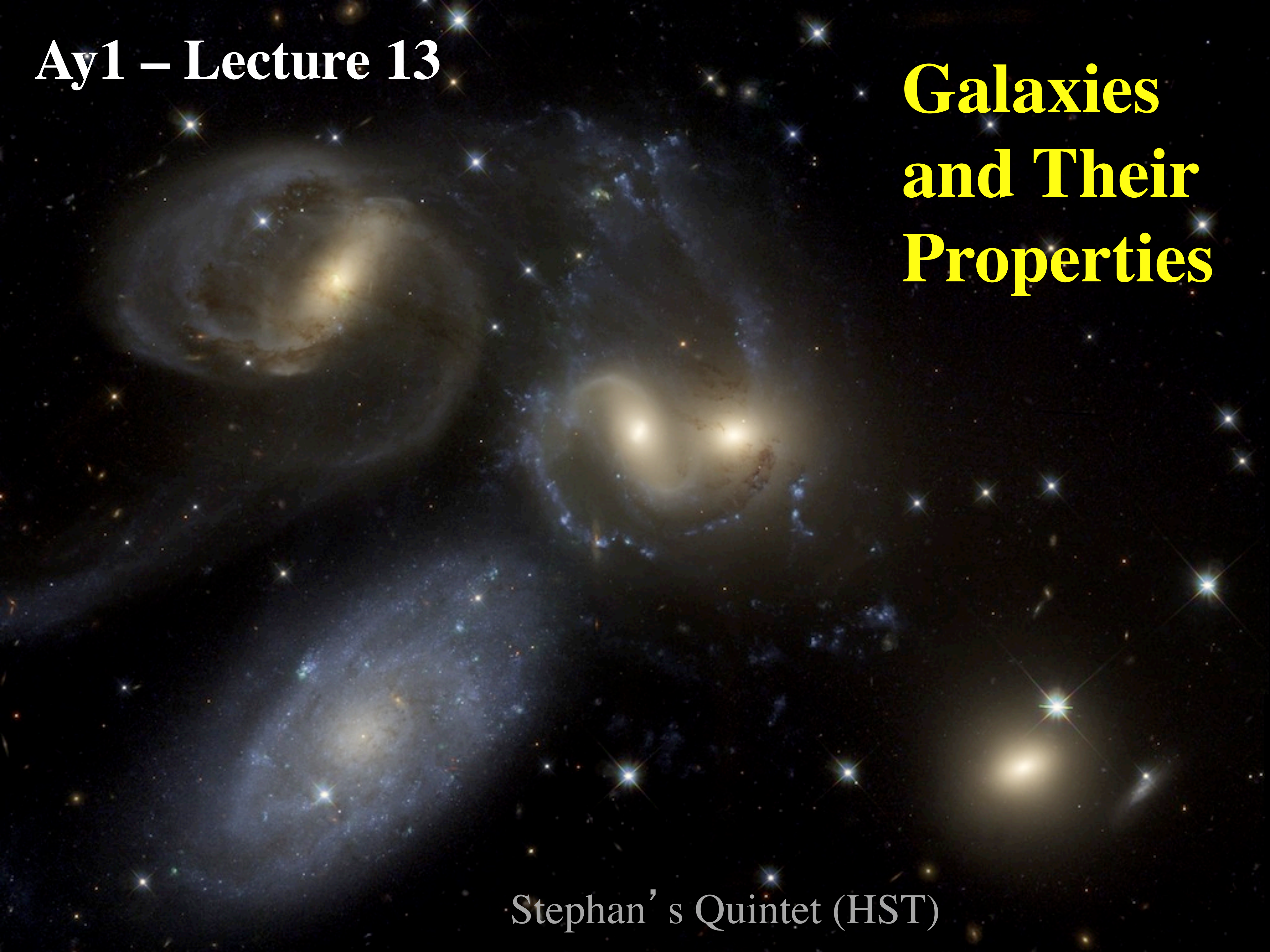
Ay1 – Lecture 13

Galaxies and Their Properties



Stephan’s Quintet (HST)

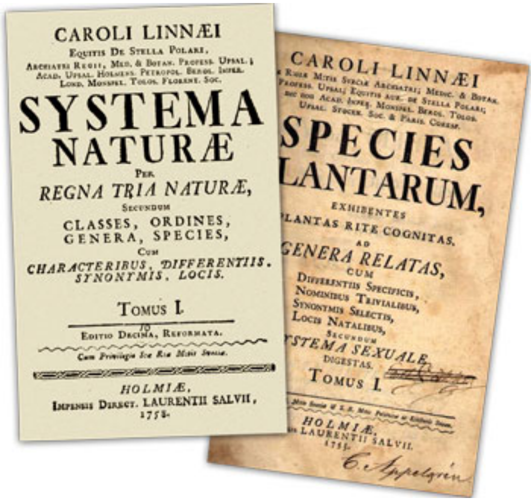
13.1 Galaxy Morphology and the Hubble Sequence

Hickson 44 galaxy group (R. Kier)

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^{11} galaxies within the observable universe
- Typical total masses ~ 10^8 - 10^{12} $M_\odot$
- Typically contain ~ 10^7 - 10^{11} stars

Morphological Classification and Galaxy Types

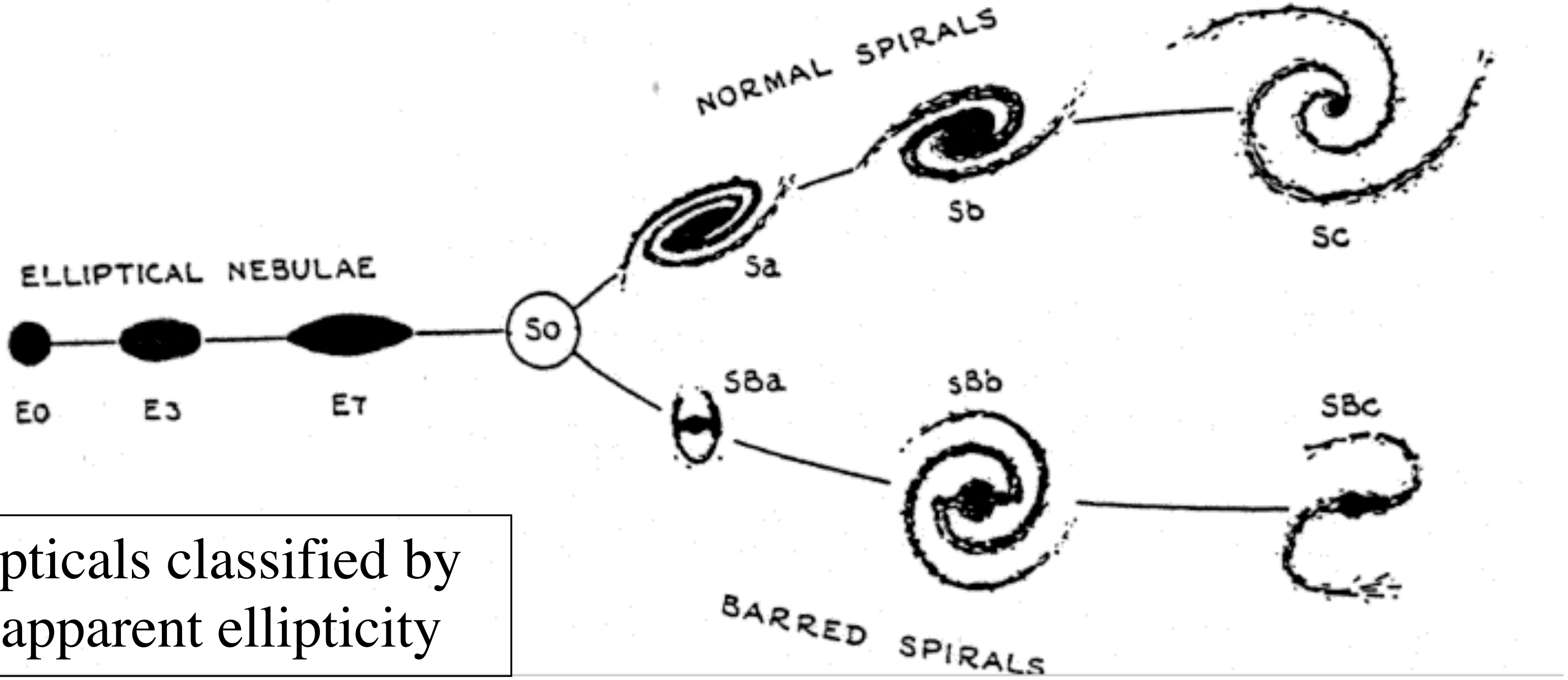


CAROLI LINNÆI
Equitis De Stella Polari,
Archiatri Regii, Med. & Botan. Profess. Upsal.;
Acad. Upsal. Holmens. Petropol. Berol. Imper.
Lond. Monspel. Tolos. Florent. Soc.
SYSTEMA
NATURÆ
Per
REGNA TRIA NATURÆ,
Secundum
CLASSES, ORDINES,
GENERA, SPECIES,
Cum
CHARACTERIBUS, DIFFERENTIIS.
SYNONYMIS, LOCIS.
Tomus I.
10
Editio Decima, Reformata.
HOLMIÆ,
Impensis Direct. Laurentii Salvii,
1758.

CAROLI LINNÆI
Regiæ M:tis Sueciæ Archiatri; Medic. & Botan.
Profess. Upsal; Equitis aur. de Stella Polari;
nec non Acad. Imper. Monspel. Berol. Tolos.
Upsal. Stockh. Soc. & Paris. Corresp.
SPECIES
LANTARUM,
exhibentes
LANTAS RITE COGNITAS,
ad
GENERA RELATAS,
cum
Differentiis Specificis,
Nominibus Trivialibus,
Synonymis Selectis,
Locis Natalibus,
Secundum
STEMA SEXUALE
digestas.
Tomus I.
HOLMIÆ,
Laurentii Salvii.
1753.
C. Appelgrén

- The first step in any empirical science: look for the 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 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
- And 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

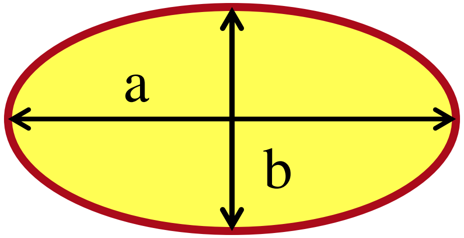
Elliptical Galaxies

M87 in Virgo

Elliptical Galaxies

- Smooth and almost featureless: no spiral arms or dust lanes
- Generally lacking in cool gas, little or no current star formation
- Contain hot, X-ray gas
- Old, metal-rich stellar population
- Classified by the apparent ellipticity:

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

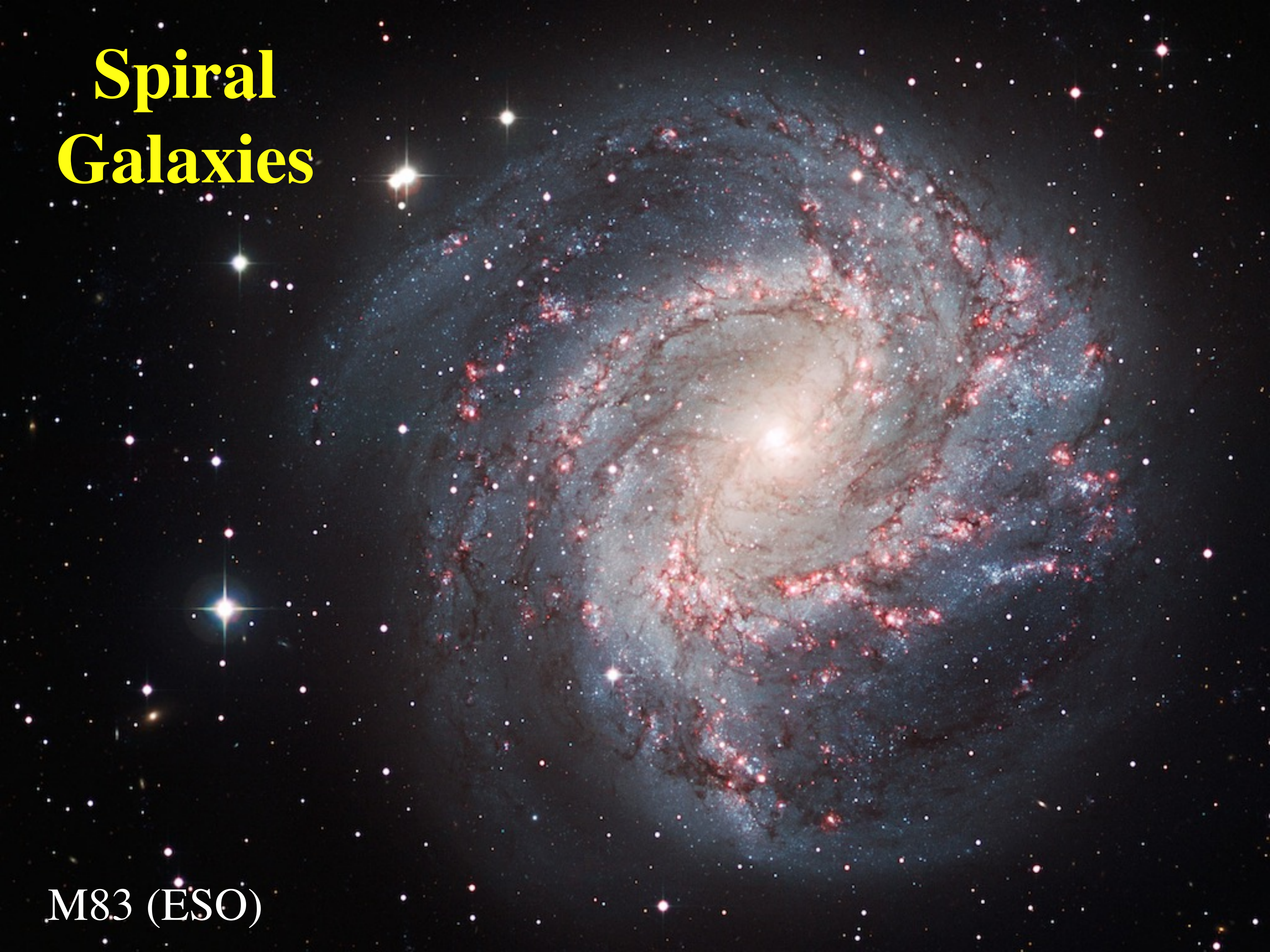


(not physically meaningful)

- Mostly found in clusters (denser environments)


M84 and M86

Spiral Galaxies



M83 (ESO)

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

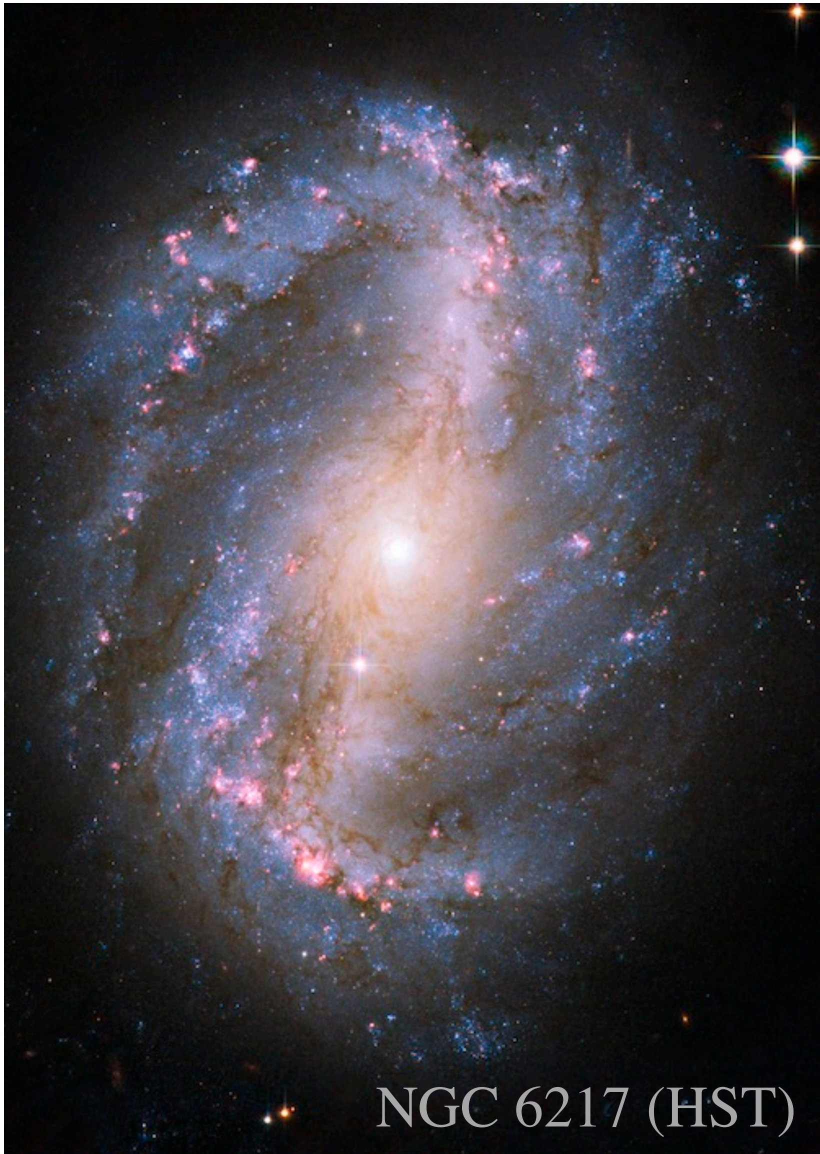
SBa **SBb** **SBc** **SBd**

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

NGC 1300,
Barred Spiral Galaxy

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
- Presence of a dark halo stabilizes the disks against the bar formation, so disks are marginally unstable
- Bars are not density waves; they rotate with a pattern speed, and stars in the bar stay in the bar
- They can funnel gas to the center of the galaxy



NGC 6217 (HST)

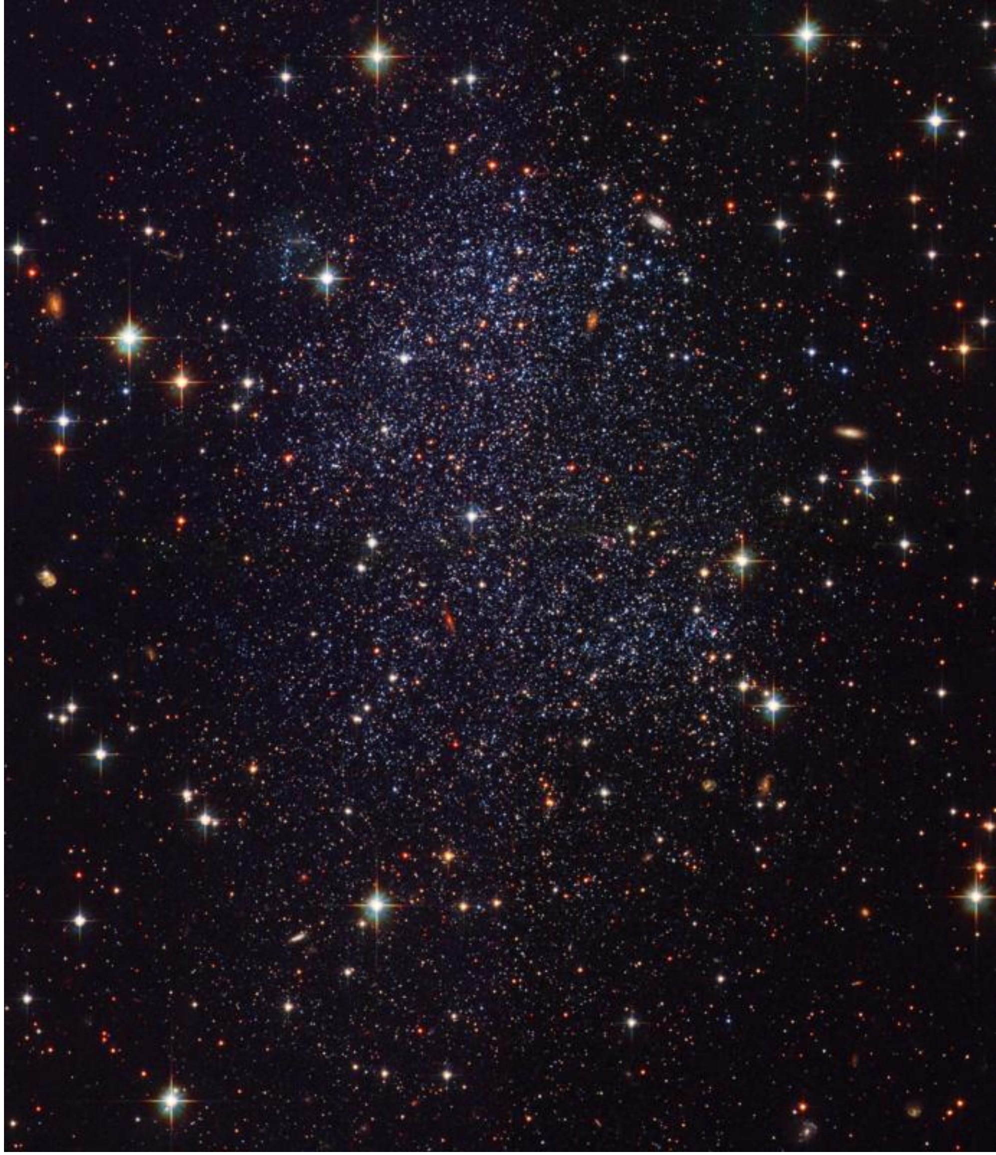
Lenticular (S0) Galaxies

- 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

Sombrero galaxy

Large Magellanic Cloud
Dwarf Irregular

Sagittarius Dwarf Spheroidal →



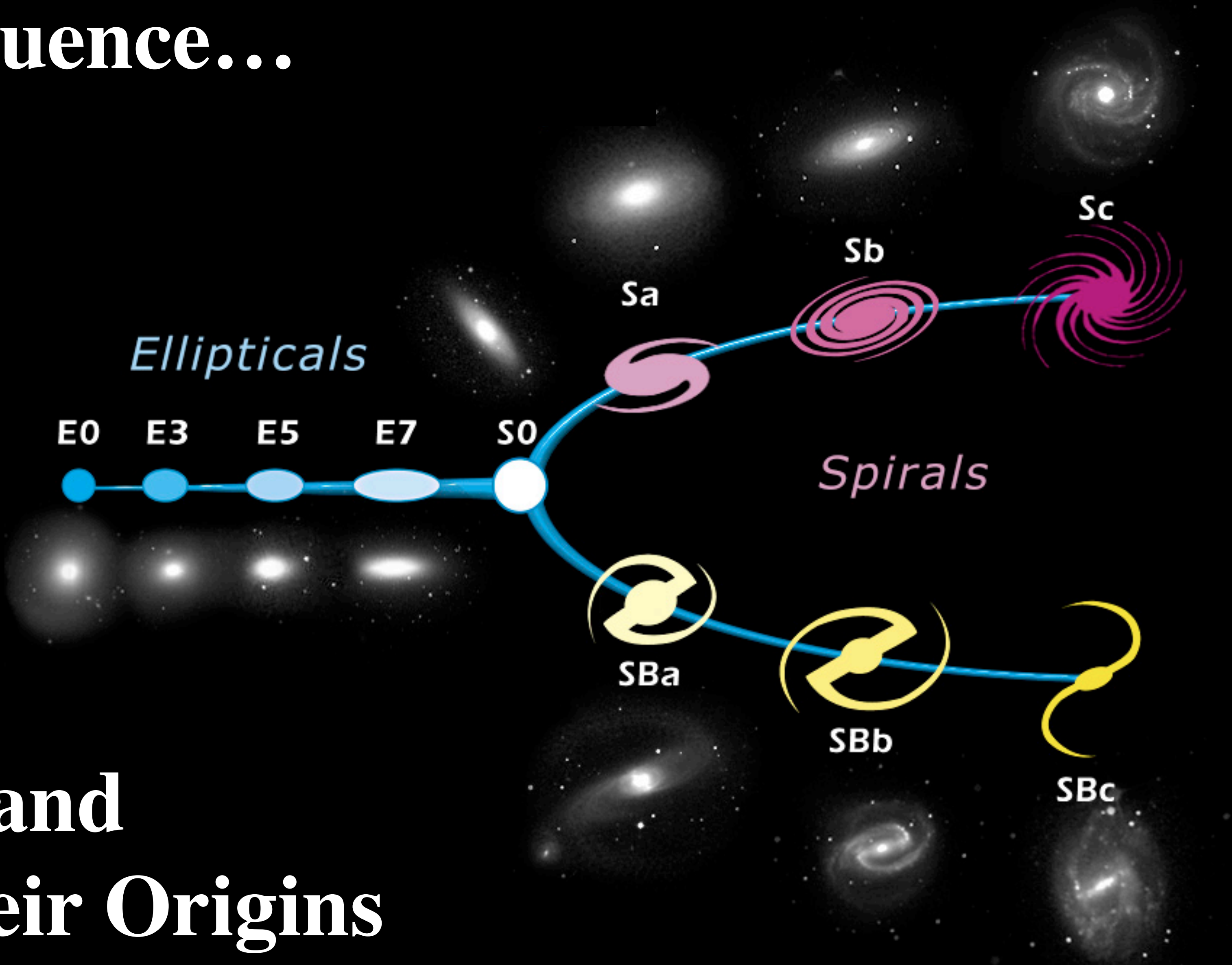
← NGC 205 Dwarf Elliptical

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: relatively simple systems, not merger products
  - Dwarf galaxies are currently being cannibalized by larger galaxies

13.2 Trends Along the Hubble Sequence…



… and Their Origins

Traditional Galaxy Classification Is …

Subjective - *especially for spiral galaxies*

Superficial - *based on appearance, not physical properties*
… and depending on the wavelength

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

e.g., the nearby galaxy M81:

X-ray UV Visible Near-IR Far-IR

Galaxies look "clumpier" in the UV, and increasingly smoother at visible and longer wavelengths, due to young, luminous stars

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
- 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

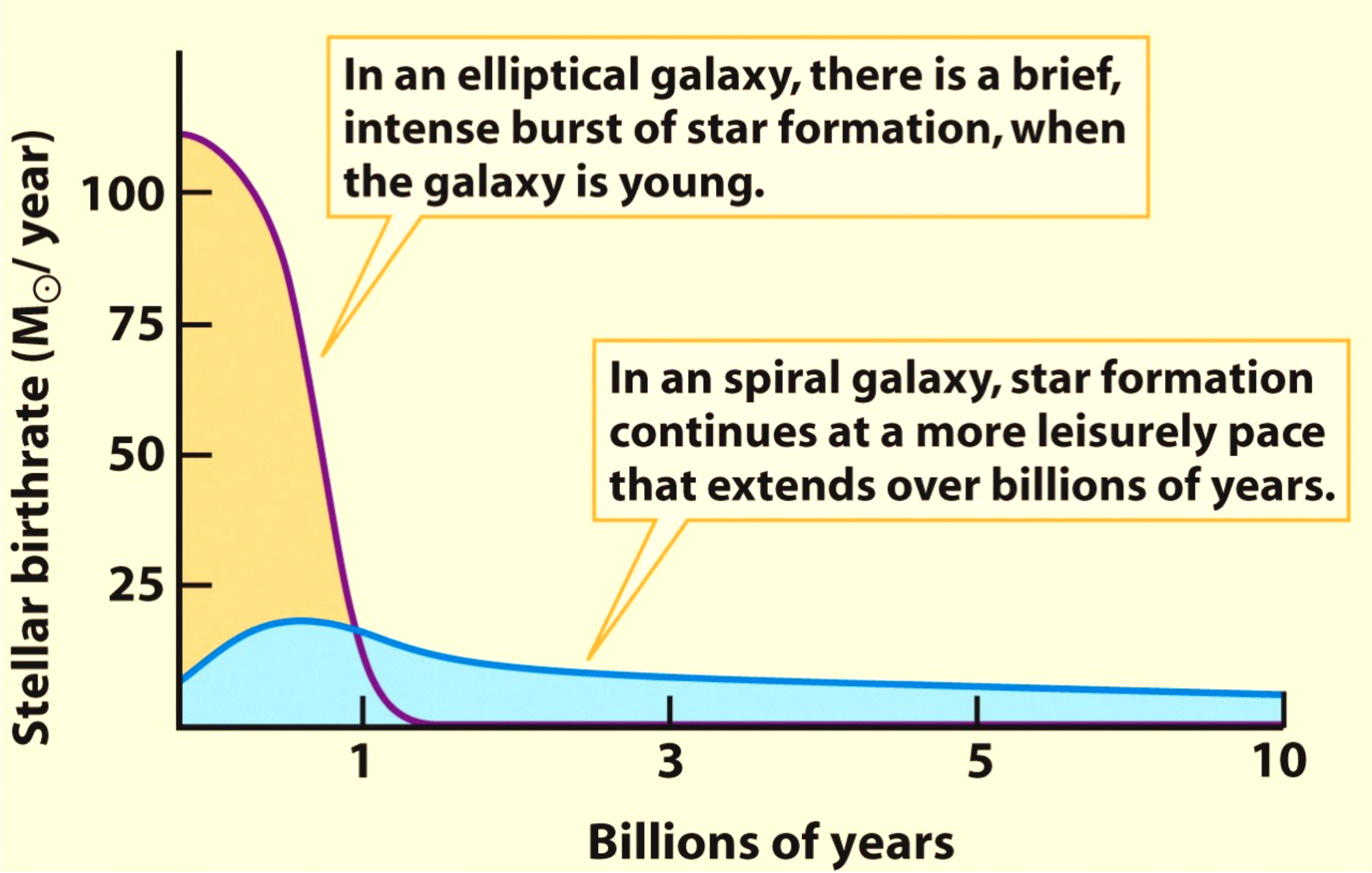
Pressure support → Rotational support
Passive → Actively star forming
Red colors → Blue colors
Hot gas → Cold gas and dust
Old → Still forming
High luminosity density → Low lum. dens.
… etc.

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.

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 × $10^9\,M_\odot$ of HI mass in a typical spiral
    - ✧ How long can spirals keep forming stars? It seems that some gas infall/resupply is needed
- These photometric/morphological properties also correlate with the dynamical properties

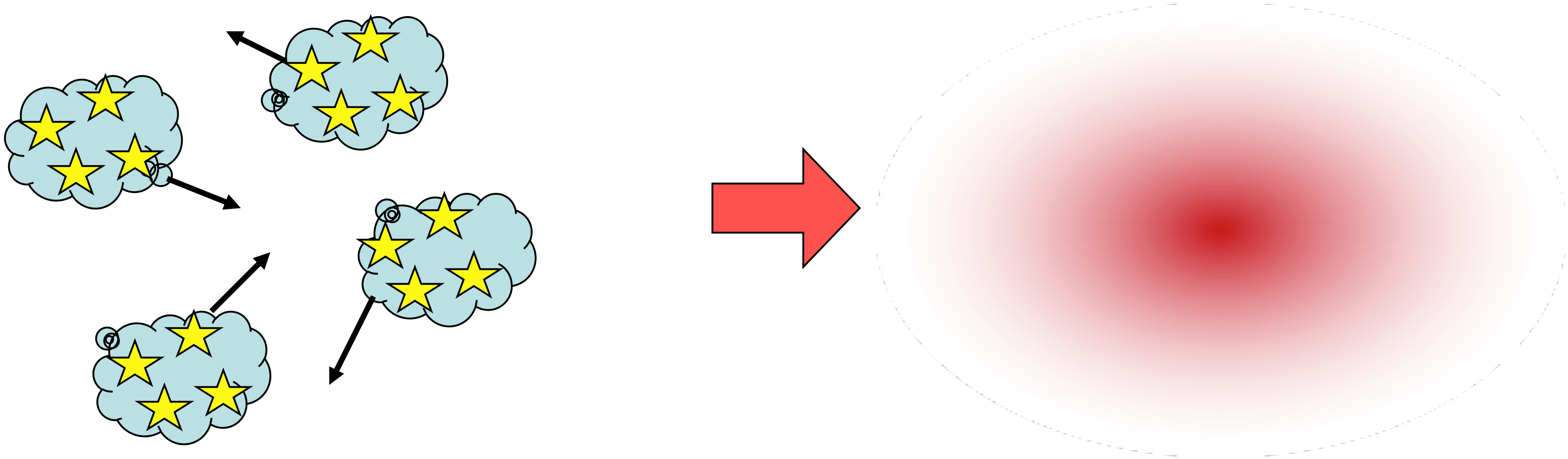
Star Formation History in Galaxies



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

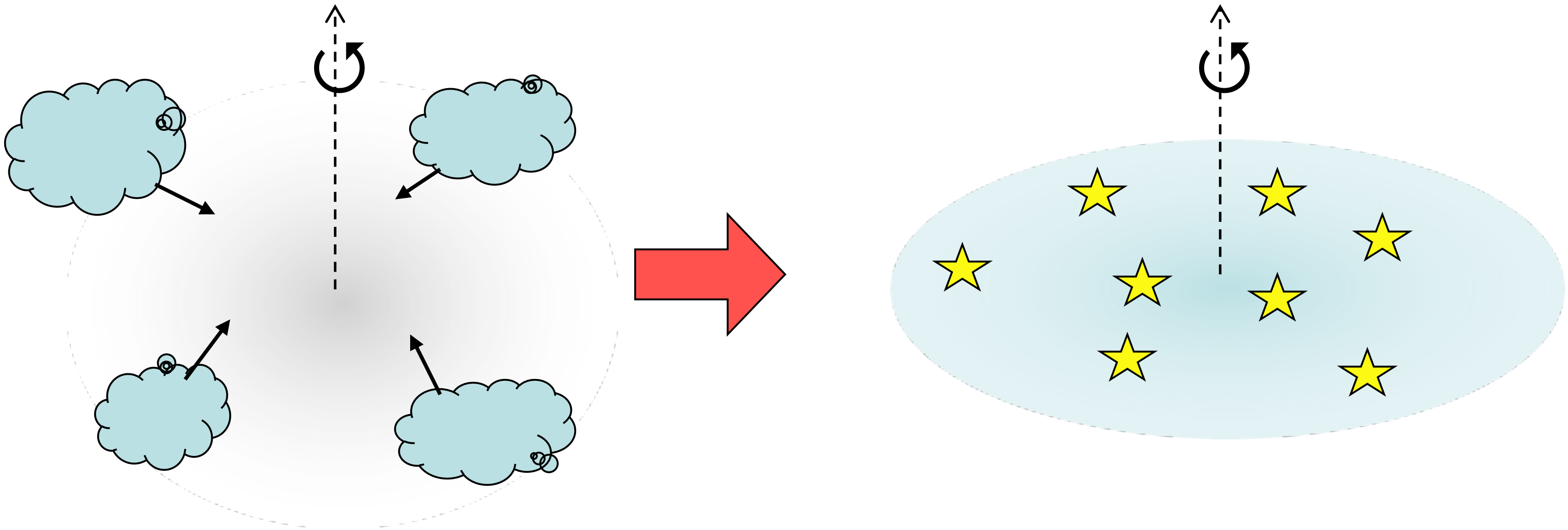
In an spiral galaxy, star formation continues at a more leisurely pace that extends over billions of years.

Formation of Galaxy Spheroids and Dynamics of Stellar Populations



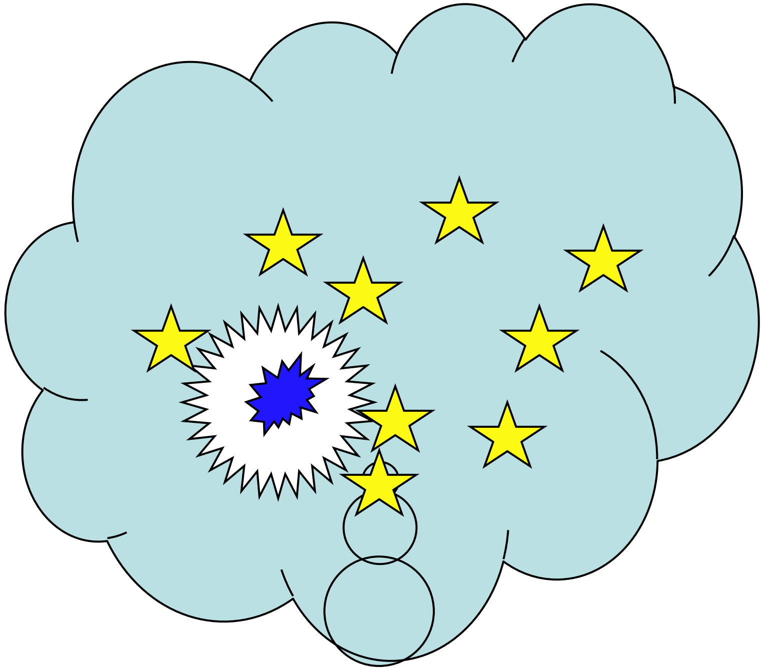
Stars "remember" the dynamics of their orbits at the time of formation, since dynamics of stellar systems is dissipationless. If stars form in dwarf protogalactic fragments which then merge, this will result in a pressure-supported system, *i.e.*, a spheroid (bulge or halo, or an elliptical galaxy).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

Formation of Galaxy Disks and Dynamics of Stellar Populations

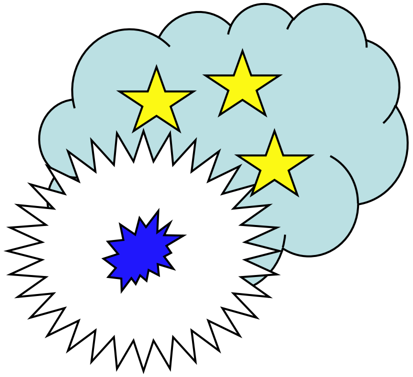


If protogalactic clouds merge dissipatively in a potential well of a dark halo, they will settle in a thin, rotating disk = the minimum energy configuration for a given angular momentum. If gas settles into a (dynamically cold) disk before stars form, then stars formed in that disk will inherit the motions 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 star winds from massive young stars expell the enriched gas and may supress any subsequent star formation. The system retains its initial (low) metallicity.

13.3 Galaxy Interactions and Mergers


1


2


3


4


5


6

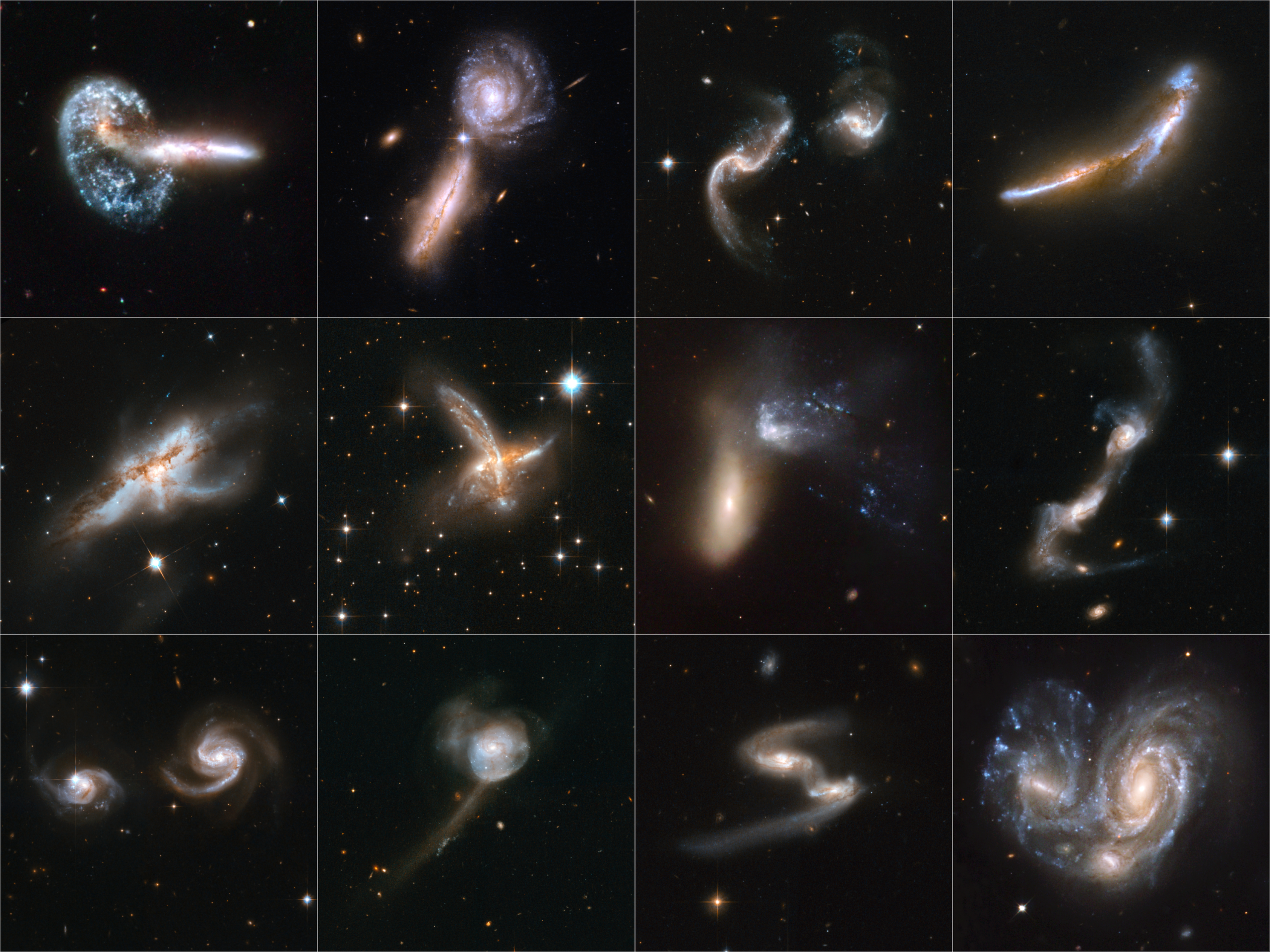
HST

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

Antennae Merger



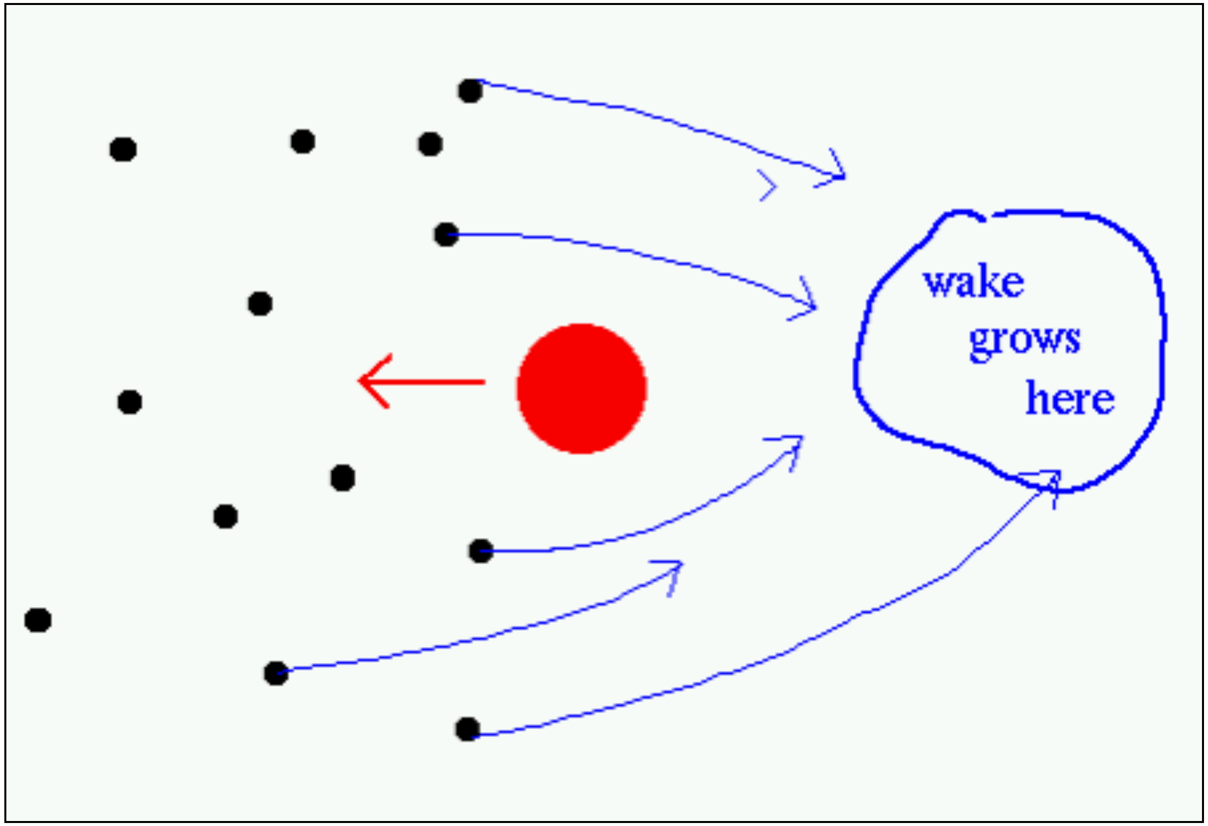
Dust lanes in E galaxy NGC 1316

Dust is surprisingly common in E’s

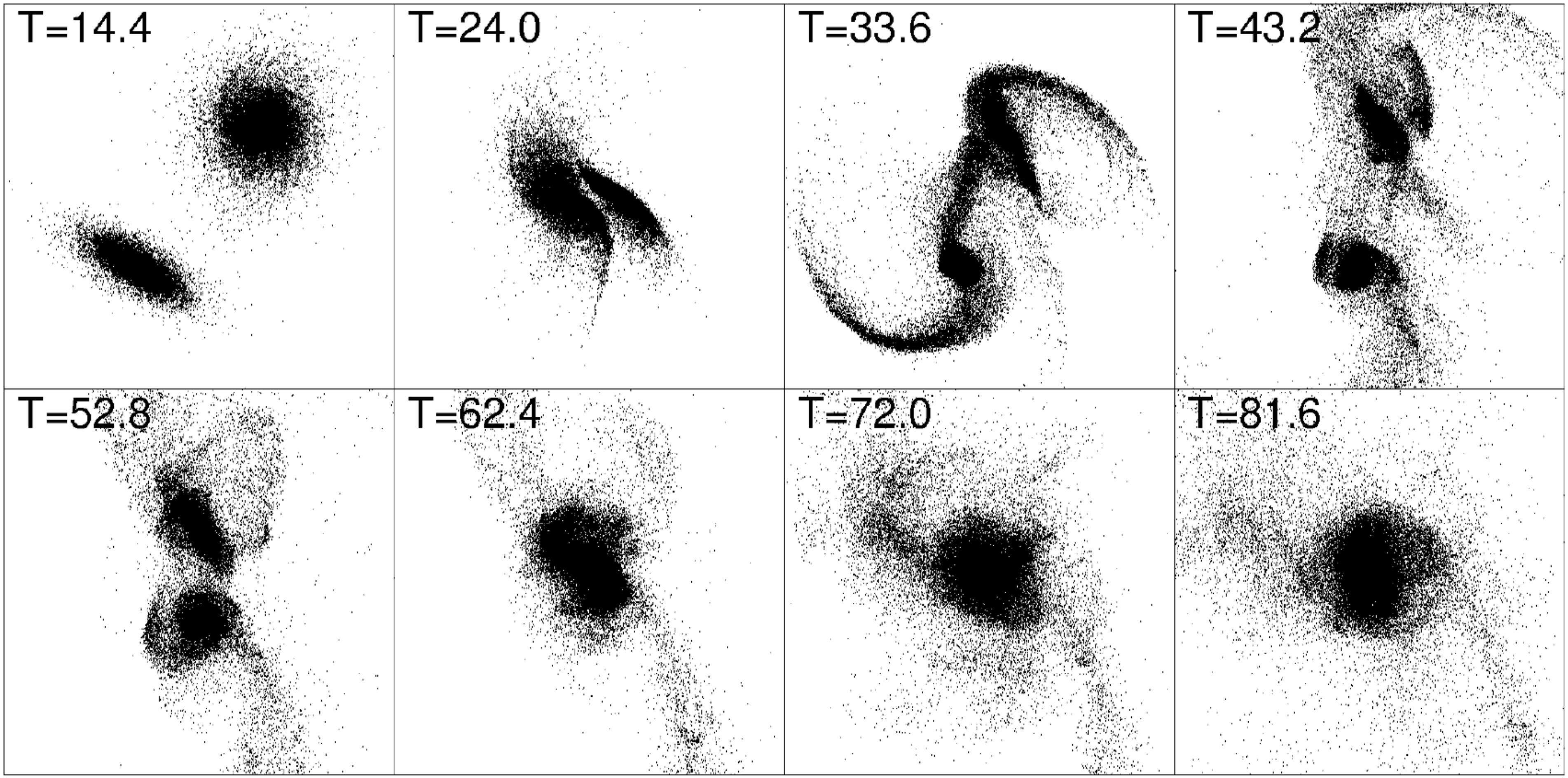
Probably it originates from cannibalized spiral galaxies

Dynamical Friction

- As a massive galaxy moves through a "sea" of stars (and the dark halo), it causes a wake behind it increasing the mass density behind it; the same effect applies to galaxy pass-bys
- This increase in density causes the galaxy to slow and lose its orbital kinetic energy
- The galaxy will eventually fall in and merge with its companion
- Local example: the Magellanic Clouds

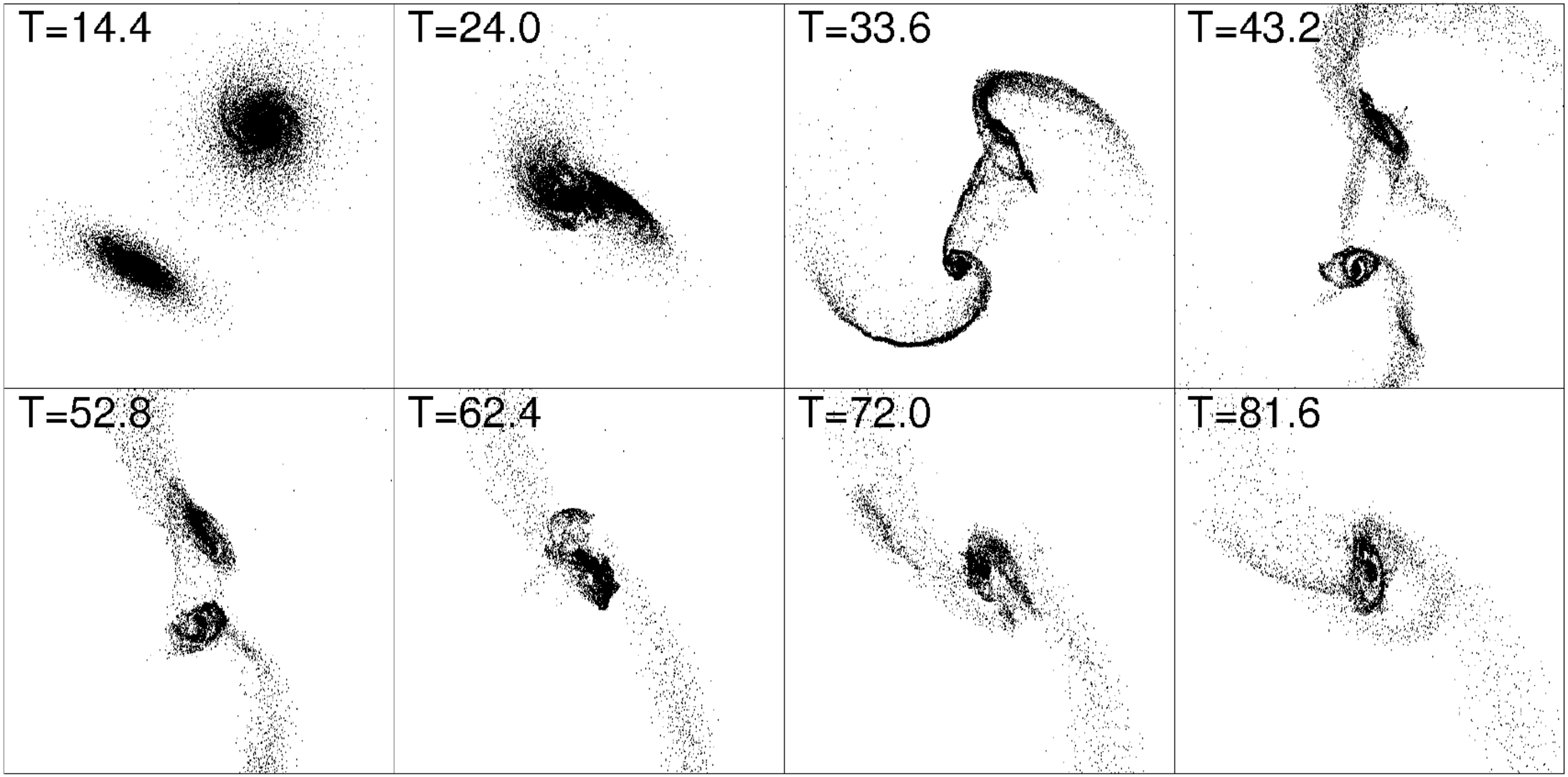


Galaxy Merger: Stars



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

Galaxy Merger: Gas



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

13.4 Quantifying Galaxy Properties

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

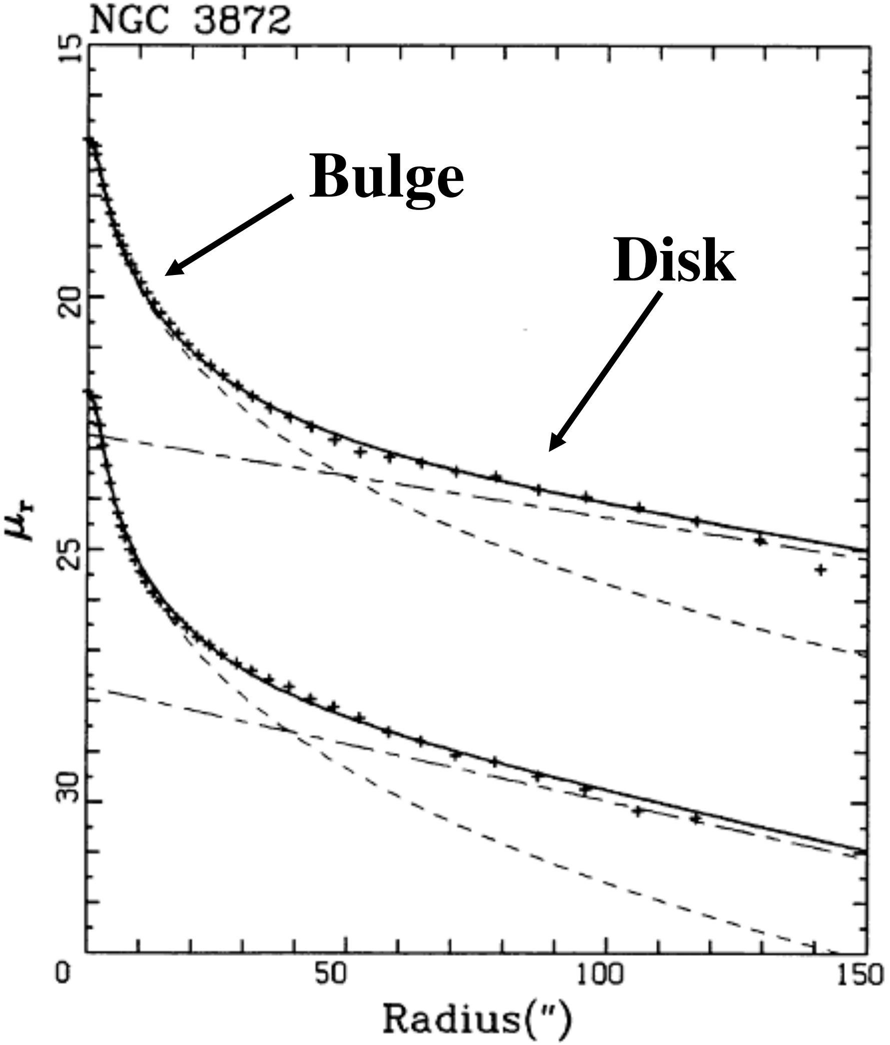
All these measurements can then be analyzed using:

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

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

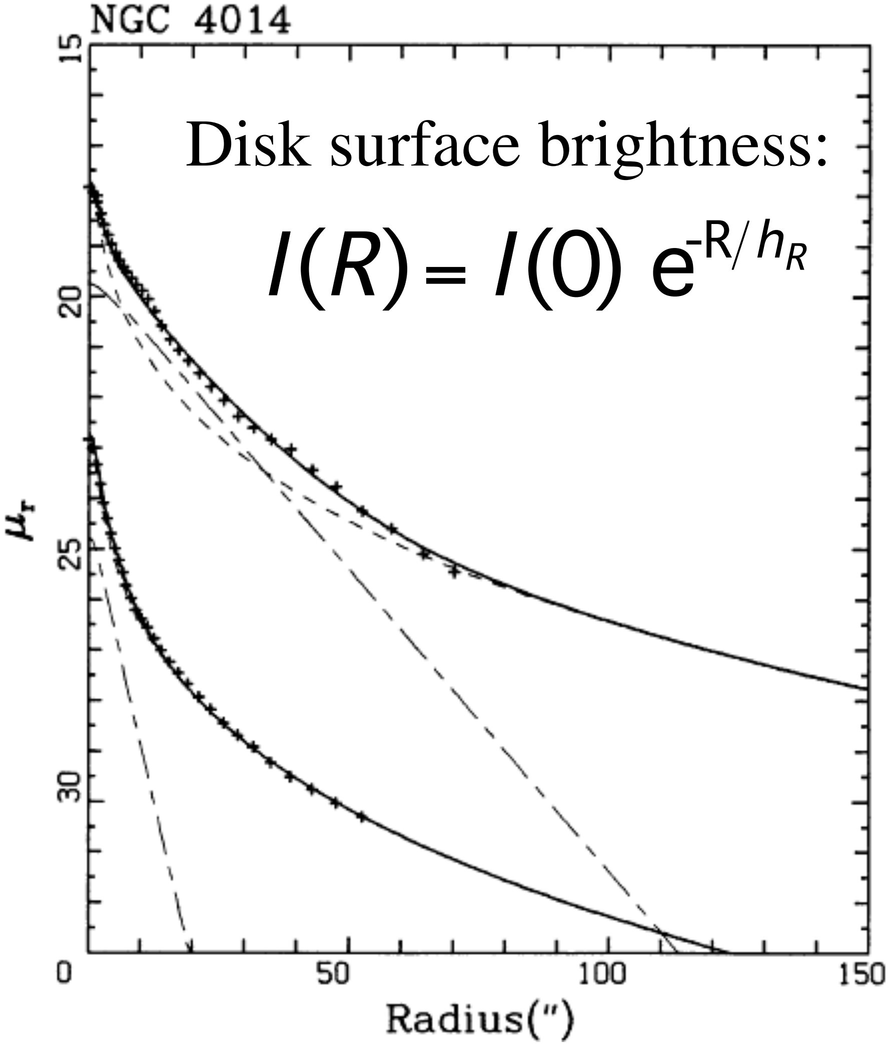
Radial Surface Brightness Profiles of Spiral Galaxies

Note: semi-log profiles



Bulge

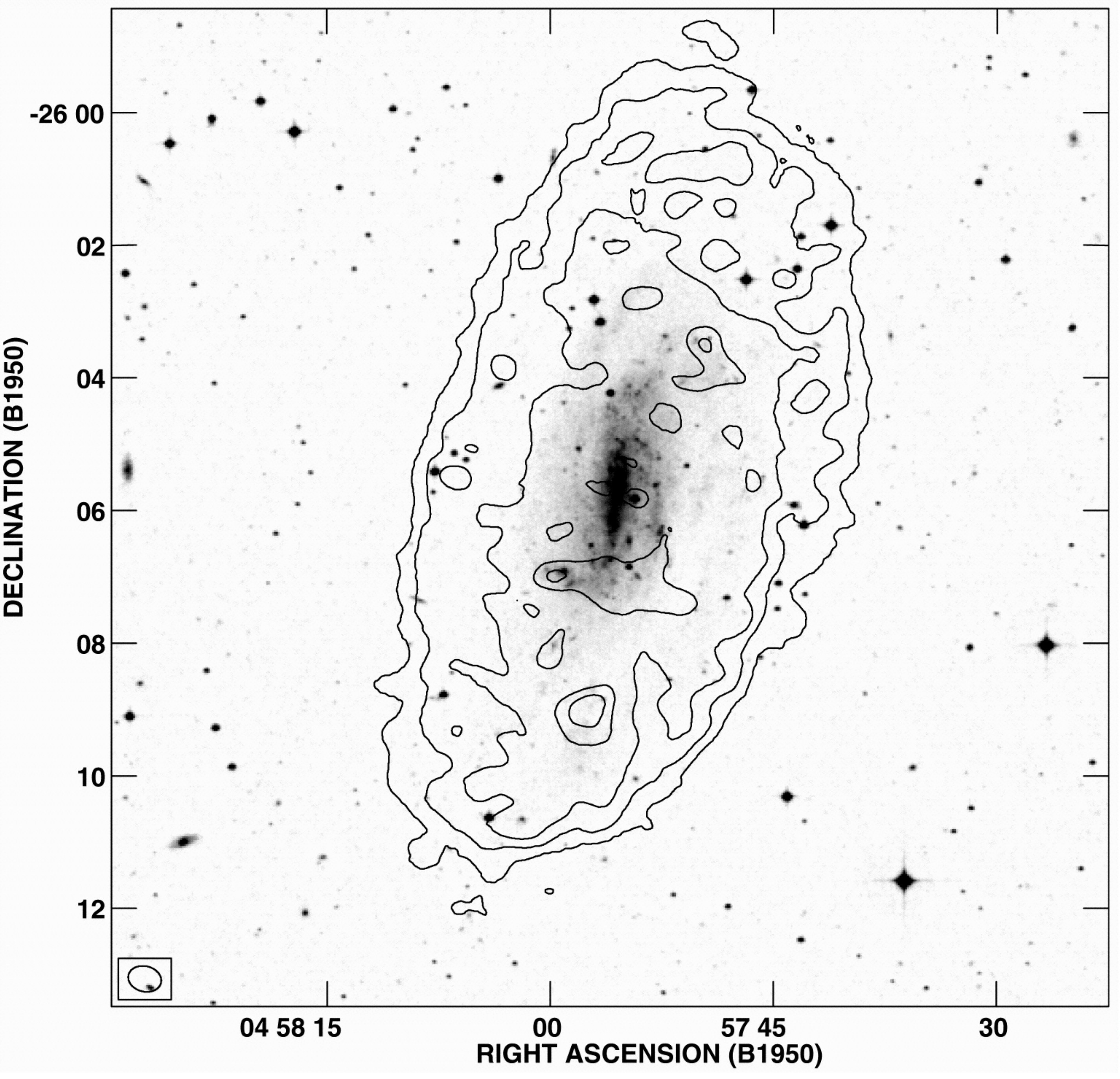
Disk



Disk surface brightness:

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

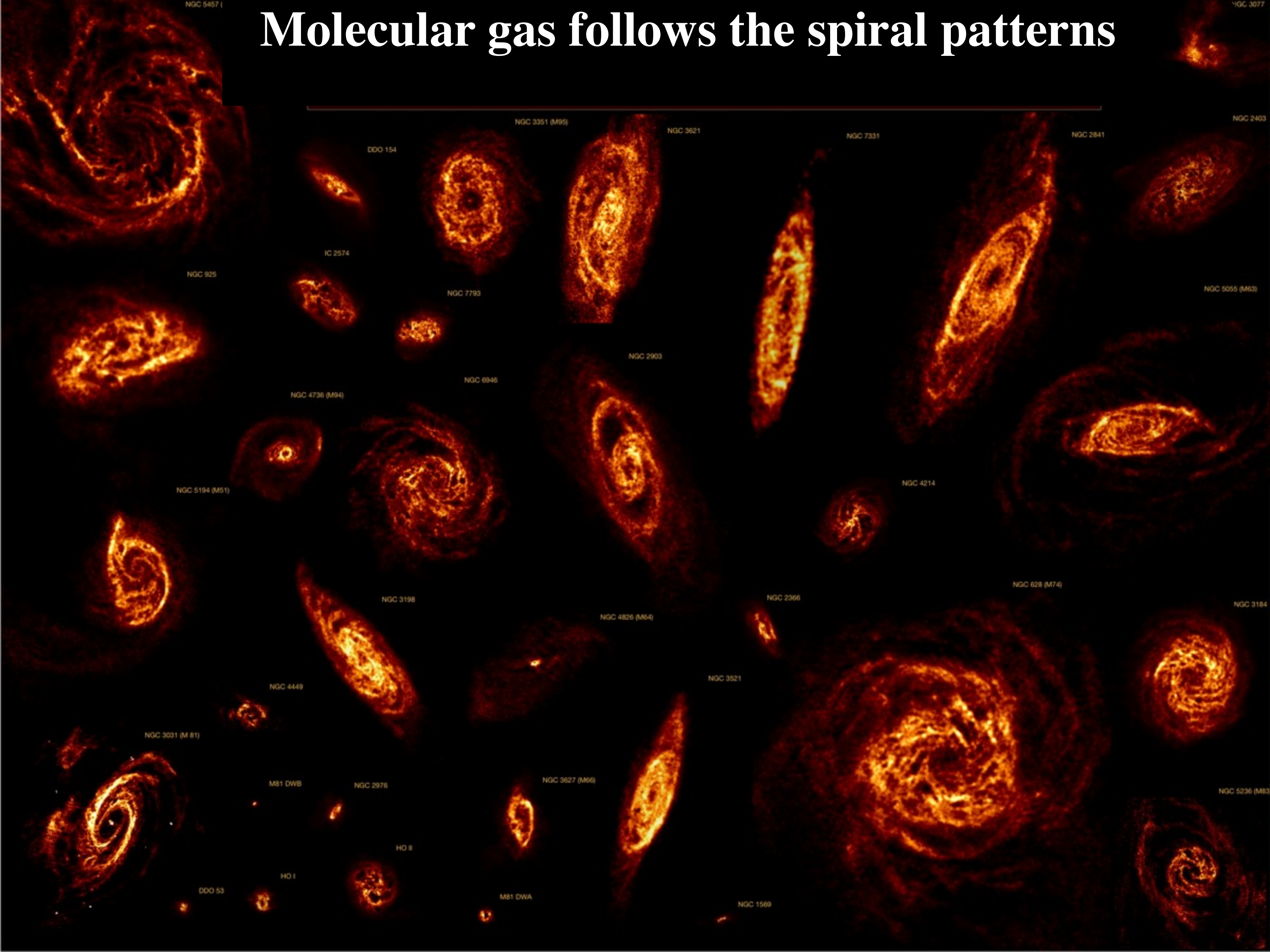
(from S. Kent)



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

Stellar disks are *smaller* than the gas disks: they probably grow from inside out

Molecular gas follows the spiral patterns



Elliptical Galaxies: Surface Photometry

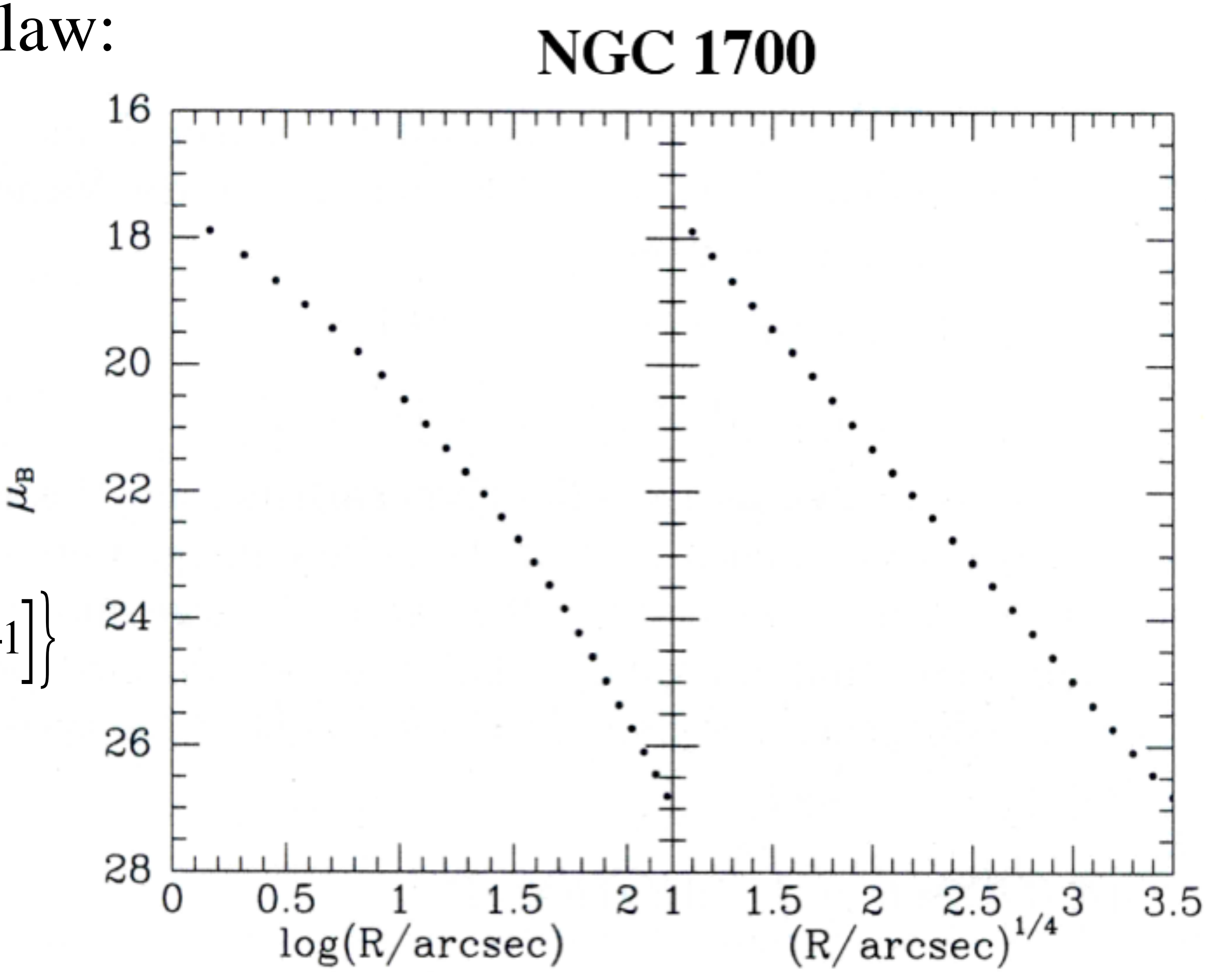
Surface brightness profile is normally well represented by the $R^{1/4}$ or de Vaucouleurs law:

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

where k is a constant.

This can be rewritten as:

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

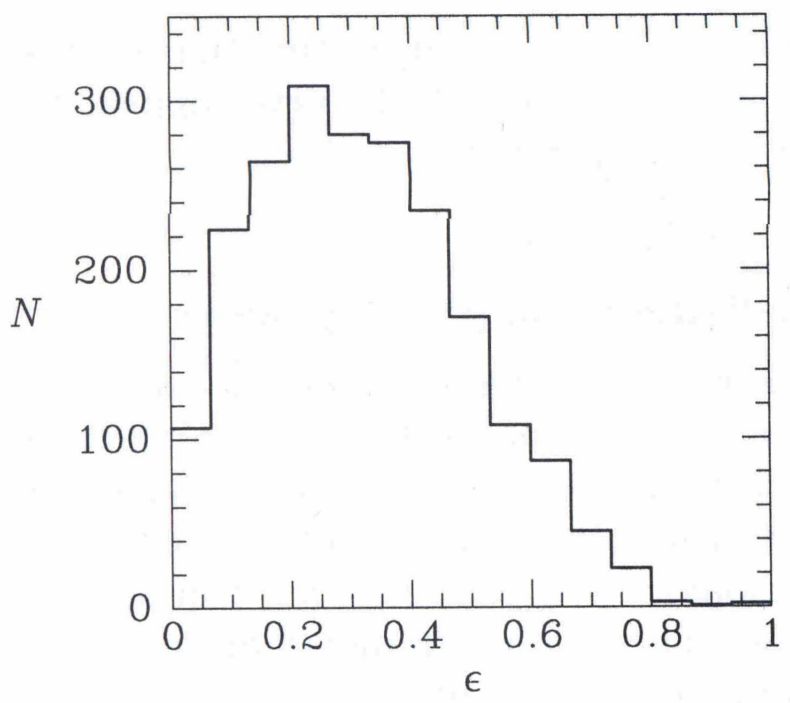


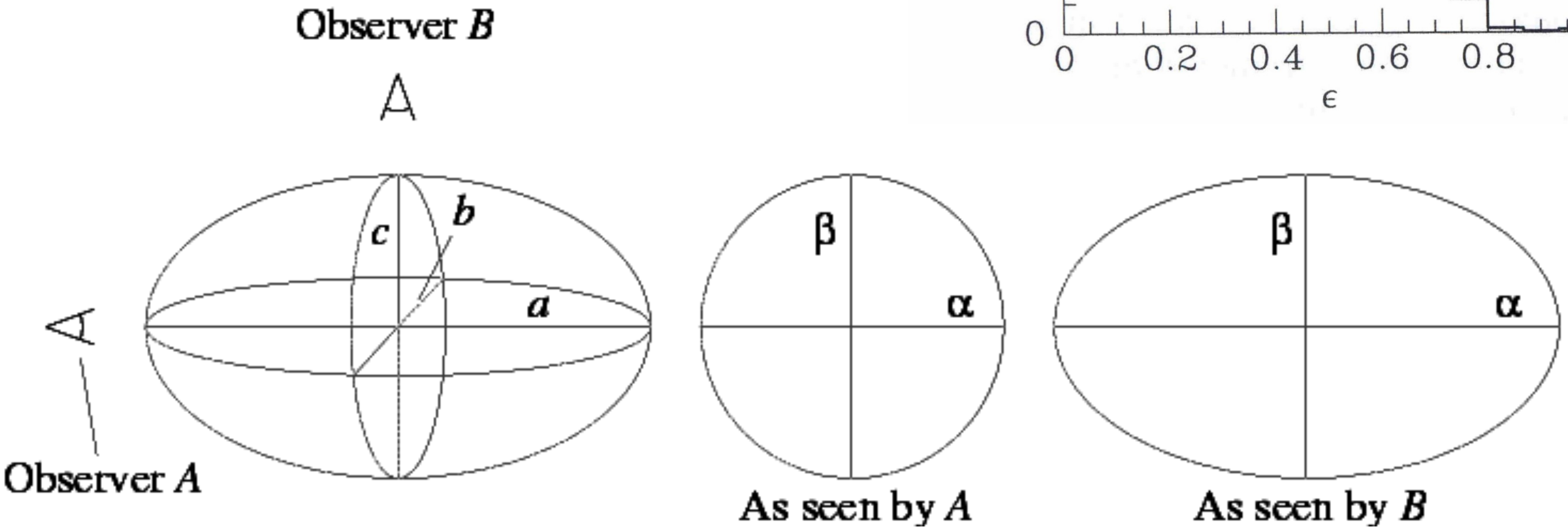
where R_e is the **effective radius,** containing half of the total luminosity, typically a few kpc

Shapes of Ellipticals

- Ellipticals are defined by En, where $n=10\varepsilon$, and $\varepsilon=1-b/a$ is the ellipticity
- Note this is not intrinsic, it is observer dependent!

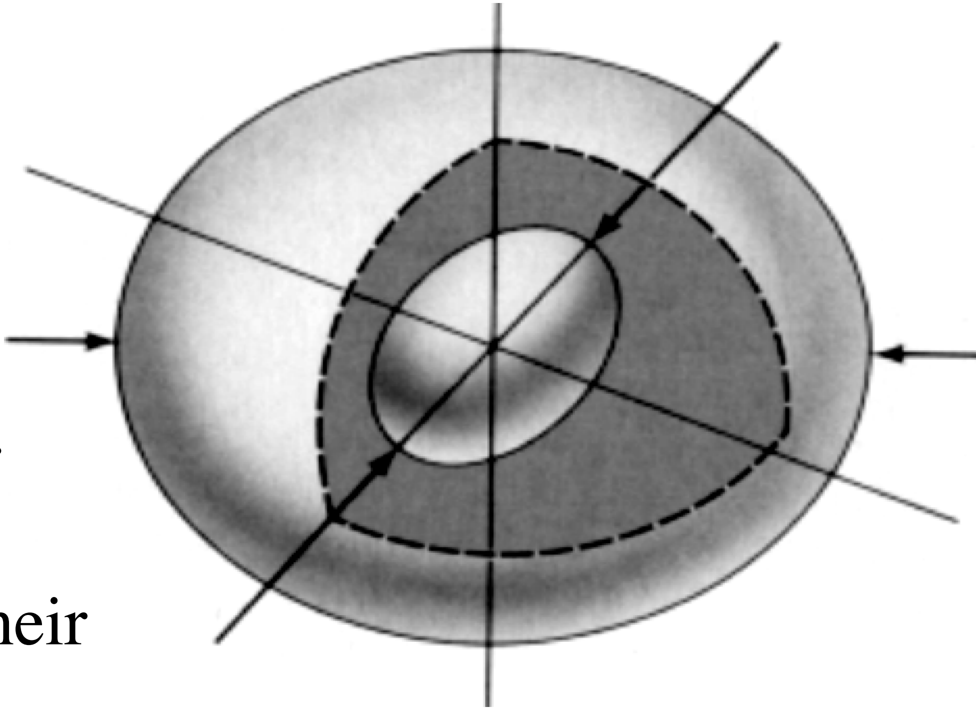
The observed distribution





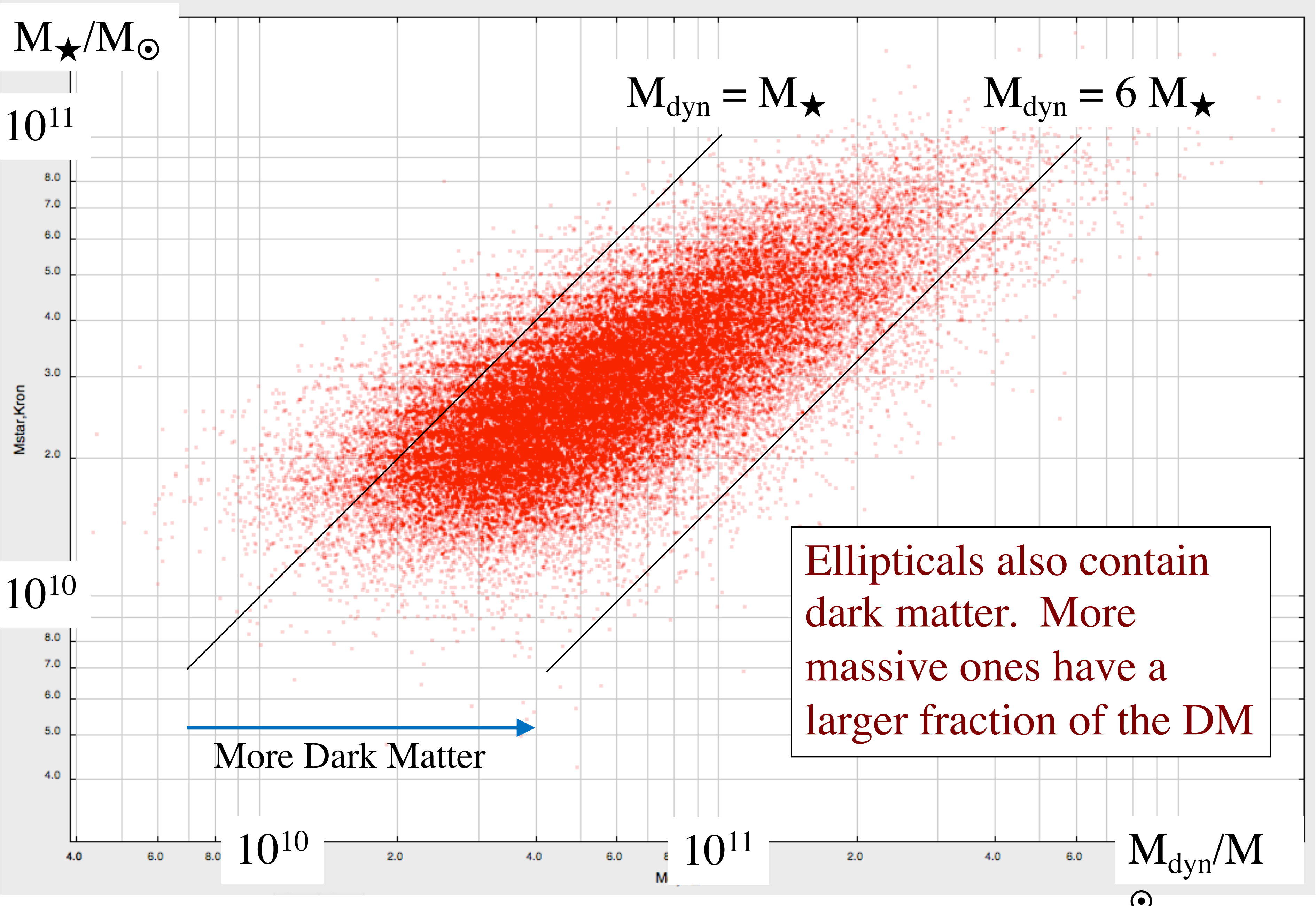
They Are Really Triaxial Ellipsoids

- 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

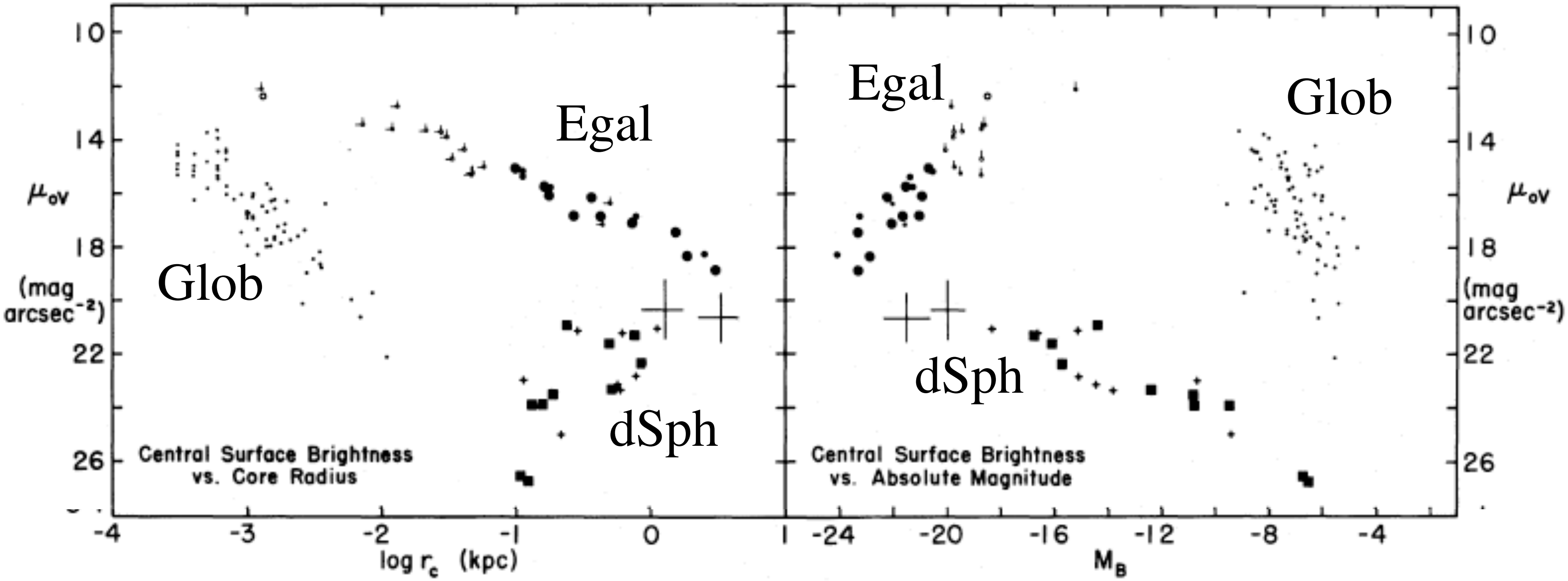
Stellar vs. Dynamical Mass

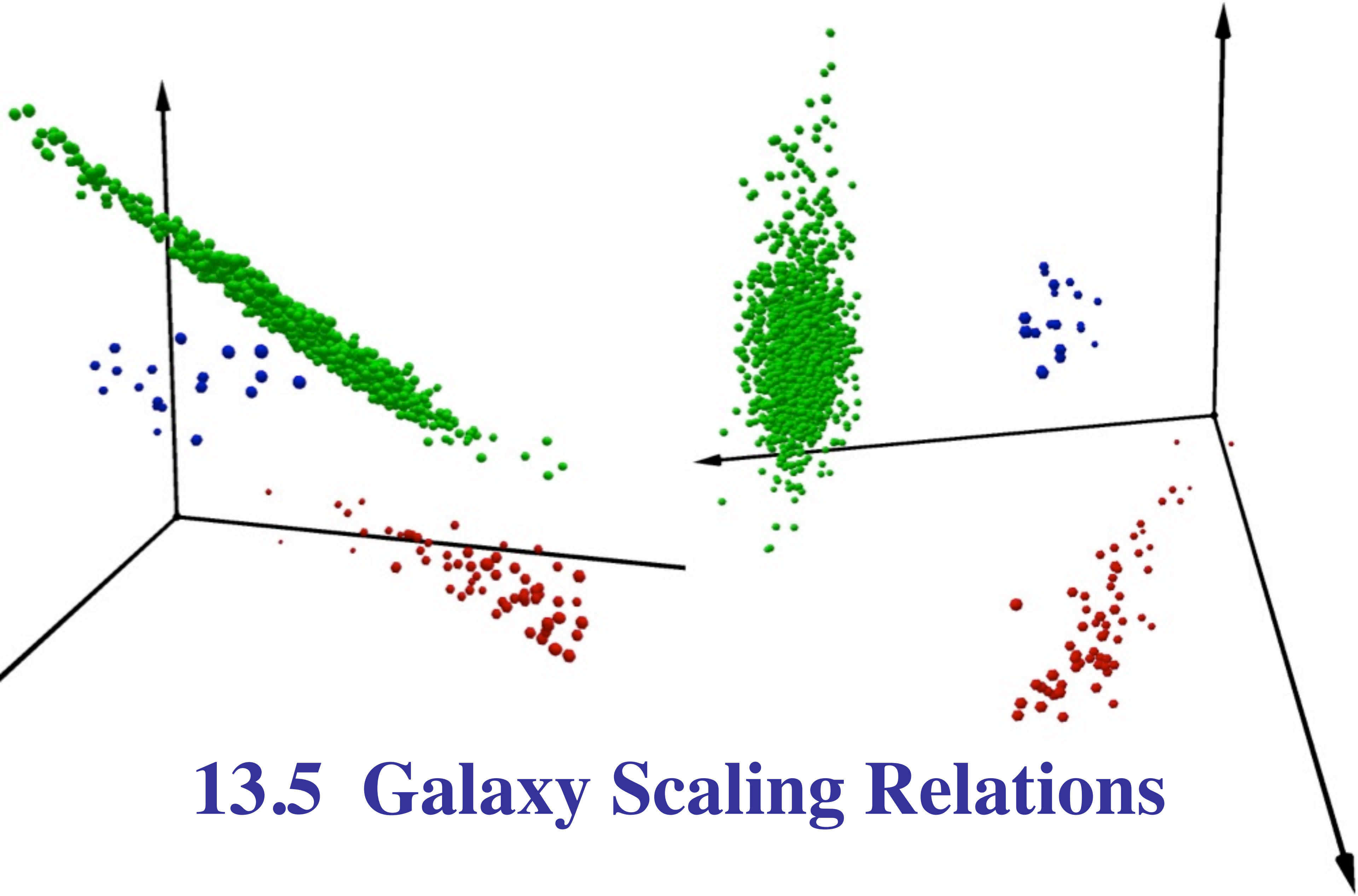


Ellipticals also contain dark matter. More massive ones have a larger fraction of the DM

Dwarf Galaxies

- Dwarf ellipticals (dE) and dwarf spheroidals (dSph) are a completely different family of objects from normal 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





13.5 Galaxy Scaling Relations

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

The Tully-Fisher Relation

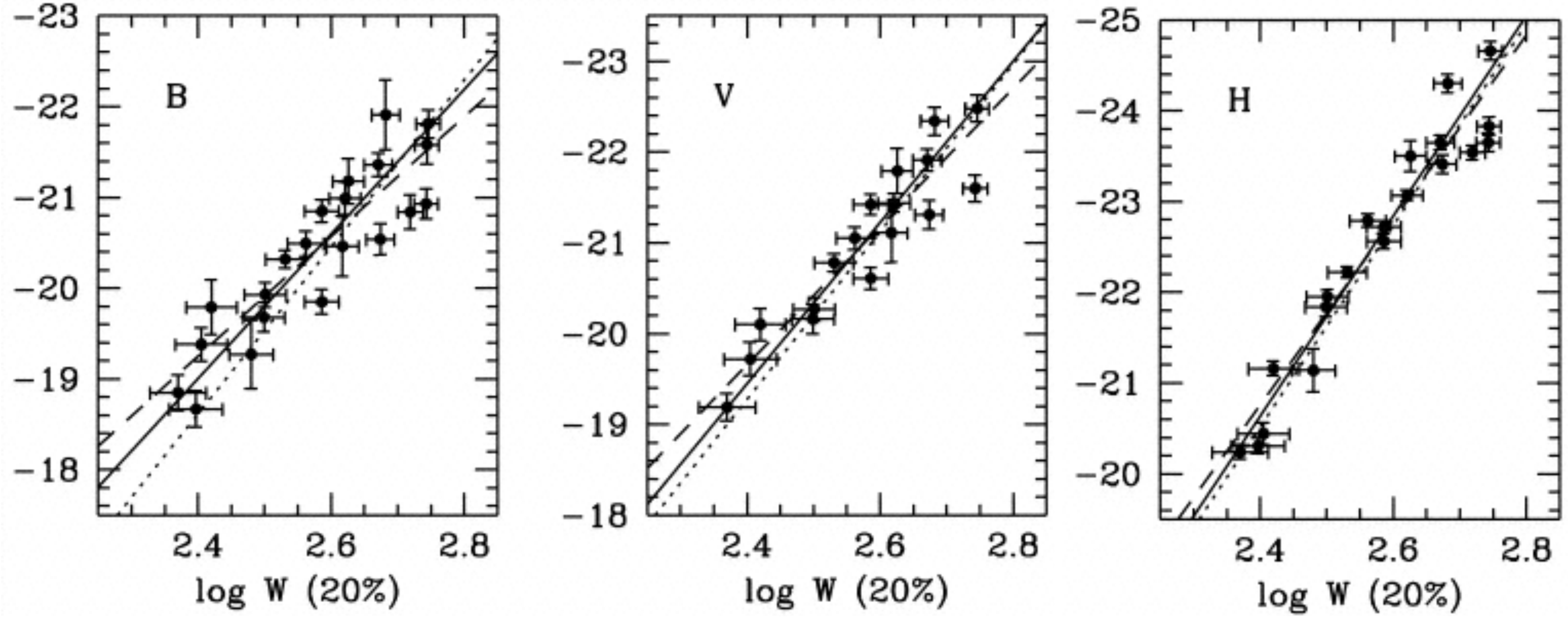
- A correlation of luminosity vs. rotational speed (often measured as a H I 21 cm line width) relation for spirals:

$$\boldsymbol{L \sim V_{\mathbf{rot}}}^{\gamma}, \gamma \approx 4, \text{ varies with wavelength}$$

- Scatter is ~ 10% at best, better in the redder bands

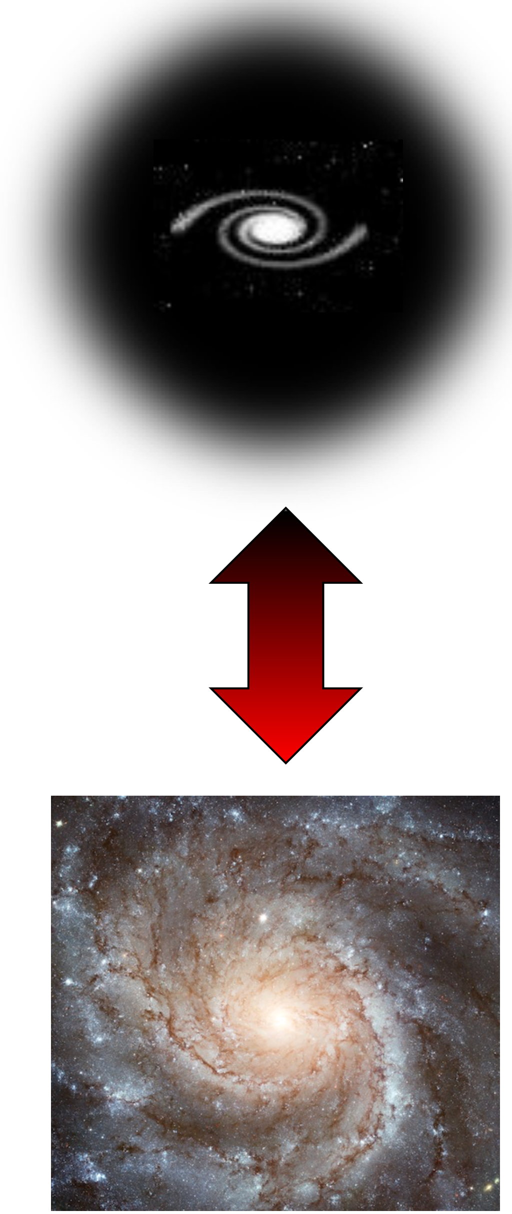
Blue **Visible** **Near IR**

Absolute Magnitude



log H I velocity width

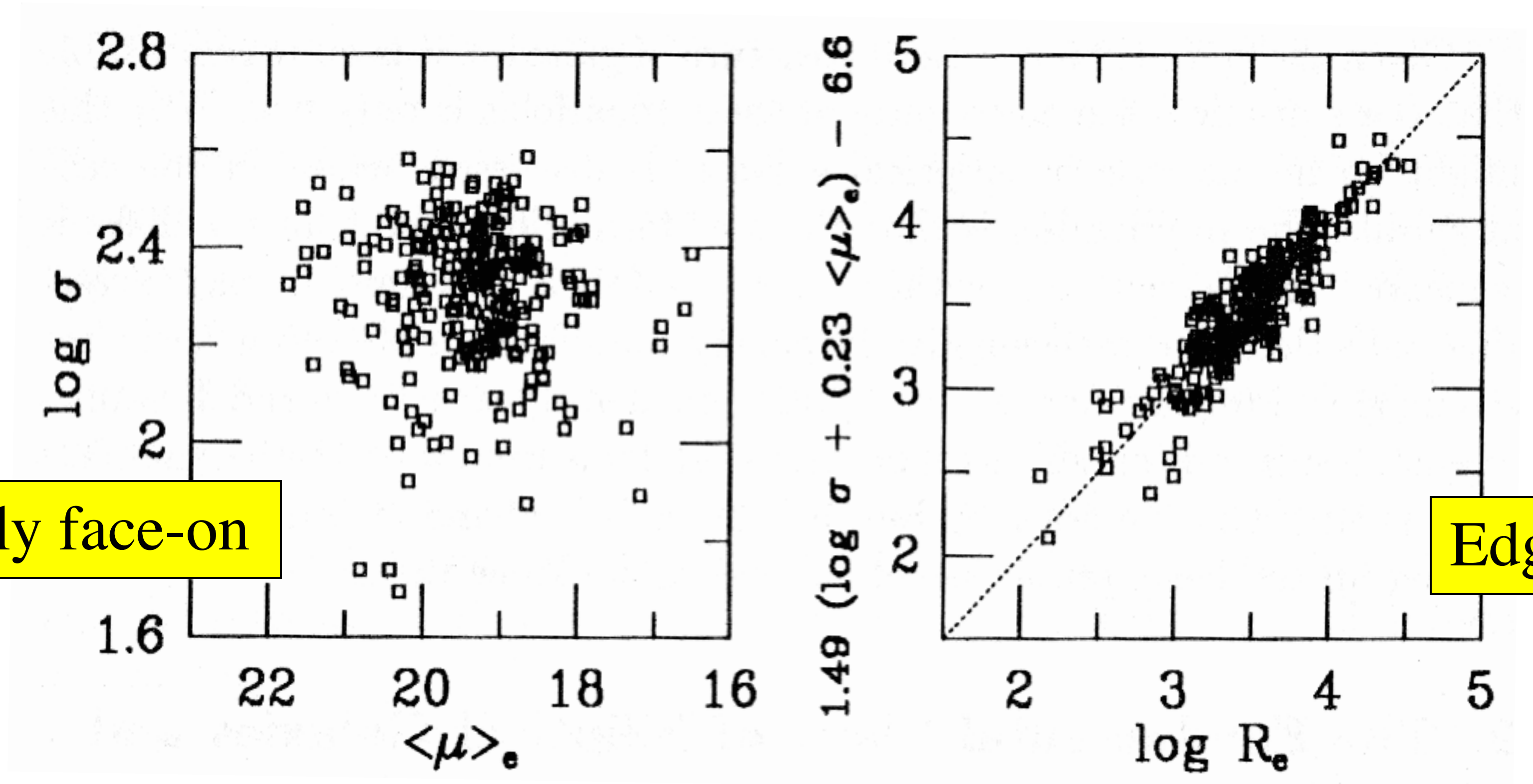
Why is the TFR So Remarkable?



- Because 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
- Halo-regulated galaxy formation/evolution?
- The scatter is remarkably low - even though the conditions for this to happen are known not to be satisfied
- Thus, the TFR offers some important insights into the physics of disk galaxy formation
- And we use it to measure relative distances to spiral galaxies

Scaling Relations for Ellipticals

Many fundamental properties of ellipticals are connected through ***bivariate scaling relations*** (derive one from 2 others), called the **Fundamental Plane**, commonly expressed as a bivariate scaling relation $\boldsymbol{R \sim \sigma^{1.4} I^{-0.8}}$, where $\boldsymbol{R}$ is the radius, $\boldsymbol{I}$ the mean surface brightness, $\boldsymbol{\sigma}$ the velocity dispersion



Nearly face-on

Edge-on

For any elliptical galaxy today, big or small,

Just Two Numbers

determine *to within a few percent or less*:

Mass, luminosity (in any OIR band),
Any consistently defined radius
Surface brightness or projected mass density
Derived 3-d luminosity, mass, or phase-space density
Central projected radial velocity dispersion
Optical and IR colors, line strengths, and metallicity
Mass of the central black hole
… and maybe other things as well

And they do so regardless of the:

Star formation and merging formative/evolutionary history
Large-scale environment (to within a few %)
Details of the internal structure and dynamics (including S0’s)
Projection effects (the direction we are looking from)

Deriving the Scaling Relations

Start with the Virial Theorem:

$$\frac{GM}{\langle R \rangle} = k_E \frac{\langle V^2 \rangle}{2}$$

Now relate the observable values of ***R*, *V*** (or ***σ***), ***L***, etc., to their "true" mean 3-dim. values by simple scalings:

$$R = k_R \langle R \rangle \qquad V^2 = k_V \langle V^2 \rangle \qquad L = k_L I R^2$$

One can then derive the "virial" versions of the FP and the TFR:

$$R = K_{SR} V^2 I^{-1} (M/L)^{-1}$$

$$L = K_{SL} V^4 I^{-1} (M/L)^{-2}$$

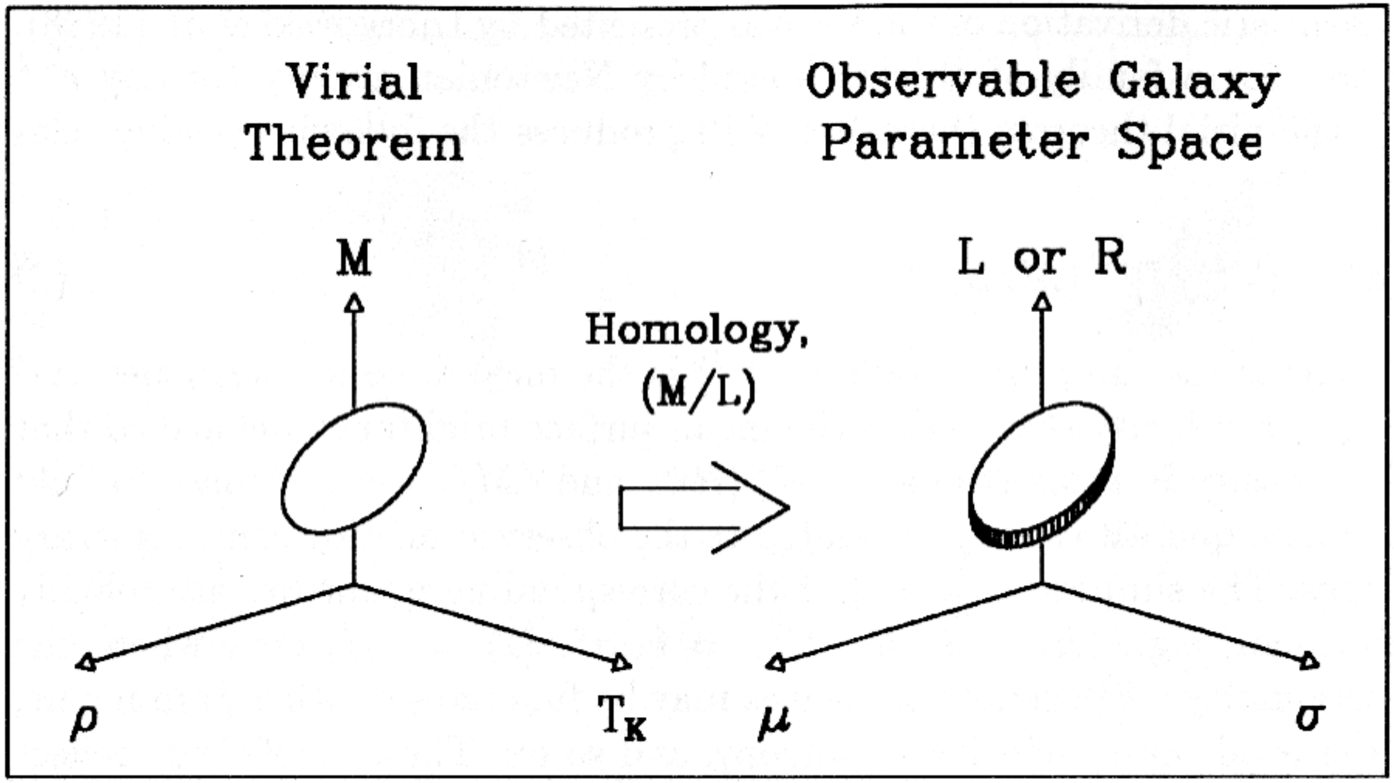
Where the "structure" coefficients are:

$$K_{SR} = \frac{k_E}{2G k_R k_L k_V}$$

$$K_{SL} = \frac{k_E^2}{4G^2 k_R^2 k_L k_V^2}$$

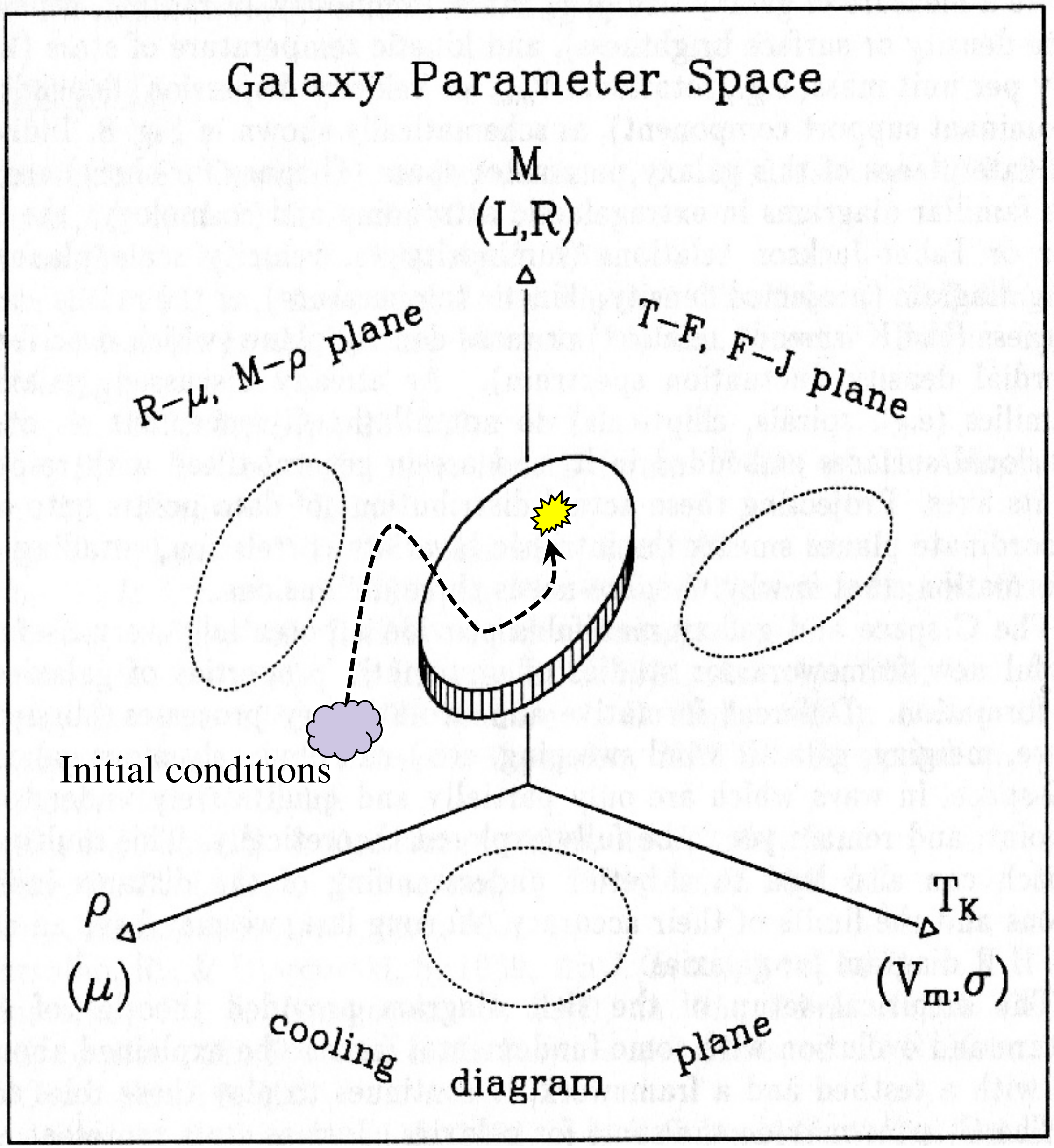
Deviations of the observed relations from these scalings must indicate that either some ***k*'**s and/or the ***(M/L)*** are changing

From Virial Theorem to FP



Virial Theorem connects mass, density, and kinetic temperature, and is thus an equation of a plane in that (theoretical) parameter space. Dynamical structure of ellipticals and their (M/L) ratios then map the VT into the tilted FP in the observable parameter space of measured quantities such as ***R*, *σ* , *I*, *L*, …**

The Galaxy Parameter Space



A more general picture

Galaxies of different families form 2-dim. sequences in a 3+ dimensional parameter space of physical properties, much like stars form 1-dim. sequences in a 2-dim. parameter space of {L,T} - this is an equivalent of the H-R diagram, but for galaxies