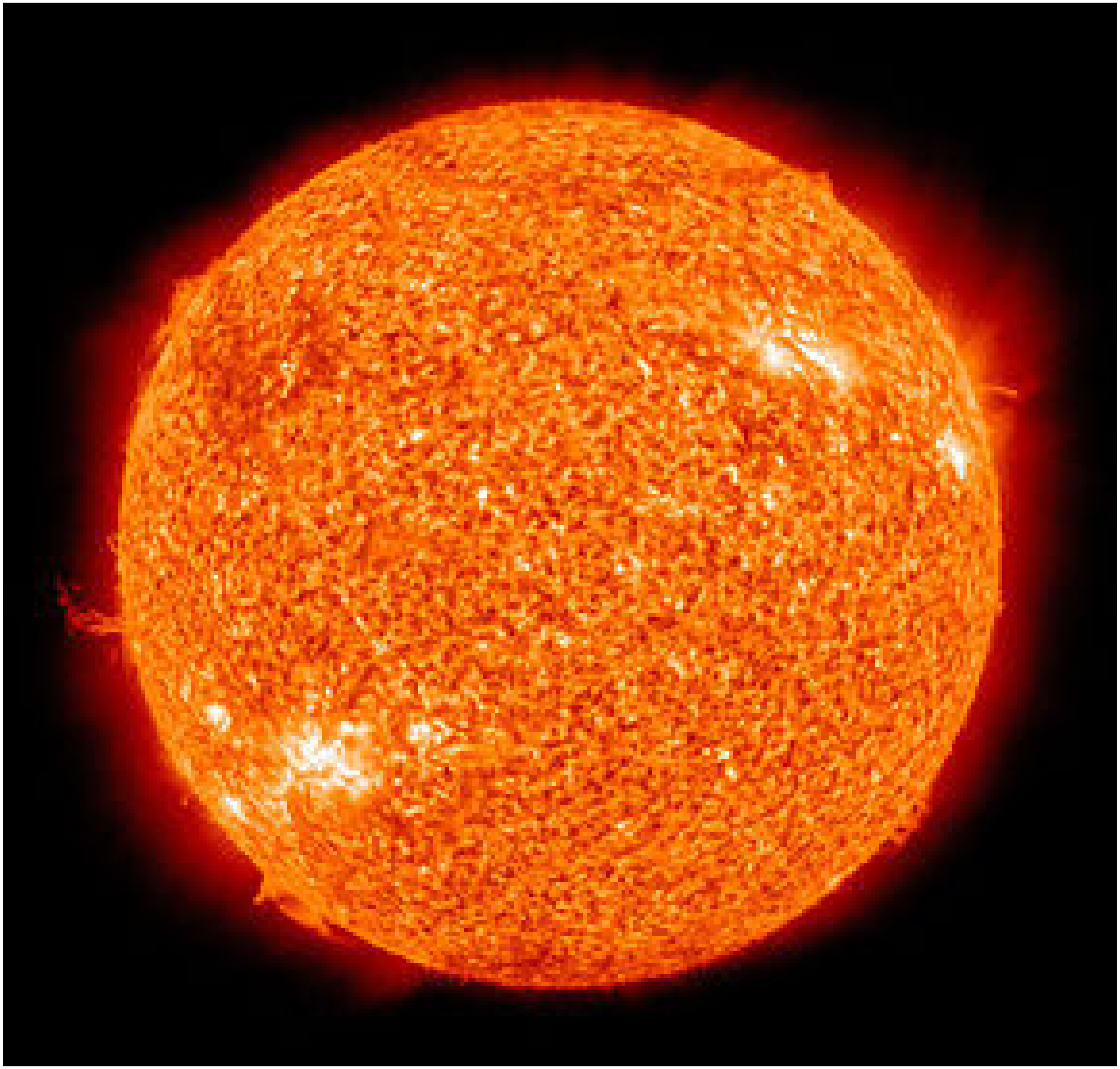
Black body radiation examples

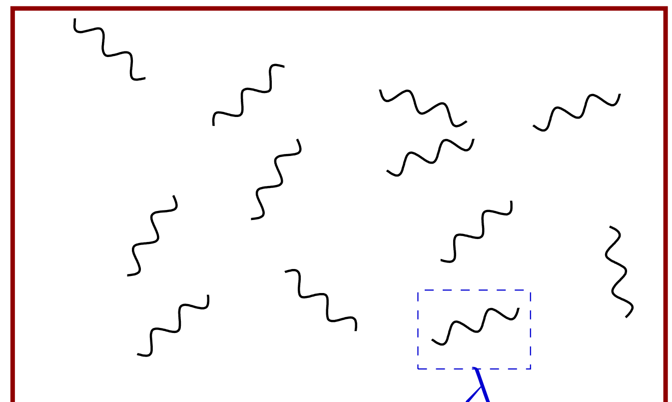
The hot walls in equilibrium with the radiation in an oven

The light from the sun which is in equlibrium with the free electrons and protons of the sun



Real Life – Black Body

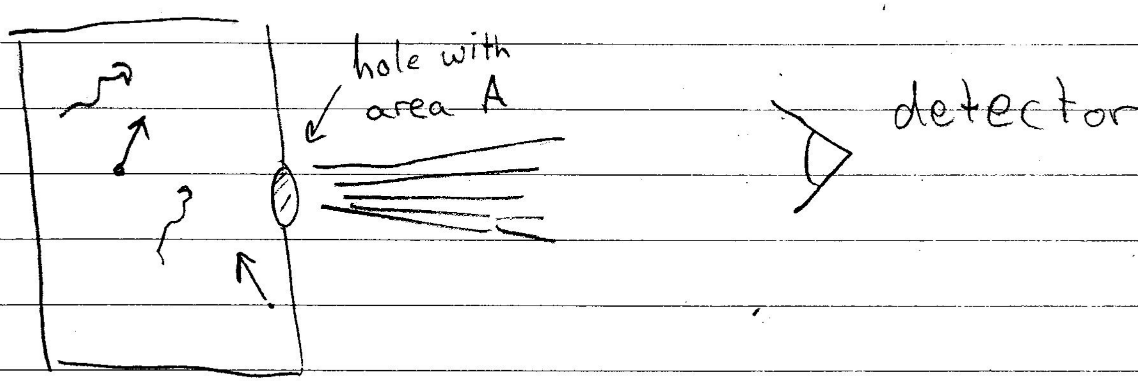
Theoretical Physicists Black Body



Photon Gas in Box

Last Time

① Hot Plasmas



a) The typical photon energy

$$hf \sim 2.8\, k_B T$$

b) The total energy emitted per area per time

$$\text{Itensity} = \frac{\Delta E}{A\,\Delta t} = \sigma T^4$$

← this enculdes the energy from all frequencies

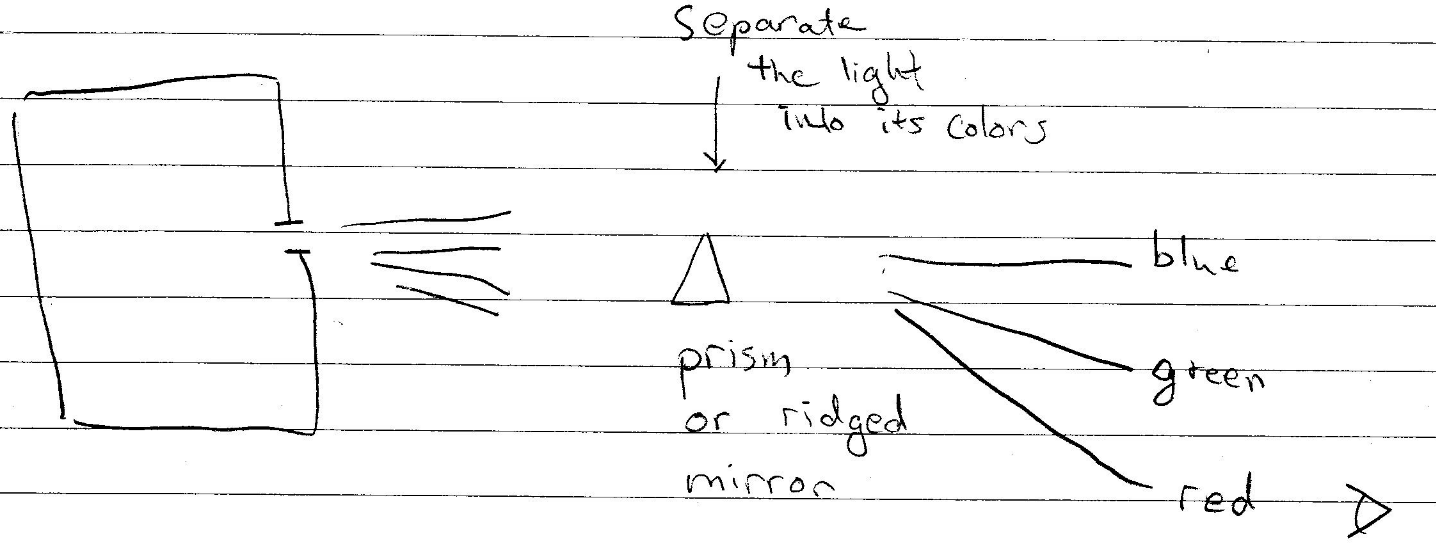
σ: $5.6 \times 10^{-8}\, W/m^2\, {}^\circ K^4$

c) The frequency spectrum ≡ The energy emitted in the form of photons with frequencies between $f_0 < f < f_0 + \Delta f$

$$\frac{1}{A}\frac{\Delta E}{\Delta t} = I_f\, \Delta f$$

← the frequency spectrum = Itensity per frequency interval Δf

Last Time (continued)



This detector measures the light energy carried by photons with photons betwen f and $f + \Delta f$.

- Separating light intow its colors is serious business

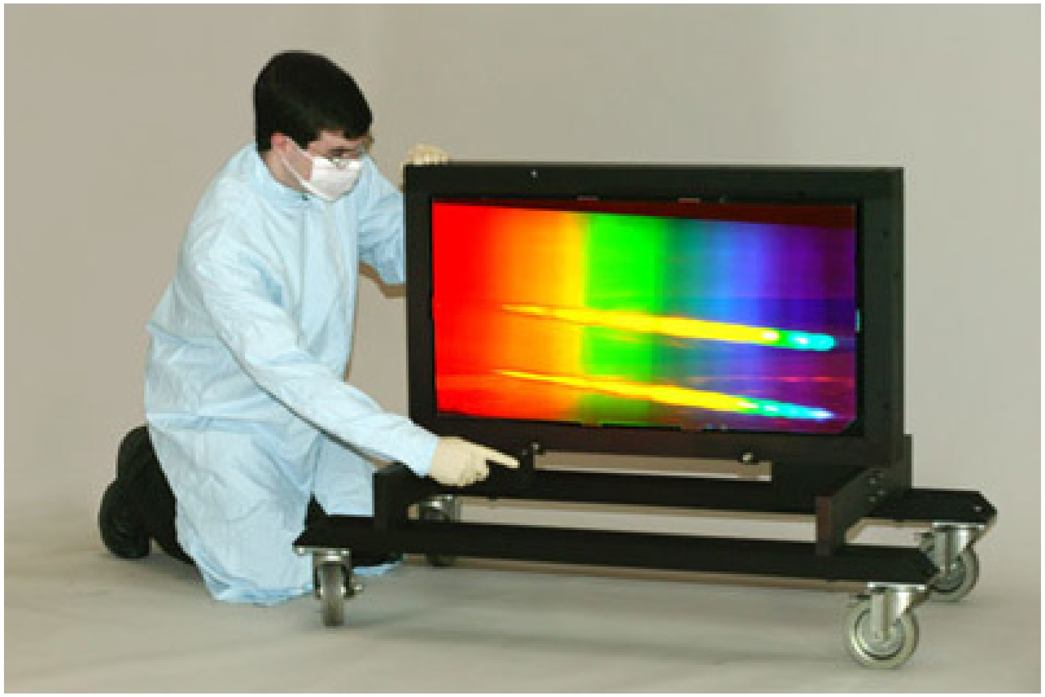
For a hot oven the frequency spectrum is very specific

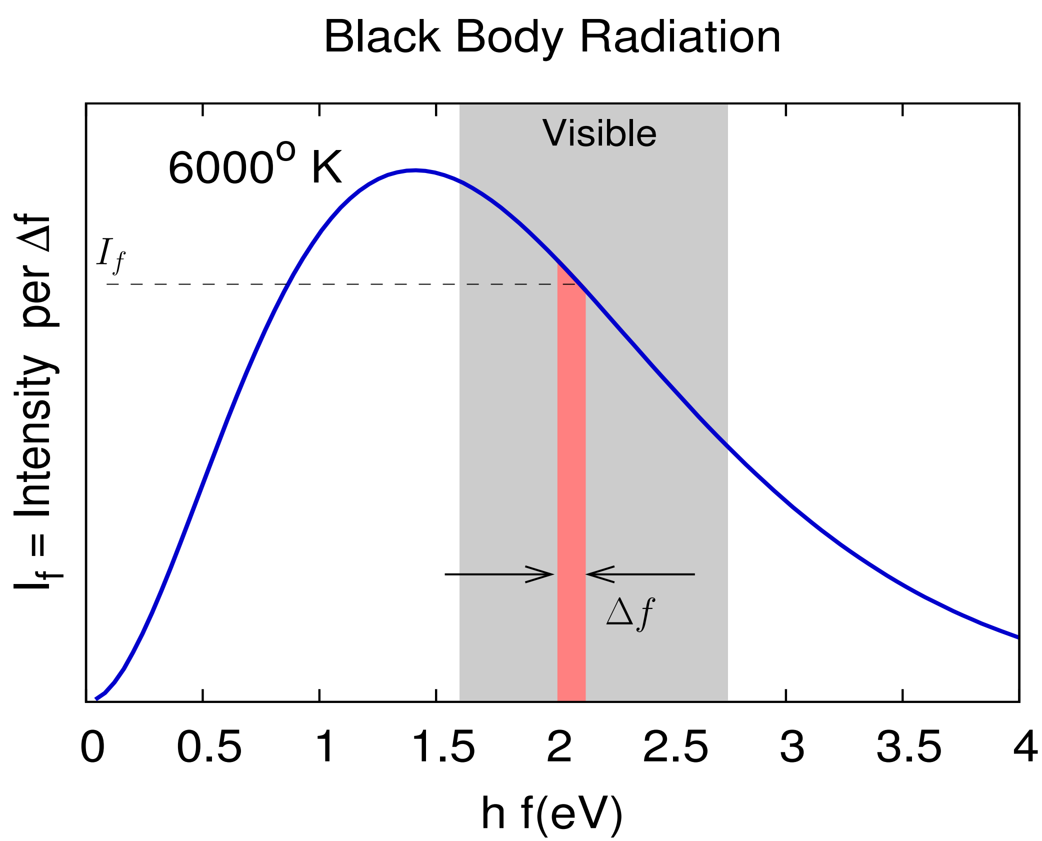
$$I_f = \frac{2h}{c^2} \frac{f^3}{e^{hf/k_B T} - 1}$$

- From the frequency spectrum, can tell if an object is hot, and what is the temperature.

Separating light into its colors with a mirror

Separating light into its colors with a much more expensive mirror





Definition of intensity per frequency

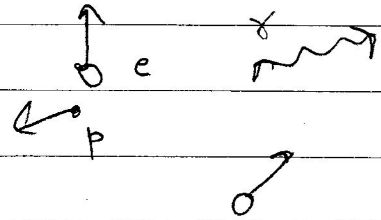
$$\frac{\Delta E}{A \Delta t} = I_f \times \Delta f$$

For a black body

$$I_f = \frac{2h}{c^3} \frac{f^3}{e^{hf/k_B T} - 1}$$

Last Time (Continued)

The early unierse



"Compton scattering"

- Hot phasma a) photons scattering on electrons b) enough photon have enough energy (> 13.6eV) to ionize hydrogen

- As the plasma cools almost no photons have enough energy to ionize hydrogen.

→ the protons and electrons "<u>recombine</u>" leaving fee free electrons

→ The photons then no longer scatter and fly freely until today

- The spectrum at recombination is thermal

$$I_f \propto \frac{f_r^3}{e^{hf_r/k_B T_r} - 1}$$

with themperature $T_r \simeq 3500$

The wavelength of each photon is increased during the expansion of the Universe

$$f_0 = a_r f_r$$

- f_r: frequency of photon at reco
- f_0: frequency observed today
- a_r: scale factor at recombination

Then today we see a "hot" bath of microwave photons (The Cosmic Microwave Background

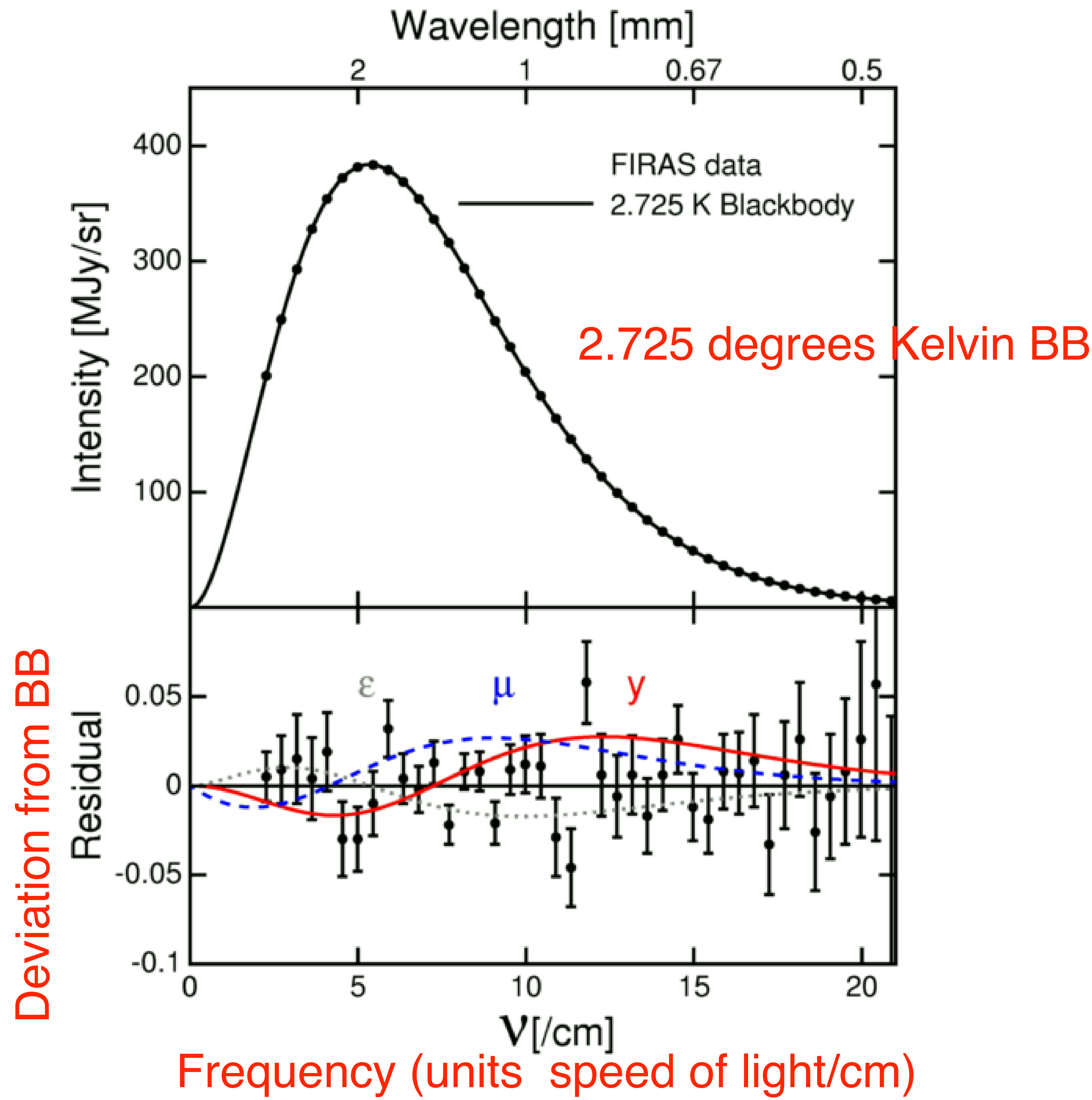
$$I_f \propto \frac{f_0^3}{e^{hf_0/k_B T_0} - 1}$$

with $T_0 = a_r T_r$

T_0 is observed to be $T_0 \simeq 2.72\,°K$

- The scale factor at recombination

$$a_r \simeq \frac{T_0}{T_r} = \frac{2.72\,°K}{3500\,°K} \simeq \frac{1}{1250}$$


Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
Intensity [MJy/sr]
FIRAS data
2.725 K Blackbody
2.725 degrees Kelvin BB
ε
μ
y
0.05
0
-0.05
-0.1
Residual
Deviation from BB
0
5
10
15
20
ν[/cm]
Frequency (units speed of light/cm)

- Determined the time after big bang at recombination from $a(t)$.

$$t_r = 400{,}000 \text{ yrs}$$

- Finally we discussed the cosmic principle

  "On the largest distance scales, everyplace is the same"

Two Examples

① The end of greatness

② The uniformity of the CMB

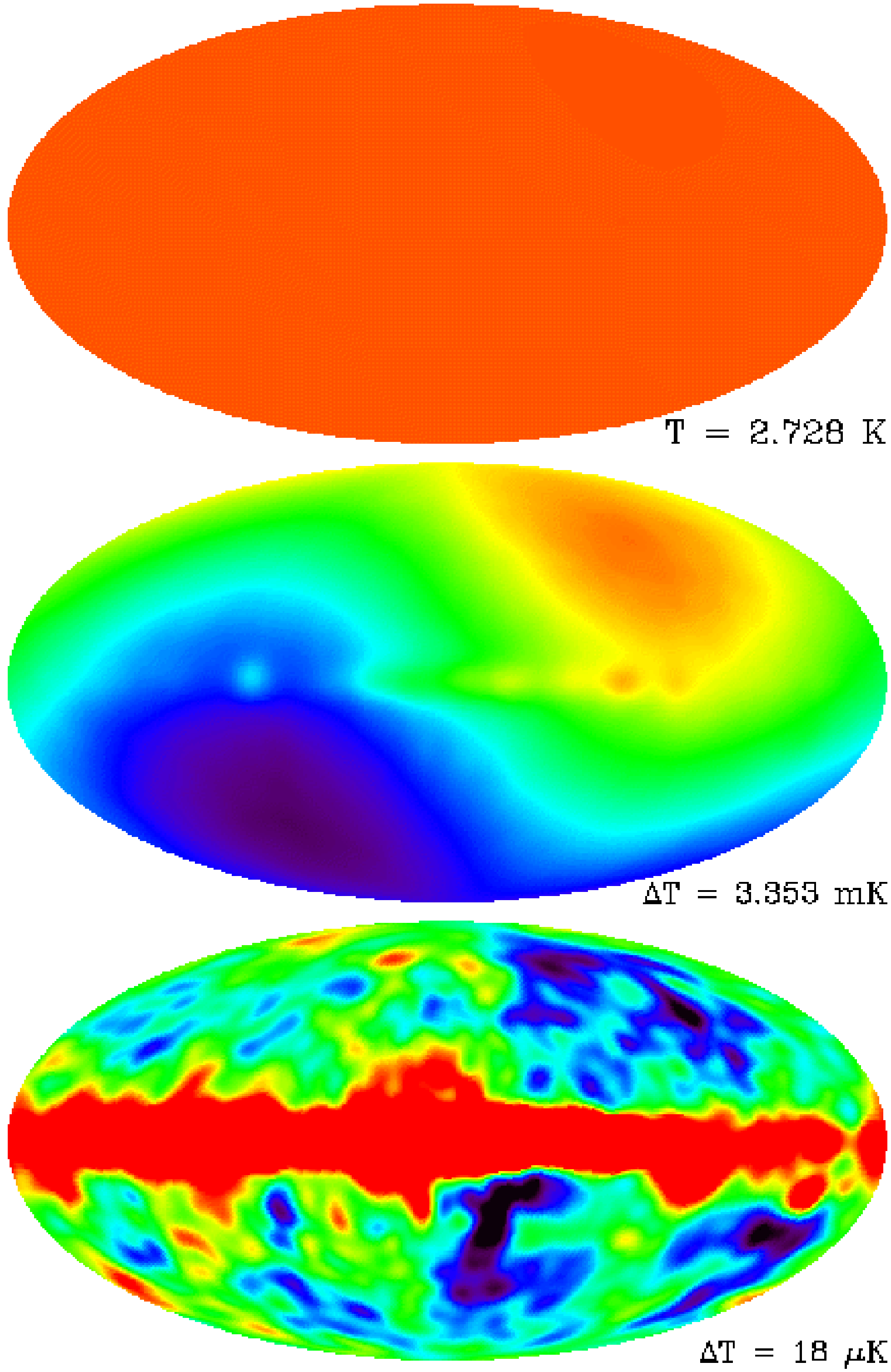
The temperature is constant throughout the sky

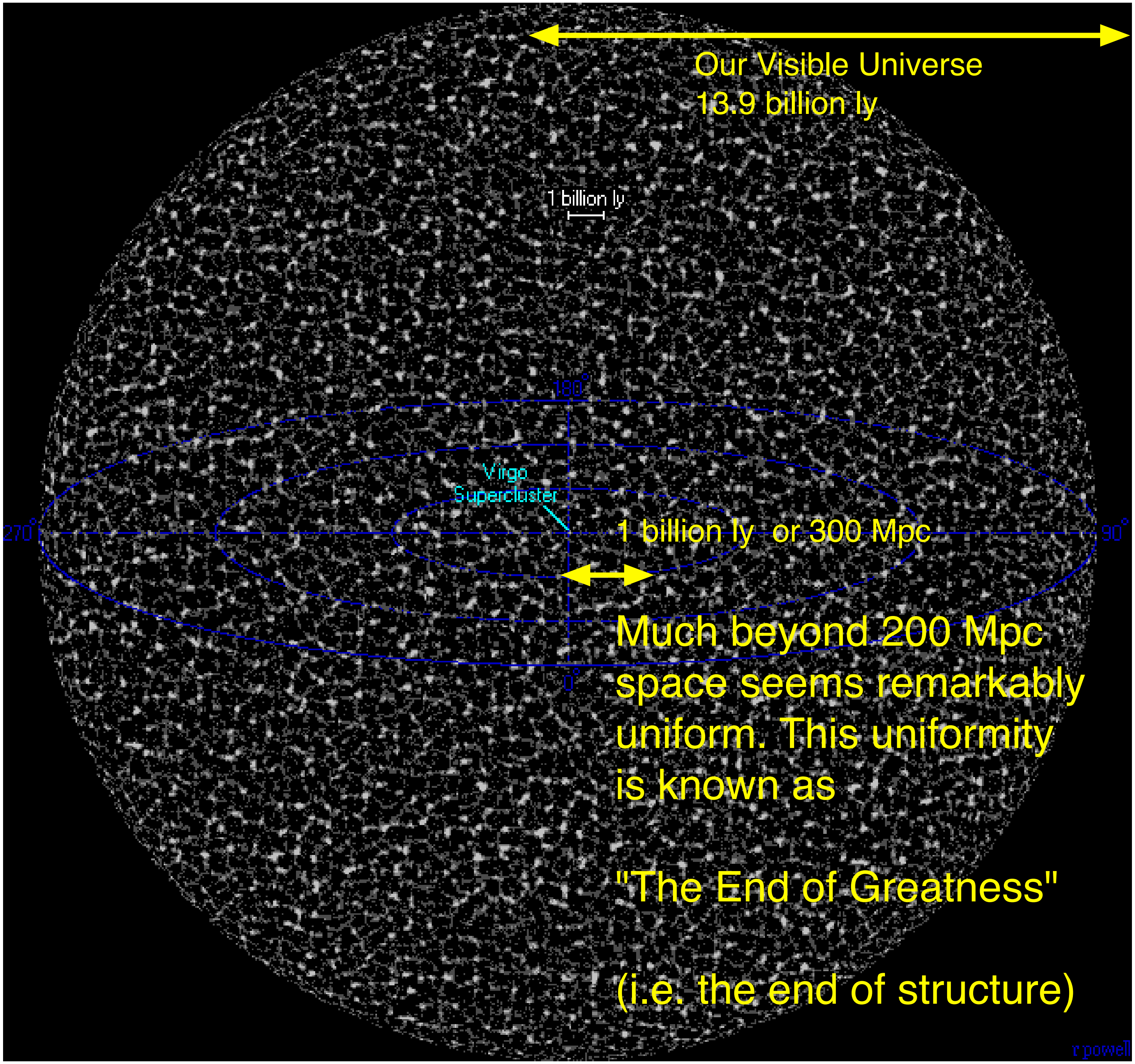
$$T \simeq 2.728 \,^\circ K$$

↑ only this digit and smaller is changing

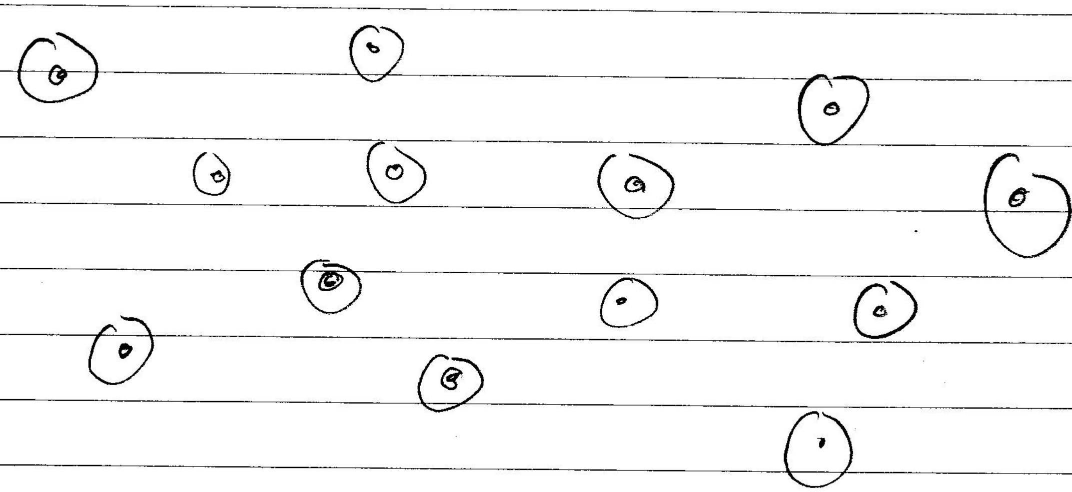
i.e.,

$$2.728 \pm 0.00353 \text{ mK}$$


T = 2.728 K
ΔT = 3.353 mK
ΔT = 18 μK


Our Visible Universe
13.9 billion ly
1 billion ly
180°
Virgo
Supercluster
270°
90°
1 billion ly or 300 Mpc
0°
Much beyond 200 Mpc
space seems remarkably
uniform. This uniformity
is known as
"The End of Greatness"
(i.e. the end of structure)
r powell

What happens after recombination?



Now we have hydrogen gas with a little bit of Helium and <u>very</u> little lithium.

- The other elements which are formed in nuclear processes in stars (Type II supernova) are non-existent (stars are not formed yet)

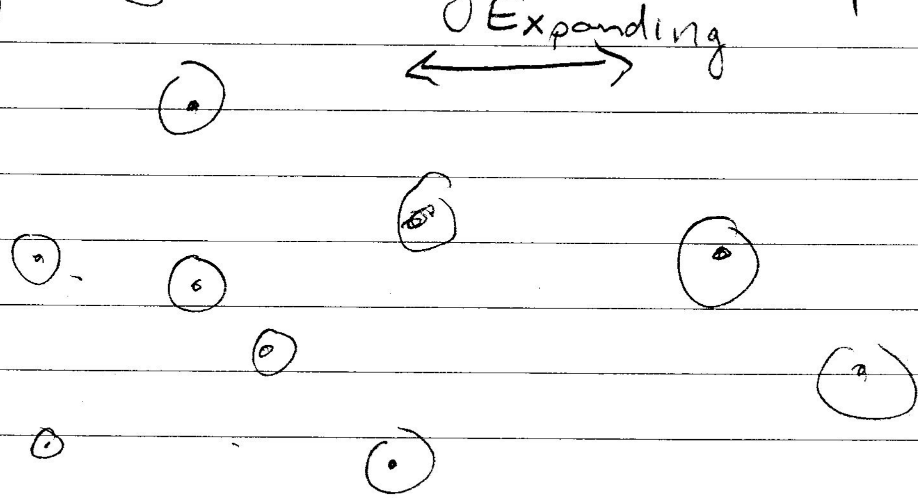
- There is no visible light from this epoch. Since everything is neutral

For this reason it is called the "dark-ages"

After Recombination (cont.)

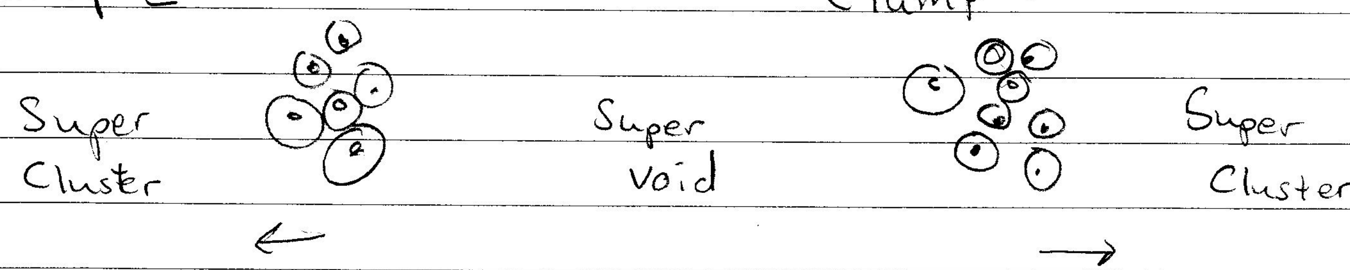
During the next ~ $\frac{1}{2}$ Billion years the hydrogen gas is pulled together by gravity making vast clumps

This configuration is unstable

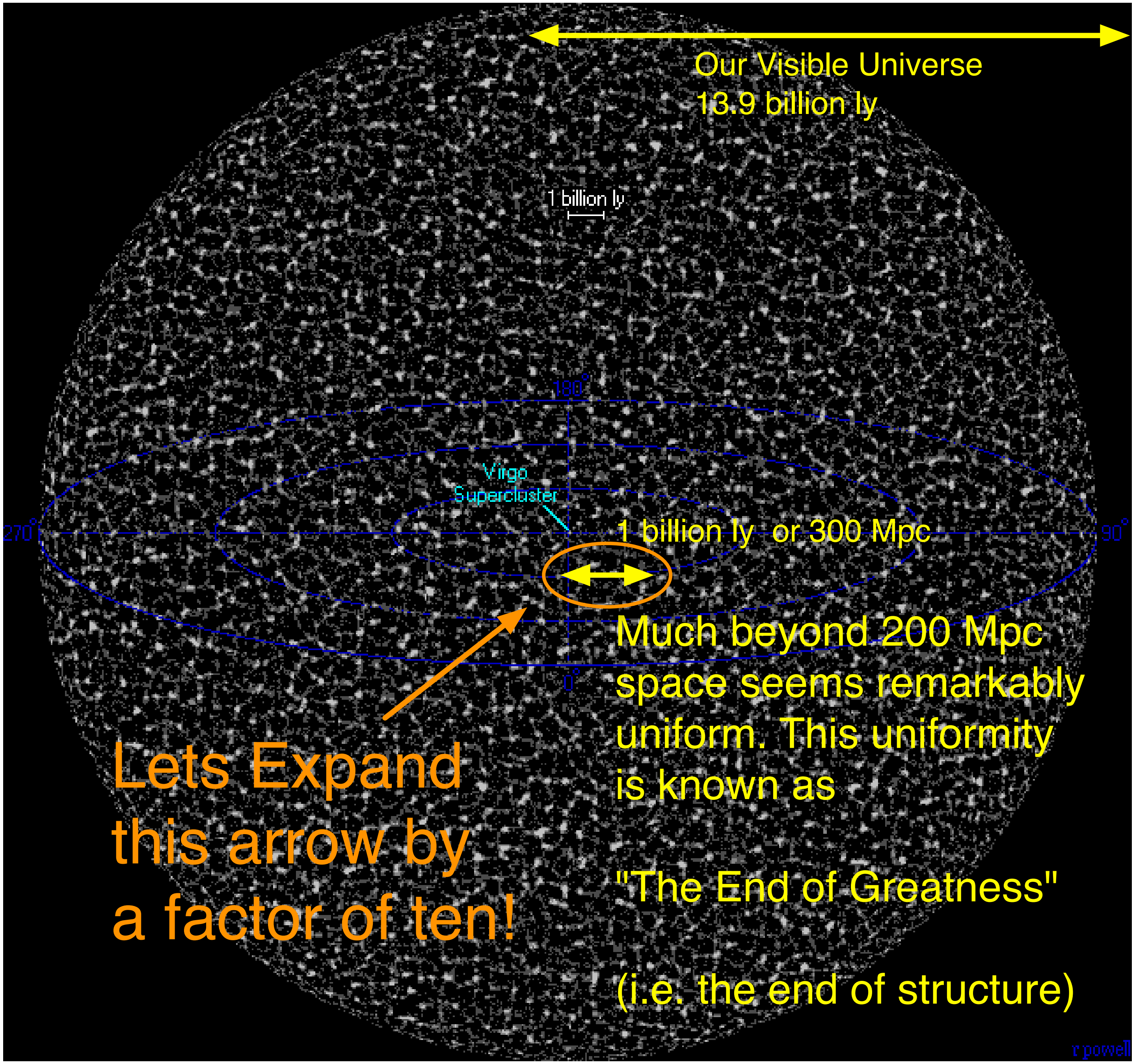


• Why? Larger Clusters have more gravity and hence pull more stuff to them. <u>Structure formation and reionization</u>:

Clump 1 Clump 2

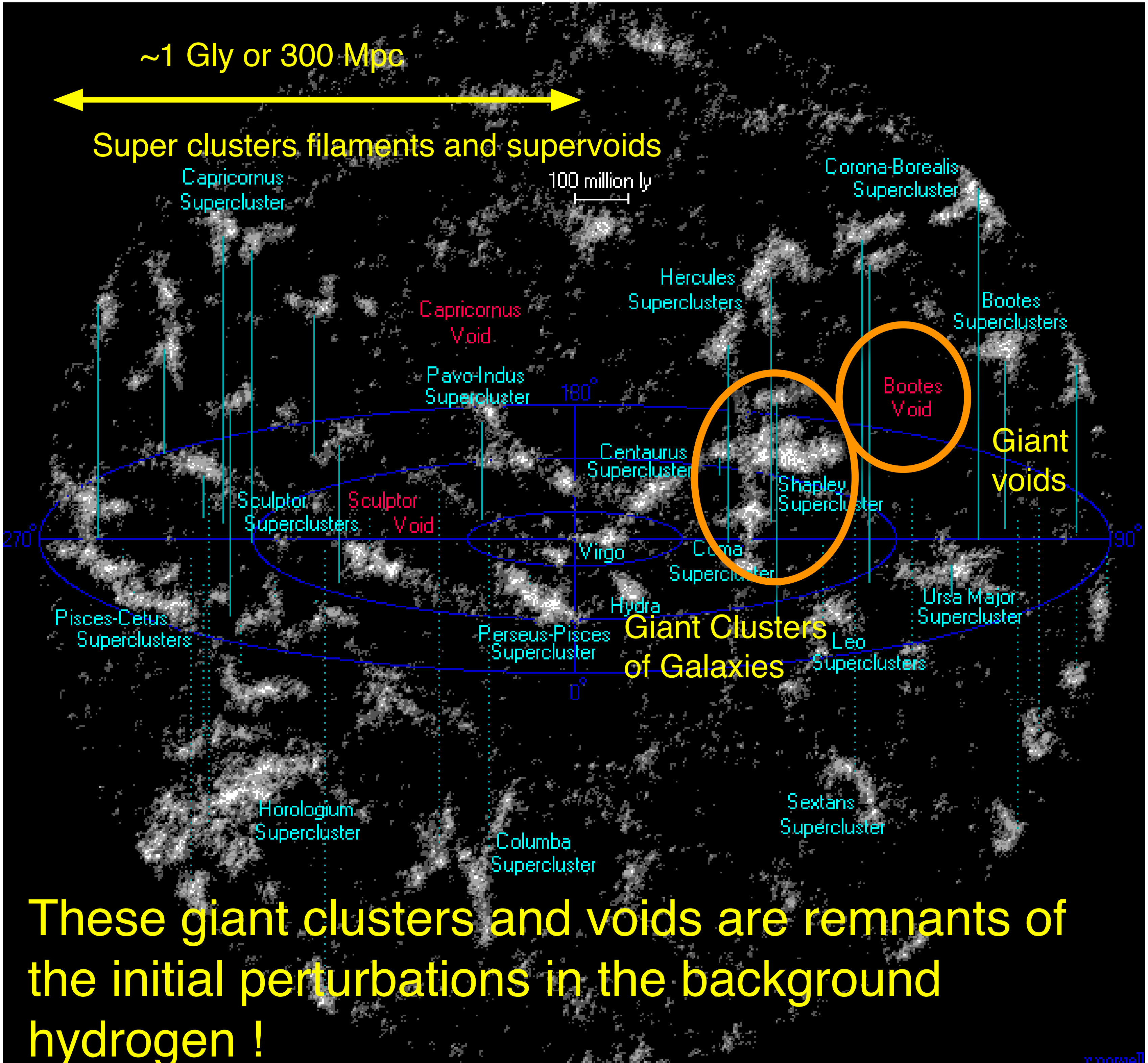


• These large super-clusters and supervoids give rise to the super-clusters and supervoids which are seen on a scale of ≤ 100 Mpc



Our Visible Universe
13.9 billion ly
1 billion ly
180°
Virgo
Supercluster
270°
90°
0°
1 billion ly or 300 Mpc
Much beyond 200 Mpc
space seems remarkably
uniform. This uniformity
is known as
"The End of Greatness"
(i.e. the end of structure)
Lets Expand
this arrow by
a factor of ten!
r powell

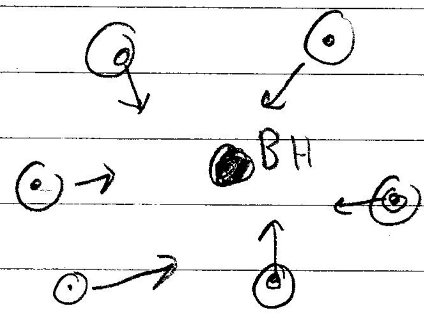
Super clusters filaments and supervoids



These giant clusters and voids are remnants of the initial perturbations in the background hydrogen !

Quasars and Formation of Active Galaxies

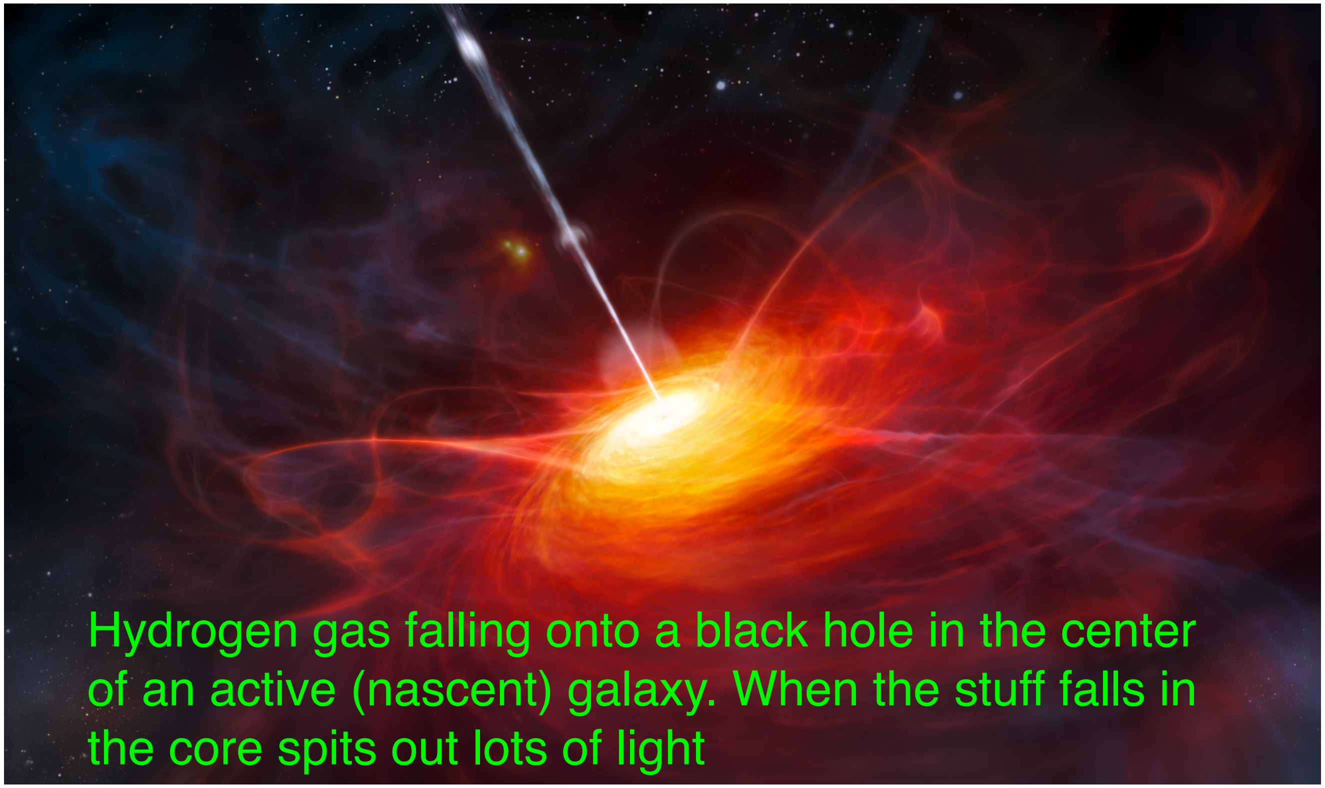
When these clumps of hydrogen gas are close enough, they can form a black hole



- Additional matter falling on the black hole becomes very energetically excited, and turns into ionized plasma of electrons and protons again, This is called "re-ionization" of the early-universe.
- The light from Quasars changes dramatically (as we will discuss later) at $z \simeq 6$ providing good evidence for this picture of reionization of early universe
- To describe what happens we will need to describe better the interaction of light and hydrogen.

Quasars (Quasi-Stellar Objects) or galaxies being born

- QSOs are bright sources from Black-Hole/Galactic-core of newly formed galaxies
- Here is an artist conception



These are observed to $z \simeq 7$

Problem:

The time of Reionization

Using a graph of $a(t)$, we find

$$a_{re\text{-}ion} = a(t_{reion}) = \frac{1}{1+z_{re\text{-}ion}}$$

↑ scale factor of Quasor

↑ red-shif of Quasar

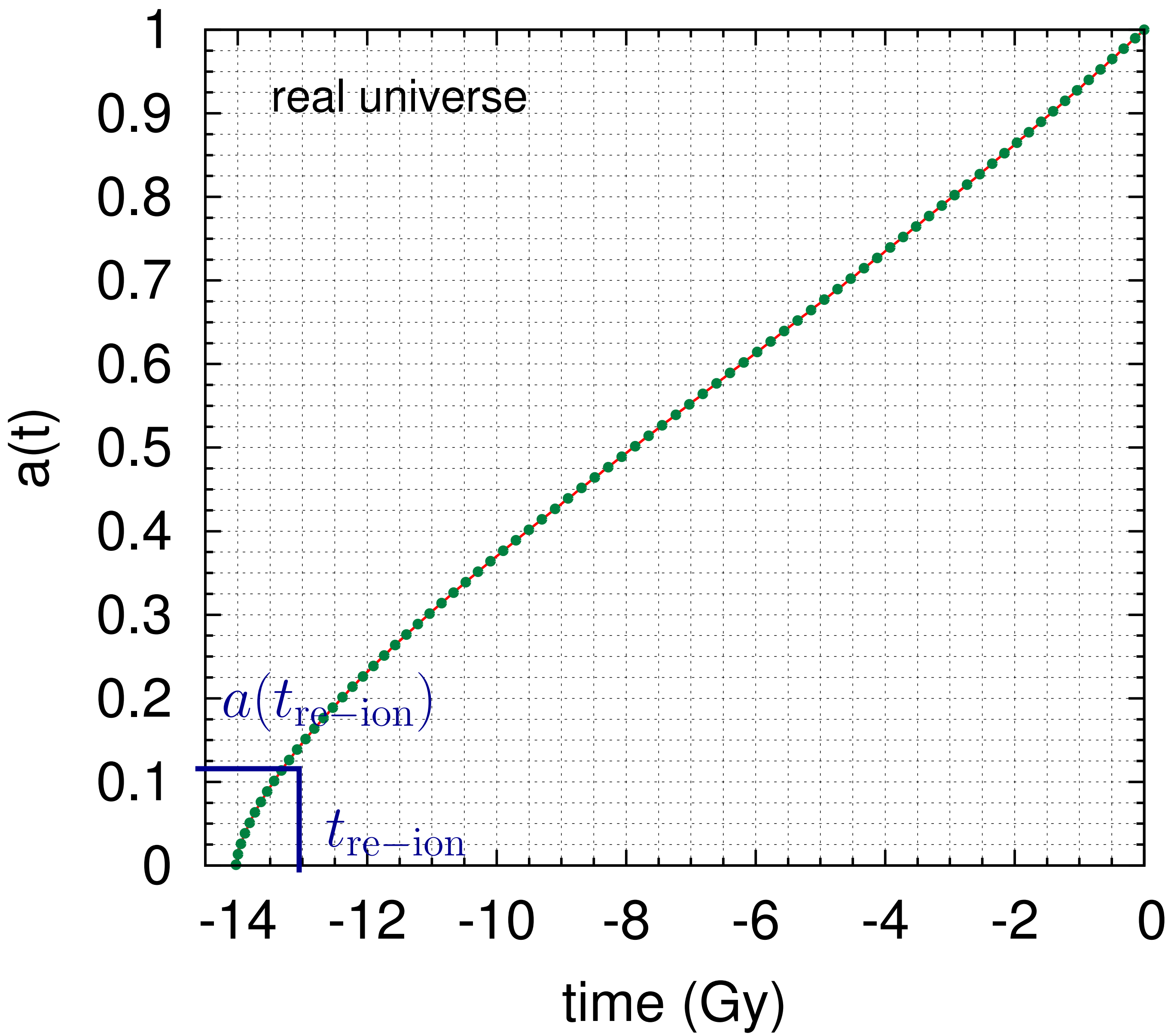
$$a_{re\text{-}ion} \approx \frac{1}{7}$$

So from graph of $a(t)$ read off the time

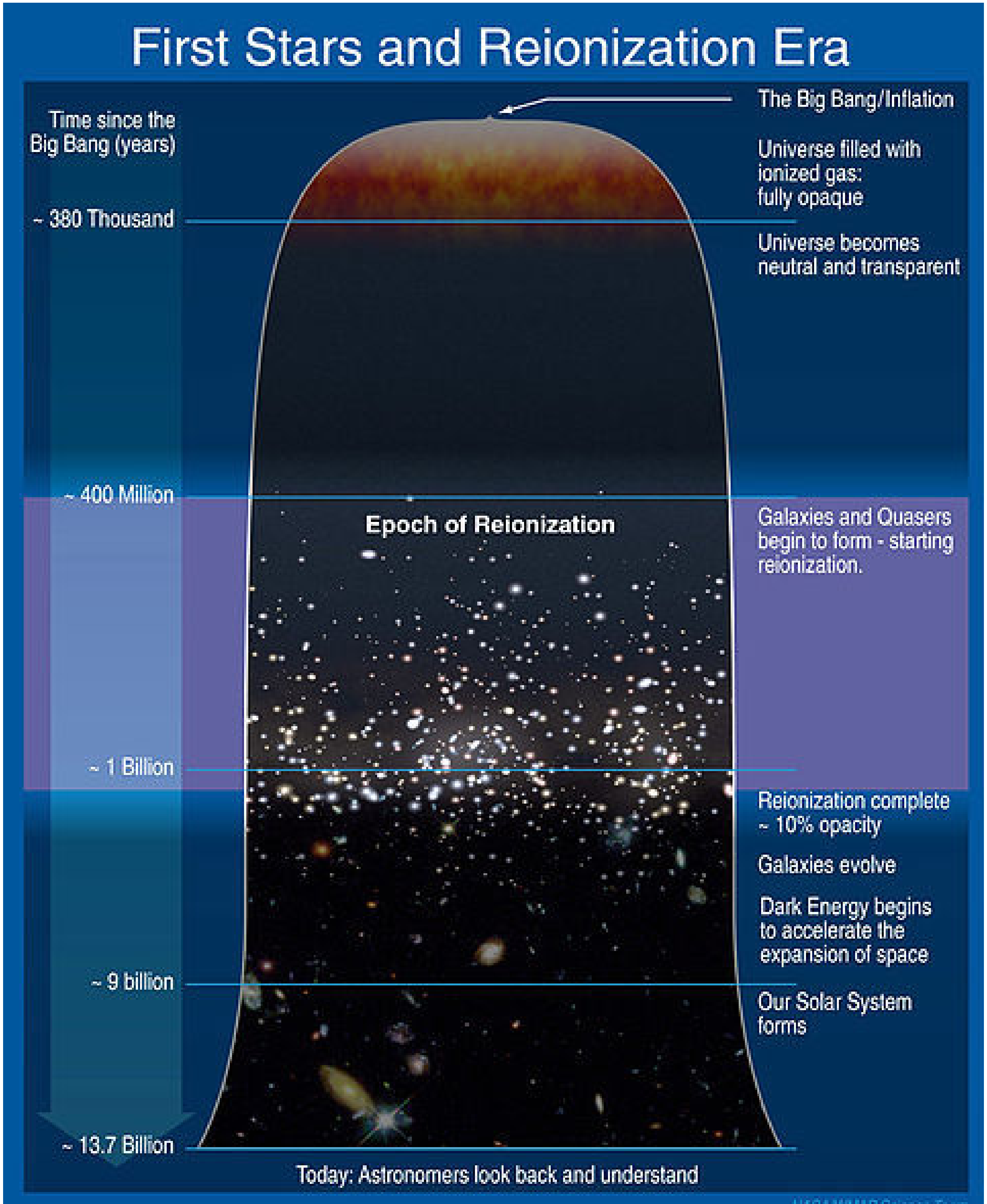
$$t_{re\text{-}ion} \simeq -13 \text{ Gy}$$

$\simeq$ or 1 billion years after BB

Observed time of re-ionziziation

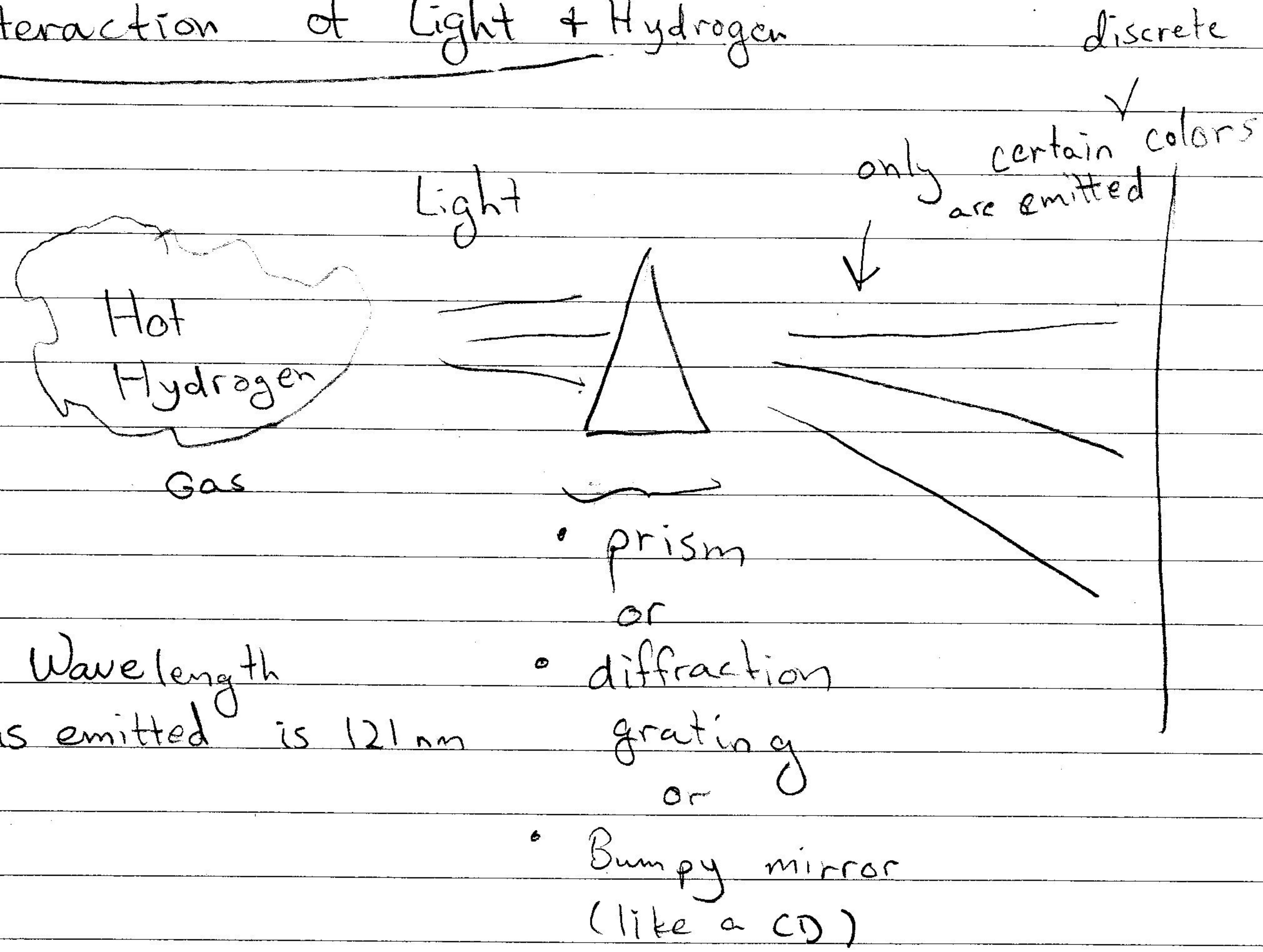


These are observed at $a = 1/(1+z) \simeq 1/8$, or approximately $1\,\mathrm{Gy}$ after big bang


First Stars and Reionization Era
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Epoch of Reionization
Galaxies and Quasars begin to form - starting reionization.
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms
Today: Astronomers look back and understand

Interaction of Light & Hydrogen

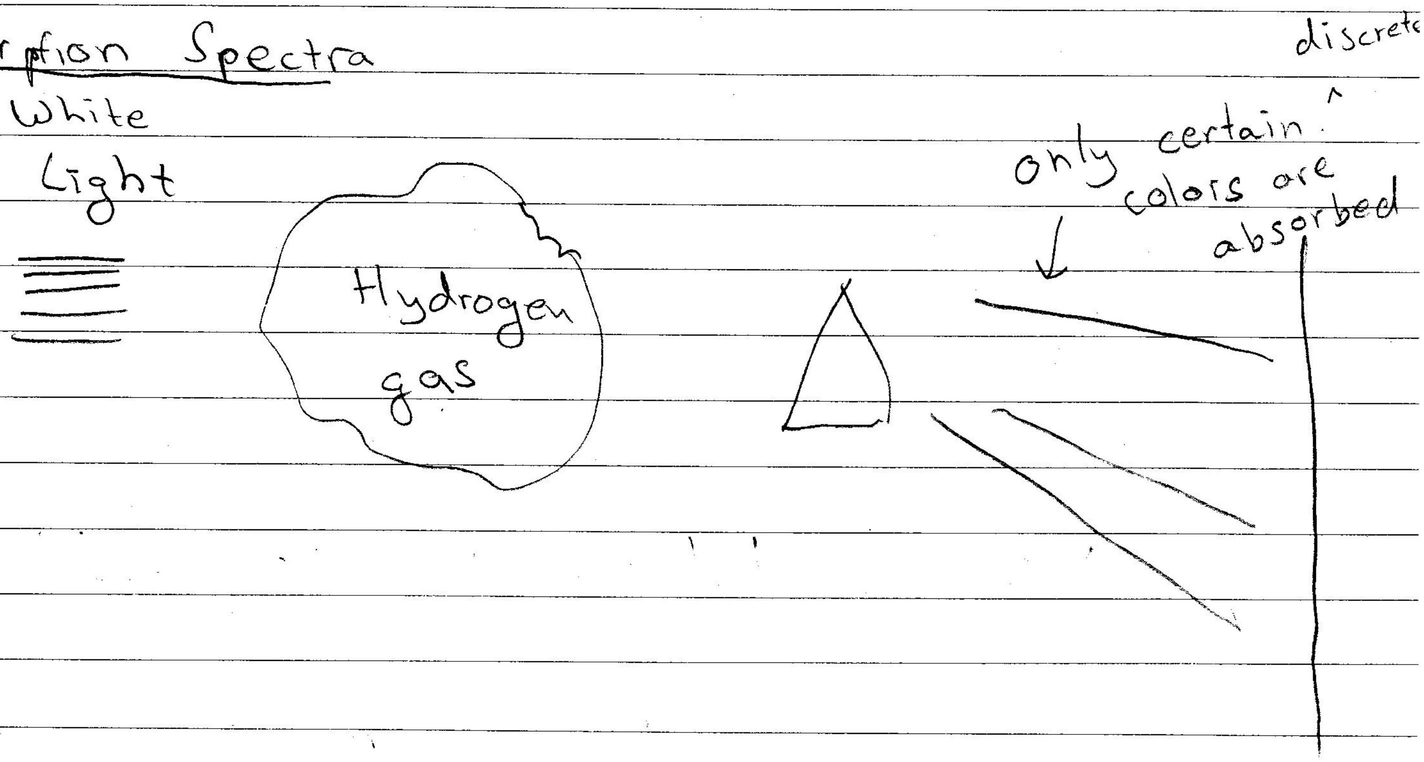
① **Emission**

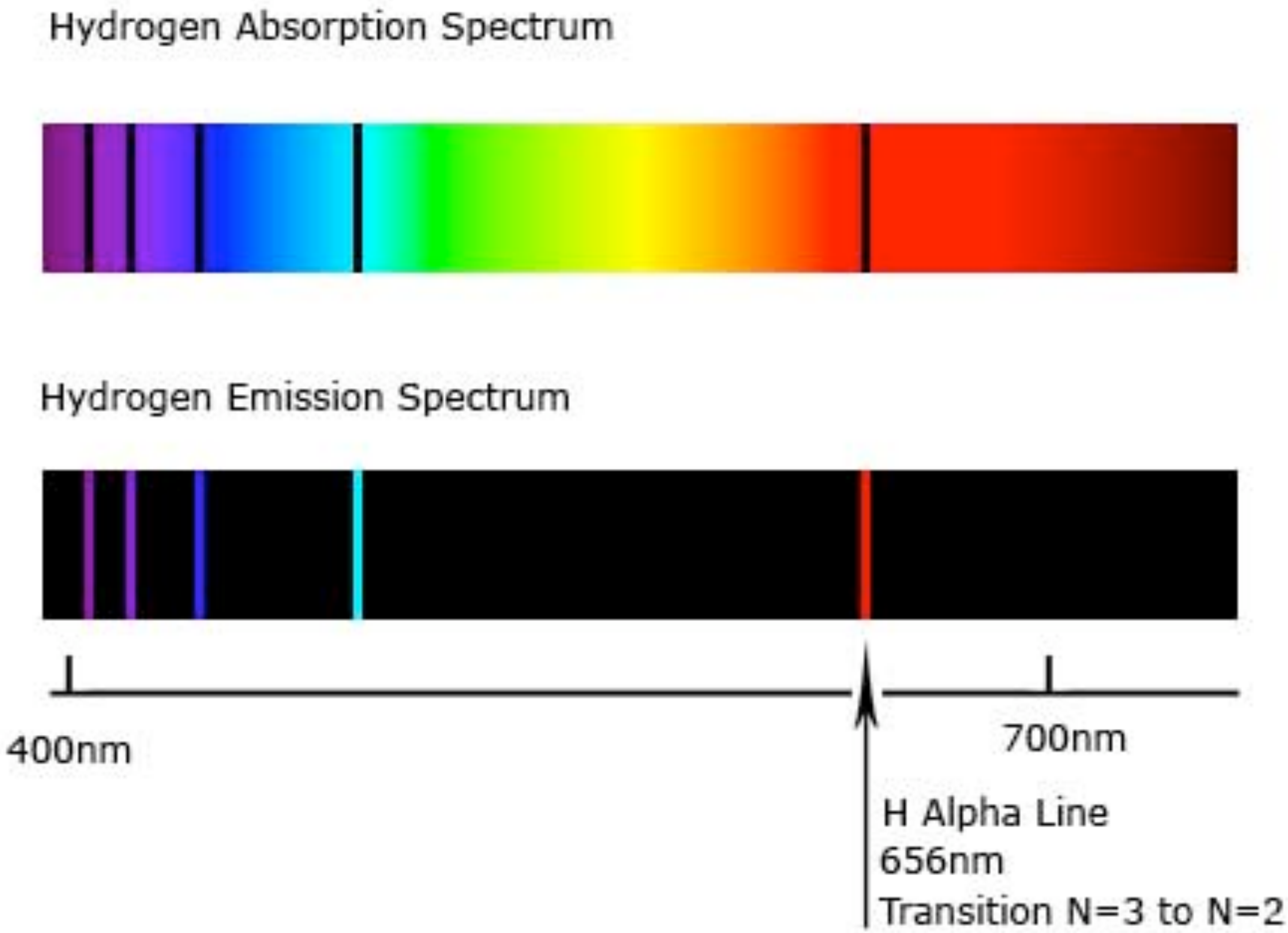


Smallest Wavelength that is emitted is 121 nm

Absorption Spectra

②





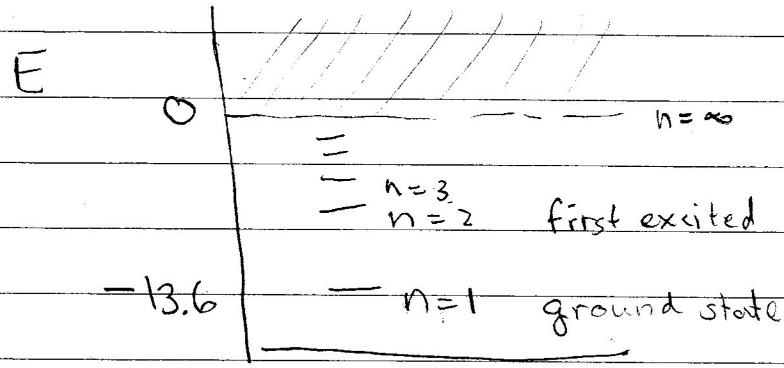
The smallest discrete wavelength that is emitted is in the UV and is known as the Lymann-α line. Watch the video

$$\lambda_{\mathrm{Ly}-\alpha} = 121\,\mathrm{nm}$$

Interaktion of Light and Hydrogen (cont)

Basic Description

$$hf_n = E_n = \frac{-13.6\,eV}{n^2}$$



↑ energy levels, or normal modes of vibration

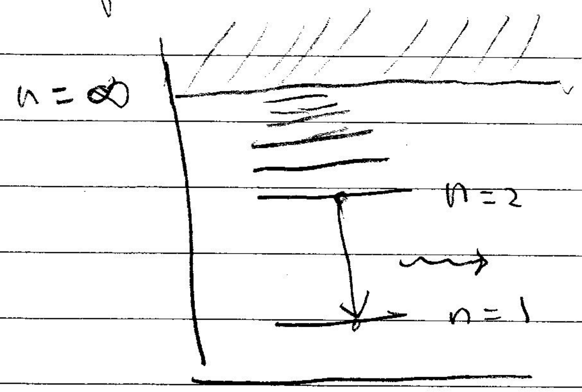
- An electron and proton far a part (which aren't moving) have zero total energy by definition
  $n \to \infty$
- When you bring an electron and proton together you lower the total erergy to the ground state energy = −13.6 eV, thats why it takes 13.6 eV to strip an eletron from a proton:
  $$E_1 = -13.6\,eV/1^2 = \text{ground state}$$
- Only certain vibrational frequencies are allowed. The first excited state has Energy
  $$E_2 = \frac{-13.6\,eV}{2^2}$$

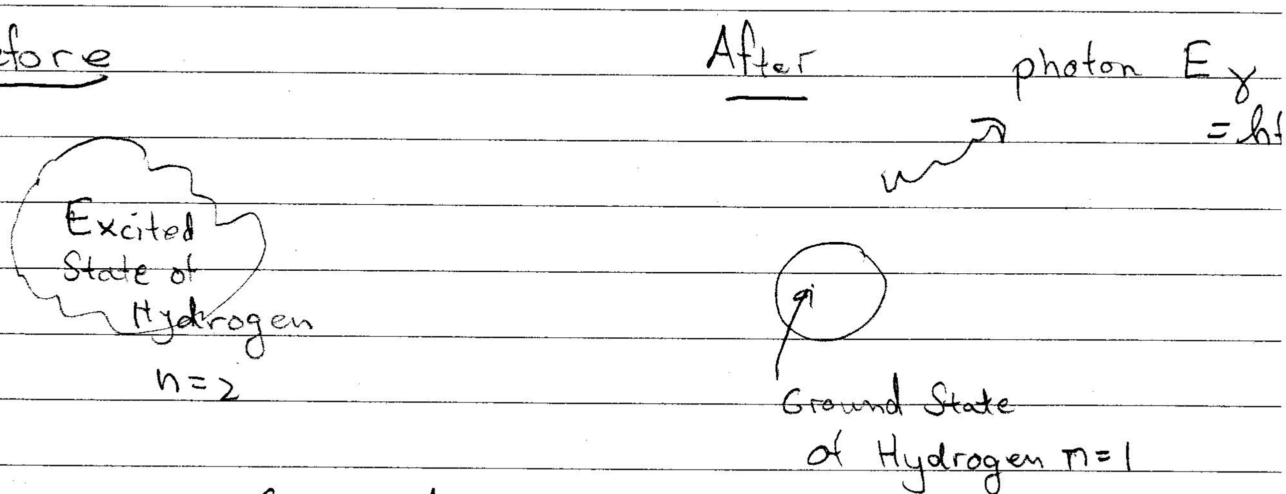
The second excited state has $n = 3$.

$$E_3 = \frac{-13.6\,eV}{n^2}$$

The interaction of Light and Hydrogen

The light that is absorbed and emitted is discrete since only certain frequencies can be absorbed and emitted





Using Energy Conservation

$$\underbrace{E_2}_{E_{init}} = \underbrace{E_1 + hf}_{E_{final}}$$

$$-\frac{13.6 eV}{2^2} = -\frac{13.6}{1^2} + hf$$

Or

$$10.2 eV = hf$$

Problem

① • Determine the wavelength of the Ly-alpha transition $n=2 \rightarrow n=1$

② • Also determine the energy and wavelength of a photon emitted in the Hydrogen-α line $(n=3 \rightarrow n=2)$

③ At a red-shift of 5.99 what would be the wavelength of the Ly-α line in Å (1 nm = 10 Å)

• The light from three quasars is shown in an attached spectrograph. Interpret the sharp peak. Why does it move in wavelength

Useful

• $E_n = \frac{-13.6\,eV}{n^2}$ • $E = hf = \frac{hc}{\lambda}$ $\lambda_{obs} = (1+z)\lambda_{emi}$

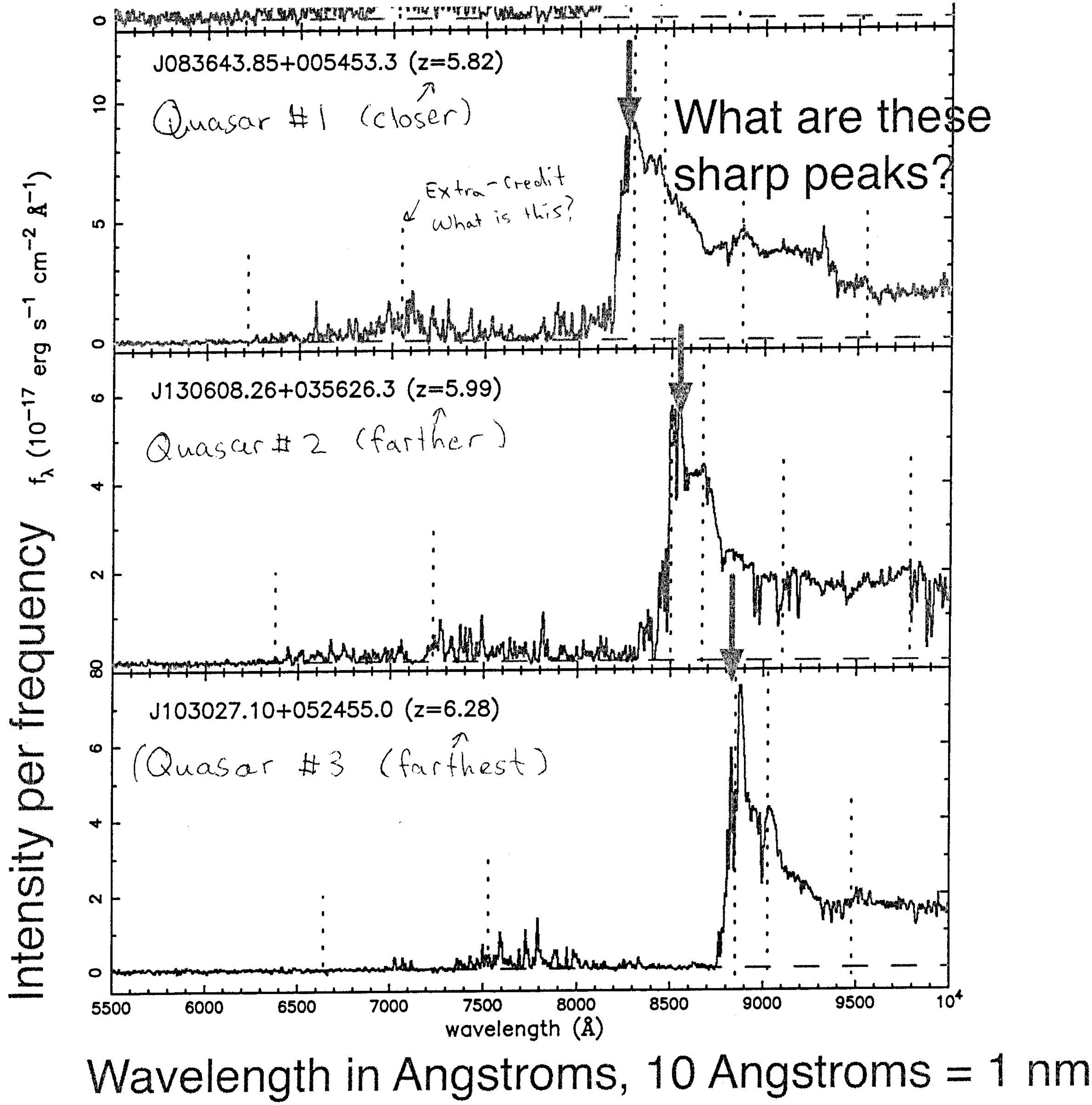
$10\,Å = 1\,nm$ $hc = 1240\,eV\,nm$

Answers

① 121 nm — UV ↑ "Ly-α line"

② 1.89 eV, 656 nm — red ↑ "H-α" line

③ 8490 Å



Intensity per frequency
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
J083643.85+005453.3 (z=5.82)
Quasar #1 (closer)
Extra-credit What is this?
What are these sharp peaks?
J130608.26+035626.3 (z=5.99)
Quasar # 2 (farther)
J103027.10+052455.0 (z=6.28)
(Quasar #3 (farthest)
wavelength (Å)
Wavelength in Angstroms, 10 Angstroms = 1 nm

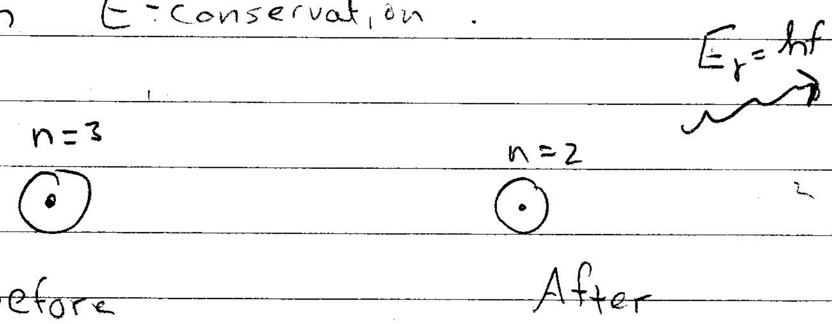
Solution

(1) $E = hf$

$= \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E} = \frac{1240\,eV\,nm}{10.2\,eV} = 121\,nm$

(2) From E-conservation.

Picture



$$\overbrace{E_{n=3}}^{E_{before}} = \overbrace{E_{n=2} + E_\gamma}^{E_{after}}$$

$$\underbrace{-\frac{13.6\,eV}{3^2} = -\frac{13.6\,eV}{2^2}} + E_\gamma \Rightarrow hf$$

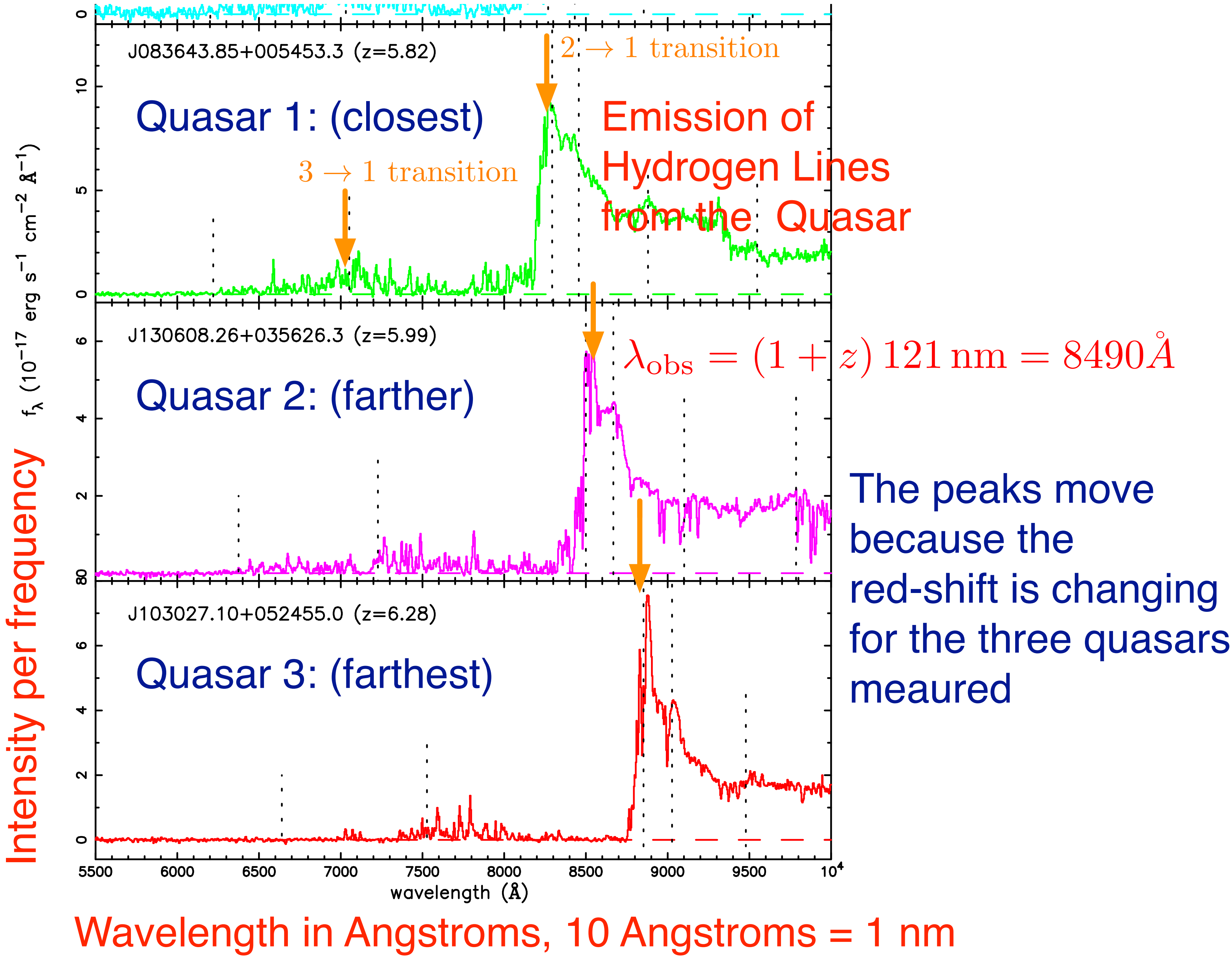
$$\boxed{1.89\,eV = E_\gamma}$$

Then, $\lambda = \frac{hc}{E} = \frac{1240\,eV\,nm}{1.89\,eV} = 656\,nm$

(3) The red shifted wavelength is longer

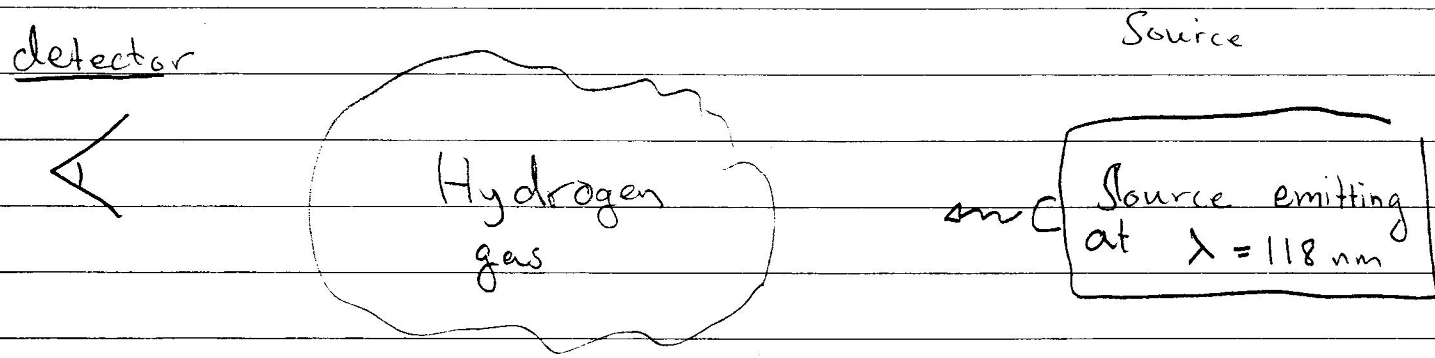
$\lambda_{obs} = (1 + z)\,\lambda_{emit}$

$\lambda_{obs} = (1 + 5.99)\,656\,nm = 849\,nm = 849 \times \underbrace{10\,\mathring{A}}_{=1nm} = 8490\,\mathring{A}$



J083643.85+005453.3 (z=5.82)
Quasar 1: (closest)
$2 \rightarrow 1$ transition
$3 \rightarrow 1$ transition
Emission of Hydrogen Lines from the Quasar
J130608.26+035626.3 (z=5.99)
Quasar 2: (farther)
$\lambda_{\rm obs} = (1+z)\, 121\,{\rm nm} = 8490\AA$
J103027.10+052455.0 (z=6.28)
Quasar 3: (farthest)
The peaks move because the red-shift is changing for the three quasars meaured
Intensity per frequency
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
wavelength (Å)
5500
6000
6500
7000
7500
8000
8500
9000
9500
10^4
Wavelength in Angstroms, 10 Angstroms = 1 nm

Problem



① What would the detector see? (how much light is absorbed)

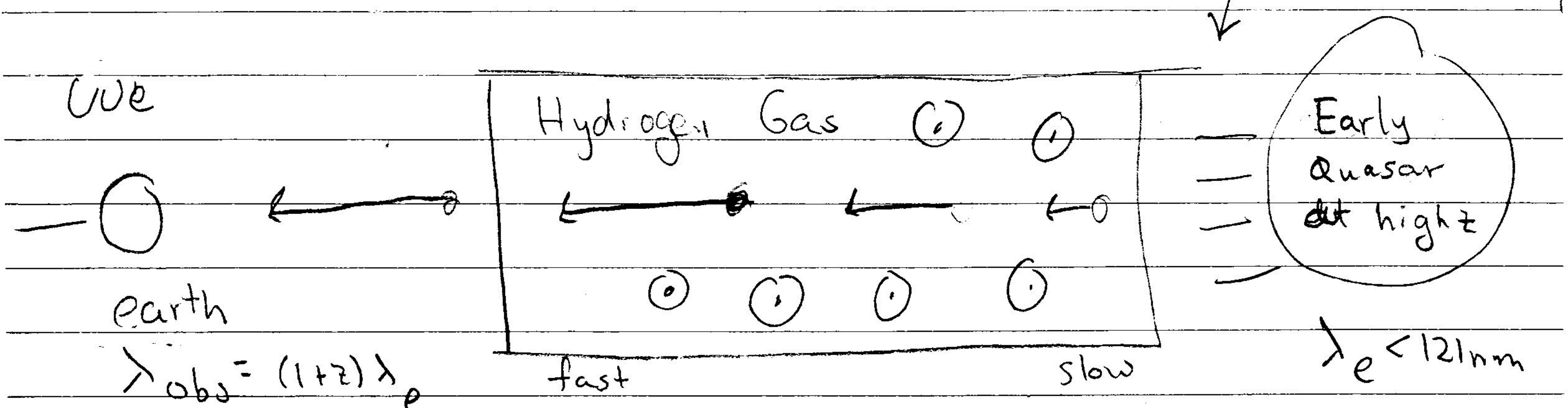
② If the source is moving to the right at speed V, describe qualitatively what the detector would see?

- Is the wavelength longer or shorter as measured by the detector and the gas
- At a particular speed, something dramatic happens as the velocity is increased from zero.

→ Extra-credit determine the special speed.

Evidence for Re-ionization

Light with many different wavelen



- Hydrogen gas moving

We see the quasar very light red-shifted.
we are moving very vast compared to quasar

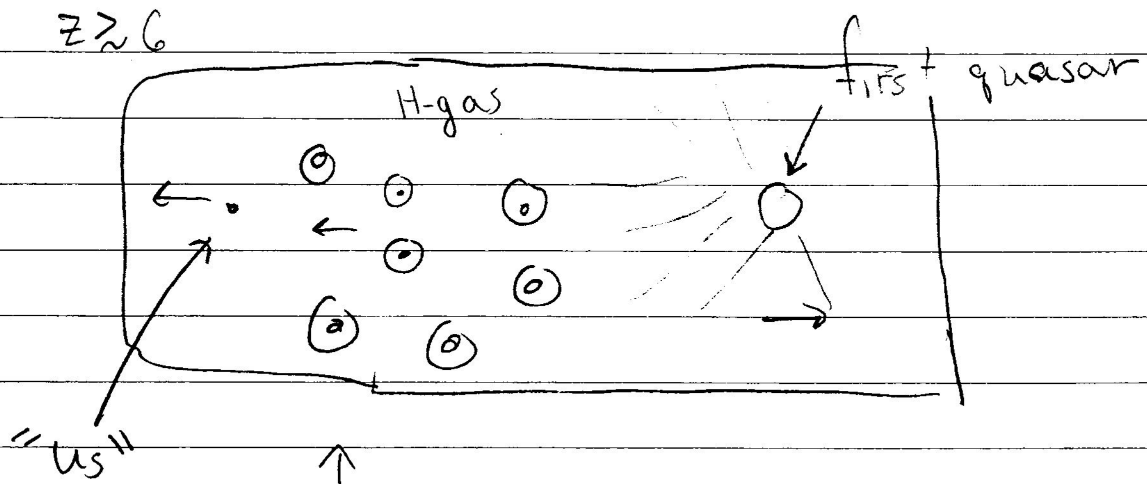
The gas here sees the light somewhat red shifted.
the gas is moving some what fast compared to quasar

The gas here sees the light slightly red shifted.

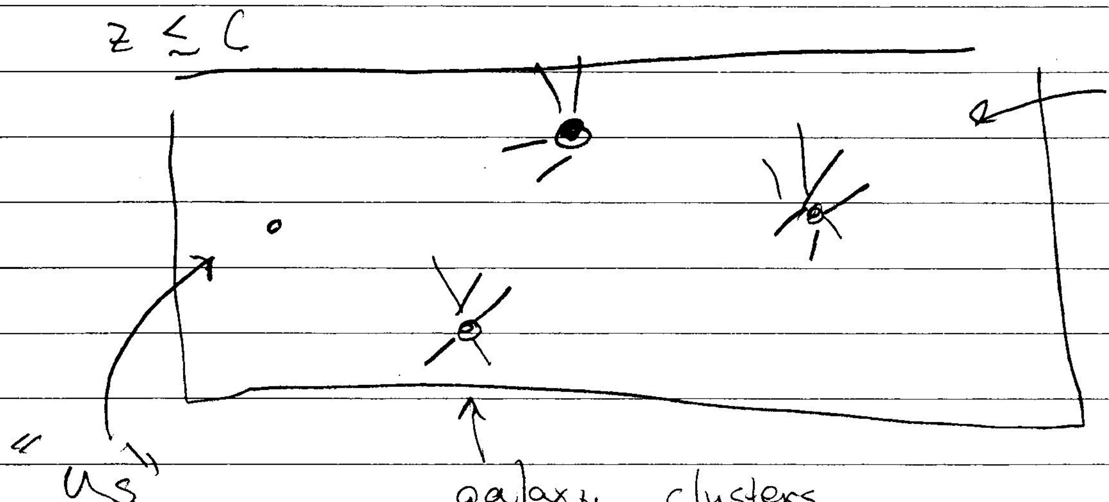
- Then for any wavelength that is emitted by the Quasar with $\lambda_e < 121$ nm, There will be a portion of the Hydrogen gas which will see a longer wavelength, a wavele that is just right to be absorbed.

Evidence for re-ionization. (Cont.)

The very first quasars versus later quasarts

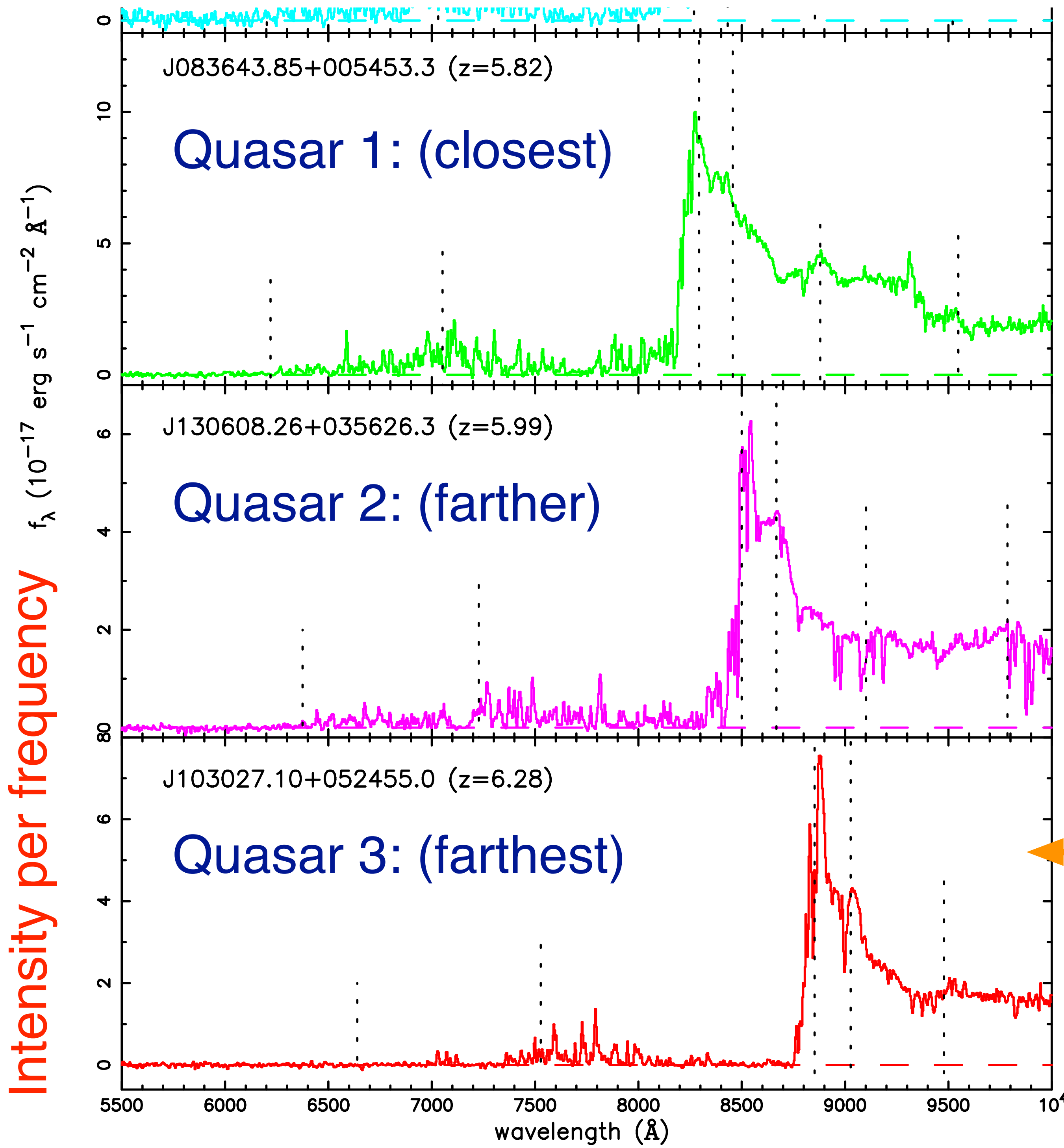


The light from the first quasars is absorbed by the free hydrogen gas at different red-shifts between "us" and the first quasars



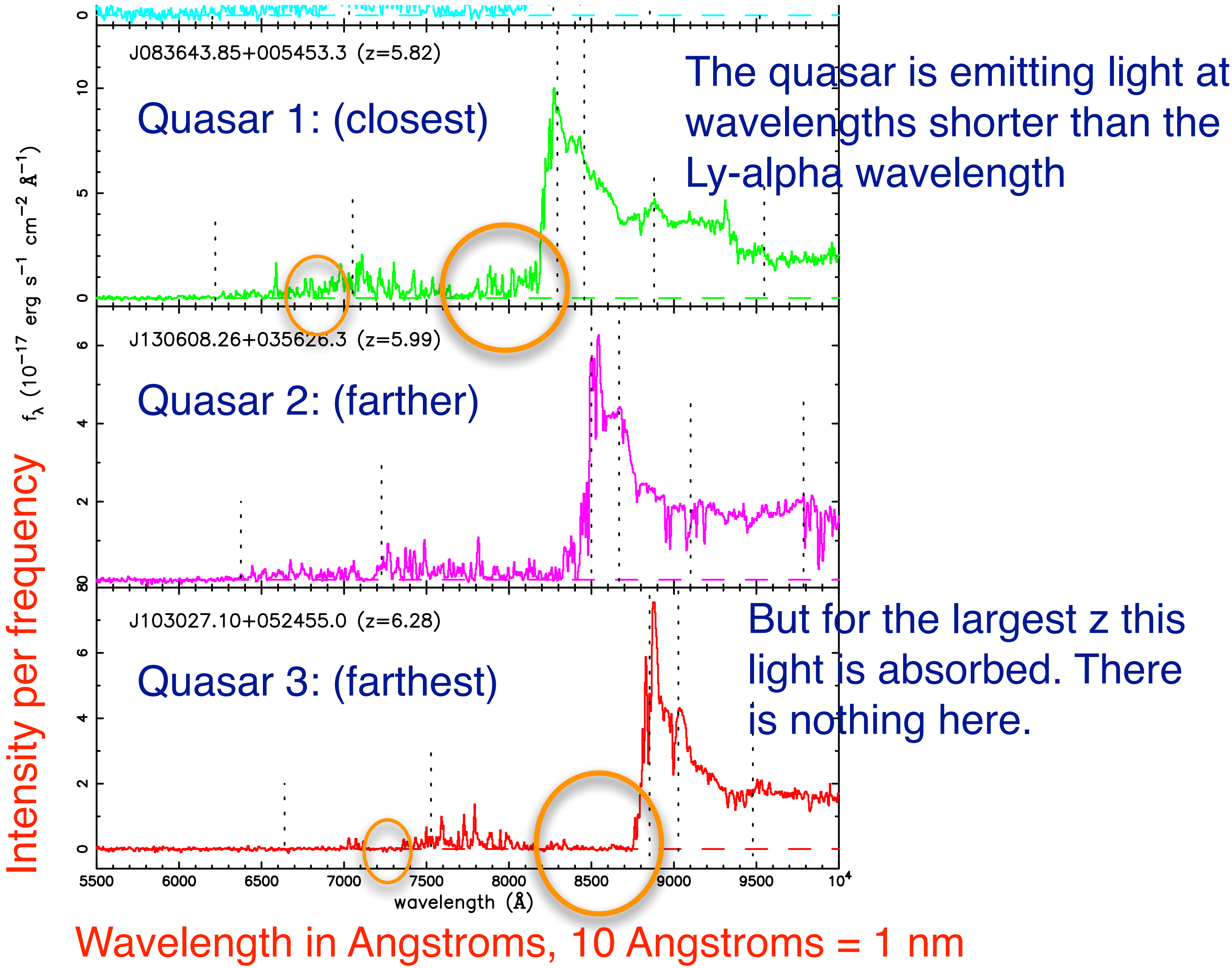
There is no (or very little) free hydrogen to absorb the light from new galaxies (Quasars)

galaxy clusters of ionized plasma



What is Different about this?

Wavelength in Angstroms, 10 Angstroms = 1 nm


J083643.85+005453.3 (z=5.82)
Quasar 1: (closest)
The quasar is emitting light at wavelengths shorter than the Ly-alpha wavelength
J130608.26+035626.3 (z=5.99)
Quasar 2: (farther)
J103027.10+052455.0 (z=6.28)
Quasar 3: (farthest)
But for the largest z this light is absorbed. There is nothing here.
f_λ (10^{-17} erg s^{-1} cm^{-2} $Å^{-1}$)
Intensity per frequency
wavelength (Å)
Wavelength in Angstroms, 10 Angstroms = 1 nm

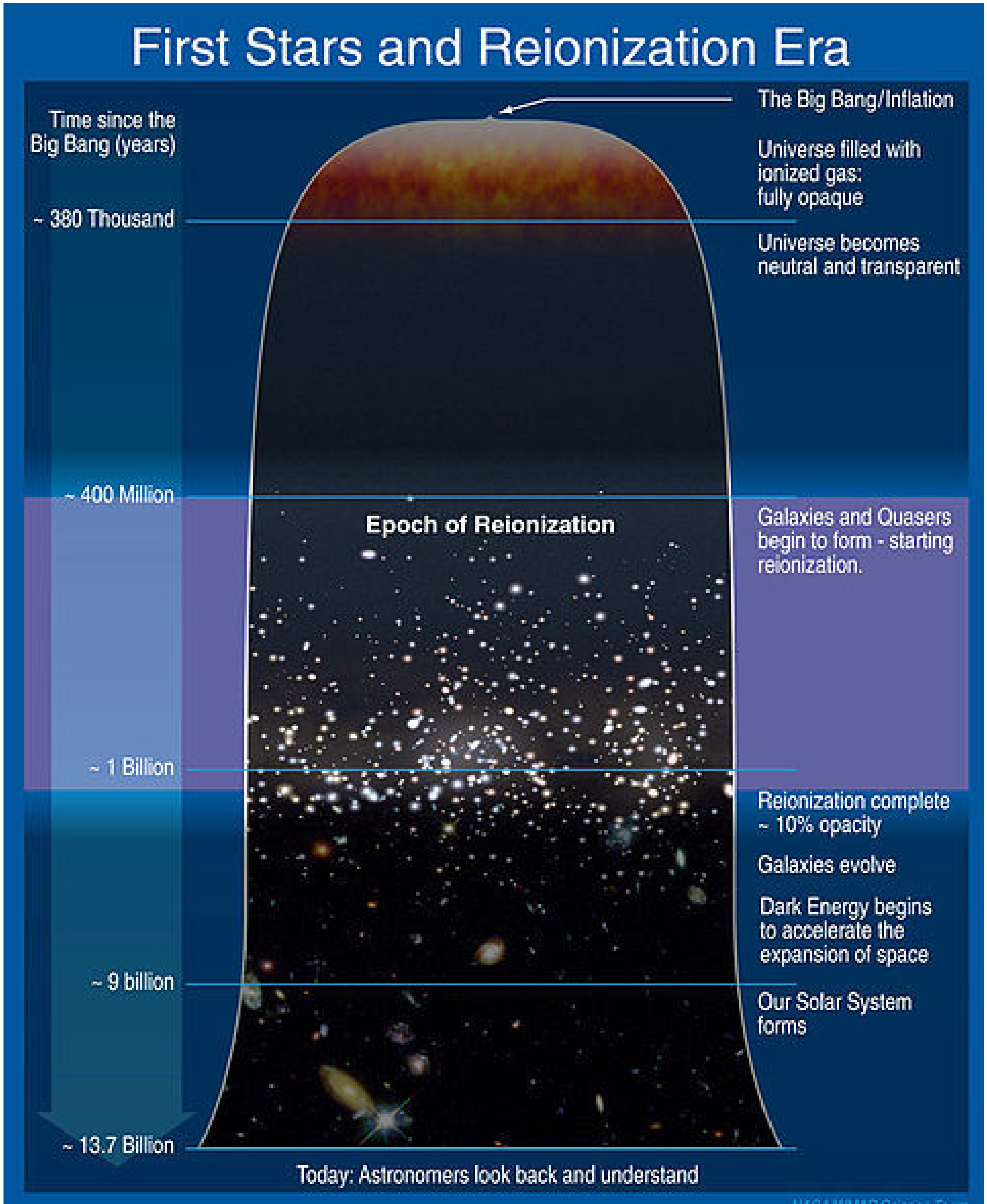
What the last slide shows:

1. When: between $z \simeq 6$ and $z \simeq 6.5$ (about $1\ \mathrm{Gy}$) after the big bang.

2. What: the amount of neutral hydrogen in the universe dramatically changed

3. Conclude:

   - The neutral hydrogen clustered into galaxies and formed ionized plasma again.


First Stars and Reionization Era
Time since the Big Bang (years)
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
~ 380 Thousand
Universe becomes neutral and transparent
~ 400 Million
Epoch of Reionization
Galaxies and Quasers begin to form - starting reionization.
~ 1 Billion
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
~ 9 billion
Our Solar System forms
~ 13.7 Billion
Today: Astronomers look back and understand