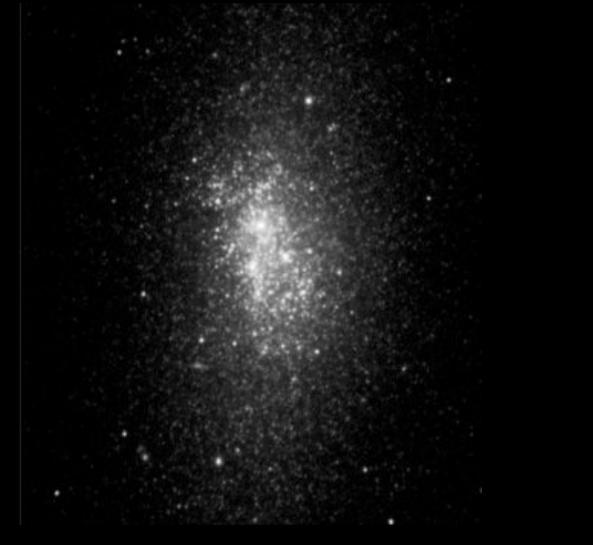
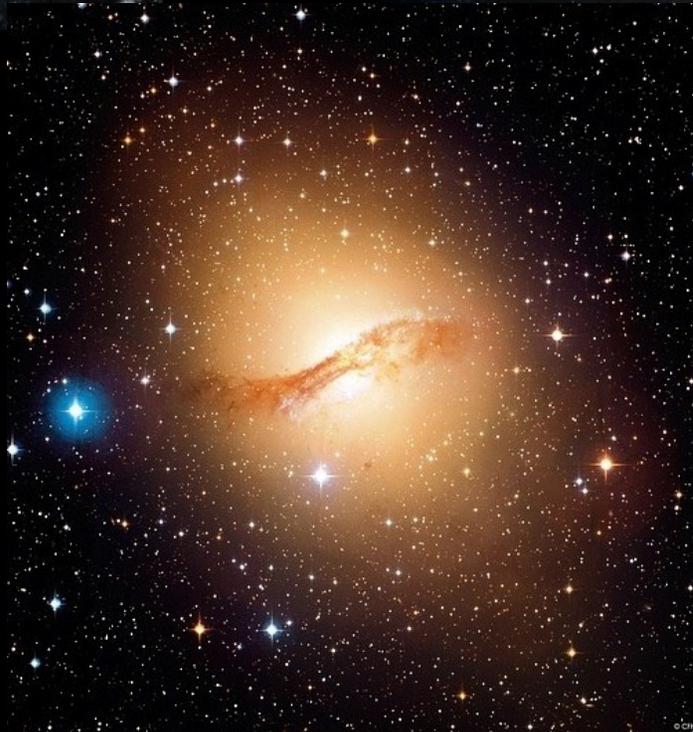
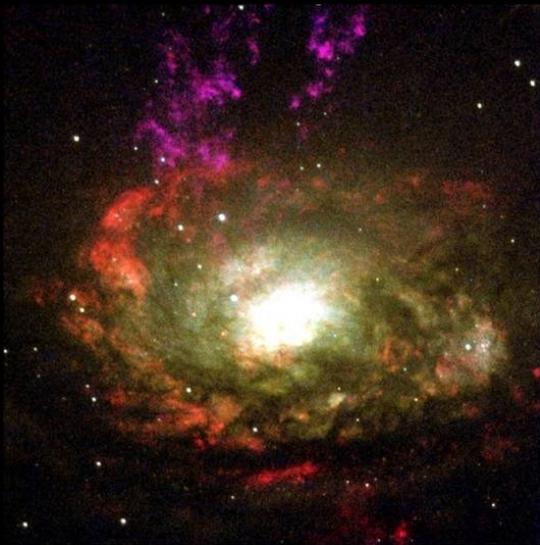


Astronomy 537



Introduction to Galaxies

Sample of Galaxies



Sample of Galaxies



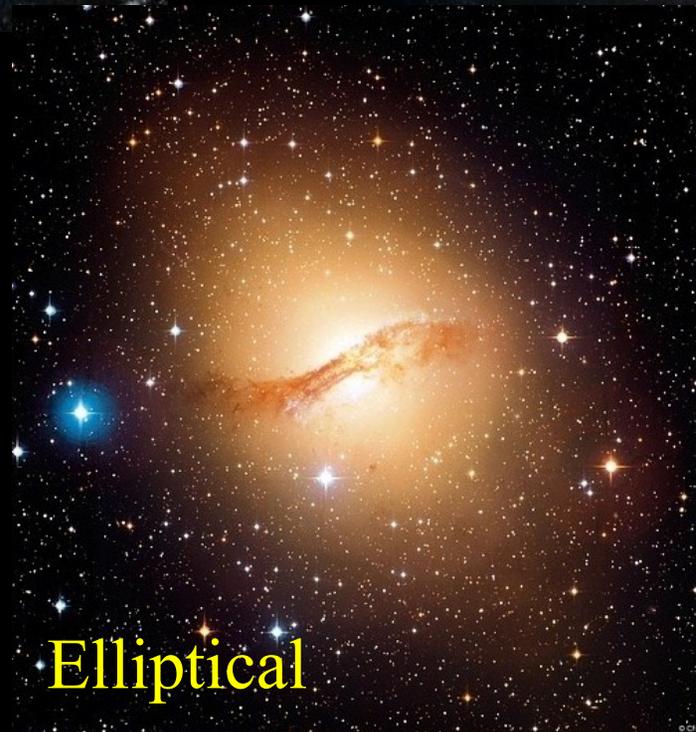
Spiral



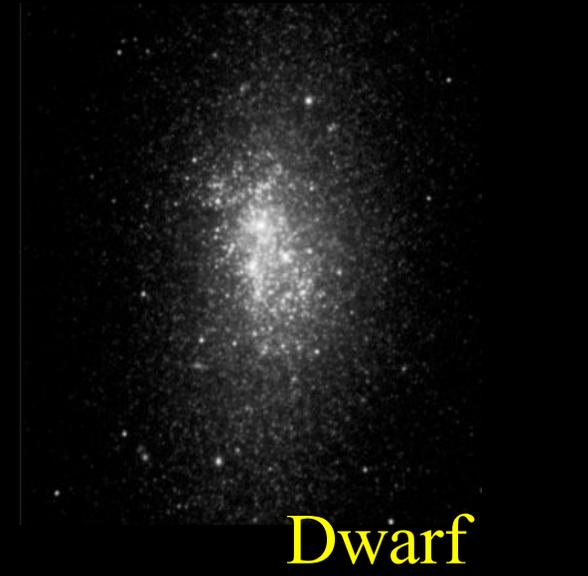
Barred Spiral



Seyfert 2

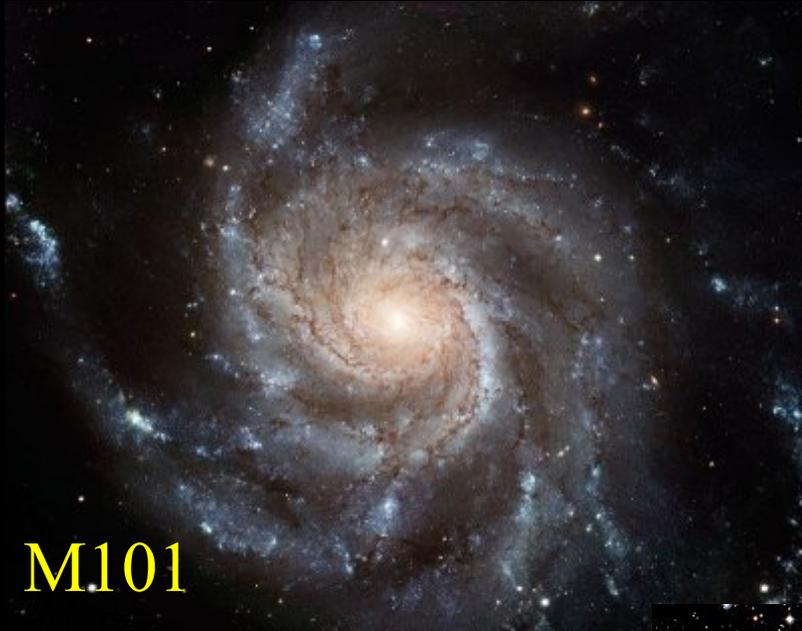


Elliptical

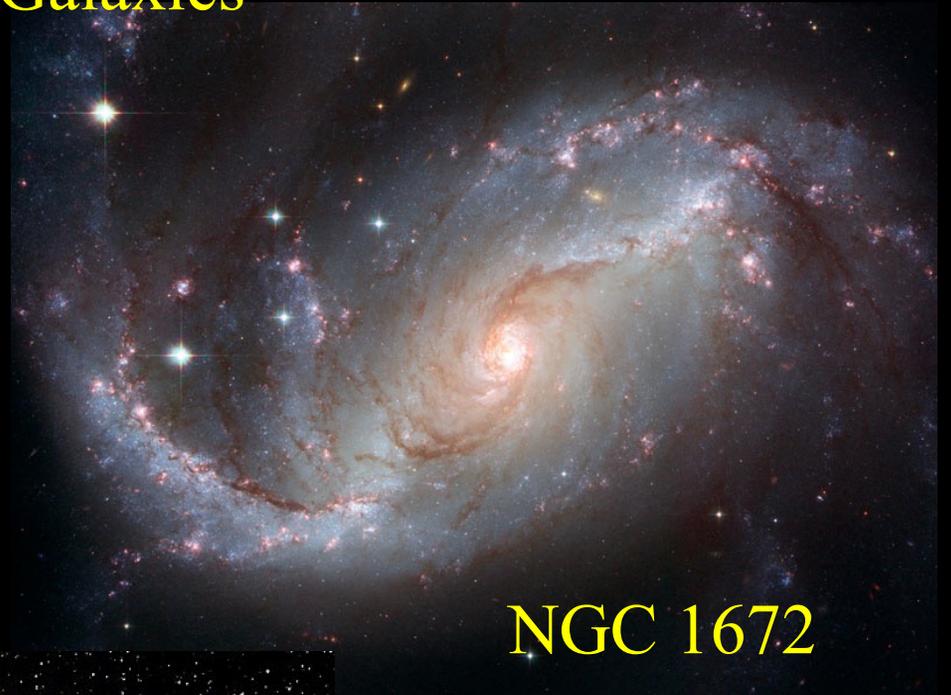


Dwarf

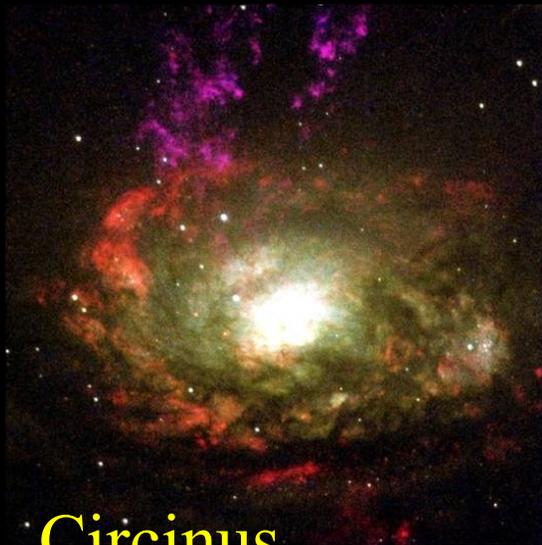
Sample of Galaxies



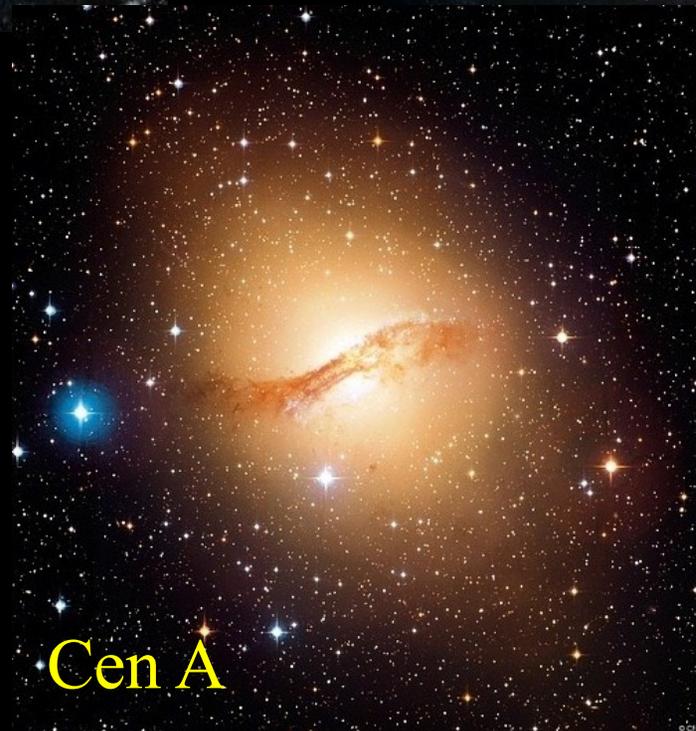
M101



NGC 1672



Circinus



Cen A



NGC 5253

About this class:

Prof: Greg Taylor

Goals: We will learn about galaxies and their evolution, with a focus on our current understanding and the future for this field.

Class Web page: <https://leo.phys.unm.edu/~gbtaylor/astr537/>

Methods:

- Galaxy Journal Club, Every Wednesday one of you leads a discussion on a paper I assign. **Order: Anthony-Semenova, Woodkensia, Pavel, Hort, Li, Burch, Stamer**
- A few homework assignments, AI use encouraged
- Worksheets (will be graded)
- Two midterms, no final
- Teaching exercise, on topics related to course (will discuss next class)

Journal Class:

- Everybody reads paper (skip the appendices)
- Leader (for Paper 1 **Anthony-Semenova**)
 - Gives a summary of the important points in the paper (~ 10 min) referring to interesting figures
 - Defines any unusual terminology
- **Group discussion**
 - Is the paper well motivated?
 - Points out any major assumptions or flaws
 - Are the results plausible? Important?

About this class:

Today

Your interests

A little history

The Hubble Sequence

Luminosity classes

Normal galaxies

Comet hunter Charles Messier (1730-1817) cataloged 103 "fuzzy things" which didn't move on the sky - not comets.

E.g.:

- M1 - Crab nebula
- M42 - Orion nebula
- M13 - globular cluster in Hercules
- M45 - Pleiades open cluster
- M31 - nebula in Andromeda

Many of these, including M31, were seen to have spiral structure when examined with better telescopes.

Galaxies

First spiral nebula found in 1845 by the Earl of Rosse.
Speculated it was beyond our Galaxy.



What are these "spiral nebulae"?

Appeared to be rotating

Have large recessional velocities Slipher (1912, 1917).

Main questions: how far away are they?

how big compared to Milky Way?

The Shapley-Curtis Debate (1920)

Harlow Shapley: *They are in the Galaxy*

Heber Curtis: *They are like the Galaxy, but separated from it.*

Shapley:

Recall Shapley thought the Milky Way was 100 kpc in diameter, so 2 times too big.

1. If M31 were like the Milky Way, its angular size ($\sim 3^\circ \times 1^\circ$) makes it so far away (2 Mpc \gg 770 kpc=true distance) that its novae are anomalously luminous.
2. Adrian van Maanen measured rotation of several spiral nebulae including M101 at 0.021 ± 0.001 arsec/yr. M101 is about $25'$ on the sky and we can assume it is also about 100 kpc across.

Worksheet:

What circular velocity would this imply for M101's outer edge if it were 100 kpc in diameter? How does that compare to V_{\max} for the Milky Way?

TABLE 3. Summary of van Maanen's results for internal motions in seven spirals.

Object	Date published	Mean $\mu_{\text{rot}} [^{\circ}/\text{yr}]$	Mean $\mu_{\text{rad}} [^{\circ}/\text{yr}]$
M101	1916 ⁸	+0.021 \pm 0.001	+0.003 \pm 0.001
M33	1921 ²²	+0.020 \pm 0.003	+0.006 \pm 0.002
M51	1921 ²²	+0.019 \pm 0.001	+0.008 \pm 0.001
M81	1921 ²²	+0.020 \pm 0.004	+0.017 \pm 0.003
NGC 2403	1922 ³⁰	+0.015 \pm 0.001	+0.014 \pm 0.001
M94	1922 ³¹	+0.020 \pm 0.002	+0.010 \pm 0.002
M63	1923 ³²	+0.019 \pm 0.001	+0.004 \pm 0.001
M33	1923 ³³	+0.020 \pm 0.001	+0.003 \pm 0.001

Berendzen, R. & Hart, R. 1973

Van Maanen used a “stereocomparator” to measure motions between two Plates taken at Mount Wilson

Note that Brunthaler et al (2005) recently measured the angular rotation rate of M33 using H2O masers of $6 \times 10^{-5} \pm 1 \times 10^{-5}$ “/yr compared to van Maanen’s 0.020 ± 0.003 “/yr (400 times bigger)

Brunthaler also use their result to derive a more accurate distance to M33

Curtis:

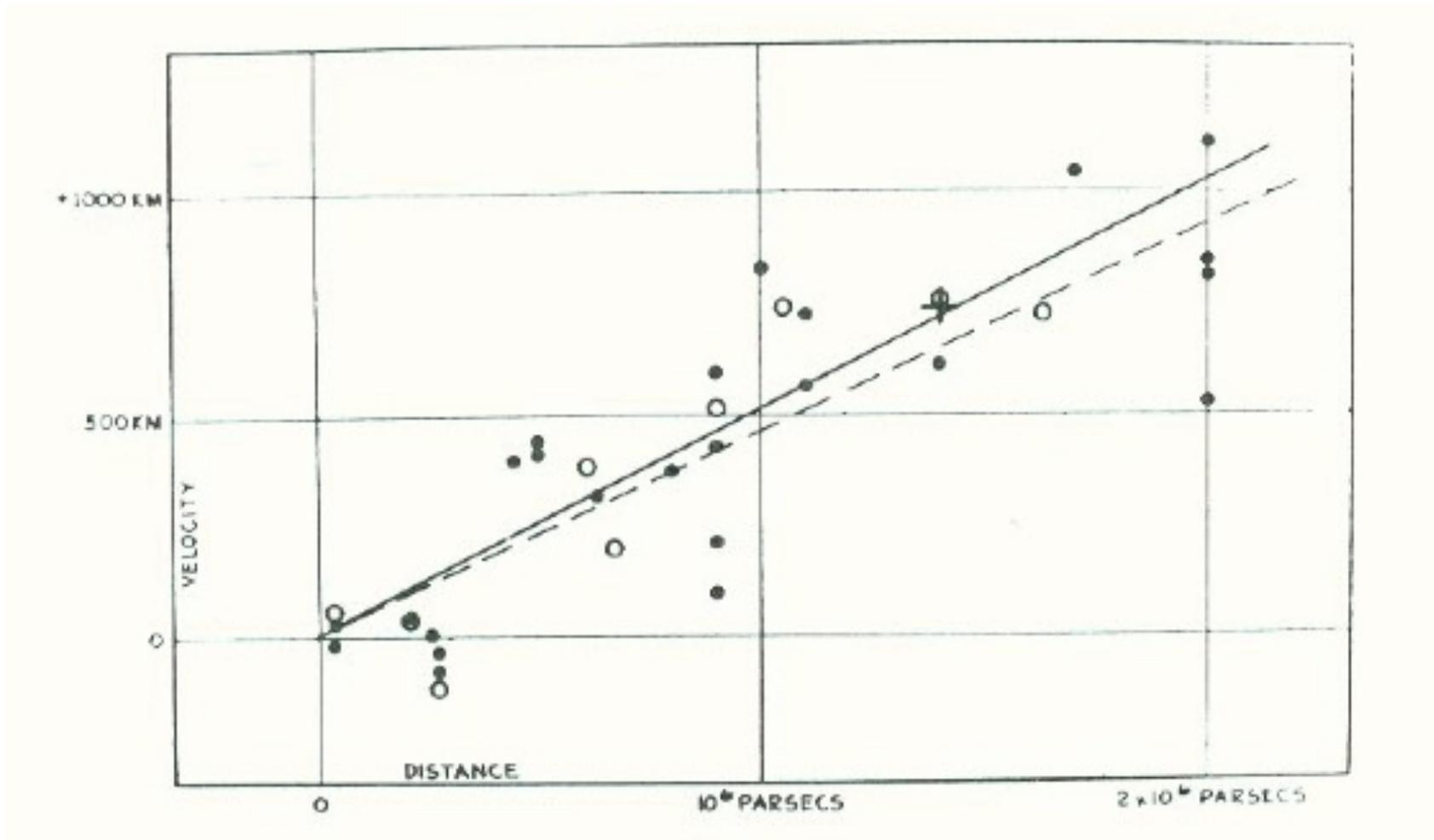
1. Brightness of novae would mean they must be > 150 kpc away, and M31 would be similar to Kapteyn's estimate of the Milky Way size (10 kpc).
2. Slipher had measured large recessional velocities for many spiral nebulae. If

$$V_r \sim V_{transverse}$$

then would have measurable proper motions if within the Galaxy. They don't! Also, large v_r implies not gravitationally bound.

3. Had more natural explanation for the *zone of avoidance*.

Hubble Law

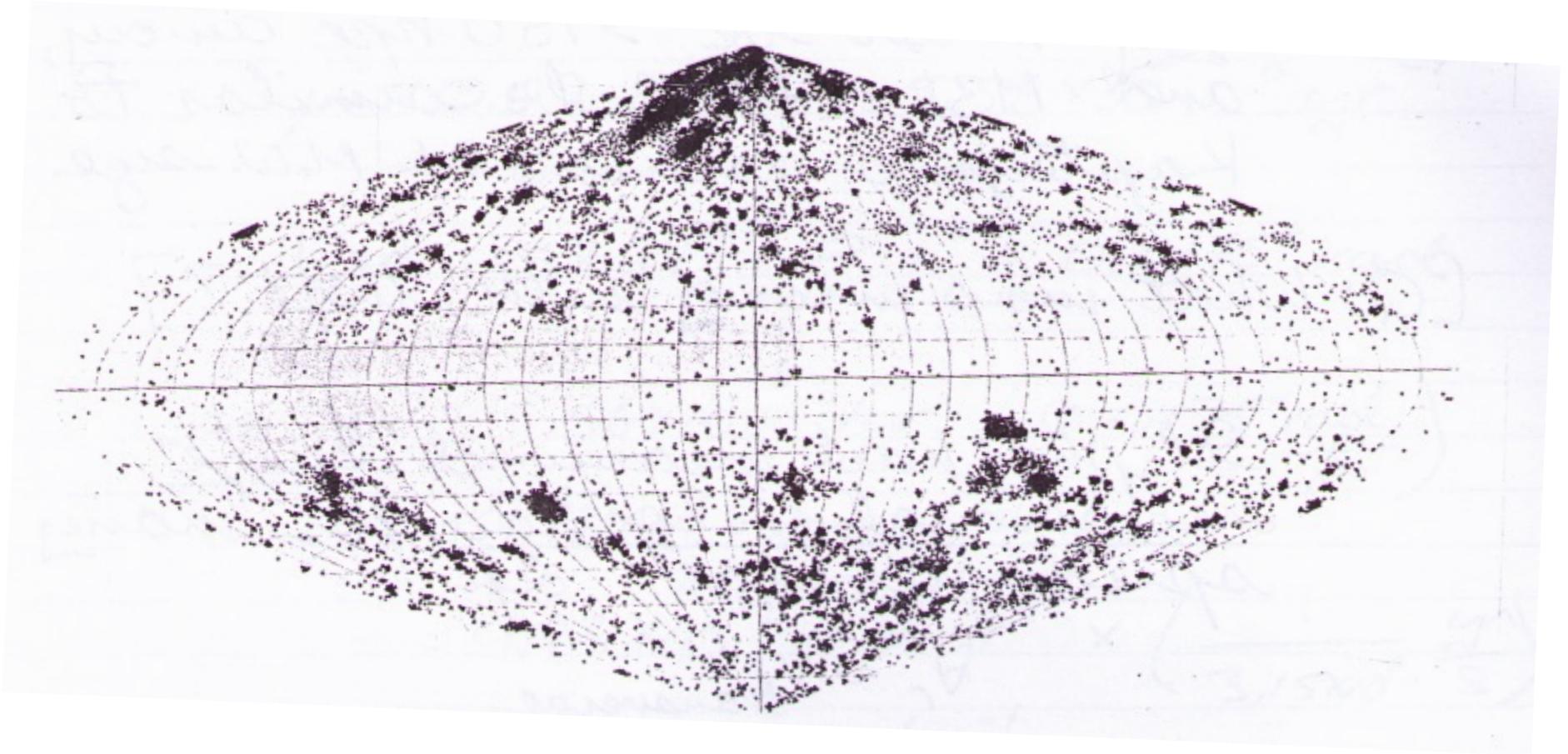


Hubble 1929

Note: All but two of the velocities come from work by Slipher

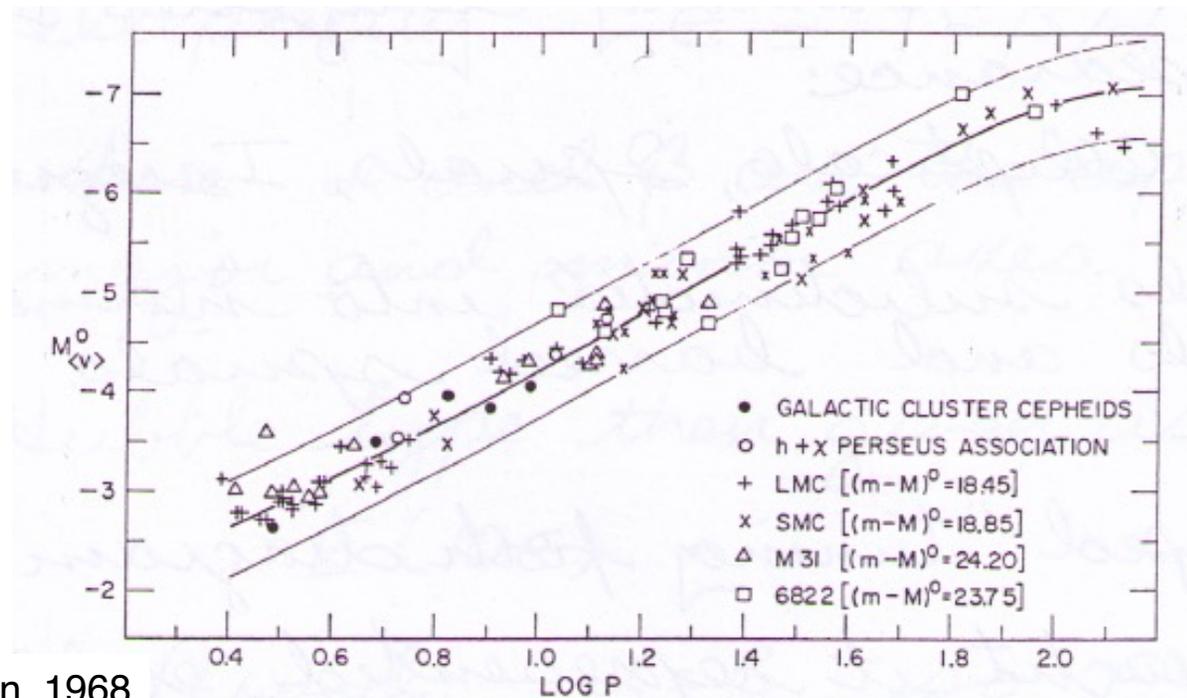
Map of distribution in Galactic lat and long of NGC objects. Made by Charlier in the 1920's.

Most noticeably, spiral nebulae were not found near Galactic plane.



- Shapley - new repulsive force, maybe related to large recessional velocities.
- Curtis - many edge-on spirals show dust lanes. If Milky Way is also like them and Sun is in dust, then zone of avoidance is due to obscuration.

Resolution: in 1923 Edwin Hubble found Cepheid variable stars in M31.



Sandage & Tammann, 1968

$M_{\langle v \rangle}$ = average absolute visual magnitude

P = pulsation period in days

$$M_{\langle v \rangle} = -2.81 \log P - 1.43$$

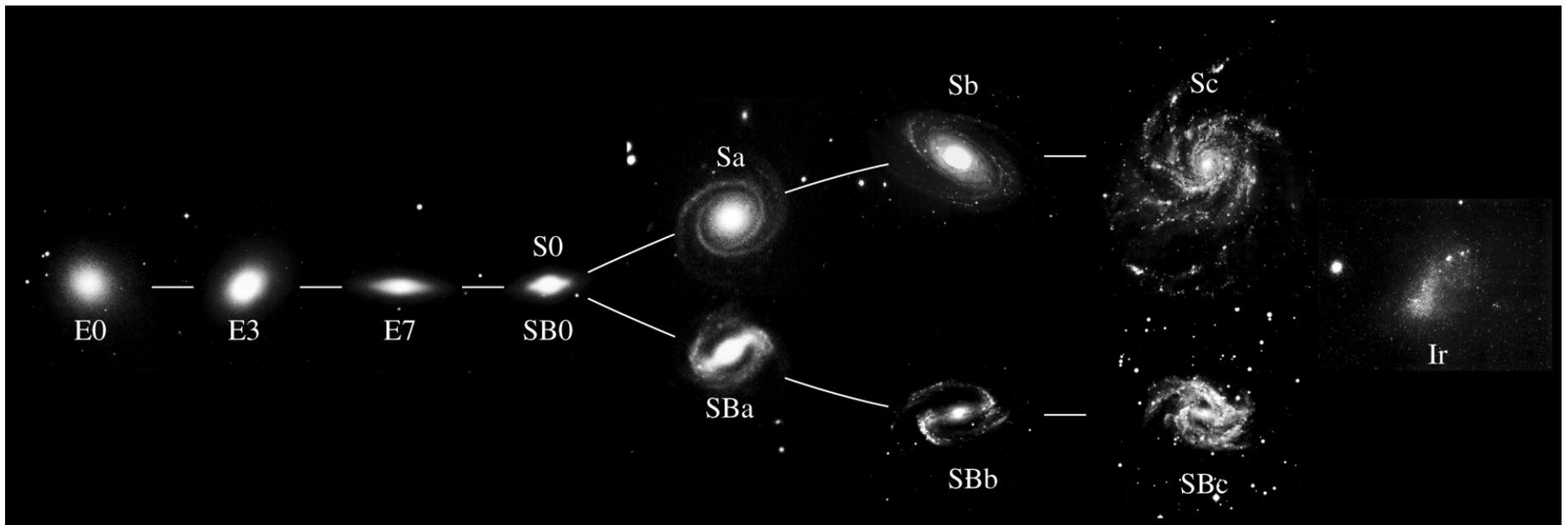
Measuring m , inferring M from P above, got distance to M31 of 285 kpc => extragalactic!

Modern value of this distance = 770 kpc.

Morphological classification

Hubble noted galaxies can be grouped into three primary categories based on appearance: ellipticals, spirals and irregulars. Spirals subdivided into normal and barred spirals.

Based on these categories, Hubble developed the *tuning fork diagram*. He thought it represented evolution (it does NOT!).



Early types

Late types

Ellipticals

Divided based on observed ellipticity $\epsilon \equiv 1 - \frac{\beta}{\alpha}$

where α and β are the apparent major and minor axes. The Hubble type is then given as:

$$E(10\epsilon)$$

Example - round: $\alpha = \beta$, so $\epsilon = 0$, type $E0$

Observed ellipticals vary between $E0$ to $E7$.

What is β/α for an $E7$?

Problem: this is based on *apparent* ellipticity.

What is ellipticity of a basketball?

Of an end-on American football?

Are they really the same shape?

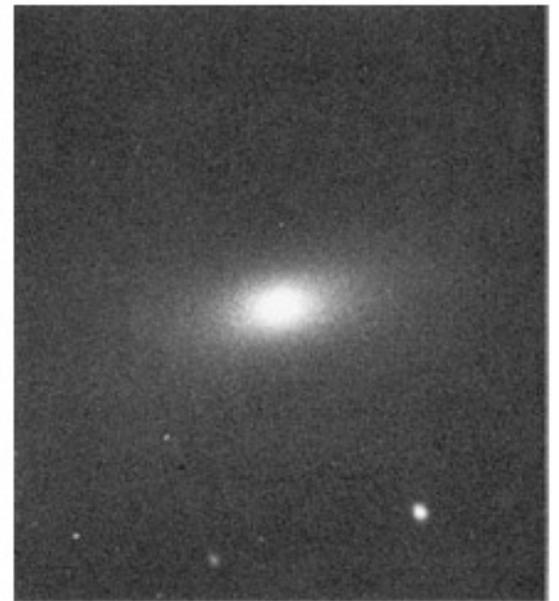
Example ellipticals



E0



E3



E6

Spirals

Subdivided by Hubble according to L_{bulge}/L_{disk} , tightness of spiral arms, and smoothness of arms.

Normal: Sa Sab Sb Sbc Sc

Barred: SBa SBab SBb SBbc SBc

where $\frac{L_{bulge}}{L_{disk}} \sim 0.3 \rightarrow \sim 0.05$

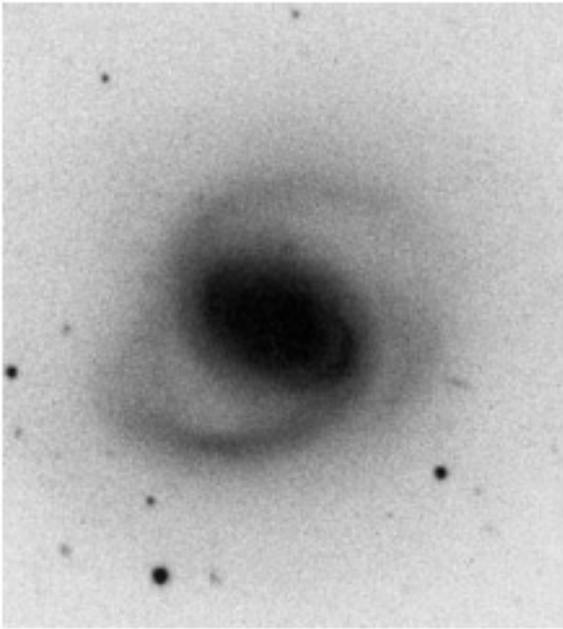
arm pitch angle $\sim 6^\circ \rightarrow 18^\circ$

pitch angle - angle between tangent to spiral arm and tangent to circle where they would cross.

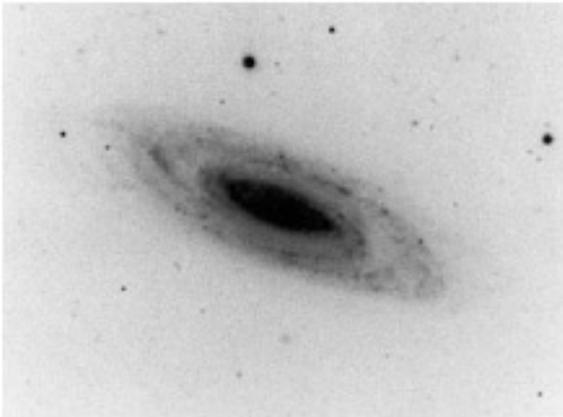
Smoothest distribution of stars -> arms resolved into clumps of stars, HII regions.



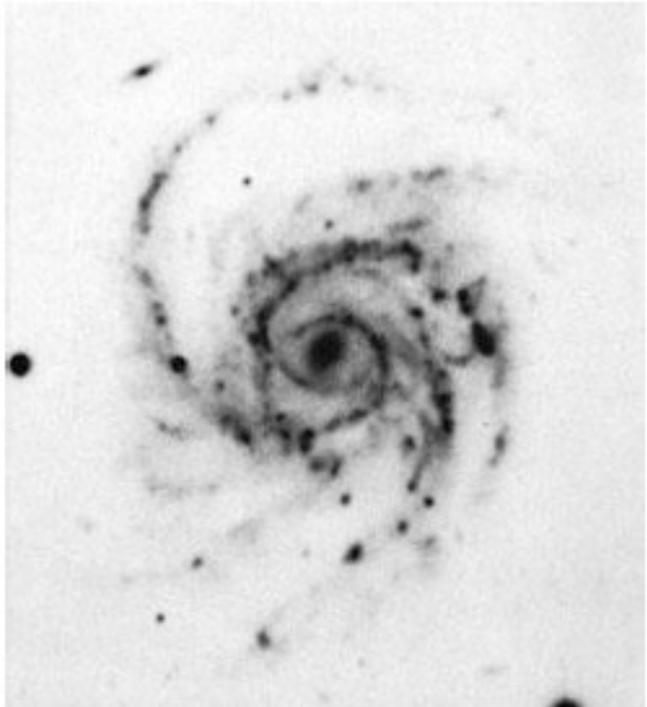
Example spirals



Sa

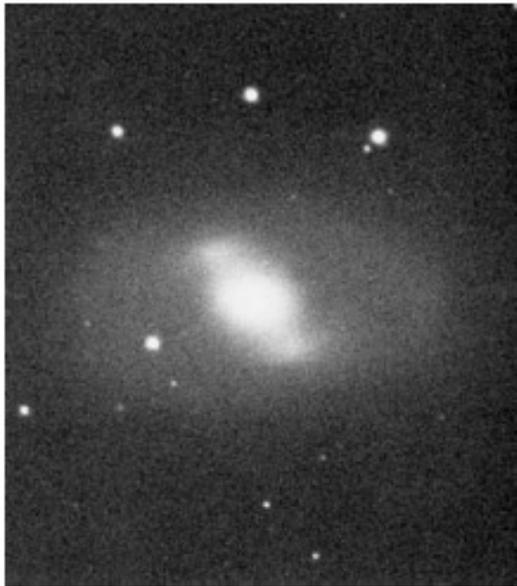


Sb

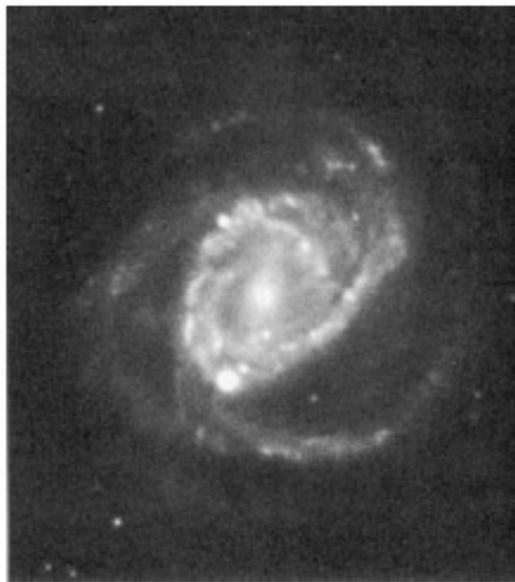


Sc

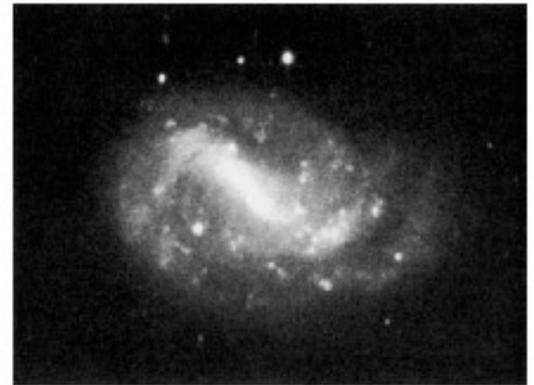
Example barred spirals



SBa



SBb



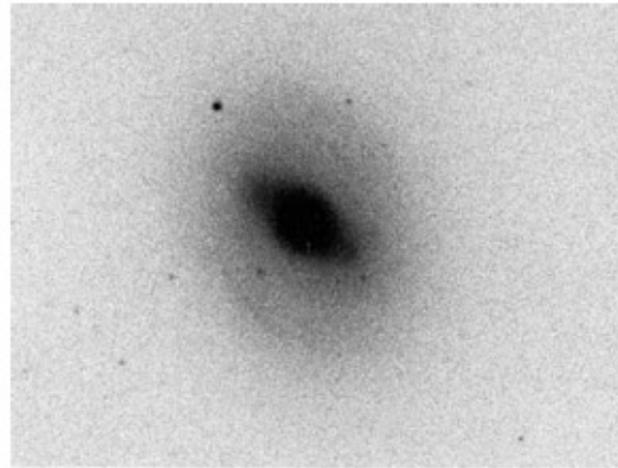
SBc

Lenticulars

S0 and SB0, a transitional class: bulge, disk, but no arms. Flatter than E7.



S0

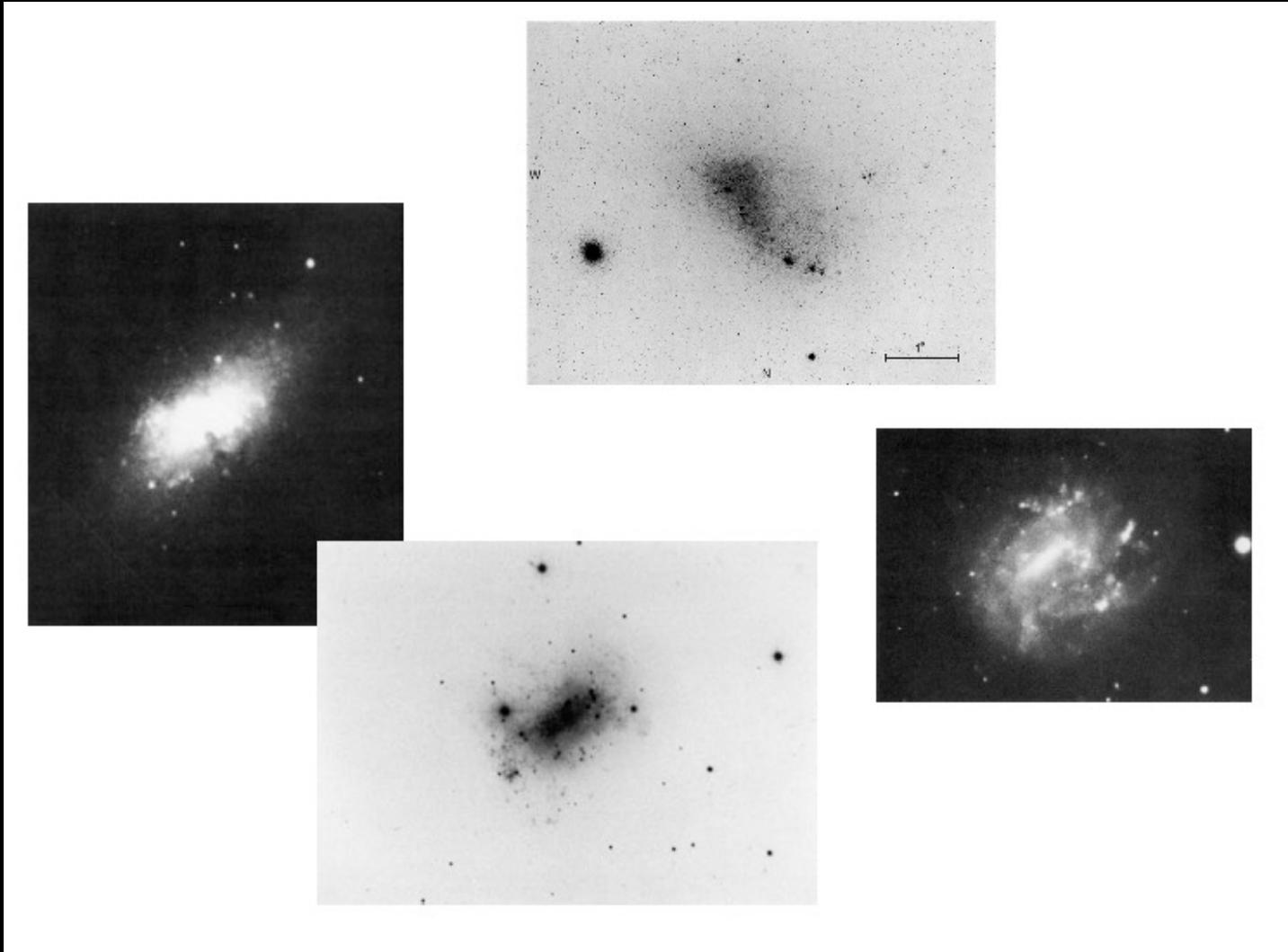


SB0

Irregulars

Irr I - some hint of organized structure

Irr II - disorganized



Since Hubble, the following changes to the classification schemes were made:

de Vaucouleurs eliminated Irr I and Irr II:

Irr I -> Sd (SBd), Sm (SBm), or Im where *m* stands for *magellanic*.

Irr II -> Ir

van den Bergh (1960) introduced *luminosity classes* I – V for Spirals

I - strong, well defined arms, high luminosity

V - least distinct arms, chaotic or “*flocculent*”, low luminosity

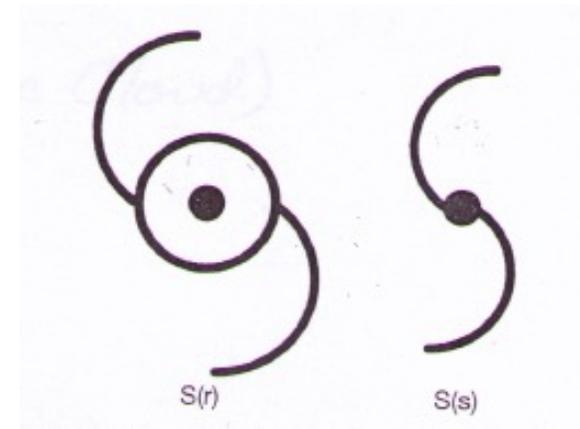
Modern sequence of late-type galaxies

S0, Sa, Sab, Sb, Sbc, Sc, Scd, Sd, Sm, Im, Ir

Similar for barred spirals.

Finally, arms spiral into central regions in different ways:

- (s) all the way into nucleus
- (r) spiral into ring around nucleus
- (rs) or (sr) intermediate

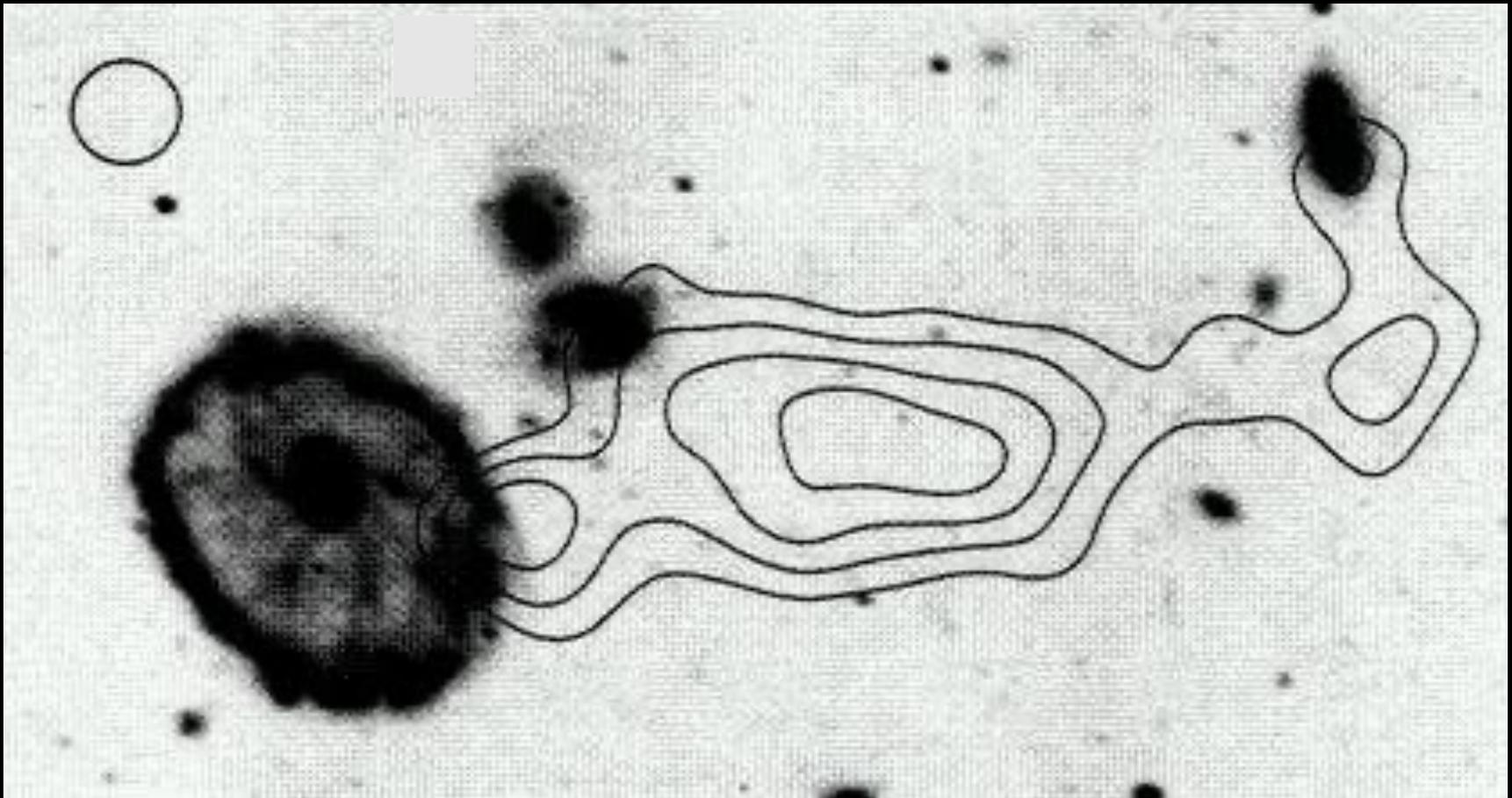


Sometimes galaxies have rings in outer disks, near end of spiral arms => an *R* in front of the type.

Cartwheel Galaxy



VLA observations show a bridge of atomic gas connecting Cartwheel and a more distant galaxy.



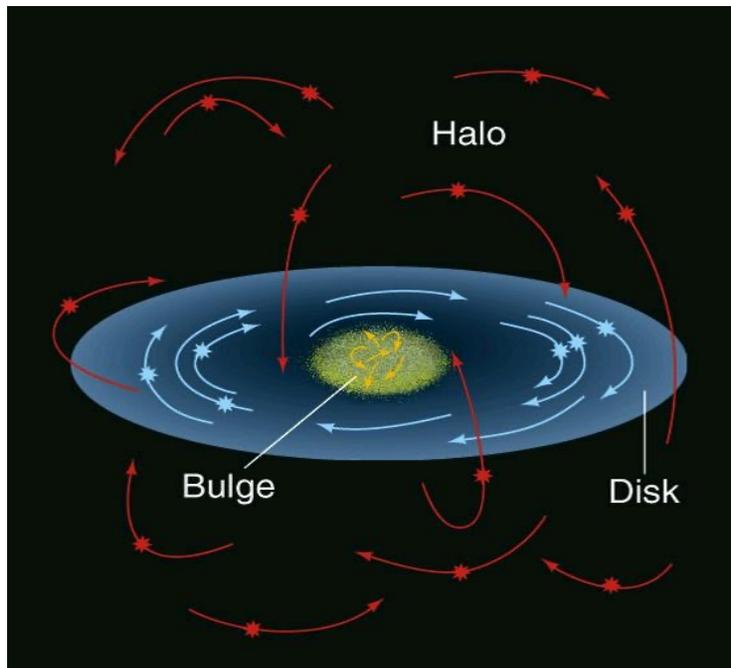
Another Ring Galaxy: AM 0644-741



Ellipticals are similar to halos of spirals, but generally larger, with many more stars. Stellar orbits are like halo star orbits in spirals. Stars in ellipticals also very old, like halo stars.

An elliptical

Orbits in a spiral



A further distinction for ellipticals and irregulars:

Giant

vs.

Dwarf

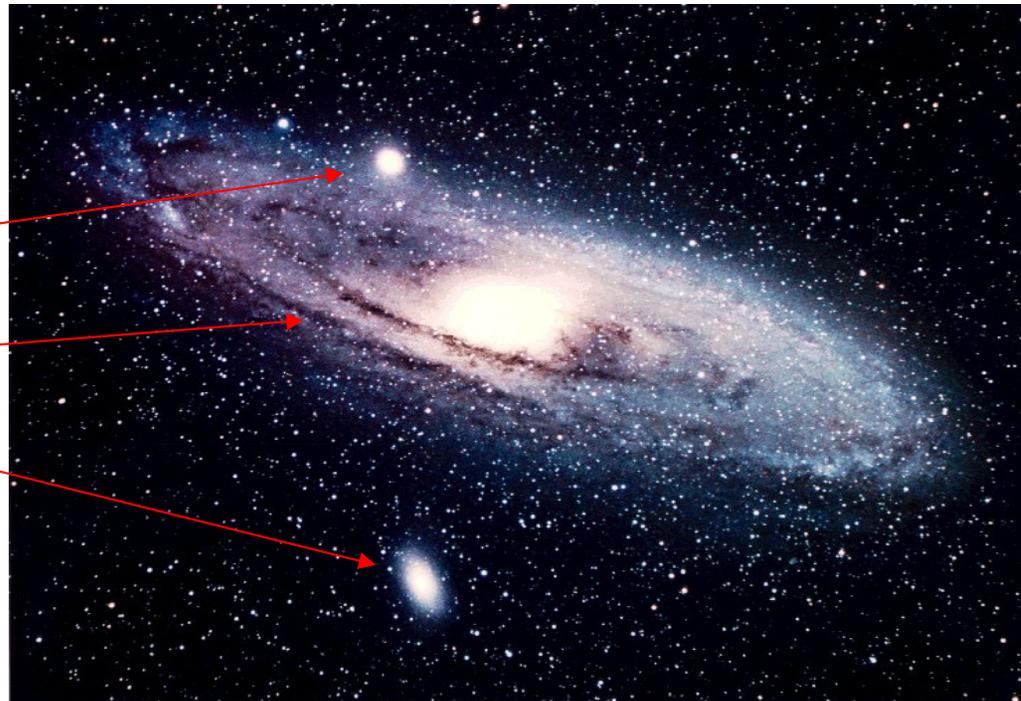
$10^{10} - 10^{13}$ stars
10's of kpc across

$10^6 - 10^8$ stars
few kpc across

Dwarf Elliptical NGC 205

Spiral M31 (Andromeda)

Dwarf Elliptical M32



In giant galaxies, the average elliptical has more stars than the average spiral, which has more than the average irregular.

What kind of giant galaxy is most common?

Spirals - about 77%

Ellipticals - 20%

Irregulars - 3%

But dwarfs are much more common than giants.

But Giants contain most of the stars

The Variety of Galaxy Morphologies



- a) elliptical
- b) spiral
- c) barred spiral
- d) dwarf
- e) irregular



<http://galaxyzoo.org/>

What is missing from the Hubble Sequence?

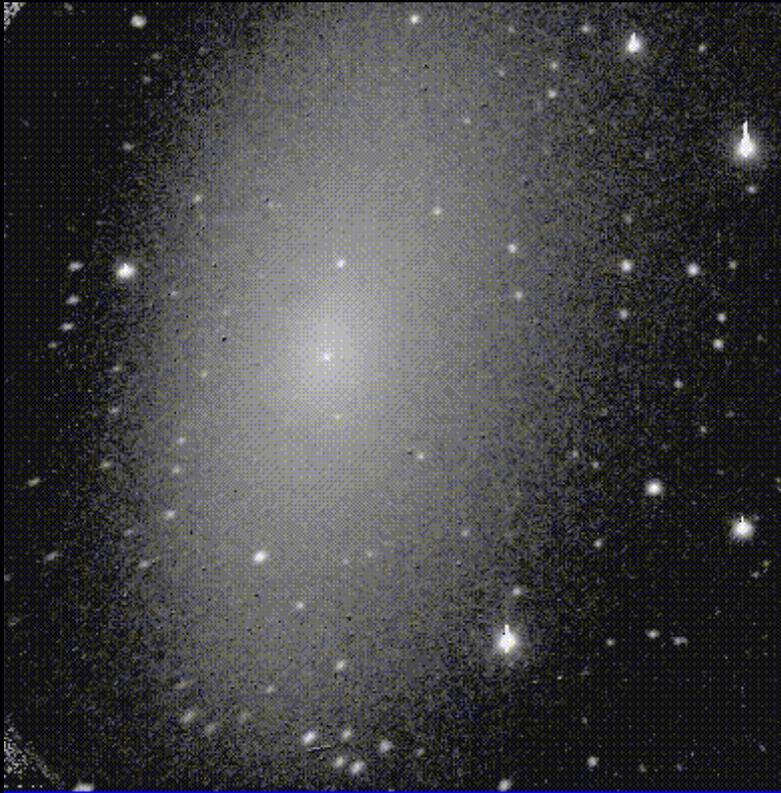
What is missing from the Hubble Sequence?

- Dwarf galaxies
 - faint ($M > -18$), dwarf ellipticals, spheroidals and irregulars
 - Probably plenty of those
- Low Surface Brightness Galaxies
 - Hard to detect, need dedicated surveys, probably lots of them
- Peculiar galaxies
 - Especially interacting galaxies
 - Many of those cataloged by Arp in 1966

Leo I - Dwarf spheroidal galaxy



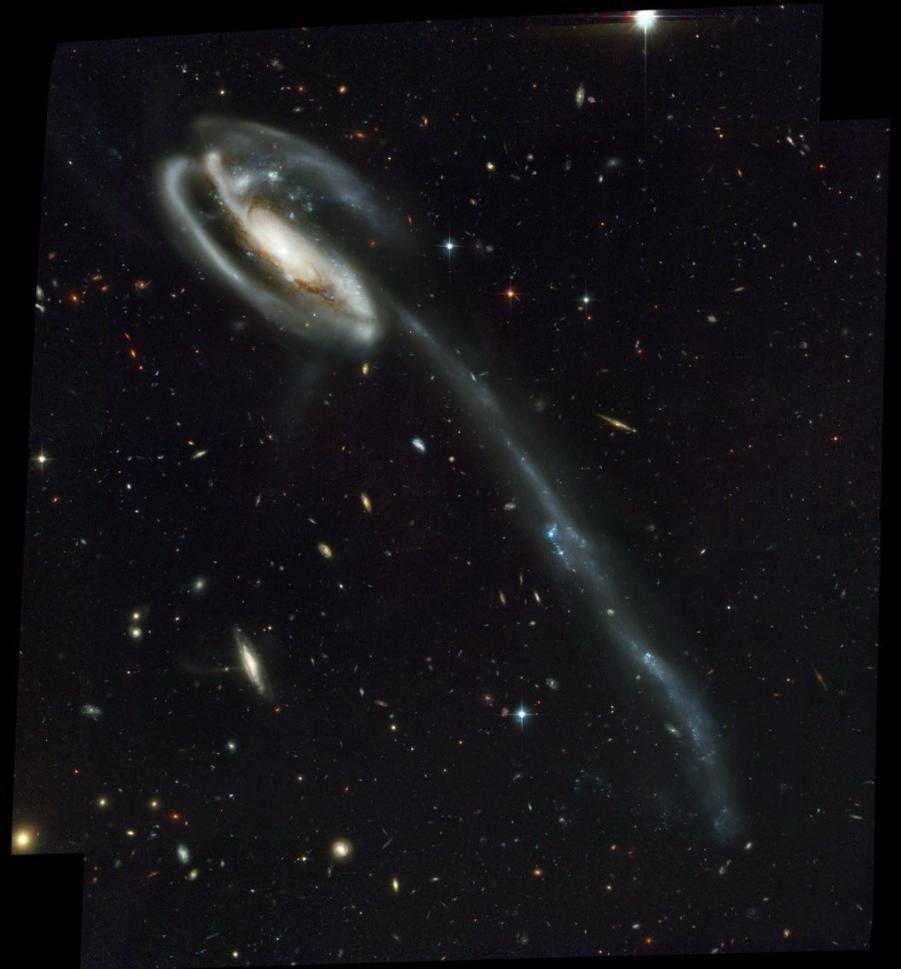
NGC205: Dwarf elliptical



IC10: Dwarf irregular



Interacting galaxies: the Mice and the Tadpole



Catalogs and atlases of galaxies

- Messier: cataloged 103 nebula that were not comets
 - ~40 are galaxies
- New General Catalog (NGC)
 - 7840 objects, ~50% galaxies
- Index Catalog (IC)
 - 6900 more objects in addition to NGC
- Shapley-Ames Catalog
 - whole-sky, bright galaxies $m < 13.2$, 1246 galaxies (all in NGC/IC)
 - revised by Sandage & Tamman in 1981
- Uppsala General Catalog (UGC)
 - based on Palomar Observatory Sky Survey (POSS), size limited $> 1'$, 13000 objects

- Morphological Catalog of Galaxies (MGC)
 - based on POSS plates, 32000 objects
- Hubble Atlas (Sandage 196) from plates used by Hubble
- Nearby Galaxies Atlas & Catalog
 - $v < 3000$ km/s
- Reference Catalog of Bright Galaxies (RC3)
 - $B < 15.5$, 23,022 galaxies
 - RC1 and RC2 previous versions
- Carnegie Atlas
 - images of galaxies in Revised Shapley-Ames

Newer catalogs includes

- Catalogs of sources in the radio, x-ray, infrared etc
- Recent galaxy surveys: APM, CfA redshift survey, 2dF redshift survey, Sloan Digital Sky Survey (SDSS)

... and so on....

Good source of information: NASA/IPAC Extragalactic Database (NED)

nedwww.ipac.caltech.edu

Why do we classify galaxies?

The classification can be shown to correlate with:

- Bulge/disk luminosity ratio
- Mass concentration
- Bulge – Black Hole Mass correlation
- Relative HI content ($M(\text{HI})/L(\text{B})$)
- Stellar population
- Nuclear properties
- Chemical abundances in the ISM
- Star formation history, and integrated stellar spectrum

Provides clues to formation and evolution of galaxies.

Overview of galaxy properties

	E	S0	Sa	Sb	Sc	Sd	Irr
Color	Red	—————→					Blue
Stellar pop	Old	Old/interm		Old + interm + young		Intermediate young	
SFR	None	Low	————→	Higher	————→		High
HI	None/Low	Low	————→	Modest	————→	High	Highest
Dust	None/Low	Higher		High	————	High	Lower (less metals)
Dyn	Bulge/halo dominated		Disk dom (rot)	————		Disk dom	

Schematic star formation histories:

