Ay 1 – Lecture 12

Galaxies and Their Properties

Galaxies

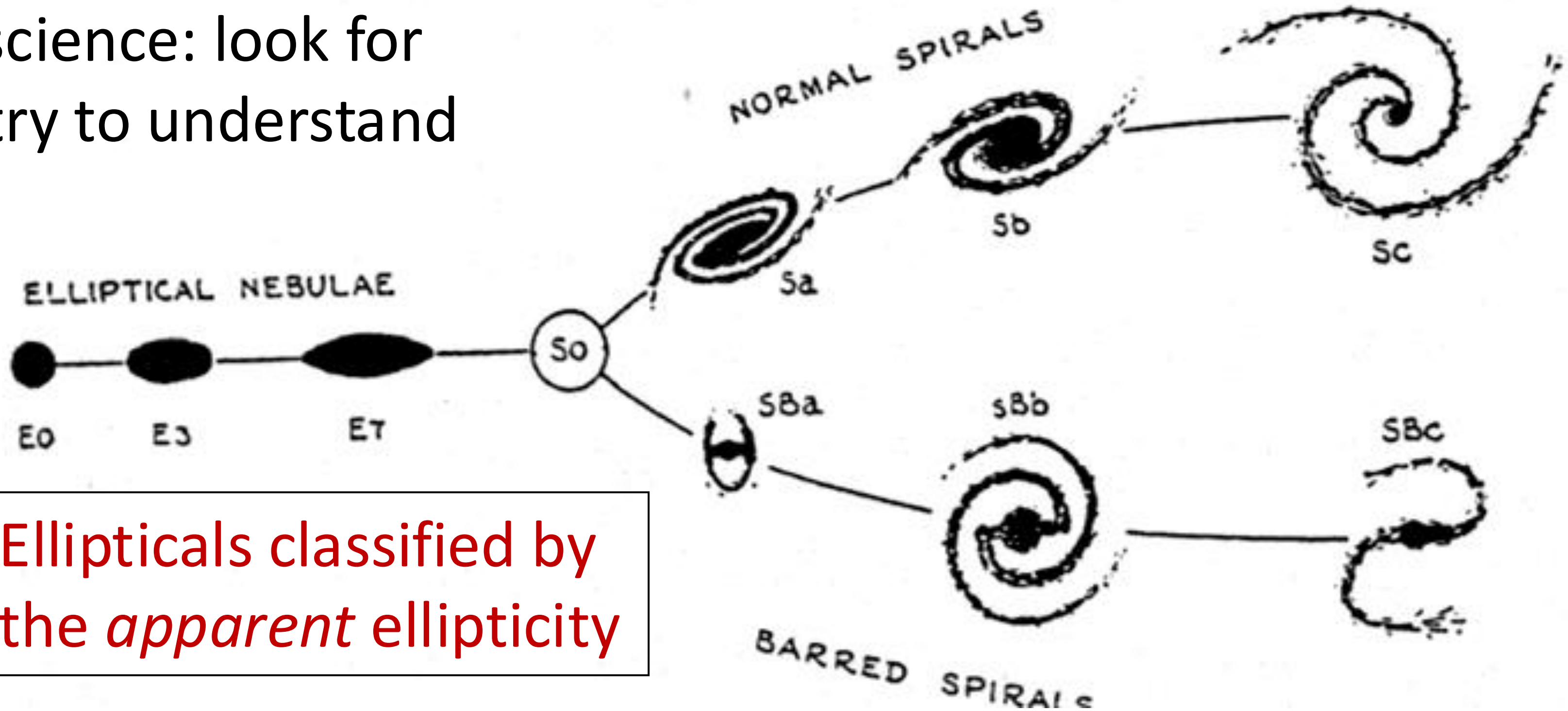
- The basic constituents of the universe at large scales, and the building blocks of the large-scale structure
- Have ***a broad range of physical properties***, which presumably reflects their evolutionary and formative histories, and gives rise to various morphological classification schemes (e.g., the Hubble type)
- Understanding of galaxy formation and evolution is one of the main goals of modern cosmology
- There are ~ 10^{12} galaxies within the observable universe
- Typical total masses ~ 10^{8} - 10^{12} $M_{\odot}$
- Typically contain ~ 10^{7} - 10^{11} stars

Hubble's Galaxy Classification Scheme

Purely empirical/morphological

The first step in any empirical science: look for the patterns and trends, then try to understand the underlying physics

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



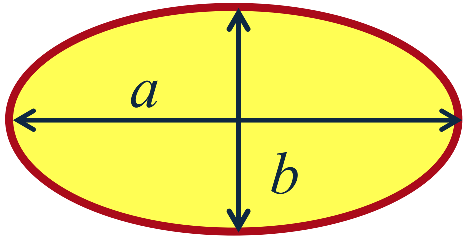
Ellipticals classified by the *apparent* ellipticity

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

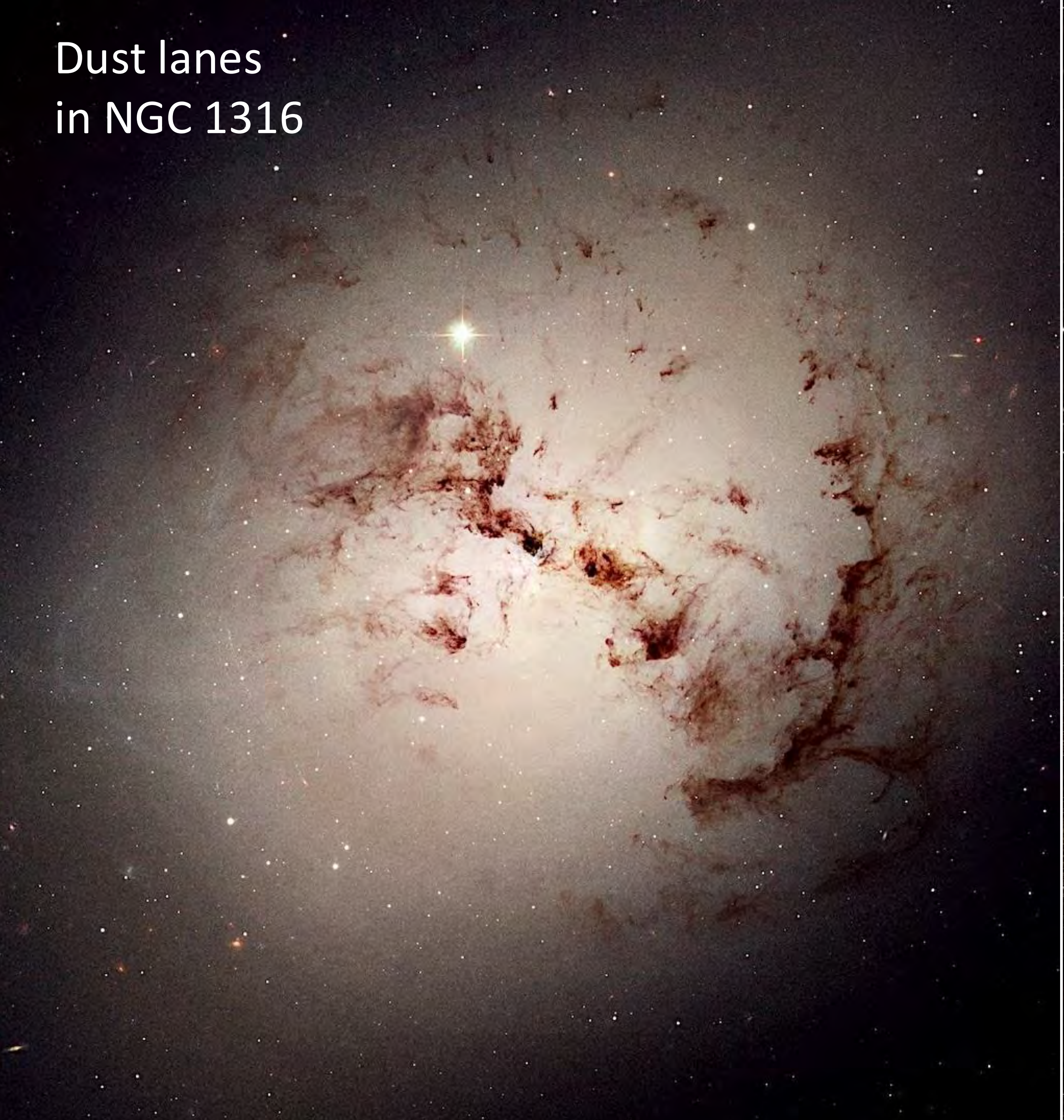
This classification scheme captures some, but not all physical properties. It also misses some galaxy types altogether

Subsequent refinements were proposed by others - but not any fundamental change

Elliptical Galaxies



- Classified by the apparent ellipticity: (not very meaningful) $\varepsilon = 1 - (b/a)$
- For the most part smooth and almost featureless: no spiral arms or dust lanes; but some post-merger ellipticals can contain both
- Generally lacking in cool gas, little or no current star formation; again, except in some post-merger ones
- Most kinetic energy in random motions; little or no rotation
- Contain hot, X-ray gas; its kinetic energy (3/2 $k_B T$) balances the gravitational potential of the dark halo
- Old, *metal-rich* stellar populations
- Mostly found in clusters (denser environments)


Dust lanes
in NGC 1316


Shell features
in NGC 1316

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

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

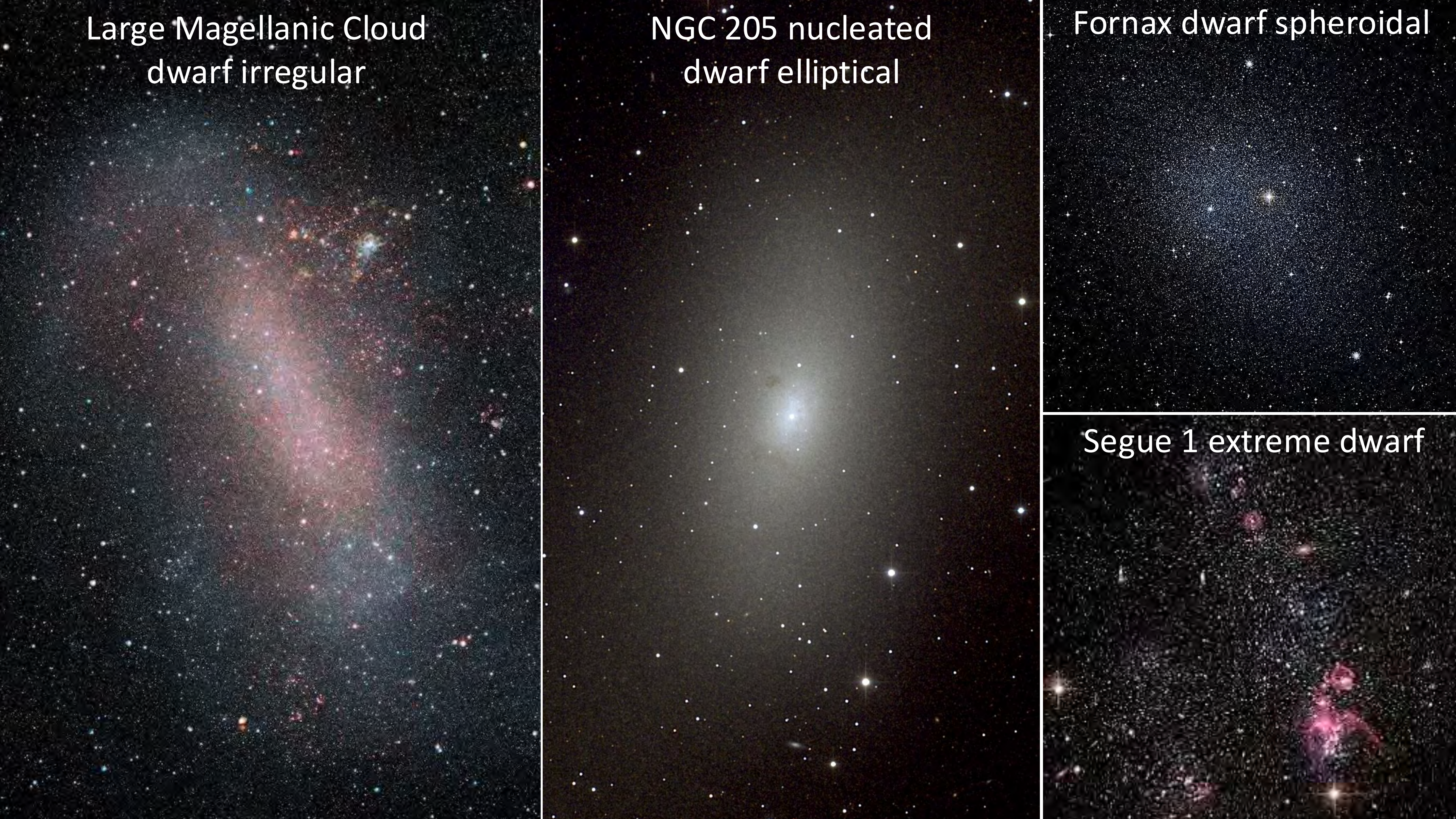
- Bar patterns are not static, they rotate with a pattern speed, but unlike spiral arms they are ***not density waves***. Stars in the bar stay in the bar
- The *asymmetric gravitational forces* of a disk+bar allow gas to lose angular momentum (via shocks) compressing the gas along the edge of the bar. The *gas loses energy* (dissipation) and moves closer to the center of the galaxy, where it can fuel an active nucleus (if present)

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 and active star formation
- They may have lost their gas through evolutionary processes
- They can also have a central bar, in which case they are labeled SB0

Dwarf Galaxies

- Low luminosity: $10^4 - 10^9\ L_\odot$, low-mass: $10^4 - 10^8\ M_\odot$, small in size, up to ~ few kpc
- Often very 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: relatively simple systems, not merger products
  - Dwarf galaxies are currently being cannibalized by larger galaxies


Large Magellanic Cloud
dwarf irregular
NGC 205 nucleated
dwarf elliptical
Fornax dwarf spheroidal
Segue 1 extreme dwarf

Hubble Sequence of Spirals Involves…

A. A change in the bulge-to-disk ratio
B. A change from normal to barred spirals
C. A change in the prominence of spiral arms
D. A change in mass
E. A change in luminosity
F. All of the above

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*:
  - Old, pressure supported bulges, where most of the star formation occurred early on
  - Young(er), rotationally supported disks, where star formation happened gradually and is still going on
- Note that this does not involve the dominant mass component - the **dark matter**

However … there are issues:

- The traditional morphological classification is **subjective**, based on visual appearance, not physical properties
- It is **biased**, based on the visible light, ignoring other wavelengths
- It is based on the luminous galaxies of the Hubble sequence, and **misses** the variety of dwarf galaxies

But ***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

No star formation □ Actively star forming

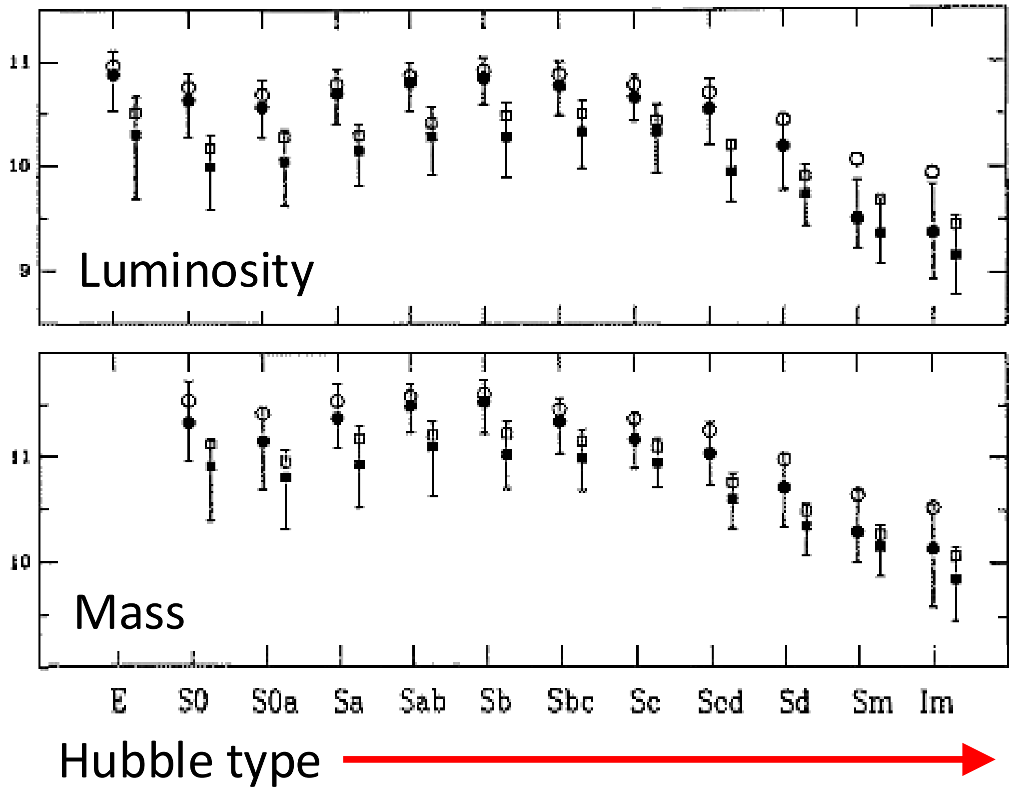
Red colors □ Blue colors

Hot gas □ Cold gas and dust

Old □ Still forming

High luminosity density □ Low lum. dens.

… etc.

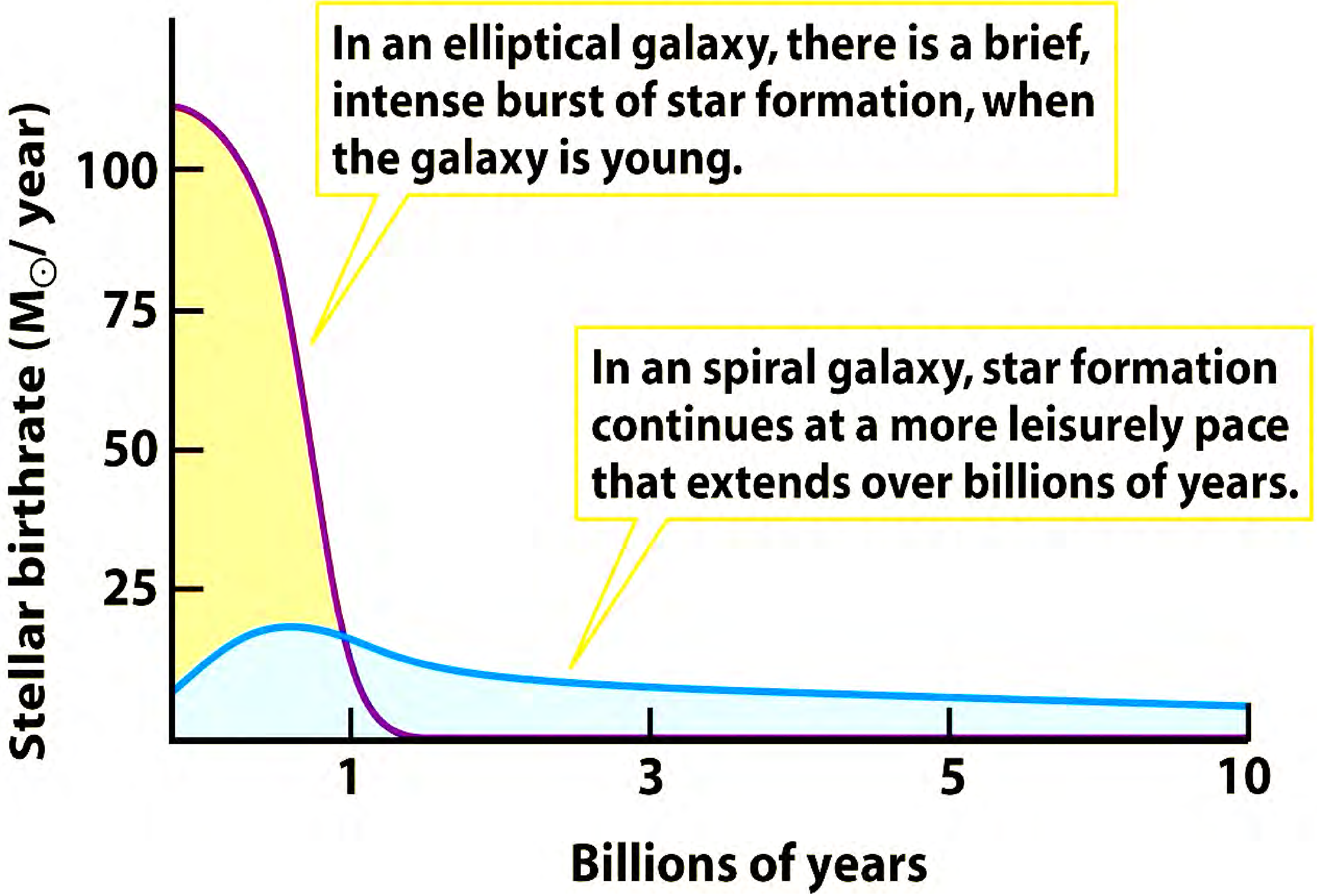


But, for example, masses, luminosities, sizes, etc., ***do not*** correlate well with the Hubble type: at every type there is a large spread in these properties

Interpreting the Trends Along the Hubble Sequence

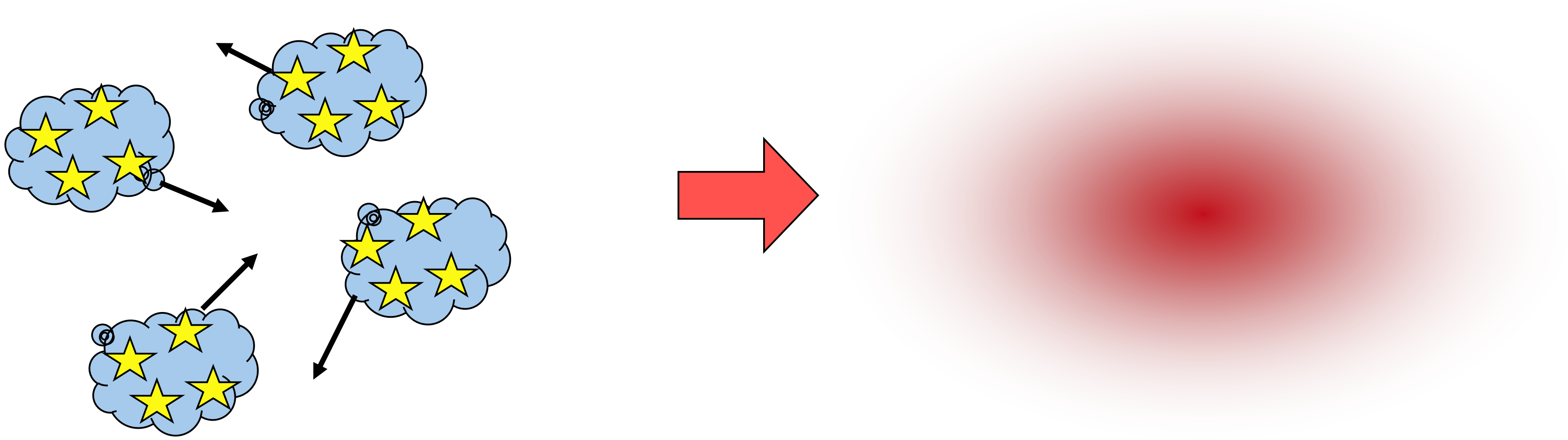
- Probably the best interpretation of many of these thends is ***a trend in star formation histories:***
  - Ellipticals and early type spirals formed most of their stars early on (used up their gas, have older/redder stars)
  - Late type spirals have substantial on-going star-formation, didn’t form 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 $\times 10^9 M_\odot$ of HI mass in a typical spiral
    - ✧ How long can spirals keep forming stars? It seems that some gas infall/resupply is needed
- The photometric/morphological properties also correlate with the dynamical properties

Star Formation History in Galaxies



This accounts for the photometric and spectroscopic properties, but not for the kinematical ones, the masses, sizes, etc.

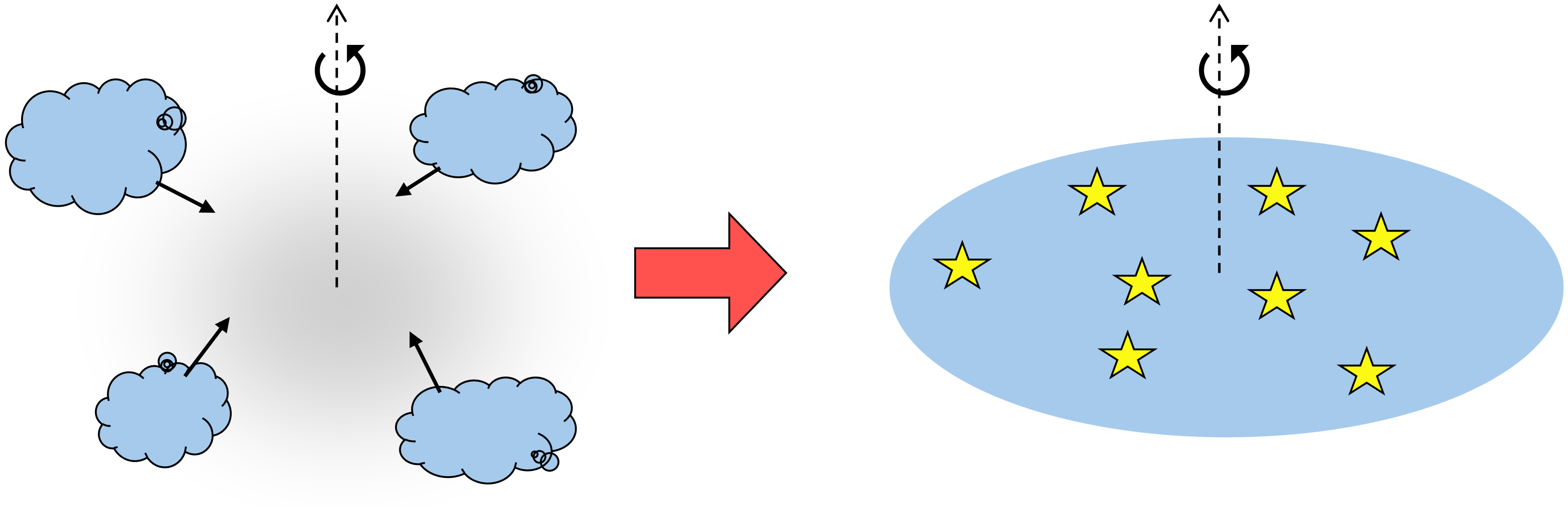
Formation of Galaxy Spheroids and Dynamics of Stellar Populations



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 randomly, 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, but more stars can also form afterwards, within the new galaxy

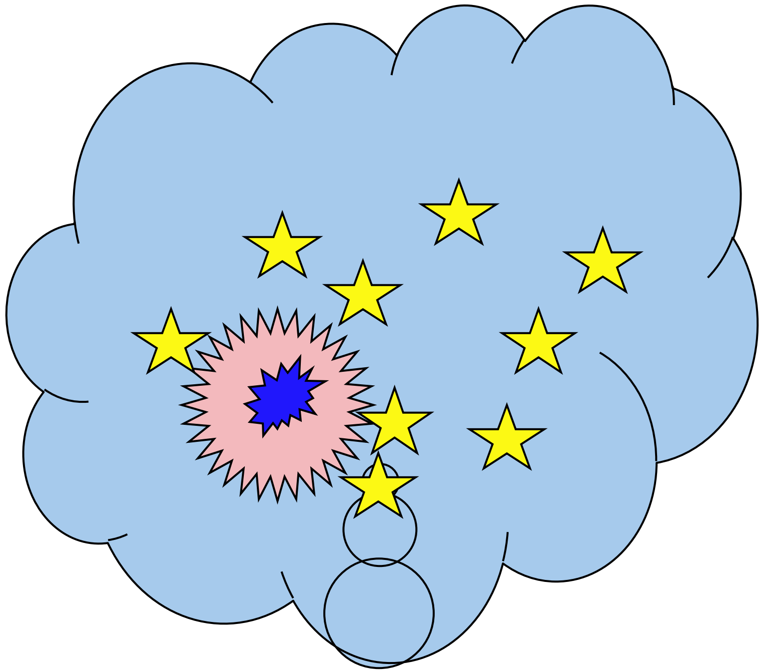
Formation of Galaxy Disks and Dynamics of Stellar Populations



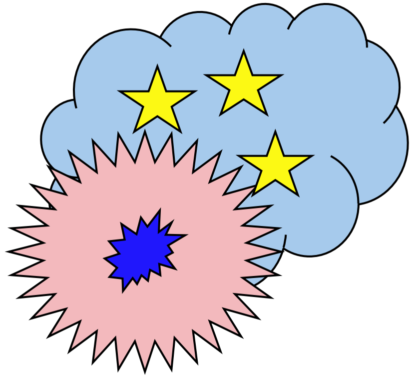
If protogalactic clouds merge dissipatively in a potential well of a dark halo, they will settle in a thin, rotating disk = the minimum energy configuration for a given angular momentum

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 star winds from massive young stars expell the enriched gas and may supress any subsequent star formation. The system retains its initial (low) metallicity

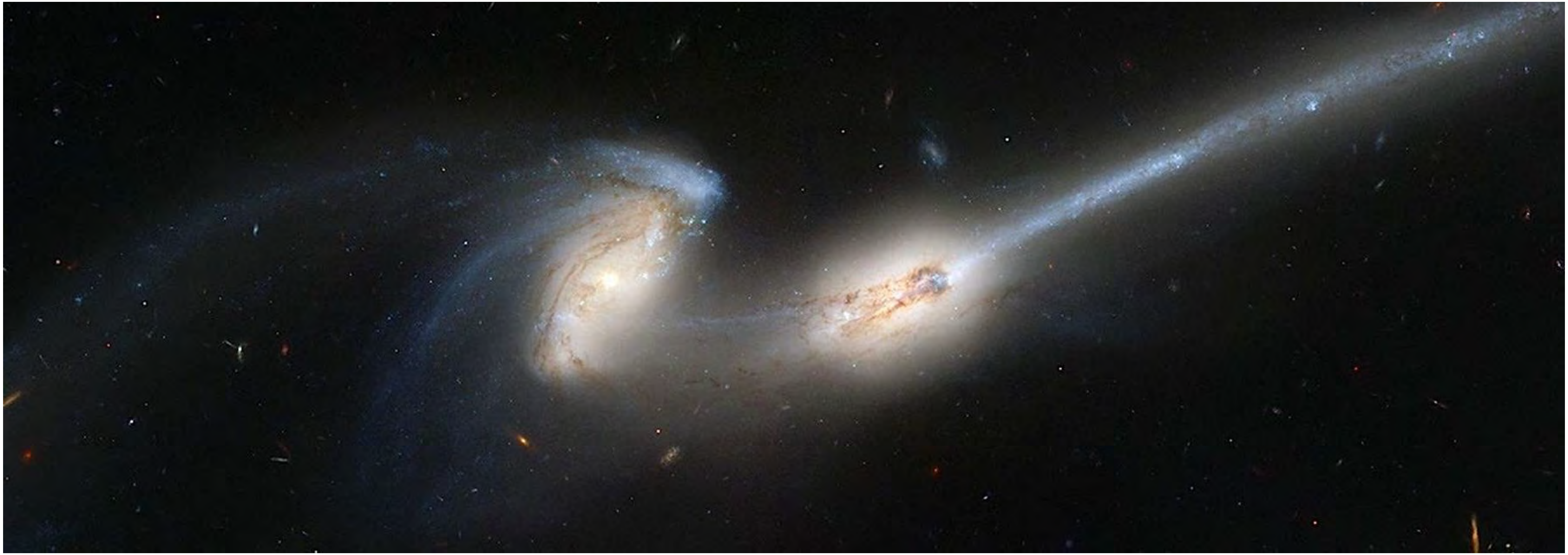
True or False?

A. Bulge stars are on average older than the disk stars
B. The ages are about the same, but their location differs
C. Disk stars on the whole have more kinetic energy than the bulge stars
D. Disk stars on the whole have more angular momentum than the bulge stars
E. Galaxies evolve in their chemical composition mainly by merging with other galaxies
F. Galaxies evolve in their chemical composition mainly by retaining their supernova ejecta

Merging / Interacting Systems

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

In late stages of a merger, the two galaxies are indistinguishable, and the product does not look like any standard galaxy type



A Sampler of Galaxy Mergers

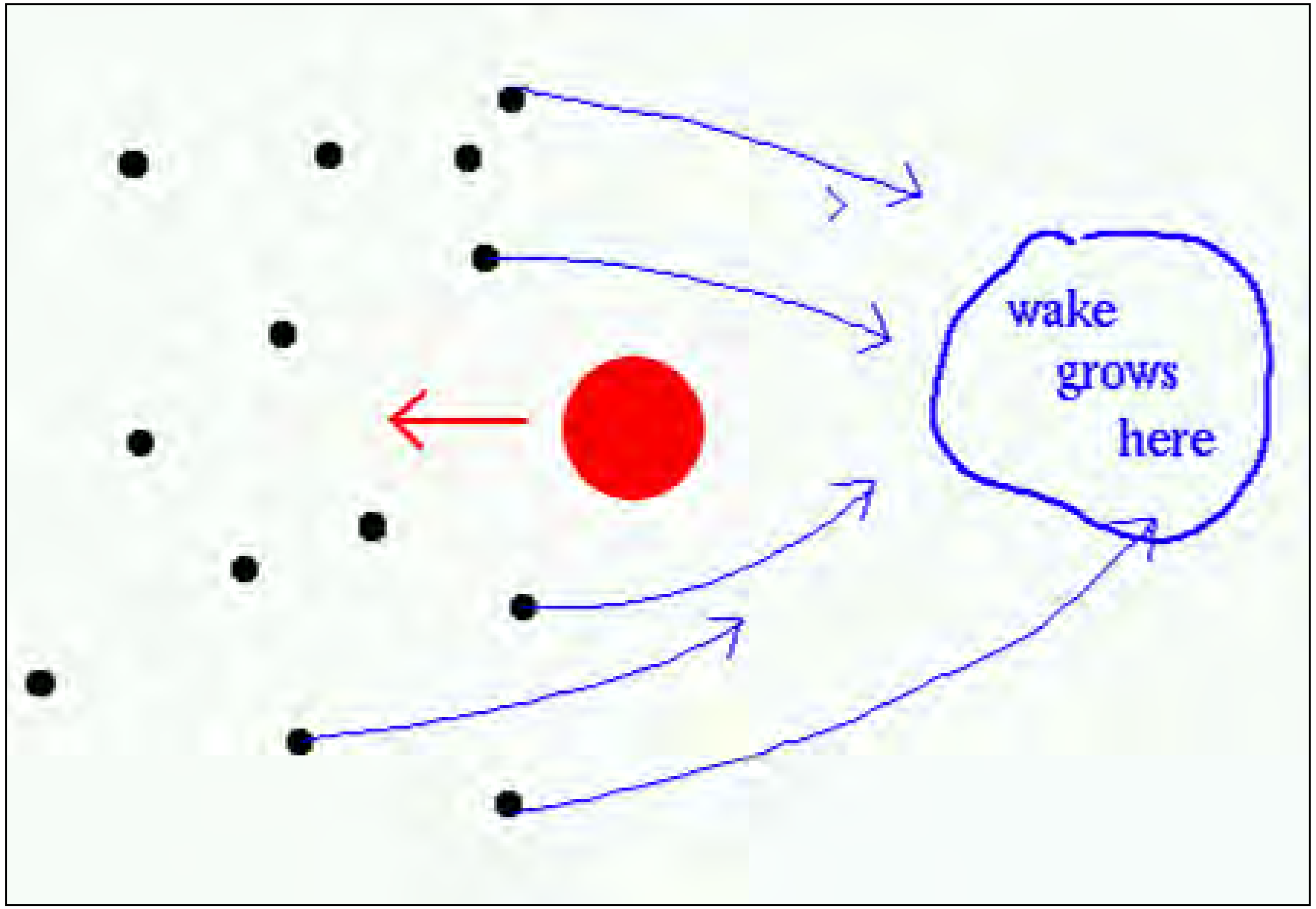




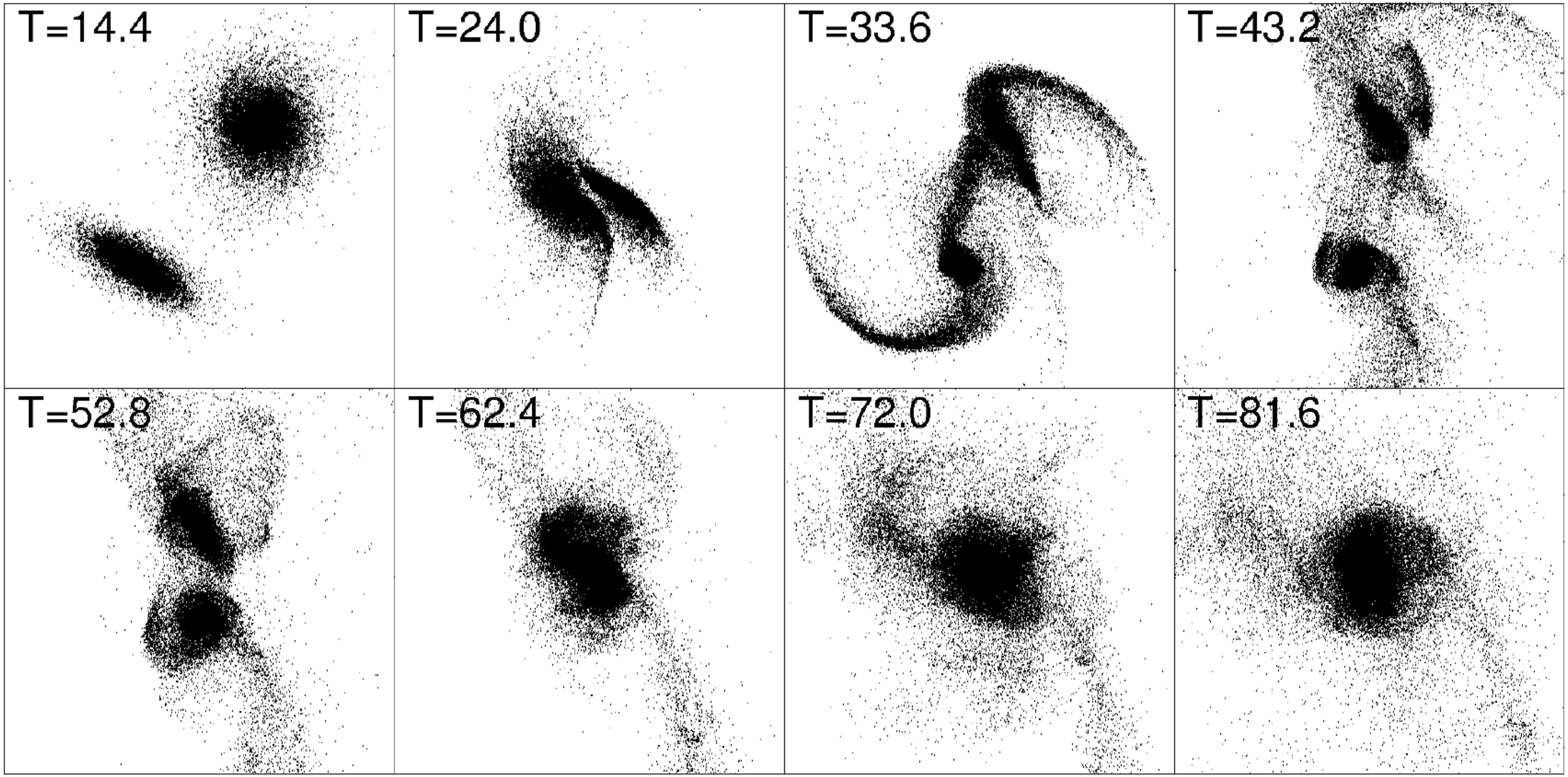

Dynamical Friction

- As a massive galaxy moves through a "sea" of stars (and the dark halo), it accelerates them towards it, but then leaves them behind in a "gravitational wake"
- This causes the galaxy to slow and lose its orbital kinetic energy

- Note: unlike in the regular friction, the energy is not being ***dissipated,*** but ***transferred***
- The galaxy will eventually fall in and merge with its companion
- The orbital kinetic energy is being transferred into internal kinetic energy, typically in random motions
- An example: the Magellanic Clouds will merge with the Milky Way

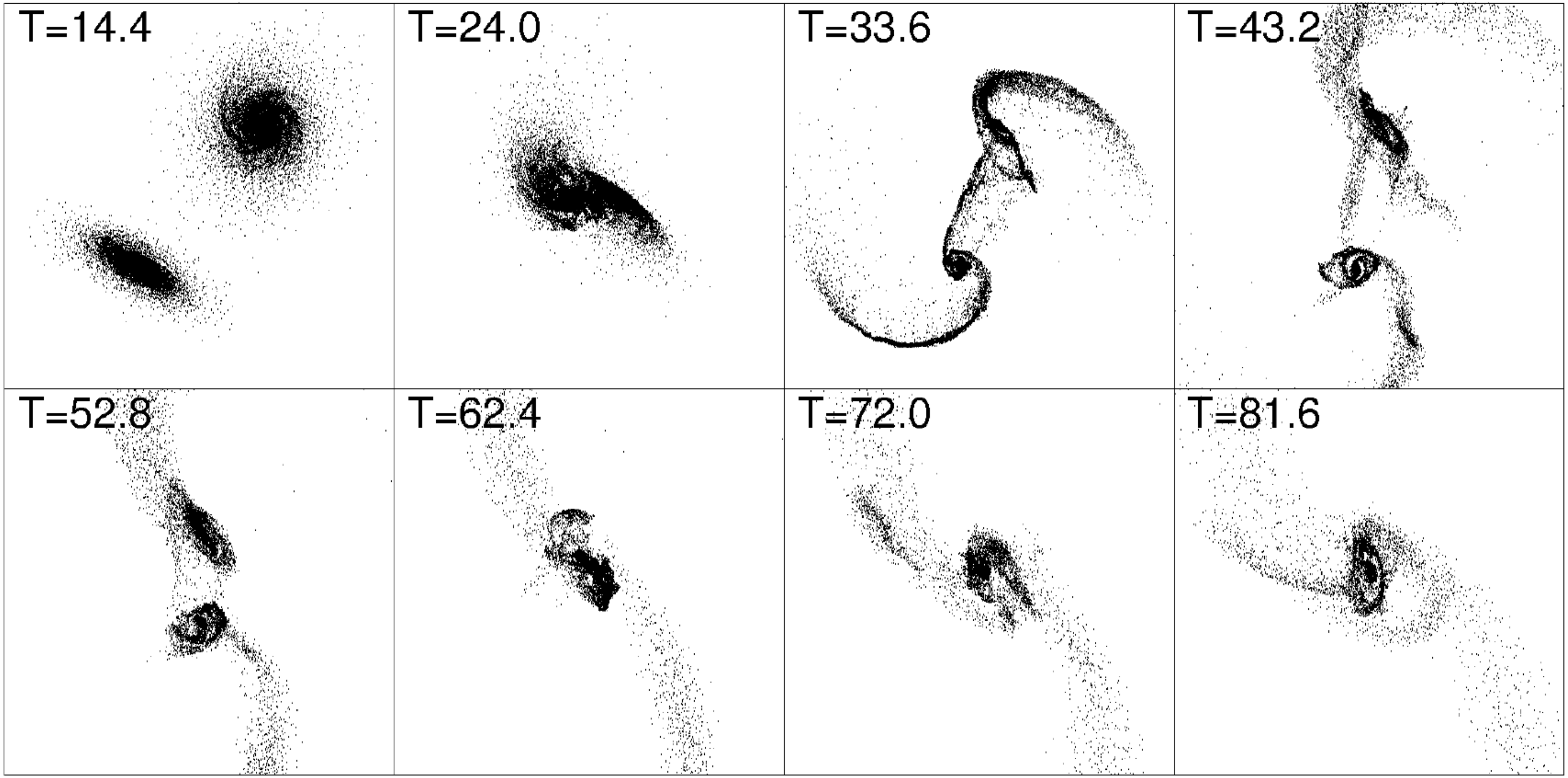


Galaxy Dissipationless Merger: Stars



Merge 2 nearly equal mass disk galaxies; in a few dynamical times, the remnant looks just like an elliptical galaxy

Galaxy Dissipative Merger: Gas



In the same merger, gas quickly looses energy (since it is dissipative), and sinks towards the center, where it can fuel a starburst, or an AGN if a massive black hole is present

Galaxies Merge Because…

A. They loose energy because of the friction as they move through each other's interstellar medium
B. Gravity is a purely attractive force
C. Their bulk motion kinetic energy is transferred into the internal kinetic energy
D. Their gas dissipates energy as they collide
E. All of this is true

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 $\rightarrow$ visible/near-IR, cold gas $\rightarrow$ radio, dust $\rightarrow$ far-IR, hot gas $\rightarrow$ 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!

Radial Surface Brightness Profiles of Spiral Galaxies

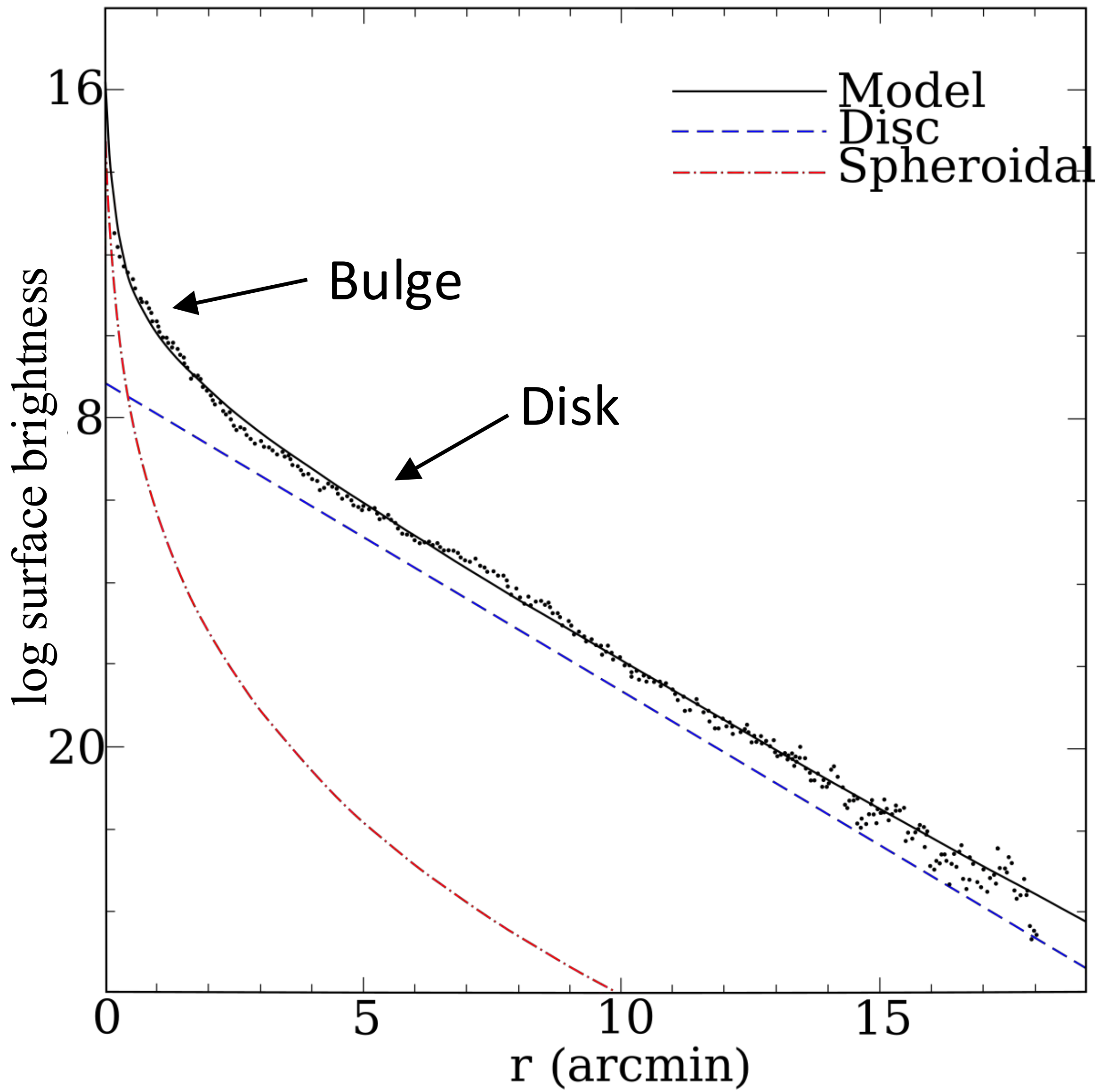
Empirically, the surface brightness declines with distance from the center of the galaxy in different characteristic ways for spiral and elliptical galaxies

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

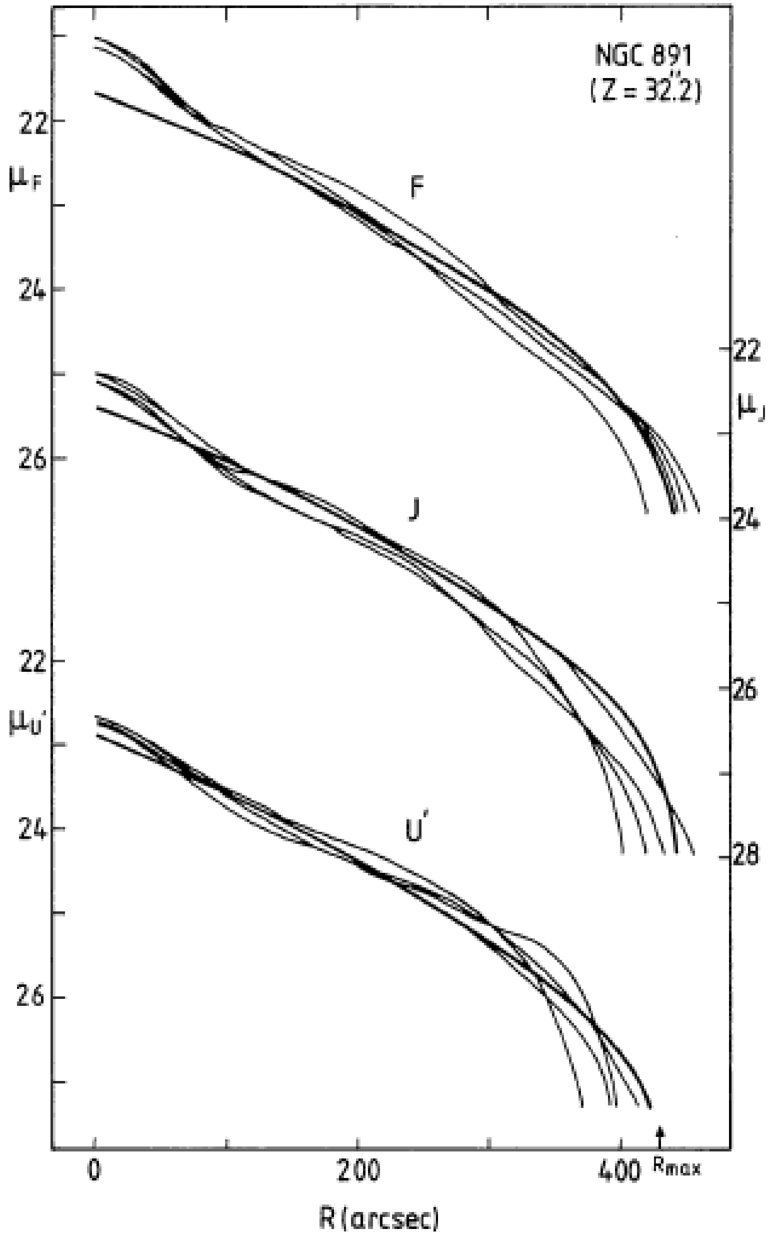
$$I(R) = I(0)\ e^{-R/h_R}$$

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:

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



Disks Have Cutoffs

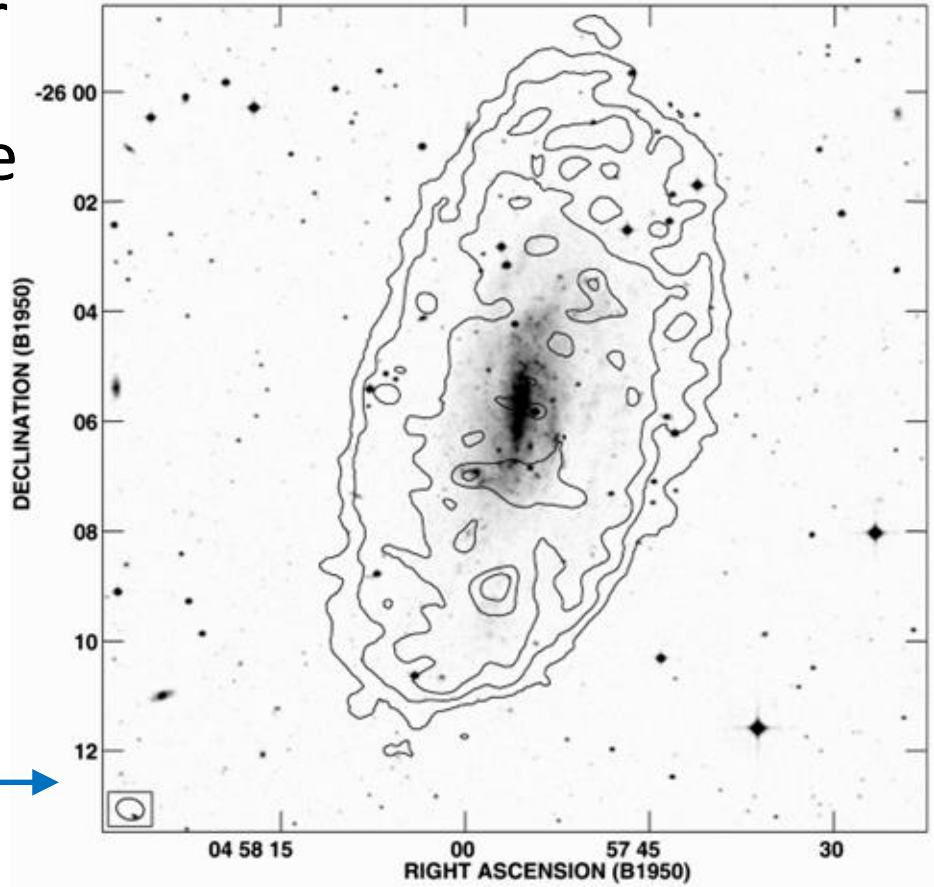


Stellar disks have finite radii, R_{max}, typically 3 - 5 h_R

This is *not* seen in ellipticals: they have no edges

The *H I gas extends well beyond the visible cutoff*, and so does the dark matter

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



NGC 1744: H I contours superposed on a visible light image

Elliptical Galaxies: Surface Photometry

Surface brightness profile is usually well represented by the $R^{1/4}$ or de Vaucouleurs law:

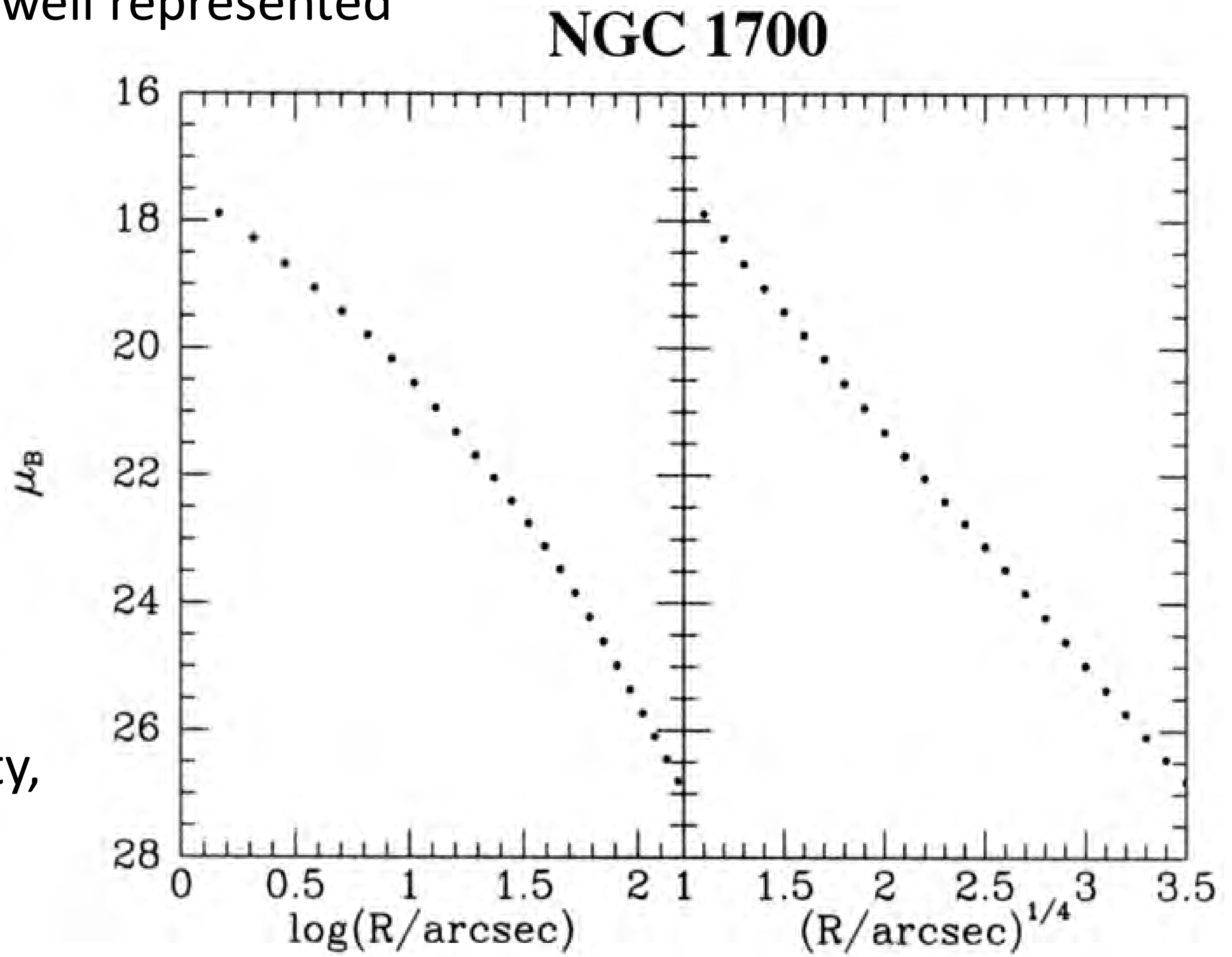
$$I(R) = I(0)\ e^{-kR^{1/4}}$$

where k is a constant.

This can be rewritten as:

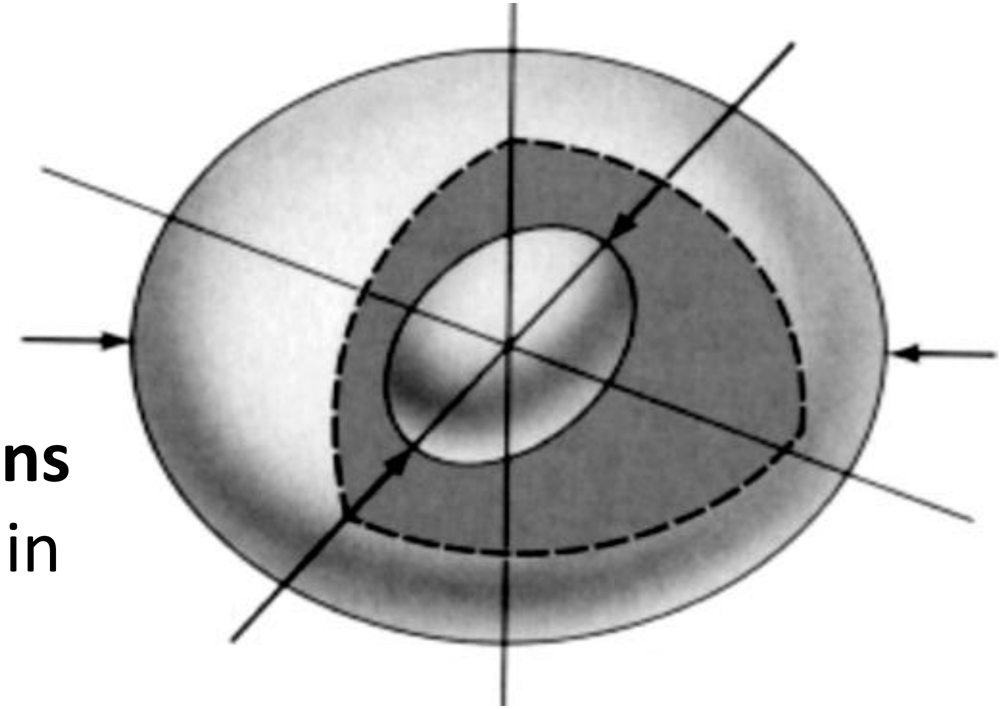
$$I(R) = I_e\ e^{\left\{-7.67\left[\left(R/R_e\right)^{0.25}-1\right]\right\}}$$

where R_e is the **effective radius,** containing half of the total luminosity, typically a few kpc



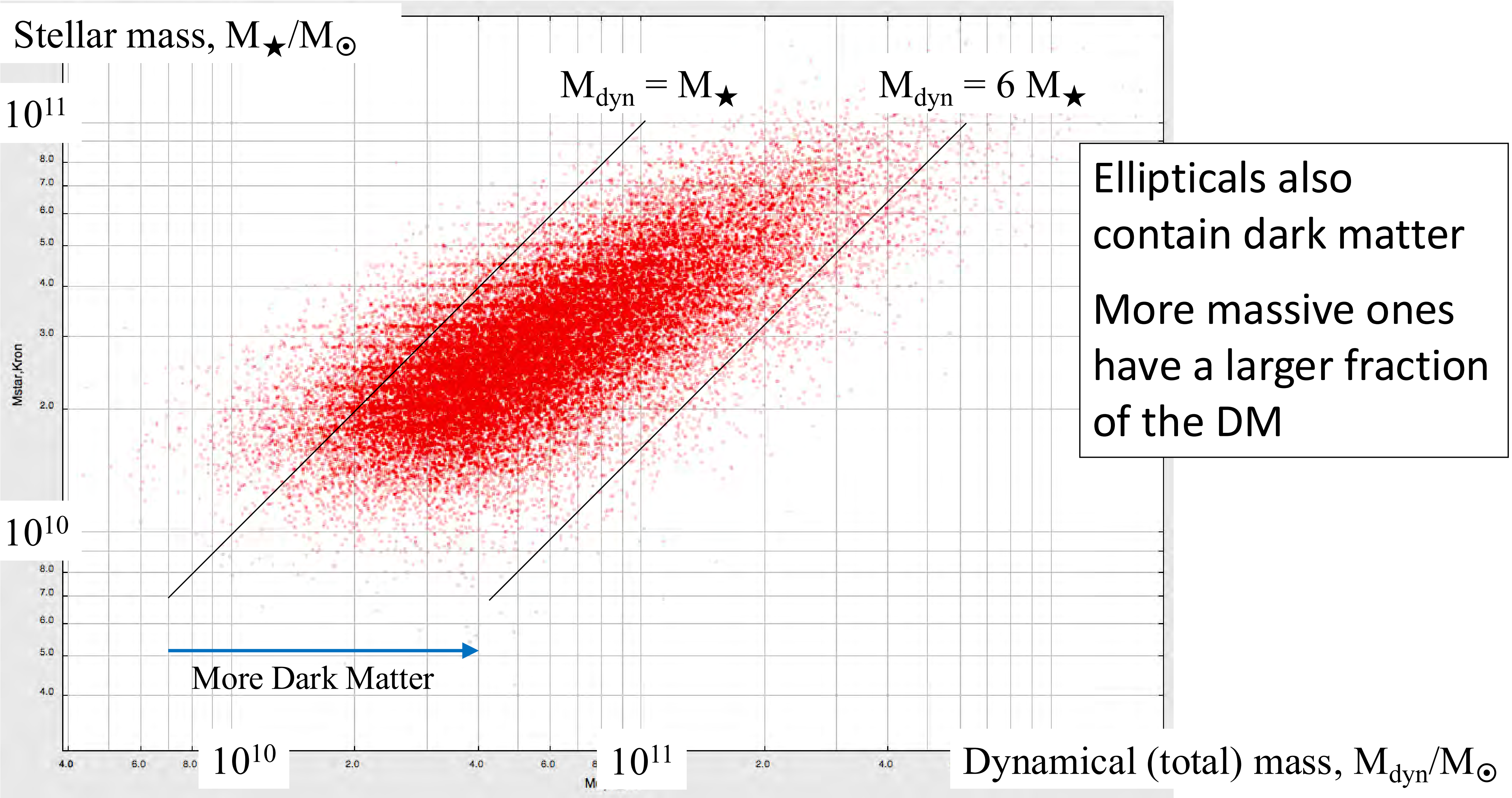
The 3D Shapes of Ellipticals are Triaxial Ellipsoids

- In general, the 3-D shapes of ellipticals can be triaxial (A,B,C are intrinsic axis radii):
  - Oblate: A = B > C (frisbee)
  - Prolate: A > B = C (cigar)
  - Triaxial A > B > C (football)



- It is due to **the anisotropic velocity dispersions** of stellar motions, which stretch the galaxies in proportion along their 3 principal axes
- Thus, elliptical galaxies are *not* flattened only by rotation
- Most of the kinetic energy is in random motions
- More massive ellipticals tend to be more anisotropic

Elliptical Galaxies: Stellar vs. Dynamical Mass



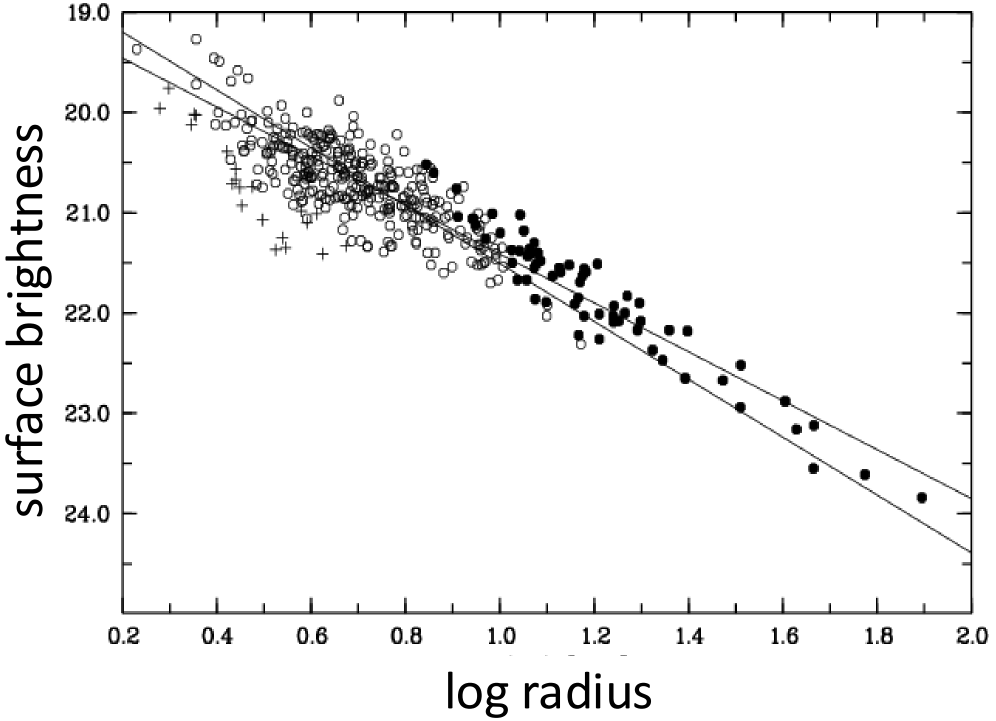
Ellipticals also contain dark matter

More massive ones have a larger fraction of the DM

Galaxy Scaling Laws

- When correlated, global properties of galaxies tend to do so as power-laws; thus "scaling laws"
- They provide a *quantitative means of examining physical properties of galaxies* and their systematics
- They *reflect the internal physics* of galaxies, and are a product of the *formative and evolutionary histories*
  - They are different for different galaxy families
  - A "fossil evidence" of galaxy formation
- Correlations between distance-dependent and distance-independent quantities can be used to *measure relative distances of galaxies*

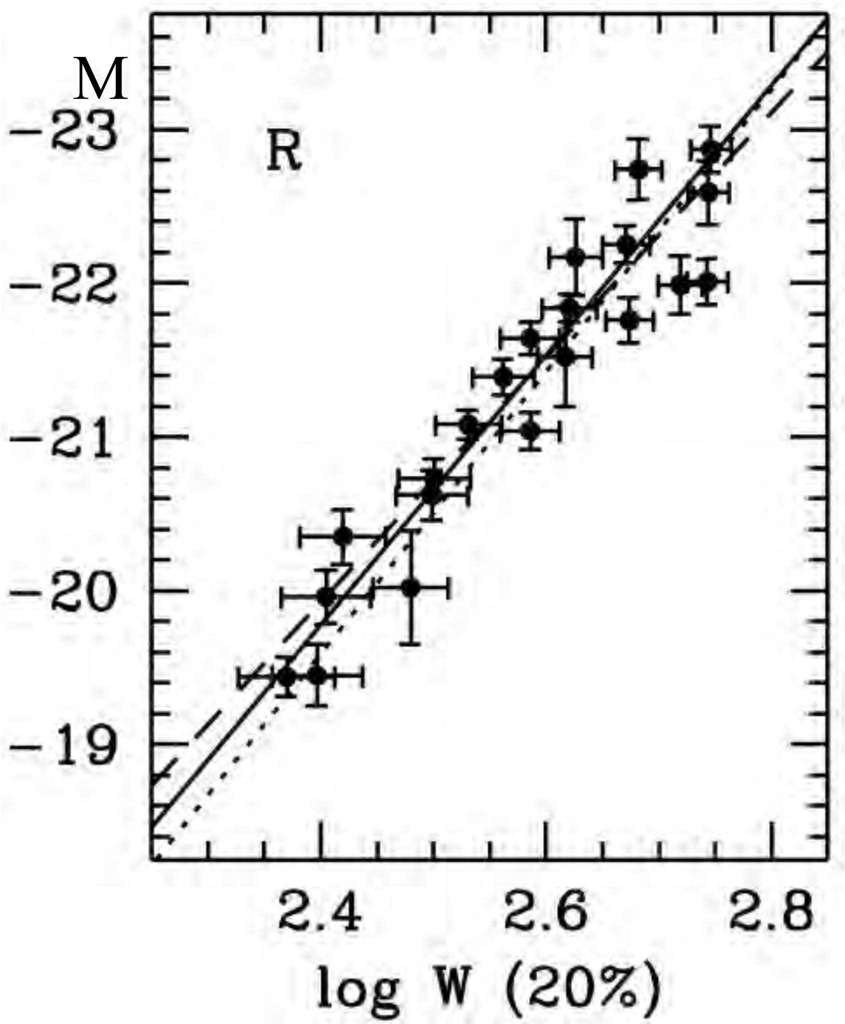
An example: power-law scaling relation between the radius (R), and the mean surface brightness (I) of elliptical galaxies, $R \sim I^{-0.8}$



Its interpretation involves the roles of mergers in formation of elliptical galaxies

The Tully-Fisher Relation

A well-defined luminosity vs. maximum rotational speed relation for spirals: $L \sim V_{rot}^{\gamma}$, slope $\gamma \approx 4$, varies with wavelength



Scatter can be as low as ~ 10%, better in the redder bands

Used as a **distance indicator** relation for spiral galaxies

It connects a *property of the dark halo*, the maximum circular speed, with the product of the net *integrated star formation history*, i.e., the luminosity of the disk

Implies important insights into the physics of disk galaxy formation

Fundamental Plane of Elliptical Galaxies

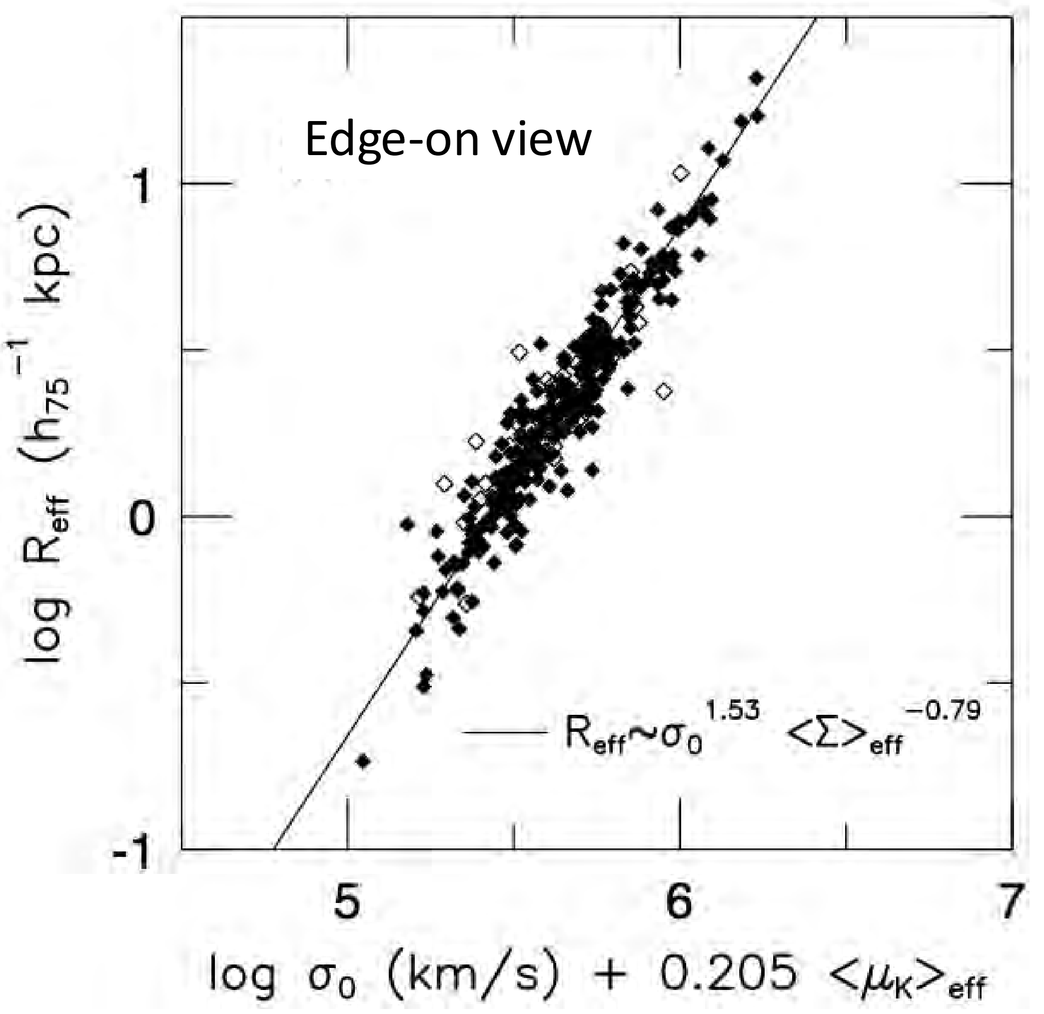
Commonly expressed as a dual power-law (bivariate scaling) relation $R \sim \sigma^{1.4} I^{-0.8}$
where R is the radius, I is the mean surface brightness, σ is the velocity dispersion

Very low scatter, also used as a **distance indicator** relation for elliptical galaxies

Many other fundamental properties of ellipticals are also expressible as similar dual power-laws

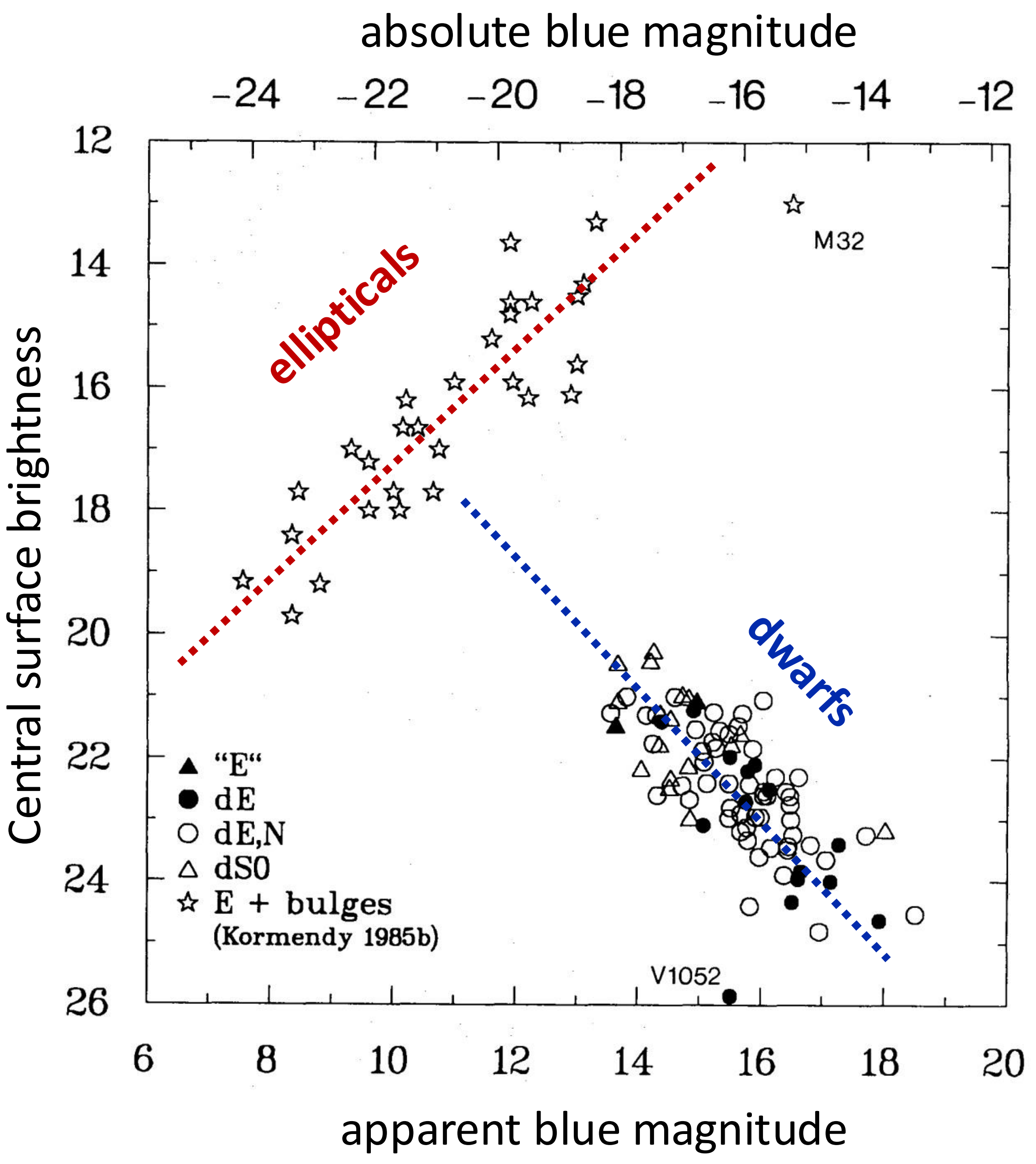
It roughly follows from the virial theorem (a relation between mass, radius, and velocity), but with some modifications

It also contains some insights into the formation and evolution of elliptical galaxies



Dwarf Galaxies

- Dwarf ellipticals (dE) and dwarf spheroidals (dSph) are ***a completely different family of objects*** from normal ellipticals – they are not just "small ellipticals"
- They follow ***completely different correlations*** from giant galaxies, suggestive of ***different formative mechanisms***
- They are generally ***dark matter (DM) dominated***, especially at the faint end of the sequence, much more so than the regular Hubble sequence galaxies



True of False?

A. Elliptical galaxies have exponential surface brightness profiles

B. Tully-Fisher relation implies that all spiral galaxies have the same dark matter halos

C. Some scaling relations can be used to measure relative distances to galaxies

D. Scaling relations can provide some insights into galaxy formation and evolution

E. Dwarf ellipticals are scaled-down version of large ellipticals

Key Concepts in This Lecture (1)

- **Hubble Sequence** is the original morphological classification of galaxies. Many, but not all important properties of galaxies correlate with the Hubble type. On the **elliptical** galaxy end, stellar populations are **older**, there is little or **no star formation**, colors are **redder**, dynamical support is mainly **random motions** (pressure), and densities are higher. On the **spiral** end, stellar populations are **younger**, **bluer, star formation is active**, and disks are supported mainly by **rotation**
- Most of these trends can be understood as a **sequence of star formation histories**, with the **order of galaxy assembly and star formation**
- Galaxy **mergers**, due to **dynamical friction**, play a major role in galaxy assembly. Generally, mergers *turn the rotationally supported disk galaxies into pressure supported ellipticals*, and may cause **bursts of star formation**

Key Concepts in This Lecture (2)

- Galaxy **disks** have **exponential density profiles**, bit in radius and vertically. Stellar disks have cutoffs, with has extending beyond them, suggestive of an **inside-out galaxy formation**
- Ellipticals and bulges have **$R^{1/4}$ projected density profiles** and **triaxial shapes** due to an **anisotropic velocity dispersions**
- **Galaxy scaling relations**, mainly the **Tully-Fisher** relation for spirals and the **Fundamental Plane** relations for ellipticals, can be used as **distance indicator relations**, and provide some **insights into galaxy formation**
- **Dwarf galaxies** follow **qualitatively different correlations**, driven by the mass loss due to Supernova winds and adiabatic expansion

?