Galaxy formation and evolution

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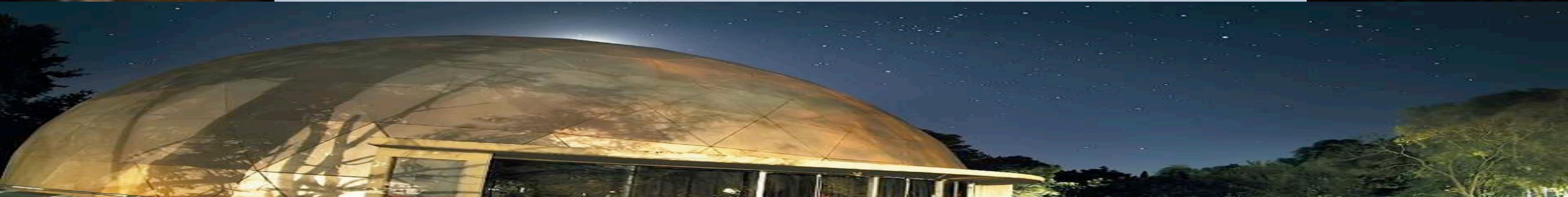
LAPIS 2018



Galaxies

- Simply put, a galaxy is a dynamically-bound system consisting of many stars
- A typical bright galaxy (e.g. our Milky Way):
  - ~10^{10} stars
  - ~10 kpc radius (1 kpc ~3×10^{16} km)

An elliptical galaxy

A galaxy similar to the Milky Way

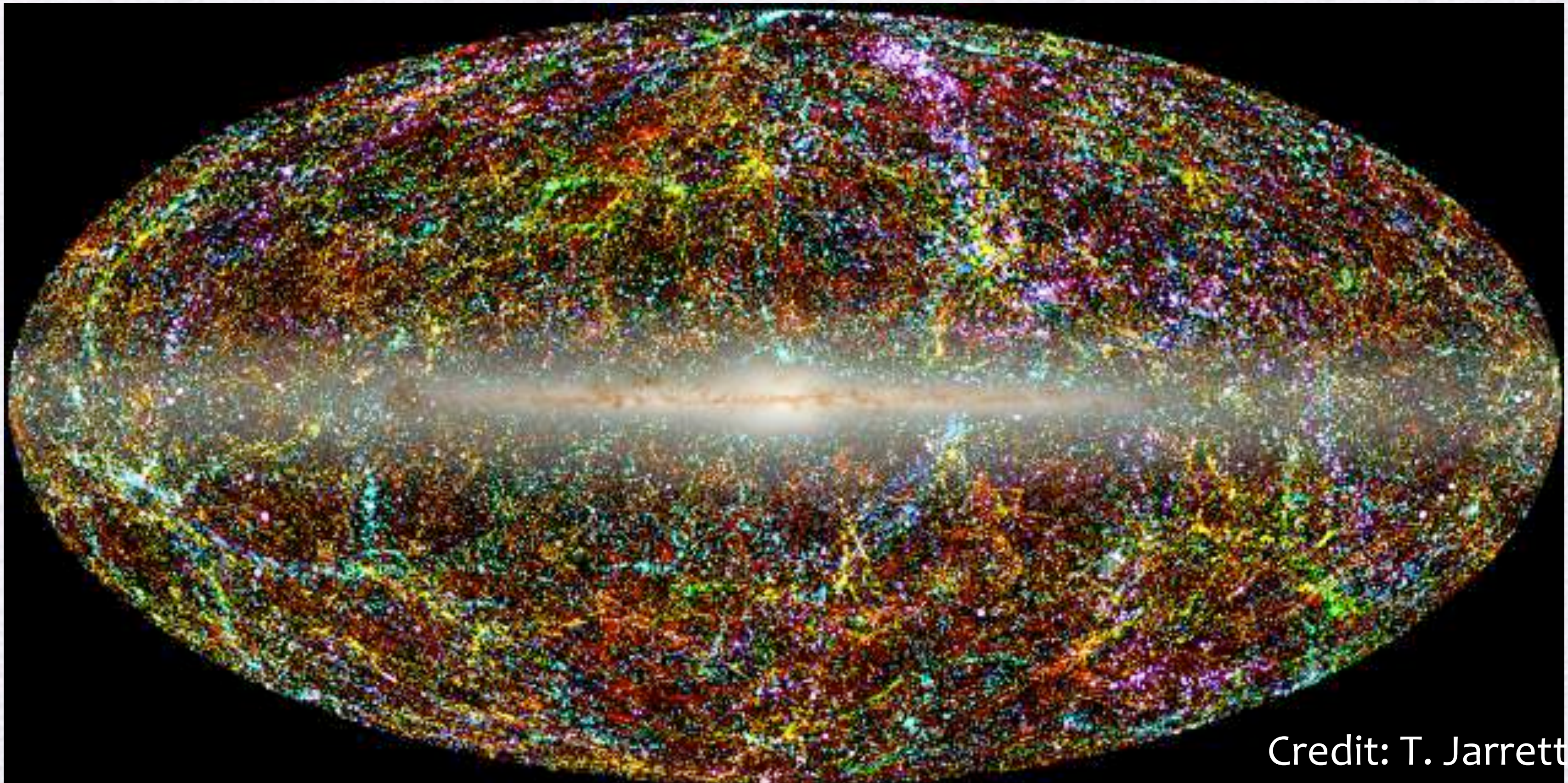
A dwarf galaxy

Galaxies & Cosmology

- Galaxies play a pivotal role in our study of the structure and evolution of the Universe:
  - They are bright, long-lived and abundant
  - They can be observed in large numbers over cosmological distances and timescales

Galaxies & Cosmology

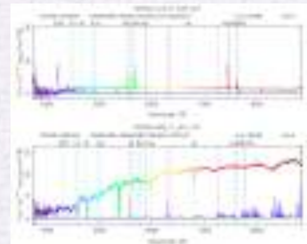
- They are unique tracers of the large-scale structure of the Universe even though they make up only a small fraction of the total amount of matter in it
- Their evolution gives us clues on the underlying physical processes occuring in the Universe at different times



Lectures 1 & 2

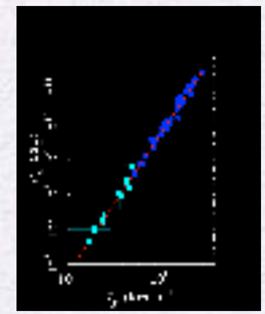
Two approaches to study the formation and evolution of galaxies

→ Observations → images

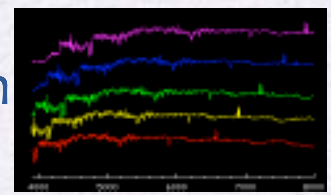


→ spectra

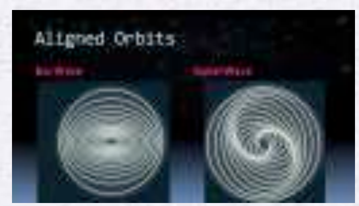
→ statistical properties/scaling relations



→ time evolution

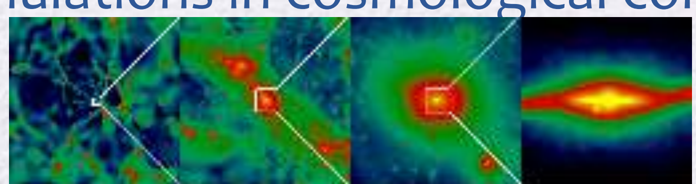


→ Theory → simple models



→ semi-analytic models

→ numerical simulations in cosmological context



Lectures 1 & 2

Two approaches to study the formation and evolution of galaxies

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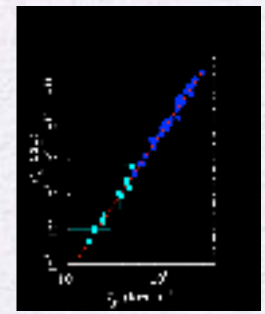
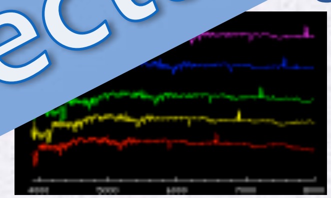
→ spectra

→ statistical r… …g relations

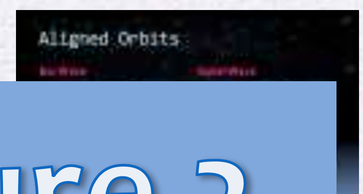


→ time e…



Lecture 1

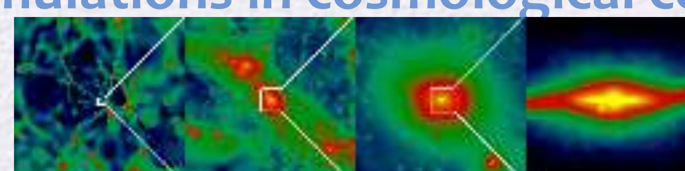
→ Theory → simple …



→ semi-a…

Lecture 2

→ **numerical simulations in cosmological context**



Basic concepts in observations

Stars and galaxies are studied observationally by analysing the electromagnetic radiation, or light, they emit.

- All objects have an internal energy which is manifested by the microscopic motions of particles → a continuum of energy levels associated with this motion
- If the object is in thermal equilibrium, it can be characterized by a single quantity, its temperature
- An object in thermal equilibrium emits energy at all wavelengths → continuum spectrum → thermal radiation

Basic concepts in observations

Stars and galaxies are studied observationally by analysing the electromagnetic radiation, or light, they emit.

- A blackbody absorbs all light that hits it, and emits thermal radiation: photons
- The amount of energy emitted (per unit area) depends **only** on the temperature of the blackbody
- The Planck law: radiation of a blackbody at different temperatures:

$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT)-1}$$

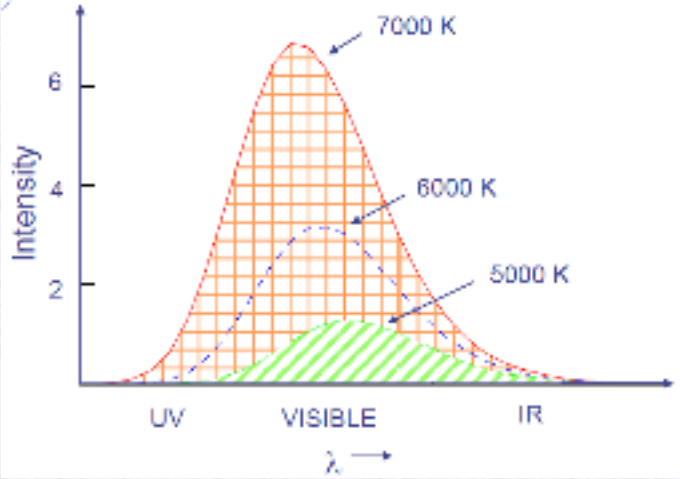
Power (energy/time)
per unit area
in the frequency range [υ,υ+dυ]
per solid angle

h=Planck’s constant, *c*=speed of light, *k*=Boltzmann’s constant

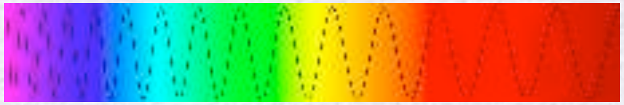
Basic concepts in observations

Stars and galaxies are studied observationally by analysing the electromagnetic radiation, or light, they emit.

- Except in their surfaces, stars behave as a blackbody



- Notes on blackbody radiation:
  - The peak shifts with T: $\lambda_{peak} \sim 1/T$ (Wien's law)
    - Cold objects look red, hot objects look blue
  - The area under the curve increases rapidly with T : $F \sim T^4$ (Stefan-Boltzmann law)
    - The hotter the blackbody, the more energy emitted at all wavelengths → bigger objects emit more radiation

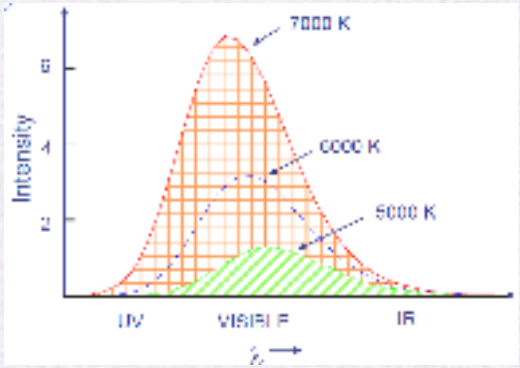


High freq. Low freq.

Basic concepts in observations

Various ways of expressing the characteristics of the energy emitted by a galaxy:

- **Surface brightness (I)**
  - Power per unit area per unit solid angle emitted by an object
  - $[I]$ = erg s^{-1} cm^{-2} sr^{-2}



- **Flux (F)**
  - power per unit area emitted by an object
    → integrate I over object image
  - $[F]$ = erg s^{-1} cm^{-2}

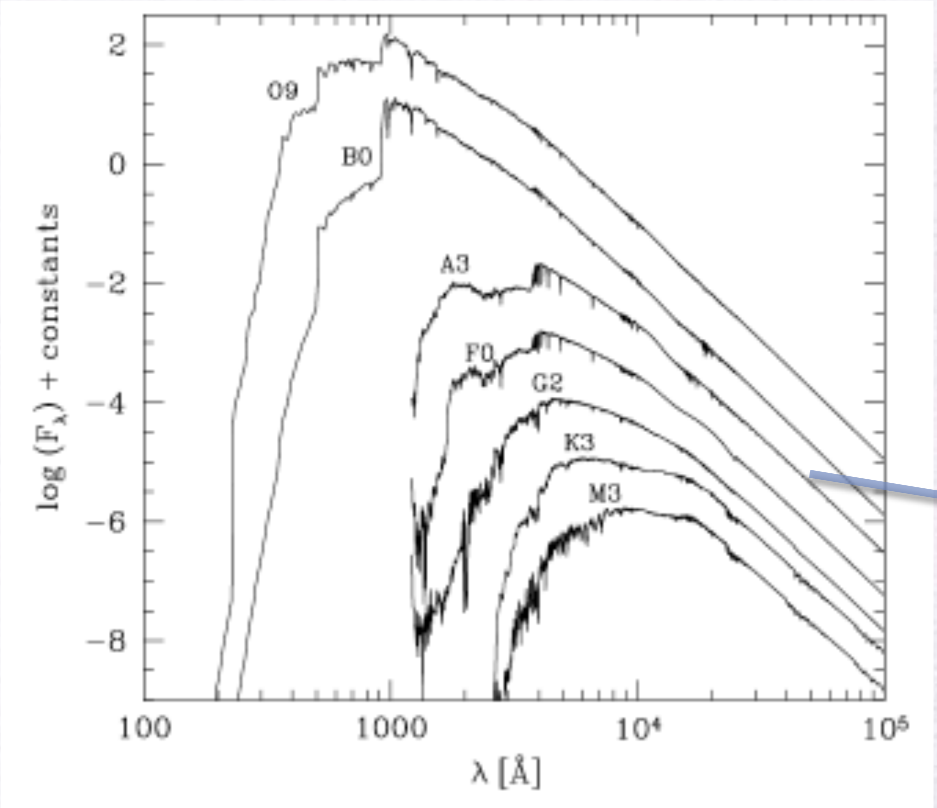
If an object has a large luminosity, it must be very hot and/or very big

Bolometric Luminosity (L):

- Total power emitted by an object of radius r
  → integral of F over radius r; $L = 4 \pi r^2 F$
- $[L]$ = erg s^{-1}, reference value is $L_{\odot} = 3.85 \times 10^{33}$ erg s^{-1}

Spectral Energy Distributions

- Almost all information of a galaxy is derived from the radiation we receive from it, characterized by its Spectral Energy Distribution (SED) $f_\lambda d\lambda$: total energy of emitted photons with wavelength between λ and $d\lambda$



The primary component of a galaxy SED is the combined light from its stellar population

Spectra of stars of different types (arbitrarily shifted to avoid confusion!)

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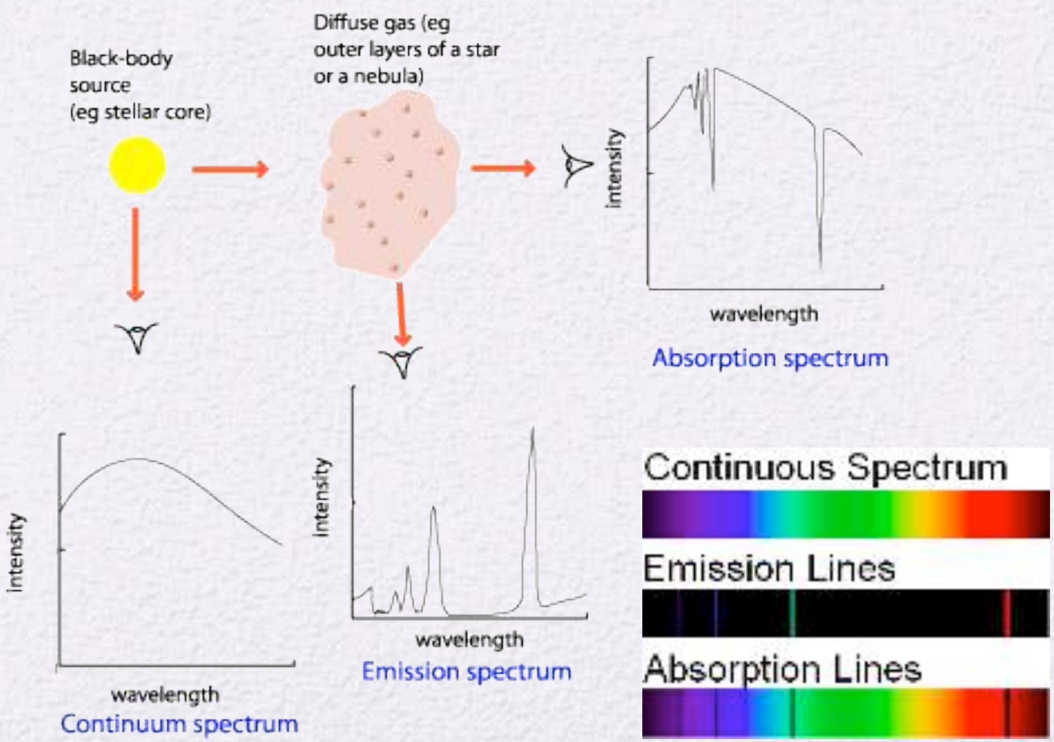

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+ Absorption/emission lines

Spectral Energy Distributions

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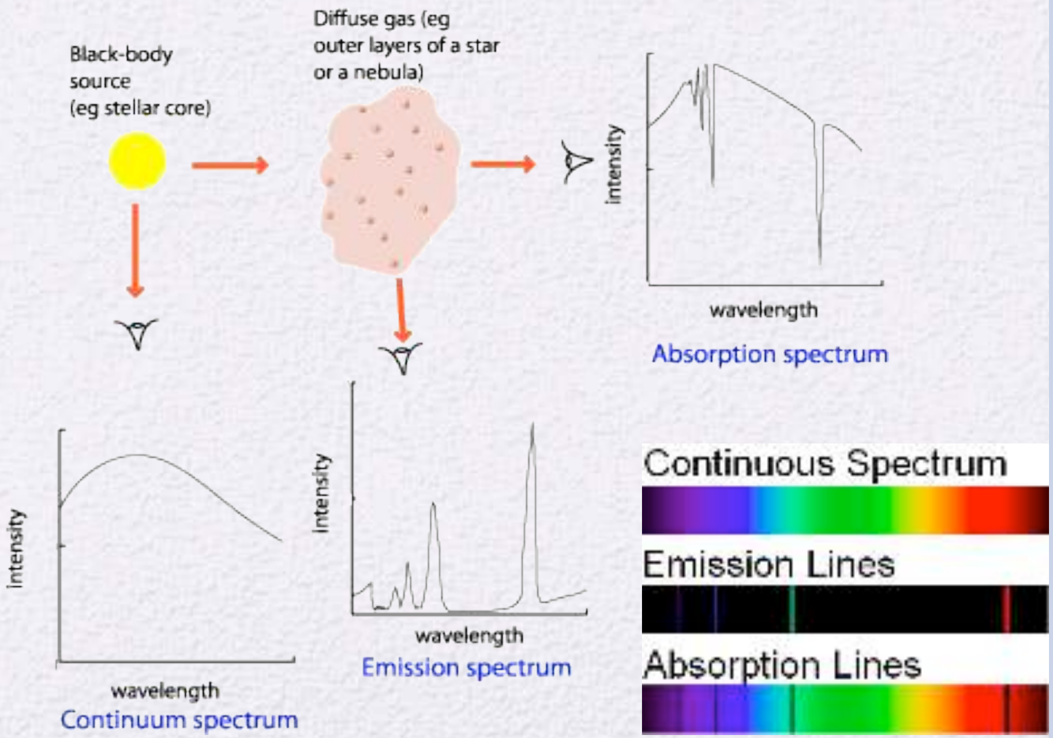


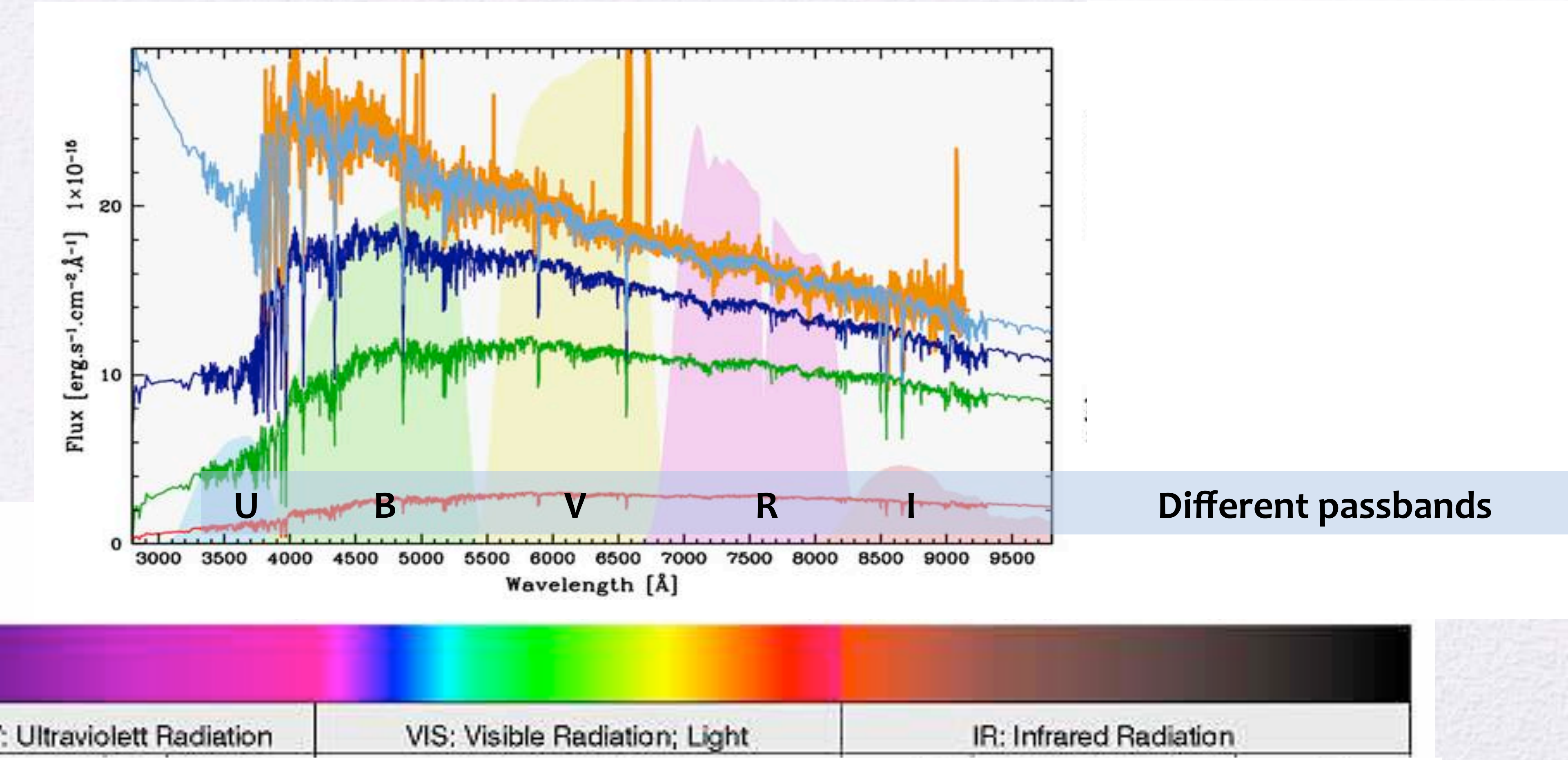
Continuum + absorption lines

Absorption occurs when photons of given frequencies are absorbed by electrons outside the core of the star. Photons of a different frequency are emitted.

Emission occurs when electrons in a gas cloud are excited by radiation coming from the nearby stars. The electrons then de-excite at spectific frequencies.

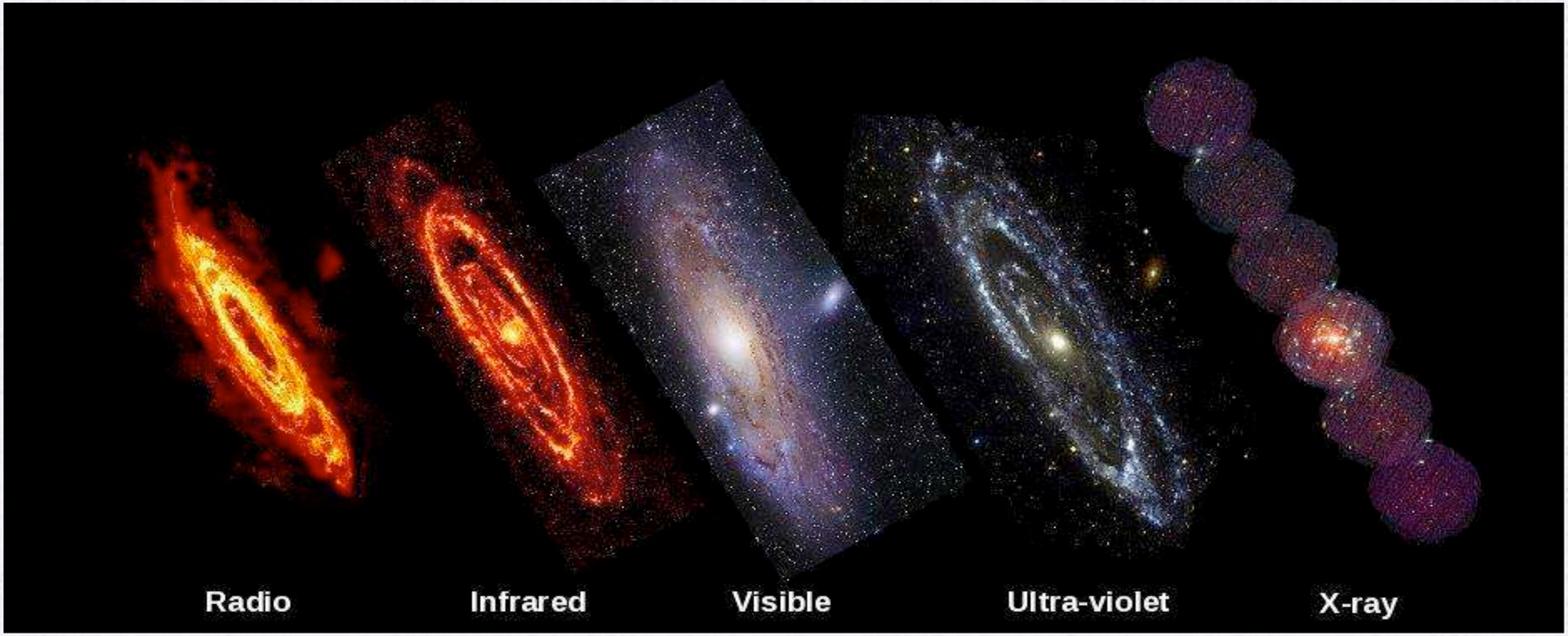
Spectral Energy Distributions

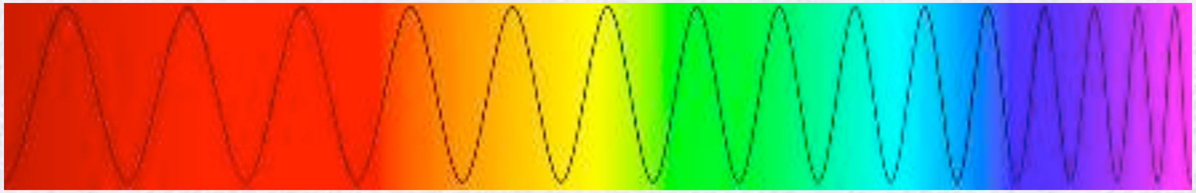
As the lifetime of a star correlates strongly with its mass, the SED of a galaxy reveals its star formation history !



Galaxies: observations

Today we can observe galaxies in virtually all wavelengths!





Low frequencies

High frequencies

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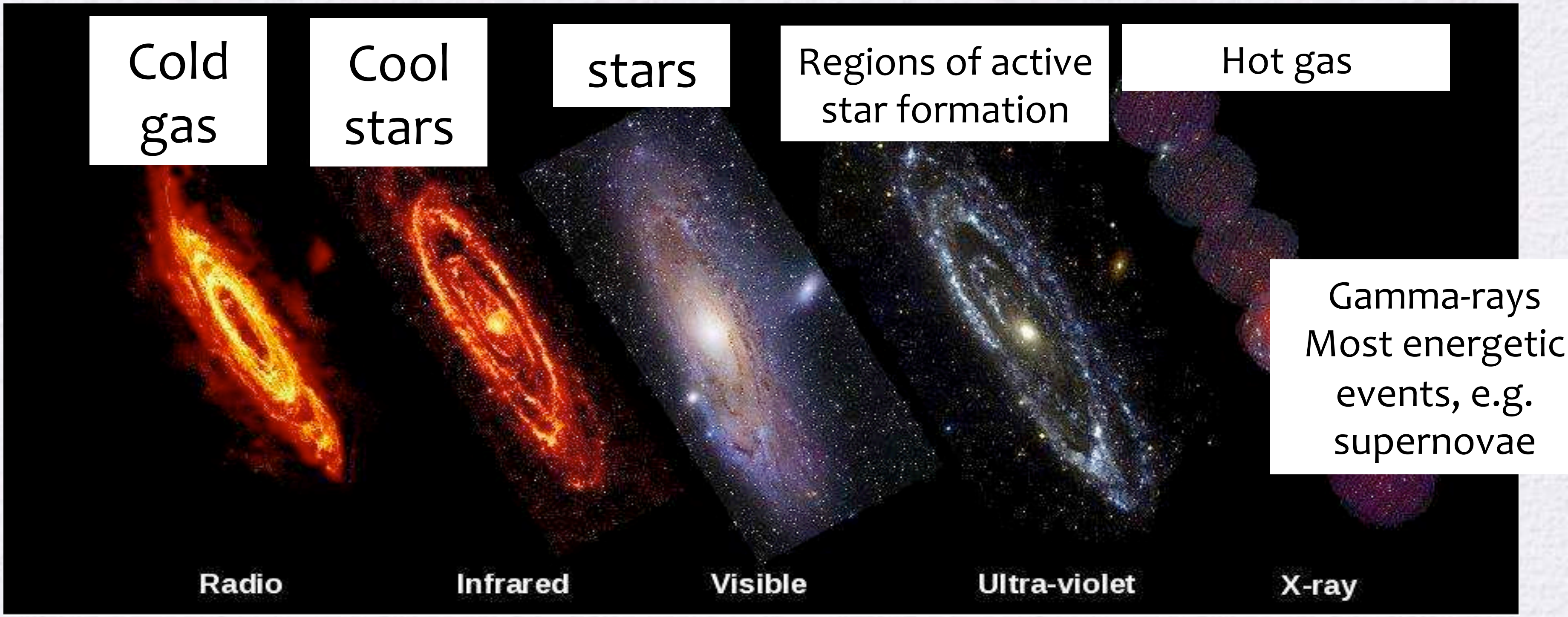
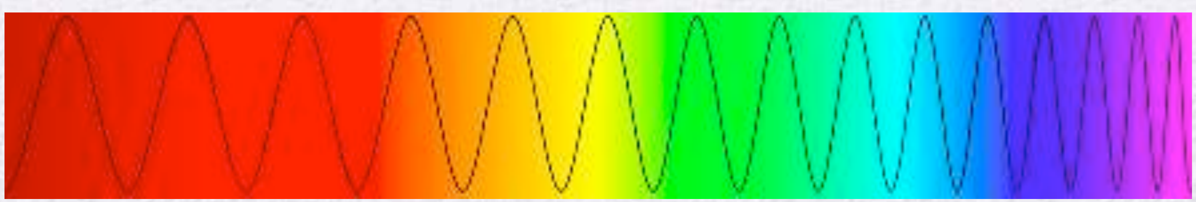




Low frequencies

High frequencies

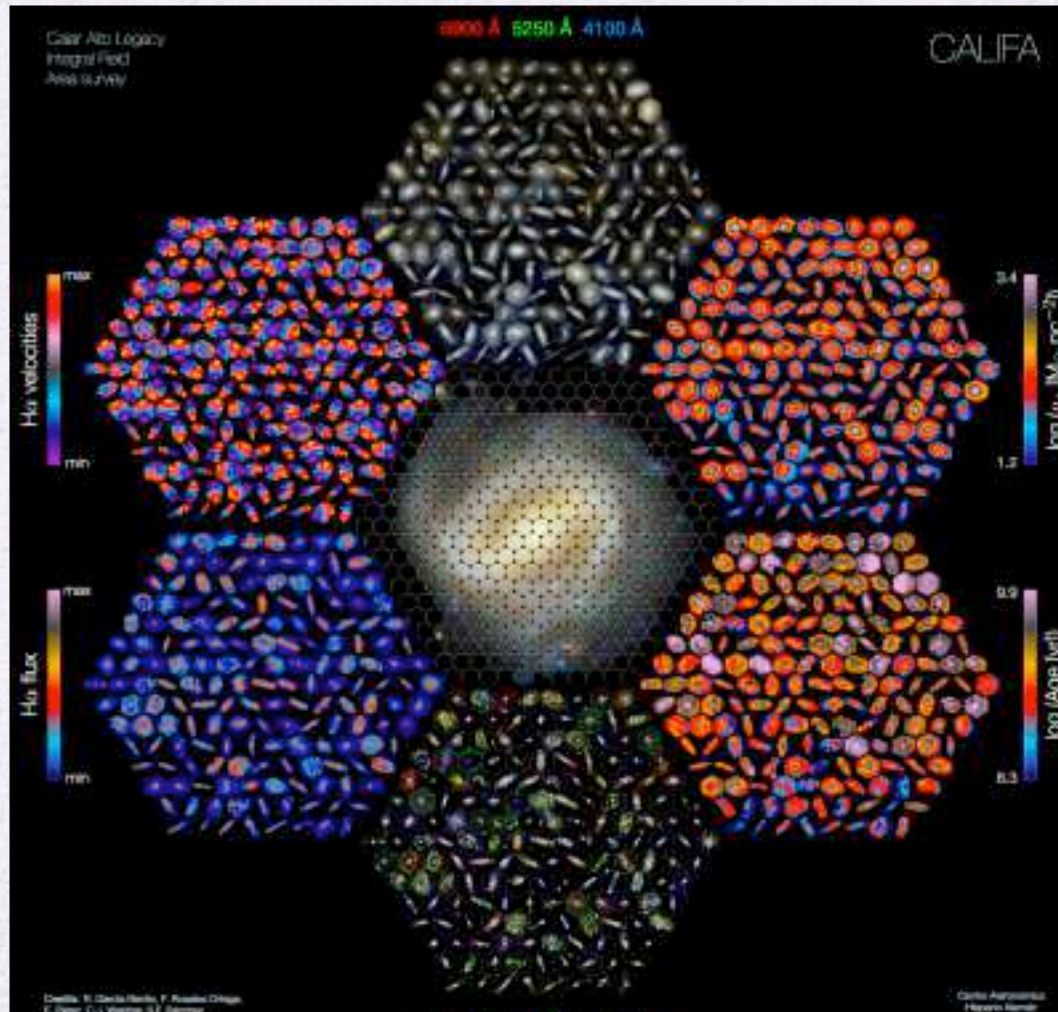
Spectral Energy Distributions

We have now access to spatially-resolved spectra of a large number of galaxies

Integral Field Spectroscopy

e.g. SAURON, PINGs, Atlas3D, CALIFA, SAMI, Manga, MUSE

And also at high redshift
SINS, KMOS^{3D}, KROSS



Observations: galaxy properties

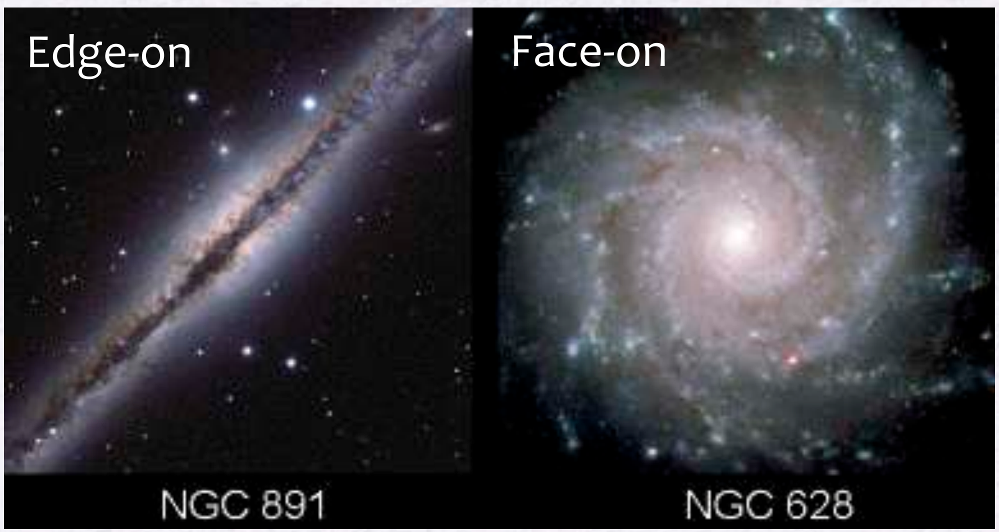
Current observations provide information on many galaxy properties:

- Morphology
- Luminosity
- Stellar mass
- Size and surface brightness
- Gas mass fraction
- Color
- Environment
- Nuclear activity
- Redshift

Galaxy morphology

- Morphology is the "shape" of a galaxy, which also encodes information on the dynamical properties
- Two basic types of galaxies: Spirals and Ellipticals

Spirals (or late-type gxs)



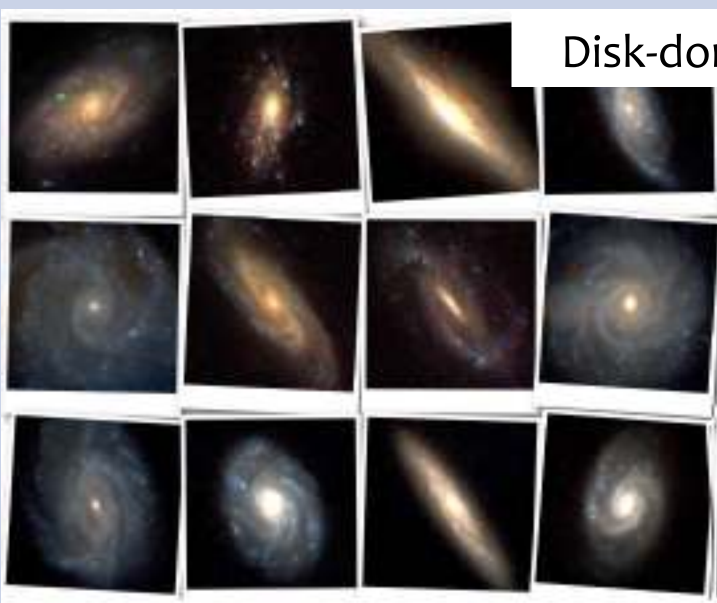
Highly-flattened disks, rotationally-supported

Ellipticals (or early-type gxs)

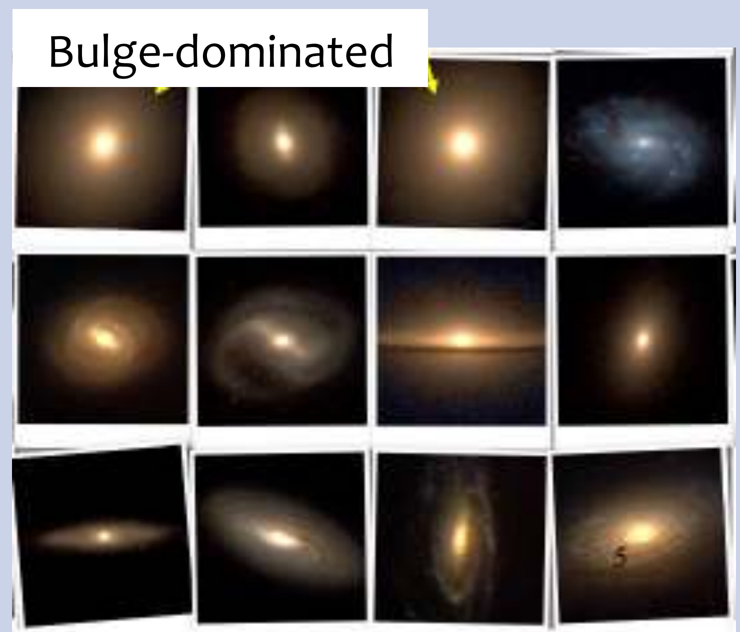
Mildly-flattened, spheroidal systems, supported by random motion

Galaxy morphology

- Most galaxies are, however, neither a pertect ellipsoid nor a perfect disk, but rather a combination of both

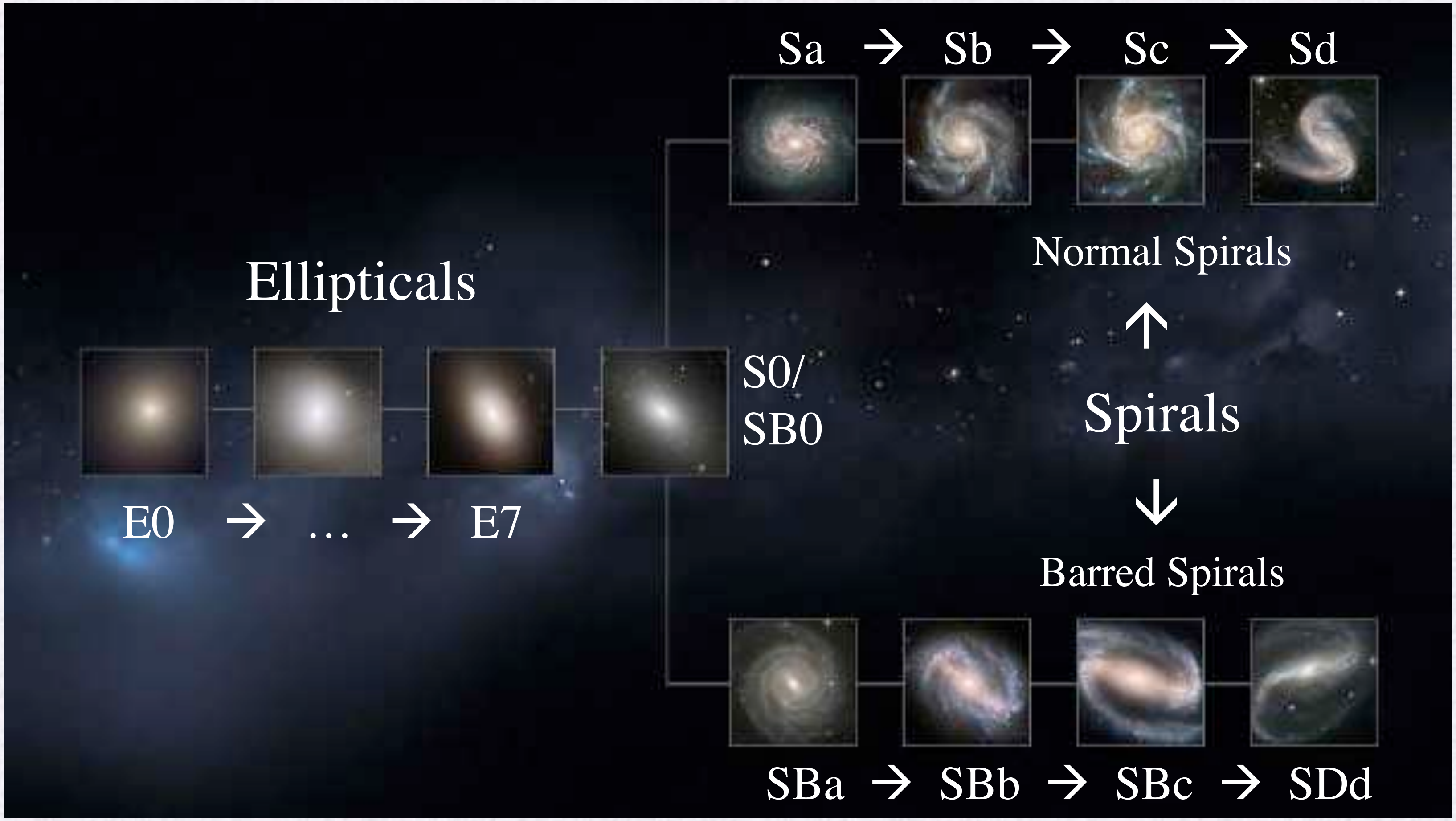


The central spheroid in disk galaxies is called the "bulge"



Galaxy morphology

The Hubble Sequence: a sequence in the mixture of disk and spheroid



Not an evolutionary sequence

Galaxy morphology

The Hubble Sequence: a sequence in the mixture of disk and spheroid

Not all galaxies fall in this classification: the “irregular” galaxies

Galaxy morphology & mass

Elliptical galaxies:

- Up to 10^{13} stars
- Up to ~100 kpc radius
- Little/no rotation
- Spheroidal shape

Spiral galaxies (e.g. the Milky Way):

- 10^{10} stars
- ~10 kpc radius (1 kpc ~3×10^{16} km)
- Supported by rotation

- Different components: disk, bulge, halo, bar

Dwarf galaxies:

- $10^{5\text{-}7}$ stars
- ~1-10 kpc radius (ellipticals) / 0.1-0.5 kpc (spheroidals)
- Ellipticals vs Spheroidal vs Irregular
- **Most abundant** type of galaxy but difficult to detect

Galaxy Luminosity & Stellar Mass

The luminosity of a galaxy is the energy emitted per unit time, and is usually measured in units of $L_\odot$, the luminosity of the sun.

- Galaxies span a wide range in luminosity:
  - The brightest galaxies have ~10^{12} $L_\odot$
  - The faintest galaxies known so far have <1000$L_\odot$

The total luminosity of a galaxy is related to the total number of stars, therefore to the total stellar mass

Note: the stellar mass of a galaxy is not an observable, but is calculated as an indirect observation!

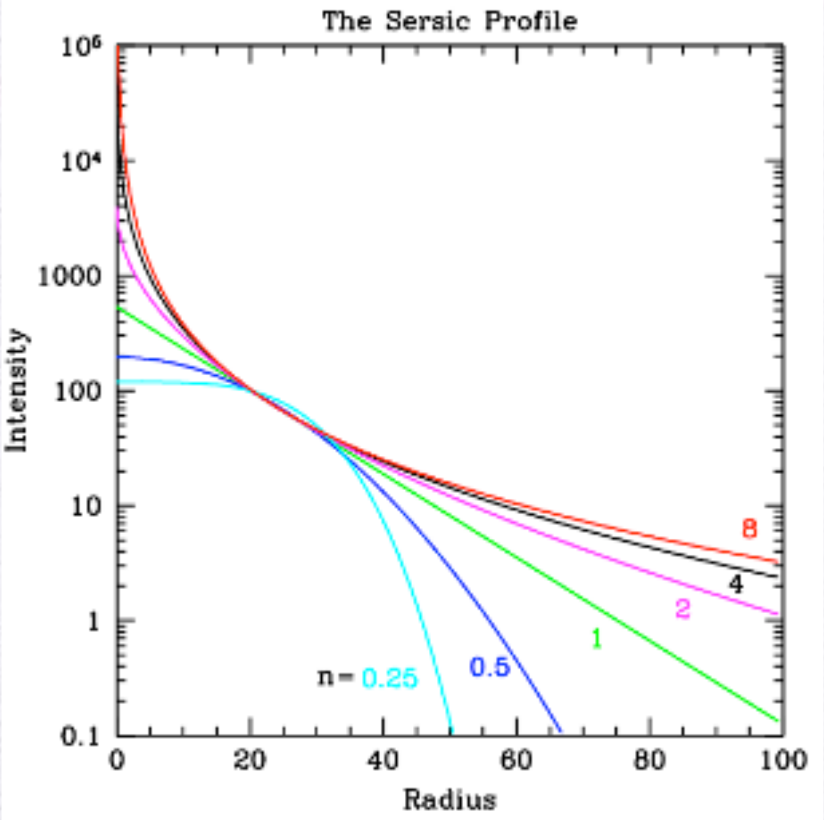
Galaxy Luminosity & Stellar Mass

Observations show 2 types of surface brightness profiles

- Sèrsic profile

$$I(R) = I_o \exp(-[R/R_0]^{1/n})$$

  - n=4 is the de Vaucouleurs profile



- Exponential profile

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  - Sèrsic with n=1

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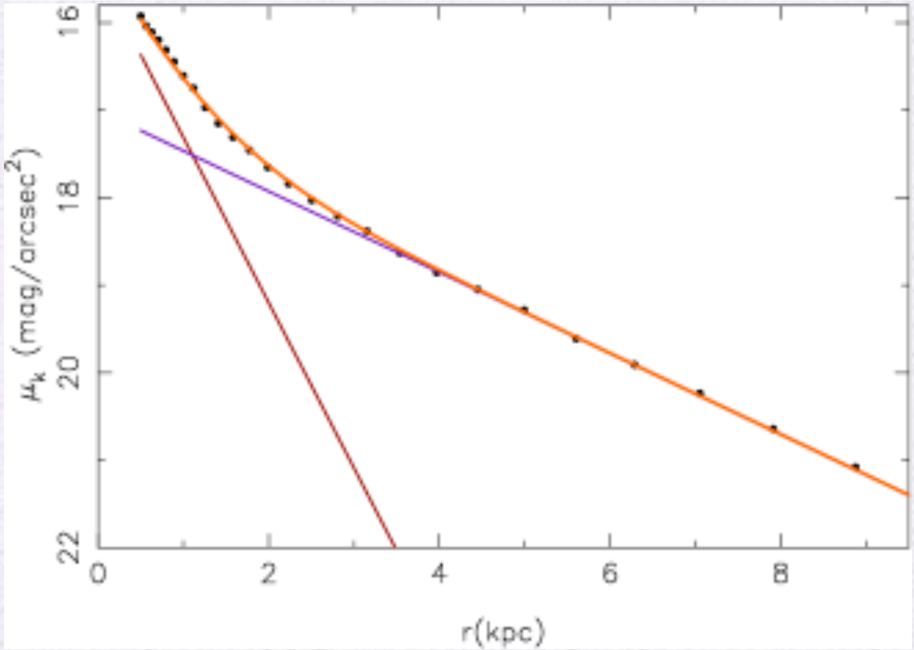
Disks → exponential profiles

Bulges/ Ellipticals → de Vaucouleurs/Sèrsic profile



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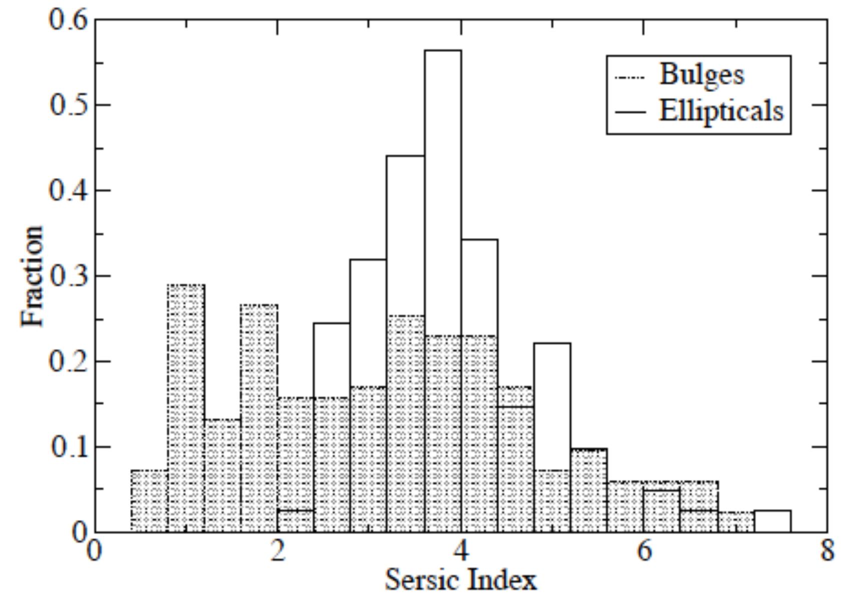

Gadotti 2007

Galaxy Luminosity & Stellar Mass

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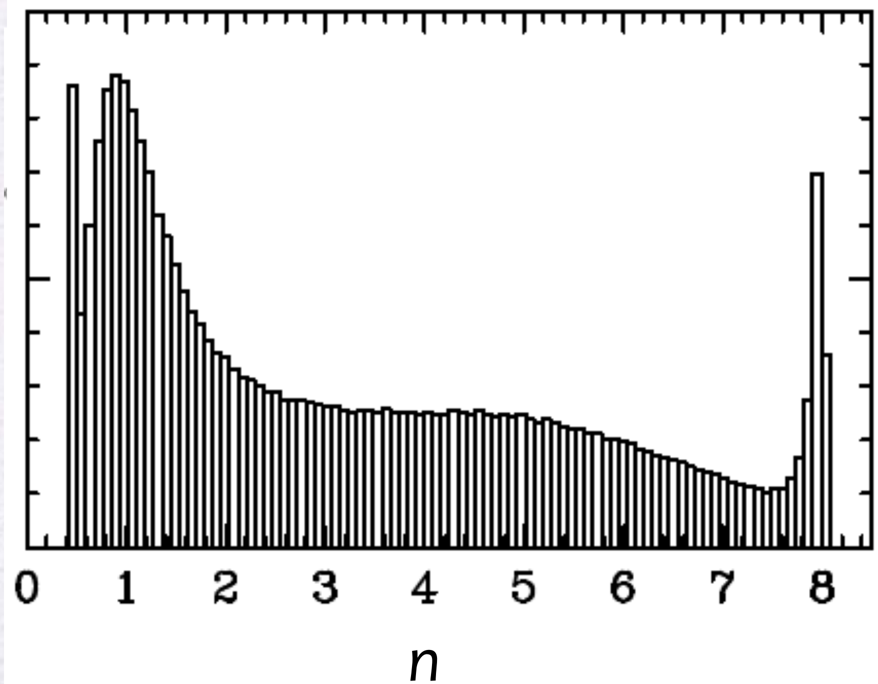

Simard + 2011

Galaxy size & surface brightness

- How do we define the “boundary” of a galaxy?
- Several definitions to the “size” of a galaxy:
  - the radius enclosing a certain fraction (e.g. half) of the total luminosity

We observe some galaxy in the sky

Galaxy size & surface brightness

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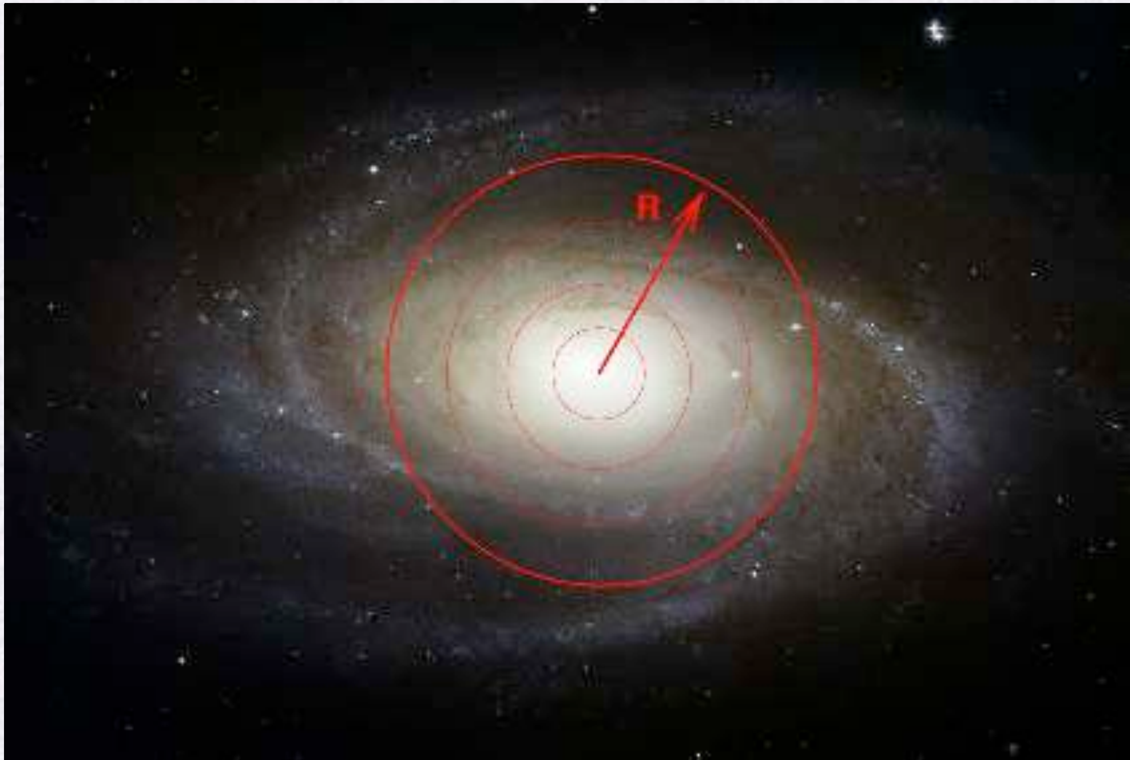
Measure light vs radius, averaged over all pixels in circular annuli



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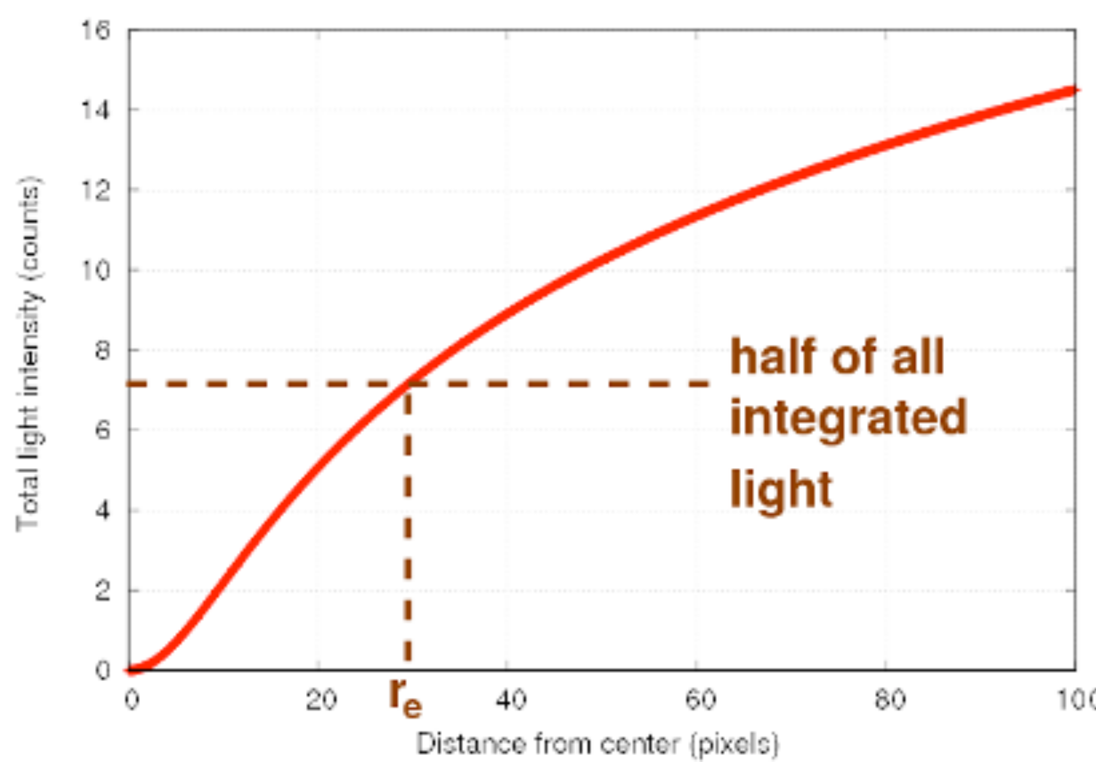
Create radial profile/integrated radial profile



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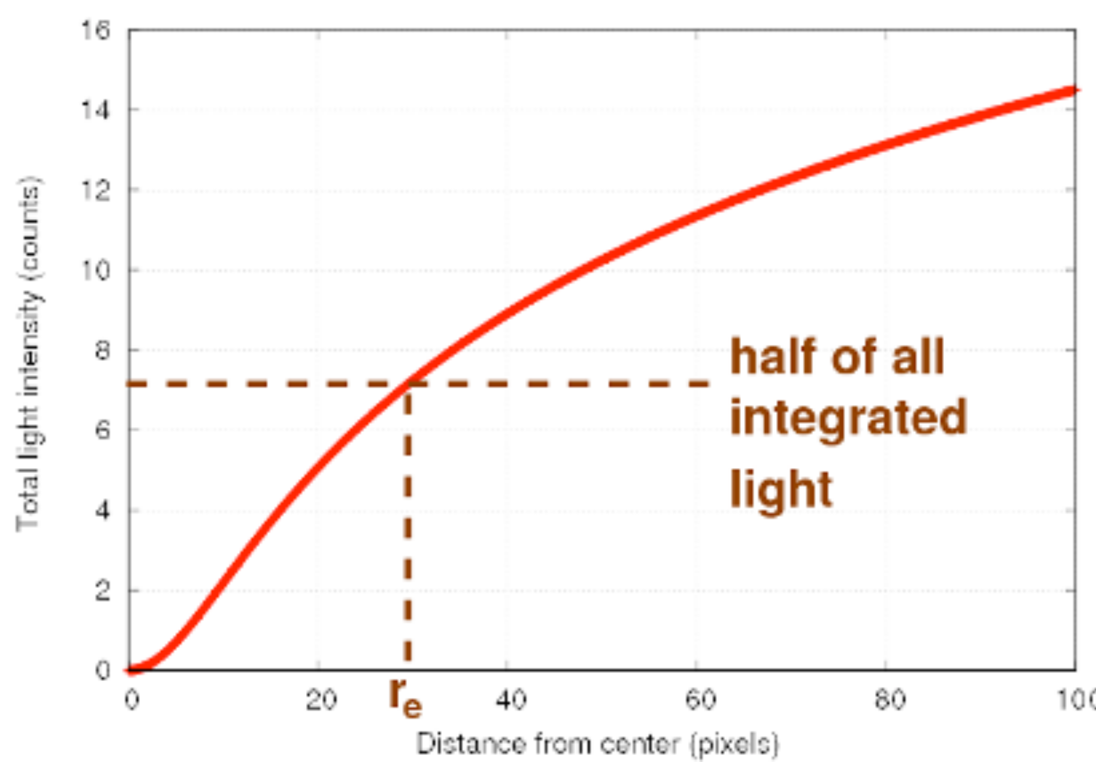
Measure light vs radius, averaged over all pixels in circular annuli

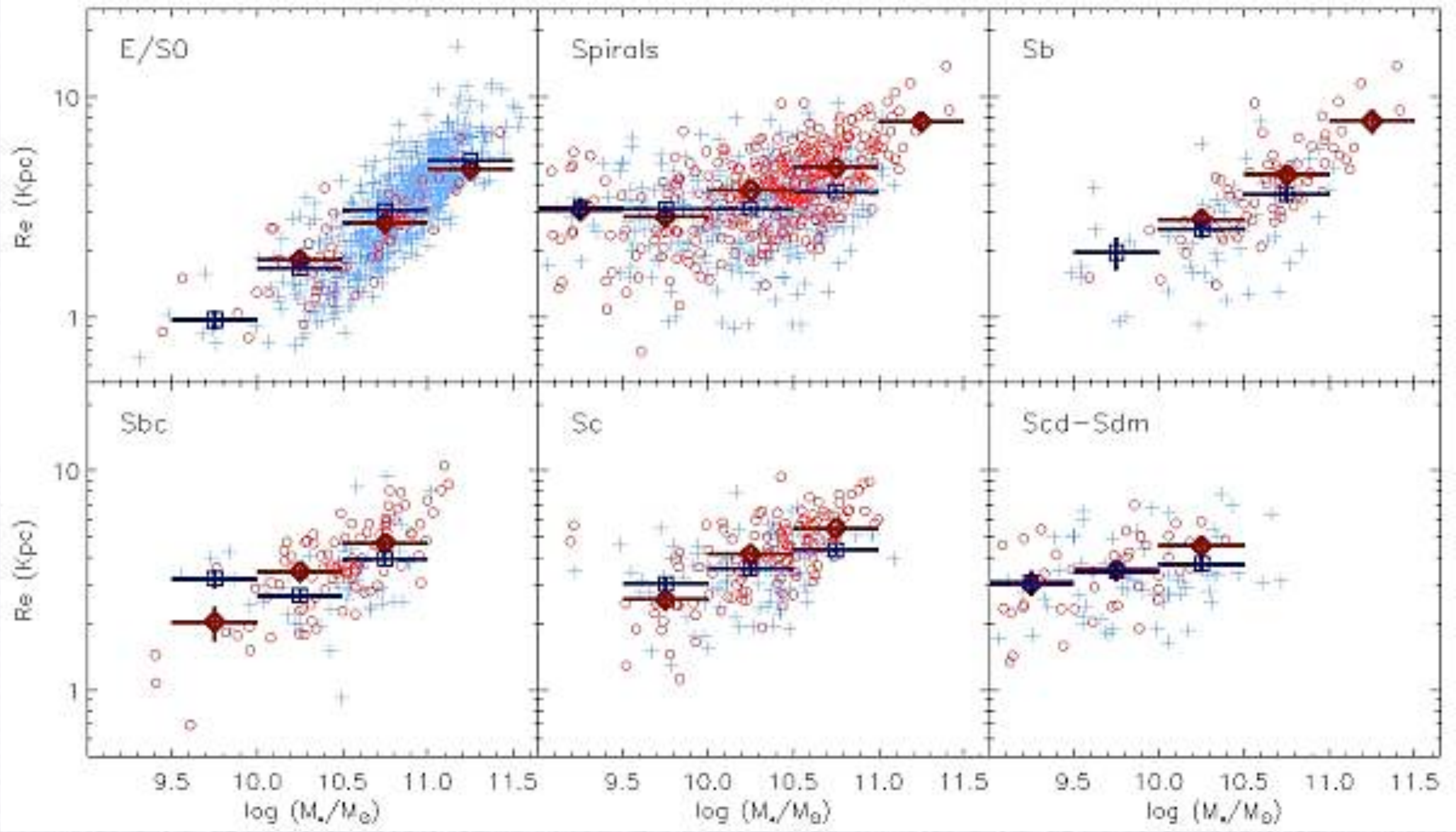
Create radial profile/integrated radial profile

Define characteristic radius



Galaxy size & surface brightness

Considerable scatter in sizes even for a given stellar mass



AMIGA survey

Galaxy size & surface brightness

- How do we define the “boundary” of a galaxy?

The size of a galaxy has an **important physical meaning**

- In disk galaxies, the sizes are a measure of their **specific angular momentum** (i.e. angular momentum per mass unit)

- In Elliptical galaxies, the sizes are a measure of the **amount of dissipation** during their formation

Galaxy (cold) gas mass fraction

- The cold gas mass fraction of a galaxy is defined as

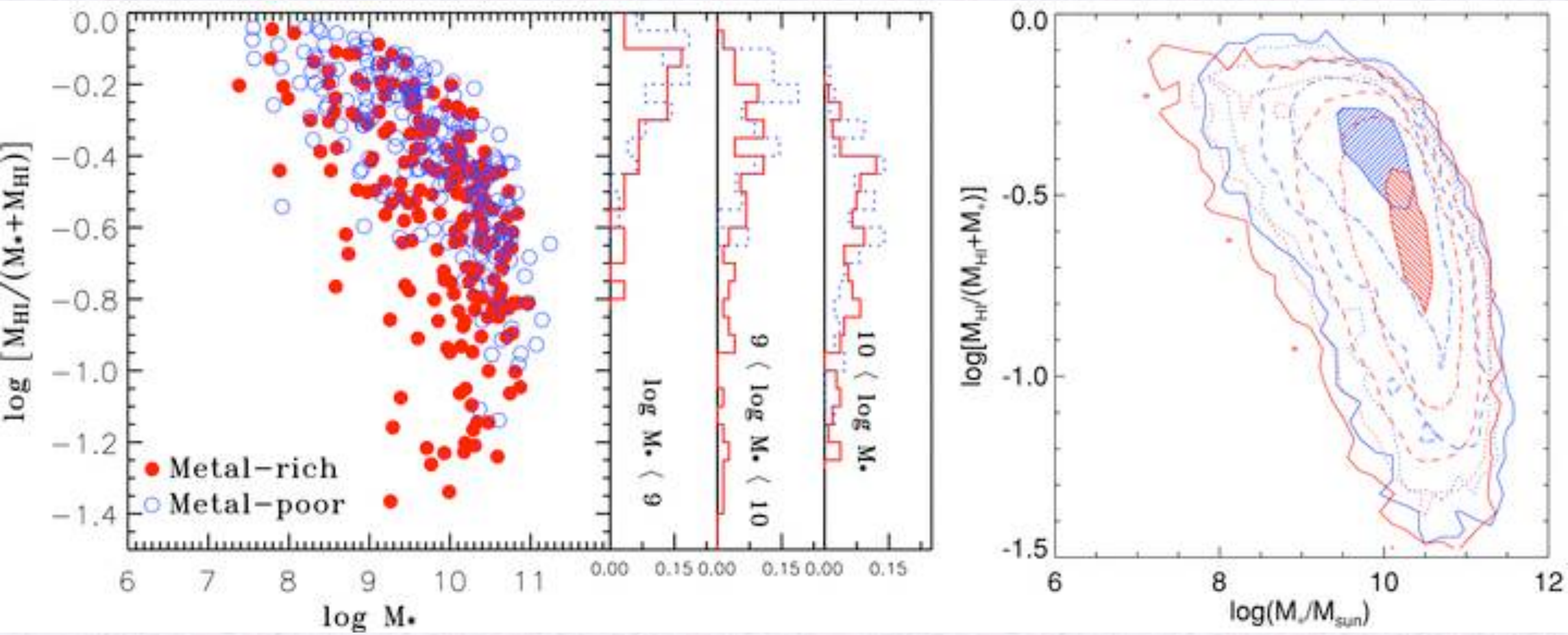
$$f_{gas} = M_{cold}/(M_{cold}+M_{star})$$

with M_{cold} and M_{star} being the cold gas and stellar masses

- f_{gas} measures the efficiency of transformation of (cold) gas into stars

  - Elliptical galaxies have negligible f_{gas}
  - Spiral galaxies span a wide range of f_{gas}, which anticorrelates with surface brightness:
    - The lowest surface brightness galaxies have f_{gas} up to 0.9 (90%)
    - The Milky Way (MW) has f_{gas} ~0.1

Galaxy (cold) gas mass fraction



Zhang+ 2009

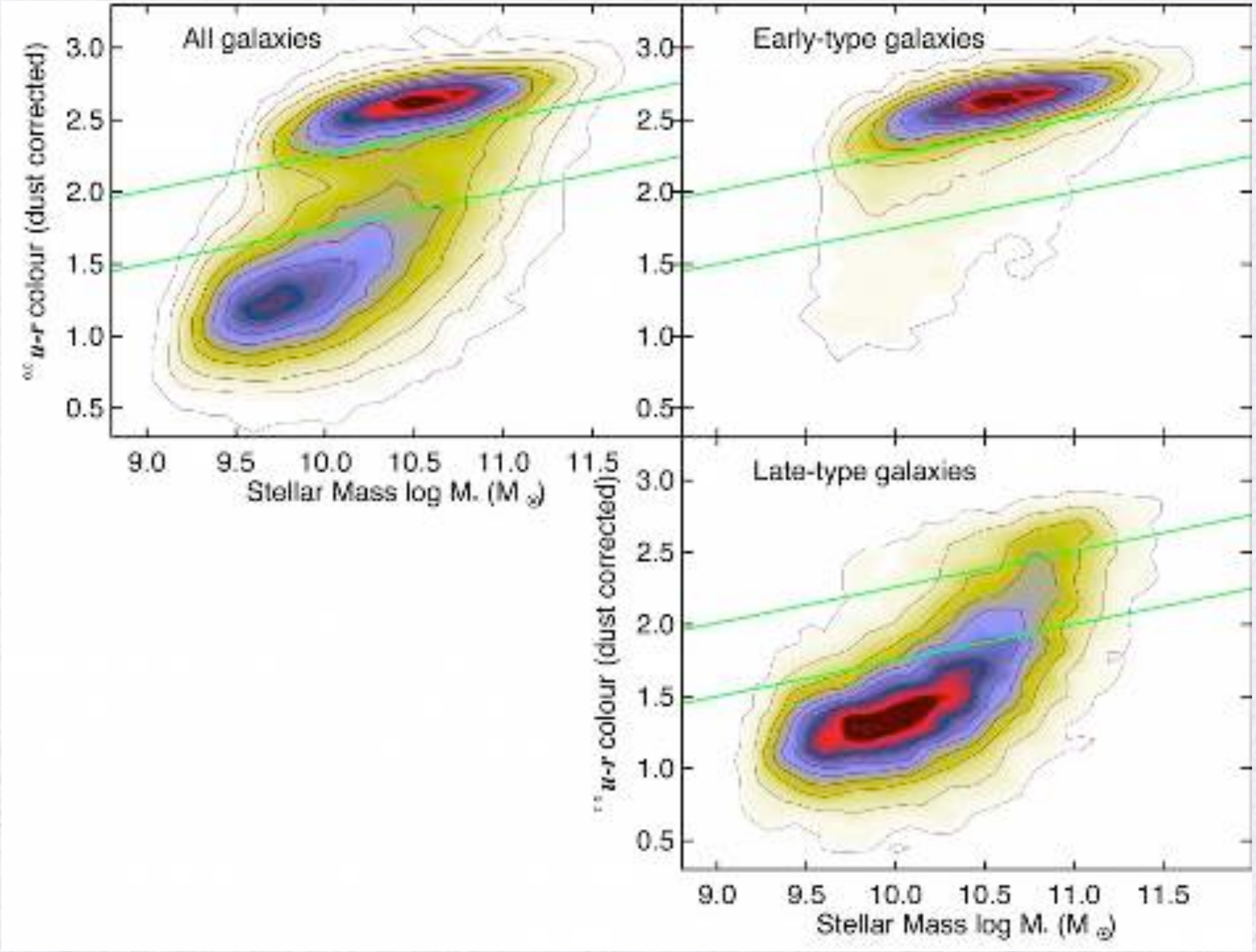
- Wide range of cold gas fractions in local galaxies
- Dependence with red (elliptical) and blue (spiral) galaxies
- Dependence with galaxy mass

Galaxy colors

- The color of a galaxy is the ratio of its luminosity in two photometric bands
  - “Red” galaxies: the luminosity in the redder passband is high compared to that in the bluer passband
  - “Blue” galaxies: the luminosity in the bluer passband is high compared to that in the redder passband
- Ellipticals are in general redder compared to Spirals
- The color reflects the characteristics of the stellar populations (SPs):
  - The SPs in red galaxies are predominantly old and/or metal-rich
  - The SPs in blue galaxies are predominantly young and/or metal-poor

Galaxy colors

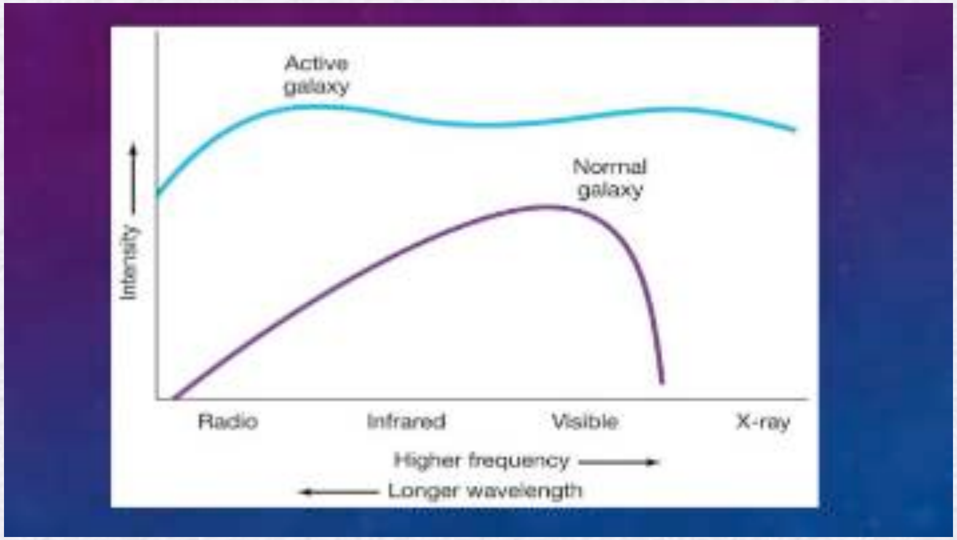
- Galaxy bimodality: red and blue clouds, green valley



Schawinski+ 2014

Galaxy nuclear activity

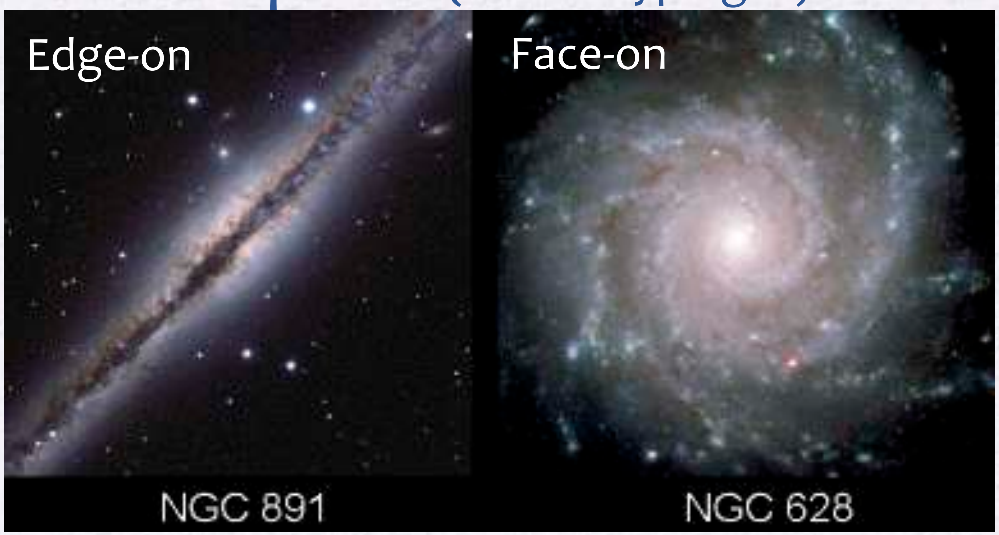
- For some galaxies, the observed emitted light is not consistent with what we expect from their stars and gas
- The "active galaxies" which show an additional non-stellar component in their spectral energy distribution
- This emission is associated with matter accretion onto a massive black hole in the center of the galaxy, the active galactic nucleus (AGN)



Galaxy classification

- Galaxies in general classified in terms of their morphologies

Spirals (or late-type gxs)



Ellipticals (or early-type gxs)

Galaxy classification

Galaxies can also be classified according to properties other than their morphology

Luminosity

Surface brightness

Color

Gas content

Star formation

Active nucleus

Bright vs faint

Galaxy classification

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- **Surface brightness**
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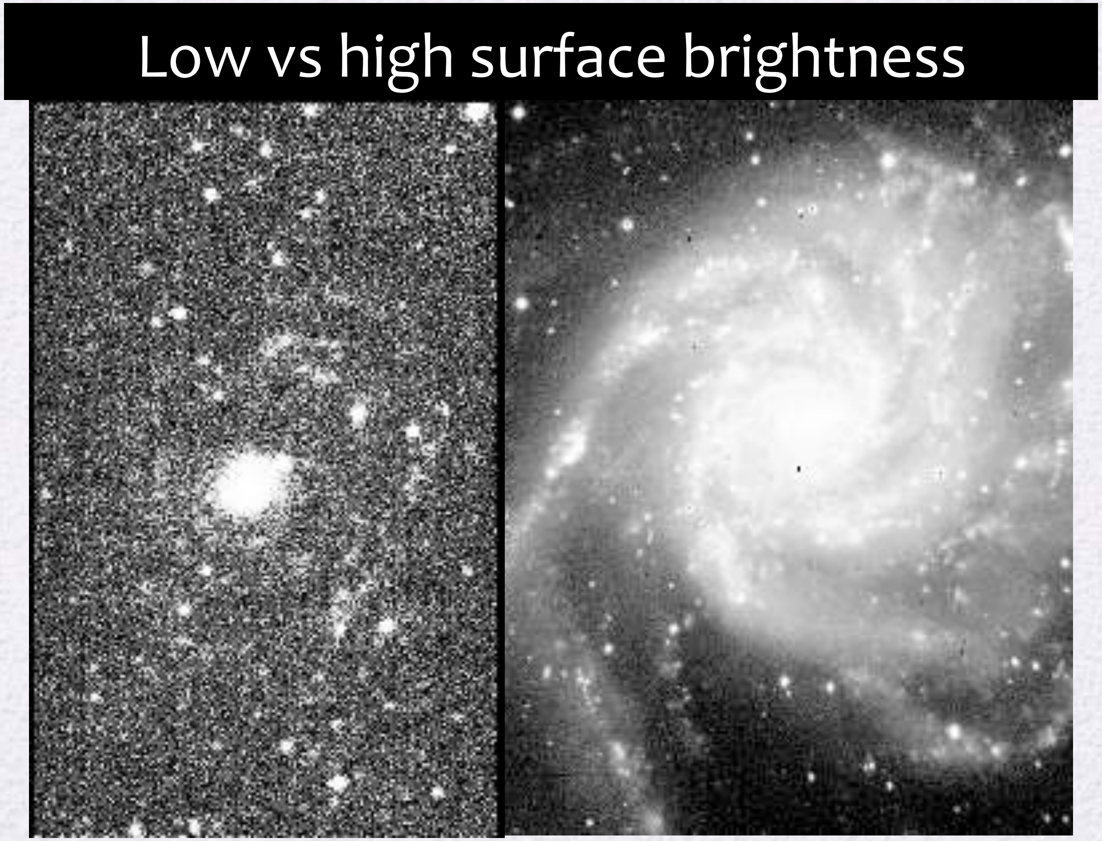

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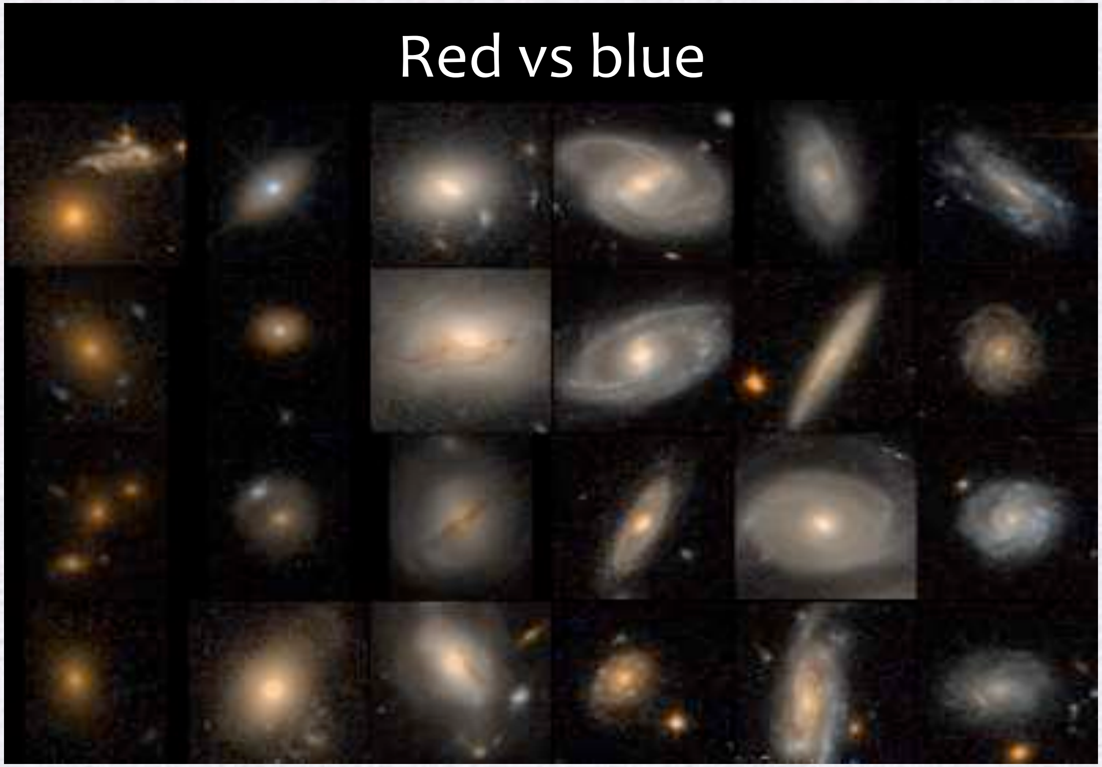

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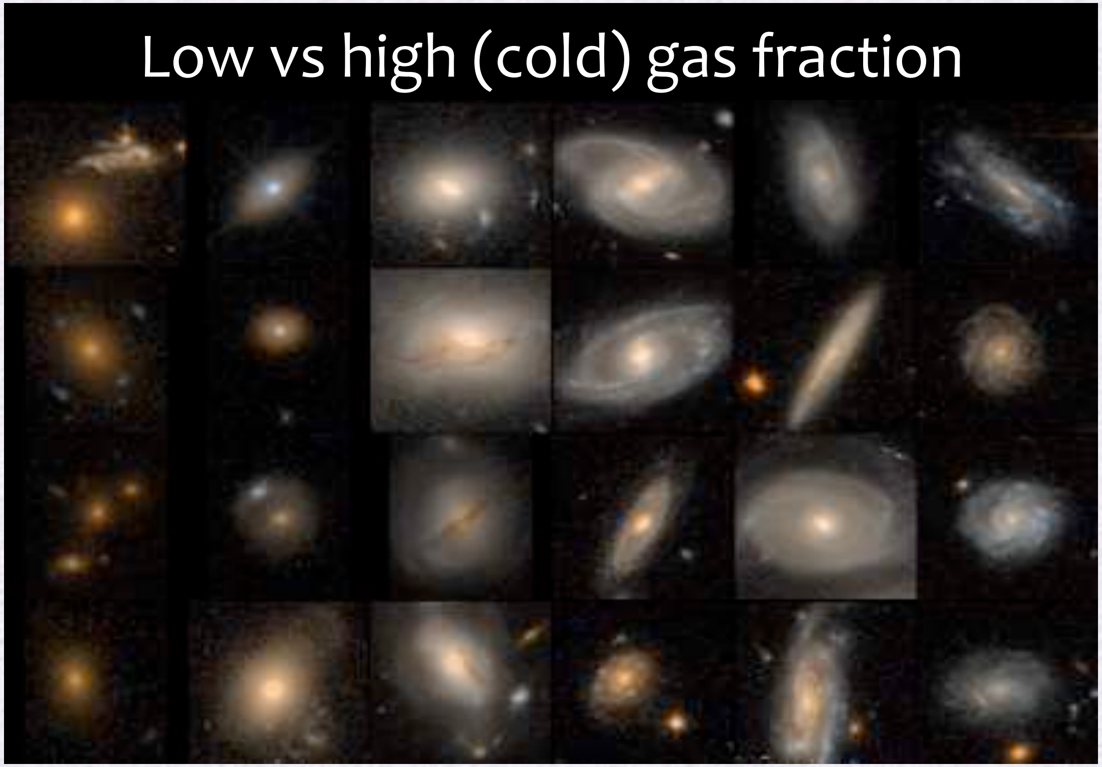
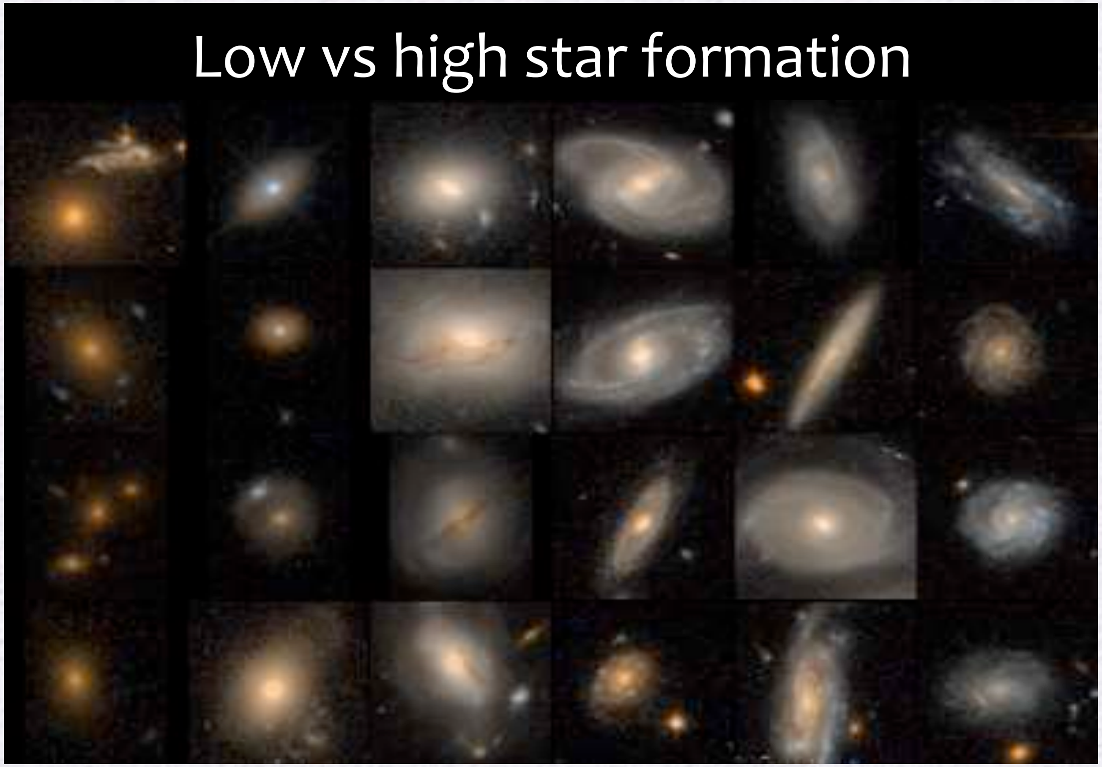
- Star formation
- Active nucleus



Galaxy classification

Galaxies can also be classified according to properties other than their morphology

- Luminosity
- Surface brightness
- Color
- Gas content
- **Star formation**
- Active nucleus



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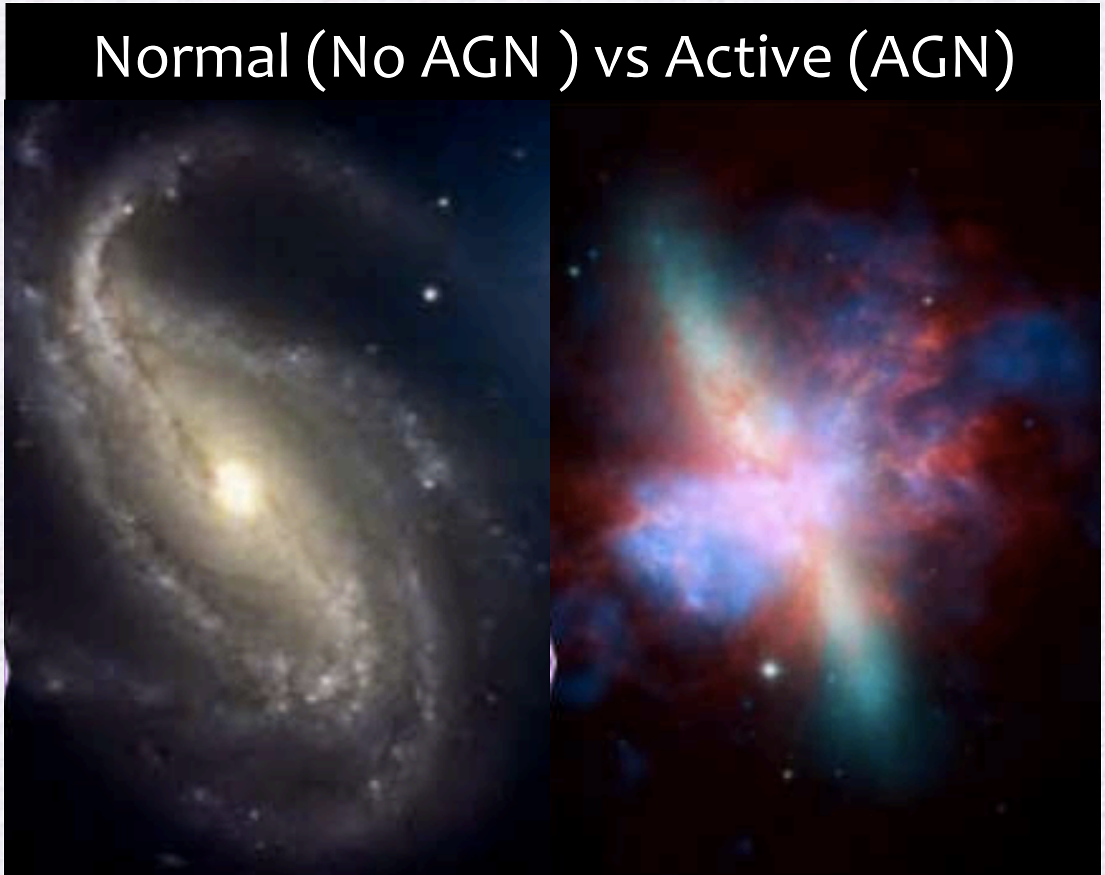


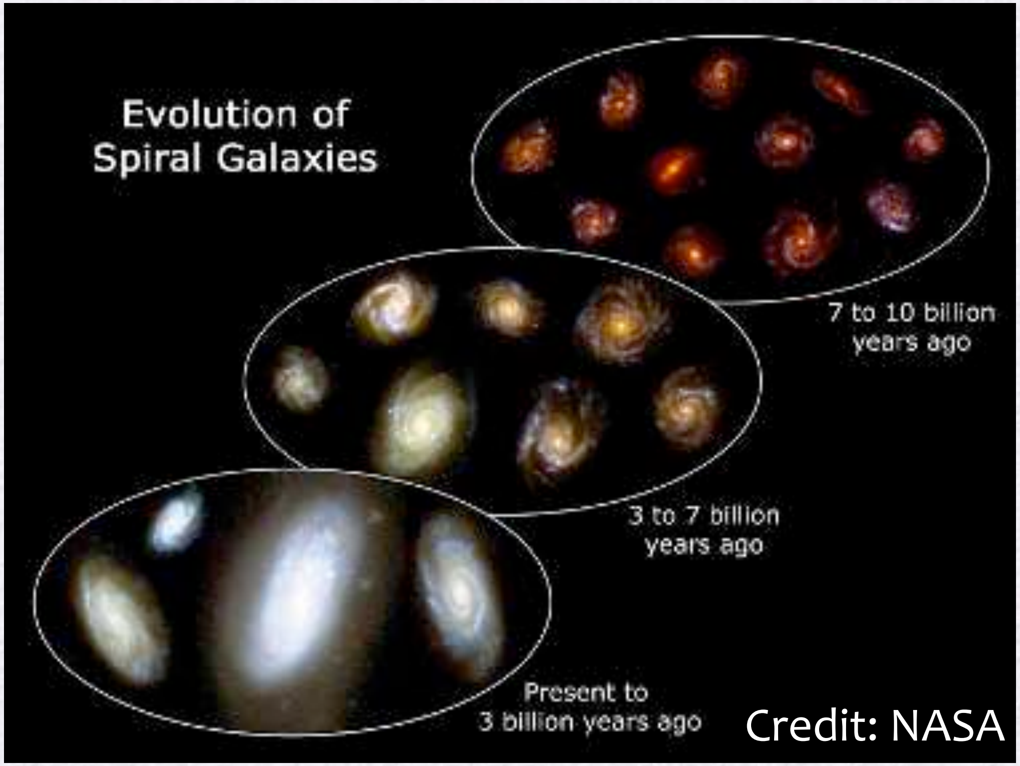
Galaxy evolution & redshift

- Because of the expansion of the Universe, an object that is farther away will have a larger receding velocity, and thus a higher redshift

- Since the light from high-redshift galaxies was emitted when the Universe was younger, we can study galaxy evolution by observing the galaxy population at different redshifts:

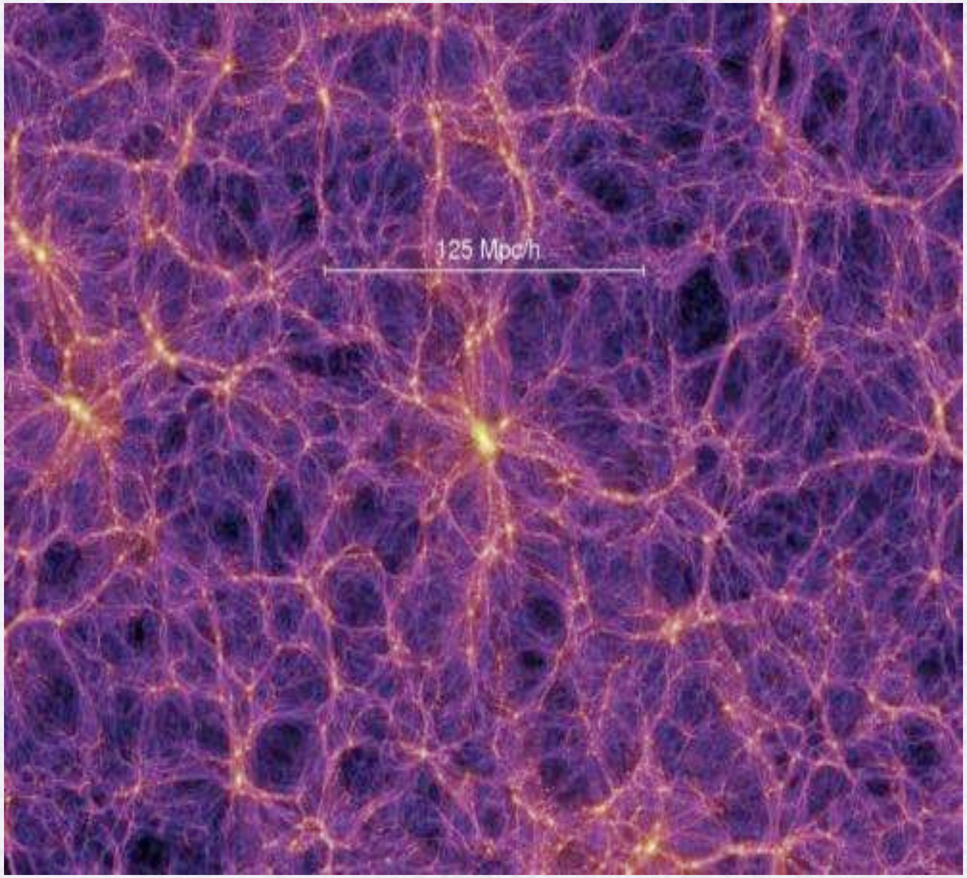
→ In a statistical sense the high-redshift galaxies are the progenitors of present-day galaxies

→ The study of variations in the properties of galaxies as a function of redshift gives us clues on the formation and evolution of the galaxy population



Galaxy environment

- Galaxies are not randomly distributed in the sky



Credit: V. Springel

Clusters: several hundreds of galaxies

Loose groups: few to tens of galaxies

Lower-density environments/“field”

Indications of relation between environment and galaxy properties

- Elliptical galaxies seem to prefer cluster environments
- Spiral galaxies are mainly found in relative isolation

Scaling relations

Relations that describe strong correlations between various physical parameters

For Elliptical galaxies:

* Faber-Jackson relation
* Kormendy relation
* Fundamental plane

For Spiral galaxies

* The Tully Fisher relation

For all galaxies:

* The mass-metallicity relation
* The colour-magnitude relation
* The morphology-density relation

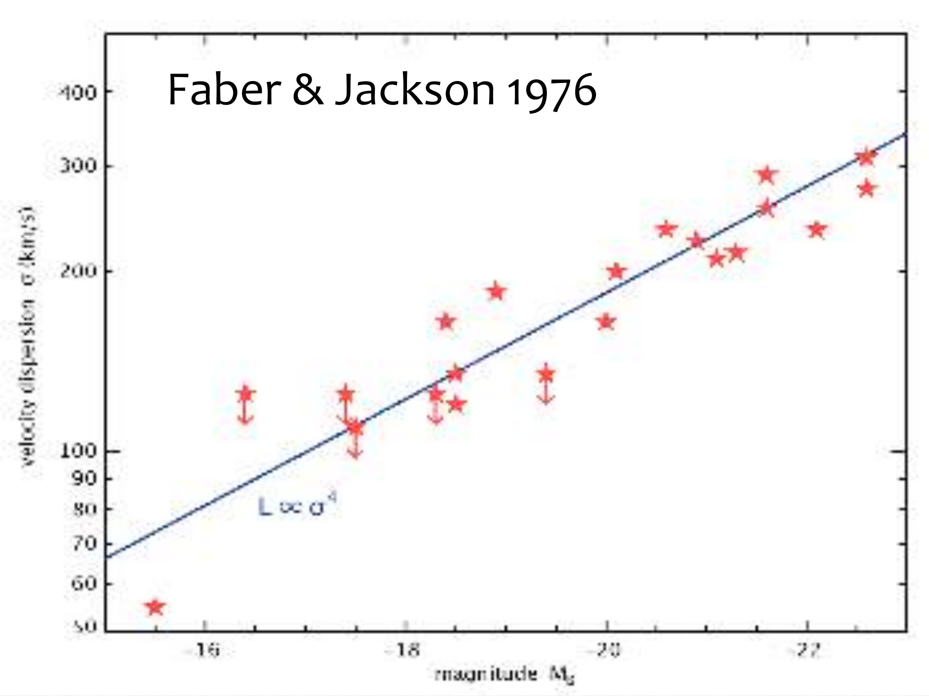
Scaling relations

Faber-Jackson relation:

a correlation between the **stellar velocity dispersion** and the **luminosity**

The more luminous the galaxy, the larger its velocity dispersion

Note: velocity dispersion is determined by the potential well → by the **total** mass of the system (dark matter+baryons)



Scaling relations

Faber-Jackson relation:

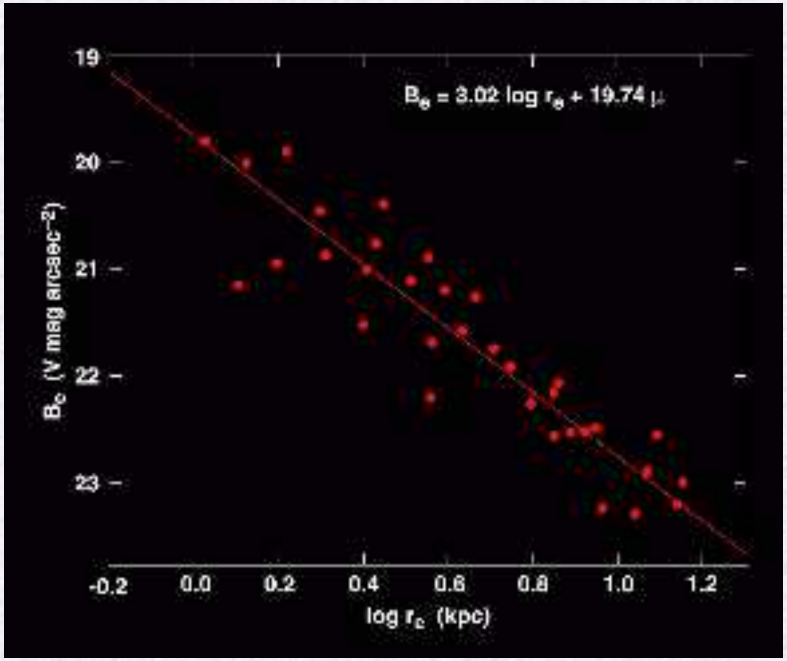
a correlation between the **stellar velocity dispersion** and the **luminosity**

Kormendy relation:

a correlation between the **effective radius** and **surface brightness**

At the effective radius (half-light radius), large (massive) galaxies are fainter than small ones

→ Large galaxies are less dense than small ones



Kormendy 1977

Scaling relations

Faber-Jackson relation:

a correlation between the **stellar velocity dispersion** and the **luminosity**

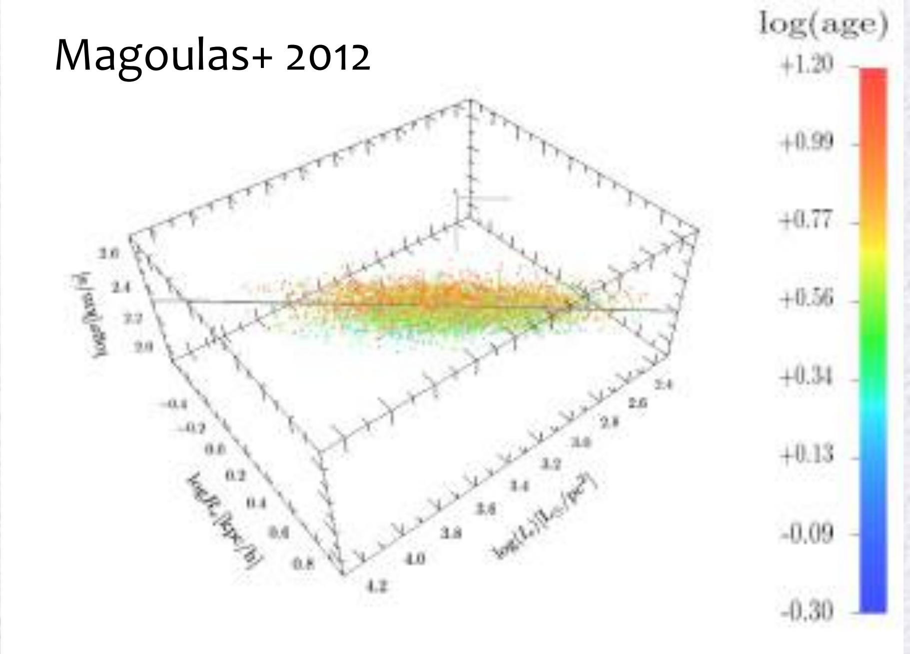
Kormendy relation:

a correlation between the **effective radius** and the **surface brightness**

Fundamental plane:

a correlation between **effective radius, surface brightness** and **stellar velocity dispersion**

Note: if you have two of these parameters, you have the third one



Magoulas+ 2012

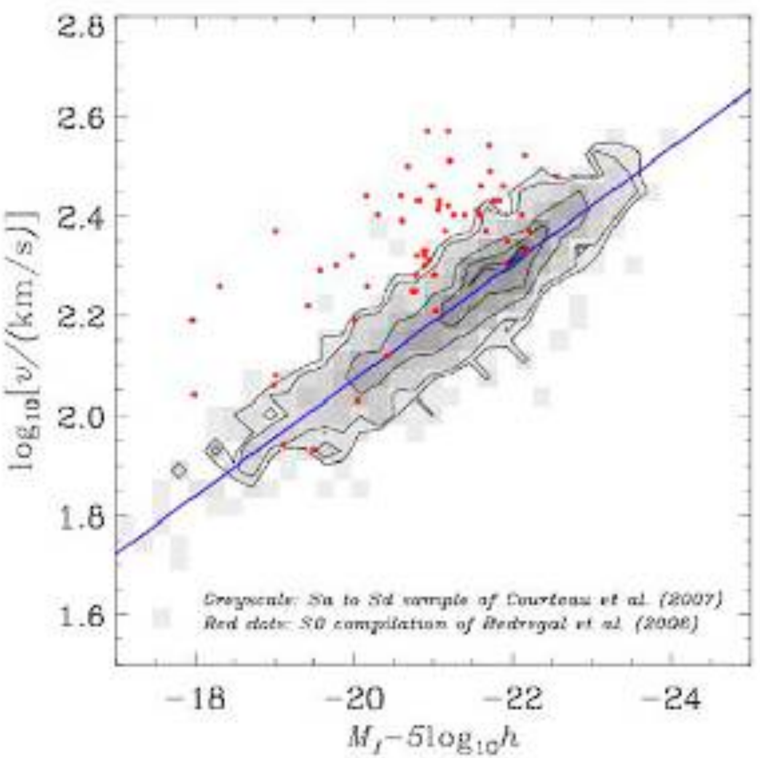
Scaling relations

<u>Tully-Fisher relation:</u>

a correlation between the **rotational speed** and the **luminosity** (remember: luminosity is used as a tracer of the mass)

This is equivalent to the Faber-Jackson relation of ellipticals, but instead of having the velocity dispersion we need the rotation velocity.

Courteau+ 2007

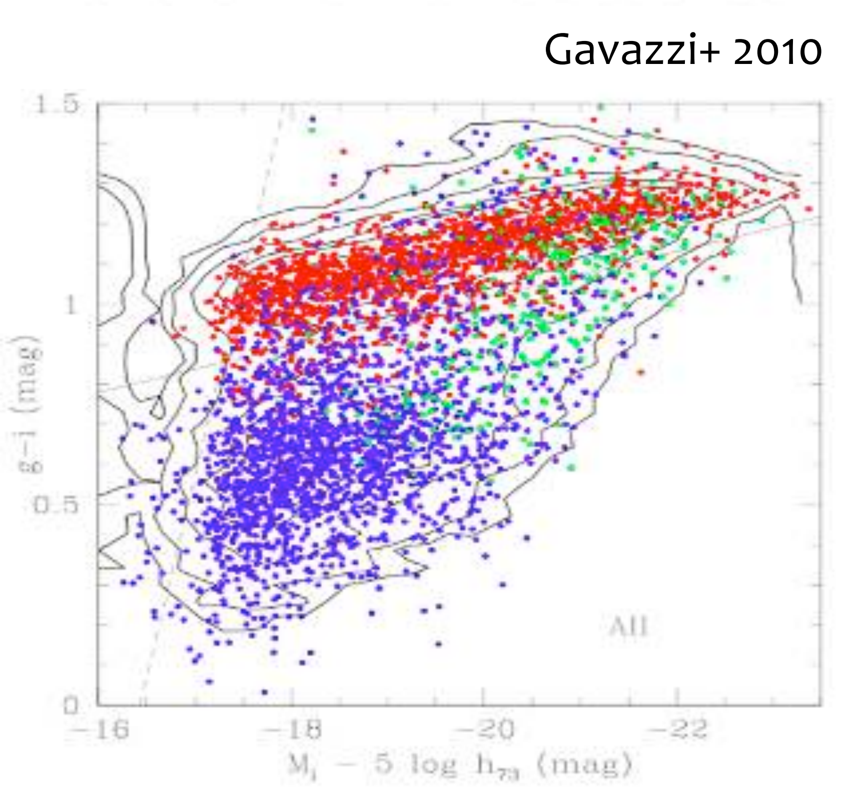


Scaling relations

<u>Colour-magnitude relation:</u>

a correlation between the **colour** and the **magnitude**

Brighter/more massive galaxies are redder and fainter/
less massive ones bluer



Scaling relations

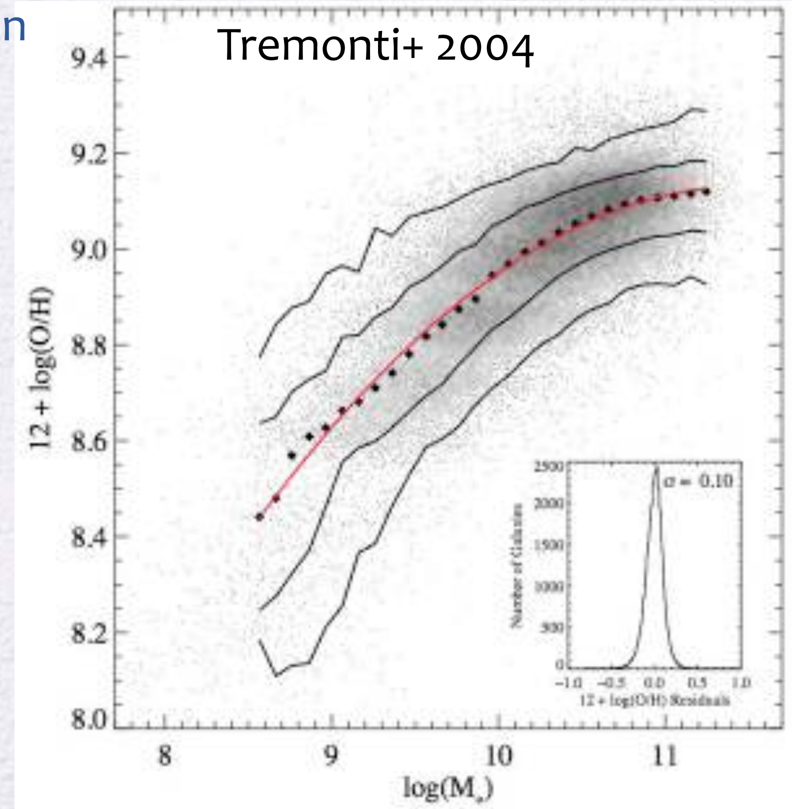
<u>Colour-magnitude relation:</u>

a correlation between the **colour** and the **magnitude**

<u>Mass-metallicity relation:</u>

a correlation between the **mass** and the **gas metallicity**

More massive galaxies have are more metal-rich than smaller galaxies



Scaling relations

Colour-magnitude relation:

a correlation between the **colour** and the **magnitude**

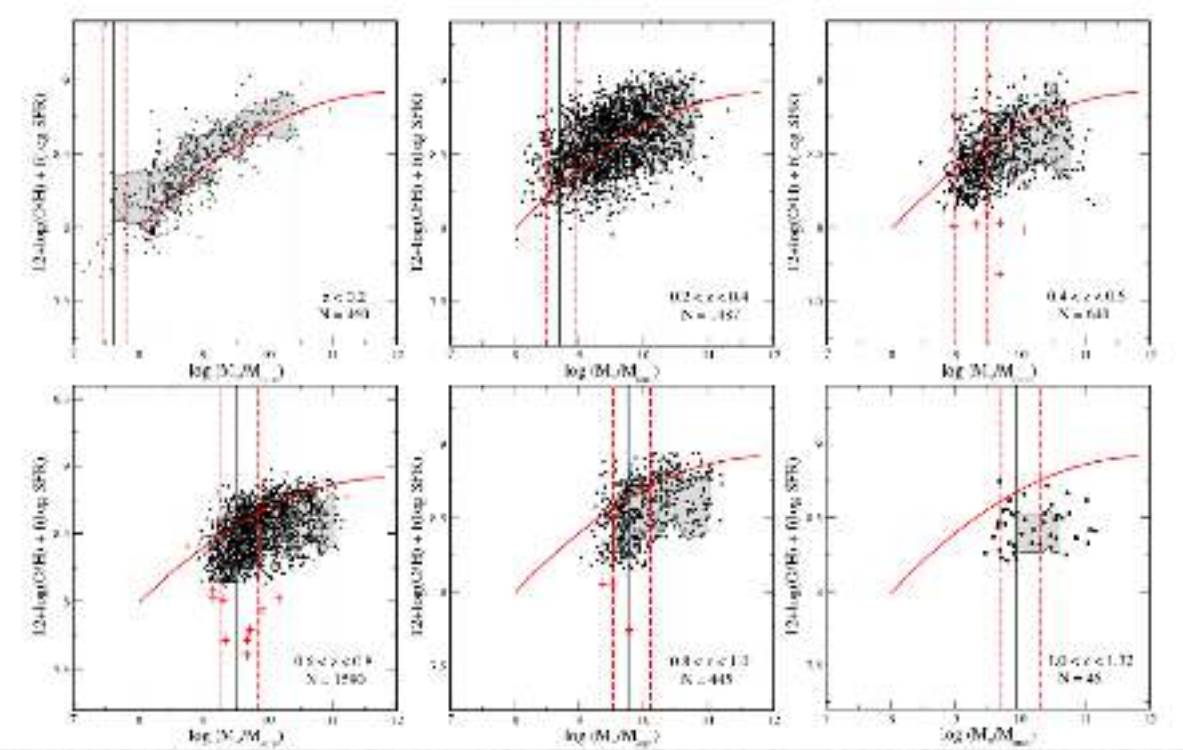
Mass-metallicity relation:

a correlation between the **mass** and the **gas metallicity**

At higher redshifts, the slope of the relation flattens → galaxies of different masses were more similar in terms of their metal content compared to local galaxies

→ Evidence for hierarchical formation?

If two smaller galaxies merge, the resulting object would have a larger mass but a low metal content



Pérez-Montero+ 2012

Scaling relations

Colour-magnitude relation:

a correlation between the **colour** and the **magnitude**

Mass-metallicity relation:

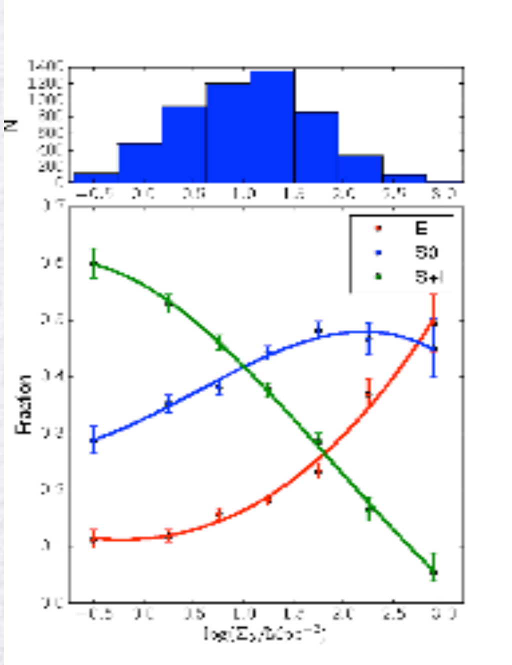
a correlation between the **mass** and the **gas metallicity**

Morphology-density relation:

a correlation between the **morphology** and the **environmental density** (Dressler 1980)

- Elliptical and SO galaxies (i.e. early type) preferentially locate at high density regions
- Spirals (late-type) galaxies prefer regions of lower density

Galaxy evolution is affected by the environment



Galaxies: summary of observations

- Galaxies are extremely complex and very diverse objects
- They appear in a wide range of morphologies, masses, and structural, dynamical and chemical properties
- Scaling relations show correlations between different characteristic parameters of galaxies, providing clues on their formation

- Although we can not witness the actual evolution of individual galaxies, looking at galaxies at large distances is equivalent to looking at galaxies when they were younger

  → We can infer how galaxies evolve comparing their statistical properties at different epochs

Dark matter in galaxies

- The rotation curves of Spiral galaxies can only be explained if there is more mass than it is observed → one of the first (indirect) evidences of dark matter