Ay 21

# Galaxy Morphology, Classification, Hubble Sequence, and Spiral Galaxies

# Galaxies

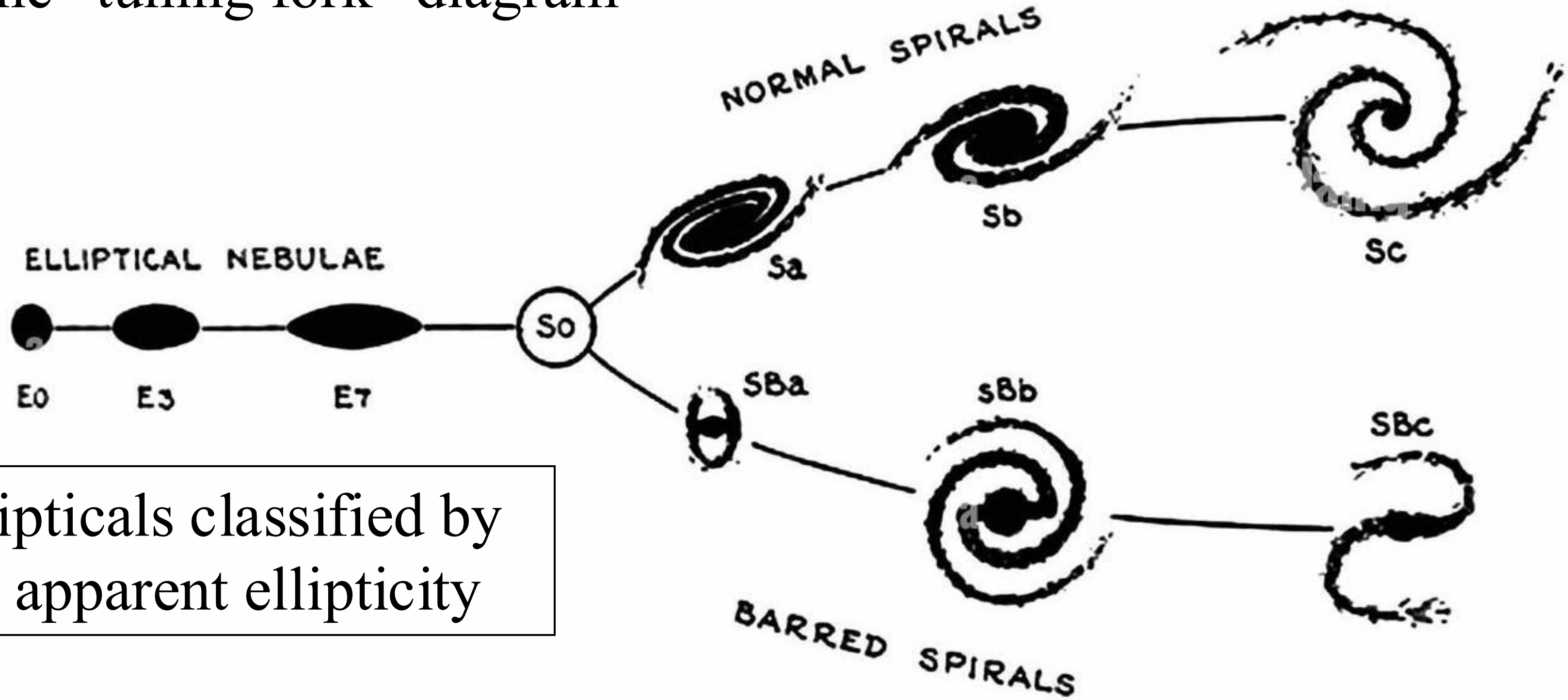
- The basic constituents of the universe at large scales
  - Distinct from the LSS as being too dense by a factor of $\sim 10^3$, indicative of an "extra collapse", and *a dissipative formation*
- Have ***a broad range of physical properties***, which presumably reflects their evolutionary and formative 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 $\sim 10^{11\text{-}12}$ galaxies within the observable universe
- Typical total masses $\sim 10^7$ - $10^{12}\ M_\odot$
- Typically contain $\sim 10^7$ - $10^{11}$ stars

# 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

The "tuning fork" diagram



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

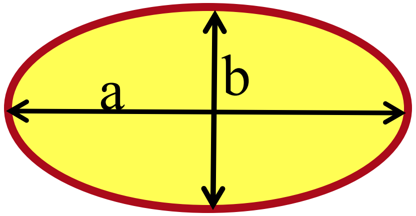
# Elliptical Galaxies

- About 20% of field galaxies are E’s, but most E’s are in clusters
- There are subtypes:
  - E’s (normal ellipticals)
  - cD’s (massive bright ellipticals at the centers of galaxy clusters)
  - dE’s (dwarf ellipticals)
  - 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:

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



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

# 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, with no active star formation*
- Lenticulars can also have a central bar, in which case they are labeled SB0
- May originate from spirals that have exhausted their gas, or that were stripped


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), and dust lanes.

Define two parallel sequences of spirals:

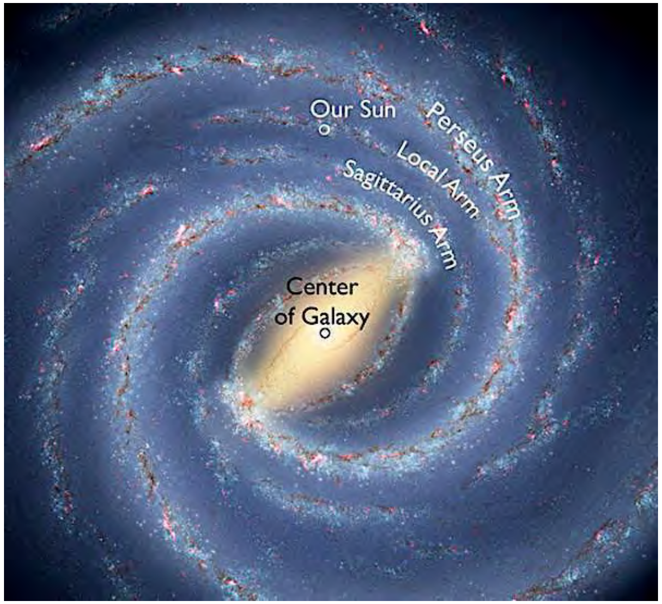
**Sa** **Sb** **Sc** **Sd**

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

**SBa** **SBb** **SBc** **SBd**

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

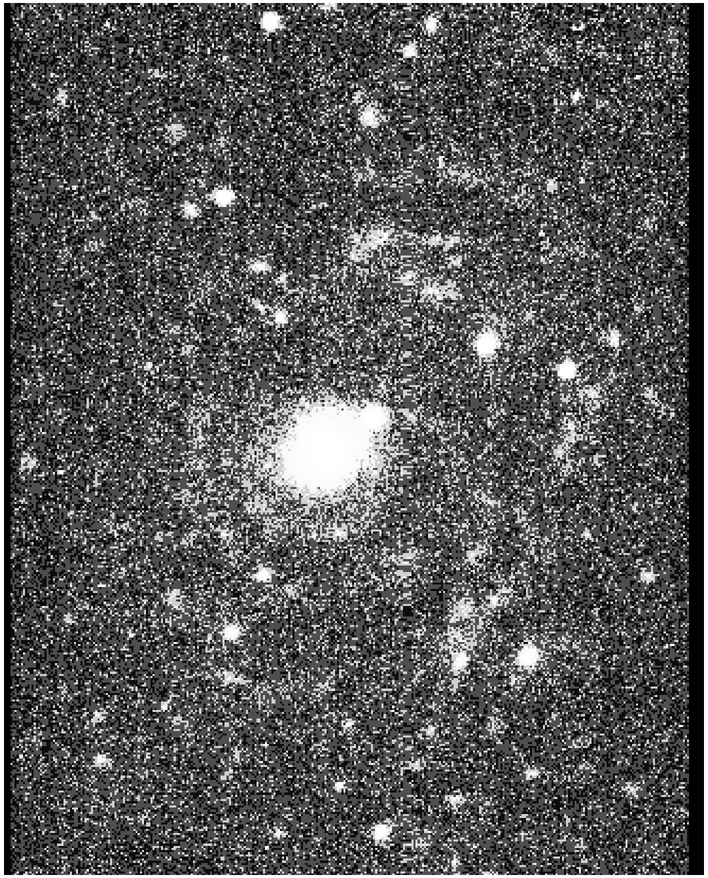
# Barred Galaxies



- 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
- 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+bar 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, where it can fuel an active nucleus (if present)

# Low Surface Brightness Disks

**Malin 1 - a prototype**



Normal size, gas, but many fewer stars

Very hard to find - surveys are biased against low surface brightness objects

Some may be dark matter deficient (?)

*(van Dokkum et al.)*

# Dwarf Galaxies

- Low-luminosity: $10^6 – 10^{10}\ L_\odot$, low-mass: $10^7 – 10^{10}\ M_\odot$, small in size, ~ few kpc
- Often (very) *low surface brightness*, so they are hard to find!
- More than one family:
    - ★ Gas-rich, star forming
    - ☆ Gas-poor, passive (dE and dSph)
- Why are dwarf galaxies important?
    - – Majority of galaxies are dwarfs
    - – They may be *remnants of galaxy formation process*: they can merge into larger galaxies (hierarchical formation)
    - – They are relatively simple systems, not major merger products


Starforming gas rich dwarf

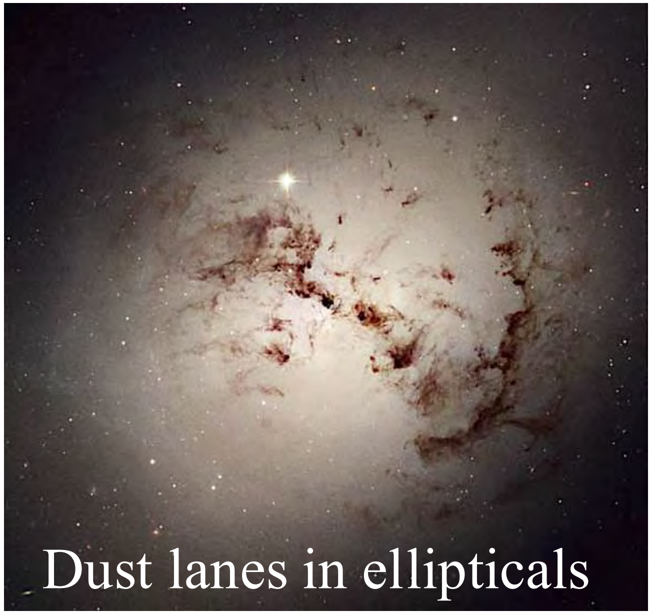

Sagittarius dSph

# Galaxy Morphology Can Change

But generally just in one direction: disks → ellipticals

We see this process in galaxy mergers

Stellar “shells”



Dust lanes in ellipticals

These are remnants of “partially digested” galaxy disks

# Traditional Galaxy Classification: Problems

*Appearance* of galaxies is strongly dependent on **which wavelength** the observations are made in

**e.g., the nearby galaxy M81:**

X-ray

Accreting binaries, possible AGN

UV

Brightest star forming regions, youngest stars

Visible

Disk and spiral arms, young and old stars

Near-IR

Disk but no spiral arms, older stars

Mid-IR

Dust in spiral arms

Different types of sources dominate at different wavelengths

# Traditional Galaxy Classification: Problems

**Subjective** - *especially for spiral galaxies*

However, there are automated, objective schemes to classify galaxies, using measured image parameters.

**Superficial** - *based on appearance, not physical properties*

Galaxy types or families can be defined in a parameter space of various measured/physical quantities. Different galaxy families follow different correlations.

**Incomplete** - *misses the major dichotomy of dwarfs and giants* (not separated in the traditional Hubble sequence)

Dwarfs also exist in gas rich / gas poor, star forming or not, and perhaps other varieties

# The Meaning of Galaxy Classification

- *Galaxy morphologies and other properties reflect different formative and evolutionary histories*
- Much can be explained by considering galaxies as *composites made of two dominant visible components*:
  1. Old, pressure supported bulges, where most of the star formation occurred early on
  2. Young(er), rotationally supported disks, where star formation happened gradually and is still going on

  \+ stellar halos, bars, …
- Note that we do not involve in this the dominant mass component - the dark matter
- Nevertheless, there are some important and meaningful trends along the Hubble sequence

# Galaxy Properties and the Hubble Sequence

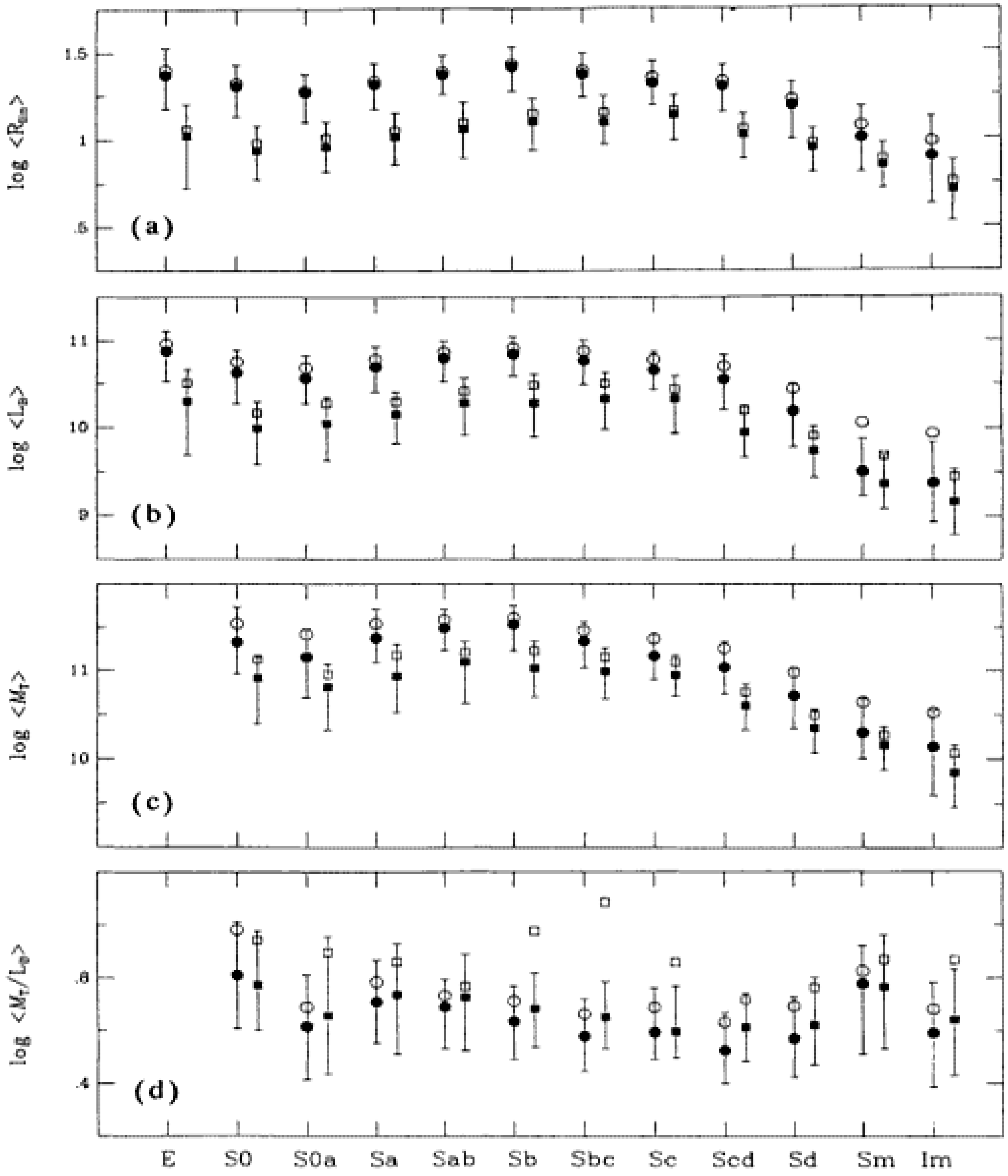
Hubble sequence turned out to be surprisingly robust: many, but not all, physical properties of galaxies correlate with the classification morphology:

E S0 Sa Sb Sc Sdm/Irr

Pressure support □ Rotational support
Passive □ Actively star forming
Red colors □ Blue colors
Hot gas □ Cold gas and dust
Old □ Still forming
High luminosity density □ Low lum. dens.
… etc.

But, for example, masses, luminosities, sizes, etc., *do not correlate* well with the Hubble type: at every type there is a large spread in these fundamental properties.

# Many Important Galaxy Properties Do Not Correlate with the Hubble Type



Radius

Luminosity

Mass

(M/L)

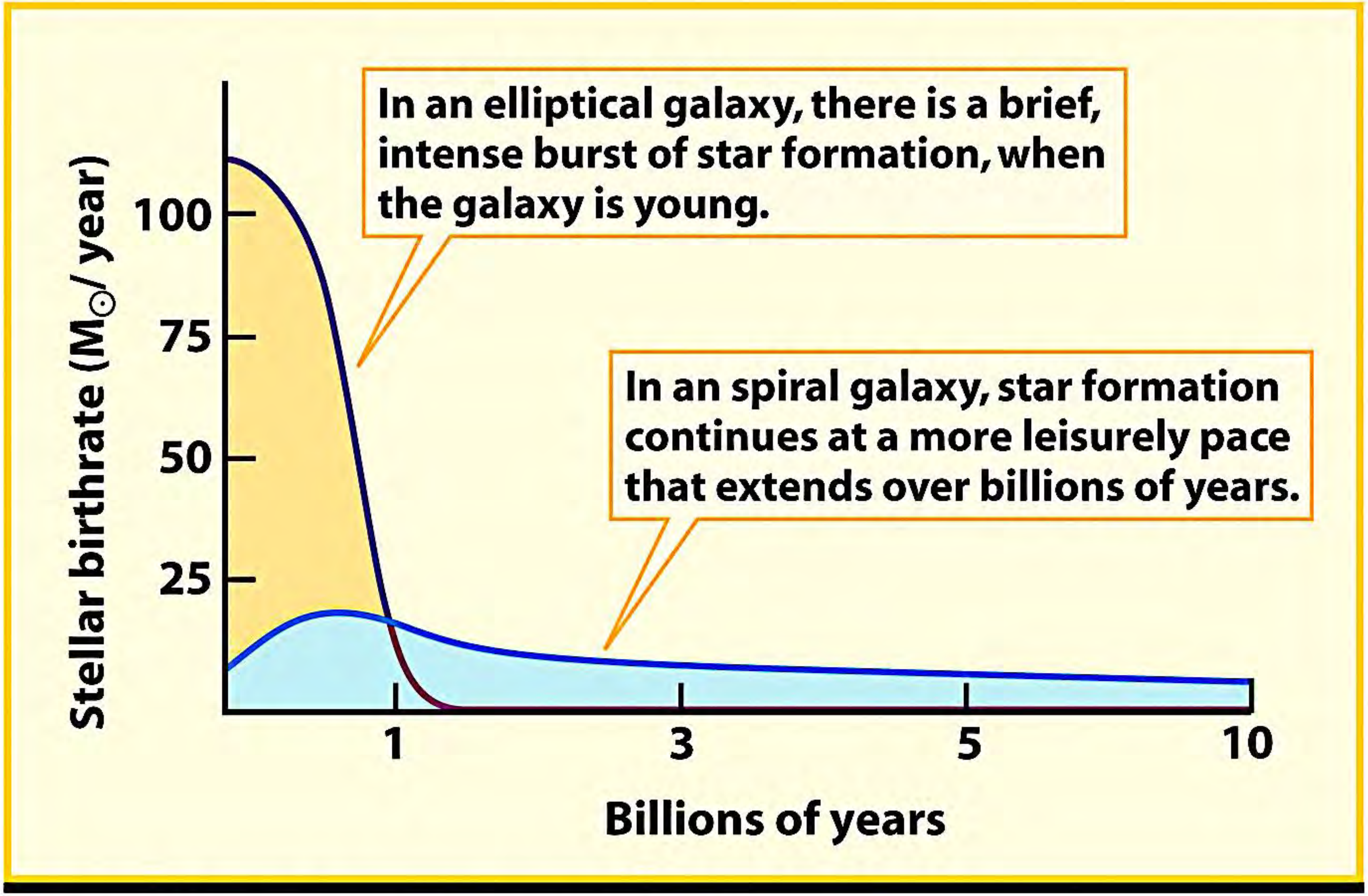
Hubble type

# Interpreting the Trends Along the Hubble Sequence

Probably the best interpretation of many of these is ***a trend in star formation histories:***

- Ellipticals and early type spirals formed most of their stars early on (used up their gas, have older/redder stars)
- Late type spirals have substantial on-going star-formation, didn't form as many stars early-on (and thus lots of gas left)
- Spirals are forming stars at a few $M_\odot$ per year, and we know that there is ~ a few x $10^9$ $M_\odot$ of HI mass in a typical spiral
  - How long can spirals keep forming stars? It seems that some gas infall/resupply is needed, e.g., from the intergalactic medium

# Star Formation History in Galaxies



In an elliptical galaxy, there is a brief, intense burst of star formation, when the galaxy is young.

In an spiral galaxy, star formation continues at a more leisurely pace that extends over billions of years.

The stellar birthrate in galaxies

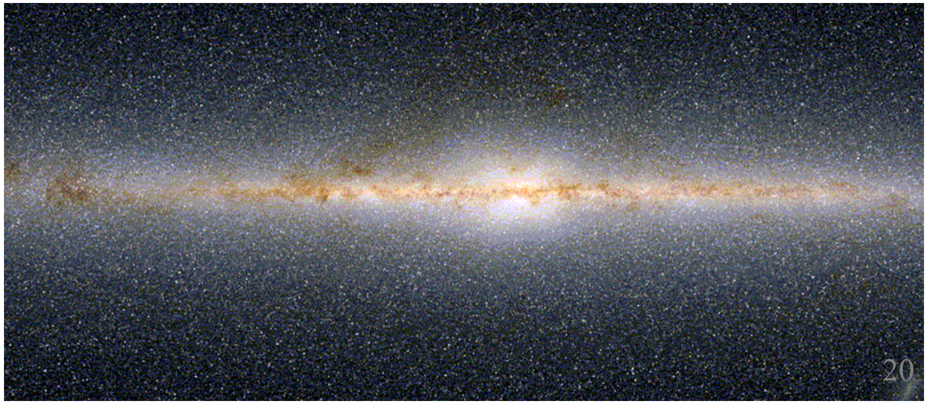
# Stellar Populations

- A key concept in our understanding of galaxies
- In 1944, Walter Baade used the 100-inch Mt. Wilson telescope to resolve the stars in several nearby galaxies: M31, its companions M32 and NGC 205, as well as the elliptical galaxies NGC 147 and NGC 145
- He realized that the *stellar populations of spiral and elliptical galaxies were distinct*:
  - **Population I:** objects closely associated with spiral arms – luminous, young hot stars (O and B), Cepheid variables, dust lanes, HII regions, open clusters, metal-rich
  - **Population II:** objects found in spheroidal components of galaxies (bulge of spiral galaxies, ellipticals) – older, redder stars (red giants), could be metal-poor (halos) or metal-rich (bulges)

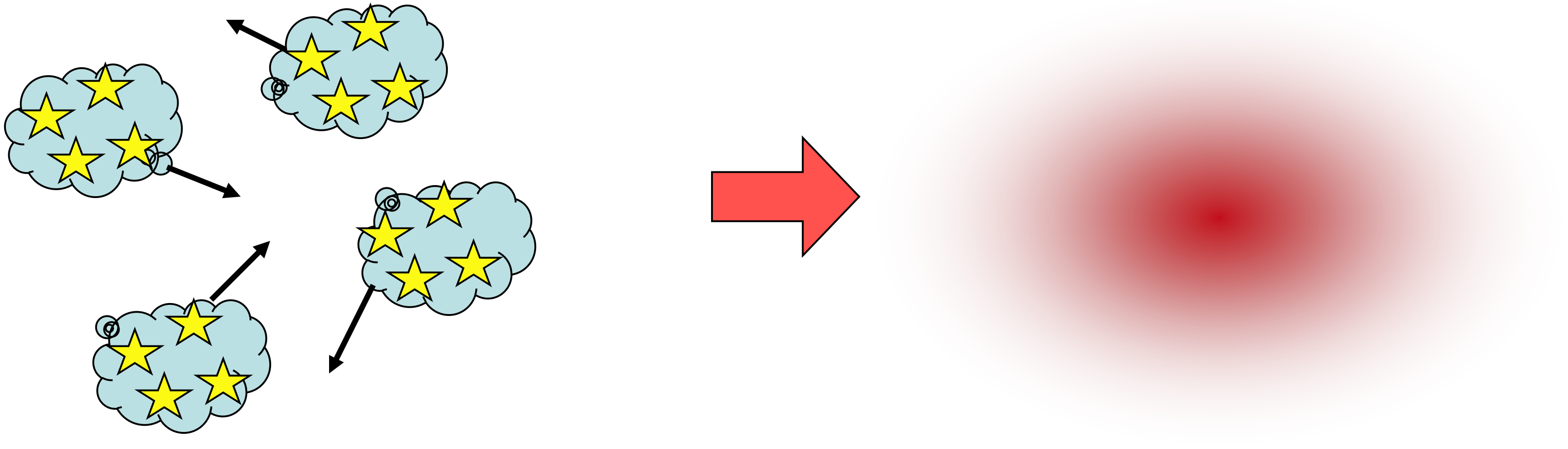
# Stellar Populations and Dynamical Subsystems in Galaxies

- The picture today is more complex: it is useful to thing about generalized stellar populations as *subsystems within galaxies*, characterized by the:
  - Location and morphology, density distribution
  - Dynamics (rotation, random motions, their distribution)
  - Star formation rate and mean age
  - The presence and nature of its interstellar medium

  etc., etc.
- For example, in the Milky Way, we can distinguish:
  - Young thin disk
  - Old thick disk
  - Metal-rich bulge and bar
  - Metal-poor stellar halo

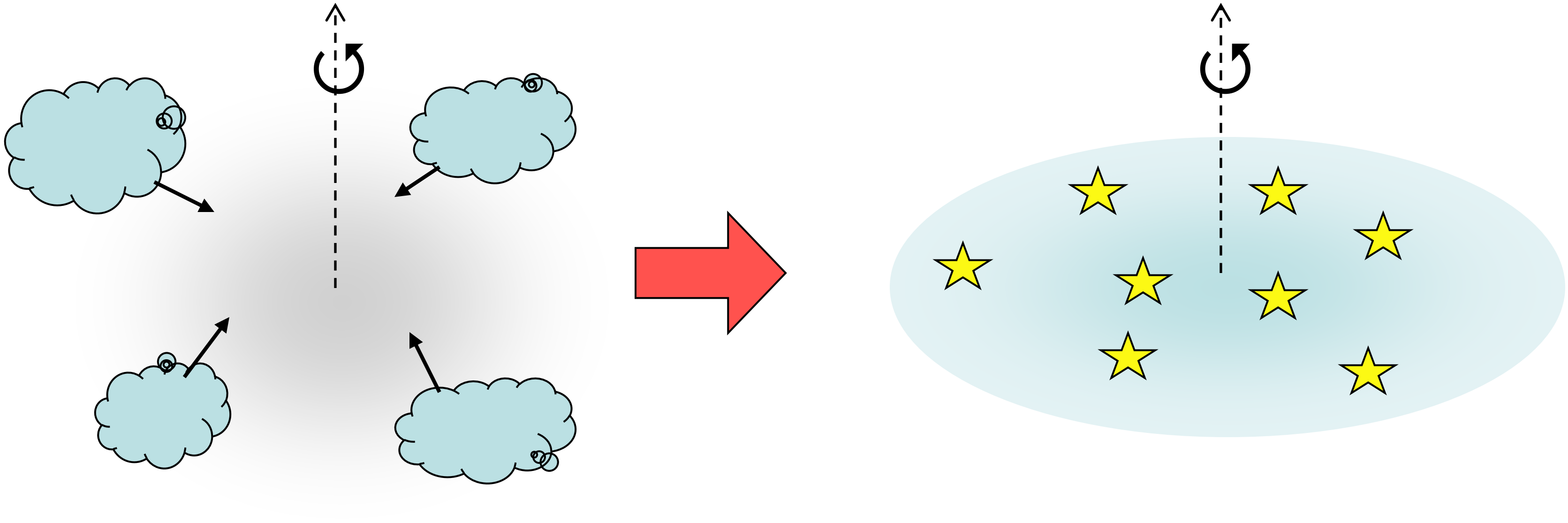


# Formation of Galaxy Spheroids and Dynamics of Stellar Populations



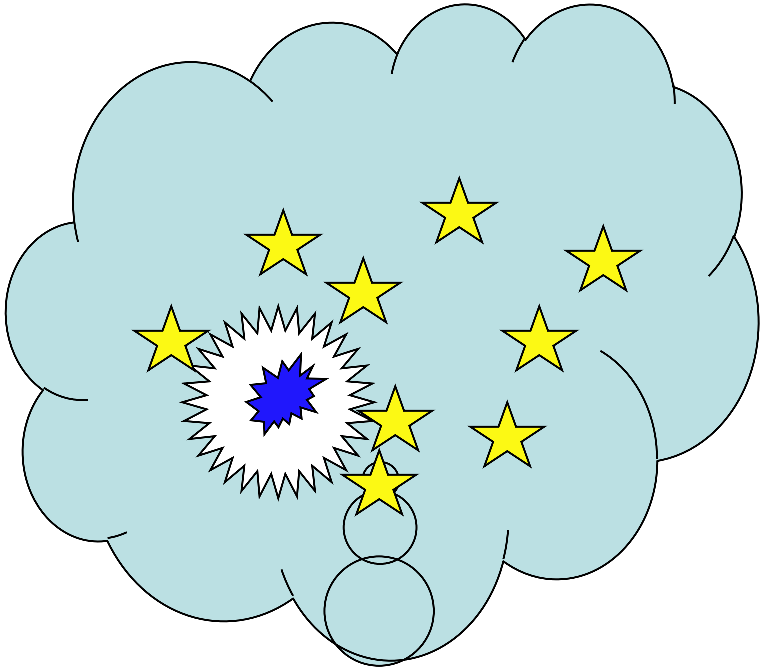
Stars "remember" the dynamics of their orbits at the time of formation, since dynamics of stellar systems is dissipationless. If stars form in dwarf protogalactic fragments which then merge, this will result in a pressure-supported system, *i.e.*, a spheroid (bulge or halo, or an elliptical galaxy). Their metallicities will reflect the abundances in their parent systems.

# Formation of Galaxy Disks and Dynamics of Stellar Populations

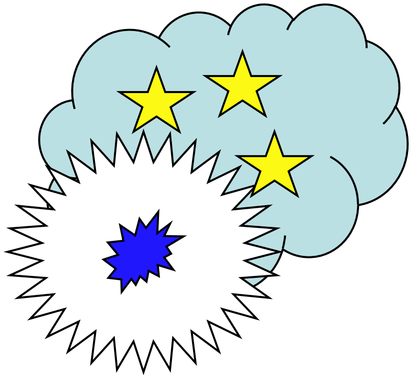


If protogalactic clouds merge dissipatively in a potential well of a dark halo, they will settle in a thin, rotating disk = the minimum energy configuration for a given angular momentum. If gas settles into a (dynamically cold) disk before stars form, then stars formed in that disk will inherit the motions of the gas (mainly an ordered rotation).

# Chemical Self-Enrichment in Young Stellar Systems



In a massive system, supernova ejecta are retained, and reused for subsequent generations of stars, which achieve ever higher metallicities.



In a low-mass system, supernova shocks and winds from massive young stars expel the enriched gas and may suppress any subsequent star formation. The system retains its initial (low) metallicity.

# Quantifying Properties of Galaxies

For galaxies of different types, we would like to quantify:

- The *distribution of light* - need photometric measurements
- The *distribution of mass* - need kinematical measurements
- Relative distributions and *interplay of various components*, e.g., stars, gas, dark matter - need multiwavelength measurements, as different components tend to emit most energy in different wavebands, e.g., stars → visible/near-IR, cold gas → radio, dust → far-IR, hot gas → x-rays, etc.
- *Chemical composition, star formation rates* - need spectroscopy

All these measurements can then be analyzed using:

- Dynamical models
- Stellar population synthesis models
- Galaxy evolution models

Note: we tend to measure different observables for different galaxy types!

# Global Properties of Spiral Galaxies

Spirals are complex systems, generally more complex and diverse than ellipticals:

- Wide range in morphological appearance
- Fine scale details – bulge/disk ratios, structure of spiral arms, resolution into knots, HII regions, etc.
- Wide range in stellar populations – old, intermediate, young, and currently forming
- Wide range in stellar dynamics:
  - "cold" rotationally supported disk stars
  - "hot" mainly dispersion supported bulge & halo stars
- Significant amounts of *cold* interstellar medium (ISM)

Spirals tend to avoid high-density regions (e.g., clusters) as they are dynamically fragile, and can be merged and turned into E's

# Spiral Galaxies: Basic Components

- **Disks:** generally metal rich stars and ISM, nearly circular orbits with little random motion, spiral patterns
  - Thin disks: younger, star forming, dynamically very cold
  - Thick disks: older, passive, slower rotation and more random motions
- **Bulge:** metal poor to super-metal-rich stars, high stellar densities, mostly random motion – similar to ellipticals
- **Bar:** present in ~ 50 % of disk galaxies, mostly older stars, some random motions and a ~ solid body like rotation
- **Nucleus:** central (<10pc) region of very high mass density, massive black hole or starburst or nuclear star cluster
- **Stellar halo:** very low density (few % of the total light), metal poor stars, globular clusters, low density hot gas, little or no rotation
- **Dark halo:** dominates mass (and gravitational potential) outside a few kpc, probably triaxial ellipsoids, radial profile ~ singular isothermal sphere, DM nature unknown

# Photometric Properties of Disk Galaxies

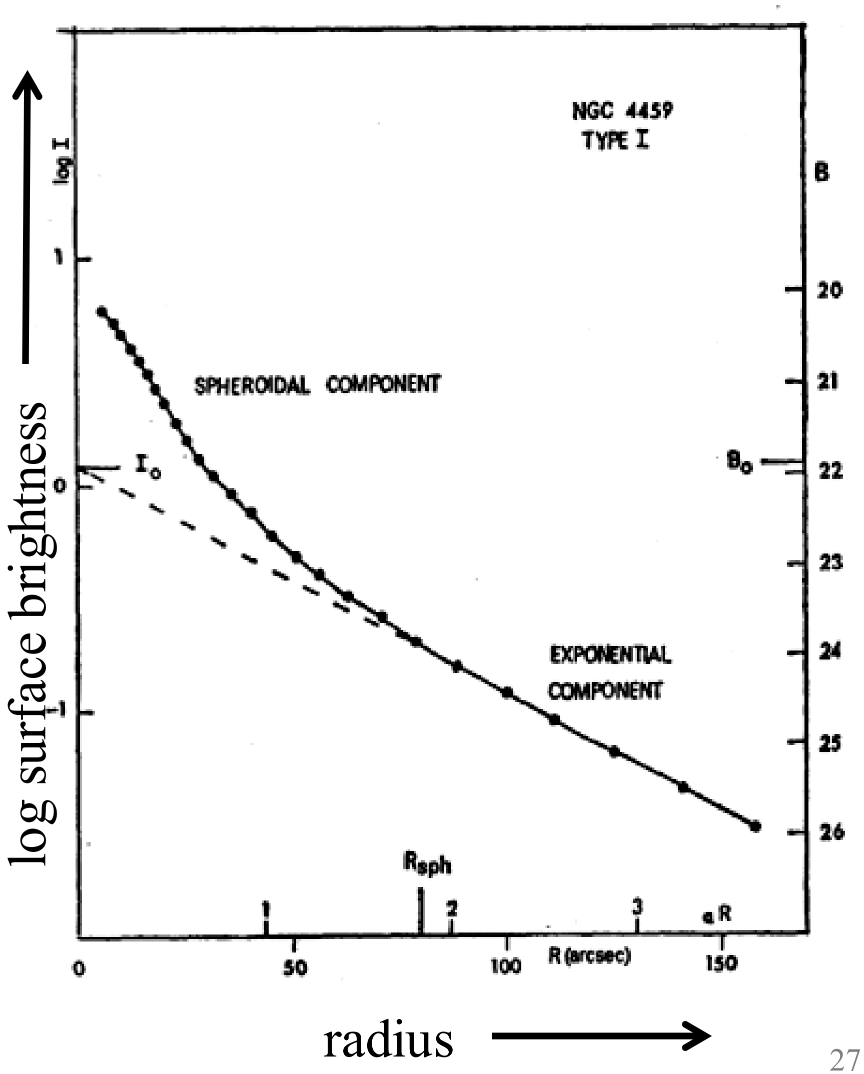
Empirically, the surface brightness declines with distance from the center of the galaxy in different characteristic ways for spiral and elliptical galaxies

For spiral galaxies, disk surface brightness (corrected for the inclination and extinction) drops off *exponentially*:

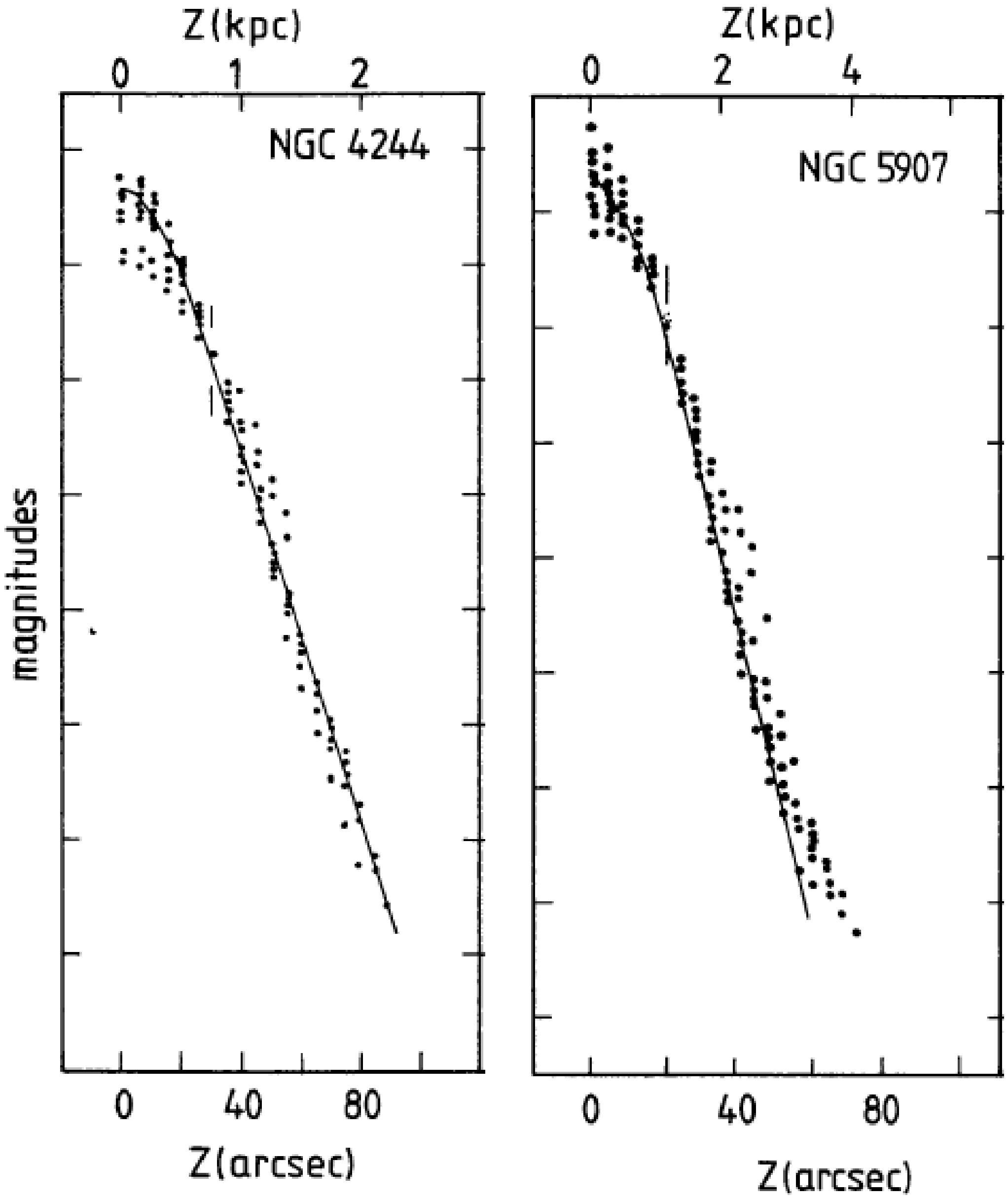
$$I(R) = I(0)\, \mathrm{e}^{-R/h_R}$$

where *I(0)* is the central surface brightness of the disk, typically ~ 21 - 22 mag/arcsec$^2$, and $\boldsymbol{h_R}$ is a characteristic **scale length**, with typical values:

$$1 \text{ kpc} < h_R < 10 \text{ kpc}$$



# Vertical Structure of Galaxy Disks



Stellar density also declines exponentially:

~ $exp(-z/z_0)$

where $z$ is the distance away from the plane of the disk

Typical values of $z_0$ range from ~ 0.1 kpc (young disk) to ~ 1 kpc (old thick disk)

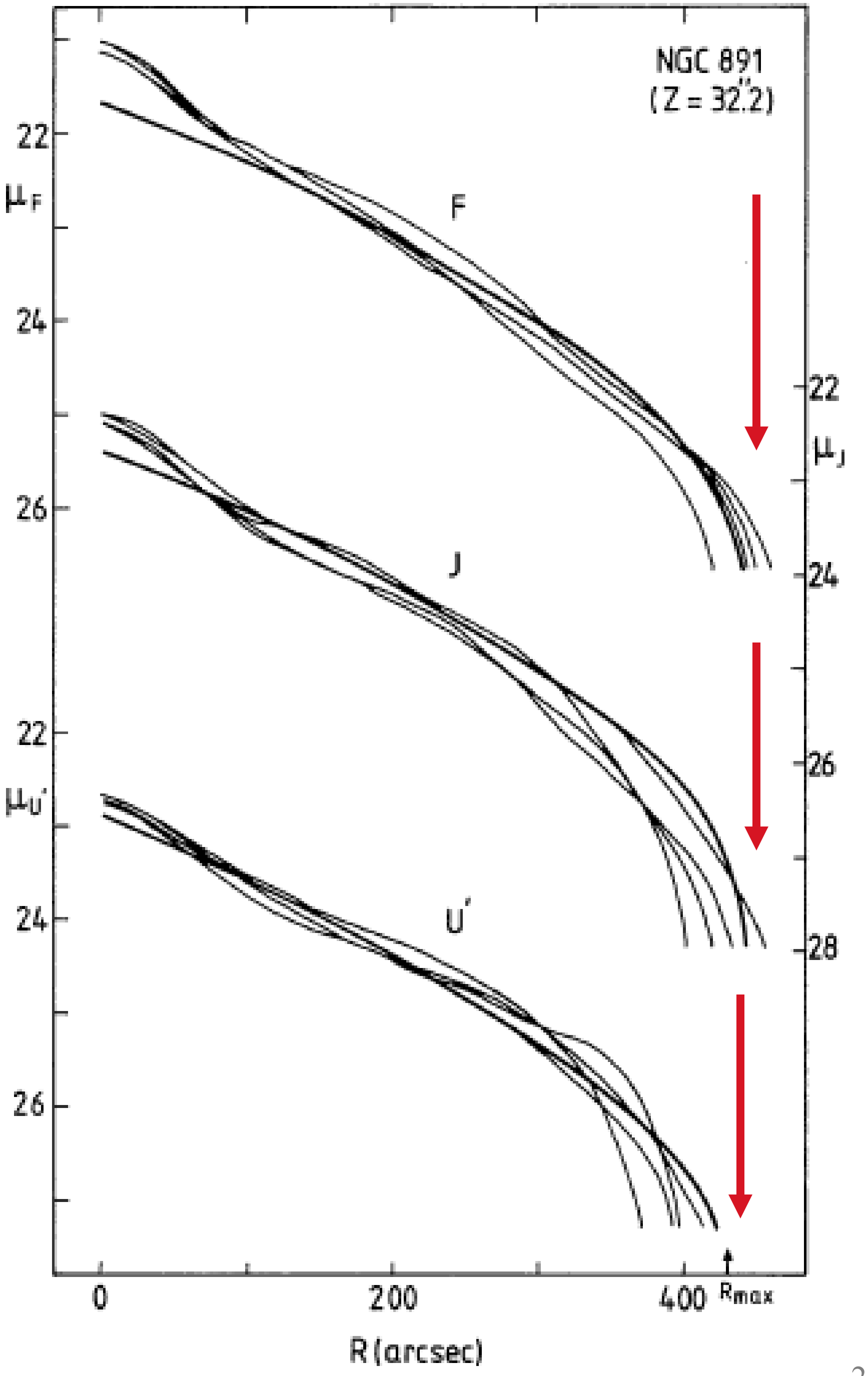
# Disks Have Cutoffs

Stellar disks have finite radii, $R_{max}$, typically 3 - 5 $h_R$

This is *not* seen in ellipticals: we have never seen their edges

Note that the *H I gas extends well beyond the visible cutoff*, and of course so does the dark matter

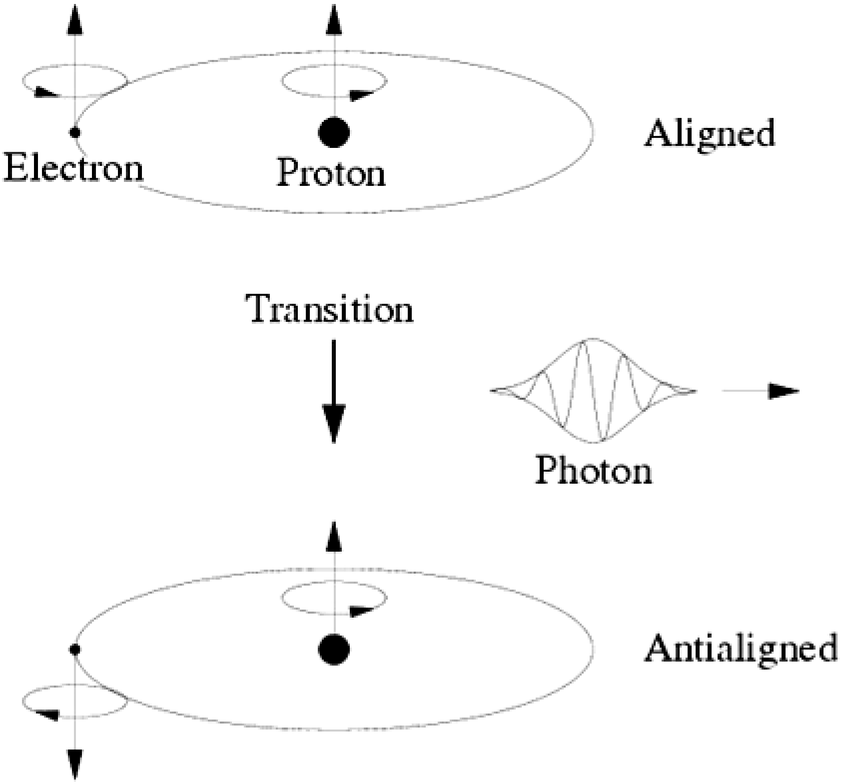
There is a trend that the *stars are also younger at large radii* in disks: inside-out formation?



# Spiral Galaxies: Gas Content

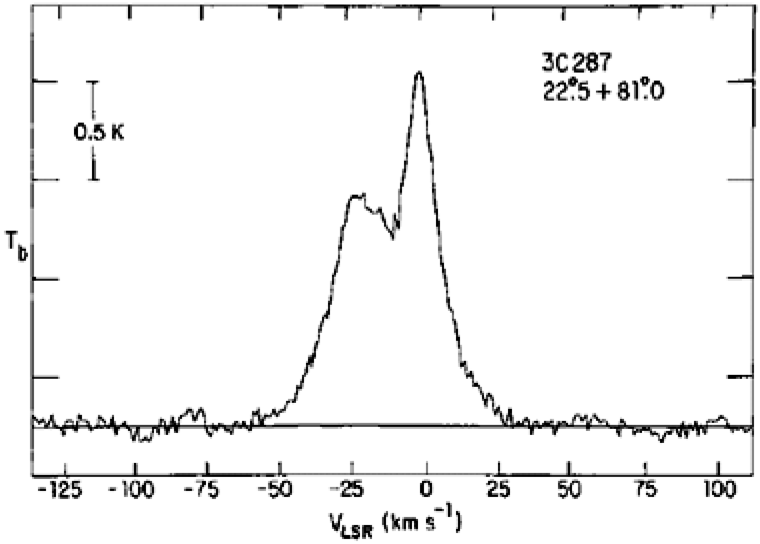
- Gas in spirals:
  - Cool atomic H I gas, amount depends on the Hubble type
  - Molecular hydrogen $H_2$, CO, many other molecules
  - *Need cold gas to form stars*! Star formation associated with dense ISM
  - Can observe ionized hydrogen via optical emission-lines ($H\alpha$)
  - Observe HI via radio emission – 21 cm line due to hyperfine structure – a hydrogen atom that collides with another particle can undergo a spin-flip transition
- *H I gas is optically thin*, 21 cm line suffers little absorption, so we can measure gas mass directly from line intensity
- H I is much more extended than optical light
- We can use radial motion of 21 cm line to measure rotation in spiral galaxies and thus distribution of the dark matter

# A Basic Tool: Spin-Flip (21 cm) Line of H I



In emission generally originates from warm (T ~ 100 - 6000 K) ISM, which accounts for ~ 30 - 65% of the total ISM volume in the Galactic disk. In absorption, it probes a cooler ISM (can be also self-absorbed).

Typical line profile □

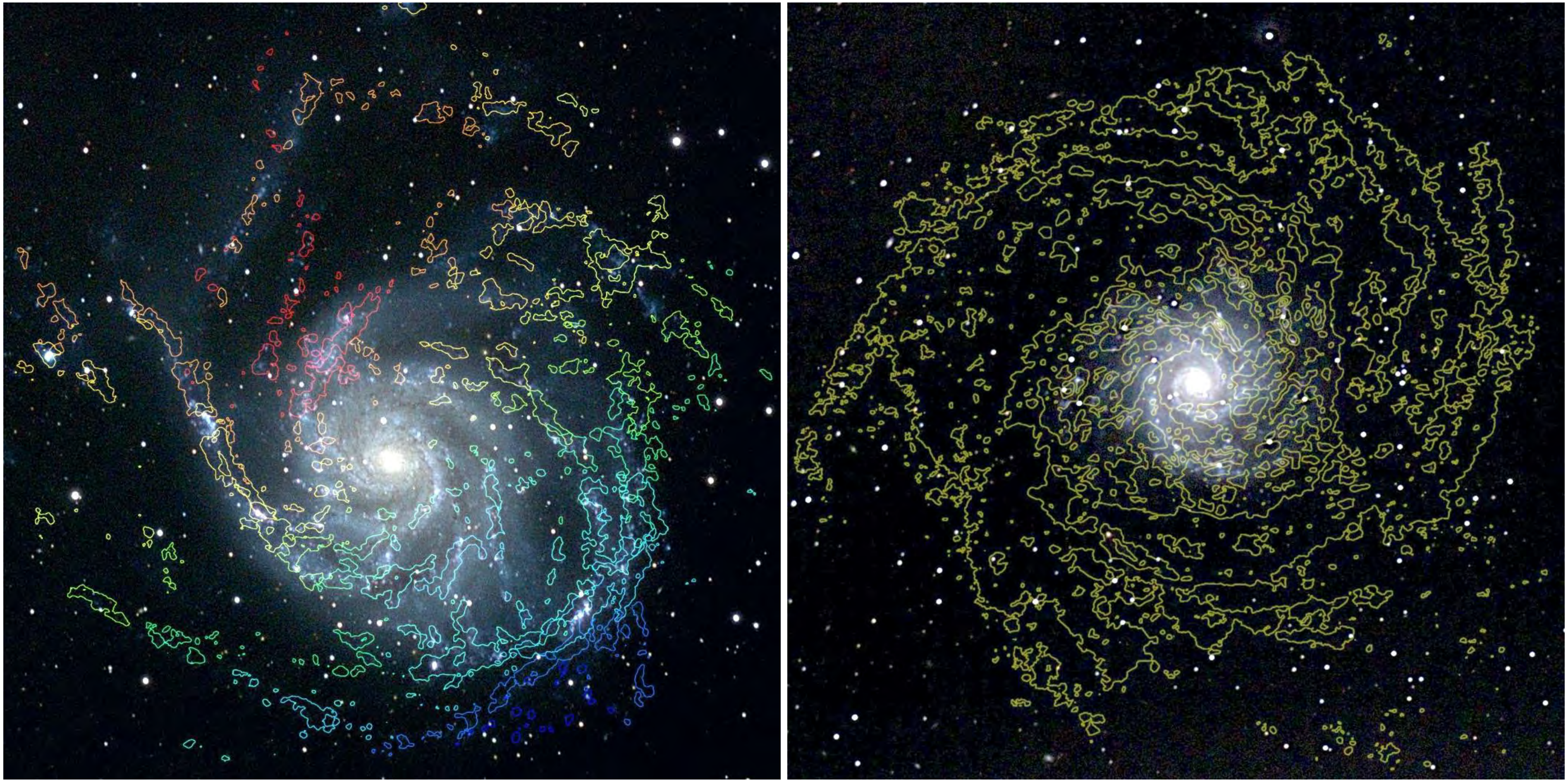


A major advantage: it is not affected by the dust absorption!

# Neutral Hydrogen vs. Starlight

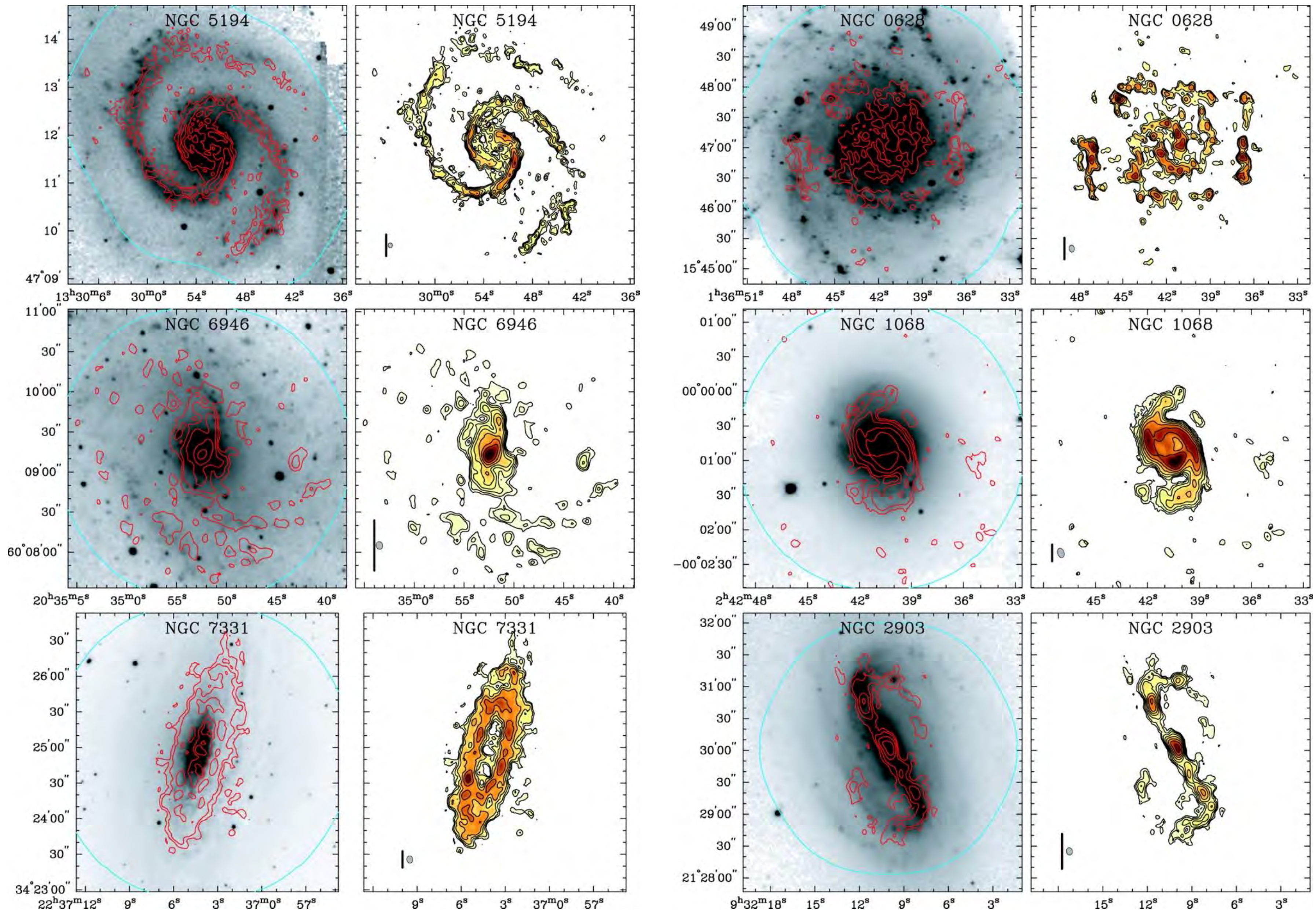
H I (contours) generally follows the spiral arms …

… but it also extends well past the visible light of the disk



This suggests that the stellar disks form from the inside out

# Visible Light and Molecular Gas (CO)

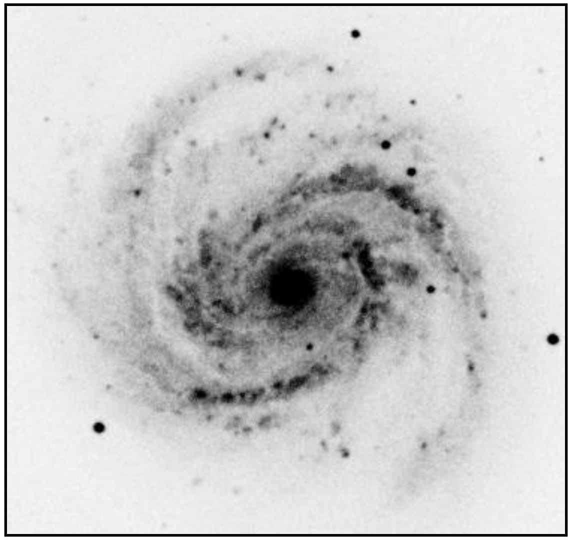


# Multi-Phase ISM

The ISM has a complex structure with 3 major components:

1. **Cold** (T ~ 30 - 100 K), dense ($n_{H\,I} > 10\ \mathrm{cm}^{-3}$) atomic (H I) and molecular ($H_2$, CO, …) gas and dust clouds
    - Only ~ 1 - 5 % of the total volume, but most of the mass
    - Confined to the thin disk
    - Low ionization fraction ($x_{H\,II} < 10^{-3}$)
    - Stars are born in cold, dense clouds
2. **Warm** ($T \sim 10^3 - 10^4$ K) neutral & ionized gas, $n \sim 1\ \mathrm{cm}^{-3}$
    - Energized mainly by UV starlight
    - Most of the total ISM volume in the disk
3. **Hot** ($T \sim 10^5 - 10^6$ K), low density ($n \sim 10^{-3}\ \mathrm{cm}^{-3}$) gas
    - Galactic corona
    - Almost fully ionized, energized mainly by SN shocks

# Density Wave Theory



- ***Spiral arms*** are seen in disks that contain gas, but not in gas poor S0 galaxy disks
- When the sense of the galactic rotation is known, ***the spiral arms almost always trail the disk rotation***
- Spiral arm patterns must be **persistent**. Density wave theory provides an explanation: the arms are ***density waves*** *propagating in differentially rotating disks*
- Spiral arm pattern is *amplified by resonances* between the epicyclic frequencies of the stars (deviations from circular orbits) and the angular frequency of the spiral pattern
  - Spiral waves can only grow between the inner and outer *Linblad resonances* ($\Omega_p = \Omega - \kappa/m$ ; $\Omega_p = \Omega + \kappa/m$ ) where $\kappa$ is the epicyclic frequency and $m$ is an integer (the # of spiral arms)
  - Resonance can explain why 2 arm spirals are more prominent

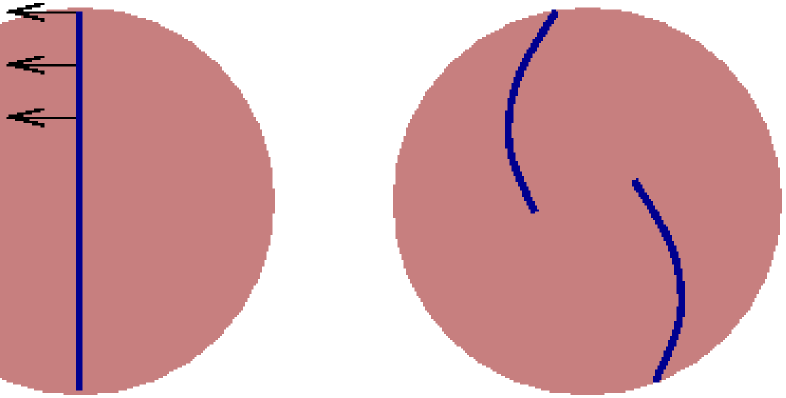
# Differential Rotation of Galaxian Disks

First ingredient for producing spiral arms is differential rotation. For galaxy with flat rotation curve:

$$V(R) = \text{constant}$$

Angular velocity $\longrightarrow$ $\Omega(R) = \frac{V}{R} \propto R^{-1}$

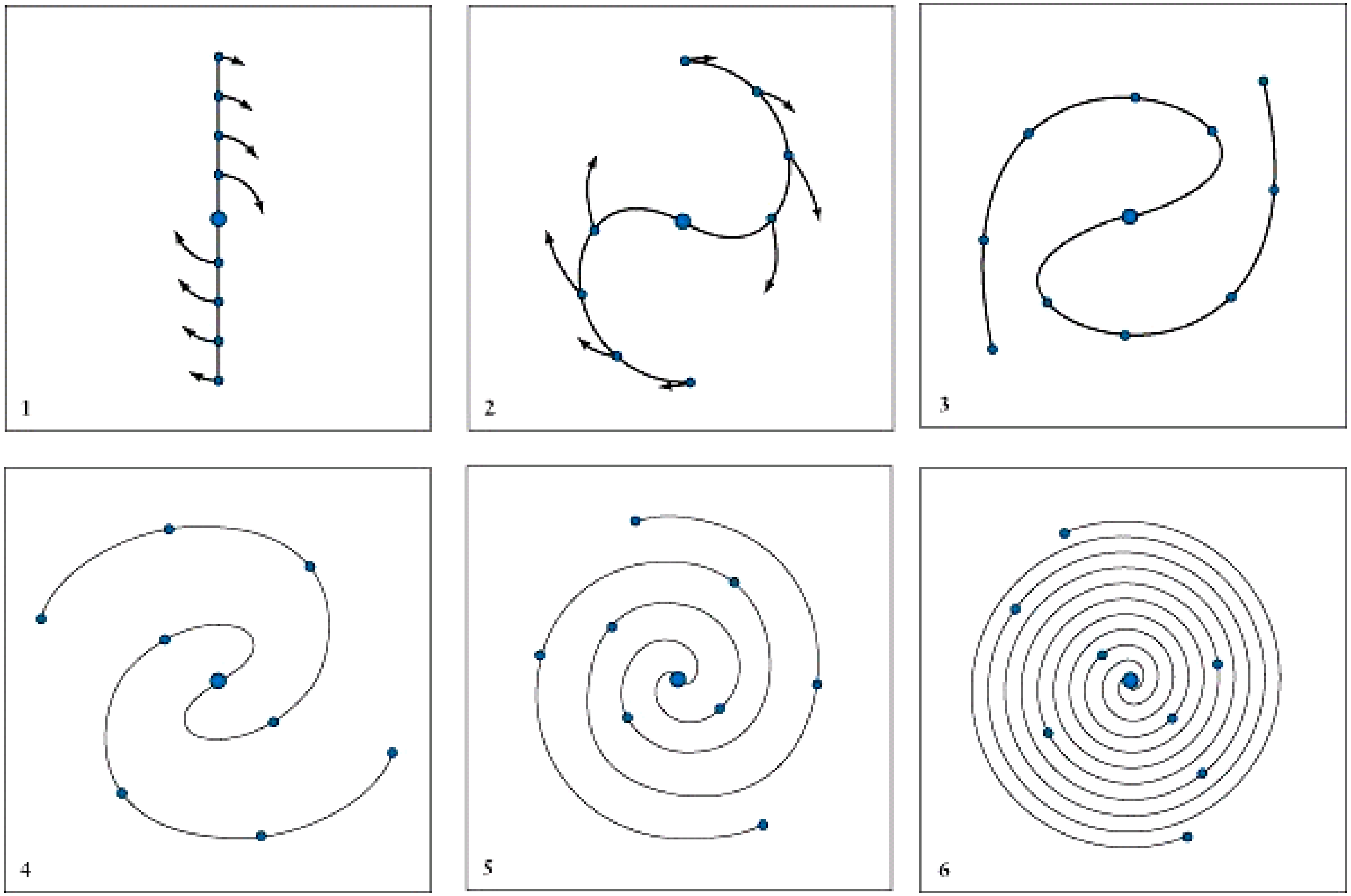
Any feature in the disk will be wrapped into a trailing spiral pattern due to differential rotation:



Tips of spiral arms point *away* from direction of rotation

# The Winding Dilemma

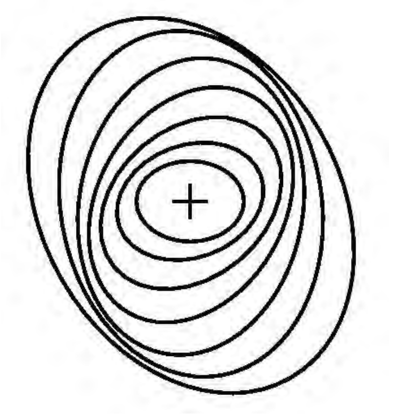
Due to differential rotation, stars near the galactic center don’t need to travel far to circle the galaxy, but stars further out can take a long time to go around.  An initial line of stars will be drawn out into a spiral:



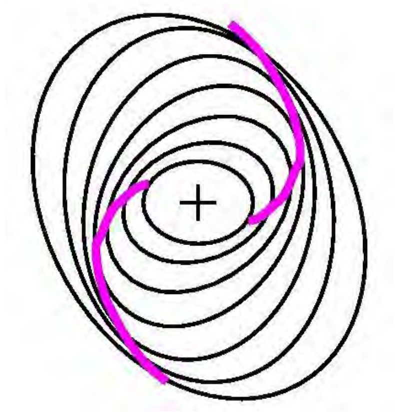
But this is not why galaxies have spiral arms!

# Spiral Density Waves

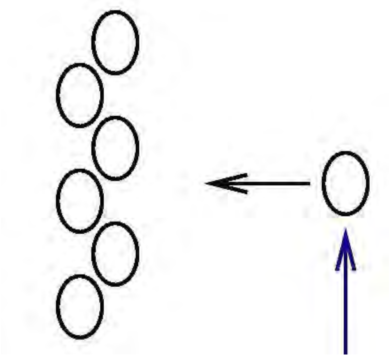
- The orbits in spiral galaxies are not quite circles – they are ellipses. These ellipses are slightly tilted with respect to each other.



- Thus there are regions of slightly higher density than their surroundings. The higher density means higher gravity.

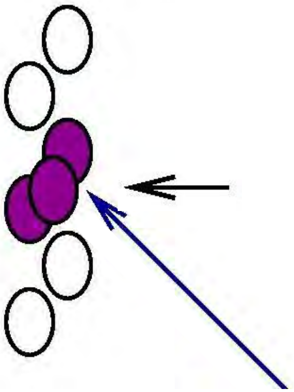


- Objects (such as a gas cloud) will be attracted to these regions and will drift towards them.

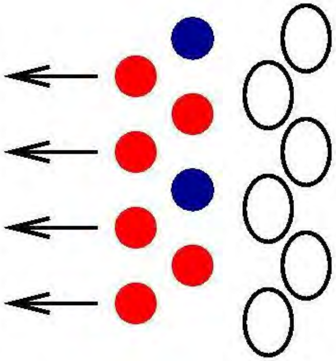


# Spiral Density Waves

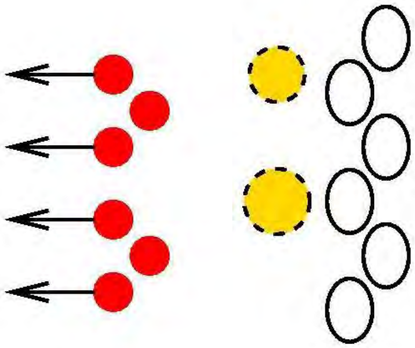
- When the gas cloud collides with other gas clouds, stars will be formed. (This is where most of the galaxy’s star formation takes place.)



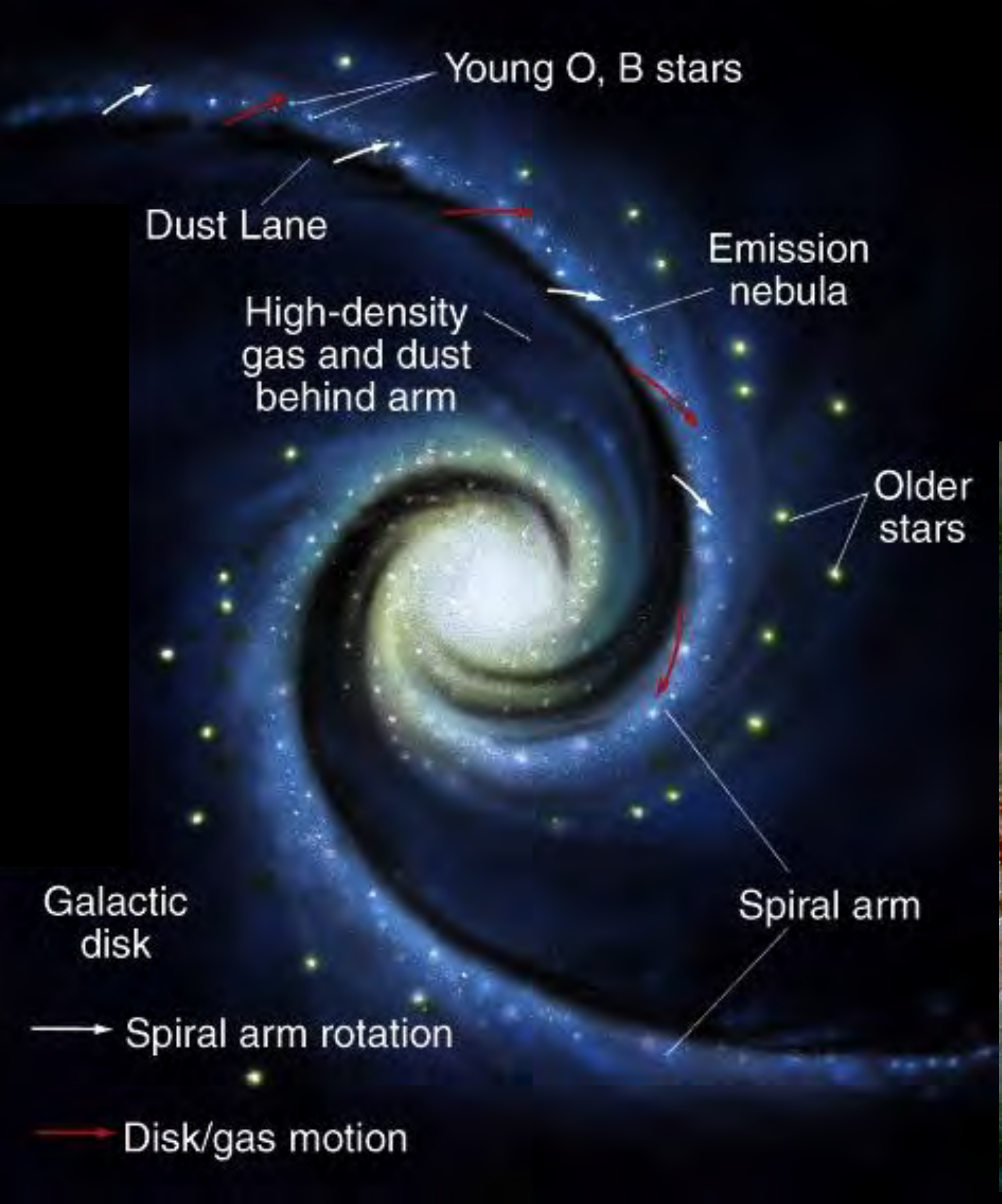
- Many of the stars will be faint, red main sequence stars, but some will be bright blue OB stars. These stars will continue to drift through the region.



- The OB stars don’t go far before they explode. The brightest (and bluest) of a galaxy’s stars will never be far from the spiral arm where they were born.



# The Density Wave Theory



M51 (HST image)

# Density Wave Theory Summary

- ***Spiral arms are waves of compression*** that move around the galaxy and ***trigger star formation*** in the gas clouds
- Stars pass through the spiral arms unaffected. Even if there was no star formation, there would be spiral arms - but star formation makes them more prominent
- However, *some disks have no spiral arms*, and yet they still form stars. Star formation can ***self-propagate*** in a differentially rotating disk, e.g., as supernova shocks compress neighboring molecular clouds
- **Two outstanding problems**:
  1. What stimulates the formation of the spiral pattern? Tidal interactions?
  2. What accounts for the branches and spurs in the spiral arms?