Today

- Class overview
  - organization
  - philosophy
- Large context of galaxy evolution
- Morphological classification

To first order, dark matter controls motion, mass, & structure

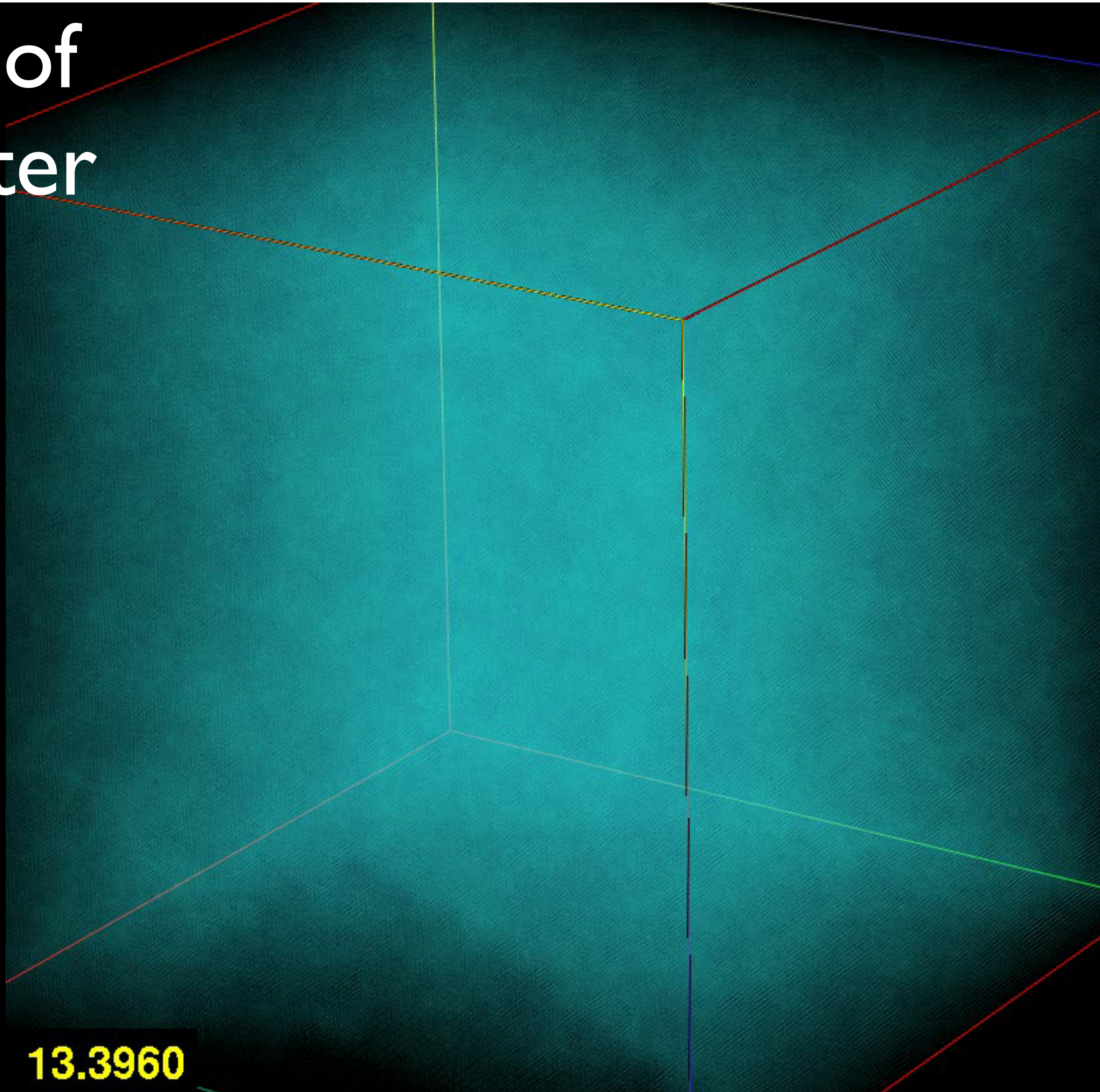
It dominates the mass, so sets the rules

Evolution of Dark Matter

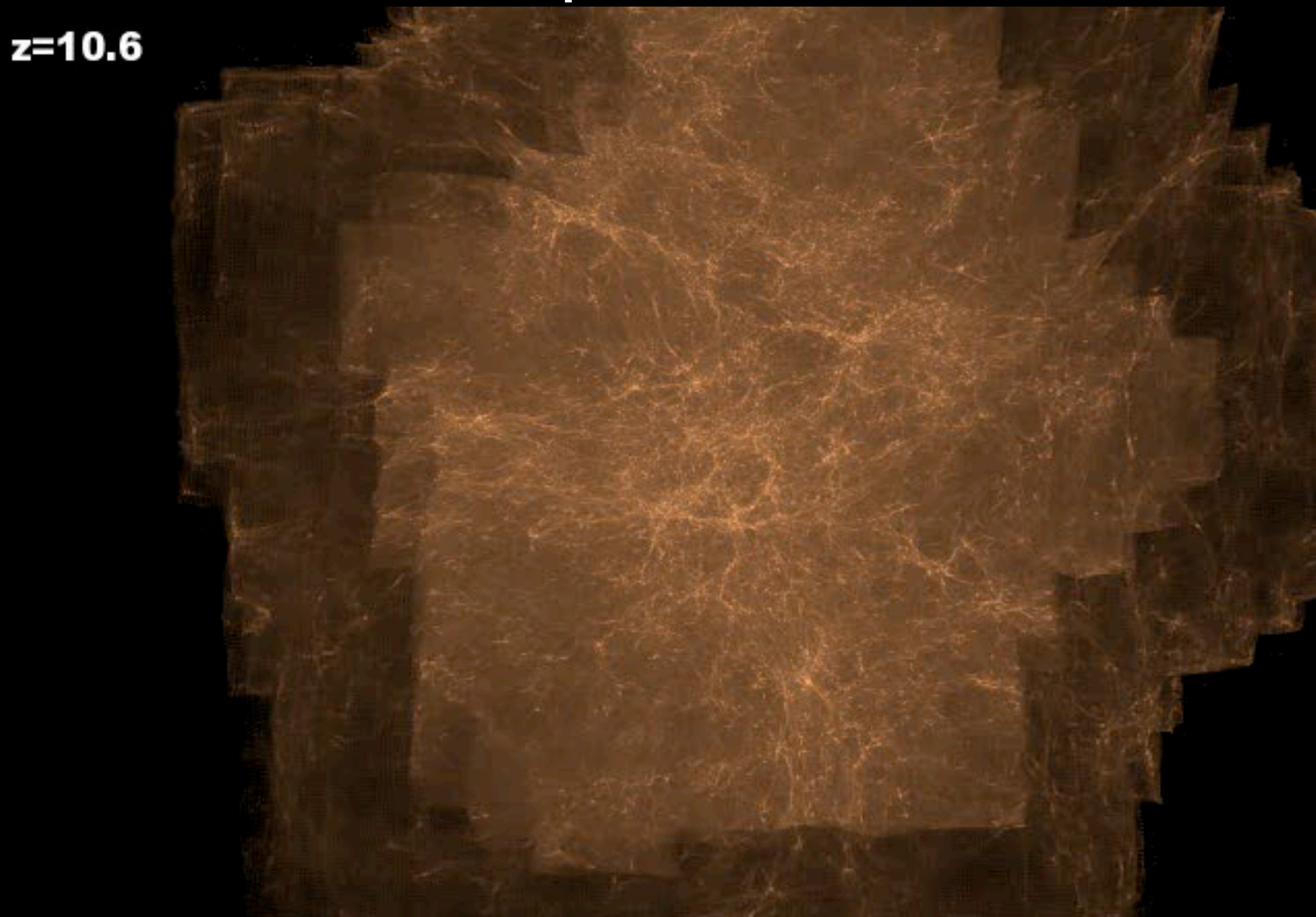
• Small density pertubations in the early universe grow with time.

• Matter accumulates in filaments, and then in individual "halos"

Courtesy B. Allgood
~10^9M/particle



Cold Dark Matter favors the formation of small halos -- “power on small scales”



MW Halo: Dark Matter Only

Dark matter is "dissipationless"

Halos roughly virialize from inside out

http://www.illustris-project.org/movies/illustris_movie_cube_sub_f

However, baryons are what we can actually measure.

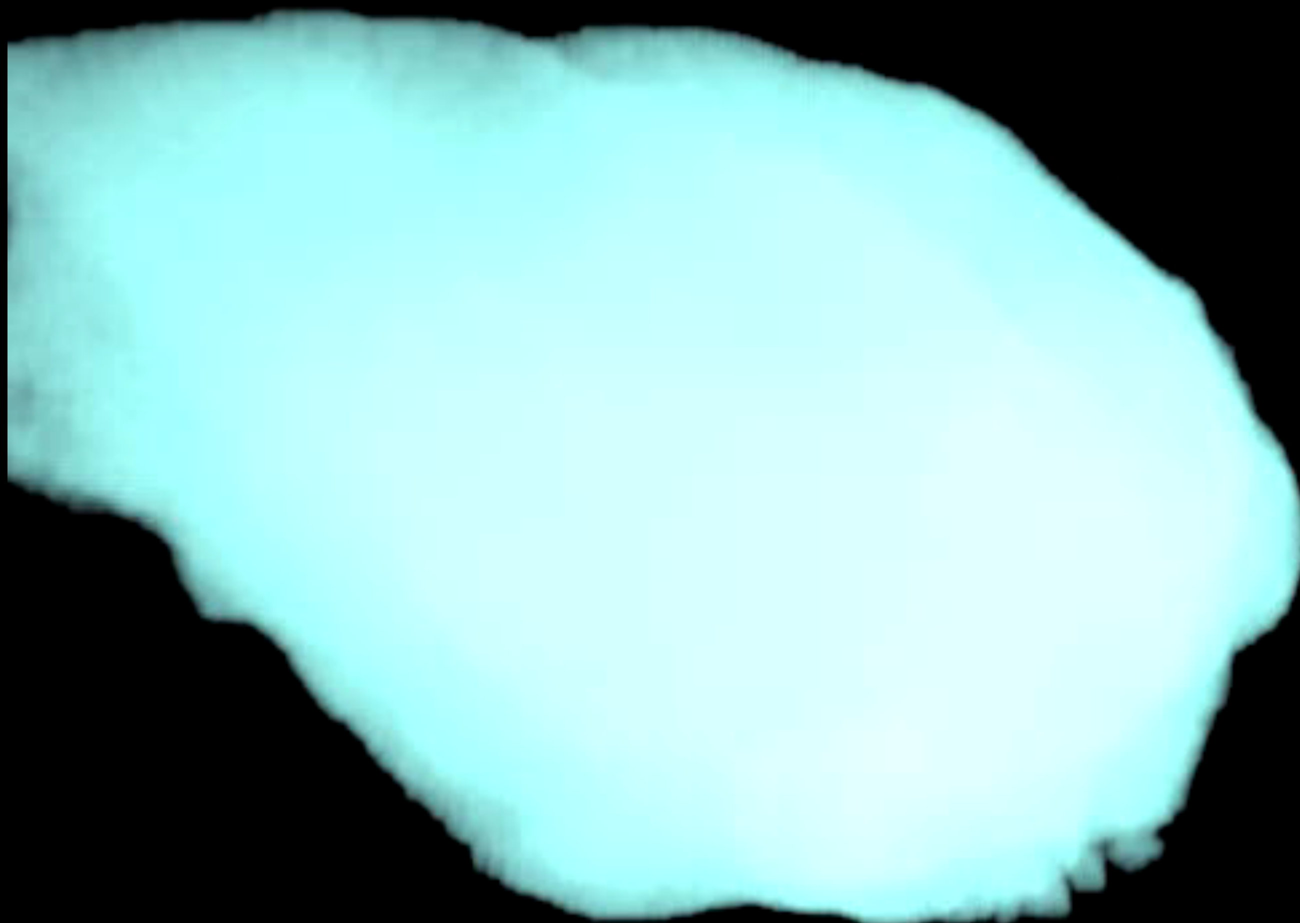
Understanding how baryons behave & how they emit light is crucial

Gas is “dissipational”

As density increases, cools & collects

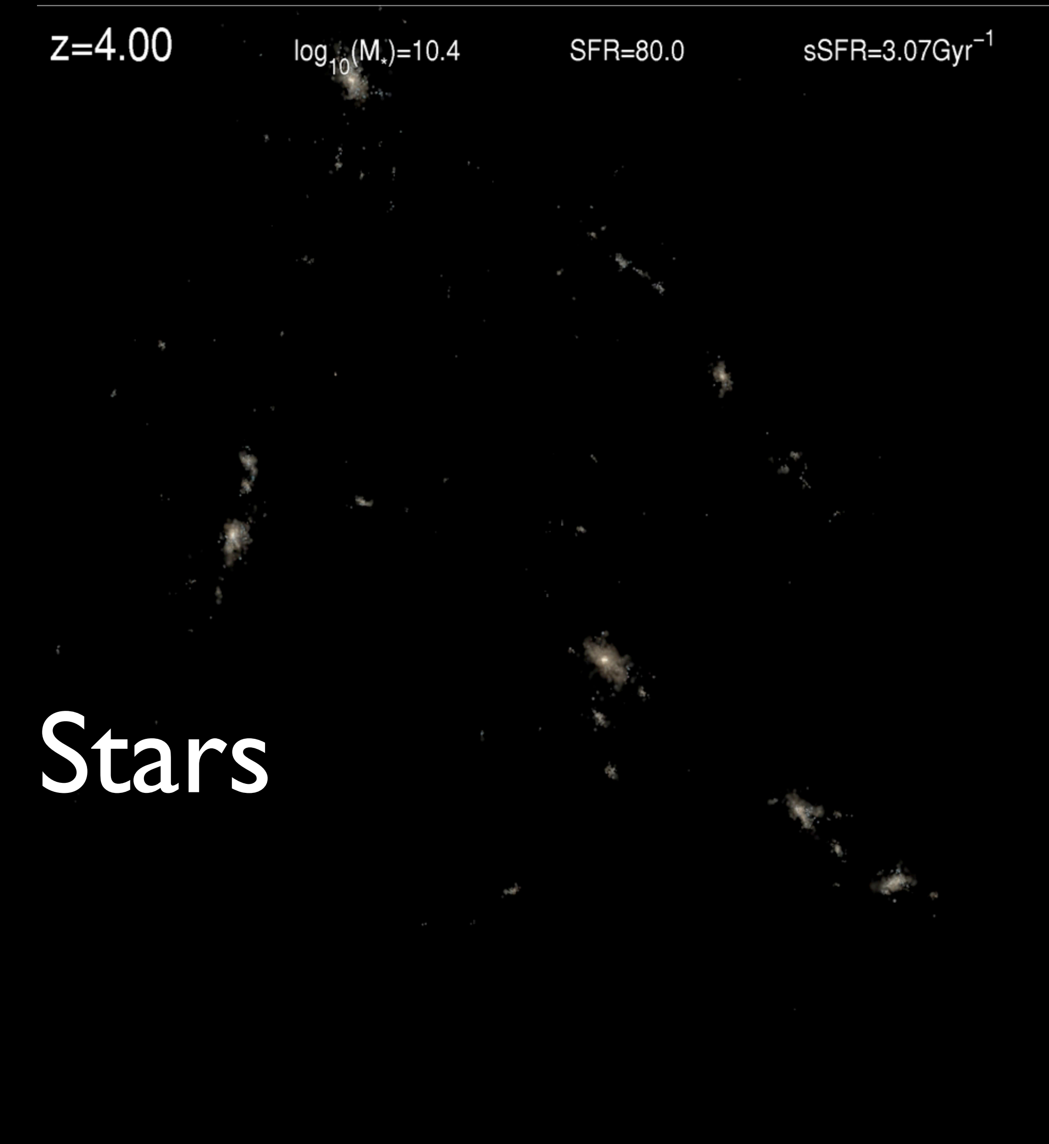
http://www.illustris-project.org/movies/illustris_movie_cube_sub_f

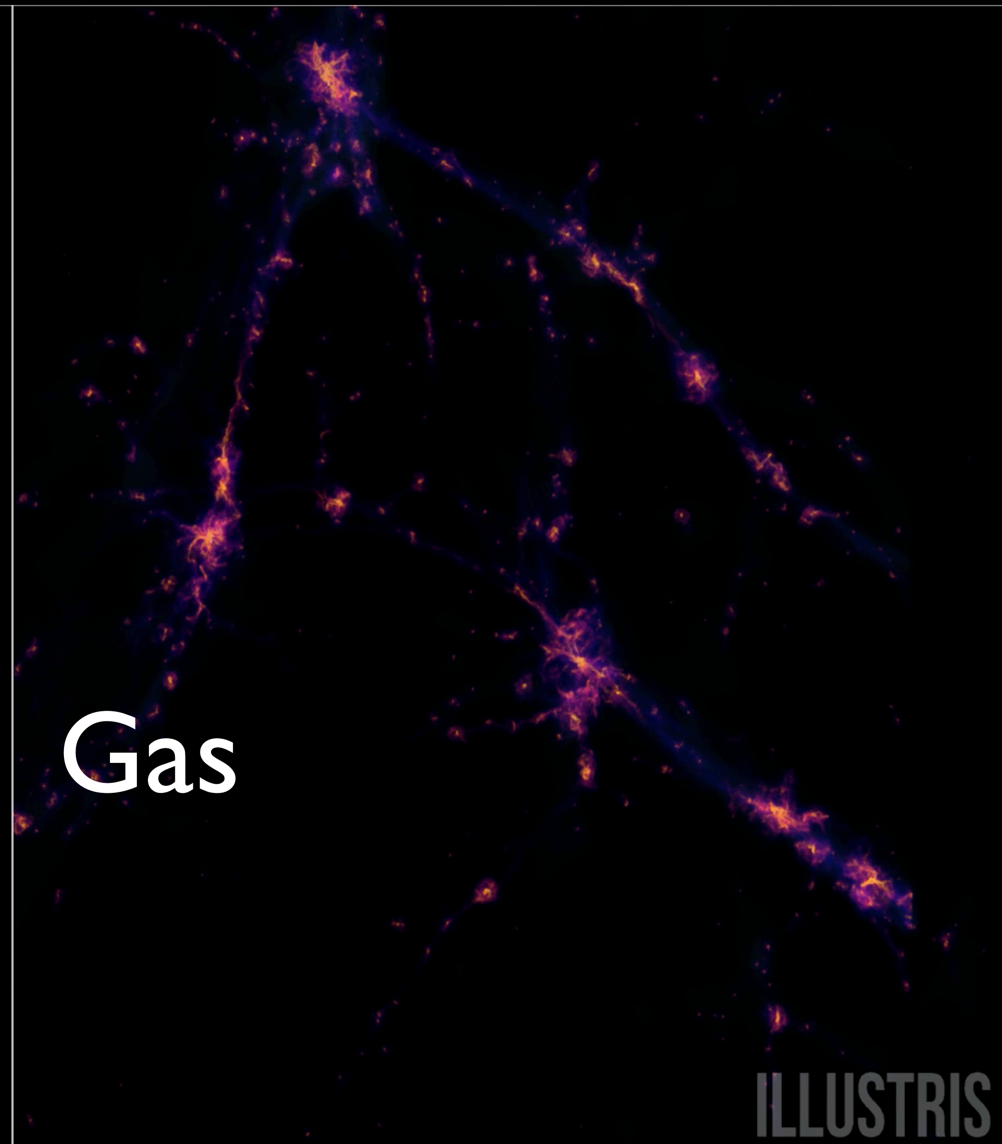
Stars form where gas density is high



They are born with the kinematics of the gas.
"Stars remember what gas forgets"

Merging & Feedback Help Drive Evolution





http://www.illustris-project.org/media/

Dissipationless

Densities typically decrease w/ merging

Dissipational

Can radiate energy to reach high density. Can also heat.

“Feedback” shapes the larger gas distribution

Time evolution of a 10Mpc (comoving) region within Illustris from the start of the simulation to z=0. The movie transitions between the dark matter density field, gas temperature (blue: cold, green: warm: white: hot), and gas metallicity.

http://www.illustris-project.org/media/

Much of the action is outside of “galaxies”

Extended gas: “Linear regime” of structure formation

$\boxed{\text{Galaxies: “Non-linear”, complicated physics}}$

Drivers

Cosmology sets:

- the structure of the initial pertubations
- the timescale over which structures form.
- how dark matter behaves

Observables

This shapes:

- the global spatial distribution of galaxies
- the timescale over which galaxies form.
- the internal dynamics of galaxies
- the relative motions of galaxies
- the internal structure of galaxies

Drivers

Gas & Stellar Physics set:

- the conditions under which gas turns into stars.
- the evolution of stellar populations.
- the impact of stellar evolution on the ISM

Observables

This shapes:

- the colors of galaxies
- the appearance of galaxies at high redshift.
- the gas content of galaxies.
- the star formation rate of galaxies.

For this class, we define galaxies to be:

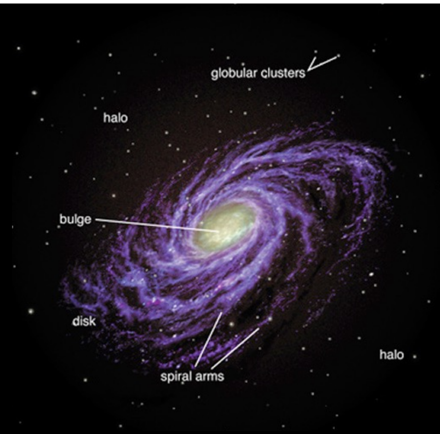
- Gravitationally bound
- Contains dark matter
- Contains baryons

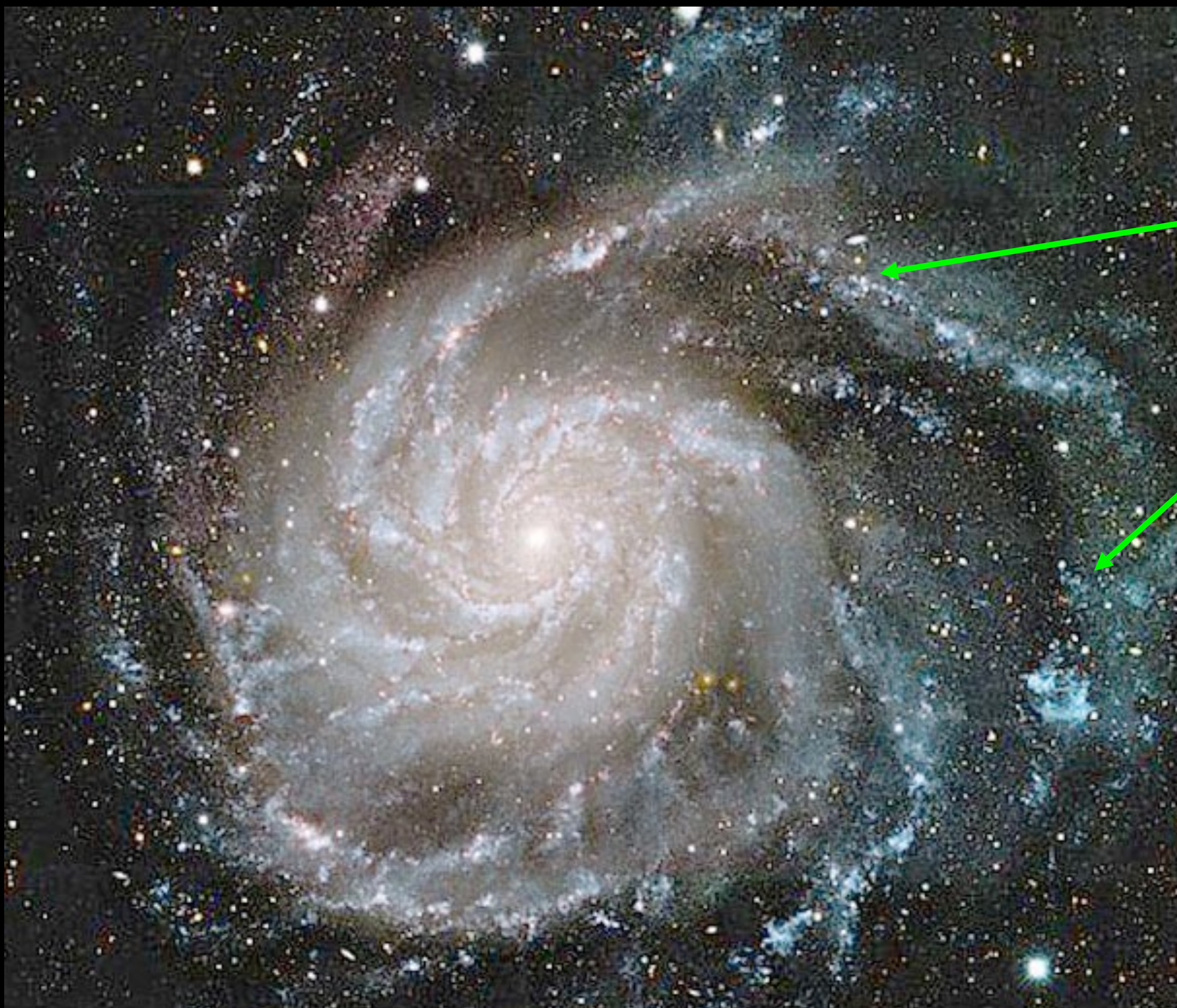
Top View of the Milky Way

“Spiral” or “late type” galaxy

The different components have different colors, motions, and chemical compositions, different origins

Top View of a Real Late-type Spiral Galaxy





HII regions and young stellar clusters = **lumps** along the spiral arms

Morphologically, lumps imply star formation

Appearance vs Inclination

Side View

"edge-on"

Inclination i=90°

Top View

"face-on"

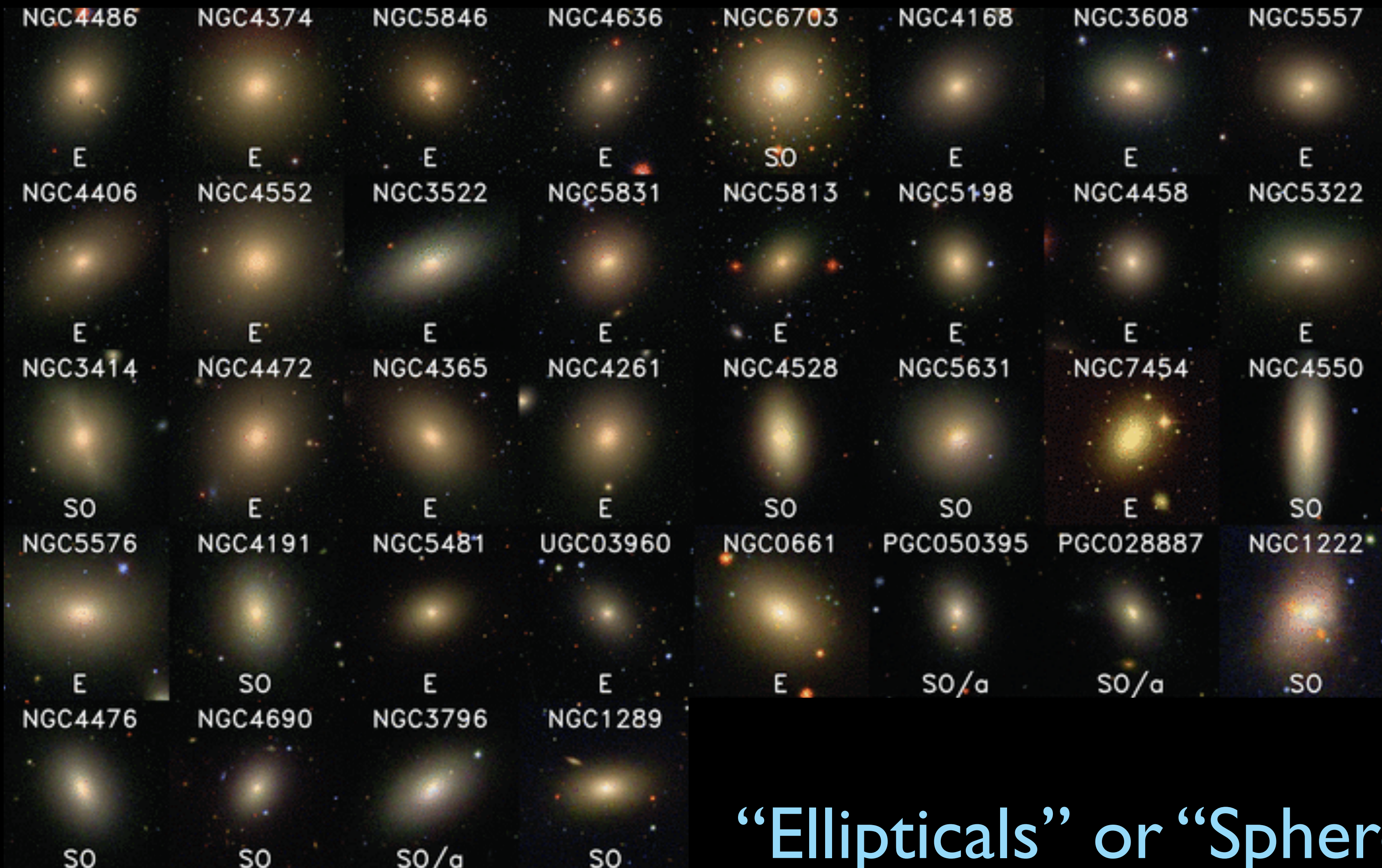
i=0°

Late-Type "Disk" Galaxies

- "Gas rich"
- current star formation
- more disk than bulge.

"Early type galaxies"

- More bulge than disk.
- Low current star formation.

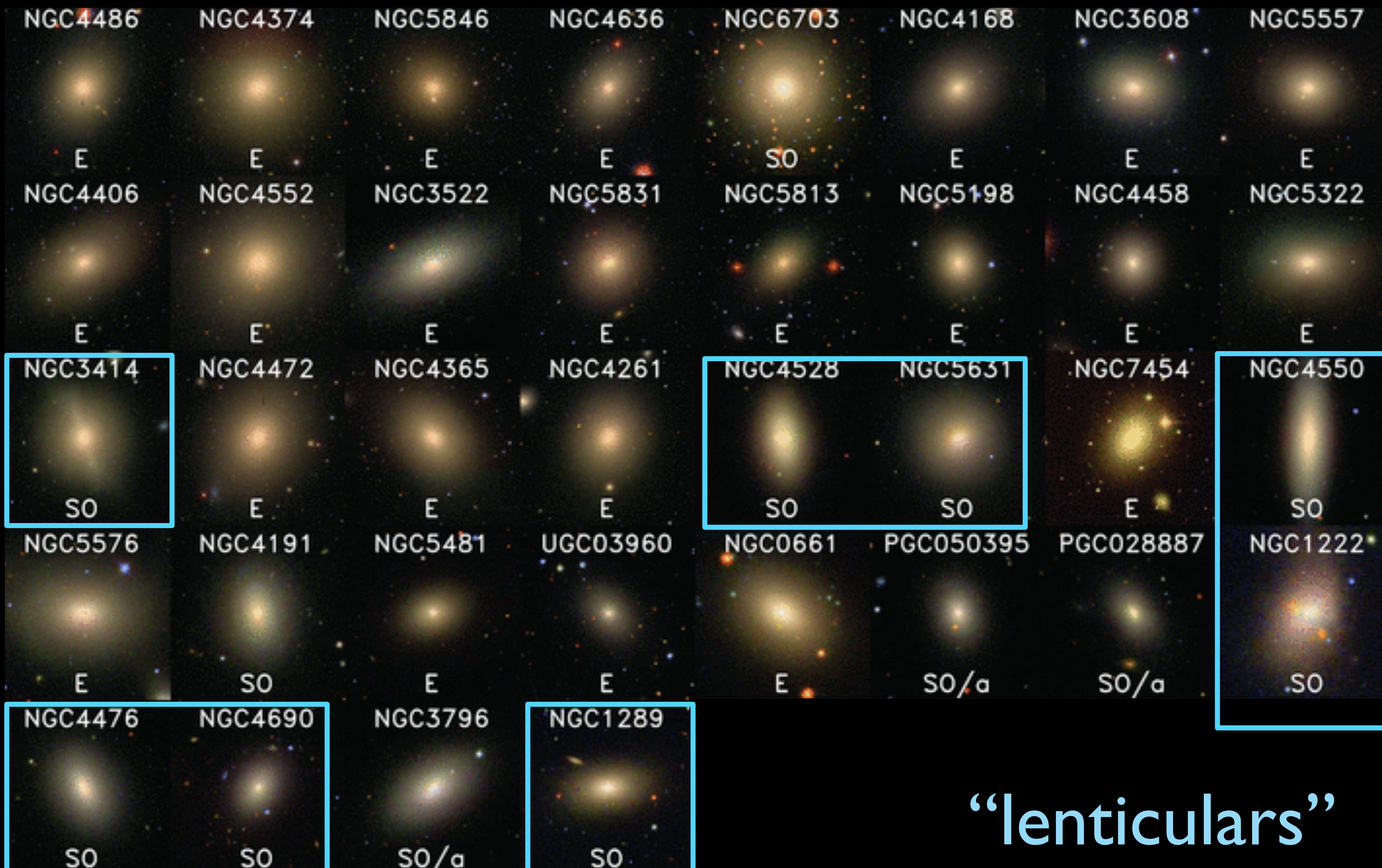


"Ellipticals" or "Spheroidals"

Atlas3D: Cappellari et al 2011

"S0": Very subtle differences from E

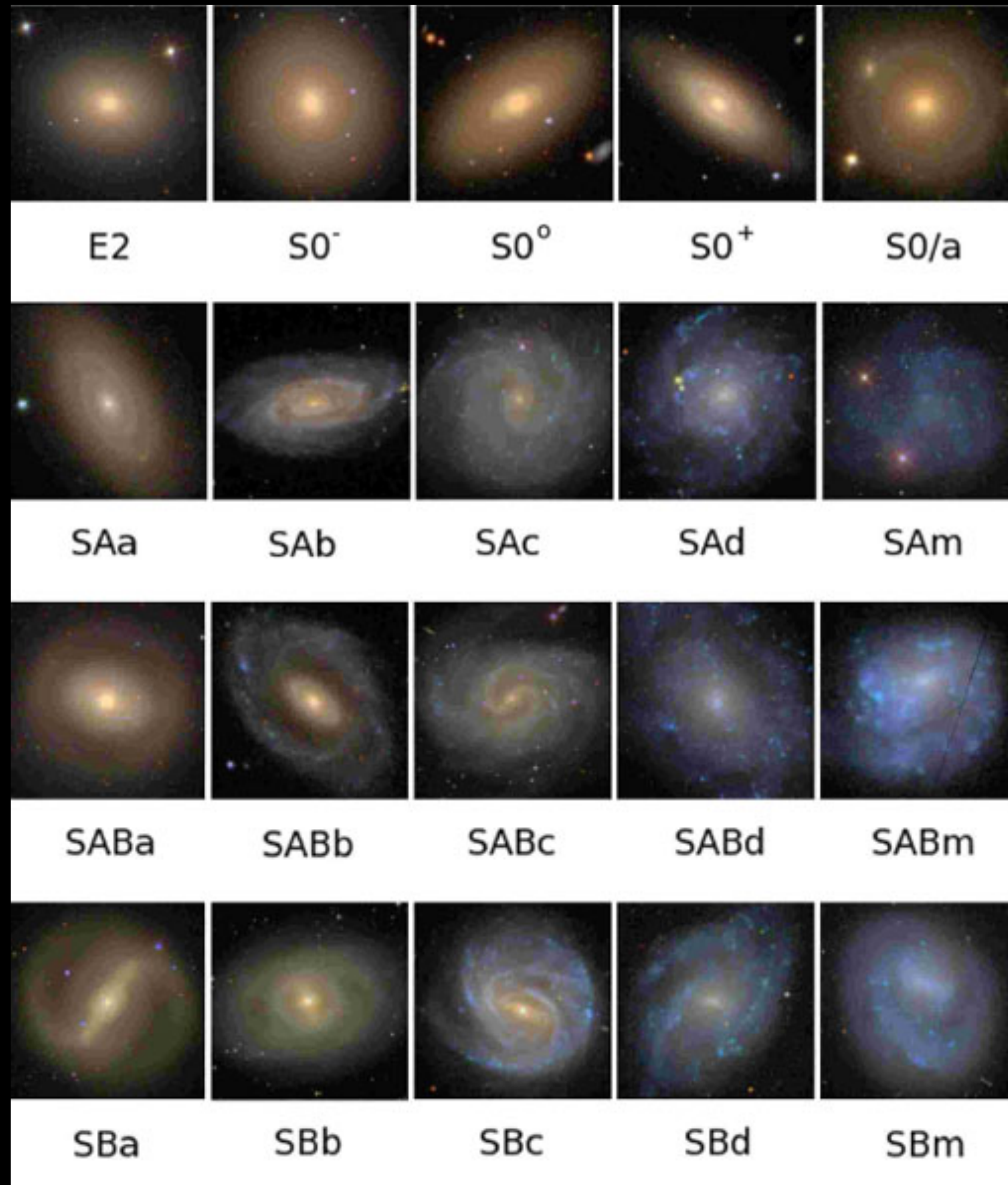
- Just a hint of a smooth disk.
- Low current star formation.



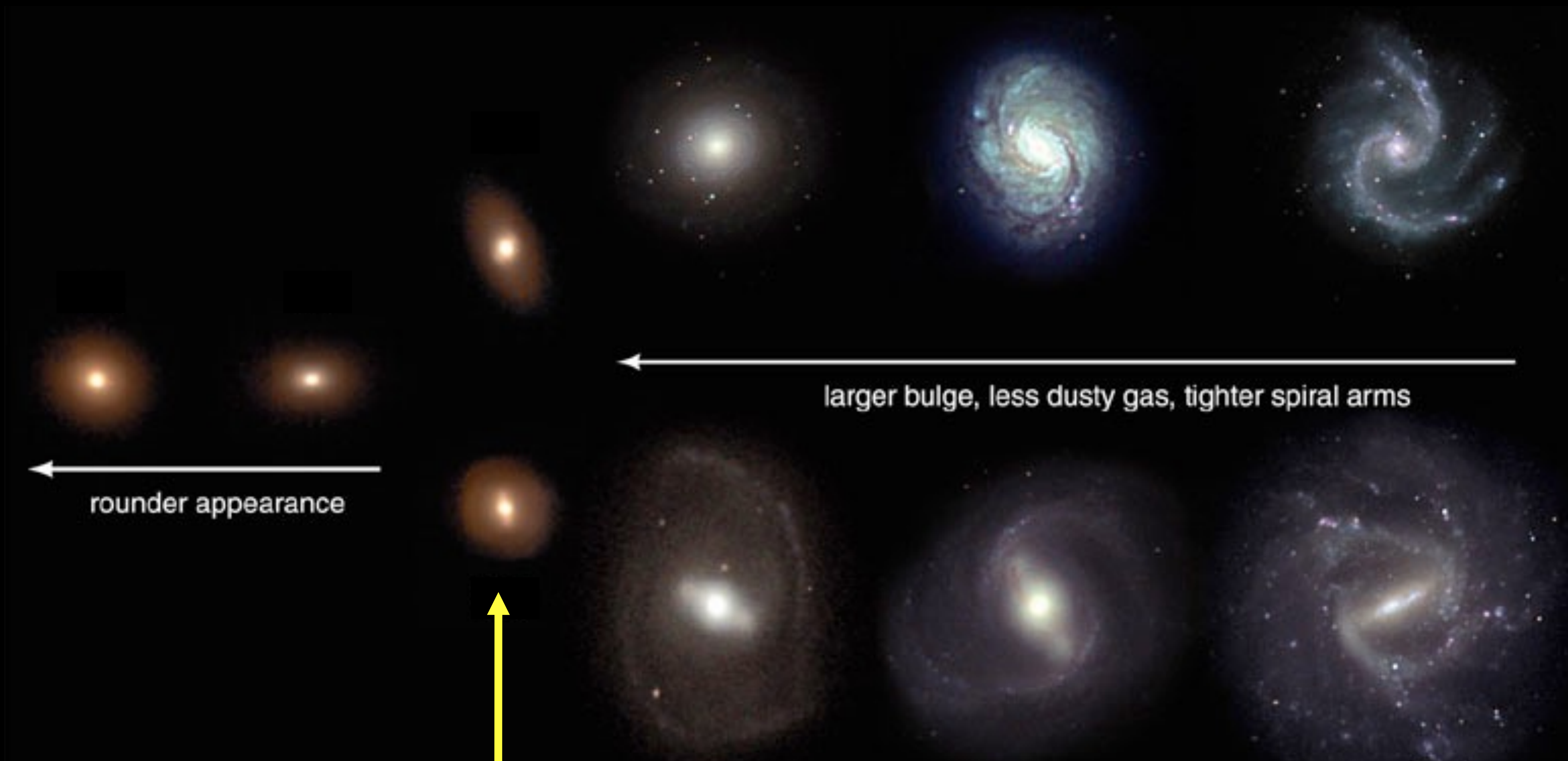
"lenticulars"

Why Galaxy Classification?

- Order from disorder.
- Compact, yet complete description.
- Find other correlations to reveal orgins.



“Tuning Fork”

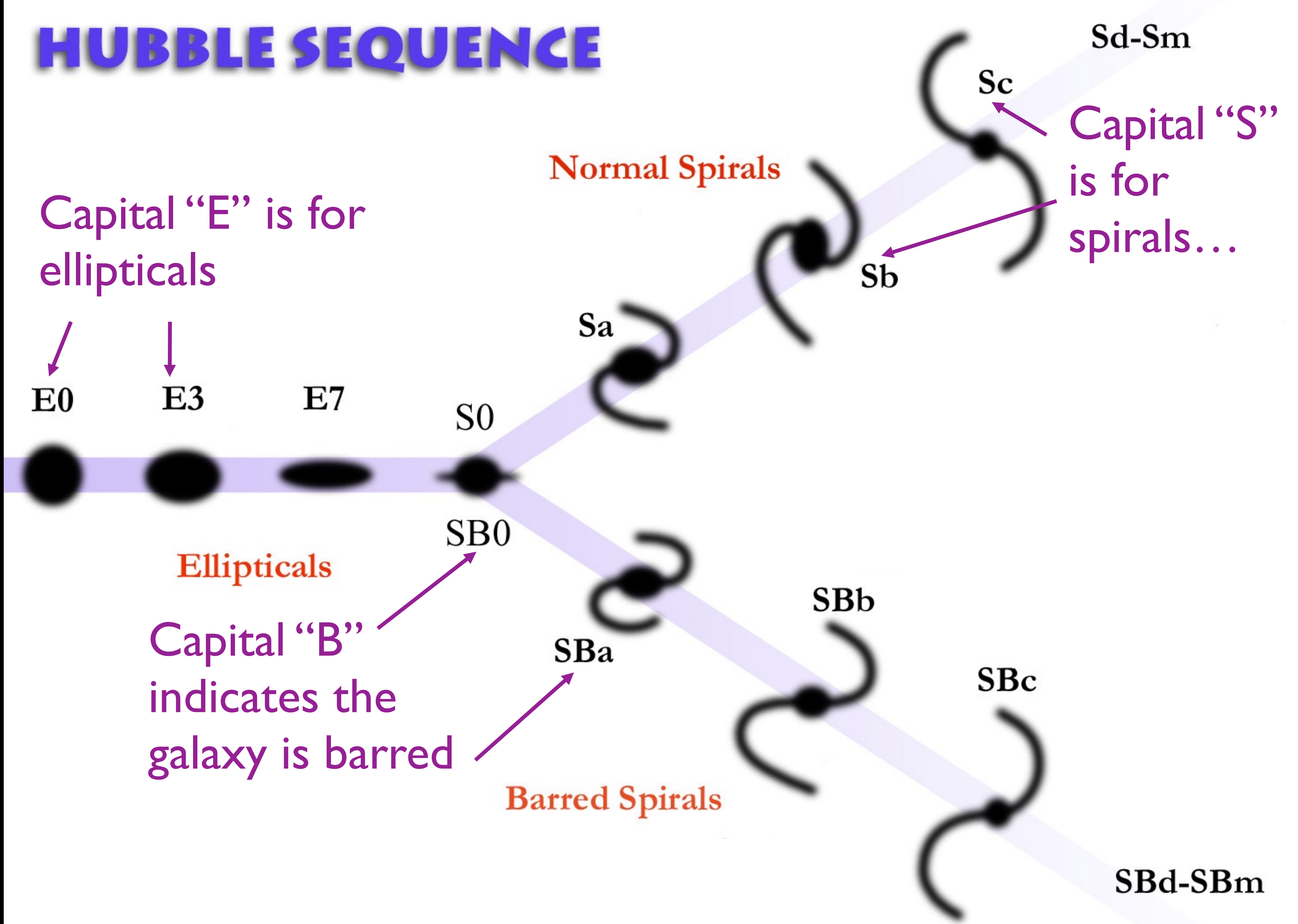


Ellipticals

Unbarred and Barred Spirals

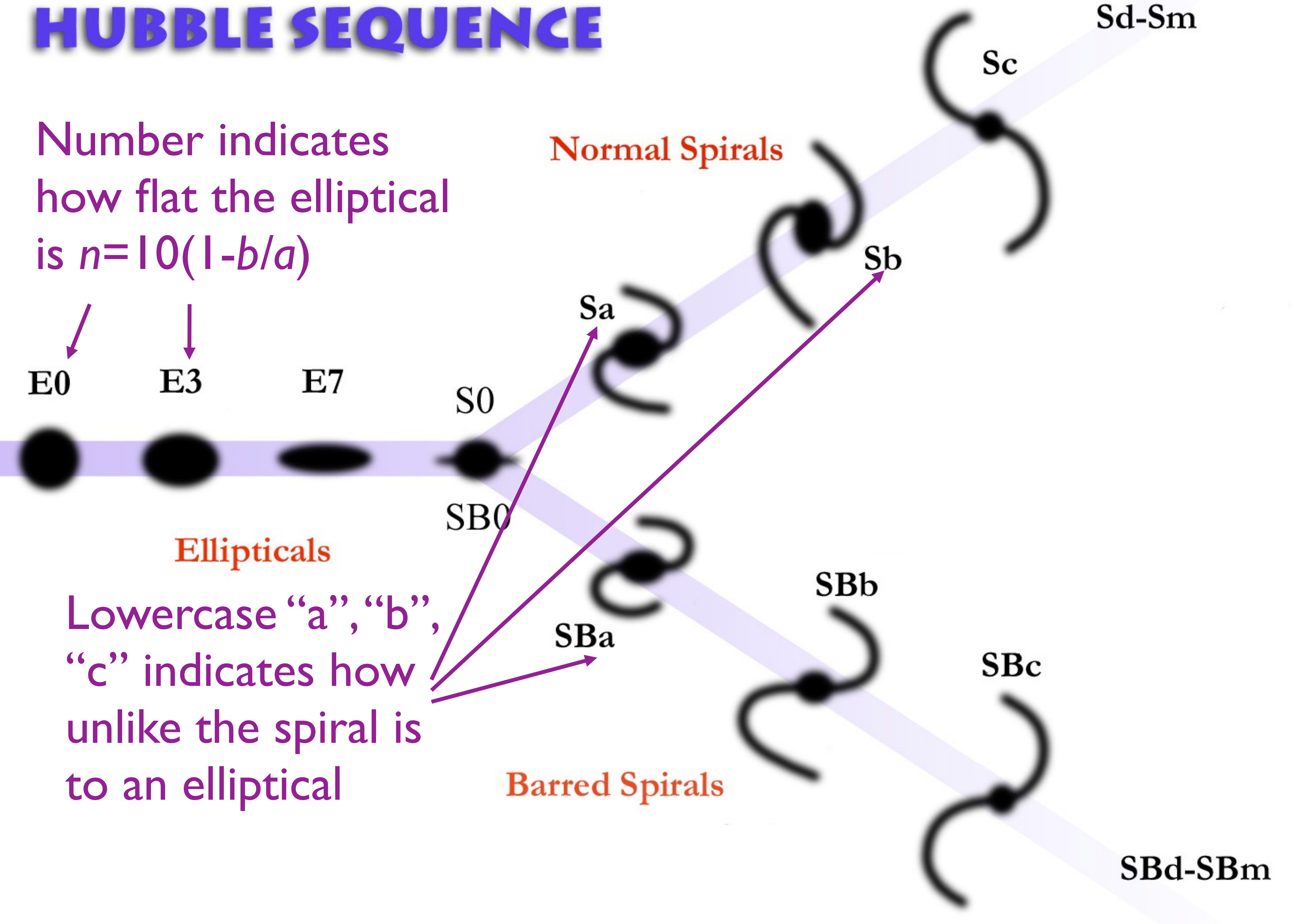
Lenticulars

HUBBLE SEQUENCE



HUBBLE SEQUENCE

Number indicates how flat the elliptical is $n=10(1-b/a)$



Lowercase “a”, “b”, “c” indicates how unlike the spiral is to an elliptical

Key elliptical classification facts

- Ellipticals are 3d: “n” in label is not an intrinsic property!
- Ellipticals are essentially never flatter than E6

Key spiral classification facts

S0: hint of disk or has "lenticular" isophotes, but entirely smooth

Sa: Tightly wound spiral arms, small lumps, prominent bulge.

Sb: like M31.

Use as your mental reference point

Sc: Lumpy arms, open arms, small bulge

Sd: Spiral arms, but no (or miniscule) bulge

Sm: "Magellanic" spiral. Disorganized spiral structure, entirely bulgeless, lumpy

Intermediate classes denoted with both letters: Sab, Scd

Classification is often translated into a single number "T"="T-type"

Table 1. T-types in the Revised Hubble system.

cE	$E0$	E^+	$S0^-$	$S0^o$	$S0^+$	$S0/a$
-6	-5	-4	-3	-2	-1	0

Naim et al 1995

Sa	Sab	Sb	Sbc	Sc	Scd	Sd	Sdm	Sm	Im	cI
1	2	3	4	5	6	7	8	9	10	11

This gives a convenient way to plot quantities (like mass, color) vs hubble type

Priority for assigning Hubble Classification*:

1. How tightly the spiral arms are wound
2. Lumpiness of the spiral arms
3. “Bulge-to-Disk Ratio”

E Sa Sb Sc

Note: Galaxies are much more complex than stars. Features are often contradictory.

*Sandage 1961 “The Hubble Atlas of Galaxies”

Many different classification schemes:

- Most share the basic E0-E7,S0,Sa,Sb,Sc tuning fork
- Morphological features get weighted differently in assigning the classification

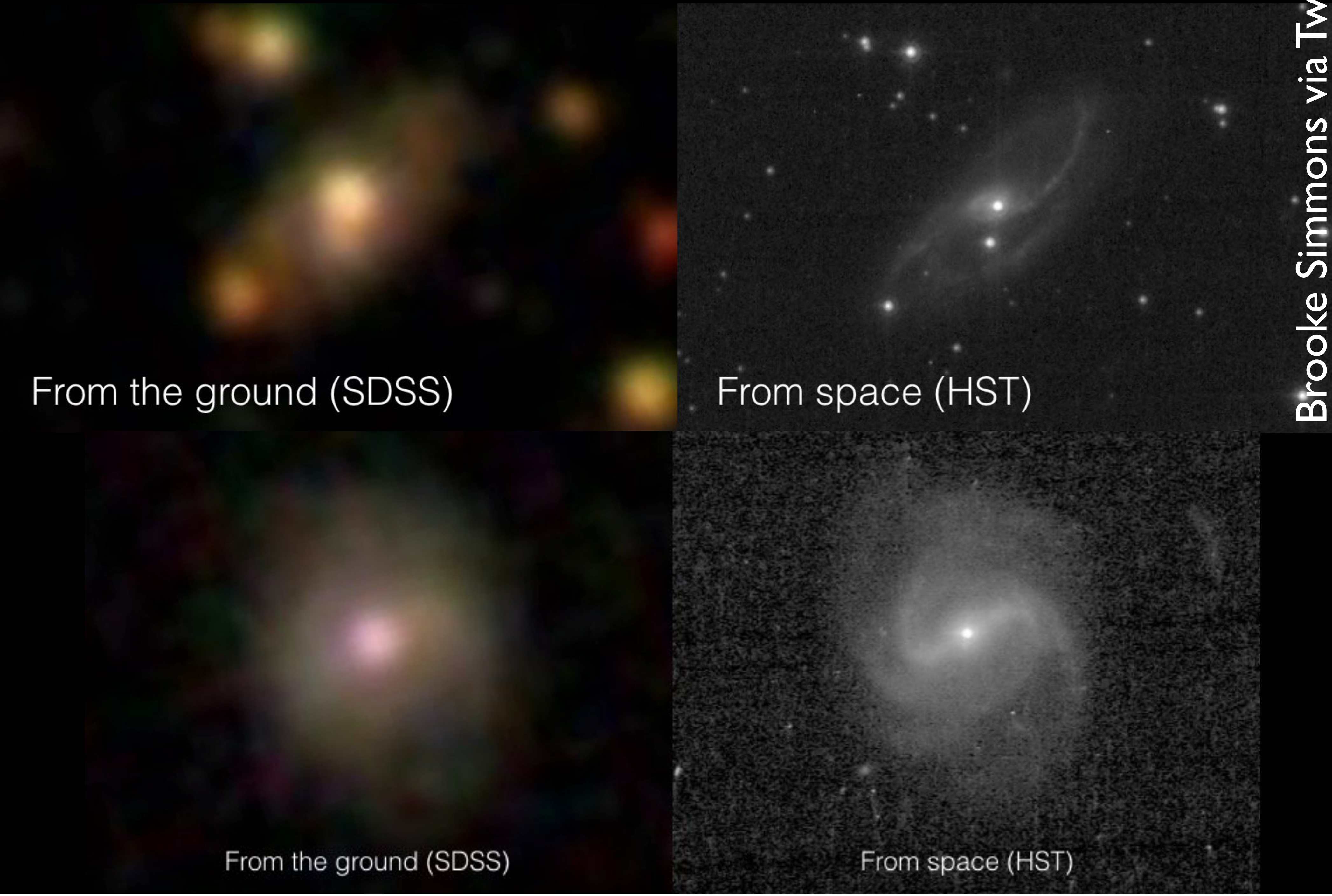
Examples:

- Hubble
- deVaucouleurs (used in the RC3 galaxy catalog, so most widely adopted)
- Sandage (used in the Carnegie Atlas)
- van den Bergh (DDO)

Caveats about morphological classification:

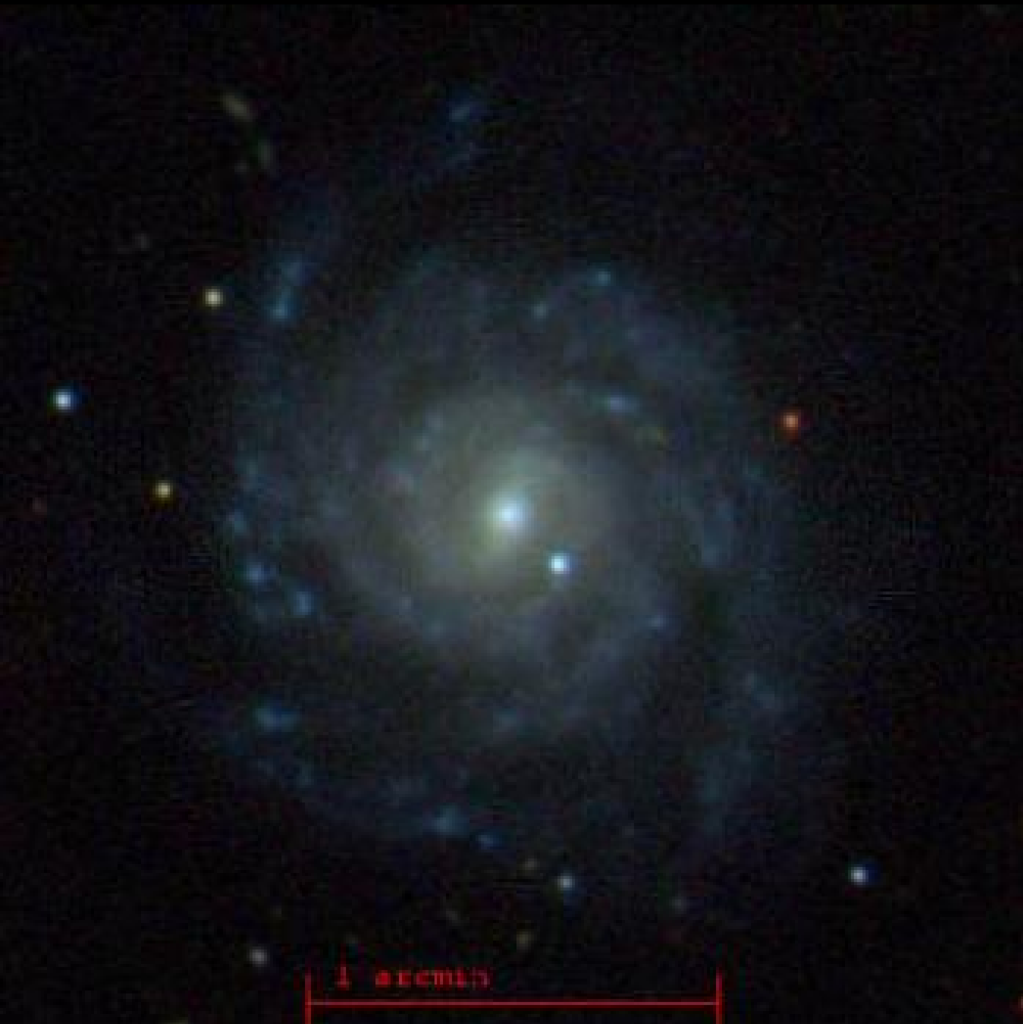
- Inclination Dependent (E0 != spherical)
- Exposure Dependent
- Distance/Resolution Dependent
- Wavelength Dependent
- Classifier Dependent

Distance/Resolution Dependent

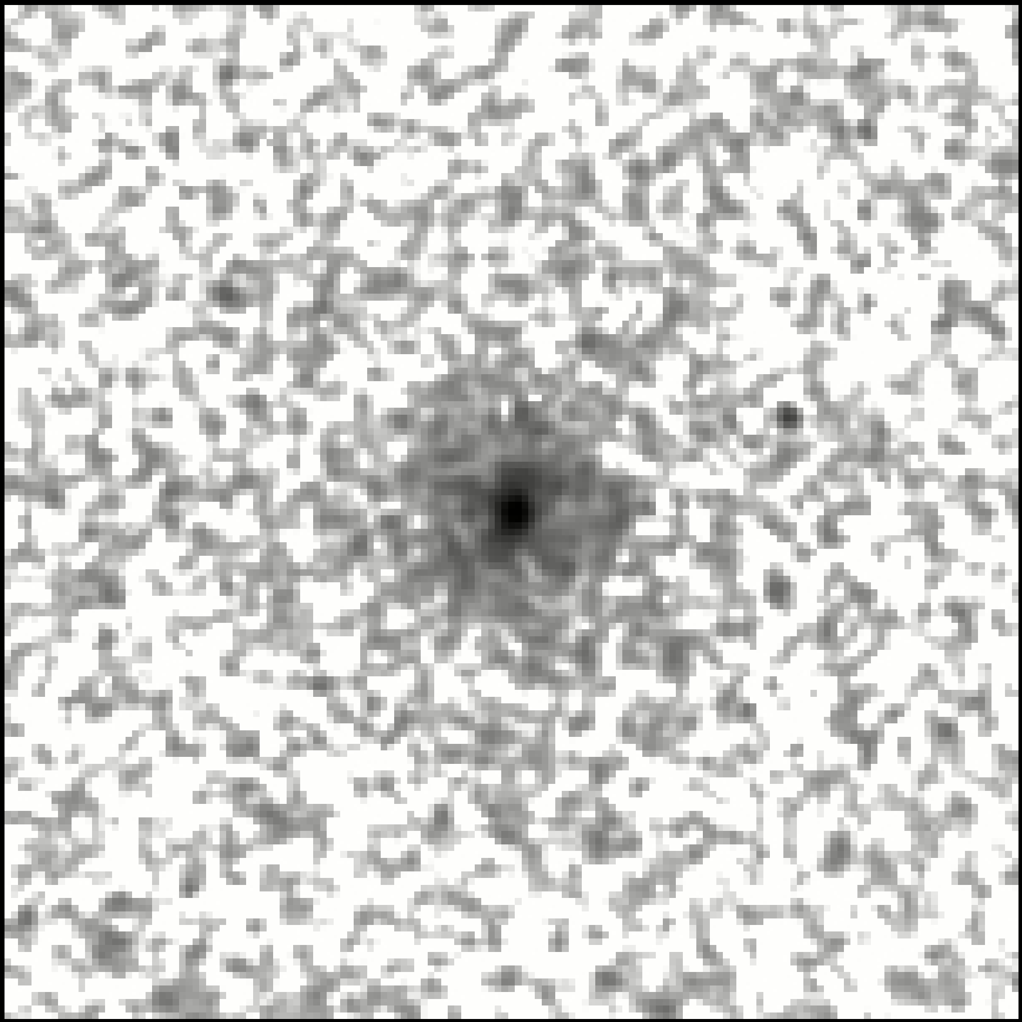


Brooke Simmons via Twitter..

Wavelength Dependent



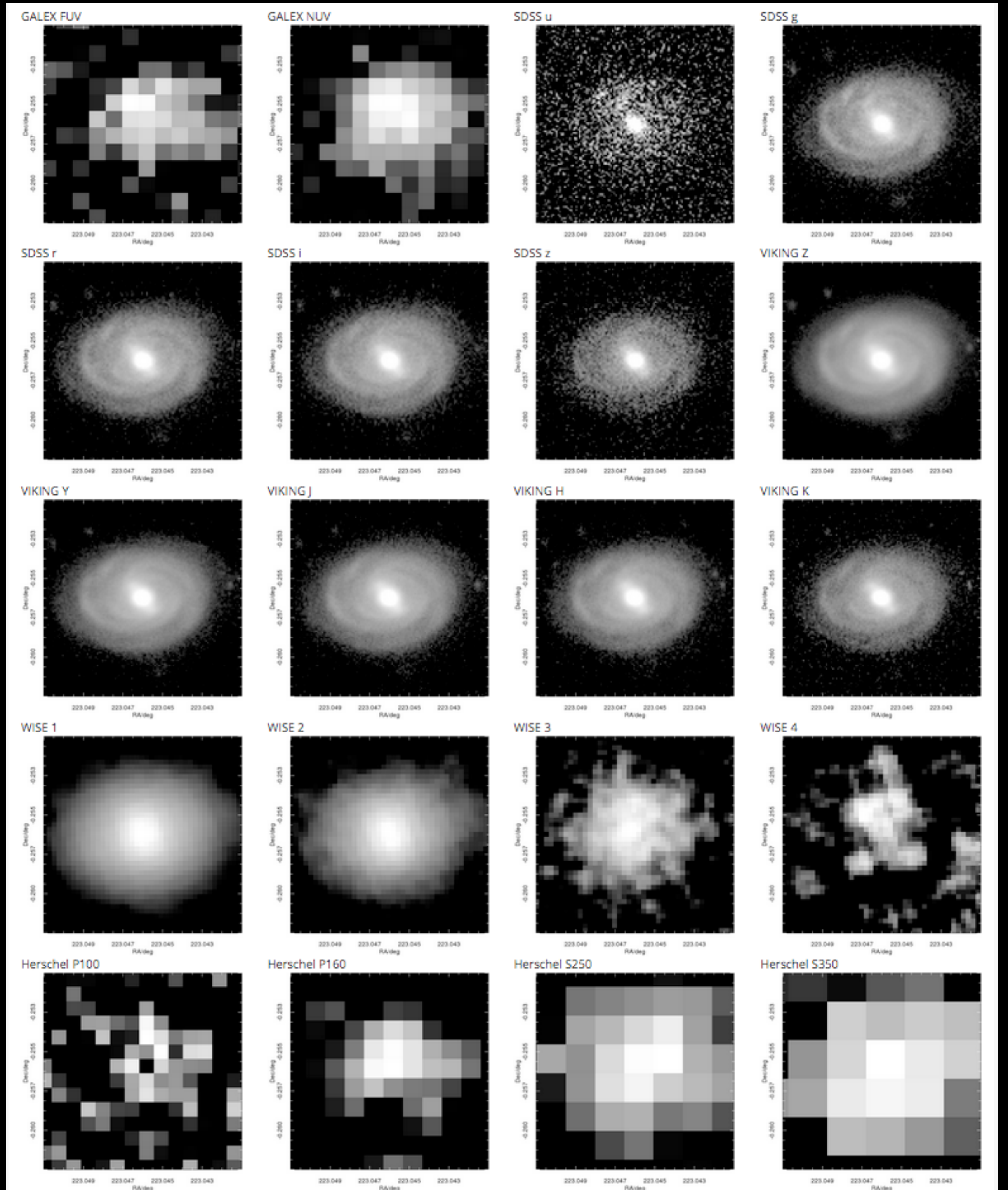
SDSS g,r,I
(optical)



2MASS K_s
(near-infrared)

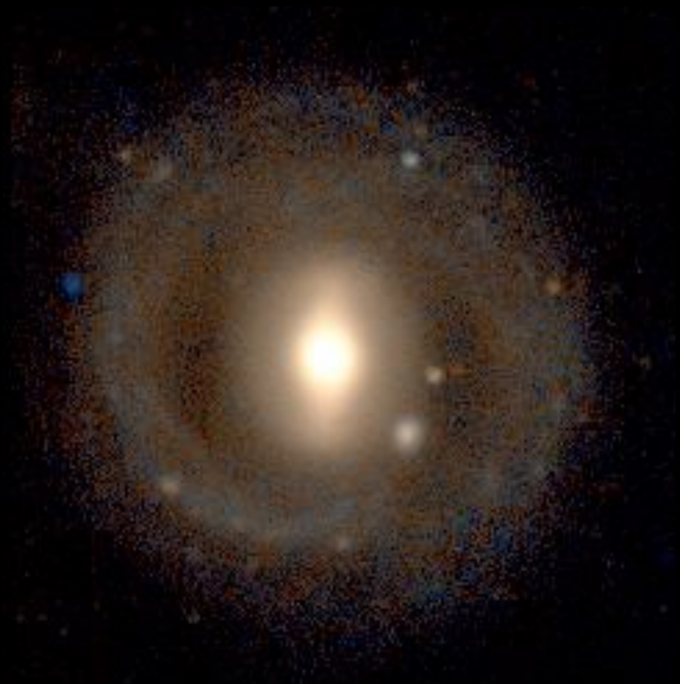
Same galaxy in different filters

(UV through far-IR)



GAMA Survey:
Courtesy Amanda Bauer
http://ict.icrar.org/cutout/

Automatic (Machine) Classification



Numbers

- Reproducable

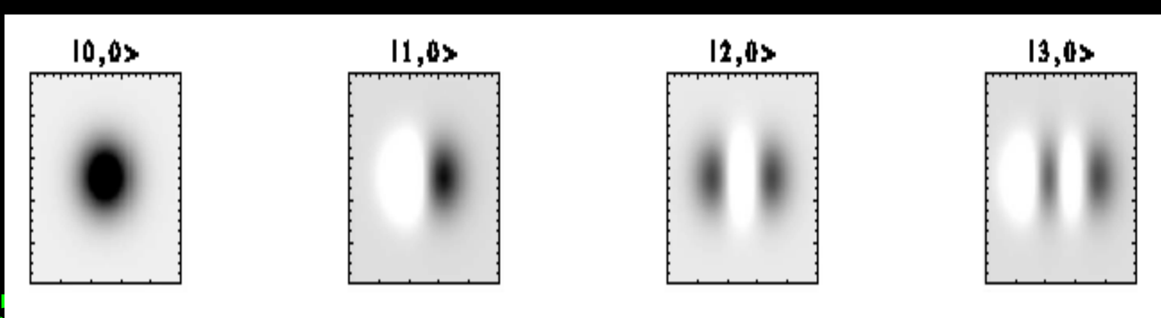
- Can quantify how results change with distance, signal-to-noise, or resolution

(Doi et al 1993, Abraham et al 1994, Simard 1998, Conselice 2003, Kelley & McKay 2004, Lotz et al 2004, Ball et al 2004, & many more!)

Quantifying Morphology

- 2-D bulge+disk fitting (GIM2D; GALFIT)
- Concentration Index

  $c = R_{20}/R_{50}$ -- ratio of radii containing 20% vs 50% of the light. Various choices of %'s made.
- Asymmetry A (rotate image, subtract, quantify residual)
- Smoothness S
- Gini Coefficient G
- Shapelet decomposition



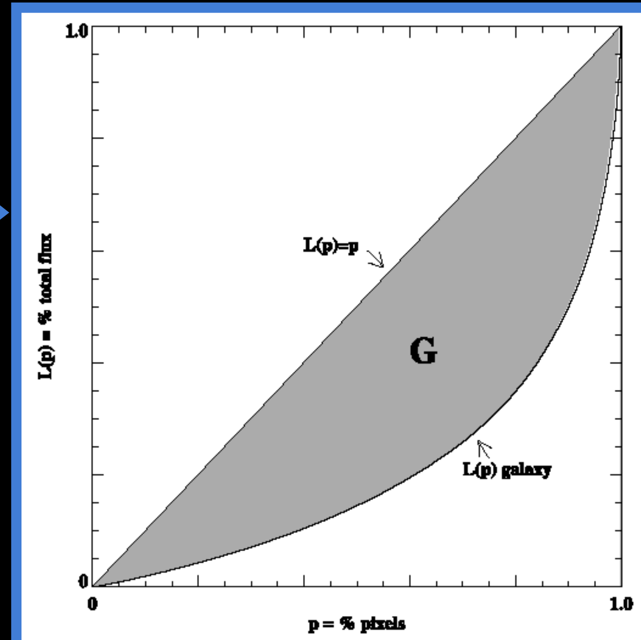
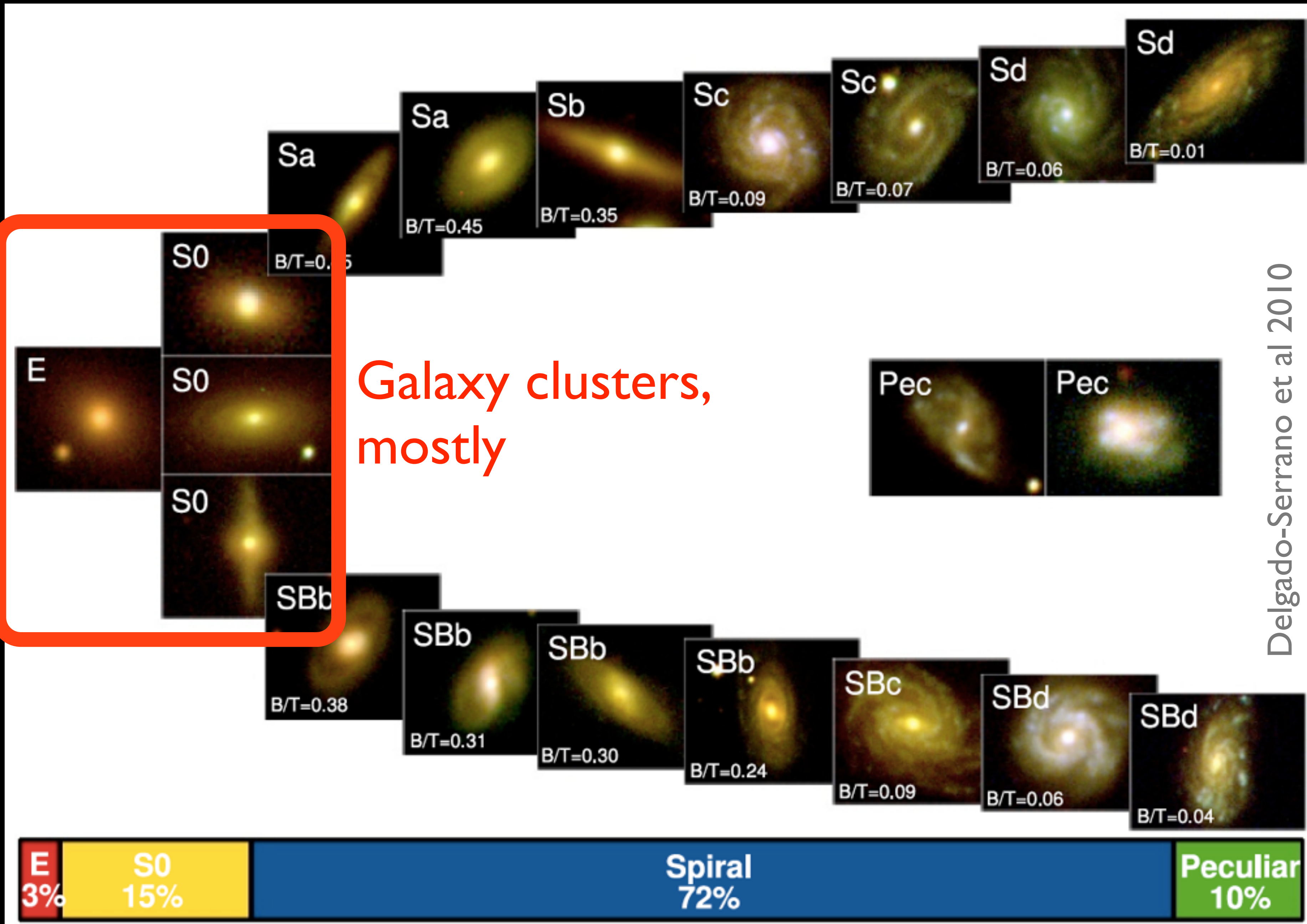


FIG. 1.—Lorenz curve: the Gini coefficient is the area between the Lorenz curve of the galaxy's pixels and that of equitable distribution (*shaded region*). The given curve is for S0 NGC 4526, $G = 0.59$.

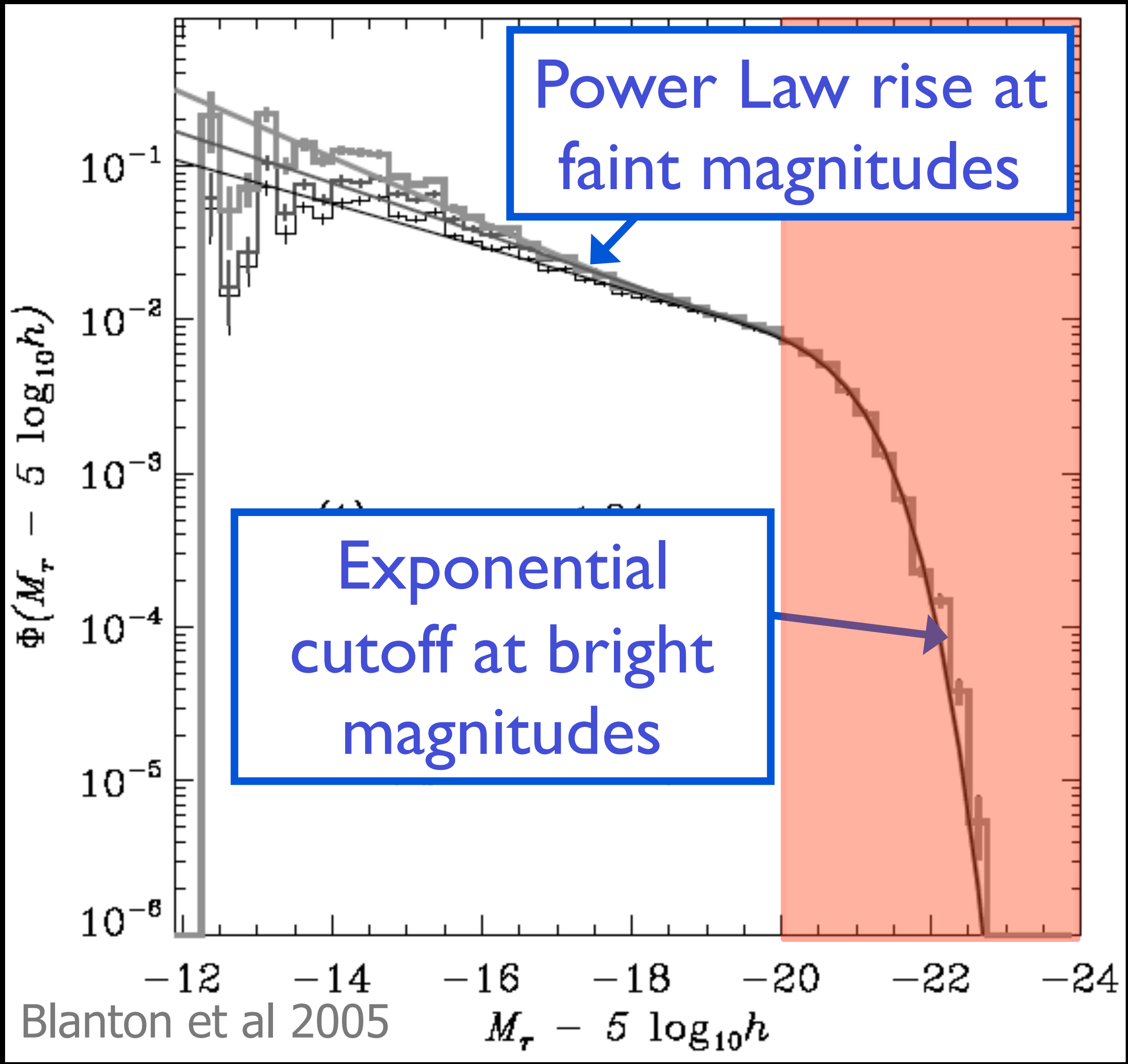
Luminous Galaxies are mostly spirals

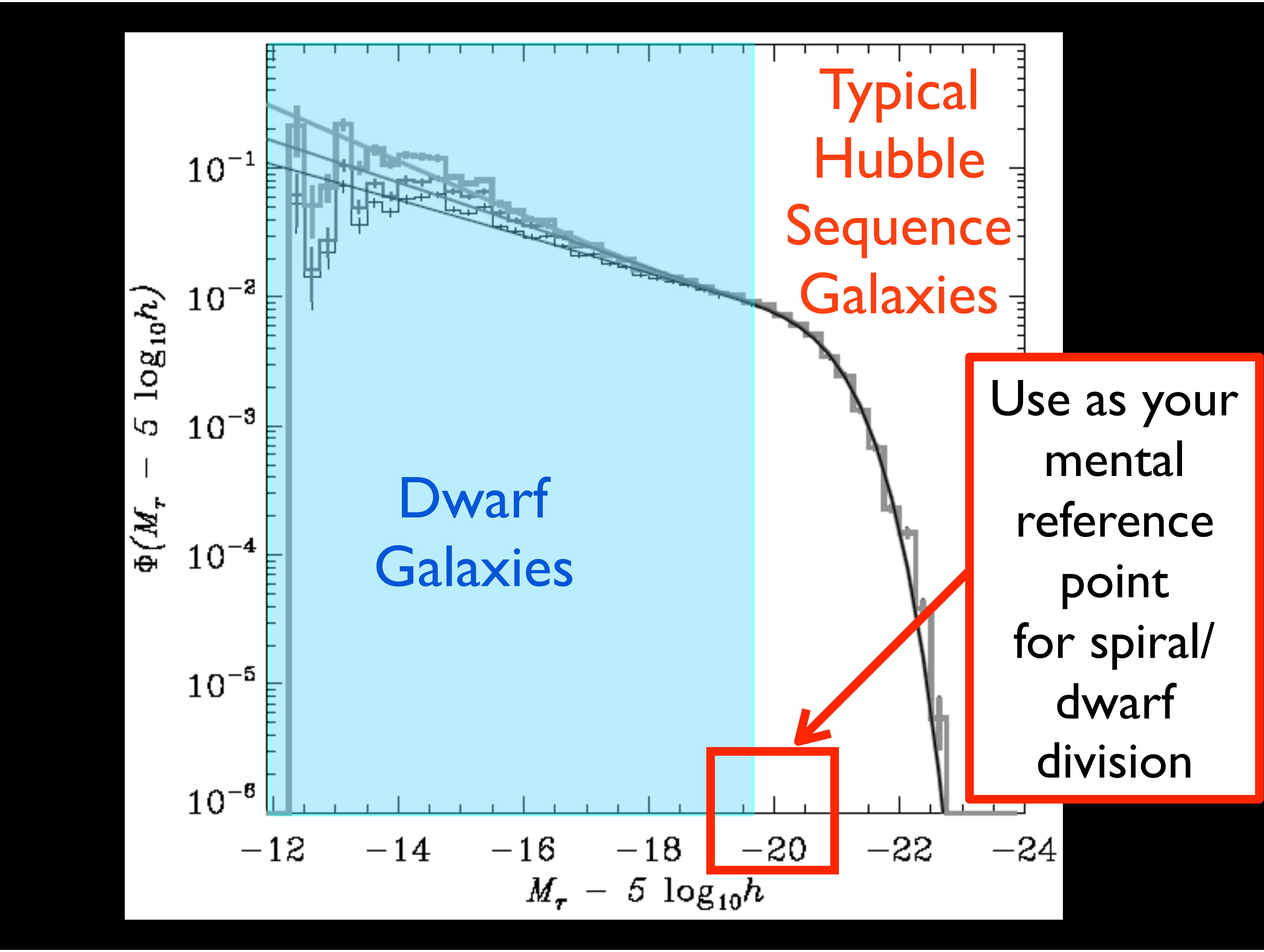


SDSS: $M_J < -20.3$

By number, most galaxies *aren't* luminous

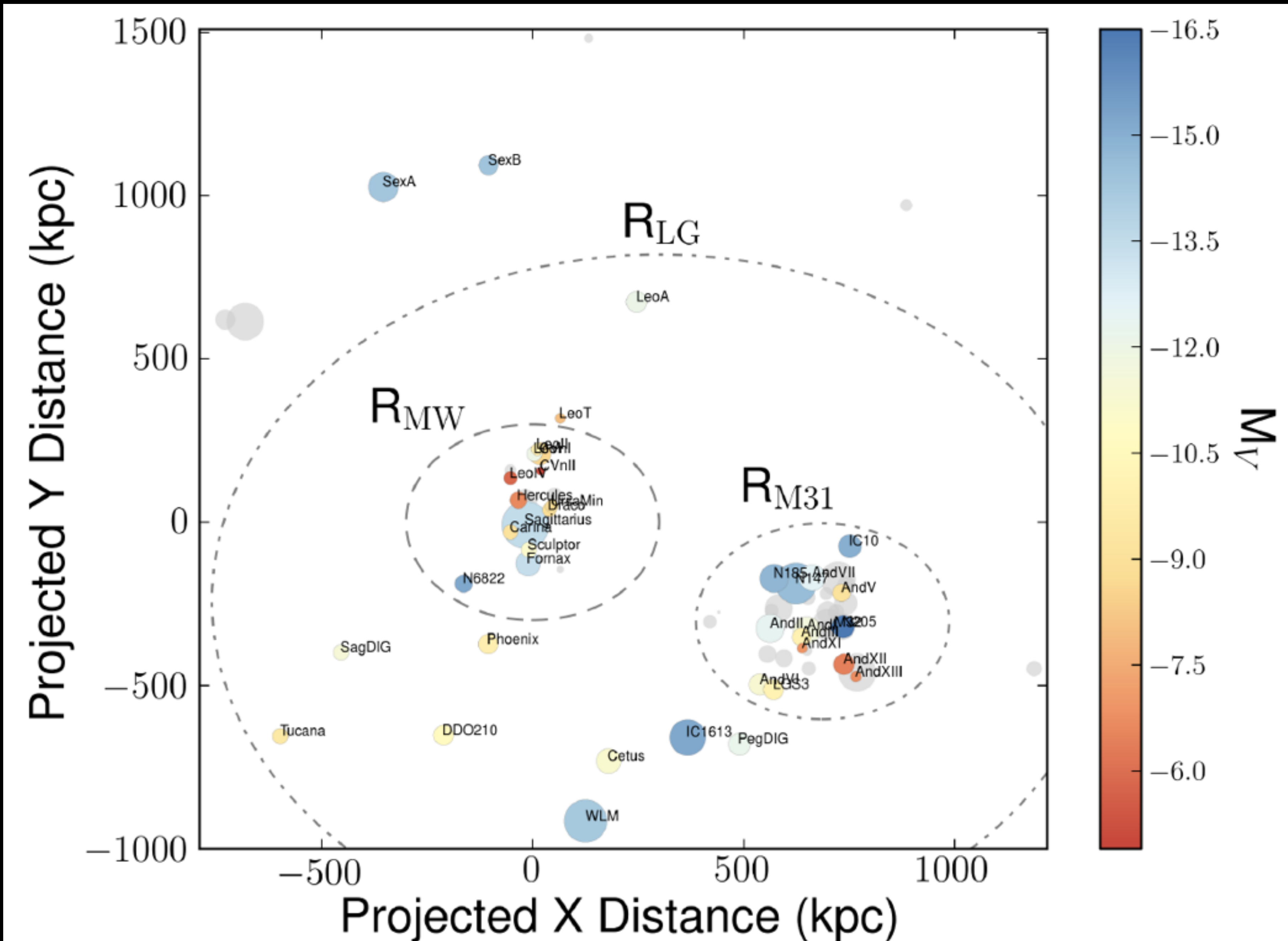
"Luminosity Function"
$\Phi(L)dL$ = # of galaxies per unit volume with luminosities between L and $L+dL$





Typical Hubble Sequence Galaxies
Dwarf Galaxies
Use as your mental reference point for spiral/ dwarf division
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\Phi(M_r - 5\log_{10}h)$
-12
-14
-16
-18
-20
-22
-24
$M_r - 5\log_{10}h$

Most Local Group galaxies are dwarfs



Weisz et al 2014

Dwarf galaxies lie outside of the standard Hubble Sequence

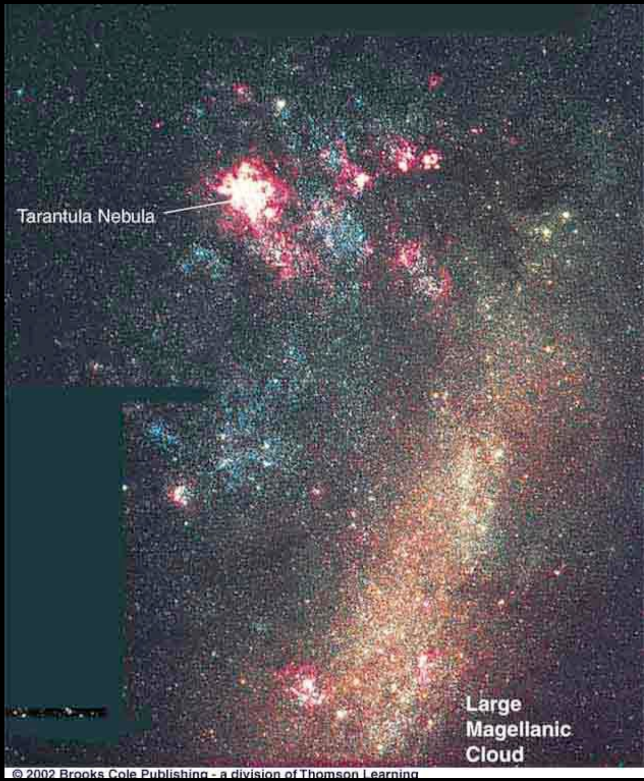
Dwarf ellipticals:
Smooth & compact
dE

Dwarf irregulars:
Lumpy & diffuse
dIrr, Sm, Im

Dwarf Spheroidals:
Smooth, diffuse
dSph

Dwarf Irregulars

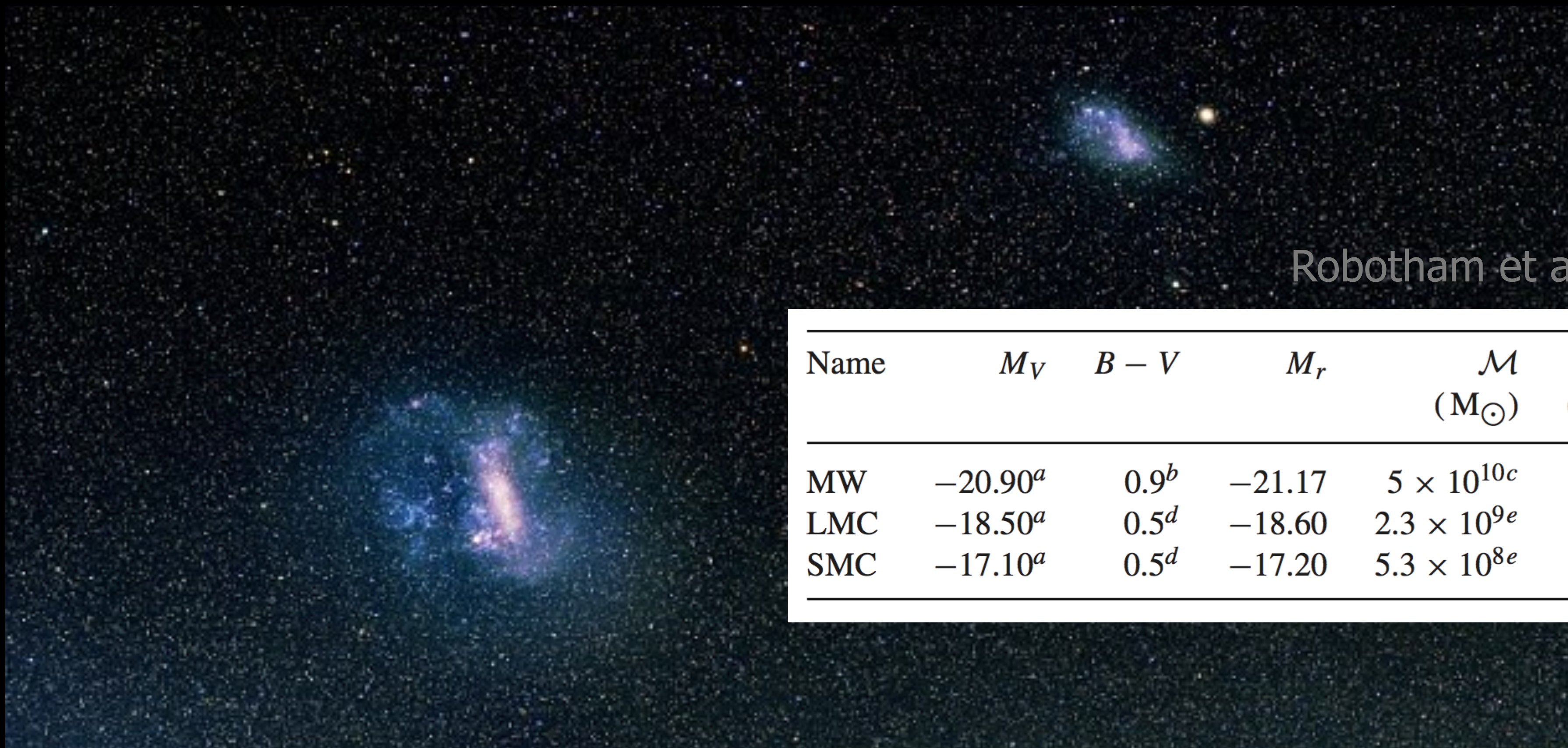
Sextans A



LMC

- No obvious bulge or spiral patterns.
- Obvious star forming regions
- Most common type of dwarf galaxy.

dIrr Reference Points: The Large & Small Magellanic Clouds



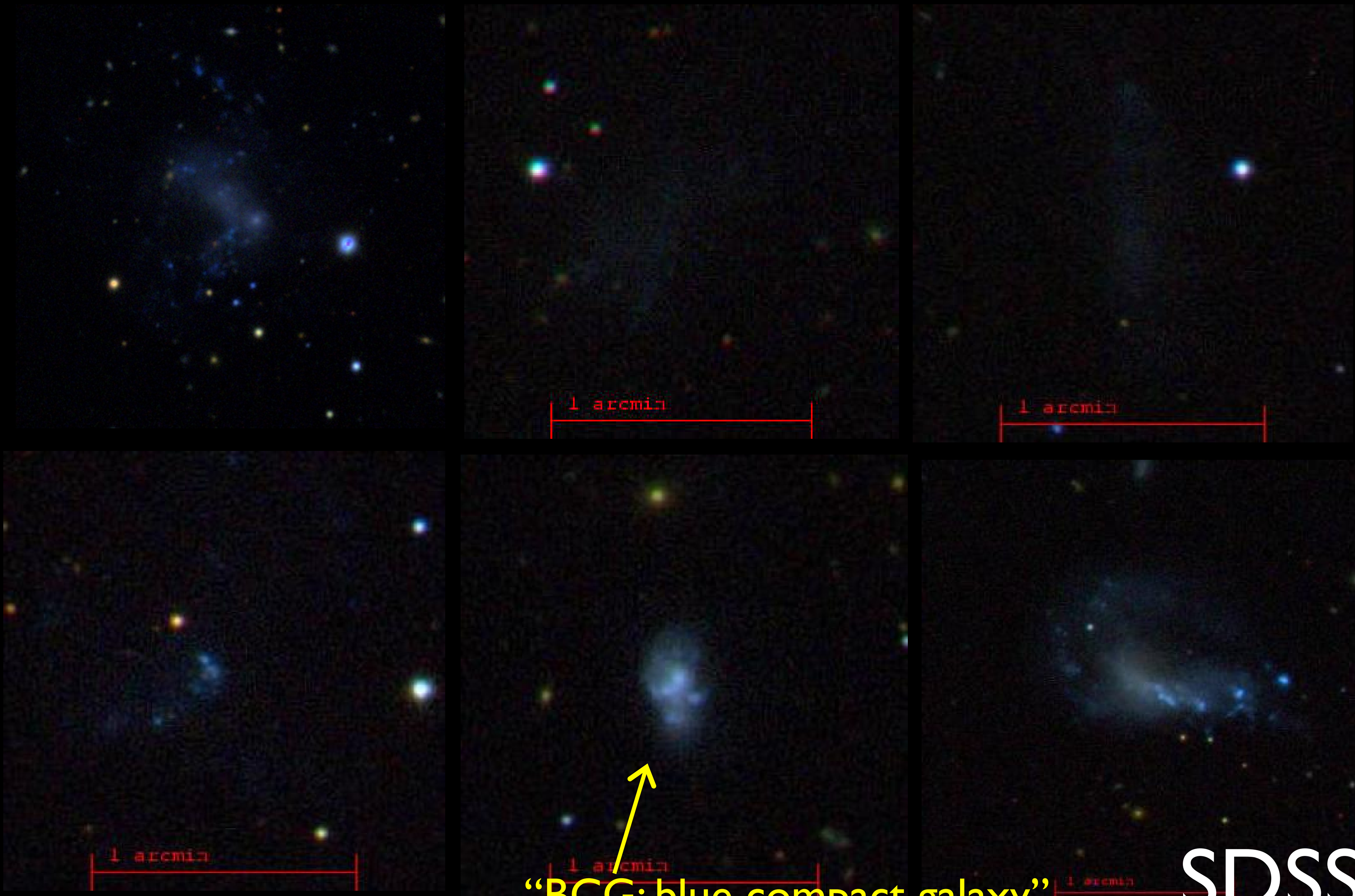
Robotham et al 2012

Name	M_V	$B-V$	M_r	$\mathcal{M}$ ($M_\odot$)	D (kpc)
MW	-20.90^a	0.9^b	-21.17	5×10^{10c}	0
LMC	-18.50^a	0.5^d	-18.60	2.3×10^{9e}	50^f
SMC	-17.10^a	0.5^d	-17.20	5.3×10^{8e}	60^f

LMC
M_V=-18.5
[Fe/H]=-0.5

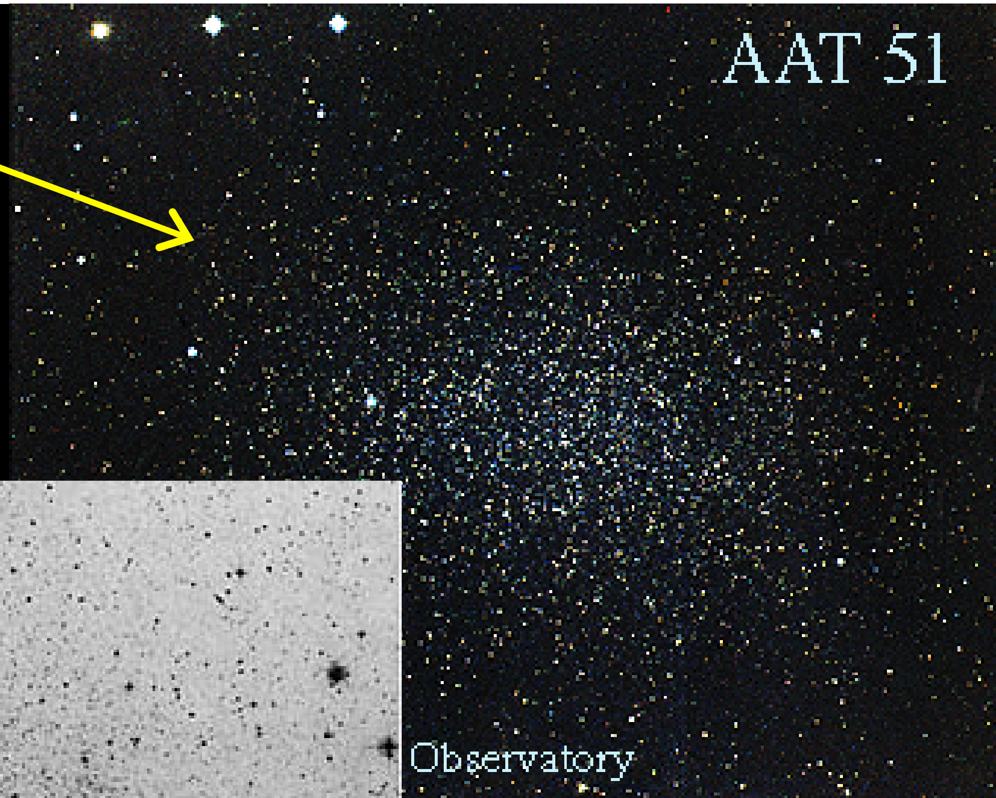
SMC
M_V=-17
[Fe/H]=-1

Most are fainter than SMC

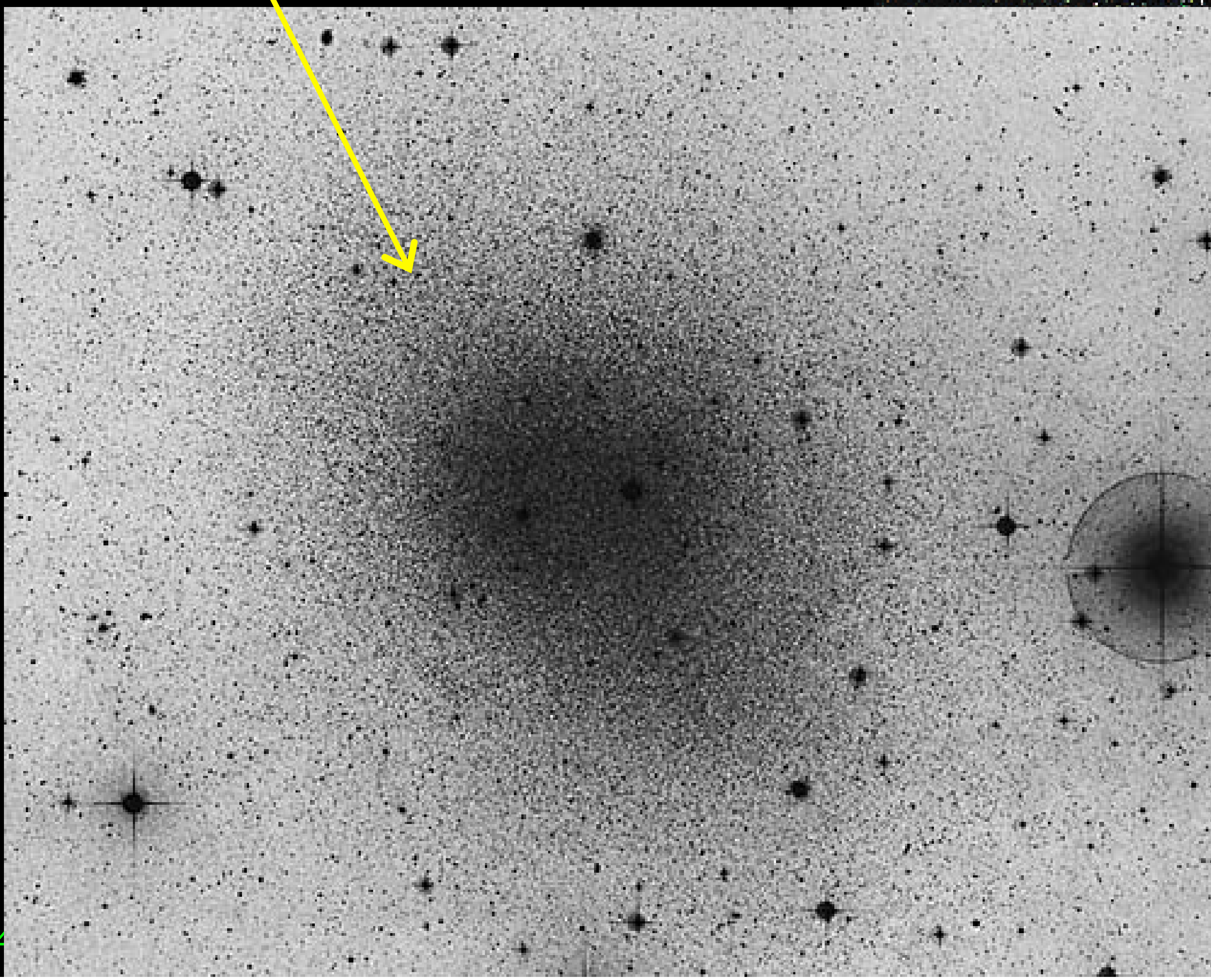


Dwarf Spheroidals

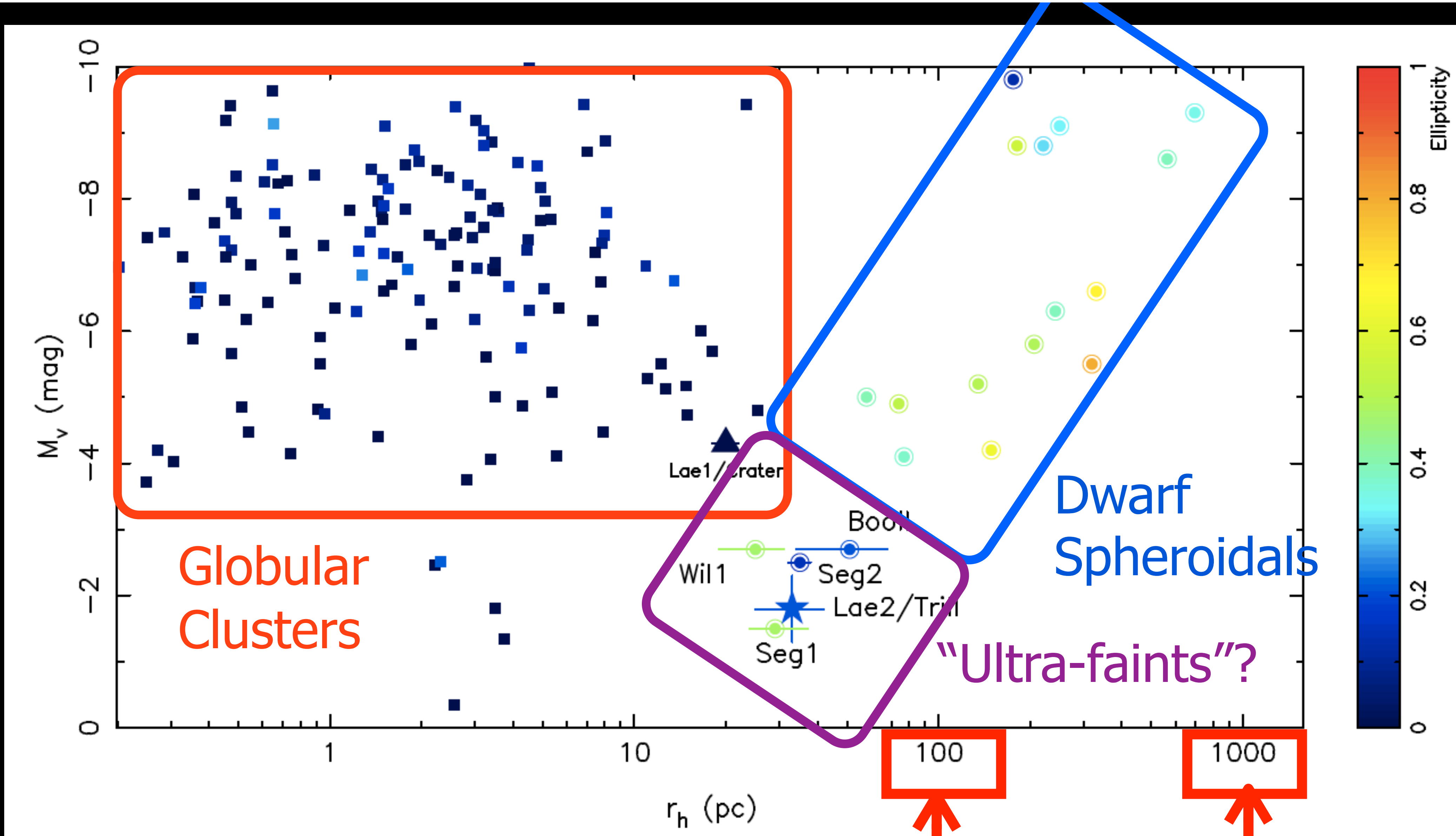
Leo I



Fornax



Faintest galaxies known are dSph. Almost all are in the Local group.



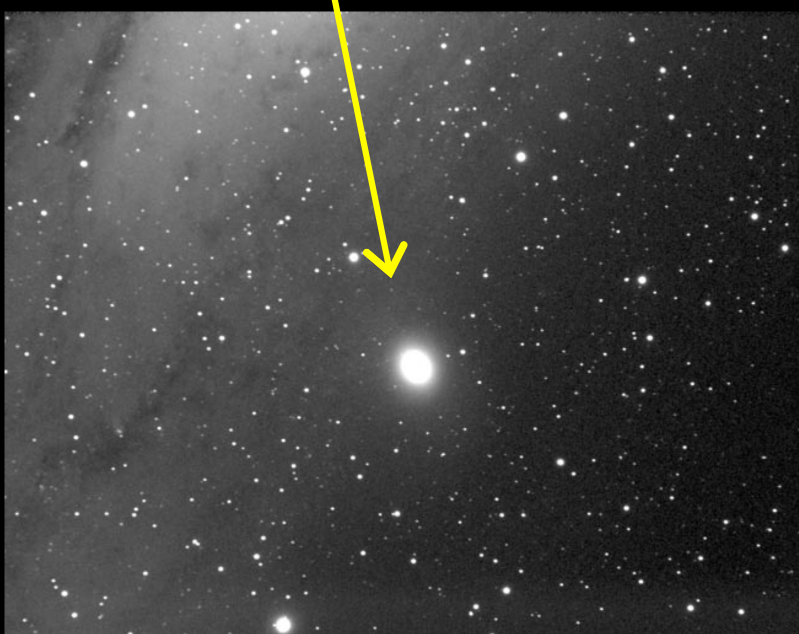
aevens et al 2015

Use as your mental reference points for size

Dwarf Ellipticals

NGC 205

M32

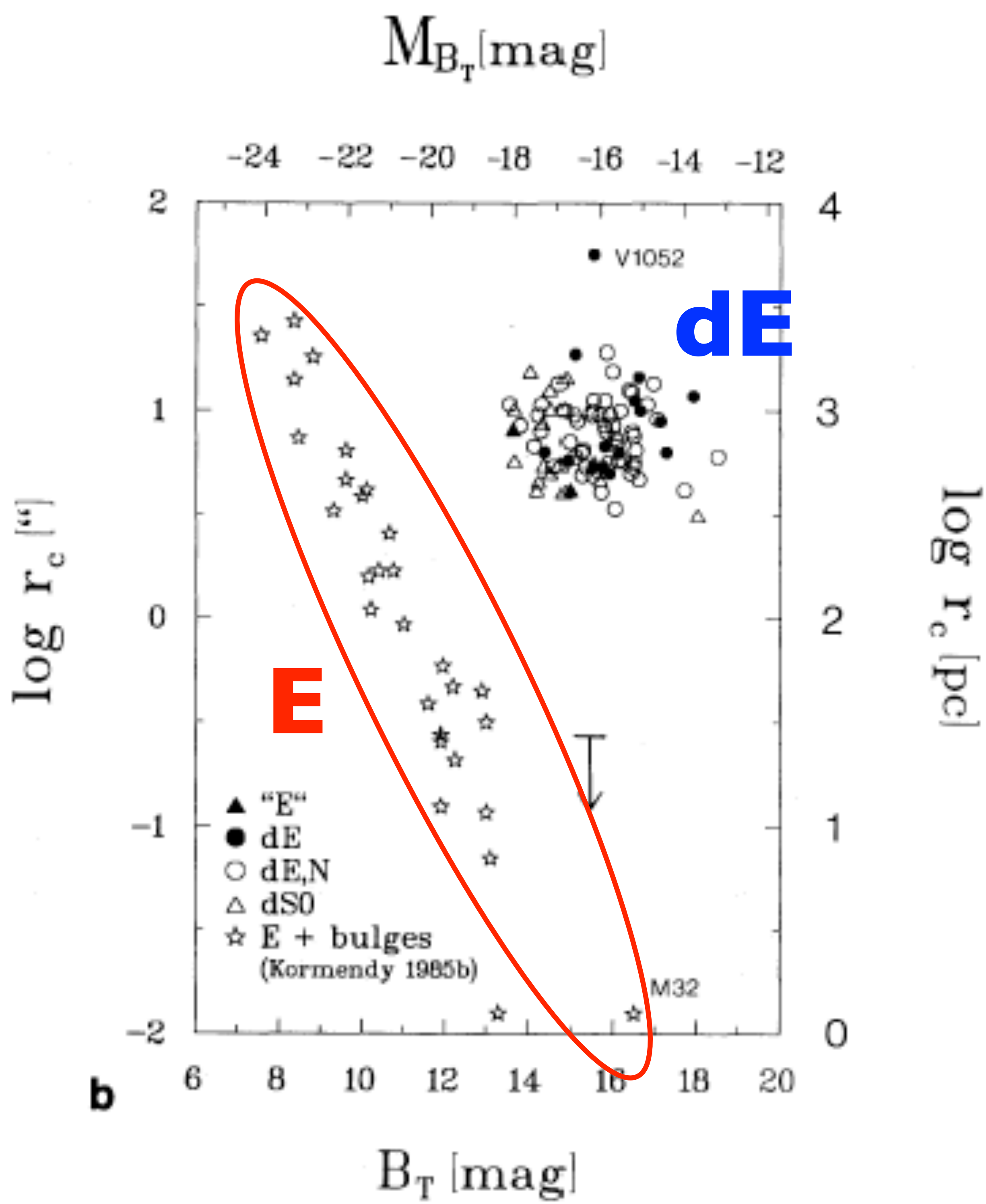


(Both are M31 companions)

Tend to be found in high density regions (Binggeli et al 90).

Dwarf Ellipticals

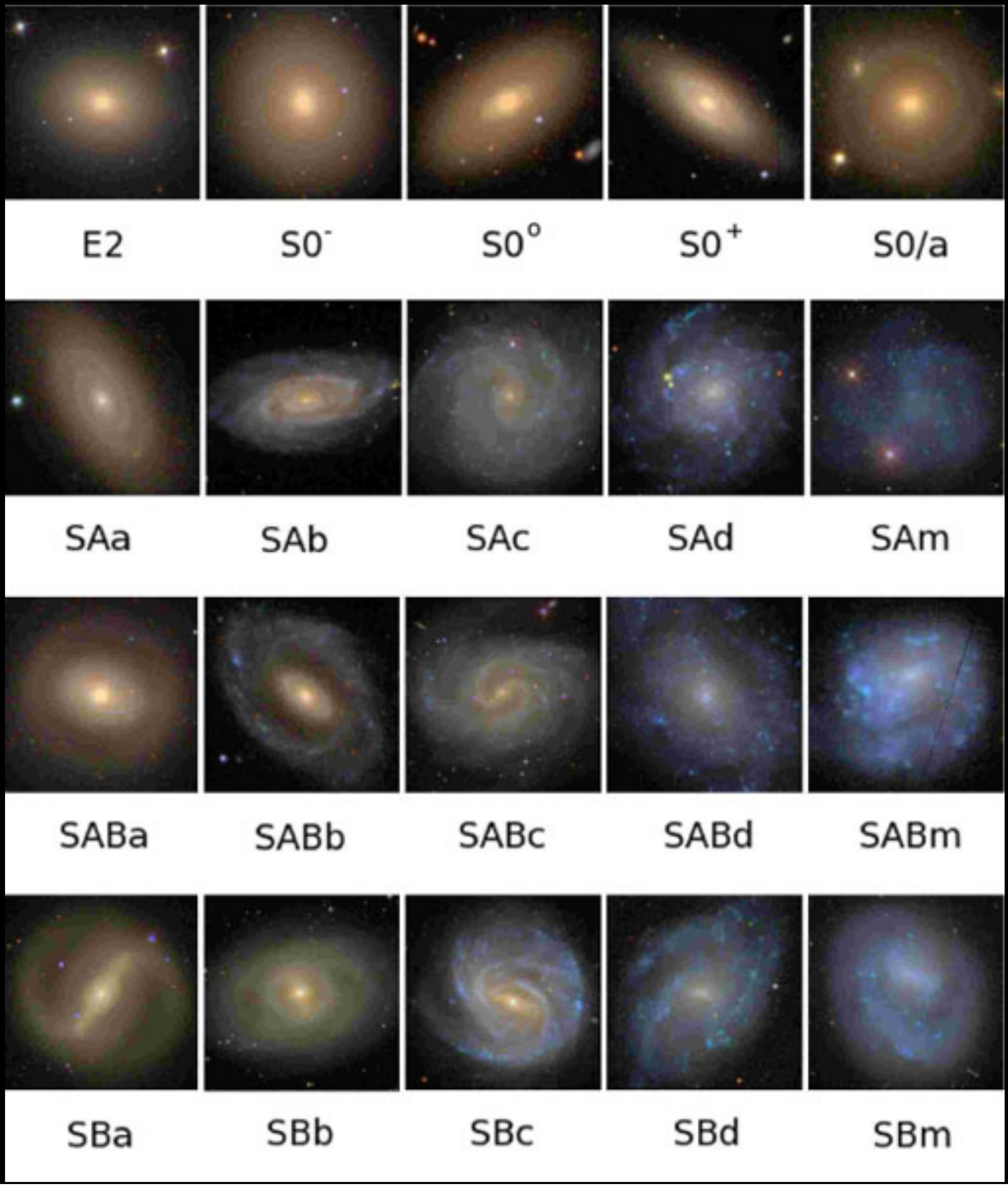
- Most not actually like ellipticals.
- Structurally more like dIrrs, but with SF turned off.



Virgo Cluster
Bingelli et al 1991

http://ned.ipac.caltech.edu/level5/Sept11/Buta/Buta15.html

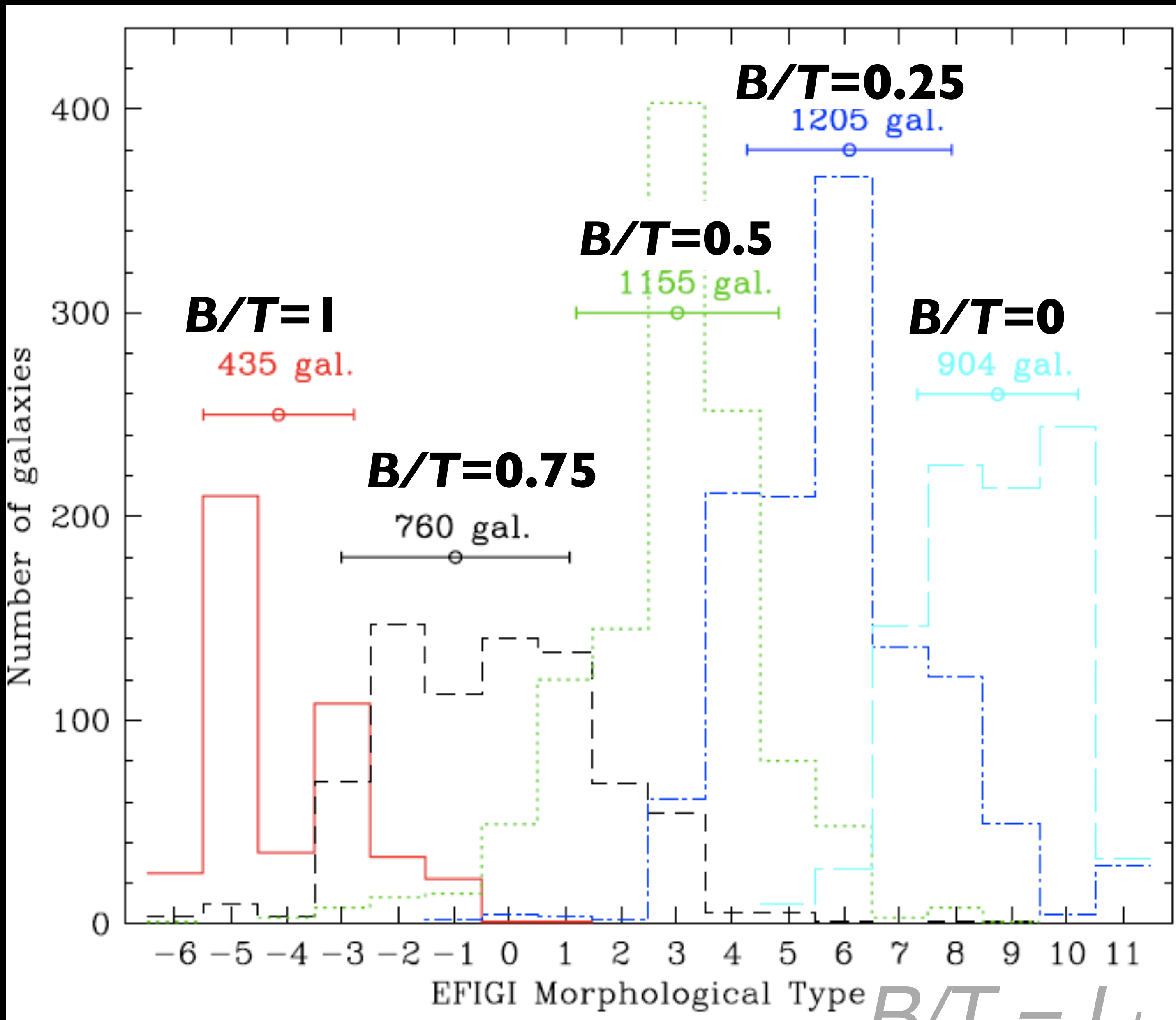
Science from Classification



Morphology vs Galaxy Properties

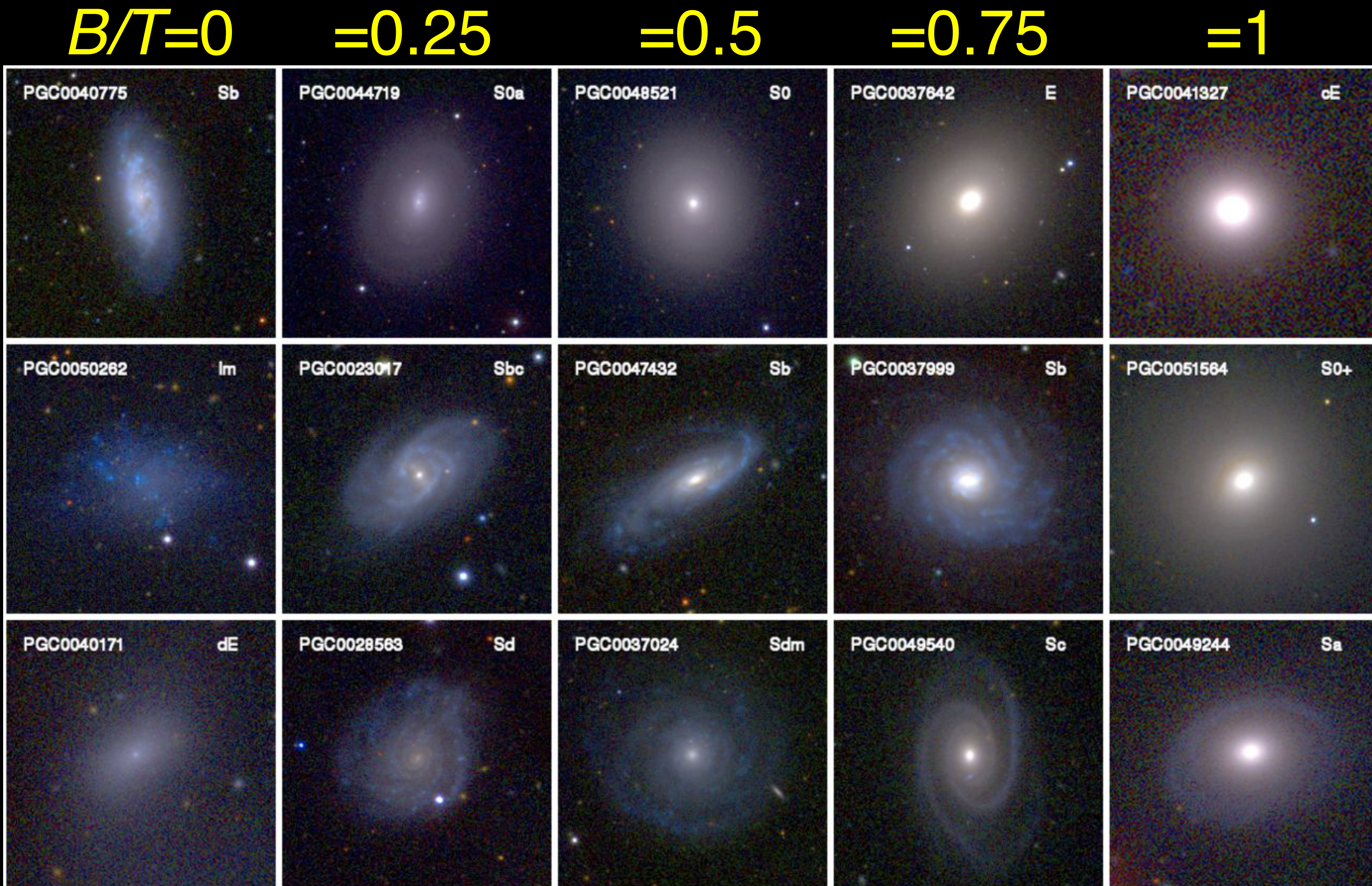
- Bulge-to-disk ratio
- Color
- Fraction of baryons in gas vs stars
- Luminosity

Broad range of T-type for fixed L_{bulge}/L_{total} (= B/T, "bulge-to-total")



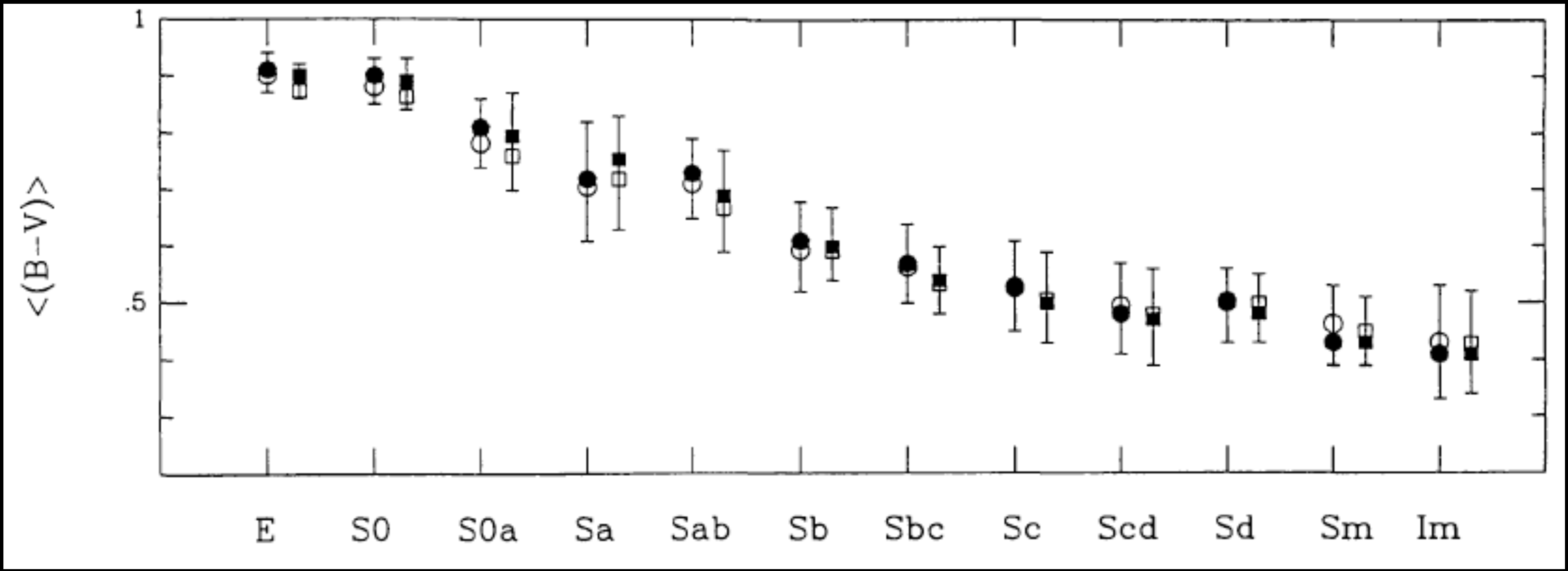
$B/T = L_{bulge}/L_{total}$

Broad range of T type for fixed B/T



SDSS; de Lapparent et al 2011; Baillard et al 2011

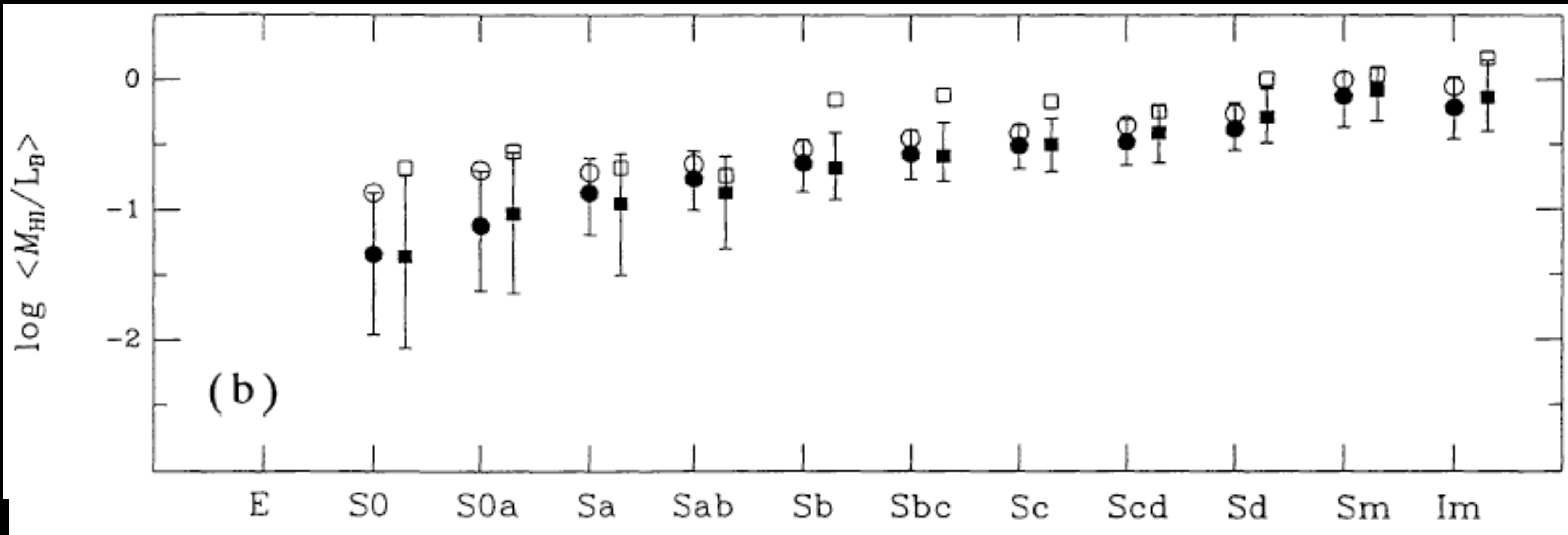
Late-type galaxies = Bluer



Not a profound correlation, since "lumpiness", an indicator of current star formation, is a critical aspect of classification, and young stars are blue

(Roberts & Haynes 1994)

Late-type galaxies = Gas Rich

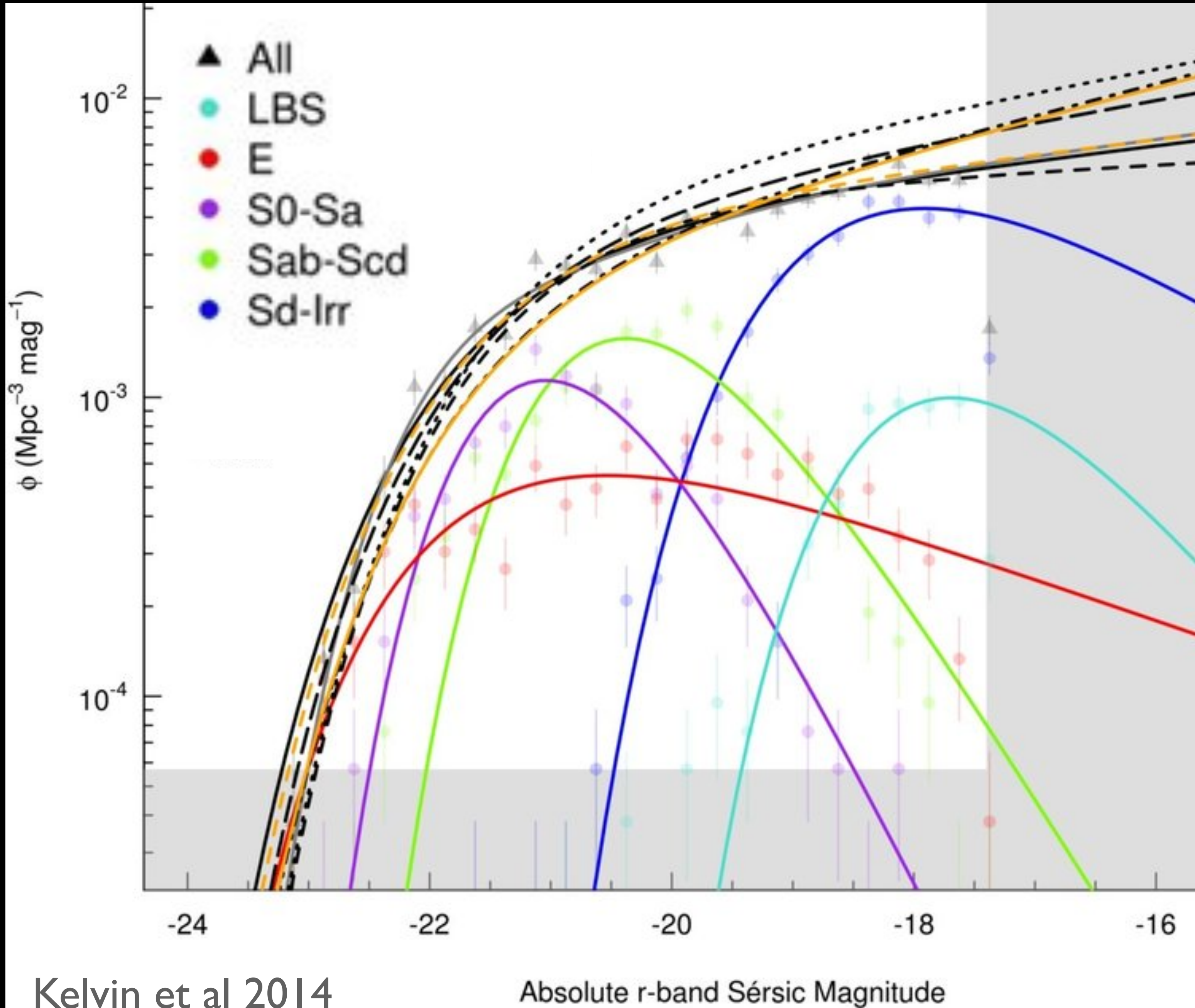


Again, not a profound correlation, since current star formation (which produces lumpy arms) also means that gas is lying around.

Later-type galaxies = Fainter

This ***is*** a meaningful correlation, because luminosity is **not** a criteria for classification

(Milky Way: $M_B \sim -20$)

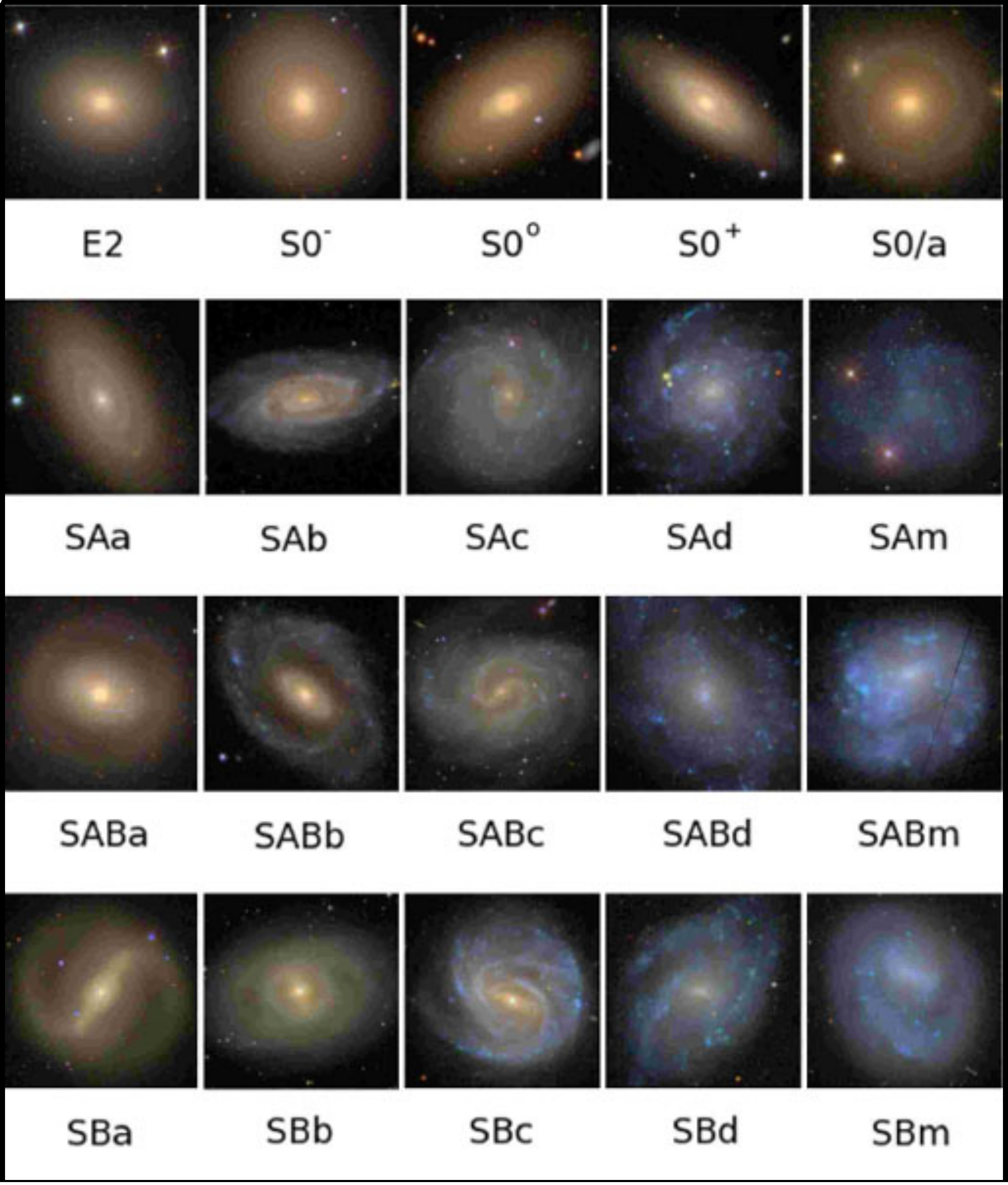


Kelvin et al 2014

http://ned.ipac.caltech.edu/level5/Sept11/Buta/Buta15.html

Summary:

- More Massive
- Gas Poor
- Redder
- Older Stars

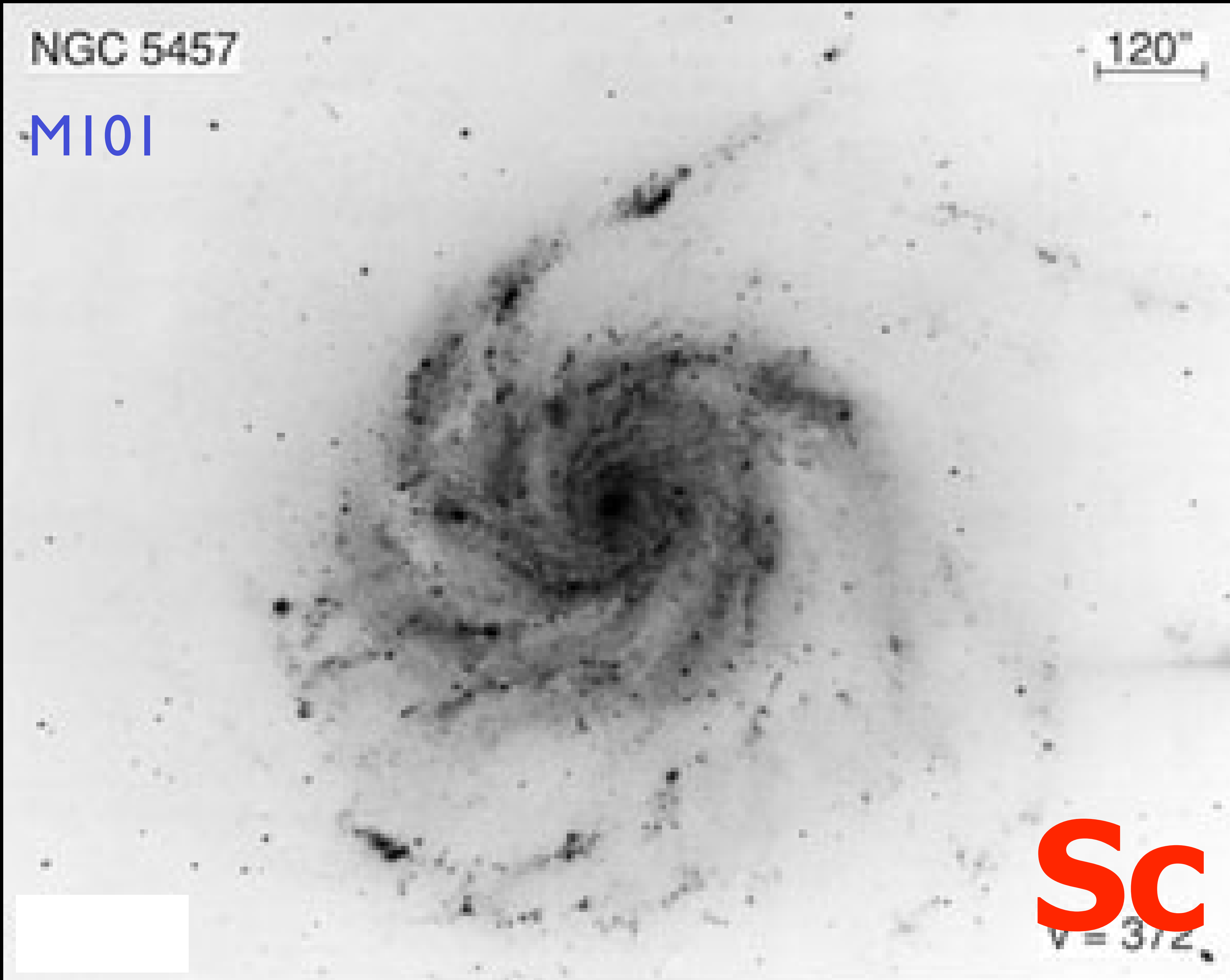


- Less Massive
- Gas Rich
- Bluer
- On-going Star Formation

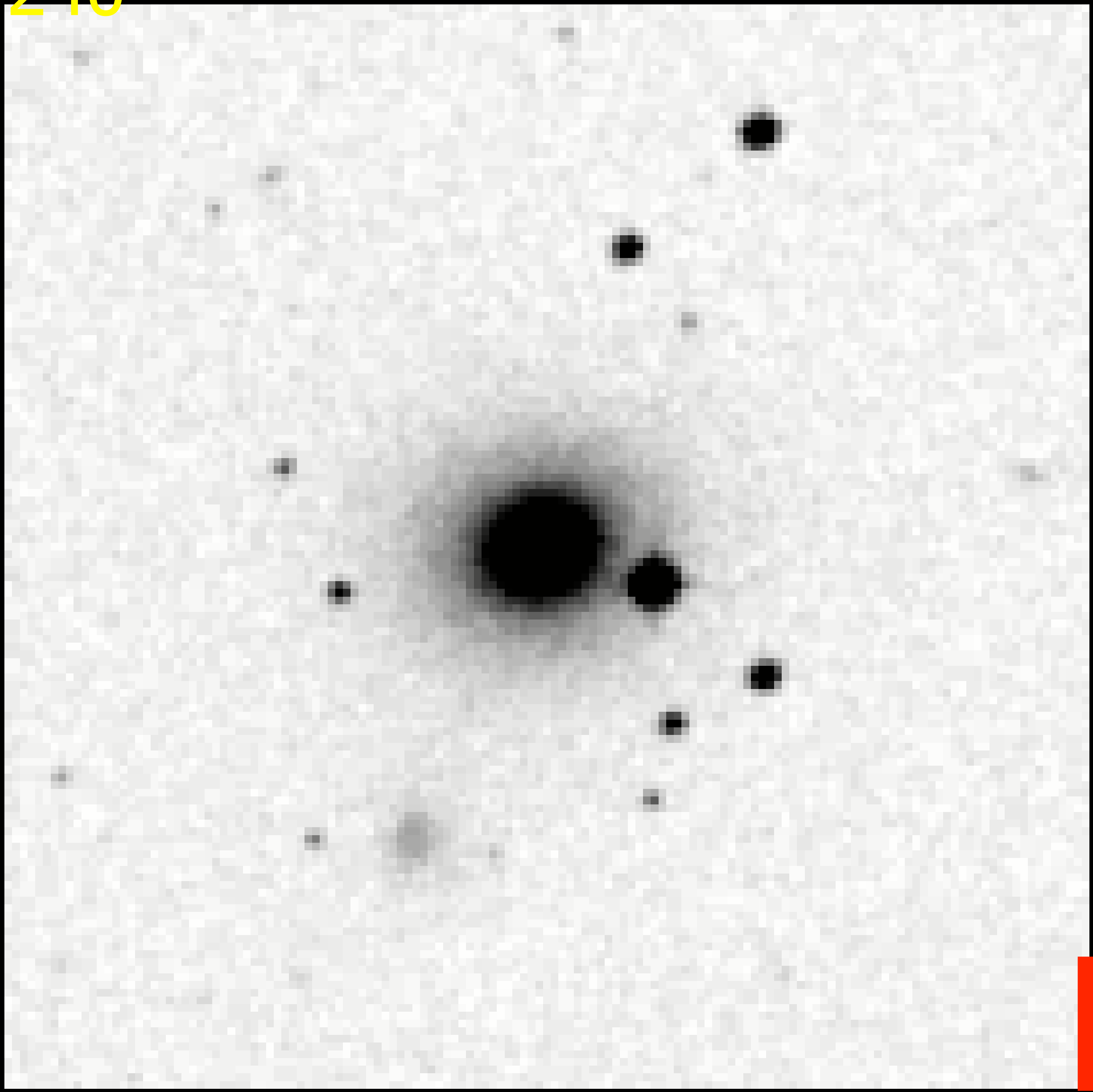
Outstanding Questions

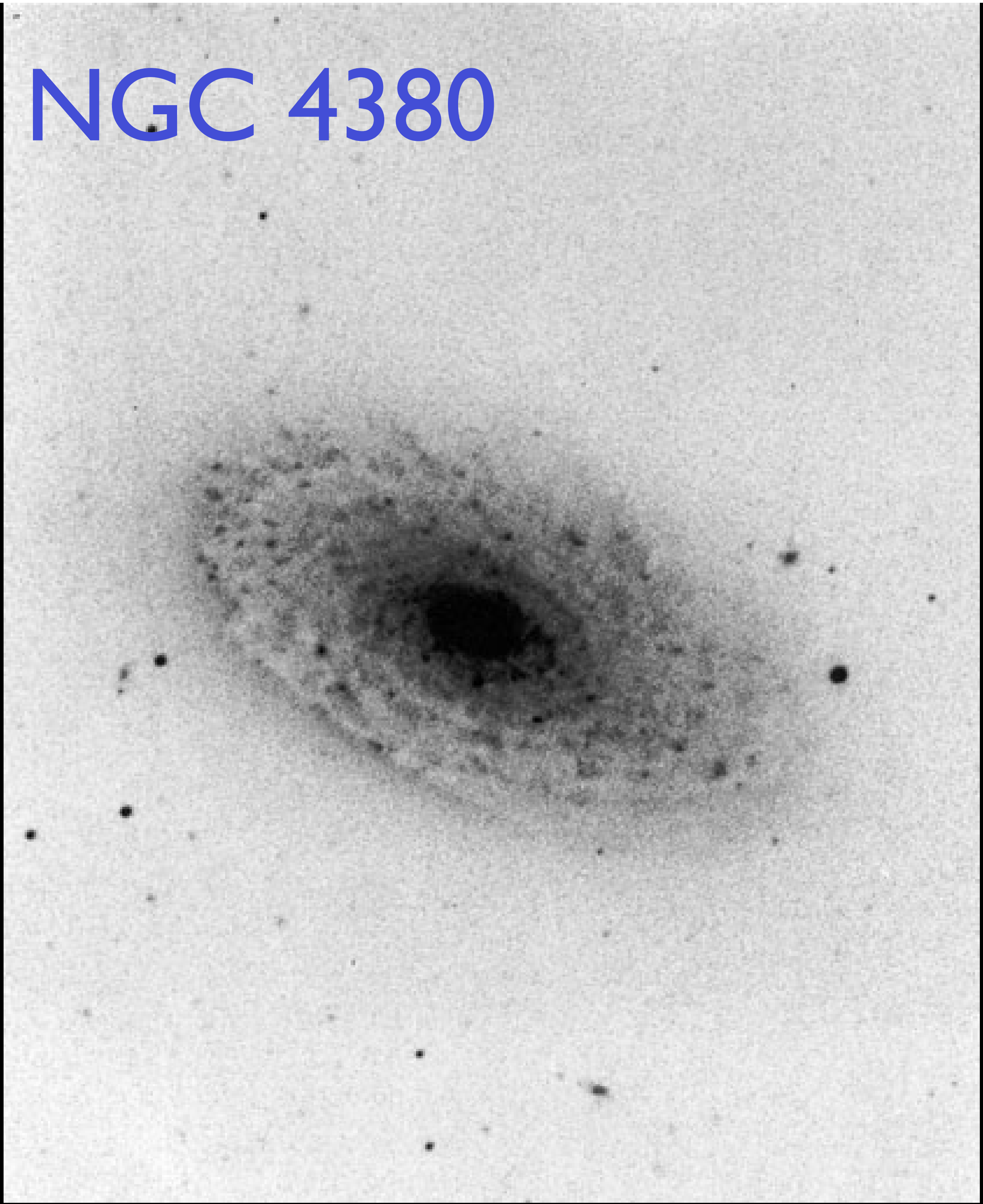
- Why do the features involved in classification go together?
- What physical conditions set a galaxy's Hubble-type? Is it predictible?
- How stable is a galaxy's Hubble type with time?
- Bars. What's up with that?
- Is the origin of bulges the same at both ends of the Hubble sequence (Sa vs Sc)?

Let's play, Classify That Galaxy!


NGC 5457
120"
M101
Sc

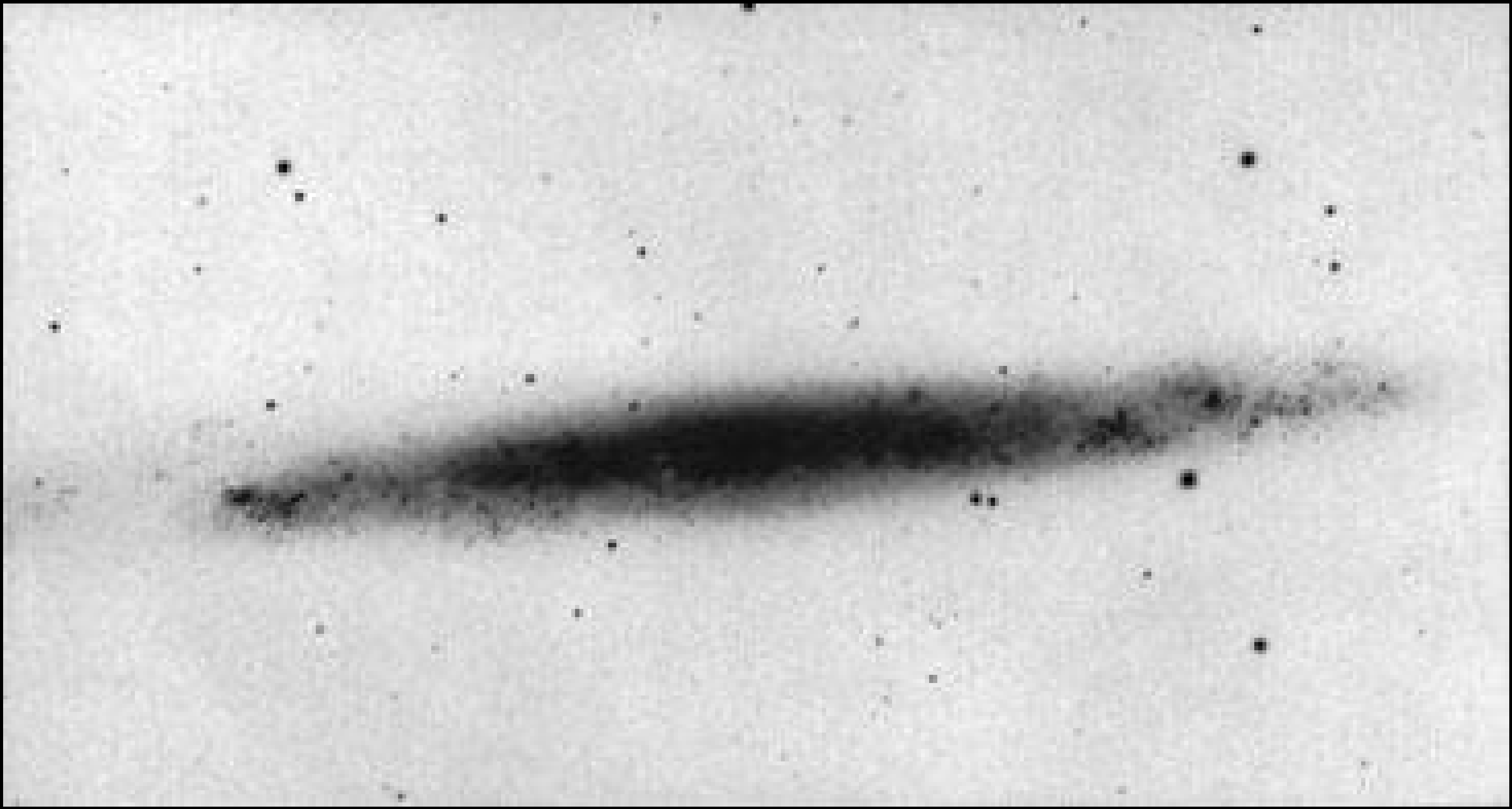
NGC 4240





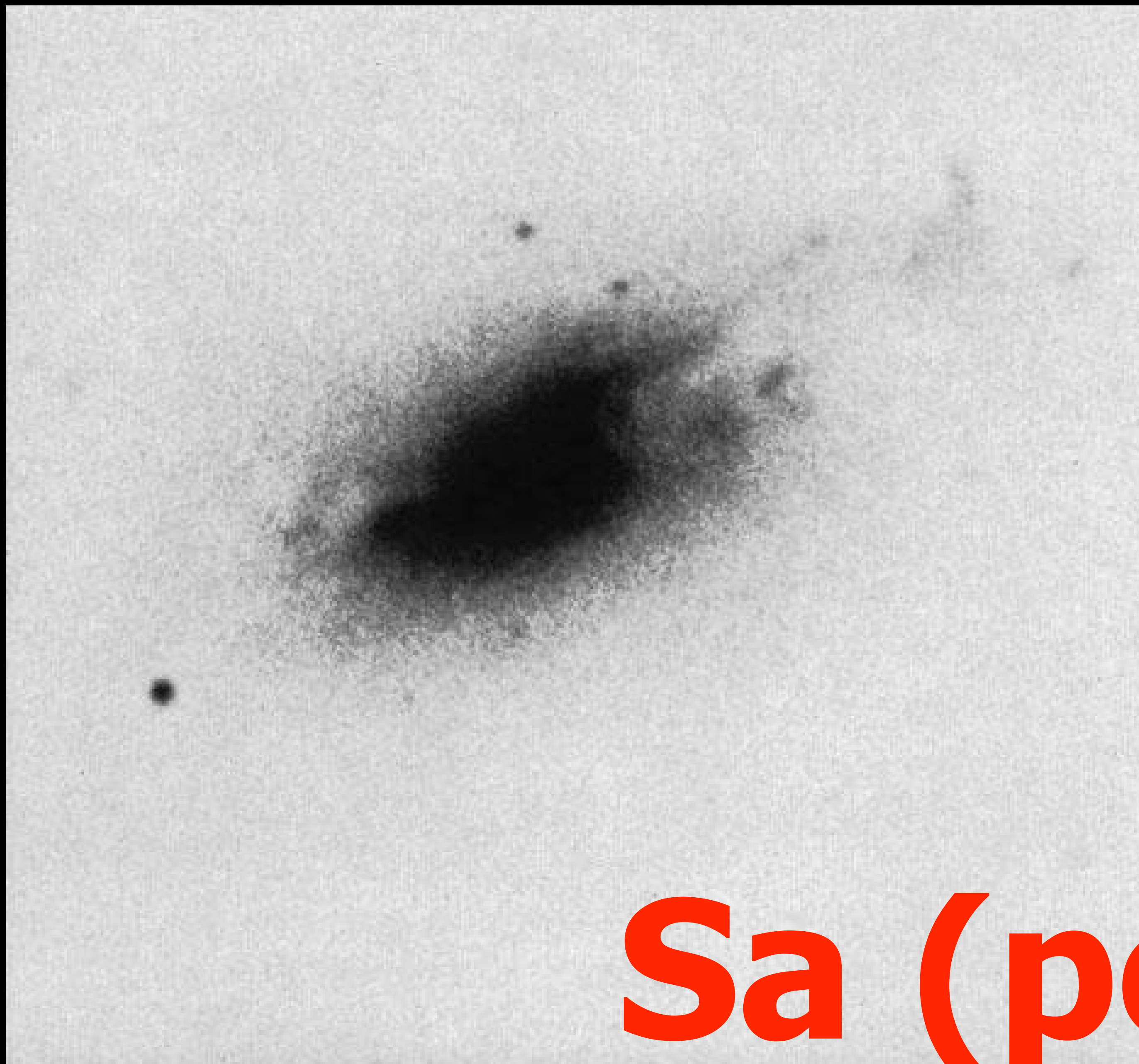
Sb

NGC 4244



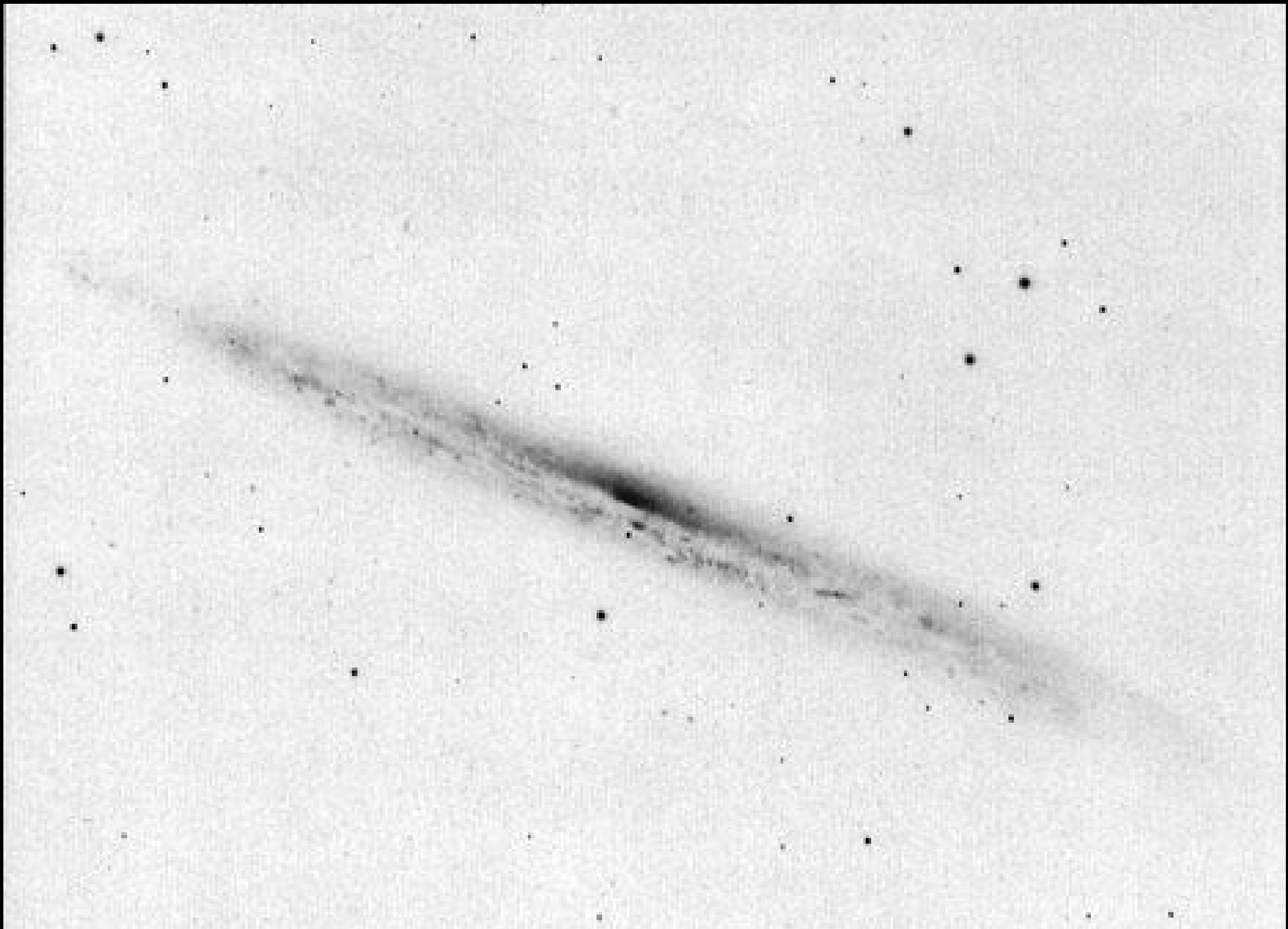
Scd

NGC 4383



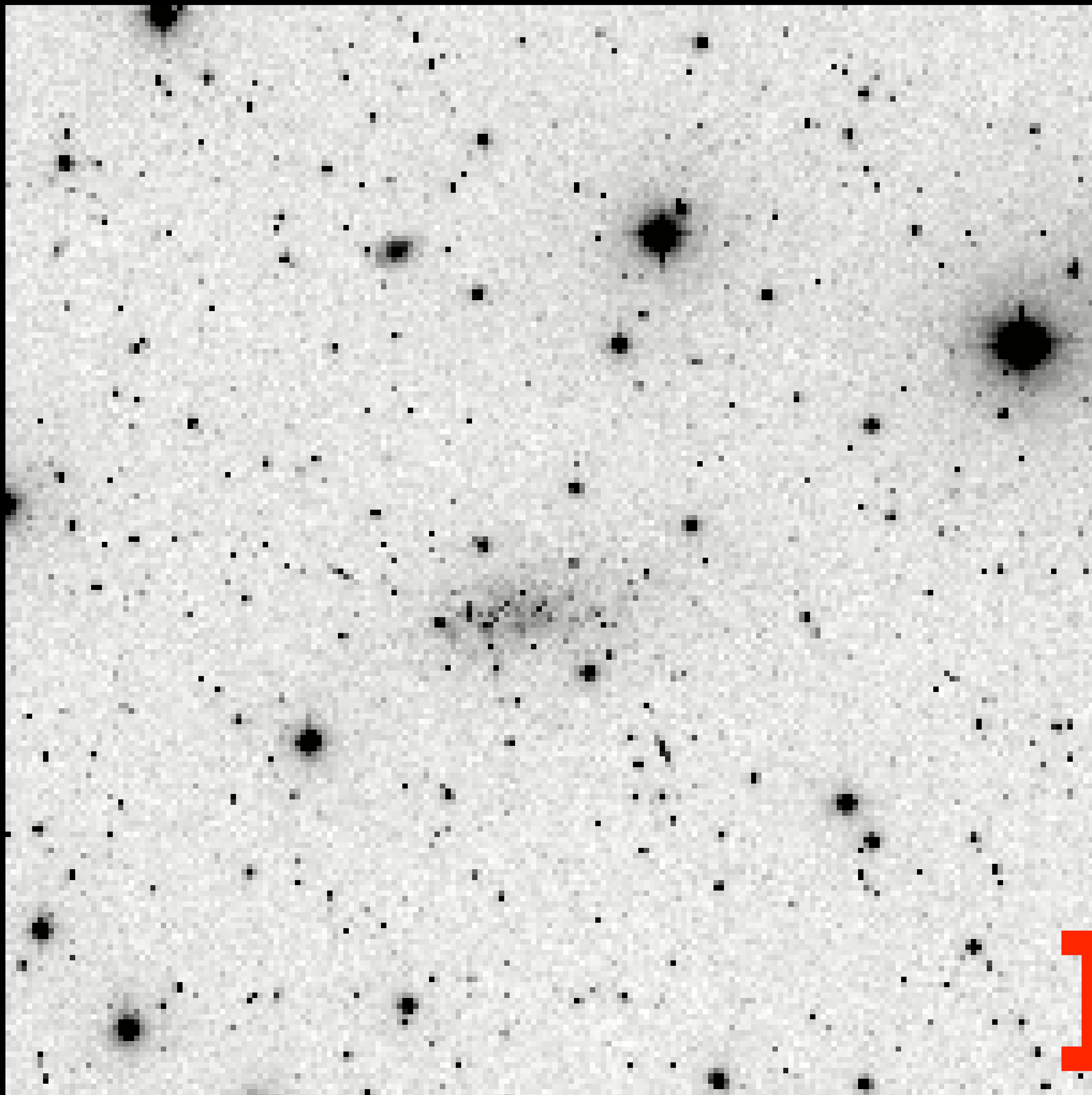
Sa (pec)

NGC 5907

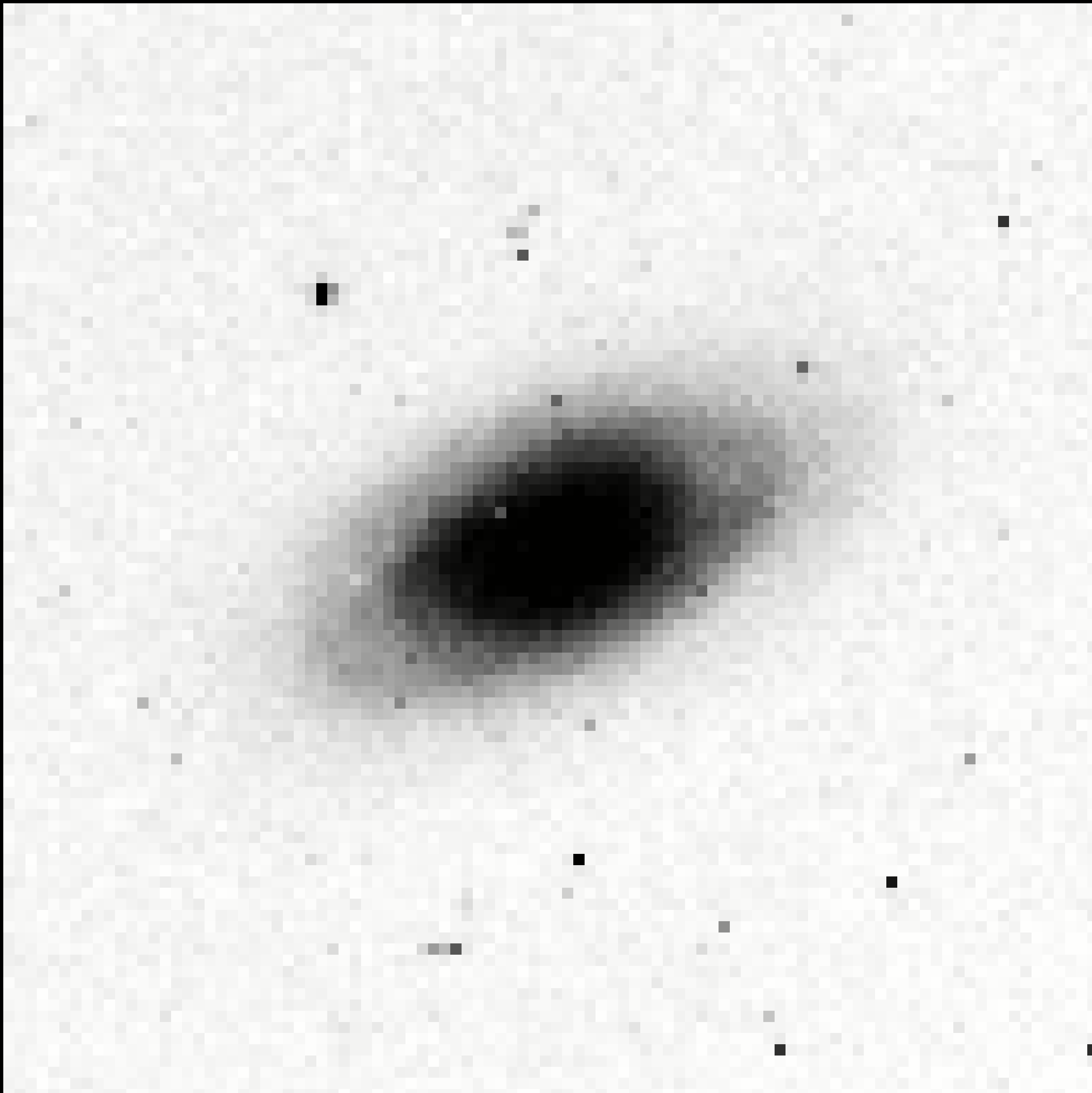


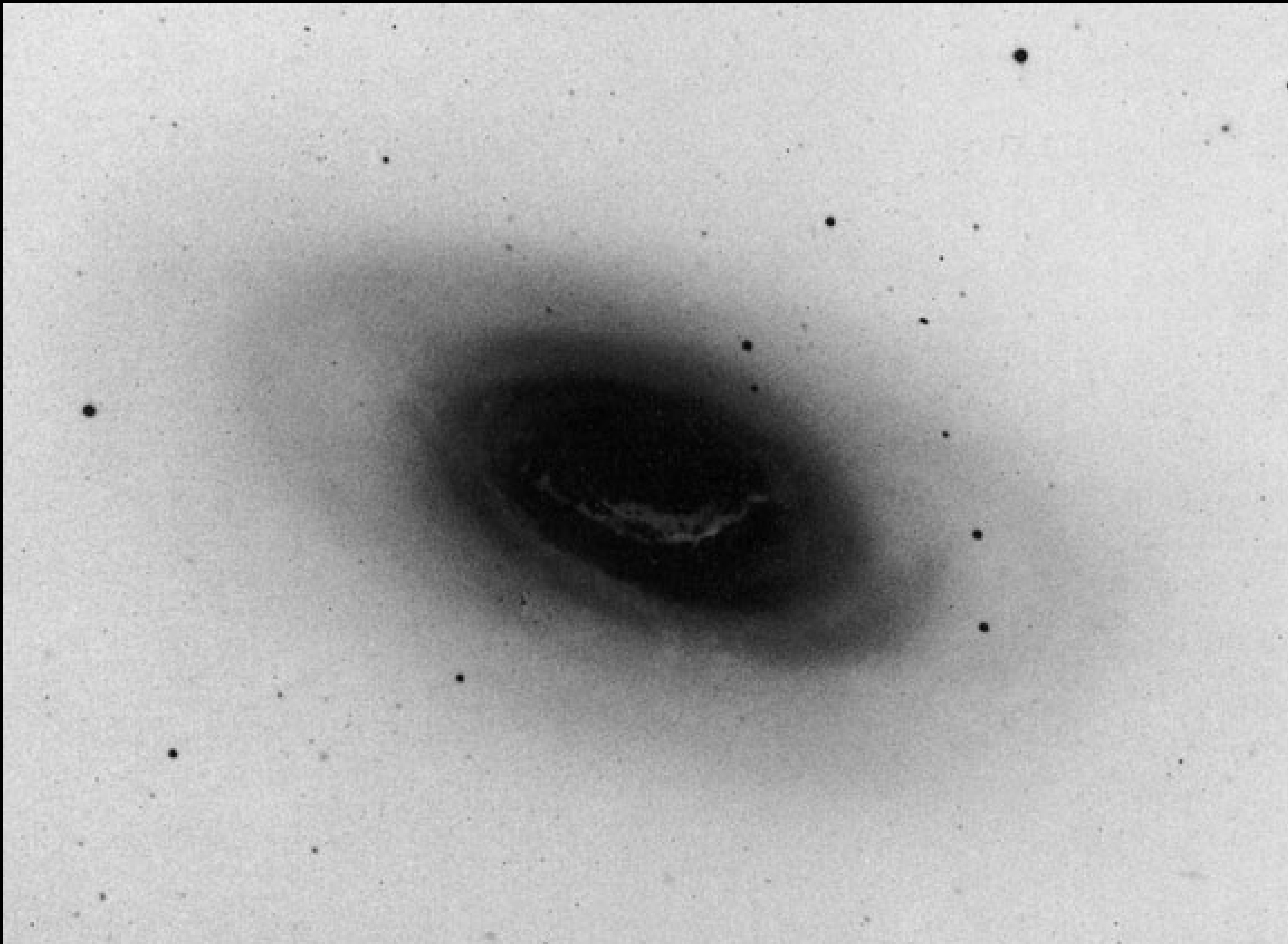
Sc

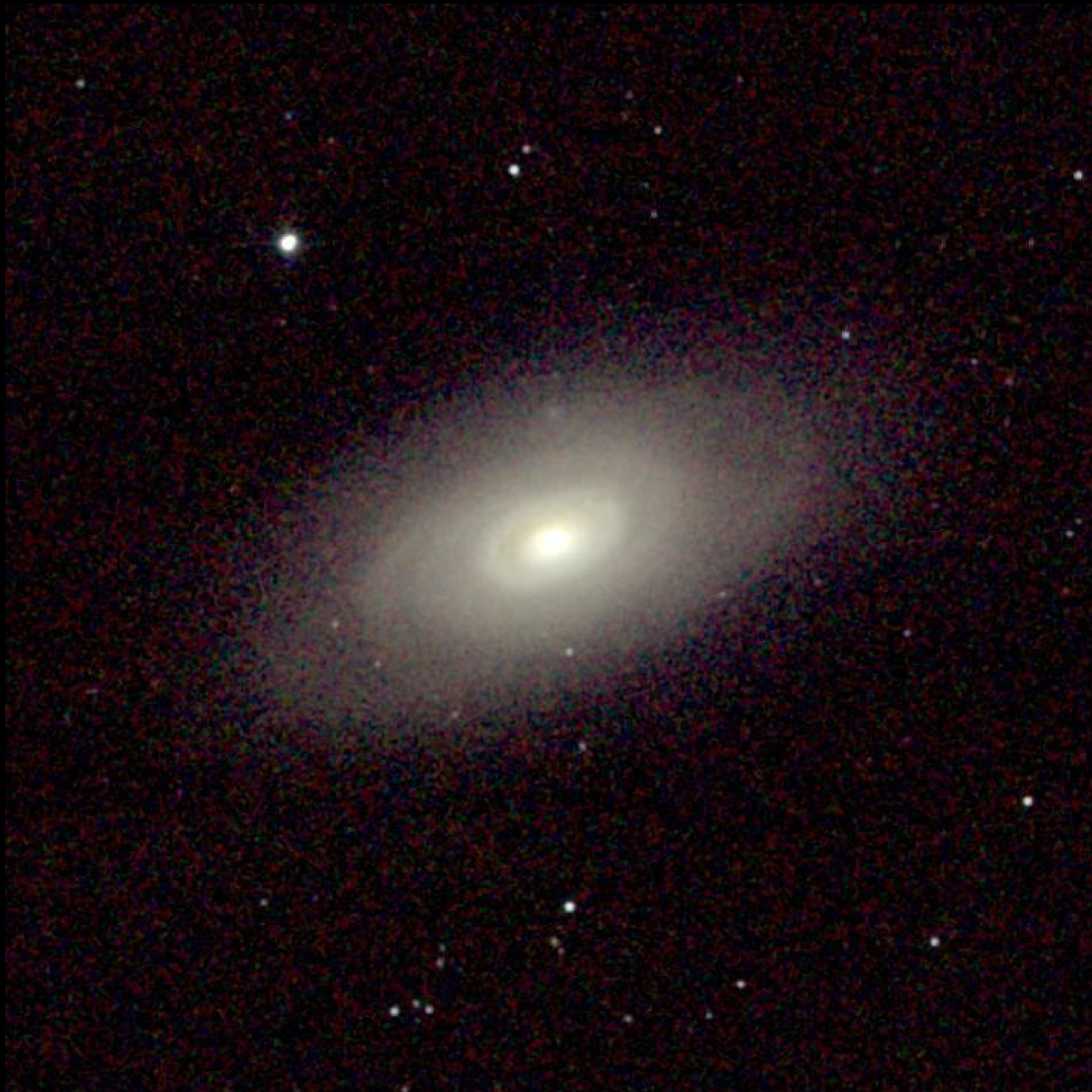
DDO 210

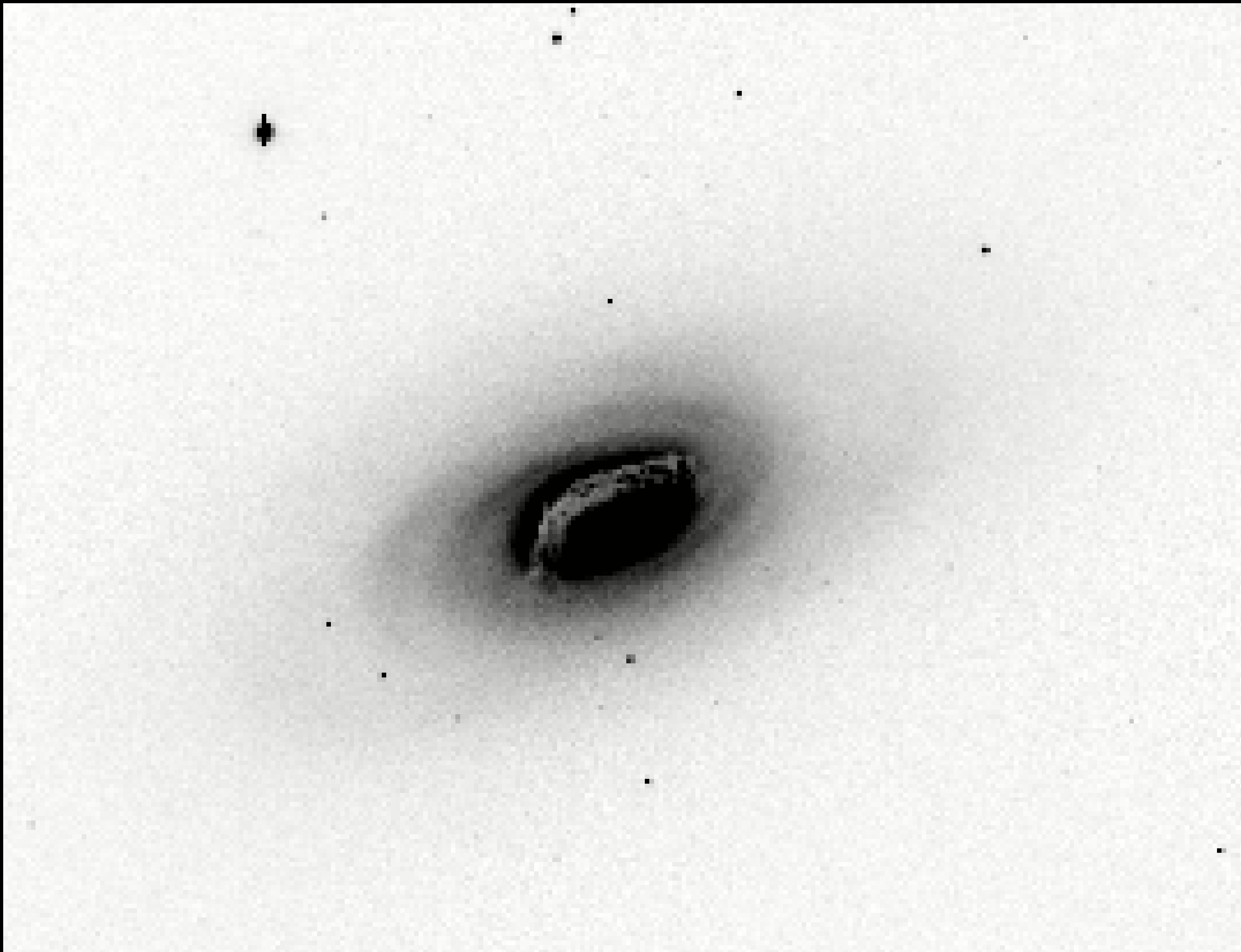


IBm



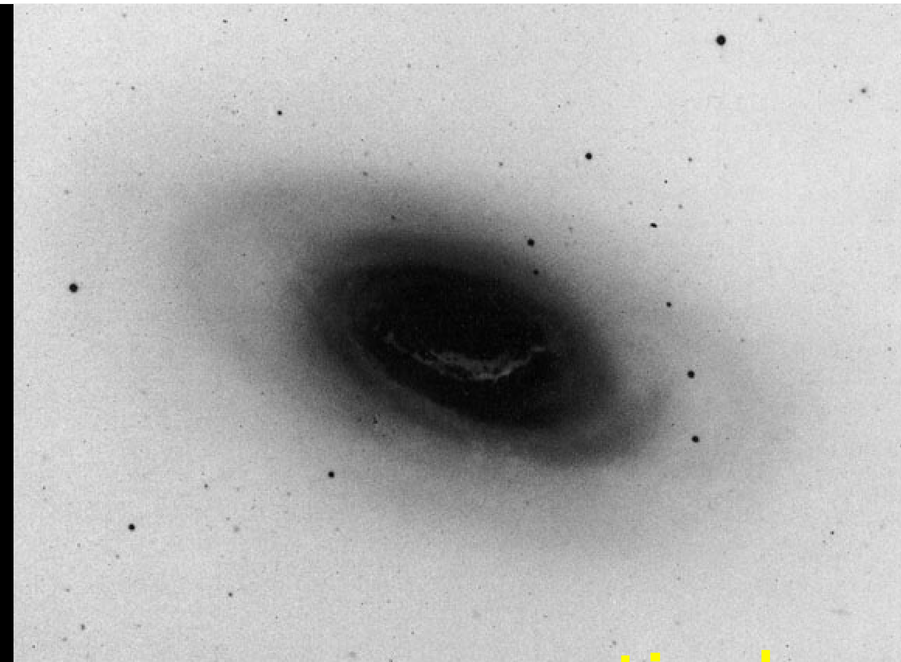




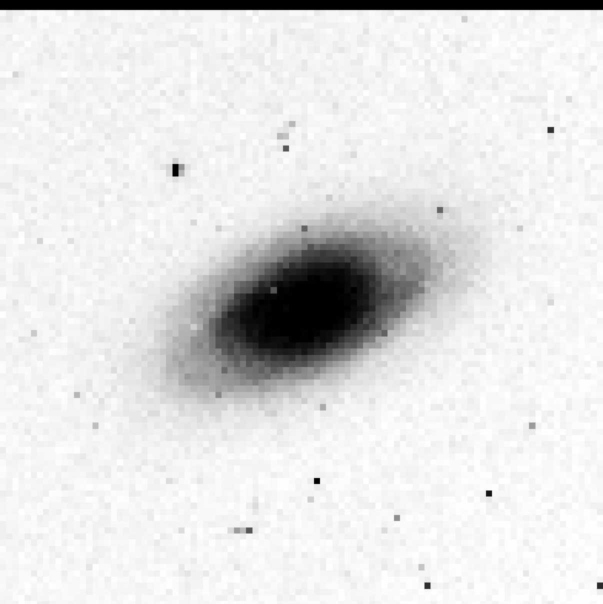


M64 Sab

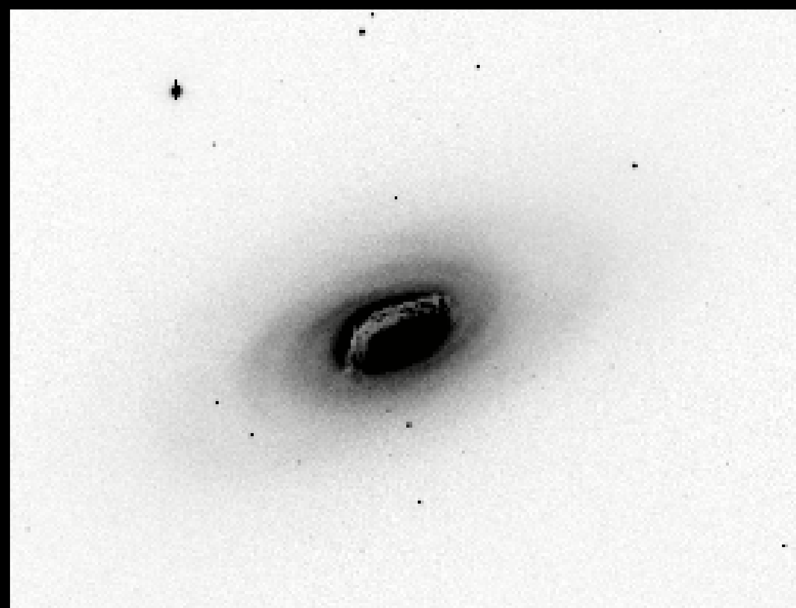
HST (optical)



optical



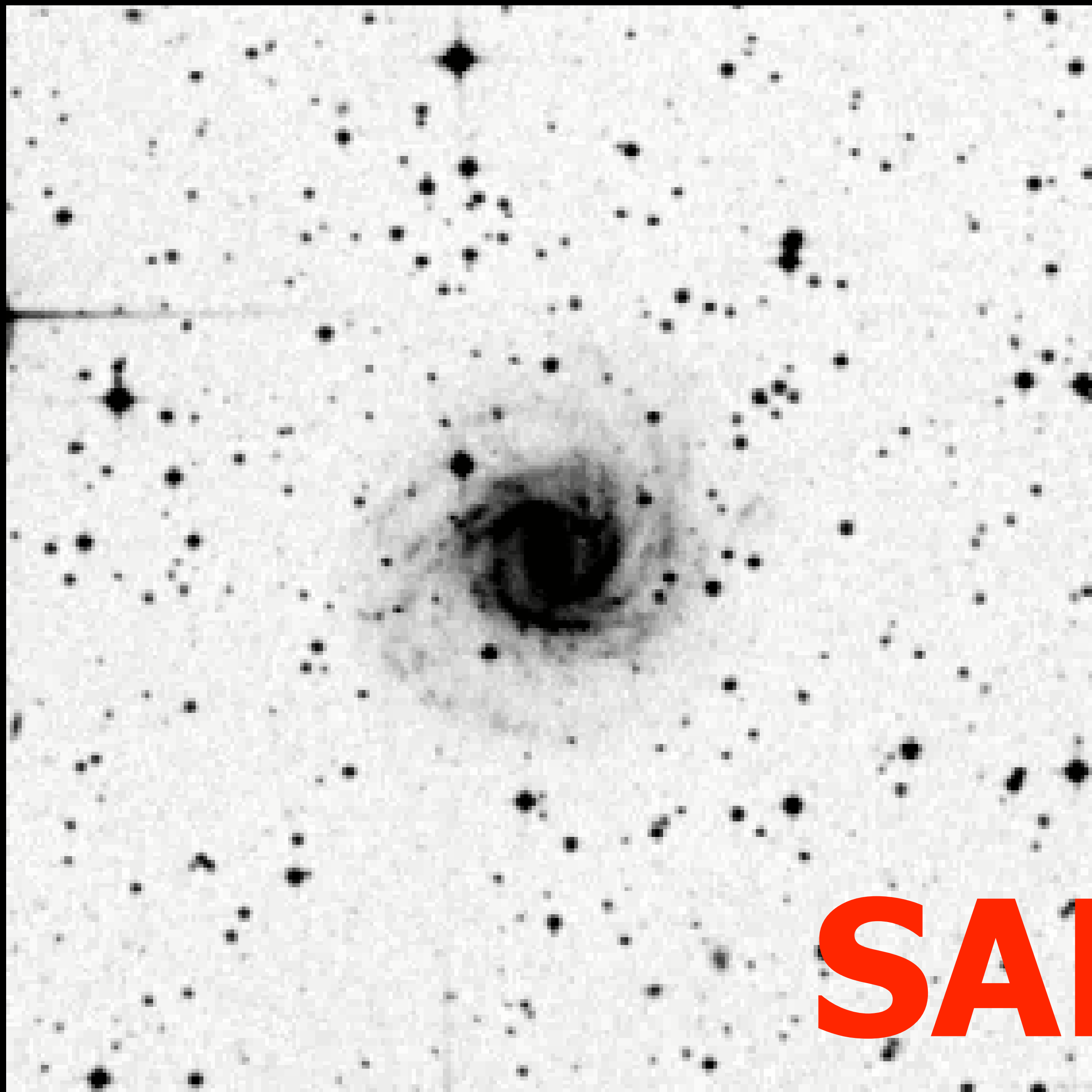
Palomar (optical, ground, digitized)



KPNO (optical)

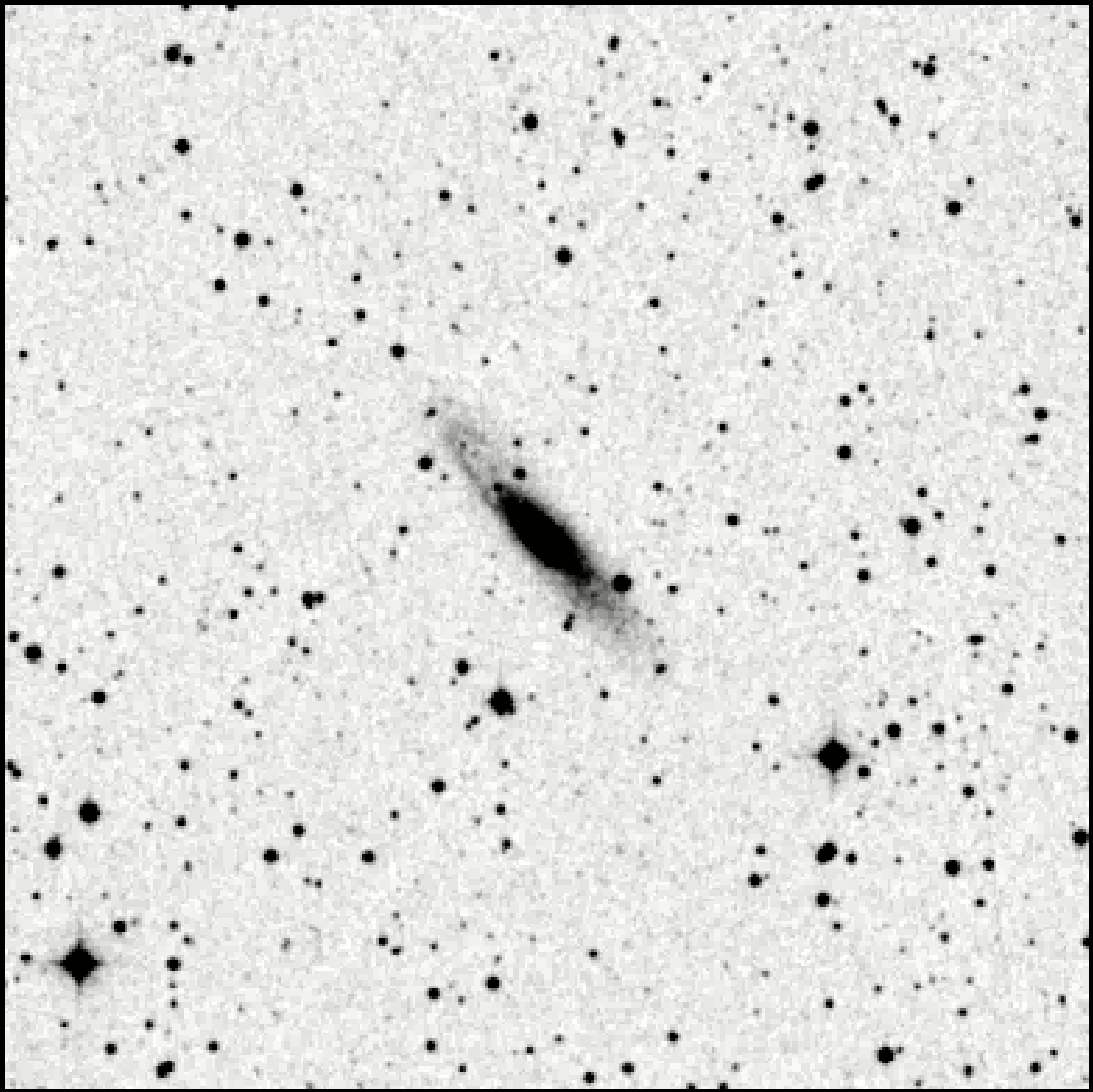
2MASS (NIR)

NGC 4444



SABbc

NGC 6368



Sb