Galaxies:
Morphology and the Hubble Sequence

Galaxies

- The basic constituents of the universe at large scales
  - Distinct from the LSS as being too dense by a factor of $\sim 10^3$, indicative of an "extra collapse", and a dissipative formation
- Have ***a broad range of physical properties***, which presumably reflects their evolutionary and formative histories, and gives rise to various morphological classification schemes (e.g., the Hubble type)
- Understanding of galaxy formation and evolution is one of the main goals of modern cosmology
- There are $\sim 10^{11}$ galaxies within the observable universe
- Typical total masses $\sim 10^8$ - $10^{12}\ M_\odot$
- Typically contain $\sim 10^7$ - 10^{11} stars

Catalogs of Bright Galaxies

- In late 1700's, **Messier** made a catalog of 109 nebulae so that comet hunters wouldn't mistake them for comets!
  - About 40 are galaxies, e.g., M31, M51, M101; many are gaseous nebulae within the Milky Way, e.g., M42, the Orion Nebula; some are star clusters, e.g., M45, the Pleiades
- **NGC** = New General Catalogue (Dreyer 1888), based on lists of Herschel (5079 objects), plus some more for total of 7840 objects
  - About ~50% are galaxies, catalog includes any non-stellar object
- **IC** = Index Catalogue (Dreyer 1895, 1898): additions to the NGC, 6900 more objects
- Shapley-Ames Catalog (1932), rev. Sandage & Tamman (1981)
  - Bright galaxies, $m_{pg} < 13.2$, whole-sky coverage, fairly homogenous, 1246 galaxies, all in NGC/IC

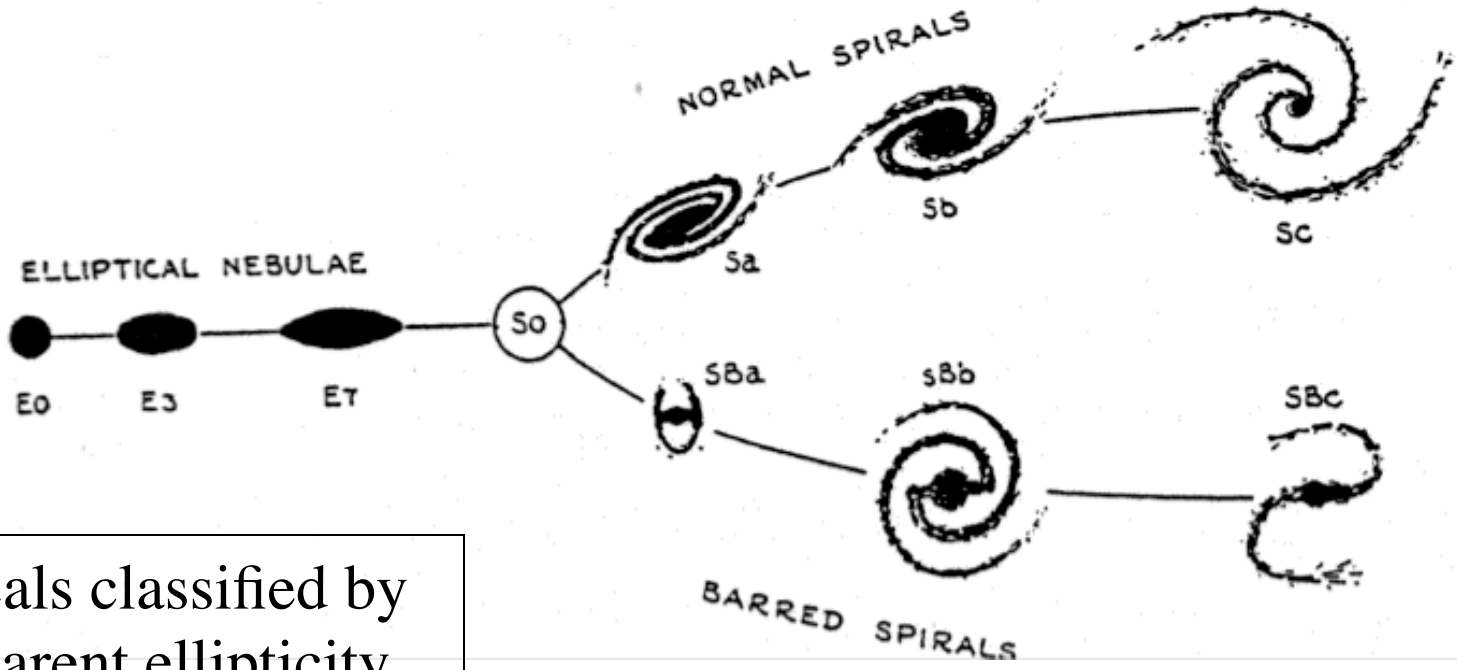
Catalogs of Bright Galaxies

- **UGC** = Uppsala General Catalog (Nilson 1973), ~ 13,000 objects, mostly galaxies, diameter limited to > 1 arcmin
  - Based ased on the first Palomar Observatory Sky Survey (POSS)
- **ESO** (European Southern Observatory) Catalog, ~ 18,000 objects
  - Similar to UGC, 18000 objects
- **MCG** = Morphological Catalog of Galaxies (Vorontsov-Vel'yaminov et al.), ~ 32,000 objects
  - Also based on POSS plates, $-2° < \delta < -18°$
- **RC3** = Reference Catalog of Bright Galaxies (deVaucoleurs et al. 1991), 23,022 galaxies, magnitude limited to $B < 15.5$
  - Essentially a heterogeneous data compilation
  - Preceded by RC1 (1964, 2599 galaxies) and RC2 (1976, 4364 galaxies)
- Nowadays we have automated surveys, e.g., DPOSS, SDSS, with tens to hundreds of millions of galaxies; and this will grow…

Morphological Classification and Galaxy Types

- The first step in any empirical science: look for patterns and trends, then try to understand the underlying physics
- Hubble proposed a scheme for classifying galaxies (the "tuning fork" diagram) in his 1936 book, *The Realm of the Nebulae*
- Subsequent refinements proposed by de Vaucouleurs (T-types), van den Bergh, and others - but not any fundamental change
- Nowadays we seek to define galaxy families through their physical properties and fundamental correlations - which reflect their physics and formative histories
- A better approach may be to look at the properties of *subsystems* within galaxies (e.g., disks, spheroids, halos, etc.), and deduce their origins and evolution

Hubble's Classification Scheme



Ellipticals classified by the apparent ellipticity

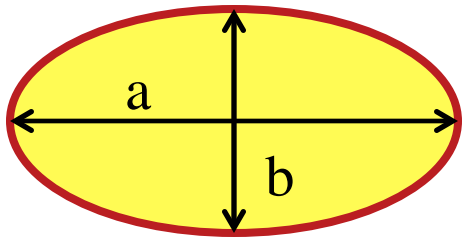
Spirals classified by the prominence of the spiral arms, and the presence of bars

Hubble thought (incorrectly) this was an evolutionary sequence, so ellipticals are called "early-type" and spirals "late-type" galaxies

Elliptical Galaxies

- About 20% of field galaxies are E's, but most E's are in clusters
- There are a number of different subtypes:
  - E's (normal ellipticals)
  - cD's (massive bright ellipticals at the centers of galaxy clusters)
  - dE's (dwarf ellipticals) } Not really ellipticals, a different class of objects
  - dSph's (dwarf spheroidals) } Not really ellipticals, a different class of objects
- Smooth and almost featureless: no spiral arms or dust lanes. Generally lacking in cool gas, and hence few young blue stars
- Classified by the apparent ellipticity:

$$\varepsilon = 1 - \frac{b}{a}$$



Elliptical galaxies are denoted E*n*, where:

$$\frac{b}{a} = 1 - \frac{n}{10}$$

A round elliptical is E0, the most elongated ellipticals are E7

Elliptical Galaxies

M87 in Virgo

M84 and M86

Lenticular (S0) Galaxies

- Transition class between ellipticals and spirals are the S0 galaxies, also called **lenticulars**
- S0 galaxies have a rotating disk in addition to a central elliptical bulge, but the disk lacks spiral arms or prominent dust lanes, i.e., no active star formation
- Lenticulars can also have a central bar, in which case they are labeled SB0

Sombrero galaxy

Spiral Galaxies

Named for their bright spiral arms, which are prominent due either to bright O and B stars (evidence for recent star formation), or to dust lanes.

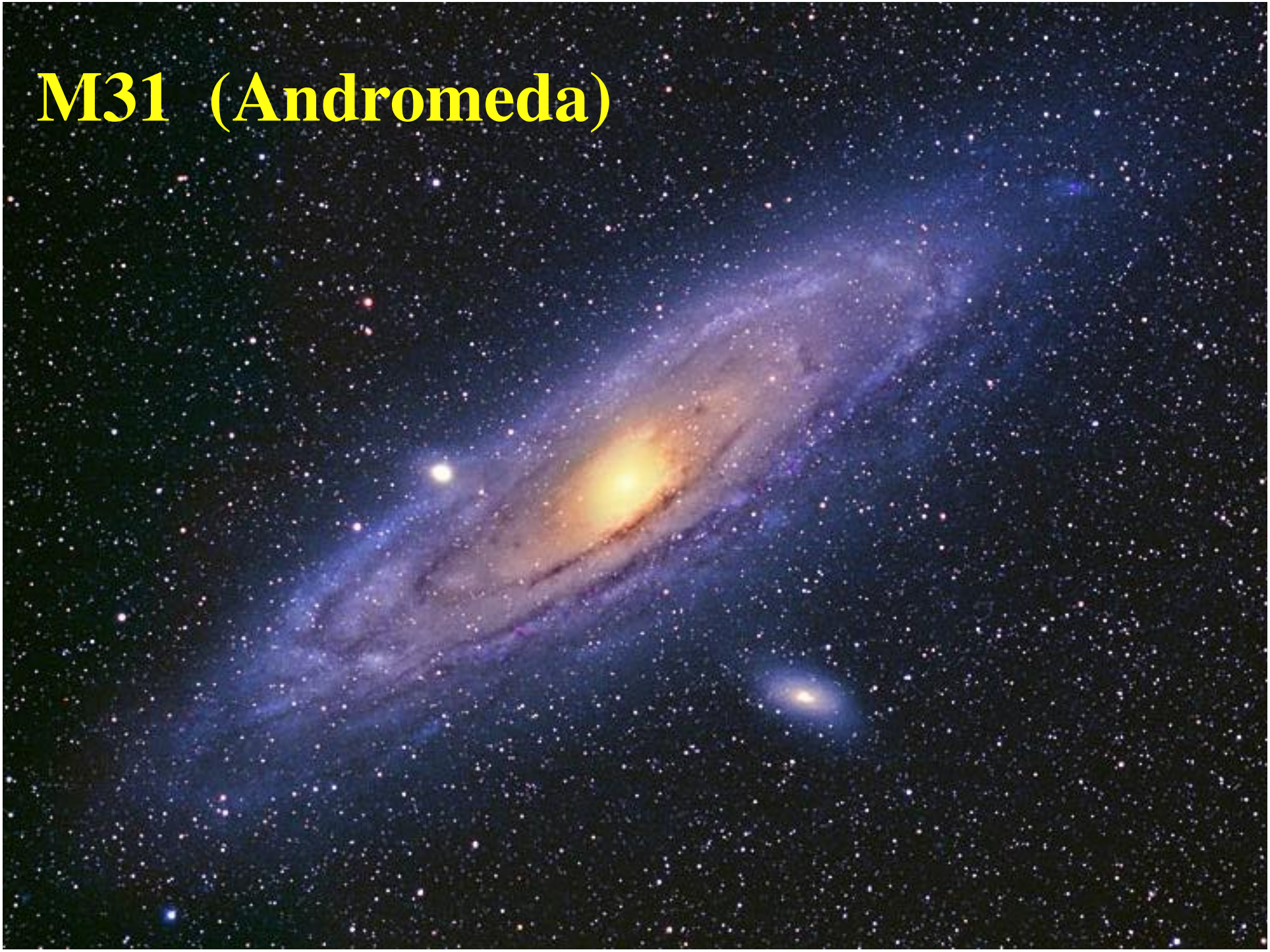
Define two parallel sequences of spiral galaxies:

Sa **Sb** **Sc** **Sd**

Central bulge becomes less important
Disk becomes more important
Spiral arms become more open and ragged

Sb **SBb** **SBc** **SBd**

As above, except that these galaxies also have a central, linear **bar**, while the Sa, Sb… are unbarred


M31 (Andromeda)


M51

Barred Galaxies

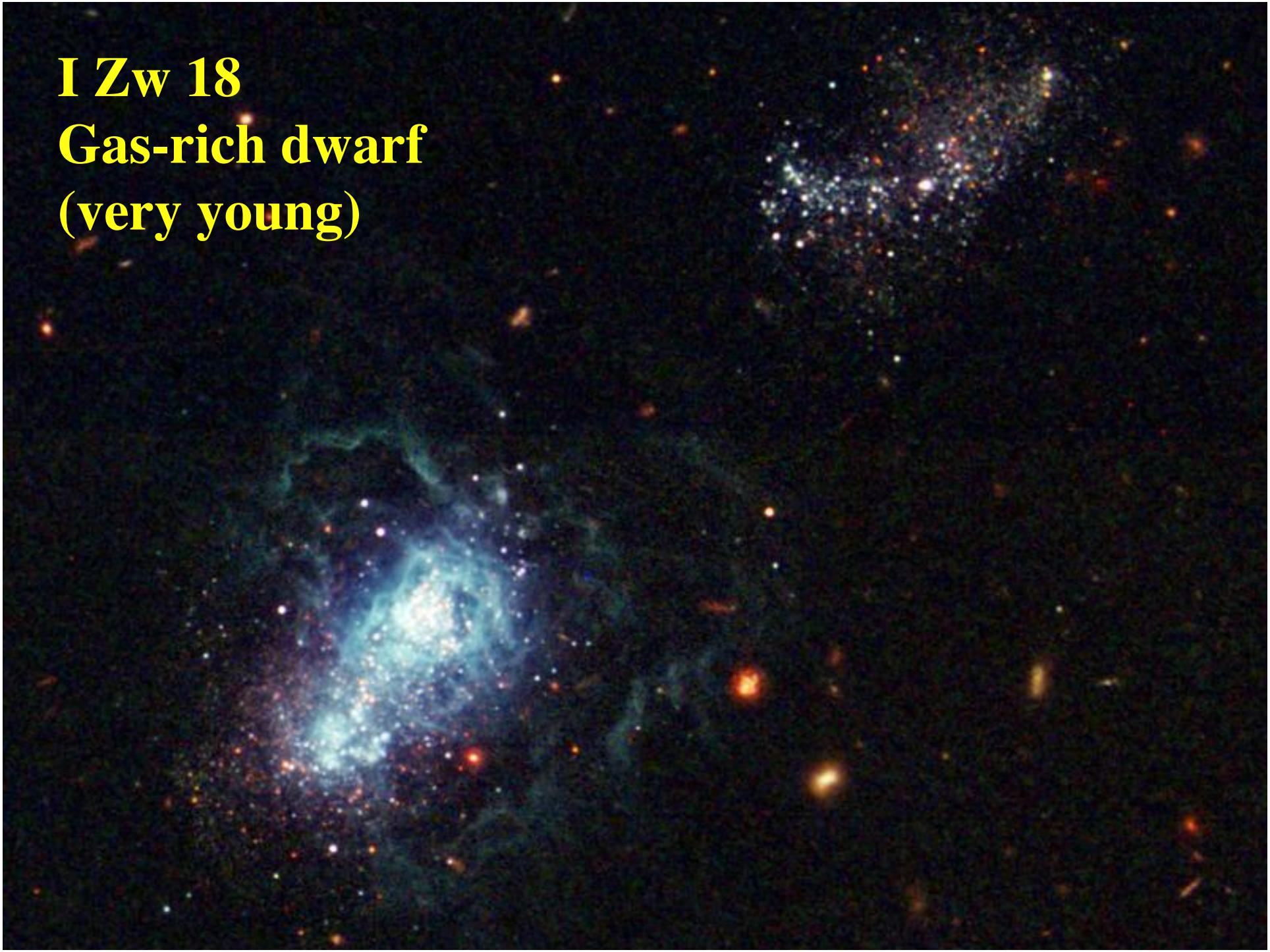
- Half of all disk galaxies - Milky Way included - show a central bar which contains up to 1/3 of the total light
- Bars are a form of dynamical instability in differentially rotating stellar disks
- S0 galaxies also have bars – a bar can persist in the absence of gas
- Bar patterns are not static, they rotate with a pattern speed, but unlike spiral arms they are not density waves. Stars in the bar stay in the bar
- The asymmetric gravitational forces of a disk allow gas to lose angular momentum (via shocks) compressing the gas along the edge of the bar. The gas loses energy (dissipation) and moves closer to the center of the galaxy

NGC 1300, Barred Spiral Galaxy

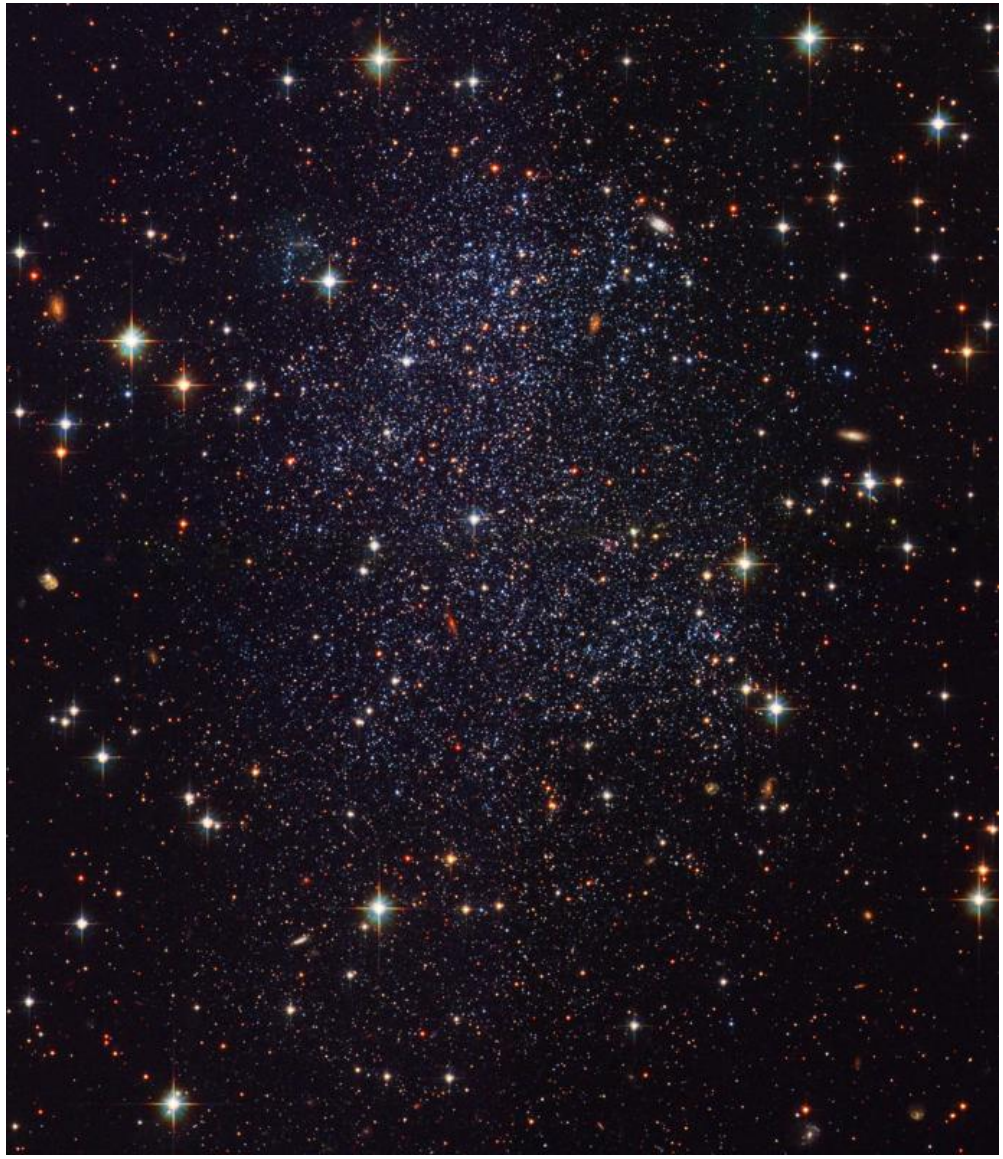
Dwarf Galaxies

- Low-luminosity: 10^6 – 10^{10} $L_\odot$, low-mass: 10^7 – 10^{10} $M_\odot$, small in size, ~ few kpc
- Often low surface brightness, so they are hard to find!
- More than one family of objects:
  - Gas-poor, passive (dE and dSph)
  - Gas-rich, star forming
- Why are dwarf galaxies important?
  - Majority of galaxies are dwarfs!
  - Dwarf galaxies may be remnants of galaxy formation process: "proto-dwarf" gas clouds came together to form larger galaxies (hierarchical formation)
  - Dwarf galaxies are currently being cannibalized by larger galaxies
  - Dwarf galaxies are relatively simple systems, not merger products: in some sense, "pristine" galaxies


LMC
dIrr


I Zw 18
Gas-rich dwarf
(very young)

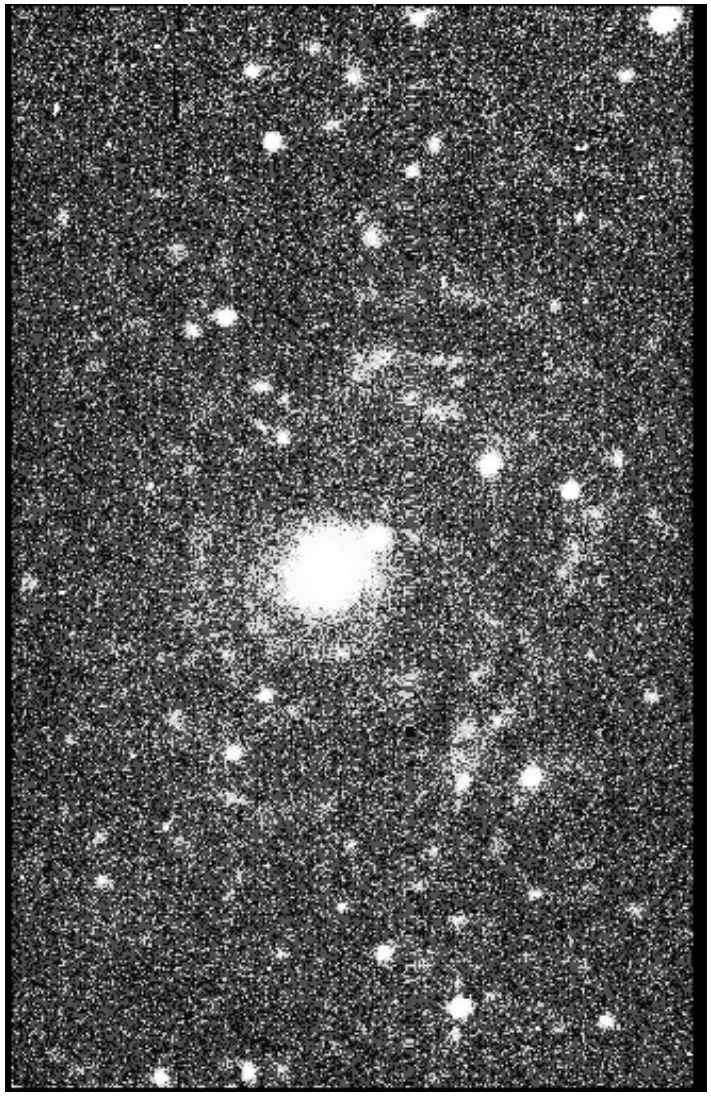
Sagittarius Dwarf Spheroidal →



← NGC 205 Dwarf Elliptical

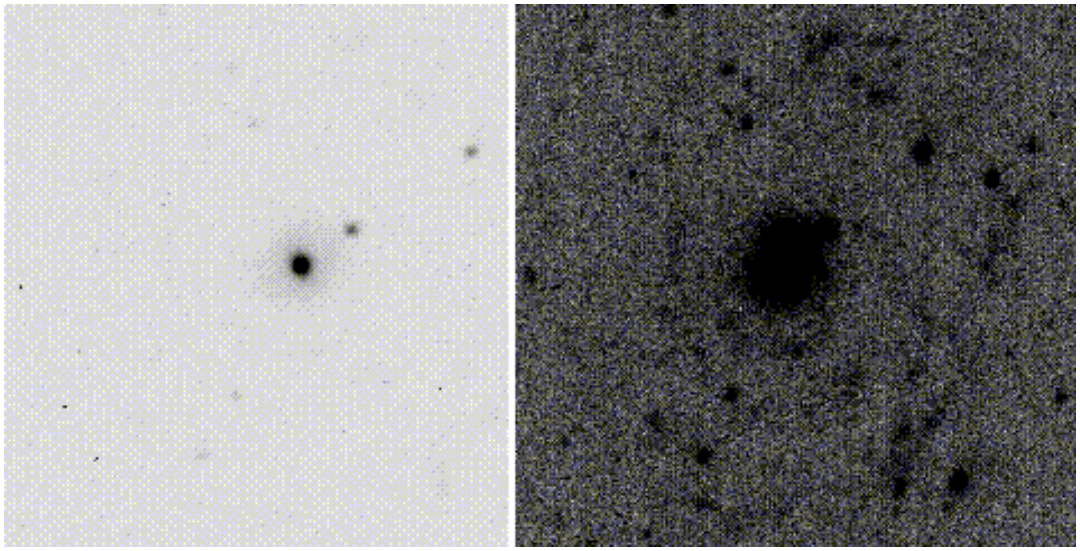
Low Surface Brightness Disks

Malin 1 - a prototype



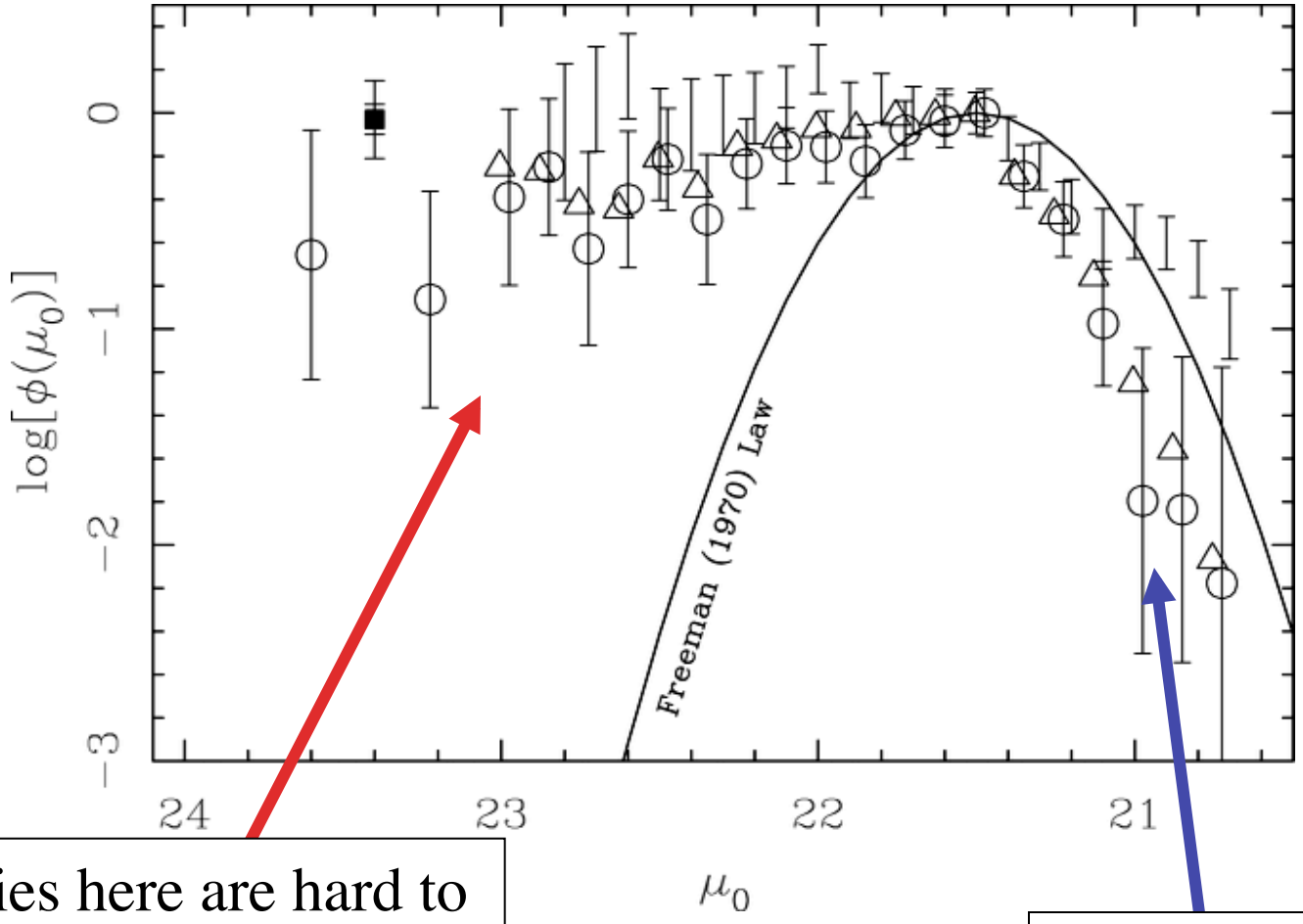
Normal size, gas, and DM content, but many fewer stars

Very hard to find, due to their diffuse nature - surveys are biased against low surface brightness objects



Surface Brightness Selection Effects

Distribution of central surface brightness for disk galaxies:



Galaxies here are hard to find, missing from most catalogs/surveys

Traditional spirals

Merging / Interacting Systems

Antennae

Tadpole

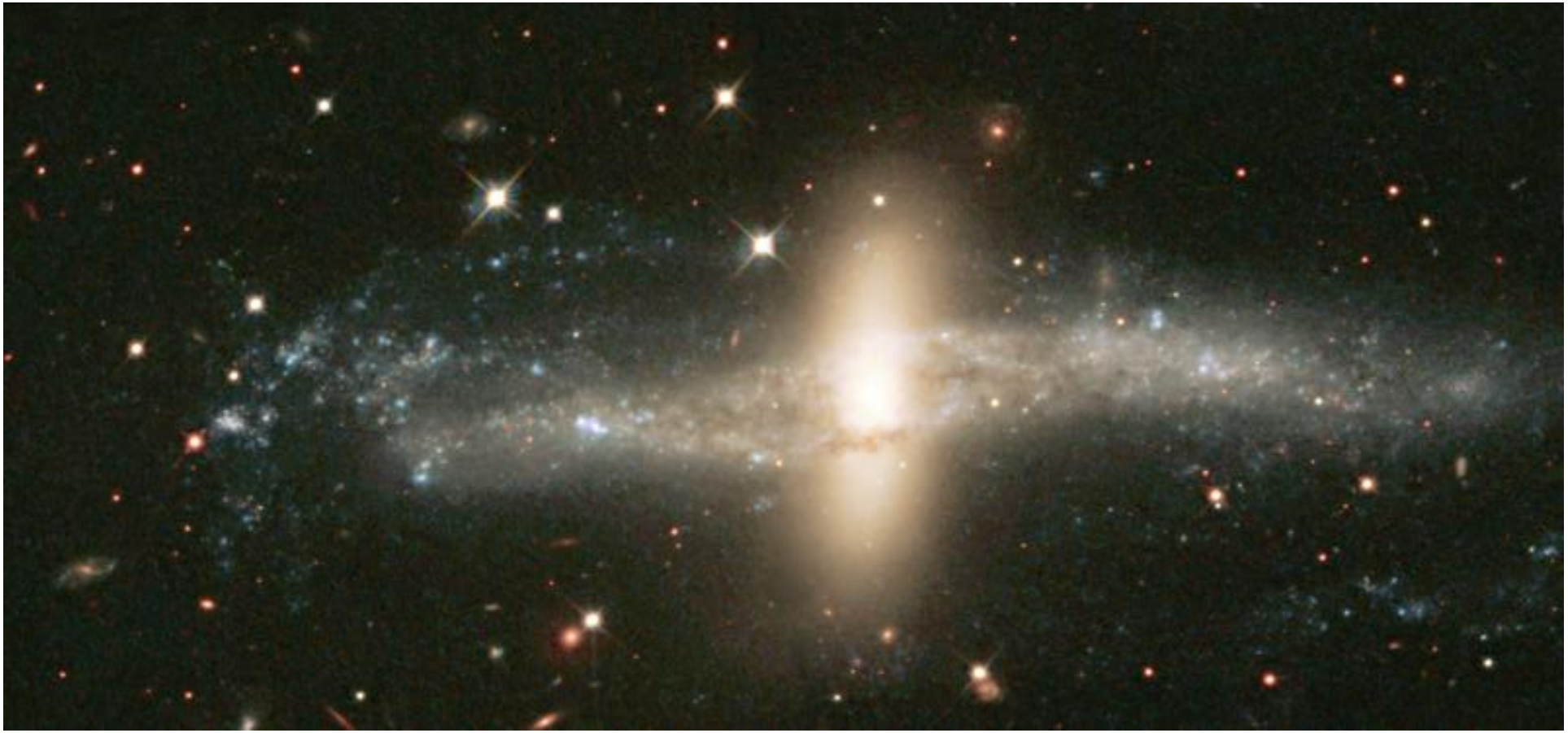
Merging / Interacting Systems

Galaxies in the process of transformation, generally from disks to ellipticals

In late stages of a merger, the 2 galaxies are no longer distinguishable, and the product does not look like any standard galaxy type

Polar Ring Galaxies

Another type of a merger-in-progress



Next: Trends Along the Hubble Sequence and Their Origins