An analogy

- "Galaxies" can be compared to "cities"

- What would you like to know about cities?
  - how does your own city look like? how big is it? what is its population? history? how did it develop?
  - how does it compare to other cities? is it bigger, smaller? are there many young people? old?
  - how are the cities distributed through the country?
  - ....

- What would you need to be able to answer these questions?
  - distance measurements
  - census of the population...
  - determination of properties

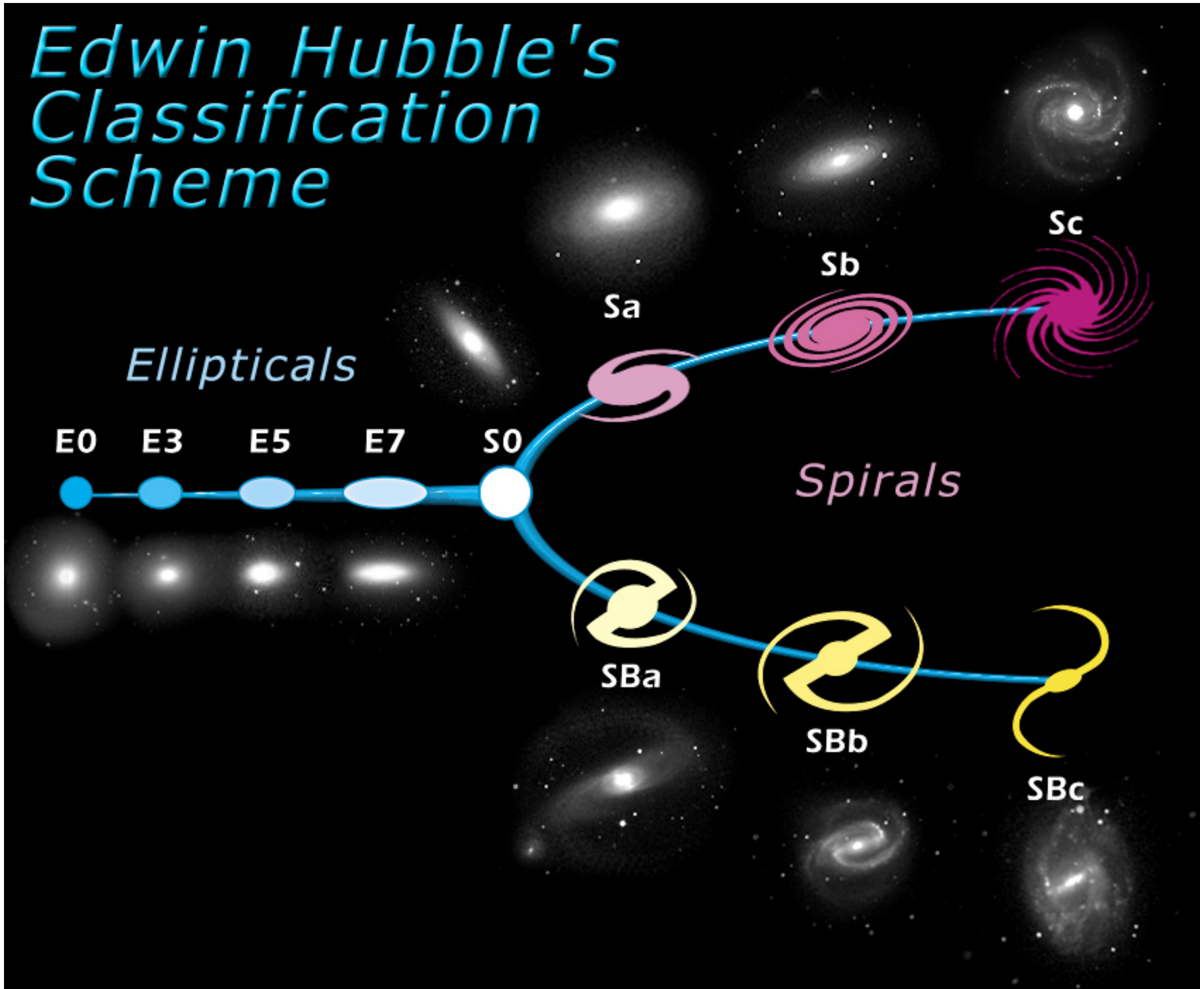
Classification scheme

•Most frequently used: "Hubble sequence"

•Based on the galaxy's image in the optical band

•Classes are E(0-7), S0, Sa, Sb, Sc, Sd, Irr

•The "tuning fork" diagram divides barred from non-barred galaxies

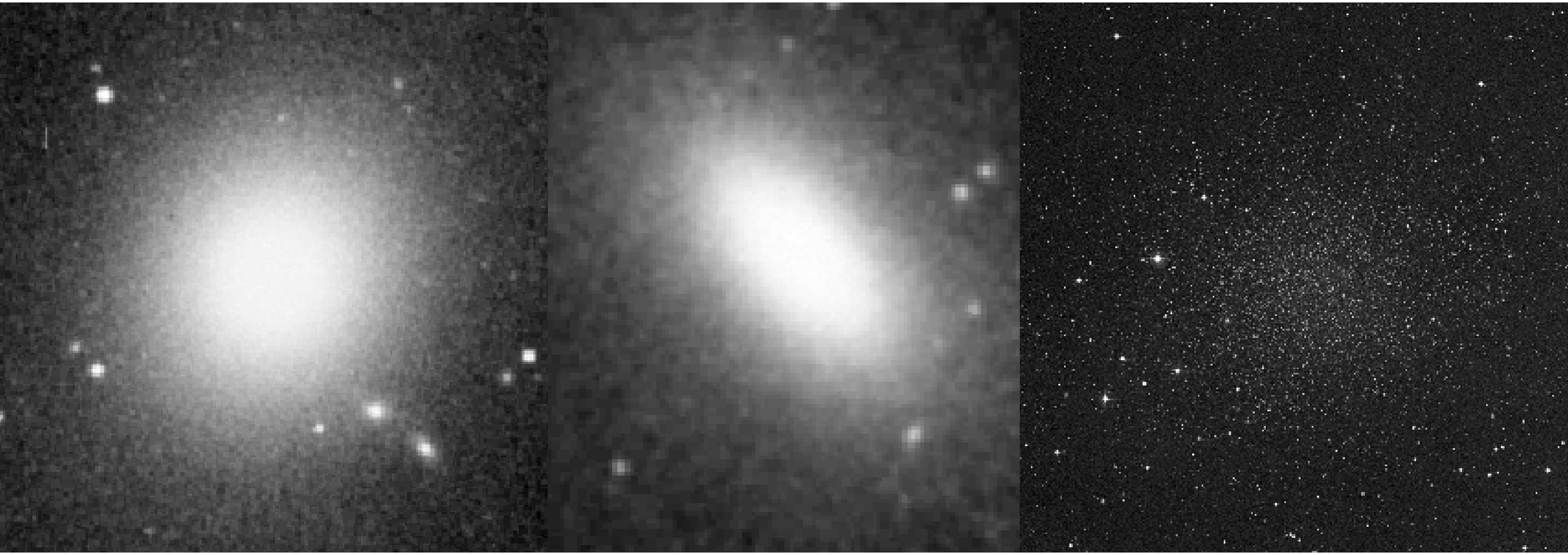


Elliptical galaxies

•smooth and structureless

•projected shapes: from round to cigar shaped

•Giant and dwarfs: divided according to total luminosity
- •dwarf Spheroidals: very low stellar density



Lenticular: S0s and SB0s

- smooth bright central concentration
- less steeply falling bright component (resembling a disk)

Disks

- contain a bulge (resembling an E) and a thin disk with spiral arms

- divided in subclasses (Sa to Sd) according to
  - relative importance of the bulge and disk
  - tightness of the spiral arms winding
  - degree to which the spiral arms are resolved

Irregulars

Asymmetrical; typical example are the Magellanic clouds

Fundamental criteria behind the Hubble sequence

1. small-scale lumpiness due to star formation now (current SFR)
   The Hubble sequence is a sequence in present-day star formation rate

2. Bulge (spheroid) to disk ratio (B/D)

3. Pitch-angle (PA), prominence, and number of spiral arms

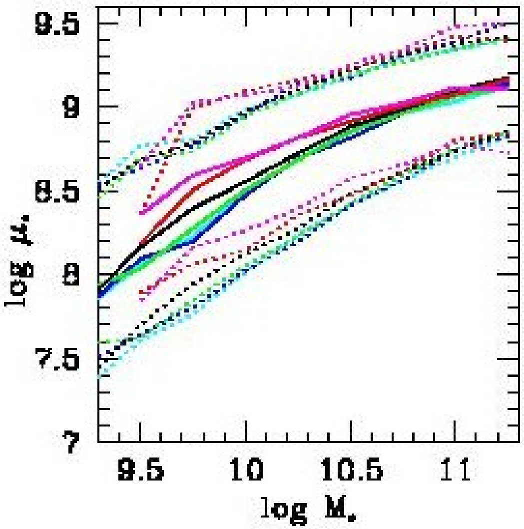
Hubble sequence: more than a morphological classification scheme

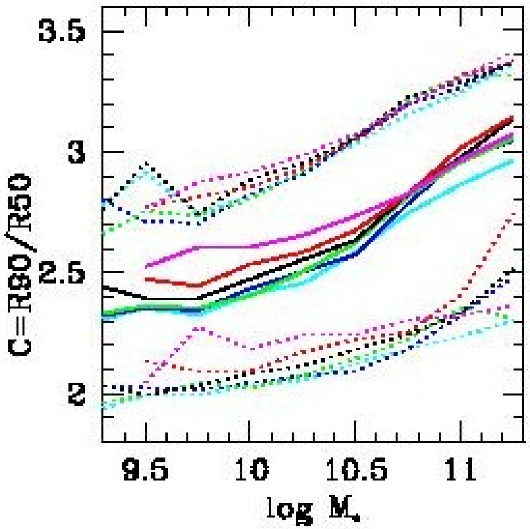
- There is a correlation between Hubble type and age of the dominant population of stars, the HI content and the environment in which these galaxies are found

- **Early type galaxies**: (E and S0)
  - no current star formation
  - redder (implying older stars)
  - primarily in galaxy clusters (high density environments)

- **Late type galaxies**: (S)
  - show star formation activity
  - bluer (younger stars)
  - mostly found in the field (75% are disks)

Correlations in galaxies properties from SDSS

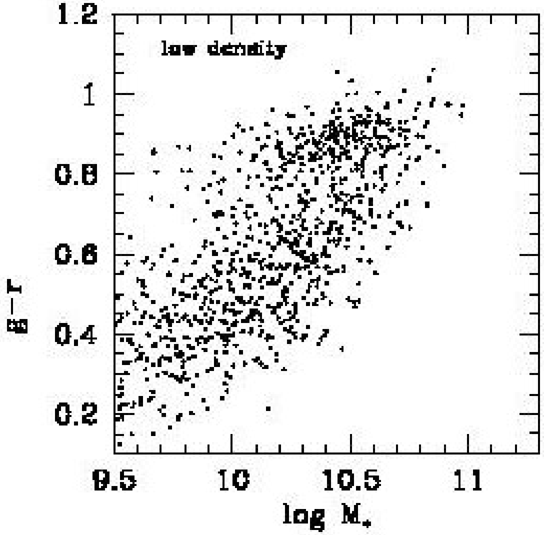


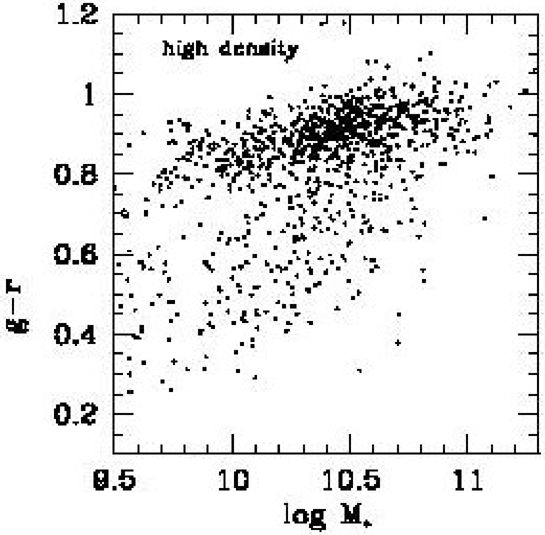


bulge dominated

mass and galaxy type

disk-dominated





mass and environment

colour and mass

Kauffmann et al 2004

Physics behind the Hubble sequence

- M_{HI}/M_{tot} increases from E to S --> fuel for star formation also increases --> SFR should increase from E to S

- This can be seen (roughly) from colors as function of type:
  - early-types are red (~ no SF)
  - late-types are blue (lots of SF)

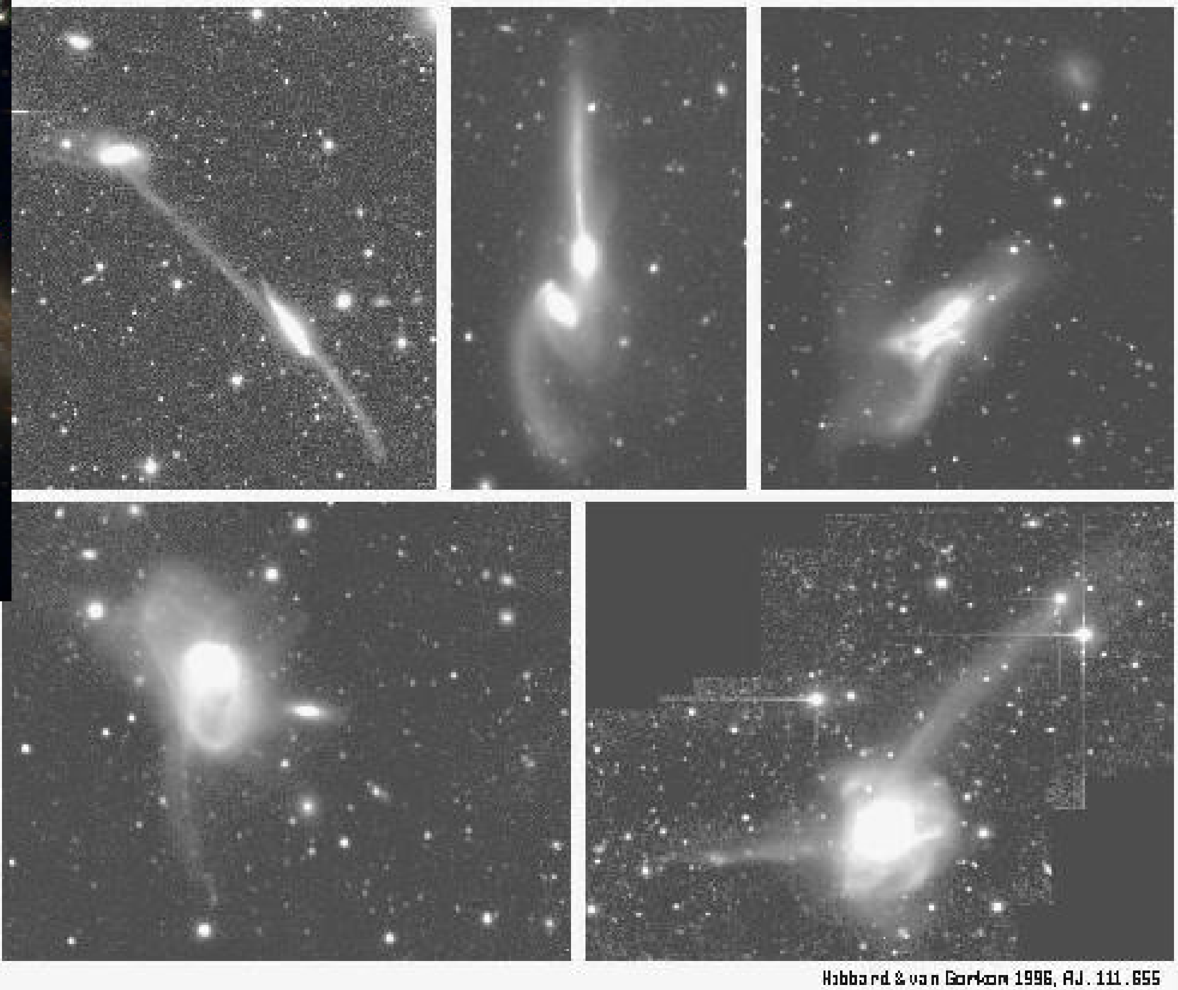
- Note that the Hubble type also correlates with mass (large B/D often implies large mass).
  - Suggests that mergers were important to build up early-type galaxies.

Static, evolving or evolutionary sequence?

- The Hubble classification was thought to be evolutionary sequence:
  - galaxies on the left part of the tuning-fork (E) would evolve into the right-hand side types (S). This is why we often speak of *early-type* and *late-type* galaxies.
- This interpretation is incorrect
  - evidence from ages, [Fe/H], galaxies without bulges
- Many processes can change the morphology of galaxies
  - minor interactions with other galaxies, environment, burst of star formation
  - mergers of galaxies

Hubble classification is “not static”

Collision between two disk galaxies



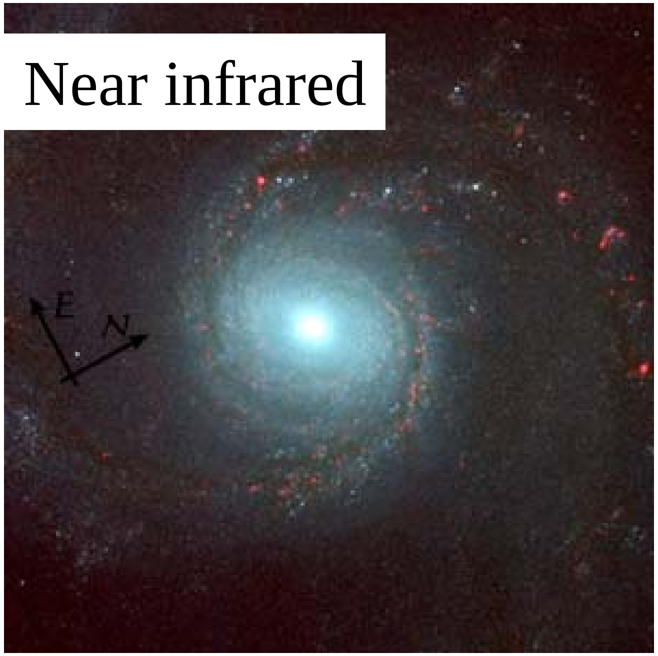
Peculiar galaxies: do not fit into the Hubble sequence. They show

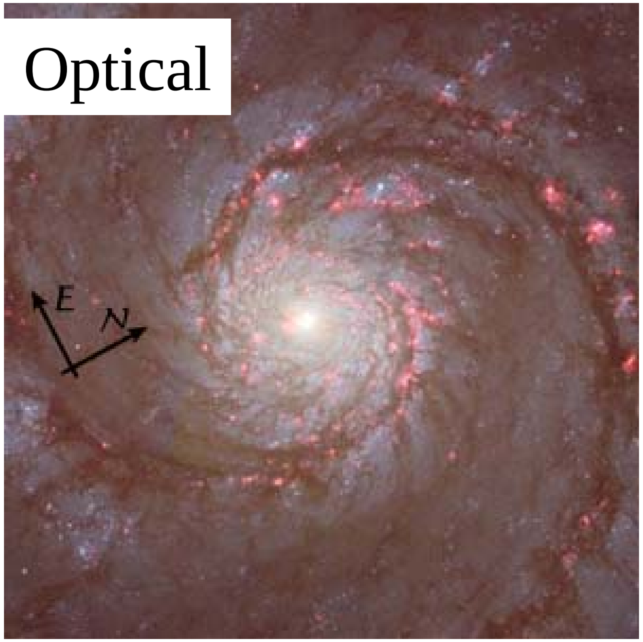
- distortions induced by gravitational processes
- gas and dust where unexpected
- strong burst of star formation

Nearly all due to mergers or interactions with other galaxies

Morphological classification of galaxies: wavelength matters!

The morphology of a galaxy can vary with waveband:
• different appearance in optical, UV, radio
• high vs low resolution spectra



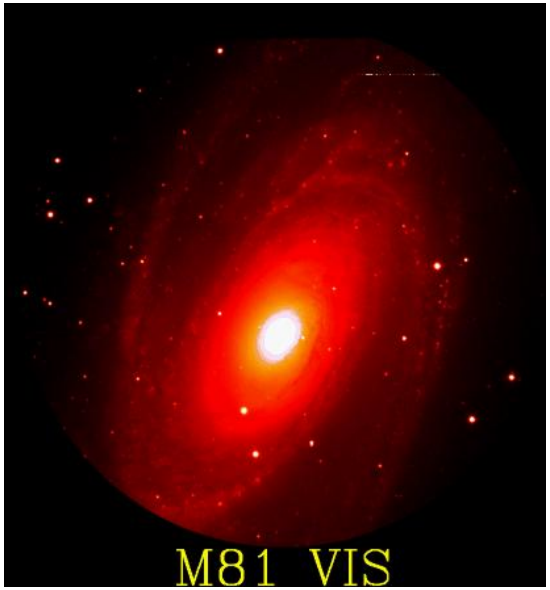


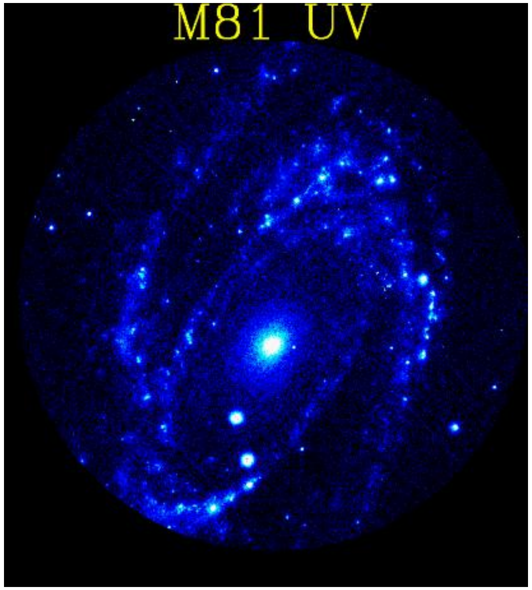
HST images of M51. Clouds are more transparent in the near-IR: stellar distribution is seen better

Fundamental that set of images is homogeneous:

– same wavebands for all galaxies

– Critical for comparison of objects at high and low redshifts:
  - rest-frame images are needed.
  - Galaxy at z=1 in R-band should be compared to z=0 galaxy observed in the U-band



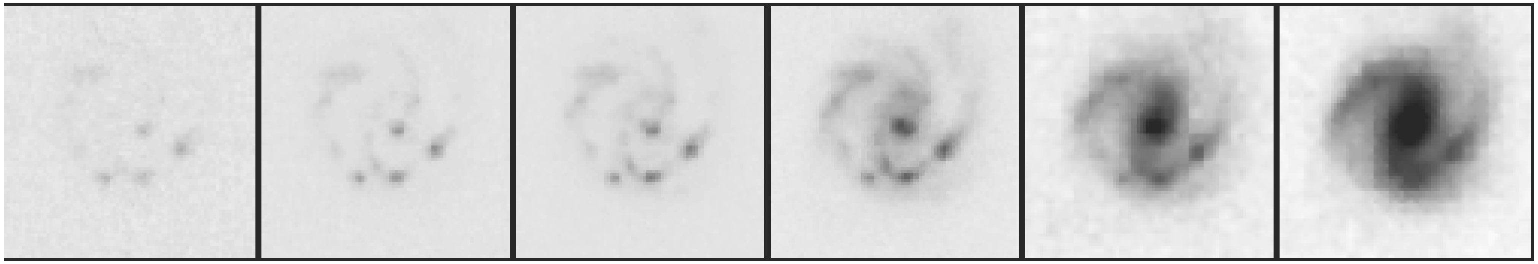


Notice how different the galaxy looks like in the UV (it would probably not be classified as Sb)

If M81 would have been at z=1, it would look like in the right image.

High-z universe

- Few issues to confront:
  - distances are required to understand both the sizes and ages of the galaxies
  - distances require redshifts AND cosmological parameters
  - distant galaxies are younger than those used to define the Hubble Sequence
  - more peculiar galaxies are observed: could be due to patchy star formation (younger age) or to interactions being more frequent (denser Universe)
  - resolution is poor compared to local galaxies and usually limited to a few bandpasses, and not necessarily those observed for nearby galaxies
  - selection effects: biases introduced by observing the brightest galaxies



Galaxies: some open questions

- What determines that a galaxy has a given type?
- Why are there correlations between the properties of a given galaxy (such as size, colour, environment, etc)?
- When do such correlations arise?
- What is the history of a galaxy?
- Are the properties of galaxies consistent/be understood in ΛCDM?

In this crash-course we will study the properties of galaxies

- how to derive ages and metallicities
- What determines the colour, e.g. if a galaxy is red, what does it mean?
- to measure the distribution of light
- to determine the mass and internal kinematics
- ….