The other galaxies

Topic 8

Material from

Chap. 20 “The cosmic perspective”, by J. O. Bennett, M. O. Donahue, N. Schneider & M. Voit

and Chap. 3 “Extragalactic Astronomy and Cosmology”, by P. Schneider, 2nd edition

Galaxies in the local universe

- Spirals
- Elliptical
- S0
- Irregular
- Hubble's morphological sequence
- Correlations between morphology and physical properties



Hubble eXtreme Deep Field

- 23 days of exposure with Hubble Space Telescope
- The area in the sky is as big as the dot on the nail at the bottom (at a distance of one arm), a tenth of the full moon
- Each of the thousands of bright spots in the image is a distant galaxy





- The galaxies in this image have very different properties:

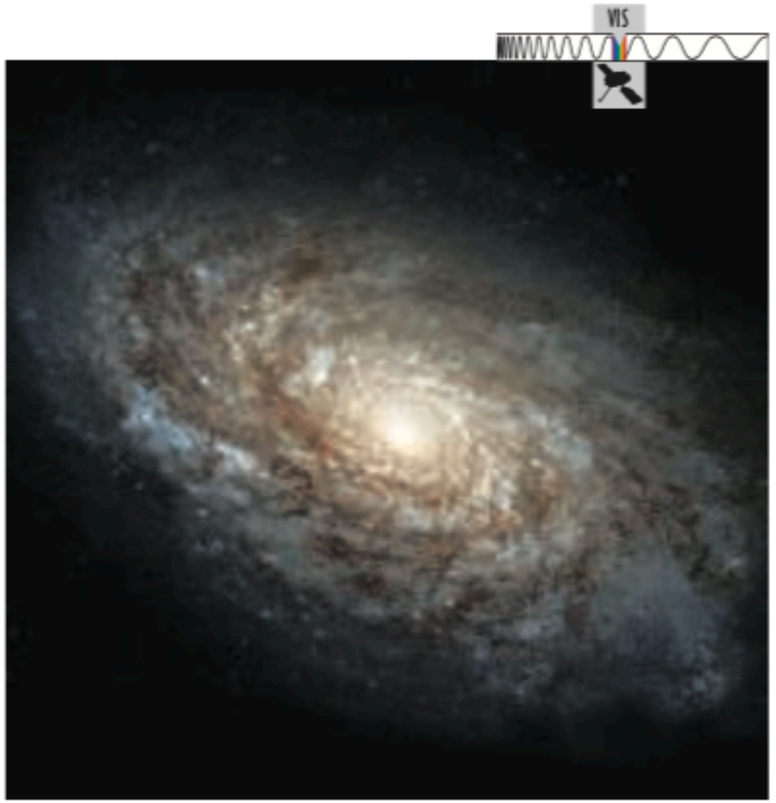
- Colors (white, red, blue, yellow...)
- Magnitude
- Size
- Shape
- "Clustering": how much they are distributed in groups

Galaxies in the local universe

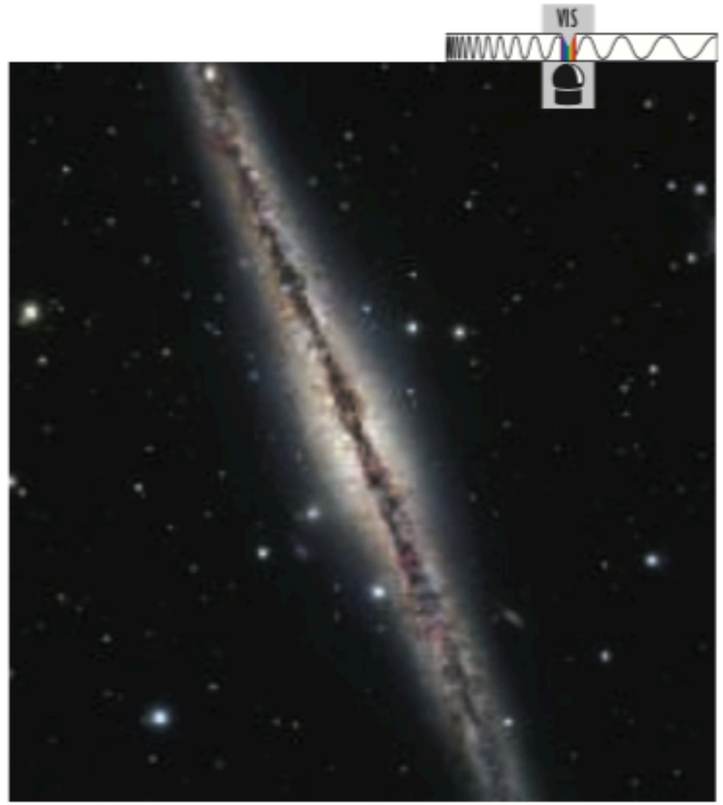
Spiral galaxies



a M101, a face-on spiral galaxy.



b NGC 4414, a spiral galaxy whose disk is somewhat tilted to our line of sight.



c NGC 891, a spiral galaxy seen nearly edge-on. Note the central streak of dust associated with the disk.

They are similar to our galaxy

The Milky way is a rather common galaxy

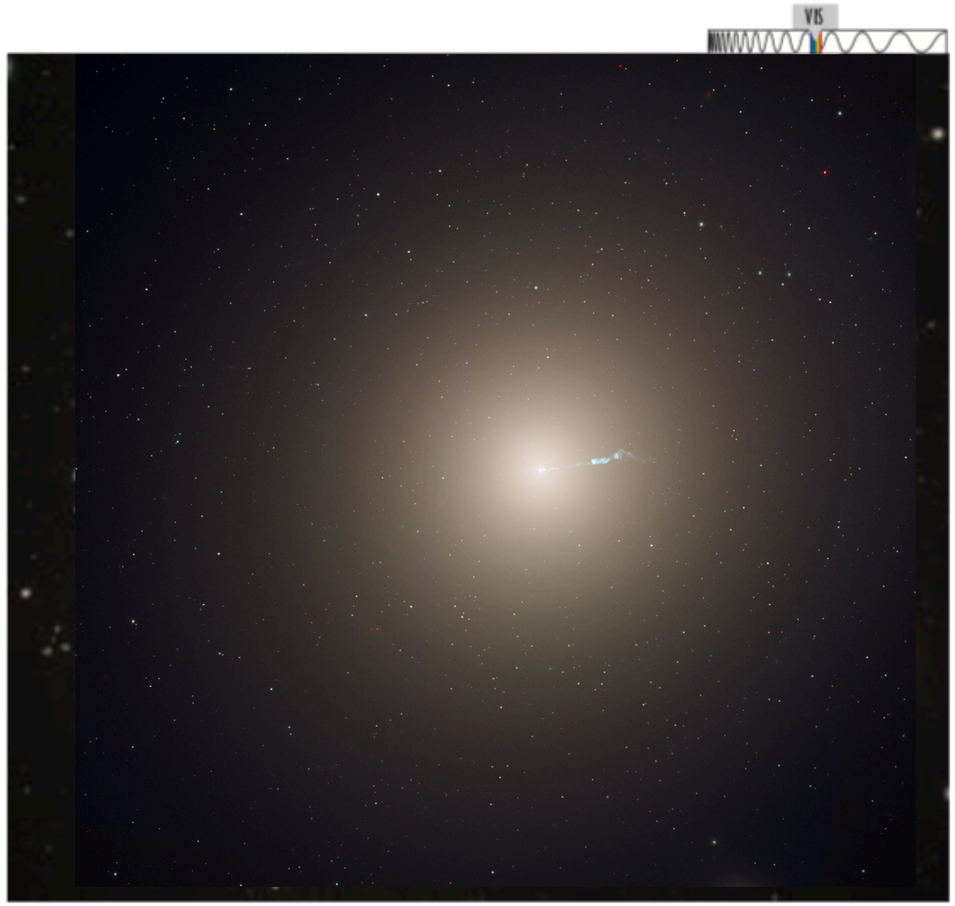
Barred spiral galaxies



They are spiral galaxies in which the arms start from a central bar

FIGURE 20.4 NGC 1300, a barred spiral galaxy about 110,000 light-years in diameter.

Elliptical galaxies



a M87, a giant elliptical galaxy in the Virgo Cluster, is one of the most massive galaxies in the universe. The region shown is more than 300,000 light-years across.



b Leo I is one of at least a dozen dwarf elliptical galaxies in the Local Group. It is only about 2500 light-years across.

No disk, only spheroidal component

Intermediate galaxies



FIGURE 20.3 NGC 4594 (the Sombrero Galaxy) is a spiral galaxy with a large bulge and a dusty disk that we see almost edge-on. A much larger but nearly invisible halo surrounds the entire galaxy. The bulge and halo together make up the spheroidal component of the galaxy. This image shows a region of the galaxy about 82,000 light-years across.

Very bright halo

Spiral galaxies with very prominent bulges

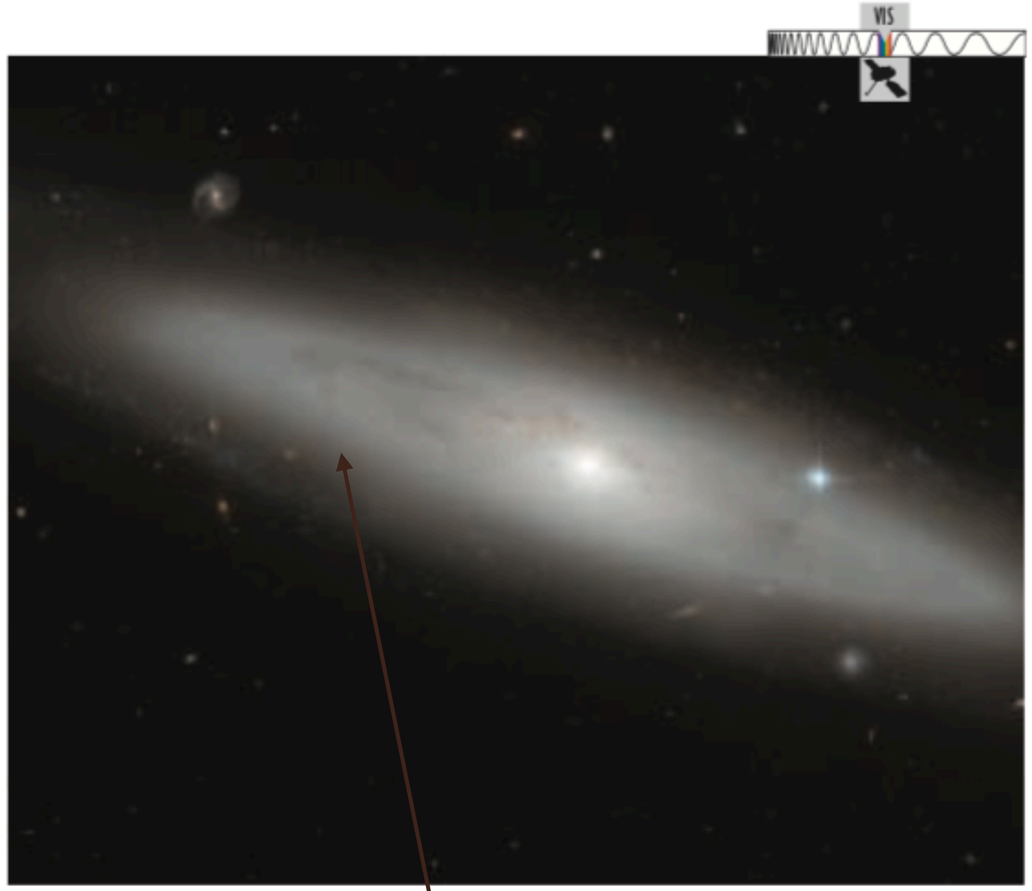


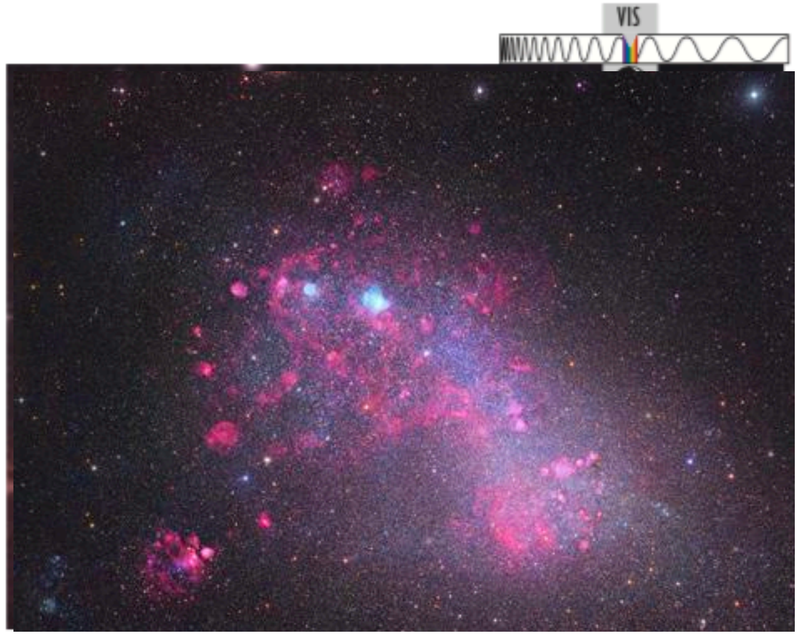
FIGURE 20.5 The lenticular galaxy NGC 4866. A few streaks of dusty gas can be seen in this galaxy's disk, but it does not contain any noticeable spiral arms. The region pictured is about 75,000 light-years across.

Arm-free disc

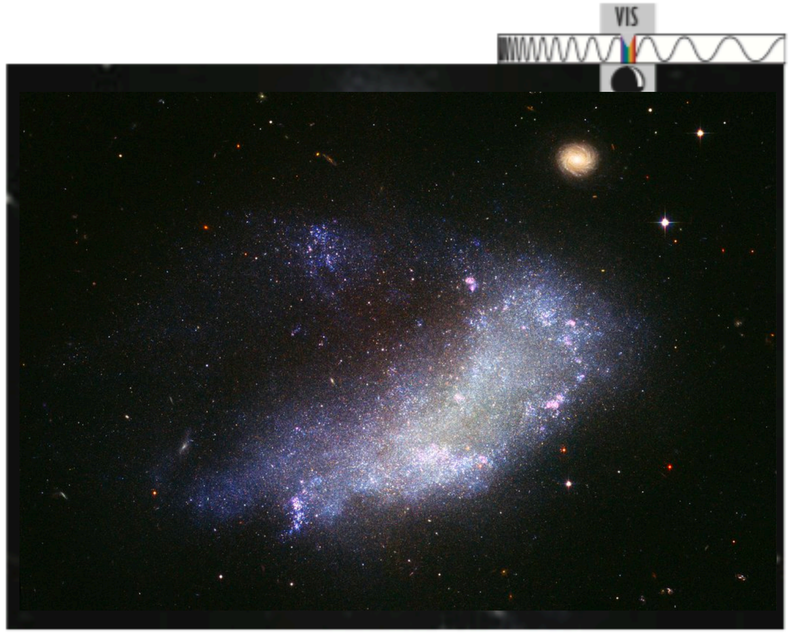
Irregular galaxies



a The Large Magellanic Cloud, a small companion to the Milky Way. It is about 30,000 light-years across.



b The Small Magellanic Cloud, a smaller companion to the Milky Way. It is about 18,000 light-years across.



c NGC 1427A, an irregular galaxy with scattered patches of star formation. The region pictured is about 50,000 light-years across.

Galaxies without a defined shape

Rich in young stars

...Recap

In the local universe, there are essentially 2 types of galaxies



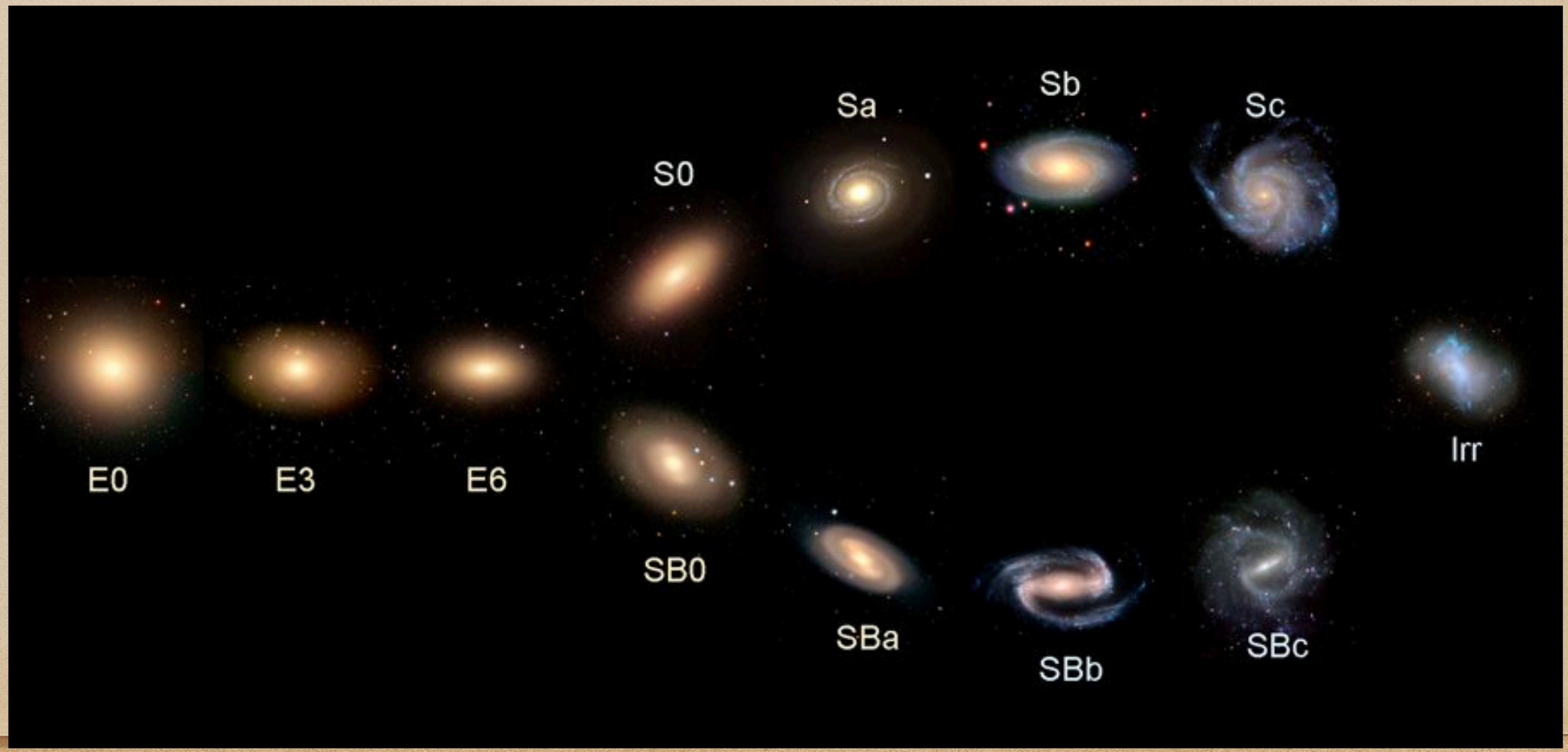
They rotate, spiral arms, blue colors...



Chaotic orbits, smooth light distribution, red colours

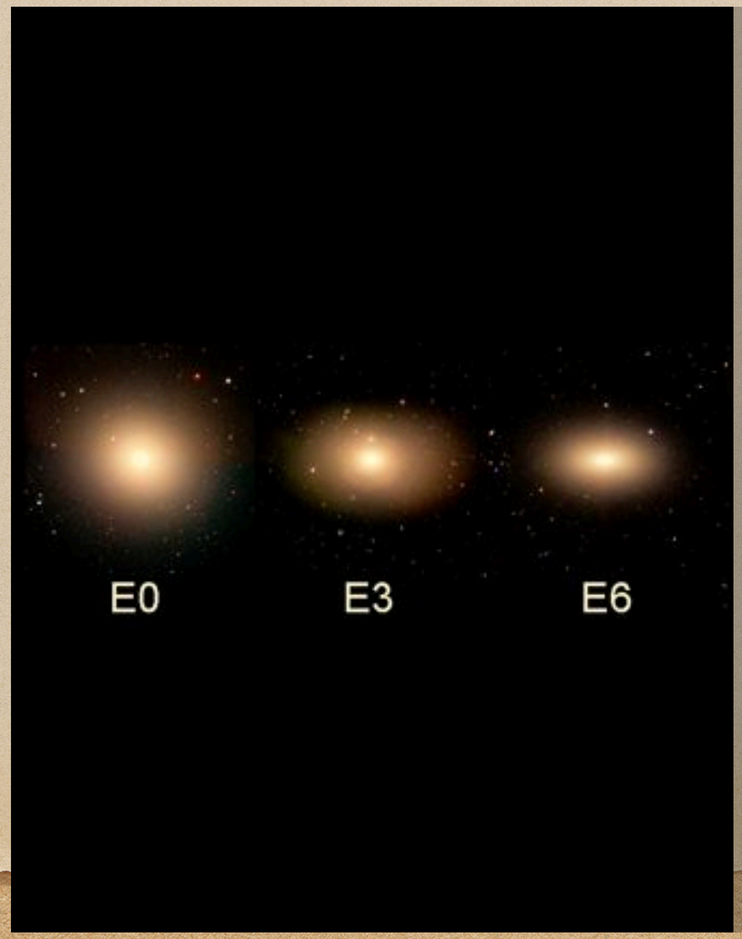
Hubble sequence

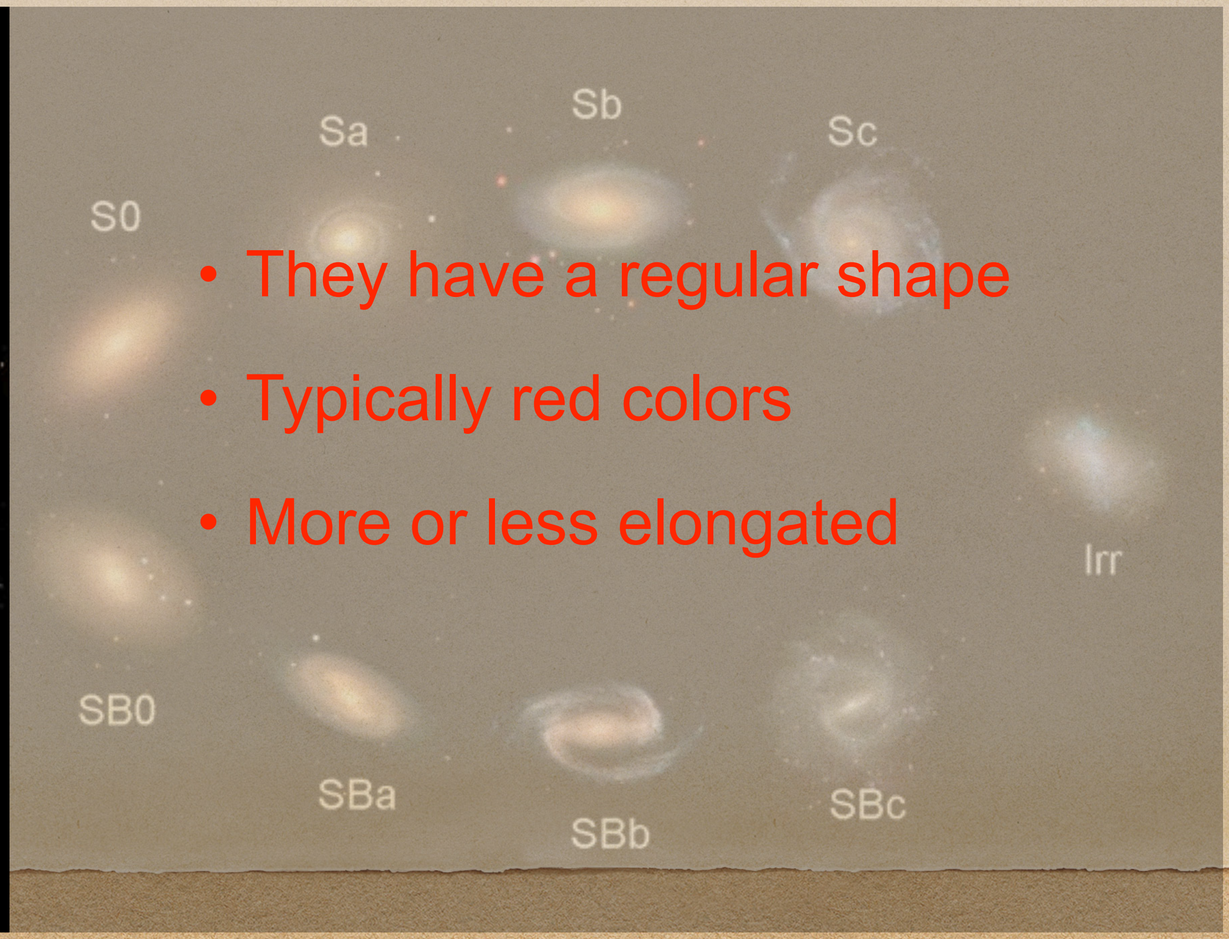
Morphological classification, based on the form of light distribution



Hubble sequence

On the one hand we have elliptical galaxies: they are indicated by the letter E followed by a number, which is linked to ellipticity (1-b/a, b and minor and major axes)



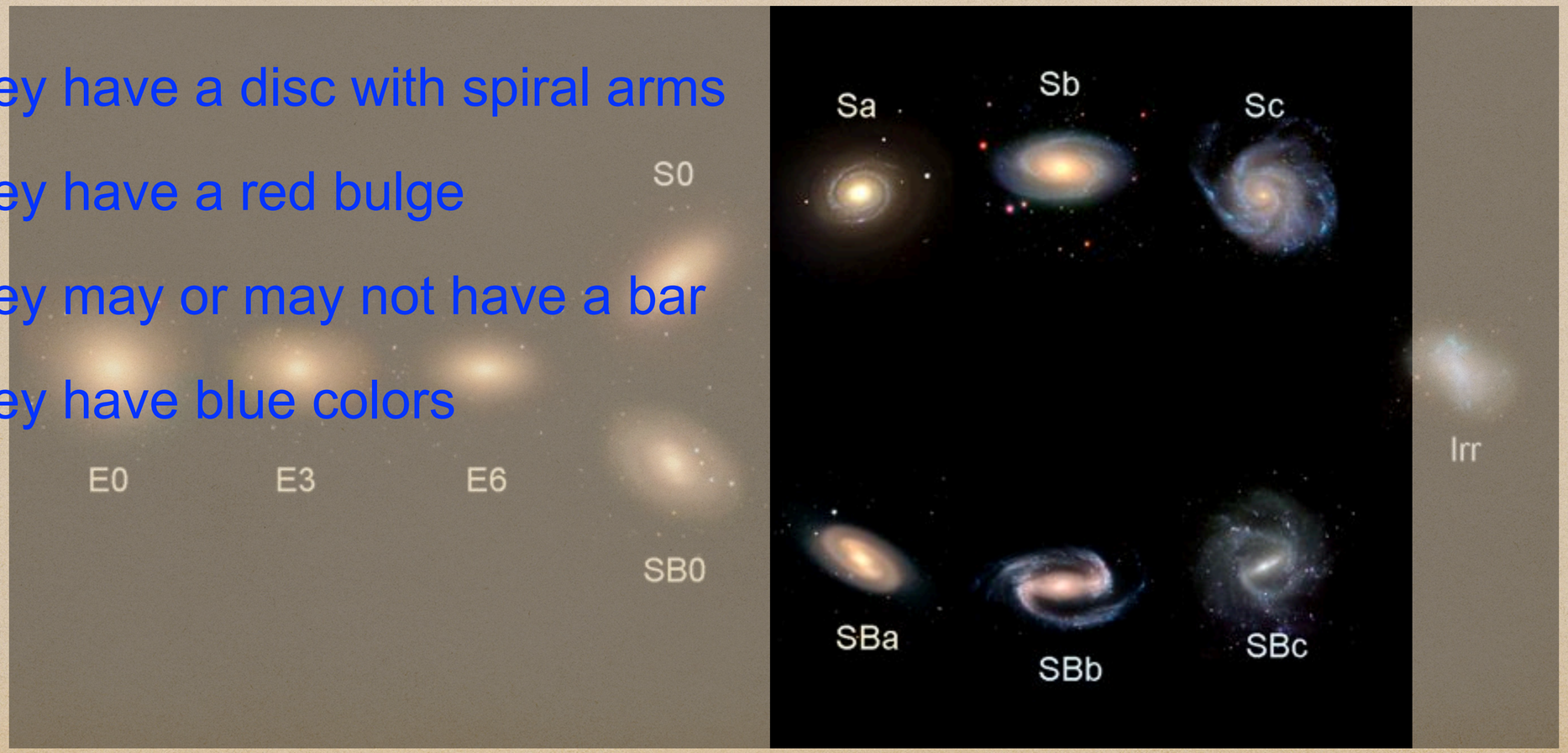


- They have a regular shape
- Typically red colors
- More or less elongated

Hubble sequence

On the other hand the spiral galaxies

- They have a disc with spiral arms
- They have a red bulge
- They may or may not have a bar
- They have blue colors

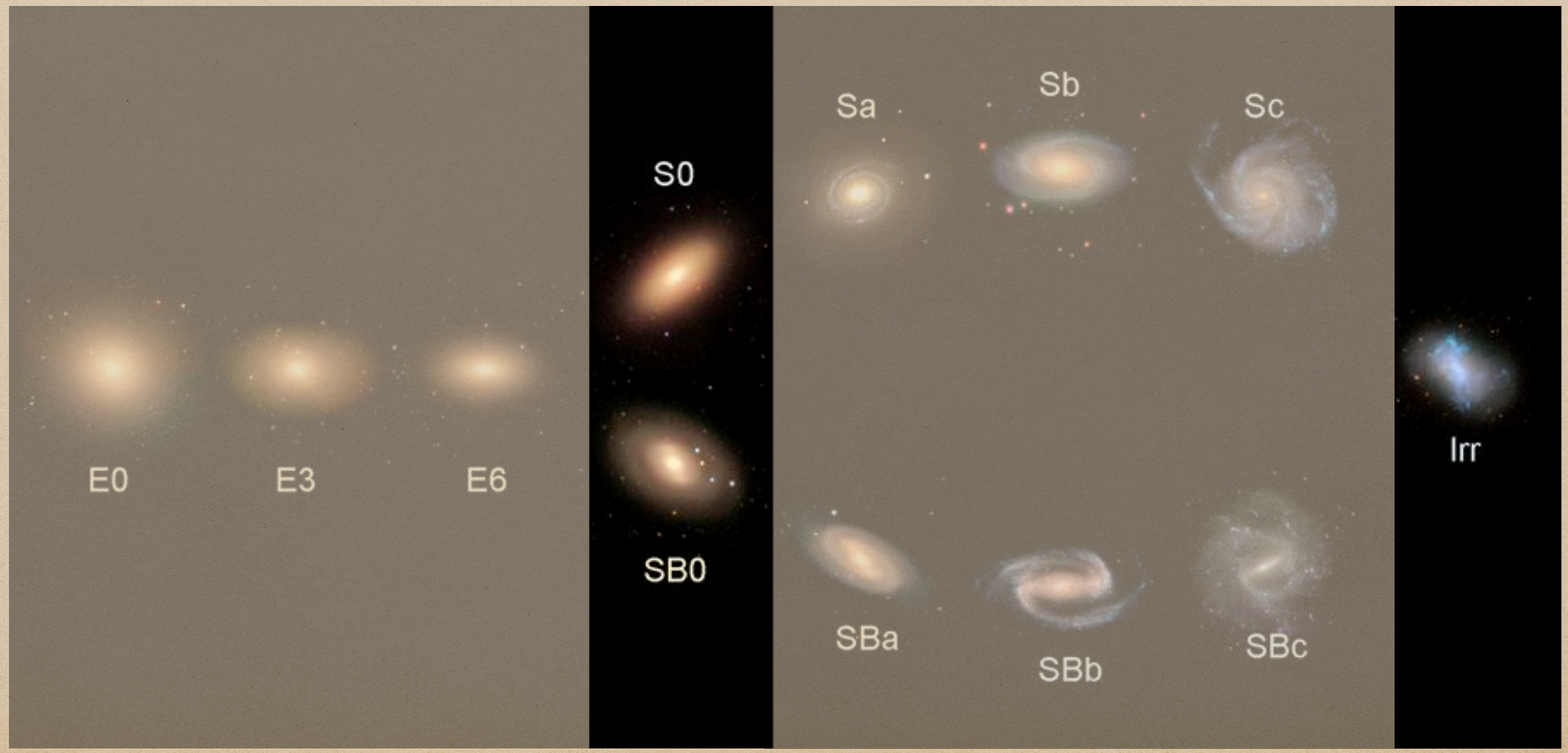


They are indicated with S (or SB, if there is a bar) followed by a, b, c or d, which indicates the prevalence of the ***bulge*** ***or of the*** ***disk***

Hubble sequence

Special classes

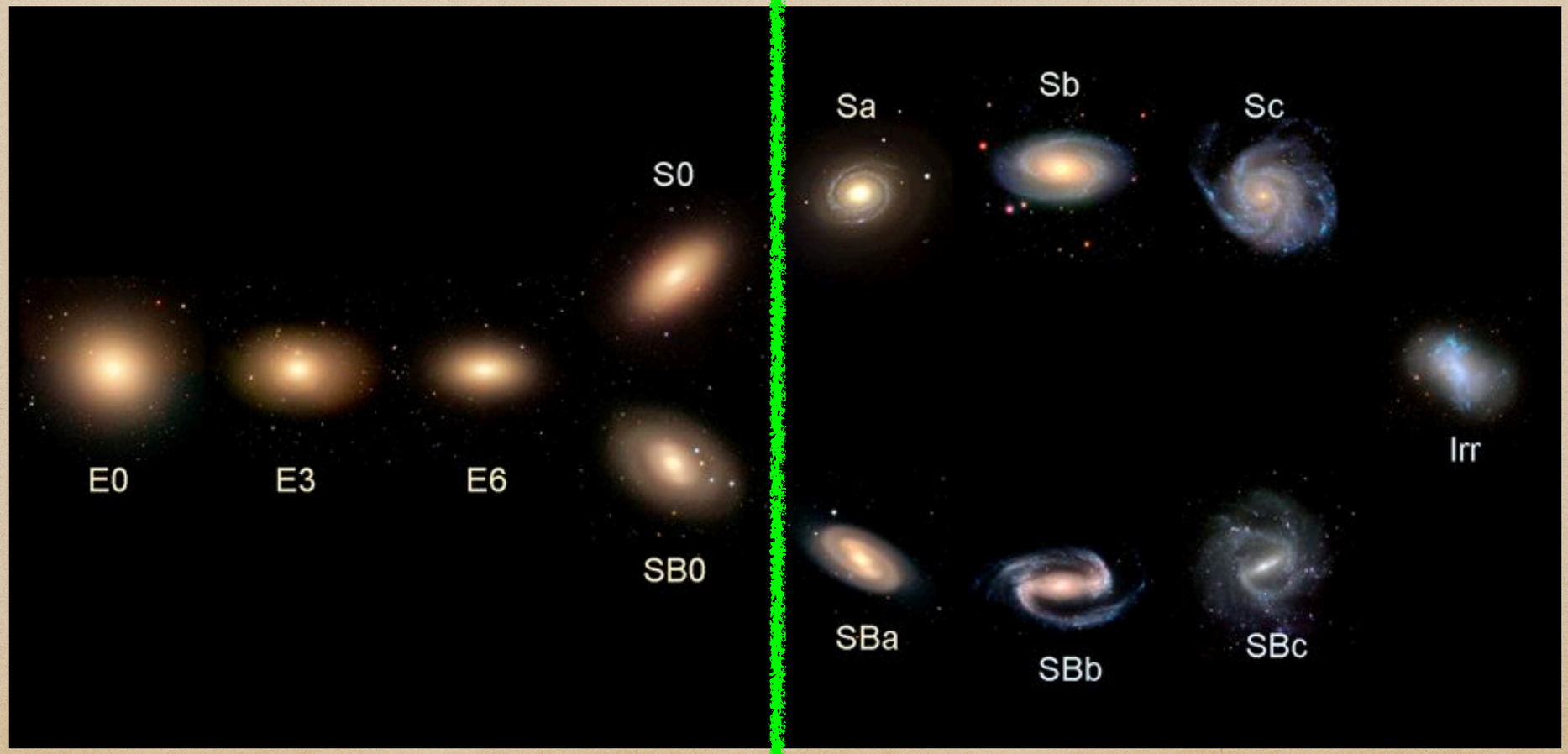
S0, SB0: Transition between spirals and ellipticals



Without a particular shape: ***Irr***

Hubble sequence

Early-types

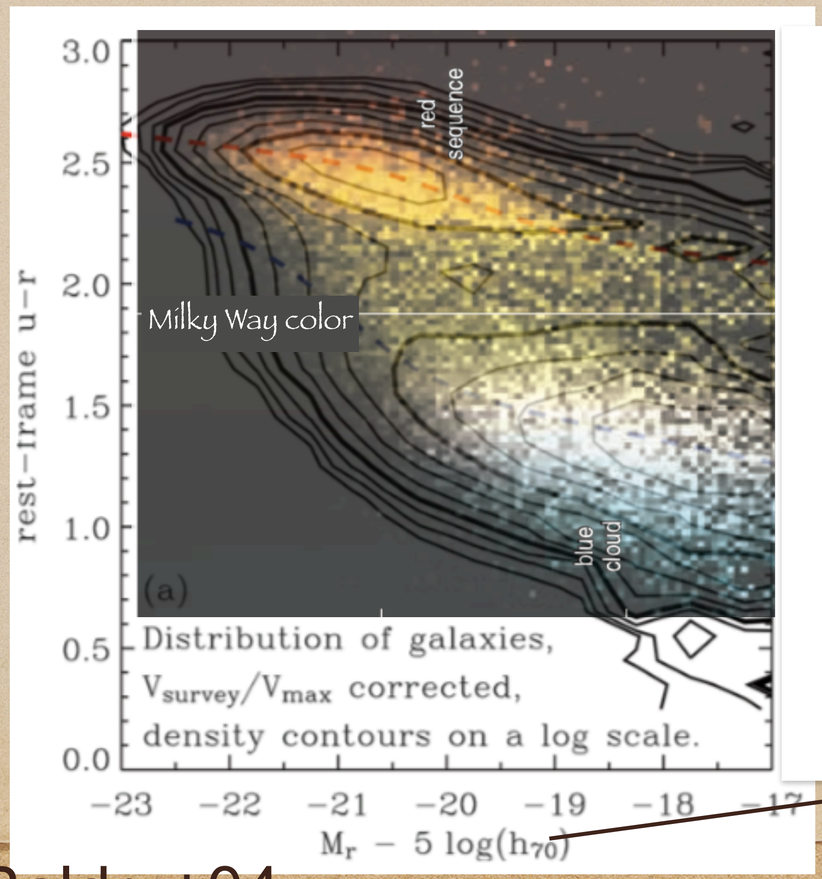


Late-types

The bimodal distribution of colors

If we put galaxies in a color-absolute magnitude diagram, we get a bimodal distribution

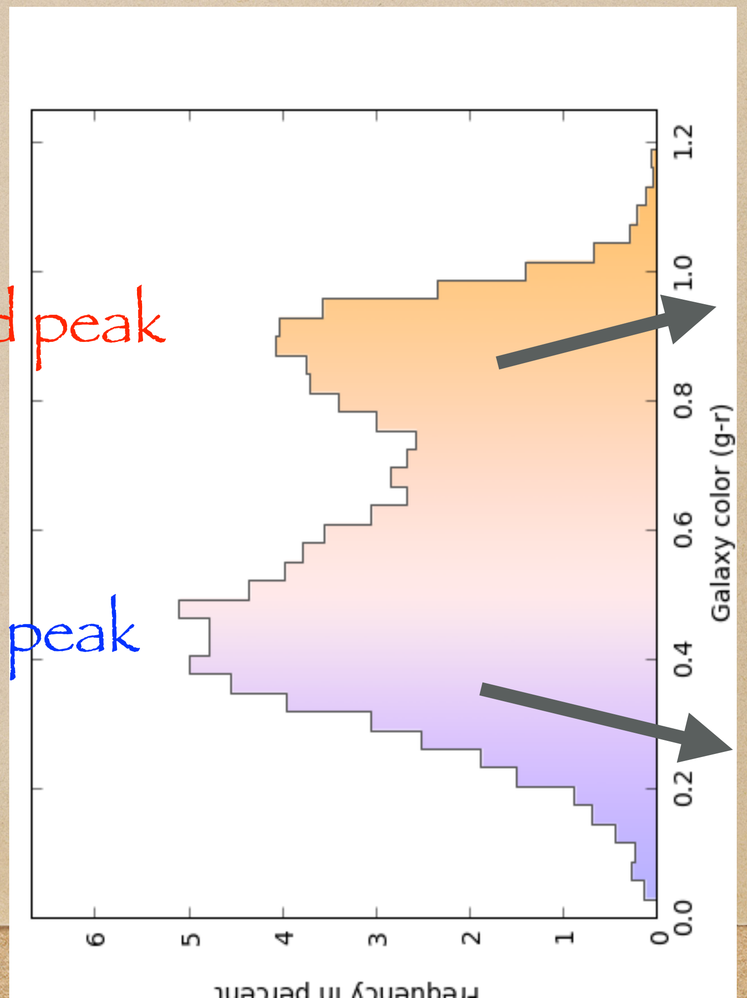
n.b.: The color is the slope of the spectral distribution of energy between these bands; red color means more flux in the second band; bluer means more flux in the first band



Baldry+04

Red peak

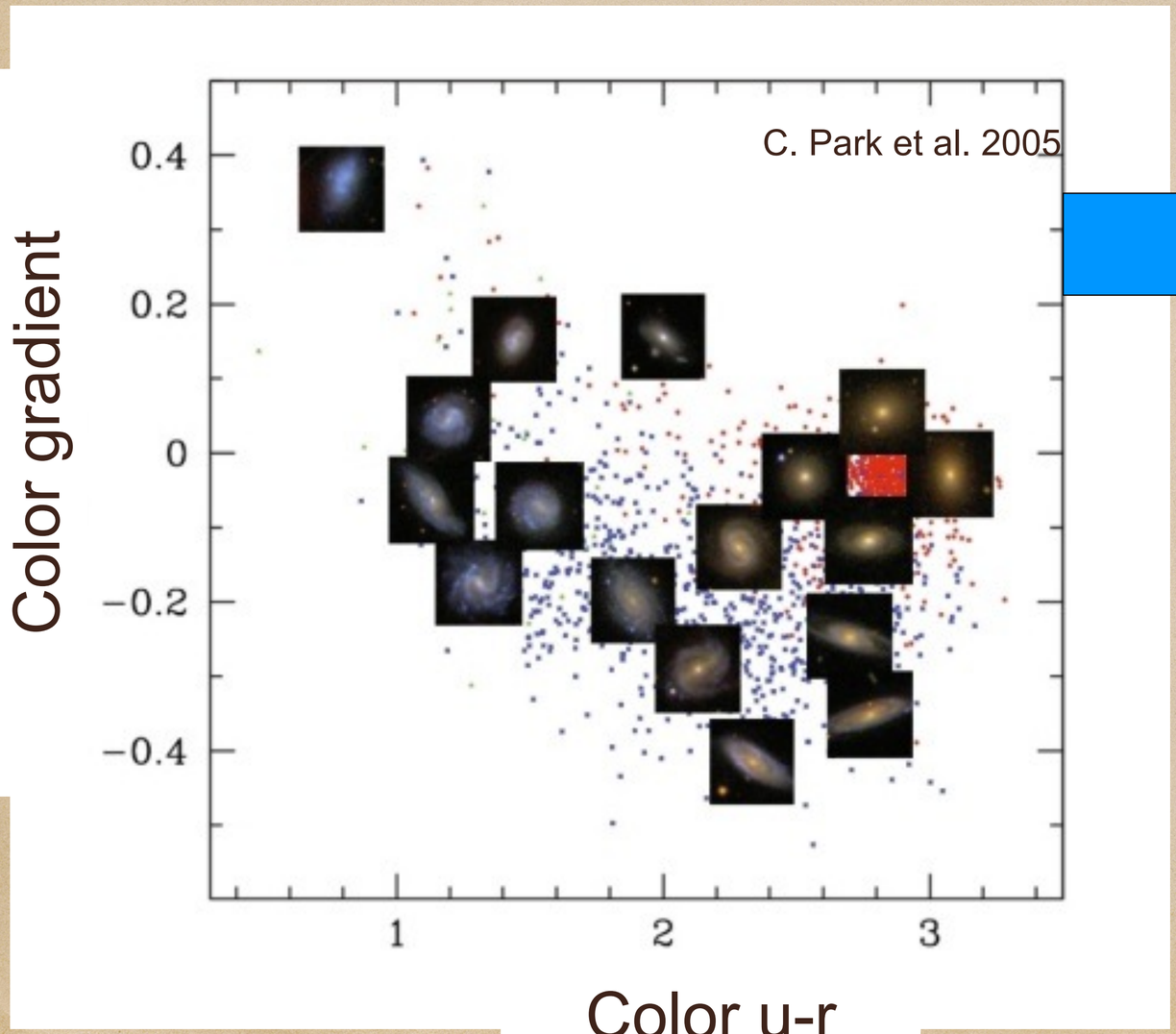
Blue peak



Early-types

Late-types

Hubble sequence

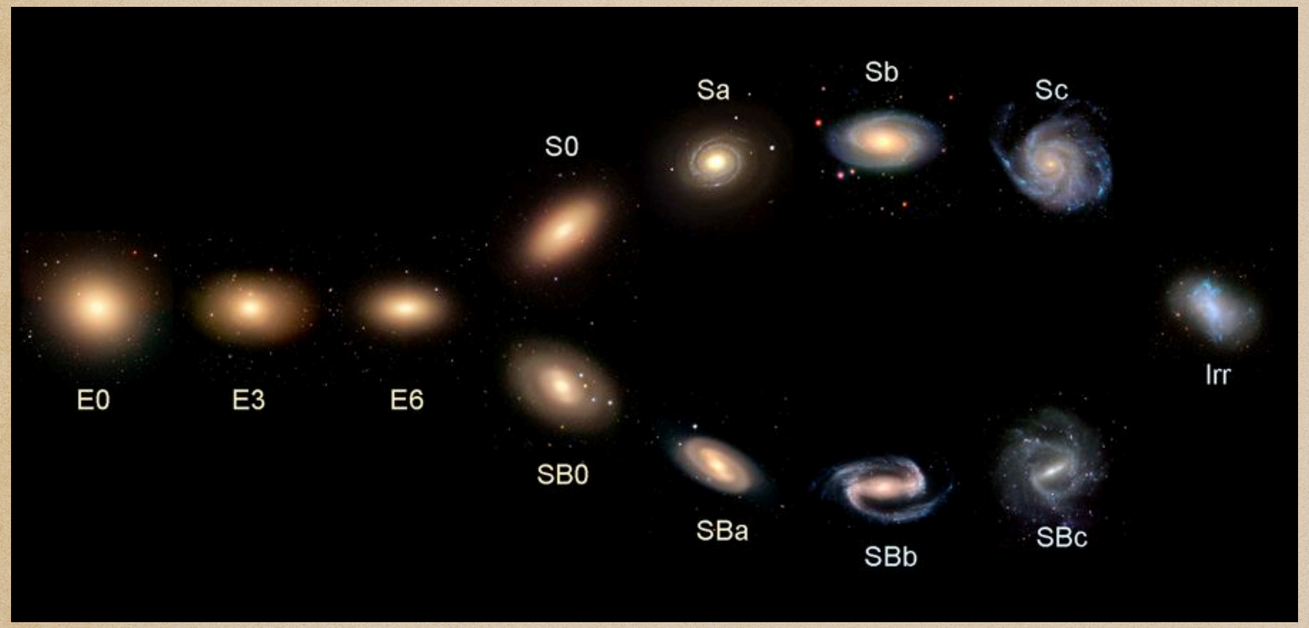


Early-types: Red, no color gradient

→ homogeneous stars

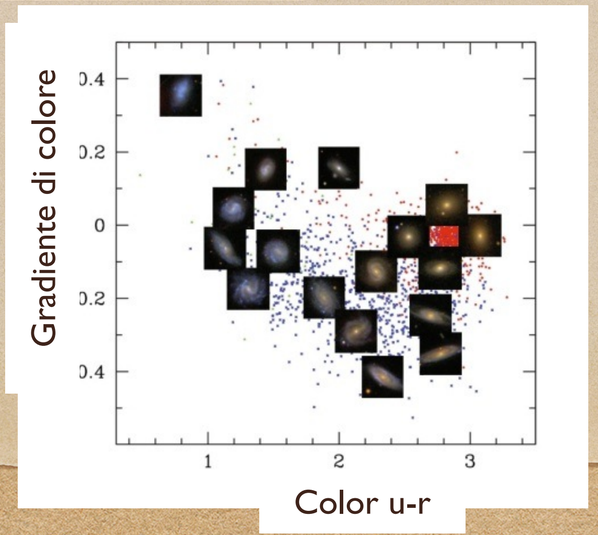
Late-types: Blue, very varied color gradients
→ more complex properties and stellar populations

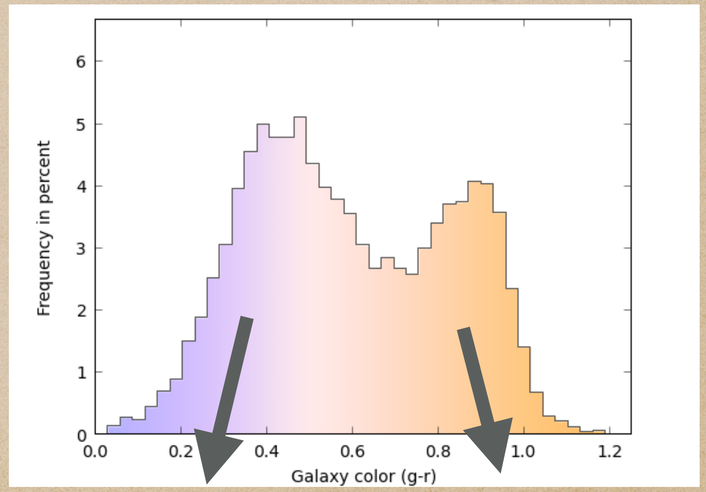
Hubble sequence



So we have a morphological classification...

...Which correlates with colors, luminosities, ...





Late-types Early-types

Elliptical galaxies



S



Elliptical



Dwarf

	S0	E	dE
M_B	−17 to −22	−15 to −23	−13 to −19
M ($M_\odot$)	10^{10}–10^{12}	10^{8}–10^{13}	10^{7}–10^{9}
D_{25} (kpc)	10–100	1–200	1–10
$\langle M/L_B \rangle$	~ 10	10–100	1–10

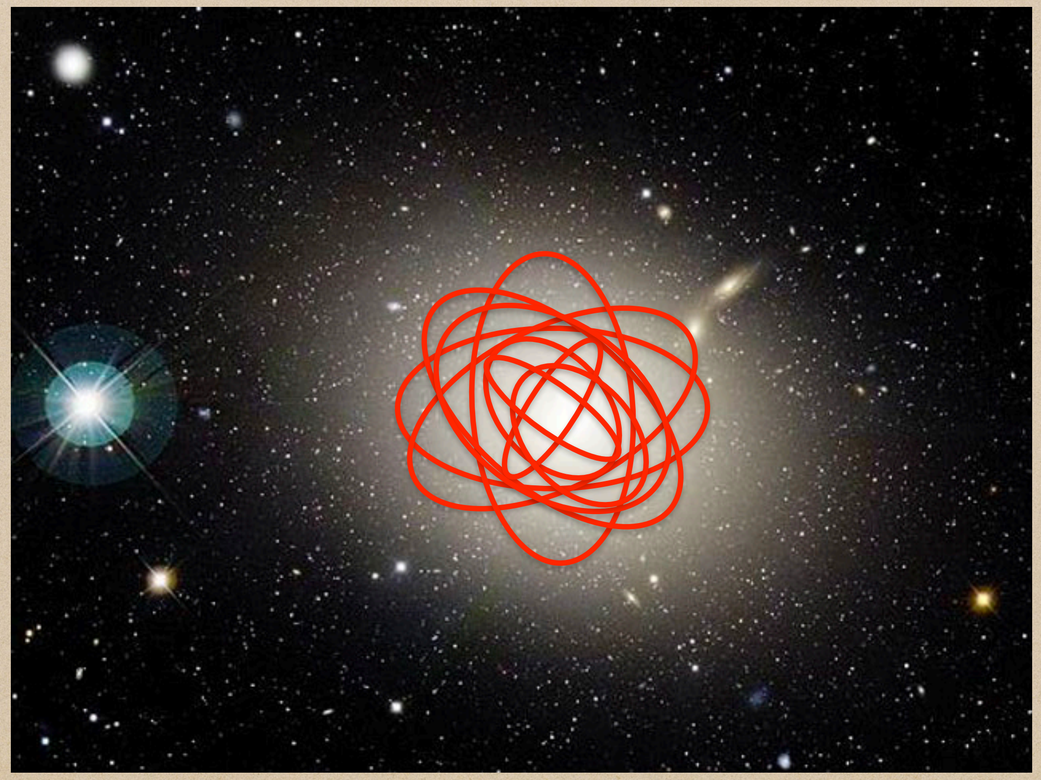
They are (almost) free of gas and dust

Mass-to-light Ratio

They are the most massive and bright galaxies

Elliptical galaxies: dynamic

Balance between gravitational attraction and random movements of the stars



Ellipticals are supported by random motions

Stellar velocity dispersion

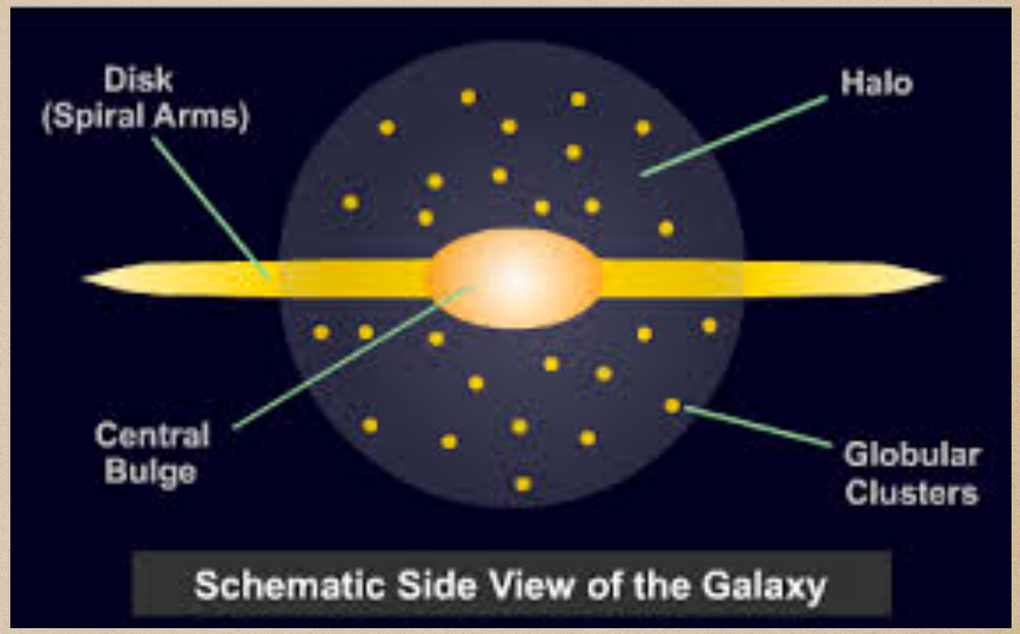
$$M_{\mathrm{dyn}} = \frac{\beta \sigma_e^2 R_e}{G}$$

The greater the mass, the greater σ

Spiral galaxies

They are typically composed of a bulge and a disk (plus a halo of stars, here almost invisible)







Sometimes there is a central bar

Spiral galaxies

	Sa	Sb	Sc	Sd/Sm	Im/Ir
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}
$\langle L_{bulge}/L_{tot}\rangle_B$	0.3	0.13	0.05	–	–
Diam. (D_{25},kpc)	5–100	5–100	5–100	0.5–50	0.5–50
$\langle M/L_B\rangle\ (M_\odot/L_\odot)$	6.2 ± 0.6	4.5 ± 0.4	2.6 ± 0.2	~ 1	~ 1
V_{max} range(km s^{-1})	193–367	144–330	99–304	–	50–70
$\mu_{0,B}$ (mag arcsec^{-2})	21.52 ± 0.39	21.52 ± 0.39	21.52 ± 0.39	22.61 ± 0.47	22.61 ± 0.47
$\langle B-V\rangle$	0.75	0.64	0.52	0.47	0.37
$\langle M_{gas}/M_{tot}\rangle$	0.04	0.08	0.16	0.25 (Scd)	–

They are less massive than ellipticals

They rotate quickly

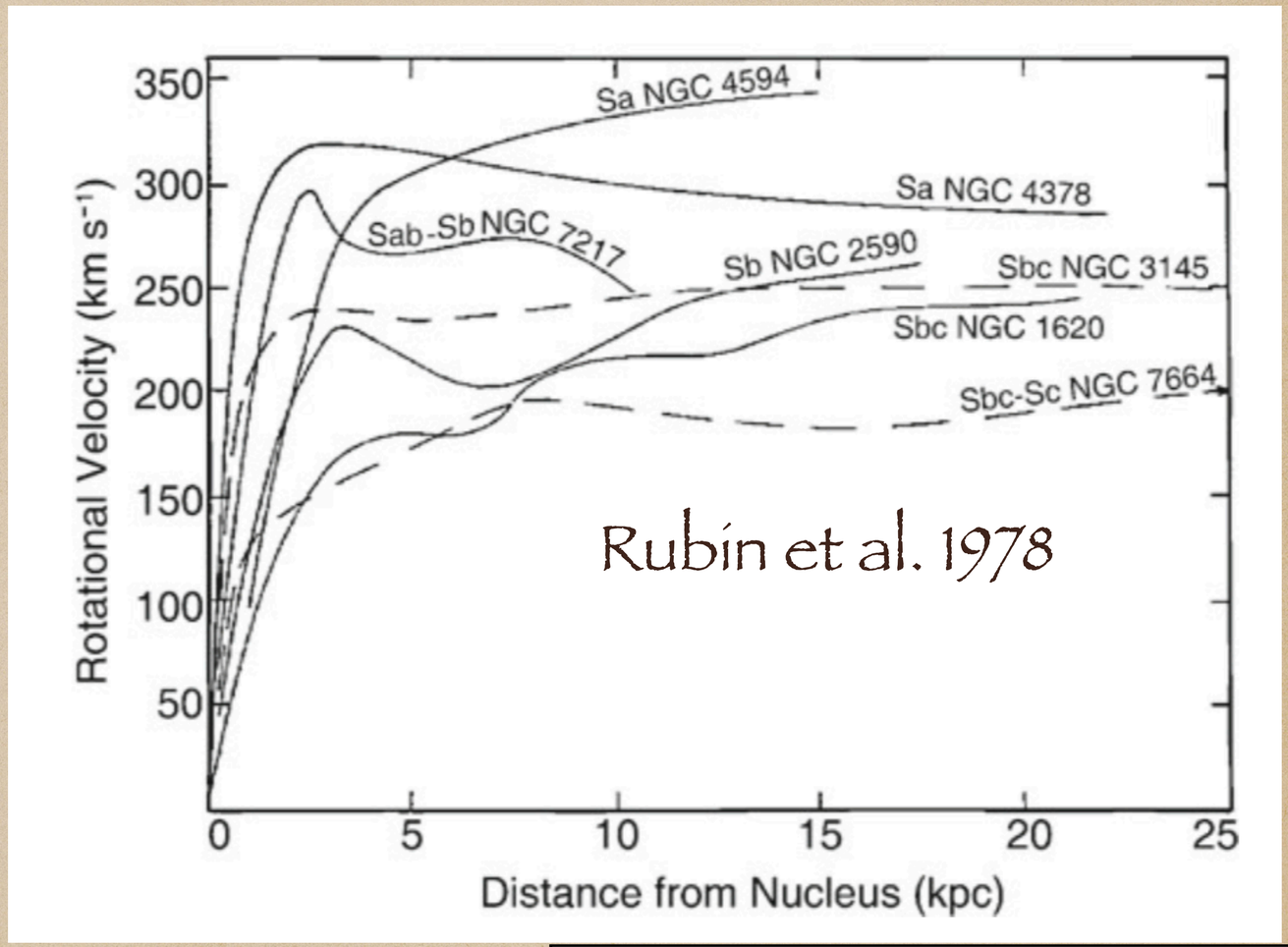
They have blue colors

They are rich in gas

Spiral galaxies: dynamic

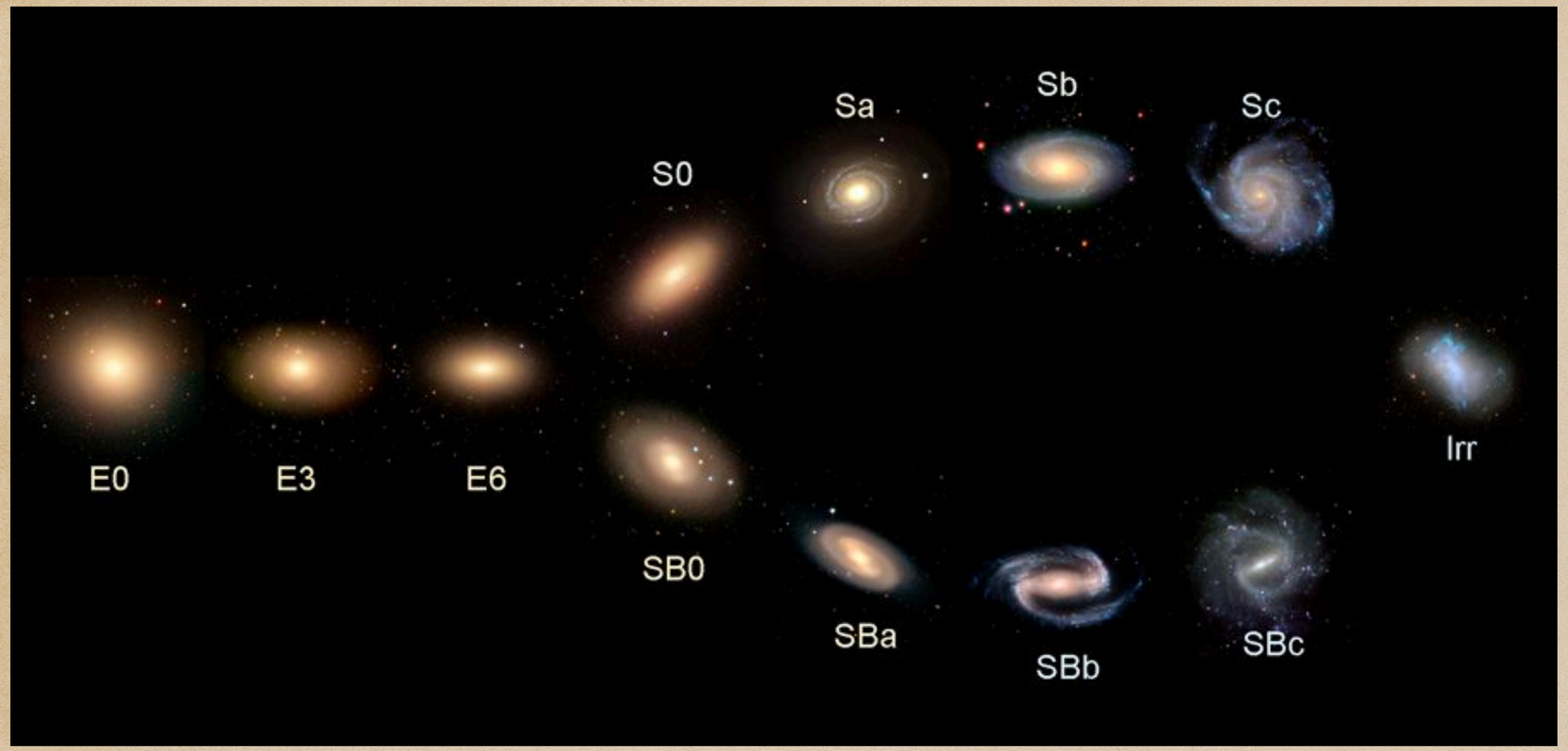


The stars in the disk rotate in ordered circular motions



The rotation curves remain flat at great distances from the center

The evidence of Dark Matter is universal



The physical origin of this sequence is one of the most studied research topics in astronomy today

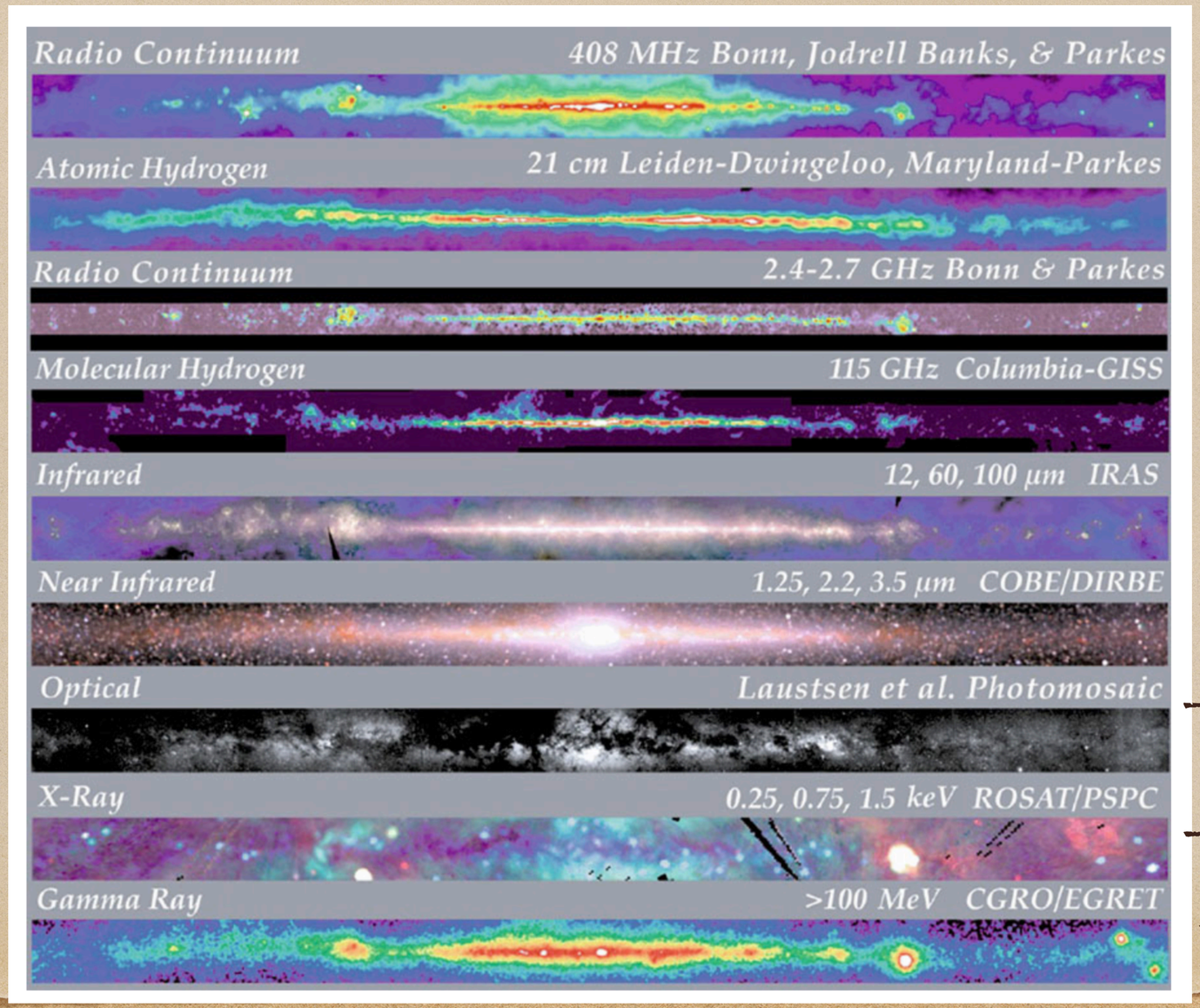
In conclusion, we can say that Hubble's morphological sequence, despite being defined purely based on the shape of galaxies, contains a lot of physical information, because morphological classes correlate with physical quantities such as mass, luminosity, dynamics, age populations, [...]

- Galaxies with different wavelengths
- X-ray
- UV
- Optical
- Infrared
- Radio

- Synthesis of stellar populations

- IMF
- Individual populations
- Composite populations
- Mass, star formation rate (SFR)

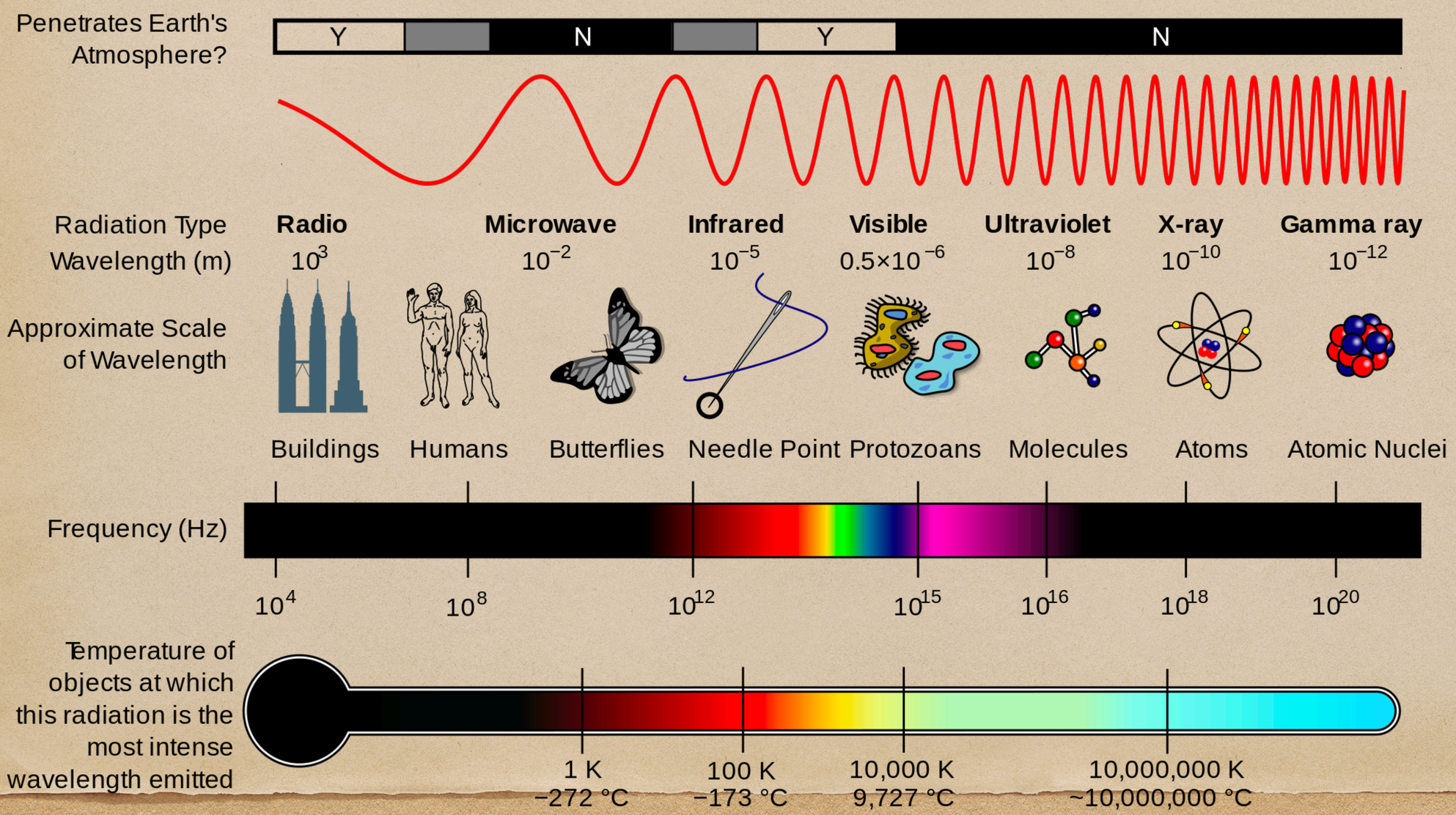
Galaxies to different wavelengths



Milky Way

Wavelength

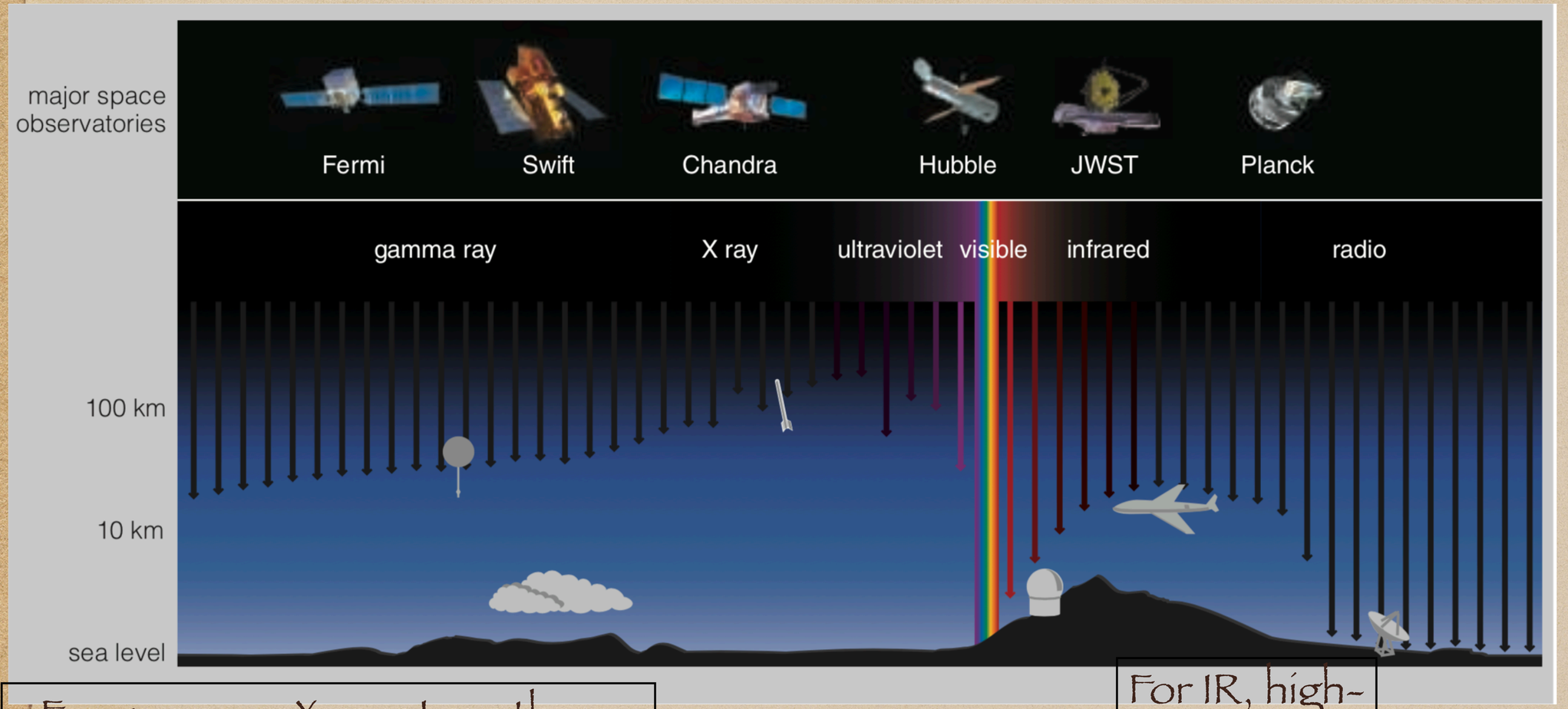
Electromagnetic spectrum



$E=h\nu$

$\nu=c/\lambda$

The electromagnetic spectrum



This diagram shows how deep in the atmosphere photons of different λ can penetrate

For gamma or X rays I can throw balloons or rockets in the high atmosphere, but the space is better

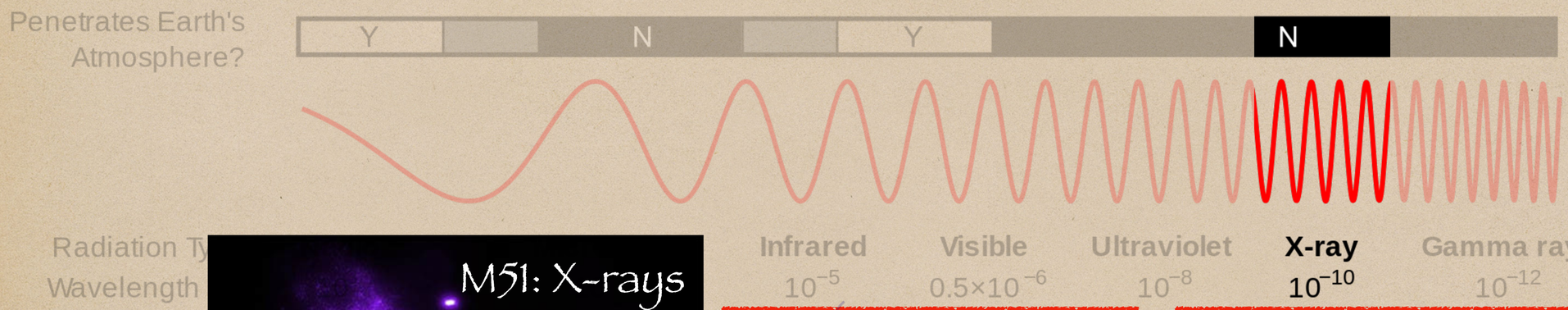
For UV, only space

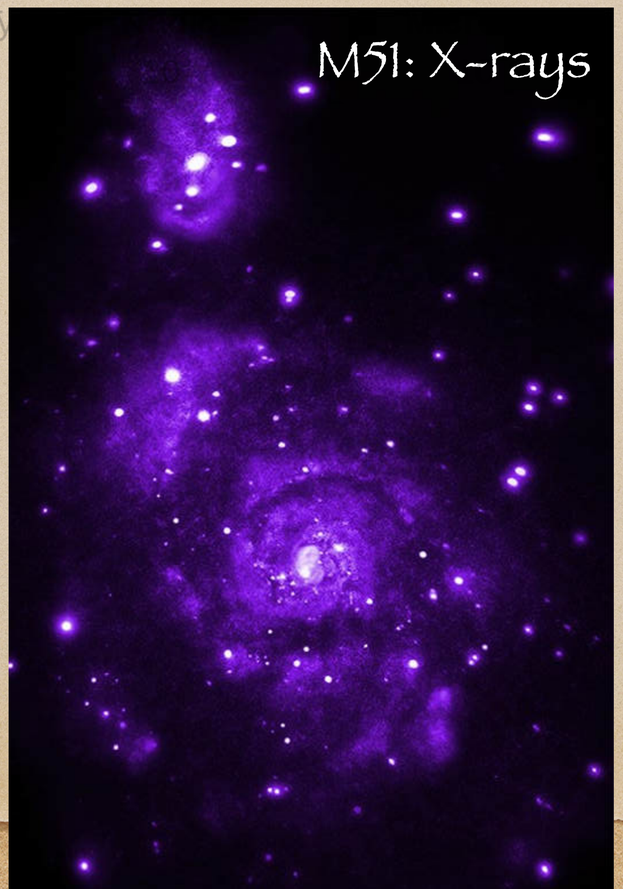
For optical, ground or space

For IR, high-altitude aircraft or space

By radio, earth or space

Galaxies at different wavelengths



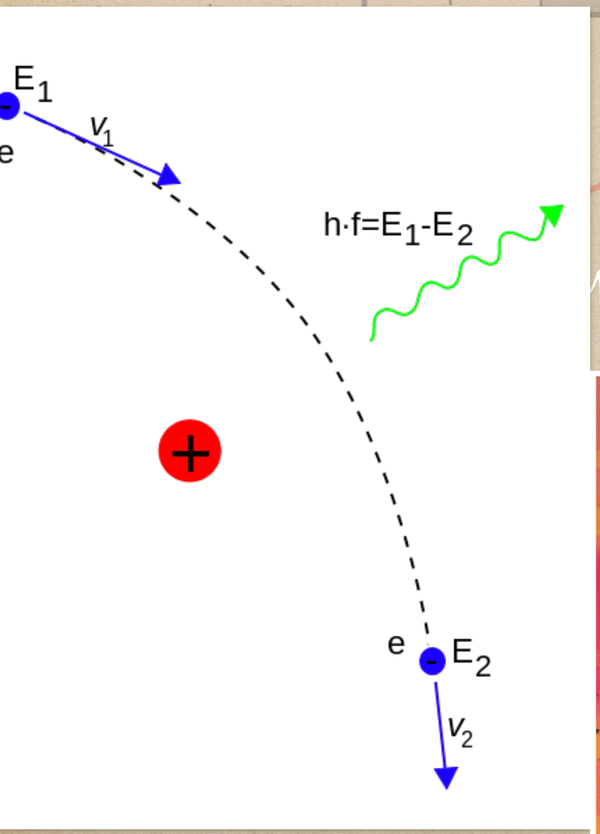


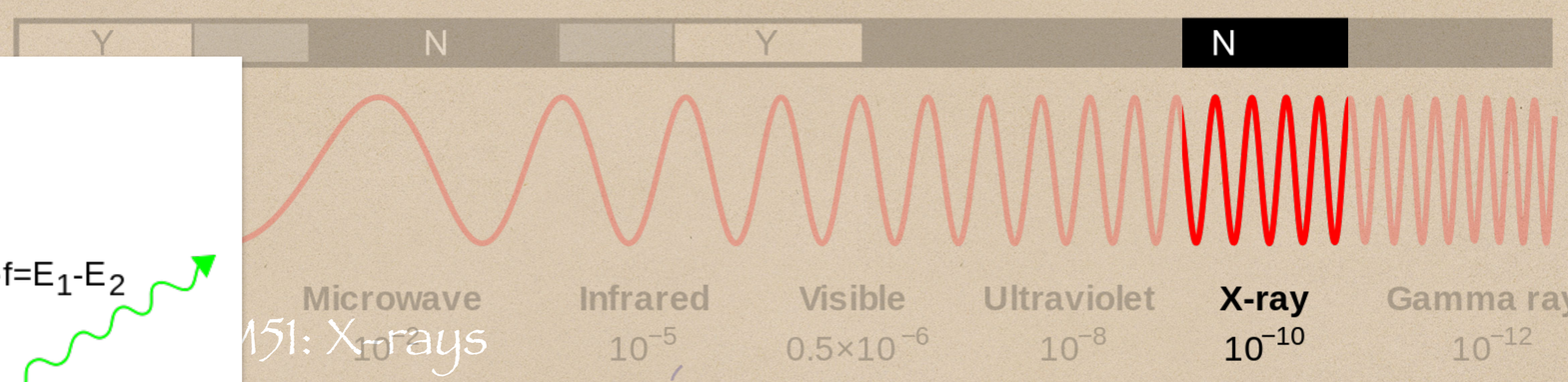
Compact sources: X binaries, active galactic nuclei (BH)

Diffuse component: hot plasma, associated with young stars

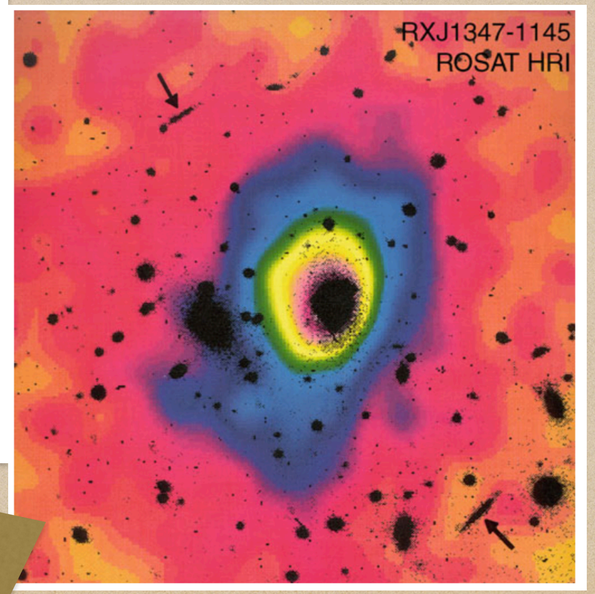


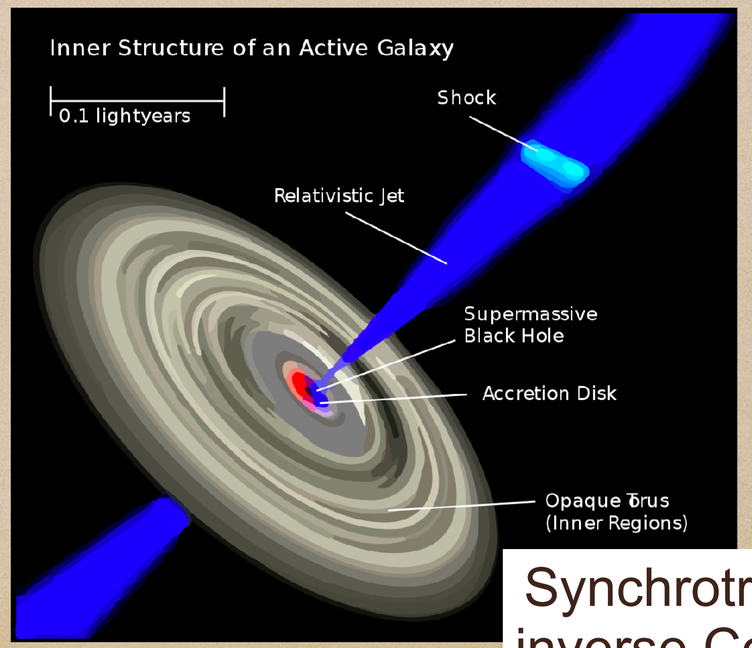
Galaxies at different wavelengths





M51: X-rays



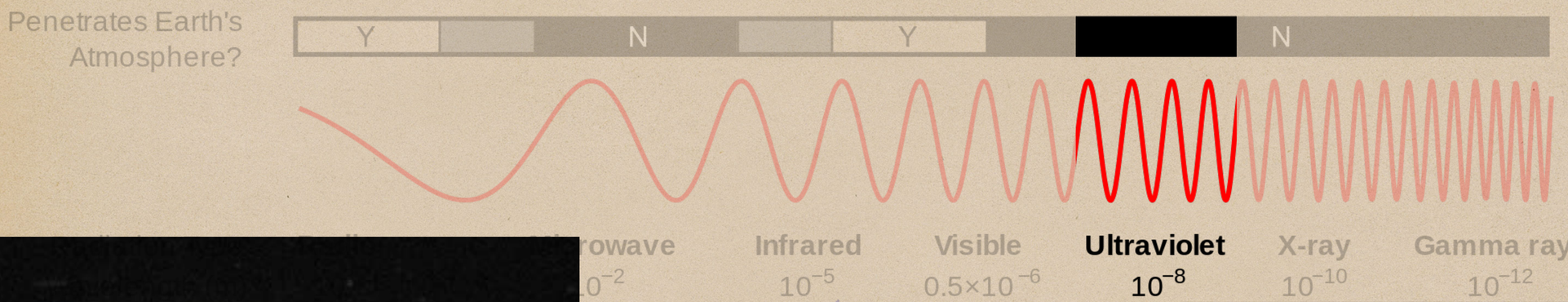


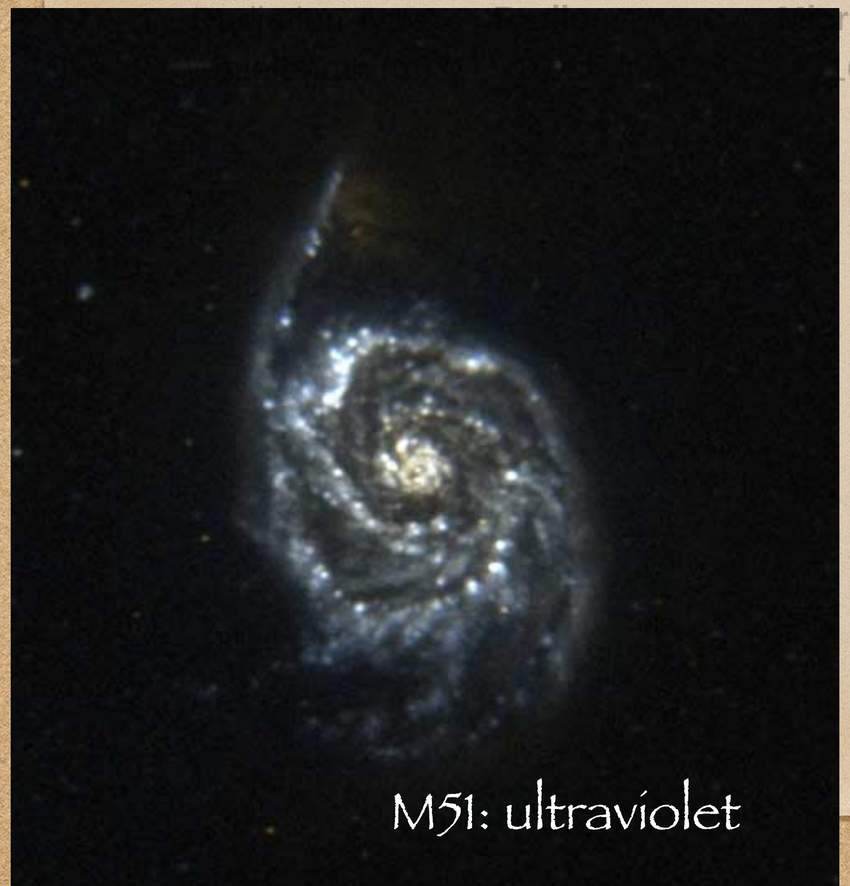
Free-free radiation; typical in hot plasmas

Satellite Chandra

Synchrotron radiation, inverse Compton, from relativistic electrons

Galaxies at different wavelengths

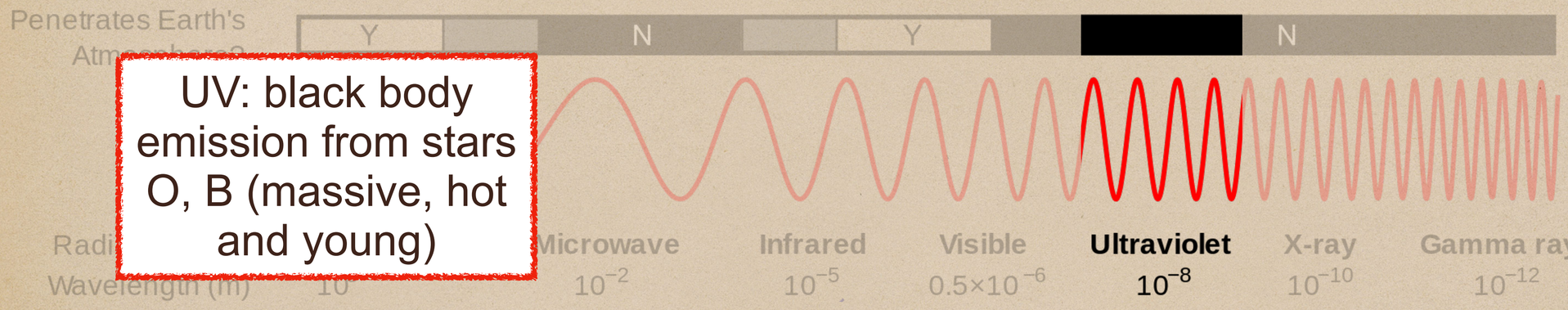




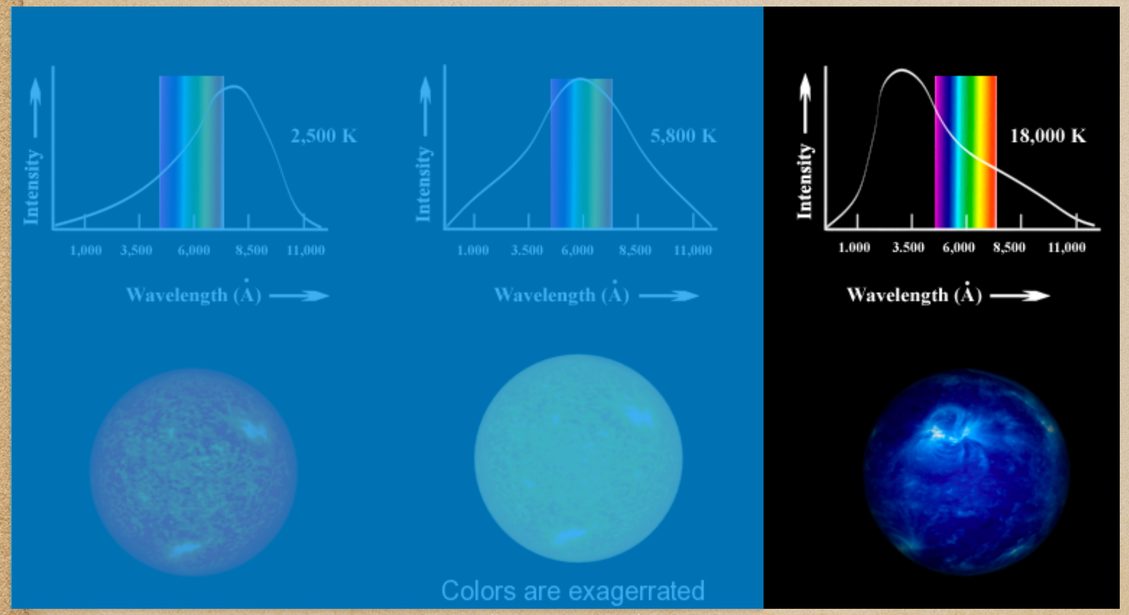
UV: black body emission from stars O, B (massive, hot and young)



Galaxies at different wavelengths



UV: black body emission from stars O, B (massive, hot and young)



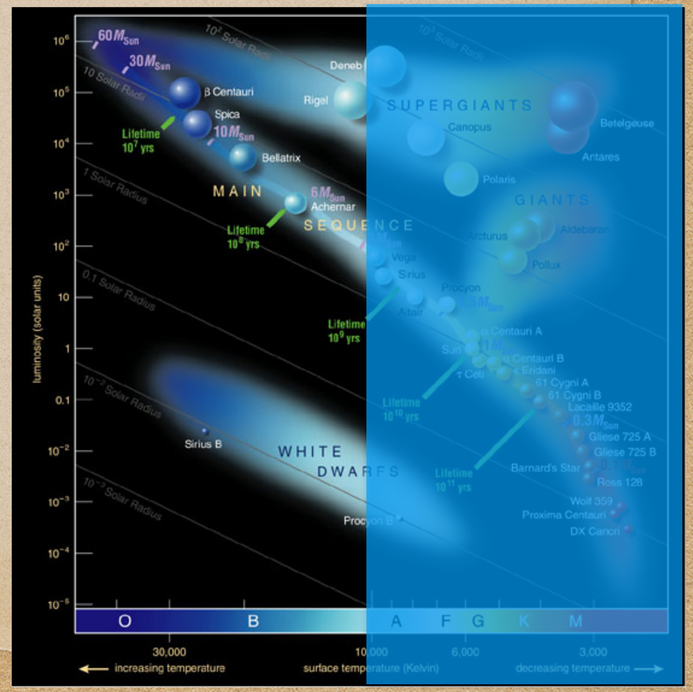
M51: ultravioletto

Although the OB stars are not very numerous, they are very bright; 1 O star has the luminosity of 10^6 Suns

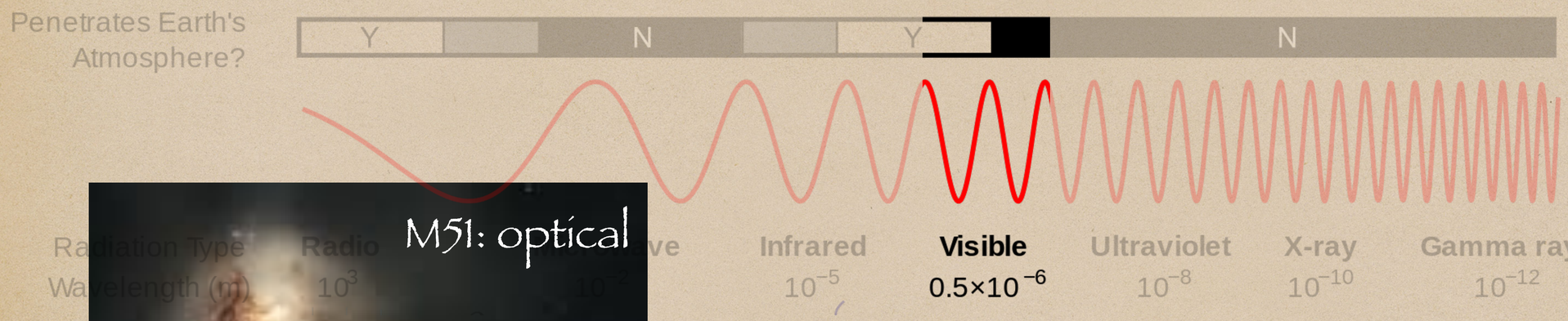
10^6

1

10^{-4}



Galaxies at different wavelengths



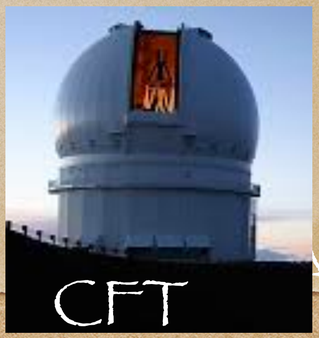


Optical: thermal emission of intermediate stars

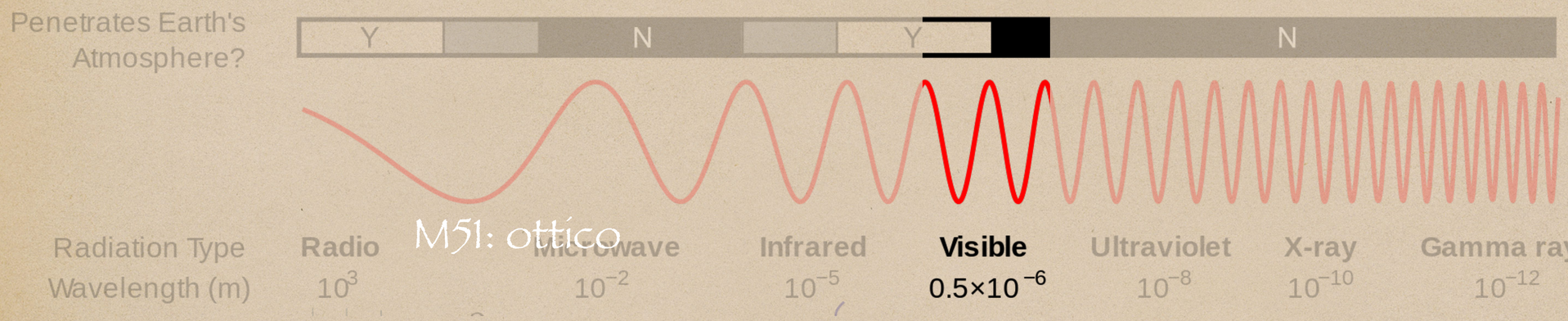




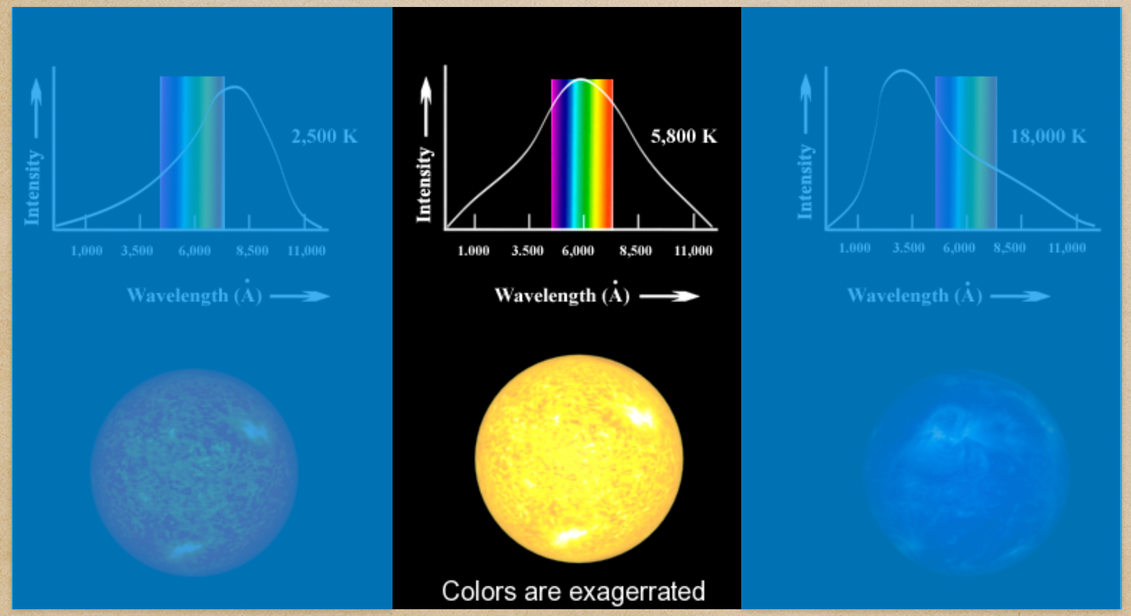




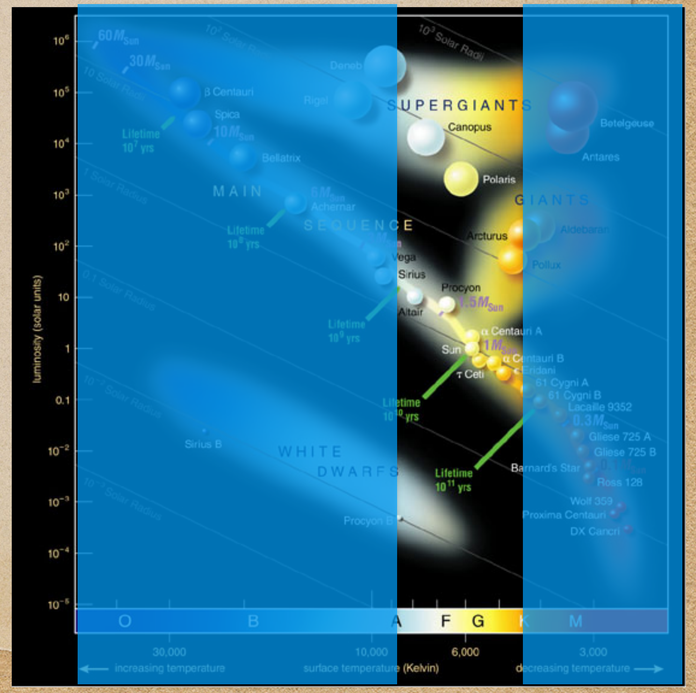
Galaxies at different wavelengths



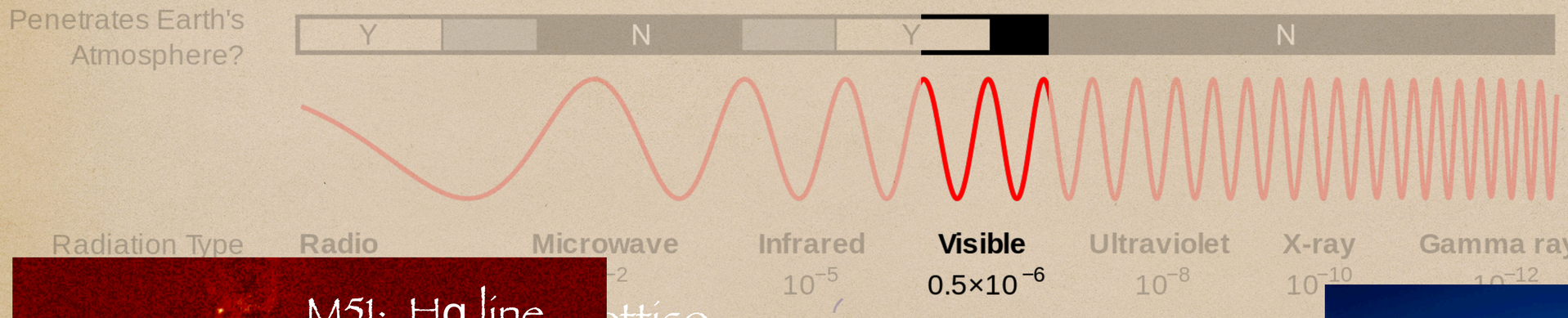
M51: ottico

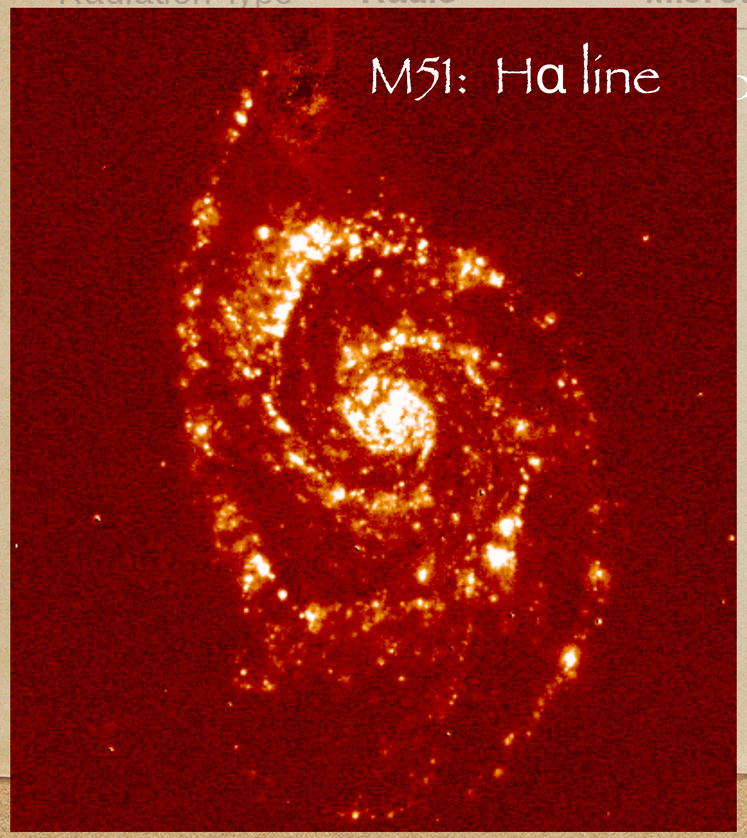


Optical: thermal emission of intermediate stars



Galaxies at different wavelengths





Hα line: Ionizing radiation from hot stars

Ionization nebulae





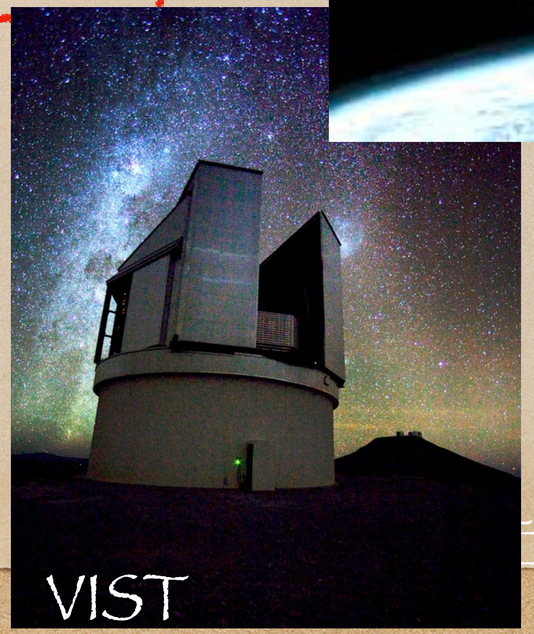
Galaxies at different wavelengths



NIR continuum: thermal emission of stars M, K

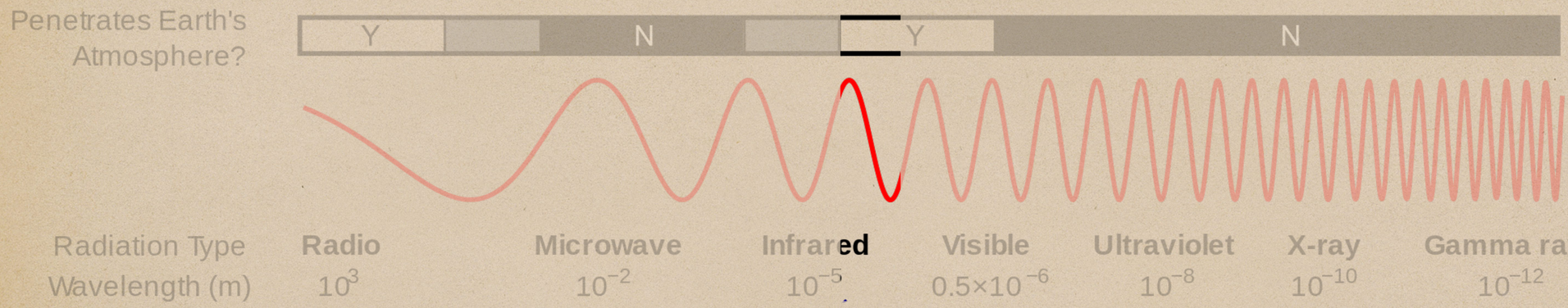




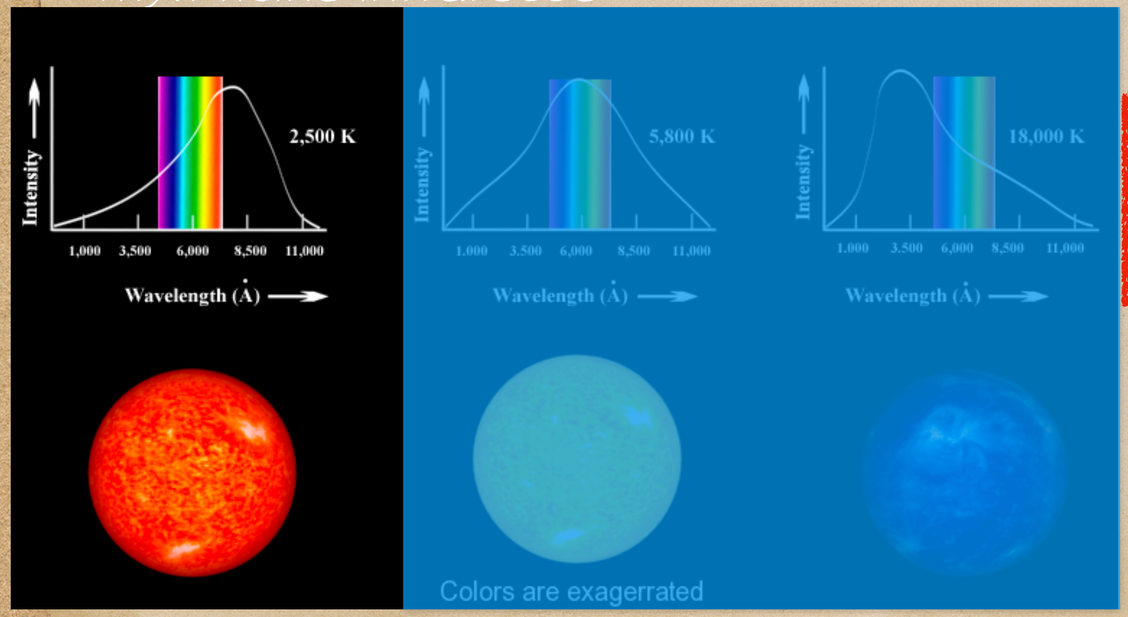




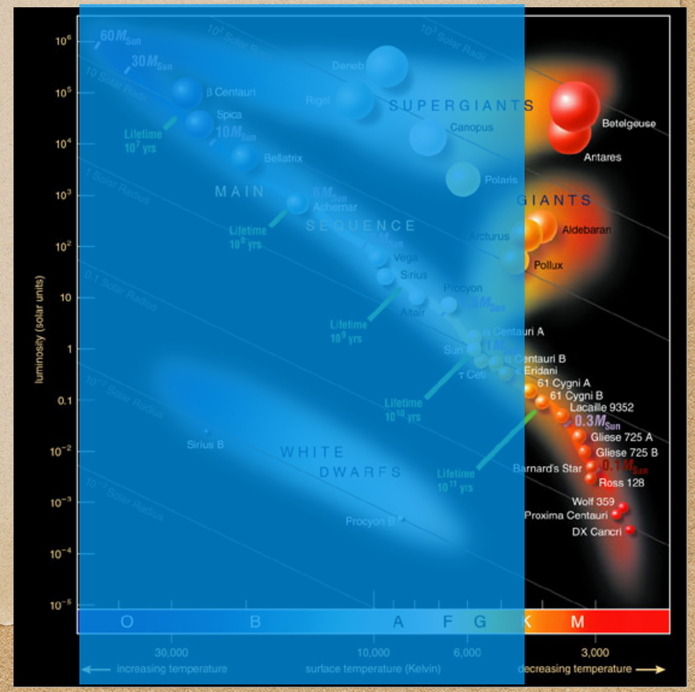
Galaxies at different wavelengths



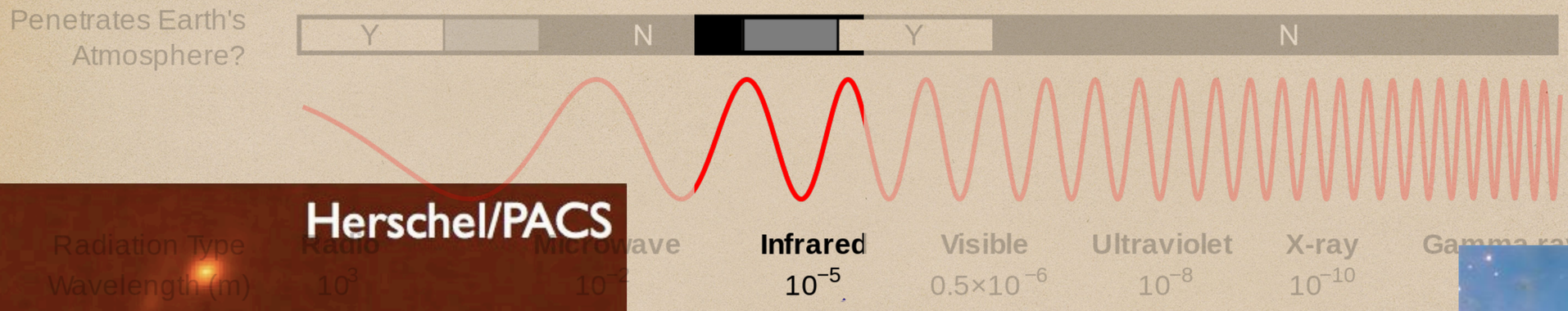
M51: vicino infrarosso

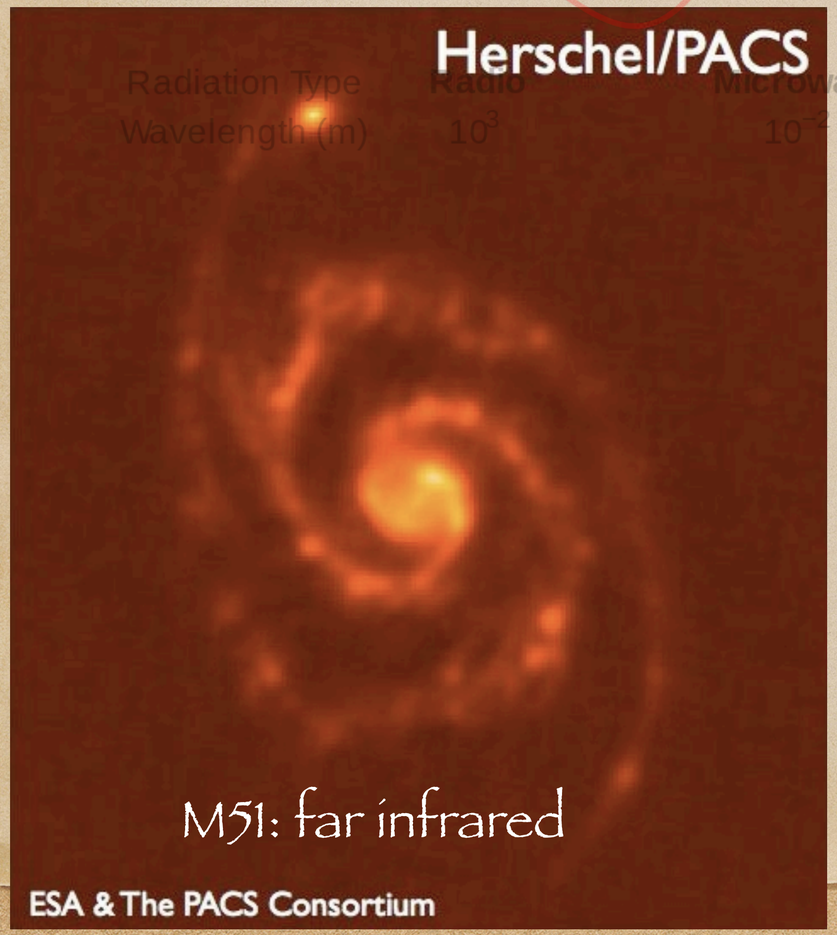


NIR continuum: thermal emission of stars M, K



Galaxies at different wavelengths



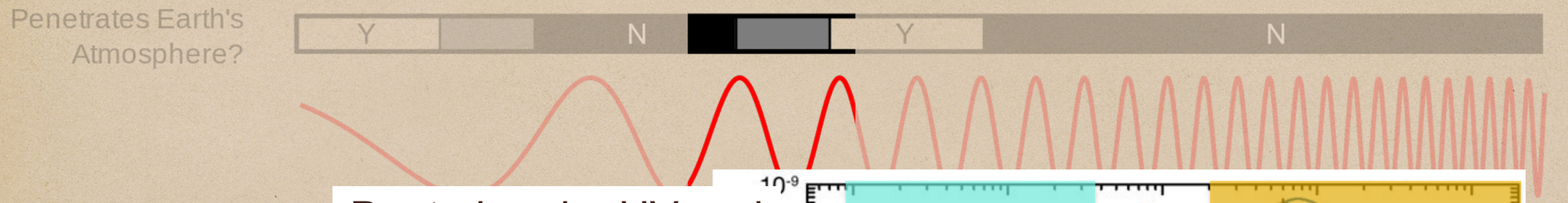


FIR continuum: thermal emission from dust

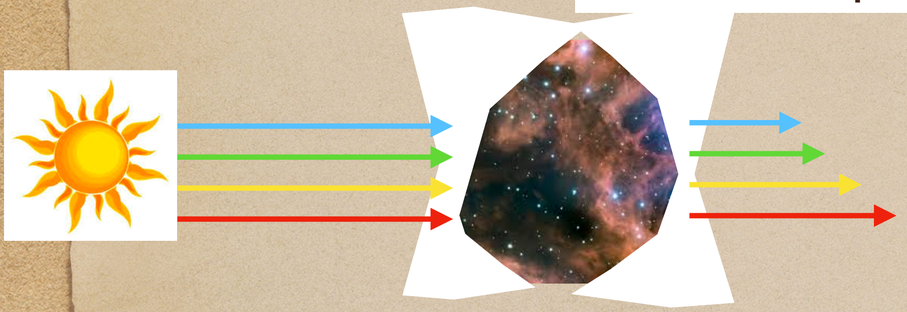




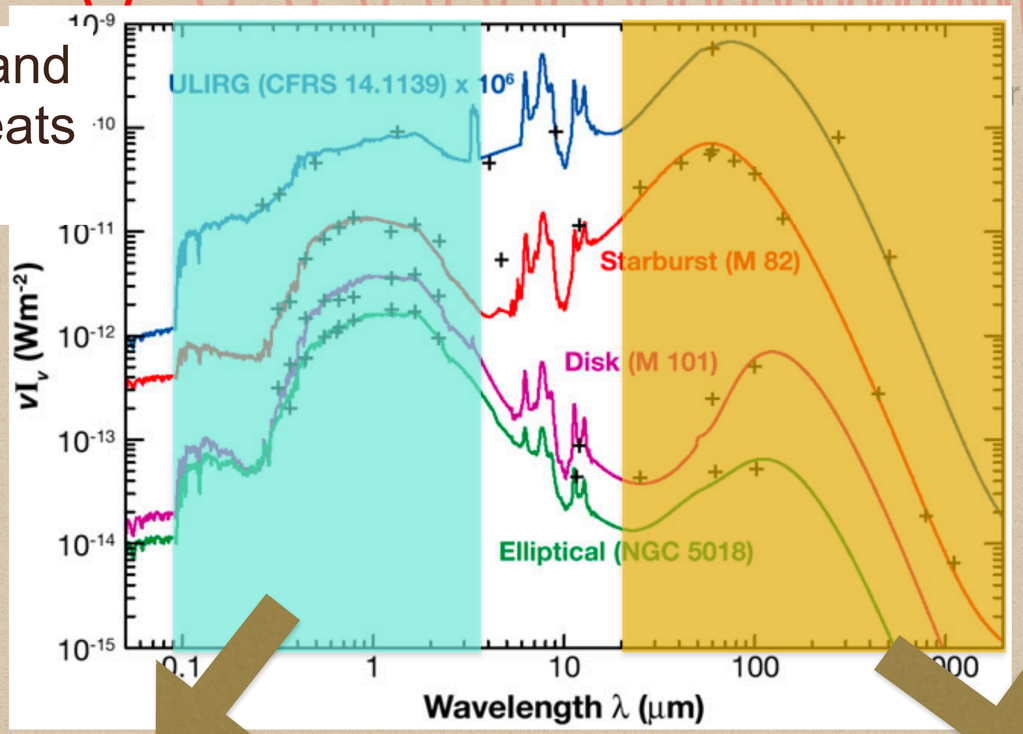
Galaxies at different wavelengths



Dust absorbs UV and optical light and heats up



Emits black body radiation T~30K

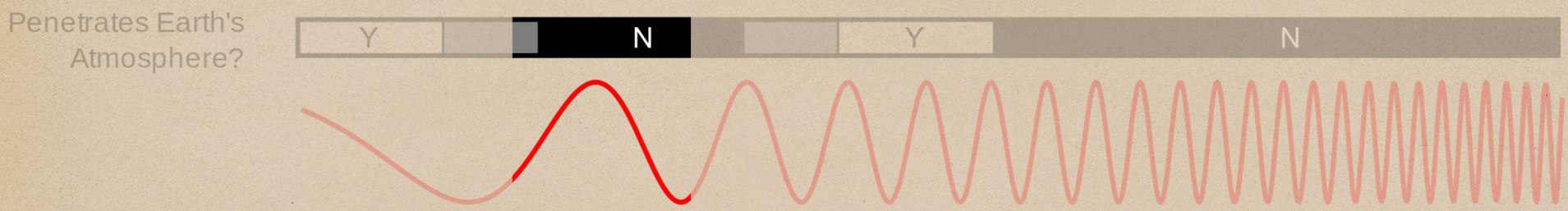


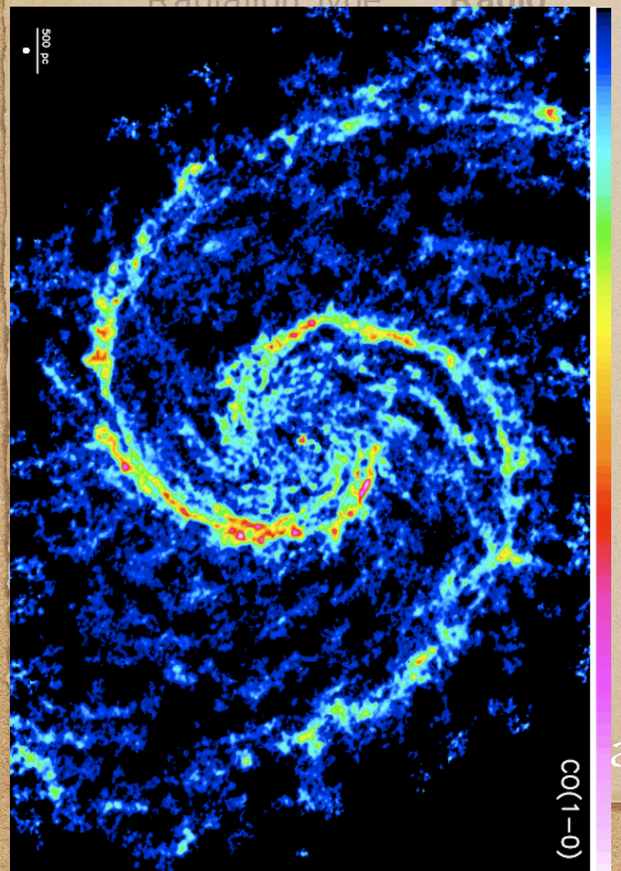
Direct stellar emission

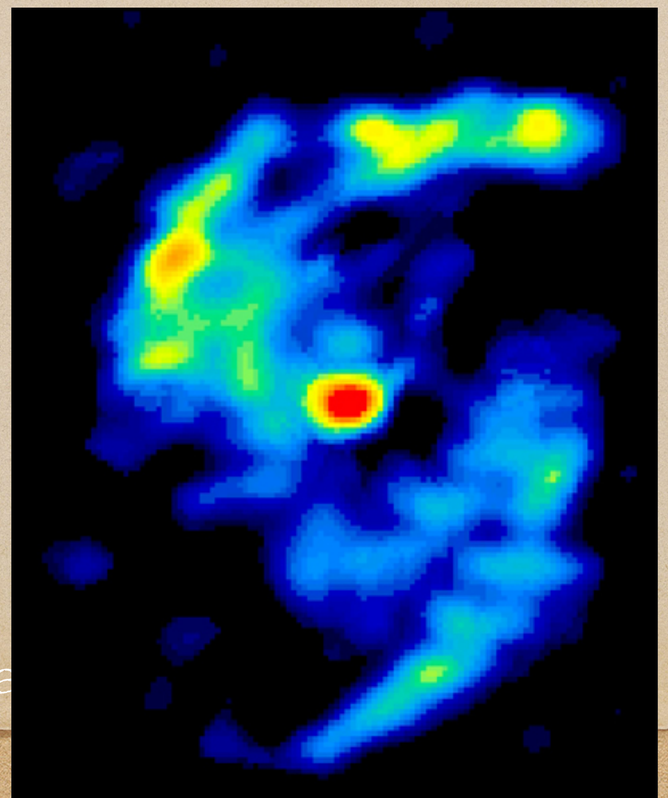
VISTA

FIR continuum: thermal emission of dust

Galaxies at different wavelengths







sub-mm continuum, microwave: dust thermal emission (RJ)

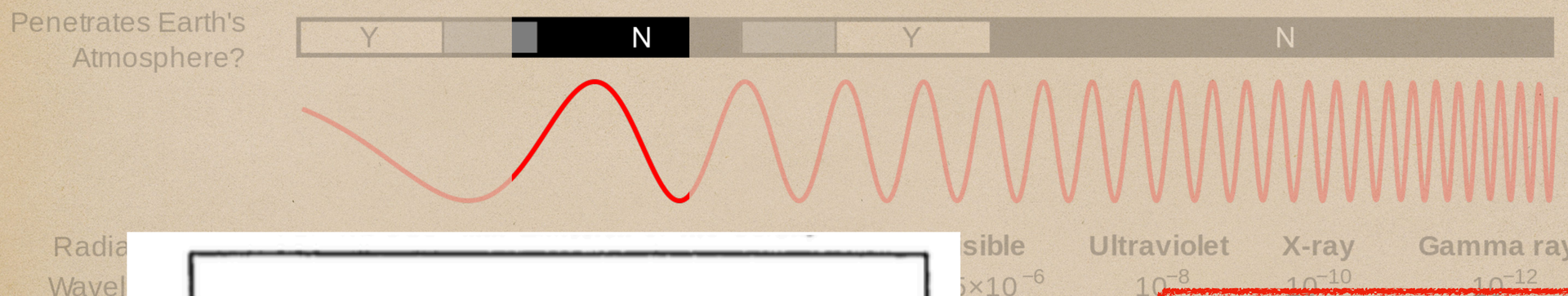
Spectral lines: molecular gas

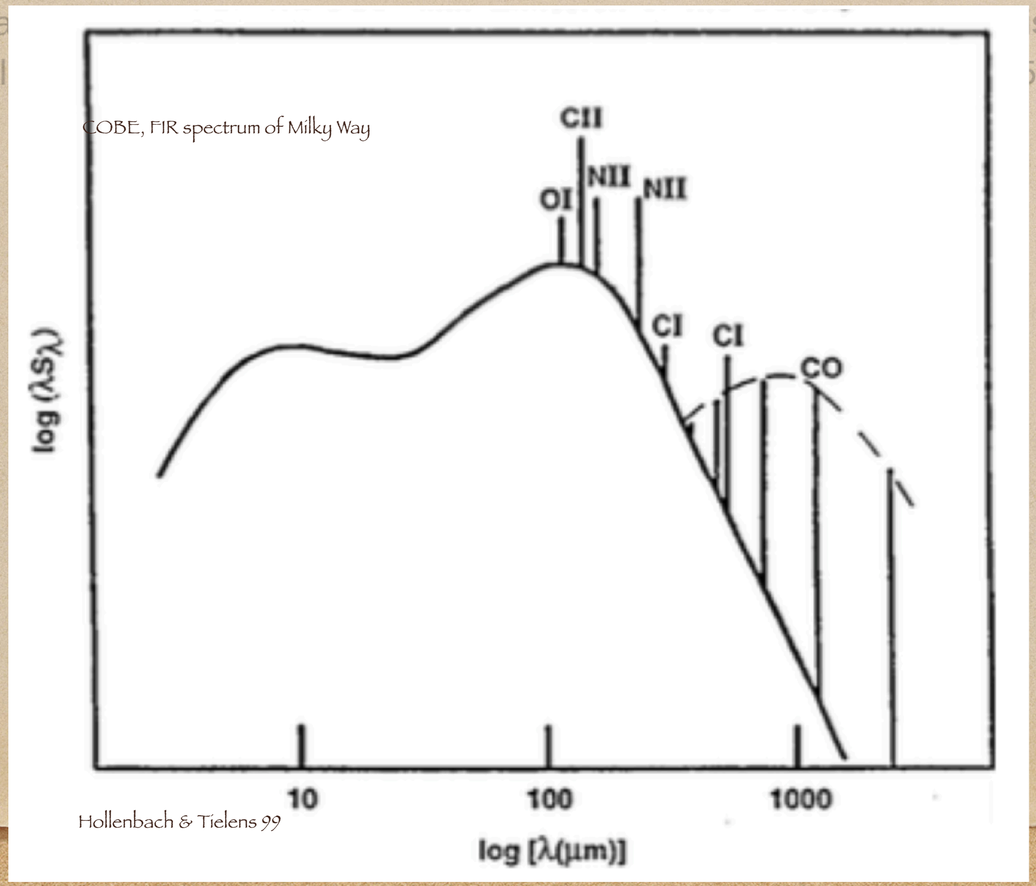






Galaxies at different wavelengths





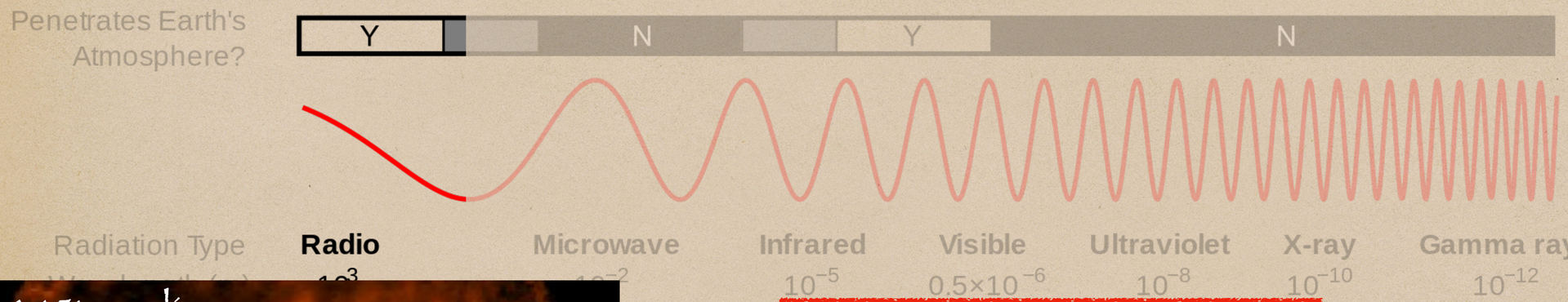
sub-mm continuum, microwave: dust thermal emission (RJ)

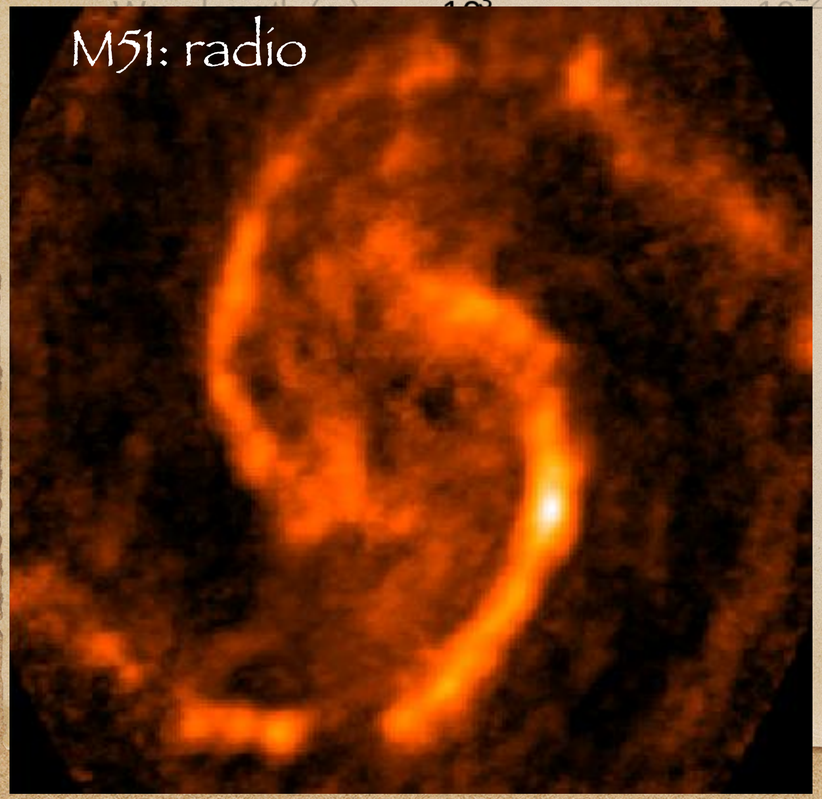
Spectral lines: molecular gas

VISTA

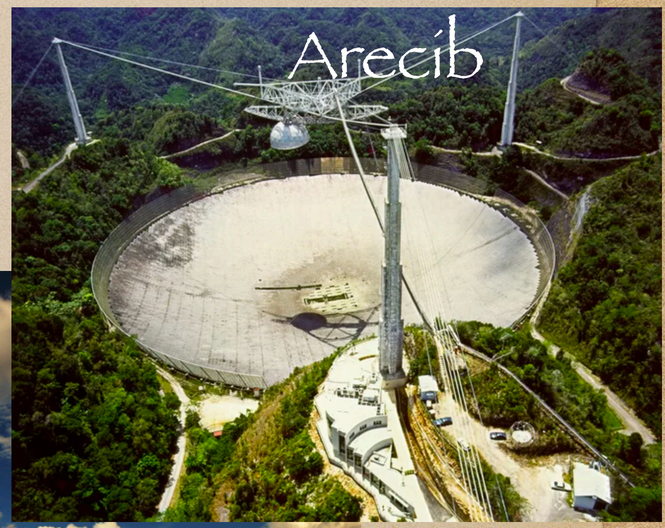
Herschel

Galaxies at different wavelengths



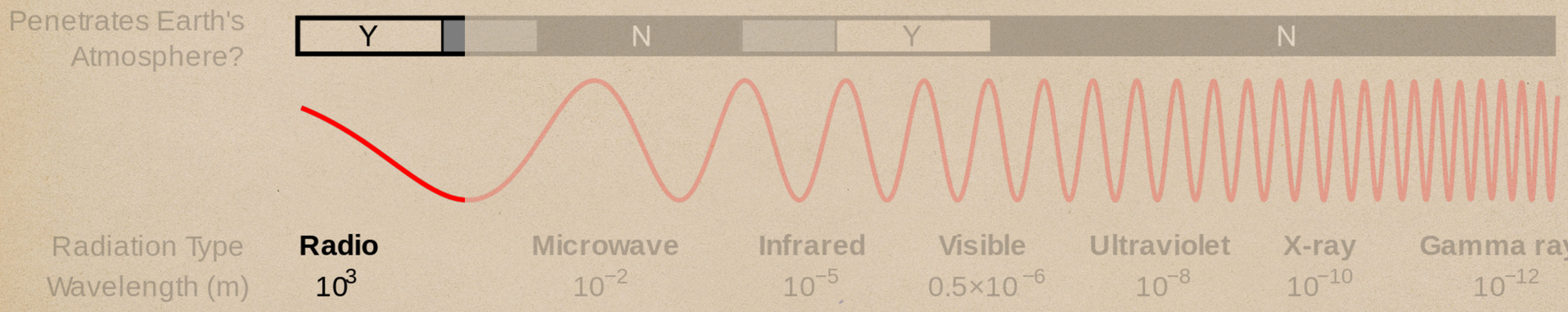


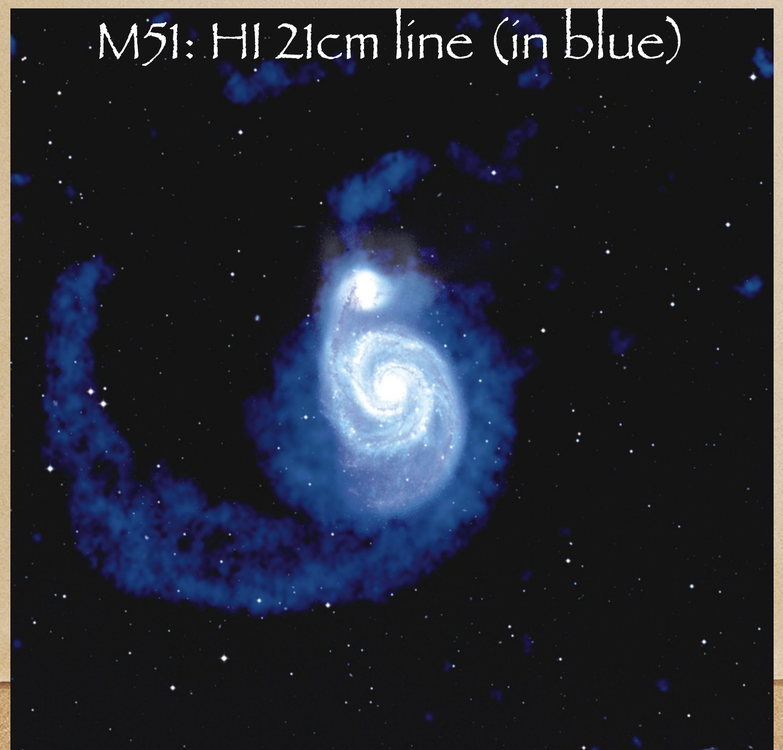
Radio continuum: star forming regions, synchrothron radiation from supernovae





Galaxies at different wavelengths





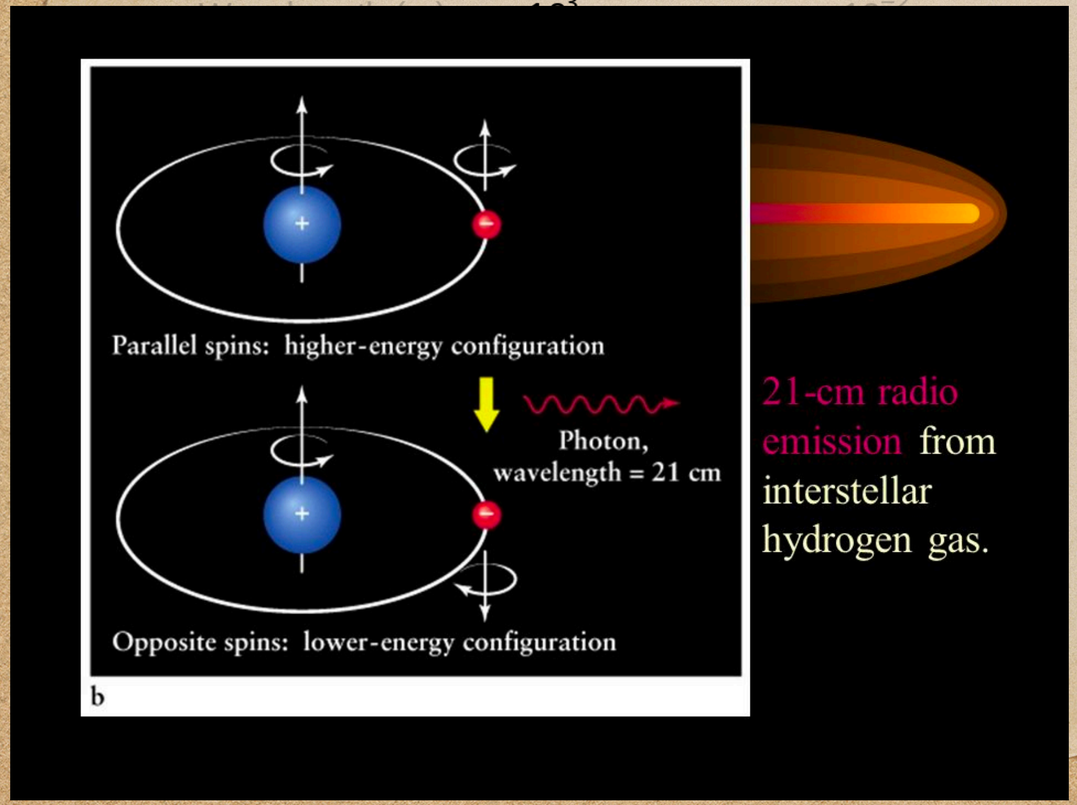
21cm HI line: cold gas





Galaxies at different wavelengths





21cm HI line: cold gas

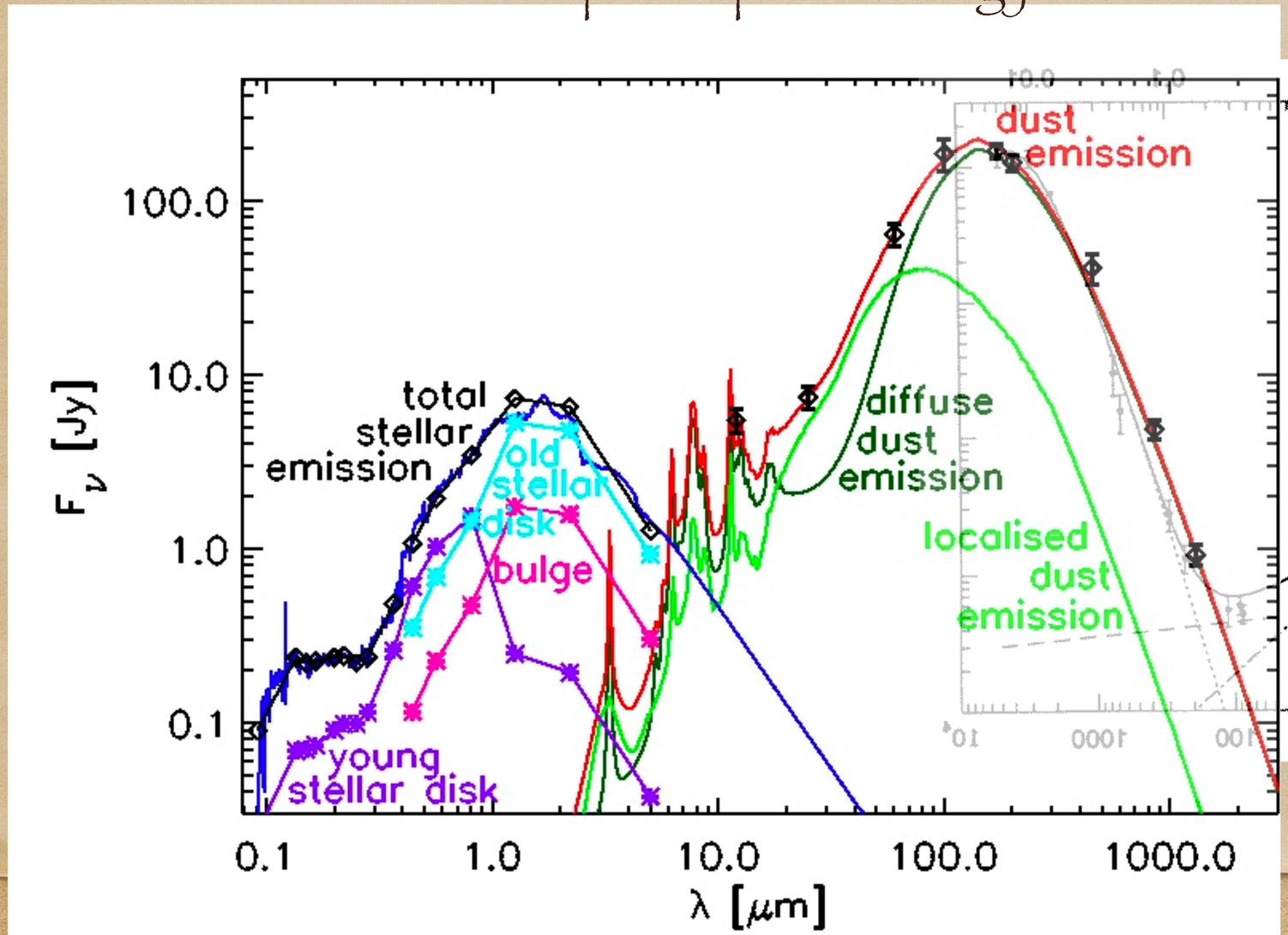
Transition between 2 energy levels of neutral hydrogen:

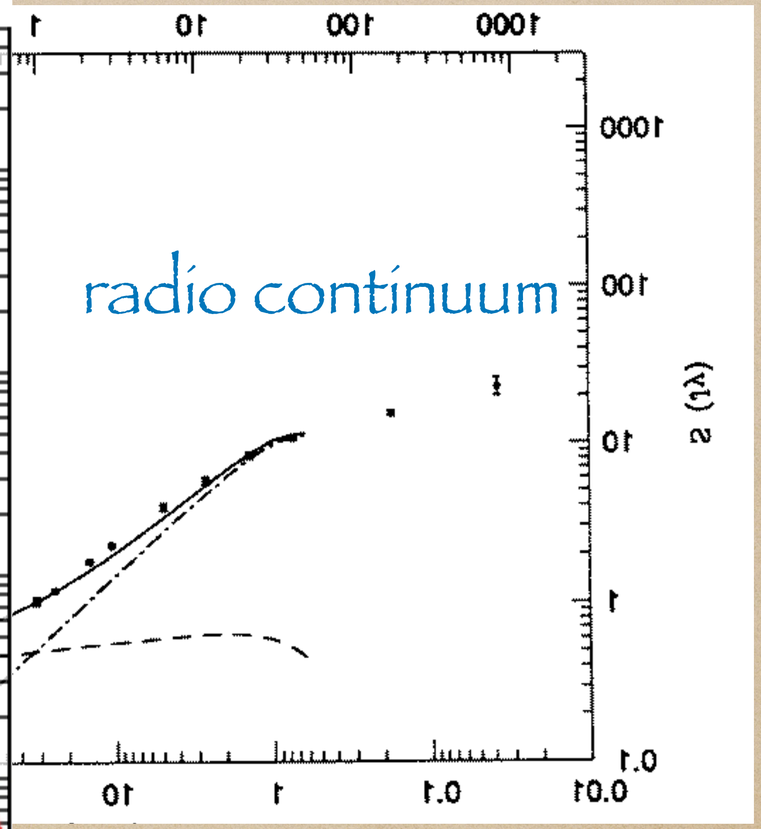
1. opposite spin, lower energy
2. parallel spin, higher energy

1 transition every $10^{7\text{-}8}$ years! Impossible to observe in the laboratory, but possible in the Universe given the abundance of HI

Galaxies at different wavelengths

Example of spectral energy distribution of a galaxy

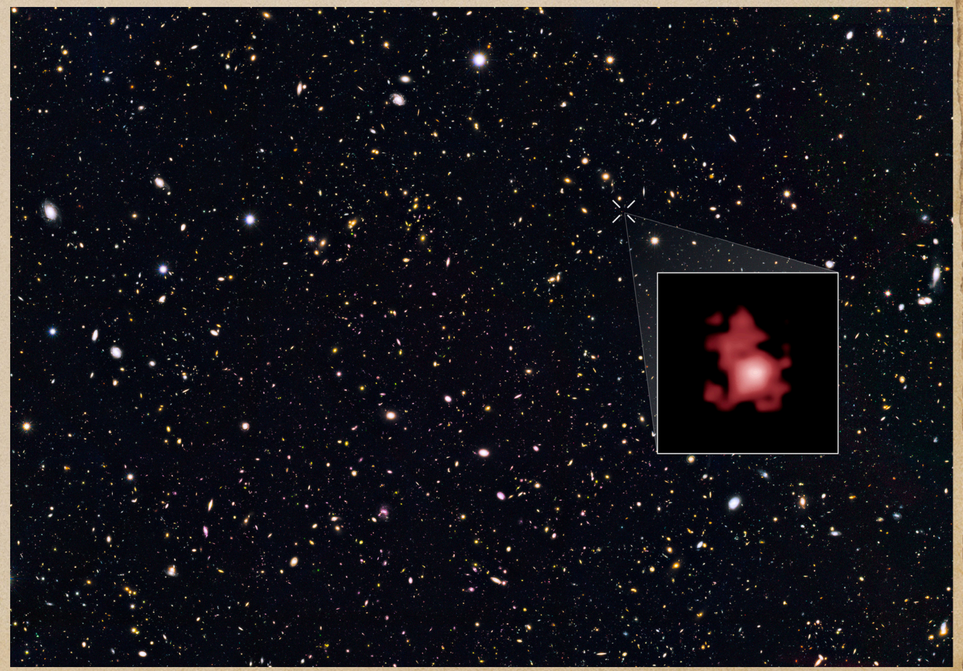




How to study stars in distant galaxies?

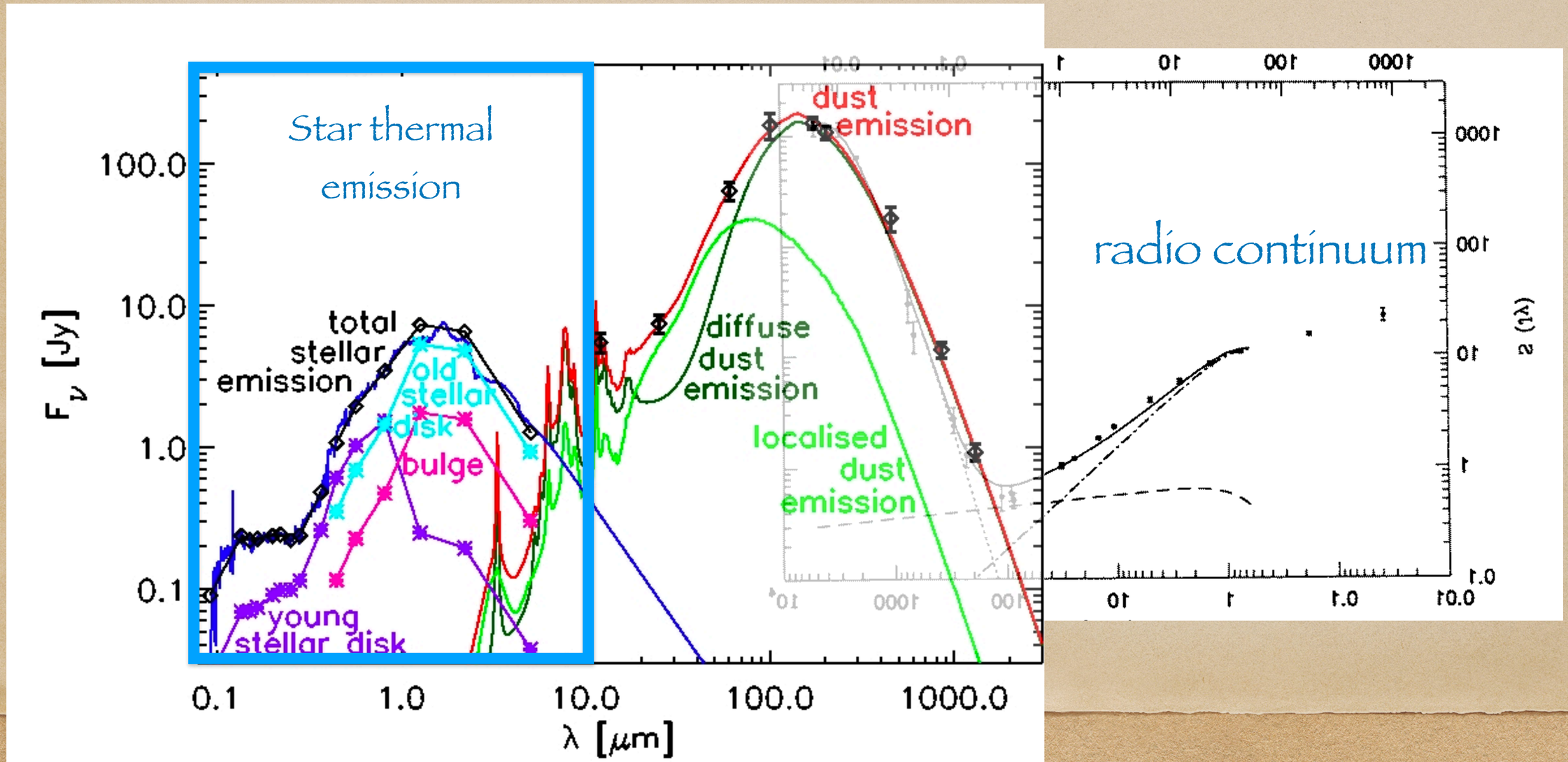






Galaxies at different wavelengths

We focus on the "stellar" part

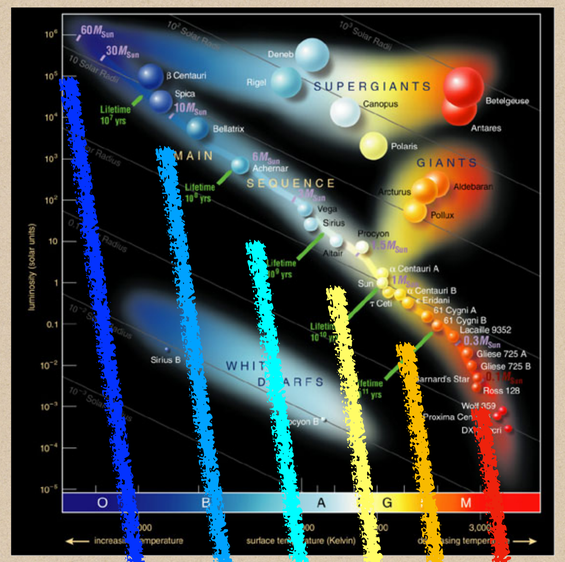


Synthesis of stellar populations

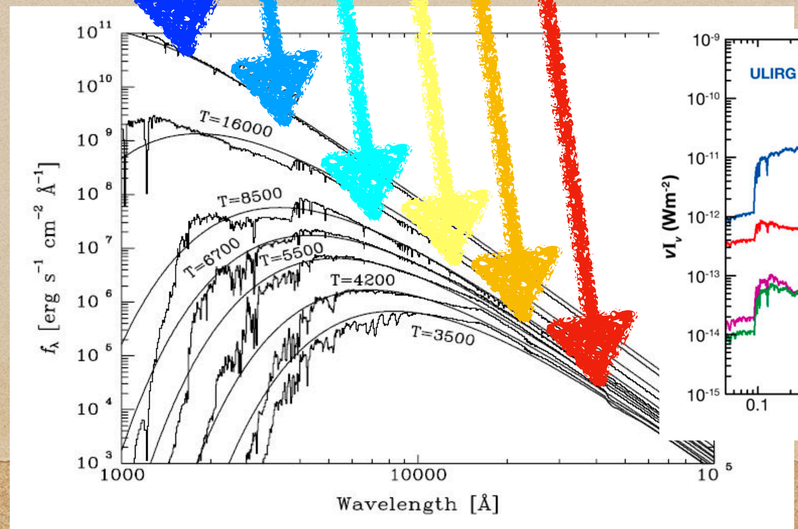
The light of galaxies originates from the stars. The spectral radiation of stars can be calculated with the theory of stellar atmospheres.

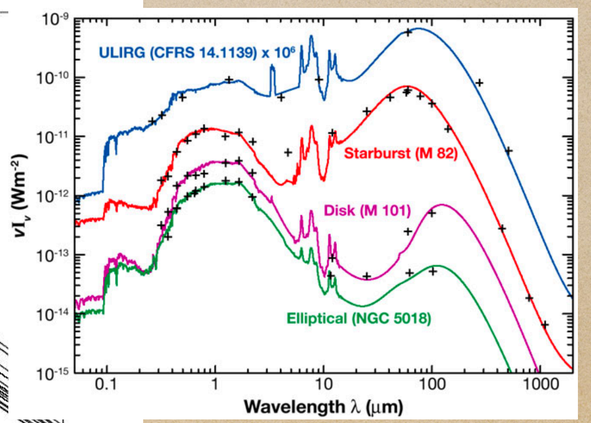
If the distribution of the numerical density of stars as a function of their mass is known, we can calculate the total light emitted by them

Synthesis of stellar populations









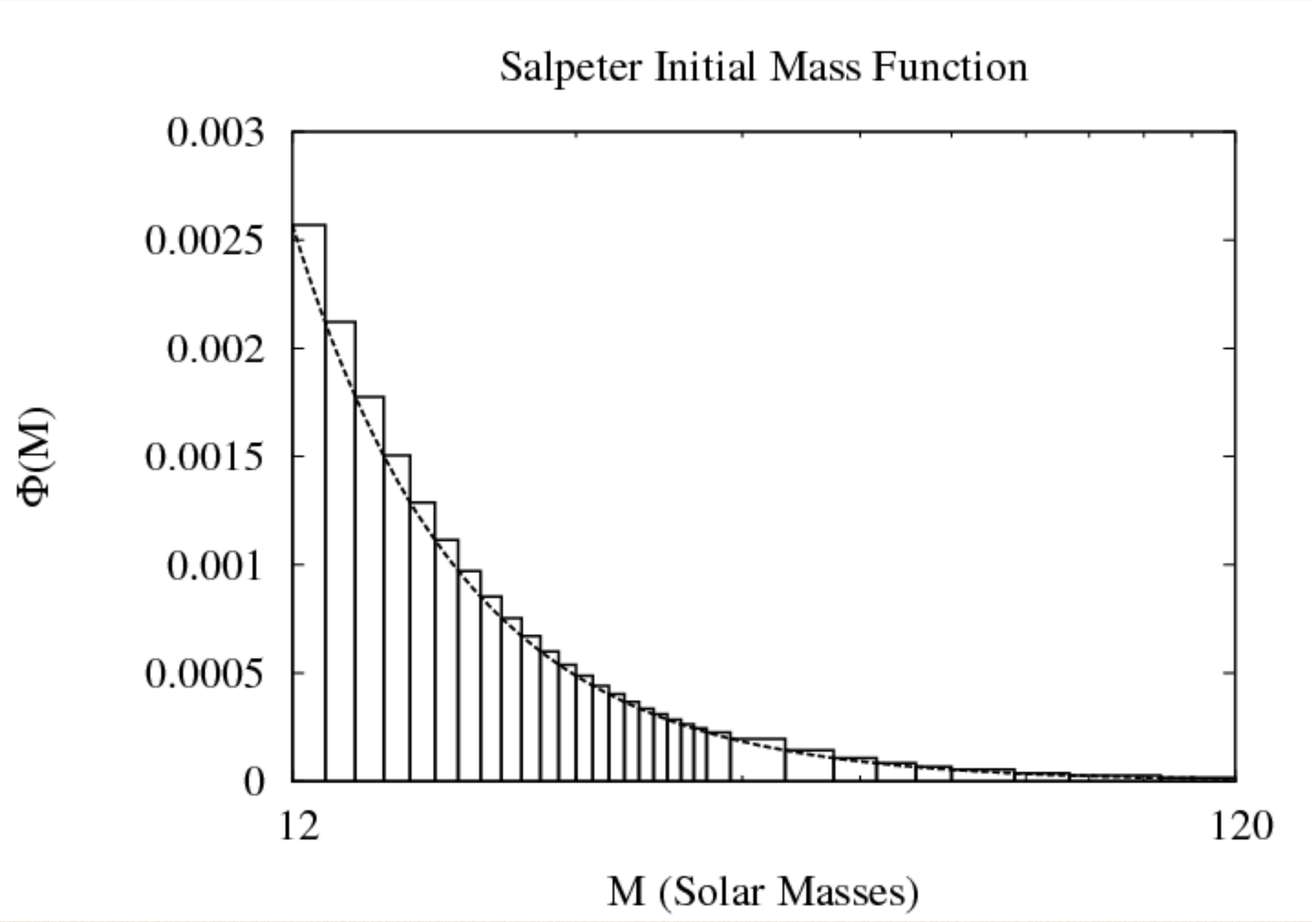
Synthesis of stellar populations

In practice, I create spectral distributions of energy for galaxies, assuming that they consist of a certain mix of stars

Synthesis of stellar populations

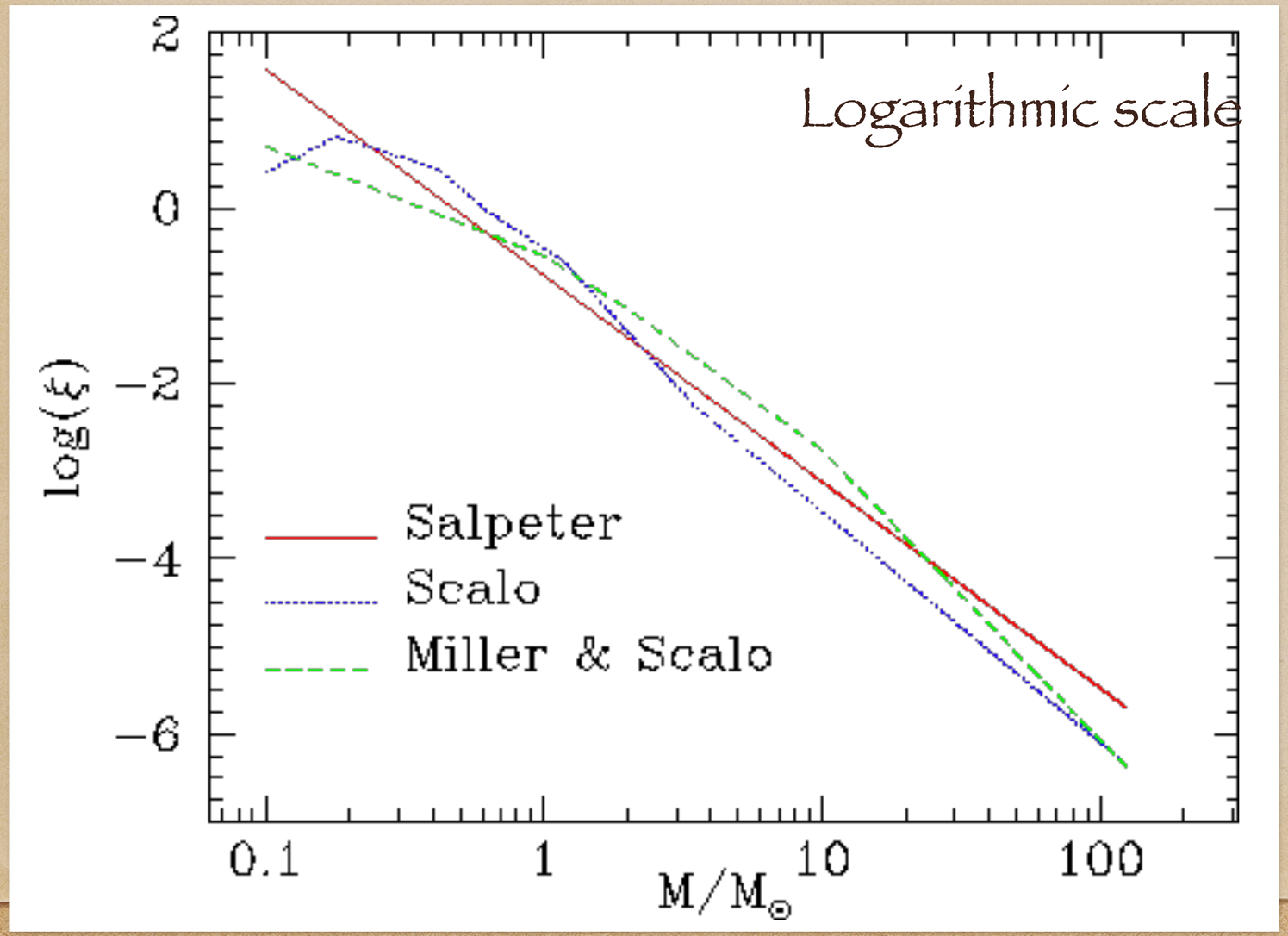
Initial mass function (IMF)

The IMF tells me the mass distribution of stars for a stellar population at its birth



- It is estimated by "counting" the stars of various spectral types in "young" environments, rich in stars O,B
- Limited to solar surroundings and some very close galaxies (Magellan clouds, ...)
- It's not "universal"

Initial mass function (IMF)

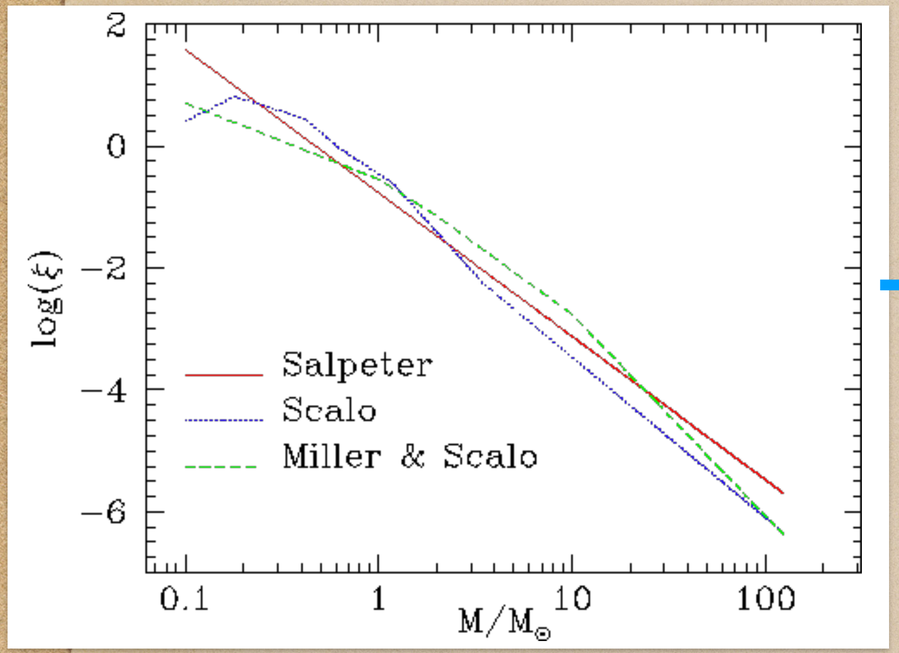


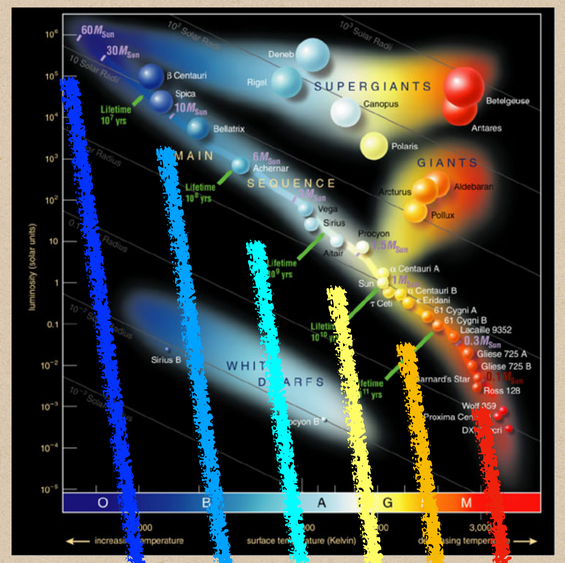
Salpeter IMF

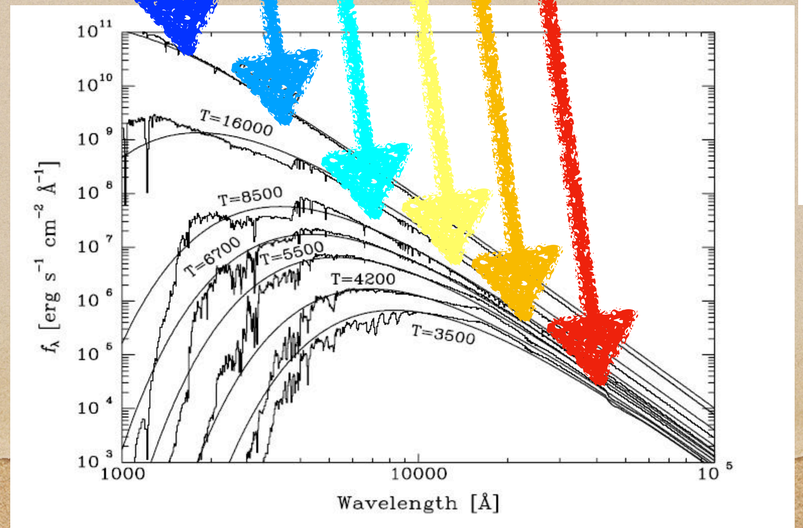
$$\phi(m) \propto m^{-2.35}$$

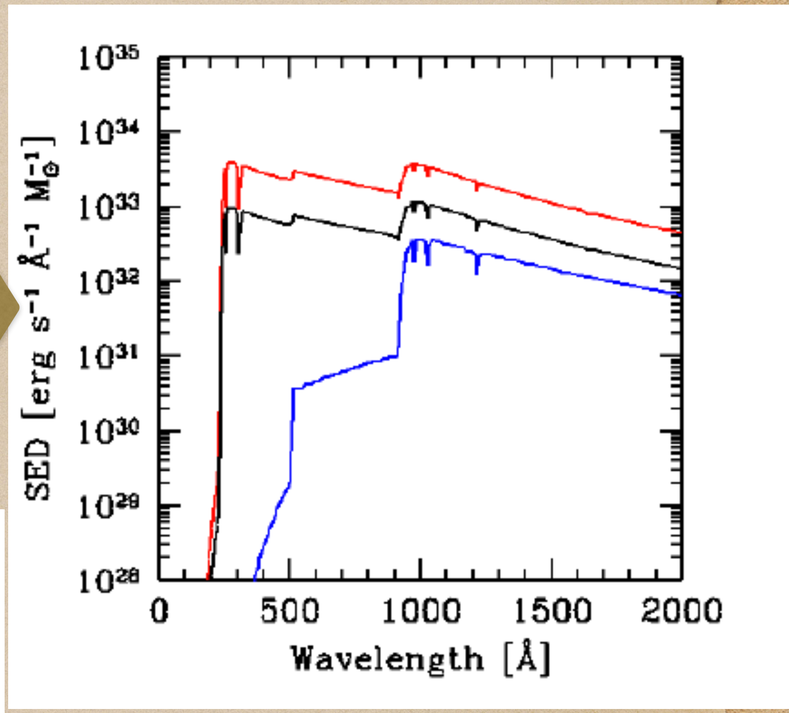
Chabrier, Kroupa:

- Similar slope
- Different cut-off to small masses





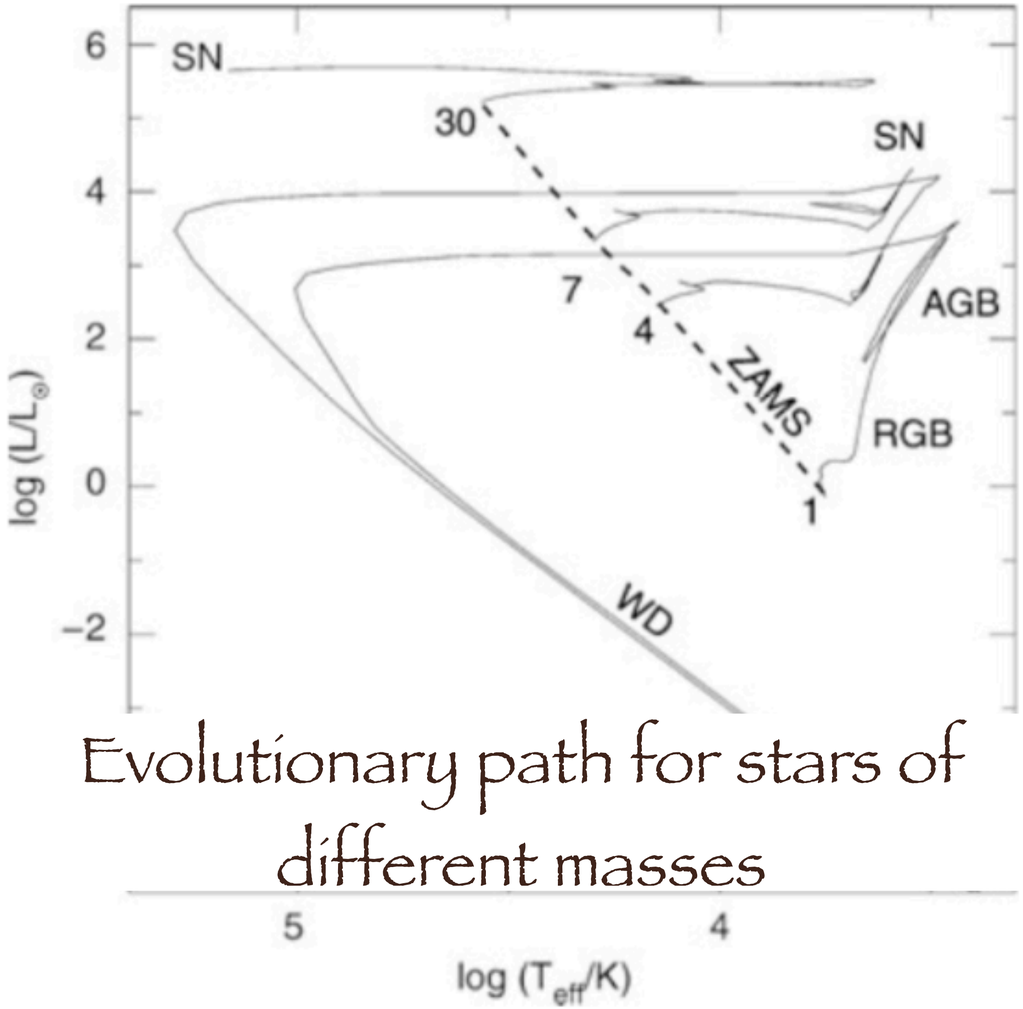




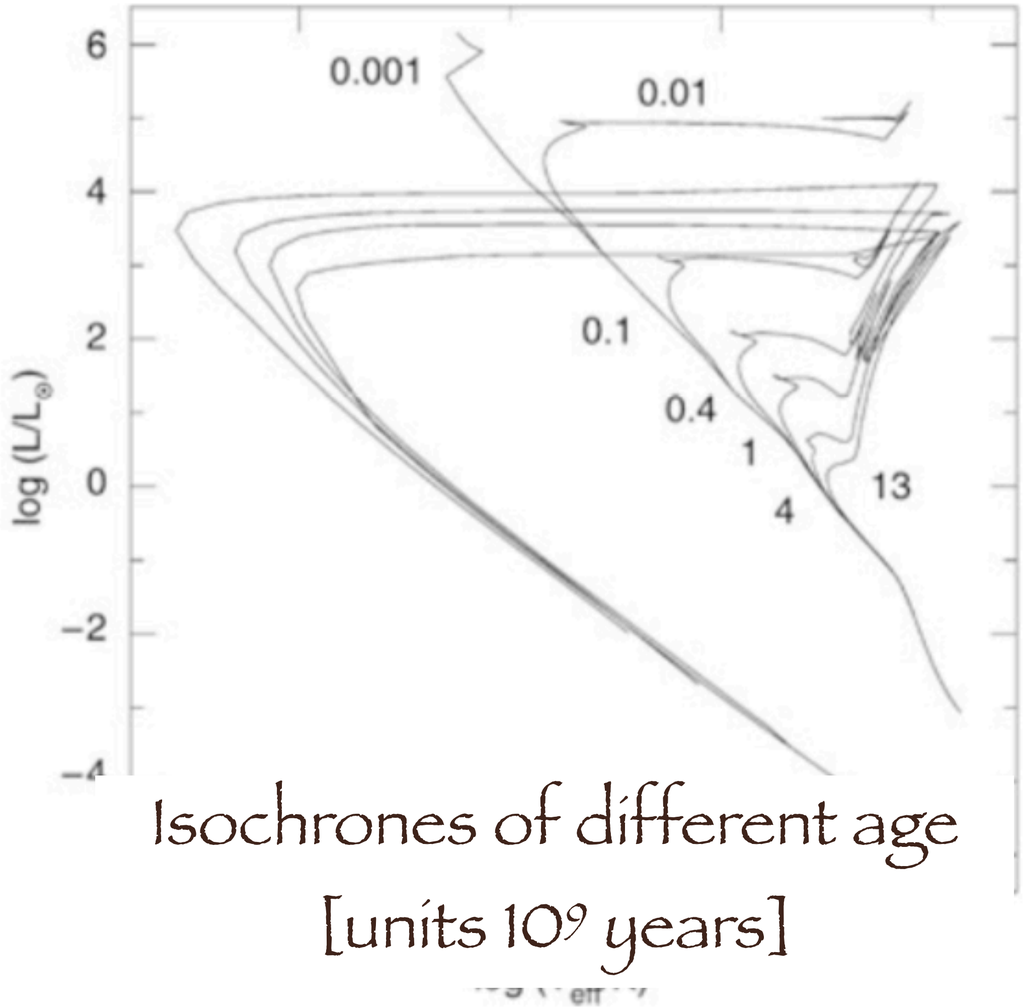
SED at zero age

Population of a fixed age

Isochrone: curve that joins the positions of stars in the HRD that have the same age

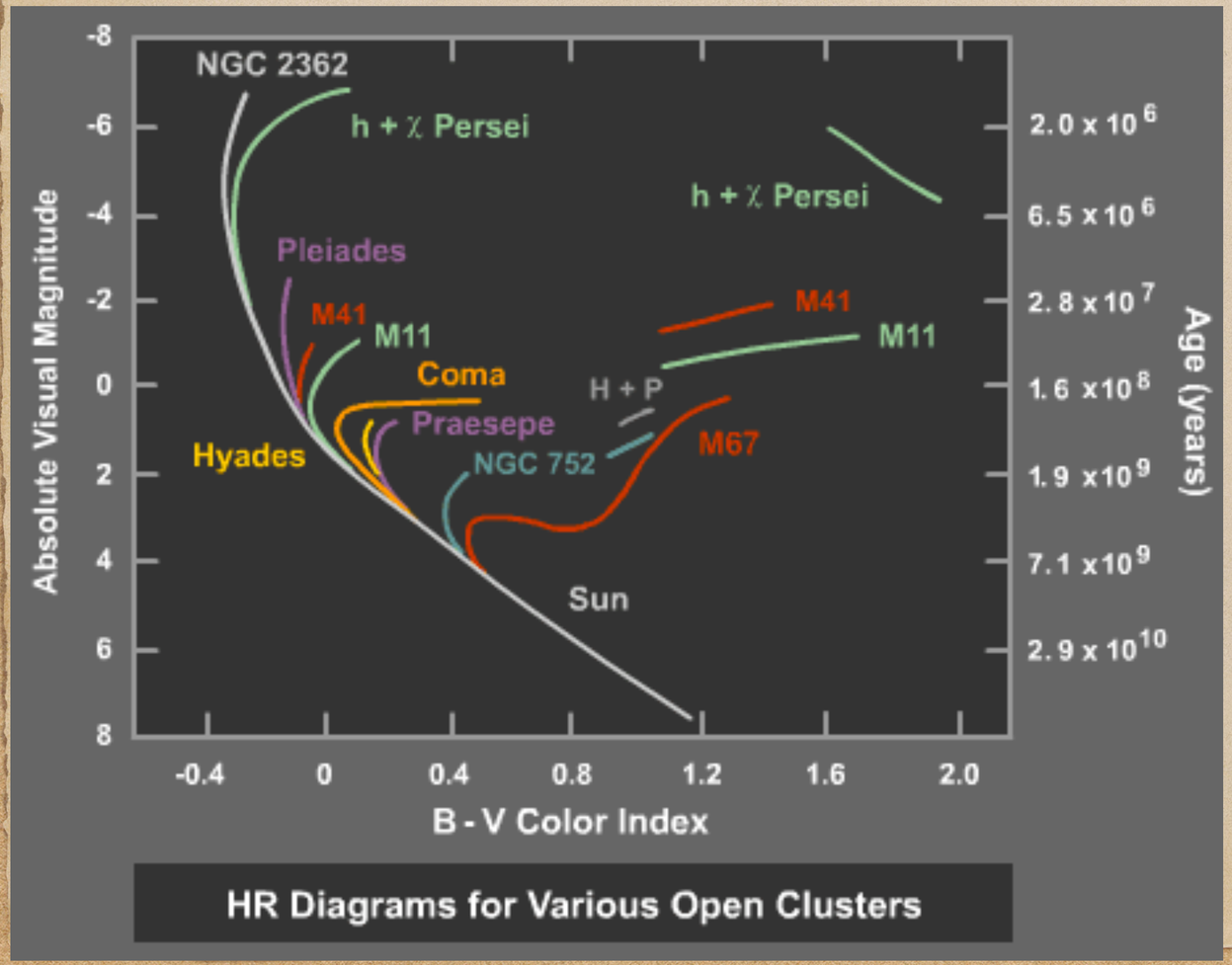


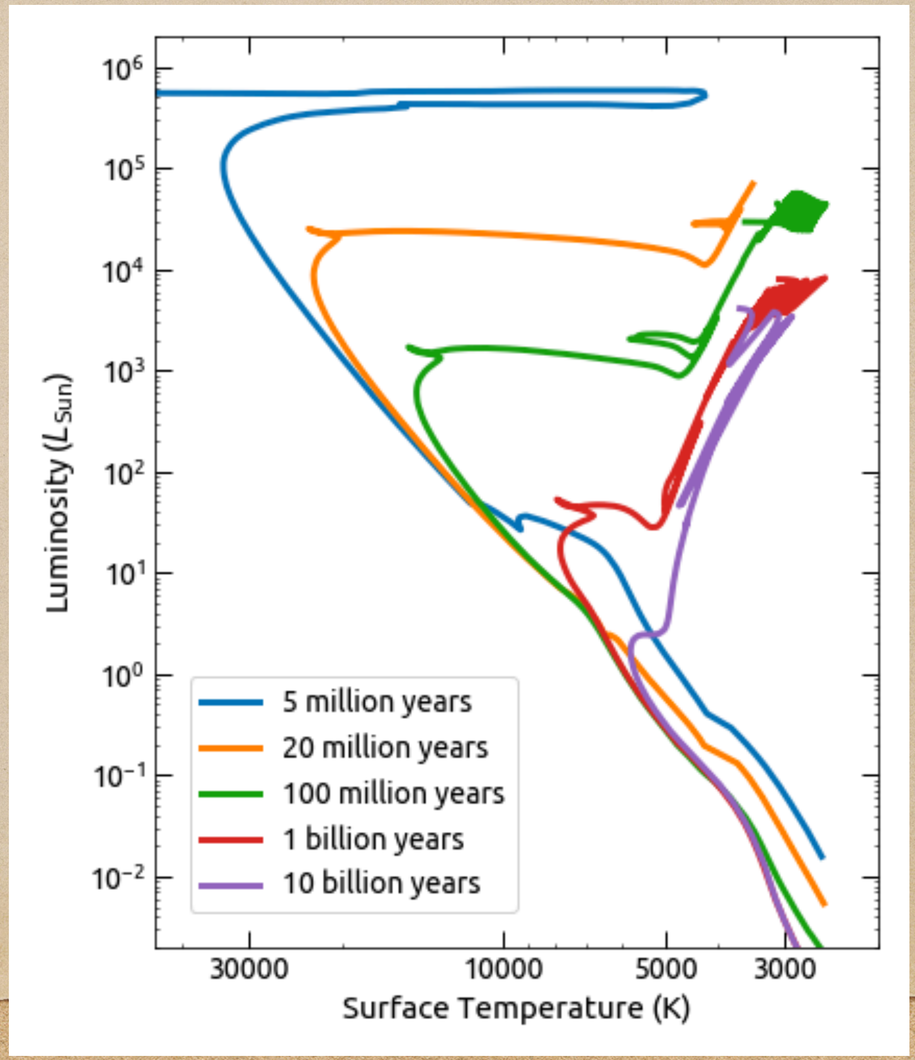
Evolutionary path for stars of different masses



Isochrones of different age [units 10^9 years]

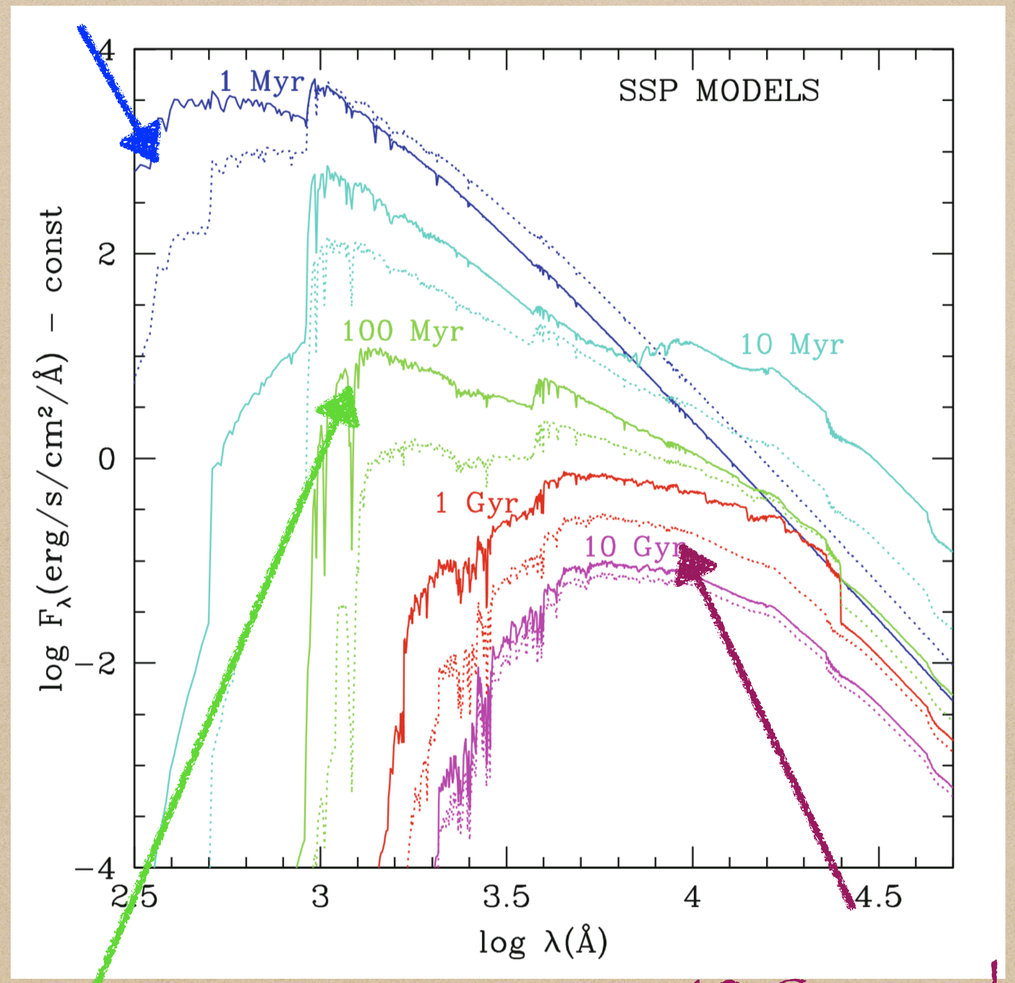
Population of a fixed age





Spectral energy distributions: Single stellar population

1 Myr: many O,B stars still in MS

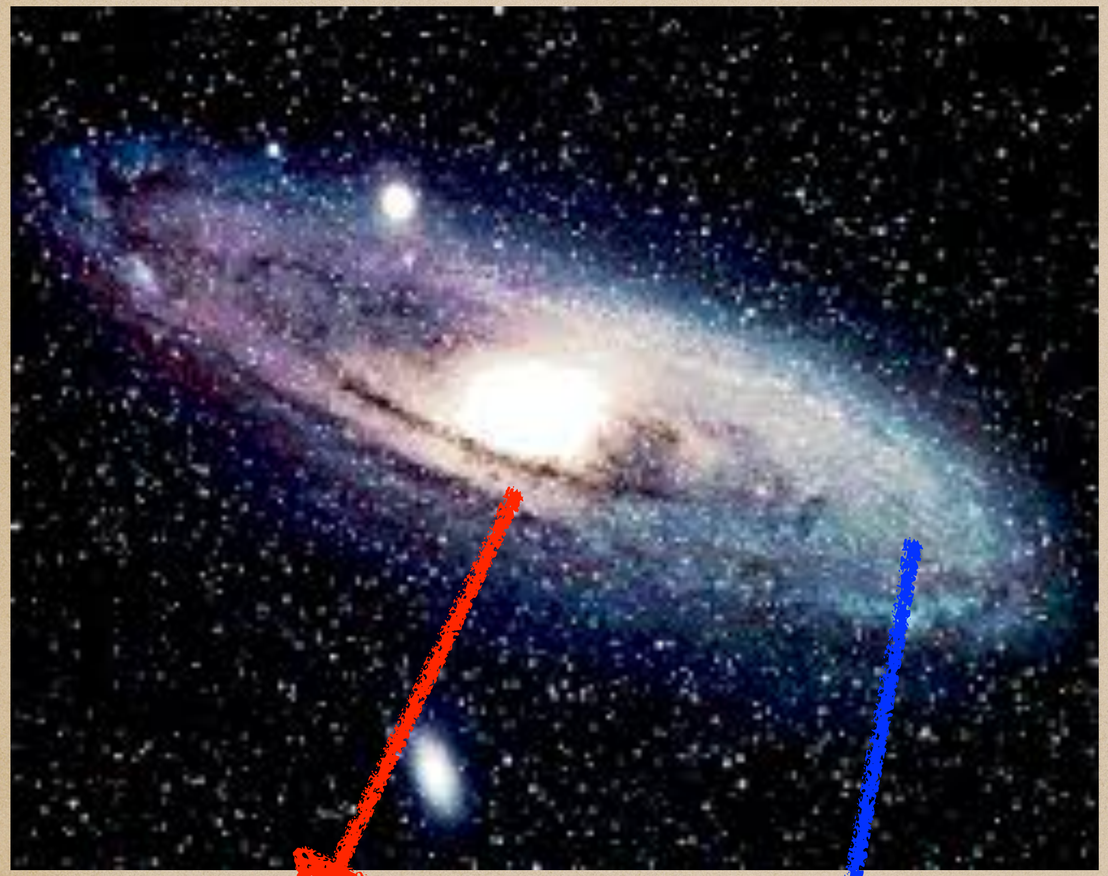


100 Myr: O,B out of MS, A, F, G, K & M stars still in MS

10 Gyr: only K, M stars in MS

- Adding the light of all the stars results in the spectral distribution of energy (SED) of a single star population (SSP, that is, the stars were all formed at the same time)
- It can be evolved over time: the most massive and blue stars gradually leave the main sequence and become red, then disappear: the total luminosity decreases
- The SEDs of an SSP become redder and redder as age increases

Real galaxies



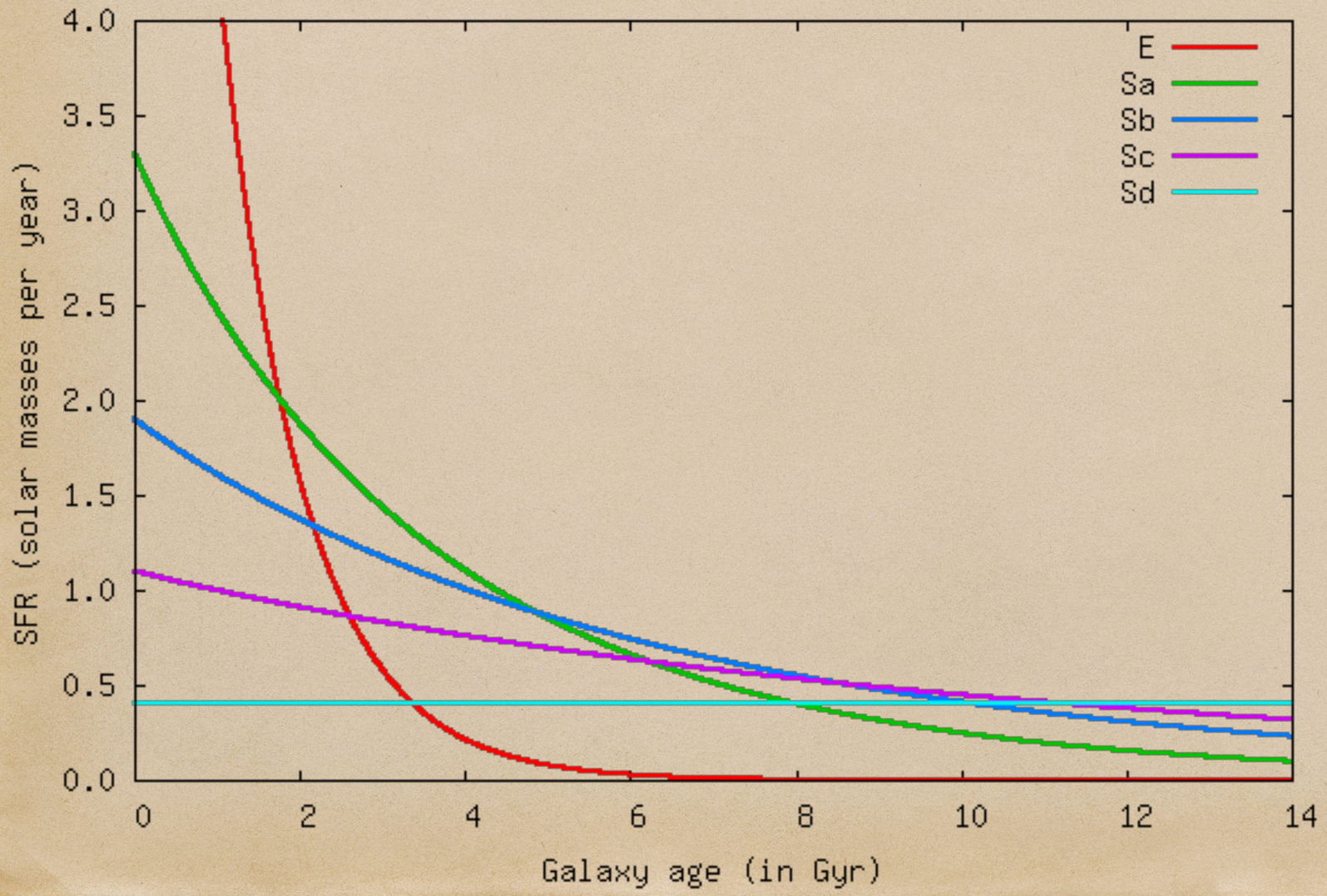
Bulge: old stars

Disk: young stars

Real galaxies are sets of stars of different ages

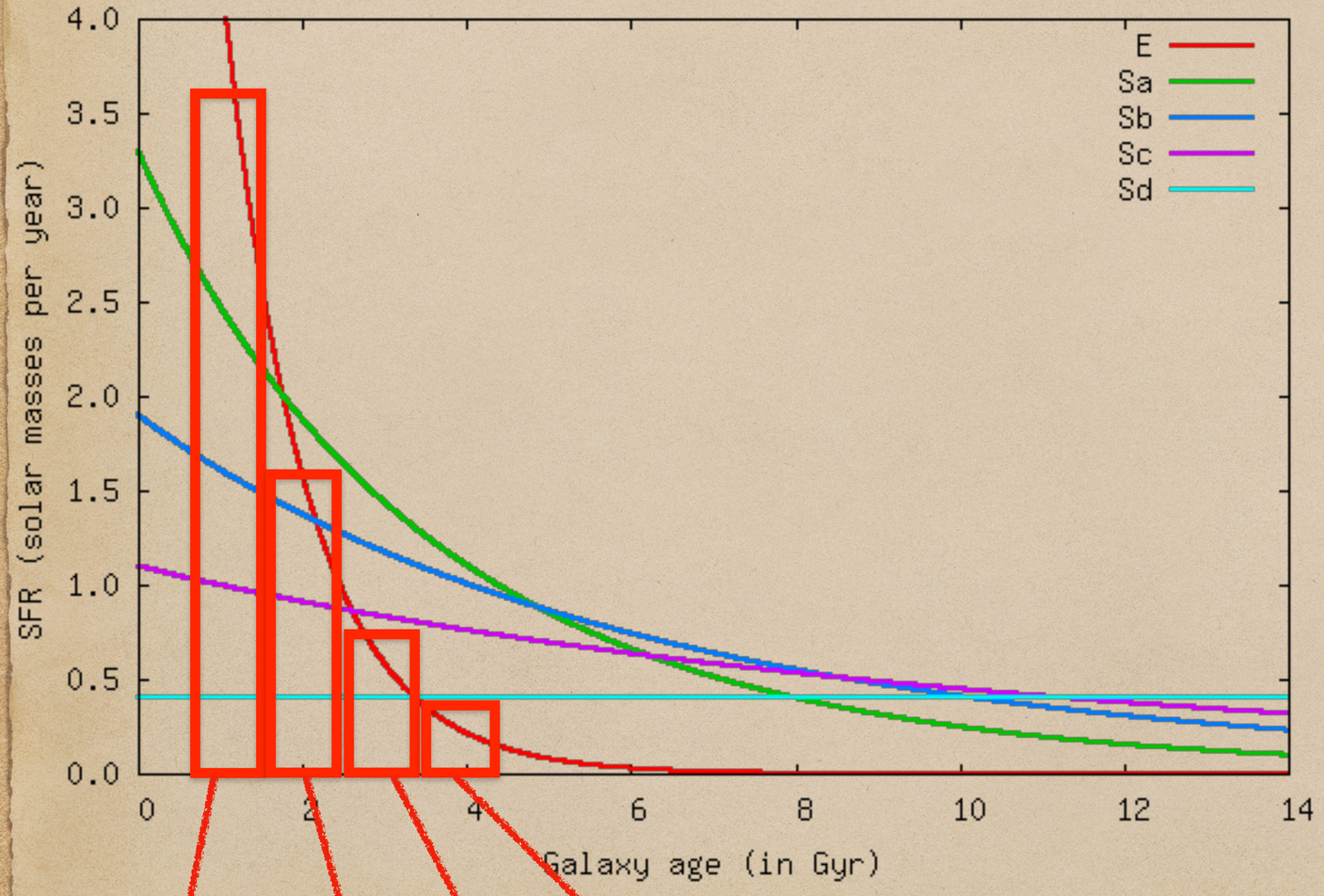
So I need to add together ***Star populations of different ages***

Composed stellar populations



- A story of star formation is assumed for each type of galaxy
- Ellipticals almost all have very old stars
- Spirals have old and young stars
- Sd spirals form stars in a constant way

Composite stellar populations

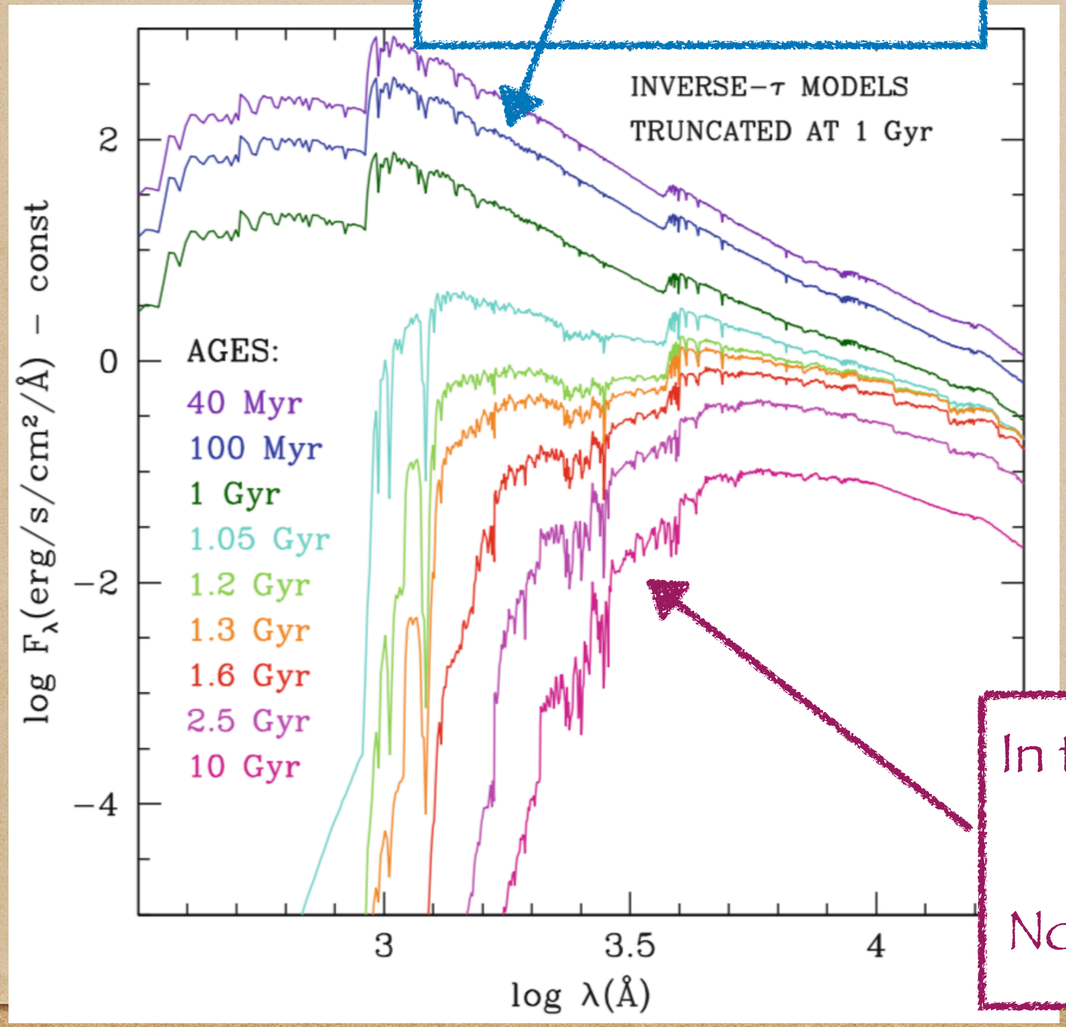


Age	1 Gyr	2 Gyr	3 Gyr	4
Weight	3.5	1.5	0.7	0.4

- They add together SED of SSP of different ages
- Each age has a weight that depends on the shape of the Star-Formation History (SFH) of that composite population

Composed stellar populations

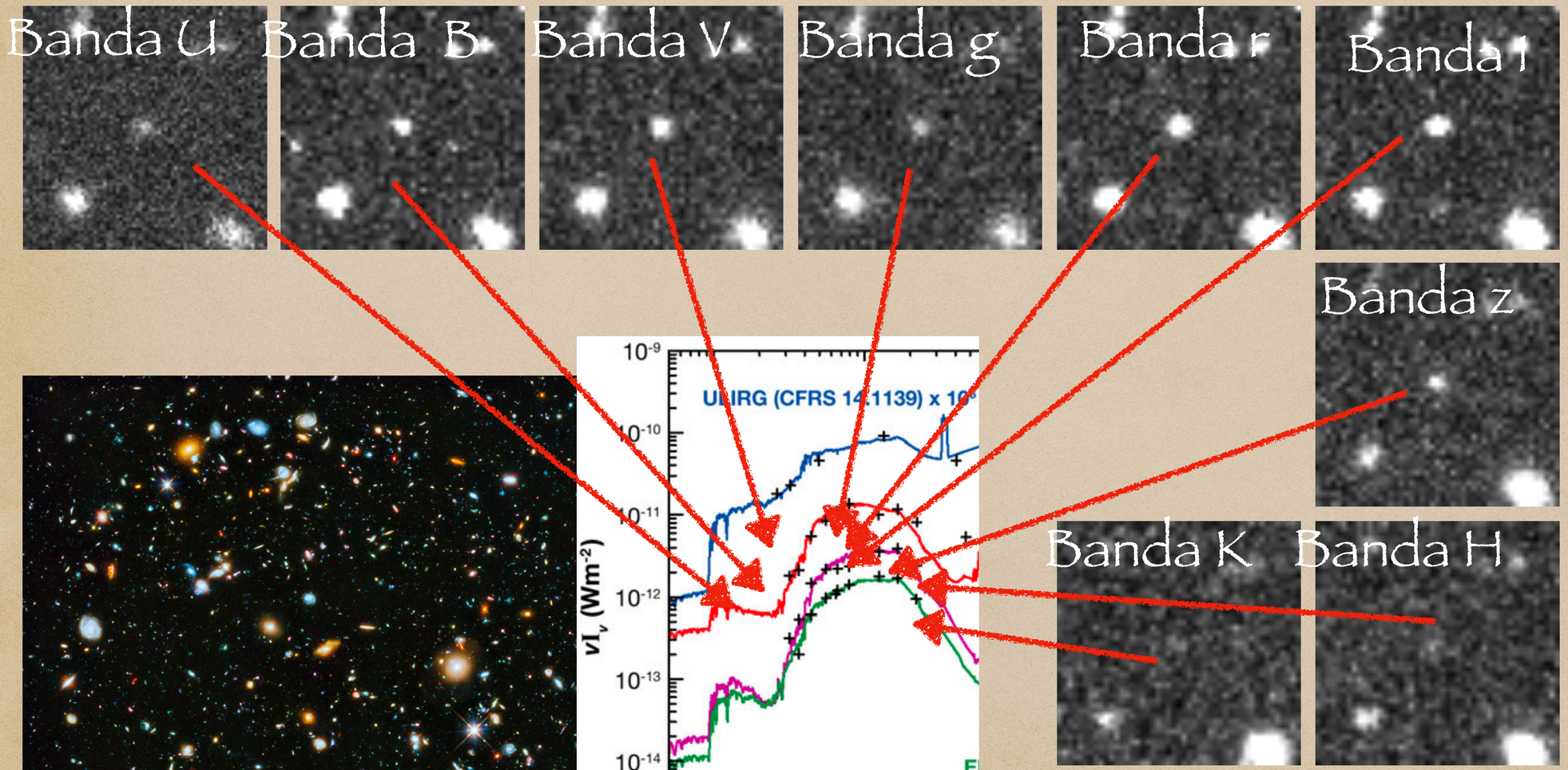
In these models there are young stars: There is recent star formation



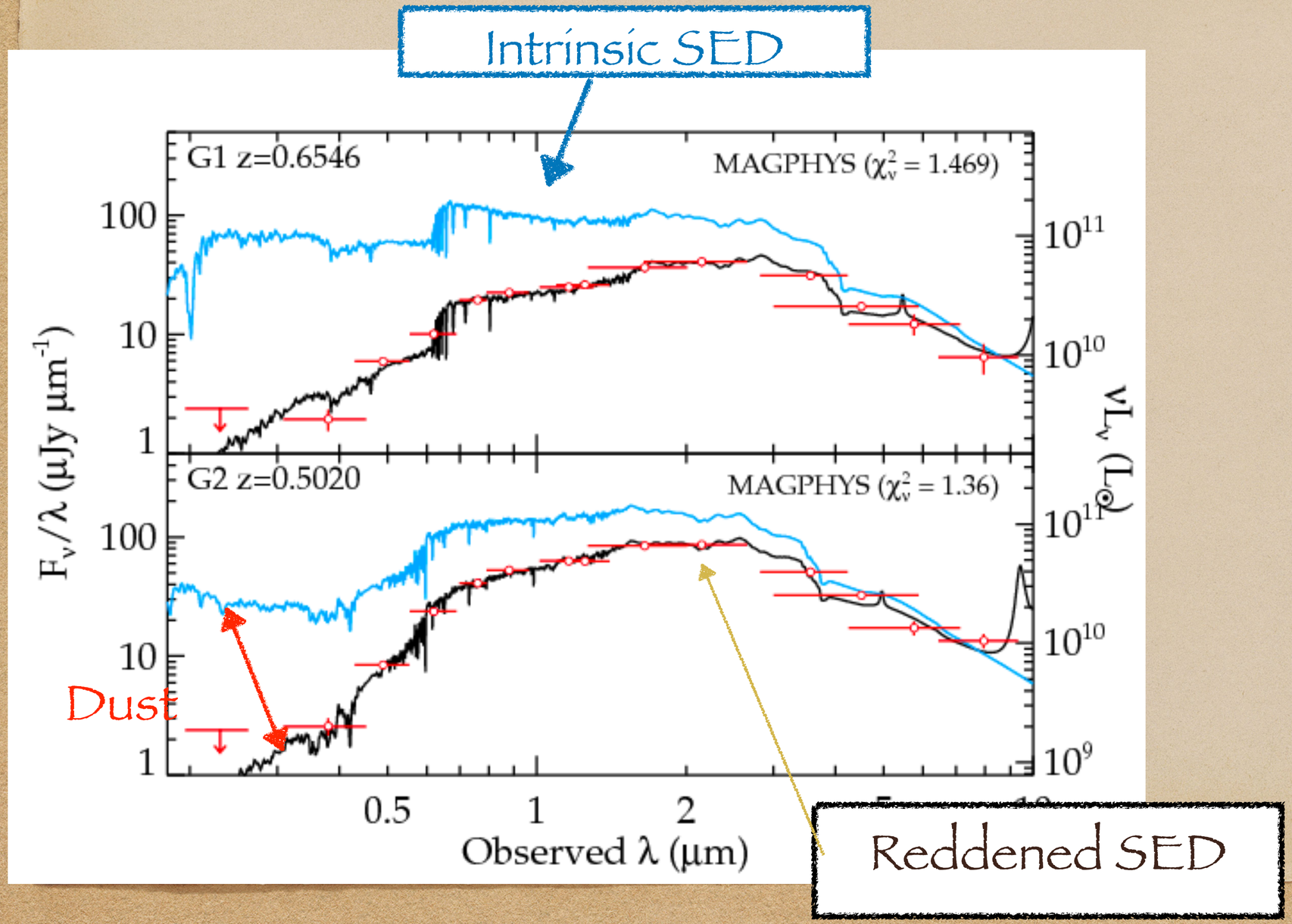
In these models there are no young stars No recent star formation

In this way you can build practically infinite combinations of galaxy SEDs, with more or less old populations compared to the young ones

Multi-band photometry

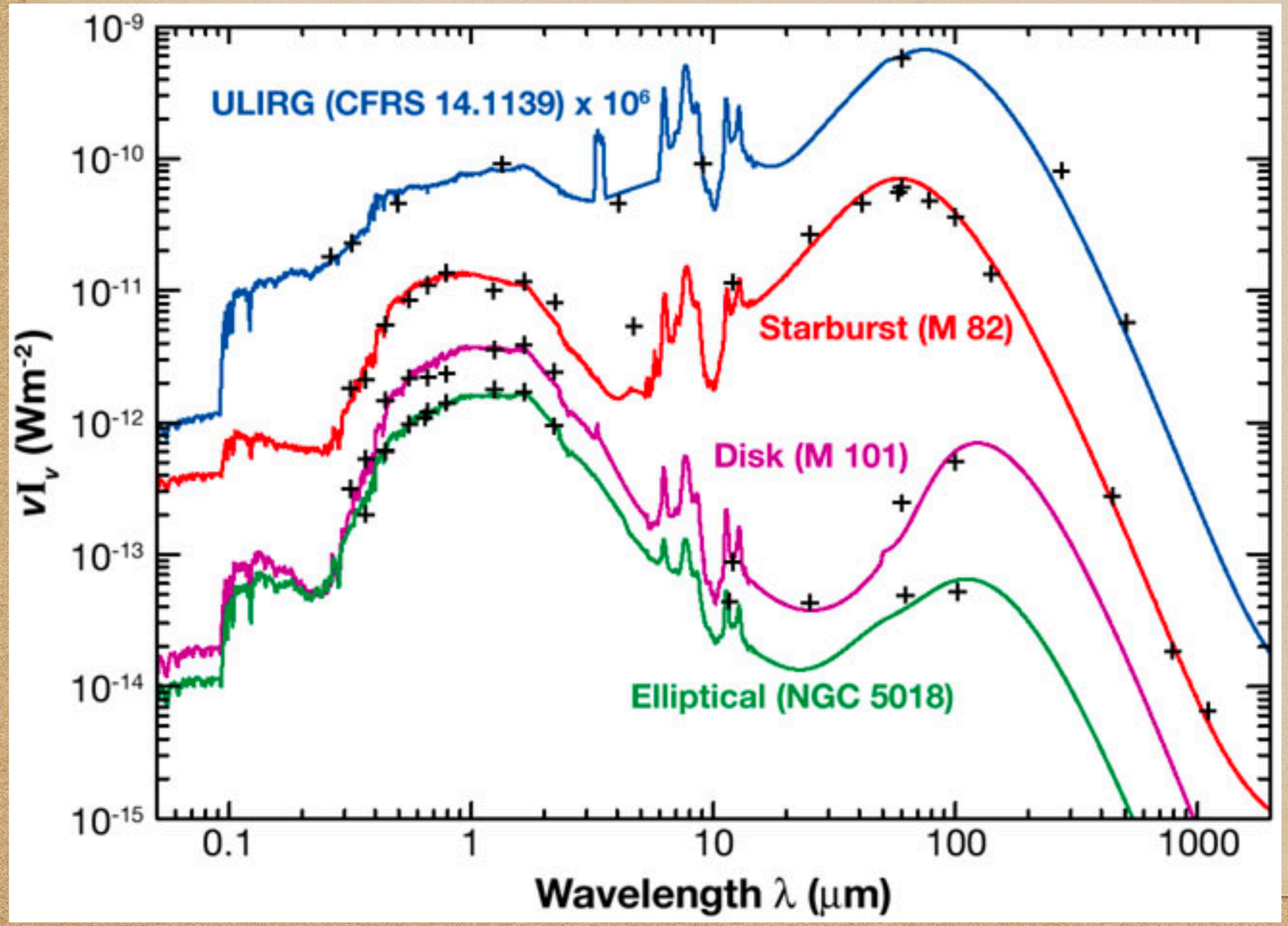


Composed stellar populations



Comparing SED of real galaxies with SED of SSP, we can go back to the total number of stars, to the t***otal mass in stars (M_*)*** and the number of young stars (***SFR, that is, how many stars are forming right now per unit of time***)

Spectral energy distributions in comparison



ULIRG: The brightest galaxies in the Universe: rich in young stars, very rich in dust

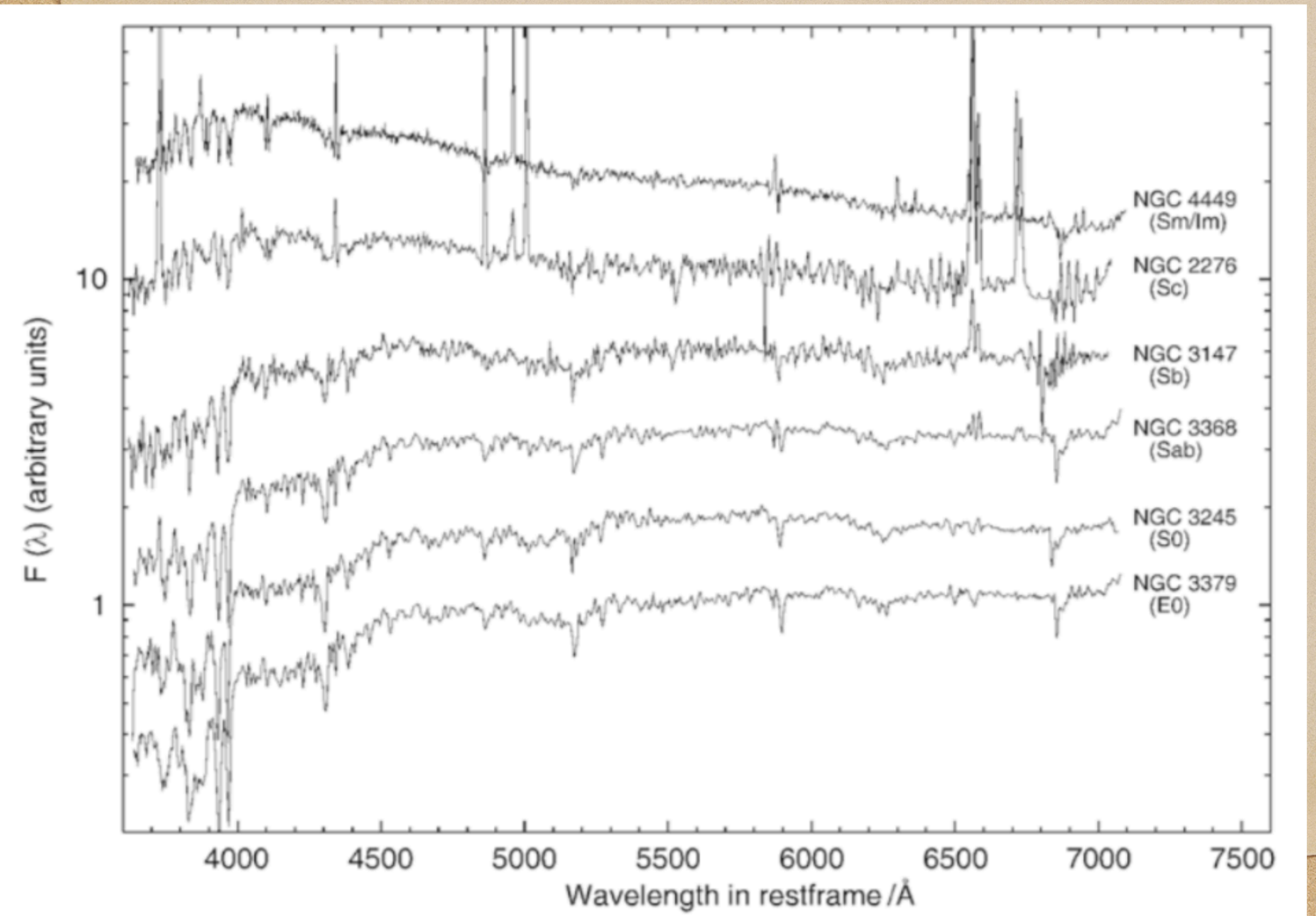
Starburst: Typically irregular galaxies in which many stars are forming right now

Disk: typical spiral galaxies, moderate SFR

Elliptical galaxy: no formation of new stars, little dust content

Galaxy spectra

Galaxy spectra give more precise indications on SFR, or metallicity (the metal content of each galaxy)



- Spiral galaxies:
- Blue spectra (slopes < 0)
- Many emission lines (formed by young stars)

Young galaxies with high formation of new stars

- Elliptical galaxies:
- Red spectra (slopes > 0)
- No emission line

Old galaxies without star formation