Astrophysics project

New insights on the first galaxies from the *James Webb* Space Telescope

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Main goals of this course

Theoretical topics :

(i) The *James Webb* Space Telescope

(ii) What is a galaxy? And what are their physical properties ?

(iii) The evolution of the Universe and the hierarchical model

Practical topics :

(i) Programming in Python

(ii) Plotting in Python

(iii) analysing large dataset

The main goal of this project: *From the deepest image obtained with the JWST, determine the distribution in luminosity of galaxies as a function of redshift, i.e. the Luminosity Function, and compare your results with previous findings from the* Hubble *Space Telescope.*

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Introduction

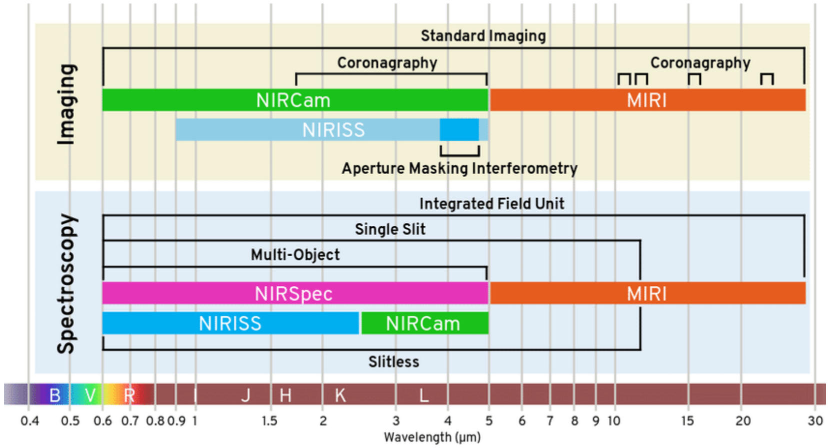
The *James Webb* Space Telescope

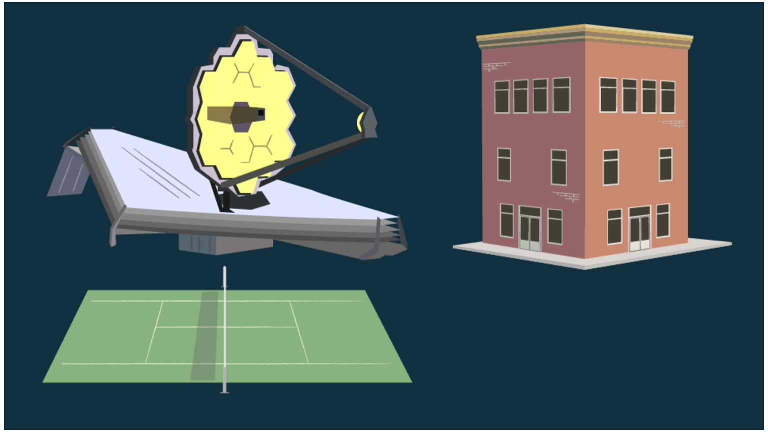
What is a galaxy ?

The *James Webb* Space Telescope (JWST)

The *James Webb* Space Telescope (JWST)

- 6.5m diameter mirror
- 4 instruments
- 3 modes : imaging, spectroscopy, coronagraph

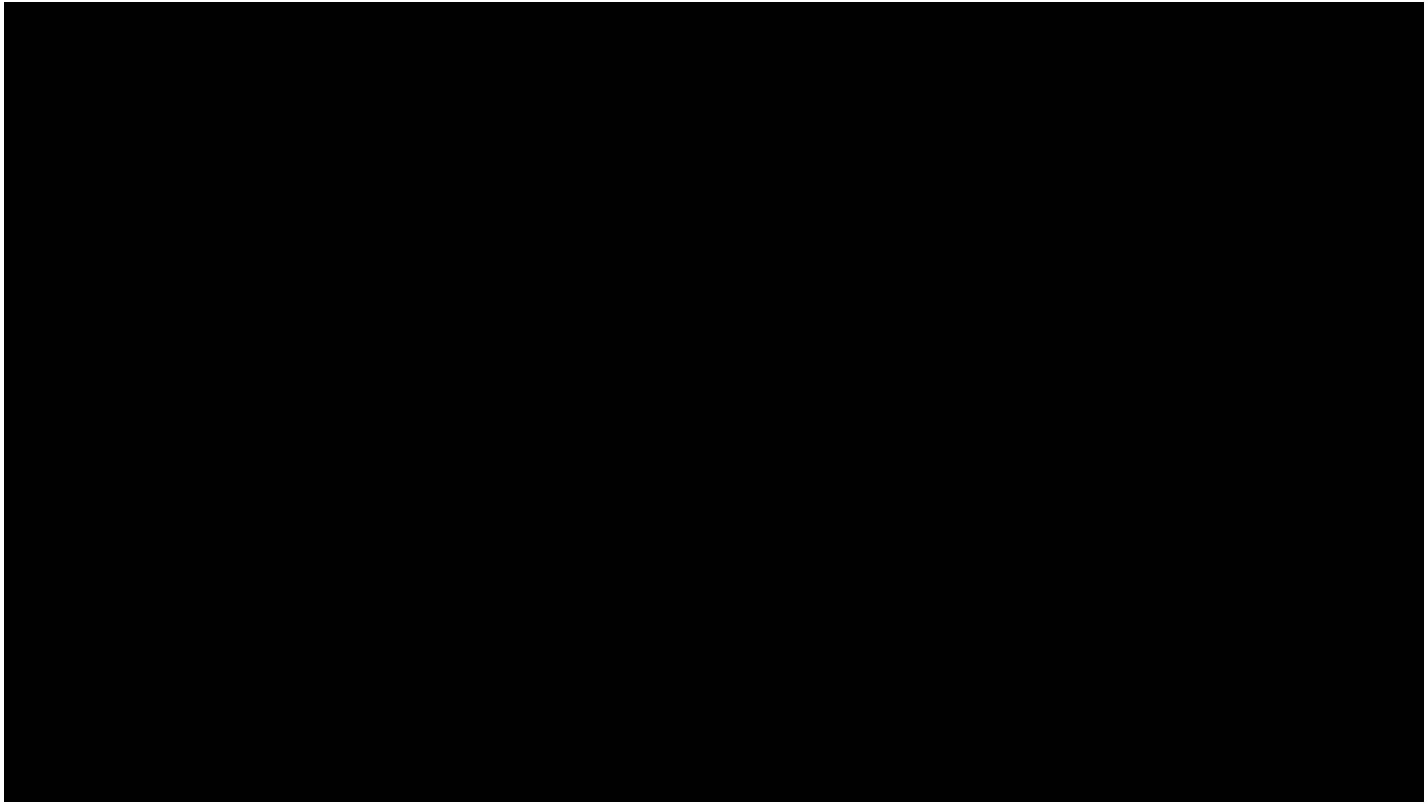




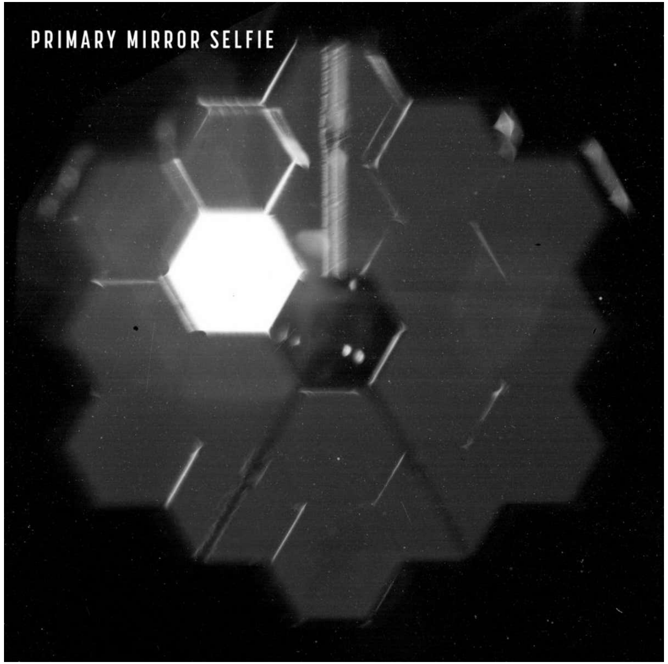
- Key questions:
  - The formation of the galaxies
  - The study of exoplanets atmospheres
  - The study of dark energy

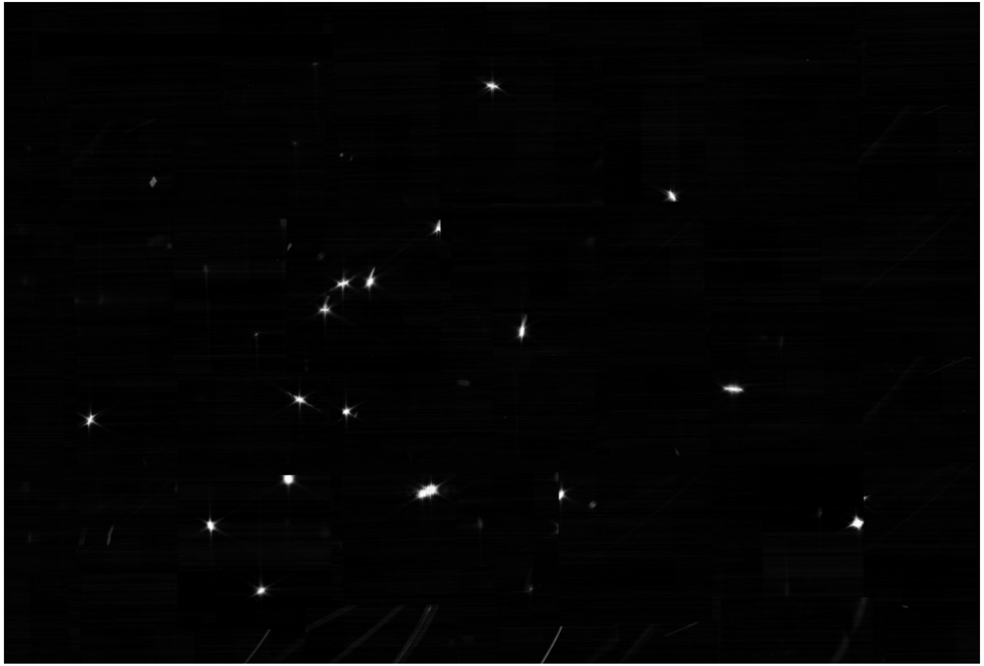
The *James Webb* Space Telescope (JWST)

The *James Webb* Space Telescope (JWST)

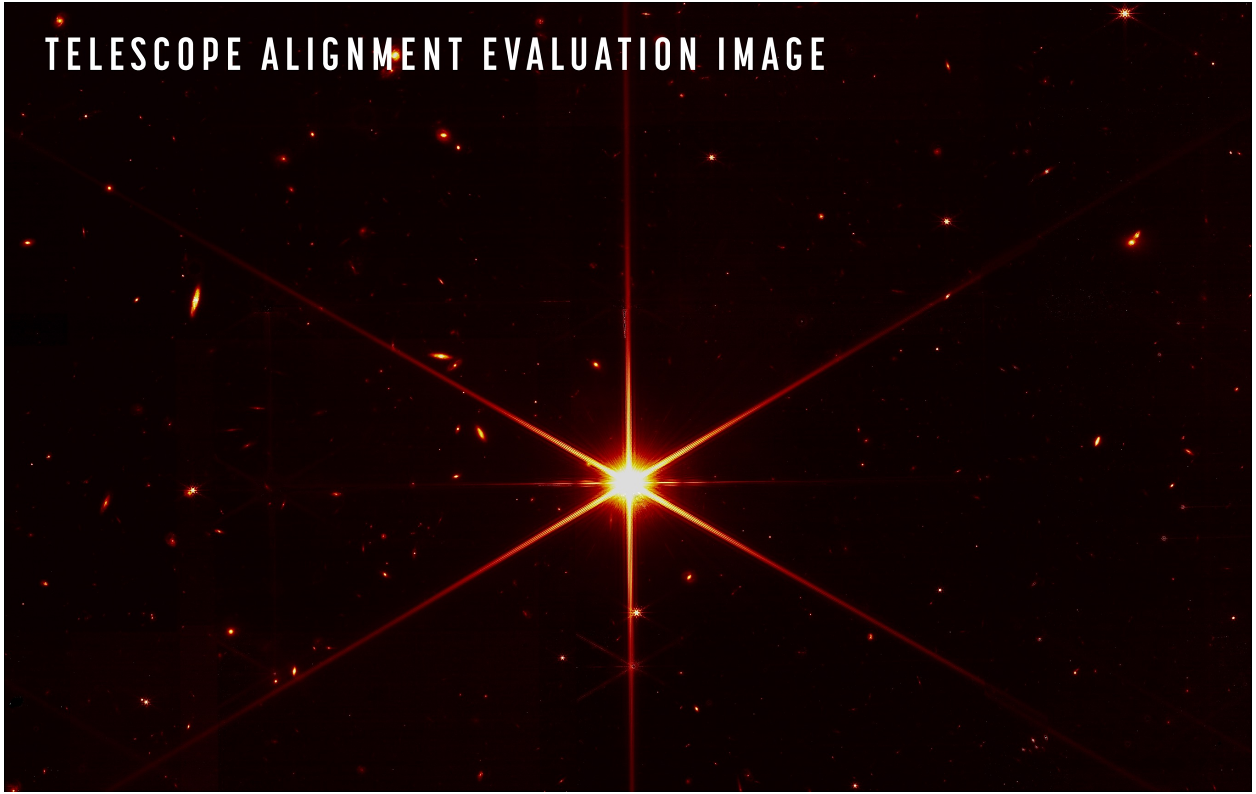


The calibration of the JWST

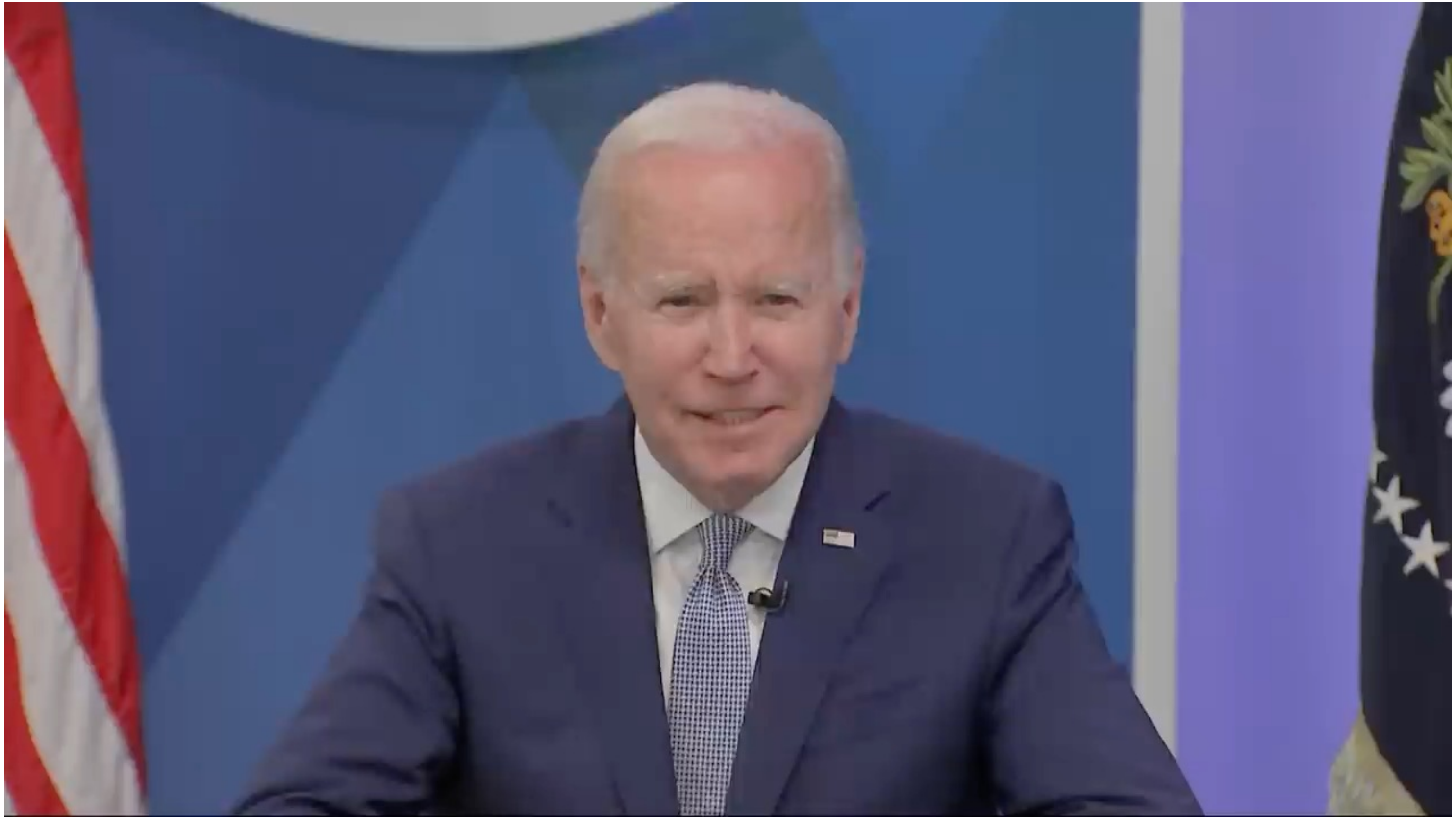




The real fist image of the JWST



12th July 2022 from the White House (US)



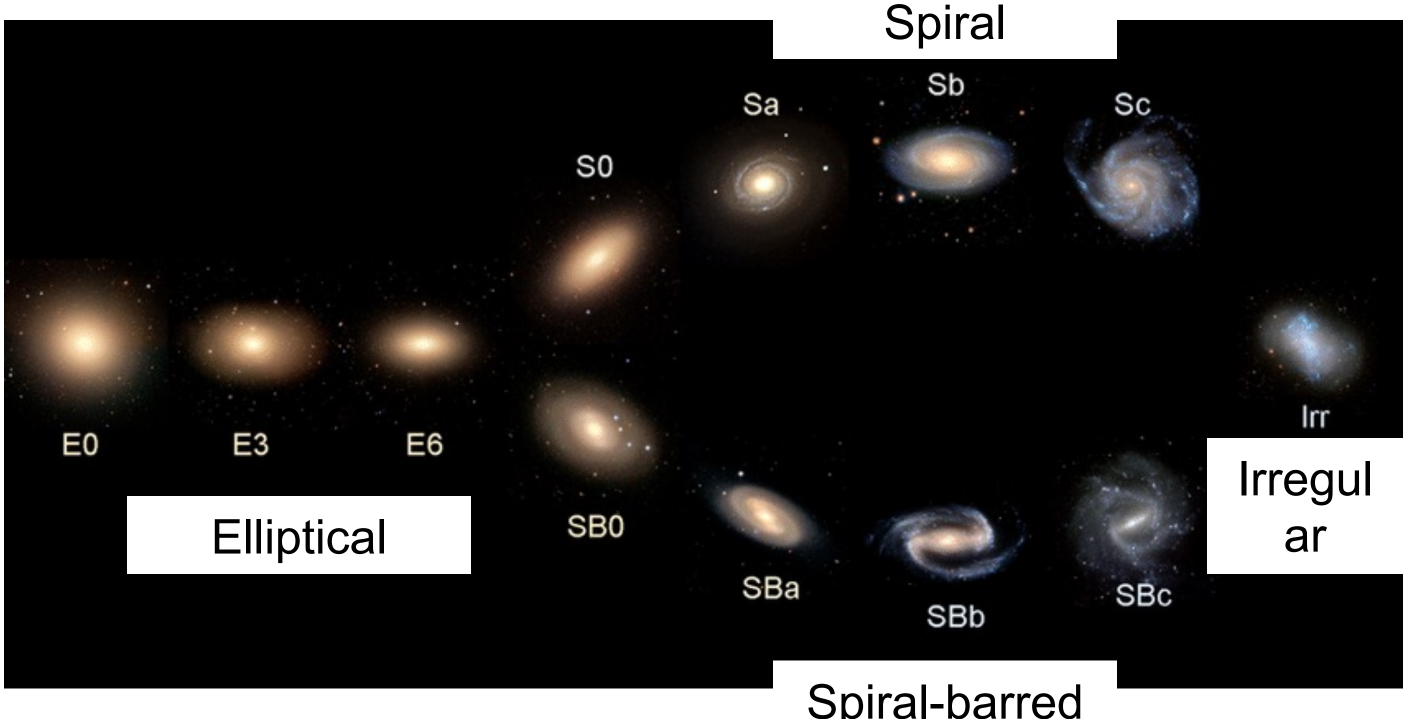
The first scientific image of the JWST

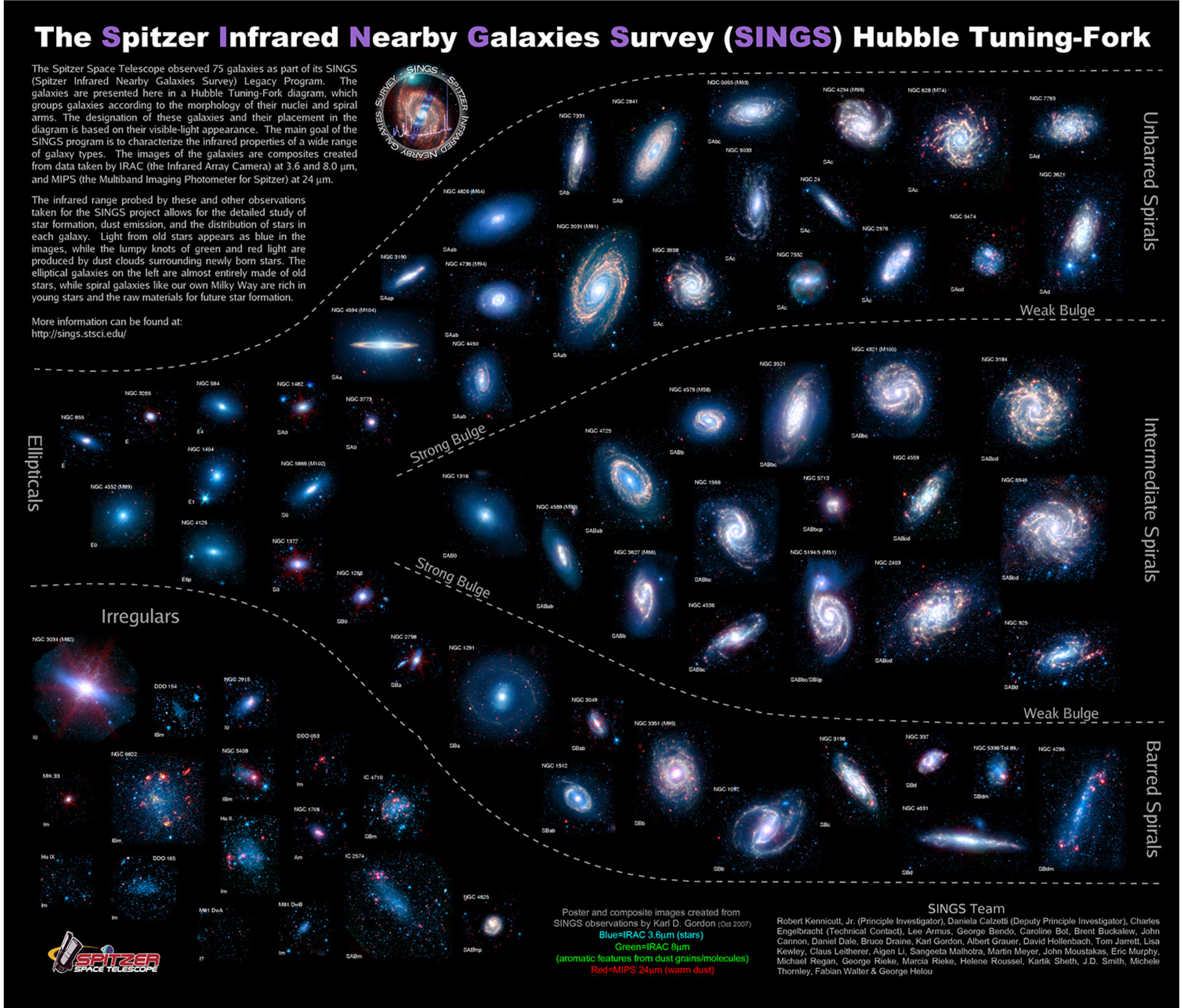
The JWST Advanced Deep Extragalactic Survey (JADES)

Properties of Galaxies in the Local Universe

THE GALAXY ZOO

Edwin Hubble
1889-1953



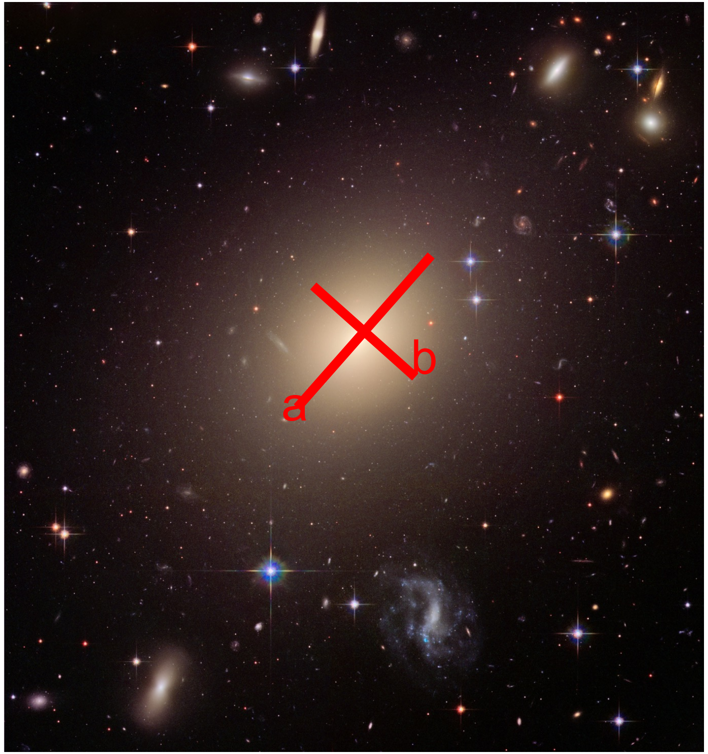

The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm.
The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.
More information can be found at:
http://sings.stsci.edu/
SINGS - SPITZER INFRARED NEARBY GALAXIES SURVEY
Unbarred Spirals
Weak Bulge
Strong Bulge
Intermediate Spirals
Strong Bulge
Weak Bulge
Barred Spirals
Ellipticals
Irregulars
Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou
SPITZER SPACE TELESCOPE

Properties of Galaxies in the Local Universe

ELLIPTICALS / EARLY TYPE GALAXIES

The elliptical galaxies are classified following the ratio between their major (a) and minor (b) axis, and named E_n with n :

$$n = 10\ \frac{a-b}{a}$$



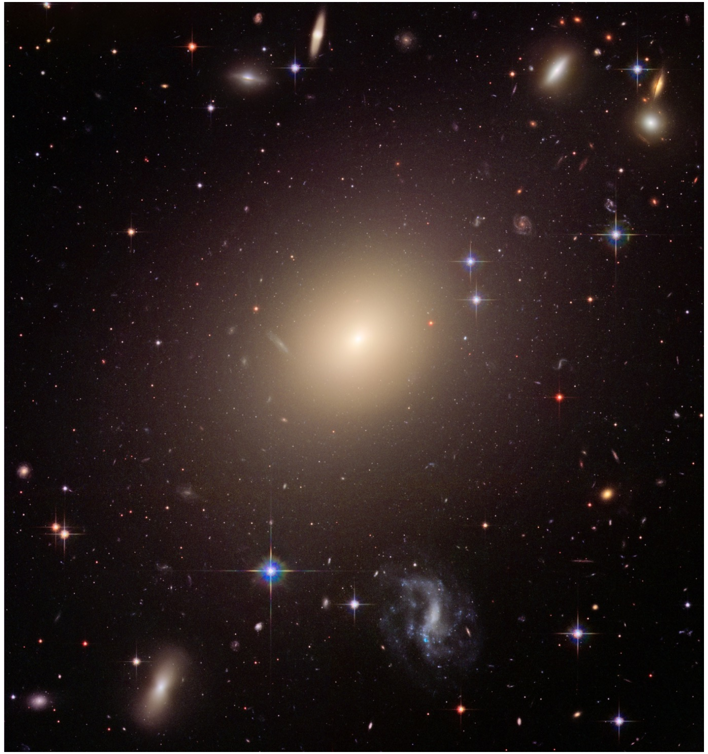
Properties of Galaxies in the Local Universe

ELLIPTICALS / EARLY TYPE GALAXIES

The main properties of ellipticals are :
- Gas poor
- No star formation
- Old stars
- Stellar mass ranging between 10^{11} and 10^{13} $M_{\odot}$

The surface brightness of an elliptical galaxy is given by :

$$I(R) = I_0 \exp\left[-\left(\frac{R}{a}\right)^{\frac{1}{4}}\right]$$



Properties of Galaxies in the Local Universe

SPIRALS / LATE TYPE GALAXIES

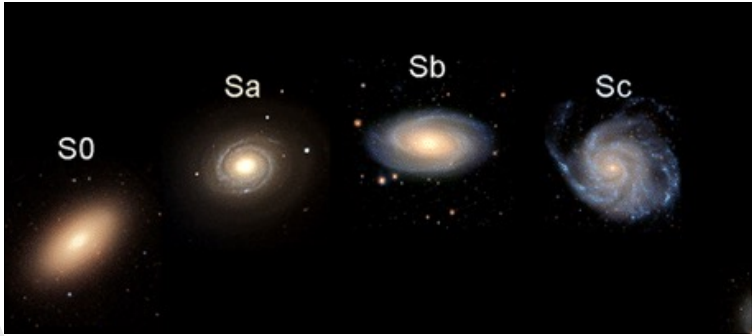
A spiral galaxy is always composed of a bright bulge and a disk

Properties of Galaxies in the Local Universe

SPIRALS / LATE TYPE GALAXIES

The classification of spirals galaxies depends on the openness of arms and the prominence of the bulge.

From Sa to Sc : the openness of the arms increases, and the bulge prominence decreases.



Properties of Galaxies in the Local Universe

SPIRALS / LATE TYPE GALAXIES

The classification of spirals galaxies depends on the openness of arms and the prominence of the bulge.

From Sa to Sc : the openness of the arms increases, and the bulge prominence decreases.

The main properties of spirals are :

- Gas rich
- star formation on-going
- Gas in both low density neutral hydrogen and dense molecular hydrogen
- The fractional mass of neutral hydrogen to the total is <0.03 for a Sa, and goes up to 0.1 for a Sc

$$f_{HI} = \frac{M_{HI}}{M_{tot}}$$

Properties of Galaxies in the Local Universe

SPIRALS / LATE TYPE GALAXIES

We can refine the classification by adding :
- The presence of a ring (r)
- The definition of the arms : from well defined 'I' to fuzzy 'V'

SBb(r)III

Properties of Galaxies in the Local Universe

SPIRALS / LATE TYPE GALAXIES

To describe the brightness profile of a spiral (or spiral-barred) galaxy, we need to consider the two components : the disc and the bulge.

A spiral seen face-on has a light profile given by :

$$I(r) = I_0 \exp\left(-\frac{r}{a}\right)$$

The overall distribution of mass in the disc is given by :

$$\rho(r, z) = \rho_0 \exp\left(-\frac{r}{a}\right) \exp\left(-\frac{|z|}{h}\right)$$

<u>Scale height</u> : the height at which the density falls of by a factor *e*

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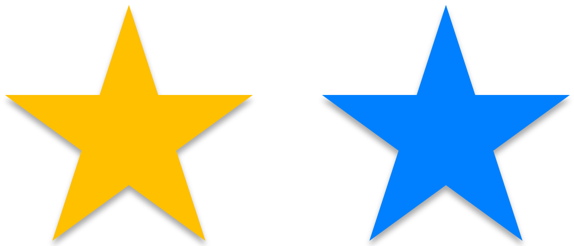
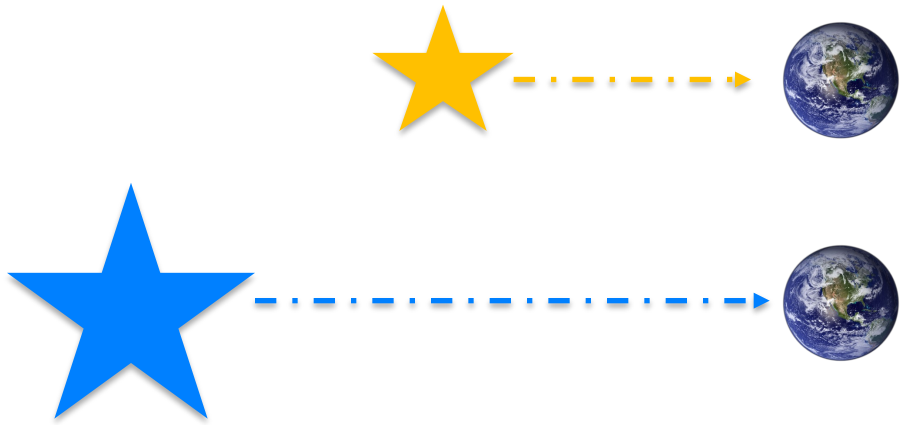
The physical properties of galaxies

Magnitudes

The luminosity of a galaxy

The luminosity of a galaxy





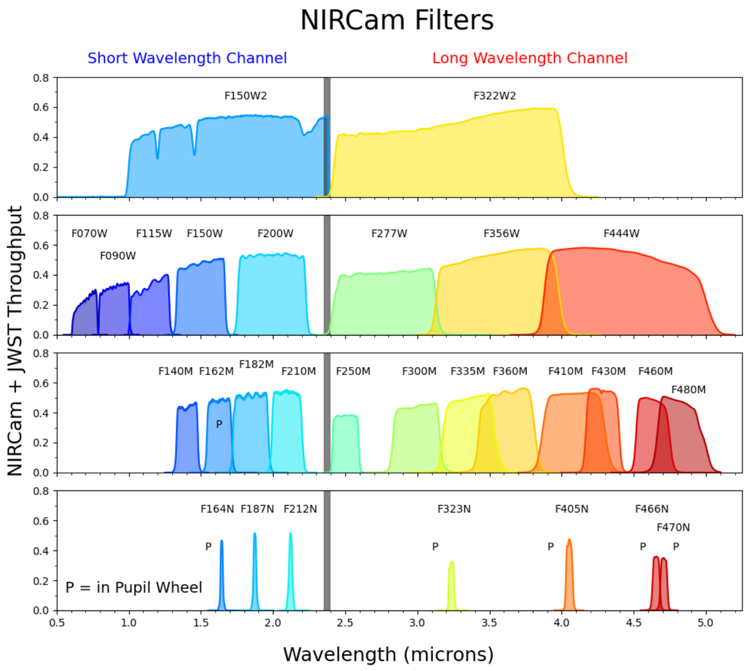
View on Sky

Apparent Luminosity

Taking into account the distance

Intrinsic Luminosity

The luminosity of a galaxy



Transmission of JWST filters

The apparent magnitude of a galaxy is always measured in a filter, i.e. within a given wavelength.

The flux is converted into a magnitude as follow :

$$m_\lambda^{obs} = ZP - 2.5\times \log_{10} f_\lambda$$

ZeroPoint

Flux measured within a filter

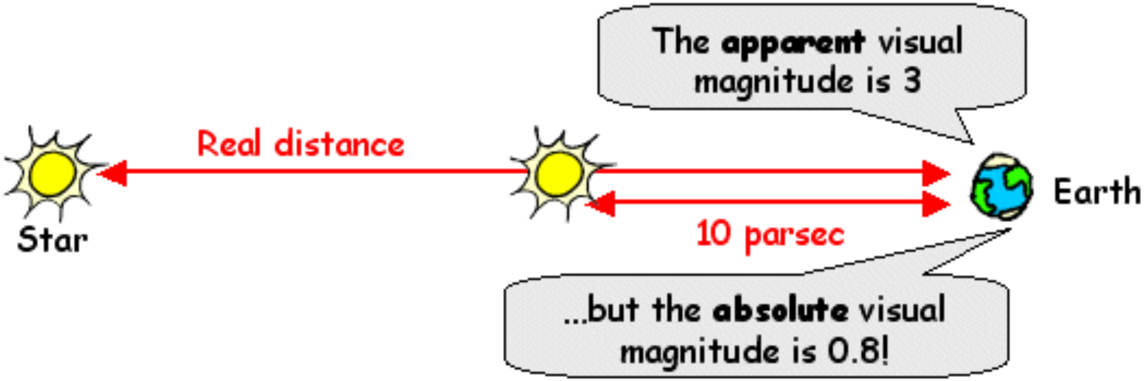
The AB magnitude system

$$m_{AB} = 23.9 - 2.5\times log_{10}(f\,[\mu Jy])$$

The luminosity of a galaxy

To compare the intrinsic luminosity of a galaxy, one has to estimate the absolute magnitude of a galaxy

By definition, the absolute magnitude of a galaxy is the magnitude a galaxy would have *if it were located at 10pc from the Earth*



The luminosity of a galaxy

The relation to compute the absolute luminosity of a galaxy is given by :

Luminosity in erg/s/cm^2/Hz

$$M_\nu = -48.6 - 2.5 \times \log_{10}\left(\frac{L_\nu}{4\pi d_L^2}\right)$$

Absolute magnitude

The distance (10pc)

The luminosity of a galaxy

Object	Apparent magnitude	Absolute magnitude
Sun	-26.8	4.83
Alpha Centuri	-0.3	4.1
Rigel	0.14	-7.1
Deneb	1.26	-7.1
Andromeda Galaxy	3.44	-20.6

First hands-on session

- Use the JWST archive to download a catalog of sources
- Using **Python**, plot the luminosity distribution of all sources

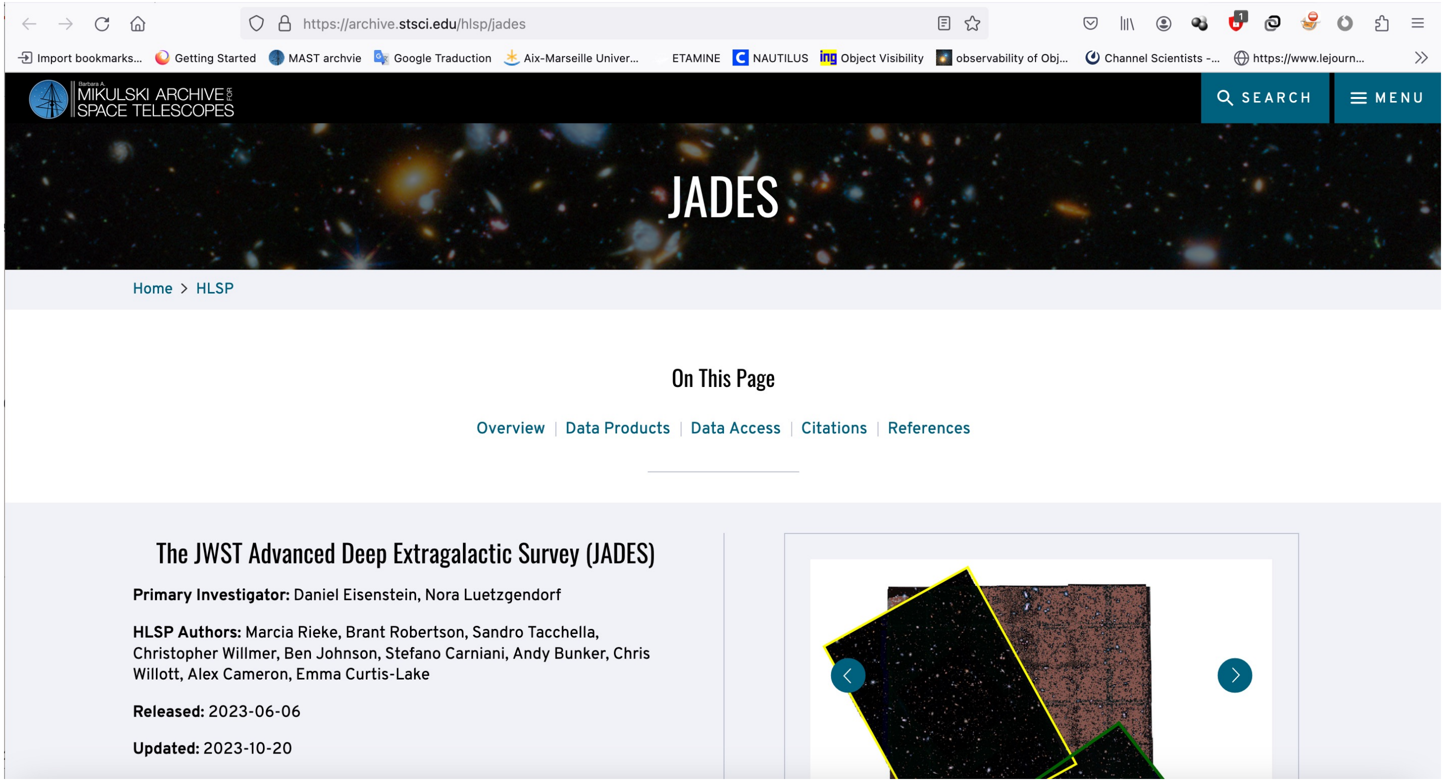
The JWST archive

https://archive.stsci.edu/

Click on “High Level Science Product”

Search for JADES

The JWST archive



The JWST archive

Barbara A. MIKULSKI ARCHIVE FOR SPACE TELESCOPES

SEARCH MENU

Catalogs
Type
NIRCam Photometry
NIRSpec Clear-Prism Line Fluxes
NIRSpec Gratings Line Fluxes

Citations

Please remember to cite the appropriate paper(s) below and the DR1 DOI and/or DR2 DOI if you use these data in a published work. If you use the Photometric Catalog please also reference the JEMS DOI .

Note: These HLSP data products are licensed for use under CC BY 4.0.

TOP

References

Bunker, A. et al. 2023	Eisenstein et al. 2023	Hainline et al. 2023
		JADES Photometric Redshifts

The Jupyter Notebook software

https://jupyter.org/

Install

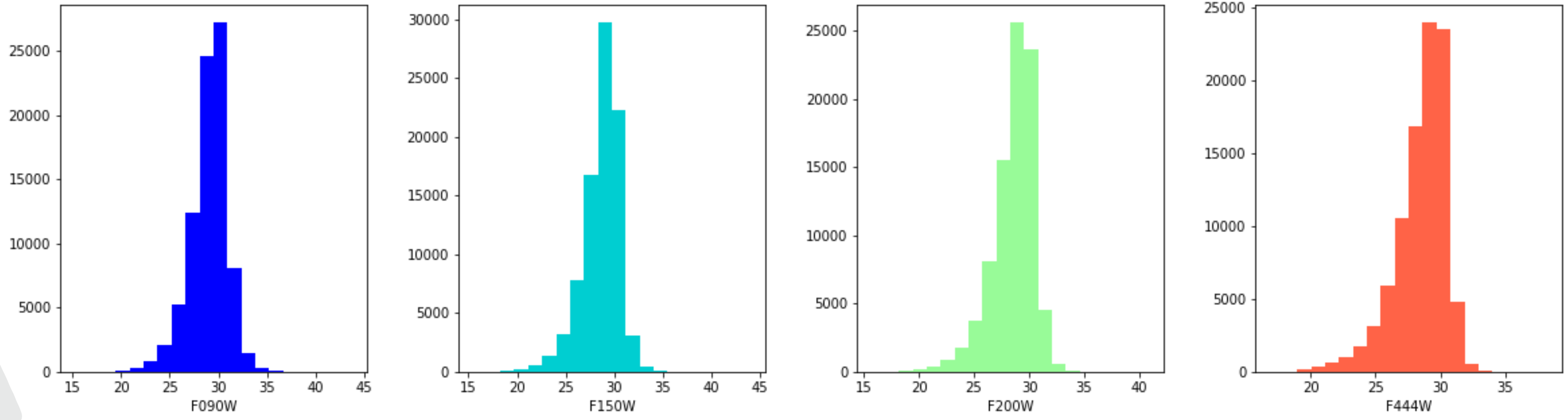
brew install jupyterlab

Python's package to install : numpy, astropy, matplotlib

Magnitudes distribution of the JADES catalogue

In the JADES catalog, fluxes are in nJy

If an object is not detected its flux is set to $f \leq 0$

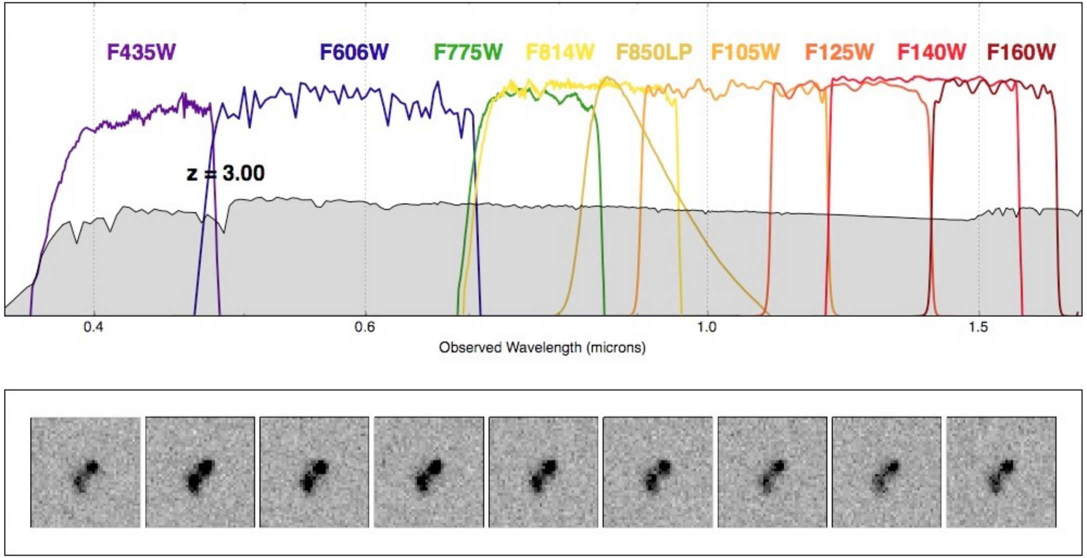


The physical properties of galaxies

Redshifts

Luminosity Function

The redshift



Properties of Galaxies in the Local Universe

THE GALAXY LUMINOSITY FUNCTION

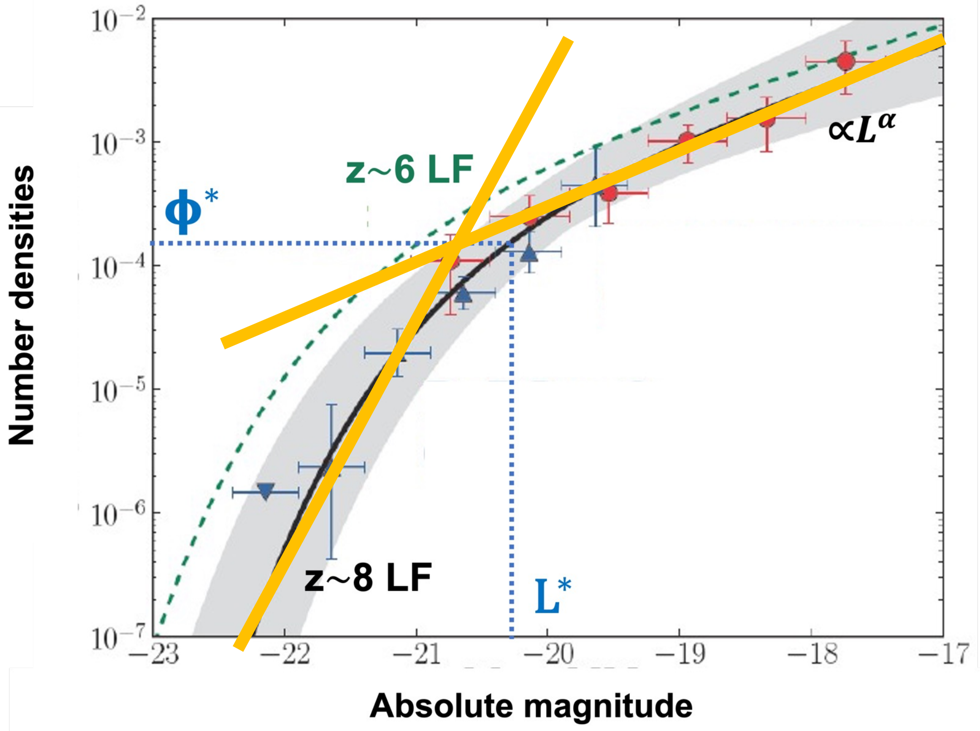
The galaxy Luminosity Function is the distribution in luminosity of the number density of galaxies at a given redshift. Its form has been described empirically by Schechter (1976) :

$$\Phi\left(\frac{L}{L^*}\right) d\left(\frac{L}{L^*}\right) = \Phi^*\left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) d\left(\frac{L}{L^*}\right)$$

which can be written as :

$$\Phi(x)dx = \Phi^* x^{\alpha} e^{-x} dx$$

Where Φ^* and L^* are the density and luminosity where there is a change in the shape of the function, and α is the slope at the faint-end.



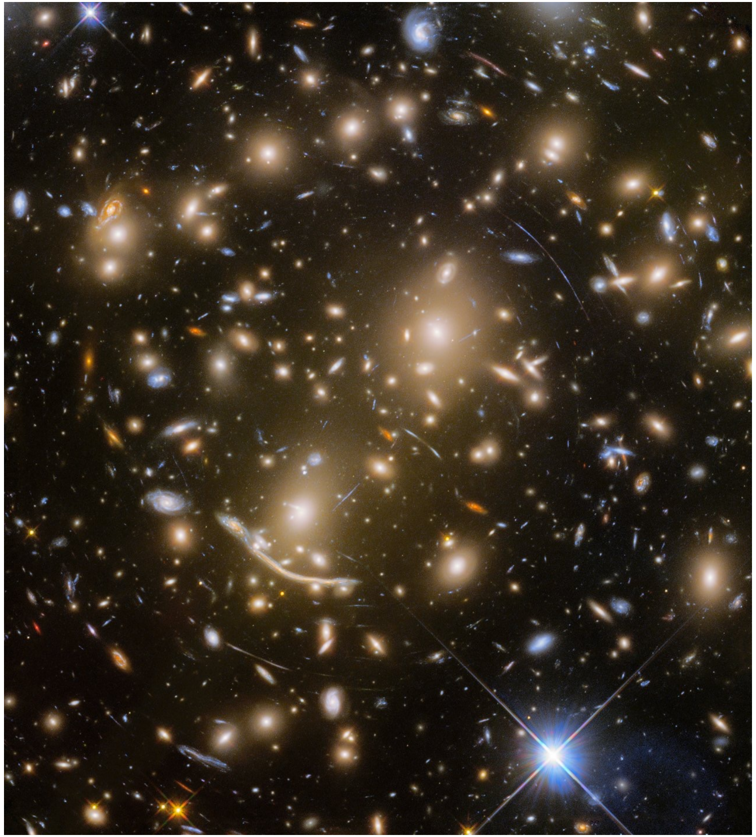
Properties of Galaxies in the Local Universe

THE GALAXY LUMINOSITY FUNCTION

To measure the LF, we need a photometric survey with a redshift for each detected galaxy.

One can naively say that the number of galaxies per given luminosity is the number density of galaxies $\Phi(L)$. This is not the case because of the *Malmquist* bias (preferential detection of intrinsically bright galaxies).

We need to correct this effect to obtain an unbiased determination of the LF.

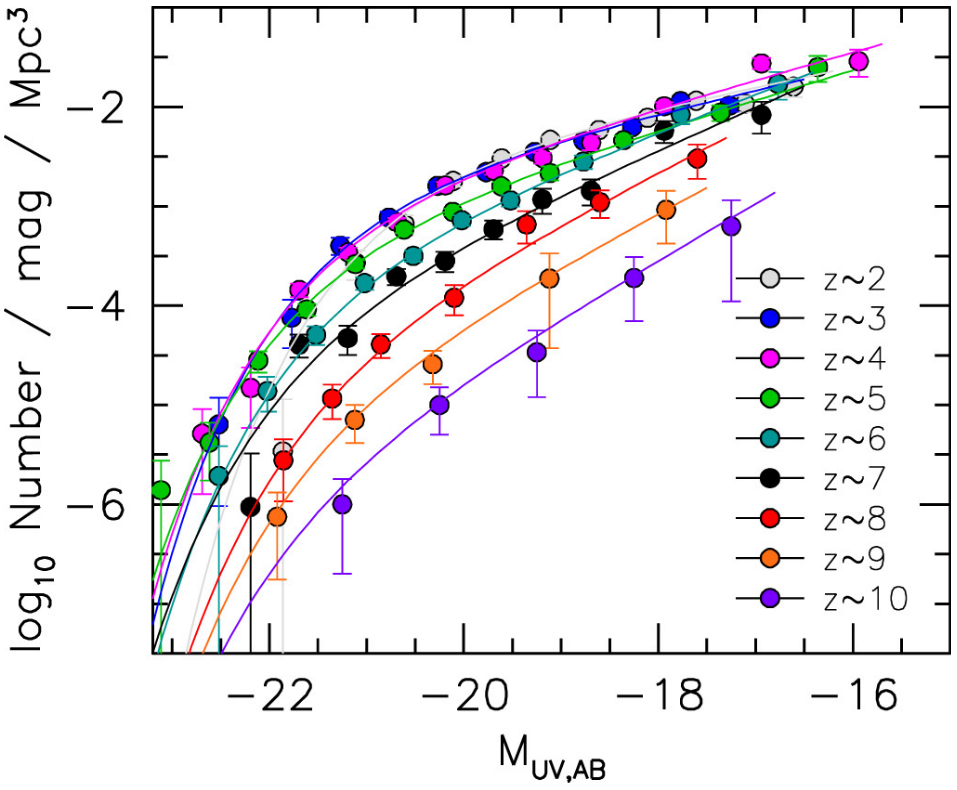


Properties of Galaxies in the Local Universe

THE GALAXY LUMINOSITY FUNCTION

The V/V_{max} method (also named the volume luminosity test) is the most successful method to determine the LF.

Taking into account the luminosity limit of the survey L_{lim} we define :
V: volume within which each source is distributed
V_{max} : maximum volume within which each source could still be detected



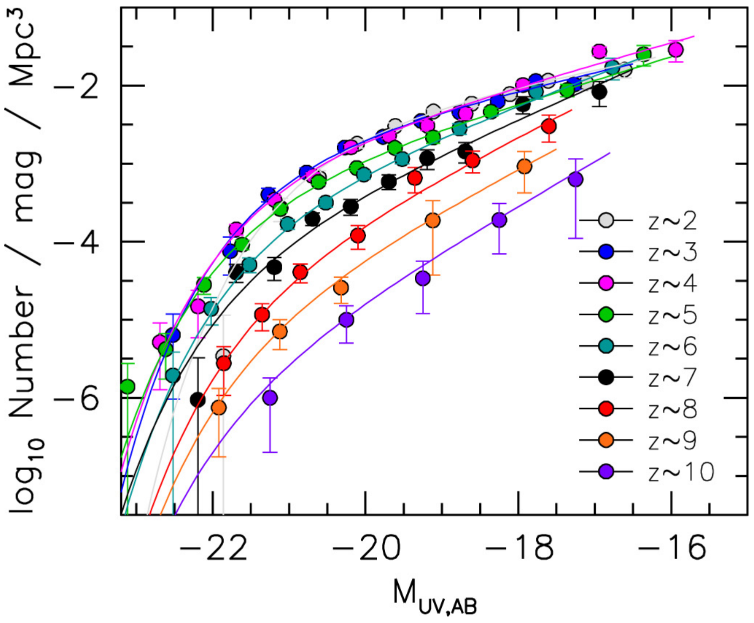
Properties of Galaxies in the Local Universe

THE GALAXY LUMINOSITY FUNCTION

$$\Phi(M) = \sum_{i=1}^{n} \frac{1}{V_{max}(m_i)}$$

$$V = \frac{4}{3}\pi R^3$$

$$R = \frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$



Properties of Galaxies in the Local Universe

STELLAR POPULATION

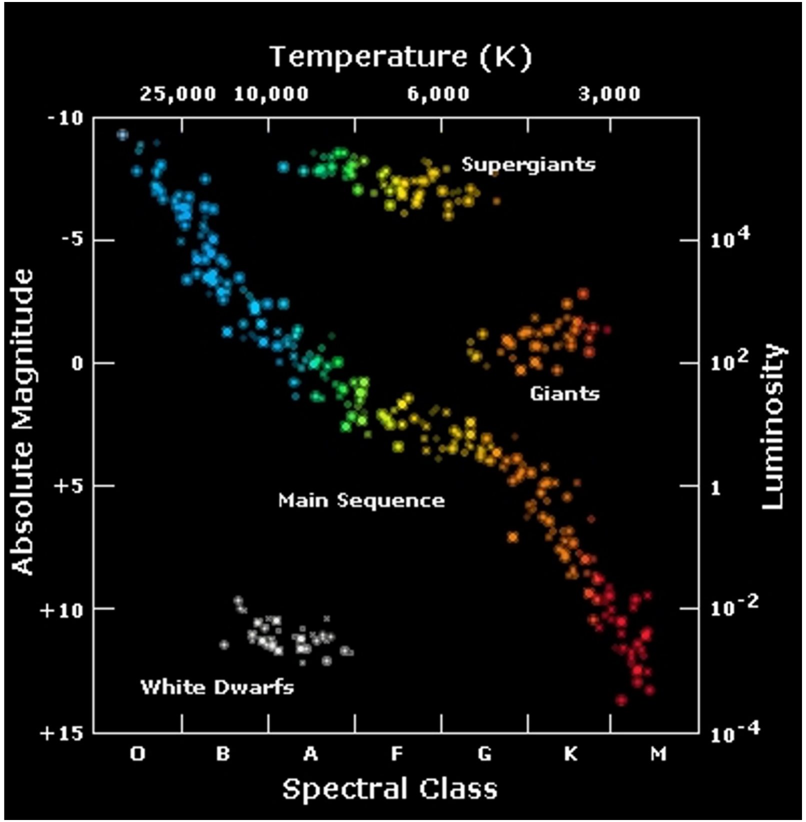
Stars are mainly characterised by their luminosity and surface temperature. They are classified according to their spectral type :

With decreasing T : O, B, A, F, G, K, M

A diagram showing the luminosity of a star as a function of its temperature is a *Hertzsprung-Russel* (HR) diagram.

Most of the stars are along the line called the Main Sequence where they are fusing hydrogen in their core.

The Giant branch is when the stars are fusing the Helium in their core.



Properties of Galaxies in the Local Universe

STELLAR POPULATION

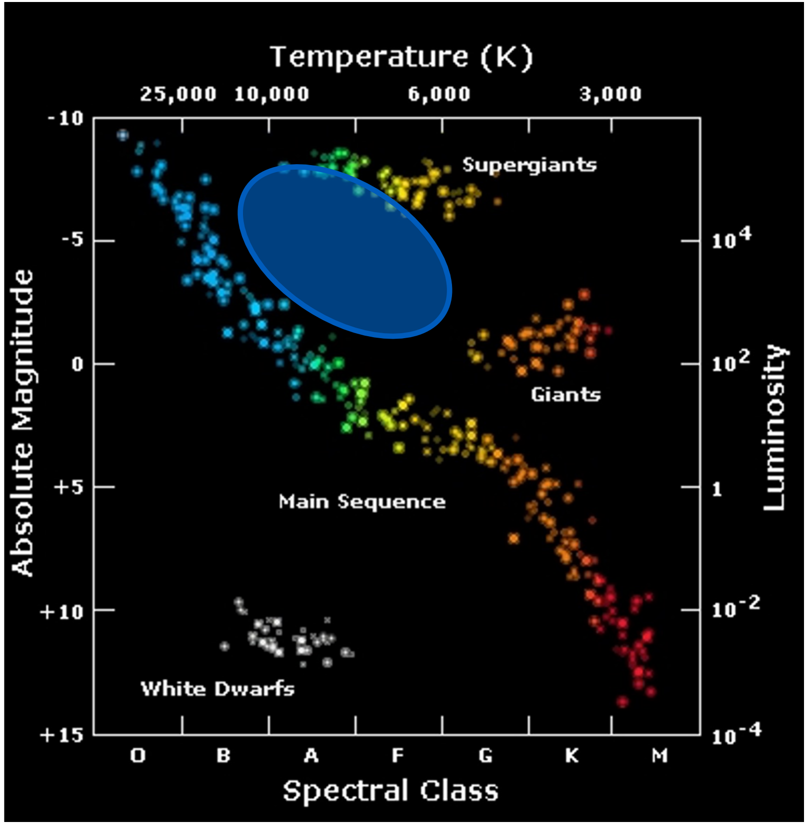
We can identify a gap in the HR diagram : that is the place where we can find variable stars (such as RR Lyrae or Cepheid).

Cepheids are evolved variable stars (helium burning stars). Their visual magnitudes vary between a ~0.01 and ~2 mag, with a period of a few days to a few weeks.

The longer the period of their variability, the brighter their intrinsic luminosity

If we can measure the period of a Cepheid, we can deduce its intrinsic luminosity and therefore its distance.

$$d_{pc} = 10^{0.2\left(\beta\left[(B-V)_0+\frac{m}{\beta}\right]-\alpha\log P+\gamma'\right)}$$



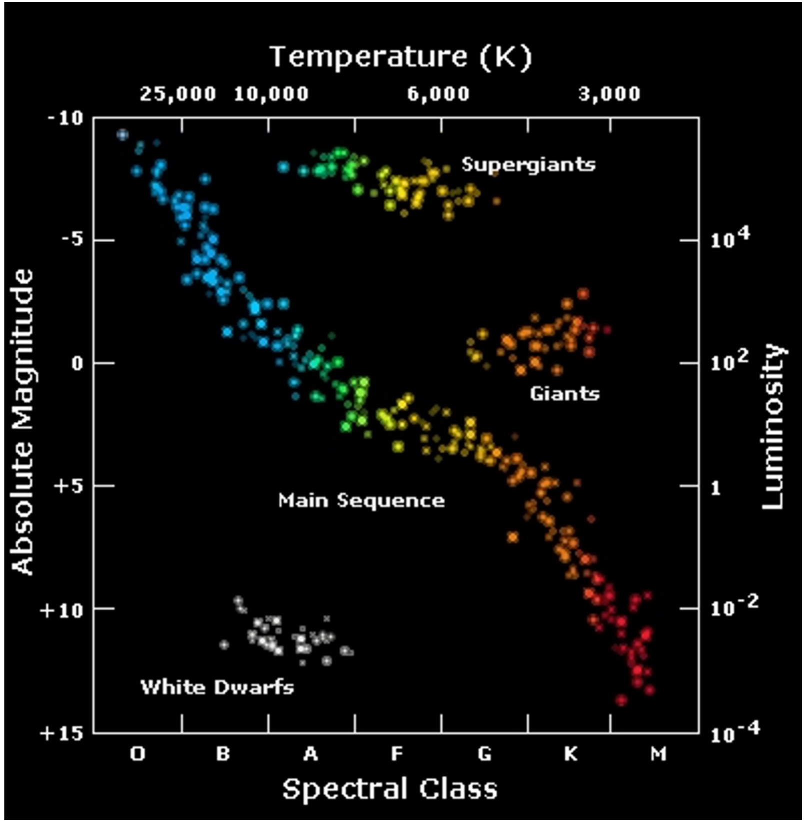
Properties of Galaxies in the Local Universe

The HR diagram ca be used to measure how far away a star cluster/galaxy is from Earth.

This can be done by comparing the apparent magnitudes of a star clusters with distance unknown, with the absolute magnitude of stars with known distance.

The observed group is then shifted in the vertical direction until it reaches the main sequence.

The different in magnitude (m-M) is a direct measure for the distance



Properties of Galaxies in the Local Universe

Stellar luminosity scales approximately as

$$L \propto M^{\alpha}$$

with $\alpha \sim 3$ for stars with $M < 0.5\ M_{\odot}$
and $\alpha \sim 4$ for stars with $M > 0.5\ M_{\odot}$

The time a star can remain on the Main Sequence is given by :

$$\tau_{ms} \propto \frac{M}{L} \propto M^{1-\alpha}$$

From previous equation, we clearly see that massive stars have shorter lifetime. Therefore, the most massive stars are excellent tracers of recent star formation. According to the HR diagram the most massive stars are O and B.

Stellar luminosity scales approximately as

$$L \propto M^{\alpha}$$

with $\alpha \sim 3$ for stars with $M < 0.5\ M_{\odot}$
and $\alpha \sim 4$ for stars with $M > 0.5\ M_{\odot}$

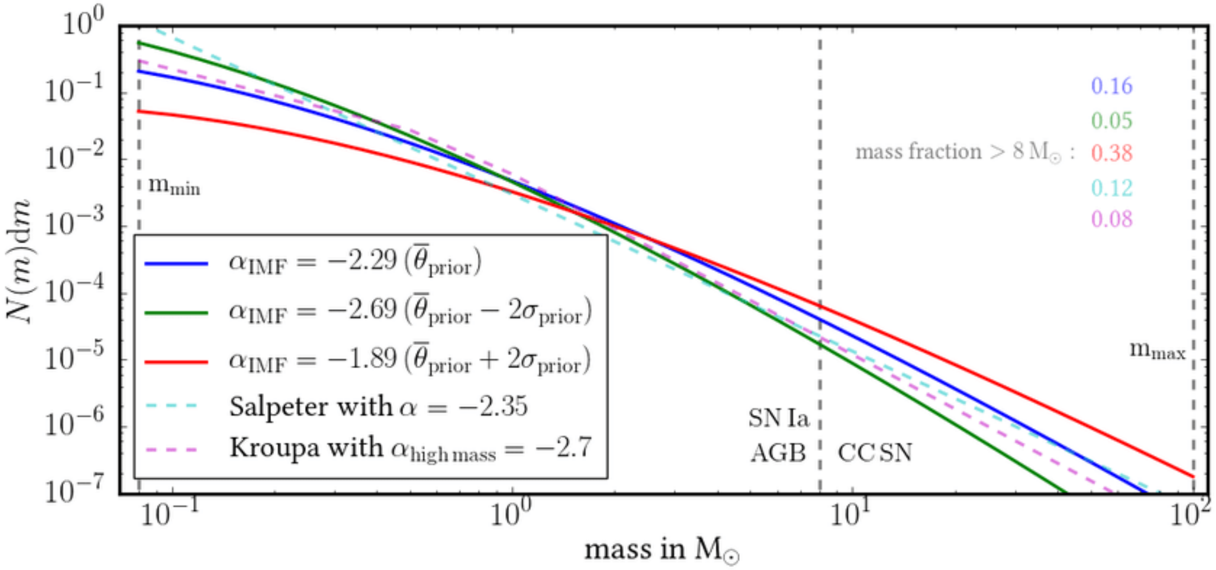
Properties of Galaxies in the Local Universe

The number of newly formed star with masses in the range $M \rightarrow M + dM$ is given by the **Initial Mass Function (IMF)**.

The commonly used IMF is the Salpeter IMF which has the shape of a power-law :

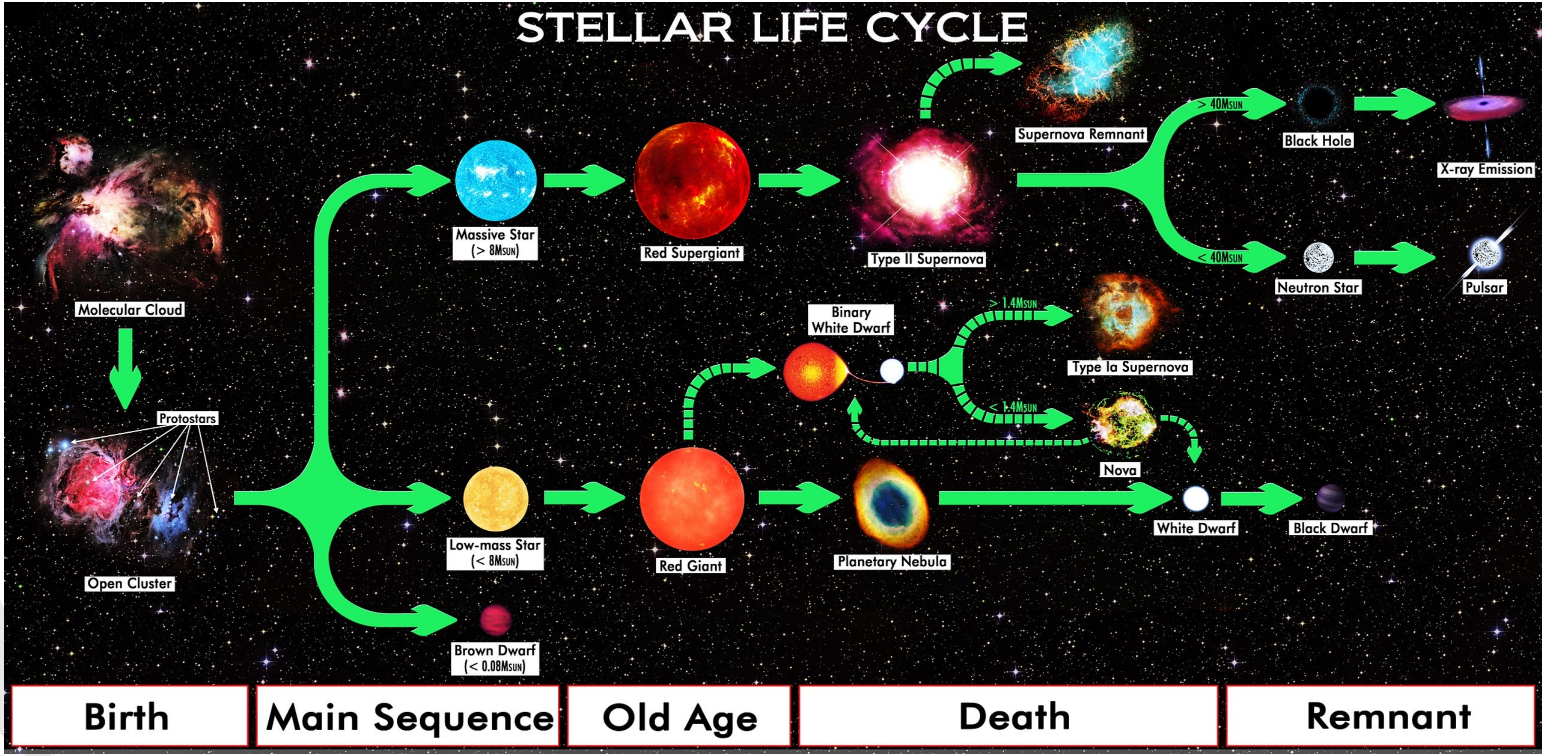
$$\frac{dN}{dM} \propto M^{\theta}$$

for a standard Salpeter IMF $\theta = -2.35$



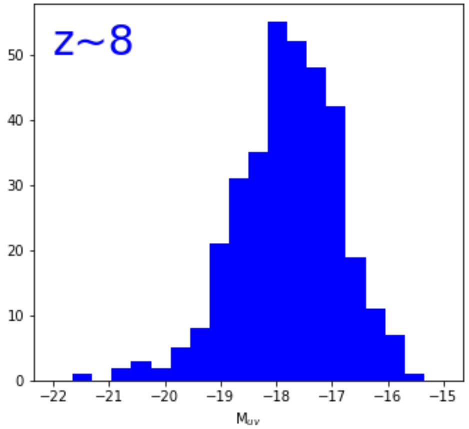
The mass budget is dominated by the low-mass stars. But according to the relation between Luminosity and Mass $L \propto M^{\alpha}$, the most massive stars dominate the luminosity budget.

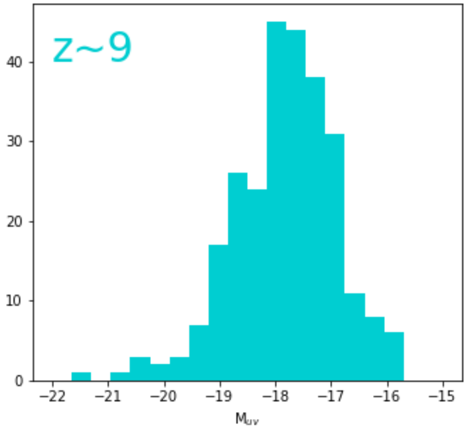
Properties of Galaxies in the Local Universe

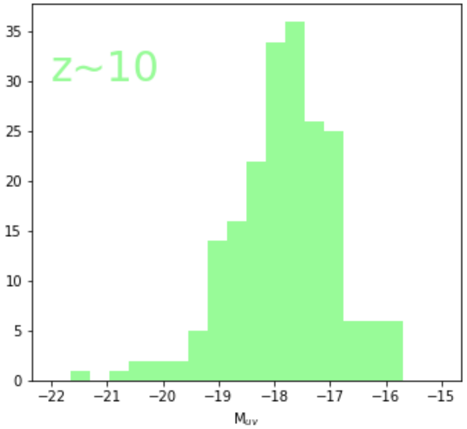


Hands-on session 2

- Select all galaxies at $z \sim 8, 9, 10$
- Plot their distribution in luminosity (or absolute magnitude


z~8
0
10
20
30
40
50
−22
−21
−20
−19
−18
−17
−16
−15
Muv

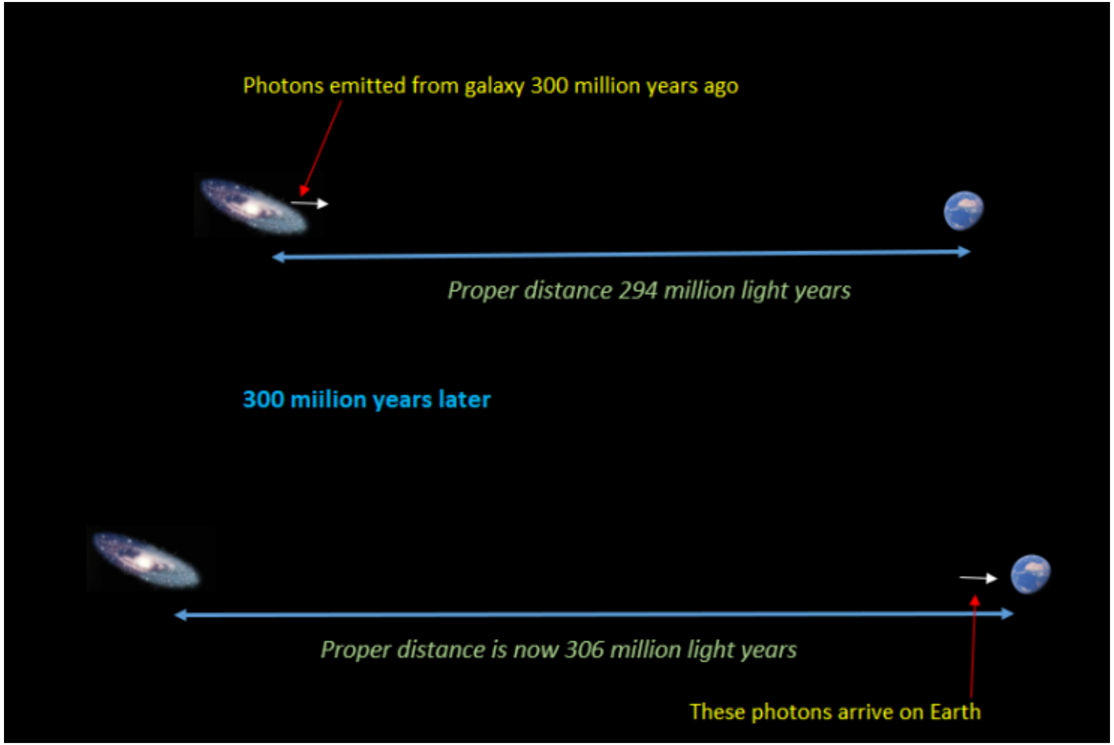

z~9
0
10
20
30
40
−22
−21
−20
−19
−18
−17
−16
−15
Muv


z~10
0
5
10
15
20
25
30
35
−22
−21
−20
−19
−18
−17
−16
−15
Muv

The physical properties of galaxies

The cosmological distances

The distances in cosmology

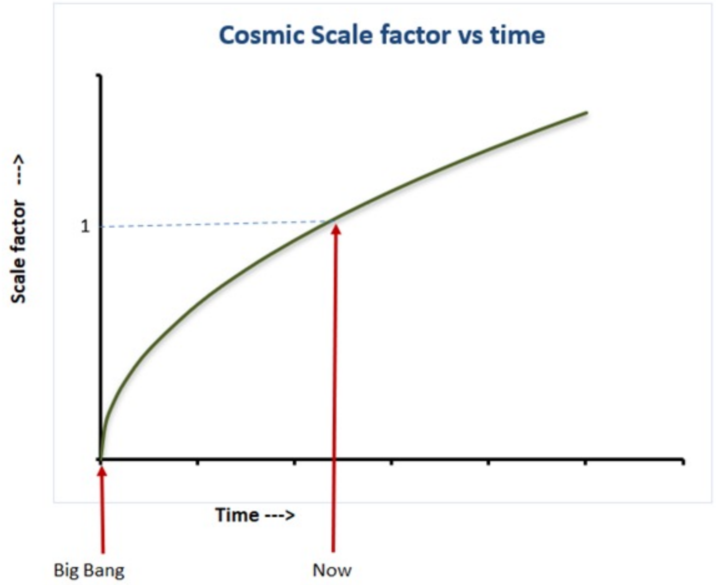


The distances in cosmology

If we consider any two objects that are far enough away from each other so that they are not bound together by gravity, then the **cosmic scale factor** is the ratio of their proper distance at time t which will call $D_p(t)$ to their current proper distance D_{p_0}.

$$\boldsymbol{a(t) = \frac{D_p(t)}{D_{p_0}}}$$

$$\mathbf{a}(\boldsymbol{t} = \mathbf{0}) = \mathbf{0}$$
$$\boldsymbol{a}(\boldsymbol{t} = \boldsymbol{now}) = \mathbf{1}$$

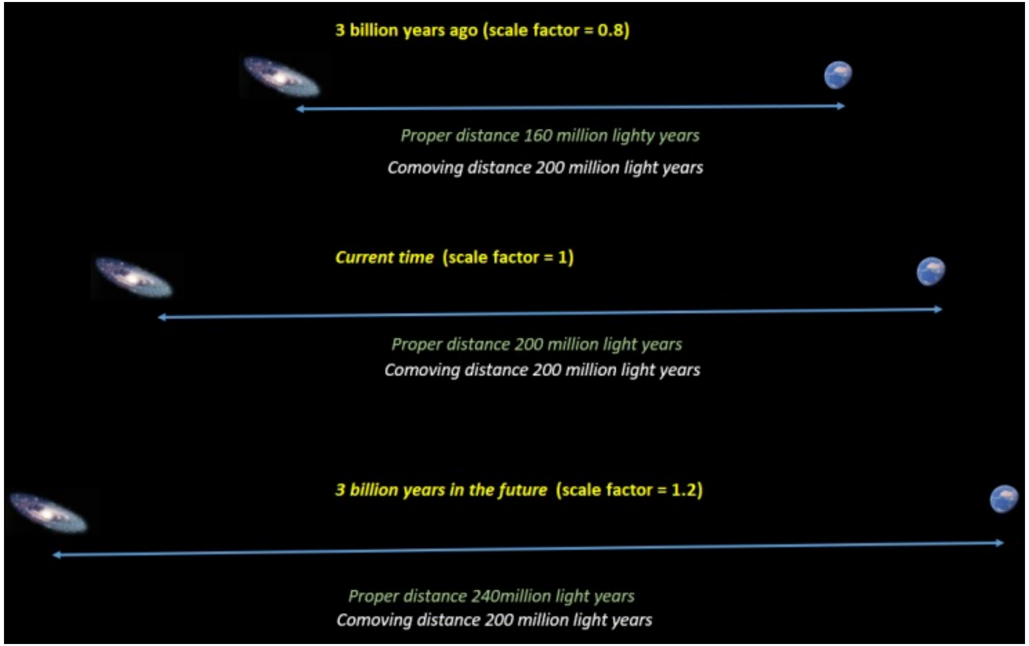


The distances in cosmology

The **comoving distance** (D_{CM}) is defined as the proper distance divided by the scale factor.

$$D_{CM} = \frac{D_P(t)}{a(t)}$$

For objects that only get further apart (i.e. their proper distance increases) as a result of the expansion of the Universe, the comoving distance between them does not change over time.



The distances in cosmology

The **Luminosity Distance** depends on cosmology, and it is defined as the distance at which the observed flux **f** is from an object.

$$D_L(z) = \sqrt{\frac{L}{4\pi f}}$$

$$D_L(z) = (1+z)D_{CM}$$

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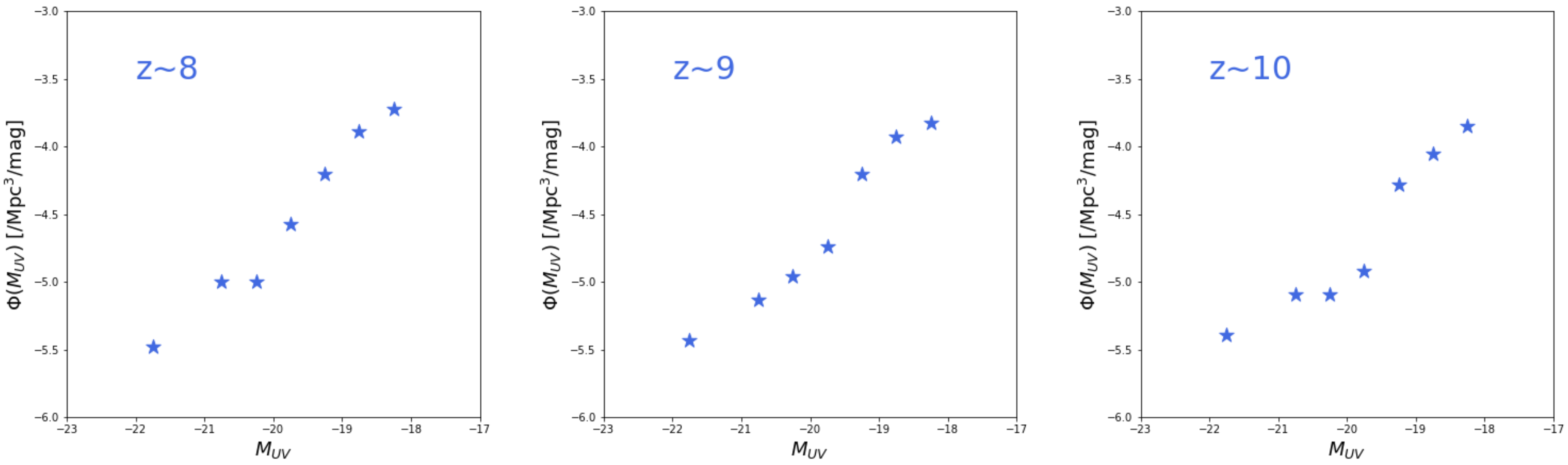
Hands-on session 3

- Plot the number density of objects per luminosity bins


z~8
z~9
z~10
$\Phi(M_{UV})$ [/Mpc^3/mag]
M_{UV}
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
−6.0
−23
−22
−21
−20
−19
−18
−17