Formation of Structure in the Universe

Lent Term 2023

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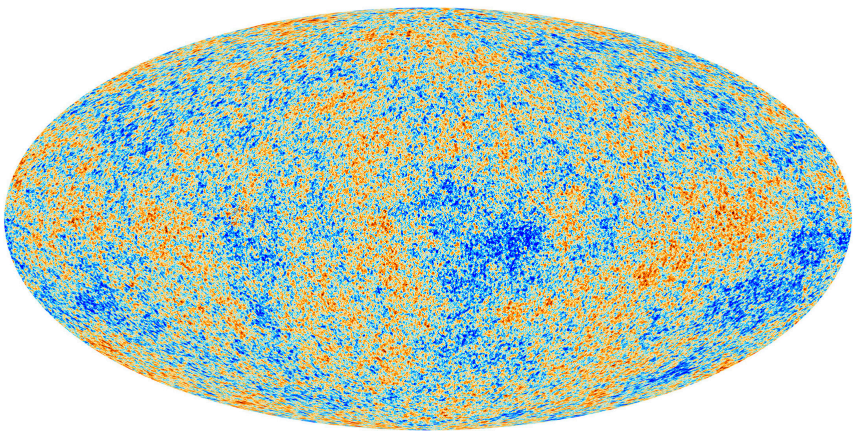
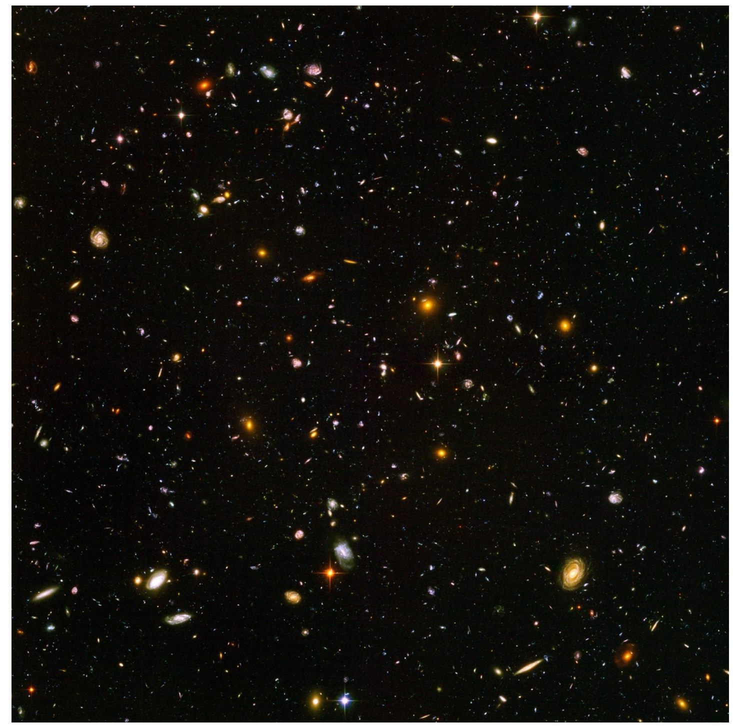
Formation of Structure in the Universe in a nutshell





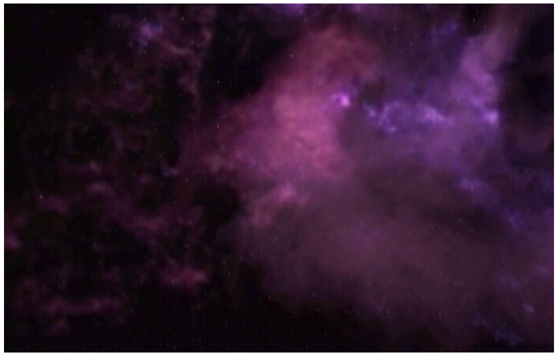
Formation of Structure in the Universe in a nutshell

Formation of Structure in the Universe in a nutshell

How can we heat and cool baryonic gas cloud ?

How stable is a gas cloud ?

How can we form a collapsed object from a gas cloud ?



How the first galaxies formed in the early Universe ?

How stars in galaxies influence the on-going star-formation ?

What are the properties of galaxies ?

Formation of Structure in the Universe in a nutshell

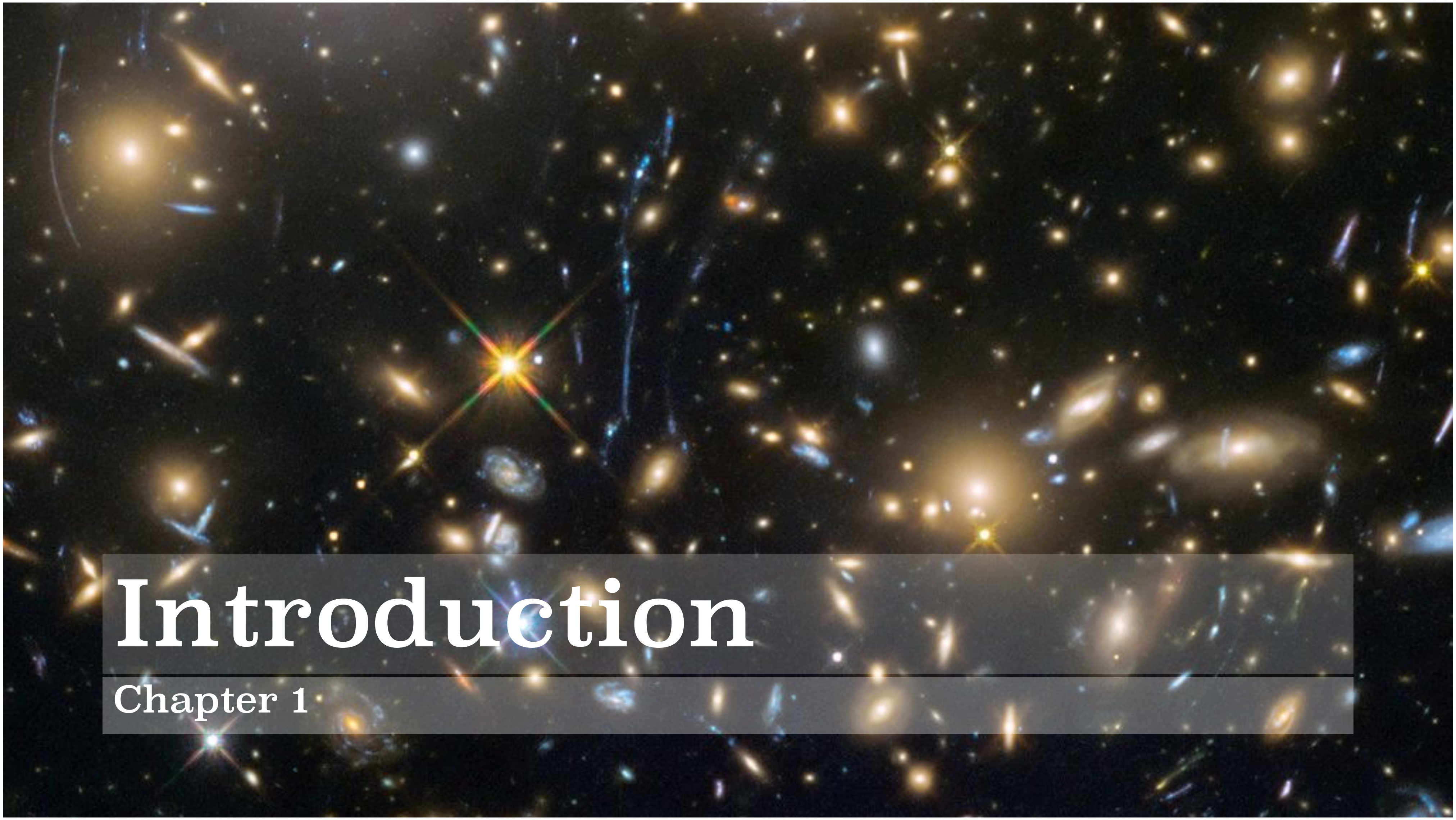
Date	Topic	Date	Topic	Date	Topic
23/01/2023	Introduction	13/02/2023	From gas cloud to collapsed object	06/03/2023	Gravitational instabilities in the cosmological context
27/01/2023	Physical process in baryonic gas (part 1)	17/02/2023	Galaxies and star-formation on galactic scales (part 1)	10/03/2023	Hierarchical structure formation (part 1)
30/01/2023	Physical process in baryonic gas (part 2)	20/01/2023	Galaxies and star-formation on galactic scales (part 2)	13/03/2023	Hierarchical structure formation (part 2)
03/02/2023	Gravitational stability and instability (part 1)	24/02/2023	Galaxies and star-formation on galactic scales (part 3)	17/03/2023	Galaxy formation and evolution
~~06/02/2023~~	Gravitational stability and instability (part 2)	27/02/2023	Feedback processes in star formation	April 2023	Exam
10/02/2023	Gravitational collapse	03/03/2023	Galaxies interaction and triggering star-formation		

Supervison

3 groups :

- 6-8 students/group
- please sign in (*email circulating soon*)
- 3 sessions

Group ID	Session 1		Session 2		Session 3	
	Date	Room	Date	Room	Date	Room
1						
2						
3						



Introduction

Chapter 1

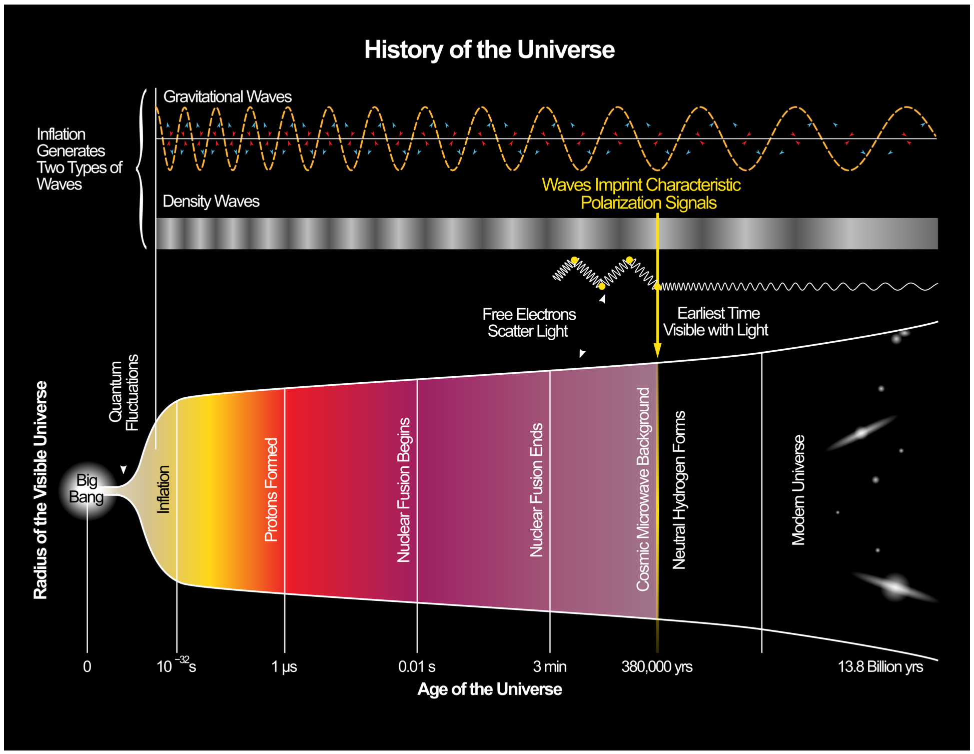
The first 3 minutes of the Universe

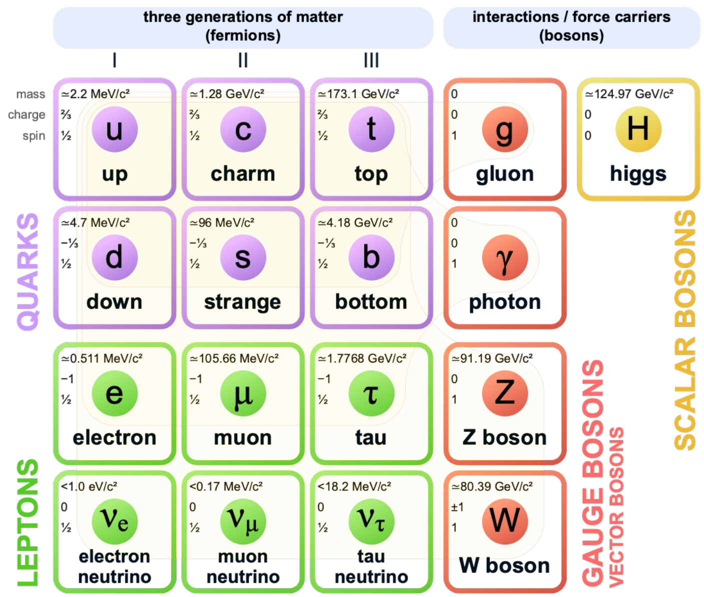
t=0s : *the Big-Bang*

t=10^{-36} to t=10^{-32}s : *inflation*

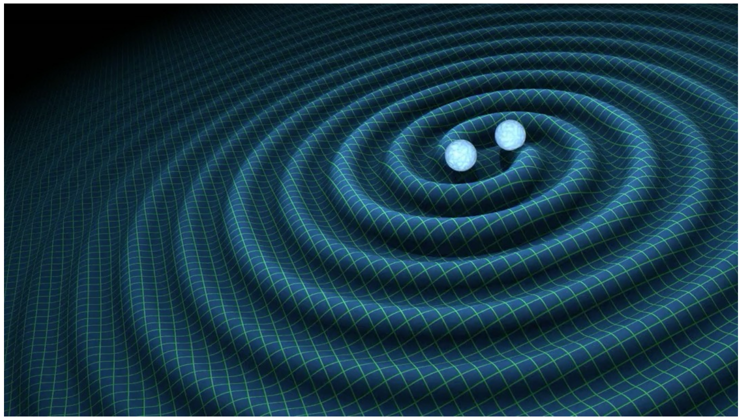
- *emission of gravitational waves*
- *emission of density waves*

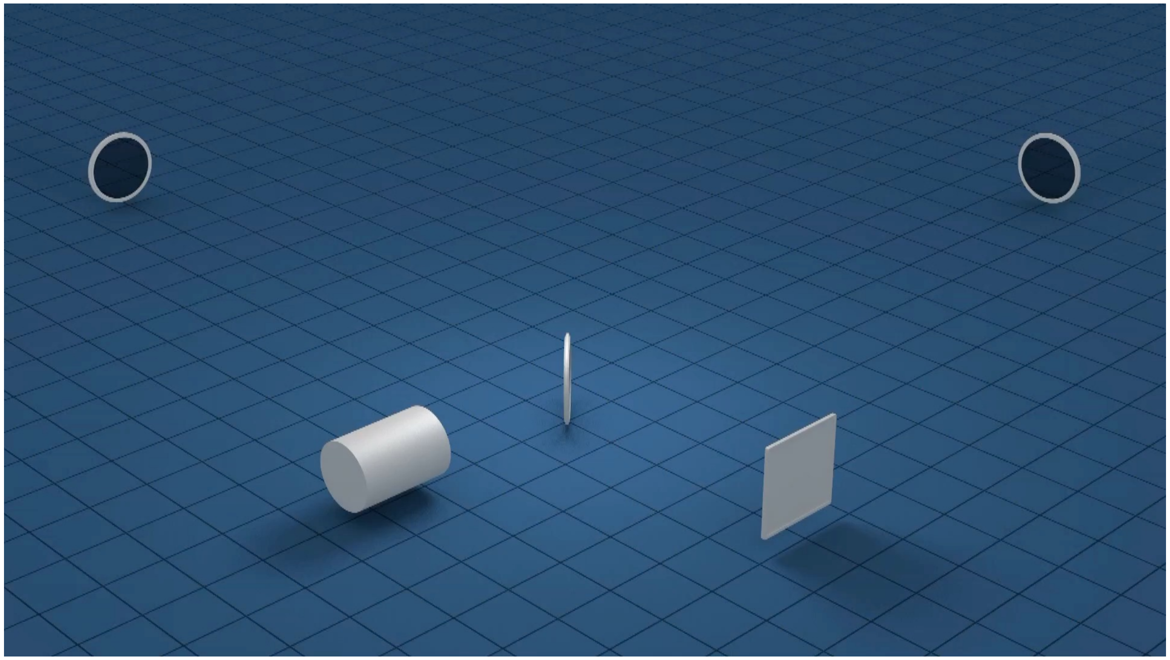
Guzzetti et al. 2016, arXiv: 1605.01615





The first 3 minutes of the Universe





Resolution of current instrumentation : 1/1000 of the size of a proton.

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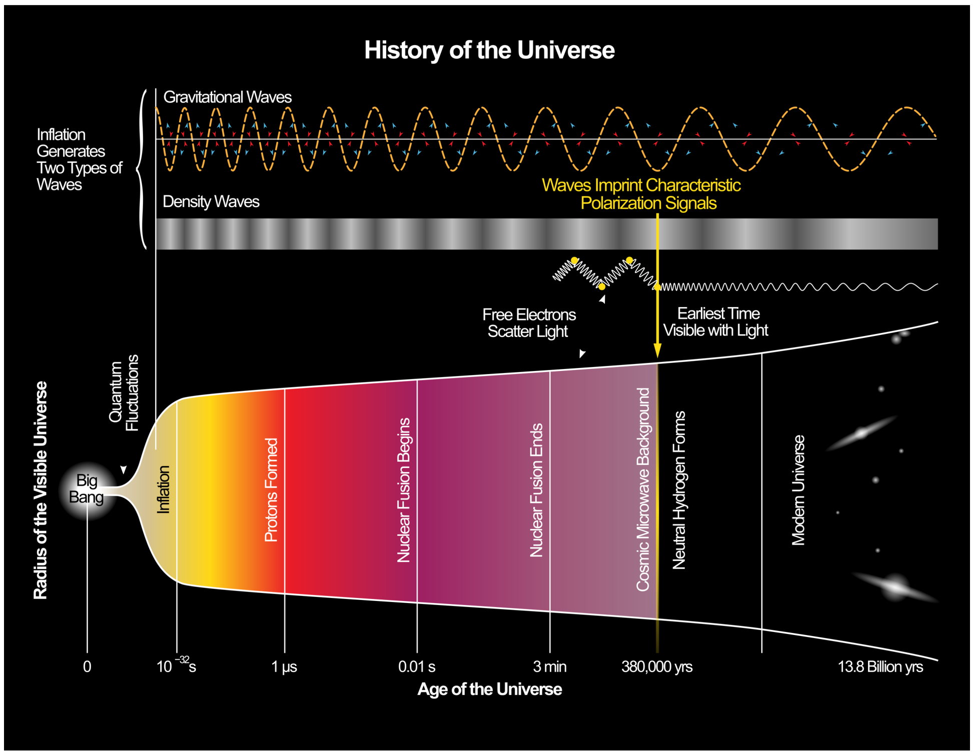

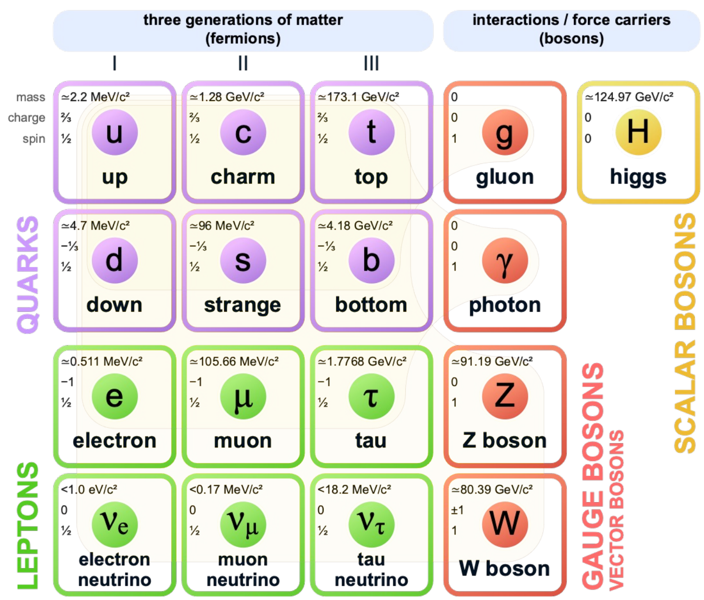

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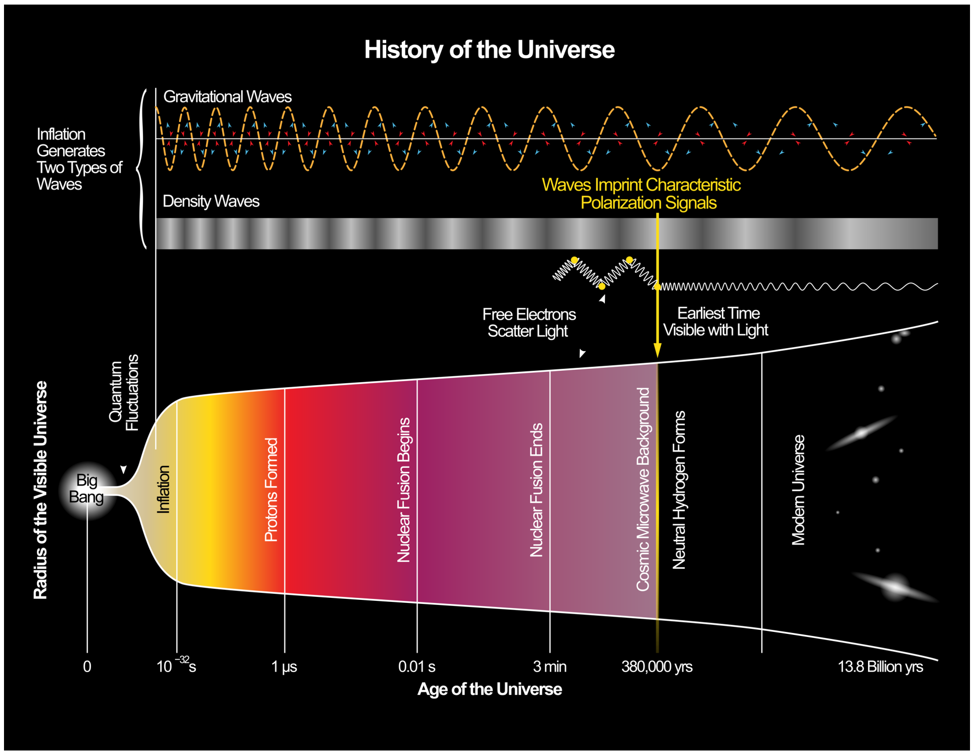

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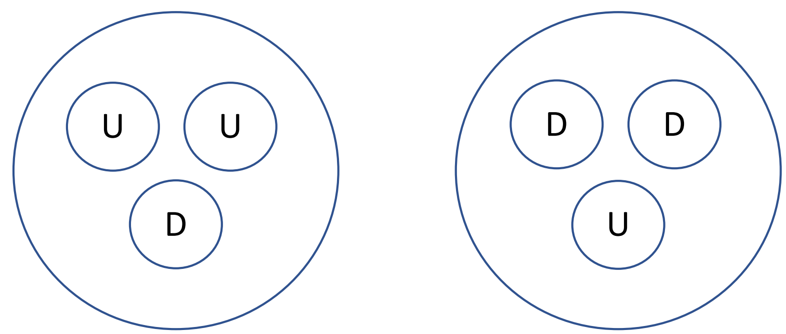
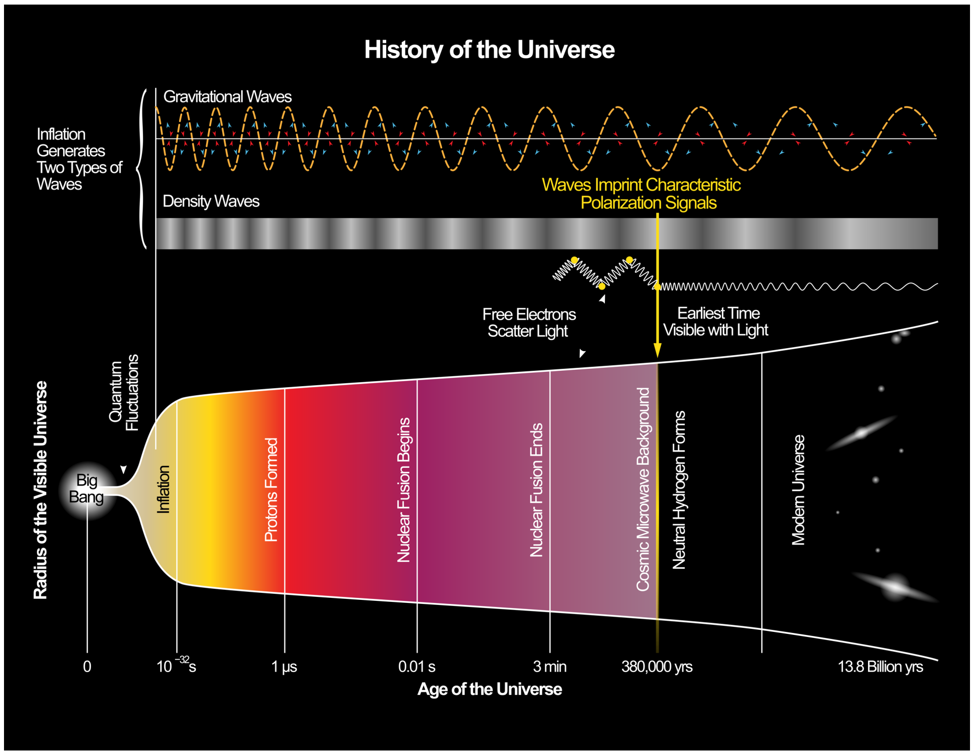
- *Universe mainly composed of quarks, leptons and photons*

t=10^{-6}s : *formation of protons and neutrons*



Proton Neutron

The first 3 minutes of the Universe



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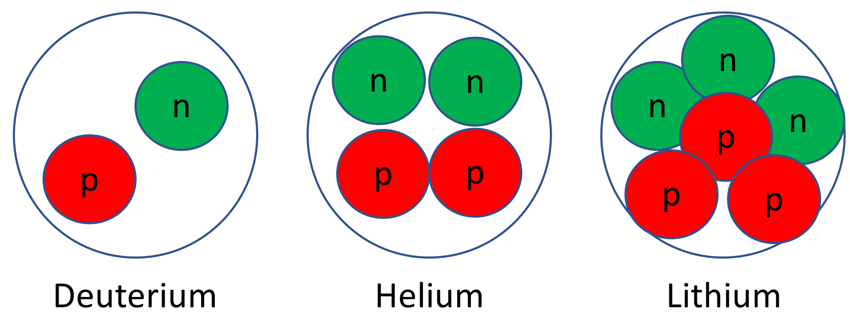
t=10^{-6}s : *formation of protons and neutrons, and then formation of nuclei of deuterium, helium and lithium*



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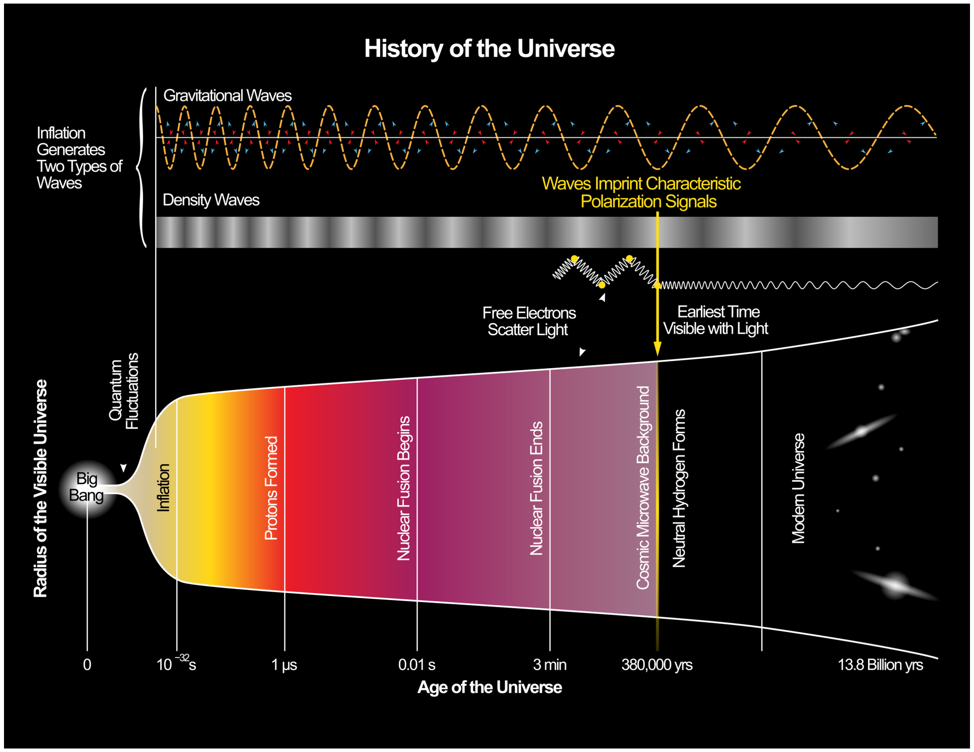

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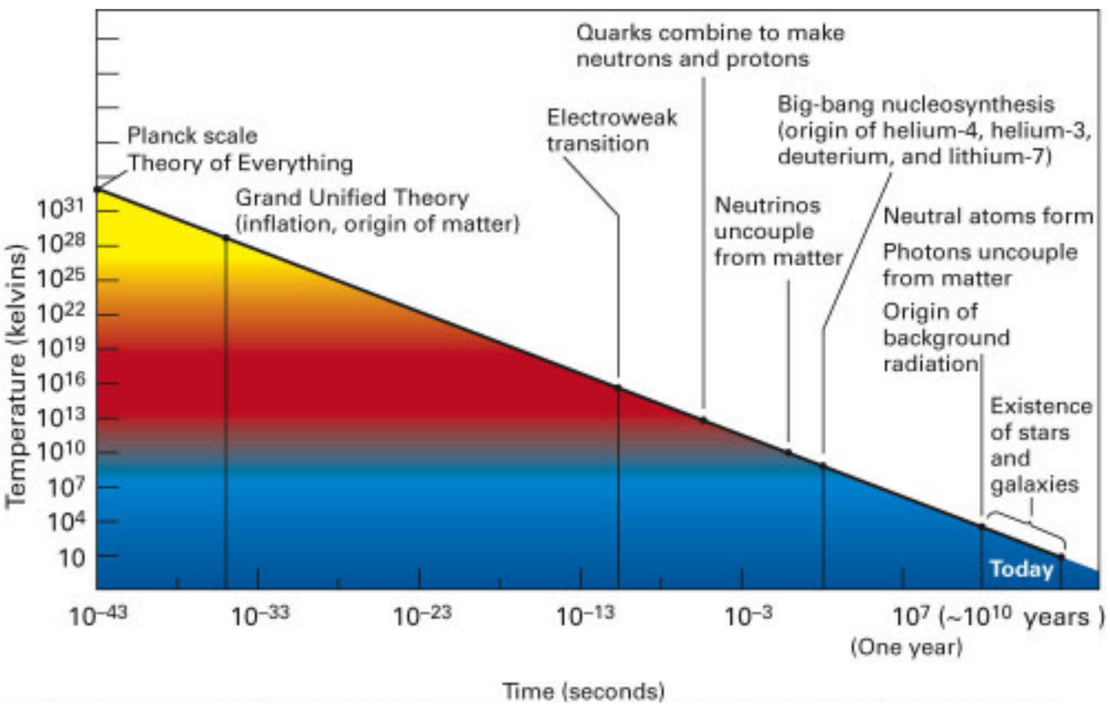
- *Universe mainly composed of quarks, leptons and photons*

$t=10^{-6}$s : *formation of protons and neutrons, and then formation of nuclei of deuterium, helium and lithium.*

t=3mn : *the Universe is mainly composed of radiation, baryonic matter, dark matter and dark energy.*

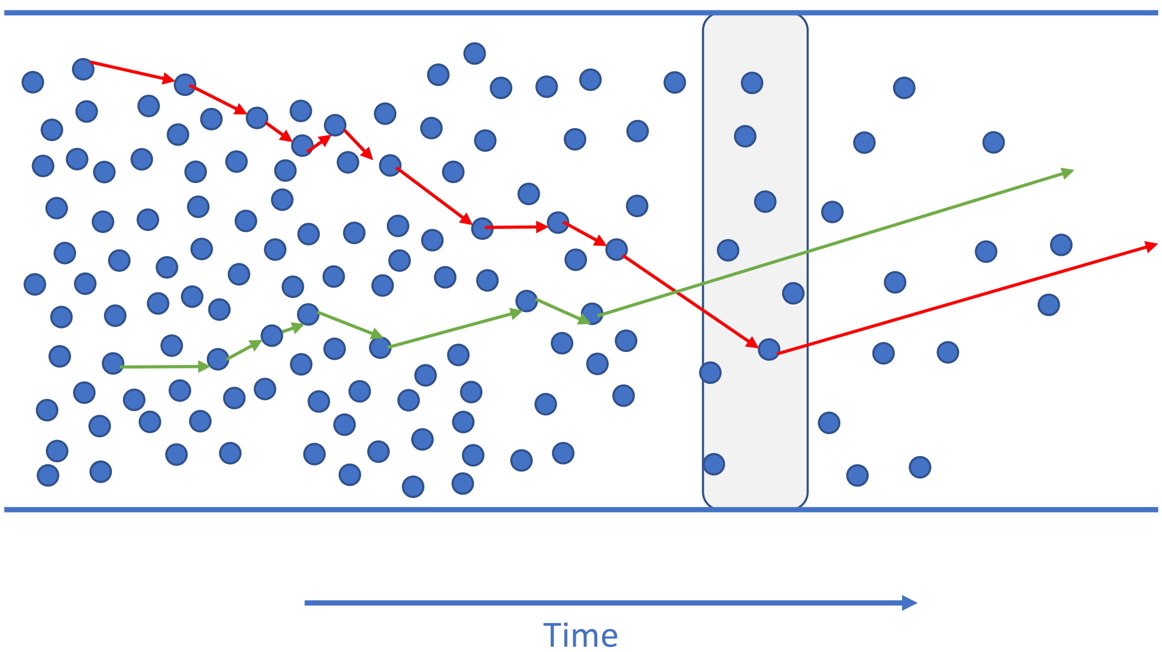
- *Electrons and nuclei are not bounded yet.*

The formation of the first stars and galaxies



- Over-dense regions grow from the initial perturbation
- As the Universe is expanding, the Universe's temperature is decreasing.
- The Universe's density is also decreasing as the Universe is expanding

The formation of the first stars and galaxies



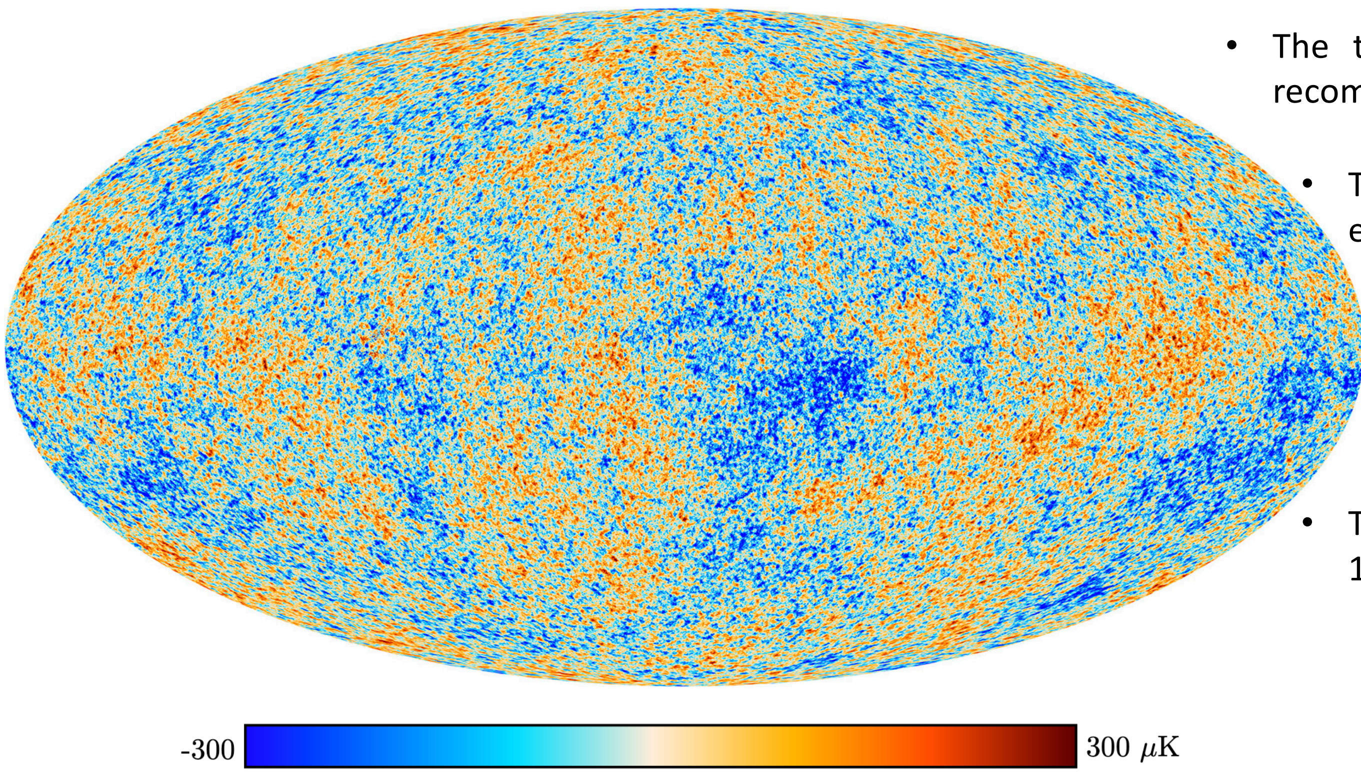
- Free electrons and protons start to be bounded but as soon as they are hit by a photon they become again unbounded :

$$e + p \Leftrightarrow H + \gamma$$

- When the Universe's density is sufficiently low to avoid interaction between photons and particles (*matter and radiation are decoupled*) :
  - The first atoms are formed (Hydrogen, Helium, Lithium)
  - Photons can escape, and form the first emitted radiation in the Universe : the **Cosmic Microwave Background**

This epoch is called **the recombination phase**

The formation of the first stars and galaxies



- The temperature of the Universe at the recombination epoch was ~3000K
- The redshift of the recombination epoch is $z \sim 1100$
- Therefore, the observed temperature of the CMB is today :

$$T \approx \frac{3000}{1+z} = \frac{3000}{1101} \approx 2.7\ K$$

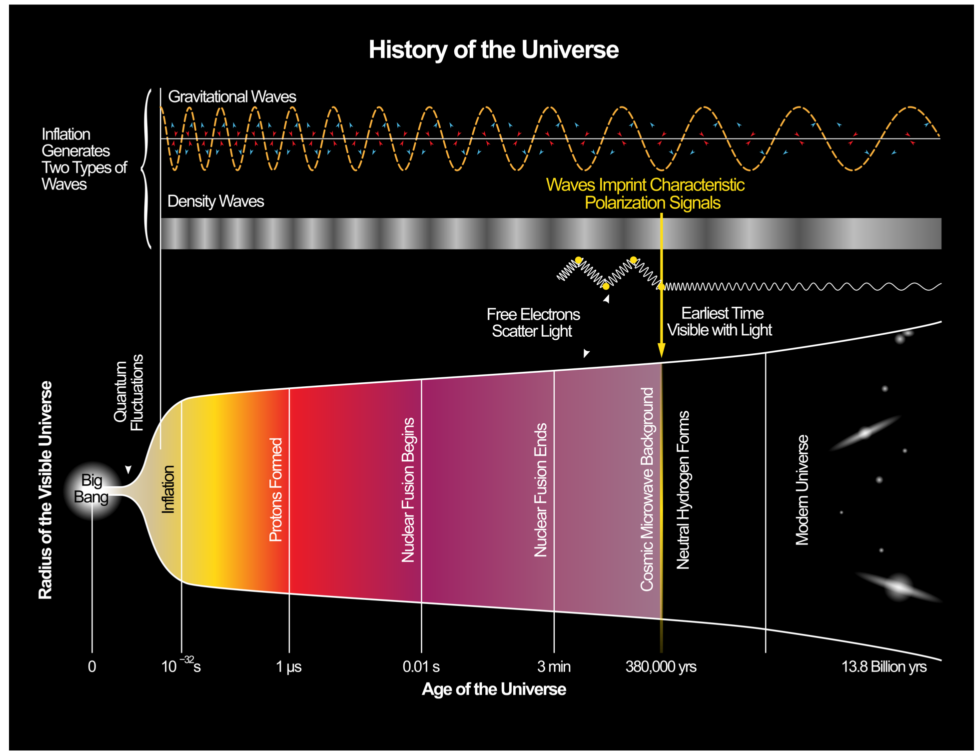
- The CMB is observed at a frequency of 160.23 GHz

The formation of the first stars and galaxies

- European Space Agency (ESA) satellite
- Launched by an Ariane 5 rocket in May 2009
- Diameter :1.5m
- Objectives :
  - Map the Cosmic Microwave Background
  - Measure the cosmological parameters
  - Study galaxy clusters

The formation of the first stars and galaxies

- After the recombination phase, the Universe enters the **Dark Ages**
- Overdense regions continue to grow
- Their density becomes sufficiently large that their gravitational field is dominated by their own mass
- Their evolution is now driven by their own gravity (self-gravitating objects) and not the evolution of the Universe (Hubble flow)
- At the center of these overdense regions, the gas cools and leads to the formation of the first stars : this epoch is called **Cosmic Dawn**



The formation of the first stars and galaxies

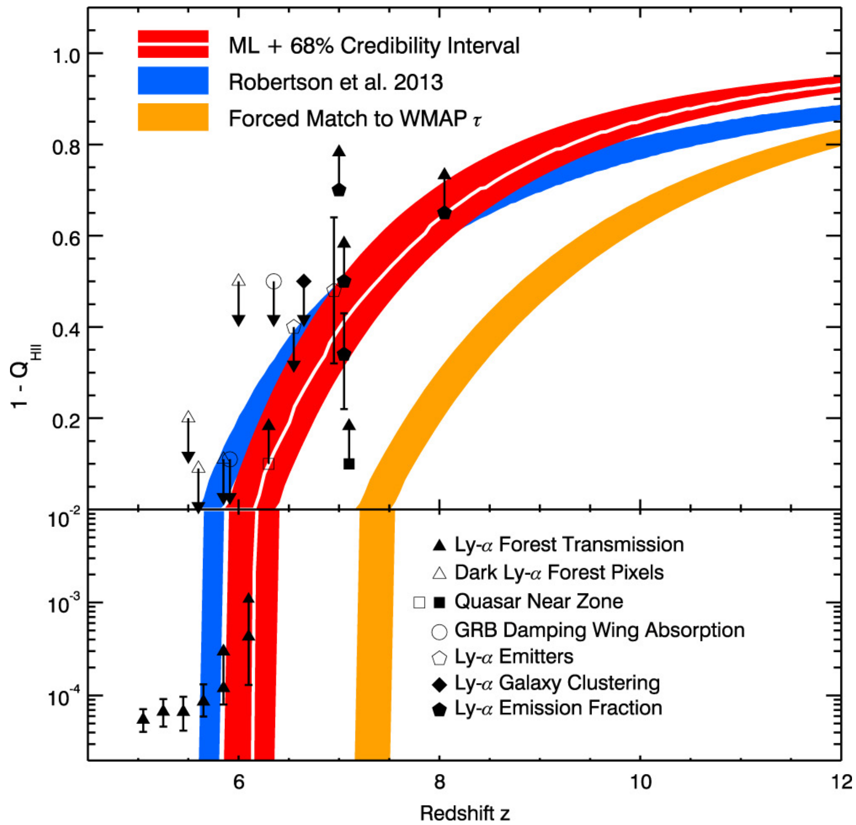
- The first stars are surrounded by neutral hydrogen

- The first stars emit UV photons* which will ionise the neutral hydrogen, creating bubbles of ionised hydrogen : this is the **epoch of reionisation**

* *This will be discussed later in this course*

The formation of the first stars and galaxies

- The first stars are surrounded by neutral hydrogen
- The first stars emit UV photons* which will ionise the neutral hydrogen, creating bubbles of ionised hydrogen : this is the **epoch of reionisation**
- CMB observations by *Planck* reveals that the hydrogen is fully ionised 1 billion years after the Big-Bang (z=6)
- The study of the first generation of galaxies shows that they grow hierarchically by merging, leading to an evolving distribution of galaxies of different masses.



Robertson et al. (2015), ApJ, 802, 19

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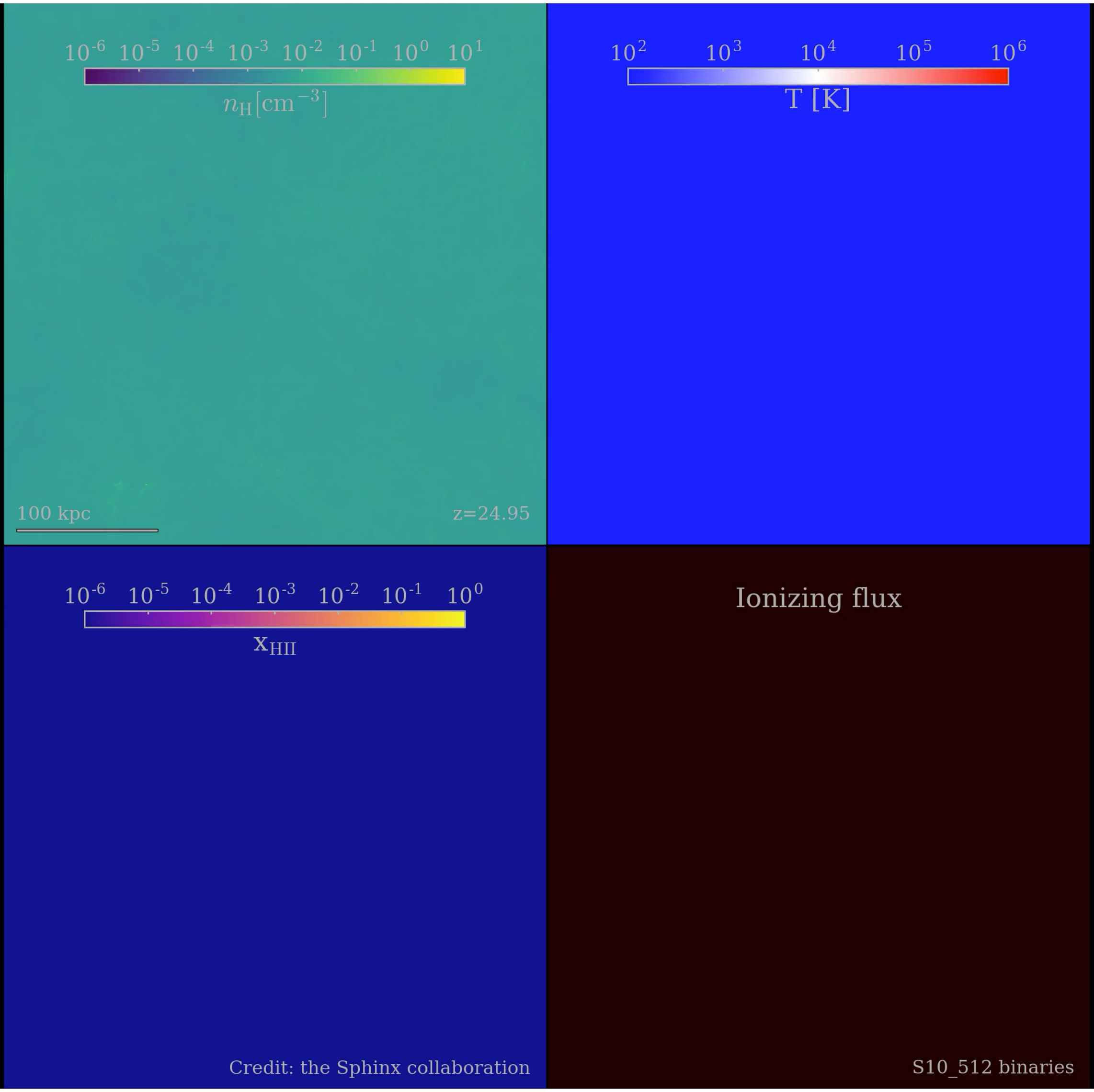
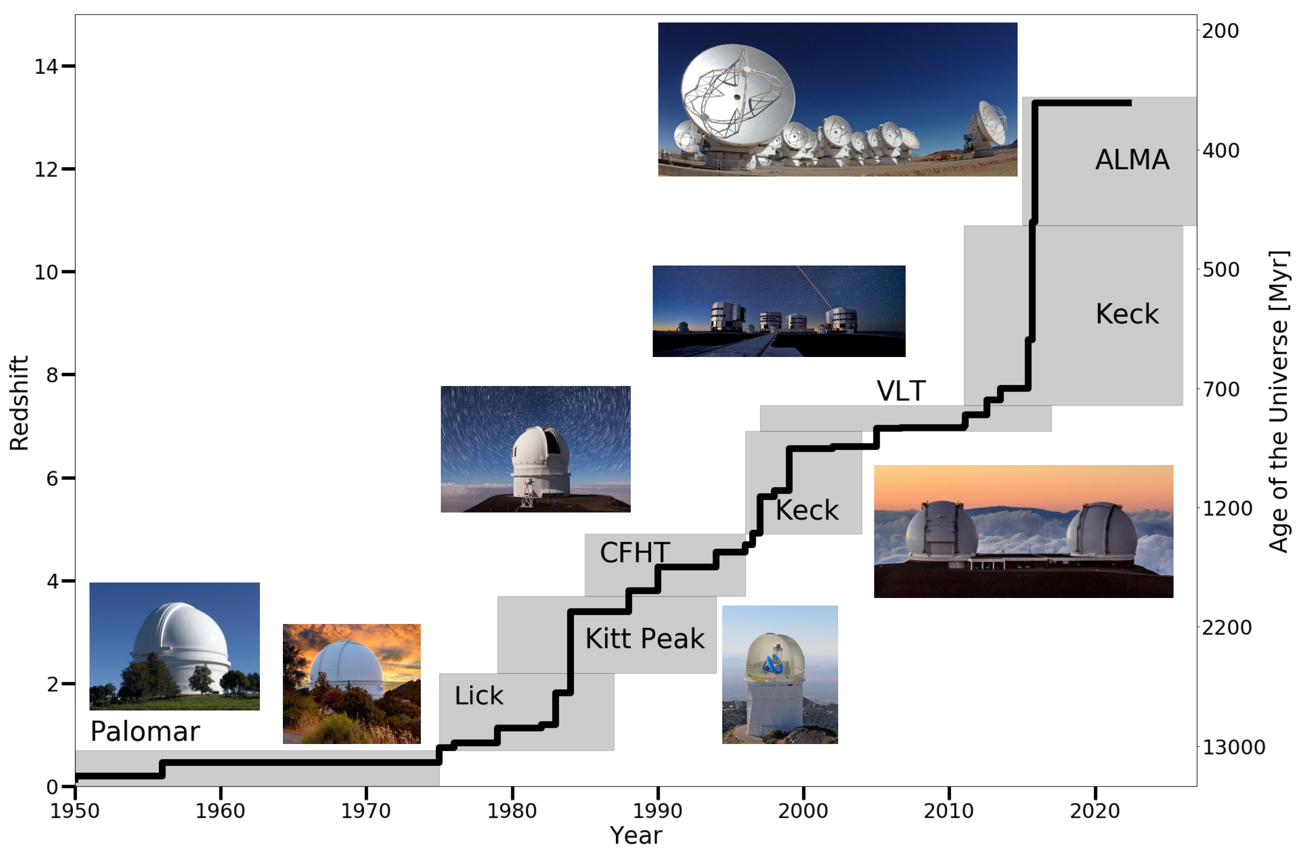
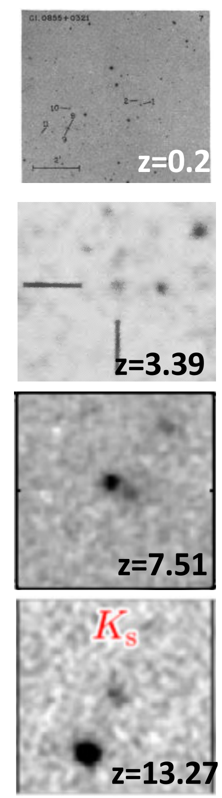


Rosdahl et al. 2018

The “hunt” for the most distant galaxies
between 1950s and 2022





Humason et al. 1956
Minkowski 1960
Spinrad et al. 1975
Spinrad & Smith 1976
Smith et al. 1979
Spinrad 1982
Spinrad & Djorgovsky 1984
Lilly 1988
Chambers et al. 1990
Lacy et al. 1994
Petitjean et al. 1996
Franz et al. 1997
Day et al. 1998
Hu et al. 1999, 2002
Pelló et al. 2004
Iye et al. 2006
Fontana et al. 2010
Vanzella et al. 2011
Ono et al. 2012
Shibuya et al. 2012
Finkelstein et al. 2013
Oesch et al 2014
Zitrin et al. 2015
Oesch et al. 2016
Harikane et al. 2022

The arrival of the *James Webb* Space Telescope

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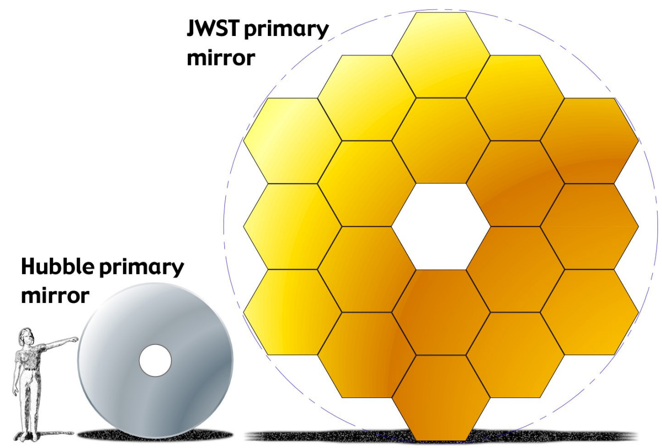
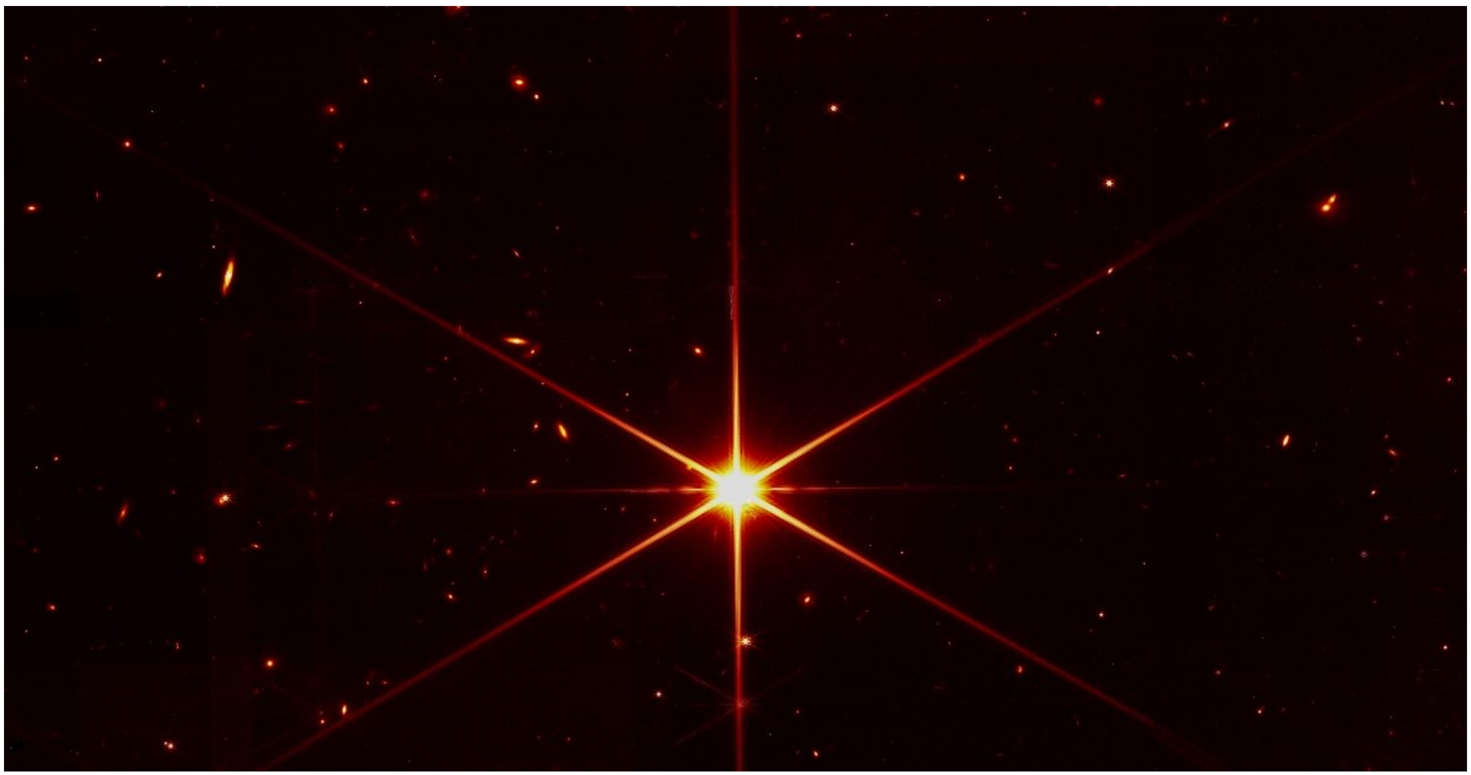


The arrival of the *James Webb* Space Telescope



The arrival of the *James Webb* Space Telescope

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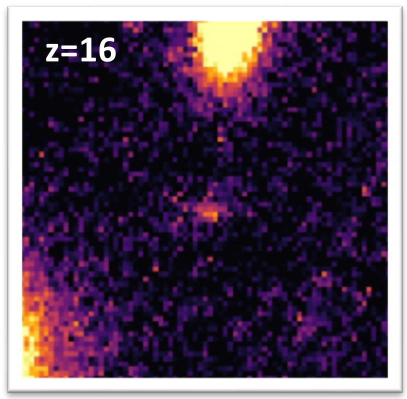
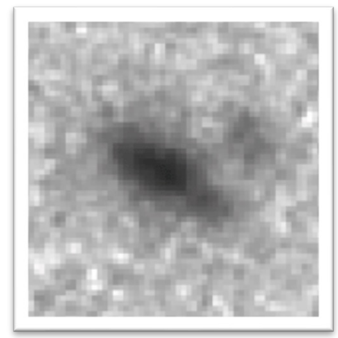
GLASS-z13 (Naidu et al. 2022)



SMACS-z16a (Atek et al. 2022)

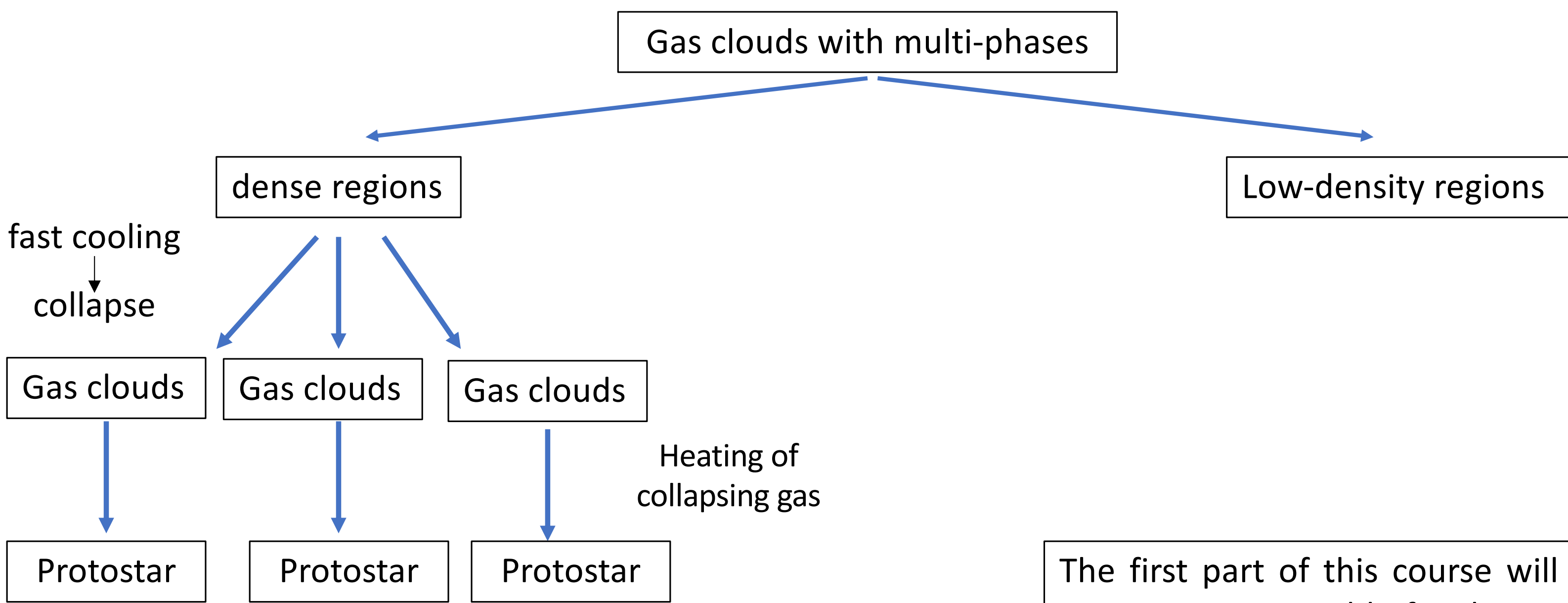
z=17



CEERS-DSFG-1 (Finkelstein et al. 2022)

Within a week, 11 papers have been submitted using the first dataset from the JWST to search for the first galaxies.

Summary of the formation of structures in the Universe



The first part of this course will be to describe the processes responsible for the cooling of the gas, the heating of the gas and the formation of protostars.

Toolbox for this course

Euler's equation

Adiabatic and inviscid flow

$$\rho \frac{d\vec{v}}{dt} + \rho(\overrightarrow{v} \cdot \nabla)\vec{v} = -\nabla P - \rho \nabla \Phi_g$$

pressure

Flow velocity

Gravitational potential

Equation of continuity

Conservation of some quantities

Density (mass/unit volume)

$$\frac{d\rho}{dt} + \nabla \cdot \vec{j} = 0$$

Flux=$\rho\vec{v}$

Poisson's equation

Differential equation

$$\Delta\Phi = \nabla^2\ \Phi = f$$

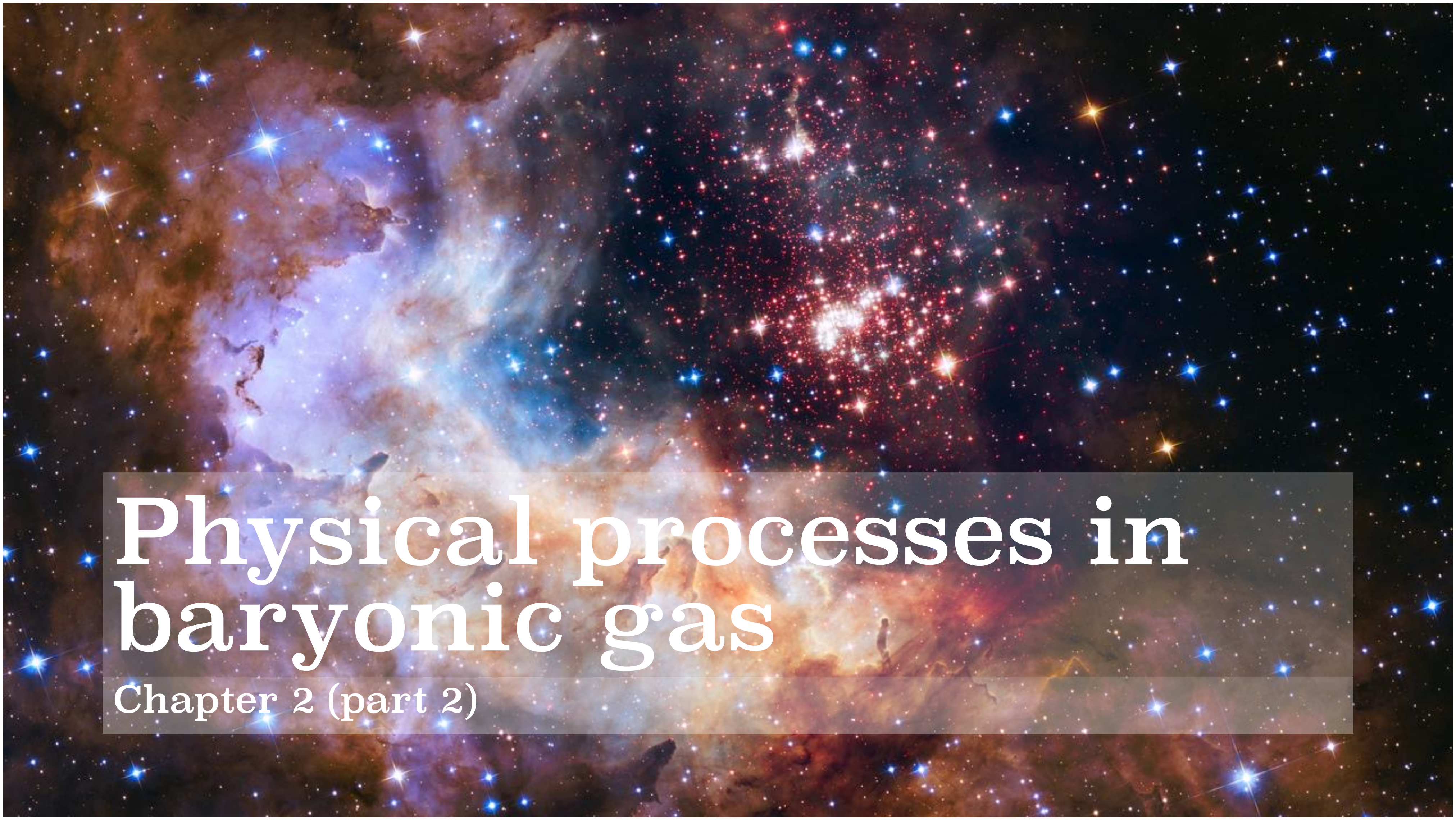
For the gravitational potential we can write :

$$\nabla^2 \Phi_g = 4\pi g \rho(\overrightarrow{r})$$

Equation of state for an ideal gas

$$P = \frac{\rho k_B T}{\mu}$$

Mass particle



Physical processes in baryonic gas

Chapter 2 (part 2)

Some definitions

The amount of energy (dE) passing through a surface should be proportional to the size of the surface (dA) and to the duration of the exposition (dt).

It is usually defined as :

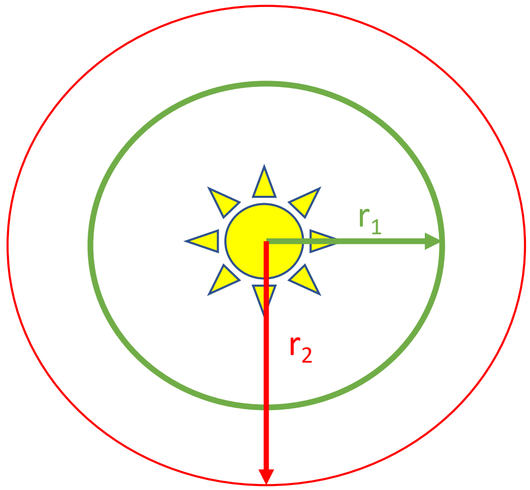
$$dE = dF \times dA \times dt$$

The <u>energy flux</u> dF is measured in erg s^{-1} cm^{-2}

A source of radiation is isotropic if it emits energy equally in all directions

By conservation of Energy, $dE(r_1) = dE(r_2)$ then :

$$F(r_1)4\pi r_1^2 = F(r_2)4\pi r_2^2$$



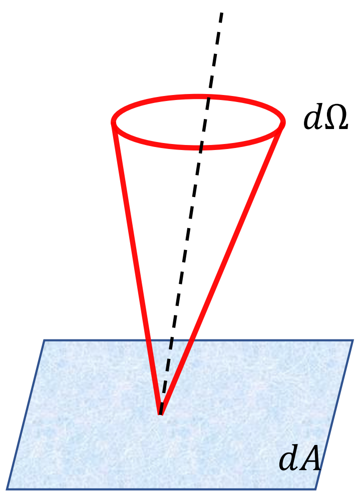
$$F(r) = \frac{F(r_1)r_1^2}{r^2}$$

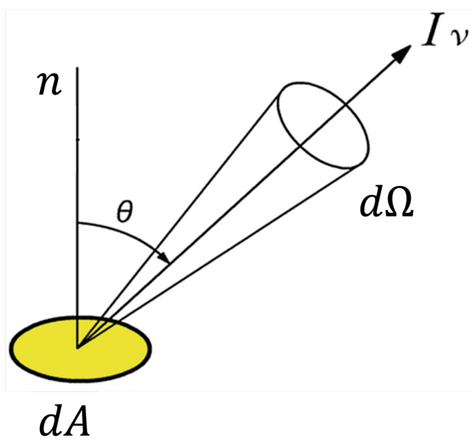
Some definitions

Considering a surface normal to the direction of a given ray, and considering all the rays whose direction is within a solid angle $d\Omega$, then the energy passing through the element dA is :

$$dE = I_\nu \, dA \, dt \, d\nu \, d\Omega$$

where I_ν is the specific intensity (or brightness)





If the surface is not perpendicular to the rays but has different orientation, then

$$dE = I_\nu \, dA \, dt \, d\nu \cos\theta \; d\Omega$$
$$= dF_\nu \, dA \, dt \, d\nu$$

N.B. : If the radiation is isotropic, then $\int dF_\nu = 0$

Some definitions

The specific energy density is the energy per unit volume per unit frequency range :

$$dE = u_\nu(\Omega)\, dV\, d\Omega\, d\nu$$

If we consider this cylinder, then $dV = dA\ c\ dT$ then

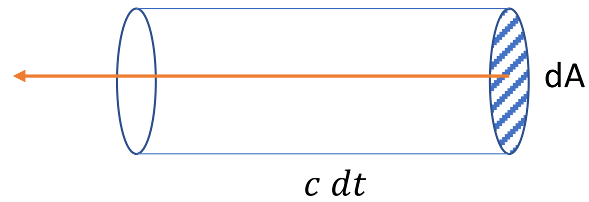
$$dE = u_\nu(\Omega)\, dA\ c\ dt\ d\Omega\, d\nu$$

but within dt all radiation will pass out of the cylinder, then :

$$dE = I_\nu dA\ d\Omega\ dt\ d\nu$$

The specific energy density is defined as :

$$u_\nu(\Omega) = \frac{I_\nu}{c}$$



Integrating the specific energy density over solid angles :

$$u_\nu = \int u_\nu(\Omega) d\Omega = \frac{1}{c}\int I_\nu d\Omega$$

or $u_\nu = \frac{4\pi}{c} J_\nu$

The mean density is defined as :

$$J_\nu = \frac{1}{4\pi}\int I_\nu d\Omega$$

The total radiation density is given by

$$u = \int u_\nu d\nu = \frac{4\pi}{c}\int J_\nu d\nu$$

Radiative transfer

We use radiative transfer each time a radiation is passing through a matter and add (absorption) or subtract (emission) energy.

I- EMISSION

The spontaneous emission coefficient is defined as the energy emitted per unit time per unit solid angle per unit volume, such as :

$$dE = j\, dV\, d\Omega\, dt$$

If the emission is monochromatic (e.g., an emission line), we can define a monochromatic emission coefficient :

$$dE = j_\nu dV\, d\Omega\, dt\, d\nu$$

If the emission is isotropic, then :

$$j_\nu = \frac{1}{4\pi} P_\nu$$

where P_ν is the radiated power

We can also define the emissivity as the energy emitted per unit frequency per unit time per unit mass, and rewrite the transmitted energy in an isotropic emission as :

$$dE = \epsilon_\nu \rho\, dV\, dt\, d\nu\, \frac{d\Omega}{4\pi}$$

For an isotropic emission, the relation between the emission coefficient and the emissivity is given by :

$$j_\nu = \frac{\epsilon_\nu \rho}{4\,\pi}$$

Considering a beam of cross-section dA traveling through a volume $dV = ds \times dA$, then the energy added by spontaneous emission is :

$$dI_\nu = j_\nu\, ds$$

(Remember that $dE = I_\nu\, dA\, dt\, d\nu\, d\Omega$)

Radiative transfer

We use radiative transfer each time a radiation is passing through a matter and add (absorption) or subtract (emission) energy.

II- ABSORPTION

The absorption coefficient is defined as the loss of intensity in a beam as it travels a distance ds :

$$dI_\nu = -\alpha_\nu \, I_\nu \, ds$$

The absorption depends on the density of absorbers along the travel of a beam.

If we assume a random distribution of absorbers, each of them with a cross section σ_ν and a density per unit volume n, then the effect of these absorbers on a radiation passing through dA within a solid angle $d\Omega$ is :

$$dE = -dI_\nu \, dA \, dt \, d\Omega \, d\nu$$

or : $dE = I_\nu (n \, dA \, ds \, \sigma_\nu) d\Omega \, dt \, d\nu$

Therefore :

$$dI_\nu = -n \, \sigma_\nu \, I_\nu \, ds$$

We can rewrite the absorption coefficient such as :

$$\alpha_\nu = n \, \sigma_\nu$$

Usually, α_ν is defined with the opacity (also known as the mass absorption coefficient) such as :

$$\alpha_\nu = \rho \, \kappa_\nu$$