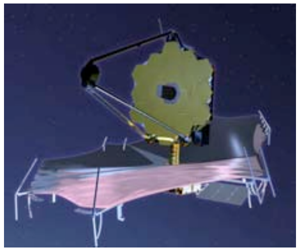


The First Stars

M. Stiavelli

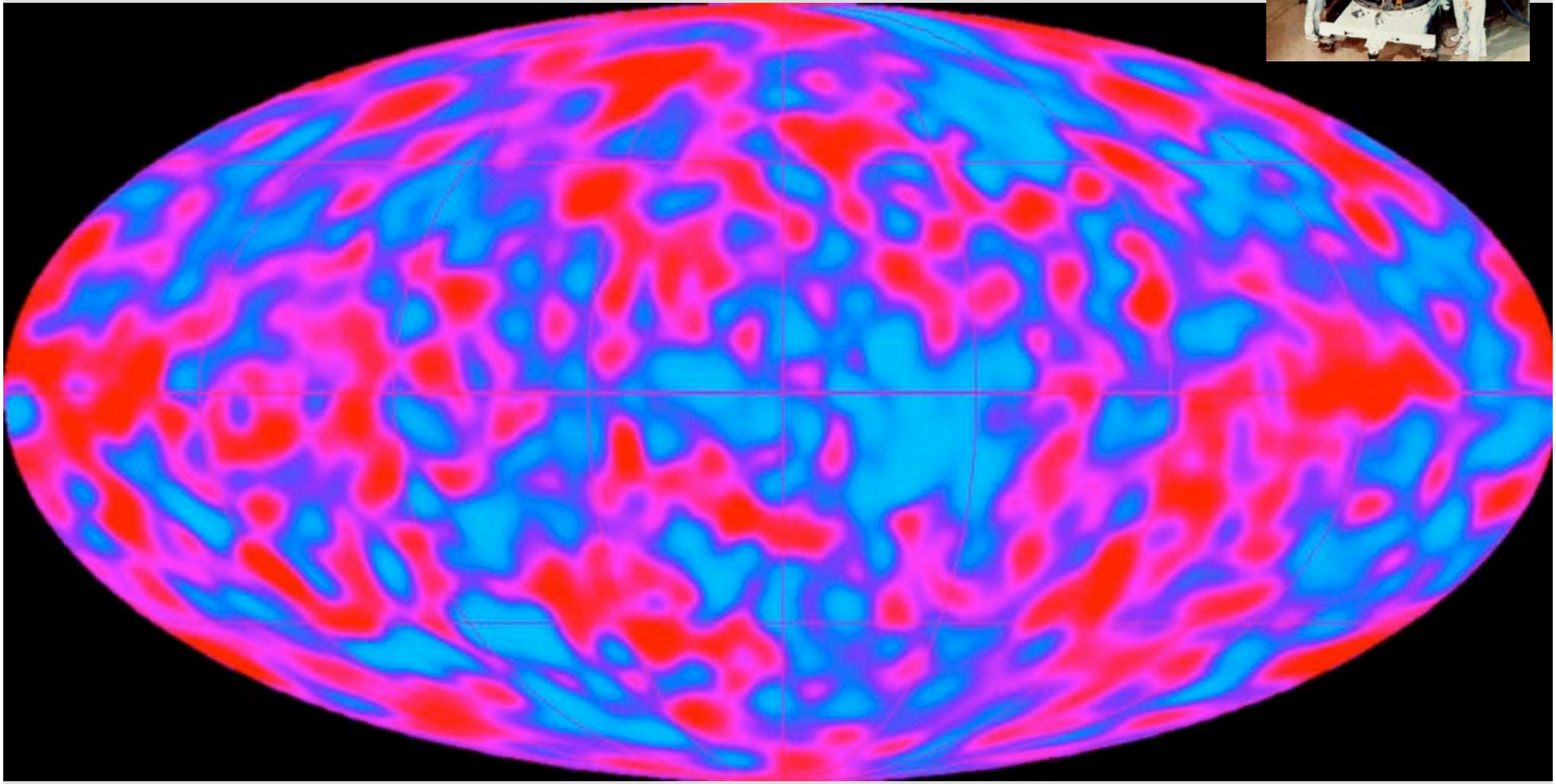
STScI, Baltimore

Plan:

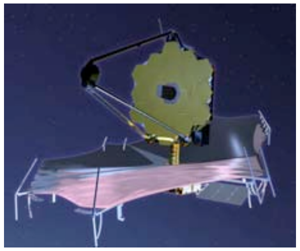
- Brief overview of cosmic history
- Meet Hydrogen
- How do you cool a gas cloud?
- The first stars

The Universe at redshift 1300

COBE satellite

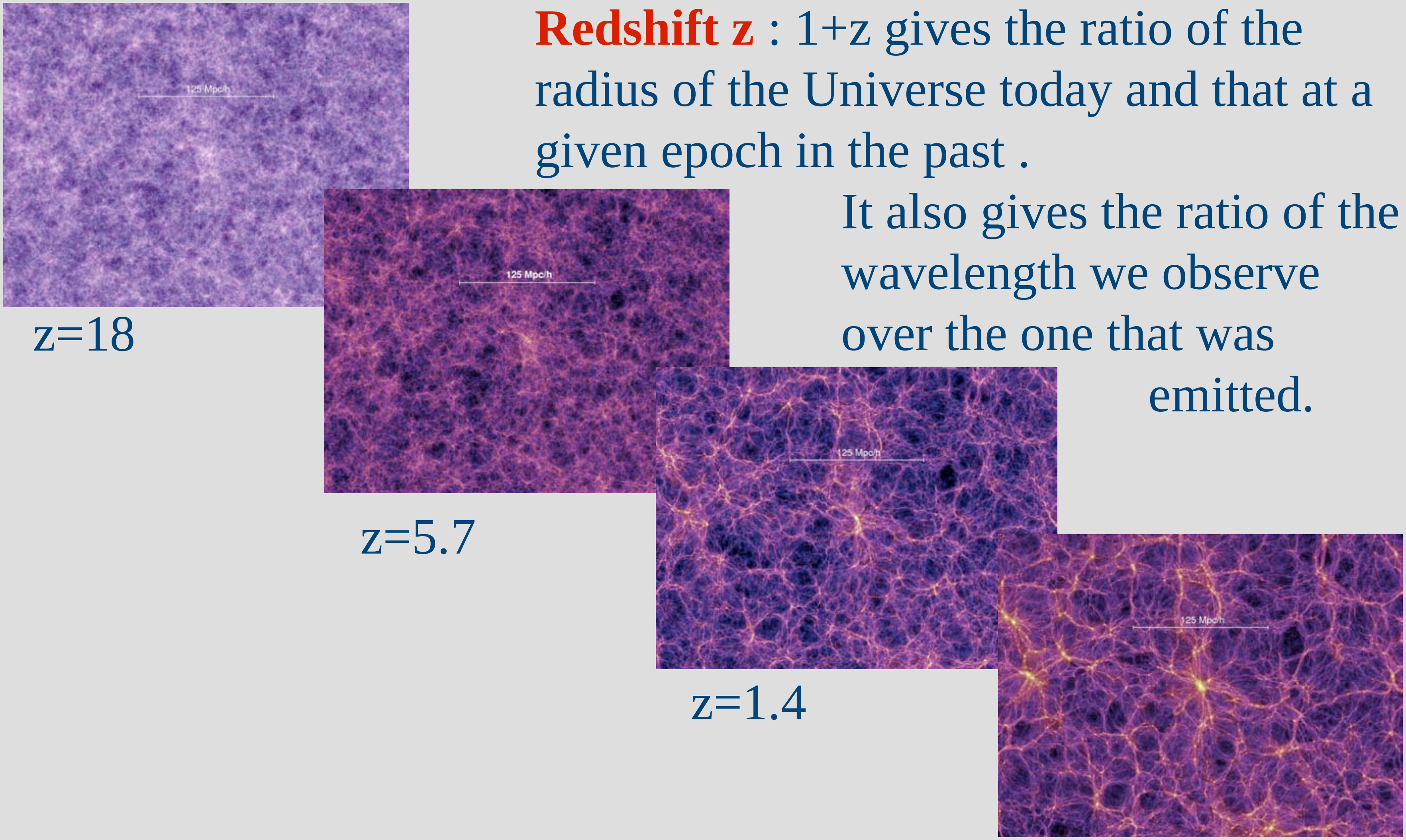


Perturbations



Redshift z : 1+z gives the ratio of the radius of the Universe today and that at a given epoch in the past .

It also gives the ratio of the wavelength we observe over the one that was emitted.



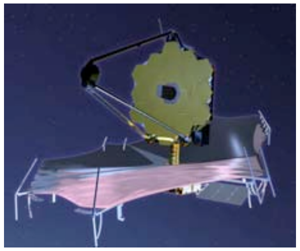
z=18

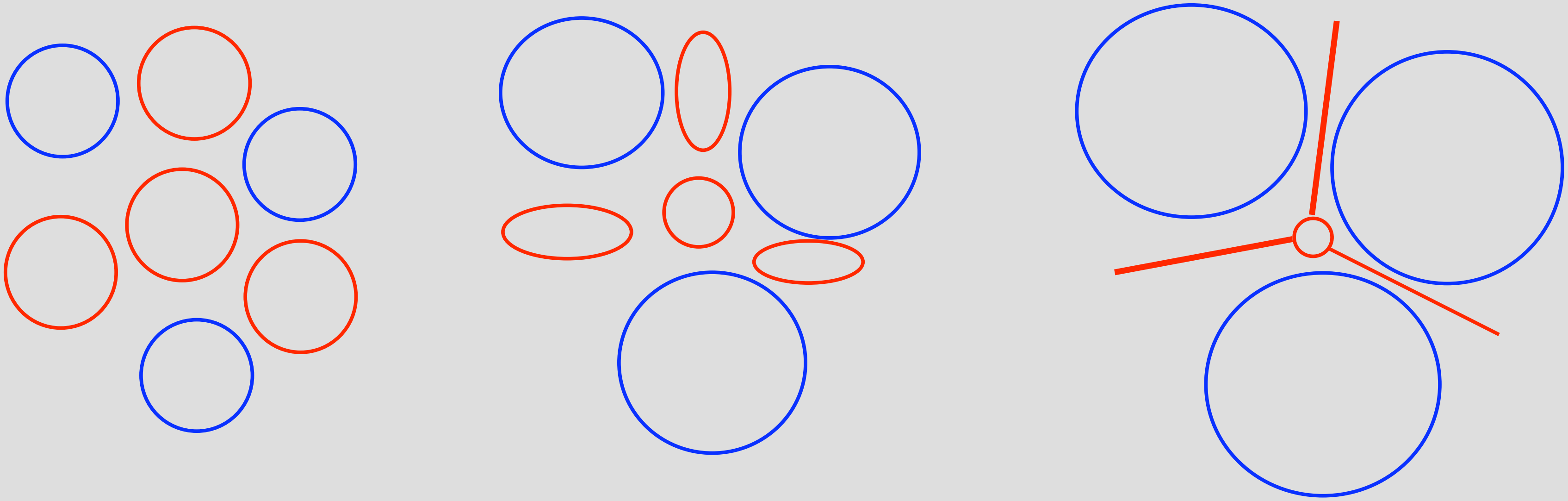
z=5.7

z=1.4

z=0

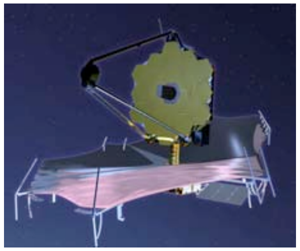
Growth of perturbations





Underdensities grow like miniature Universes. The expand becoming rounder. **Overdensities** collapse and can become flattened or filamentary.

Forming a star



The mean density of gas in the Universe is ~ $4 \times 10^{-31} (1+z)^3$ g cm^{-3} - at z~10 this is like distributing an ice cube over the volume of the Earth.
The mean density of the Sun is similar to that of water ~ 1 g cm^{-3}

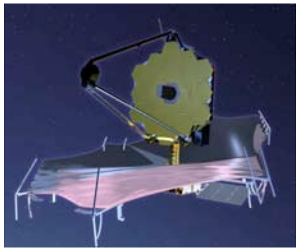
What mechanism can compress gas by 27-30 orders of magnitude to form a star?

No single mechanism can do it!

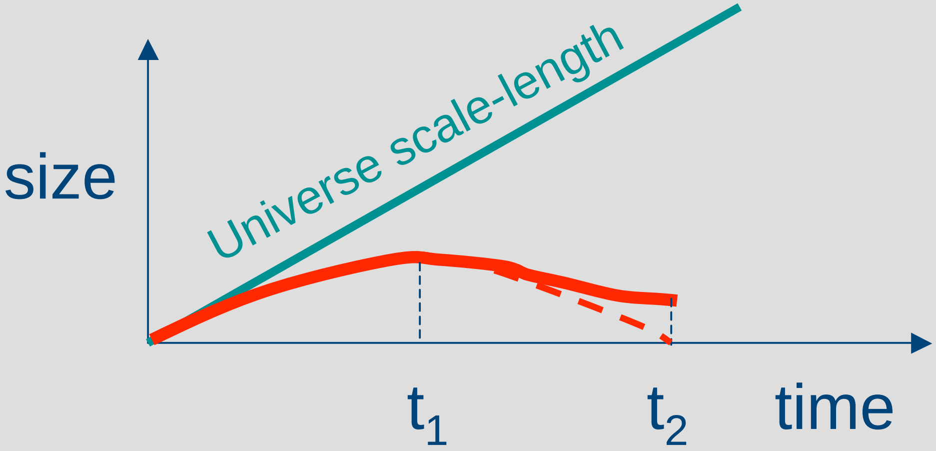
- overdense structures collapse under the pull of gravity
- they reach a virialized equilibrium state where the pull of gravity is balanced by gas pressure from the now warmer gas
- gas cools until the system becomes gravitationally unstable (Jeans instability)
- the collapse is halted by heat sources at the center and a star forms

In the following, we will review these mechanisms.

Structures at high redshift



Let‘s focus on the evolution of an overdensity.

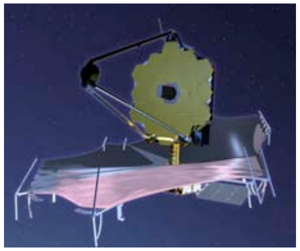


Gravity for the structure we are considering is stronger than for other similar volumes because it is overdense. Thus, it slows down its expansion and ultimately it stops expanding. We call this *turnaround.*

t_1 is the turnaround time, the collapse time $t_2 = 2\ t_1$

At turnaround the perturbation has a density $9\pi^2/16 \sim 5.55$ times higher than the Universe. It has some potential energy but no kinetic energy. Thus nothing compensates gravity and it begins to collapse.

Structures at high-z - cont’d



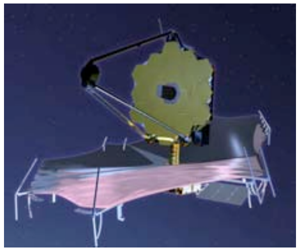
The virial theorem states that for a self-gravitating equilibrium system there is a simple relation between kinetic energy and gravitational potential energy:

$2K + W = 0$

Here K includes internal motions of the gas = heat. As the system collapses |W| increases and so does K: the sytems heats up.

No further collapse is possible unless the system can cool → reduce K → $2K+W \neq 0$ → collapse restarts.

Structures at high-z - cont'd



$W \sim -G\,M^2 / R$ with M the mass of the system and R its radius

$K \sim N\,T$ where the number of particles N = M/m with m mean mass of each atom

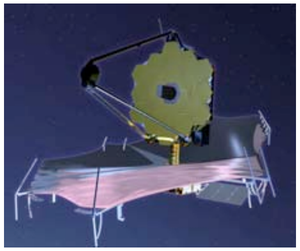
The virial theorem requires 2K+W = 0

To understand what this means let's represent W and K graphically.

M	●	●●
W	●	●● ●●
2K	●	●●
2K+W	0	●●

Increasing the mass, W grows faster than K. A system in equilibrium at some mass is no in equilibrium for a larger mass.

Structures at high-z - cont’d



$W \sim -G M^2 / R$ with M the mass of the system and R its radius

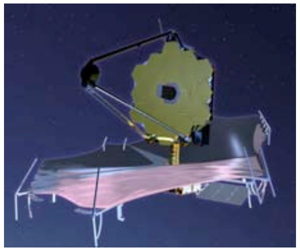
$K \sim N T$ where the number of particles N = M/m with m mean mass of each atom

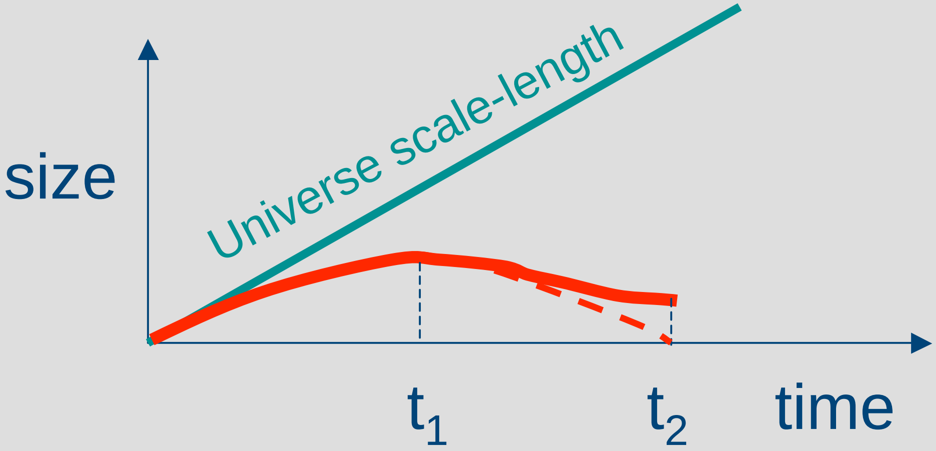
If the radius R is constant, the virial theorem implies that T is proportional to M.

However, the radius changes like $M^{1/3}$ so that $T \sim M^{2/3}$ → More massive halos are hotter.

$$T_{vir} = 2525\mathrm{K}\left(\frac{M}{10^6 M_\odot}\right)^{2/3}\left(\frac{1+z}{31}\right).$$

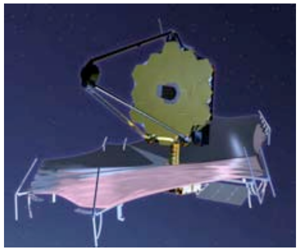
Structures at high-z - cont’d





When the perturbation virializes at collapse time its density increases by another factor of 8 but the density of the Universe will have decreased by another factor 4 so that the perturbation has now a density ~5.55 × 8 × 4 ~ 179 times higher than the Universe.

Cooling

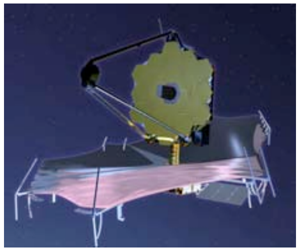


In our everyday experience cooling generally occurs by thermal conduction to a colder object. Heat flows from the warm to the cold object and the warm object cools.

However, an object can cool radiatively, emitting light (e.g. infrared light). In our homes normal light bulbs cool radiatively. The filament heats because of its resistivity to an electric current and cools radiatively. Indeed, the filament is in vacuum (otherwise it would burn).

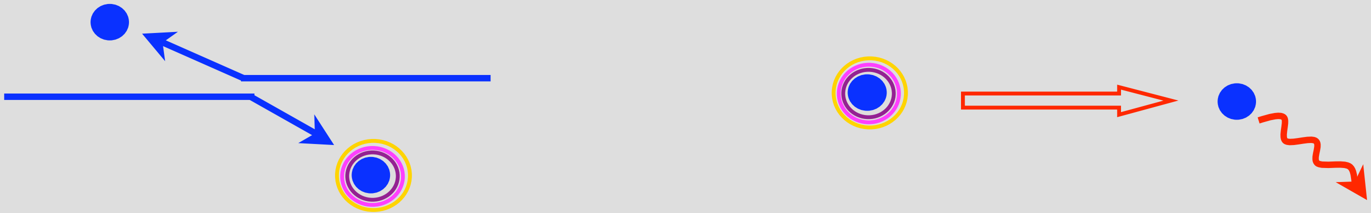
Thus, unlike thermal conduction, radiative cooling can happen in vacuum and is the most important cooling mechanism in space.

How do you cool a gas cloud?



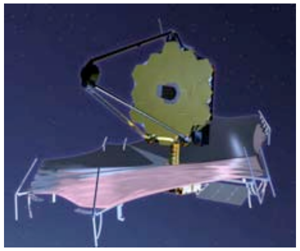
At the microscopic level and for an isolated gas cloud cooling means radiating away kinetic energy. Let’s consider the collision of two atoms:

If the energy is sufficient to excite an atomic energy level…



This excited level decays to the ground state emitting a photon carrying away the energy, i.e. cooling the gas.

This is what happens in the filament of a light bulb. In fact, atoms in the filament are arranged in a crystal and they have so many energy levels that it is very easy for collisions to excite one level and produce light.



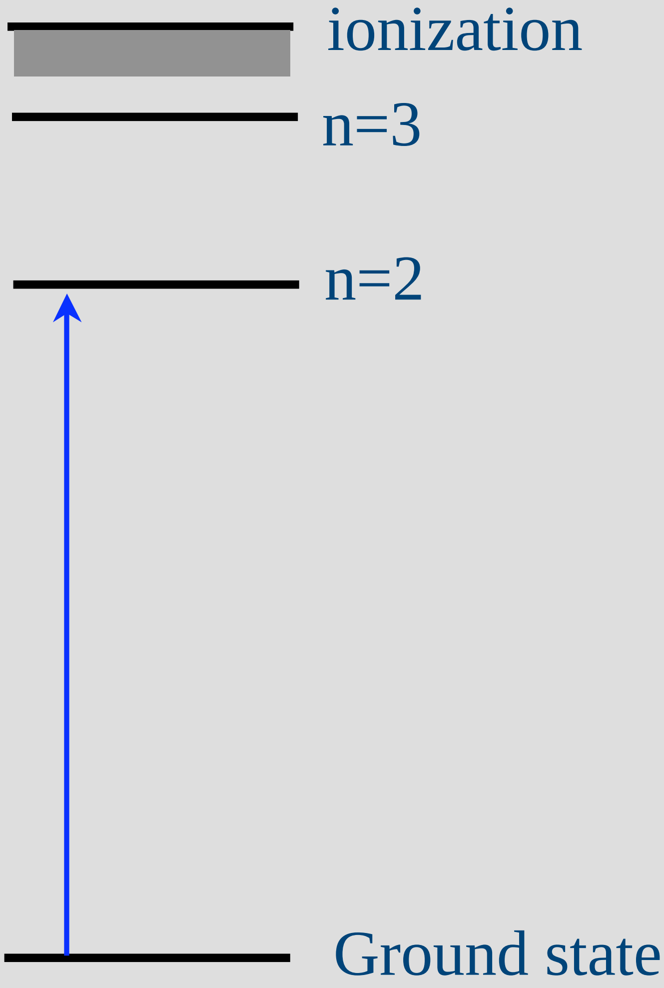
Meet Hydrogen

Hydrogen is the most common element in the Universe (> 90% in number).

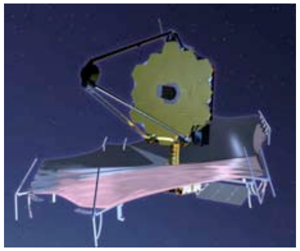
The energy necessary to reach its first energy level is 10.2 eV. This is just below the energy that an electron acquires when accelerated by 7 AA batteries connected one after the other.

This energy corresponds to temperatures of about 100,000 K.

When the temperature is much below 100,000 K most hydrogen will be in the ground state.



How do you cool then?



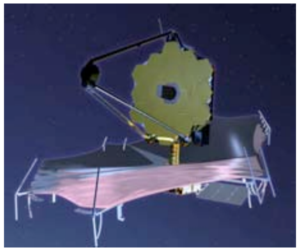
Helium requires even higher energies and other elements are too rare to make a difference.

In the proper conditions one can form molecular Hydrogen: H_2.

H_2 has extra transitions and it can cool gas even at temperatures in the range 100-1000 K.

H_2 cools more efficiently when the temperature is higher and becomes progressively less efficient at lower temperatures.

The mass of cooling structures



The ability of gas in a structure to cool depend on its mass. To define what cools and what doesn't, one compares the time to the age of the Universe at the redshift we are considering. If the time to cool is longer than the age of the Universe the structure cannot cool.

Virial theorem → more massive structures are hotter.

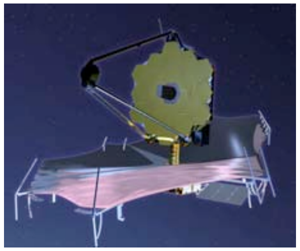
Thus:

- halos of larger mass require less molecular hydrogen to cool and cools more easily

However:

- halos of lower mass are more common at any given redshift

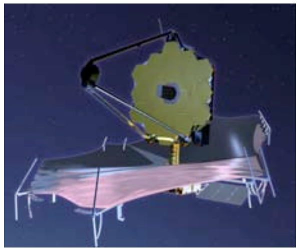
The mass of cooling structures



In practice the first stars will form from the smallest structures able to cool. These are structures with mass between a few 10^5 and 10^6 solar masses and they will form the first stars in the Universe.

The gas in these structures begins to slowly increase its density as it cools since cooling removes kinetic energy that compensates gravity.

The Jeans Mass



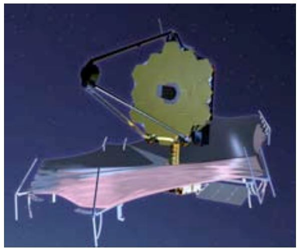
The gas will not form a star until it has cooled enough to become Jeans unstable.

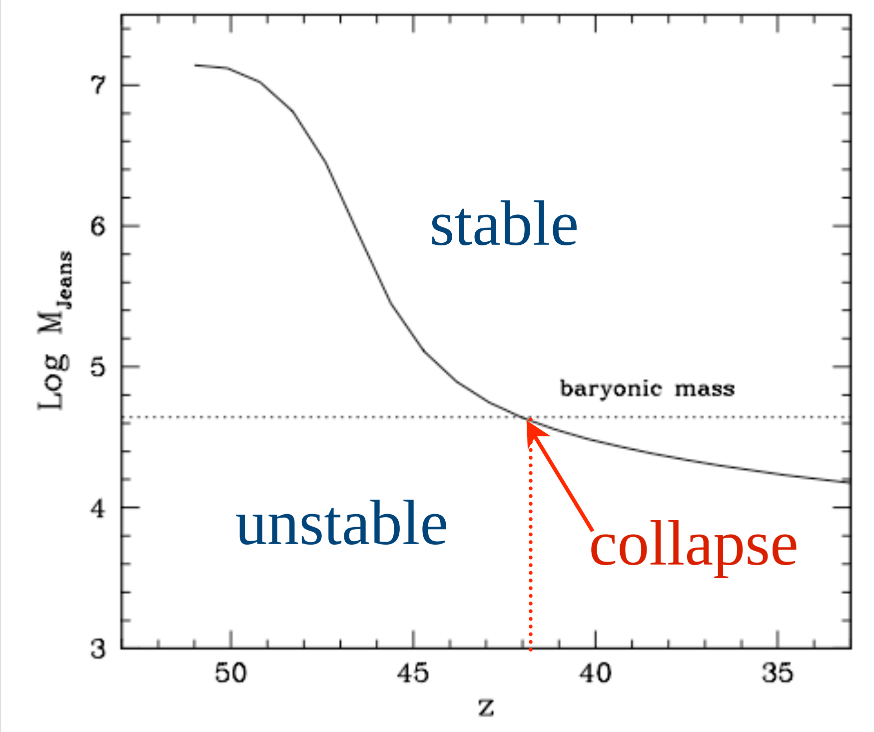
For masses below the Jeans mass a compression of the gas will generate enough extra pressure to compensate the increase in gravity and the gas will begin expanding and start a series of oscillations.

For masses above the Jeans mass a compression does not generate enough pressure to compensate the increase in gravity and the gas continues to collapse.

$$M_J = \frac{\pi}{6}\rho^{-1/2}\left(\frac{\gamma\pi kT}{G\mu m_p}\right)^{3/2},$$

How many stars per halo?

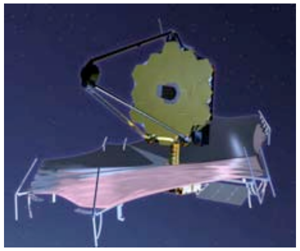


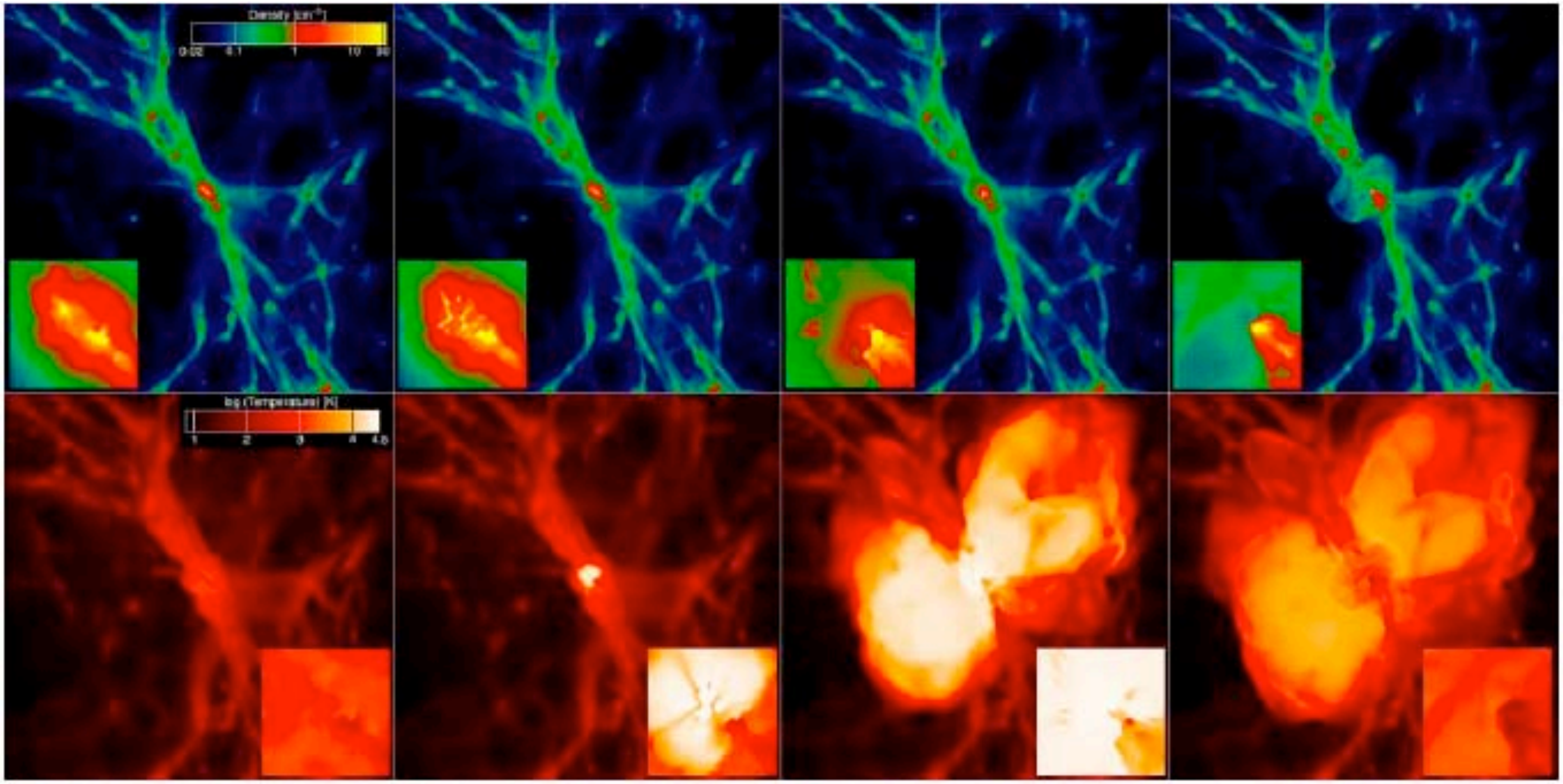


One can model the cooling and track the Jeans mass as it decreases. When the Jeans mass equals the total gas mass available in the halo the system can collapse.

At the moment the system becomes unstable one can estimate the timescale for further cooling with the collapse time scale. If collapse is faster than further cooling, only one star will form and this is the case for masses below 10^6 solar masses. The star will be massive.

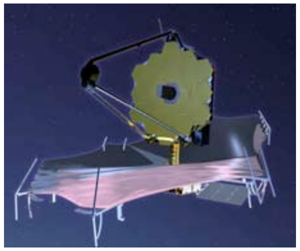
A star is born





Density and temperature of gas around a first star. From left to right the images refer to a time 0, 1, 2.7, and 8 Myrs after its formation.

Paving the way for the first galaxies

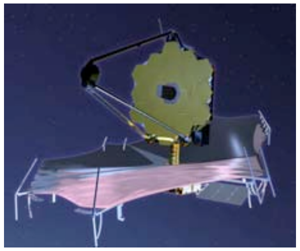


The first stars will enrich the Universe with heavier chemical elements (“metals”) and will produce the first black holes.

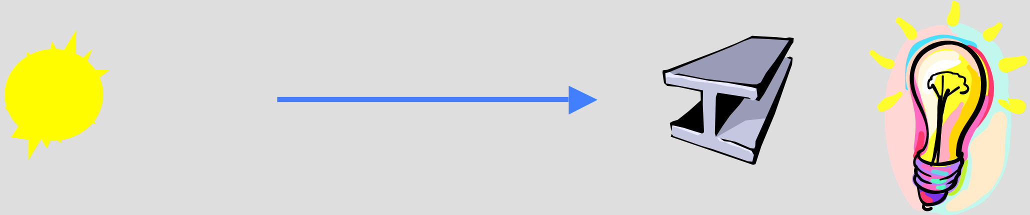
After the first and possibly second generation of stars gas in the Universe begins to have metallicities different from primordial. The additional metals change the way gas cools and make the formation of smaller mass stars easier.

The first galaxies probably formed at $z \geq 10$ while the present observational boundary is $z \sim 6$.

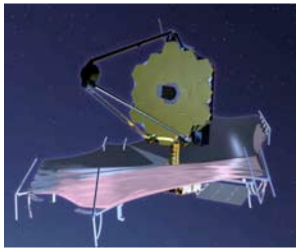
The role of metallicity



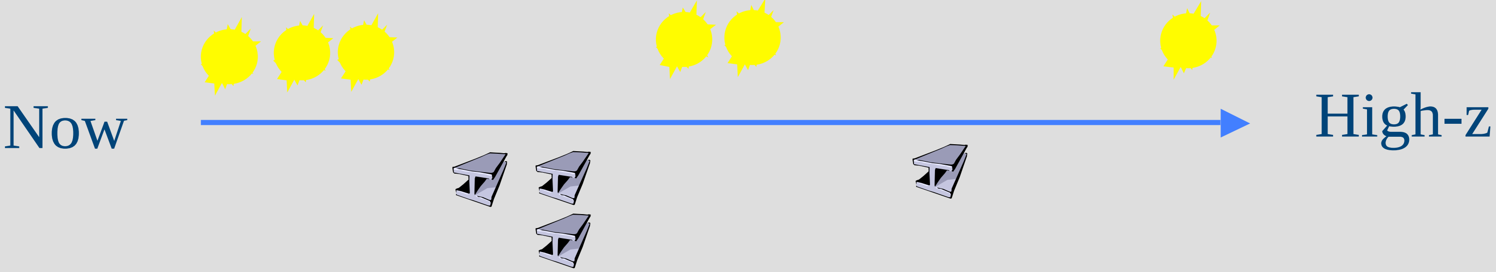
When stars fuse hydrogen into heavier elements, they produce both energy and metals.



The first stars have practically no metals but during their lifetime they produce metals. Some end their life as black holes others undergo a supernova explosion and enrich the Universe with metals.



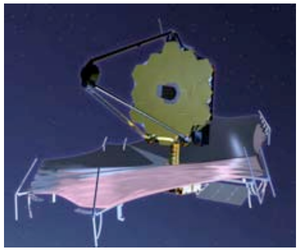
Early in the life of the Universe when only few generations of stars had been formed the metallicity was very low.



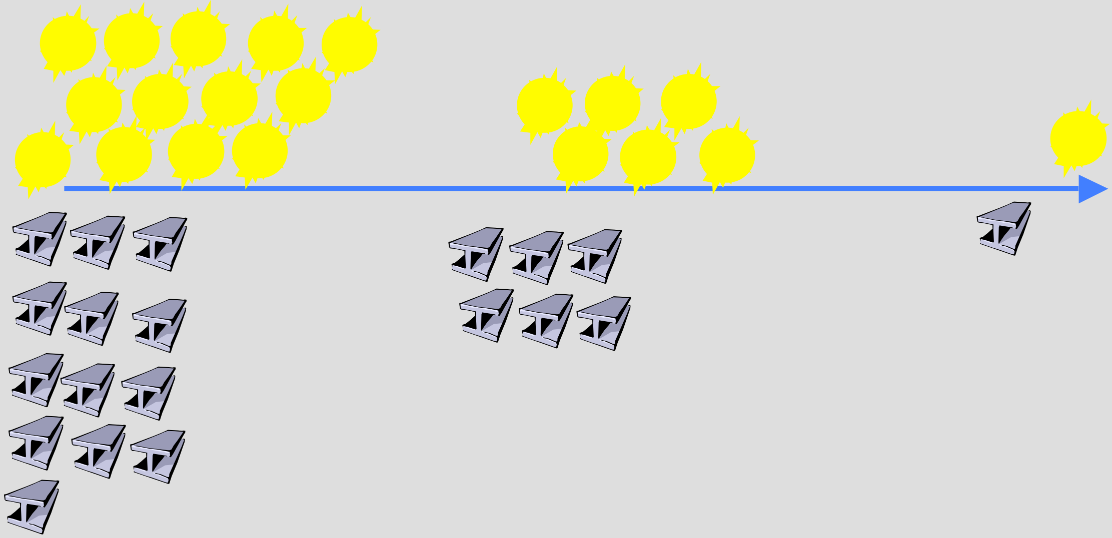
Now

High-z

Each generation of stars incorporates metals produced by the previous generations. Once the metallicity is high enough stars form as in the Milky Way.



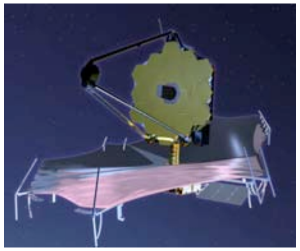
If we assume that stars formed at a constant rate over the lifetime of the Universe, there were at z=6 only 7 per cent or less of the stars we see today. Thus, the mean metallicity of the Universe was also likely (much) less than 7 per cent of the present value.



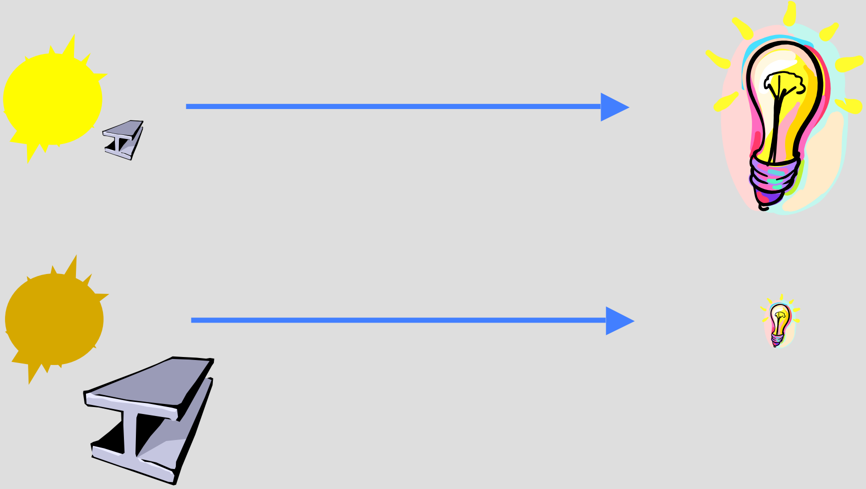
Now

z=6

Age is only
7 per cent
of present age

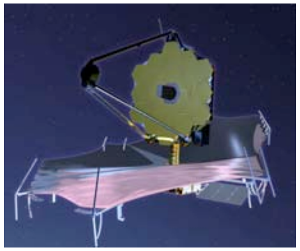


Metal poor stars are hotter and may have very different properties from present day stars.



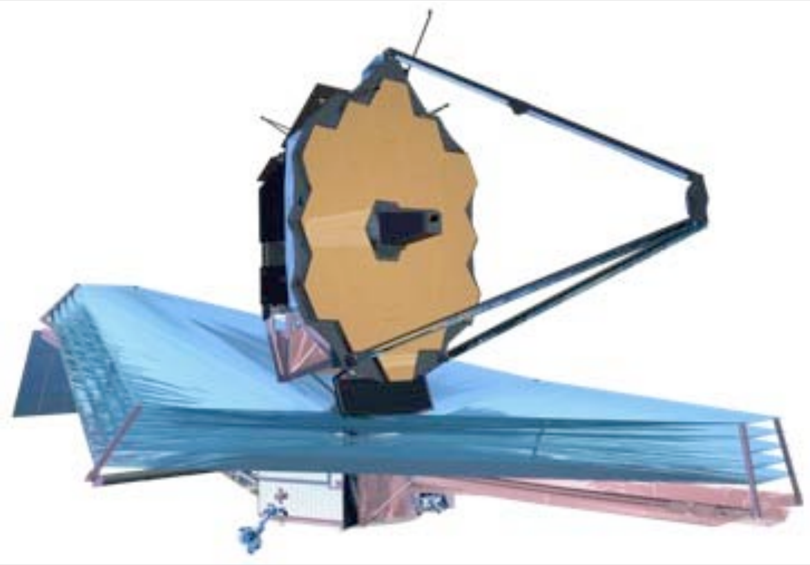
Detecting individual primordial stars is going to be very hard but it will be possible to detect primordial galaxies.

Beyond Hubble



Studying galaxies at z>10 or measuring the properties of galaxies at z=6 requires an instrument more sensitive than Hubble :

the **James Webb Space Telescope**



End of the dark ages:

- **First light**
- Nature of reionization sources