Galaxies, part 1

Sterrenstelsels & Kosmos

deel 4

Are galaxies “island universes”?

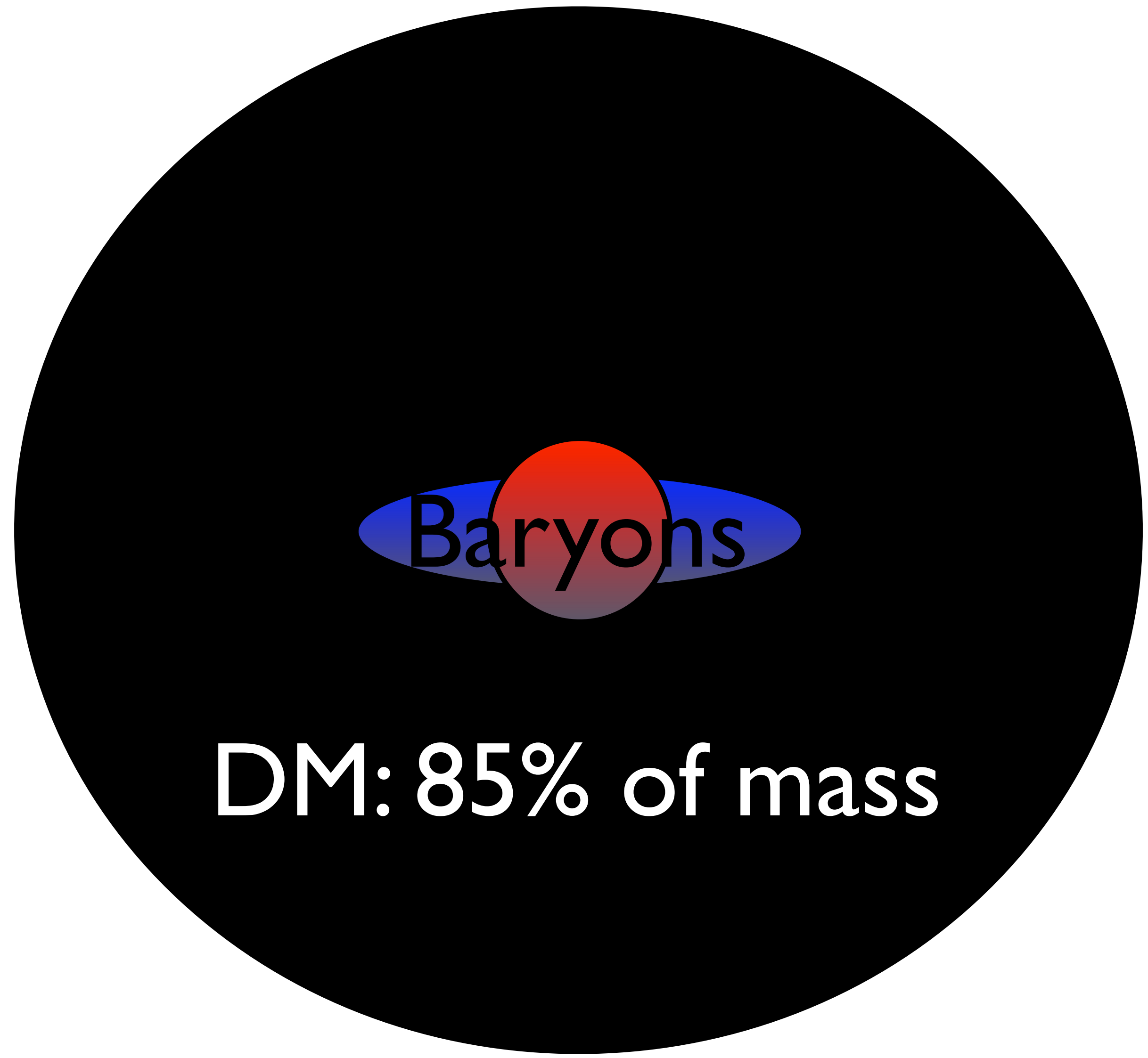
- In 1920, it was still unclear whether *spiral nebulae* were small members of our own Milky Way galaxy or other “island universes” and therefore actually galaxies in their own right
  - This led to the Shapley-Curtis “Great Debate” on 20 April 1920: Shapley argued for the “galactic” hypothesis and Curtis for the “extragalactic” hypothesis
  - Both used faulty data!

- In 1923/1924, *Edwin Hubble* detected the pulsations of **Cepheid variables** in M31 (Andromeda) and showed that it ***must*** be more than 250 kpc away (it's actually 770 kpc away; he misclassified the *kind* of Cepheid variable they were...)
    - This is **much** larger than the diameter of the Milky Way
- This was the proof that *galaxies are "island universes" in their own right*, just like the Milky Way

Structure of galaxies

- Galaxies are composed of two types of matter:
  - Baryonic matter---the stuff we're all made of---which composes roughly 15% of the matter (but only 4.4% of the energy density) in the Universe
  - Dark matter---the vast majority of which is not baryonic---which composes the other 85% of the mass of the Universe (but only 27% of the energy density)

- These types of matter have different radial distributions:
  - Baryons are concentrated (primarily) to the inner tens of kpc;
  - Dark matter can extend to hundreds of kpc
- Why?
  - Dissipation --- baryons can lose energy through radiation, but DM can't



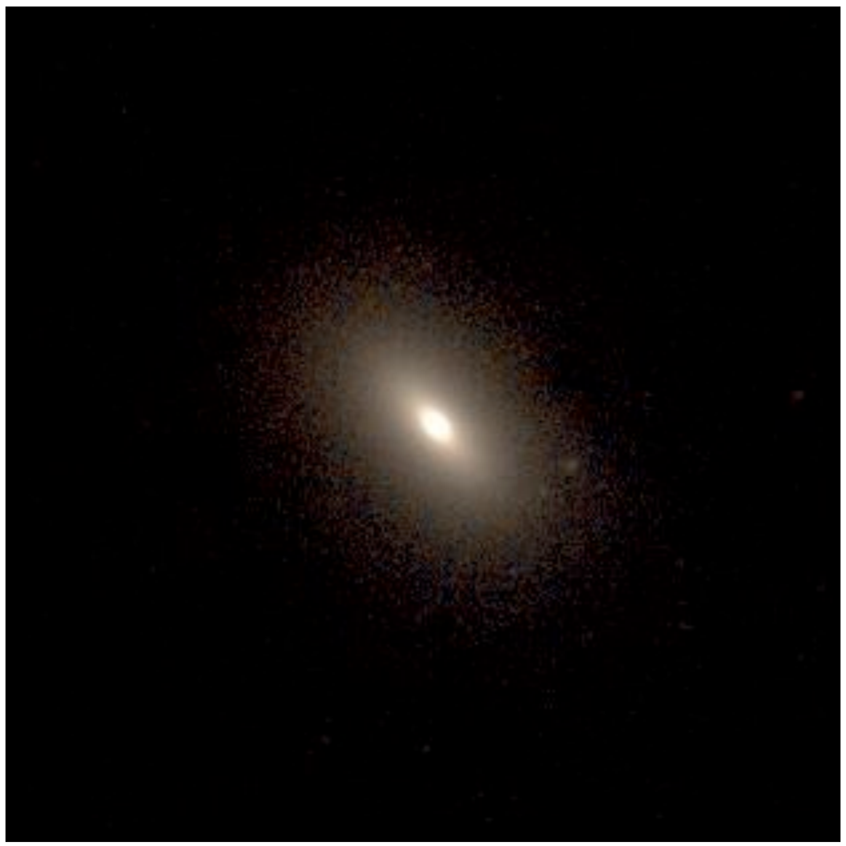
- Visible (baryonic) components of galaxies
  - two basic structural components:
    - spheroids
      - round(ish), stars on eccentric orbits, low net rotation (usually), high entropy: “hot” systems
    - disks
      - flattened, rotating structure, circular orbits, low entropy: “cold”

Galaxy morphology

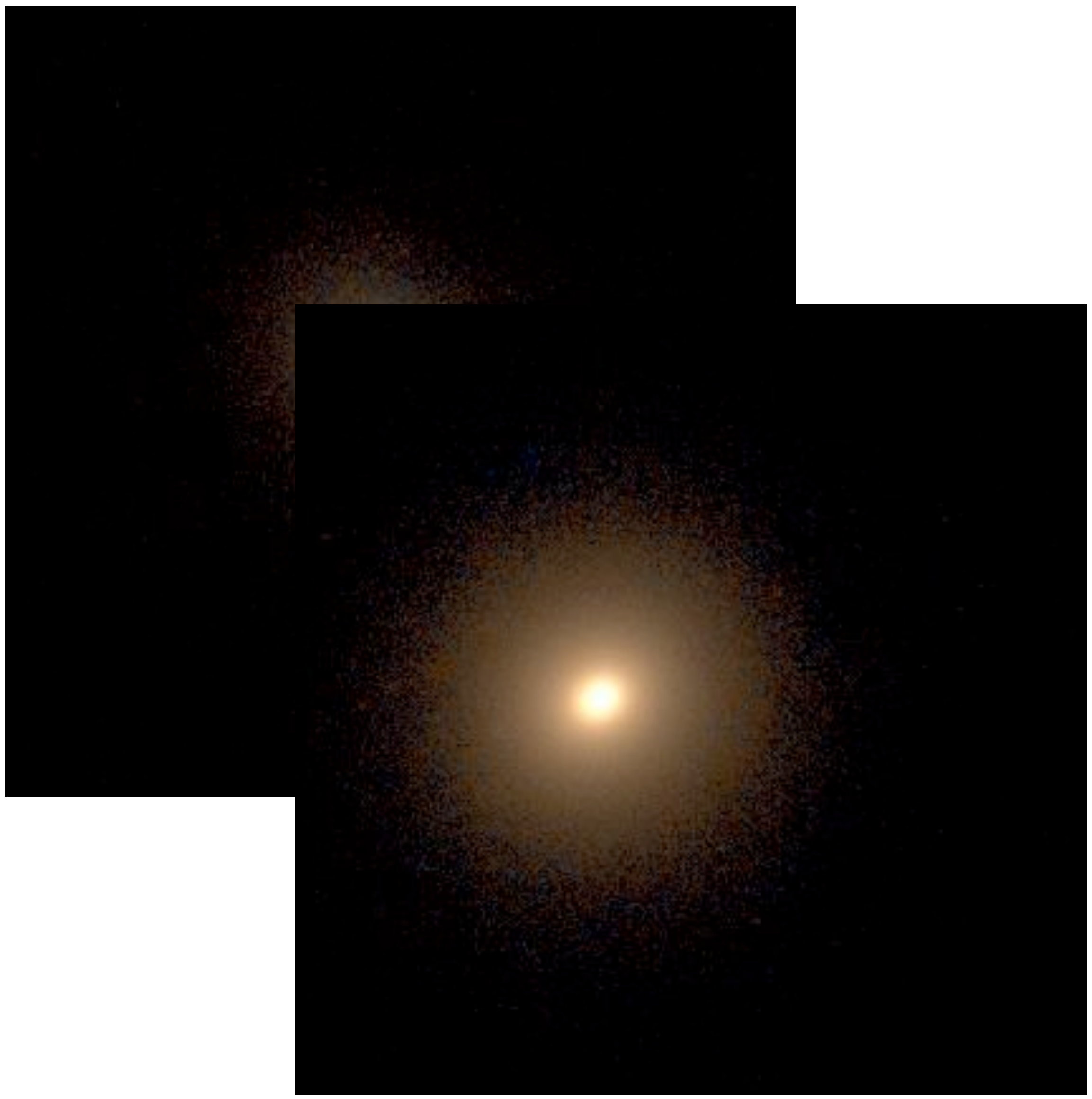
or, "what do galaxies *look* like?"

- Galaxies appear to fall into a few broad "types":
  - **elliptical** galaxies, which are smooth, (usually) featureless (in the optical) balls of stars: dominated by *spheroid* component
  - **spiral** galaxies, where lumpy disks of stars and gas dominate the optical light: dominated by *disk* component
  - **irregular** and **peculiar** galaxies

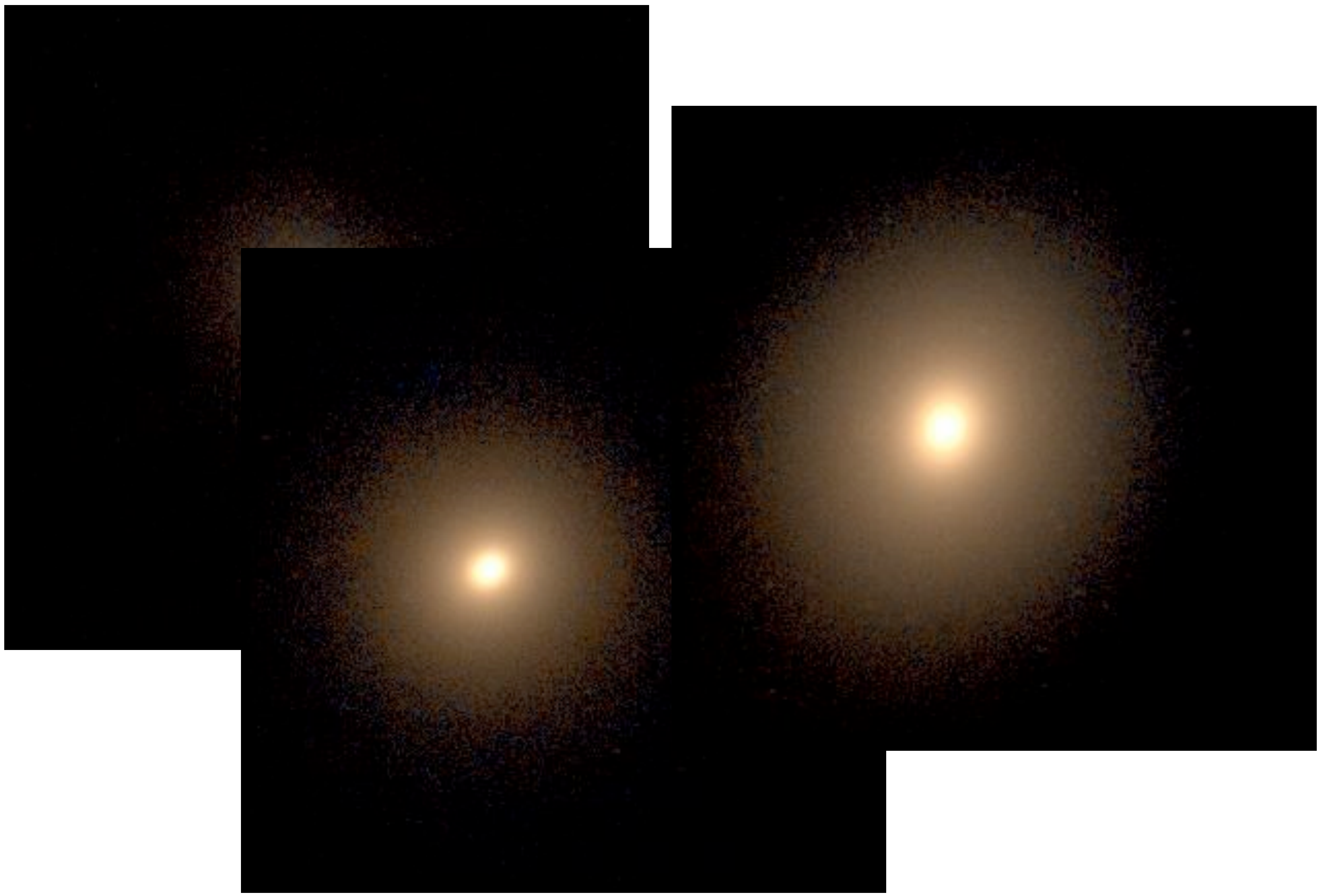
Elliptical galaxies



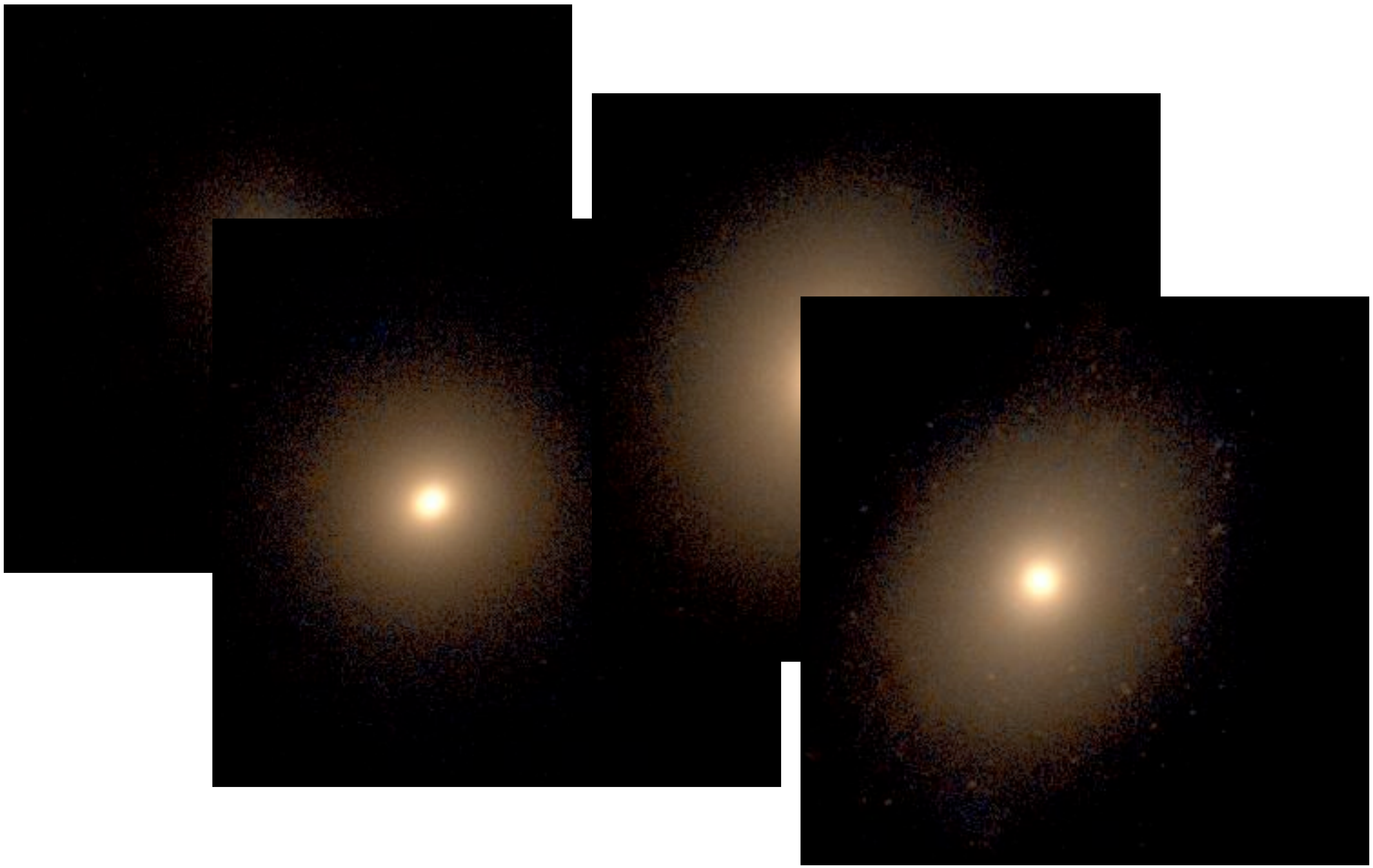
Elliptical galaxies



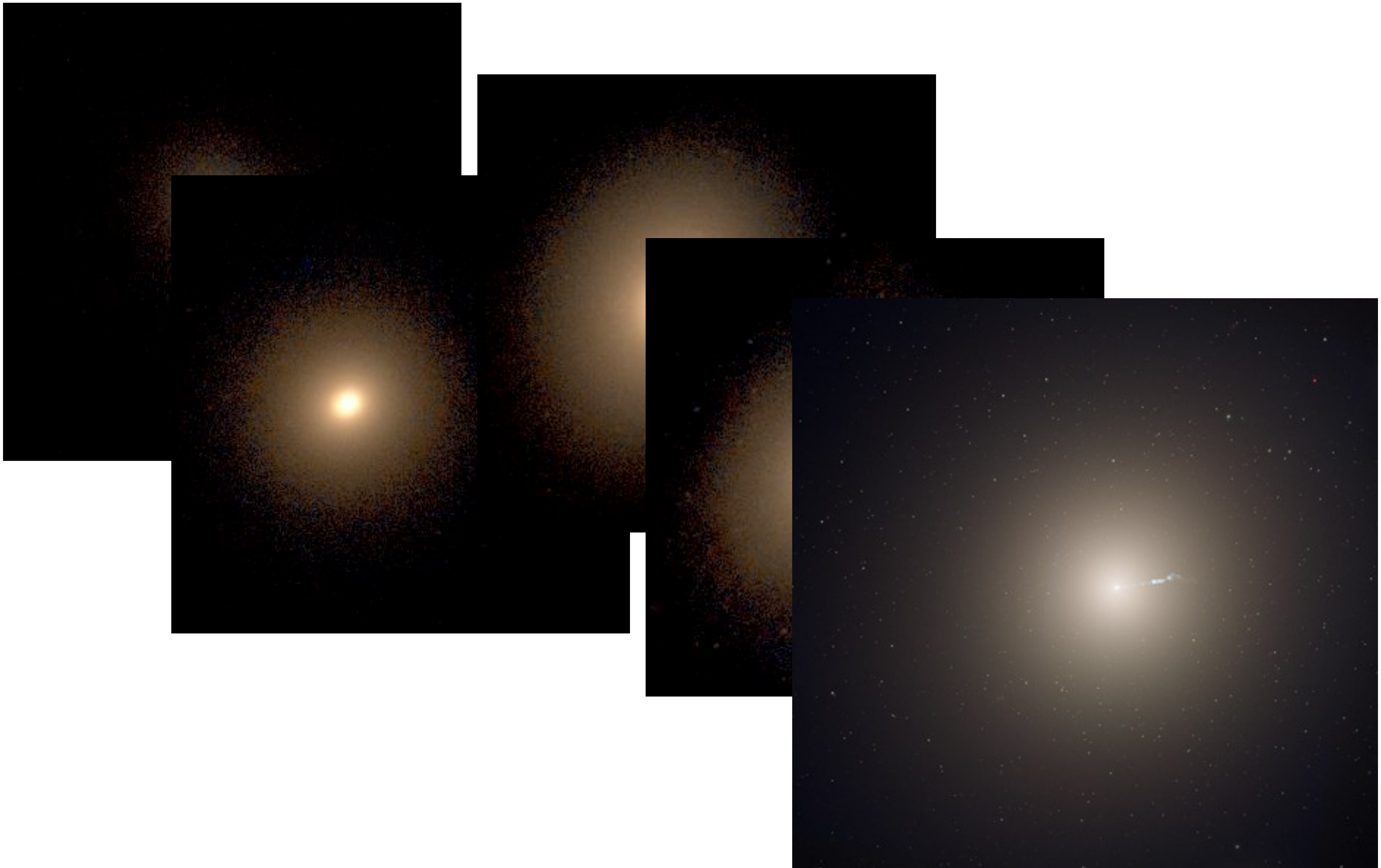
Elliptical galaxies



Elliptical galaxies



Elliptical galaxies



note the variety of colors, arm types, and bar/no bar

Spiral galaxies

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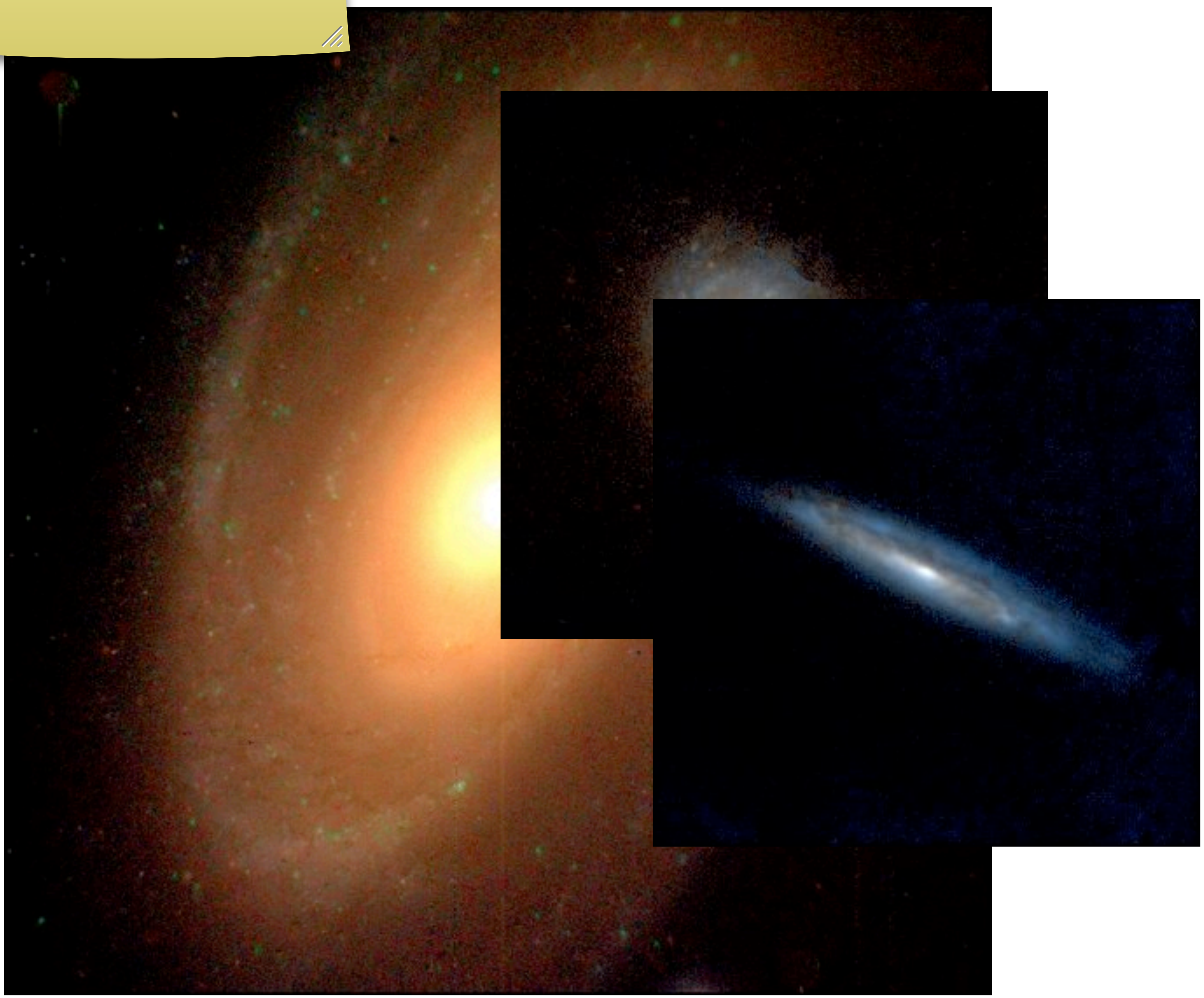
Spiral galaxies



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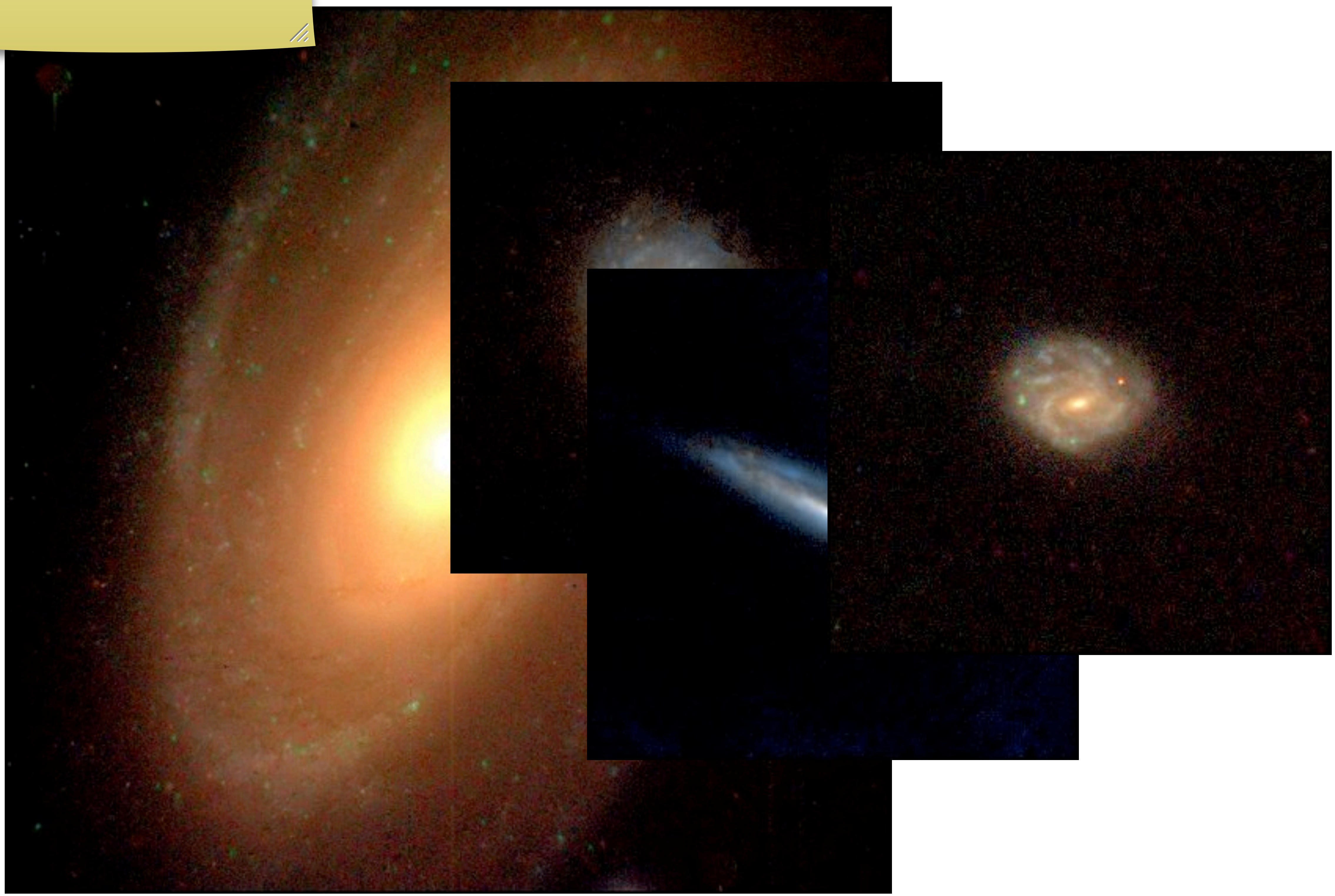

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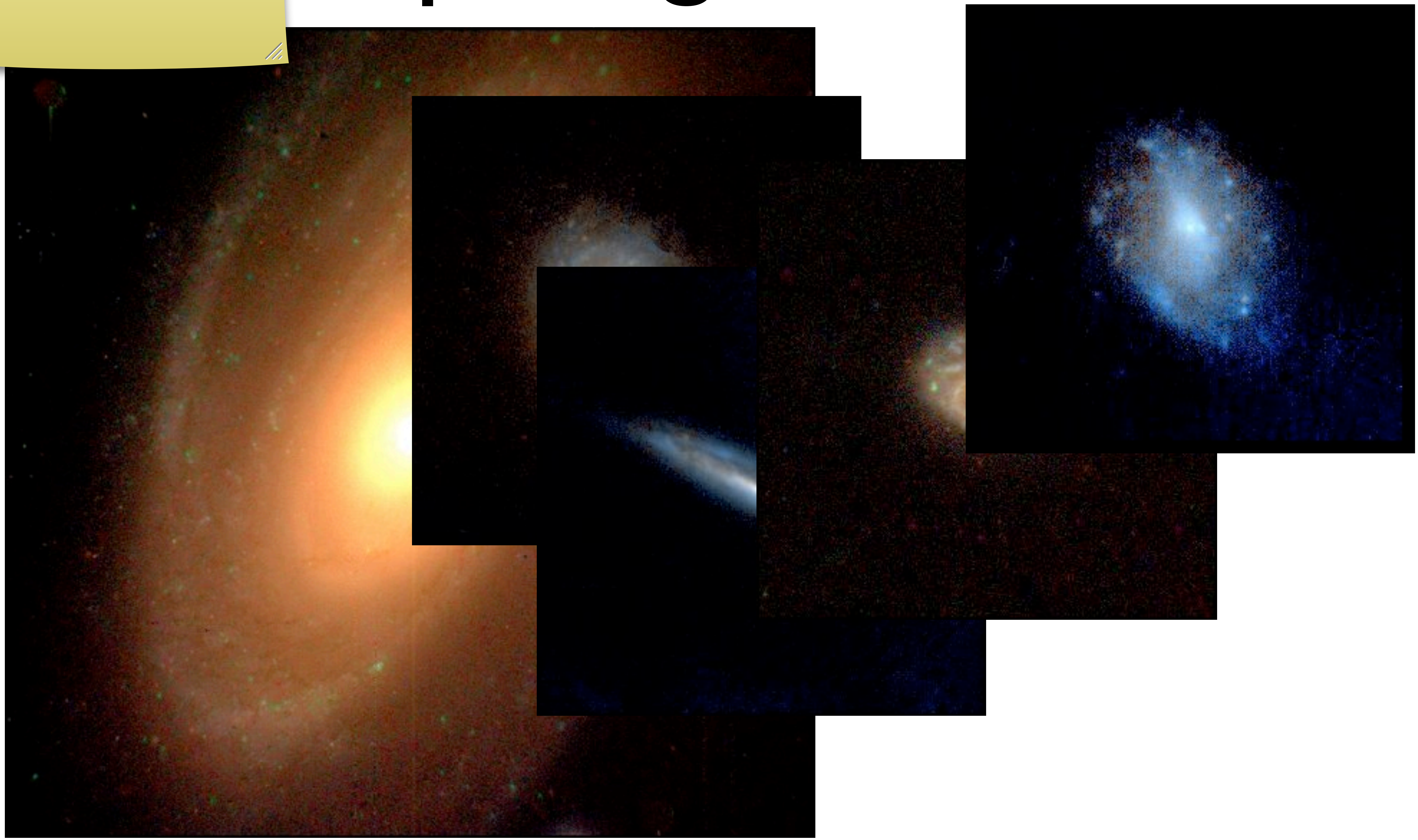

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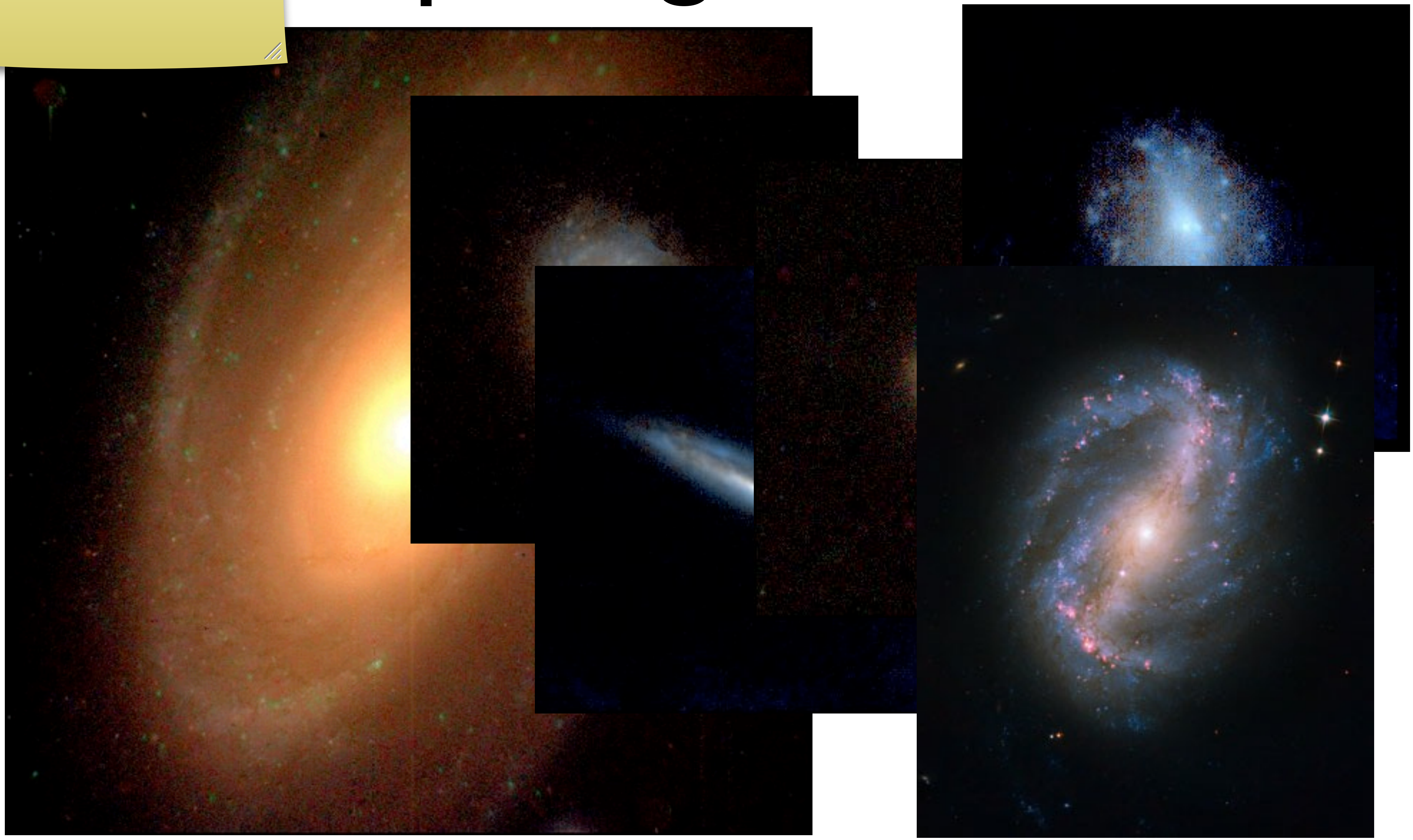
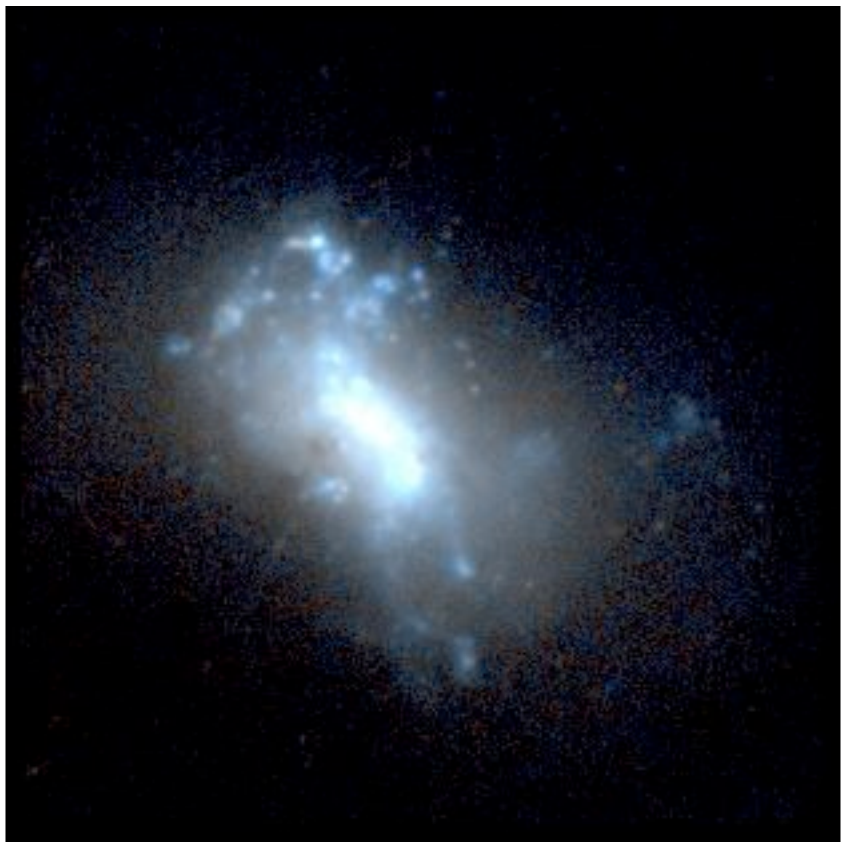
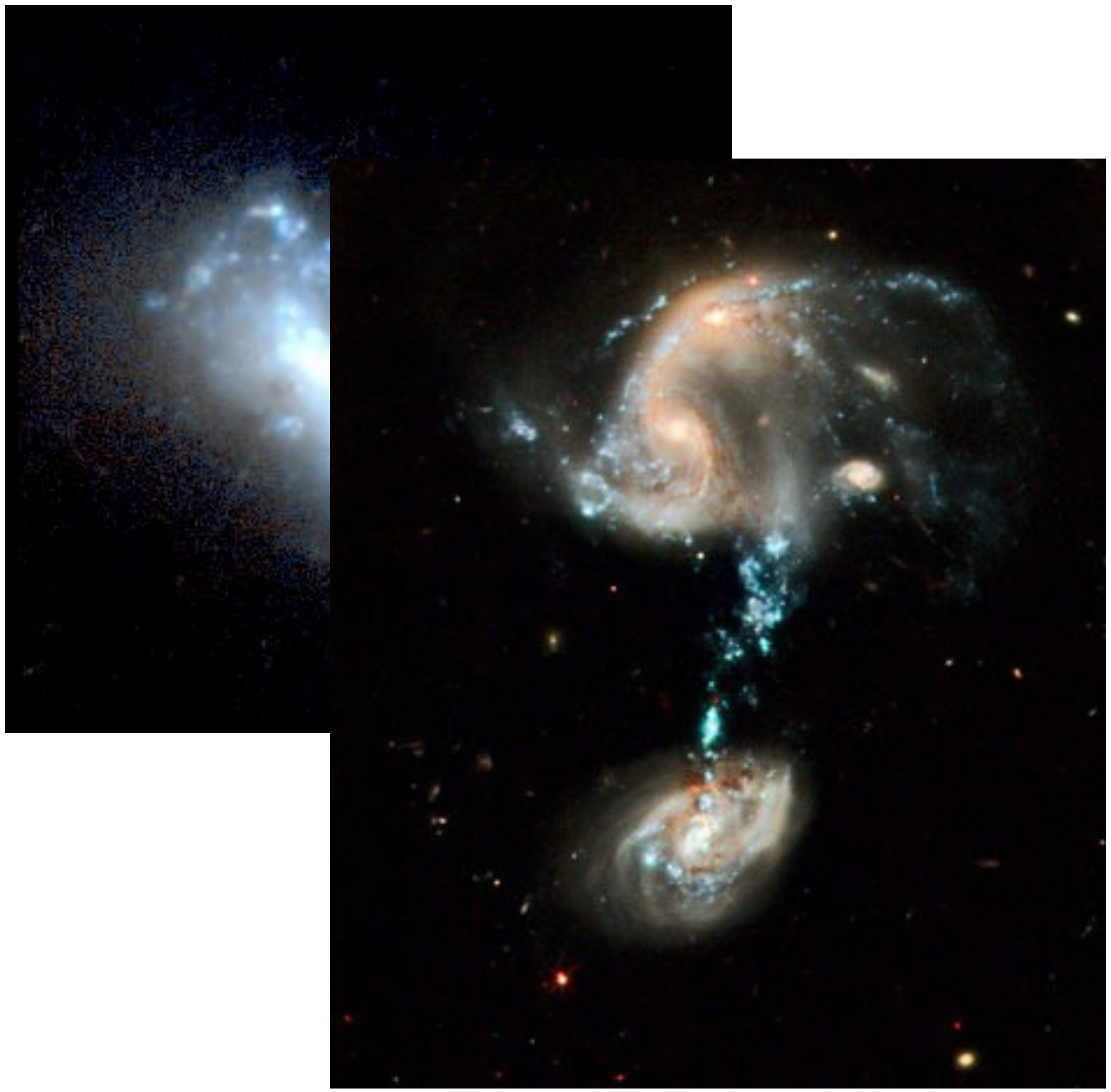


Irregular and peculiar galaxies



Irregular and peculiar galaxies



Irregular and peculiar galaxies

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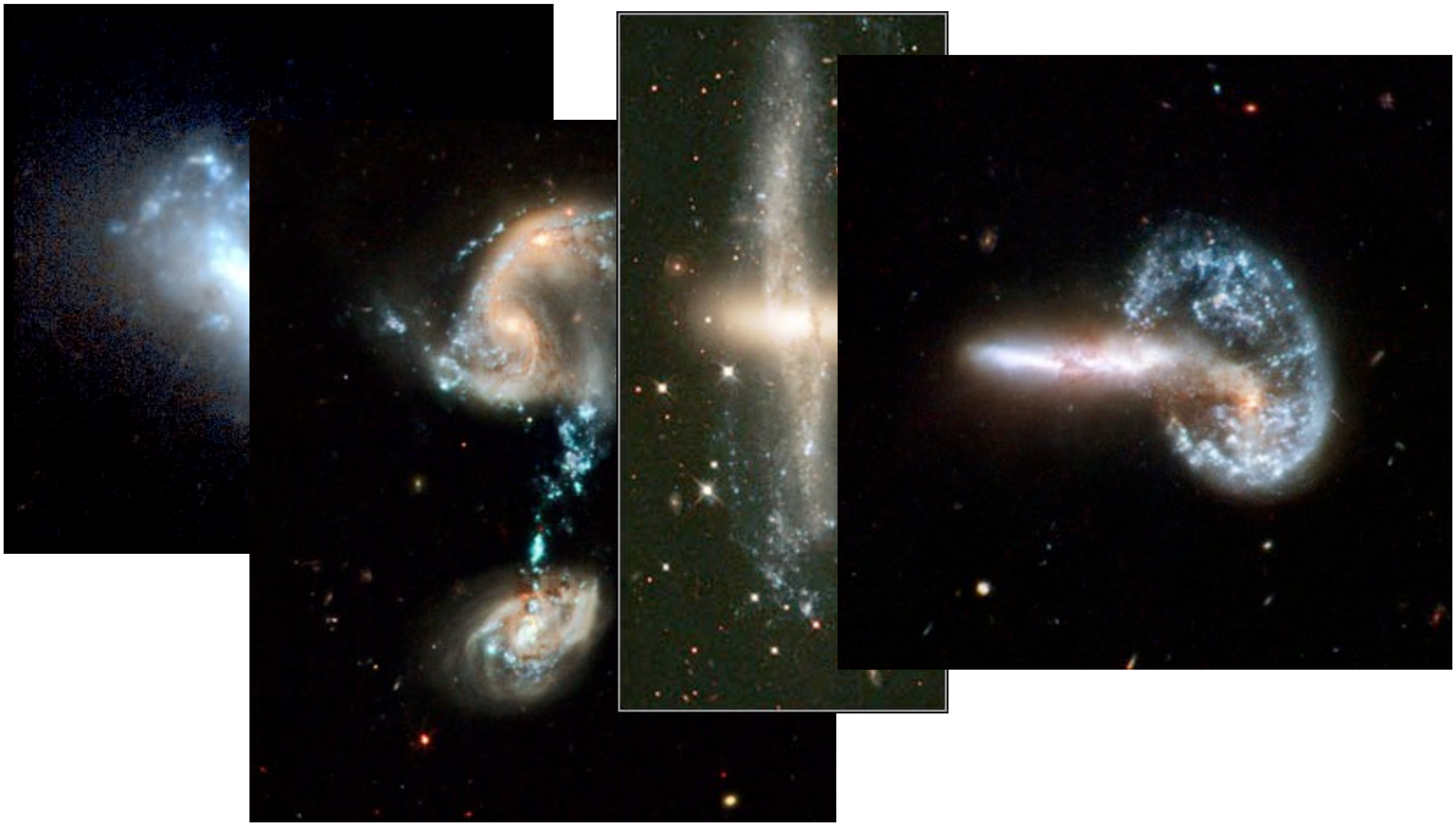


Irregular and peculiar galaxies

- So what do we *do* with this mess?

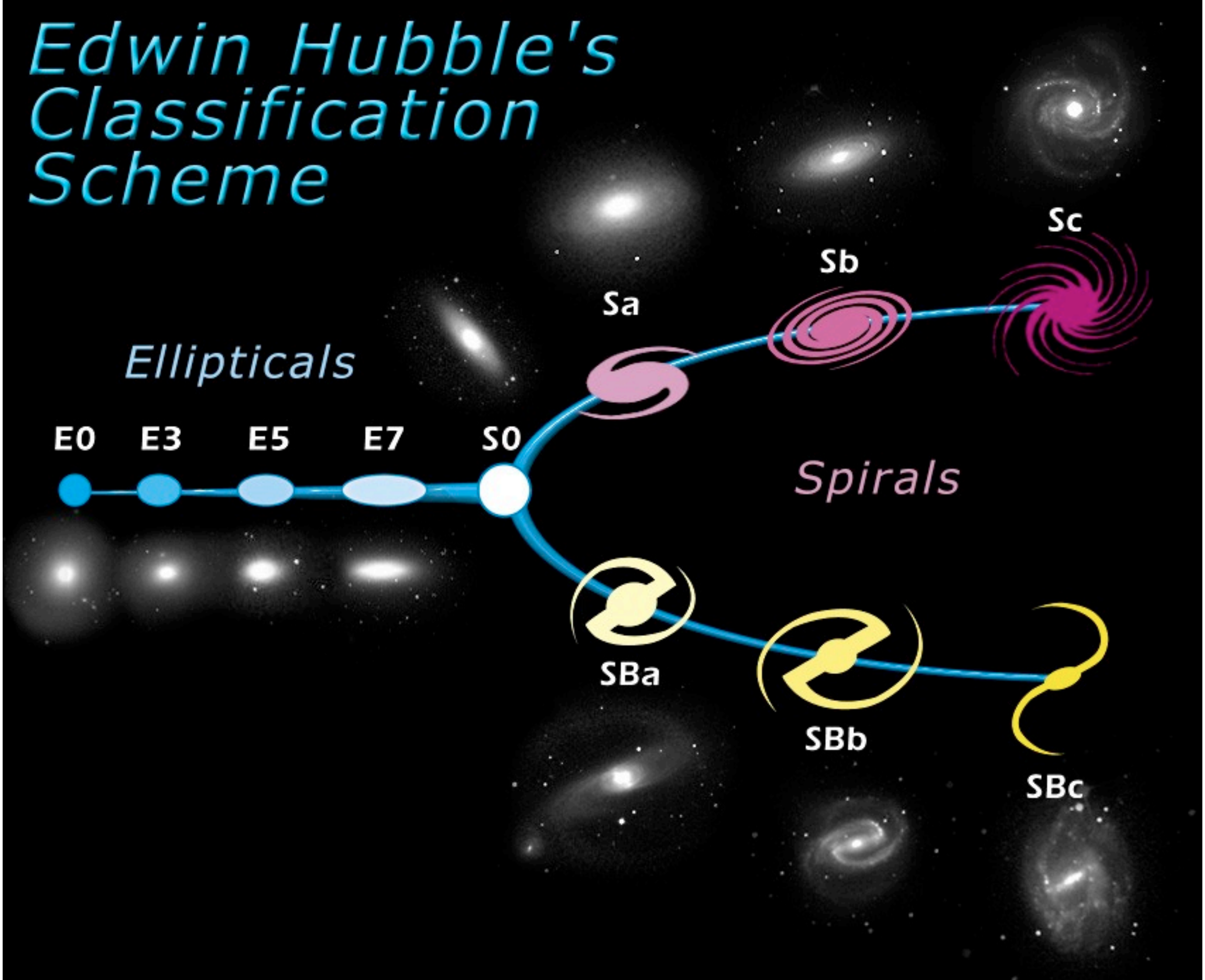
- We want to *classify* the galaxy images somehow

Morphological classification

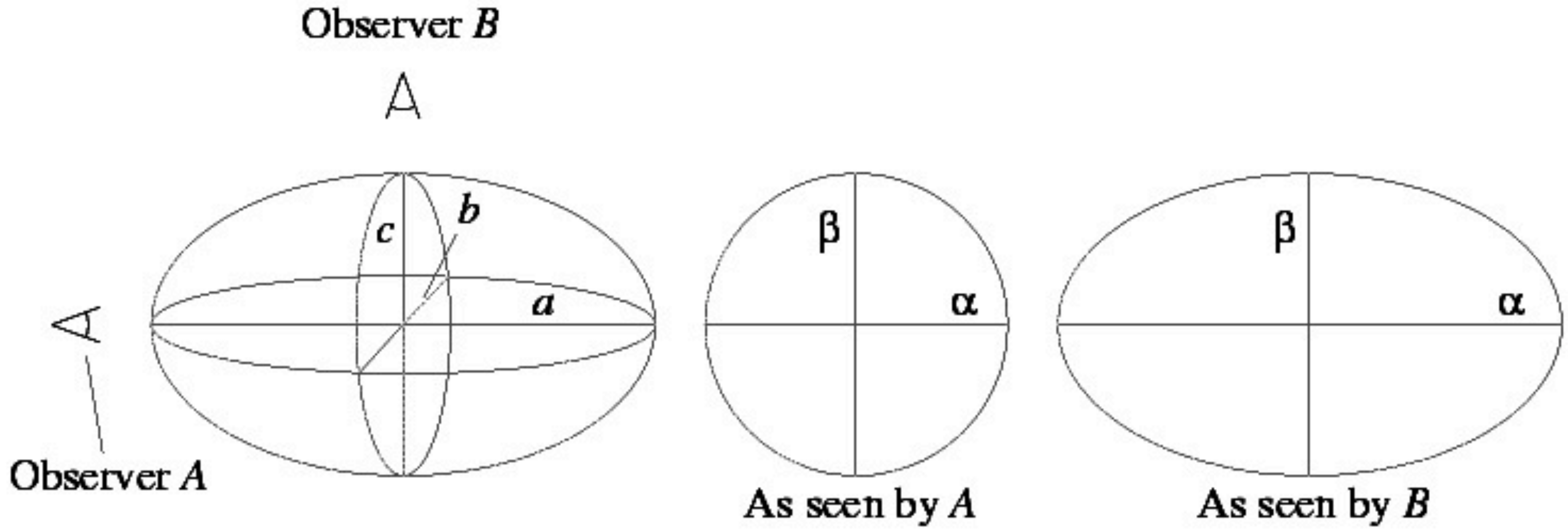
- What are the basic aims of *any kind* of classification scheme?
  - Transform qualitative impression into quantitative information
  - Complete
  - Unambiguous assignment of every object to a class
  - Illuminate physical processes
  - Avoid irrelevant detail: economical description

The Hubble Sequence

- Hubble (1926) used the clear split in galaxy types to create the "tuning fork diagram"
- The Hubble Sequence is a continuum of the ratio of the disk to spheroid components in galaxies

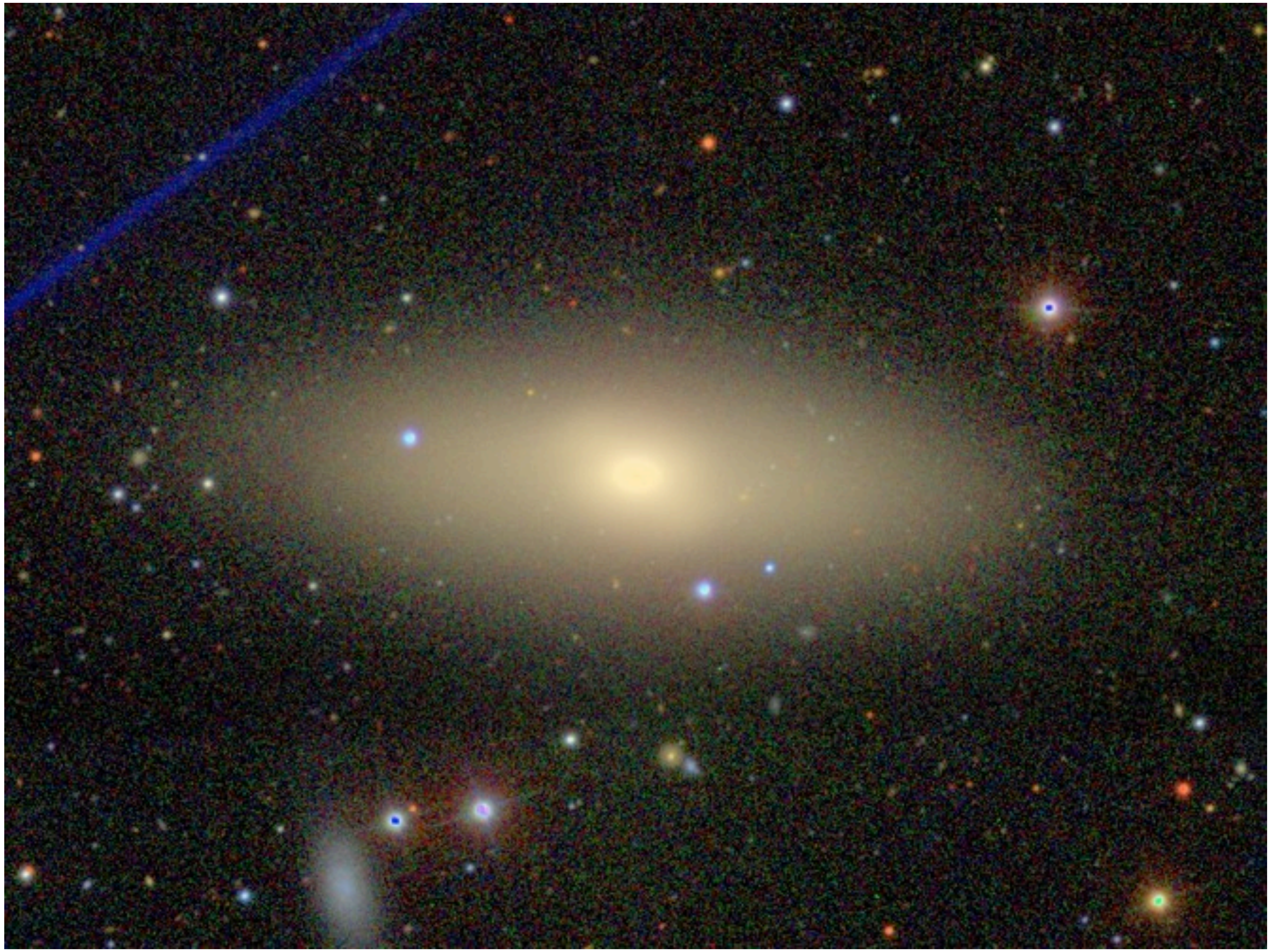

Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

- Elliptical galaxies on the left, called "early-type"
    - arranged by *ellipticity*: $\epsilon = 1 - b/a$
    - where *a* and *b* are the *semi-major* and *semi-minor axis* lengths, <u>projected on the sky</u>



- note that this is *not* the *intrinsic* ellipticity!
- from the morphology of a single galaxy alone, we cannot tell if it is
    - spherical (a=b=c)
    - prolate (a>b=c) --- a cigar
    - oblate (a=b>c) --- a poffertje
    - triaxial (a>b>c)

- In 1936, Hubble added the *S0* classification to his system, to provide a transition between ellipticals and spirals
  - These galaxies have *no* (obvious) lumpiness and (usually) a large bulge



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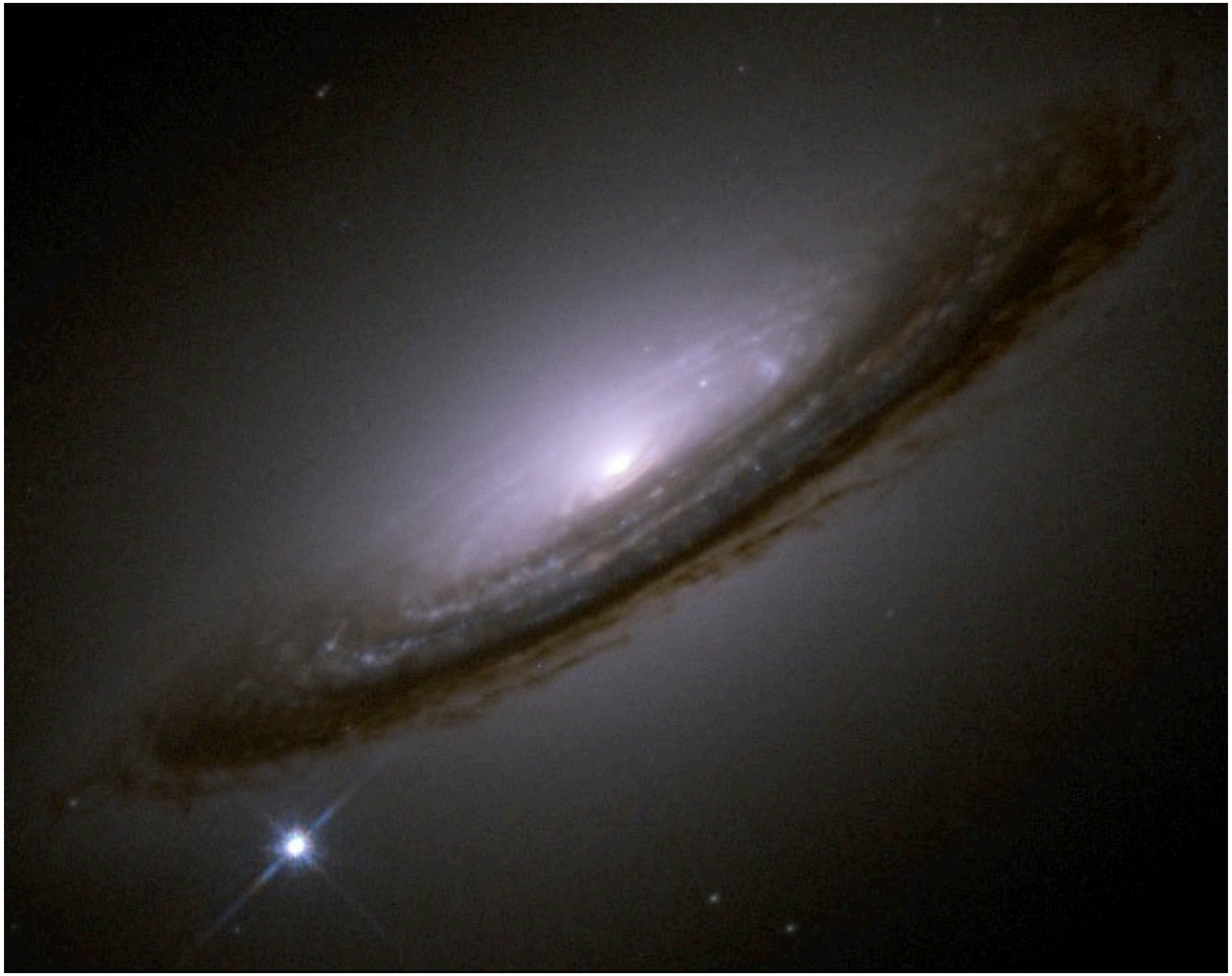

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Types of "early-type" galaxies

- **cD** galaxies: found near the centers of clusters; very bright elliptical galaxies with (very) extended, (very) faint envelopes
- **elliptical** galaxies: can be roughly broken into giant ellipticals, intermediate ellipticals, and *compact* ellipticals (cE, like M32)
- **dwarfs**: broken into dSph ("dwarf spheroidal") and dE ("dwarf elliptical") classes

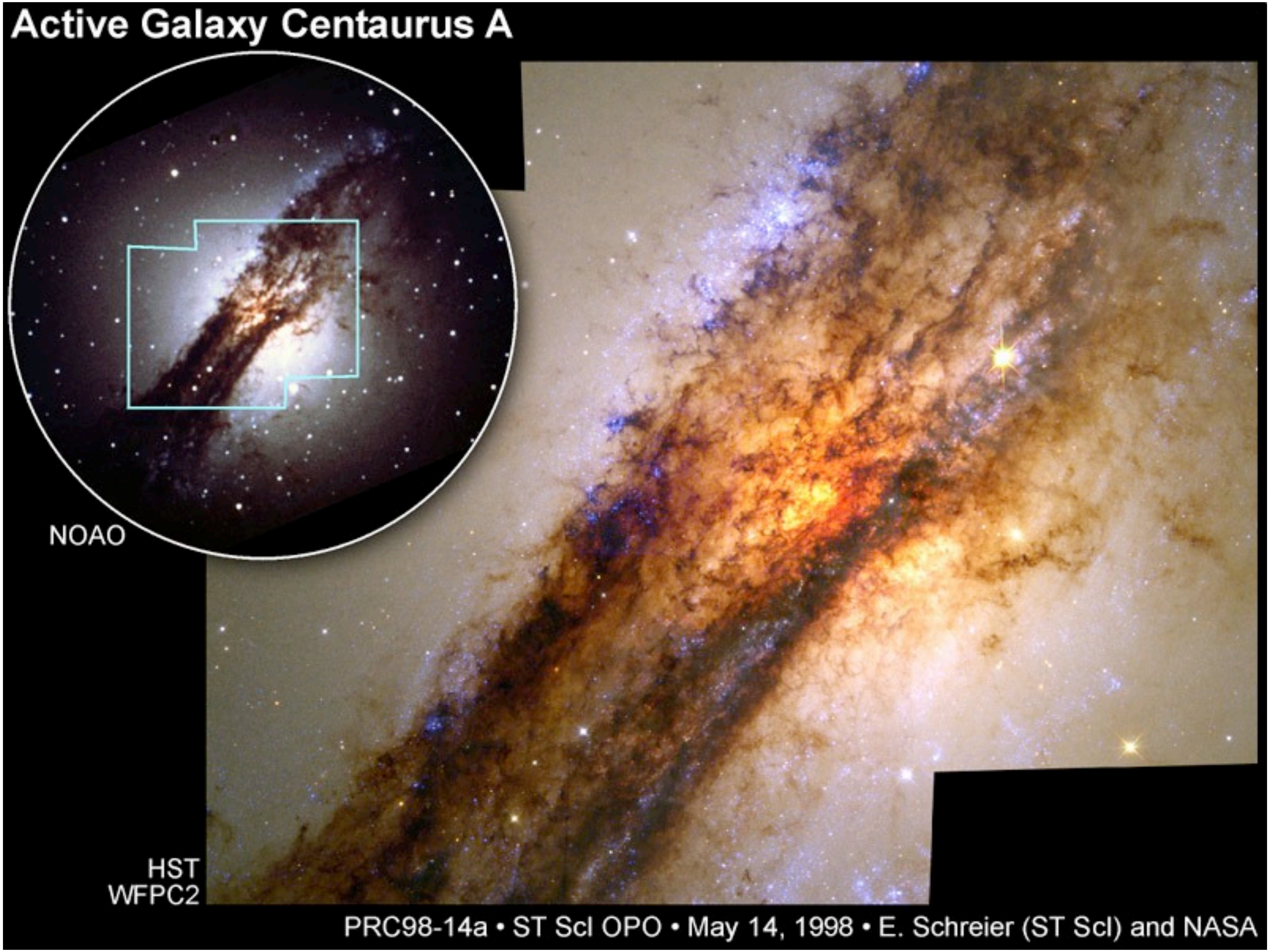
Characteristics of big "early-type" galaxies

	cD	E	S0
M_B	-22 to -25	-15 to -23	-17 to -22
M ($M_\odot$)	10^{13}-10^{14}	10^{8}-10^{13}	10^{10}-10^{12}
Diameter (kpc)	300-1000	1-200	10-100
$\langle M/L_B \rangle$	>100	10-100	~10

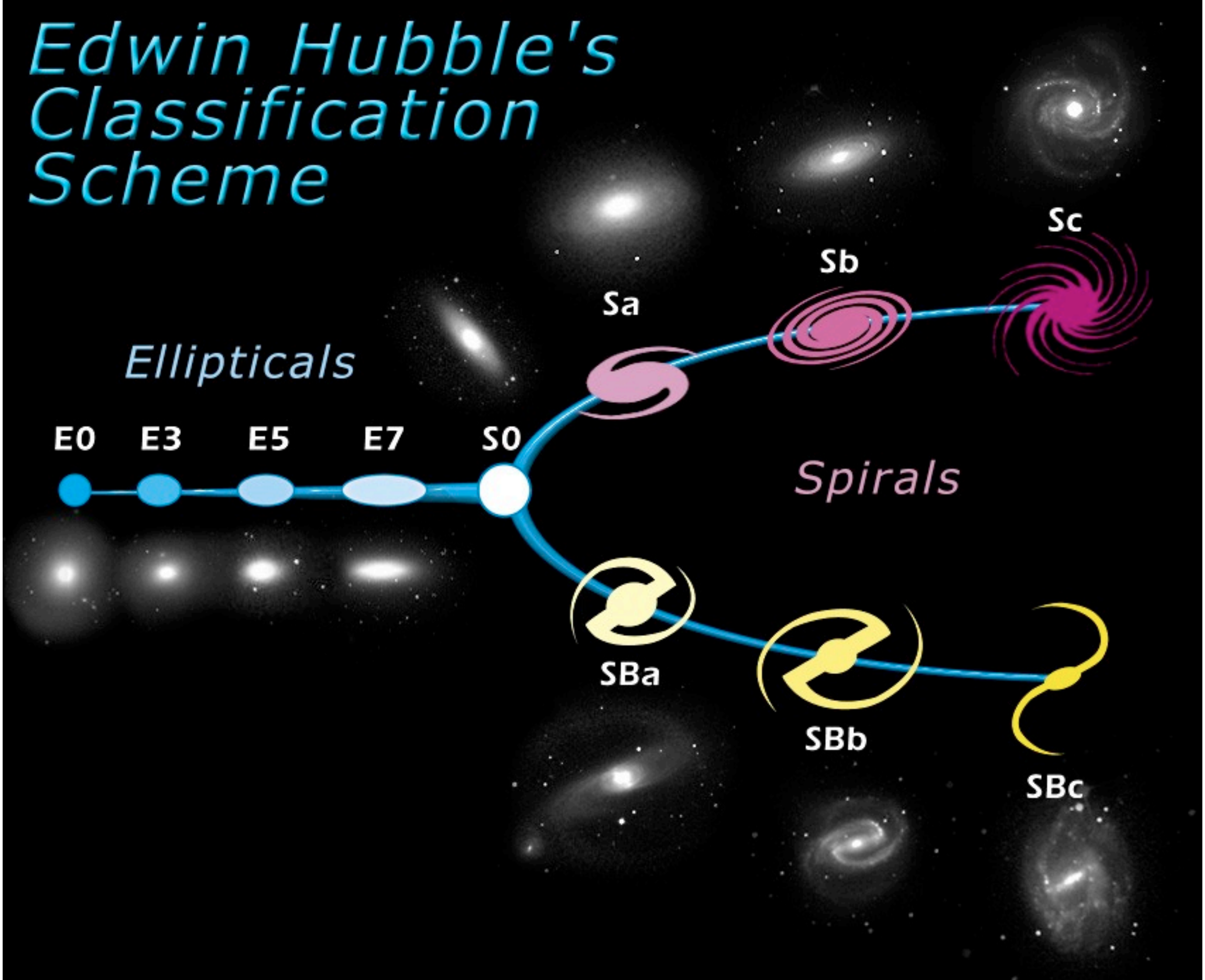
Characteristics of dwarf "early-type" galaxies

	dE	dSph
M_B	-13 to -19	-8 (or lower) to -15
M ($M_\odot$)	10^7-10^9	10^7-10^8
Diameter (kpc)	1-10	0.1-0.5
$\langle M/L_B \rangle$	~10	5-100 (or higher)

- Early-type galaxies contain little or no dust
  - except sometimes near their centers...
- ...and little gas...
  - except that ~40% of them have detectable HI and roughly the same amount have detectable H_2 (or at least CO)
- ...and no star formation
  - except sometimes!



Centaurus A has *all* of these!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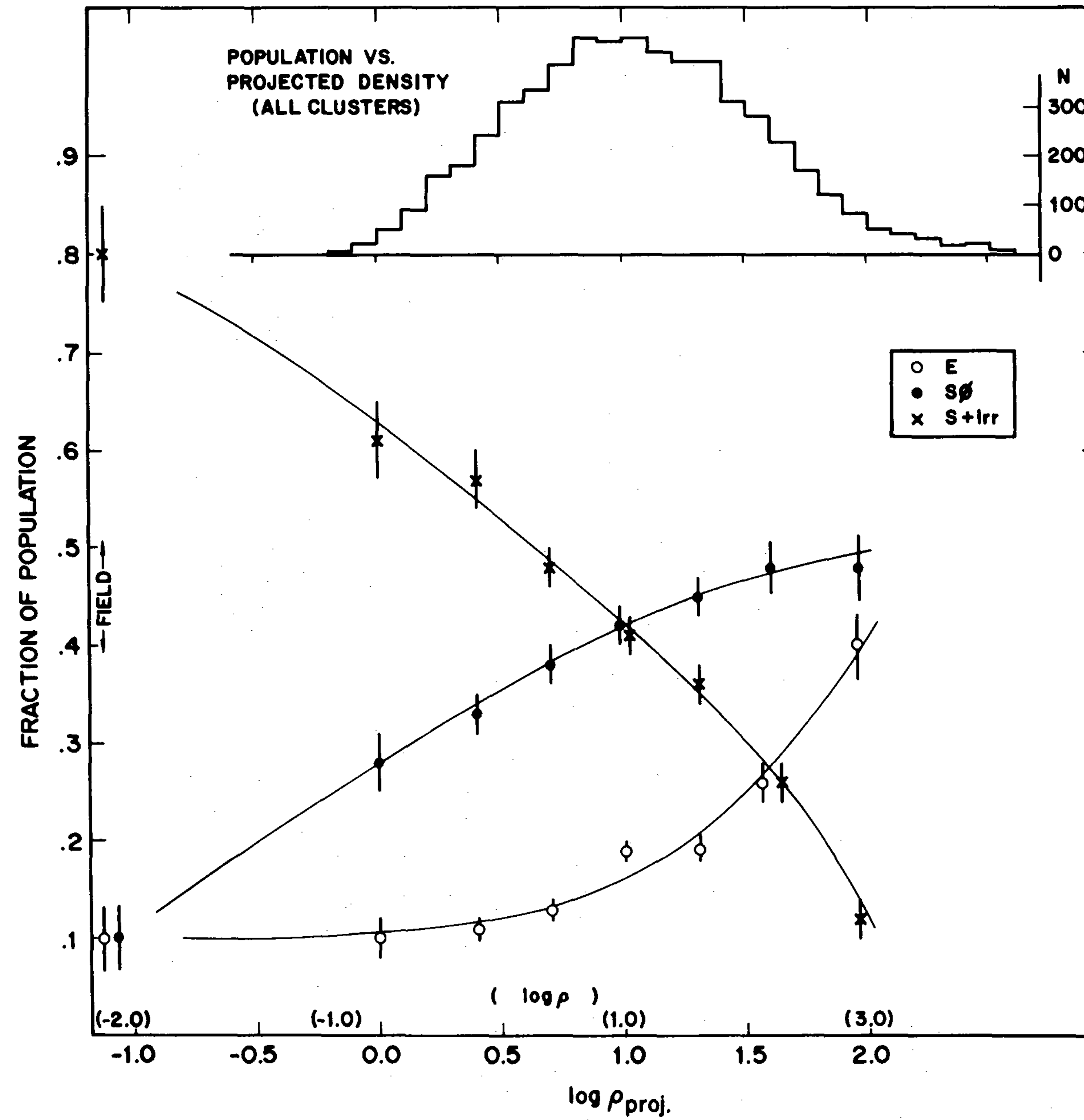
- Spiral galaxies on the right, called “late-type”
  - Spirals split into *barred* and *unbarred* types
  - arranged by <u>three</u> criteria:
    - *primary*: small-scale lumpiness
    - *secondary*: bulge-to-disk ratio
    - *tertiary*: pitch angle, prominence, and number of spiral arms

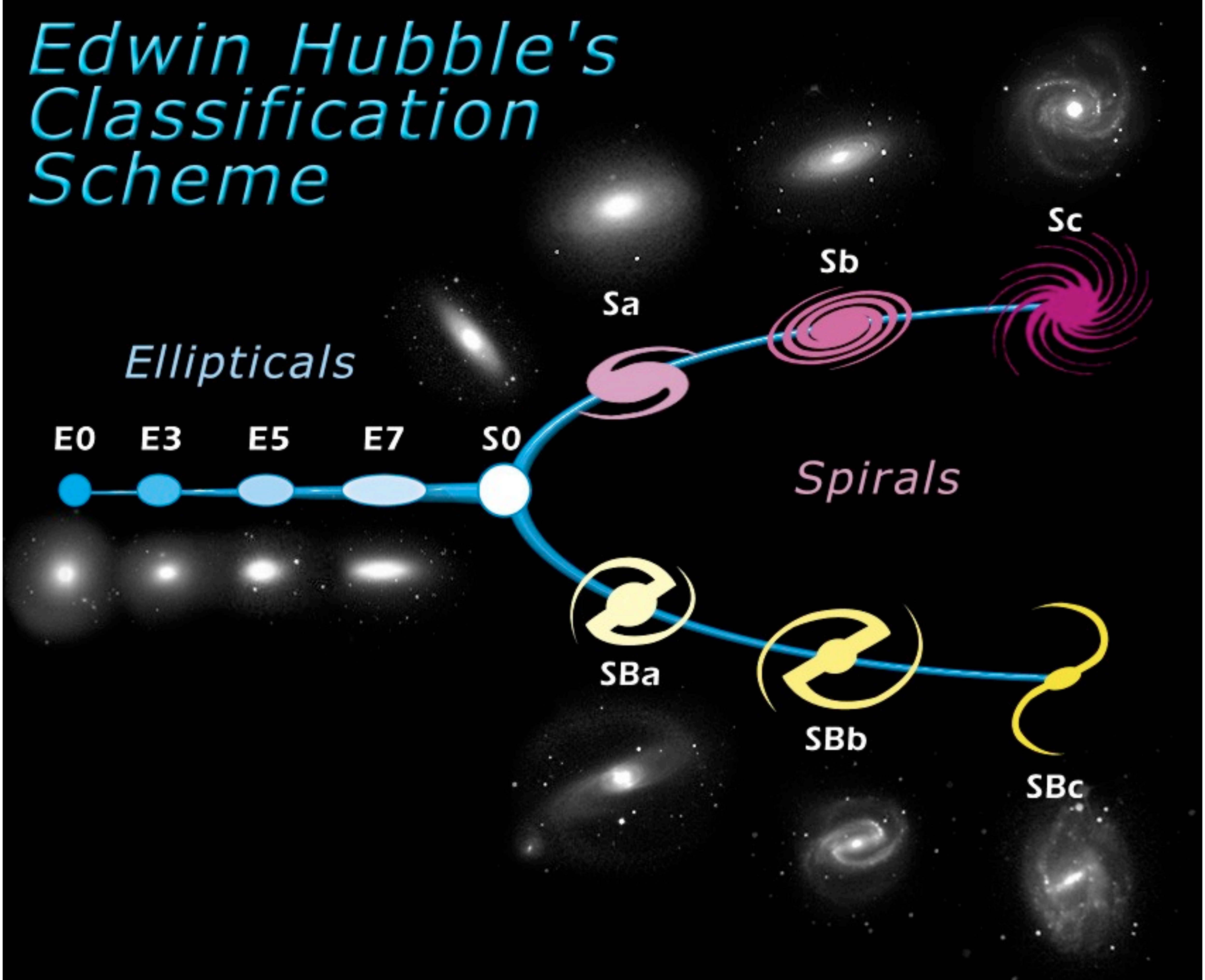
	Sa	Sb	Sc	Sd/Sm	Im/Irr
M_B	-17 to -23	-17 to -23	-16 to -22	-15 to -20	-13 to -18
M ($M_\odot$)	10^9-10^{12}	10^9-10^{12}	10^9-10^{12}	10^8-10^{10}	10^8-10^{10}
Diameter (kpc)	5-100	5-100	5-100	0.5-50	0.5-50
$\langle M/L_B \rangle$	6	4.5	2.5	~1	~1
$\langle L_{bulge}/L_{tot} \rangle_B$	0.3	0.13	0.05	~0	~0
V_{max} (km/s)	165-365	145-330	100-300	80-120	50-70
pitch angle	~6°	~12°	~18°		
$\langle (B-V) \rangle$	0.75	0.64	0.62	0.47	0.37
$\langle M_{gas}/M_{tot} \rangle$	0.04	0.08	0.16	0.25	0.5-0.9
$\langle M_{H2}/M_{HI} \rangle$	2.2	1.8	0.73	0.03-0.3	~0

- In the local Universe, ~80% of elliptical and ~70% of S0 galaxies live in *clusters of galaxies*

- Conversely, ~80% of spiral galaxies live in the *field*---i.e., the "average" environment of galaxies



- The fact the *primary criterion for the Hubble Sequence* is "lumpiness"---which is caused by **star formation** *now* in a galaxy---means that the Hubble Sequence is basically a *sequence in present-day star formation rate!*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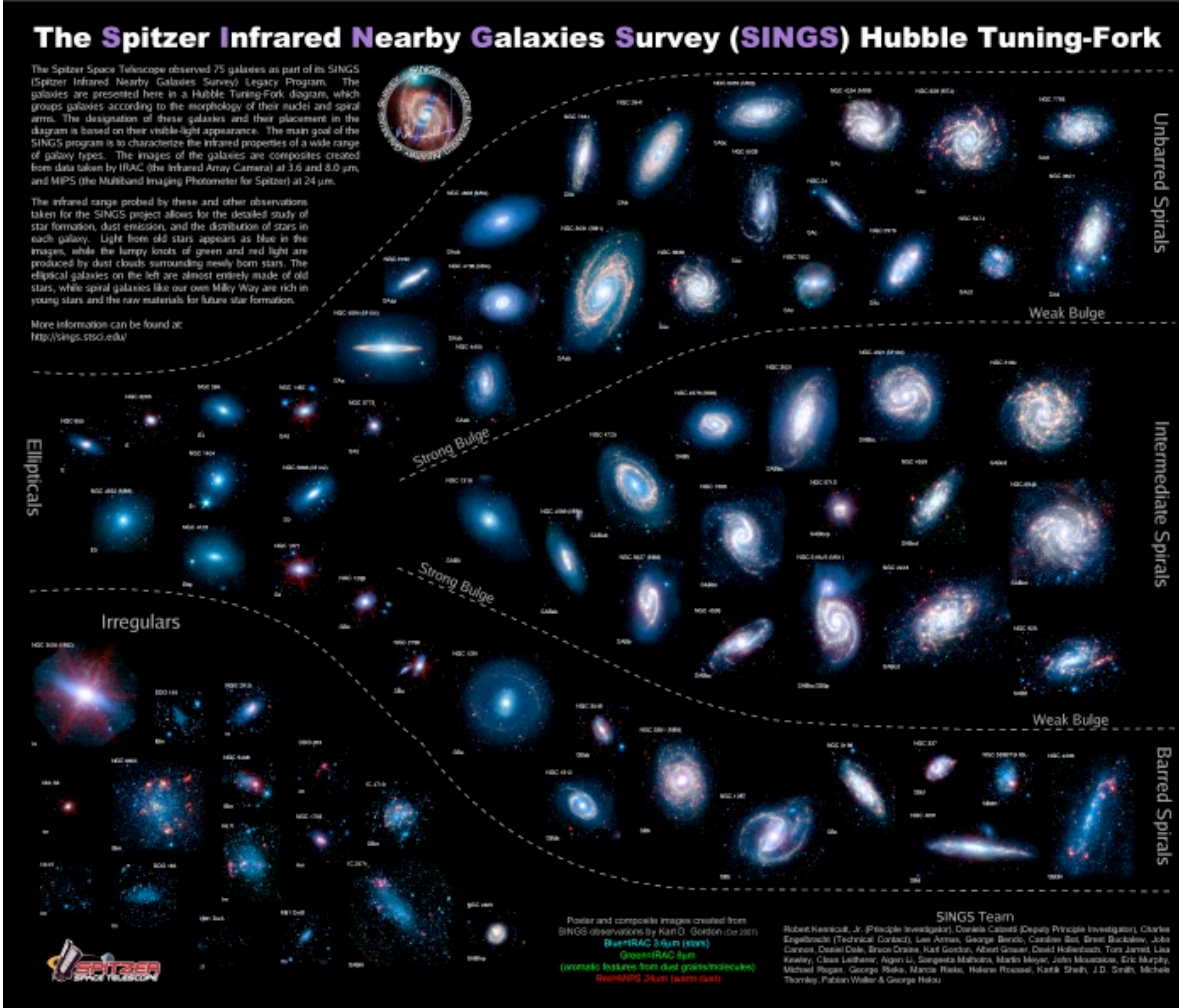
A recent *infrared* view of the Hubble Sequence



Hubble Sequence classification score card

- Transform qualitative impression into quantitative information
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- Unambiguous assignment of every object to a class
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Hubble Sequence classification score card

- Transform qualitative impression into quantitative information
- Complete Peculiars?
- Unambiguous assignment of every object to a class
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- Avoid irrelevant detail: economical description

Hubble Sequence classification score card

- ✓ Transform qualitative impression into quantitative information
- ✗ Complete *Peculiars?*
- ✗ Unambiguous assignment of every object to a class *Ring galaxies?*
- Illuminate physical processes
- ✓ Avoid irrelevant detail: economical description

Hubble Sequence classification score card

- Transform qualitative impression into quantitative information
- Complete *Peculiars?*
- Unambiguous assignment of every object to a class *Ring galaxies?*
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- Avoid irrelevant detail: economical description

B/D ratios along the Hubble Sequence

- B/T ratio systematically varies along sequence, as desired, but <u>not</u> monotonically (Kent 1985):
    - bulge-to-disk ratio *not* accurate predictor of Hubble type!

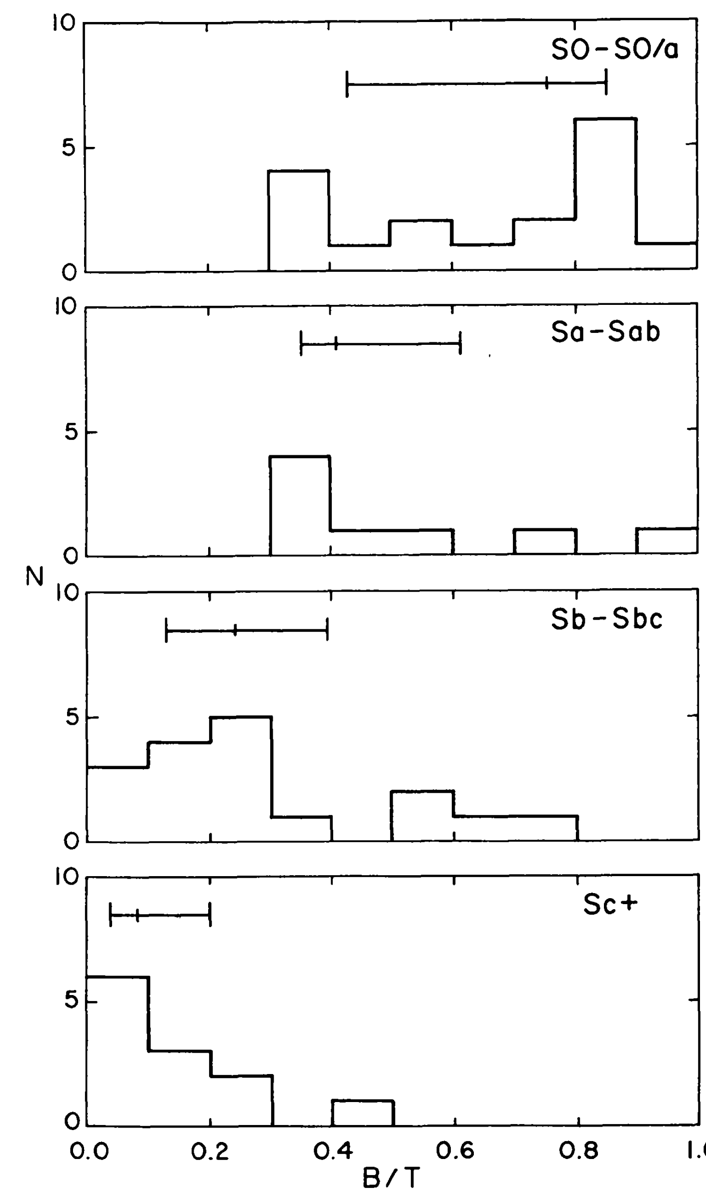


FIG. 6.—Distribution of B/T as a function of morphological type

Why do the Hubble criteria correlate?

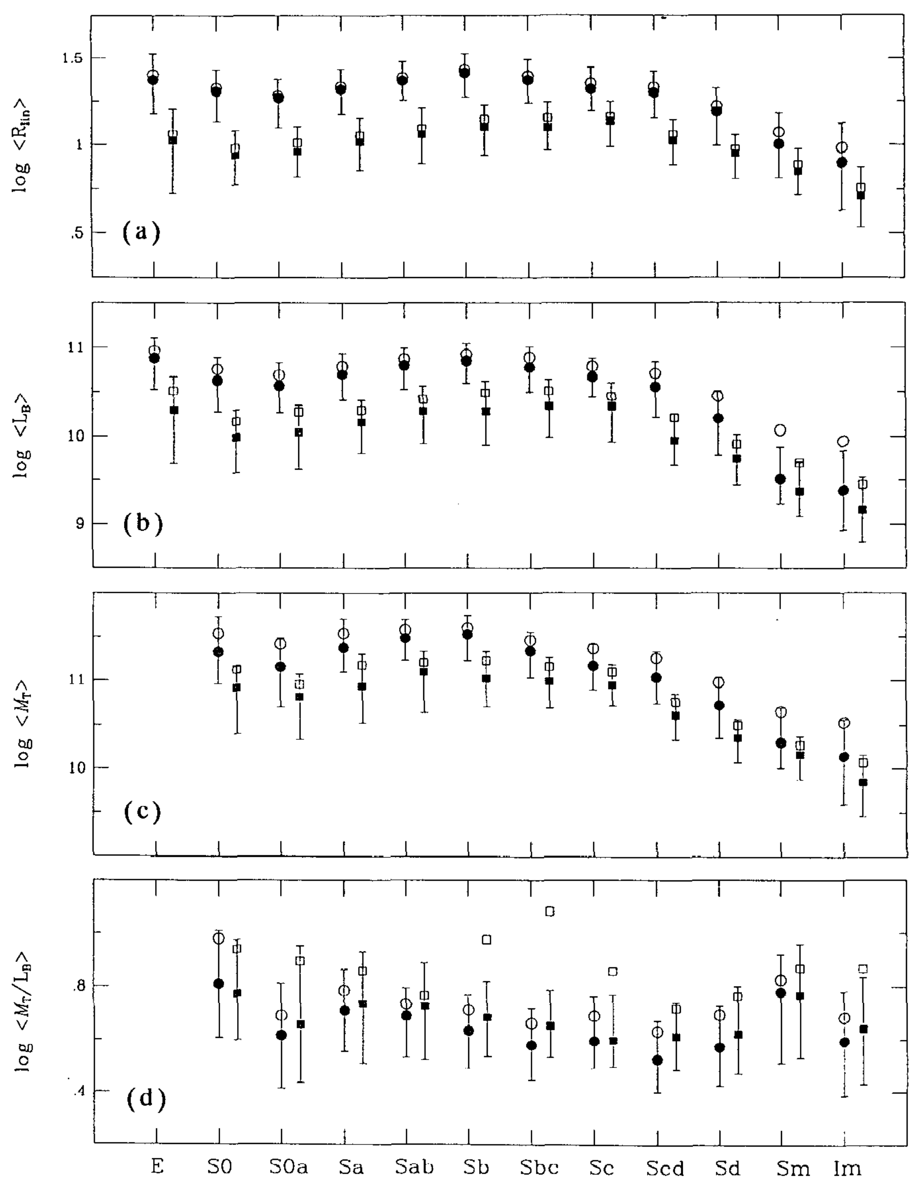
- Density-wave theory for spiral structure predicts that number of arms increases when disk mass decreases
  - if $f=\Sigma(\text{disk})/\Sigma(\text{spheroid})$, where Σ is surface mass density, then $m \sim 1/f$, where m is the number of arms
  - Bulges are dense and concentrated, so they have rapidly rising rotation curves and significant differential rotation
  - so as B/D increases, arms get tightly wound
- So as B/D increases, lots of tightly-wound arms; as B/D decreases, few loosely-wound arms

Physical parameters along the Hubble Sequence

radius

blue luminosity

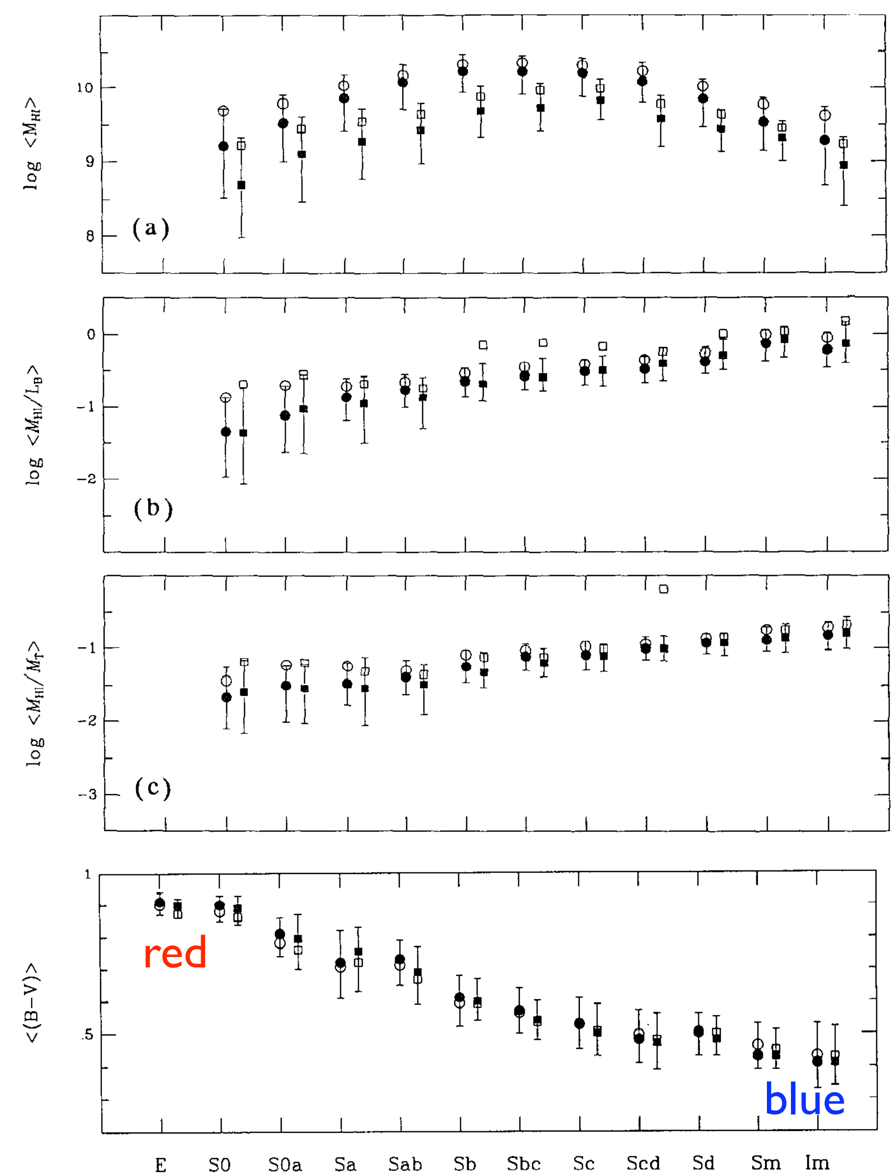
total mass



HI mass

HI/total mass

color



E S0 Sa Sb Sc Irr

E S0 Sa Sb Sc Irr

- Note that the fractional mass of HI (neutral hydrogen) relative to the total galaxy mass increases as B/D decreases
  - fuel for star formation increases as B/D decreases, so SFR should increase as B/D decreases
    - can be seen (roughly) from colors as function of type:
      - early-types are red (~no SF)
      - late-types are blue (lots of SF)

- <u>integrated overview of Hubble sequence:</u>
  - mass increases, B/D increases
  - most massive galaxies, largest B/D: EARLY TYPES
    - bulges
    - rising rotation curves -> differential rotation
      - <u>tightly-wound arms</u>
    - low disk mass
      - <u>large number of arms</u>
    - low HI content
      - <u>low SFR today</u>

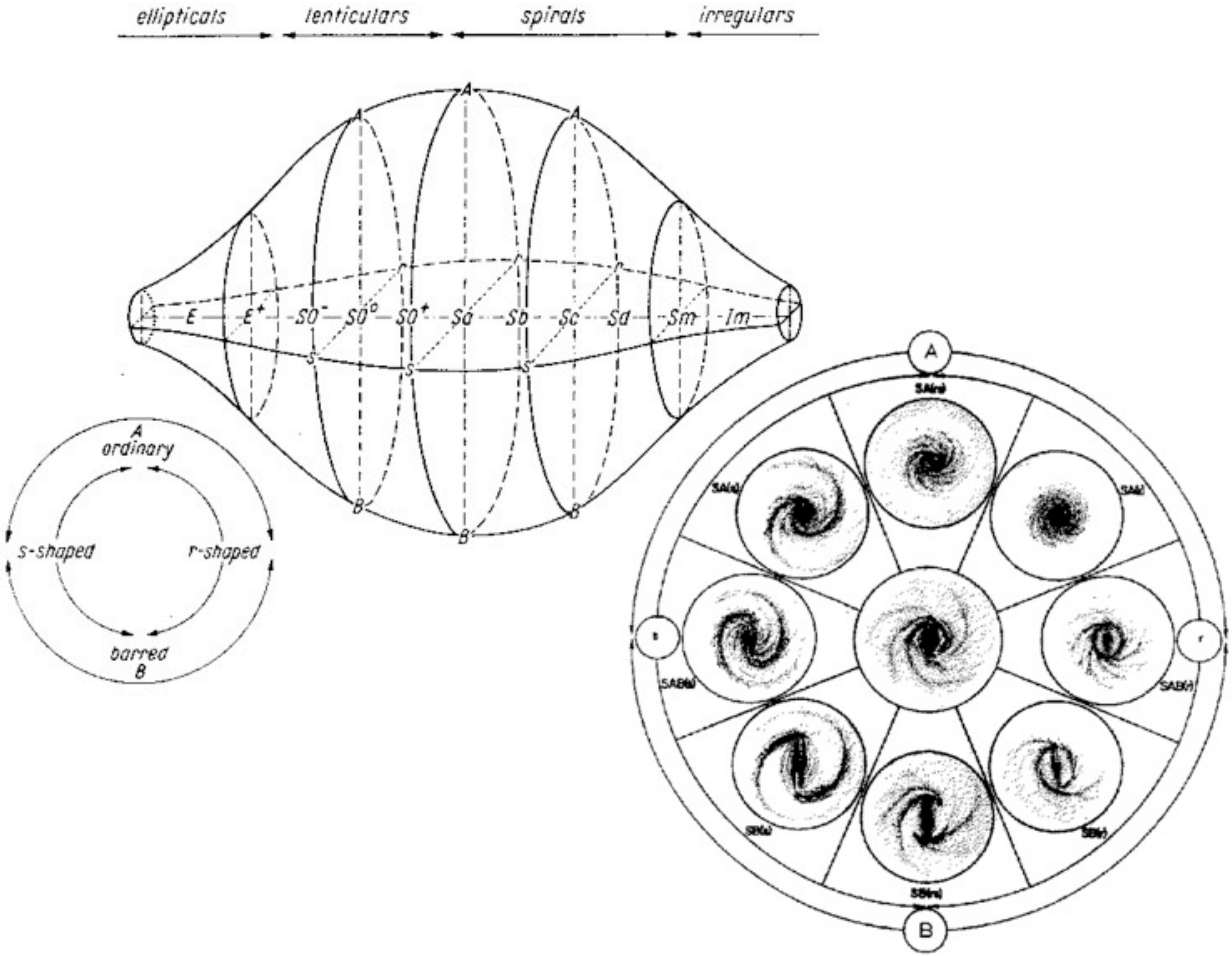
- least massive galaxies (still on Hubble Sequence): LATE TYPES
    - disks
    - linear rotation curves -> solid-body motion
        - <u>loosely-wrapped arms</u>
    - high disk mass
        - <u>small number of arms</u>
    - high HI content
        - <u>high SFR today</u>

- Main question about Hubble Sequence:
  - <u>why does B/D increase with mass?</u>
    - We will see later that mergers help to explain this:
      - mergers make bulges by destroying disks, and make galaxies bigger
      - therefore, mergers tend to have mass increase as B/D increases
  - but how did big spirals settle down to have big gas disks without forming stars along the way?

Extensions to the Hubble Sequence

- Because the Hubble Sequence is not complete and does not describe *every* feature seen in galaxies, people have extended it to include other information
- de Vaucouleurs (1959): "3-D" classification, with s-shaped vs. ring morphology as third axis
  - also added "Sd" to replace some irregular classifications

The “3D” de Vaucouleurs classification system

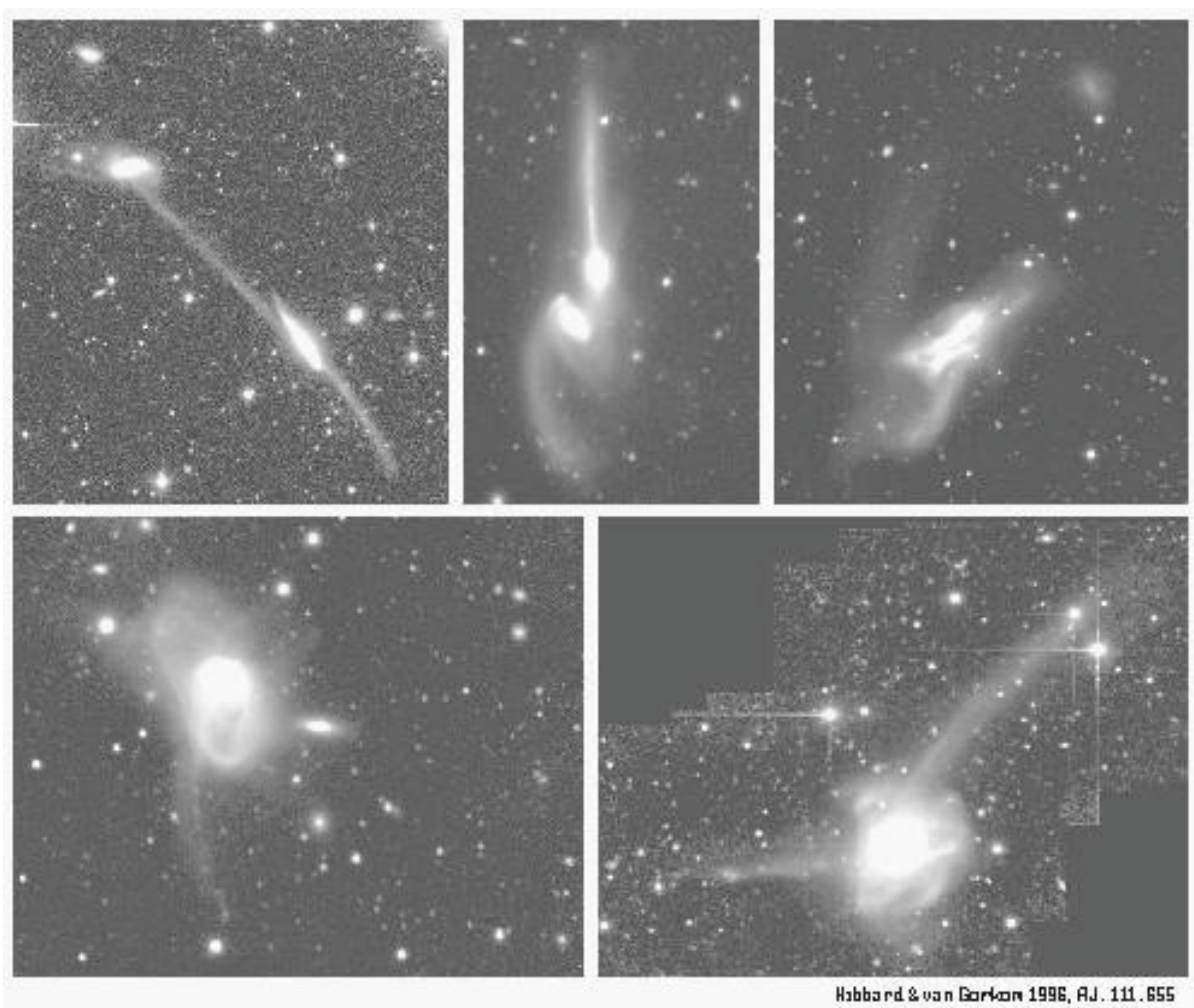


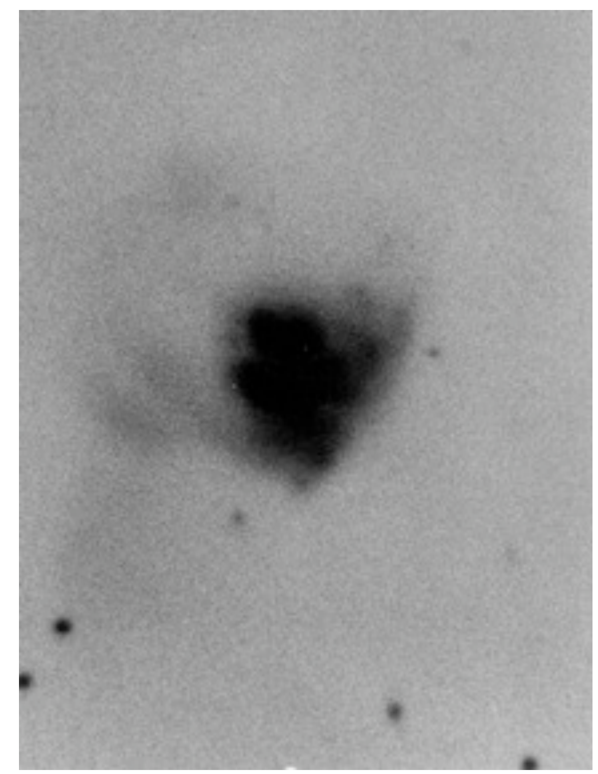
- van den Bergh (1960): DDO system
  - adds "luminosity classes" to Hubble classifications
    - stars are classified by temperature (OBAFGKMLT) and by luminosity/surface gravity (Ia, Ib, II---supergiants; III---giants; IV---subgiants; V---dwarfs)
    - DDO luminosity class is based on strength of spiral arms
  - van den Bergh wanted to be able to look at a galaxy and tell how bright it was, so he could determine a distance knowing its apparent magnitude --- unfortunately, it doesn't really work!

What else is missing?

- Dwarf galaxies
  - dIrr: "dwarf irregular" (like SMC)
  - "smooth" dwarfs
    - dSph: "dwarf spheroidal"
    - dE: "dwarf elliptical"
      - we'll return to these later...

Peculiar galaxies: the "trash heap"



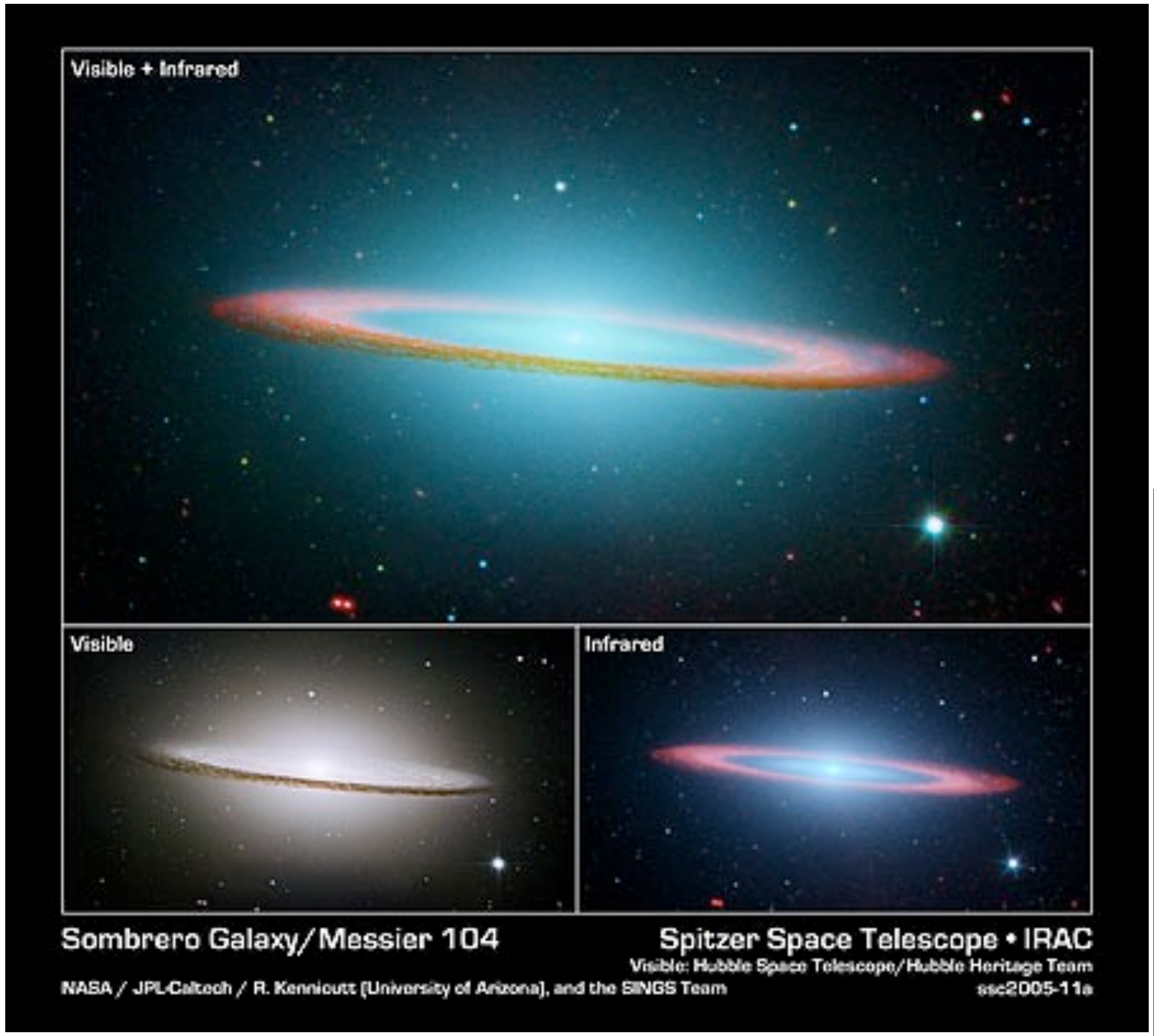


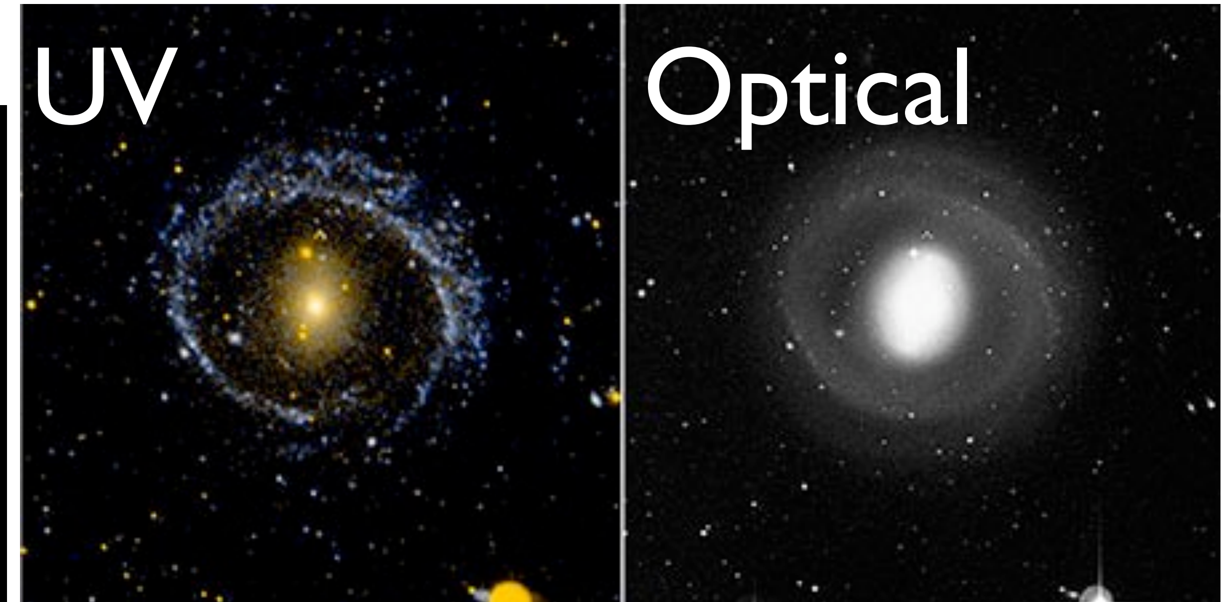
- “Peculiar” galaxies can have
  - distortions of bulges and disks by gravitational processes
  - gas and dust in systems where unexpected, often unrelaxed
  - starbursts
- Nearly <u>all</u> due to mergers or interactions with other galaxies

- Galaxies can move between Hubble classes through the "peculiar" stage
- IRONY:
  - "peculiar" galaxies are actively forming
  - Hubble Sequence only fits galaxies that are passively evolving!

Other issues with the Hubble Sequence

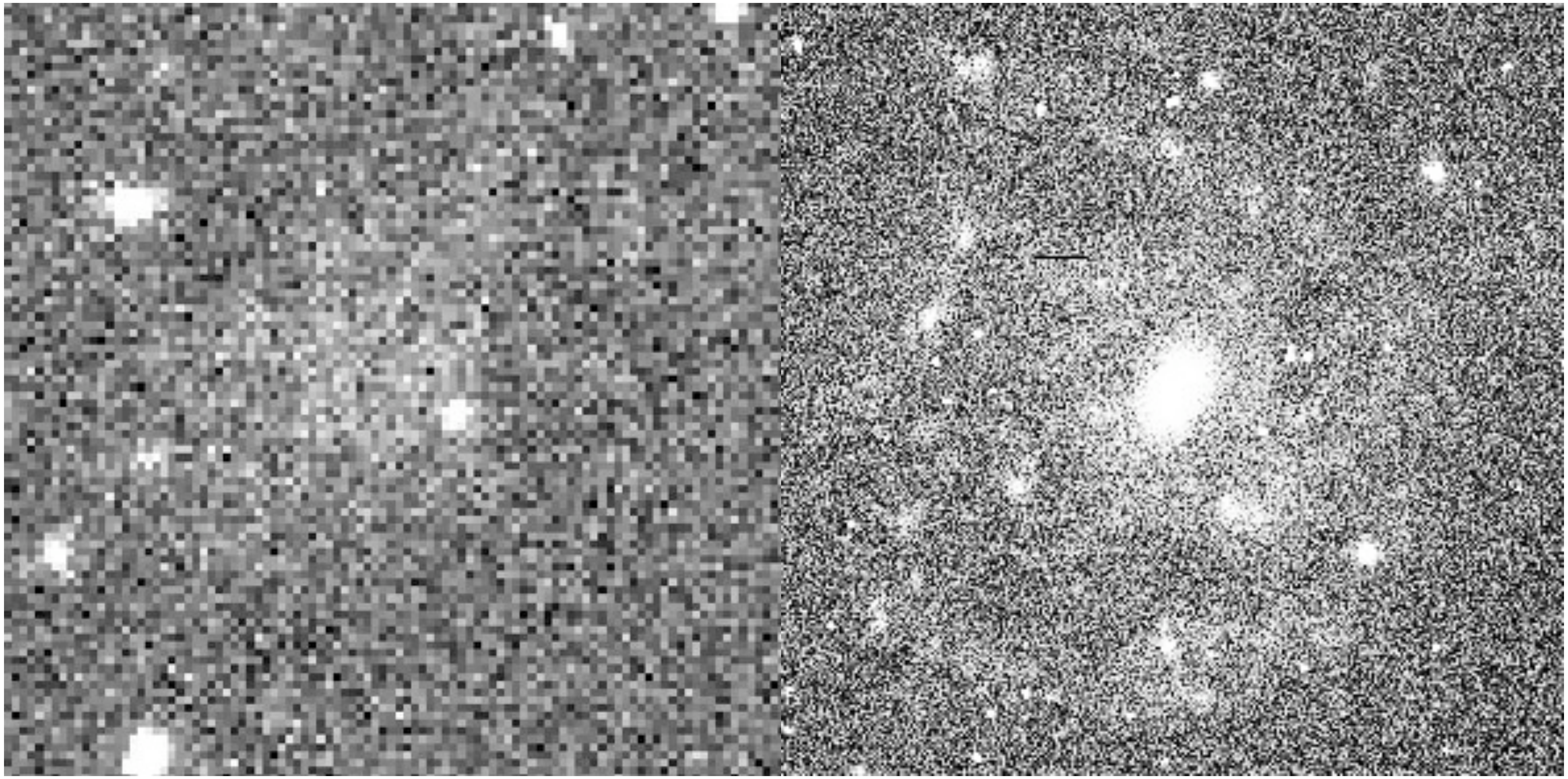
- Bandpass “bias”: Hubble Sequence is defined in the blue part of the optical window!





- Clearly, observing galaxies (especially spirals) at other wavelengths would give different classifications!

- Finally, another related problem is "surface brightness bias"
    - the "surface brightness" is the *flux per unit area* on the sky, usually expressed as magnitudes per square arcsecond
    - surface brightness is a measure of *contrast* against the sky, particularly because the night sky itself has a surface brightness (which depends on the bandpass)



- These are both *low surface brightness* (LSB) galaxies
  - How do we classify these?

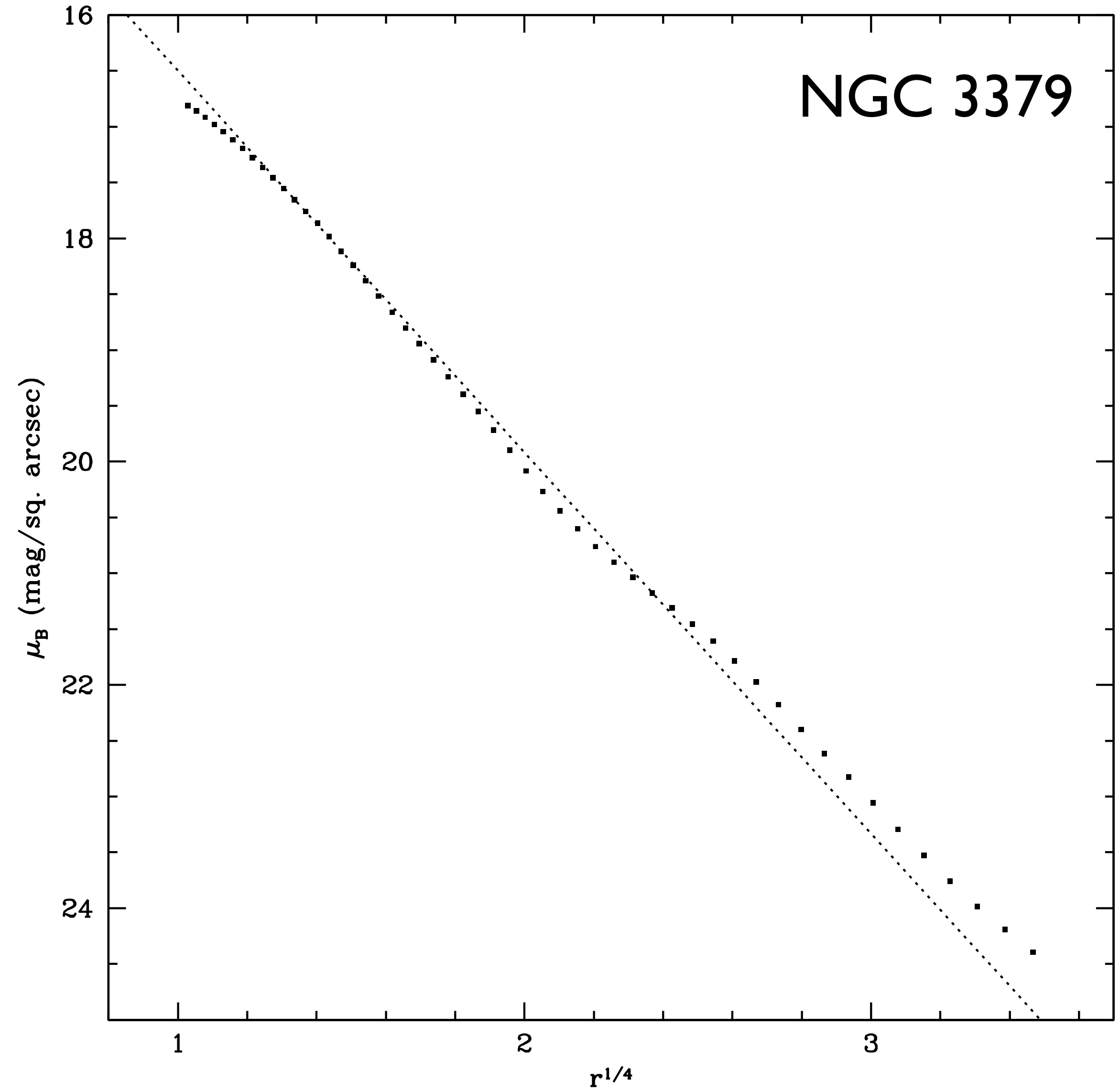
Galaxy surface brightness profiles

- A closely related idea to morphology is *surface brightness profiles*: how is the light in galaxies distributed in detail?

- For giant elliptical galaxies and the bulges of (early-type, i.e., Sa) spirals, the light follows a "de Vaucouleurs" or $r^{1/4}$ profile:

$$\log_{10}\left[\frac{I(r)}{I_e}\right] = -3.33\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]$$

- where r_e is the "effective radius", the radius which contains half the light of the galaxy, and I_e is the surface brightness $I(r_e)$ at that radius



In *magnitudes per square arcsecond*, we can write

$$\mu = \mu_e + 8.33\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]$$

- For the disks of spiral galaxies, bulges of late-type (i.e., Sc) spirals, and for many dwarf galaxies, the light follows an *exponential* profile:

$$\frac{I(r)}{I_d} = \exp\left(-\frac{r}{r_d}\right)$$

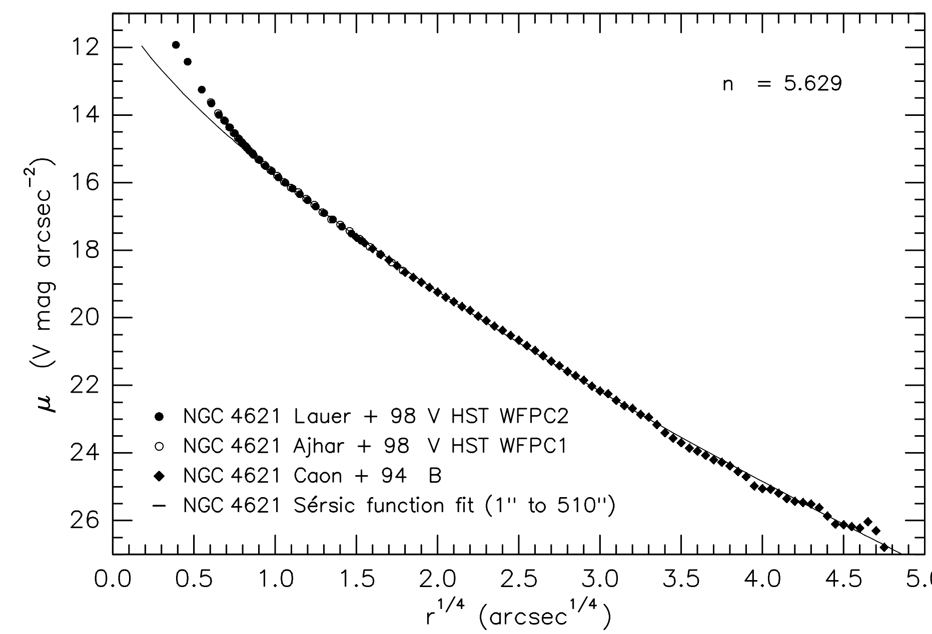
- here r_d is the disk *scale length*---the radius at which the surface brightness has fallen to $1/e$=0.37 of its central value---and I_d is the surface brightness at this radius

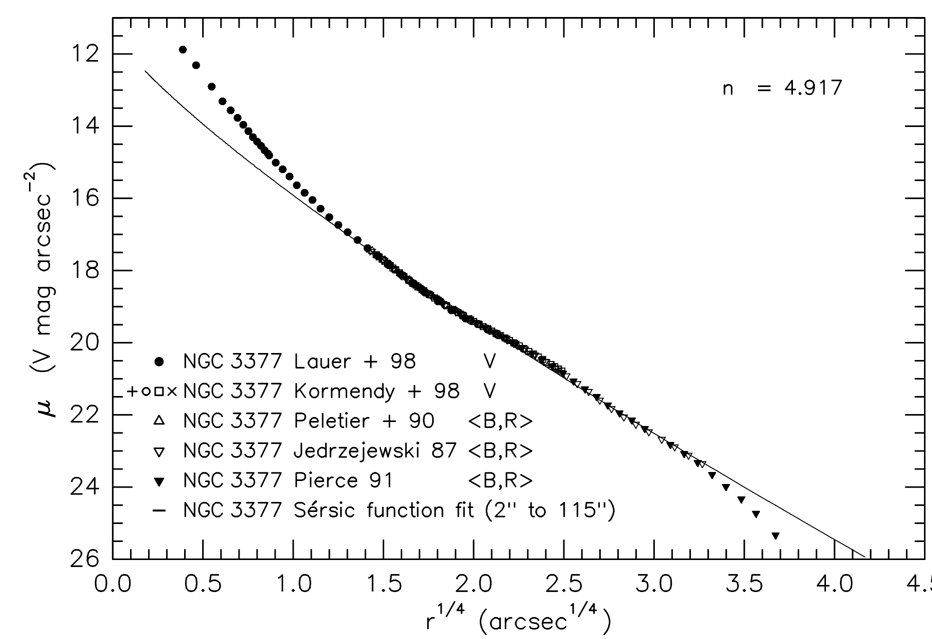
In *magnitudes per square arcsecond*, we can write $\mu = \mu_d + 1.09\left(\frac{r}{r_d}\right)$

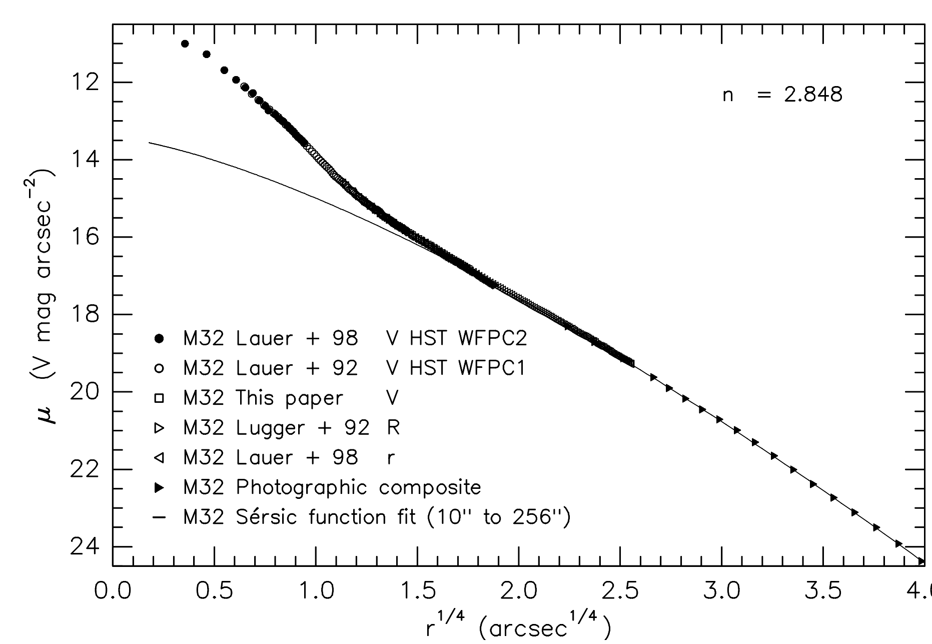
- These two profiles can be combined into the *generalized de Vaucouleurs* or *Sérsic profile*:

$$\log_{10}\left[\frac{I(r)}{I_e}\right] = -b_n\left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right]$$

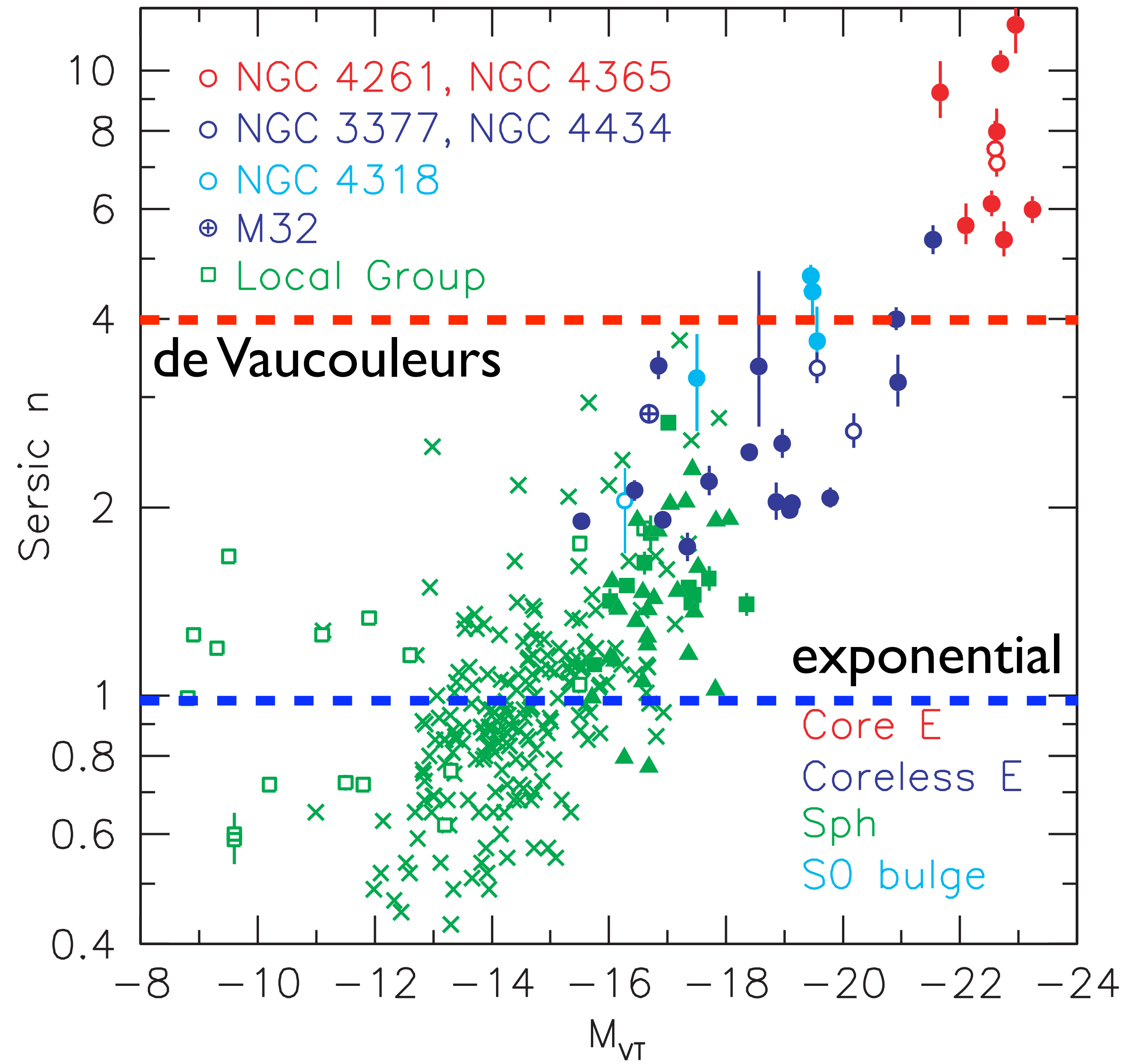
  - here b_n is a constant that depends on the shape of the profile n
  - when n=1, this is an exponential profile; when n=4, it's a de Vaucouleurs profile



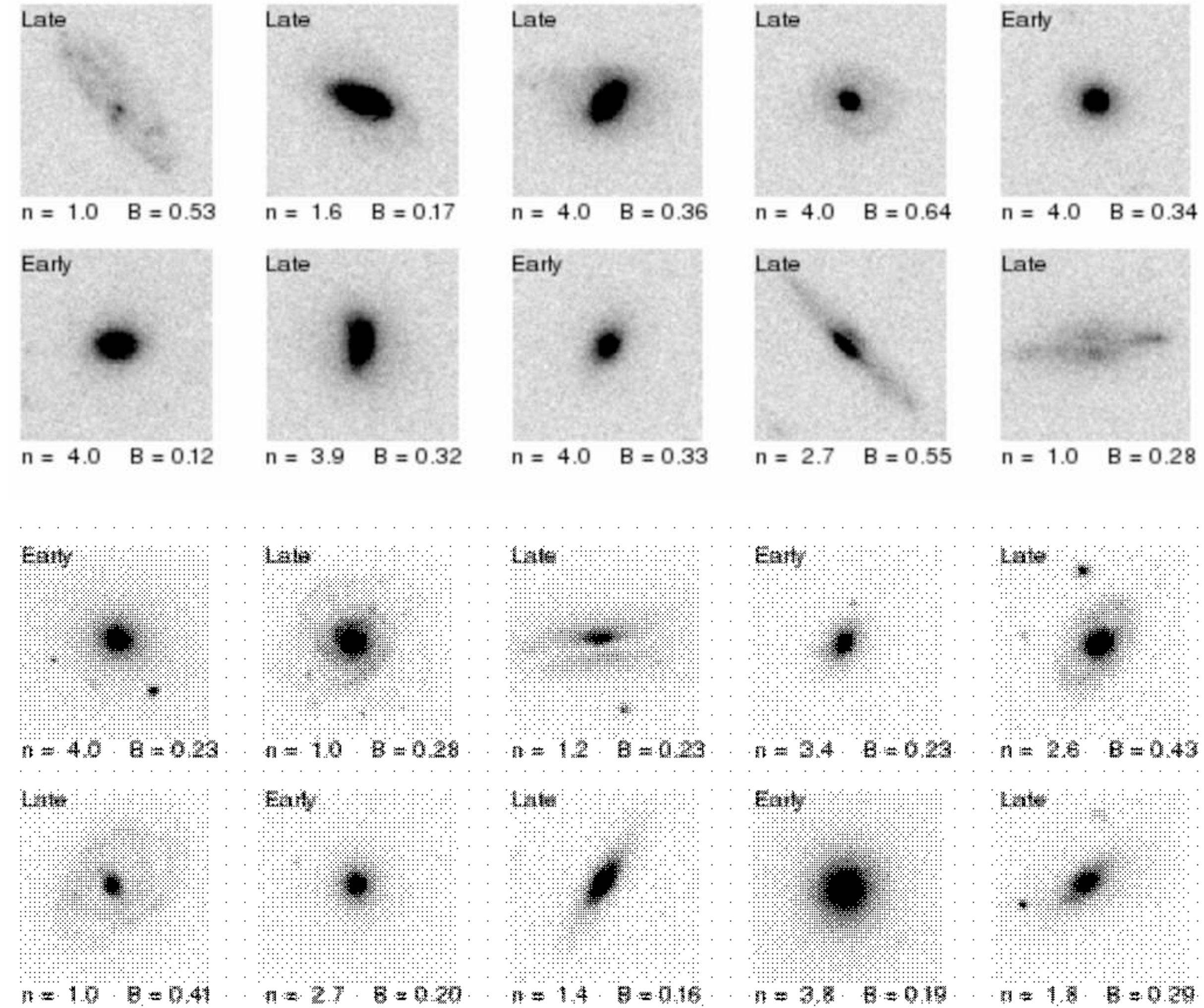


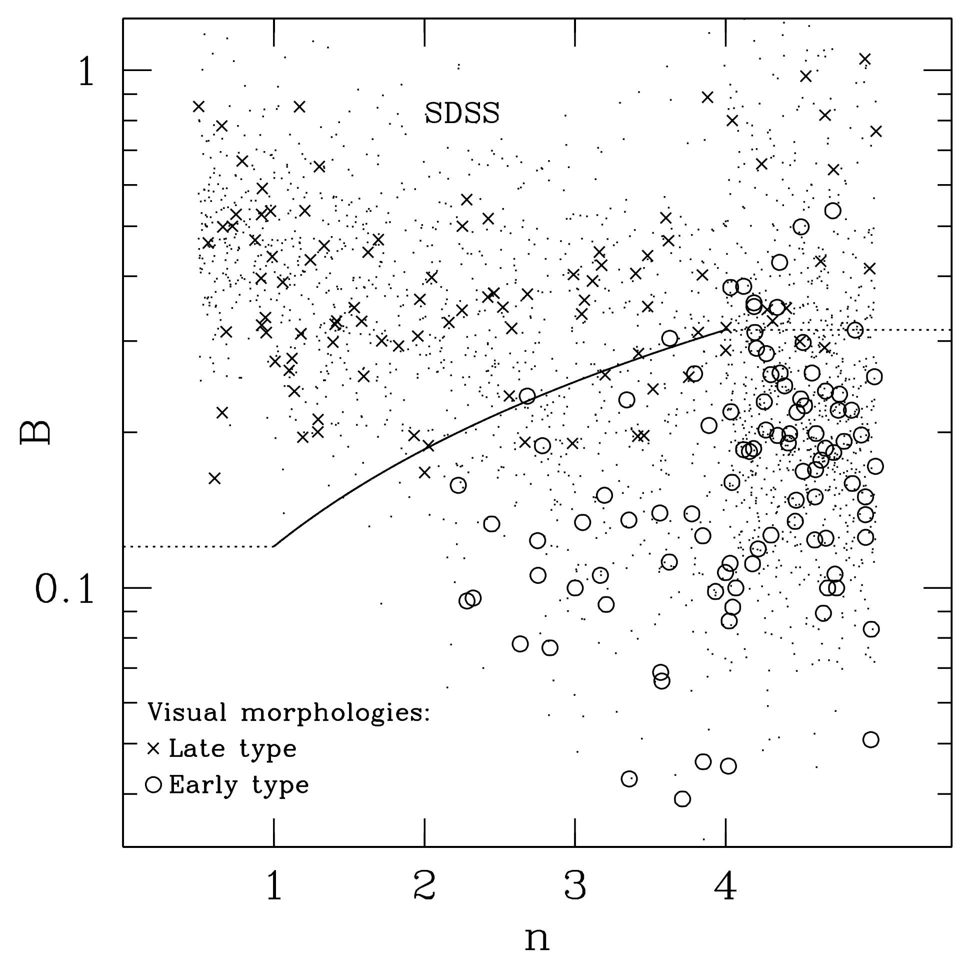


- Roughly, larger (more massive/brighter) galaxies have larger *n*

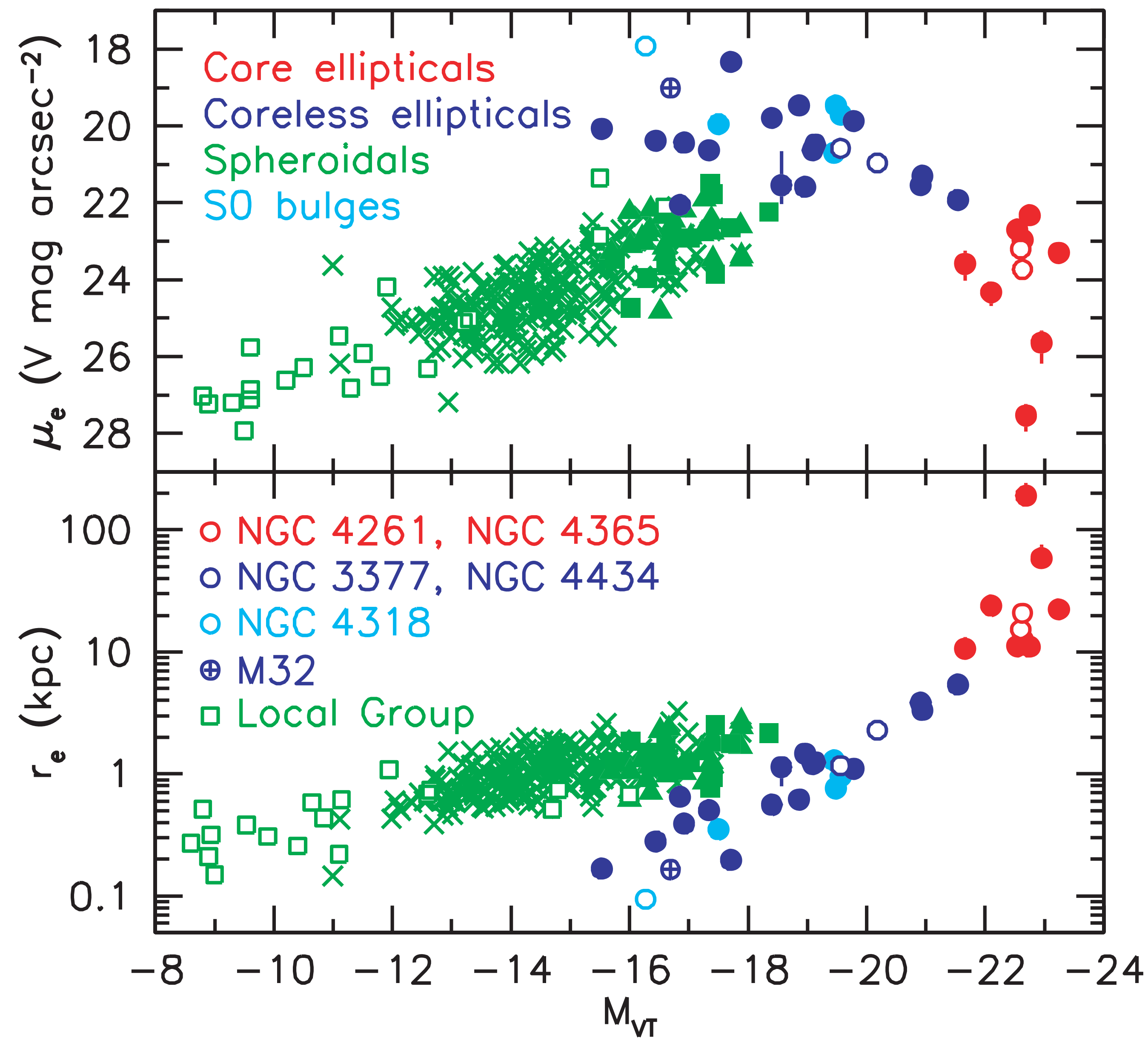


- Because of the close connection between *morphological type* and *surface brightness profile*, many authors have used the slope parameter *n* as a substitute for visual classification
    - for example, it is often assumed that "disk" galaxies have *n*<2.5 and "spheroidal" galaxies have *n*>2.5
    - But this isn't always the case!





- Plotted as a function of luminosity (absolute magnitude), surface brightness (or effective radius, which is based on the surface brightness profile) provides a useful means of distinguishing elliptical and S0 galaxies from dwarf spheroidal and dwarf elliptical galaxies

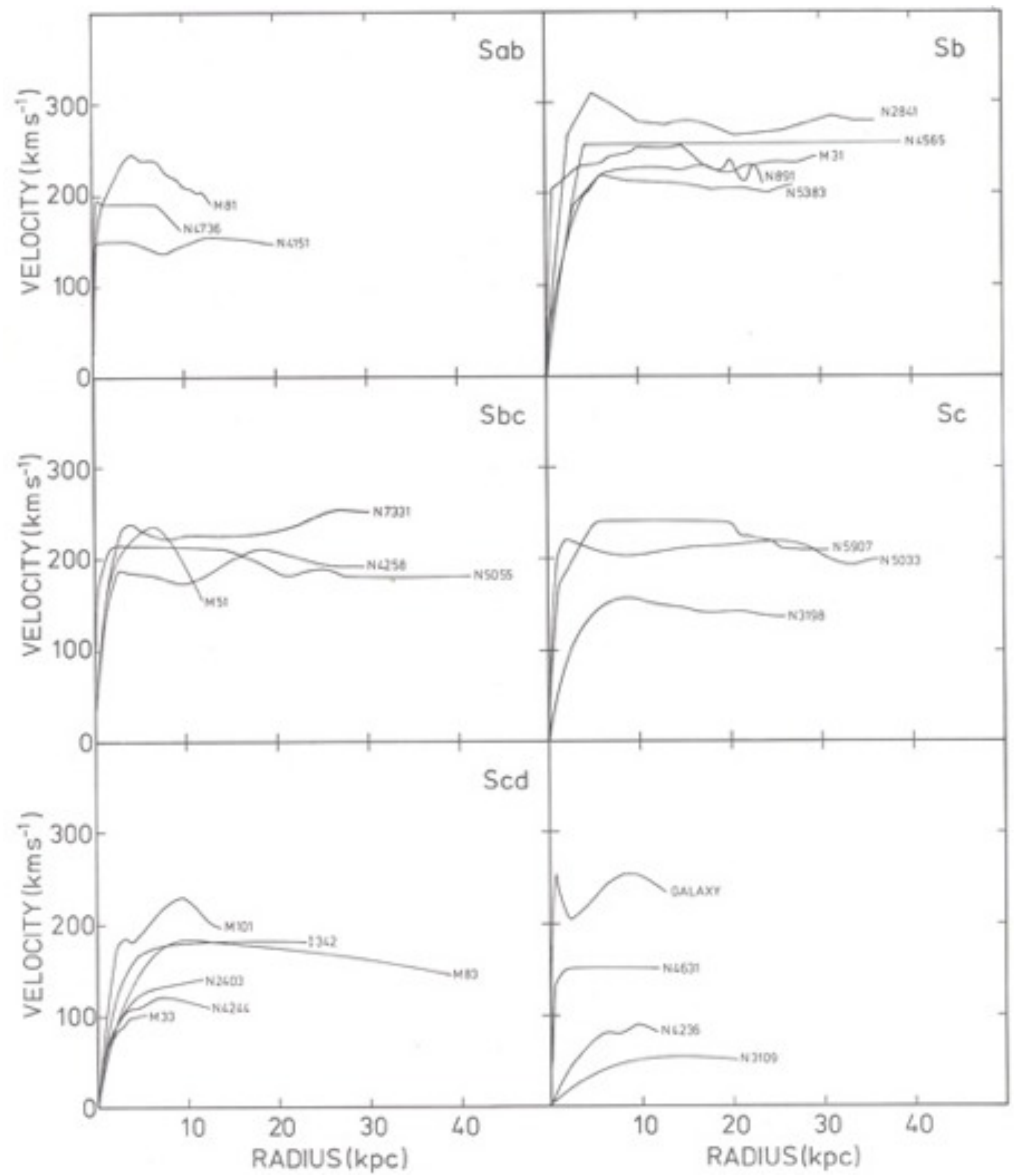


Galaxy kinematics

or, "how much mass do galaxies really have?"

Kinematics of spiral galaxies

- Recall from our earlier discussion that the Milky Way has a *flat rotation curve*
    - The same is true for *nearly all* spiral galaxies that have been observed (to have gas) far enough out in their disks



Bosma (1977): PhD thesis, RuG

- Remember that by relating the acceleration from gravity of some mass shell at radius *r* to the acceleration of a particle on a circular orbit at that radius,

$$\frac{GM(r)}{r^2} = \frac{v^2(r)}{r}$$

- we can determine the mass contained within *r* if we know *v*(*r*):

$$M(r) = \frac{rv^2(r)}{G}$$

- Now let's use the equation of mass conservation,

$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

- to determine the density as a function of radius, *assuming a flat rotation curve* such that $v(r)=v_0$:

$$\begin{aligned} \frac{dM}{dr} &= \frac{v_0^2}{G} \\ \rho(r) &= \frac{v_0^2}{4\pi G r^2} \end{aligned}$$

- This means that the *mass density* of the disk falls off like $1/r^2$, much more slowly than the exponential decay of the *surface brightness* (i.e., the *light* surface *density*) of the disk!

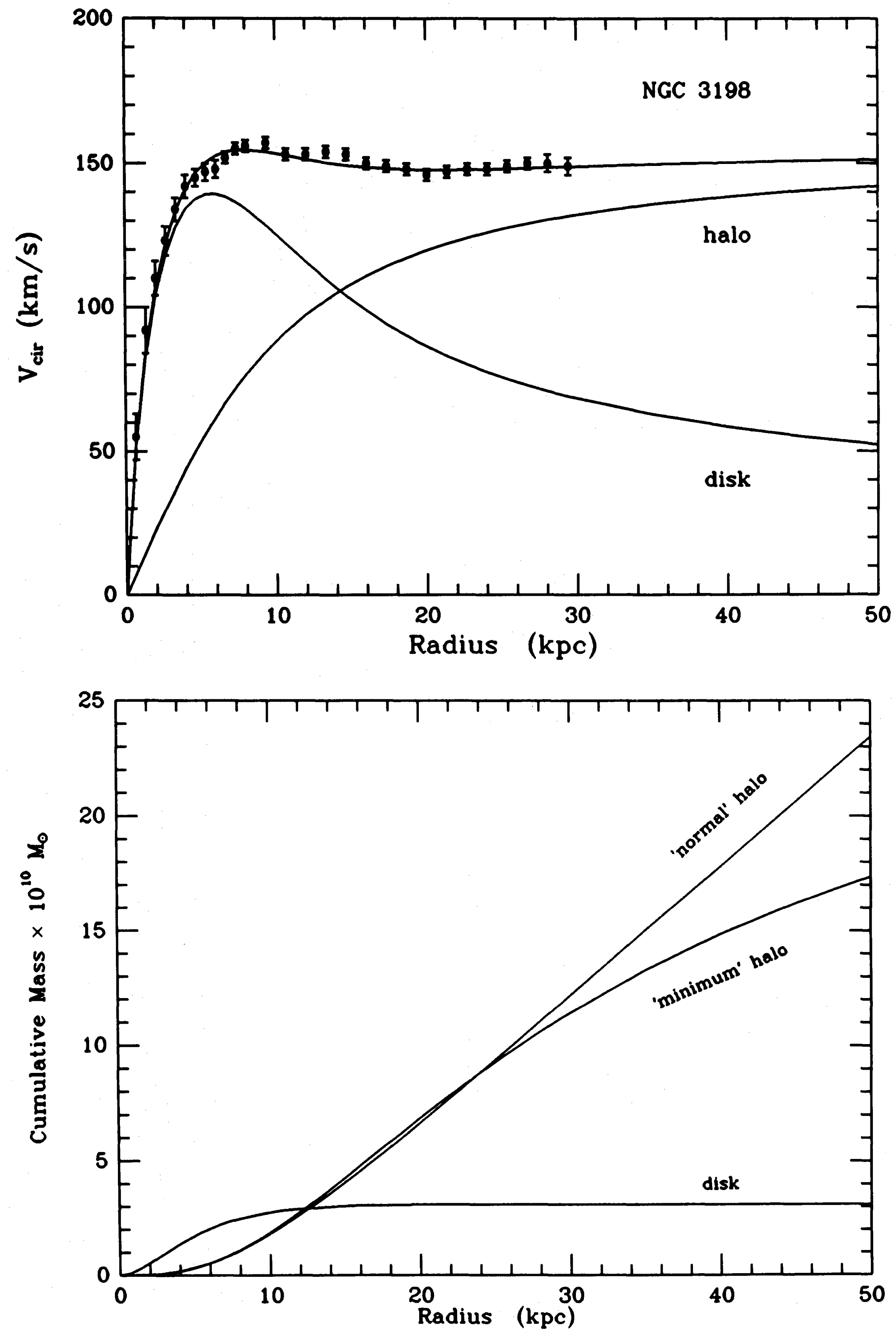
- More importantly, it means that, because
$$dV = 4\pi r^2 dr$$
for some shell at *r*, *the mass in each shell is **constant**!*

- So as we continue outwards in a galaxy with a flat rotation curve, we continue to need more mass!

- This means that there must be *something besides luminous matter contributing to the mass of spiral galaxies!*

- As you already know, most people think this is a *halo* of **dark matter**

- If we “maximize” the disk contribution to the rotation curve of a given galaxy, we get the “minimum” dark matter halo needed to make up the extra mass needed to make a flat rotation curve
    - It is *ongoing question* whether disks are truly “maximal”



MOND

- There is another option: Modification Of Newtonian Dynamics (MOND)
- In this case, no unseen, not-yet-detected "dark matter" is required
- Rather, we need to *modify gravity itself!*

- Milgrom (1983) realized that by writing

$$\mathbf{F} = m\mathbf{a}\mu(a/a_0)$$

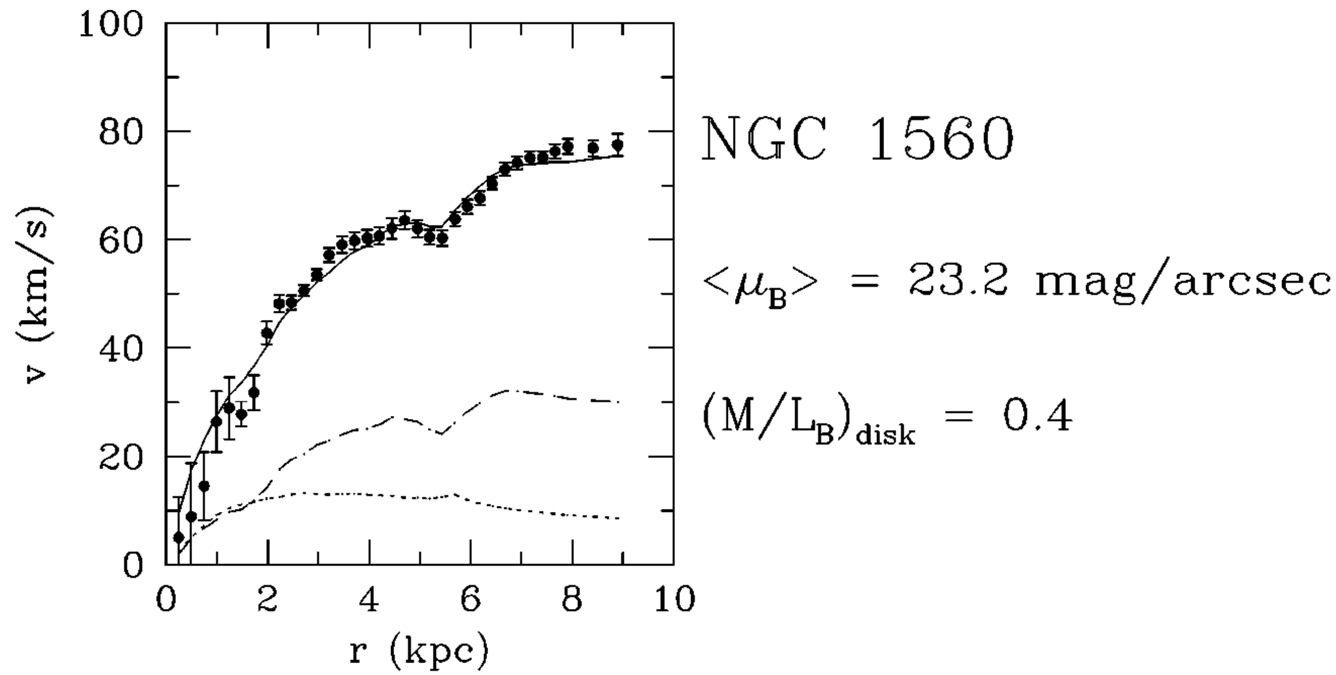
where a_0 is constant acceleration and μ is some function that acts like $\mu(x)=x$ when $x \ll 1$ and like $\mu(x)=1$ when $x \gg 1$, he could recover flat rotation curves (*and* the Tully-Fisher relation, which we'll see shortly)

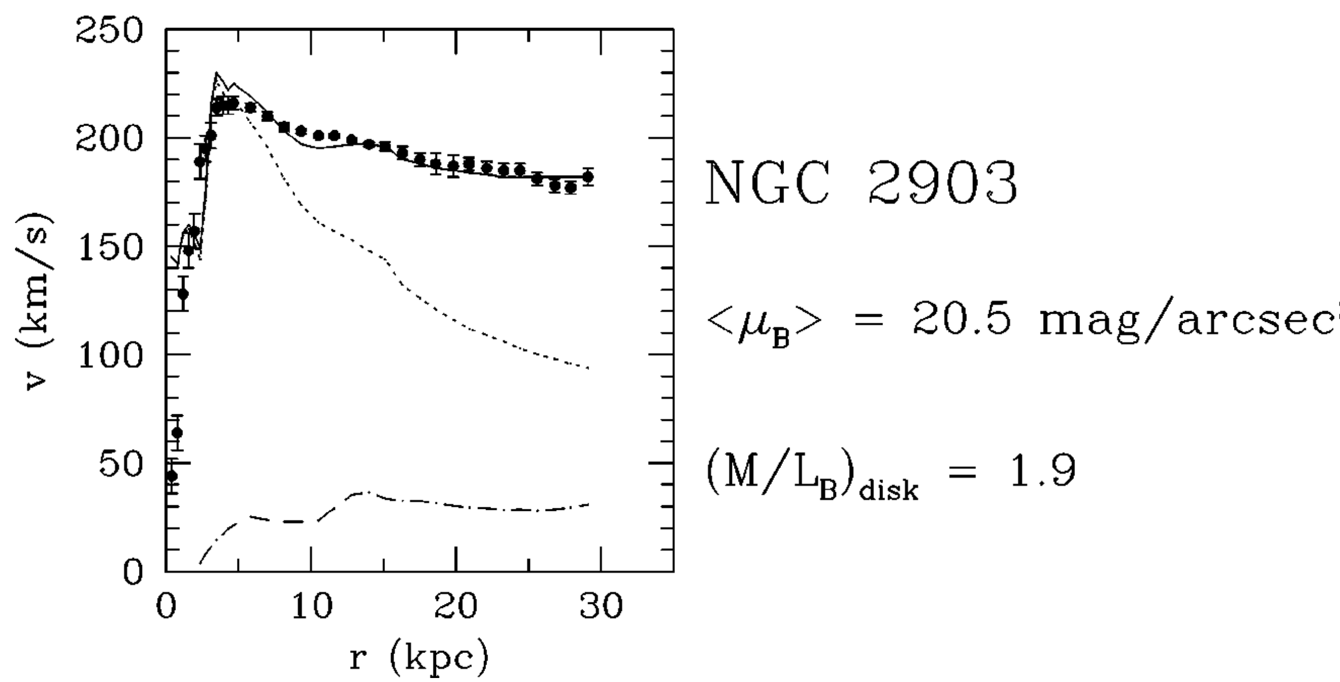
- This is because viewed as a modification of gravity, the "true" gravitational acceleration is $\mathbf{g}\mu(|g|/a_0)=\mathbf{g_n}$, where $\mathbf{g_n}$ is the Newtonian gravitational acceleration

- This means that in the low-acceleration ($a \ll a_0$) regime, the effective gravitational force $g=(g_n a_0)^{1/2}$

- So for a point mass *M* in this regime, equation the centripetal acceleration with gravitational acceleration, $v^2/r=g$, means that $v^4 = GMa_0$

- Therefore *all rotation curves <u>must be</u> asymptotically <u>flat</u>* in MOND





Note also that "bumps" in the light correspond to "bumps" in the rotation curves, too!

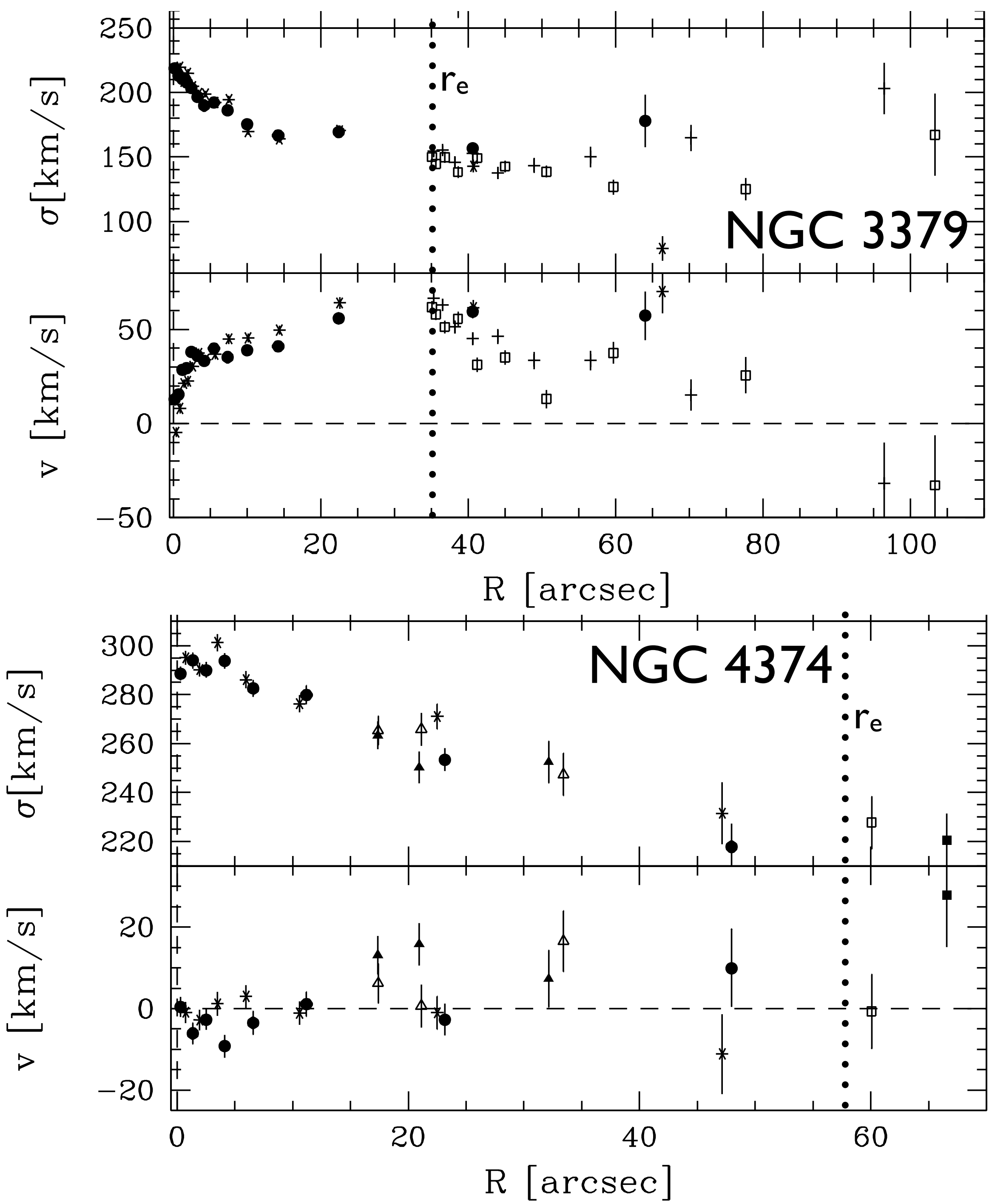
- So what is the value of a_0? How low must the acceleration be to be in the "MOND regime"?

- Using the Tully-Fisher relation (which we'll come to shortly) and a reasonable guess at the mass-to-light ratio in some band, Milgrom found $a_0 \approx 10^{-8}$ cm/s^2 --- very small, but just about what you expect for V^2/R in the outskirts of spiral galaxies

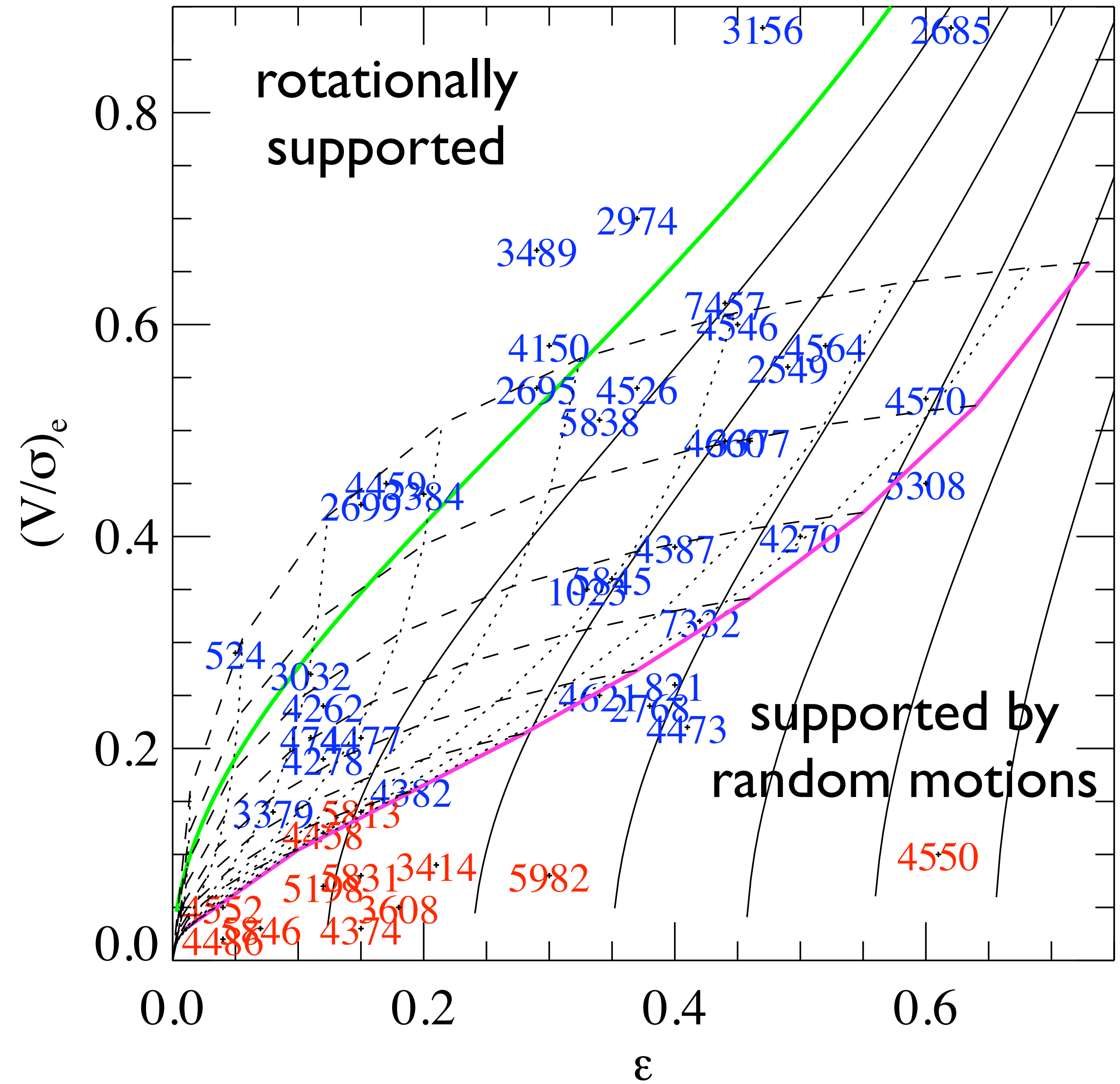
Kinematics of elliptical galaxies

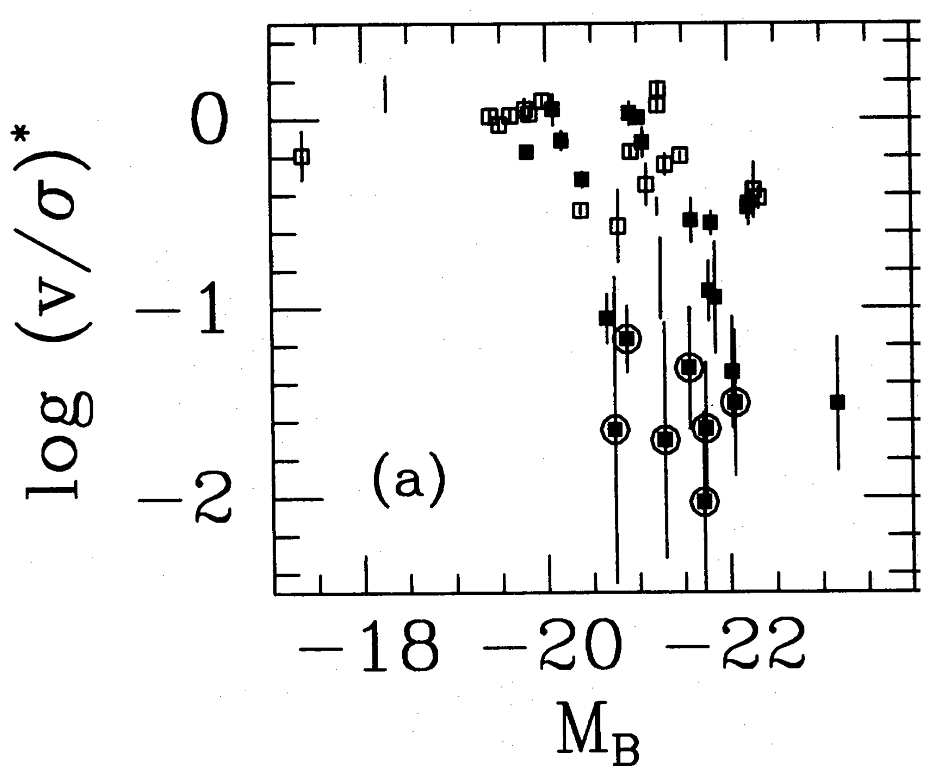
- Giant elliptical galaxies are primarily supported by *random motions*, not by rotation

- We call these systems “hot” because their stars are moving quickly and randomly in their potentials

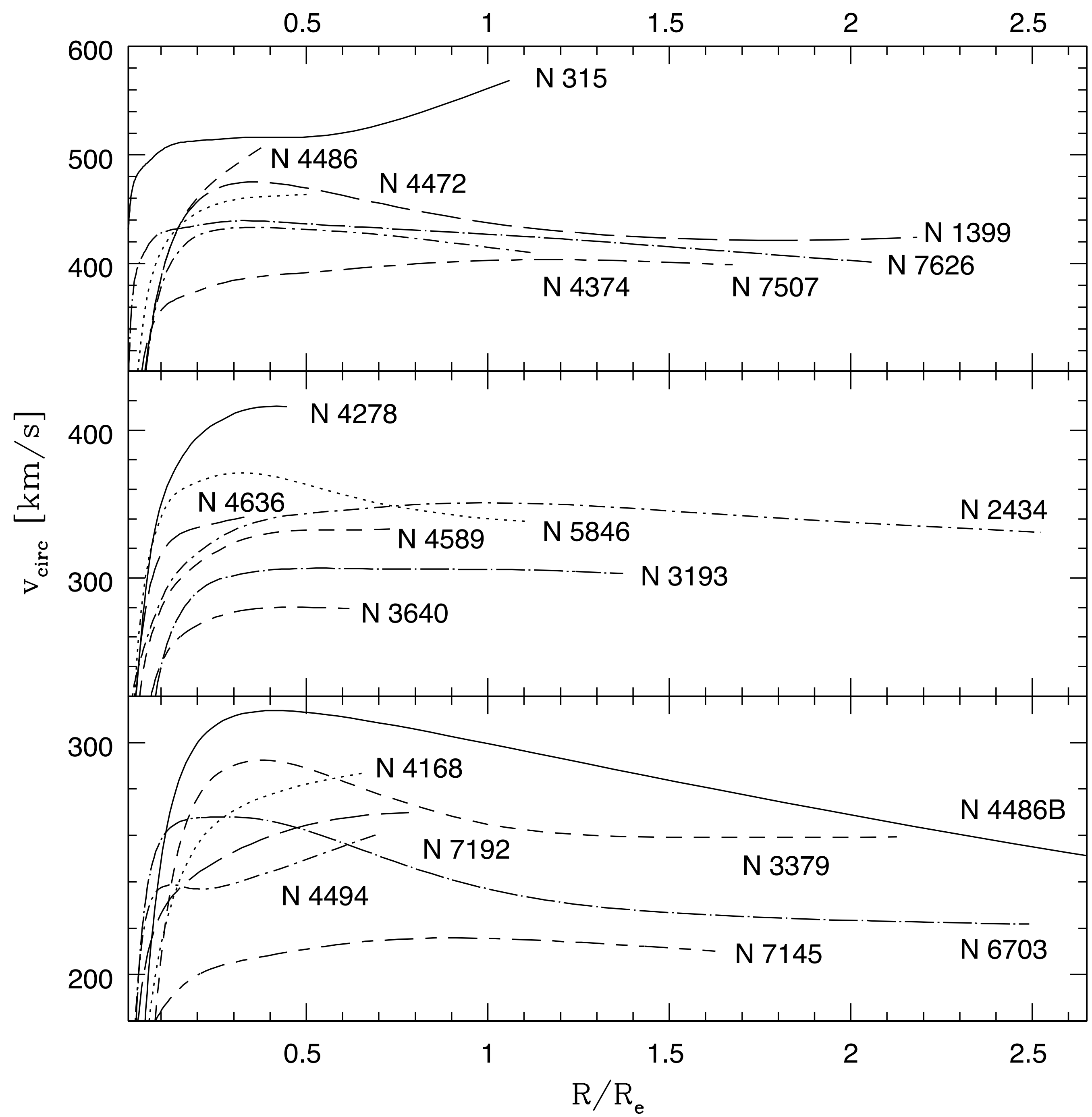


- We measure how "hot" a dynamical system is using the ratio of its rotational velocity V_c to its random velocity σ (which we previously called $\langle v^2 \rangle^{1/2}$)
    - for the disk of the Milky Way, V_c/σ=220 km/s / 30 km/s = 7 ---very cold!
    - elliptical galaxies have V_c/σ= 0-1 because V_c is low (<100 km/s) and σ is high (>100 km/s)
- Note that *big* early-type galaxies have low V_c/σ but *intermediate-mass* early-type galaxies have higher V_c/σ





- Do elliptical galaxies have dark matter?
    - **yes.**
- By combining observed circular velocities and velocity-dispersion profiles with a model (and some educated guesses!), it can be shown that most *early-type galaxies have flat rotation curves too!*
    - other methods: gravitational lensing; stellar populations vs. kinematics

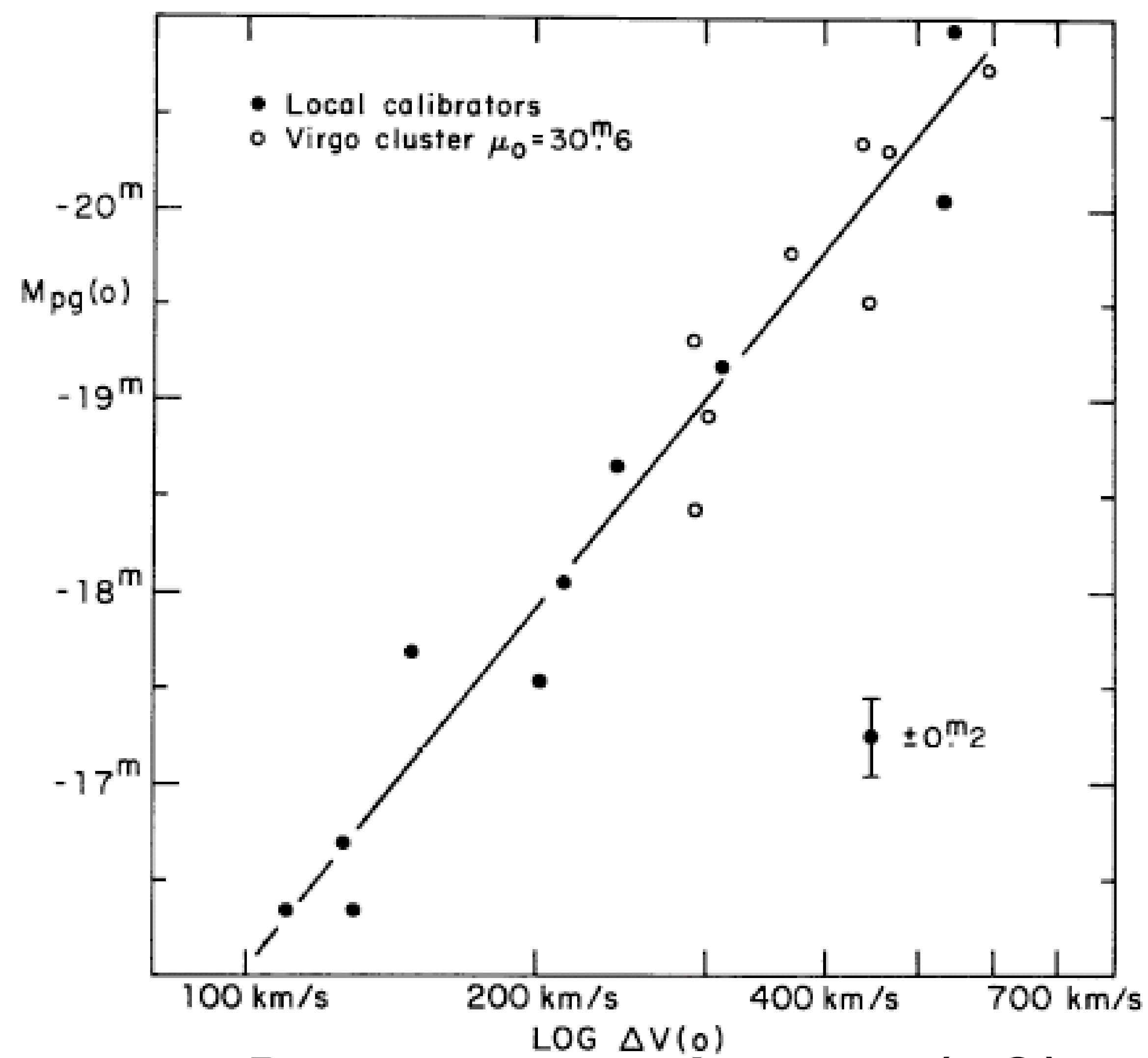


Galaxy scaling relations

or, "what happens when galaxies get big?"

The Tully-Fisher relation

- In the mid-1970's, Fisher and Tully realized that, for spiral galaxies, brighter galaxies rotate faster than faint galaxies
- Plotted as log V_c vs. absolute magnitude, the relation was a straight line with slope -10
- This means that $L \propto V^4$
- This is the *Tully-Fisher (TF) relation*



Absolute magnitude

Rotation velocity (x2)

- How does the TF relation come about?

- Remember from our discussion of rotation curves that we can write, using the Virial Theorem, $M = RV^2/G$

- ...but we can't measure *M* directly, but we *can* measure a galaxy's luminosity *L*

- These are related by a quantity called the *mass-to-light ratio*, which is a property of the stars and dark matter in a galaxy:

$$L = M\left(\frac{M}{L}\right)^{-1}$$

- Now, the surface brightness of a galaxy is just its luminosity divided by its surface area,

$$I = \frac{L}{\pi R^2}$$

- so solving for *R* (ignoring constants),

$$R \propto \sqrt{\frac{L}{I}}$$

- Then we can write our equation for mass as (ignoring constants)

$$L\left(\frac{M}{L}\right) \propto \sqrt{\frac{L}{I}} V^2$$

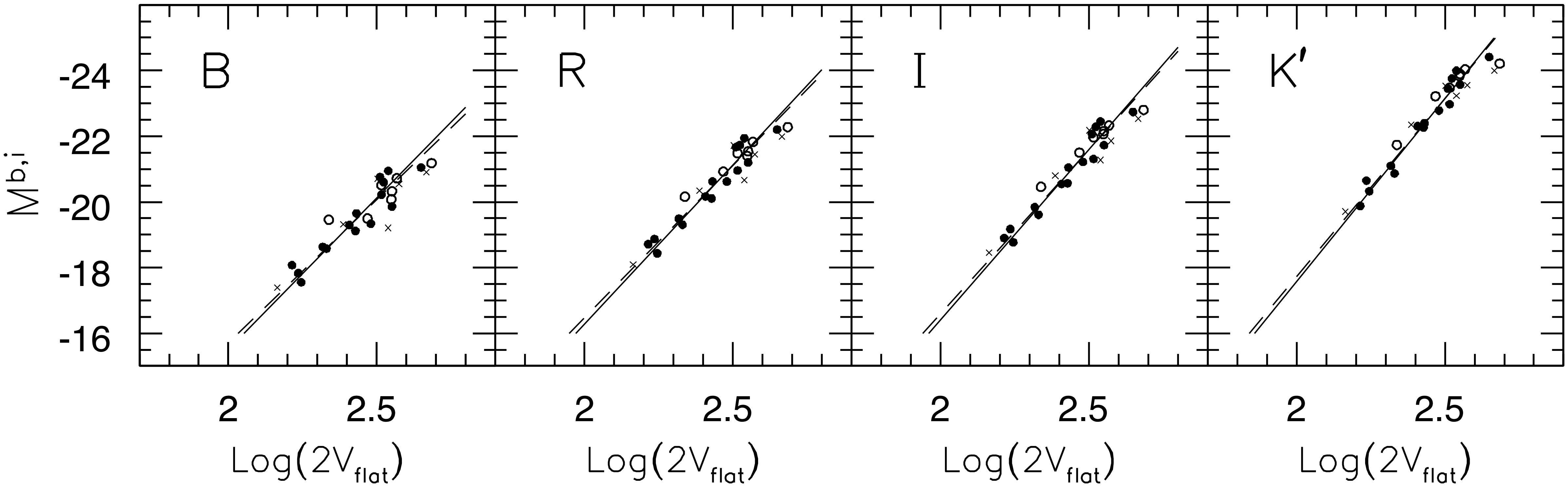
- Finally, solving for *L* we have

$$L \propto \frac{V^4}{I(M/L)^2}$$

- So the TF relation works *if the surface brightness times the mass-to-light ratio (squared) is a <u>constant</u>*

- So somehow *dark matter and stars are <u>linked</u> in spiral galaxies*!

- Two things to note:
    - If you know V_c for a galaxy, then you know L and therefore its *absolute magnitude*! The TF relation is a good *distance indicator* because you also know its *apparent magnitude* --- and therefore the distance modulus m-M=5log(d/pc)+5
    - We'll soon see the use of this when we examine the *cosmic distance ladder*



- The hidden dependence on *L* on (*M*/*L*) means that the TF relation depends on *in which band you observe the TF* because different stars contribute to the light in different bands

    - so *L* depends on the band you use and therefore (*M*/*L*) depends on that band --- so the slope of the TF depends on that band as well

    - but we *cannot directly measure* (*M*/*L*)!

The TF relation and MOND

- As we saw earlier, MOND "predicts" the TF relation exactly: $v^4 = GMa_0$
- ...if (*M*/*L*) is constant with *M* so that $L \propto V^4$
- But this isn't really a prediction, because MOND was actually *built* to give the TF relation with the exact slope of 4, and the mass-to-light ratios are inferred from observed *L* and inferred *M* (knowing a_0)

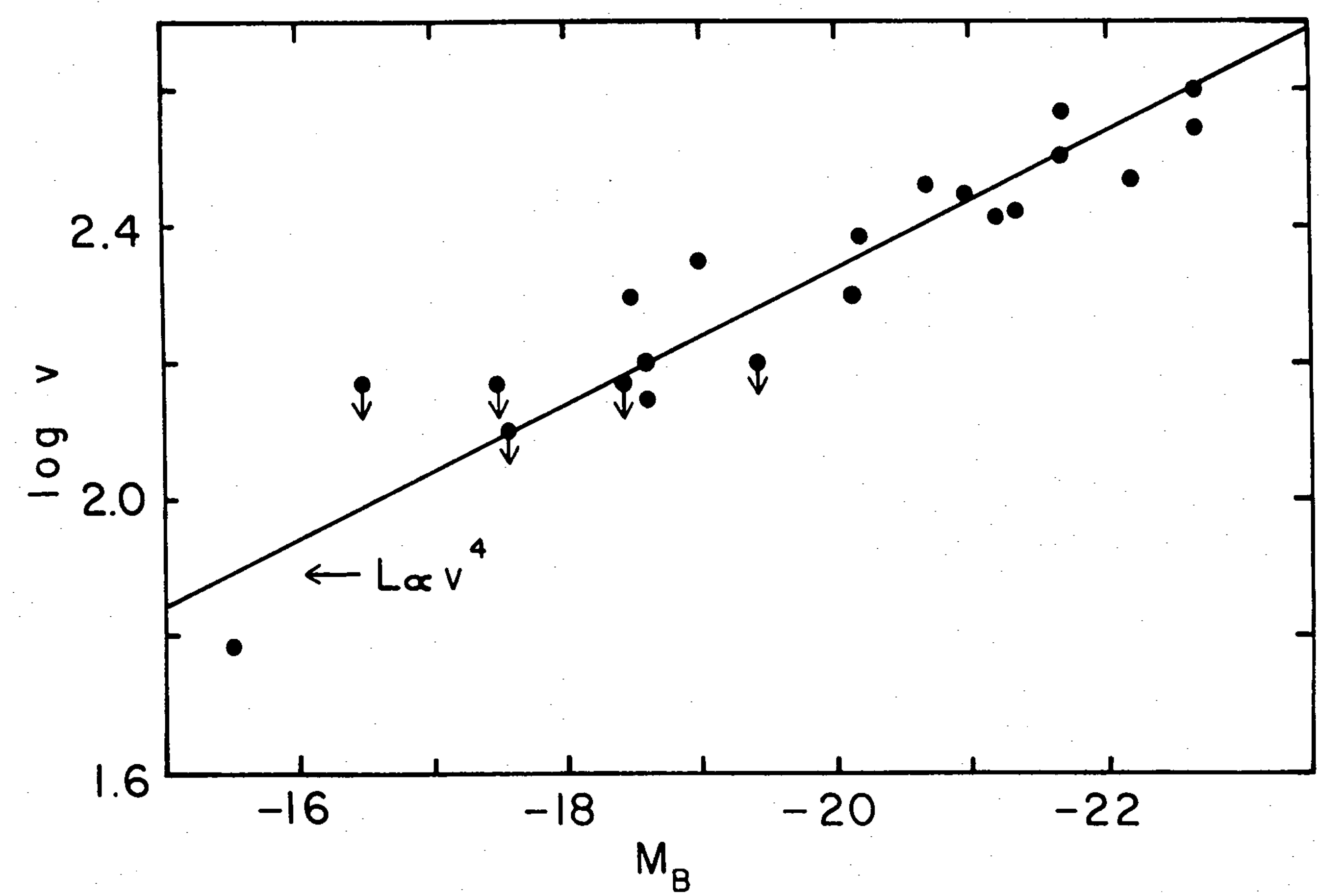
- On the other hand, it is then a *requirement* of MOND that the stellar population mass-to-light ratios match the MOND predictions
  - This is very hard to test, because the stellar population mass-to-light ratios are quite uncertain!

The Faber-Jackson relation

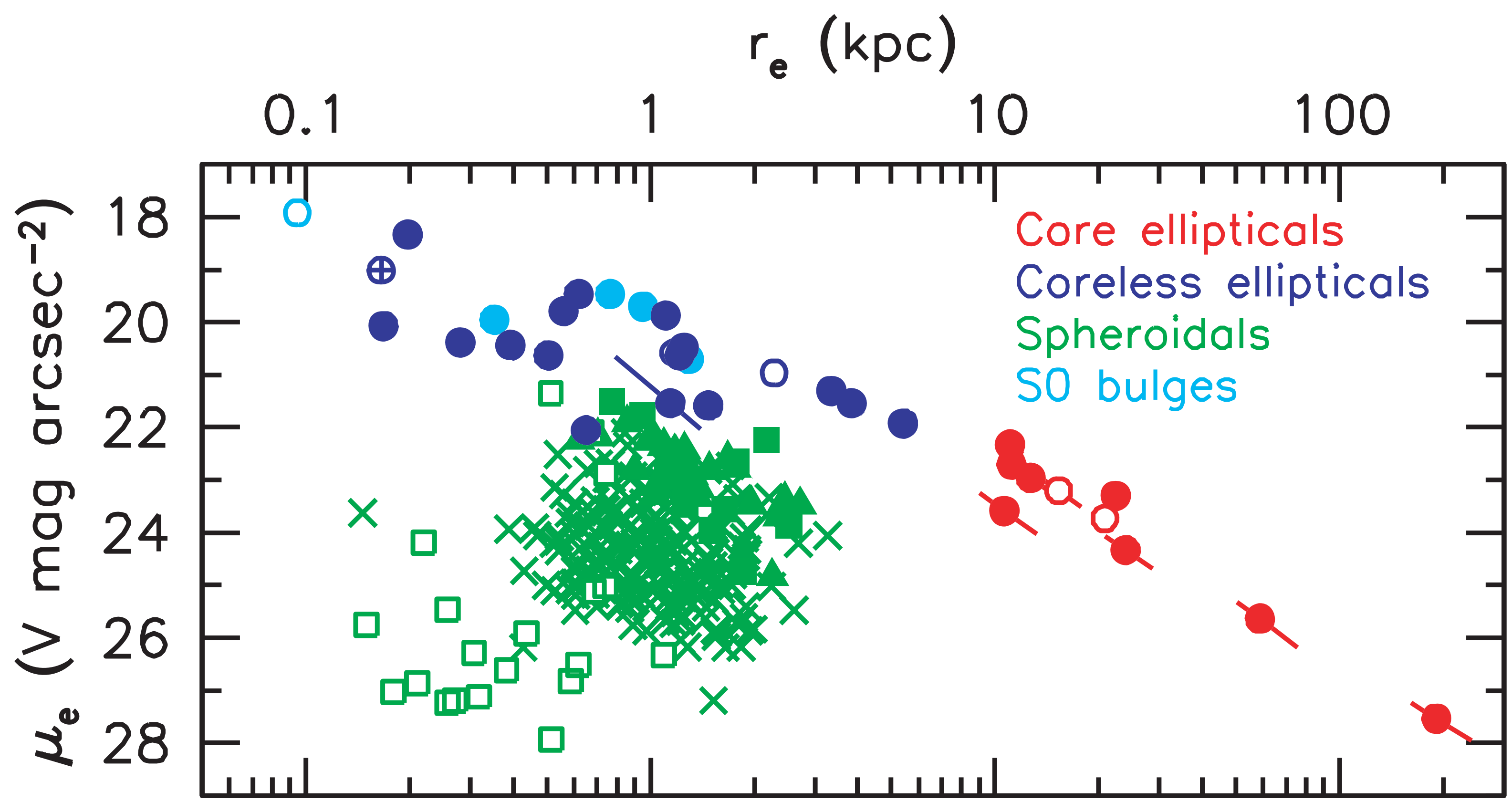
- Around the same time as the discovery of the TF relation, Faber and Jackson noticed that the absolute magnitudes of early-type galaxies were linearly correlated with their velocity dispersions

- Similarly to the TF relation, the *Faber-Jackson relation* has the form $L \propto \sigma^4$

- We'll come back to the explanation soon!



The Kormendy relation



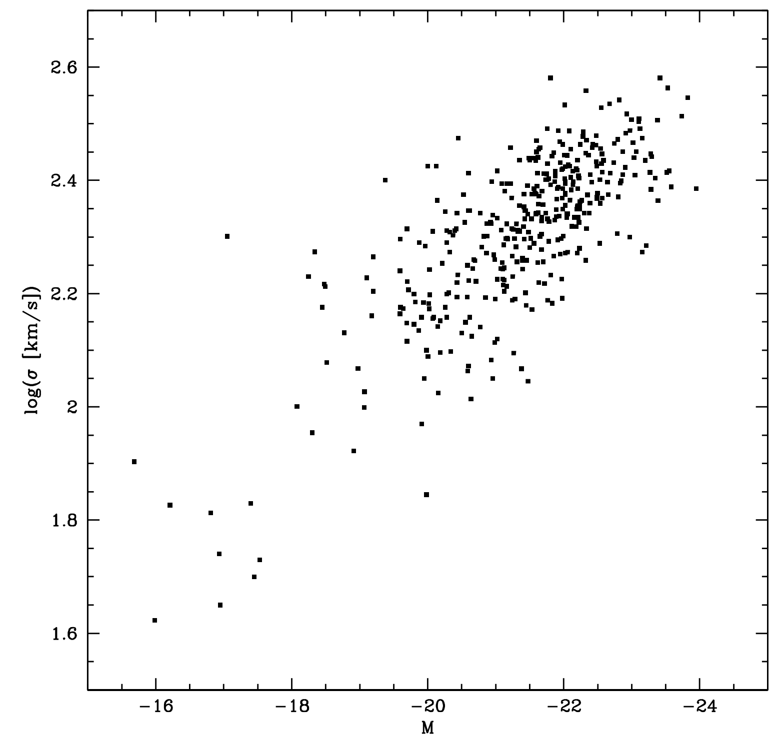
note that re and mue are somewhat degenerate, because they're measured from the same surface brightness profile, so the errors are coupled

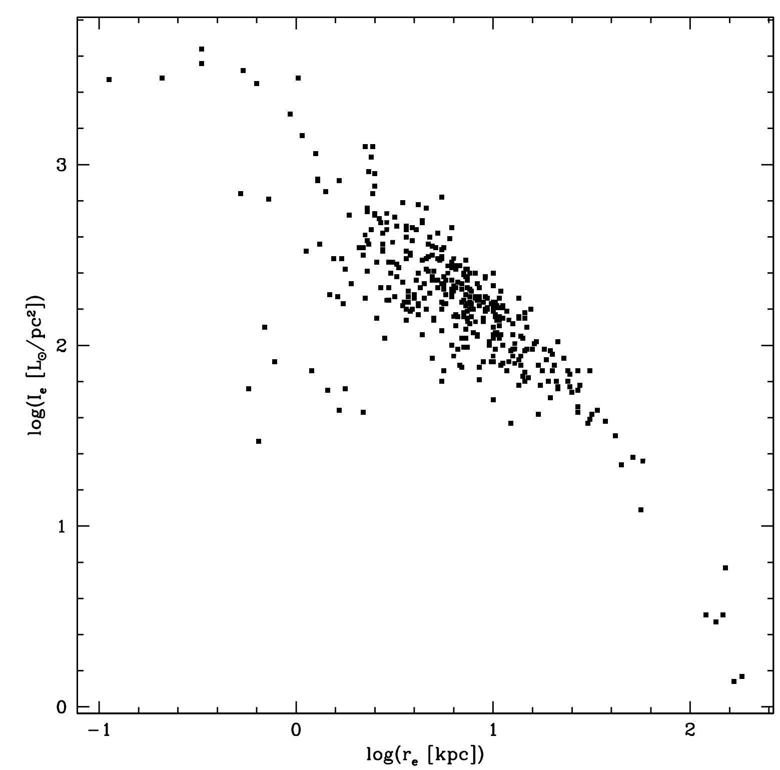
- Another scaling relation for early-type galaxies is the *Kormendy relation*, a relation between the *surface brightness* and *effective radius* of early-type galaxies

- Recall the that the effective radius is the radius that contains half the light of a galaxy

The Fundamental Plane

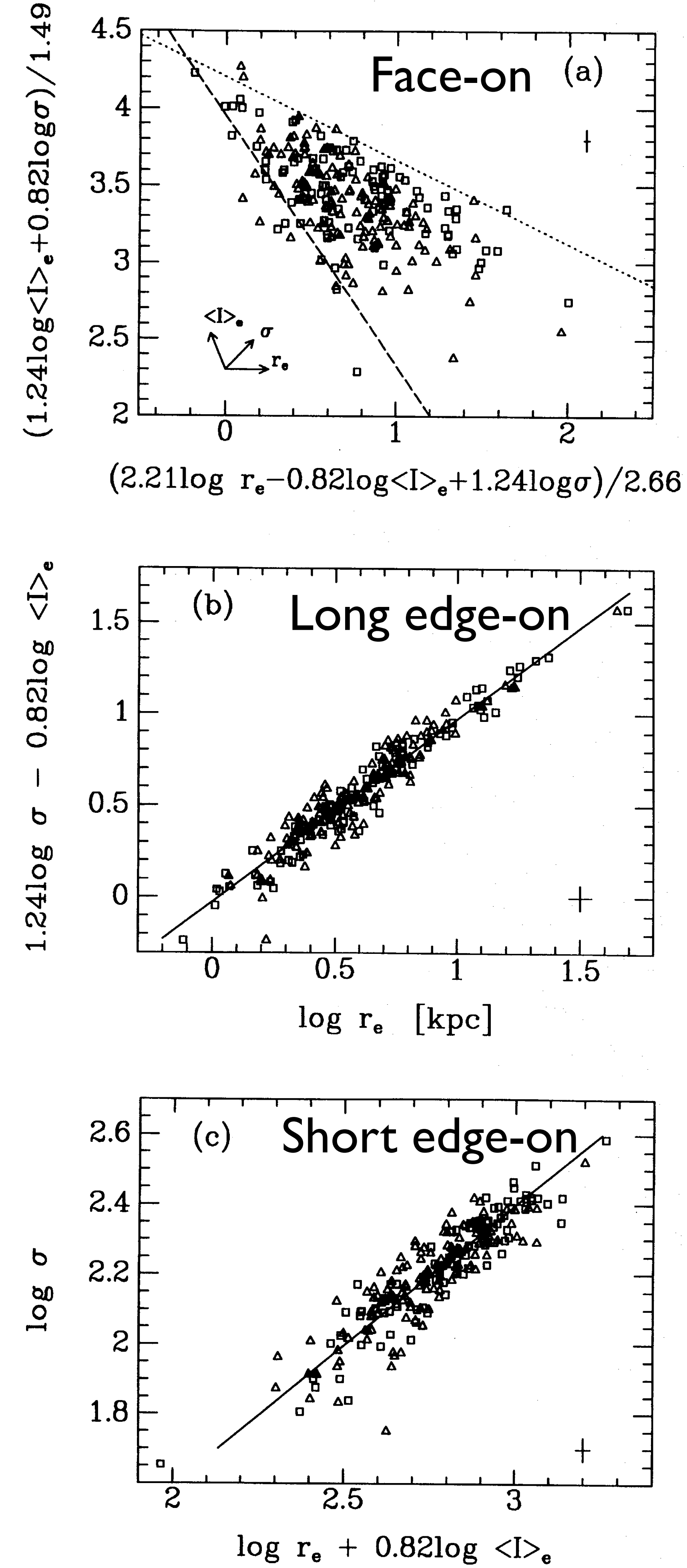
- Let's look at both of these relations for early-type galaxies again
- Clearly, the scatters in both relations are large!
- Also, since $L \propto IR^2$, the two relations should be related





- Following from work by Lauer (1985), Dressler et al. (1987) and Djorgovski & Davis (1987) independently discovered that a *two-parameter family* could connect the velocity dispersions, radii, and surface brightness of early-type galaxies

- We now call this manifold the "Fundamental Plane" of early-type galaxies



- We can write the FP as

$$r_e \propto \sigma^{1.24} \langle I \rangle_e^{-0.82}$$

- How does this come about?

- Just like for the TF, we can write the velocity (dispersion) in terms of the mass-to-light ratio, radius and surface brightness, *assuming the Virial Theorem holds*

- Again, we can write the mass as $M = RV^2/G$
- Let's divide this by the surface area to get the *mass surface density*
$$\eta = \frac{M}{\pi R^2} \propto \frac{V^2}{R}$$
- Then the surface brightness can written in terms of this mass surface density and the mass-to-light ratio as
$$I = \eta \left(\frac{M}{L}\right)^{-1}$$
- Combining these together we get
$$I \propto \frac{V^2}{R(M/L)}$$

- Rewriting this in terms of the radius R=r_e and identifying V as the velocity dispersion σ, we have

$$r_e \propto \left(\frac{M}{L}\right)^{-1} \sigma^2 I_e^{-1}$$

- But the observed coefficients aren't 2 and -1, they're ~1.25 and ~-0.8!

- With a little bit of algebra, you can show that comparing this "Virial plane" with the observed "Fundamental plane" implies that

$$\left(\frac{M}{L}\right) \propto L^{1/4}$$

- which means that as early-type galaxies get brighter, their masses(-to-light ratios) increase!

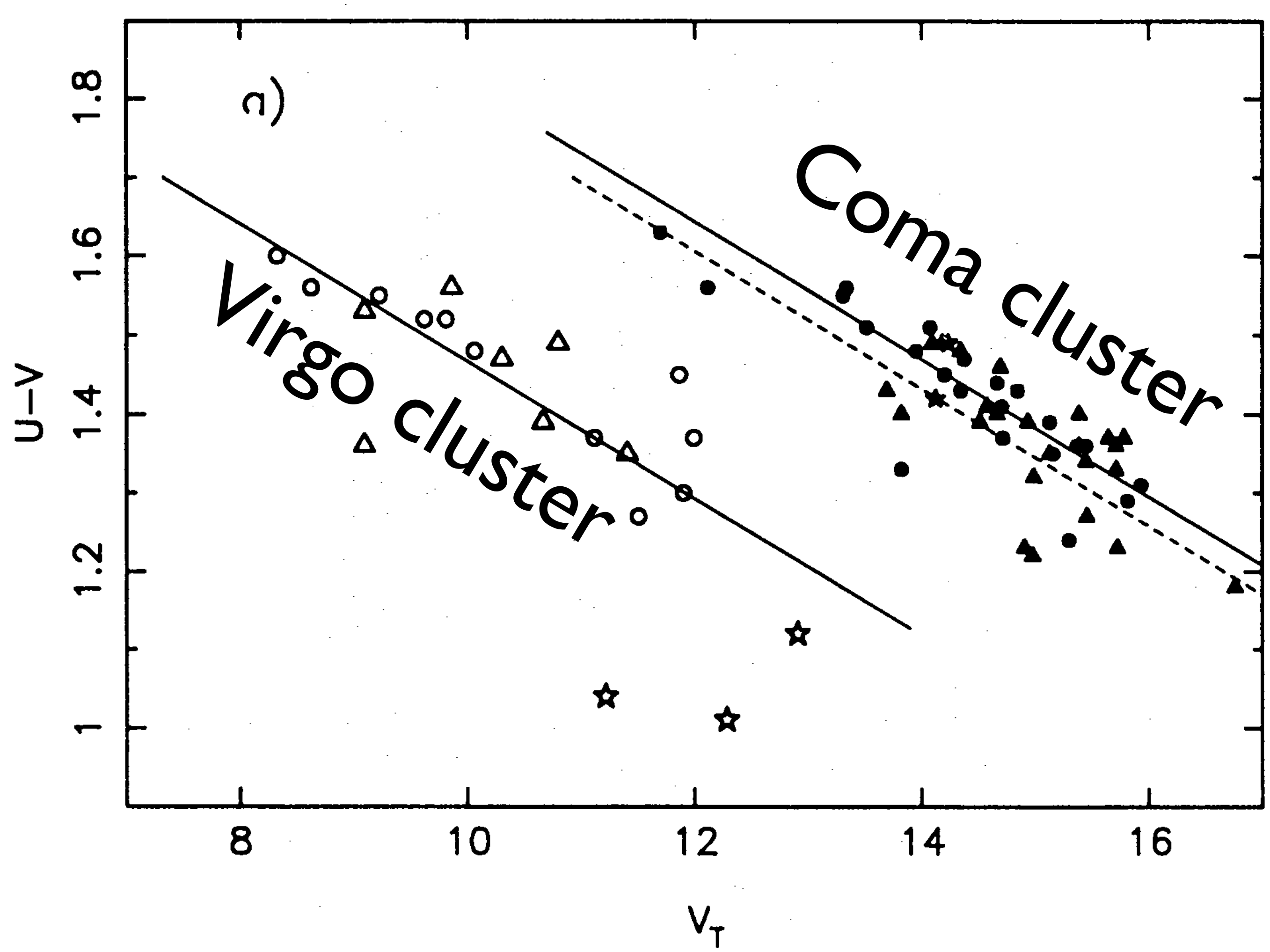
- Why is this?
- There are three possible culprits:
  - Dark matter: if the amount of dark matter increases faster than increasing luminosity, then (M/L) will increase with L
  - Stellar populations: since older stellar populations are *fainter per unit mass* than younger stellar populations, if brighter galaxies are older than fainter galaxies, then (M/L) will increase with L
  - "Broken homology": we've assumed that mass and velocity scale similarly at all masses ("homology"); if this isn't true, one can image that you can construct a scenario in which (M/L) will increase with L

- It appears that perhaps *all three possibilities* are at work here...
  - We'll come back to the stellar population explanation a bit later

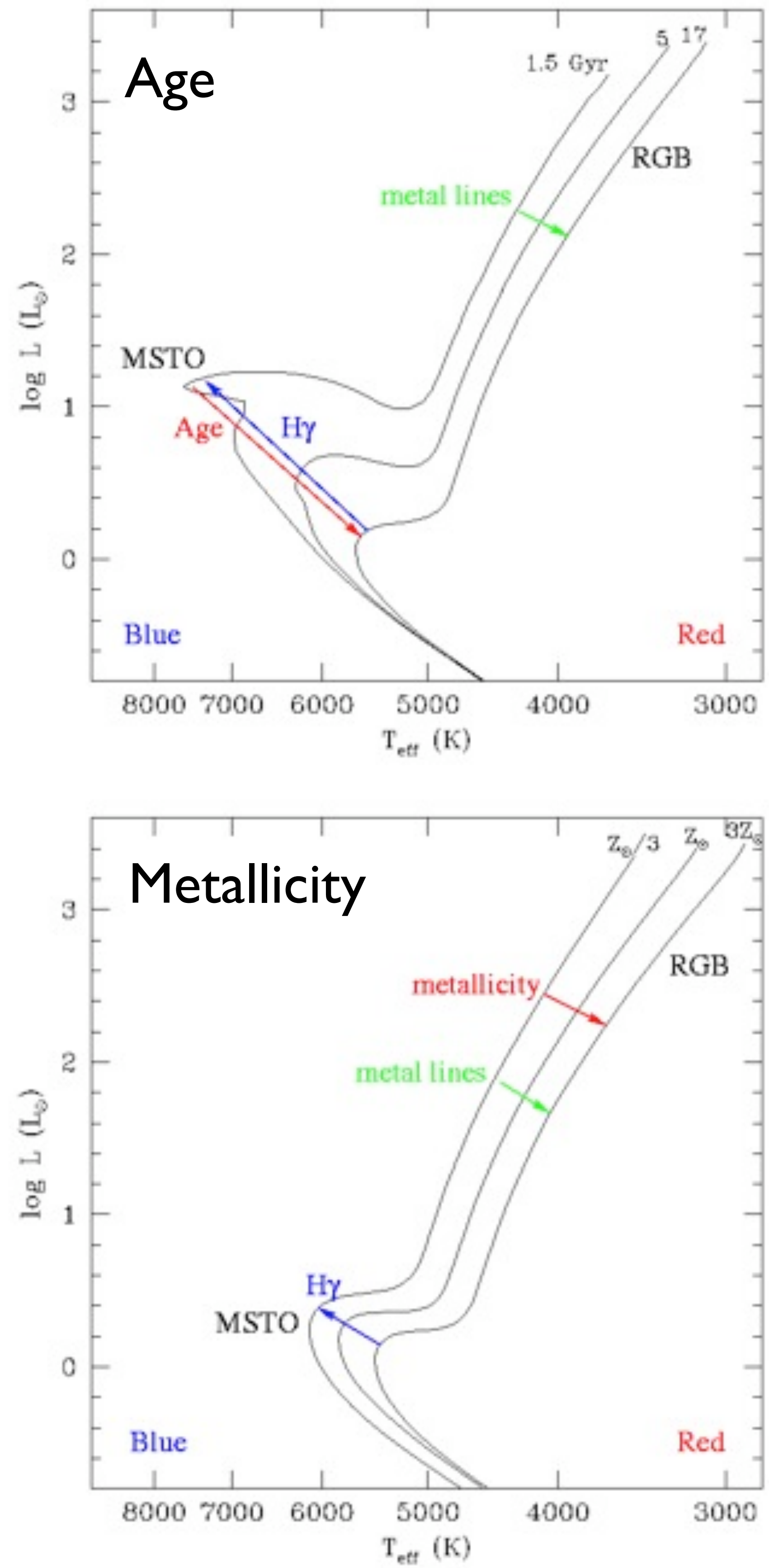
Colour-magnitude diagrams of galaxies

- Another scaling relation is that between the *colour* of a galaxy and its *absolute magnitude* (i.e., its luminosity): the *colour-magnitude relation* (CMR)

- In general, this holds (in the optical) only for early-type galaxies

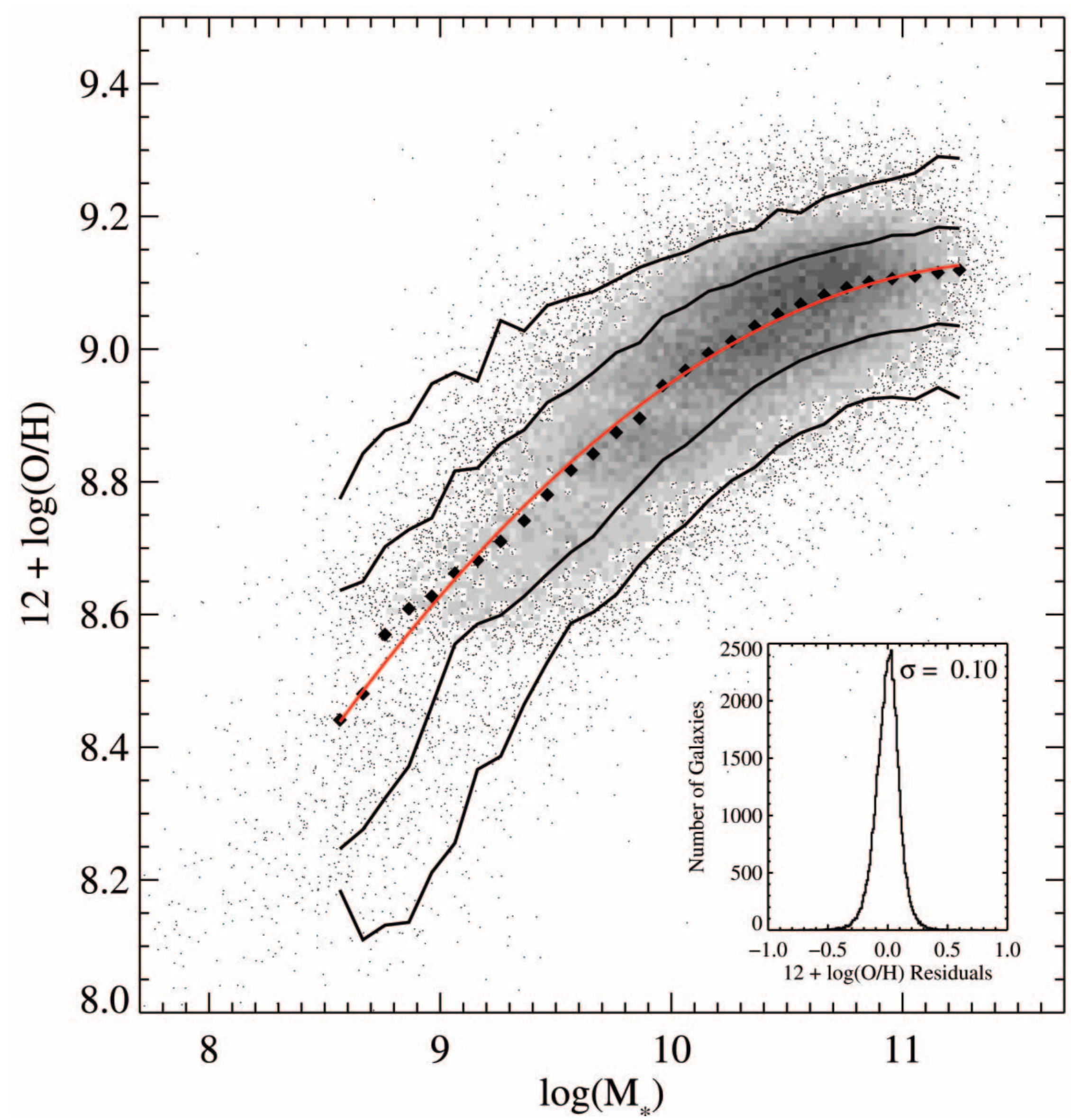


- To understand the cause of this, let's take a look at isochrones again
- Remember that as a population of stars that were formed all at the same time (and with the same composition) gets *older*, it gets *redder* (and fainter)
- However, there is another possible effect: populations with the same age but different populations also have different colours: *metal-rich* populations are *redder* and *fainter* than *metal-poor* populations
    - This is because metal-rich stars have more electrons to give in their atmospheres, so they have higher *opacities* and are therefore cooler (and fainter) than metal-poor stars



The mass-metallicity relation

- We can test which explanation --- age or metallicity --- is correct
- What is the variation of metallicity with mass?
  - In the *gas phase*, the metallicity increases with increasing (stellar) mass
- But notice the <u>flattening</u> in this relation at high masses!

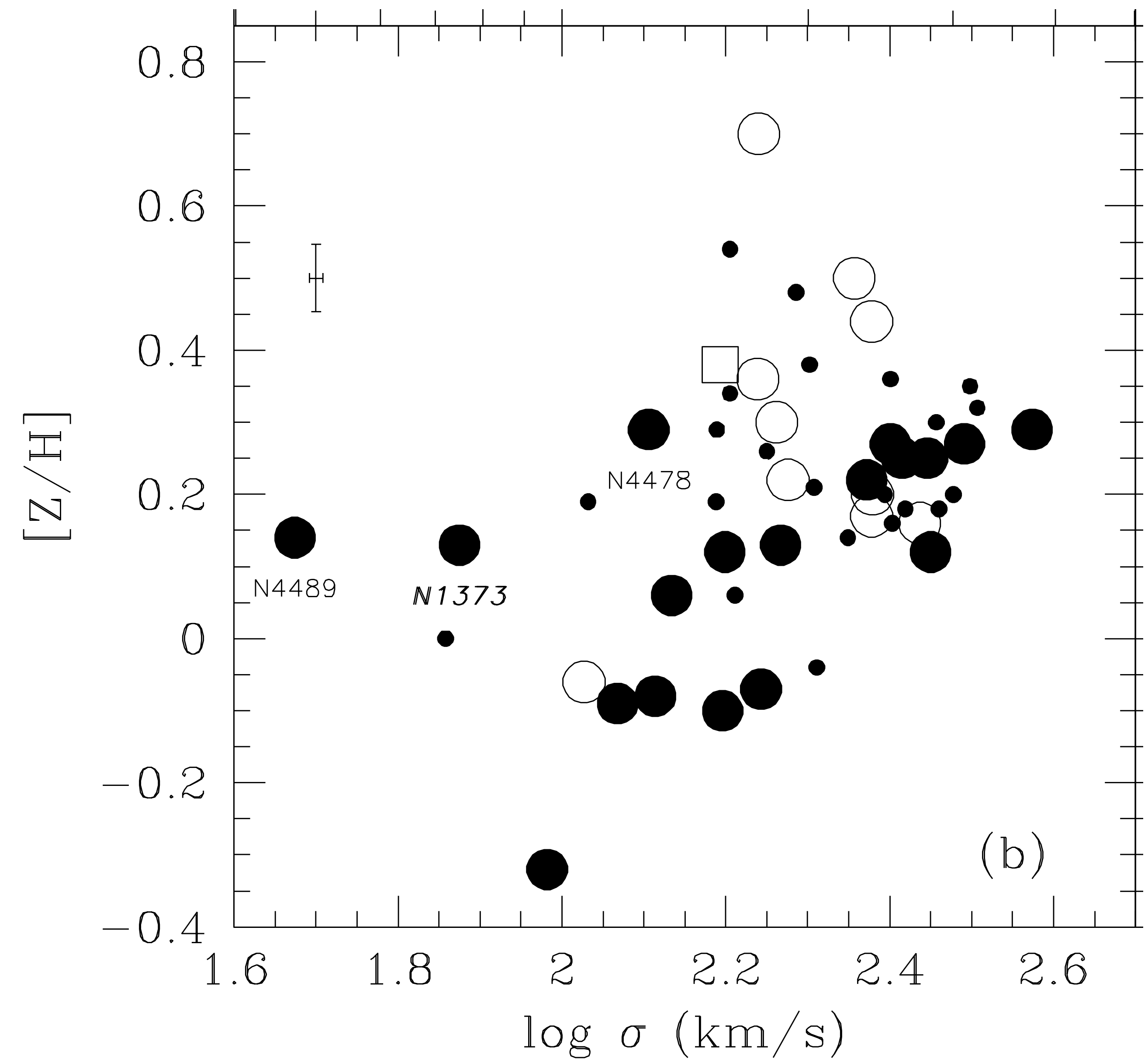


The mass-*gas phase metallicity* relation from Tremonti et al. (2004)

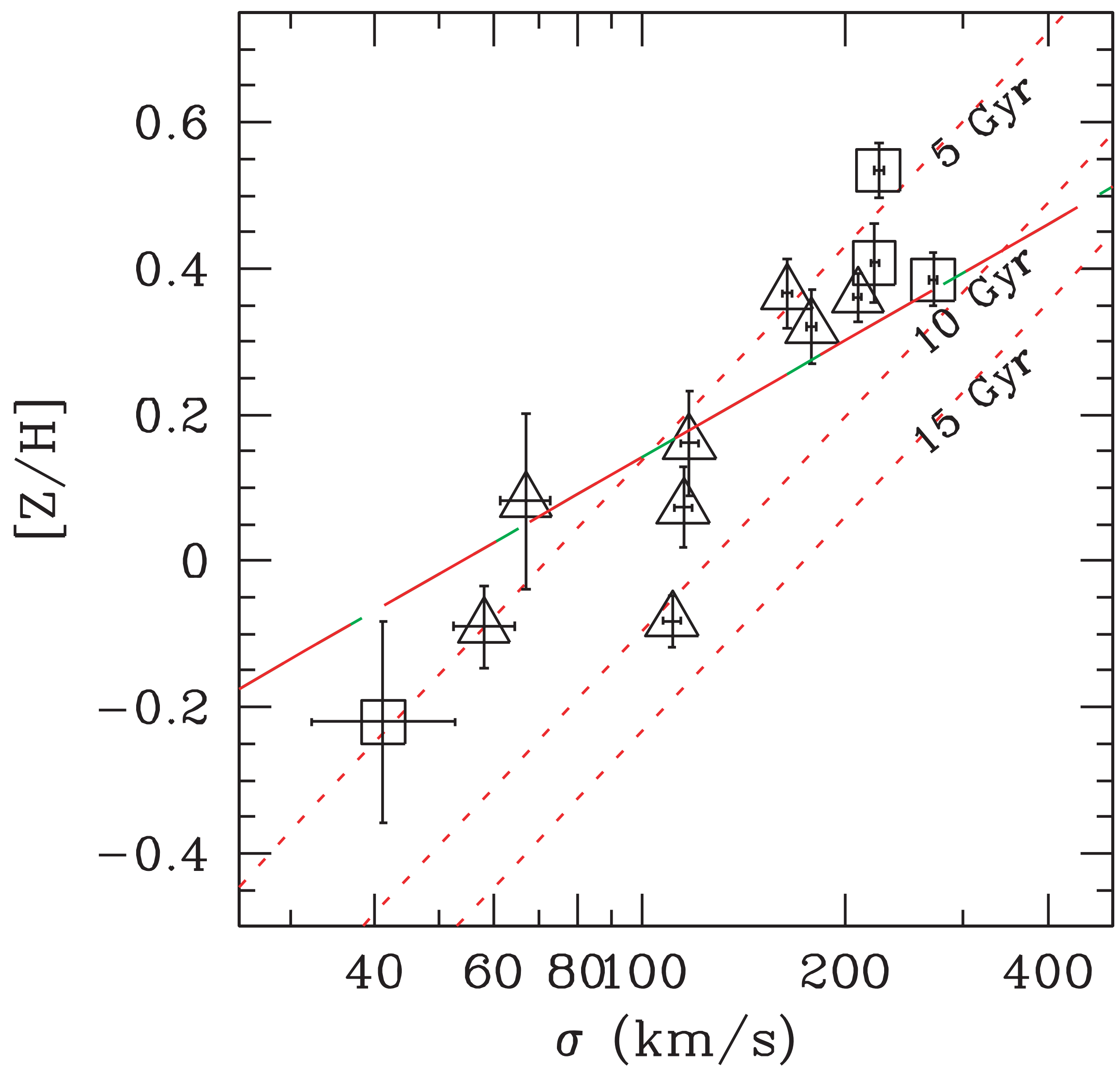
- Note that to get *gas-phase* metallicities, we need gas!
- This means observing *spiral galaxies*, not elliptical galaxies!
    - we'll come back to the origin of the mass-metallicity relation of *spiral* galaxies in a bit...

- For stars in early-type galaxies, the situation is quite different!

- *There is <u>nearly no</u> mass-metallicity relation for early-type galaxies* taken as an ensemble!

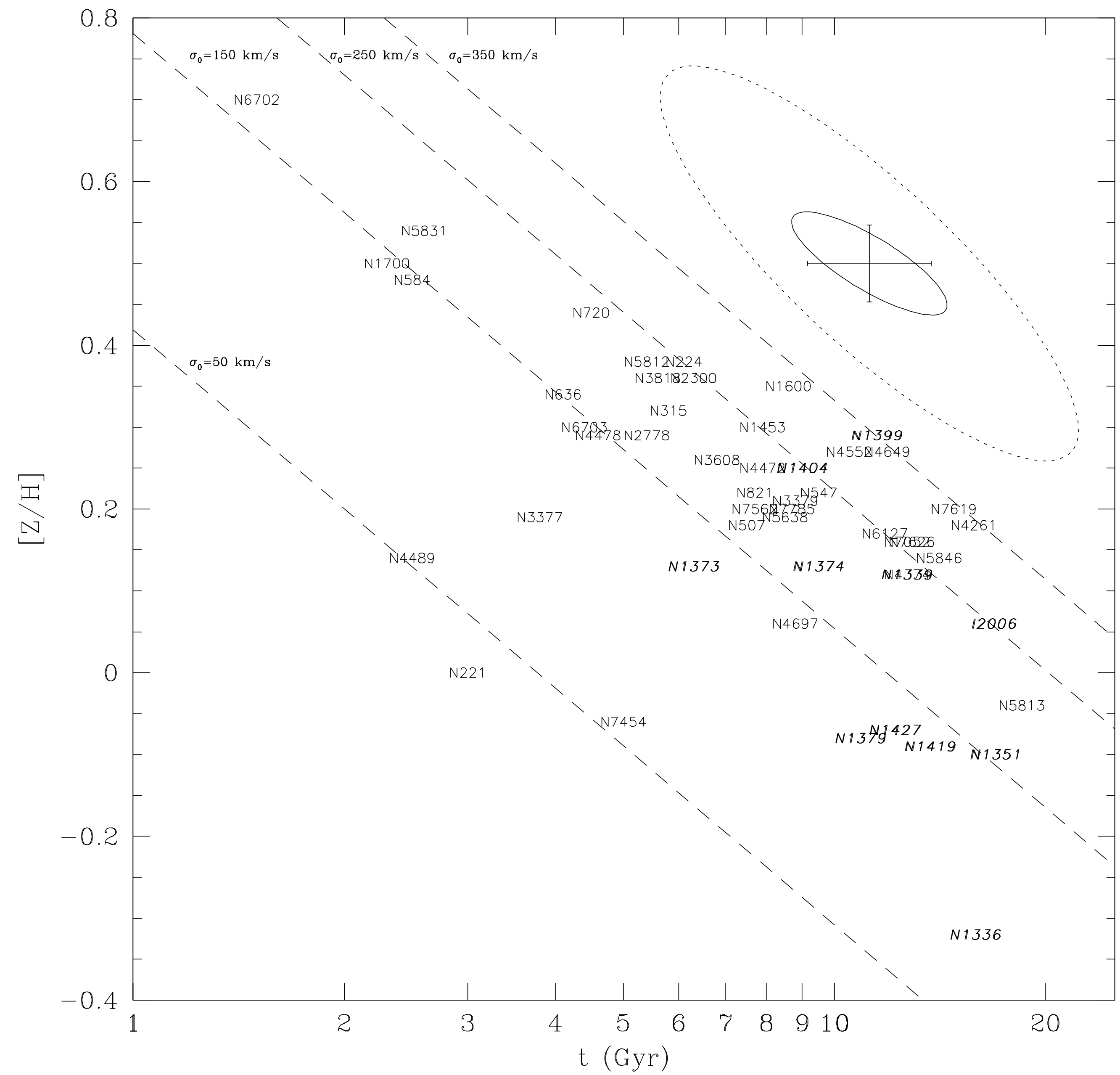


- However, considering a single cluster at a time, there <u>is</u> a mass-metallicity relation



- Why is there an apparent contradiction between these two observations?

- Because the *amount of recent star formation*, as parameterized by the "age" of the galaxy, *affects its metallicity*

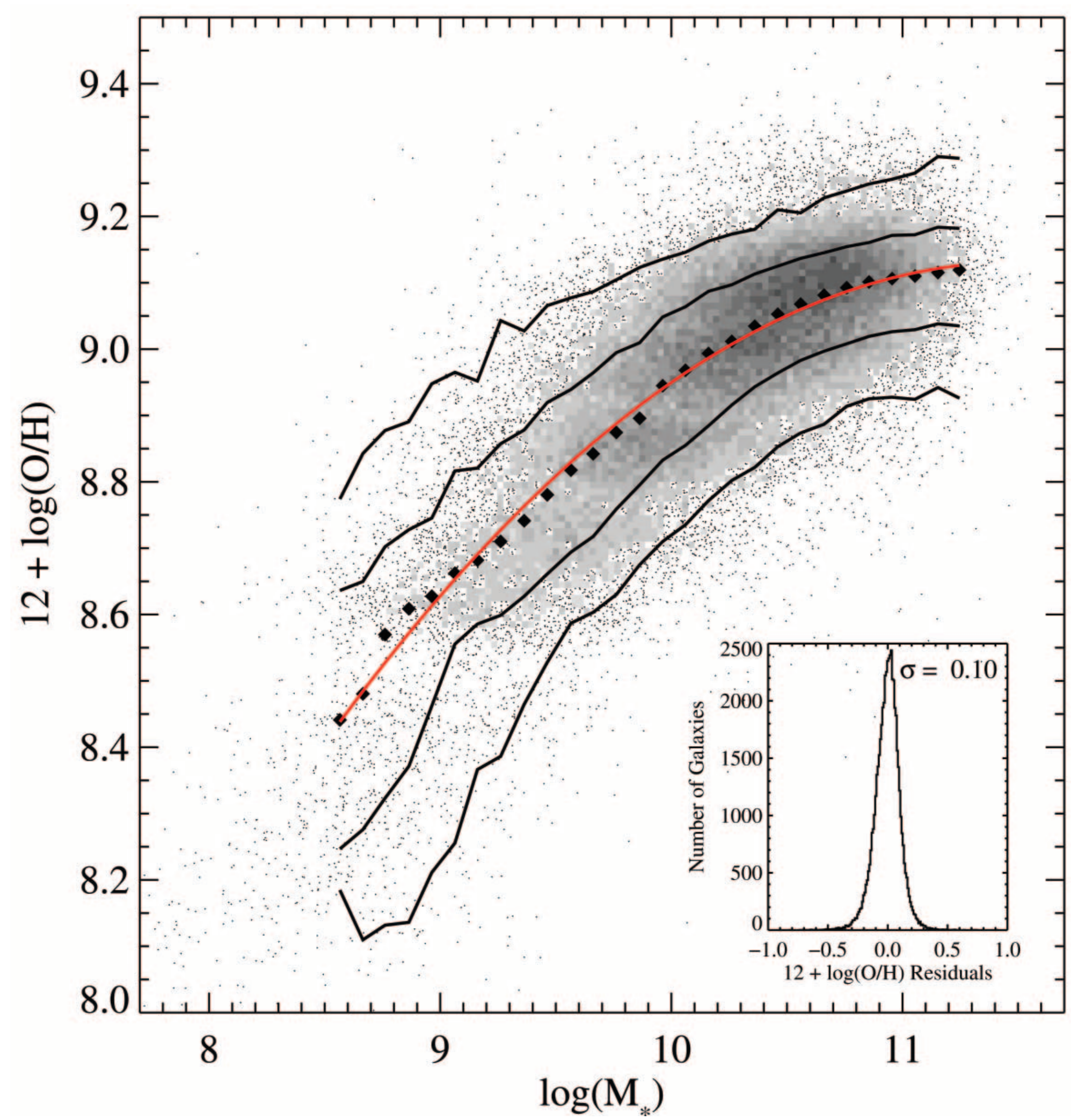


- But why is there a colour-magnitude relation for early-type galaxies?
- It’s not completely clear!

- If we look back time, we would expect different behaviors if the CMR
    - if metallicity is the cause, we would expect *no* evolution in the CMR other than the change in colours and magnitudes caused by the stars getting *younger*
    - if age is the cause, we expect a stronger evolution due to galaxies "dropping" out of the relation at the times when the "age" says that they formed

- The jury is still out --- we are not certain of the cause
    - the answer may be that *both* are correct --- age *and* metallicity may play a role
    - If age is the primary culprit, we call this “downsizing”, because we then require *smaller, fainter galaxies* to be *younger* than *bigger, brighter galaxies*
        - The idea is that star formation continues in small galaxies for *longer* than in big galaxies

- Let's return to the origin of the mass-metallicity relation of *spiral* galaxies: how might this come about?



- We know that the mass of the galaxy is related to the “depth” of its “potential well”: that is, the more massive the galaxy, the harder it is for stars or gas to escape that galaxy (recall our discussion of *escape velocity* of clusters)

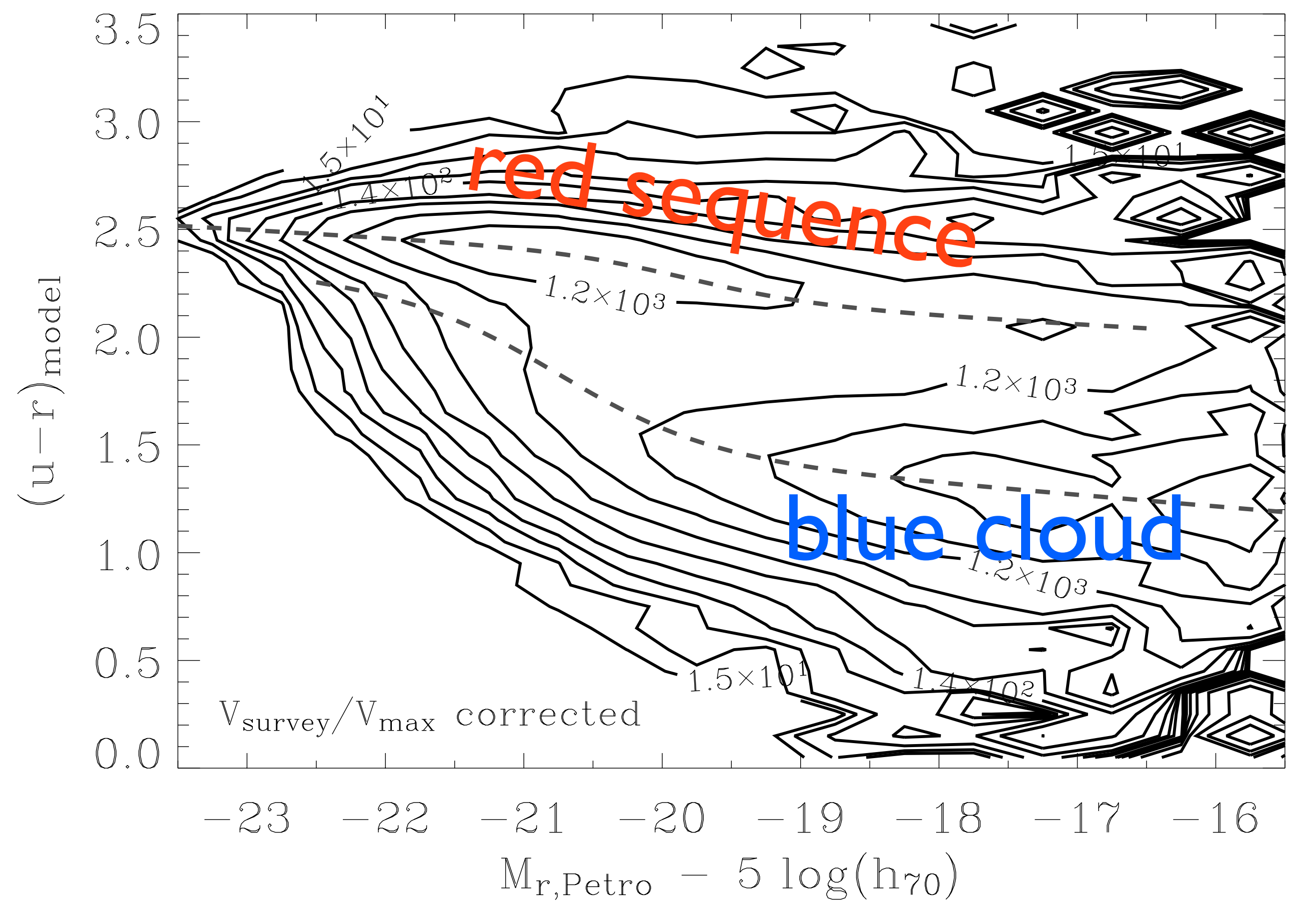
- The longer a galaxy can retain its gas, the more “metals” it can form through supernova explosions
    - That is, every new generation of stars makes new metals by processing the metals in the gas leftover from the previous generation of stars

- Now, remember that supernovae produce a lot of energy as well as metals
- So if *too many* supernovae go off in a low-mass galaxy, this gas has too much energy to be retained by the galaxy
- Bigger galaxies can retain more gas
- Therefore, big galaxies can have *more generations* of stars and therefore *higher metallicities* than small galaxies

- This scenario (and it's just a scenario, but it seems like a good one!) is called "metal-enriched winds" because the supernovae blow out gas (in "winds") that has been enriched in metals from the previous generation of stars
  - What happens to this gas? It depends on *where* the galaxy lives
    - in a group or cluster of galaxies, it's likely trapped in the dark halo that surrounds that group or cluster --- this hot gas can be detected in X-rays
    - in a single galaxy, it is likely lost altogether to the "intragalactic medium"

The colour-magnitude diagram of galaxies

- In fact, there is even a colour-magnitude relation for spiral galaxies, although it is *much* broader than the CMR of early-type galaxies
  - We call the red CMR populated (mainly) by early-type galaxies the "red sequence" and
  - the blue CMR population (almost entirely) by late-type galaxies the "blue cloud"



- Brighter blue galaxies (i.e., spirals) are *redder* than fainter blue galaxies because they
    - are more massive and have higher metallicities, because of the mass-metallicity relation, and
    - have less star formation and therefore older populations of stars