Astronomy 120

The Cosmic Microwave Background

Class 22

Prof J. Kenney

November 28, 2016

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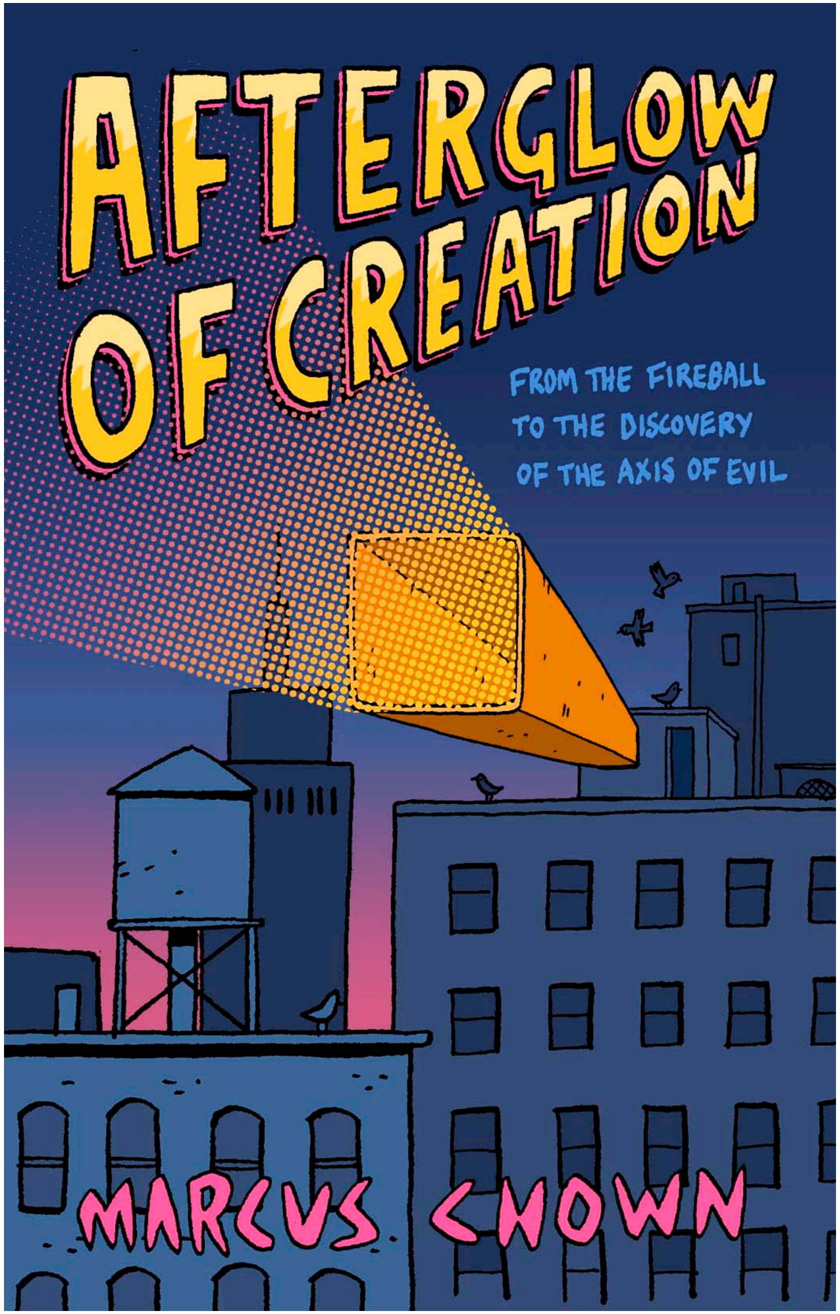
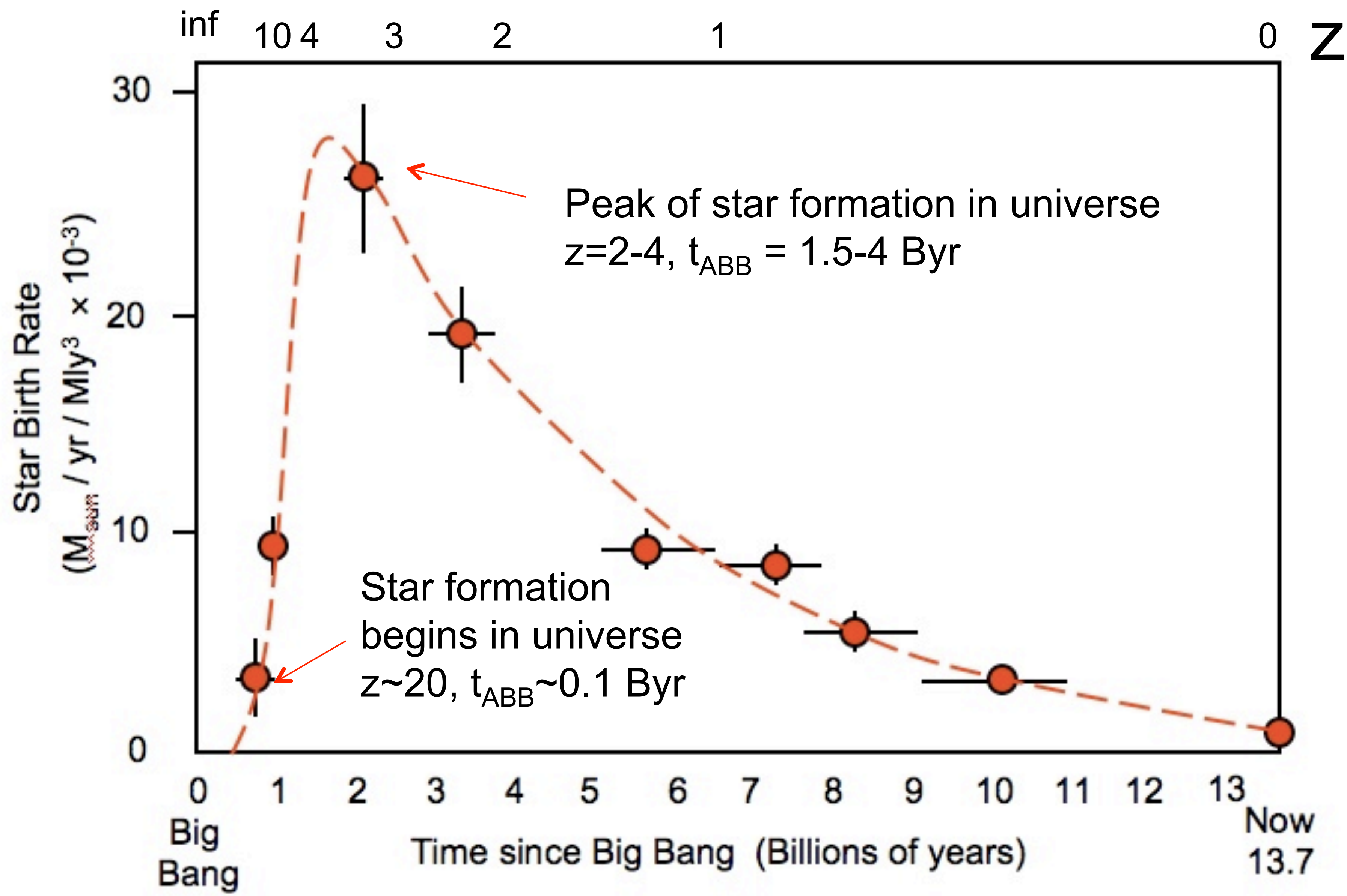
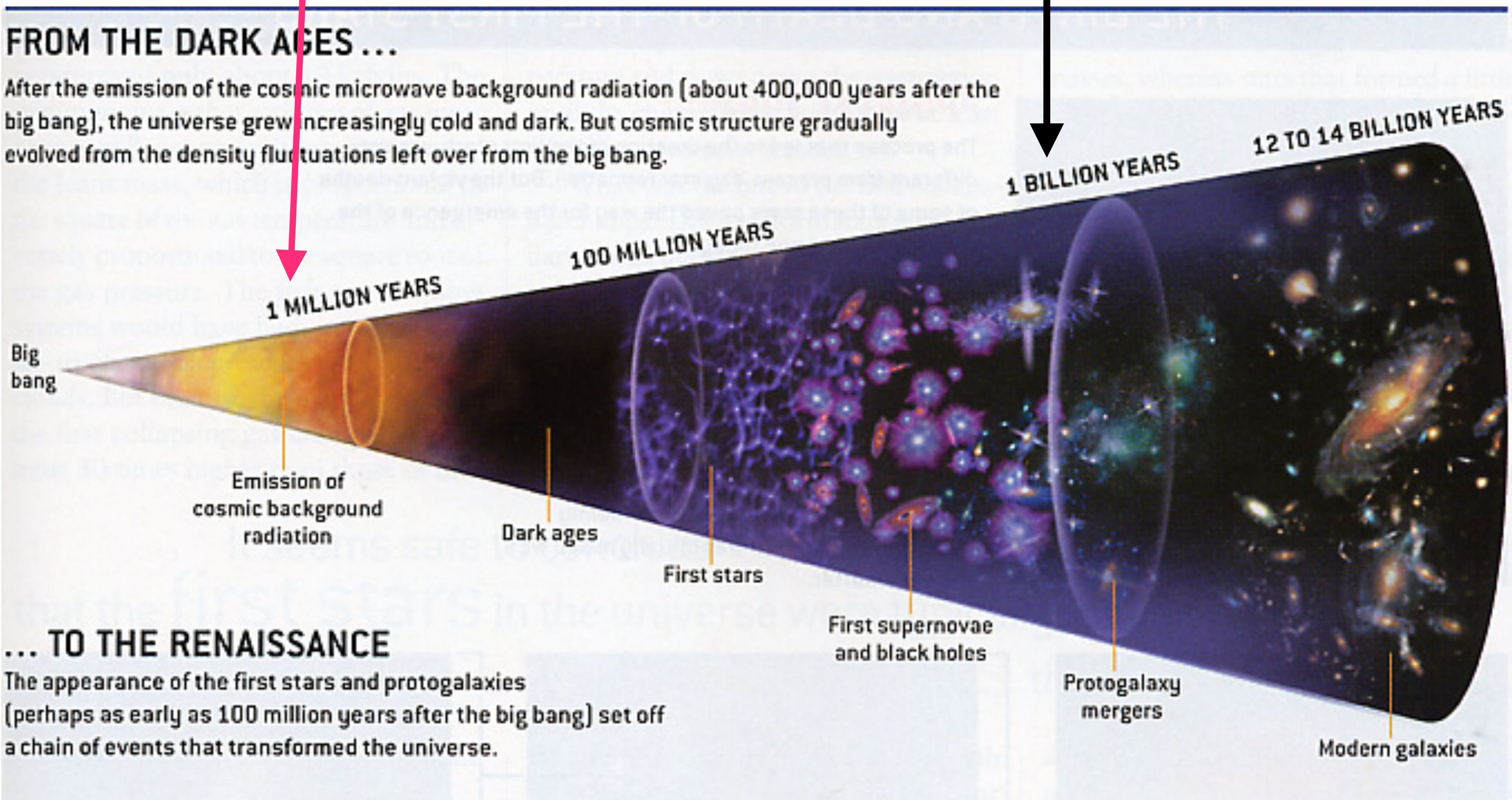


Cosmic star formation history



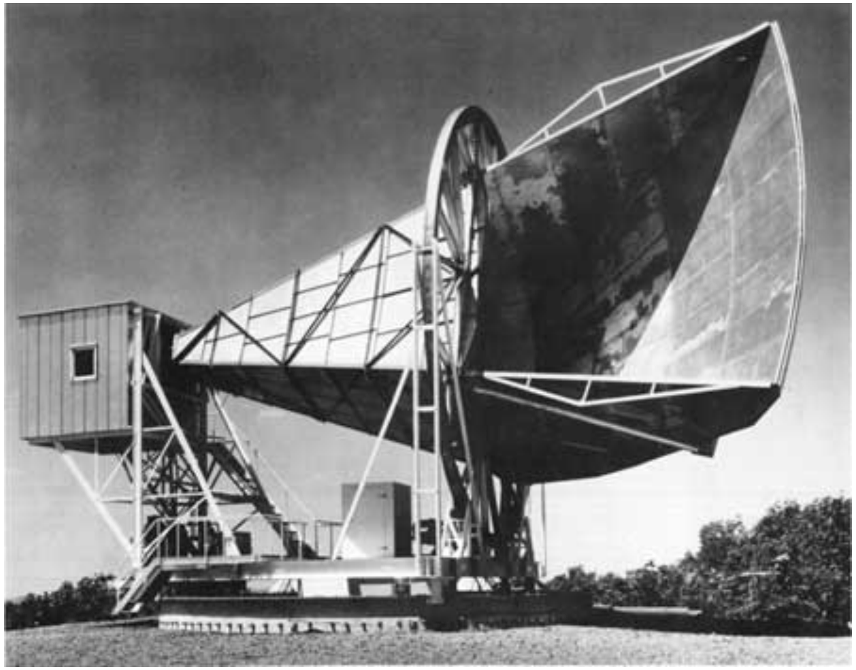
Emission of cosmic background radiation

Era of Peak star, galaxy & black hole formation



BIG BANG Cosmic Time NOW

Discovery of Cosmic Microwave Background (CMB)

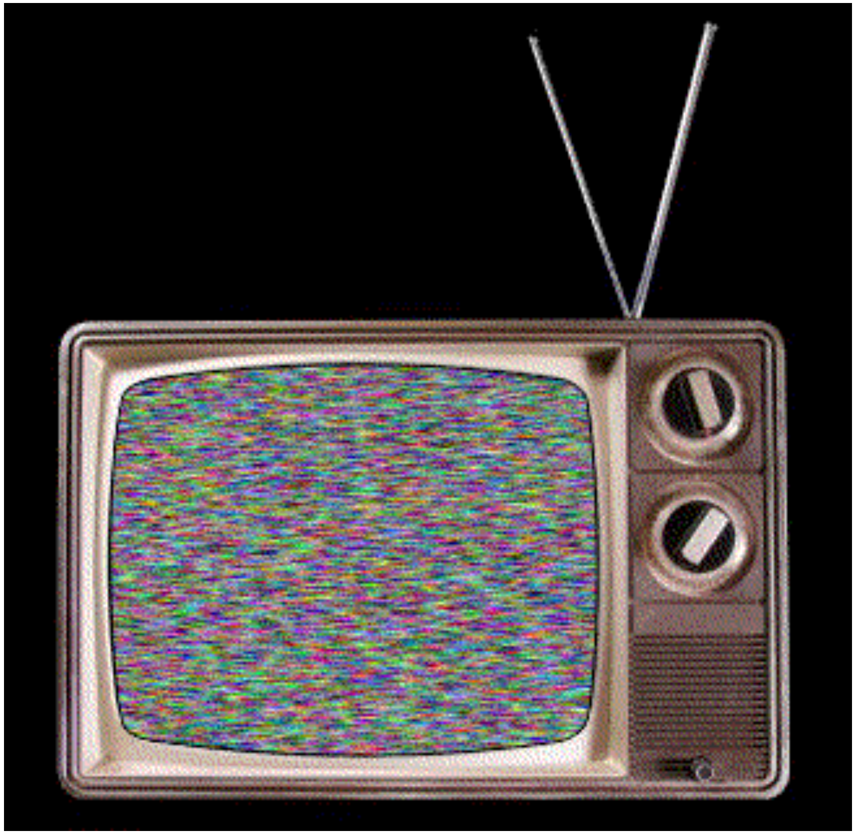


"telescope" used to discover CMB

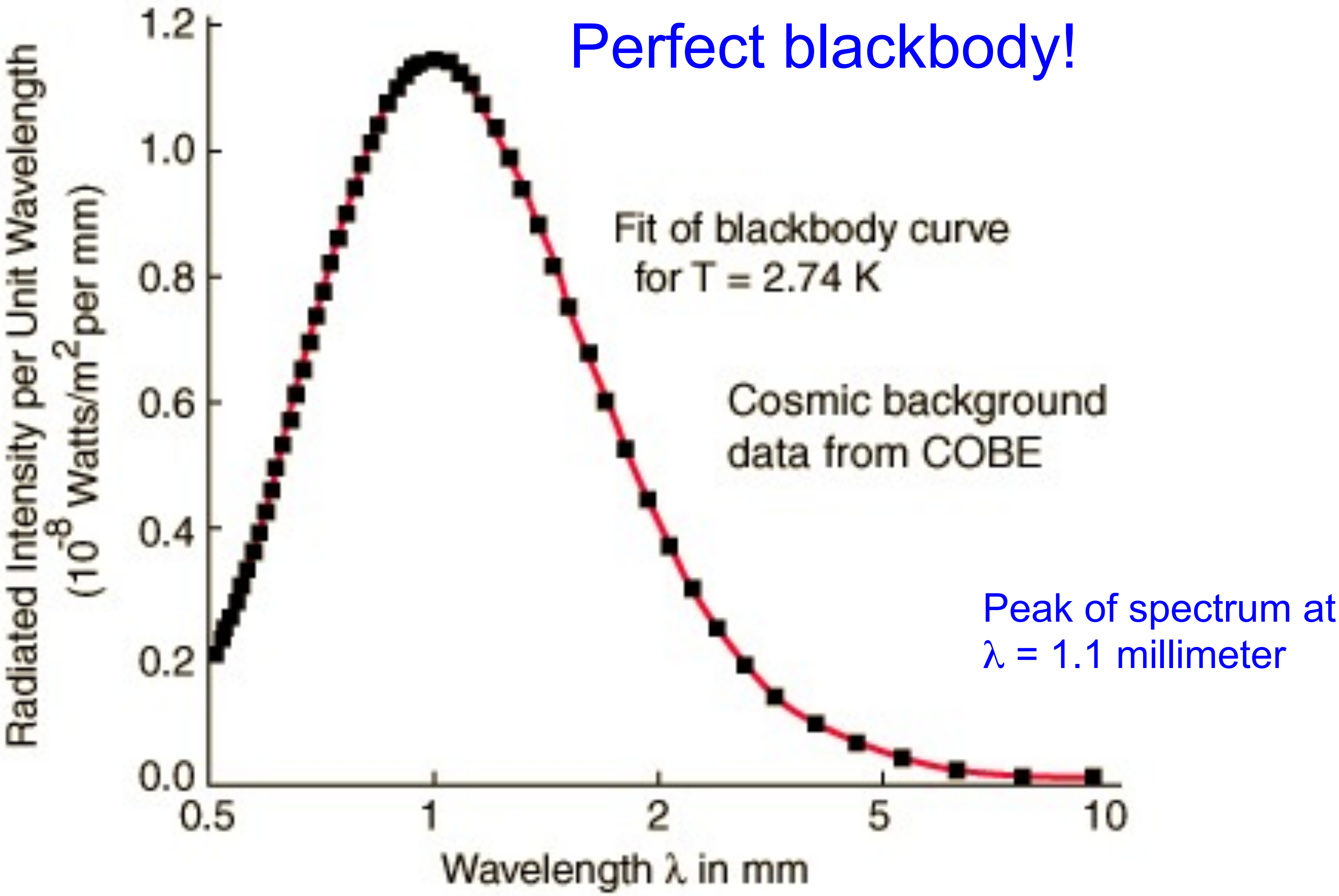
Radio horn at Bell Labs 1964

Penzias & Wilson
with their "telescope"

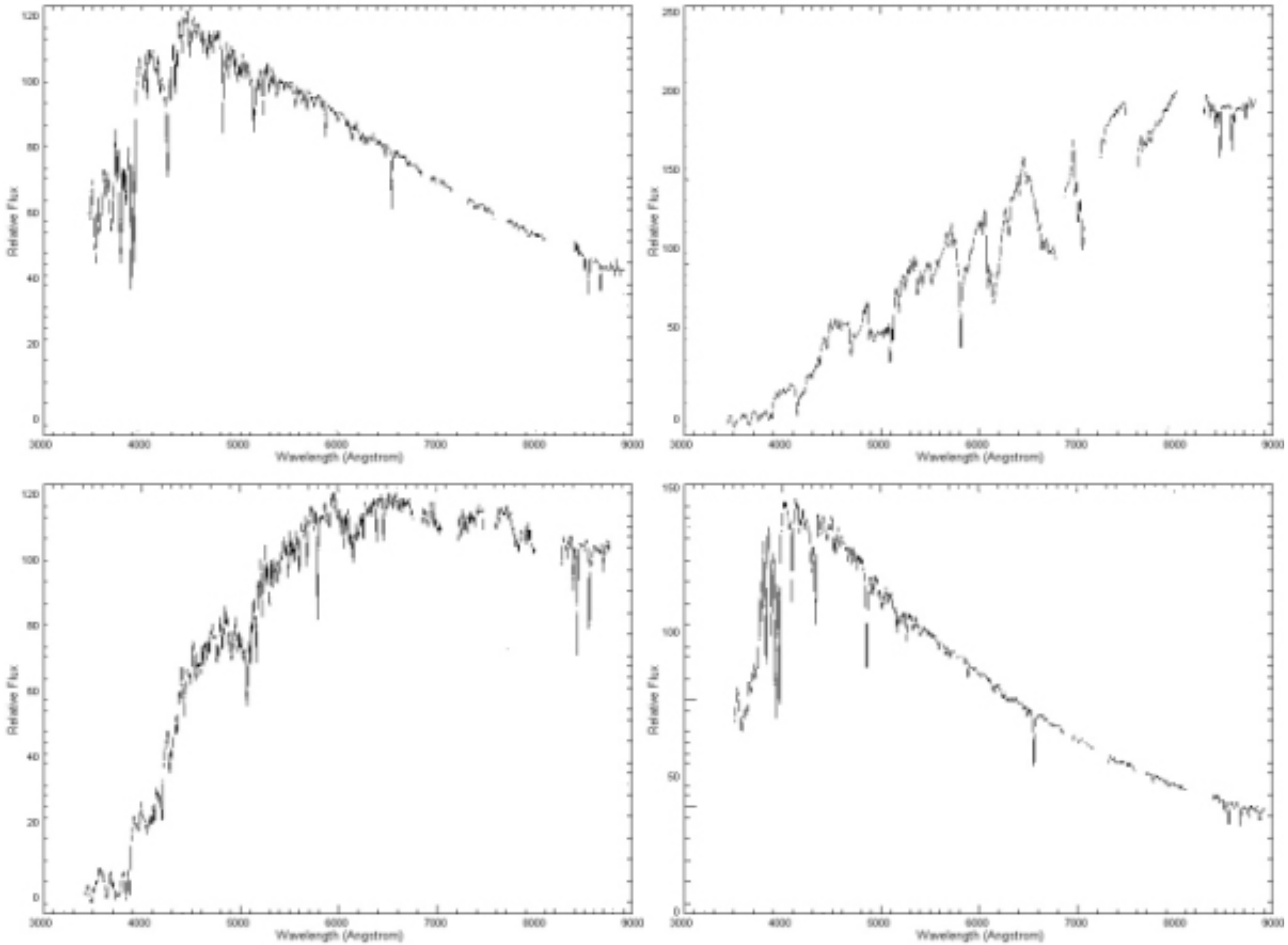
Some TV static is CMB radiation!



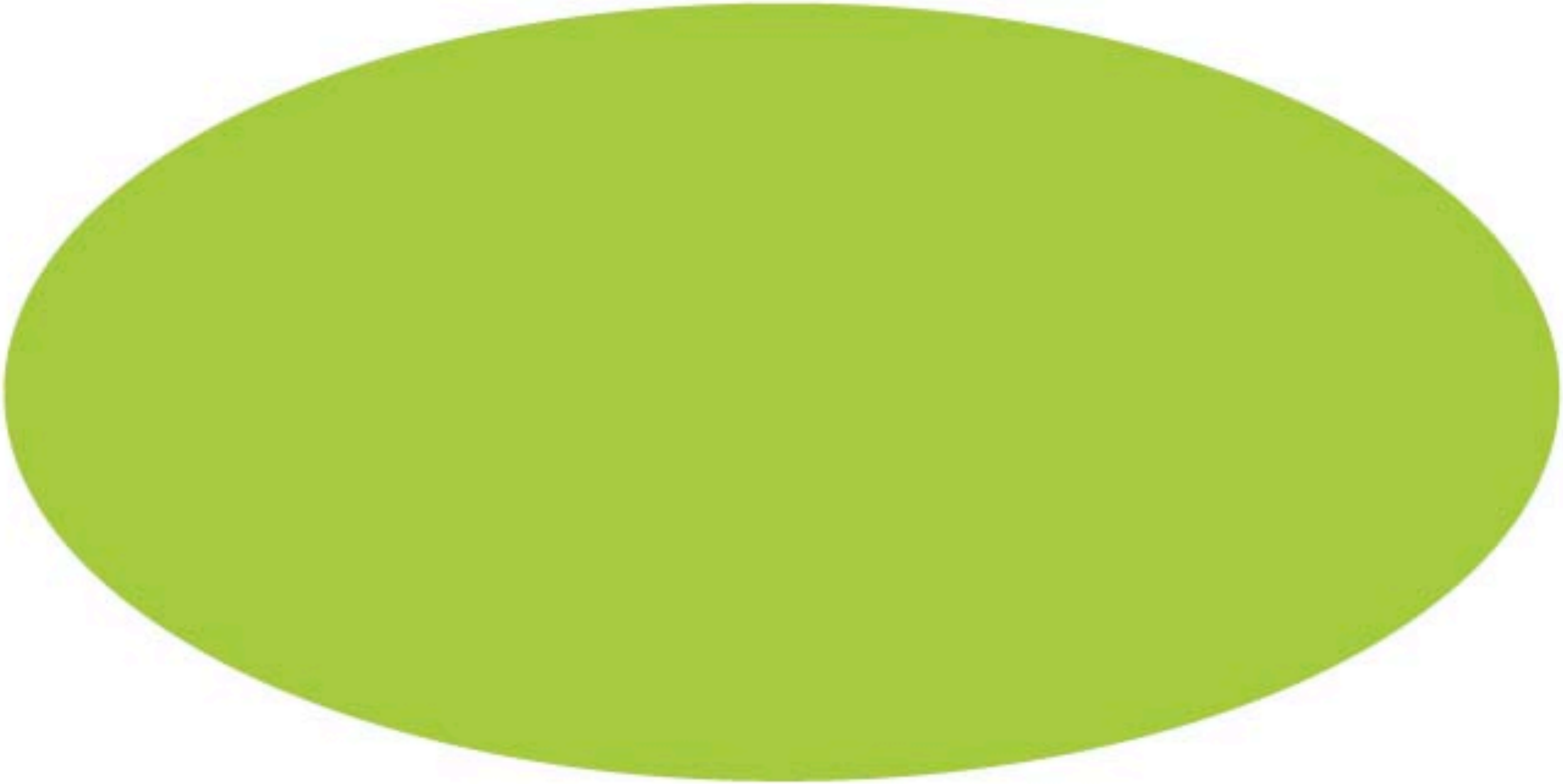
Spectrum of cosmic microwave background



Spectra of stars – NOT perfect blackbodies



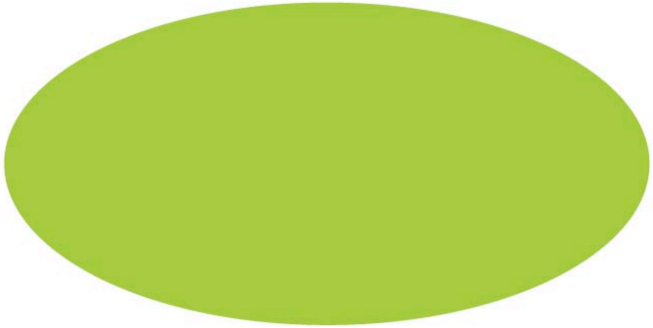
Isotropy of the Cosmic Microwave Background



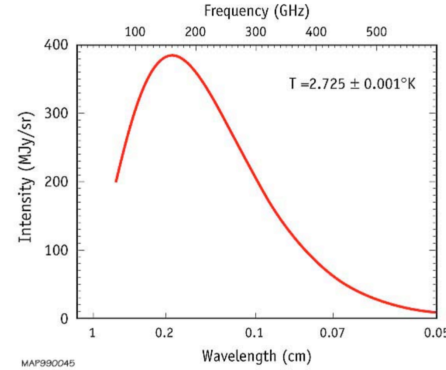
Map of whole sky at millimeter wavelengths ("microwaves") -- very nearly uniform!

Where is "center" of "Big Bang explosion"?

Isotropy of the Cosmic Microwave Background



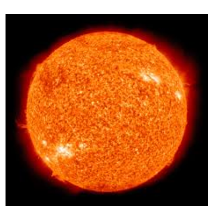
Spectrum of the Cosmic Microwave Background

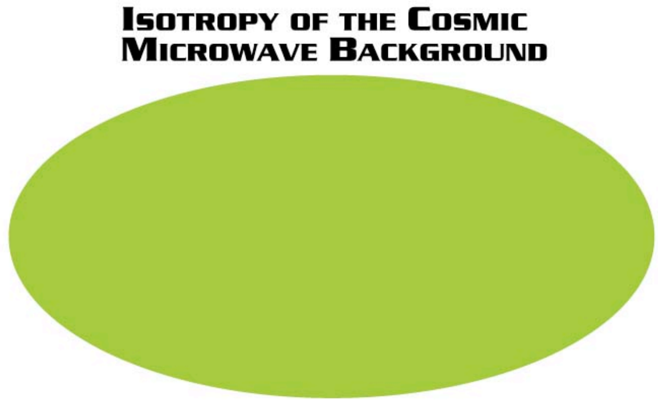


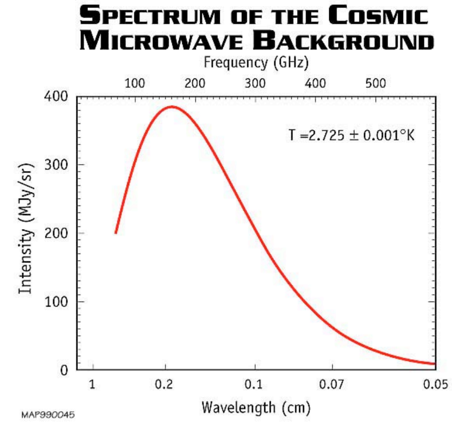
Near isotropy & *perfect blackbody spectrum* of CMB indicate that

CMB photons come from universe as a whole,

not from individual, localized sources within it (like stars, galaxies, AGN)







Near isotropy & *perfect blackbody spectrum* of CMB indicate that

CMB photons come from universe as a whole,

not from individual, localized sources within it (like stars, galaxies, AGN)

CMB photons are:

- much older than those from stars and galaxies
- a relic from early universe, long before stars and galaxies existed, when universe was very smooth
- evidence of a Big Bang

Big Bang predicts CMB.... why?

if universe was once hot enough to ionize atoms, then collisions between electrons and nuclei would unavoidably make lots of photons

(accelerating electrically-charged particles make EM waves)

Photons inevitably produced in Big Bang predicted to cool due to expansion to T~3K by 13.7 Byr after Big Bang

How far could these photons have travelled through space?

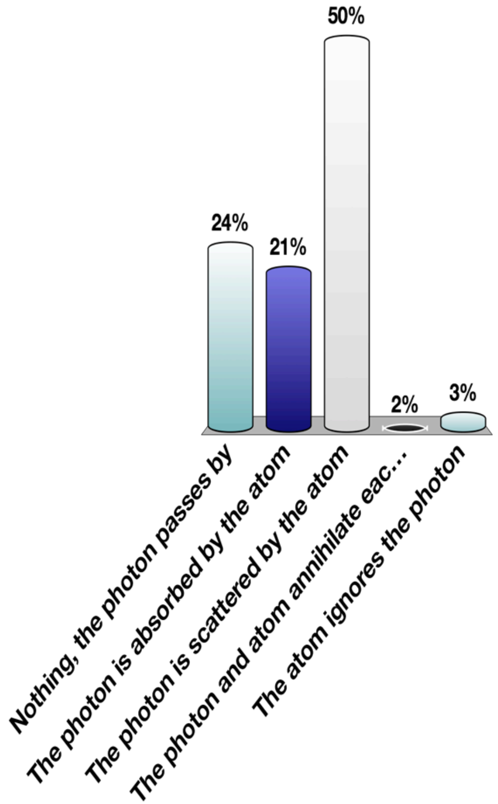
What happens to them as they go through space?

What happens to these photons if they run into an atom in space?

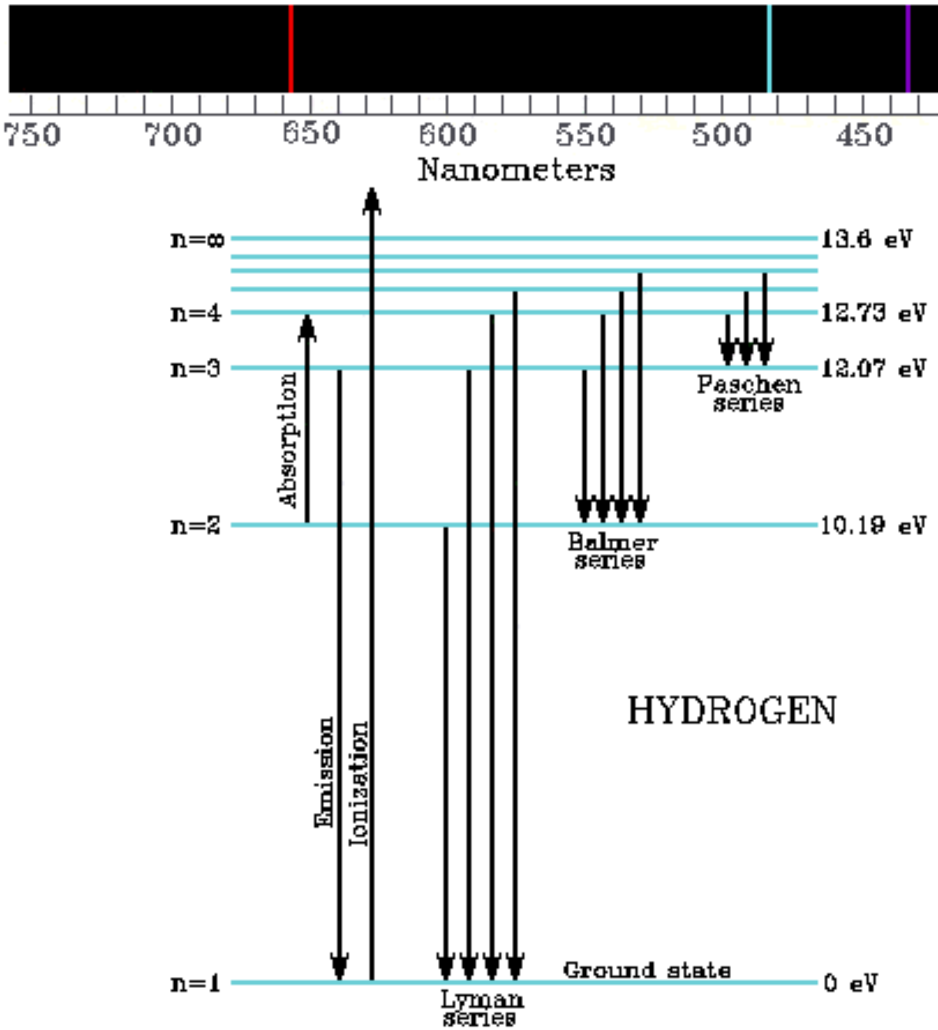
Think of 2 constituents of universe + how they interact: Atoms in space & Cosmic photons

A photon with a wavelength of 1 millimeter (10^{-3} m; radio) encounters an H atom. What happens?

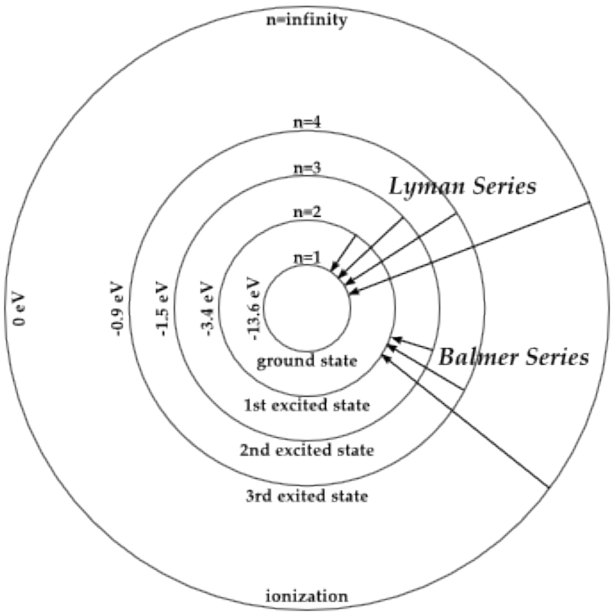
1. Nothing, the photon passes by
2. The photon is absorbed by the atom
3. The photon is scattered by the atom
4. The photon and atom annihilate each other
5. The atom ignores the photon



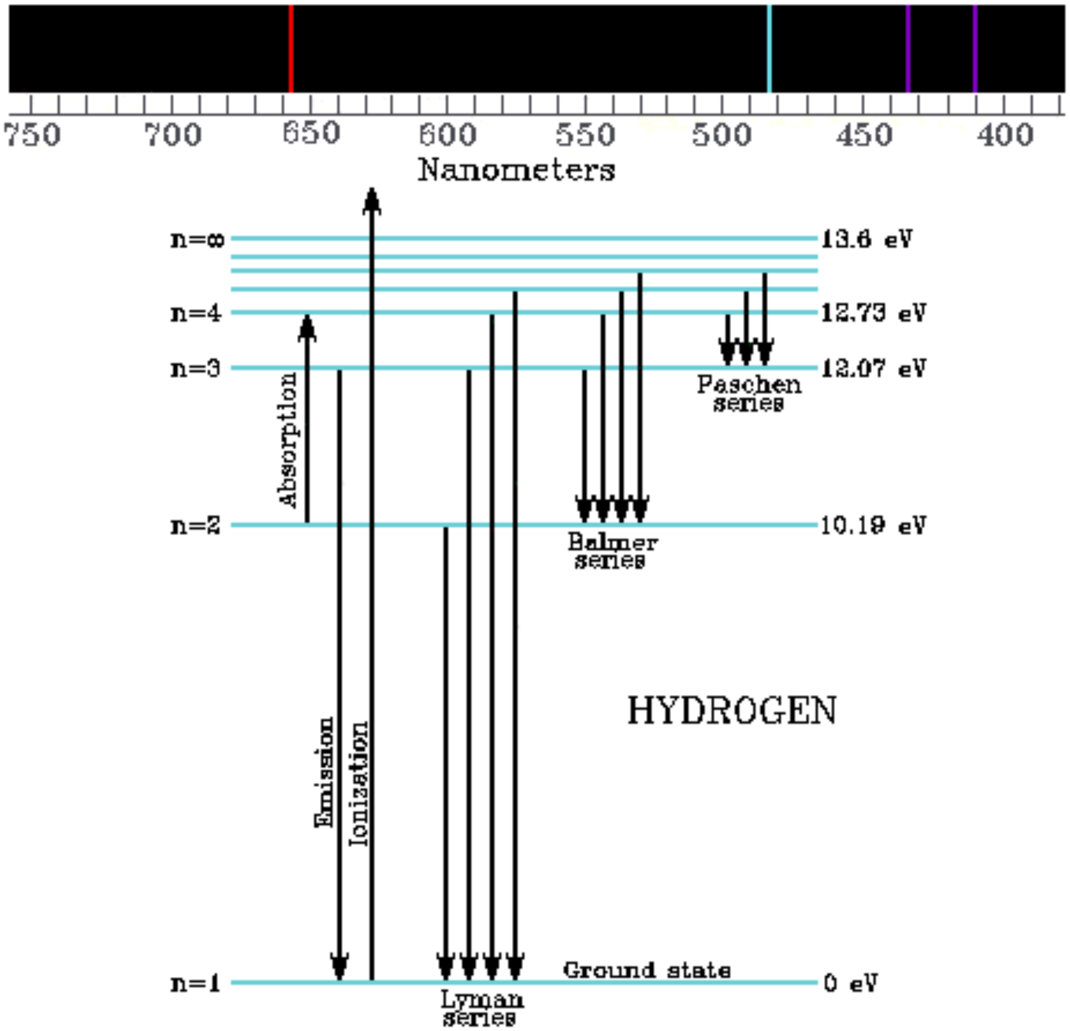
Energy level diagram of Hydrogen



What does a photon with λ = 1mm do to an H atom?

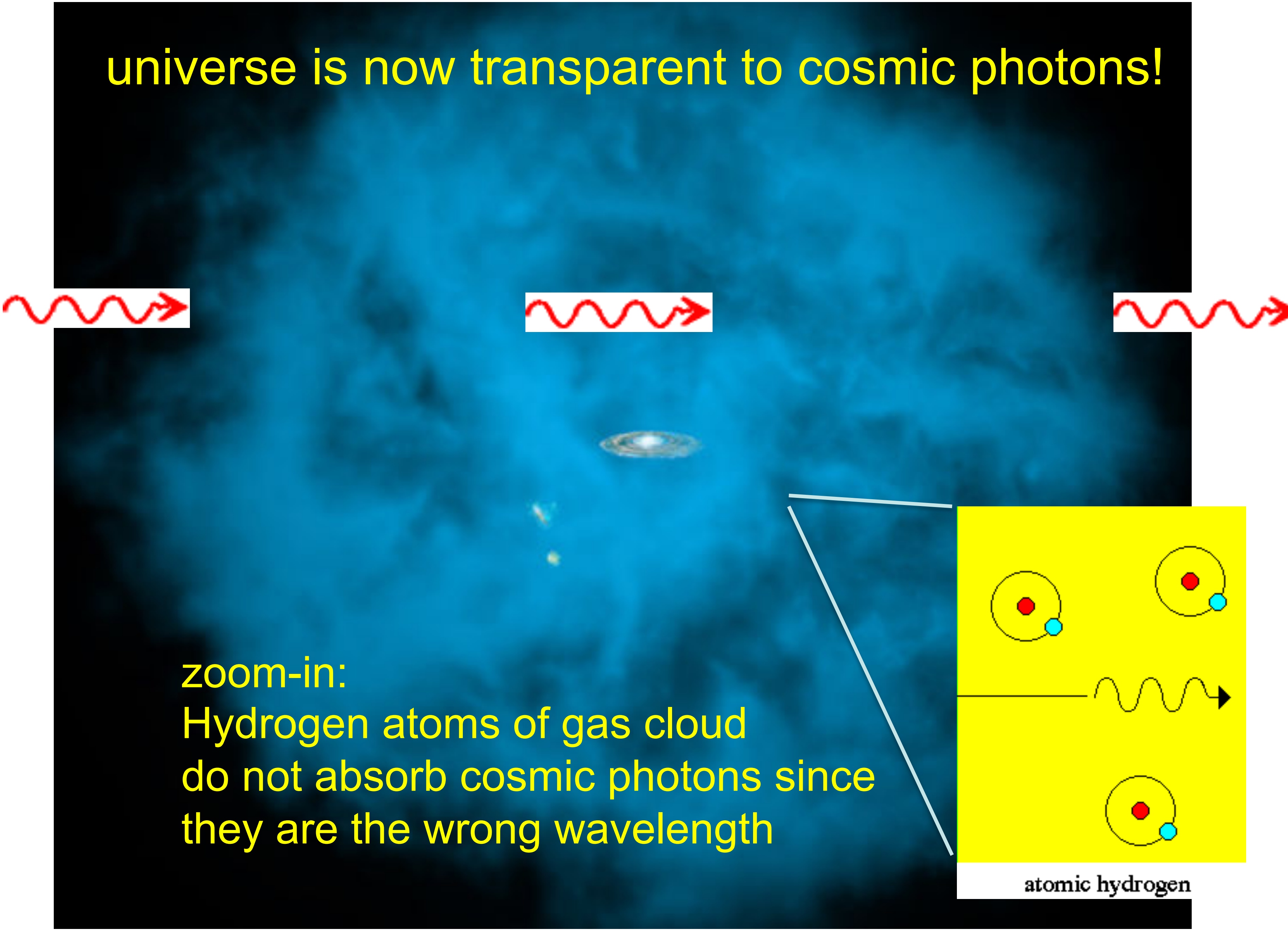


Energy level diagram of Hydrogen

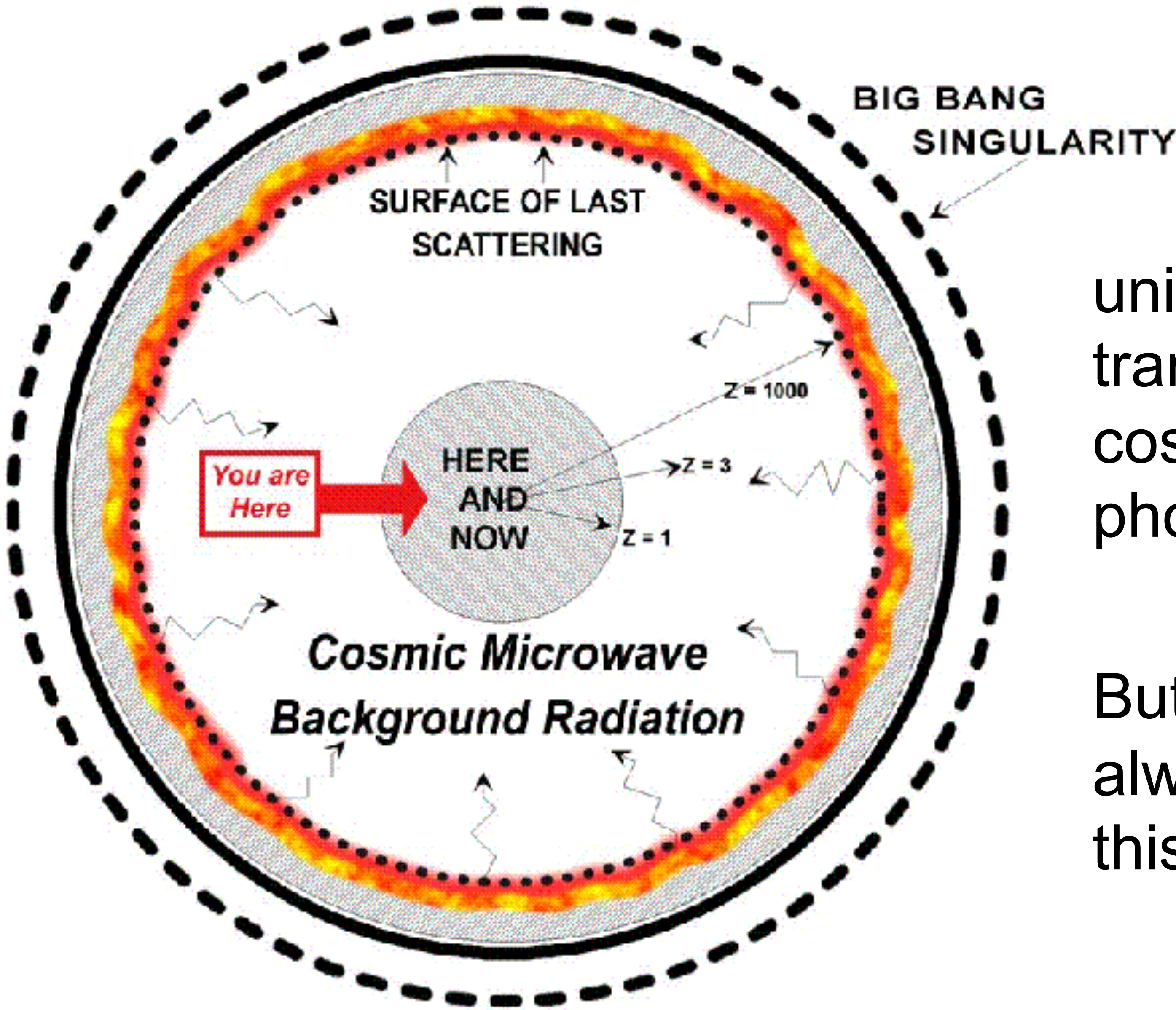


What does a photon with λ = 1mm do to an H atom?

NOTHING!


universe is now transparent to cosmic photons!
zoom-in:
Hydrogen atoms of gas cloud
do not absorb cosmic photons since
they are the wrong wavelength
atomic hydrogen

observable universe

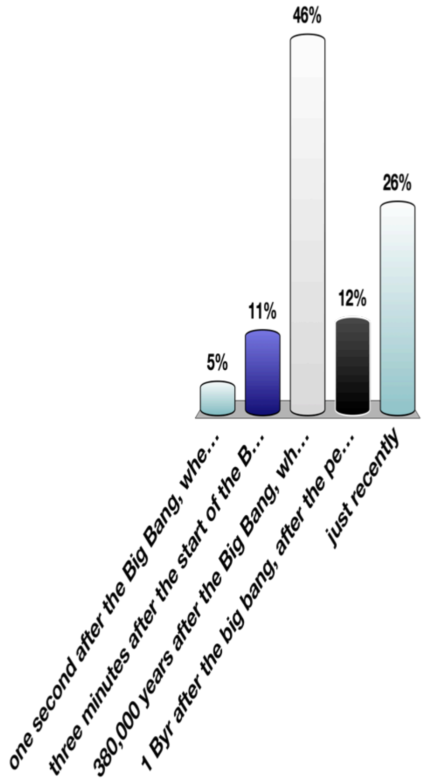


universe is now transparent to cosmic photons!

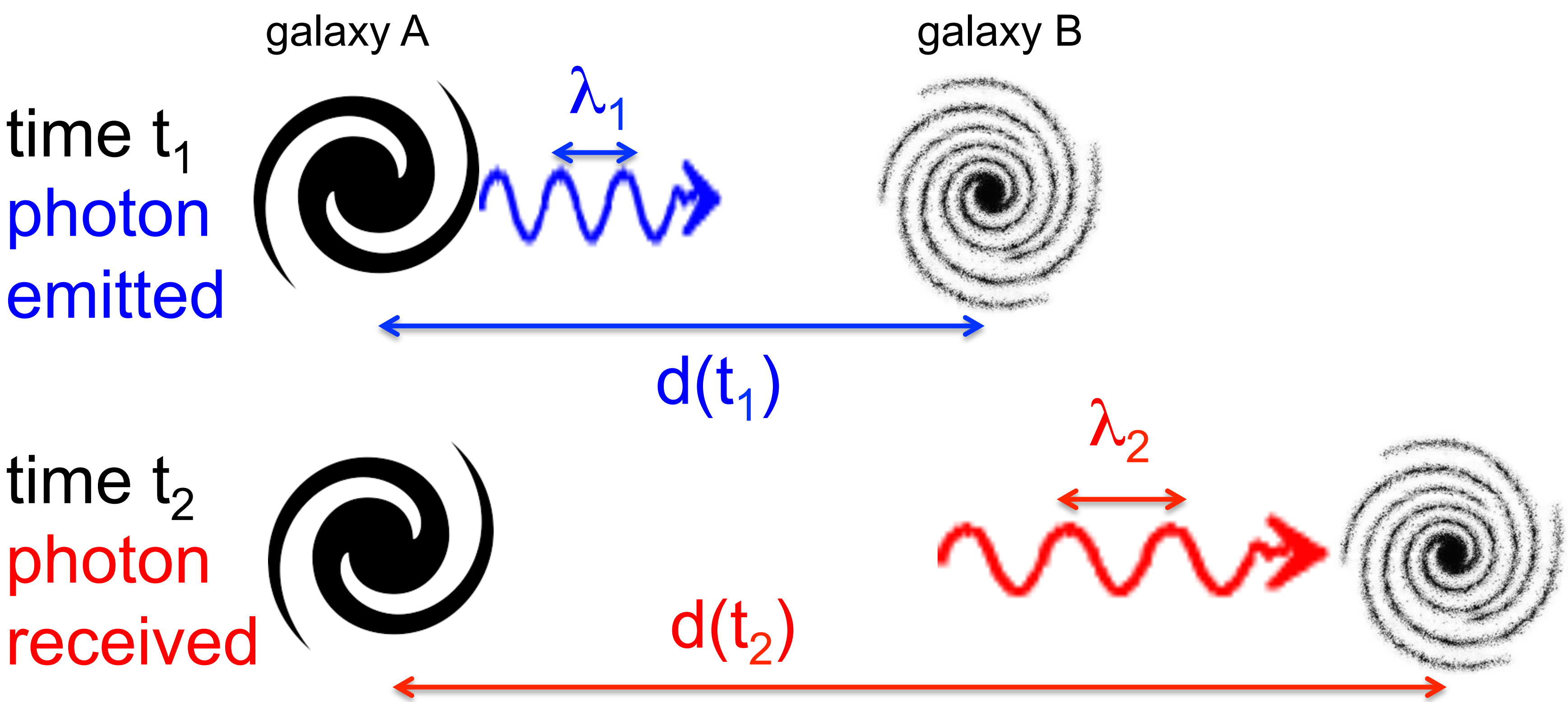
But it wasn't always like this…

I thought that the Big Bang was hot! If the cosmic microwave background radiation is the radiation left over from the Big Bang, when did the universe cool down to about 3 K?

1. one second after the Big Bang, when electron-positron pair production ceased
2. three minutes after the start of the Big Bang, when primordial nuclear reactions ended
3. 380,000 years after the Big Bang, when the universe became transparent to radiation
4. 1 Byr after the big bang, after the peak of the quasar era
5. just recently



why do CMB photons cool? expansion! photons are "stretched out" to longer wavelengths as space in universe expands



for a photon emitted at time t_1 and detected at time t_2

$$\lambda_2/\lambda_1 = 1 + z_{cos} = d(t_2)/d(t_1)$$

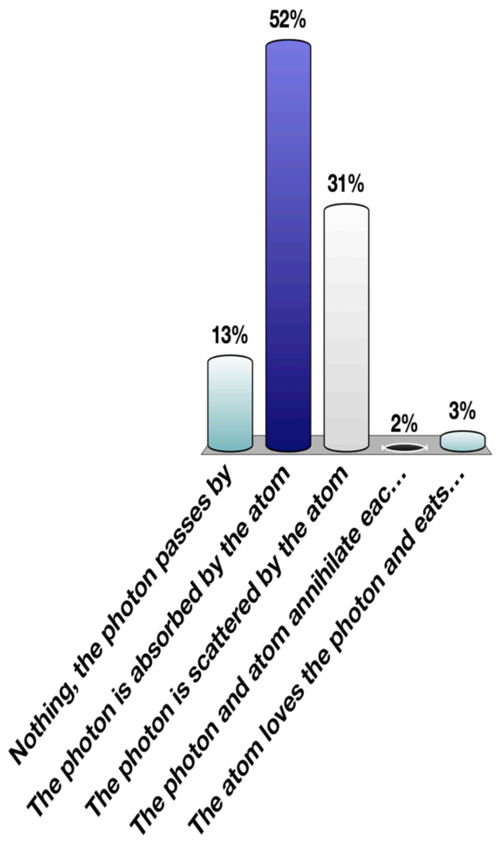
Because of expansion, in the past not only were things closer together, but photons each had more energy … so it was hotter in the past. Photons lose energy and ‘cool’ continuously as universe expands.

Think how expansion and cooling has changed interaction of CMB photons & matter

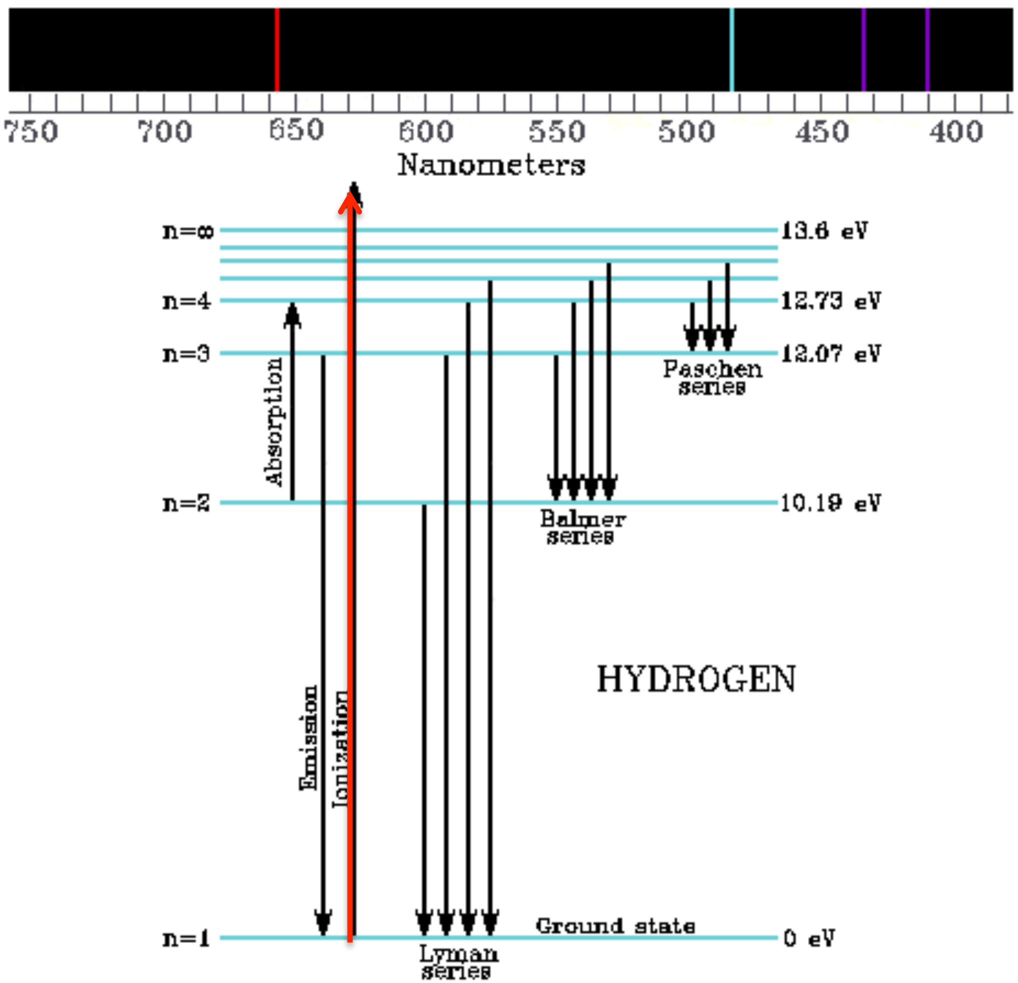
If photons had more energy, how might interactions with matter change?

A photon with a wavelength of 0.1 microns (10^{-7} m; UV) encounters a H atom. What happens?

1. Nothing, the photon passes by
2. The photon is absorbed by the atom
3. The photon is scattered by the atom
4. The photon and atom annihilate each other
5. The atom loves the photon and eats it right up



Energy level diagram of Hydrogen



What energy and wavelength does a photon need to ionize an H atom?

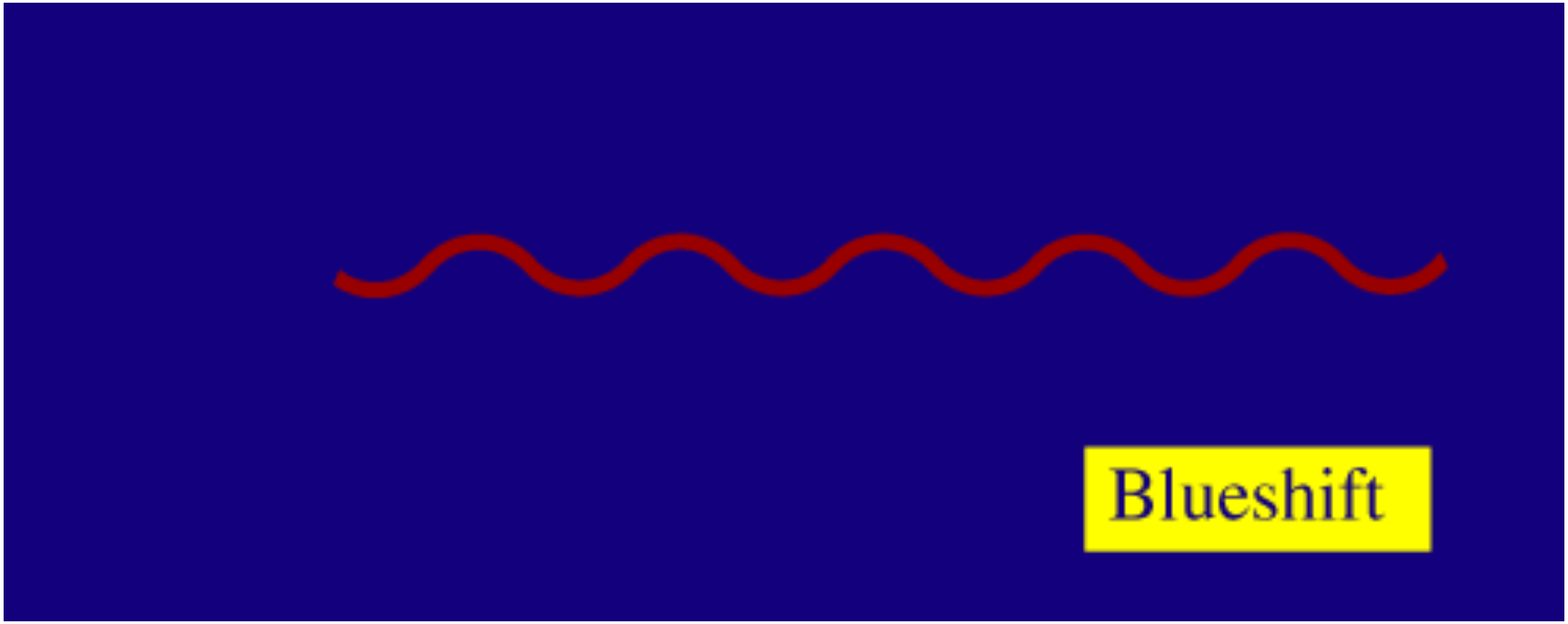
$E > 13.6\text{eV}$

$\lambda < 0.1\ \mu\text{m}$

so when the cosmic photons had shorter wavelengths (& higher energies) in the early universe, they interacted strongly with matter! They were absorbed or scattered by interactions with atoms and electrons.

This means the universe was opaque to cosmic photons!!

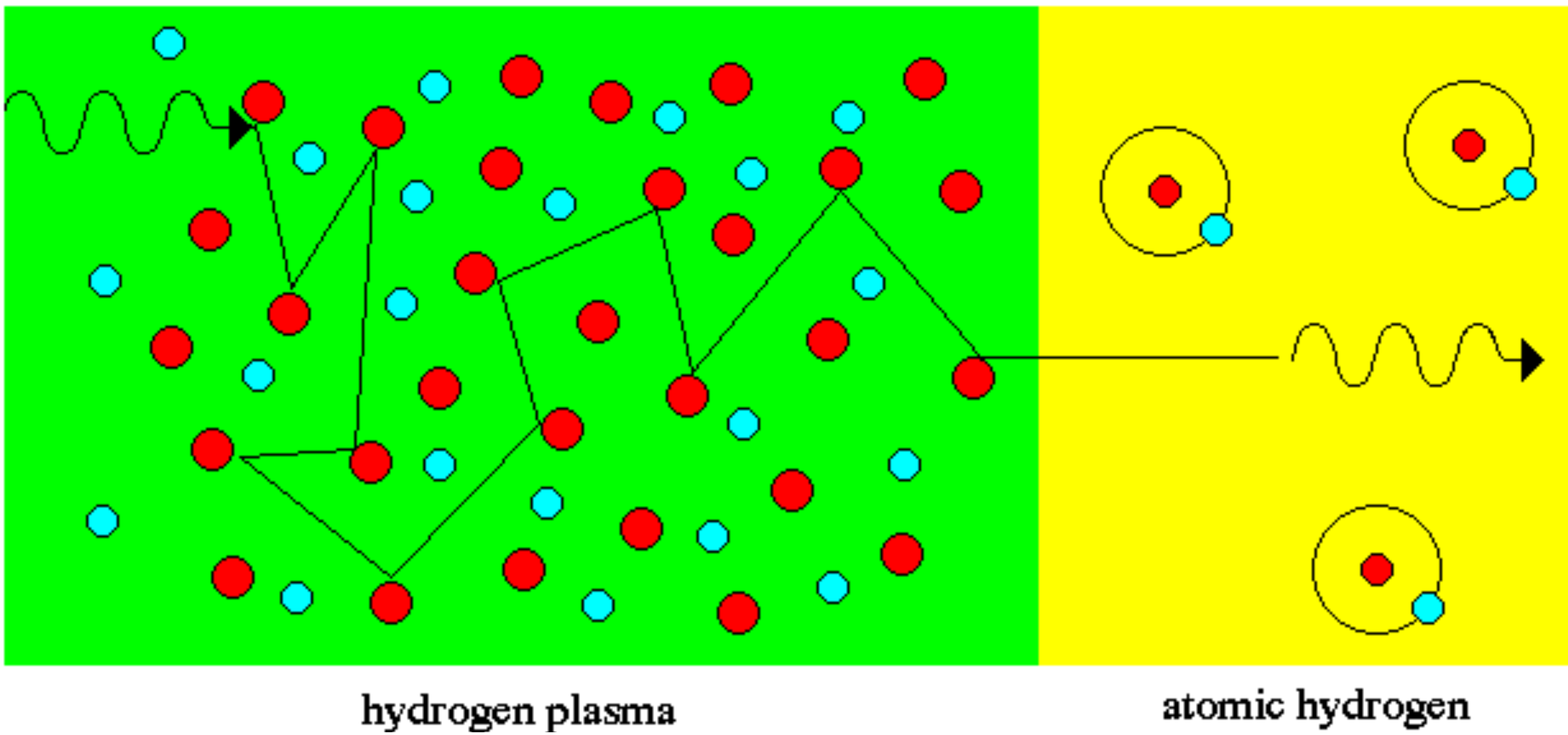
imagine running the expansion backwards…



cosmic photons NOW don't ionize atoms
but AT MUCH EARLIER TIME cosmic photons had enough energy to ionize atoms

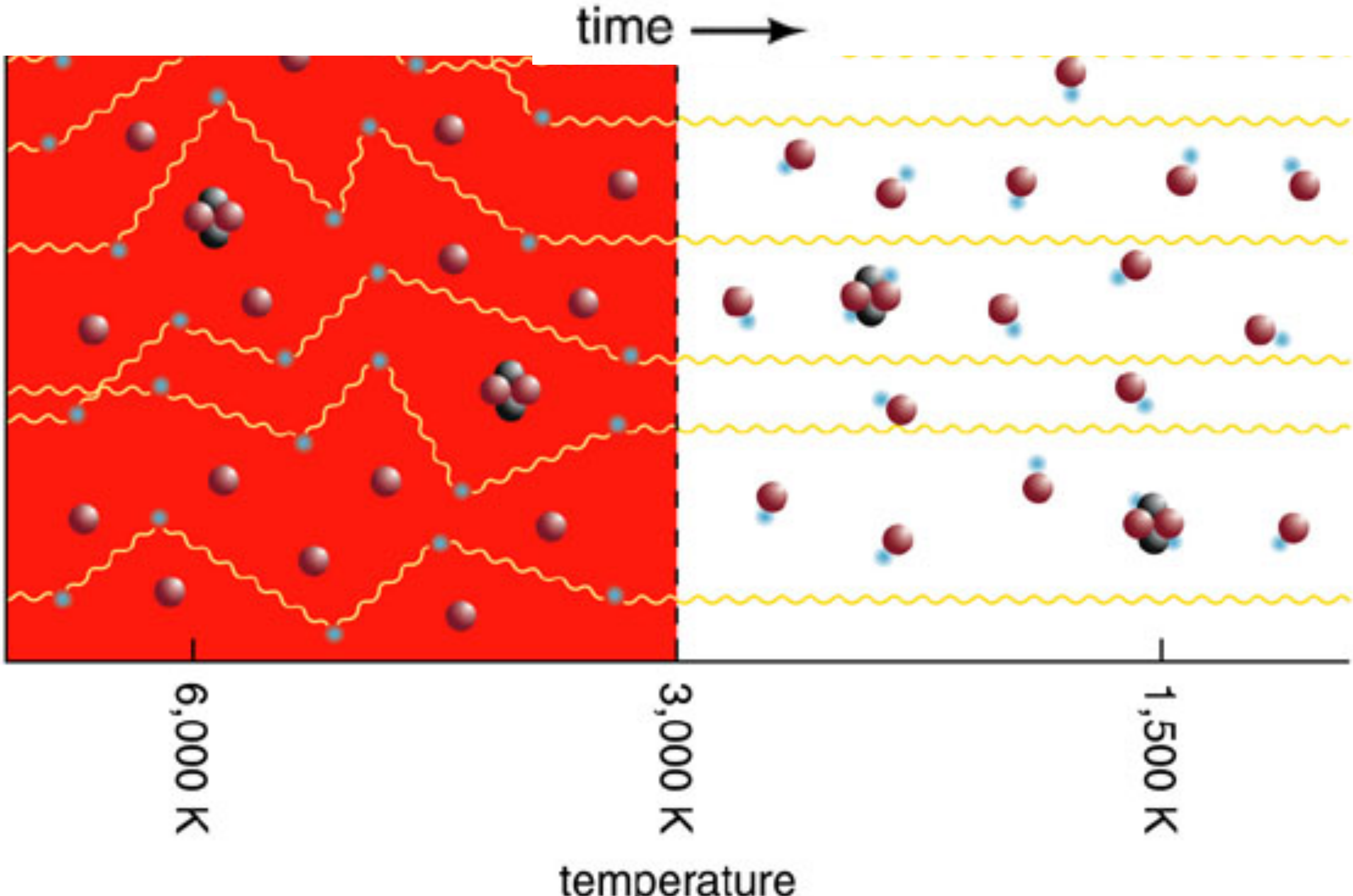
Before recombination

After recombination



Before recombination:
era of nuclei (or plasma)

After recombination:
era of atoms



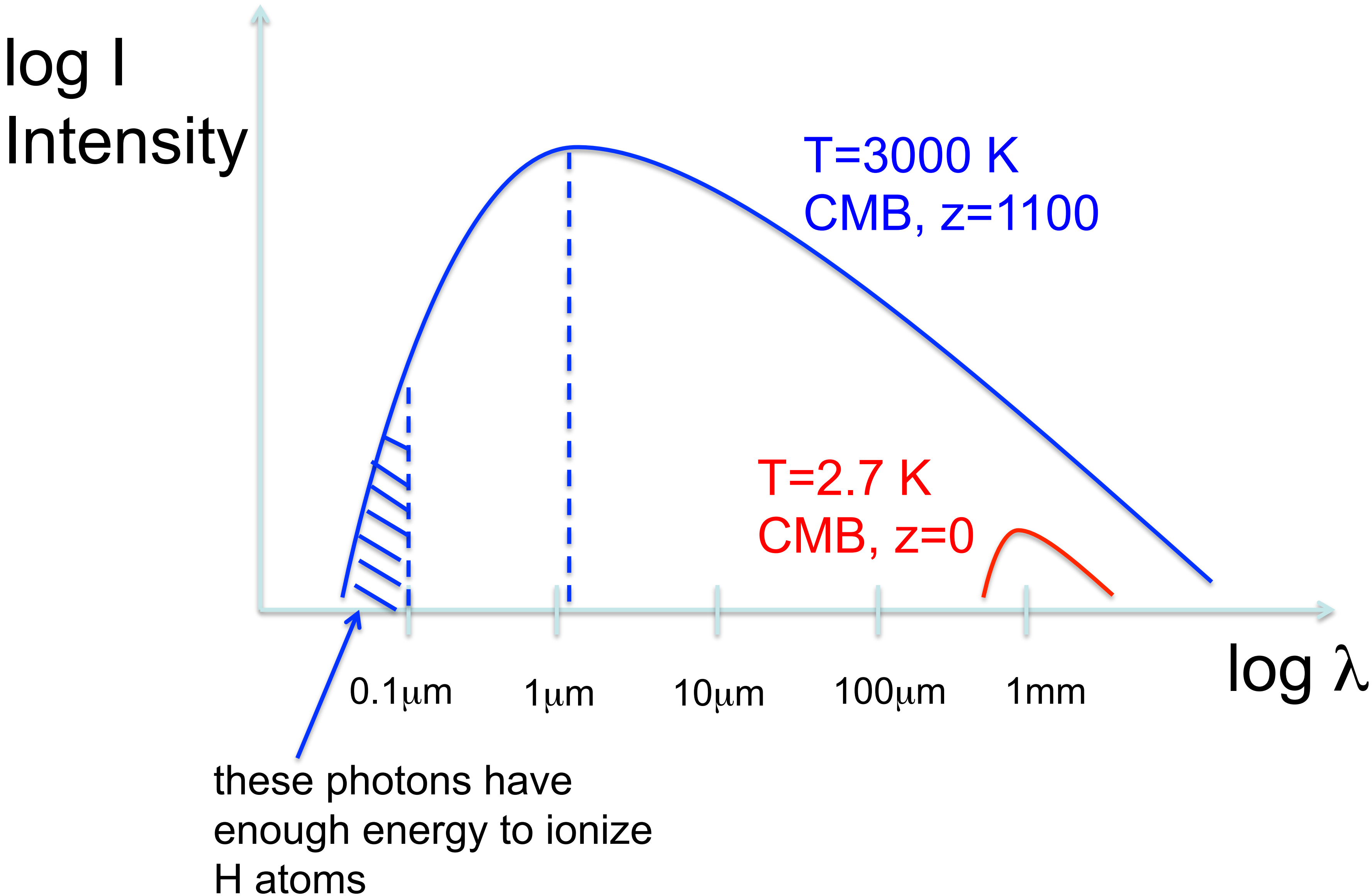
When did the Cosmic Background Radiation have enough energy to ionize all the H in the universe?

When did it have enough photons with $\lambda<0.1$ μm ?

Expansion has stretched wavelengths of cosmic photons.

How does this change temperature which characterizes cosmic photons?

blackbody spectra of CMB at z=0 and z=1100



T=3000K is sufficient to ionize all H in the universe. WHY?

Since there are

10^9 cosmic photons for each atom ,

There are ***enough photons in the high energy tail*** of a 3000K photon distribution to ionize all the H in the universe

what was redshift z when cosmic photons had enough energy to ionize H?

temperature of CMB was T = 3000K when cosmic photons had enough energy to ionize H

T_{then} = 3000K

T_{now} = 2.7K **-> T was 1100 x higher**

what was redshift z? (use Wiens law)

$\lambda_{max,em} = 0.29 / T_{then}$

$\lambda_{max,obs} = 0.29 / T_{now}$

$\lambda_{obs} / \lambda_{em} = T_{then} / T_{now}$ for CMB photons

what was redshift z when cosmic photons had enough energy to ionize H?

$\lambda_{obs} / \lambda_{em} = T_{then} / T_{now}$ for CMB photons

but we also know:

$\lambda_{obs} / \lambda_{em} = 1 + z$

thus…

$1 + z = T_{then} / T_{now}$ for CMB photons

since $T_{then} / T_{now} = 1100$, $1 + z = 1100$ → $z = 1099 \cong 1100$

so cosmic photons originate from z=1100

what was redshift z when cosmic photons had enough energy to ionize H?

temperature of CMB was T = 3000K when cosmic photons had enough energy to ionize H

T_{then} = 3000K

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thus…

$1 + z = T_{then} / T_{now}$ for CMB photons

since $T_{then} / T_{now} = 1100$, $1 + z = 1100$ → $z = 1099 \cong 1100$

so cosmic photons originate from z=1100

What time does at z=1100 correspond to?

t = 380,000 yr after the Big Bang (ABB)

How do we know this?

We figure out what z had to be at time of decoupling in order for cosmic photons to ionize all H,

then get t from z and the cosmological parameters (H_o, Ω_m, Ω_Λ)

Universe before z>1100, T>3000K, t_{ABB}<380,000 yr

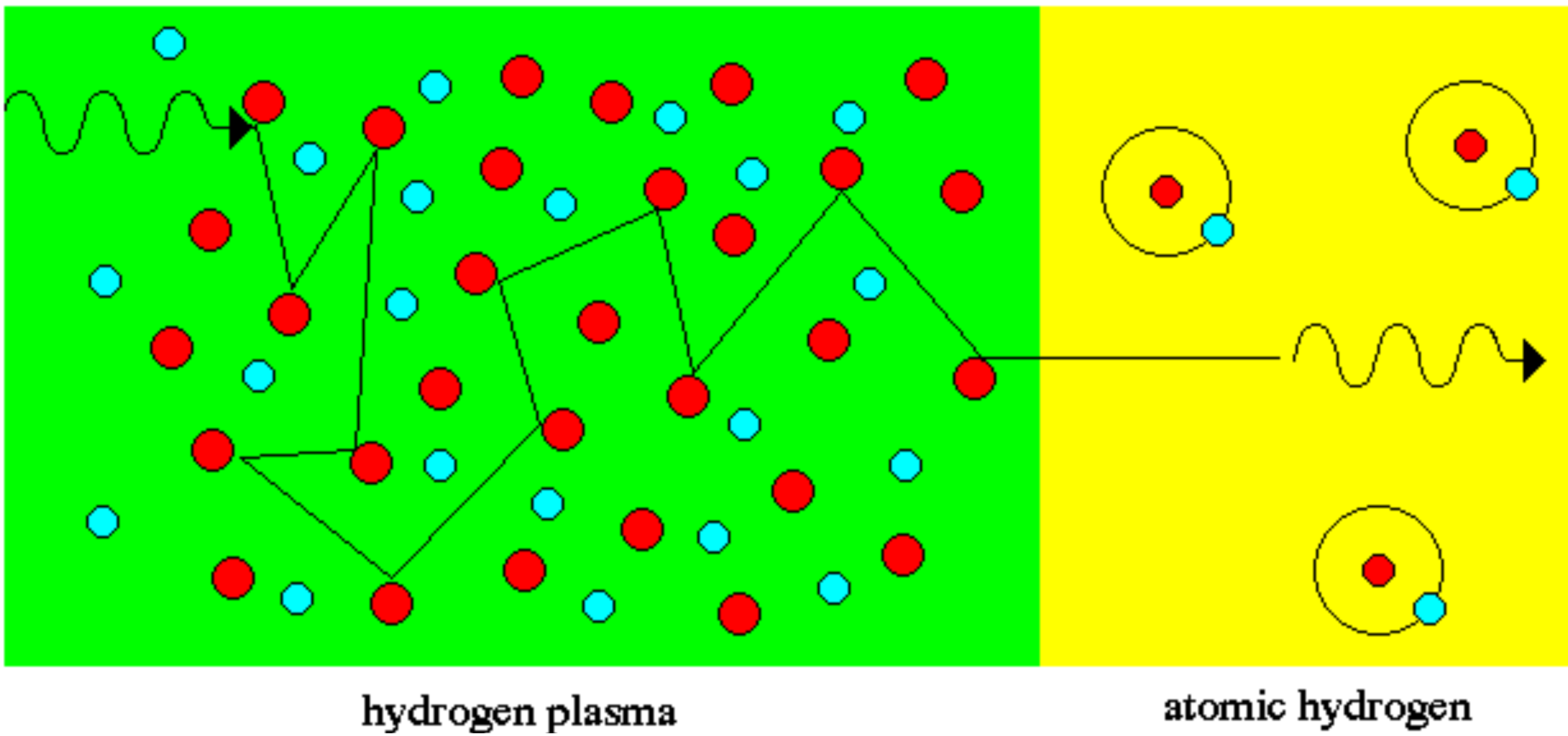
- Matter is in the form of plasma (p's & e's)
- Cosmic photons collide with p's and e's, scattering them – changing energy & direction
- Atoms can form but are quickly destroyed (ionized) by cosmic photons
- Cosmic photons had enough energy to ionize atoms
- Universe opaque to cosmic photons
- Matter & energy (cosmic photons) tightly coupled

Universe AT z=1100, T=3000K, t_{ABB}=380,000 yr

- Cosmic photons suddenly no longer have enough energy to ionize atoms (due to expansion)
- p’s & e’s combine to form atoms (not ionized)
- “era of recombination” (combination?)
- “era of decoupling” (of matter & cosmic photons)
- Moment when universe changed from being opaque to transparent (for cosmic photons)
- all cosmic photons we see now were created or last scattered (direction or energy changed) at this time

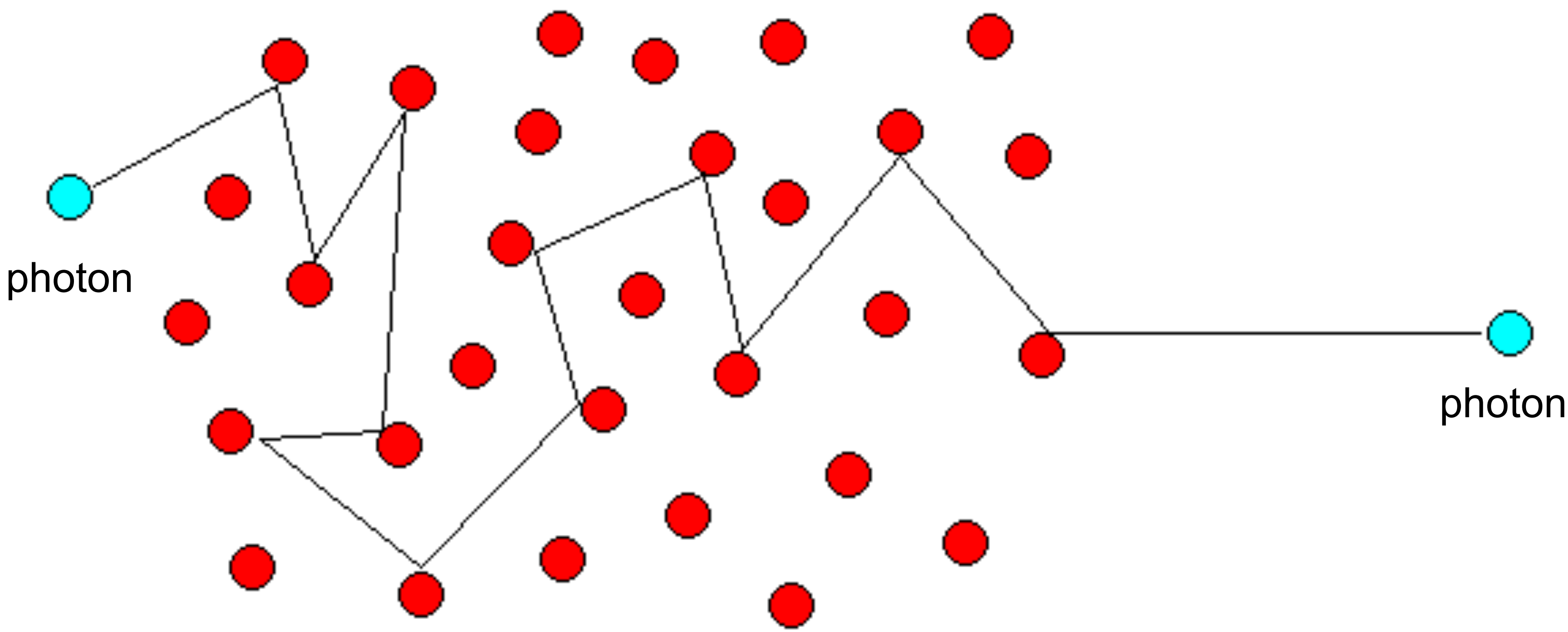
Before recombination

After recombination



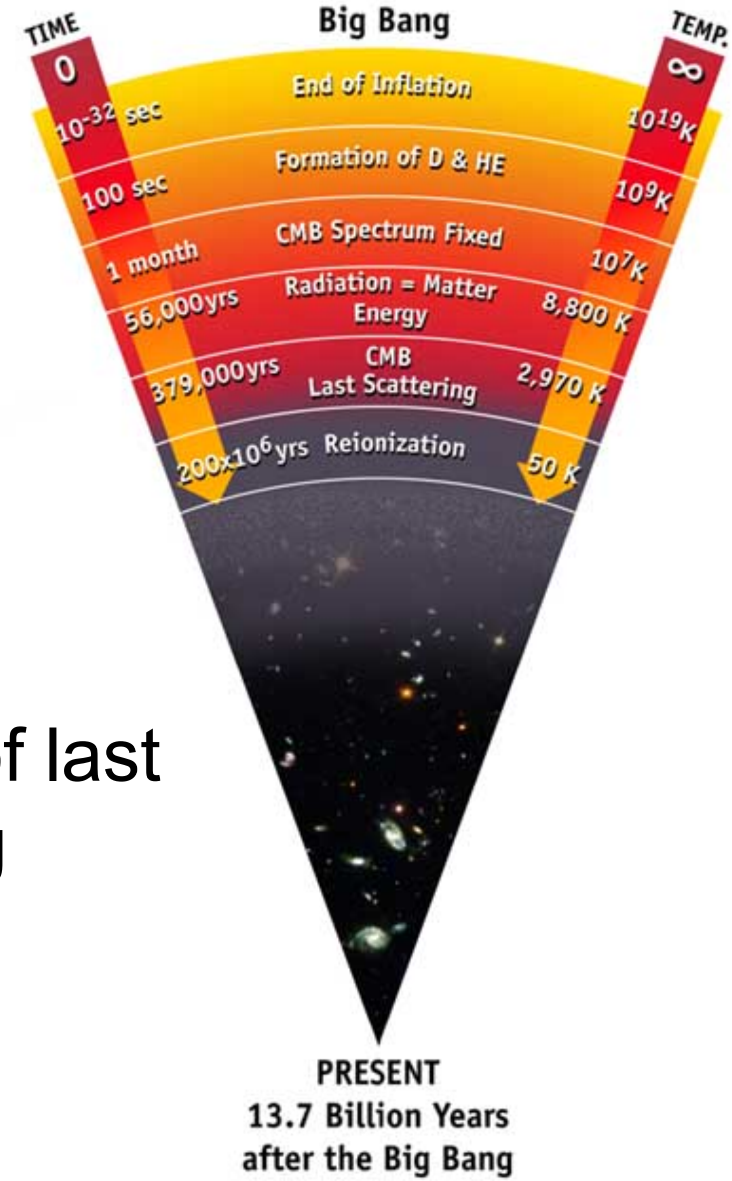
Mean Free Path

all particles, including photons, suffer from collisions with other particles such that their path through space is very short the higher the densities. This typical path length is called the mean free path.

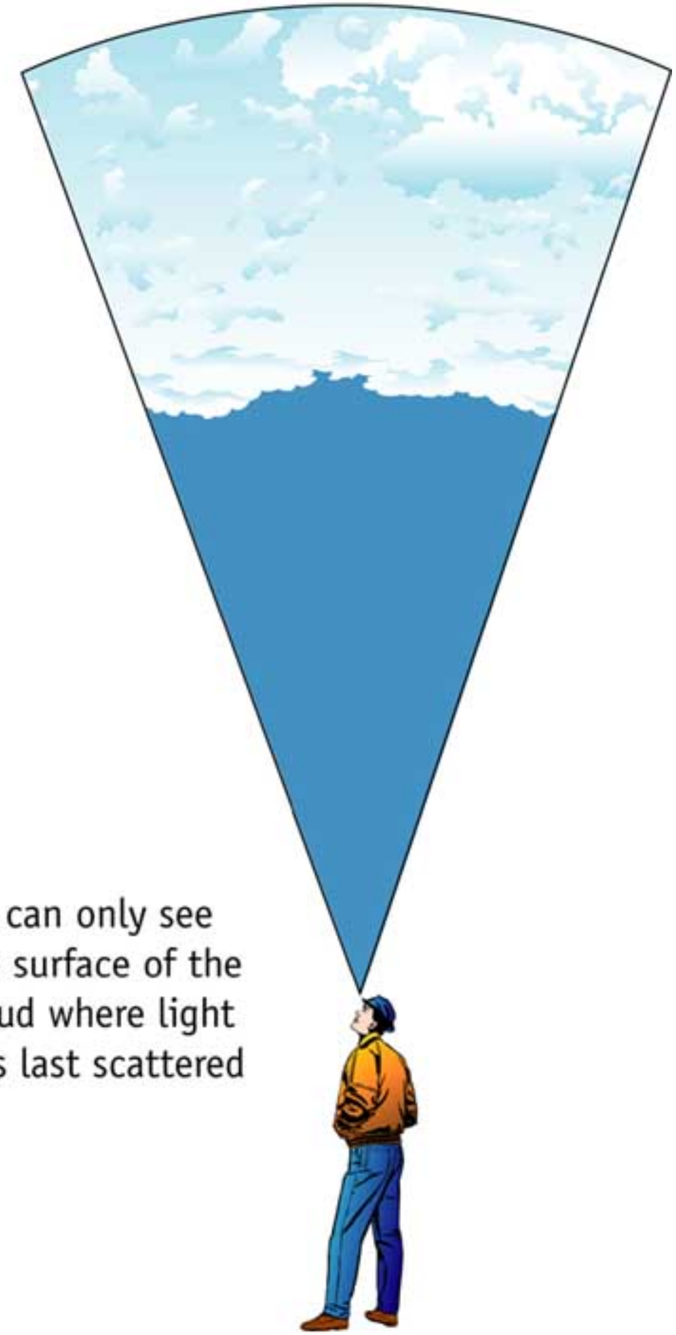


the Universe is opaque at high densities (the mean free path of a photon is very short), as the density drops with time, the Universe becomes transparent (the mean free path of a photon becomes very large).

Surface of last scattering

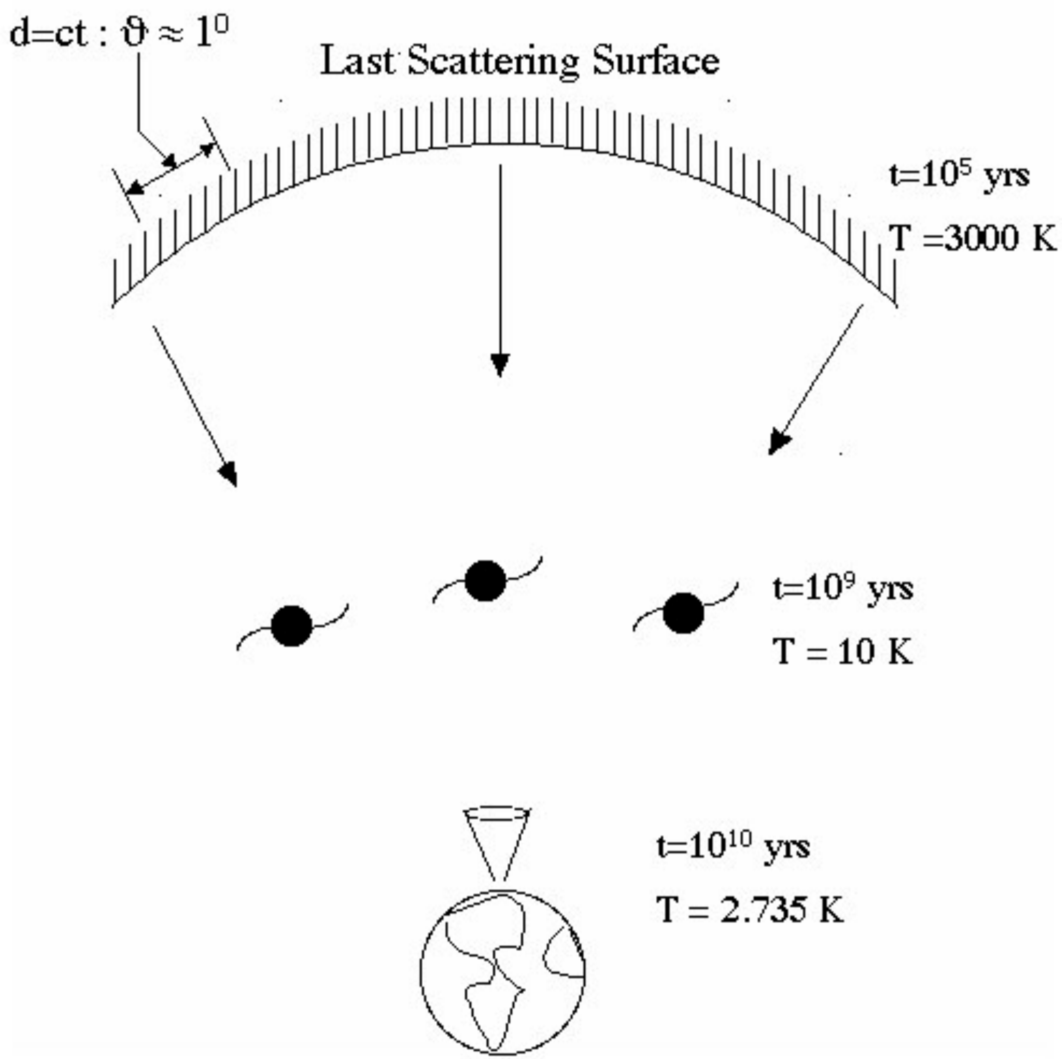


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



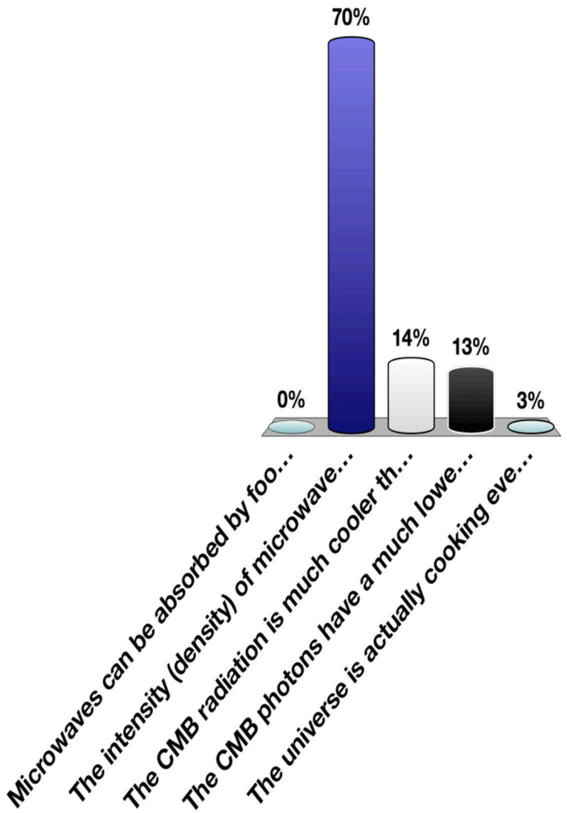
We can only see the surface of the cloud where light was last scattered

COSMIC MICROWAVE BACKGROUND

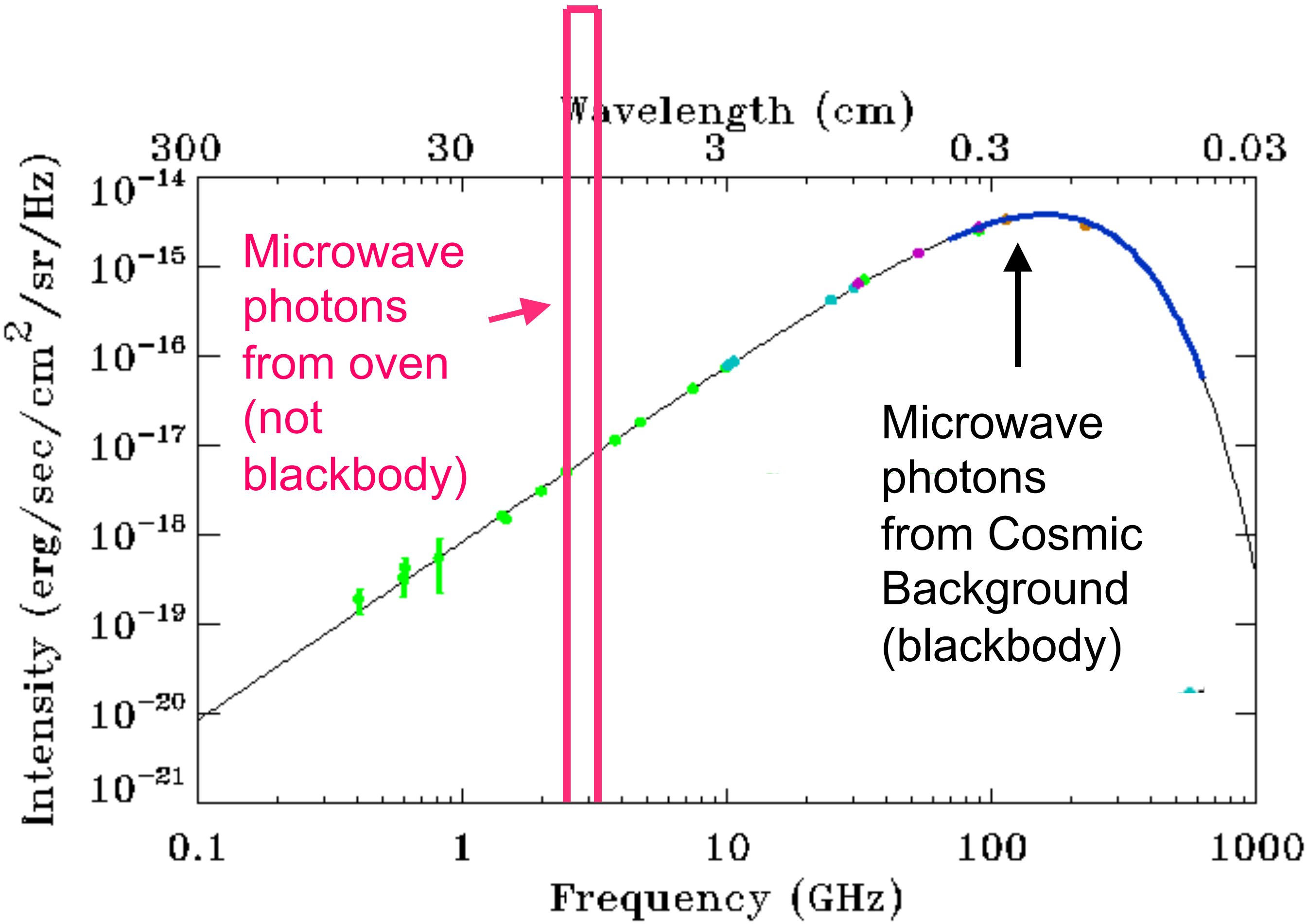


If the universe is full of microwave radiation, then why does food in a microwave oven heat up, but not food sitting on the countertop?

1. Microwaves can be absorbed by food only if they first reflect off metal surfaces
2. The intensity (density) of microwaves in an oven is much higher than the intensity of the CMB
3. The CMB radiation is much cooler than the microwaves used to cook food.
4. The CMB photons have a much lower velocity (kinetic energy) than microwave photons used to cook food
5. The universe is actually cooking everything right now!

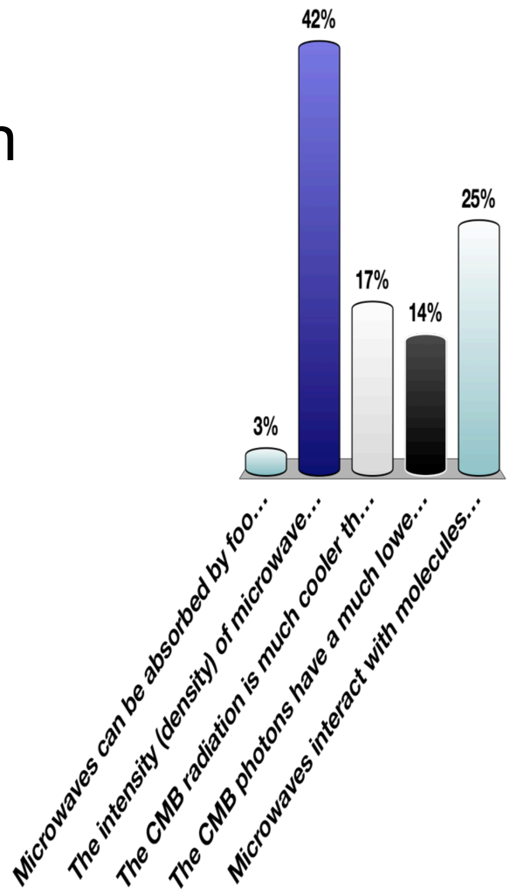


Microwaves from universe vs. oven



If the universe is now transparent to cosmic microwave background radiation, then how come microwaves can heat up my dinner?

1. Microwaves can be absorbed by food only if it is surrounded by air.
2. The intensity (density) of microwaves in an oven is much higher than the intensity of the CMB
3. The CMB radiation is much cooler than the microwaves used to cook food.
4. The CMB photons have a much lower velocity (kinetic energy) than microwave photons used to cook food
5. Microwaves interact with molecules in food but not atoms and the universe is mostly atoms



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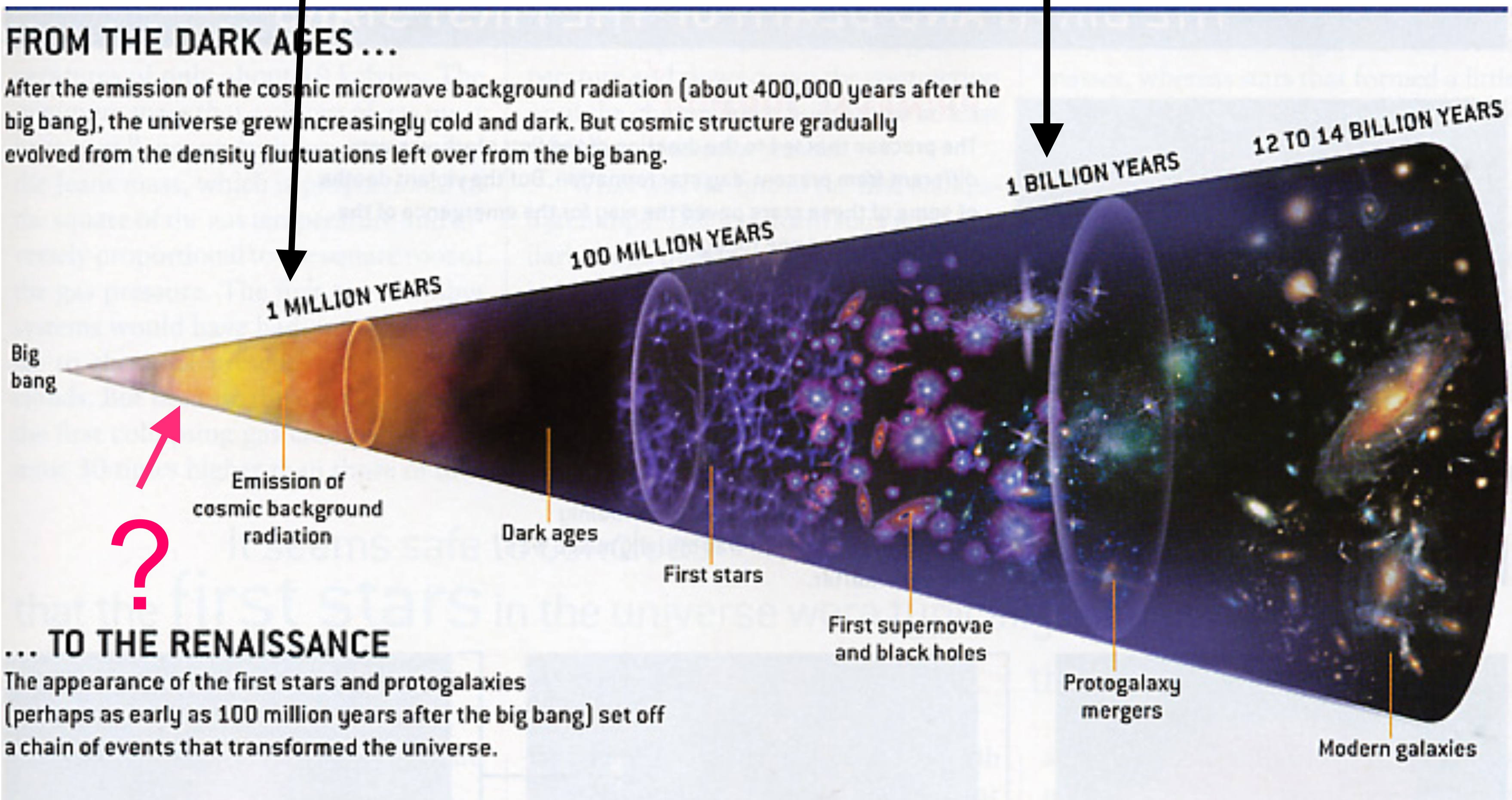

BIG BANG Cosmic Time NOW