Today

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

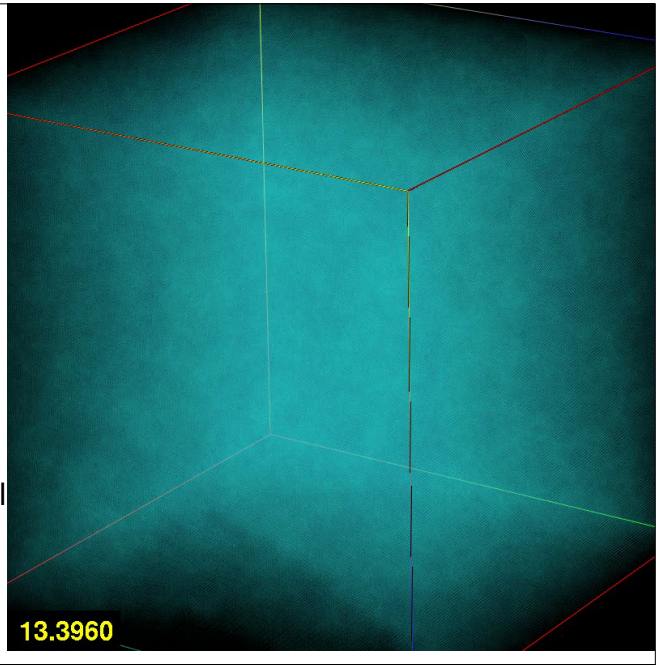
The Big Picture

Small density pertubations in the early universe grow with time.

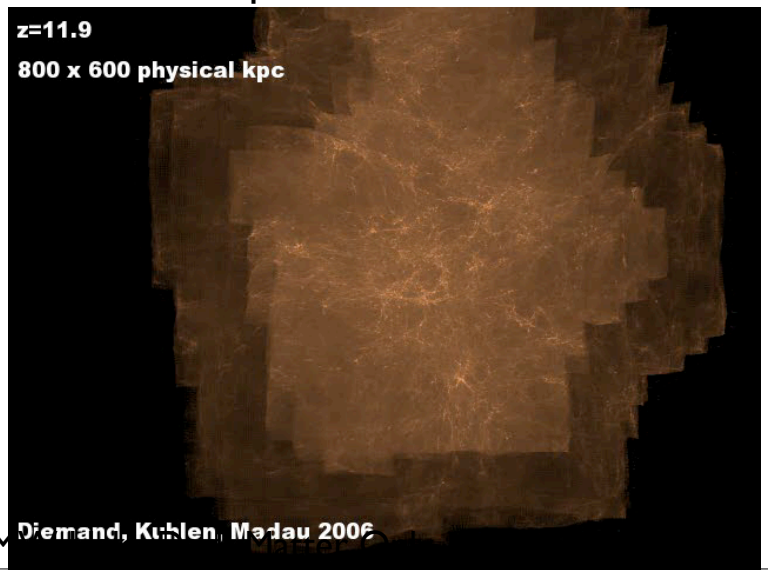
Matter accumulates in filaments, and then in individual "halos"

Courtesy B. Allgood

$\sim 10^9 M/particle$



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



The Smaller Picture

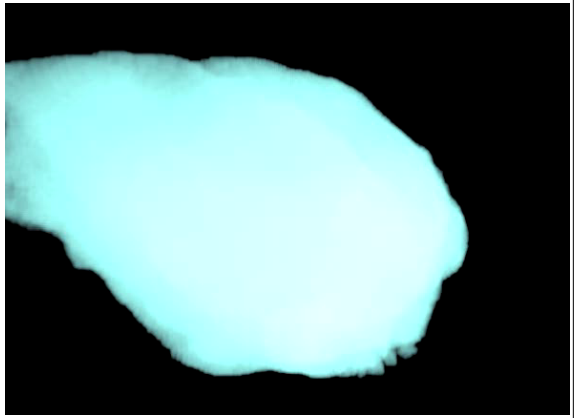
Matter collects in gravitationally bound halos.

Dissipationless dark matter remains in extended halo.

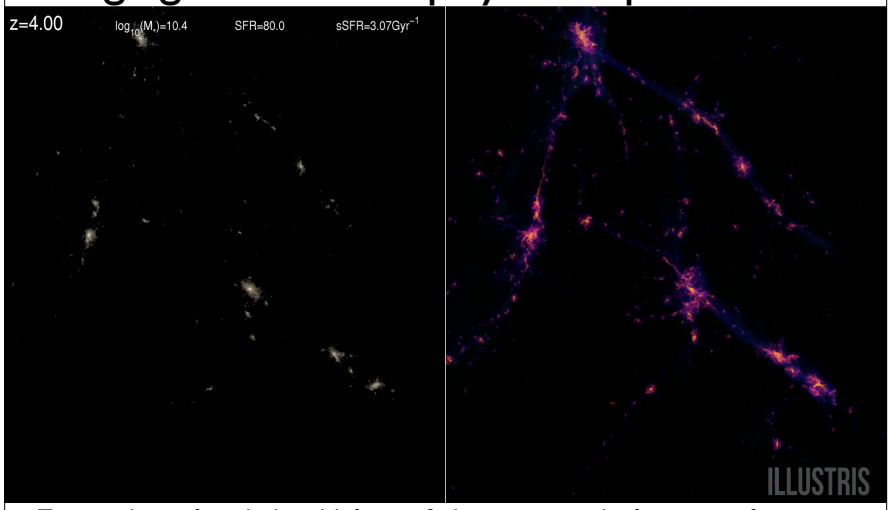
Gaseous baryons can cool and collapse further into dark matter halo.

"Feedback" sends energy/baryons/ metals outwards

Stars dissipationless once formed



Merging & feedback play an important role



Time evolution from high redshift to z=0, demonstrating the formation of a massive elliptical 'red-and-dead' galaxy as a result of a multiple merger around z~1. Panels show stellar light (left) and gas density (right) in a region of 1 Mpc on a side.

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

"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"

Continuous zoom-in from the scale of the entire simulation volume (~100 Mpc) to the scale of an individual spiral galaxy (~10 kpc), highlighting the diversity of structure across spatial scale, the large dynamic range of the simulation (10^6 per dimension), and the relationship between dark matter, gas, and stars.

Why this matters:

Cosmology sets:

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

This shapes:

- the global spatial distribution of galaxies
- the timescale over which galaxies form.
- the internal dynamics of galaxies
- the relative dynamics of galaxies (with respect to each other)
- the internal structure of galaxies

Why this matters:

Gas & Stellar Physics set:

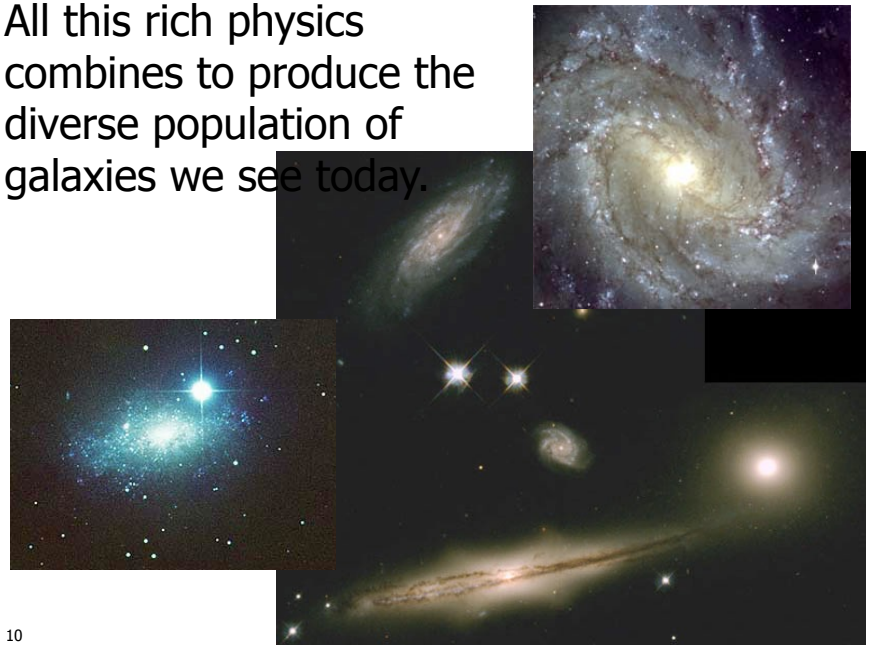
- the conditions under which gas turns into stars.
- the evolution of stellar populations.
- the impact of stellar evolution on the ISM

This shapes:

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

9

All this rich physics combines to produce the diverse population of galaxies we see today.



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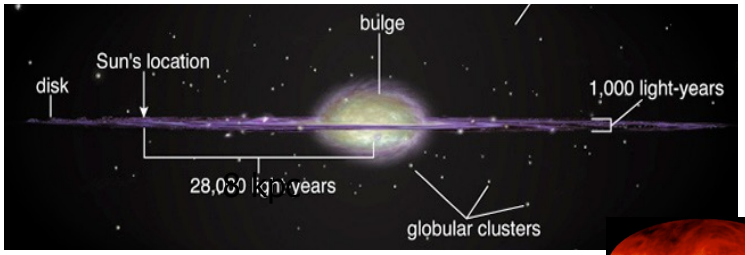
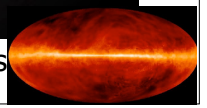
Galaxy Definition:

- Gravitationally bound
- Contains dark matter
- Contains baryons

11

The Milky Way





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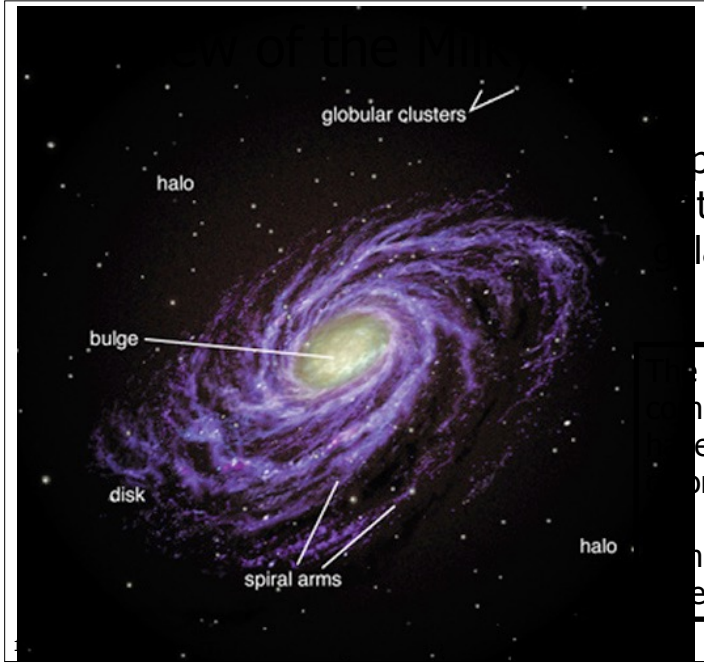

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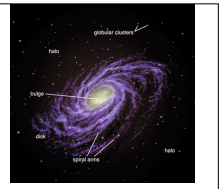
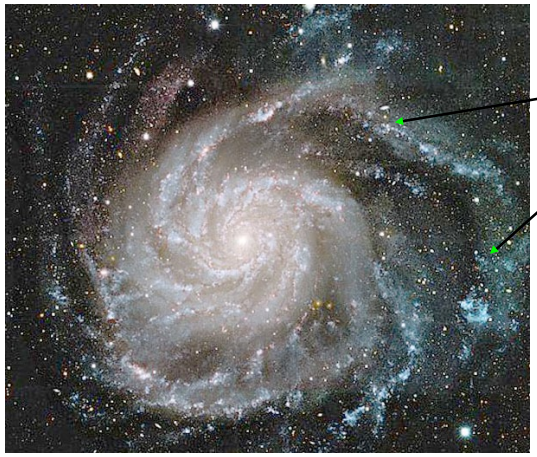
Top View of a Real Late-type Spiral Galaxy





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

14 Morphologically, lumps imply star formation

14

Appearance vs Inclination

Side View
"edge-on"
Inclination i=90°

Top View
"face-on"
i=0°

15

15

Late-Type "Disk" Galaxies

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

16

16

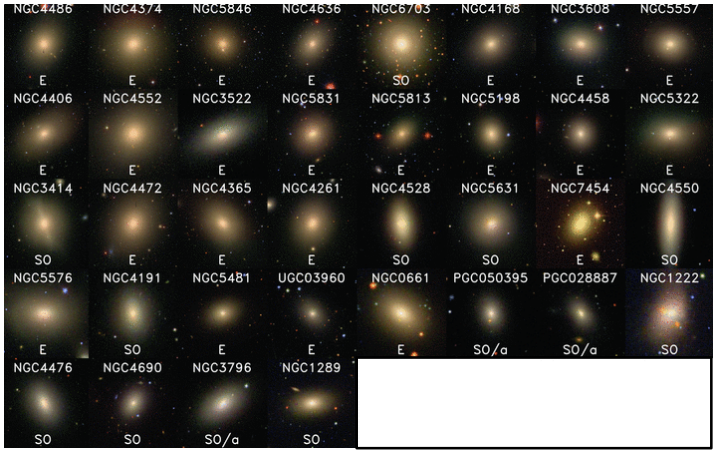
Edge-on views of similar late-type disk galaxies

17

"Early type galaxies"

More bulge than disk.

Low current star formation.



Atlas3D: Cappellari et al 2011

Early Type Galaxies: Ellipticals

"spheroidals"

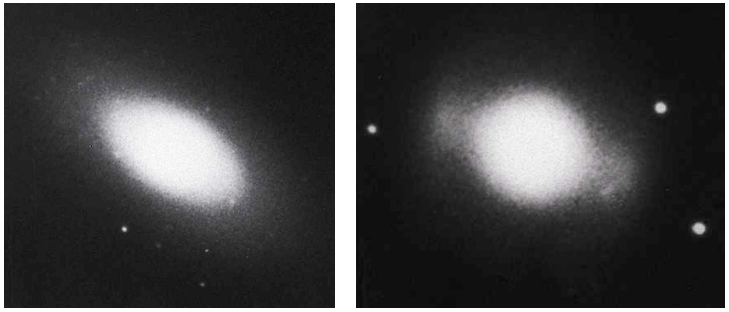
No disk, All bulge
Very little gas
Smooth
Little recent star formation

Have evolved to the point where no gas is left for making new stars

Early-ish Type Galaxies: "lenticulars"

Just a hint of a smooth disk.

Low current star formation.



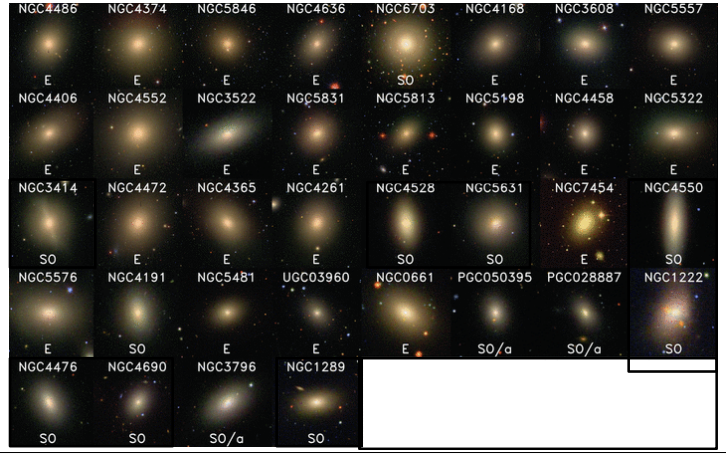
"S0" galaxies: Like ellipticals, but usually a bit flatter, or with structure in envelope.

20

"S0": Very subtle differences from E

Just a hint of a smooth disk.

Low current star formation.



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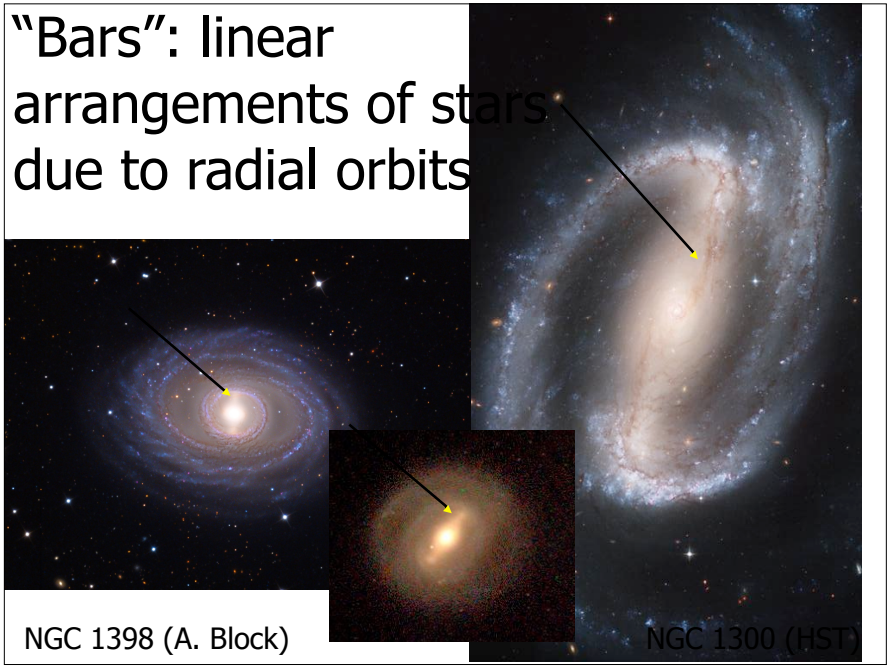
"Bars": linear arrangements of stars due to radial orbits



22

Double bar

23

23

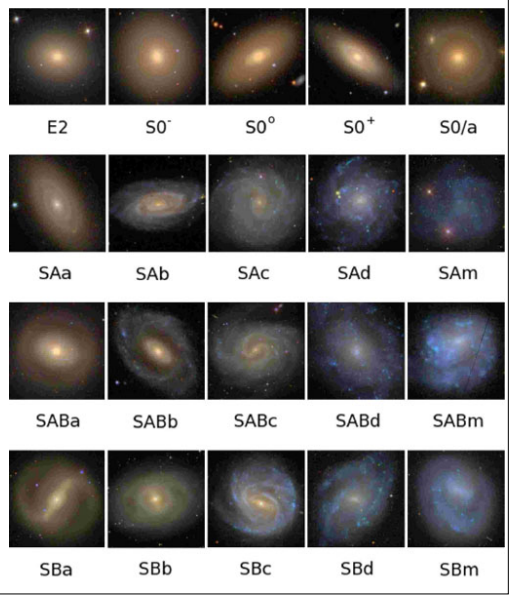
Galaxy Classification:

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

Order from disorder.

Compact, yet complete description.

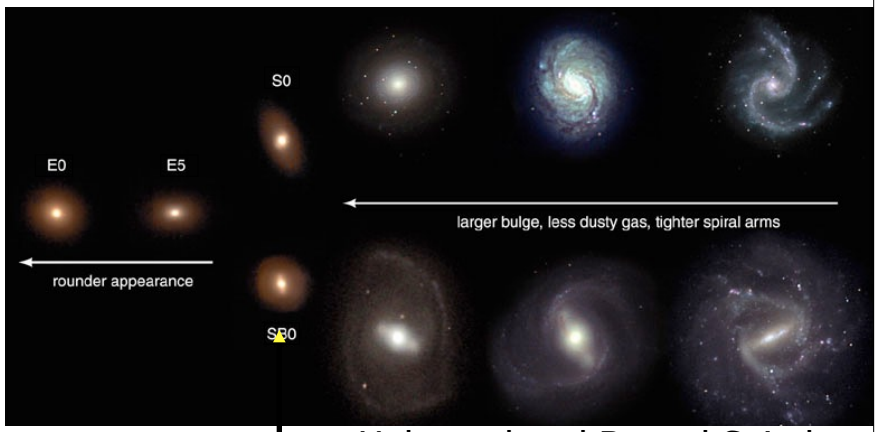
Find other correlations to reveal orgins.



24

24

"Tuning Fork"



Ellipticals

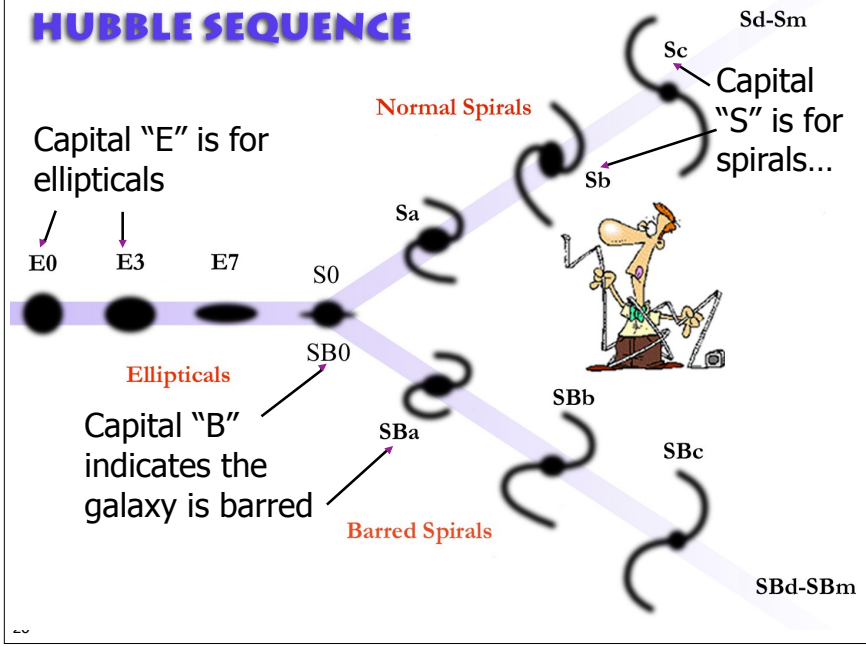
Unbarred and Barred Spirals

Lenticulars

25

25

HUBBLE SEQUENCE



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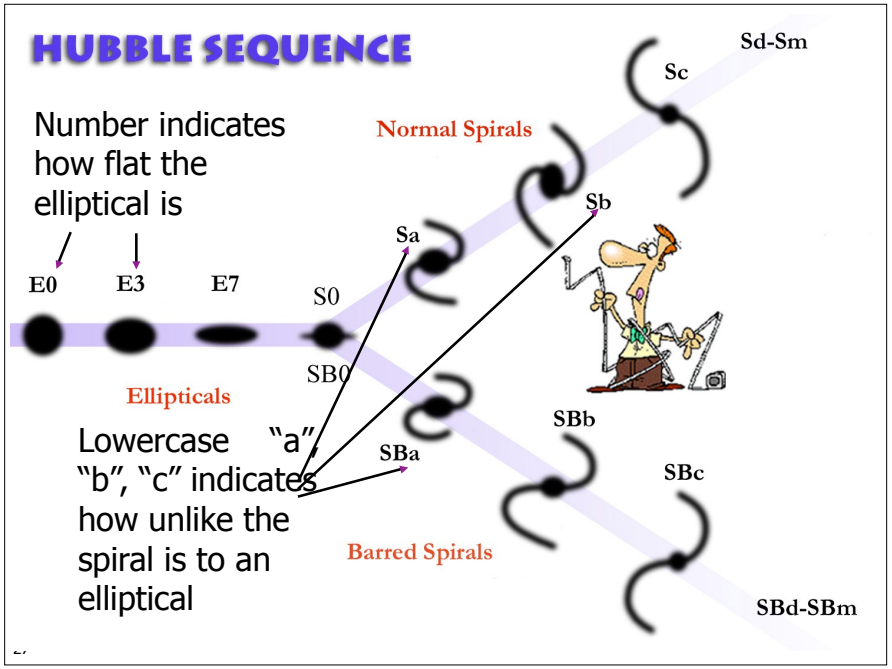
HUBBLE SEQUENCE



27

27

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:

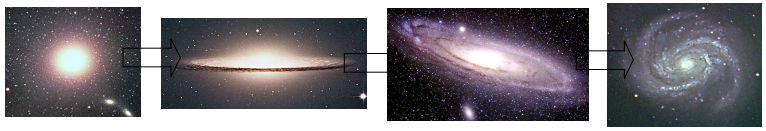
- Hubble
- deVaucouleurs (used in the RC3 galaxy catalog, so most widely adopted)
- Sandage (used in the Carnegie Atlas)
- van den Bergh (DDO)

28

28

Factors for assigning Hubble Classification:

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



E Sa Sb Sc

Note: These are not exact trends. Galaxies are much more complex than stars. Features are often contradictory.

29

Details of classification:

Ellipticals: **En** where $n=10(1-b/a)$

- perfectly round: "E0"
- highly flattened: "E6"
- almost none flatter than E6: unstable?
- n depends on orientation (not an intrinsic property)

30

Details of classification:

Unbarred Spirals: **Sx** x=0,a,b,c,d,m

- "S0/a", "Sbc" indicate galaxies with properties of adjacent types
- Sometimes denoted "SAx" to distinguish from barred sequence
- Value of x depends on specific classification scheme.

31

Details of classification:

Unbarred Spirals: **Sx**

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

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

Sb: like M31.

Sc: Lumpy arms, open arms, small bulge

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

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

32

Details of classification:

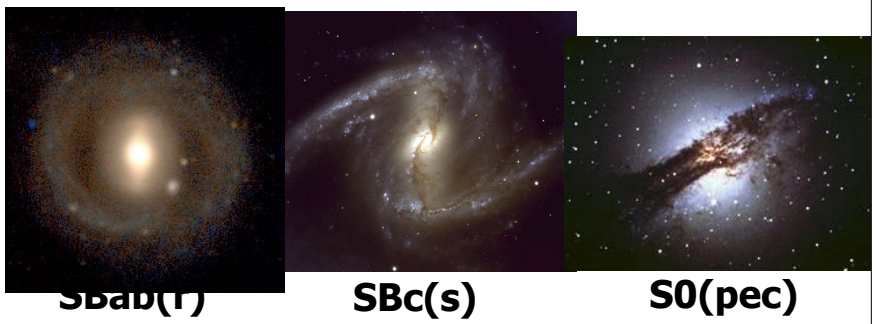
Barred Spirals: **SBx** x=0,a,b,c,d,m

- Value of x uses same criteria as for unbarred sequence.

33

Other classification symbols:

Ringed galaxies: have (r) appended
S-shaped galaxies: have (s) appended
Peculiar galaxies: have (pec) appended

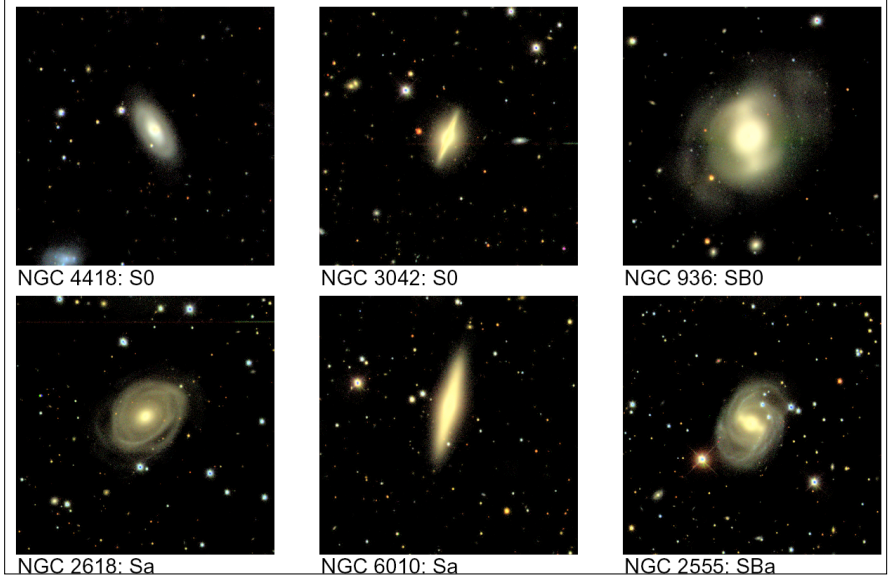


SBab(r) **SBc(s)** **S0(pec)**

(Galaxies can have more than one of these symbols)

34

Early-Type Galaxies from SDSS

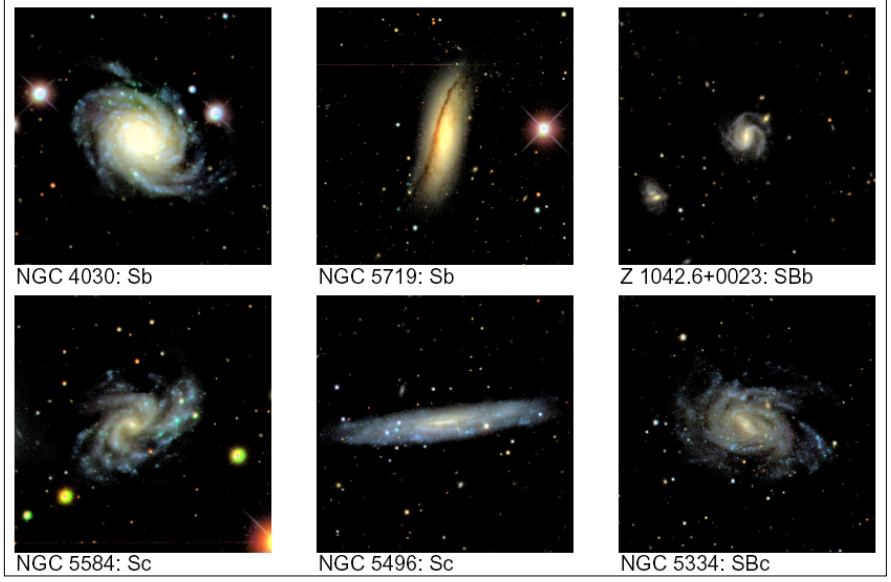


NGC 4418: S0 NGC 3042: S0 NGC 936: SB0

NGC 2618: Sa NGC 6010: Sa NGC 2555: SBa

35

Late-Type Galaxies From SDSS

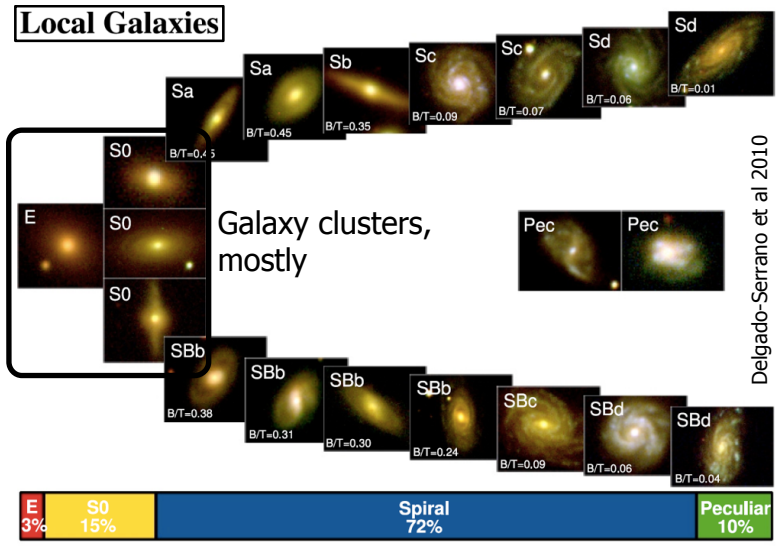


NGC 4030: Sb NGC 5719: Sb Z 1042.6+0023: SBb

NGC 5584: Sc NGC 5496: Sc NGC 5334: SBc

36

Luminous Galaxies: Mostly spirals

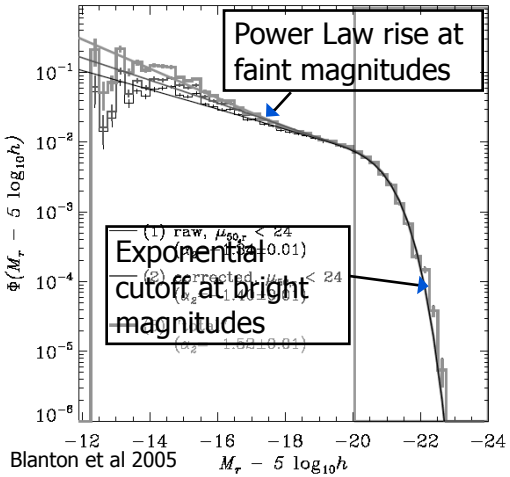


SDSS: M_J<-20.3

37

By number, most galaxies aren't luminous

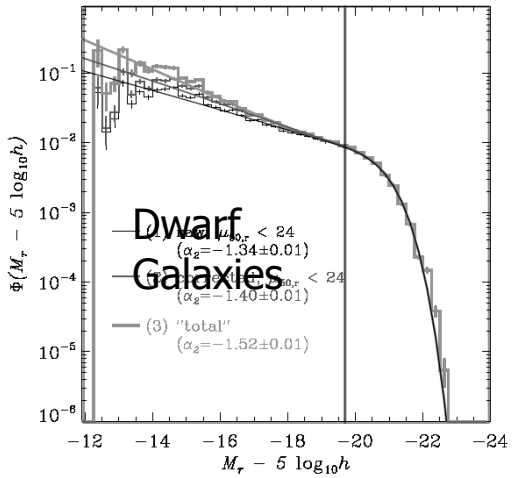
"Luminosity Function" $\Phi(L)dL$ = # of galaxies per unit volume with luminosities between L and $L+dL$



Blanton et al 2005

38

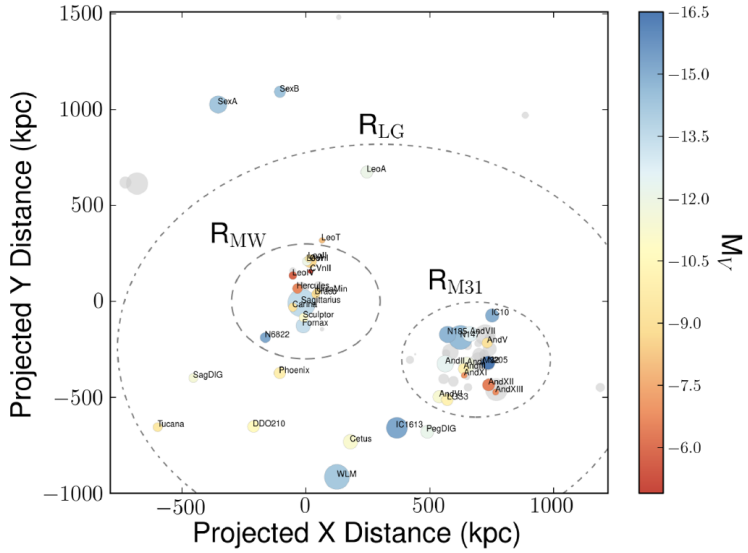
By number, most galaxies aren't luminous



Typical Hubble Sequence Galaxies

39

Most Local Group galaxies are dwarfs



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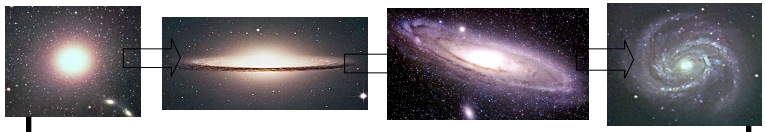
Dwarf galaxies lie outside of the standard Hubble Sequence



Dwarf ellipticals: Smooth & compact dE

Dwarf irregulars: Lumpy & diffuse dIrr, Sm, Im

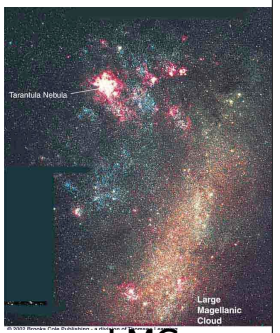
Dwarf Spheroidals: Smooth, diffuse dSph

41

41

Dwarf Irregulars

Sextans A



LMC

No obvious bulge or spiral patterns.

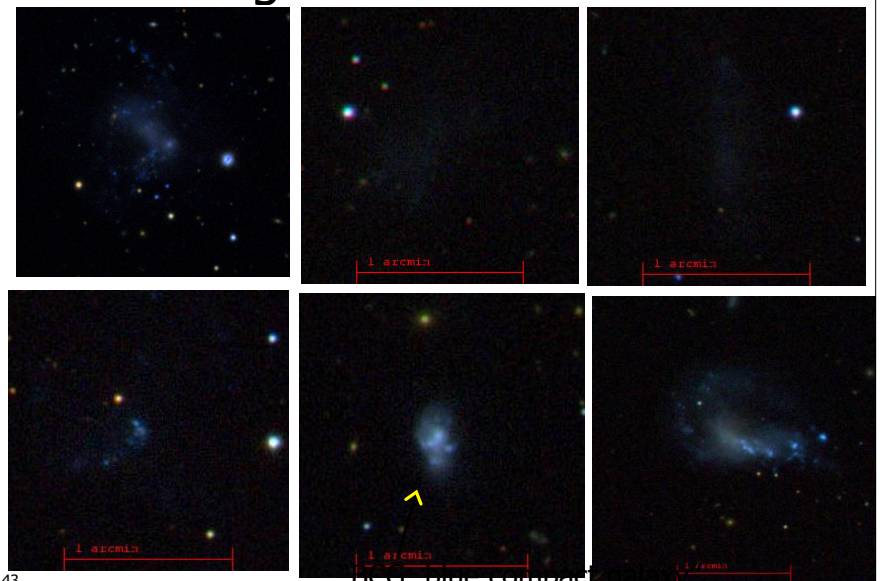
Obvious star forming regions

Most common type of dwarf galaxy.

42

42

Dwarf Irregulars from SDSS



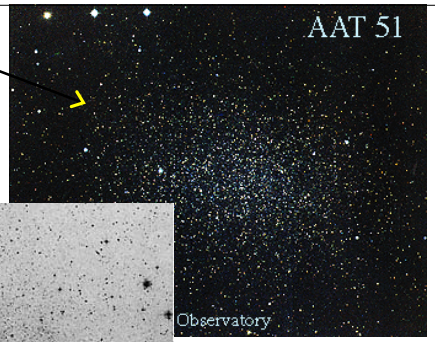
43

BCG: blue compact galaxy

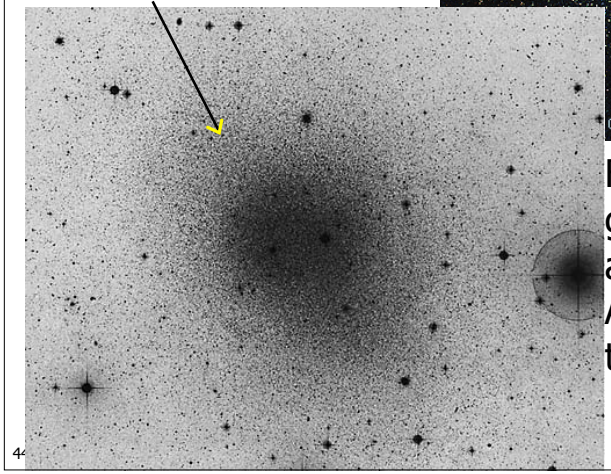
43

Dwarf Spheroidals

Leo I



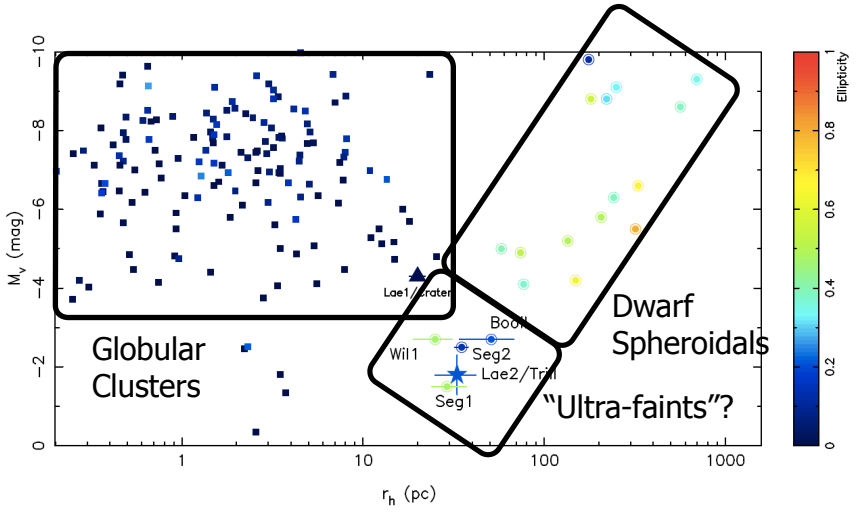
Fornax



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

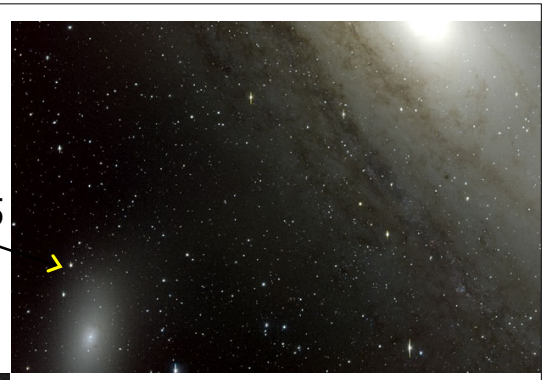
44

44



45

Dwarf Ellipticals



(Both are M31 companions)

Tend to be found in high density regions

(Binggeli et al 90).

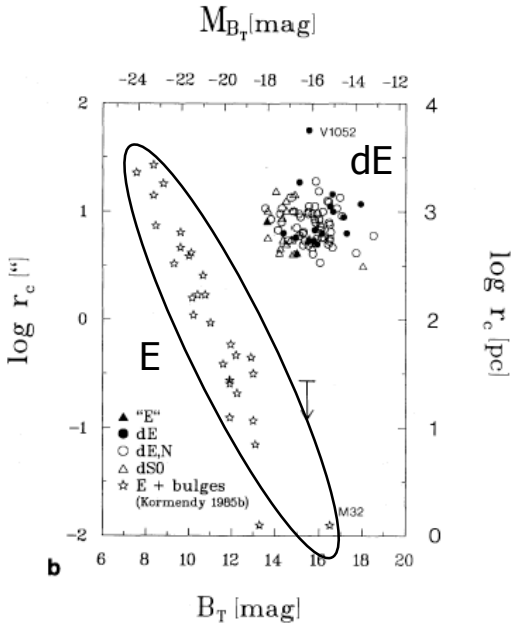
46

46

Dwarf Ellipticals

Most not actually like ellipticals.

Structurally more like dIrrs, but with SF turned off.



Virgo Cluster
Bingelli et al 1991

47

47

Caveats about morphological classification:

Inclination Dependent (E0 != spherical)

Exposure Dependent

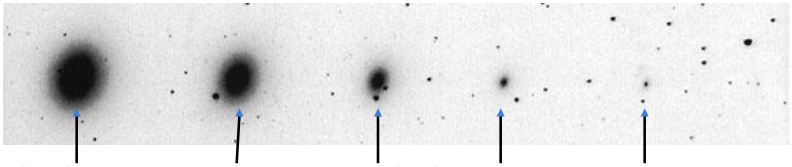
Distance/Resolution Dependent

Wavelength Dependent

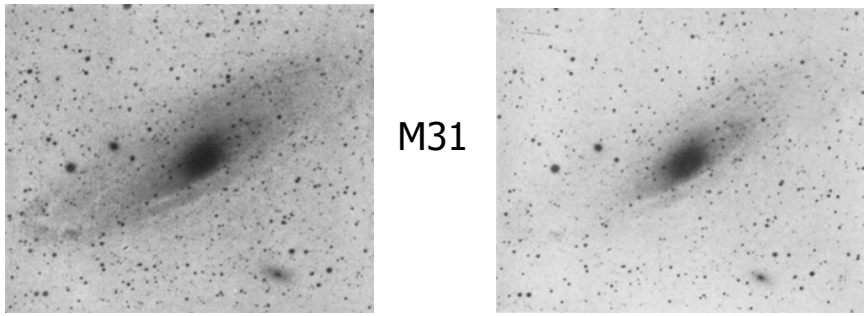
Classifier Dependent

48

Exposure Dependent:

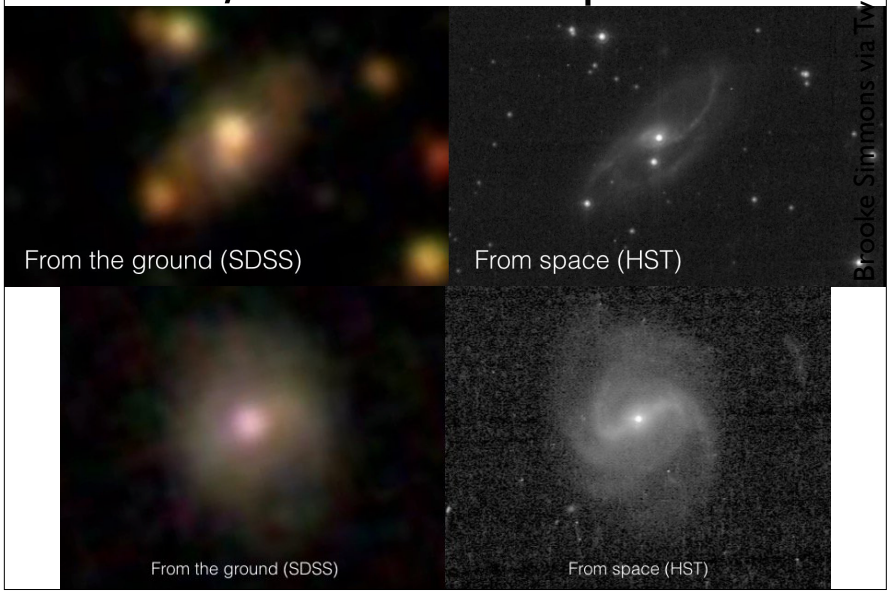


Multiple-exposure of M32 with different exposure times



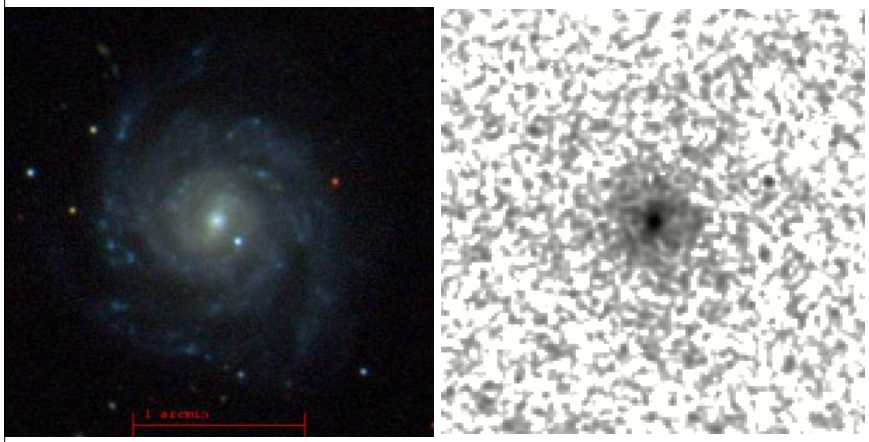
49

Distance/Resolution Dependent:



50

Wavelength Dependent:



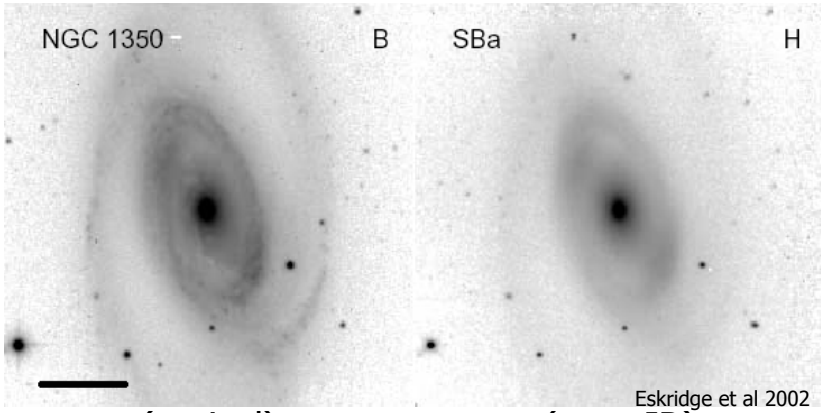
SDSS g,r,I
(optical)

2MASS K_s
(near-infrared)

51

51

Wavelength Dependent:



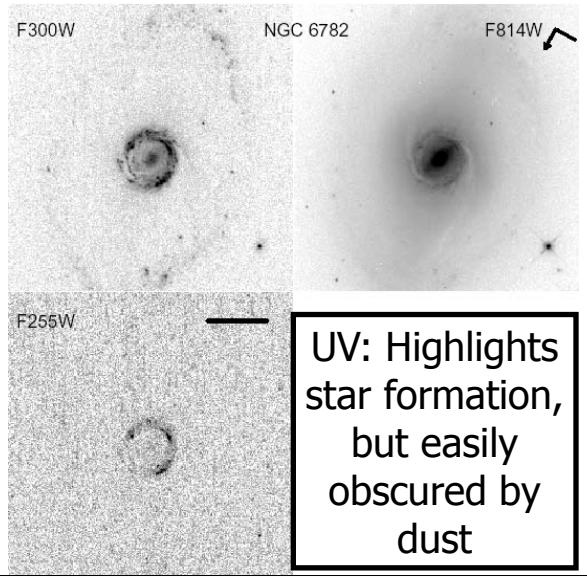
(optical) (near-IR)

IR: SF regions faint + Sky bright.
Dominated by old stars (stellar mass)

52

52

Wavelength Dependent:



(UV)

(optical)

UV: Highlights star formation, but easily obscured by dust

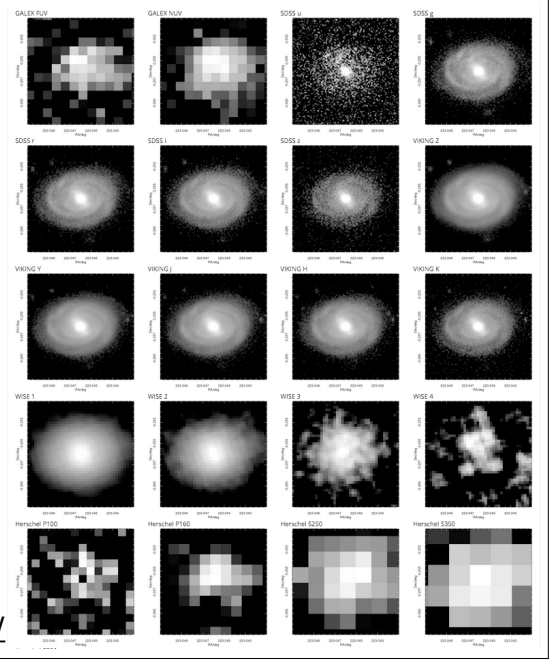
Eskridge et al 2004

53

Same galaxy in different filters

(UV through far-IR)

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



Classifier Dependent:

Galaxies may have conflicting features (e.g. large bulge, but very lumpy arms)

Different observers have different biases

Even using identical images, "expert" classifiers only agree within 2 T-types

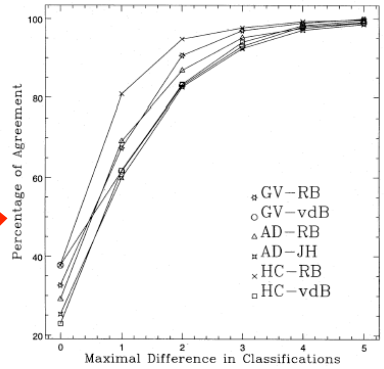
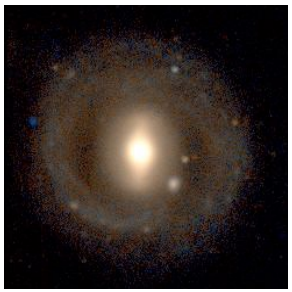


Figure 5. Percentage of agreement between selected pairs of observers to within n types.

55

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!)

56

Quantifying Morphology

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

Concentration Index

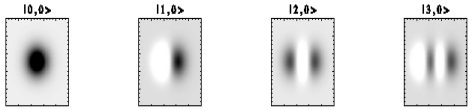
$c=R_{20}/R_{50}$ -- ratio of radii containing 20% vs 50% of the light. Various choices of %'s made.

Asymmetry A (rotate image, subtract, quantify residual)

Smoothness S

Gini Coefficient G

Shapelet decomposition



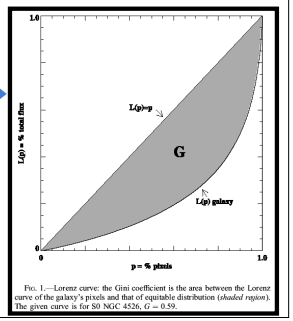


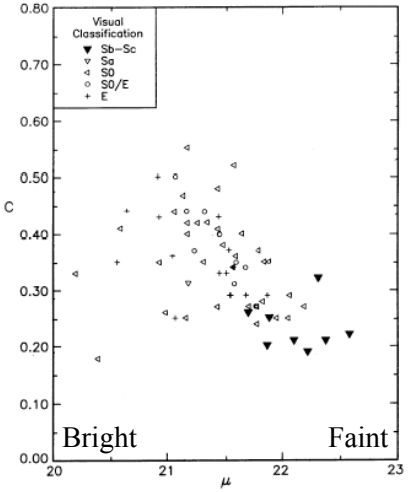
Fig. 1.—Lorenz curve: the Gini coefficient is the area between the Lorenz curve of the galaxy's pixels and that of equitable distribution (*shaded region*). The given curve is for S0 NGC 4526, $G = 0.59$.

57

Quantifying Morphology:

- Find quantitative measures that reproduce traditional "visual" classif

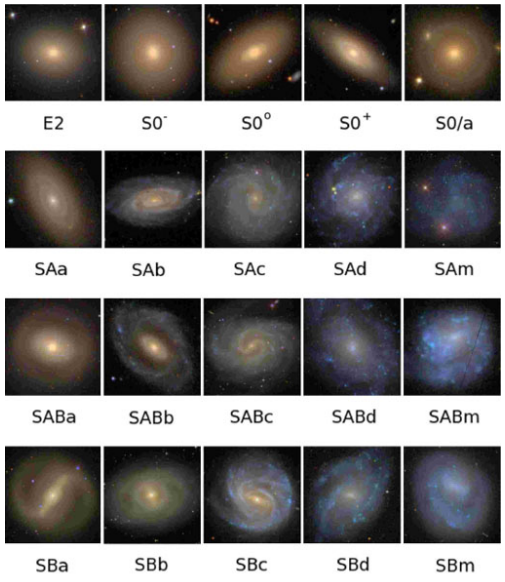
Example: Low concentration and low surface brightness suggests later morphological type



58

Science from Classification

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



59

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

60

Morphology vs Galaxy Properties

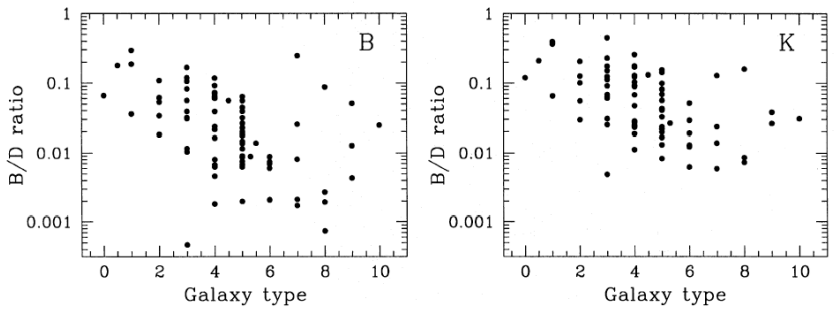
Bulge-to-disk ratio

Color

Fraction of baryons in gas vs stars

Luminosity

Late-type = Small "bulge-to-disk" ratio

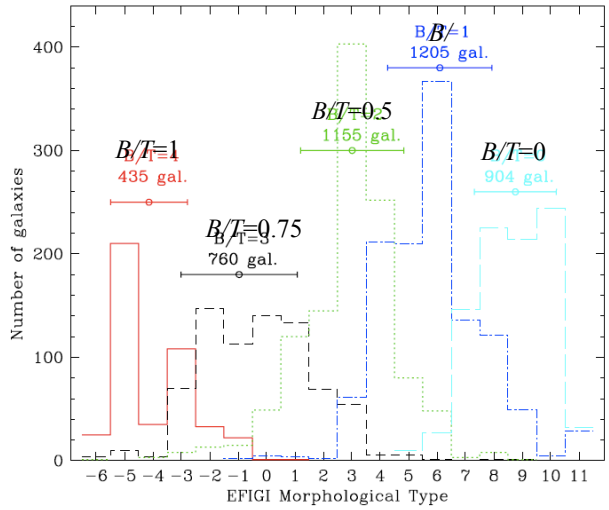


Lots of scatter though, since B/D is not the only quantity that goes into the classification

($B/D = L_{bulge}/L_{disk}$, based on fitting 2-D bulge+disk models to galaxy images; de Jong 1996)

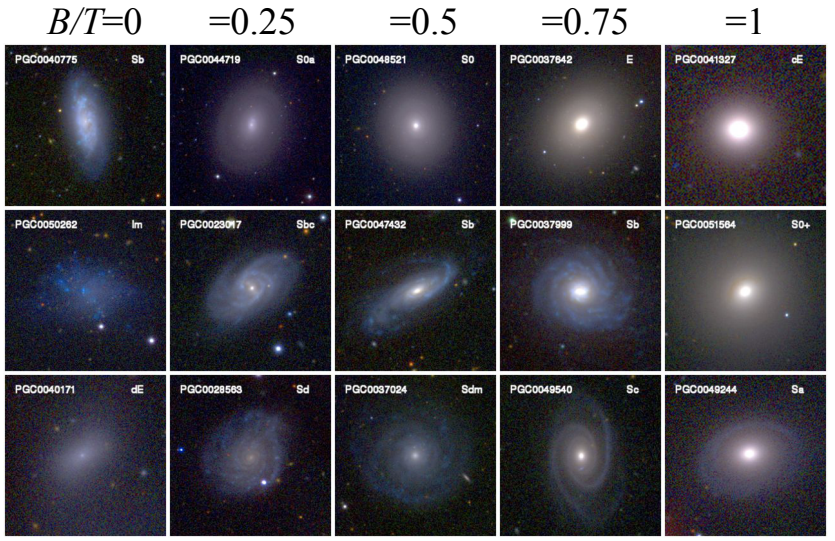
62

Broad range of T type for fixed B/T



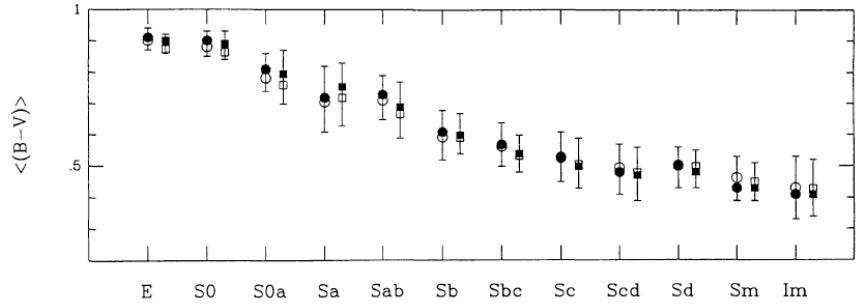
$B/T = L_{bulge}/L_{total}$

Broad range of T type for fixed B/T



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

Late-type galaxies = Bluer



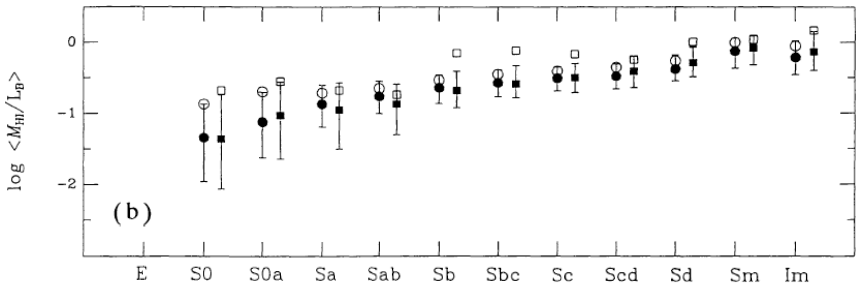
Not a profound correlation, since "lumpiness", an indicator of current star formation, is a critical aspect of classification, and young stars are blue

(Roberts & Haynes 1994)

65

65

Late-type galaxies = Gas Rich

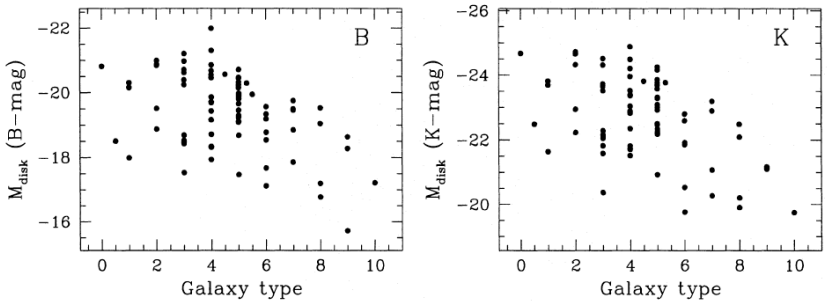


Again, not a profound correlation, since current star formation (which produces lumpy arms) also means that gas is lying around.

66

66

Later-type galaxies = Fainter



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

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

de Jong 1996

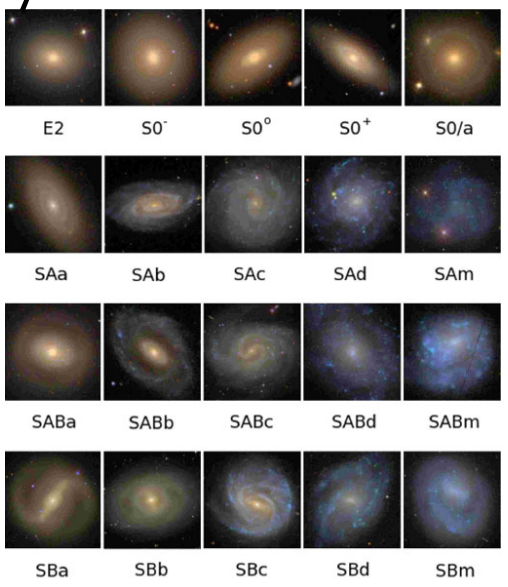
67

67

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

68

68