Astro 301/ Fall 2005

(48310)

Introduction to Astronomy

Instructor: Professor Shardha Jogee

TAs: David Fisher, Donghui Jeong, and Miranda Nordhaus

Lecture 27 = Tu Dec 6

http://www.as.utexas.edu/~sj/a301-fa05/

Announcements

1) Quiz 6 today. Relaxed rules: will drop TWO worst quizzes

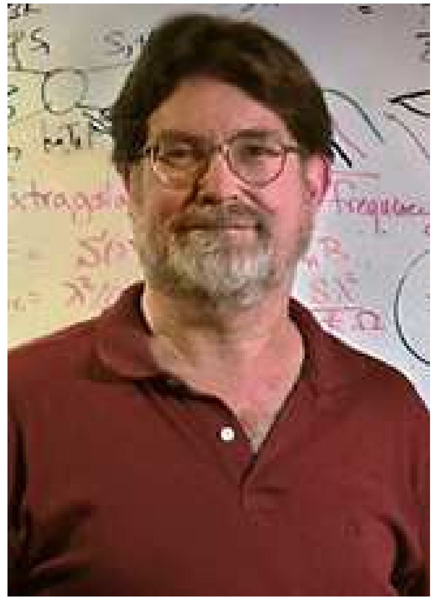
2) Pick up your homework 4 : solution set posted outside

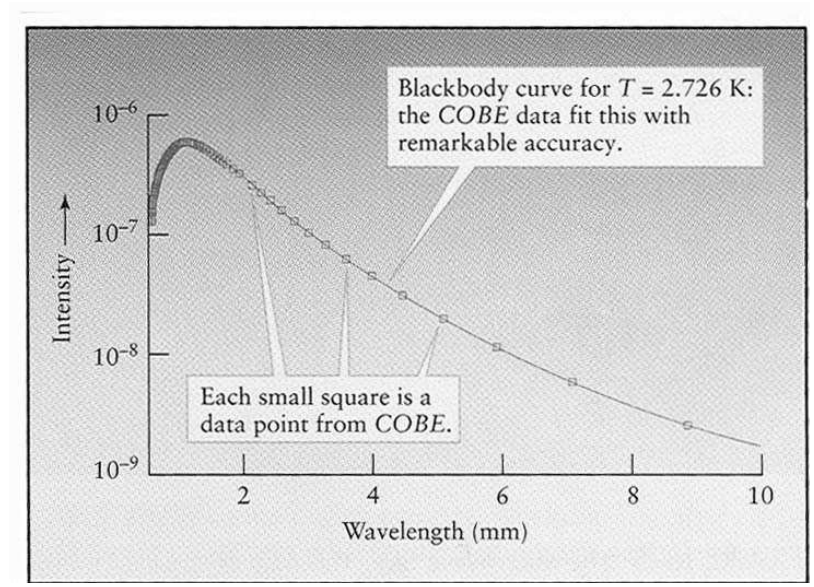
3) Information of Extra Credit (types 1, 2 ,3) posted on class website.
   Please check your entries under EC1 EC2 and EC3 by Th Dec 7

4) Exam 3 is on Thursday Dec 7. Please bring a blue book
   Details on class website
   Similar to Exam 2: focus on concepts. Use QEDEX tips.

5) I will hold office hours in lieu of Candace Gray on Wednesday 4.30-5.30
   Please come to RLM 16.224

Picture of the Day





John Mather and George F Smoot: awarded Nobel Prize in Physics in 2006 "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation".

Topics in class

--- The Beginning of time, from 10^{-43} s to the first second in the Big Bang Model

The Planck Era
Inflation
Production of matter

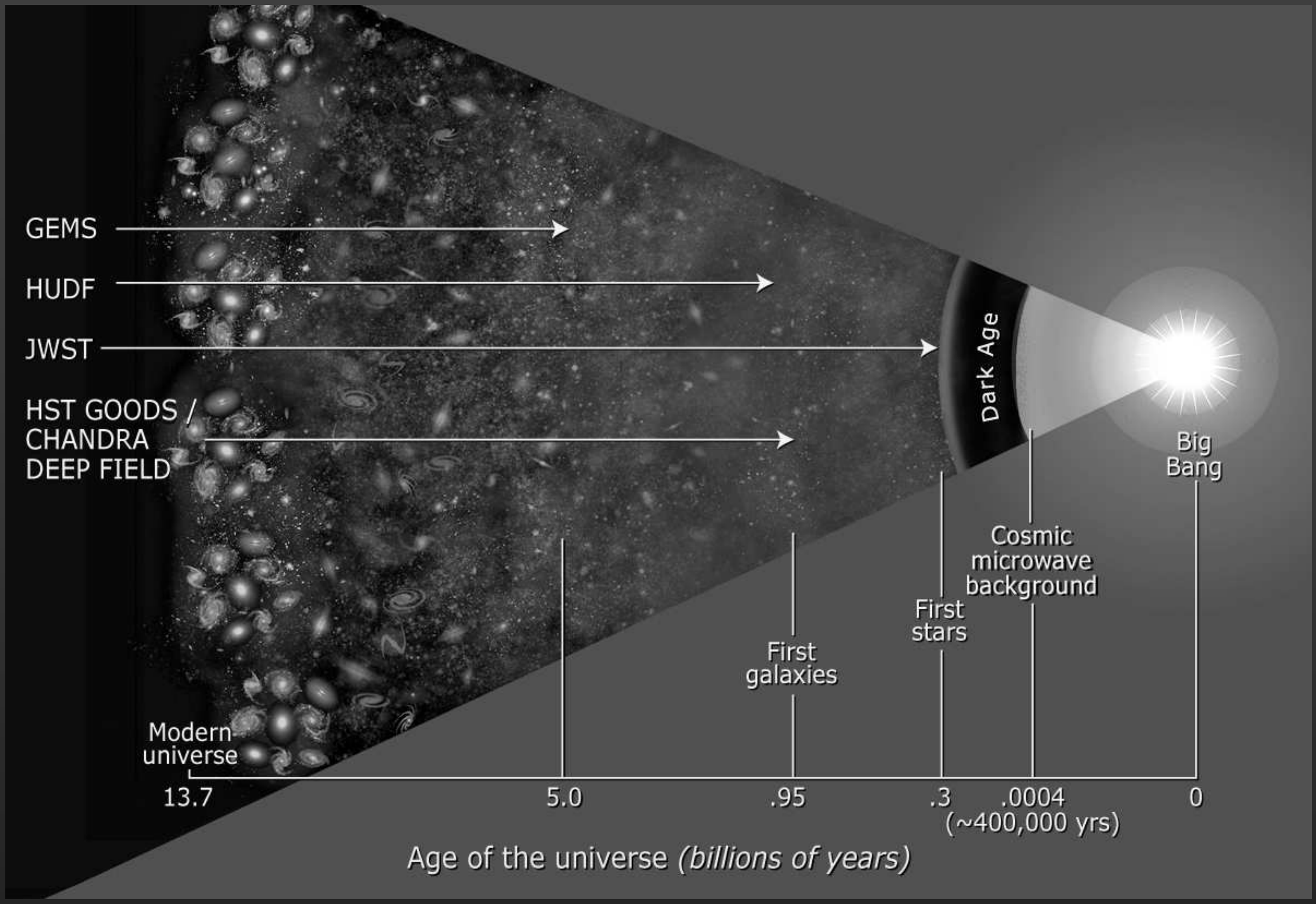
--- From the first second to the first billion years in the Big Bang Model

Formation of (H, He, Li) nuclei by the third minute
Universes changes from opaque to transparent at recombination
Relationship between recombination and the Cosmic Microwave background
The End of the Dark Ages : The First Luminous Objects Form
The formation of the First Proto-galaxies

--- Overview of the Big Bang Model

Main features and predictions of the Big Bang Model
Observational tests of the Big Bang model .
Why do we need inflation ?

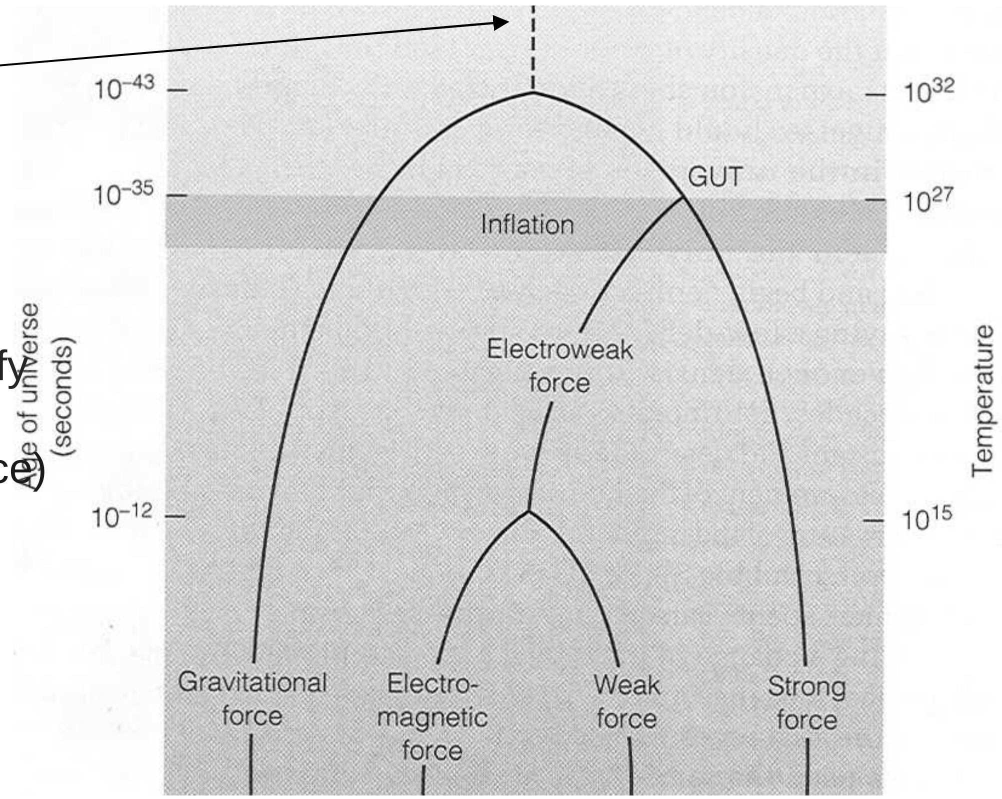
The Beginning of Time In the Big Bang Model :
From the Planck Time (10^{-43} s) to the First Second



So far , we have discussed the evolution of the Universe over the last 13 Gyr,
à from the time it was ~0.7 Gyr old till the present-day when it is 13.7 Gyr old.
But what happened when the Universe was even younger than 0.7 Gyr?
We now focus on the very first billion years….from time t= 10^{-43} s to time t=1 Gyr

The Planck Era : t < 10^{-43} s

The Planck era refers to the epoch when the Universe was less than 10^{-43} s old



In the Planck era

- current laws of physics cannot make any prediction. We need a theory that can unify the 4 fundamental forces (gravity, strong force, electromagnetic force and weak force)

-To find this theory (called superstring, supergravity) is a key goal of modern physics

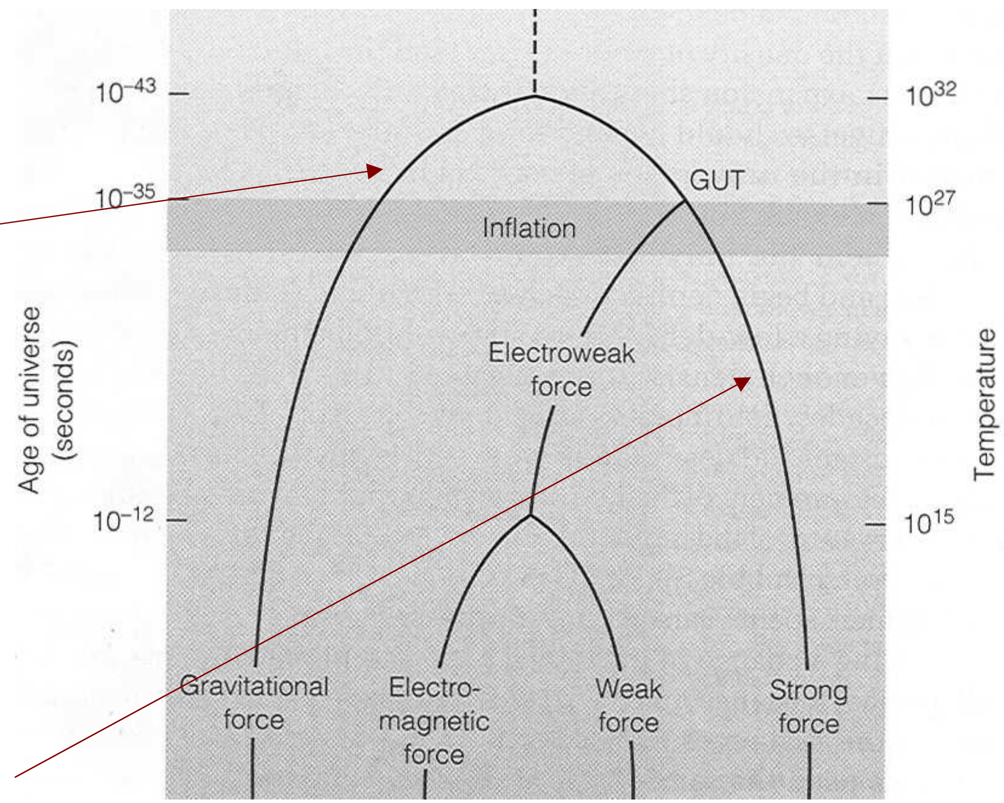
"Science cannot solve the ultimate mystery of Nature. And it is because in the last analysis we ourselves are part of the mystery we are trying to solve

Max Planck

The GUT and Electroweak Era

For this class, we will skip details of the Grand Unified Theory (GUT) era and electroweak era

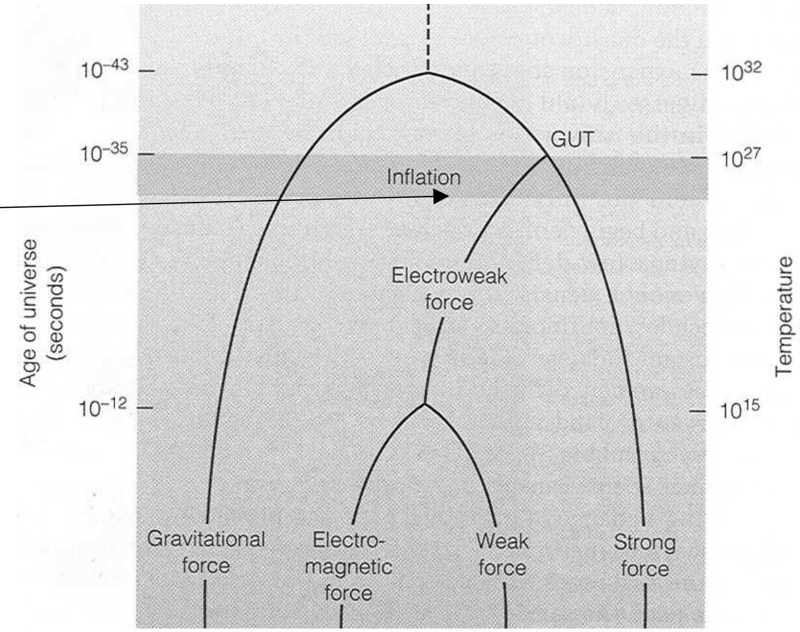
GUT era
(t=10^{-43} to 10^{-38} s)
The electromagetic (EM), weak & strong forces remain unified as a GUT force, but the force of gravity freezes out



Electroweak era
(t=10^{-35} to 10^{-32} s)
The EM and weak force remain unified as the electroweak force, but the strong force freezes out.
.

The Inflation Era ($t=10^{-35}$ to 10^{-32}s)

Inflation kicks in during the very early Universe ($t=10^{-35}$ to 10^{-32} s).



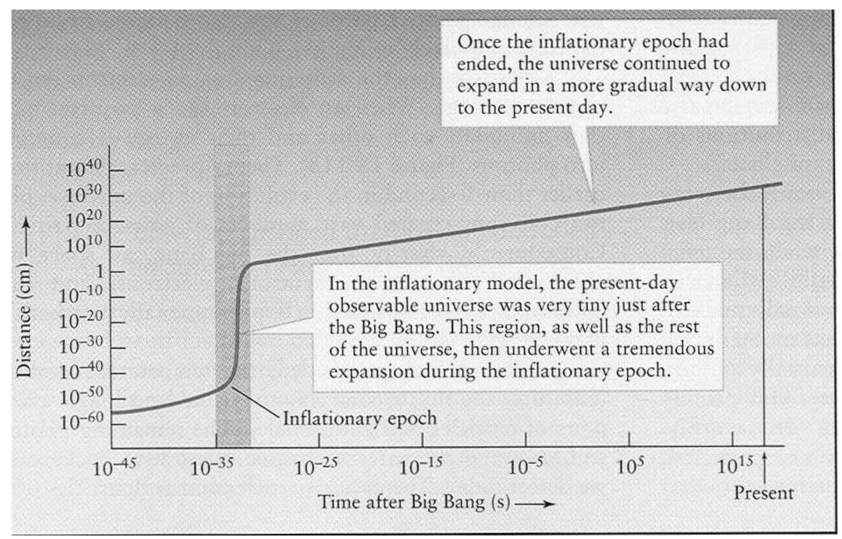
Inflation

- is a critical part of modern Big Bang models

- blows up the size of Universe by a factor of 10^{25} in a short time ($t=10^{-35}$ to 10^{-32} s).

- causes an extremely rapid expansion of the Universe, a few trillion (10^{12}) times faster than the expansion , which we see today and describe with Hubble's law

After inflation end, the universe continues to expand, but a much slower rate. As it expands, it becomes less dense and cools



The Universe transition from having only photons to having matter!

After the extremely fast expansion in the inflation era (t=10^{-35} to 10^{-32} s), the Universe

- is full of high energy, short wavelength photons,
- but contains no matter particles (electrons, protons, and neutrons) , which are the building block of atoms.

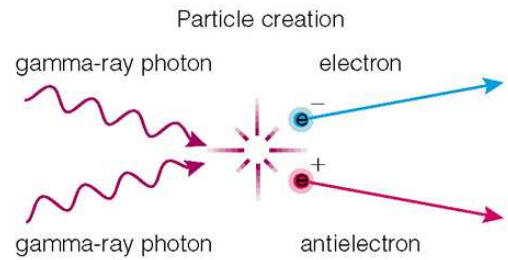
When did matter particles (electrons, protons, and neutrons) come into existence?
à as the Universe aged to t=10^{-10} to 1 s

How did matter particles (electrons, protons, and neutrons) come into existence?
à from photons via an intriguing effect called symmetry breaking

Production of excess matter over anti-matter (t=10^{-10} s to 1 s)

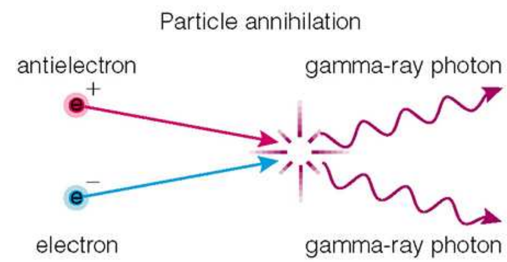
1) Early on, photons (radiation) were hot enough that they can produce matter-antimatter pairs
A matter-antimatter pairs has 2 particles, that are made of matter and antimatter, and have opposite charges

Example
2 very high energy photons à proton and anti-proton
2 very high energy photons à neutron + anti-neutron
2 high energy photons à electron + anti-electron



2) The 2 particles can annihilate each other to give back a photon.

Example
proton and anti-proton à 2 very high energy photons
neutron + anti-neutron à 2 very high energy photons
electron + anti-electron à 2 high energy photons



3) If the number of matter particles was exactly equal to the number of anti-matter particles
à we would have all matter be completely anihilated by anti-matter
à there would be no matter particles (protons, neutrons, electrons)
à we would not exist

Production of excess matter over anti-matter (t=10^{-10} s to 1 s)

Luckily for us, there was symmetry breaking:

à photons produced slightly more matter particles than anti-matter particles
à for every 10^9 pairs of matter-antimatter particles produced, there is 1 excess matter particle

Thus, not all matter particles get anihilated by anti-matter particles, and an excess of (neutrons, protons, and electrons) are left over.

à neutron and protons formed at $t < 10^{-6}$ s when T falls below 10^{13} K
à electrons formed at $t \sim 1$ s when T falls below 10^9 K

These excess (neutrons, protons, and electrons) make up all the atoms and nuclei that we see in the Universe today, in galaxies,stars, planets, humans, etc

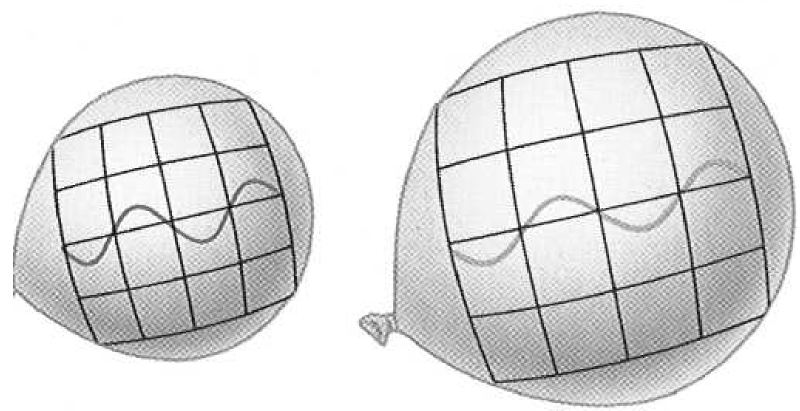
We owe our existence to symmetry-breaking

Why does matter production stop after t=1 s

QFC :Why does the production of matter (neutrons, protons, and electrons) not continue as the Universe ages beyond t~ 1 s?

Recall: After the extremely fast expansion in the inflation era (t=10^{-35} to 10^{-32} s), the Universe keeps expanding at a slower rate, becoming cooler . As the Universe expands:

à photon λ stretches due to the expansion of the Universe
à the photon energy falls as (E = prop to 1/ λ) .
à soon the photon energy is too low for it to produce any new matter-antimatter pairs, or excess matter particles
à after t>1 s, no more matter is produced



Summary: From 10^{-43} s to to the First Second

0 — 10^{-43} s — 10^{-38} s — 10^{-10} s — 10^{-3} s — 1 s — Time

$t < 10^{-43}$ s
Planck era

10^{-43}-10^{-38} s
GUT era

10^{-38} - 10^{-10} s
Electroweak era

10^{-35}-10^{-32}
Inflation

10^{-10} s - 1 s
Radiation produces matter-antimatter pairs. Due to an excess of matter over anti-matter, matter (n, p+, e-) form.

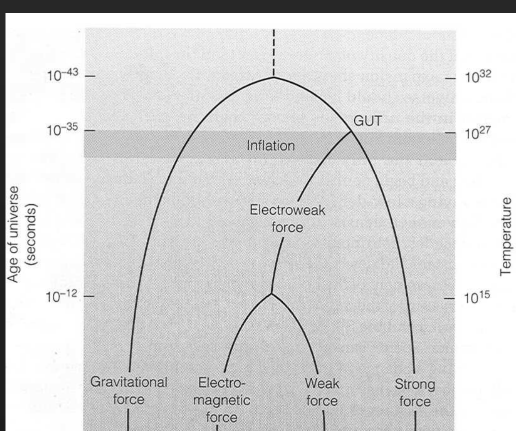
In GUT era, …..

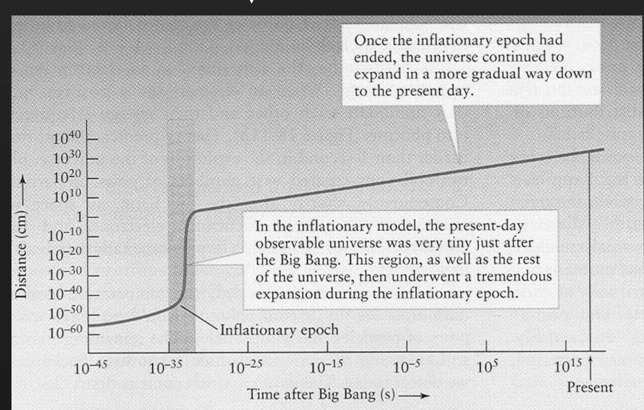
In the electroweak era,……

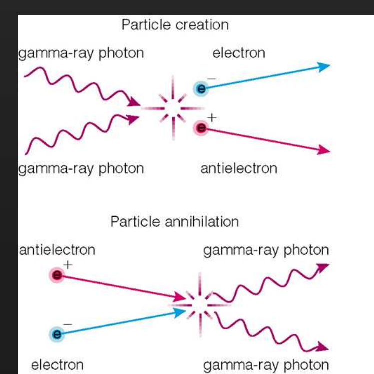
Inflation blows up the size of the Universe by a factor of 10^{25}.

n, p freeze out at t~ 10^{-6} s when T drops below 10^{13} K

e- freeze out at t ~1 second when T drops below 10^{9} K







From the First Second to the First Billion Years

Formation of (H, He, Li) nuclei by the third minute

1) Recall that protons (H nuclei), neutrons and electons from by t=1s when there was a a slight excess of matter over anti-matter, preventing complete matter annihilation.

2) By t=3 minute, protons and neutrons combine to form 90% of the helium nuclei and 10% of the lithium nuclei that exist today.

Hydrogen nucleus = 1 proton
Helium nucleus = 2 protons + 2 neutrons
Lithium nucleus = 3 protons + 3 neutrons

3) The Big Band model predicts that at the end of 3 minutes, the Universe had
- about 25% of its mass as Helium
- about 75% of its mass as Hydrogen
- a very tiny tiny fraction (well below 0.01 %) of its mass as Li

4) One important confirmation of the Big Bang is that elemental abundances observed in objects around us are consistent with the elemental abundance predicted by Big Bang

à no object is observed to have a He abundance less than 25%
à Galaxies observed to have a He abundance of 25% to 28% , a H abundance 75-72%
QFS : Where does extra 3% He abundance come from ?

Formation of (H, He, Li) nuclei by the third minute

Question: Some stars and planets have some % of their mass as heavier elements (C, N, O, Sulfur, Silicon). These heavy elements were not produced ih the first 3 minutes of nucleosynthesis. When and how are they produced?

Much later, when the Universe was around t = (50 to 100) million years, massive stars formed.

à Nuclear fusion in the core and surrounding layers of these stars fused H and He to produce heavier elements

à When the first massive stars form and die

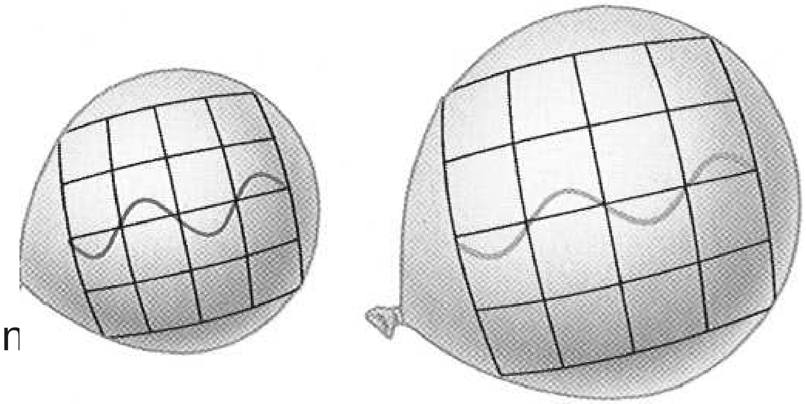
- the iron core becomes a black hole or neutron star
- the outer layers of gas are blown by a supernova (SN) explosion into a glowing hot ball of gas called a SN remnant .
- The remnant contains H, He, C, and heavy elements O, N, Sulfur, Silicon, Iron, which gets mixed in the surrounding gas
- This gas later forms new stars and planets that will contain heavy elements

Universe changes from radiation-dominated to matter-dominated (t=3x10^4 yr)

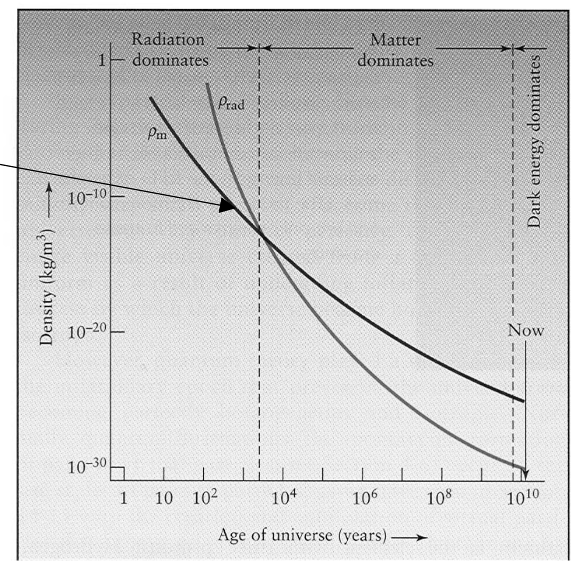
Radiation-dominated era (t< 3x10^4 yr)
Energy density in photons (radiation) is larger than energy in matter

Transition to matter-dominated era (t > 3x10^4 yr)

As Universe expands,
à photon λ stretches due to the expansion of the Universe
à photon energy E falls as E depends on 1/ λ
à energy in matter also falls because the separation of matter particles increases



à the energy in photons drops faster than does the energy in matter. Soon the energy density in matter exceeds the energy in photons and the Universe is said to transition from being radiation dominated to being matter-dominated.

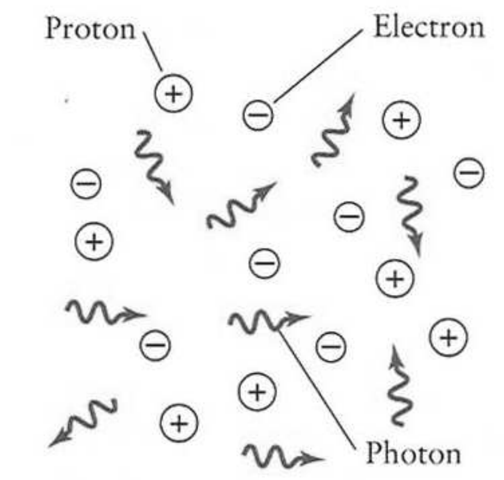


à After the Universe becomes matter dominated
- Matter/gas then responds to gravitational forces and forms clumps. These clumps act like glue and cause other matter to pile up on them to form more massive structures such as ther first stars and proto –galaxies

Neutral atoms form: Univ. becomes transparent at recombination (t=3x10⁵ yr)

Before recombination (t< $3x10^5$ yr)

- Temperature is above 10,000 K : e- and p+ exist separately and do not combine to from neutral H
- Photons collide frequently with e- and get trapped Therefore, the Universe is opaque

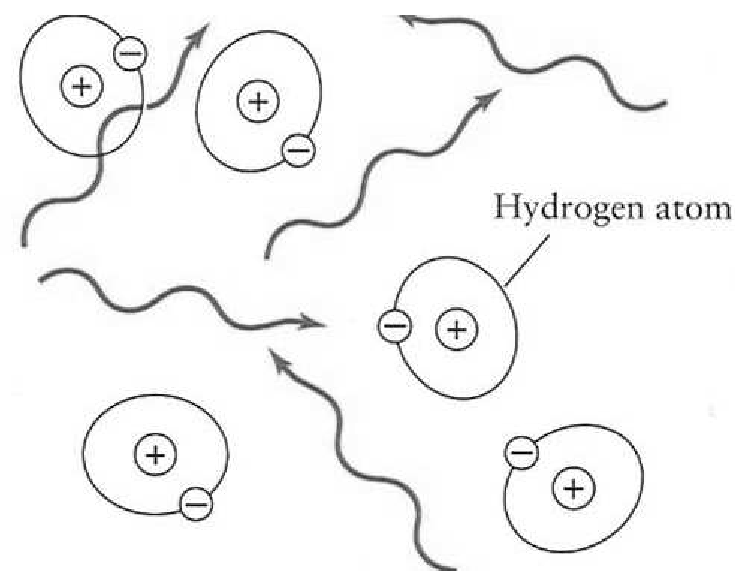


Ar recombination (t = $3x10^5$ yr)

- Temperature falls to 3000 K, causing all p^+ and e^- combine into neutral H atoms:

  p^+ + e^- à H atom

- Photons collide only rarely with neutral atoms, and they can now travel freely à the Universe becomes transparent for the first time.



How the Cosmic Microwave Background Relates to Recombination

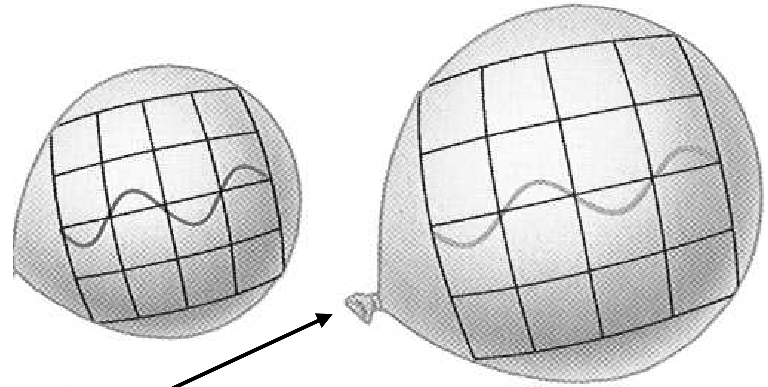
The photons released at recombination, when the Universe was 300,000 yrs old

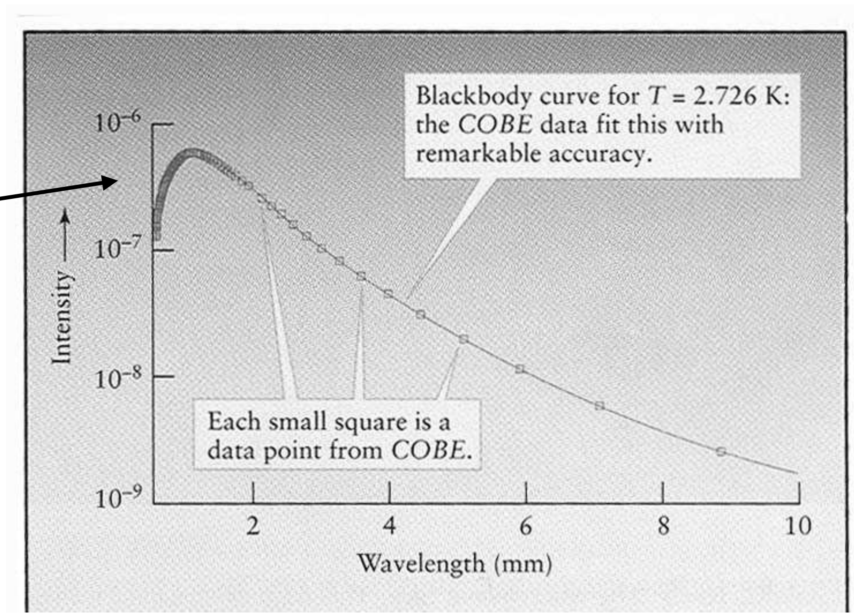
à are the oldest photons that we can see, as the Univ. was opaque before recombination

à are emitted at infrared wavelength λ=10^{-6} m (and temp T=3000 K)

à reach us today as photons of larger radio wavelength λ=1.1 x 10^{-3} m, because the expansion of the Universe between the recombination era and today has stretched the photon wavelength

à form the Cosmic Microwave background (CMB) that we receive today all over the sky. The CMB spectrum peaks at λ=1.1 x 10^{-3} m, which corresponds to a blackbody temperature of T= 2.73 K.





The End of the Dark Ages : The First Luminous Objects Form (t > 0.05 Gyr)

- Right after recombination,

  à neutral hydrogen gas and dark matter exist

  à no stars (luminous objects) have yet formed because existing tiny clumps of hydrogen gas and dark matter are not massive and dense enough

- However, as time proceeds,

  à the tiny clumps of gas and dark matter respond to gravity and merge with other clumps to form more massive and denser clumps.

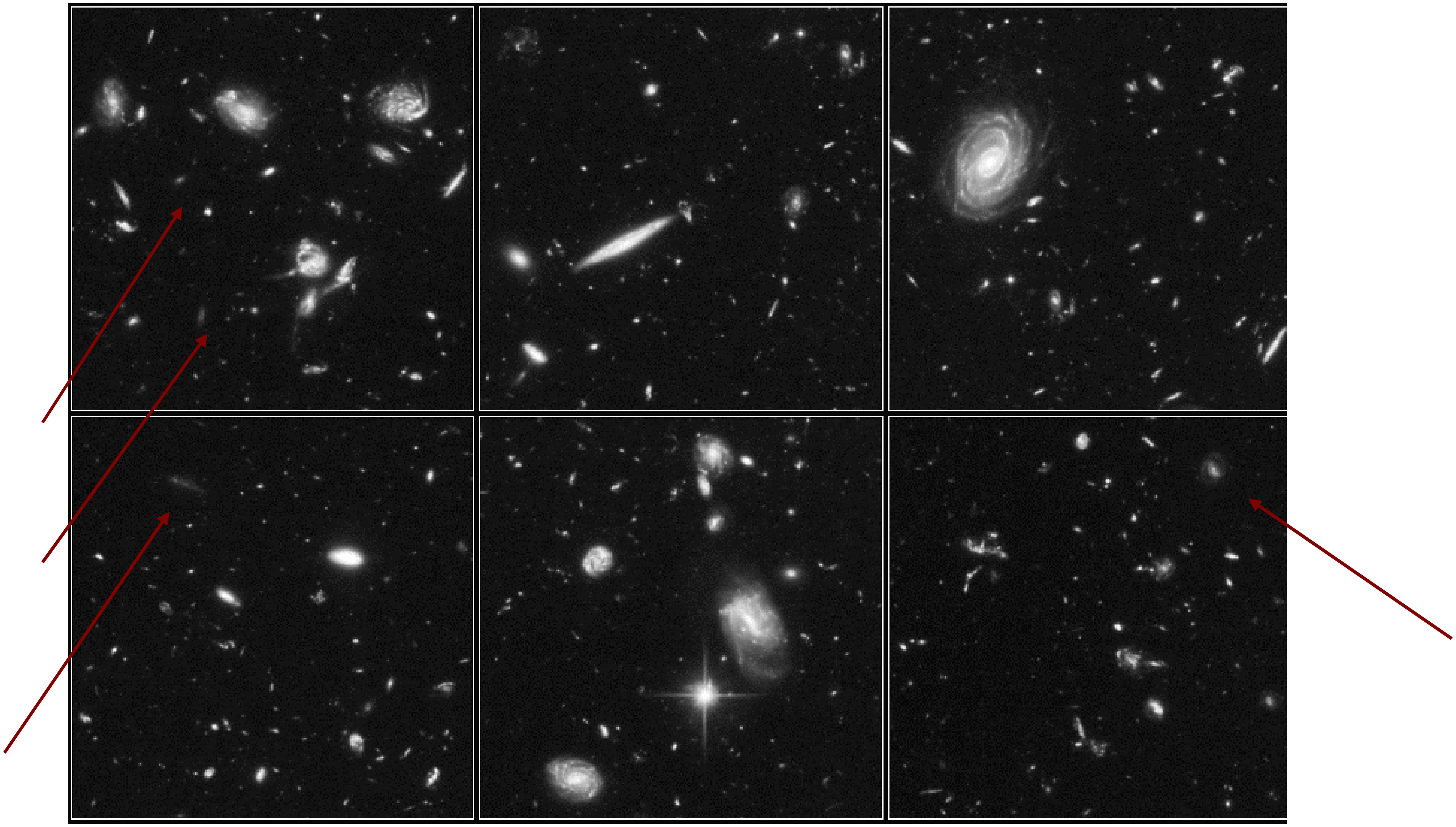
- Eventually, when a clump is massive and dense enough, gravity wins over pressure and the gas collapses to form a star, whose core produces luminosity via nuclear fusion

atomic hydrogen à molecular hydrogen à star

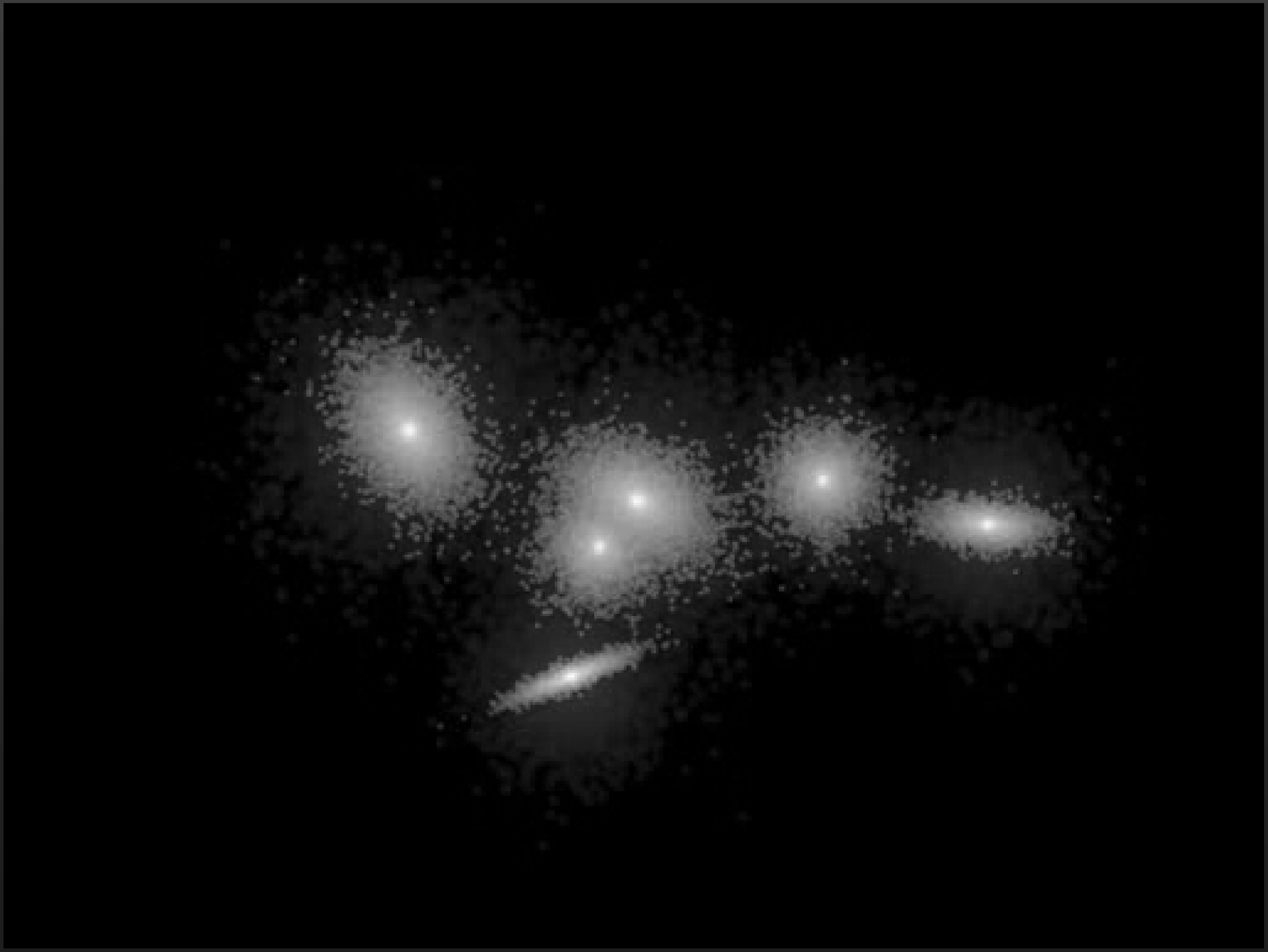
- The 'dark ages' end when the first luminous objects (stars) form. The time of formation depends on many things including the type of dark matter (cold vs hot) present. For a Universe dominated by cold dark matter, this happens when the Universe is around 0.05 Gyr to 0.1 Gyr old.

The First Proto-Galaxies Form (t > 0.3 Gyr)

- First proto-galaxies (made of gas, stars and dark matter) form when the Universe was 0.3 to 0.7 Gyr old
- They are seen in the Hubble Ultra Deep Field (HUDF) which probes lookback times of 13 Gyr , when the Universe was a mere 0.7 Gyr old.



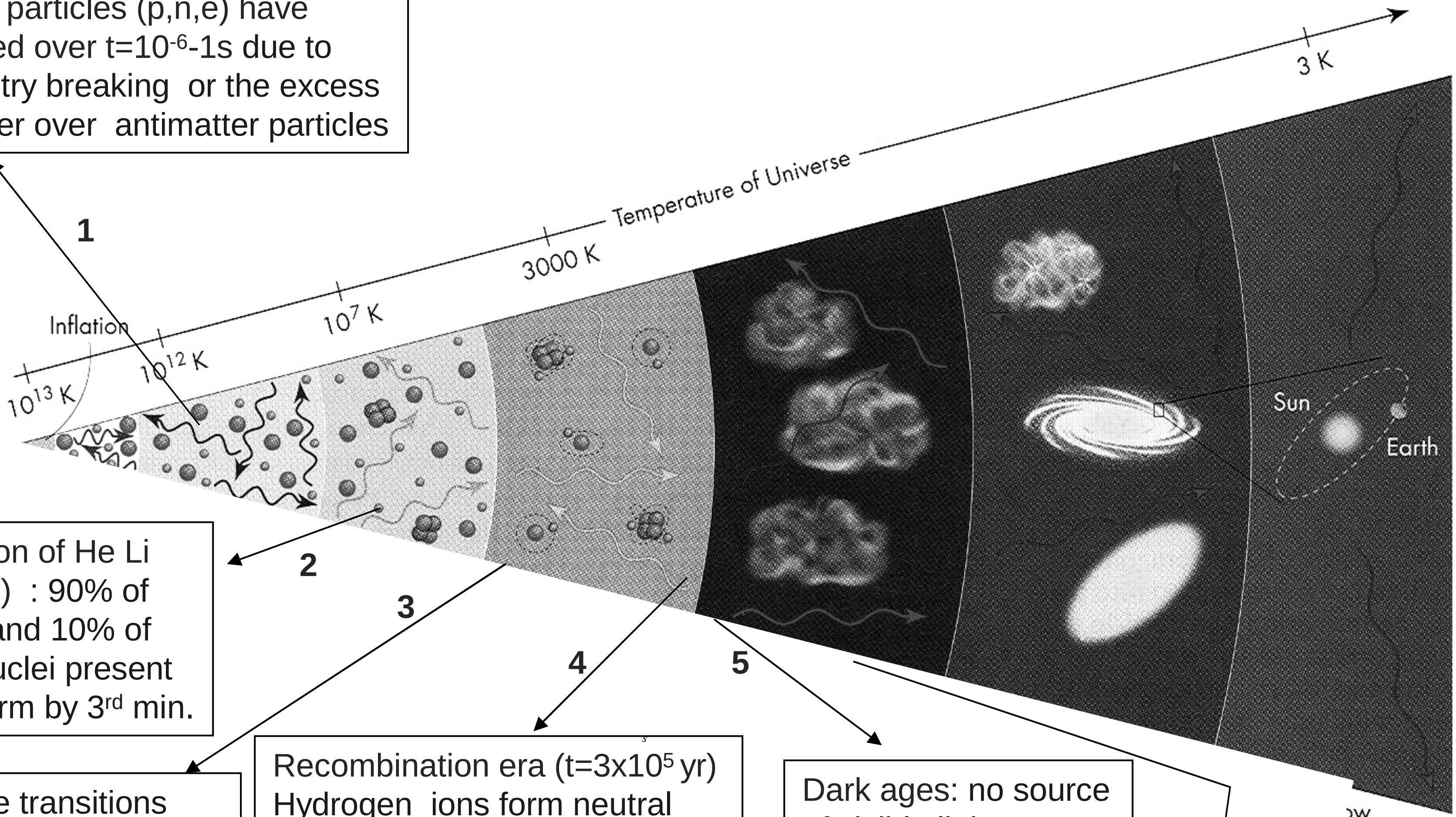
Some of these proto-galaxies then undergo frequent mergers at very early epochs (first few billion years) to grow into full-fledged galaxy components (bulges, disks, etc)



Credit : Joshua Barnes (University of Hawaii)

Summary : From the first second to the first billion years

Matter particles (p,n,e) have emerged over $t=10^{-6}$-1s due to symmetry breaking or the excess of matter over antimatter particles



Formation of He Li (t=3 min) : 90% of the He and 10% of the Li nuclei present today form by 3rd min.

Universe transitions from radiation-dominated to matter-dominated ($t=3x10^{4}$ yr)

Recombination era ($t=3x10^{5}$ yr) Hydrogen ions form neutral atoms, and Universe changes from opaque to transparent. The photons released are the oldest ones we see and get redshifted to form the CMB a wavelength of 1.2 mm and T=2.7 K

Dark ages: no source of visible light yet.

First luminous objects form: stars at t=0.05-0.1 Gyr), then proto-galaxies (t=0.3-0.7 Gyr) These end the dark ages and their UV light also reionized neutral H back to protons and electrons (reionizaion era) .

A Summary of Important Features of the Big Bang Model

All the stages that we looked at, from time t= 10^{-43} s to 0.7 Gyr form part of the Big Bang model. Some important aspects and predictions of the model are:

1) Current laws of physics cannot yet unify the four fundamental forces into one, and can therefore not predict anything before t= 10^{-43} s (the Planck time)

2) Inflation expands the Universe tremendously fast, increasing it size by a factor of 10^{25} from t= 10^{-35} to 10^{-32} s .

3) After inflation ,the Universe keeps expanding till today, but this expansion rate is a trillion times slower than that produced by inflation !

4) Matter-antimatter pairs form at t= 10^{-10} s . There is a slight excess of matter over antimatter (symmetry-breaking) that prevents the total annihilation of matter. This leads to the production, by t=1s, of baryons (n, p+,e-) that make us and other material objects

5) By t=3 minutes, p and n form 90% of the He and 10% of the Li nuclei that exist today

6) At t=300,000 yrs, the recombination of p+ and e- into neutral H atom frees photons that were previously trapped by e-. The 'released' infrared photons
   - à cause the Universe to change from opaque to transparent
   - à produce the present-day cosmic microwave background (CMB) at mm wavelengths

7) Tiny clumps of gas and dark matter grow more dense and massive with time until gravity causes the gas to collapse into the first luminous objects: stars and proto-galaxies. For a Universe dominated by cold dark matter, this happens at t >0.05 Gyr.

Observational Evidence in Support of the Big Bang Model

1) Hubble's law demonstrating the expansion of the Universe

According to the Big Bang model, the Universe keeps expanding at a slow rate, even after inflation. Hubble's law (that all galaxies are observed to be receding from each other with a speed that is directly proportional to their separation) shows that the Universe is expanding

2) Elemental abundances

The Big Bang model predicts that most of the Helium we see today was produced in the first 3 minutes of primordial nucleosynthesis such that at the end of 3 minutes, the Universe had

- about 25% of its mass as Helium
- about 75% of its mass as Hydrogen
- a very tiny tiny fraction (well below 0.01 %) of its mass as Li

Elemental abundances observed in galaxies around us are consistent with the elemental abundance predicted by Big Bang

- no object is observed to have a He abundance less than 25%
- Galaxies observed to have a He abundance of 25% to 28% , a H abundance 75-72%

Observational Evidence in Support of the Big Bang Model

3) The Cosmic Microwave Background (CMB), as predicted by recombination and inflation

According to the Big Bang model, the recombination of p+ and e- into neutral H atom frees photons, which travel to us and today form the CMB. The CMB is

a) radiation whose continuum spectrum has a perfect black body shape that peaks at radio wavelengths of l=1.1 x 10^{-3} m, corresponding a temperature of 2.73 K.

b) radiation that is extremely but not perfectly uniform: it looks nearly the same all over sky, with a temperature variation of less than 1 part in 10^{5}.This uniformity can only be explained if there was a period of inflation before recombination

Such a CMB has been observed. and led to the Nobel prize in Physics in 1978 and 2006!

First Detection of the Cosmic Microwave Background in 1965!

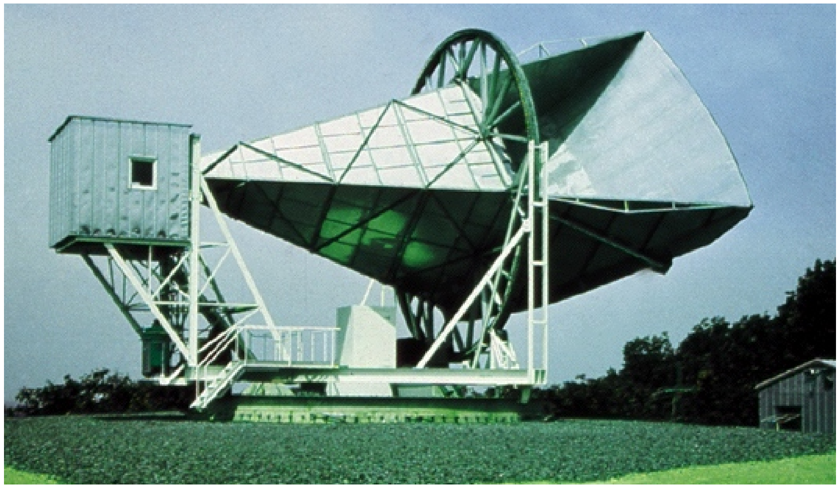
CMB was predicted from Big Bang models by Gamow & Alpher in the 1940s

In 1960s, Dicke, Peebles & Wilkinson at Princeton were designing a microwave (radio wavelength λ=1.1 x 10^{-3} m) telescope to detect the CMB

In 1965, Arno Penzias and Robert Wilson, at Bell Labs in NJ, scooped them…by accident!

They were using Bell Labs Horn Antenna to relay telephone calls to satellites and found a persistent and annoying noise all over the sky, which they could not get rid of!

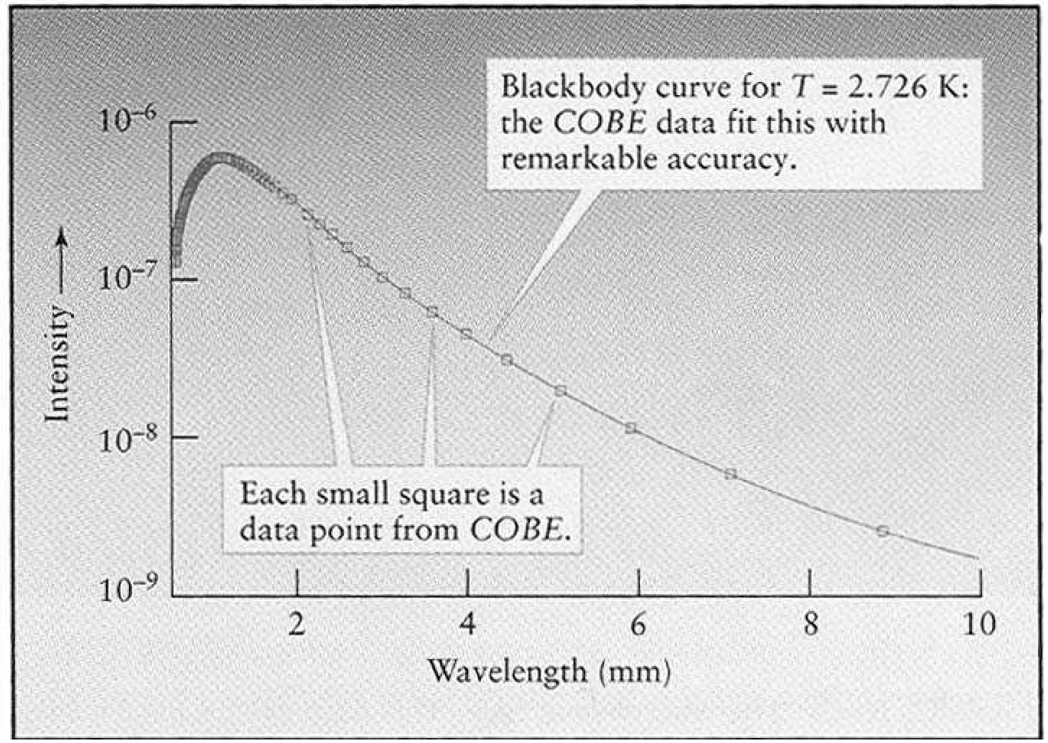
They eventually realized it was the CMB predicted by the Big BangModel … and were awarded the Nobel Prize in Physics in 1978.



First Precise Measurement of the Cosmic Microwave Background by COBE

Cosmic Microwave Background Explorer (COBE) = NASA satellite launched in 1990's

COBE made the very first precise measurements of the CMB (1990-1994). It had 2 key results

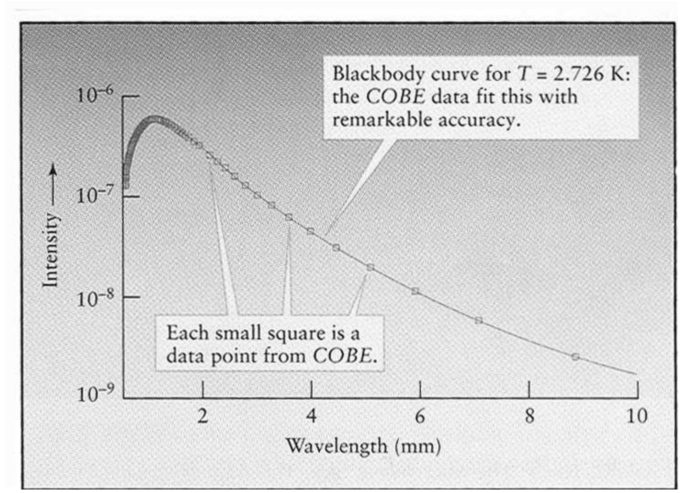


Result 1 : COBE showed that the CMB spectrum could be fit by a quasi-perfect black body spectrum at T= 2.73 K. that has a maximum flux at a radio wavelength λ=1.1 x 10^{-3} m.

These are the exact properties predicted by the Big Bang model for radiation that was produced during the recombination era at an infrared wavelength $\lambda=10^{-6}$ m and temp T=3000 K), and then was subsequently redshifted to large radio wavelength λ=1.1 x 10^{-3} m and cooler temperatures, due the expansion of the Universe

First Precise Measurement of the Cosmic Microwave Background by COBE

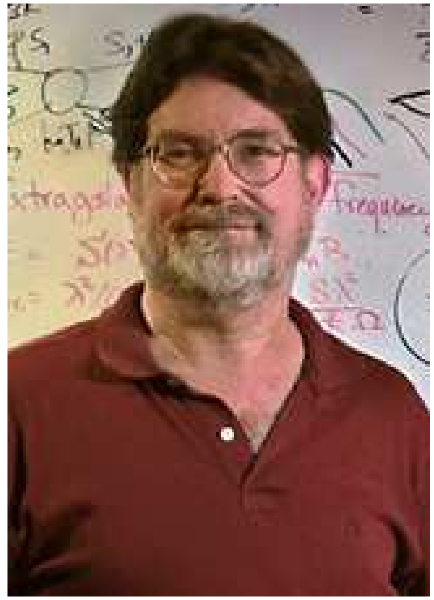
Result 2: COBE showed that the CMB radiation is extremely but not perfectly uniform: it looks nearly the same all over sky, but has a tiny temperature variation of less than 1 part in 10^5. This tiny temperature variation in the CMB across the sky is called the anisotropy of the CMB.

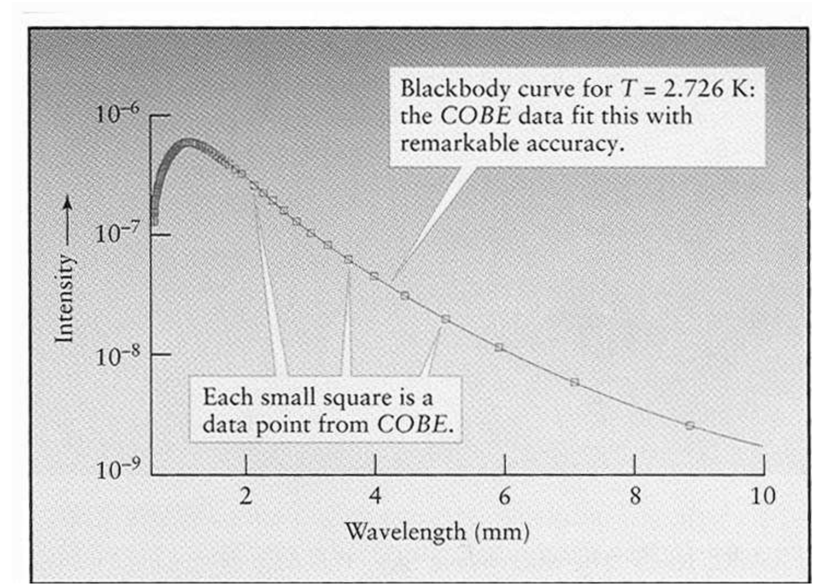


The temperature anisotropy of the CMB is a measure of the density inhomgeneities (matter clumps), which were present in matter during the recombination era, and grew with time to become the first massive object like stars and galaxies

By measuring the temperature anisotropy and hence the density inhomogeneity in the CMB, we can test the seed or origin of present-day massive objects

Nobel Prize in Physics in 2006





John Mather and George F Smoot: awarded Nobel Prize in Physics in 2006 "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation".

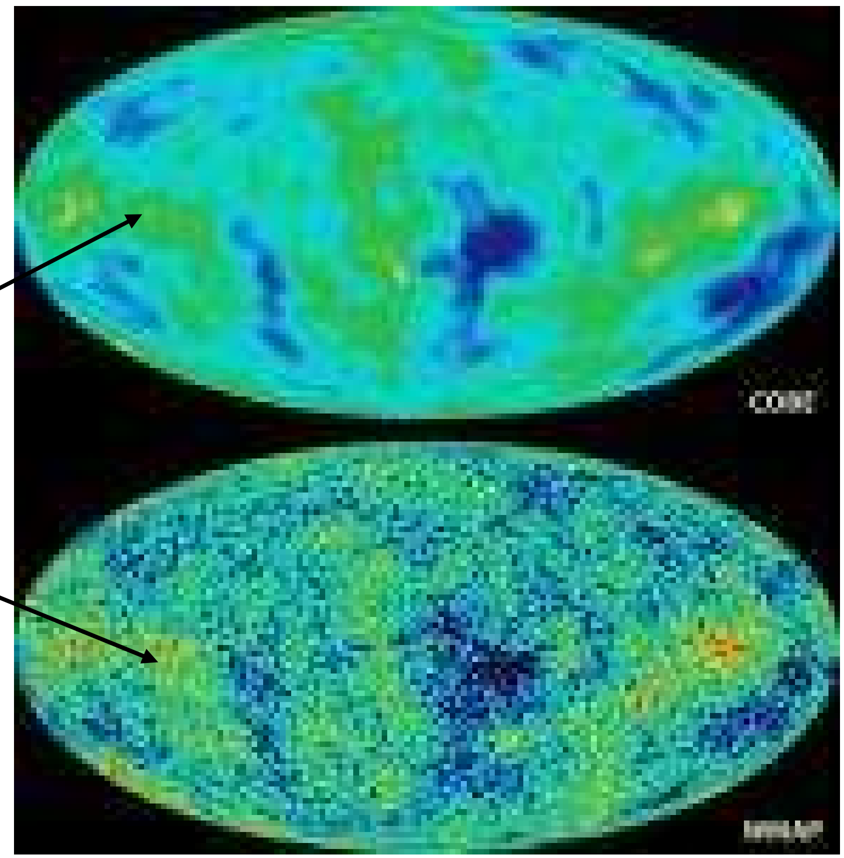
The success of COBE was the outcome of prodigious team work involving more than 1,000 researchers, engineers and other participants.

à John Mather coordinated the entire process and also had primary responsibility for the experiment that revealed the blackbody form of the microwave background radiation measured by COBE.

à George Smoot had main responsibility for measuring the small variations in the temperature of the radiation.

WMAP observations of the Cosmic Mircrowave Background

WMAP = Wilkinson Microwave Anisotropy Map (2001-now)



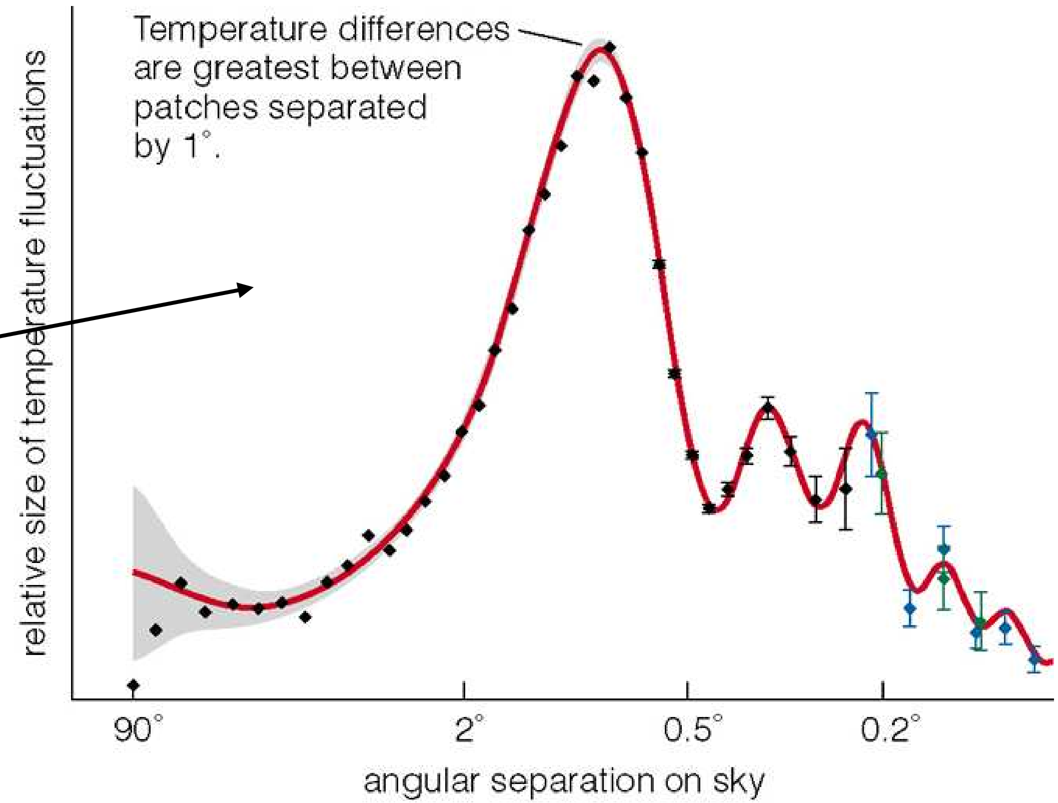
COBE.

WMAP has 10 times better angular resolution than COBE.

WMAP

WMAP observations of the Cosmic Mircrowave Background

WMAP observations provide the best measurements to date of the CMB.



WMAP observations of CMB

à not only test the recombination phase of the Big Bang model of the Universe

à directly test inflation

à constrain the nature of dark matter, favoring non-baryonic cold dark matter (WIMPS) over hot dark matter (neutrinos)

Why do need inflation in the Big Bang model?

1) To account for the extreme (but not perfect) uniformity) of the Cosmic Microwave Background

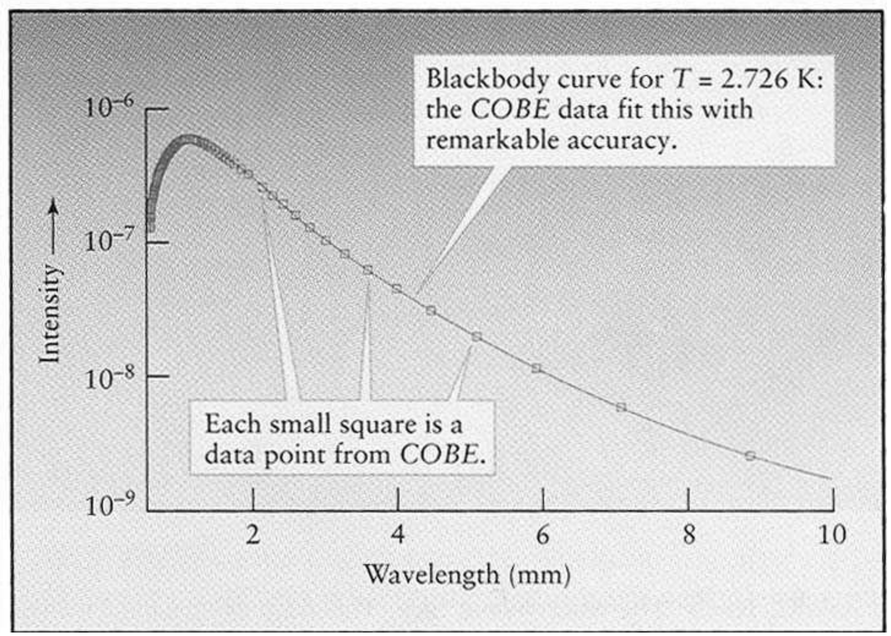
Analogy: I arrive in class and see all 190 students wearing a red cap. The cap is not exactly the same shade of red but is nearly the same across all students

à This means the students must have somehow been able to communicate in the past before coming to class and "get their act together"

à Sometime in the past they must have been close enough to communicate via conversation (sound waves) or phone (light waves)

The observed CMB all over the sky is extremely but not perfectly uniform: it looks nearly the same all over sky, but has a tiny temperature variation of less than 1 part in 10^5.

This large degree of uniformity can only come about if points that are very distant on the sky today, were able in the past, to communicate with each other, and synchronize their properties in the past, before or at recombination.



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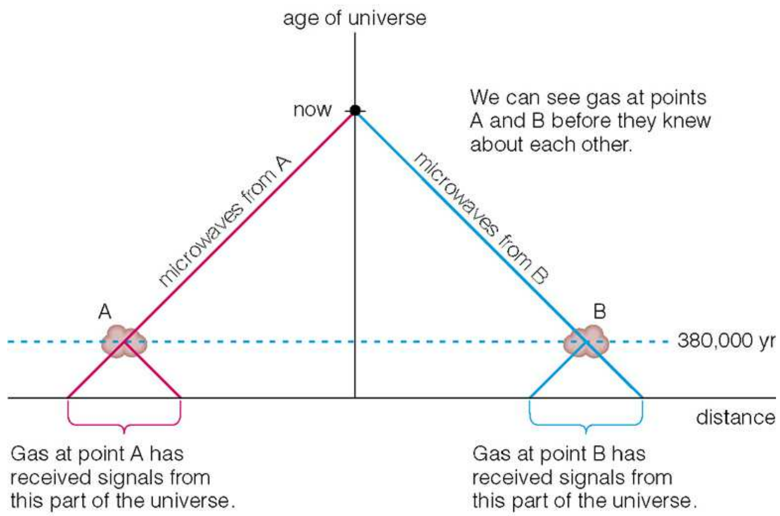

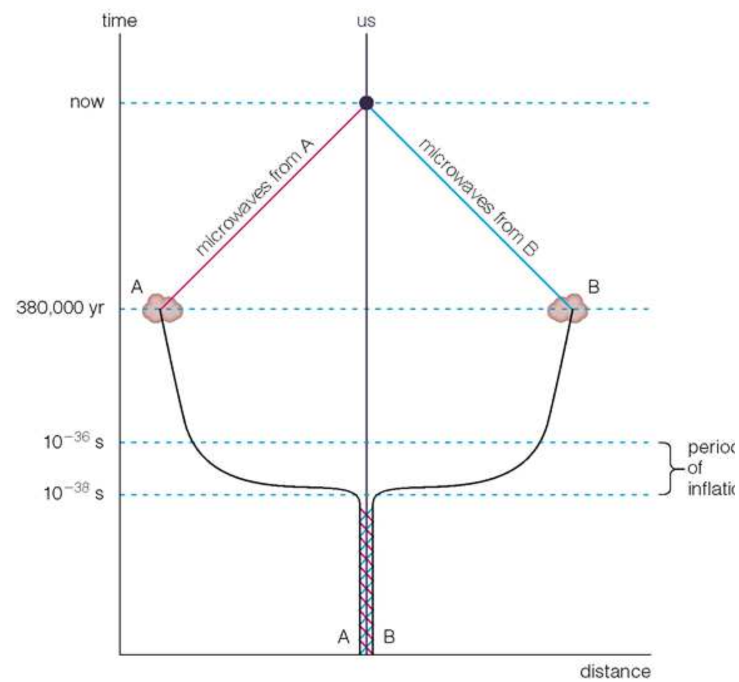

In a Big Bang model without inflation

à the Universe would **always** have expanded at a slow rate

à points that are distant on the sky today, *were never close enough in the past, at or before the era of recombination, to communicate even at the speed of light*.

In a Big Bang model with inflation

à points that are distant on the sky today were very close together in the past --- close enough for them to communicate via light signals and synchronize their properties.

à Inflation then produced an extremely rapid expansion of the Universe, by a factor of 10^{25} at very early times causing the points to separate out to very different points on the sky