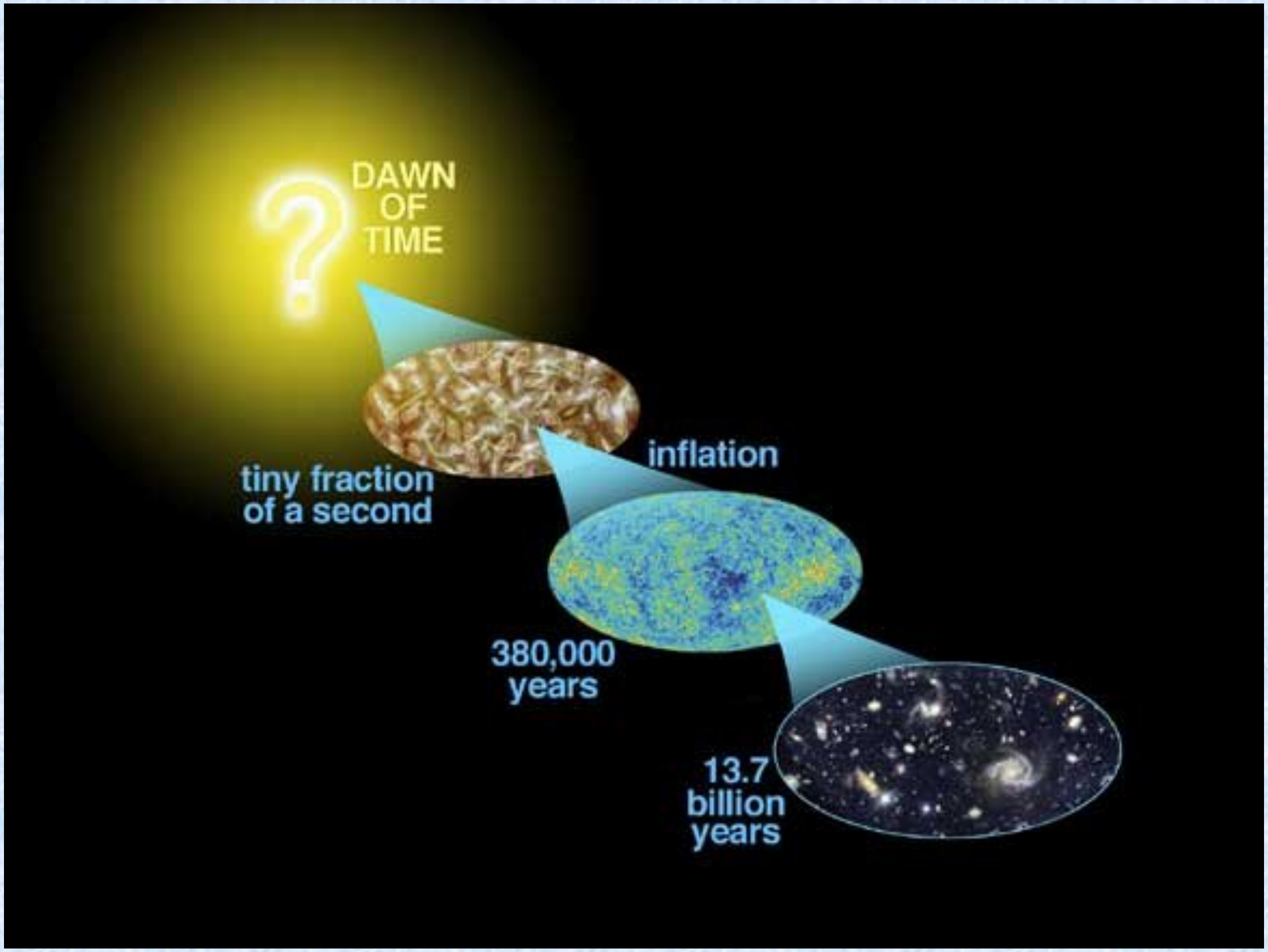
Astro-2: History of the Universe



Lecture 13; May 30 2013

Previously… on astro-2

- Energy and mass are equivalent through Einstein's equation and can be converted into each other (pair production and annihilations)
- What is the meaning of Heisenberg's principle?
- During inflation matter (and antimatter) is created using energy from the inflaton field.
- As the universe cools down matter freezes out because photons are not energetic enough to do pair production
- Some interactions are slightly asymmetric, do not conserve baryonic number, and produce more matter than antimatter, resulting in the current matter dominated universe.

Previously… on astro-2

- As the universe cooled, it left behind a certain number of neutrons and protons (1/6) as a result of weak interactions
- Neutrons are unstable. Lifetime?
- 11 minutes
- They interact strongly with protons to form stable systems. Called?
- Nuclei
- During the first few minutes the universe was hot and dense enough that it produced elements up to Li.
- After that it was too cold. What does that mean?
- The measured abundance ratio is a measure of baryonic mass density. What does it prove?
- Where are all the other elements formed?

Today.. On Astro-2.

1. Galaxy formation
    1. Jeans instability
    2. Cold vs hot dark matter
    3. Disk and spheroid formation
2. Observations of high redshift galaxies
    1. First light. Reionization
    2. The most distant galaxies
    3. Gunn-Peterson effect

Jeans instability.

- Do you remember when we talked about the mass of galaxies?
- Why are elliptical galaxies not collapsing even if they are heavy?
- What counteracts gravity?
- Pressure
- Given a certain mass, in order to be in equilibrium it must be “hot” enough to counterbalance gravity (remember the balloon vs elliptical galaxy analogy?)

When does gravity overcome pressure?

- This problem has been worked out in detail in the early XX century by British Physicist James Jeans, and therefore it is called "Jeans instability"
- Given a certain volume, and temperature there is a maximum mass that it can support, this is called the Jeans mass
- Similarly, given a temperature and a density there is a maximum size for such a cloud to be stable, called the Jeans length

When does gravity overcome pressure?

- Consider a cloud of particles of individual mass m, at a temperature T, and density density ρ_m
- The Jeans length is:
- $L_J=\sqrt{\pi}\ kT/mG\ \rho_m$
- Where k and G are?
- Similarly the Jeans mass is?
- $M_J \sim\ \rho_m L_J^3 \sim T^{3/2}/(\rho_m m)^{1/2}$
- [MOVIE!]

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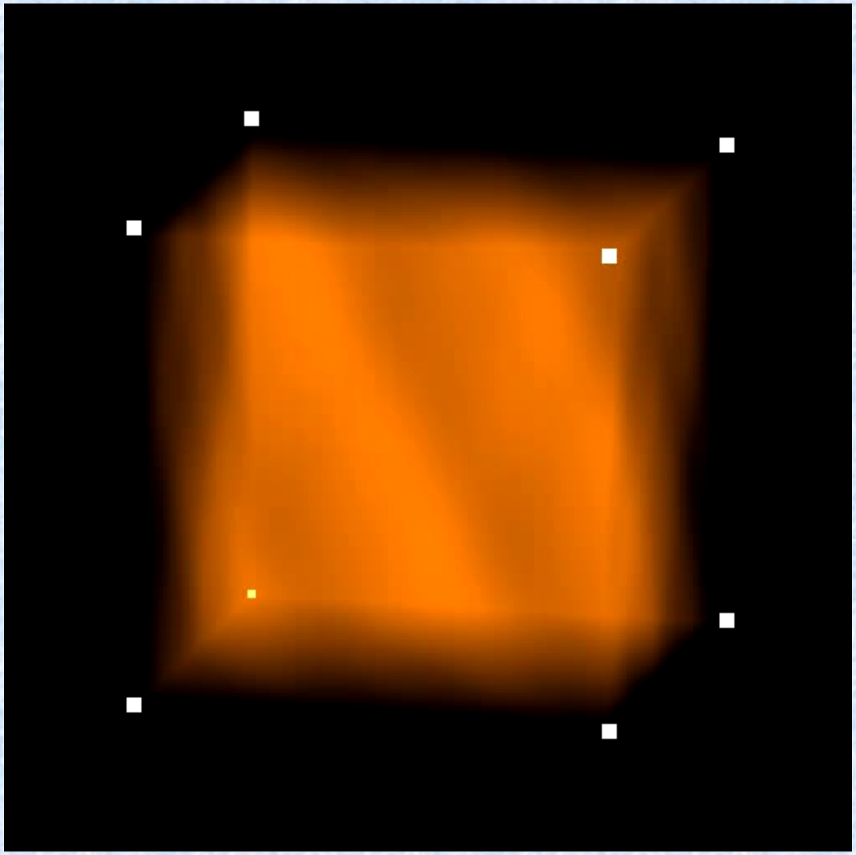
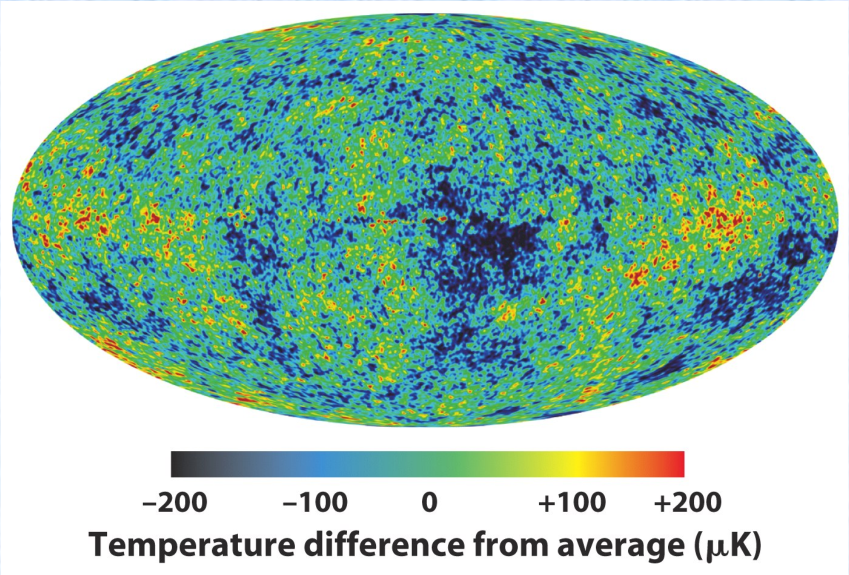


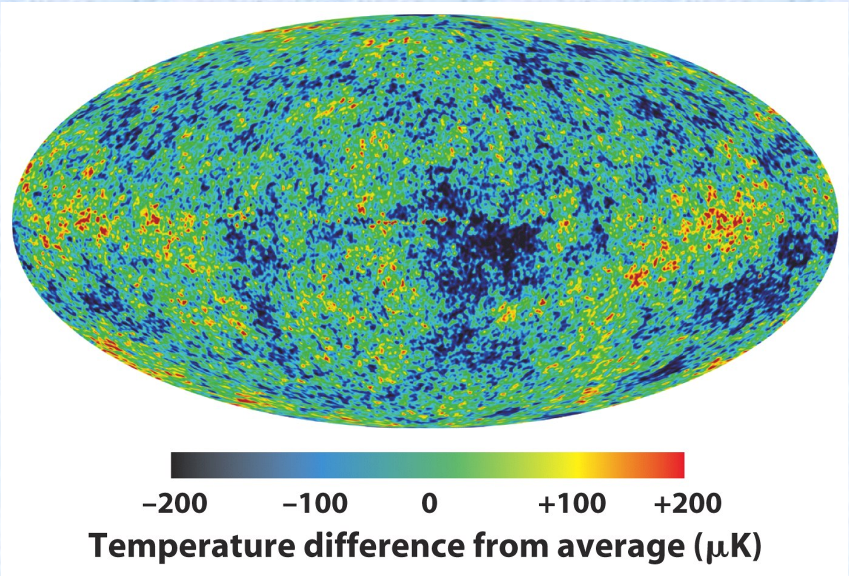
What does this have to do with the early universe?

- Inflation not only flattens and homogenizes the Universe, but it also amplifies quantum fluctuation, leaving behind small but macroscopic homogeneities, that are seen in the anisotropies of the CMB.
- At what redshift?
- ~1000 (recombination or decoupling)



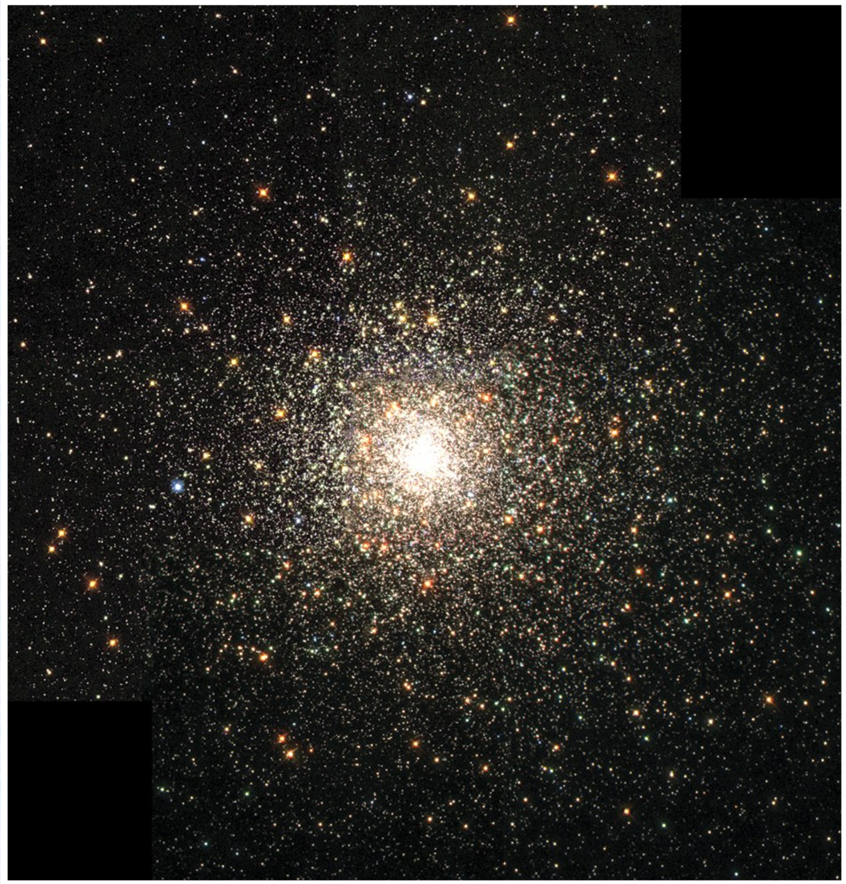
What does this have to do with the early universe?

- Before decoupling, the Jeans length is very large, since temperatures are high and photons have zero mass (and so large “sound speed”)
- You can’t use the same expression, obviously for photons, why?



But… after decoupling…

- The sound speed suddenly drops!
- For T=3000K, density of $10^9\ \rho_{crit}$ [why?] the Jeans mass and Jeans lengths are:
- 10^5 solar masses and 100 light years
- The first "objects" that collapsed are the size of a globular cluster.
- Those are the building blocks of modern structures

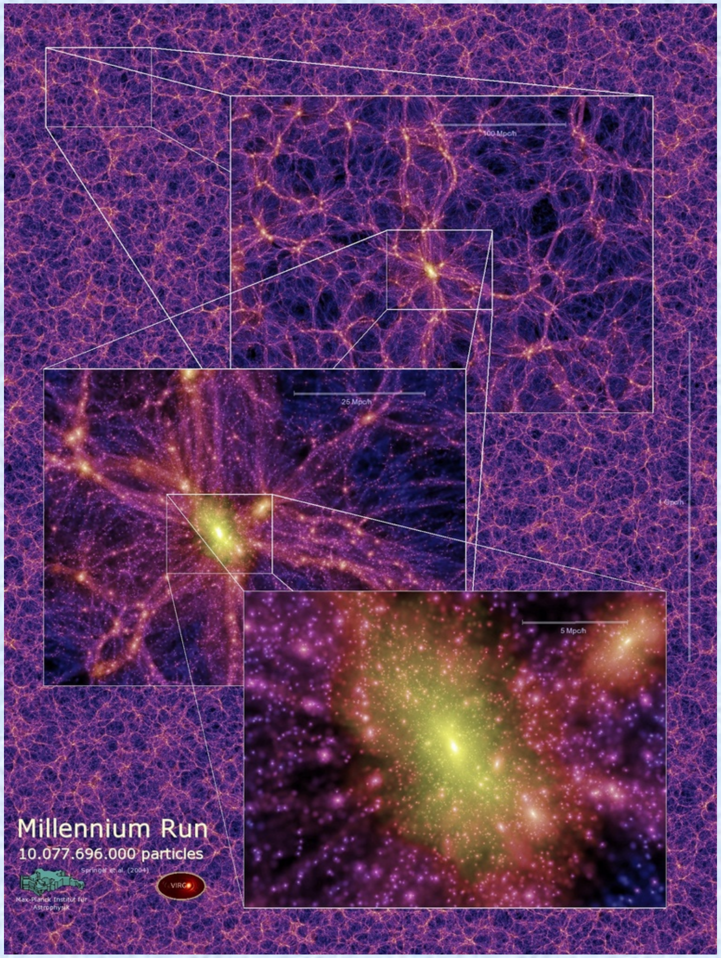


Jeans instability. Summary

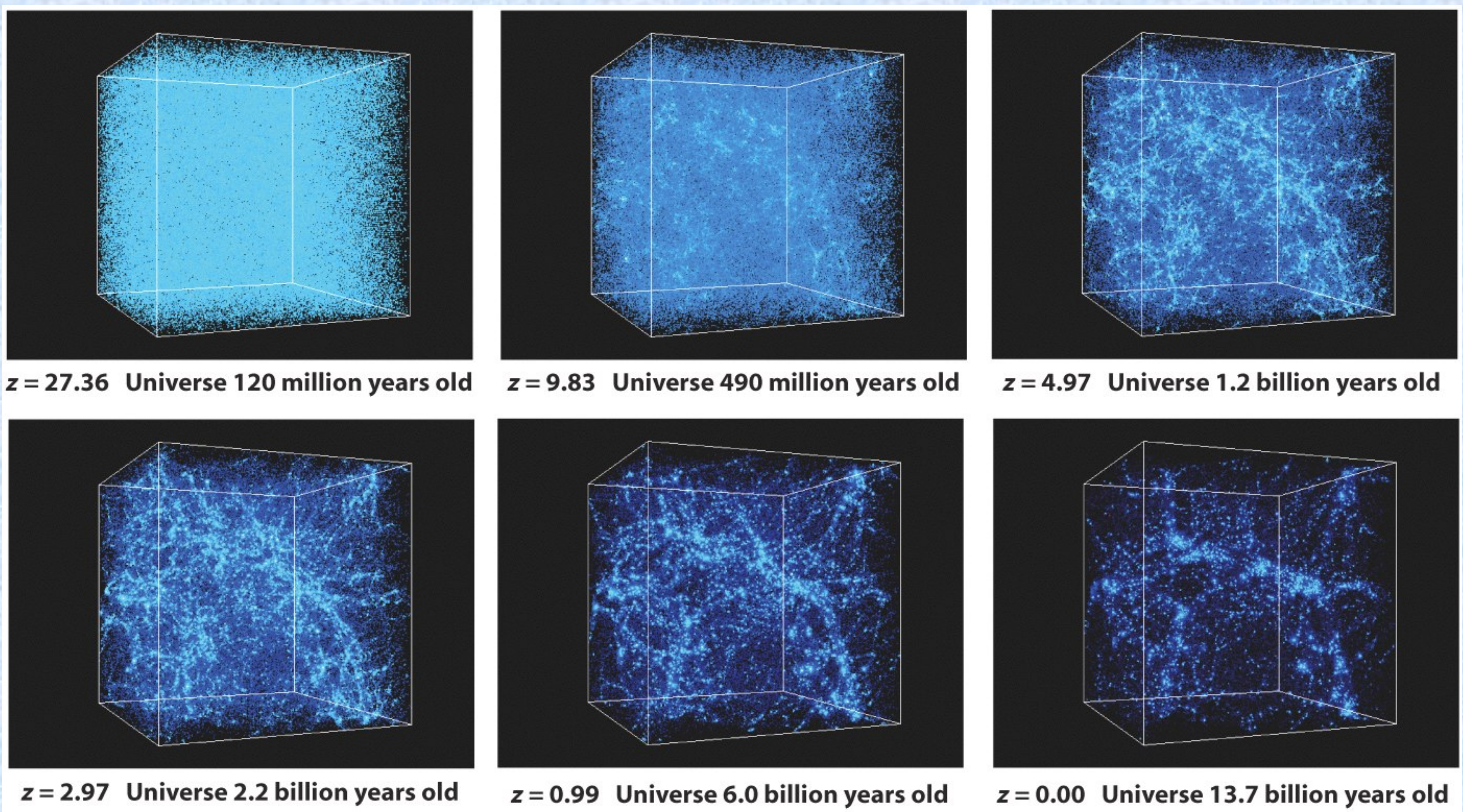
- Jeans instability arises when a self-gravitating object is heavier than its pressure can support
- After inflation small quantum fluctuation are amplified to macroscopic scales and we see them as anisotropy in the CMB.
- Before decoupling they do not collapse because radiation is keeping the sound speed very high.
- After decoupling, chunks of the universe of about 100,000 solar masses become Jeans unstable and form the first “objects” in the universe.

The growth of structure

- As time goes by the initial perturbations grow as a result of gravitational forces
- Dark matter dominates the mass density of the universe and thus dominates the evolution of structure.
- The growth of structure can be simulated on supercomputers
- [Show movies]

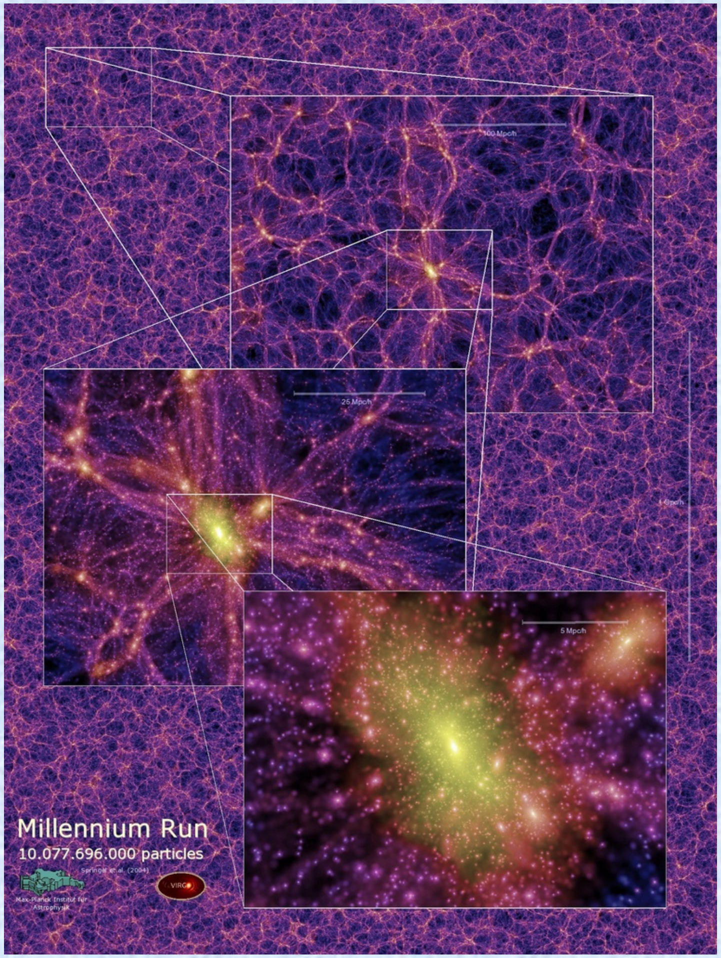


The growth of structure



The growth of structure

- The observed growth of structure is inconsistent with different form of dark matter, other than cold (i.e. mass larger than kinetic energy)
- Also, it constrains the matter content of the universe (dark energy, etc)

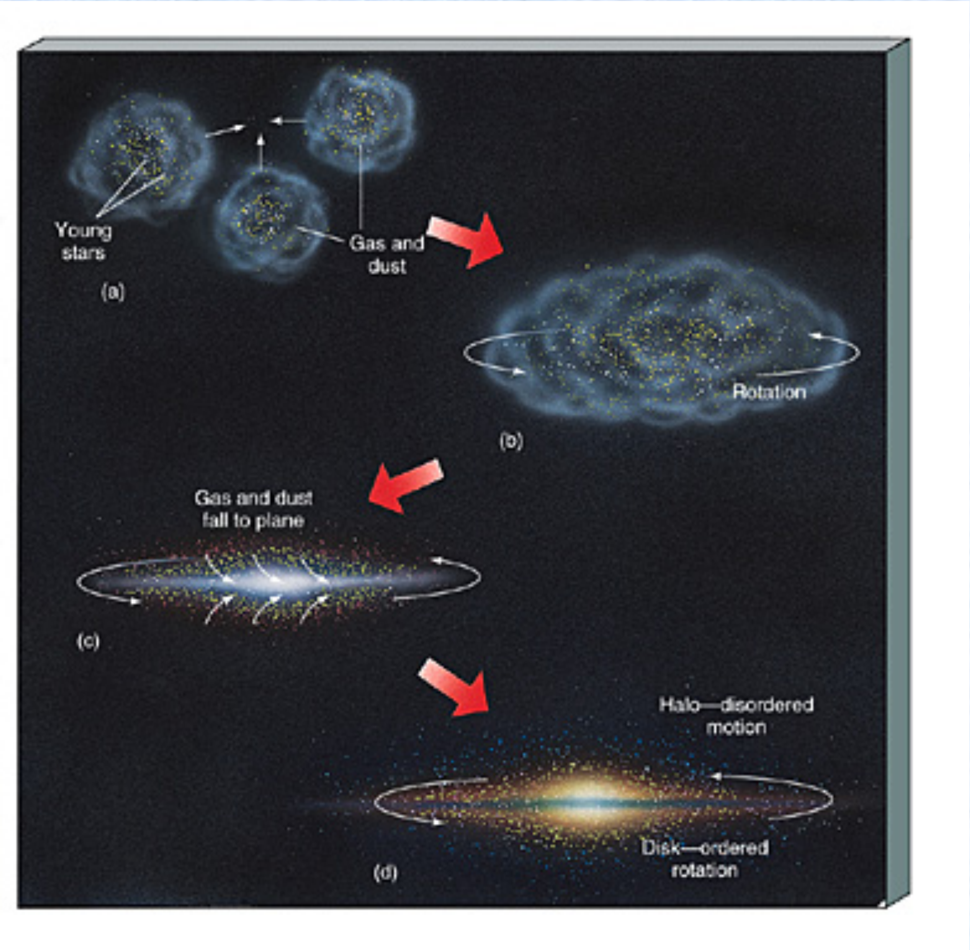


Galaxy formation

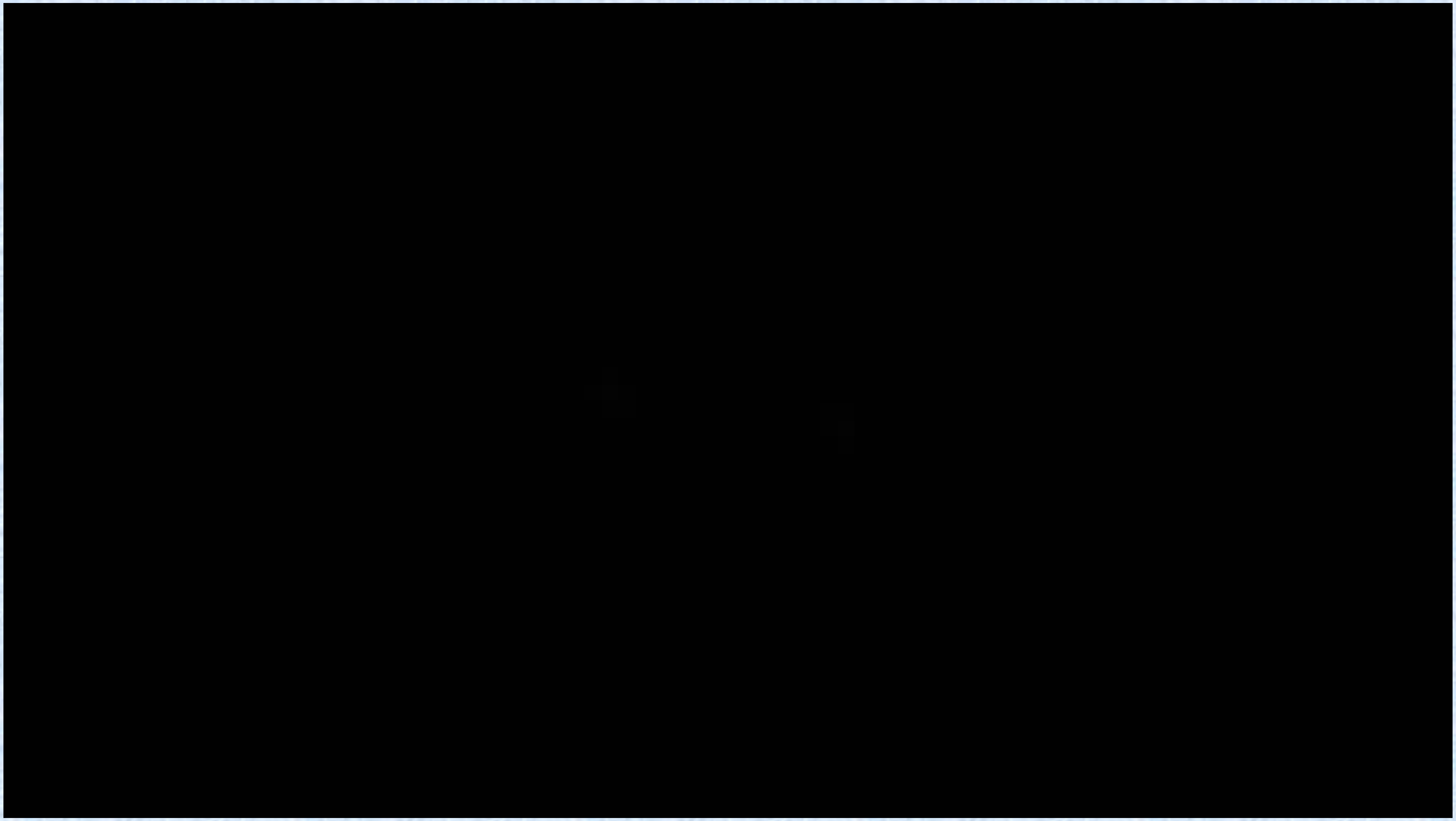
- Halo grow “bottom” up, assembling small chunks into larger and larger halos
- Inside halos there are baryons
- Torques from nearby halos spin up the halos (and the baryons)
- Baryons cool by emitting radiation and collapse because of Jeans instability
- As the baryons collapse, they need to preserve their spin and so they settle into a rotating disk

Galaxy formation. Disks

- How do stars form?
- Jeans instability



Galaxy formation. spheroids



Galaxy formation. Chemical enrichment

- As stars are born, evolve and die, they disperse heavy elements in the gas between stars via supernovae winds
- New stars are born from this gas starting the cycle over and over again
- At every cycle the gas is more abundant in heavy elements which them form planets, dust, etc

Galaxy formation. An open problem

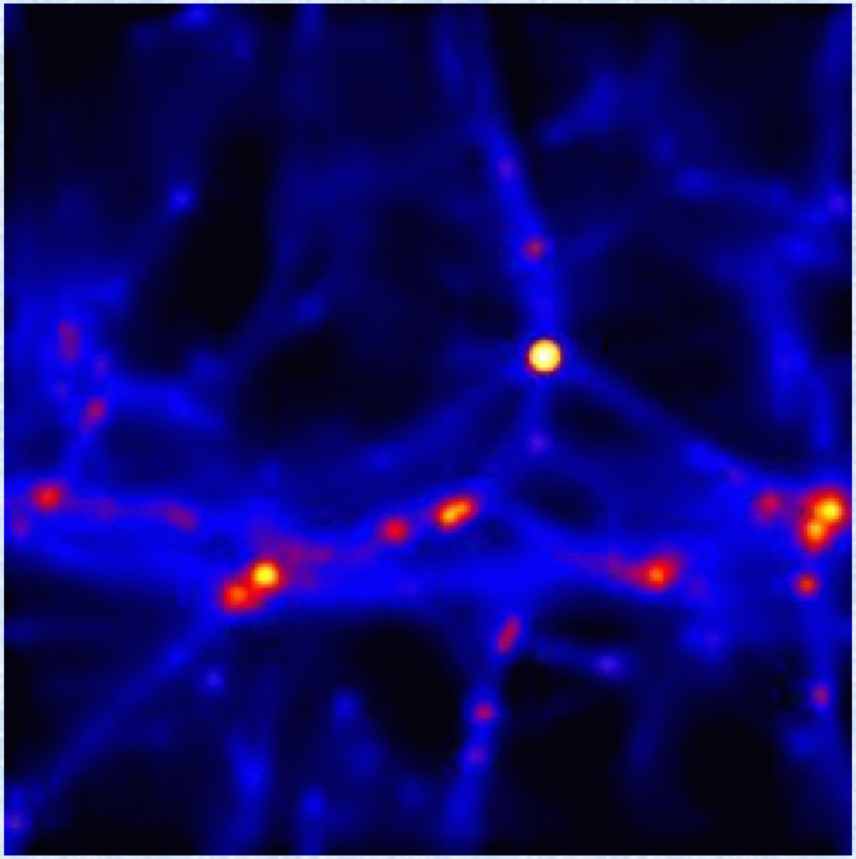
- Although the theory is quite good at Mpc scales it lacks predictive power at small scales because calculations and physics are too difficult when processes other than simple gravity are involved
- Observations do not always seem to be consistent with predictions of theory.
- For example, it is observed that the stellar populations of early-type galaxies are oldest for the most massive galaxies, as if they stopped forming stars early on.
- This is called “downsizing” and it is difficult to explain in hierarchical models, although the jury is still out.

Galaxy formation summary.

- In the currently standard picture of galaxy formation galaxies form hierarchically from the initial quantum fluctuations amplified by inflation.
- Dark matter halos grow larger and larger (bottom-up) via mergers.
- At some point baryons (mostly hydrogen) cool down sufficiently via radiation and becomes Jeans unstable collapsing into disks.
- Spheroids are formed by mergers of disks.
- The details of galaxy formation are poorly understood.

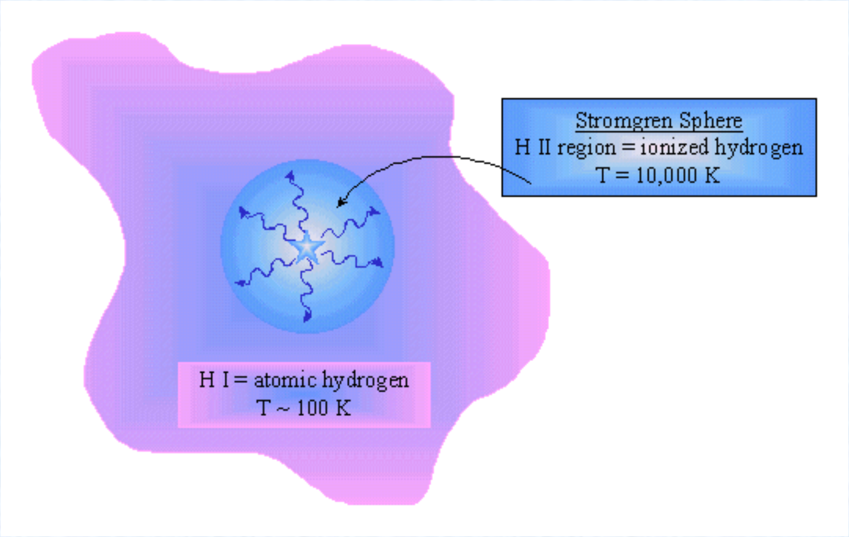
The first stars

- The first stars form out of primordial gas, with just a little Helium and Deuterium
- They are extremely massive and emit a lot of hard photons



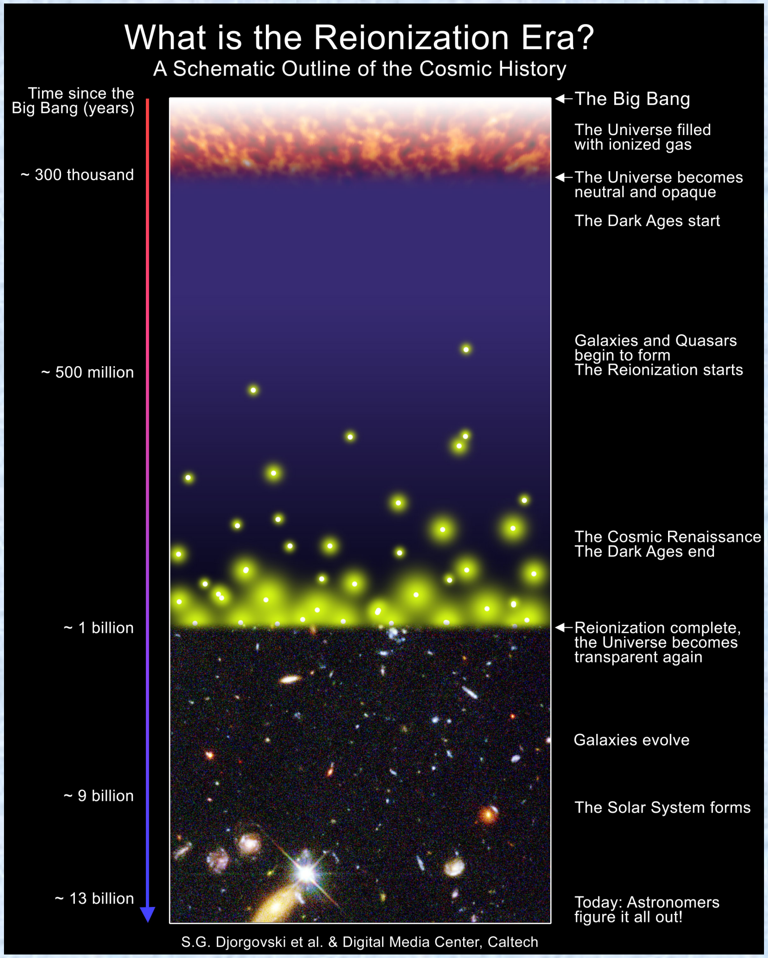
The first stars. Stromgren Spheres.

- What do hard photons from the first star encounter?
- Neutral hydrogen
- Why?
- Recombination
- Neutral hydrogen interacts a lot with hard photons and therefore it is said to be opaque
- However, the photons carve a bubble around the star of ionized hydrogen which is very transparent.



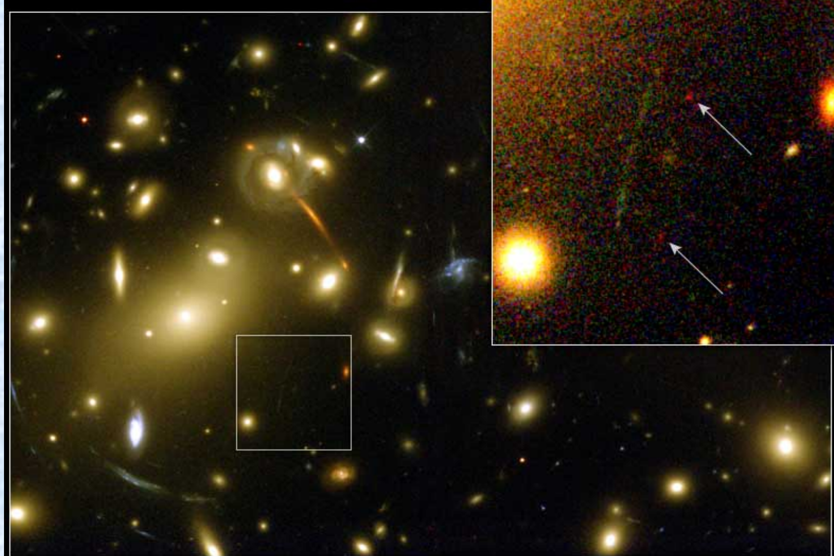
The first stars. Reionization.

- As the bubbles grow in number and size they start to overlap and slowly reionize the entire universe
- Now optical/UV photons are free to travel and they universe is now transparent again
- It is not clear whether the first stars have enough photons to do the job or if they need help from the first quasars
- This is believe to have happened at a redshift of around 10



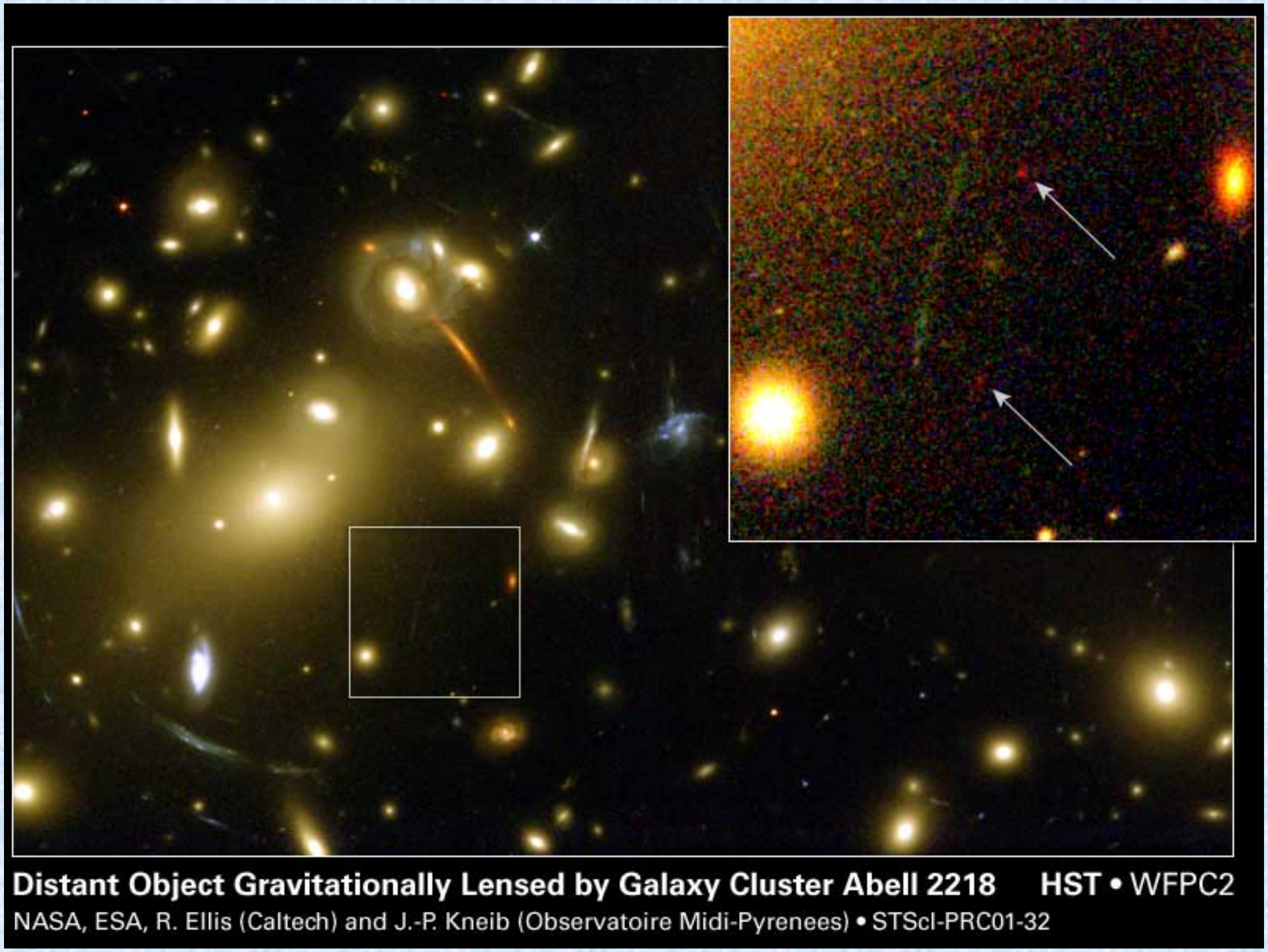
The most distant galaxies and the epoch of reionization

- We can measure the epoch of reionization by finding the most distant sources of light
- How do we find the most distant galaxies?
- They are very faint!



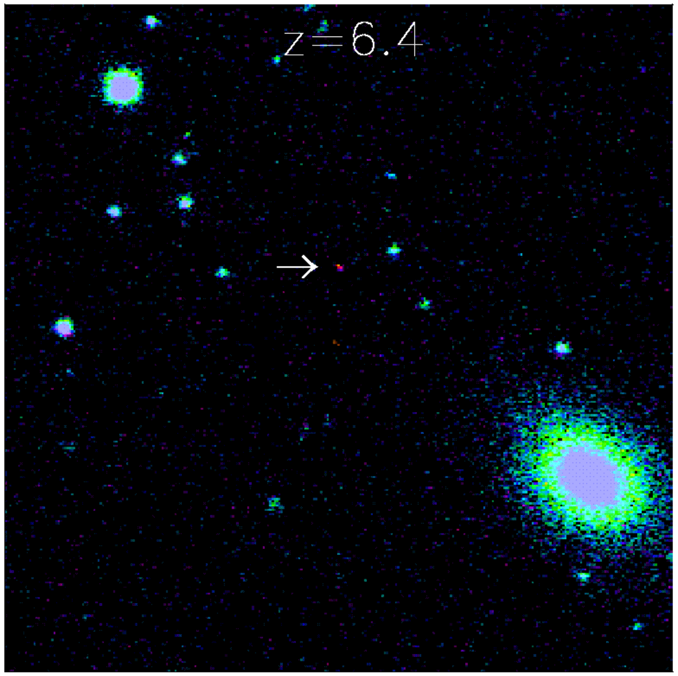
Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218 HST • WFPC2
NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32

The most distant galaxies and the epoch of reionization



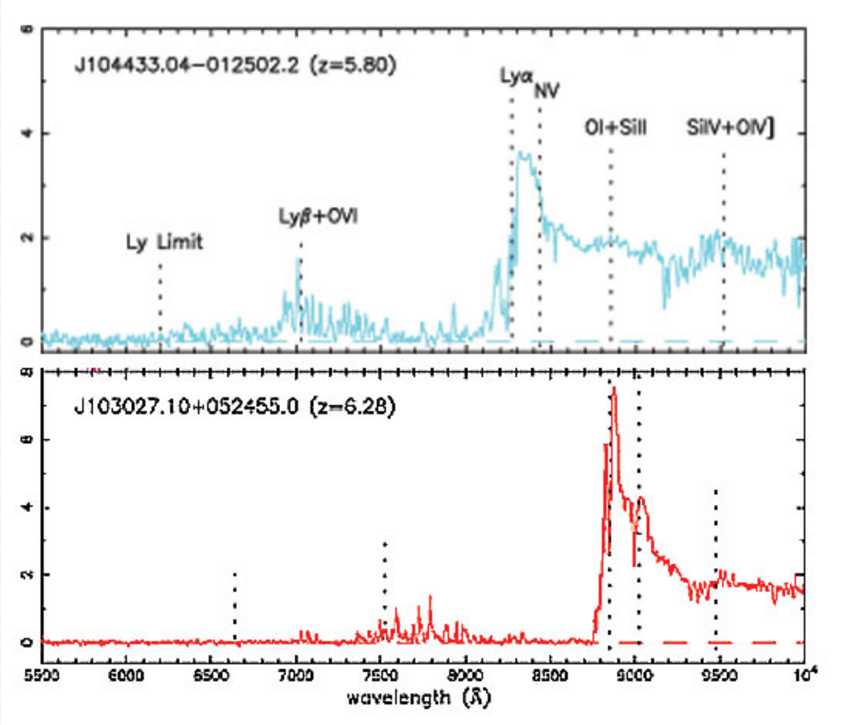
The most distant galaxies and quasars

- Galaxies and quasars have been found all the way out to z~8
- The universe was less than a billion years old then
- It means that reionization happened before z~8



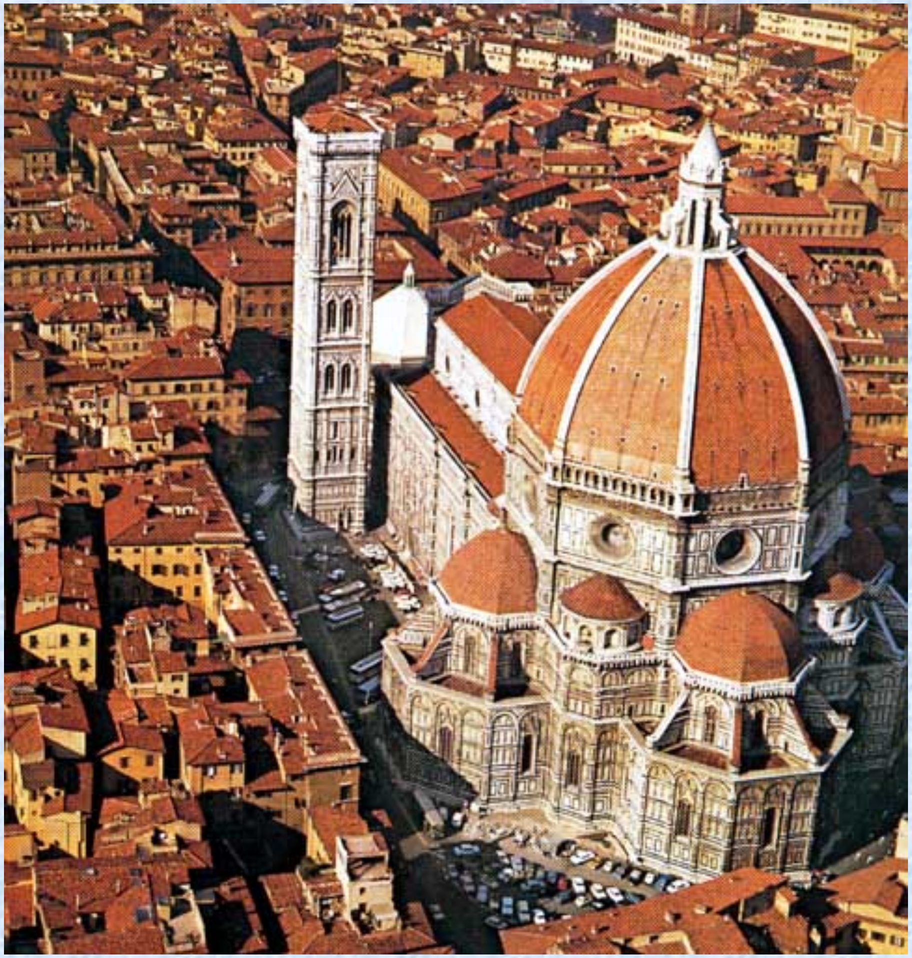
The gunn-peterson effect

- Neutral hydrogen is extremely opaque at energies higher than that of hydrogen ionization
- Every photon is absorbed because it just knocks off the electron, whatever its energy
- This means that when the universe is neutral you should not receive any photon at wavelength shorter than lyman alpha



No flux. Gunn-Peterson?

Have we reached the end of the dark ages?



First stars and reionization. Summary.

- Until z~20 the universe has been neutral since recombination
- Neutral hydrogen is opaque to UV radiation and so light from the first stars cannot propagate far. These are called the cosmic dark ages.
- However, the first stars and quasars carve bubbles of ionized gas around them
- When enough bubbles are formed and start to fill in the entire universe UV radiation can finally travel again, this is called reionization
- Finding out the epoch of reionization and its sources is one of the hot topics in cosmology at this time.
- We may be close to an answer
- Between z=8 and 15 maybe?

The End

See you on Tuesday!