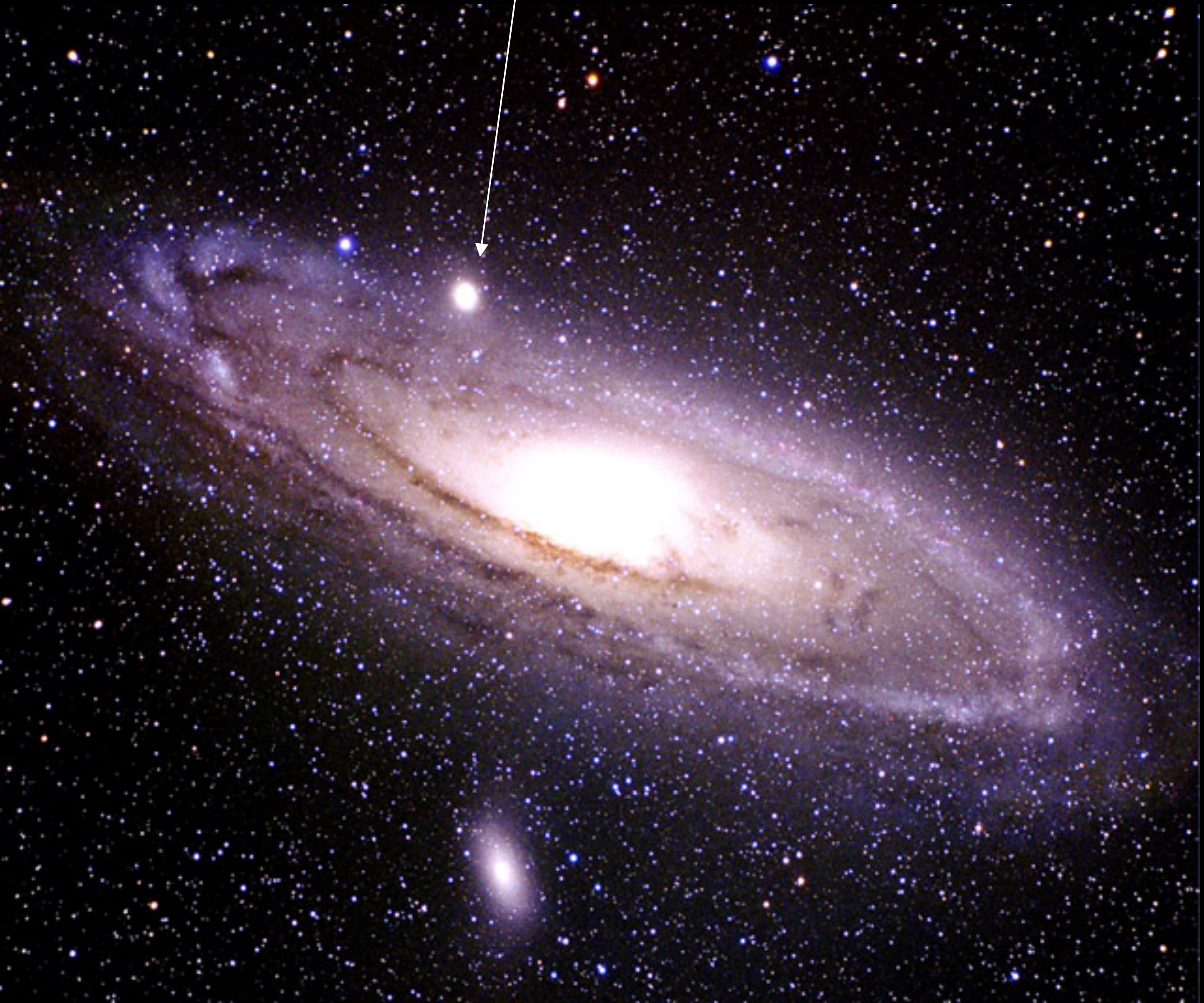
Table 1-2. Properties of the Galaxy

Global properties:	
Disk scale length R_d	$3.5 \pm 0.5\,\mathrm{kpc}$
Disk luminosity (V band)	$1.2 \times 10^{10}\,\mathrm{L}_\odot$
Spheroid luminosity (V band)	$2 \times 10^{9}\,\mathrm{L}_\odot$
Total luminosity (V band)	$1.4 \times 10^{10}\,\mathrm{L}_\odot$
Disk mass-to-light ratio Υ_V	$5\Upsilon_\odot$
Disk mass	$6 \times 10^{10}\,\mathrm{M}_\odot$
Hubble type	Sbc
Solar neighborhood properties:	
Solar radius R_0	$8.5 \pm 1\,\mathrm{kpc}$
Circular speed v_0	$220 \pm 15\,\mathrm{km\,s^{-1}}$
Angular speed $\Omega_0 = v_0/R_0$	$25.9 \pm 4\,\mathrm{km\,s^{-1}\,kpc^{-1}}$
	$= 8.4 \pm 1 \times 10^{-16}\,\mathrm{s^{-1}}$
Rotation period $2\pi/\Omega_0$	$2.4 \times 10^{8}\,\mathrm{yr}$
Oort's A constant	$14.5 \pm 1.5\,\mathrm{km\,s^{-1}\,kpc^{-1}}$
Oort's B constant	$-12 \pm 3\,\mathrm{km\,s^{-1}\,kpc^{-1}}$
Epicycle frequency $\kappa_0 = \sqrt{-4B(A-B)}$	$36 \pm 10\,\mathrm{km\,s^{-1}\,kpc^{-1}}$
Vertical frequency $\nu_0 = \sqrt{4\pi G\rho_0}$	$(3.2 \pm 0.5) \times 10^{-15}\,\mathrm{s^{-1}}$
Vertical period $2\pi/\nu_0$	$6.2 \times 10^{7}\,\mathrm{yr}$
Radial dispersion at $z = 0$	$30\,\mathrm{km\,s^{-1}}$
Radial dispersion (z-averaged)	$45\,\mathrm{km\,s^{-1}}$
Metallicity Z	$\simeq Z_\odot = 0.02$

NOTES: See §2.7 for more detail on global properties. Solar vertical frequency has been computed using total density ρ_0 from Table 1-1 and §4.2.1(b). Radial velocity dispersion is a mass-weighted average, taken from Wielen (1977).

Other galaxies M 31 Andromeda galaxy (Sb)

companions: M 32 (E2) (foreground object) & M 110 (E6p) (below M31)



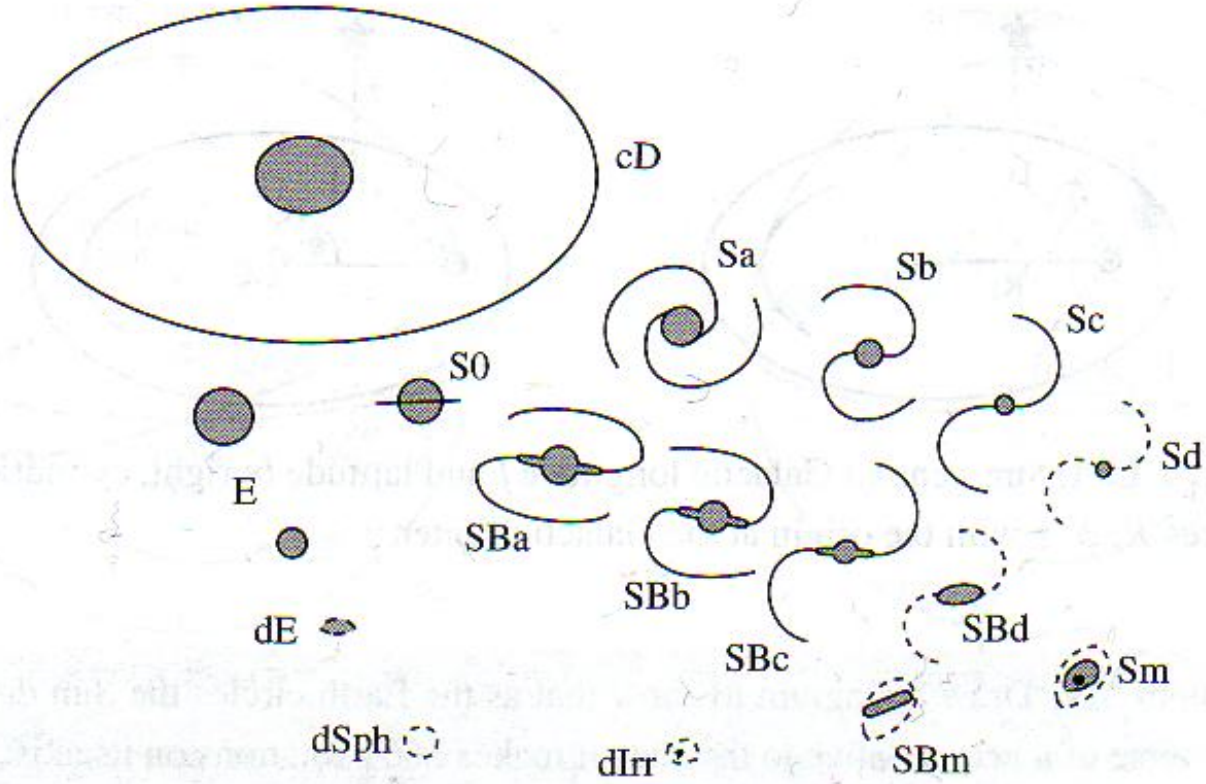
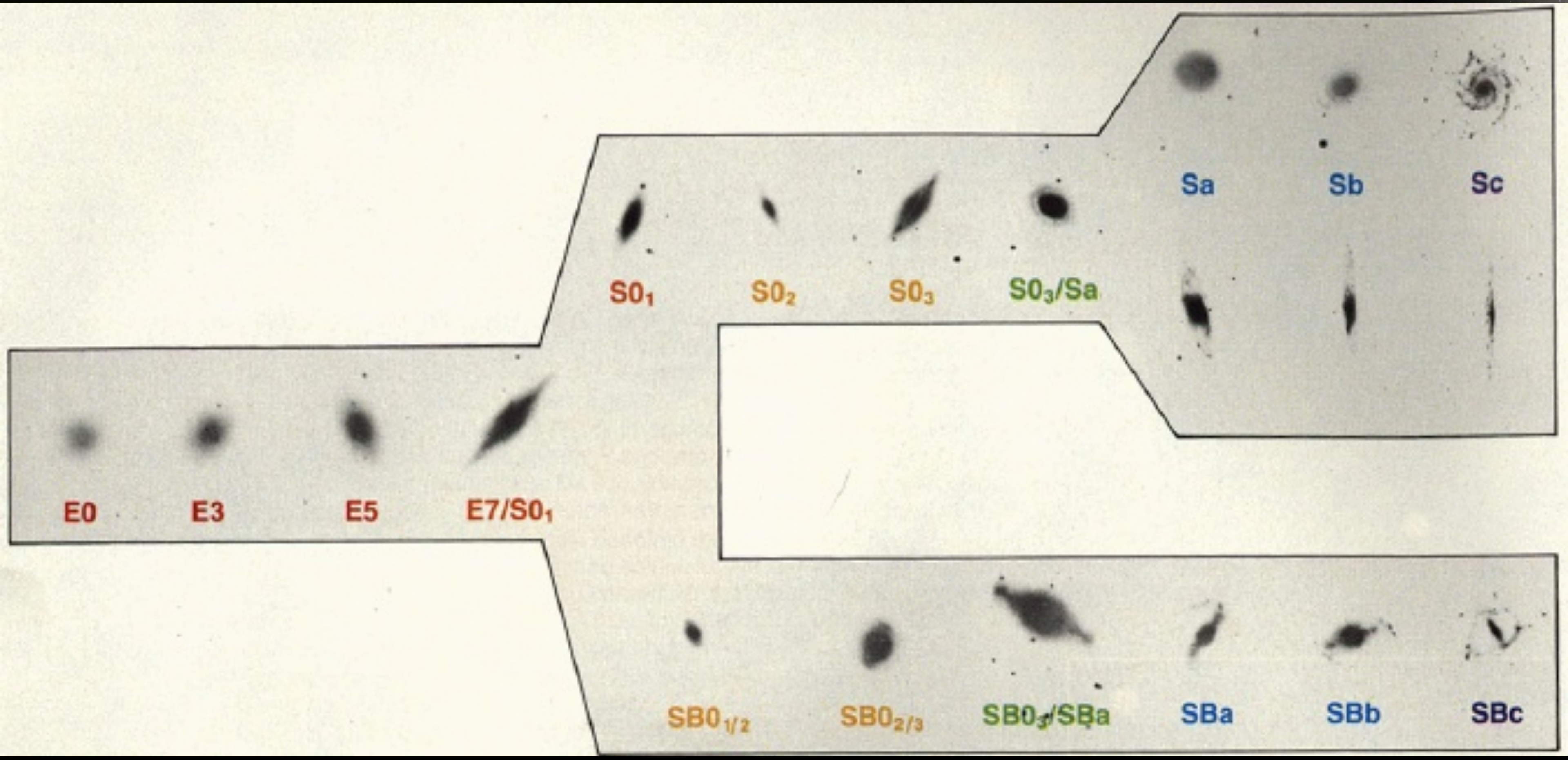


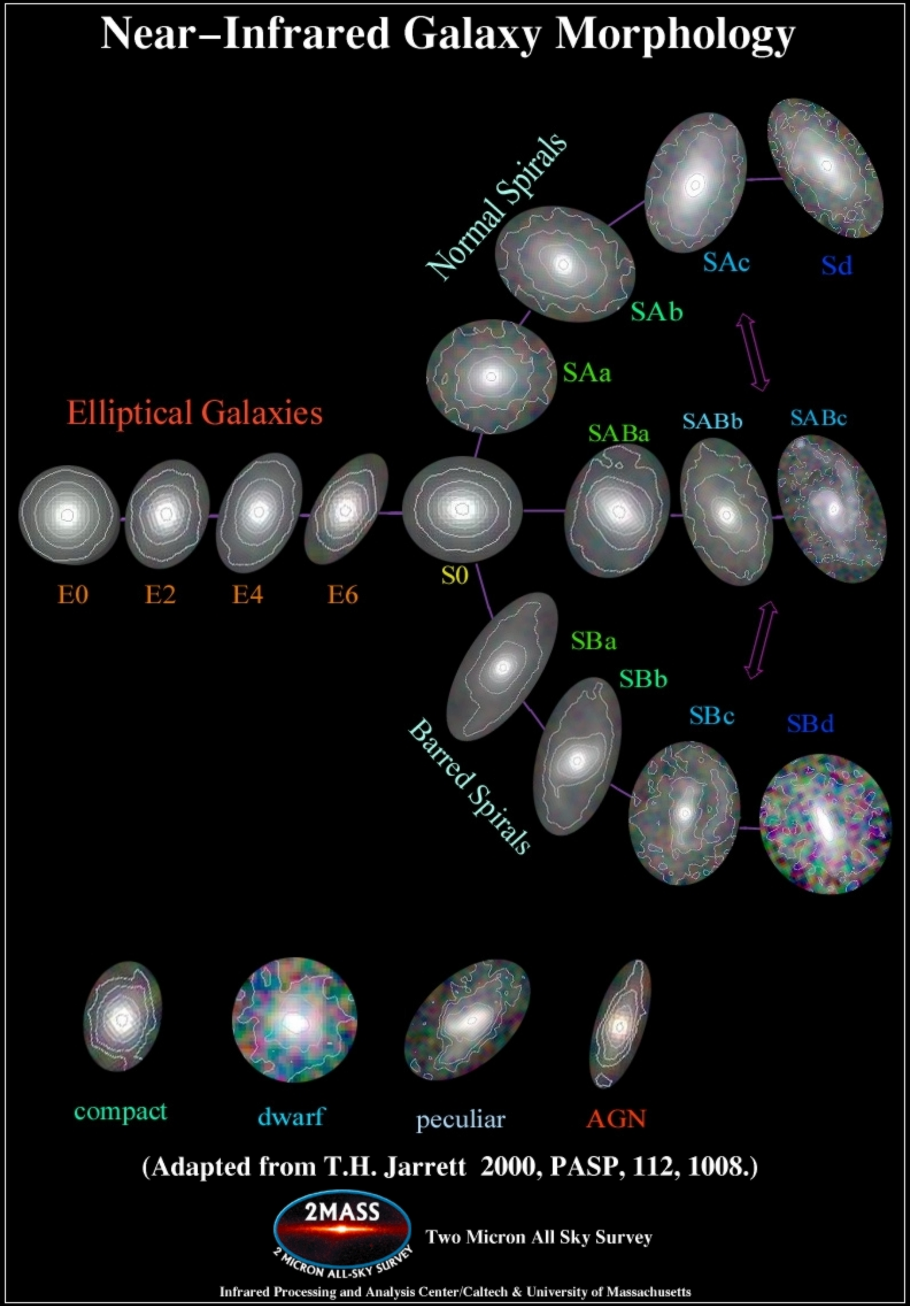
Figure 1.11 Galaxy classification: a modified form of Hubble's scheme.

1.3 Other galaxies

This section introduces the study of galaxies other than our own Milky Way. We discuss how to classify galaxies according to their appearance in optical light, and how to measure the amount of light that they give out. Although big galaxies emit most of the light, the most common type of galaxy is a tiny dim dwarf.

Hubble sequence (tuning fork diagram)

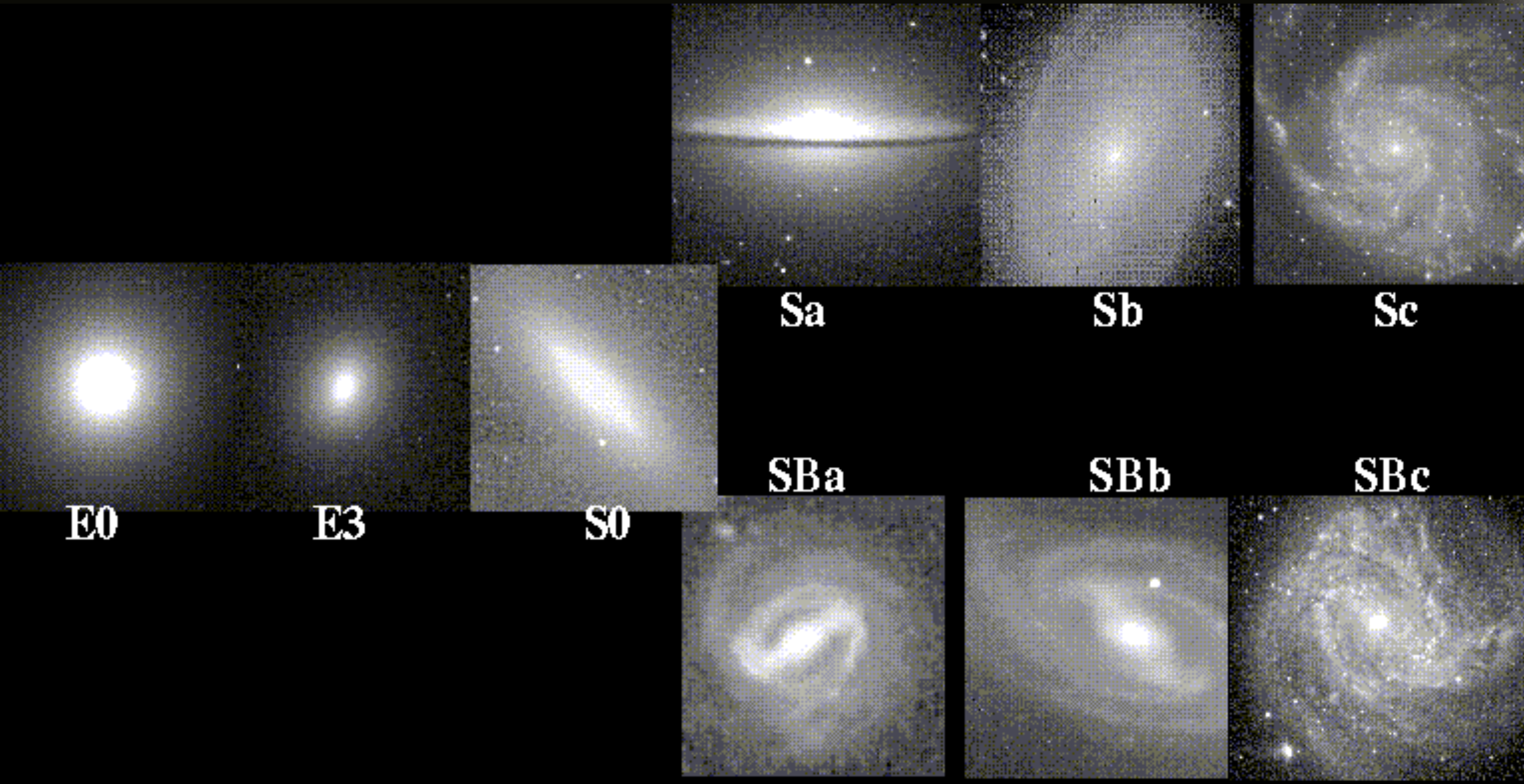




Similar classification applies to other bandpasses (near-IR, in this case) but there's *no guarantee* that the morphological type will be the same in the visible (here Hubble sequence is defined) and the other wavelengths.

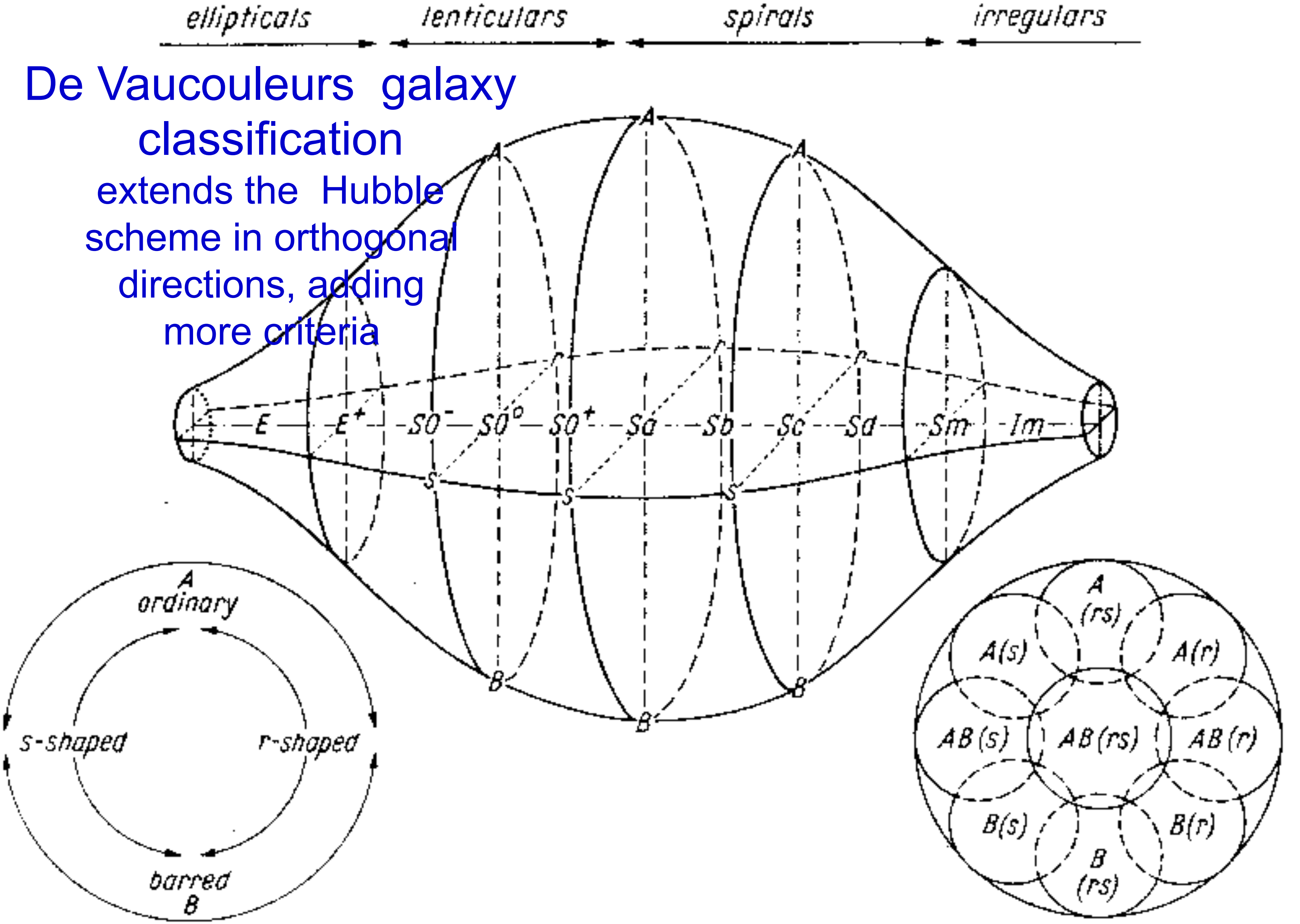
On the contrary, there are sometimes bars and rings which are revealed only in the UV, IR, or radio wavelengths.

Hubble sequence (tuning fork diagram)

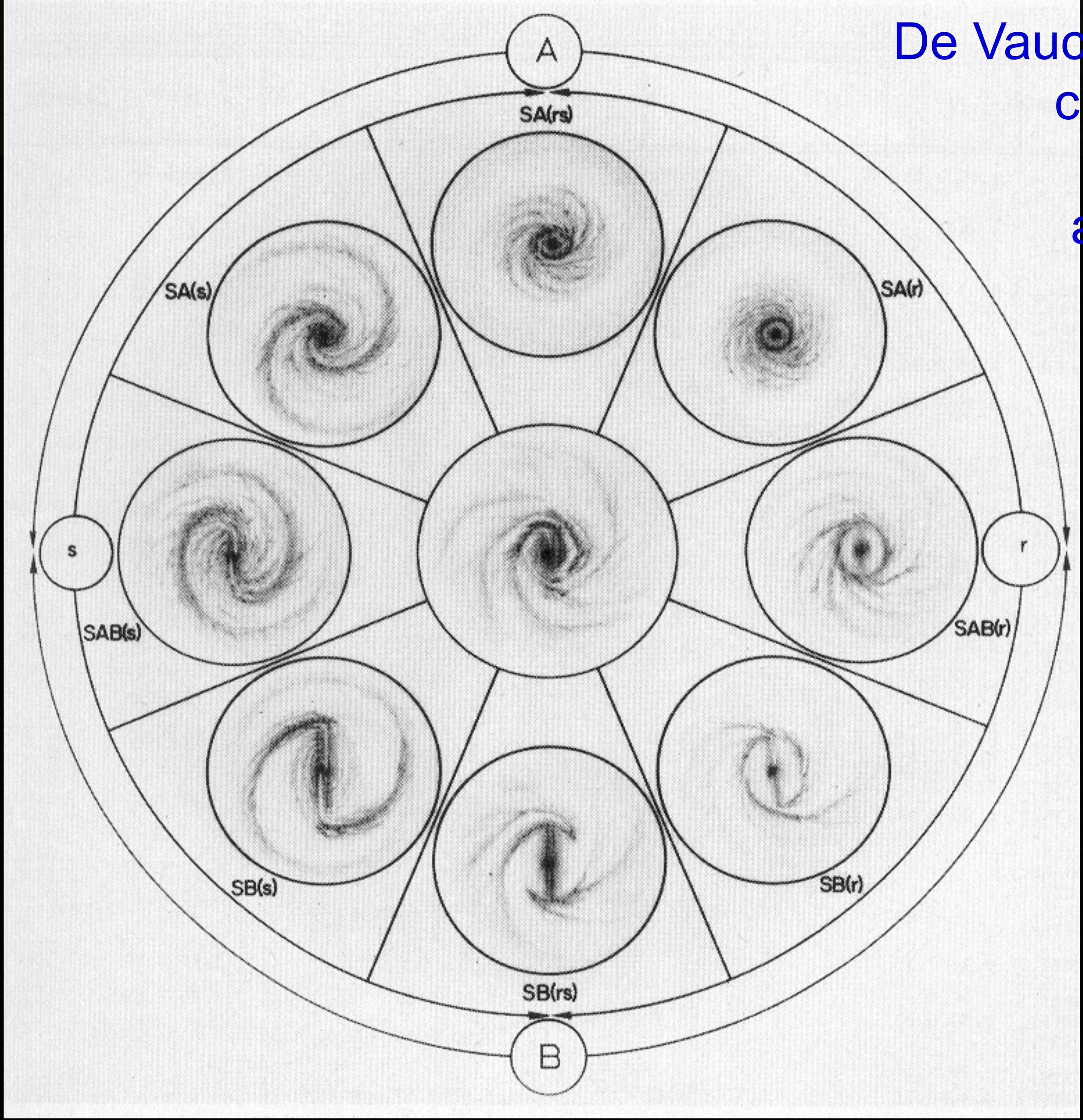


De Vaucouleurs galaxy classification

extends the Hubble scheme in orthogonal directions, adding more criteria



De Vaucouleurs galaxy classification (cross-section at Hubble type Sb)



Bulk Properties of differet classes of Galaxies

Spiral /Barred Spiral

M=10^9...10^{11} M_{sun}, L=10^8 ....10^{10} L_{sun}, D=5...250 kpc

f=77%

Elliptical

10^5 to 10^{13} M_{sun} 10^5 to 10^{11} L_{sun}, D= 1...205 kpc

f=20%

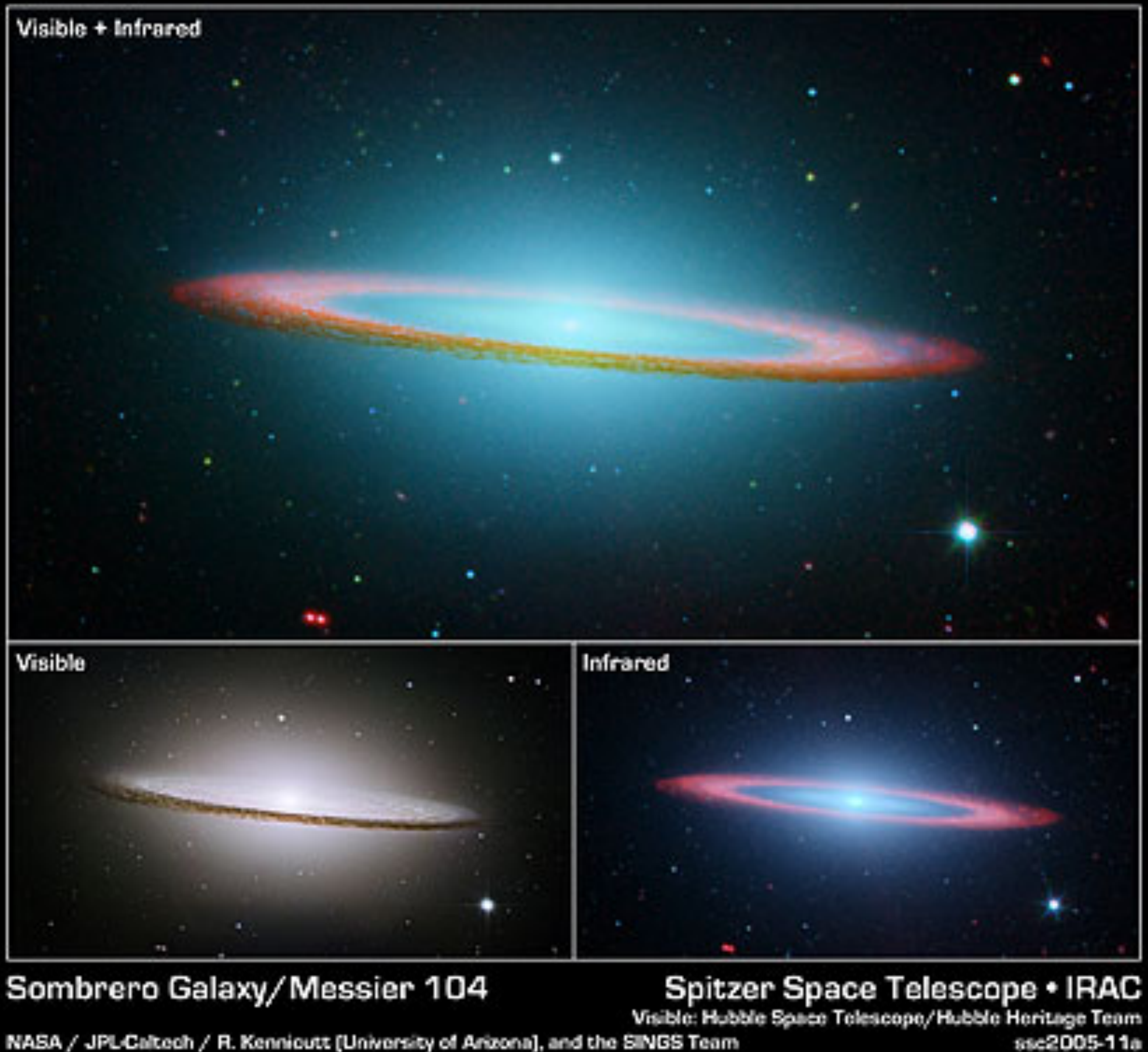
Irregular

10^8 to 10^{10} M_{sun} 10^7 to 10^9 L_{sun}, D= 1...10 kpc

f=3%

(f=Percentage of Observed Galaxies; D = diameter)

M 104
(Sa)



Visible + Infrared
Visible
Infrared
Sombrero Galaxy/Messier 104
Spitzer Space Telescope • IRAC
Visible: Hubble Space Telescope/Hubble Heritage Team
NASA / JPL-Caltech / R. Kennicutt (University of Arizona), and the SINGS Team
ssc2005-11a

M 81 (Sb)

M 51 (Sc) + NGC 5195 (peculiar SBb?)

Whirlpool Galaxy ▪ M51

Hubble Heritage

NASA, ESA, S. Beckwith (STScI), and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC05-12a

Are these colliding or is it just projection effect?
Can you say what type they are?

Criteria for distinguishing spirals along the sequence of ‘early-type’ to ‘late-type’: Sa--Sb--Sc

1. Bulge-to-disk light (mass) ratio, size of the bulge (decreases)

2. Prominence of spiral arms, arm-interarm contrast (increases)

3. Visibility and number of population I objects such as: H II regions, OB associations, dark lanes of dust (increases)

4. Pitch angle (openness) of spiral arms (increases)

in the outer reaches of the Galaxy but plunge deeply inward at pericenter.

In all, the luminosity of the disk is about 15–20 $\times 10^9 L_\odot$, and the mass in stars is around $60 \times 10^9 \mathcal{M}_\odot$. For the bulge $L \approx 5 \times 10^9 L_\odot$, while the mass of stars is about $20 \times 10^9 \mathcal{M}_\odot$. The halo stars form only a small fraction of the Galaxy's mass, accounting for no more than about $10^9 \mathcal{M}_\odot$.

When we measure the orbital speeds of gas, stars, and star clusters at large distances from the center of the Milky Way, and use Equation 3.20 to find the mass required to keep them in those orbits, we find that the total mass of the Galaxy must be more than just that present in the stars and gas. In particular, most of the Galaxy's mass appears to lie beyond 10 kpc from the center, where there are relatively few stars. We call this the *dark matter* and usually assume, without a

The most famous formula in dynamical astronomy

Circular speed *V* depends on the mass *M(r)* inside radius *r*: $V^2 = G\,M(r)/r$, (G=grav. constant)

Knowing velocities as a function of radius, we can calculate the mass distribution in a galaxy.

of a solar-type star is only about 10^{-7} pc, so most of interstellar space is empty of stars; but it is filled with gas and dust. This dilute material makes itself apparent both by absorbing radiation from starlight that travels through it and by its own

Table 1-1. Inventory of the solar neighborhood

Component	Volume density ($M_\odot\ pc^{-3}$)	Surface density ($M_\odot\ pc^{-2}$)	Luminosity density ($L_\odot\ pc^{-3}$)	Surface brightness ($L_\odot\ pc^{-2}$)
Visible stars	0.044	26.4	0.067	15
Stellar remnants	0.028	18.2	0	0
Gas	0.042	5.3	0	0
Other matter	0.07	25	0	0
Total	0.18	75	0.067	15

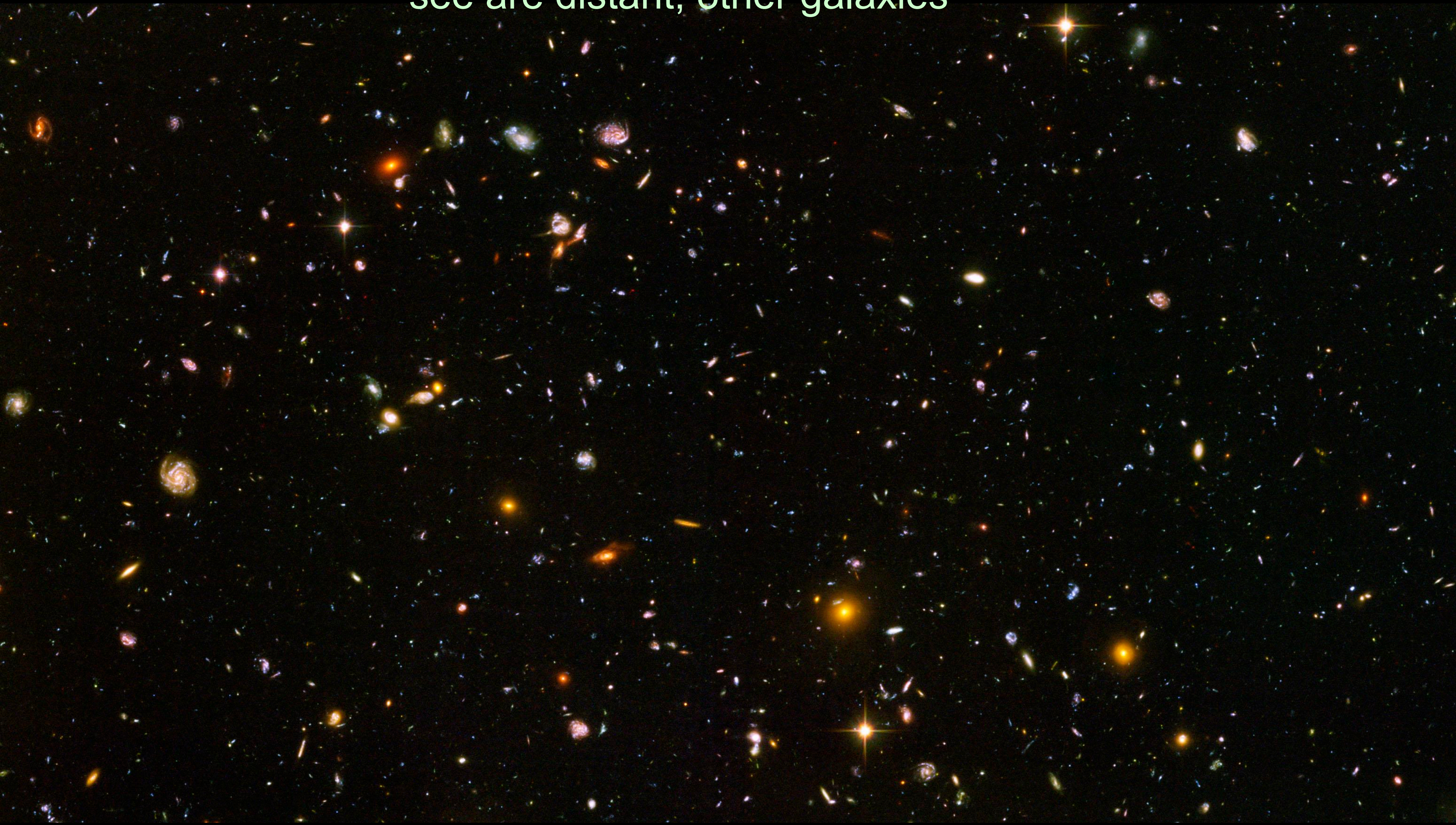
NOTES: Volume densities are taken from §4.2.1(b). Surface densities are computed from volume densities following Bahcall and Soneira (1980). Luminosity density is measured in the V band and is taken from Table 4-5 of MB. Surface brightness is taken from Bahcall and Soneira (1980) and de Vaucouleurs and Pence (1978). Volume and luminosity densities are measured in the galactic plane.

conclusions:

- The mean distance between stars is a couple of parsecs or ~ 10 light-years
- An average star has perhaps ~½ the solar mass → we know both the number and the mass of stars in our Galaxy
- In the solar neighborhood we have a substantial complement of gas (H + He + a few percent of “metals”)

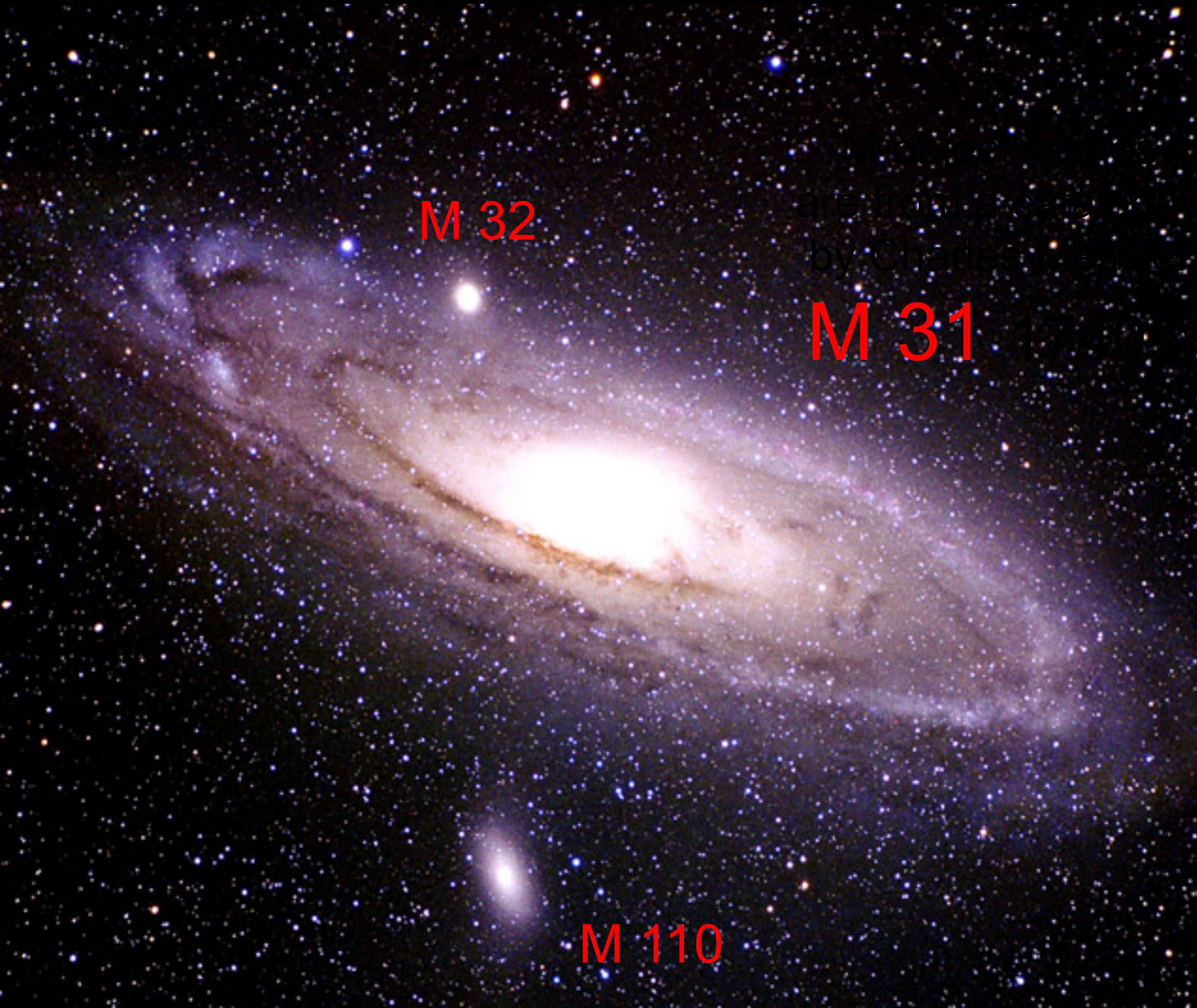
Universe as seen by Hubble Space Telescope

when you look at a very small patch of the sky with a powerful telescope, you look between the stars of the Milky Way and most of the objects you see are distant, other galaxies



Hubble observations of M 106 with additional information captured by amateur astronomers Robert Gendler and Jay GaBany. Gendler combined Hubble data with his own observations to produce this stunning color image. M 106 is a relatively nearby spiral galaxy, a little over 20 million light-years away.

Spiral Andromeda galaxy M31with two elliptic companions:



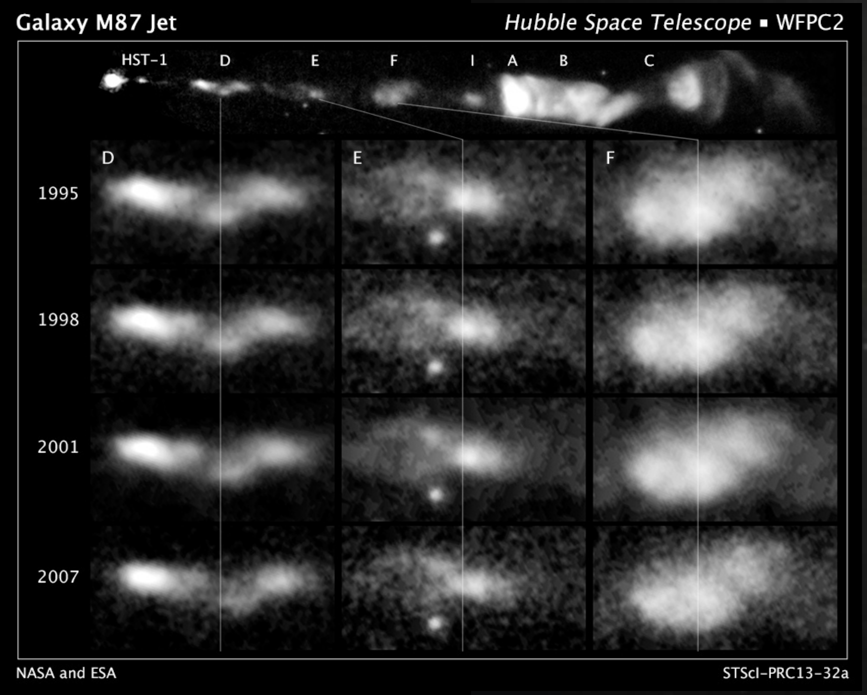
Elliptical galaxy
ESO 325-G004

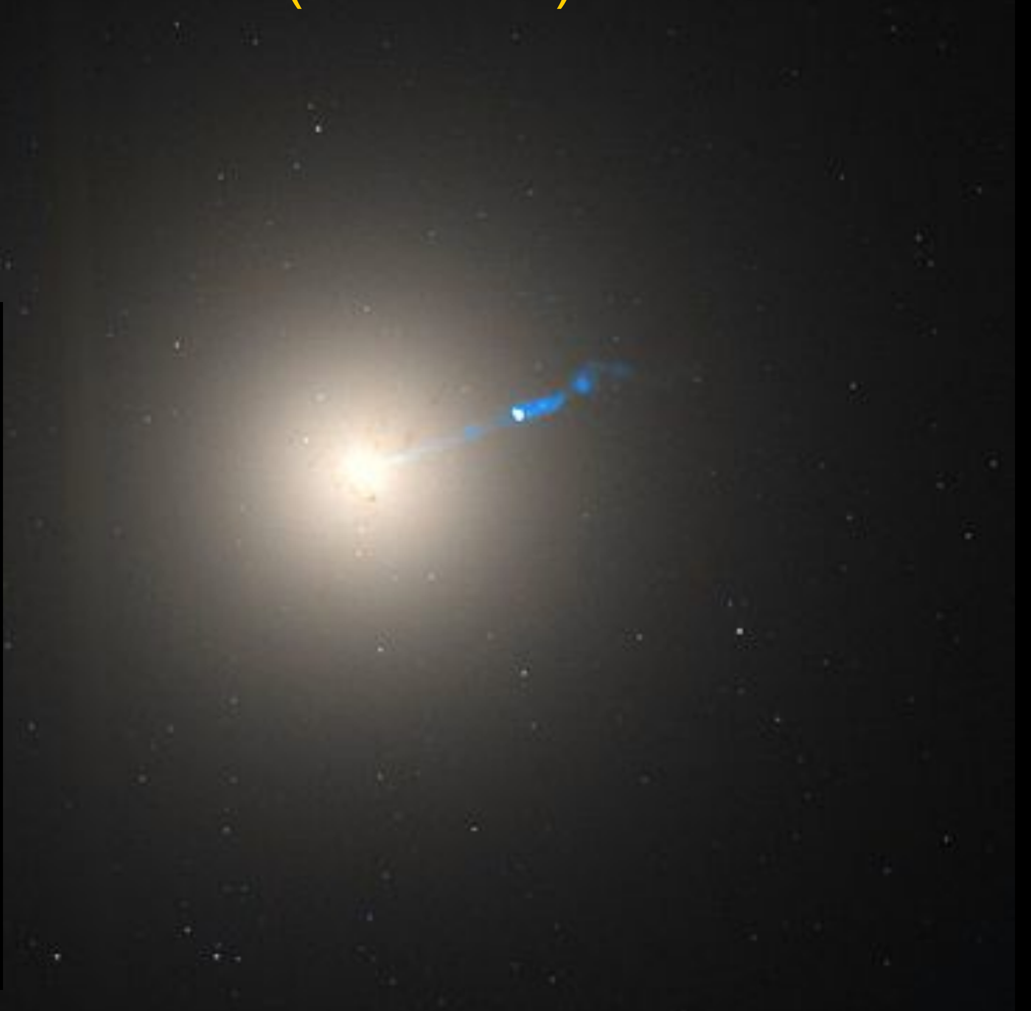
Such giant ellipticals (type denoted as cD) usually live in centers of galaxy clusters, have little gas but many globular clusters.

They are cannibals, themselves formed in collisions (mergers) of disk galaxies

M87 and its jet noticed by Heber Curtis (Lick Obs)

the second-brightest
member of Virgo cluster
of galaxies





M87 has ~10 times more
globular clusters than Milky Way and is much more massive