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/

Recent and Upcoming topics in class (Lecture 22 onwards)

-- Using the Doppler shift of an emission line to infer the distance of the source

- Doppler shift of a wave: redshift and blueshift
- Using the Doppler redshift of an emission line to get the recession speed of a source

---Telescopes : Our Eyes on the Universe

-- Important properties of a telescope

1) Collecting Area: Current and Next Generation Largest telescopes. GMT
2) Resolving power
3) Space-based vs ground-based
   NASA's four Great Observatories : Hubble, Compton, Chandra, Spitzer

-- Using observations at different wavelengths to unveil mysteries of the Universe

- Gamma-ray, X-ray, Ultra Violet , Visble,
- Near-Infrared, Mid-Infrared,
- Radio 3mm line to trace molecular hydrogen
- Radio 21cm line to trace atomic hydrogen

Recent and Upcoming topics in class

---Galaxy Formation and Evolution

-- Types of galaxies : An amazing diversity (covered in Lec 2+3)
-- Galaxy interactions: Cosmic Fireworks (covered in Lec 4+5)
Major mergers vs Minor mergers. The Toomre sequence
Interactions of the Milky Way.
-- Looking back in time using images of distant galaxies
-- Galaxy surveys: GEMS, HUDF surveys
What is difference between GEMS and HUDF? What have we learnt from them?

--- Dark matter content of galaxies and of the Universe

- What is Dark Matter?
- How do we measure it ? How much of it is there?
- Dark Matter Candidates. How are they detected?
MACHOS= Massive Compact Halo Objects
Cold Dark matter = WIMPS = Weakly Interacting Massive Particles
Hot dark matter = Neutrinos

Recent and Upcoming topics in class

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

The Planck Era

The GUT era, The Electroweak era

Inflation

Production of Matter-Antimatter Pair + Formation of n,p,e

--- 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 ?

--- Dark Energy and the Fate of the Universe

Lecture 27: Announcements

1) Today

- Last lecture
- Discussion of Exam 3
- Class Evaluations
- Quiz 6 + Answers to quiz

2) I will do a review for Exam 3 and Homework 6 today in

WRW (W. R. Woolrich Labs), Room 102, from 5 to 7 pm

3) Th Dec 8 : Hwk 6 due back. Exam 3 scheduled

See class website for details.

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

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

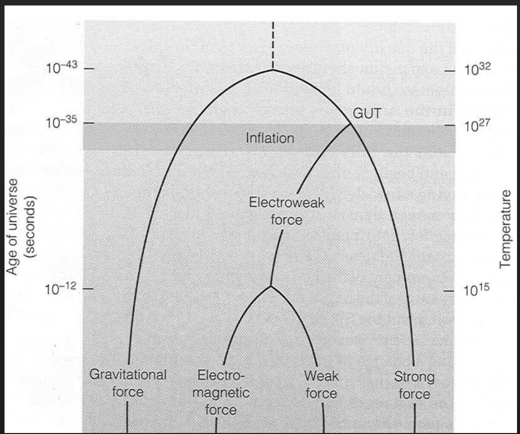
10^{-10} s - 1 s
Radiation produces matter-antimatter pairs. Due to an excess of matter over anti-matter, matter (n, p+, e-) form.

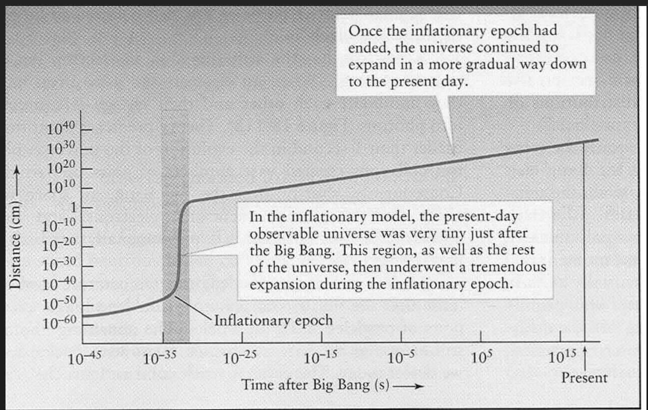
In GUT era, the EM, weak & strong forces remain unified as a GUT force, while gravity freezes out

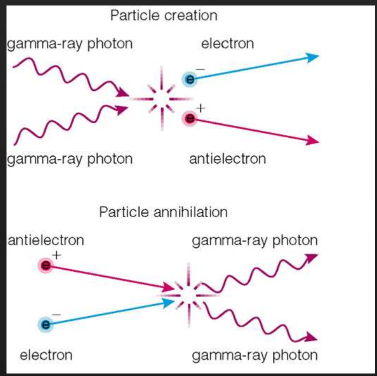
In the electroweak era, the EM and weak force remain unified as electroweak force, while the strong force freezes out. Inflation blows up the size of the Universe by a factor of 10^{25}.

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 H nuclei (protons) already form by t< 10^{-6} s 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) Where are the rest nuclei of all the heavy elements (e.g., carbon, oxygen, nitrogen, oxygen, silicon, sulphur, iron) produced?

Much later, after the first massive stars form and die

--> 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 that were made via advanced fusion in the core of the star.

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

Radiation-dominated era (t< 3x10^4 yr)

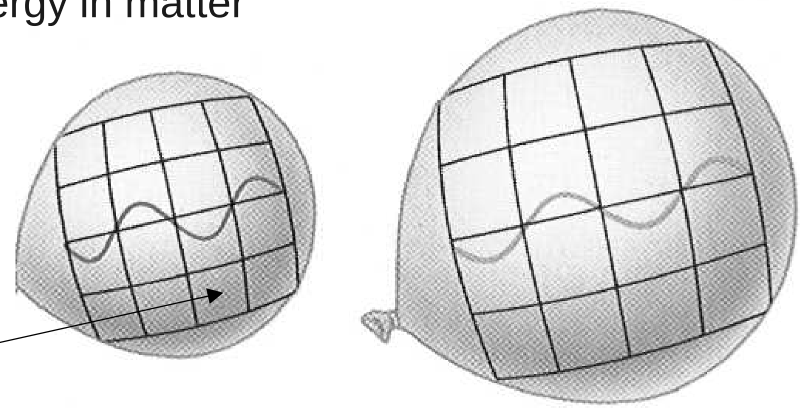
Energy density in photons (radiation) is larger than energy in matter

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

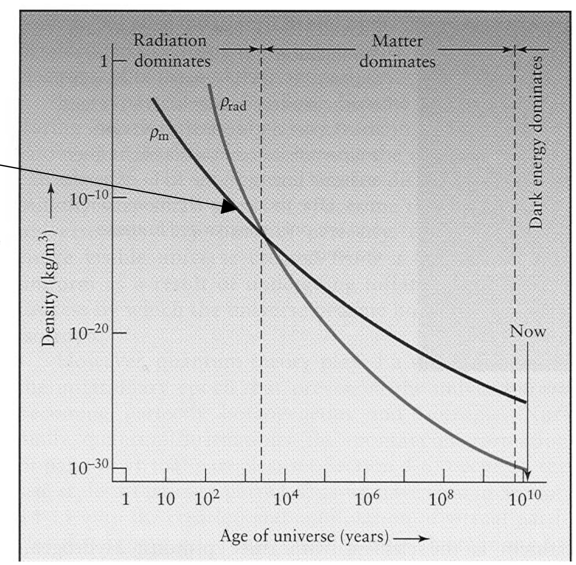
As Universe expands,

à photon λ stretches due to the expansion of the Universe and its energy falls (E = prop to 1/ λ) .

à matter energy falls because the separation of matter particles increases



The drop faster in the case of photons and soon the energy density in matter exceeds the energy in photons. à Universe transitions to being matter-dominated.

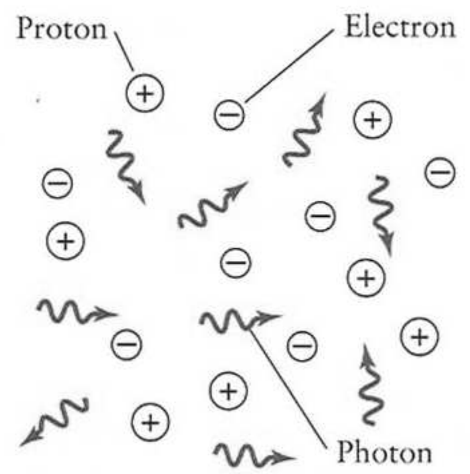


Matter/gas then responds to gravitational forces and forms clumps. These clumps are the seed from which larger structures such as stars and proto-galaxies will come from

Universes changes from opaque to transparent at recombination ($t=3x10^5$ 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

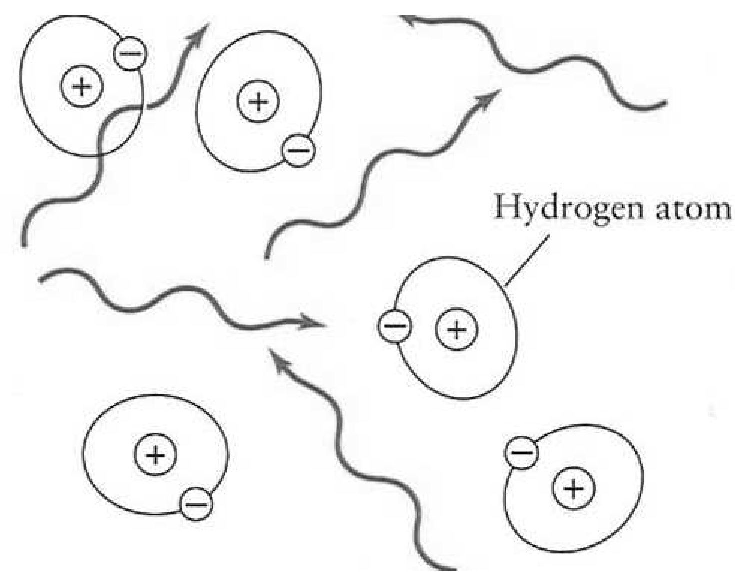


Ar recombination ($t = 3x10^5$ yr)

- 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.



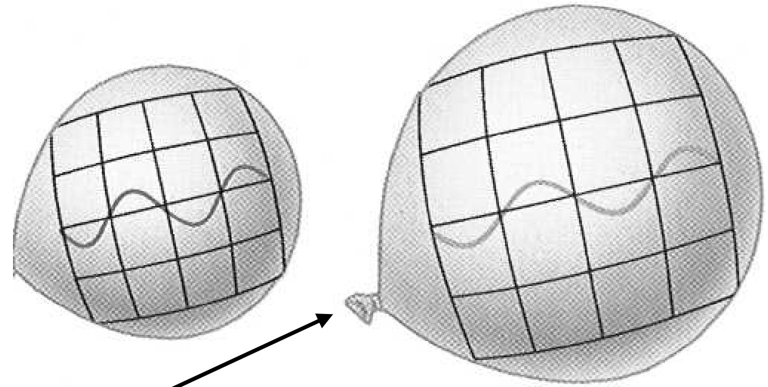
How the Cosmic Microwave Background Relates to Recombination

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

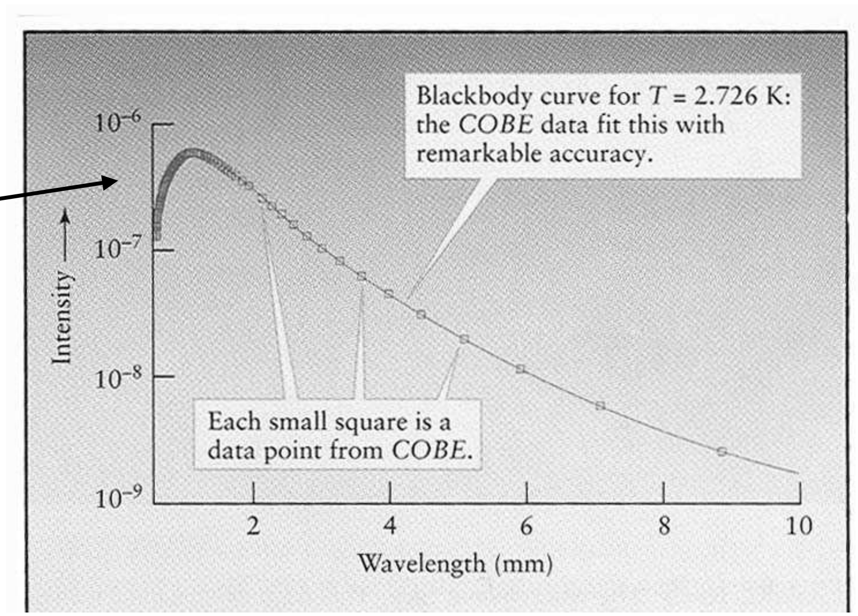
à are the oldest photons that we can see, as the Univ. was opaque before recombination

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

à reach us today as photons of larger radio wavelength $\lambda=1.1 \times 10^{-3}$ 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 $\lambda=1.1 \times 10^{-3}$ 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,

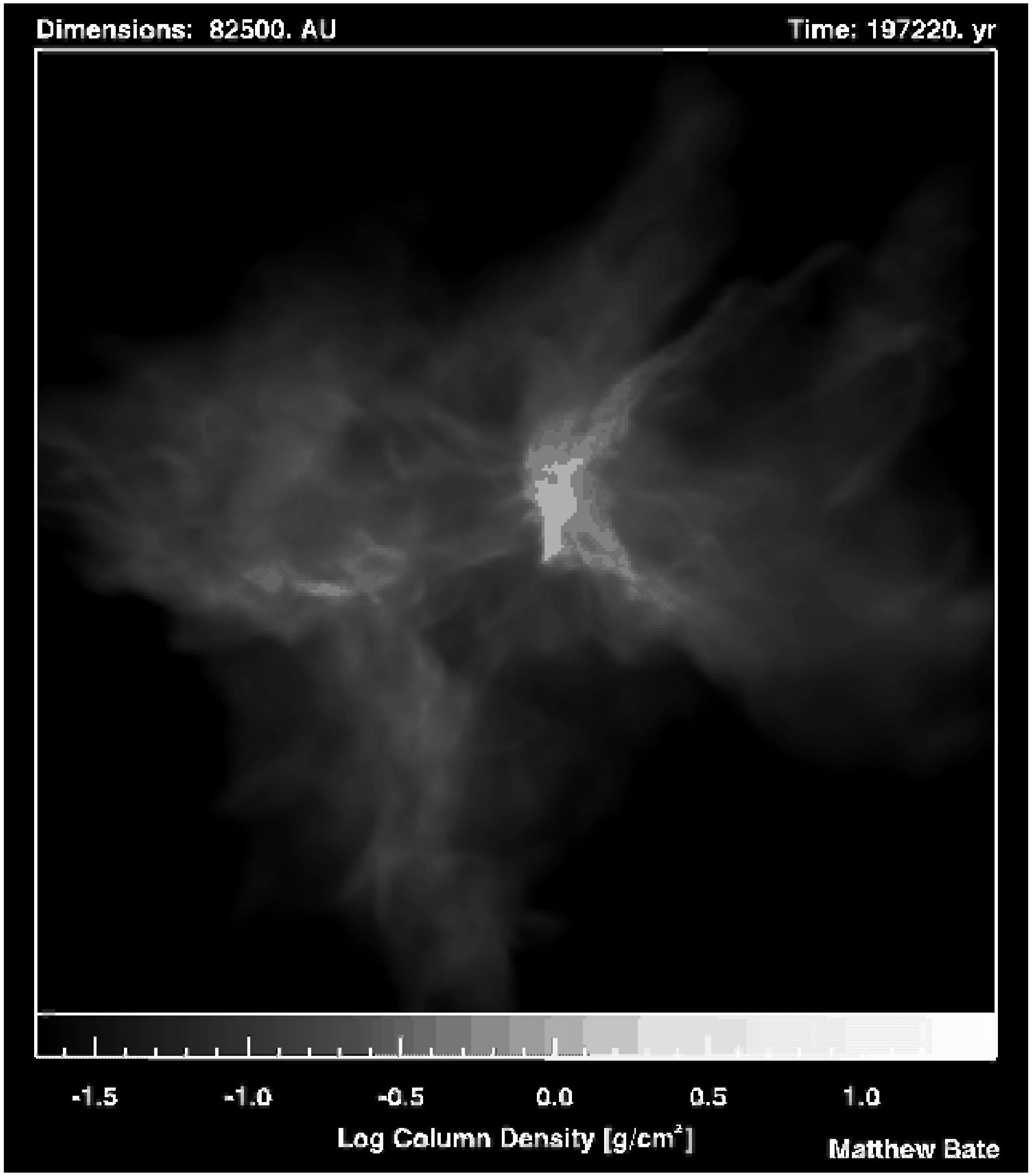
  à the tiny clumps of gas and dark matter respond to gravity and merge with other clumps to form more massive and denser clumps.

- 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.

Collapse of a cloud to form a Sun-like star and its planetary system



The simulation shows the collapse and fragmentation of a molecular cloud with a mass 50 times that of our Sun.

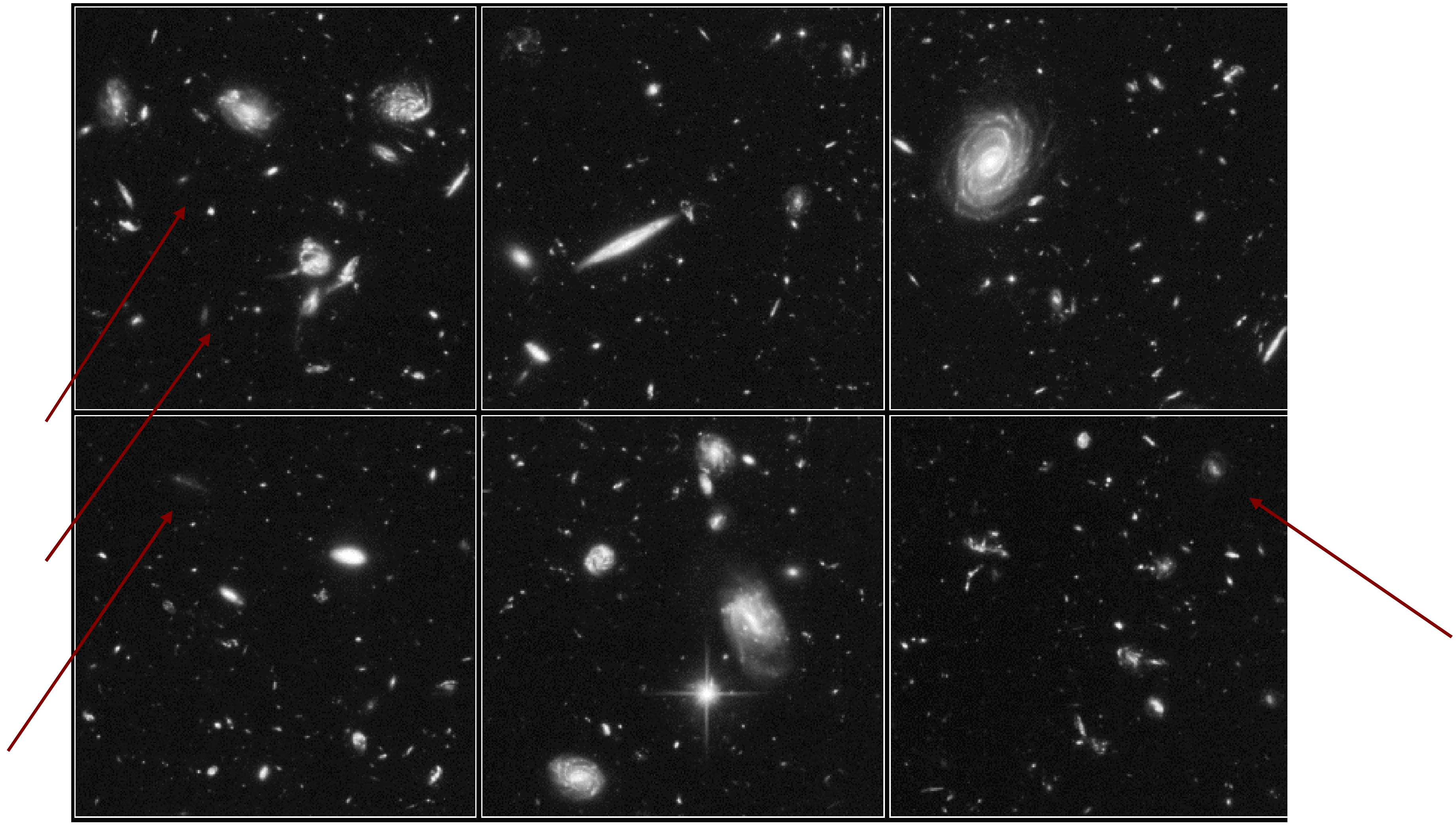
The cloud initially has a diameter of 1.2 light-years (9.5 million km) and a temperature of 10 K.

The cloud collapses to form stars.

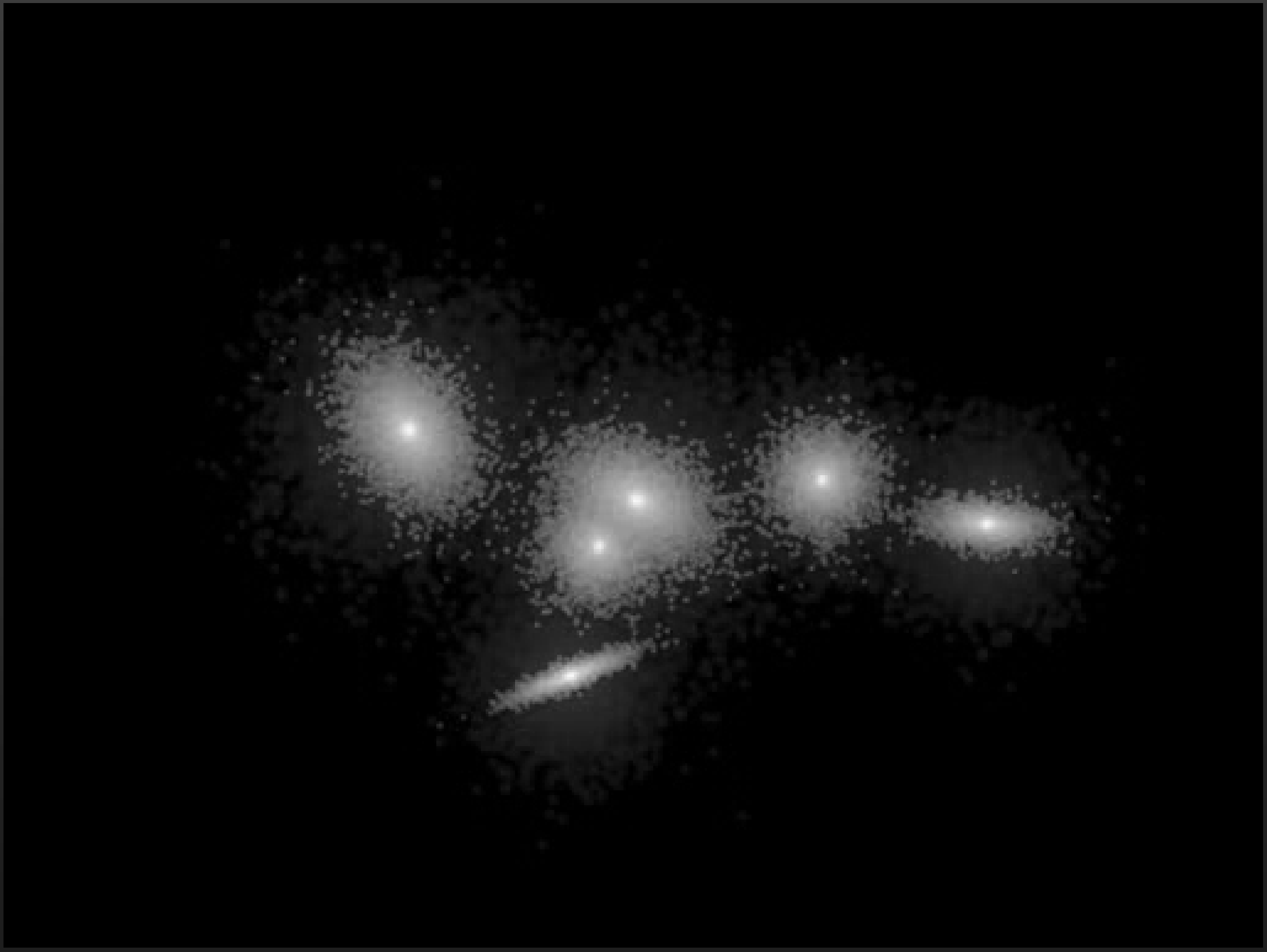
Surrounding some of these stars are swirling discs of gas which may go on later to form planetary systems like our own Solar System.

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.



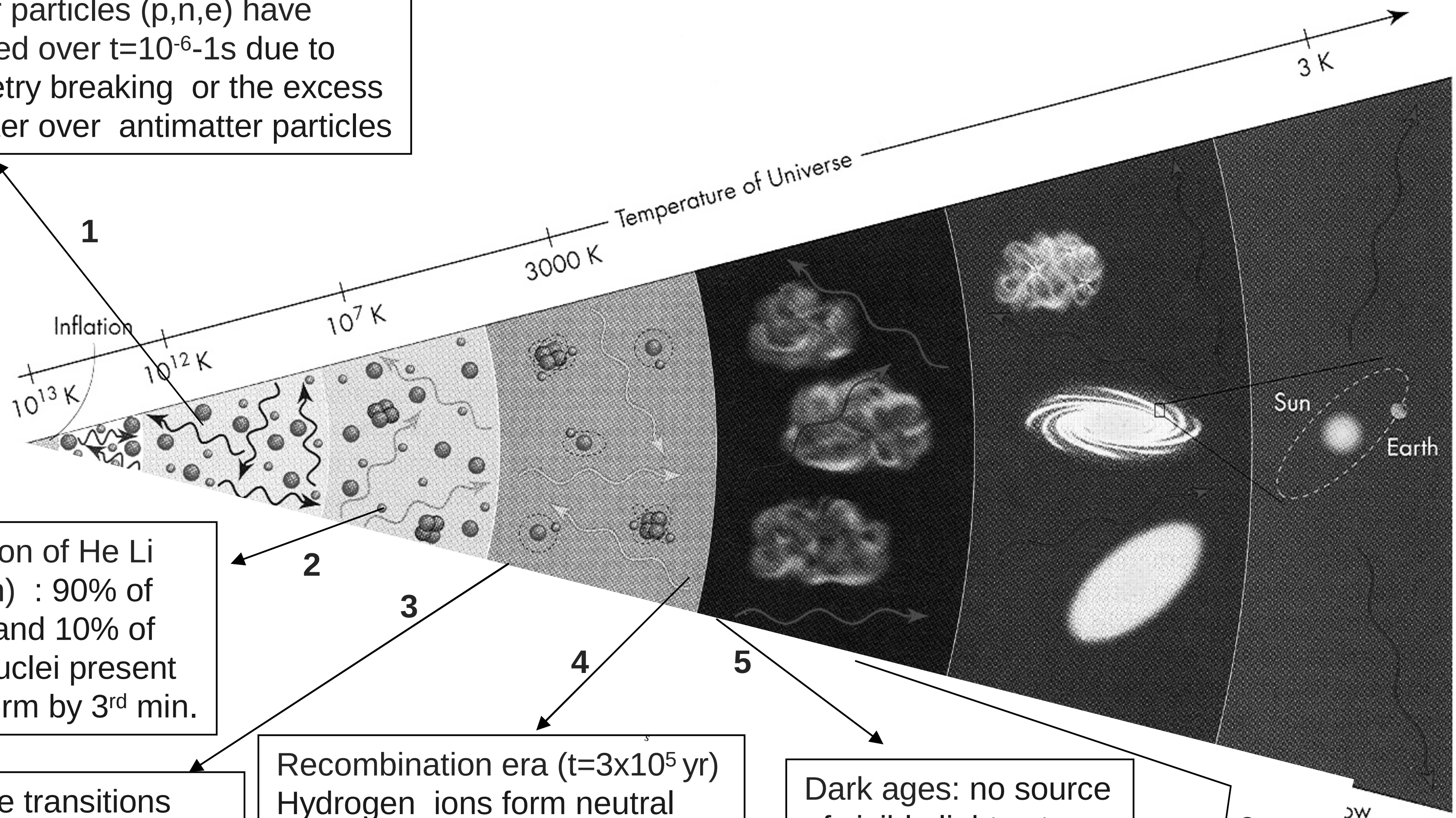
Some of these proto-galaxies then undergo frequent mergers at very early epochs (first few billion years) to grow into full-fledged galaxy components (bulges, disks, etc)



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 ($t=3\times10^{4}$ yr)

Recombination era ($t=3\times10^{5}$ 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) .

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

According to the Big Bang model, 90% of the helium we see today was produced in the first few minutes of the Big Bang. The predicted abundances match those observed.

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 by today, would form the CMB, i.e., thermal radiation that is received all over the sky and whose flux peaks at radio wavelengths of $\lambda=1.1 \times 10^{-3}$ m, corresponding to a temperature of 2.73 K. Such a CMB has been observed.

Furthermore, the observed CMB is extremely 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

First Detection of the Cosmic Microwave Background in 1965!

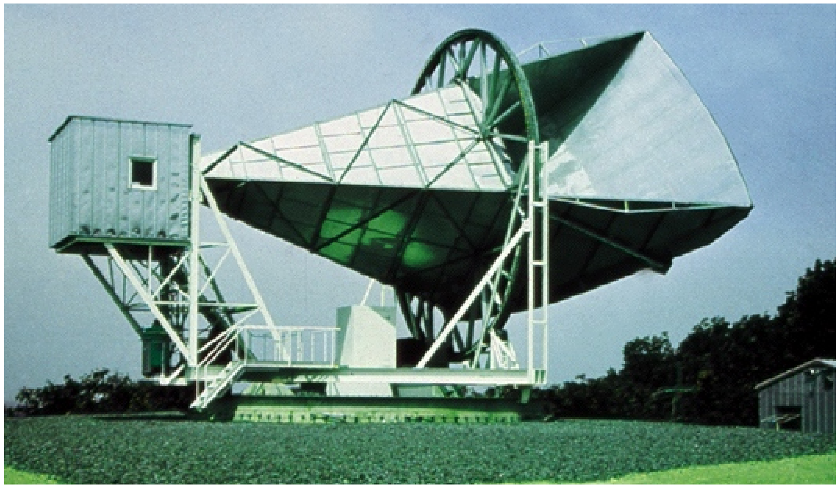
CMB was predicted from Big Bang models by Gamow & Alpher in the 1940s

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.

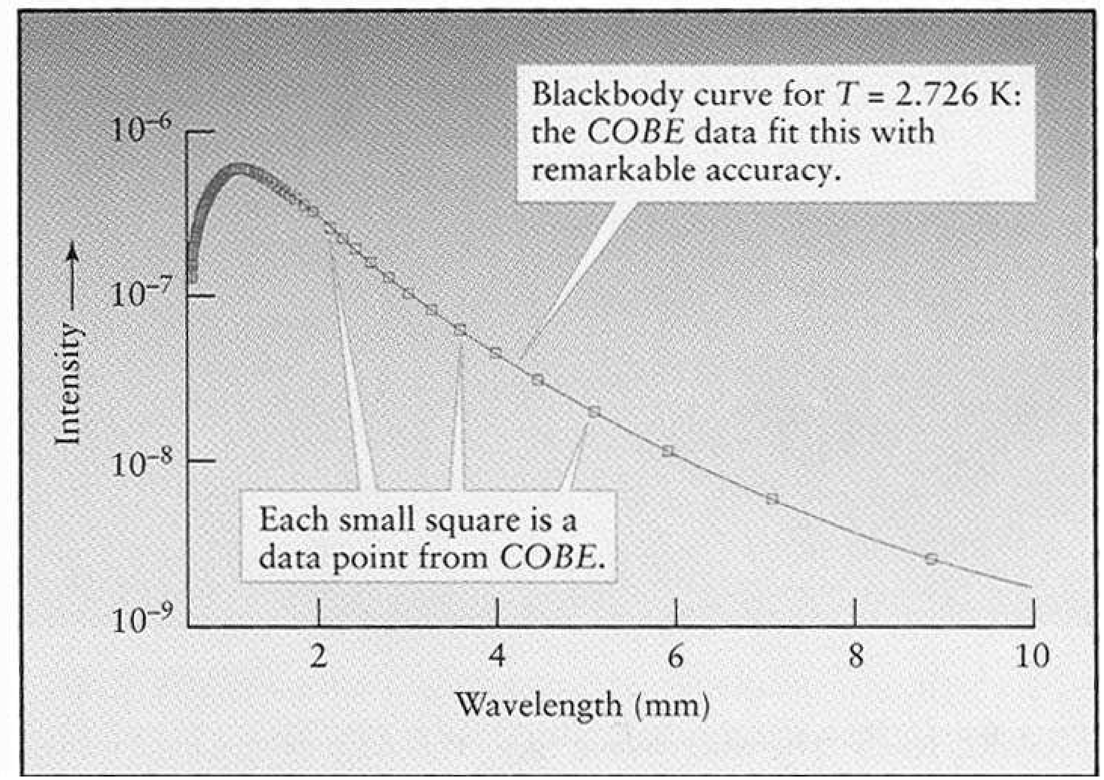


First Precise Measurement of the Cosmic Microwave Background by COBE

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

COBE made the very first precise measurements of the CMB (1990-1994)

Showed that tha CMB spectrum could be fit by an almost perfect black body spectrum at T= 2.73 K. that shows 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 λ=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

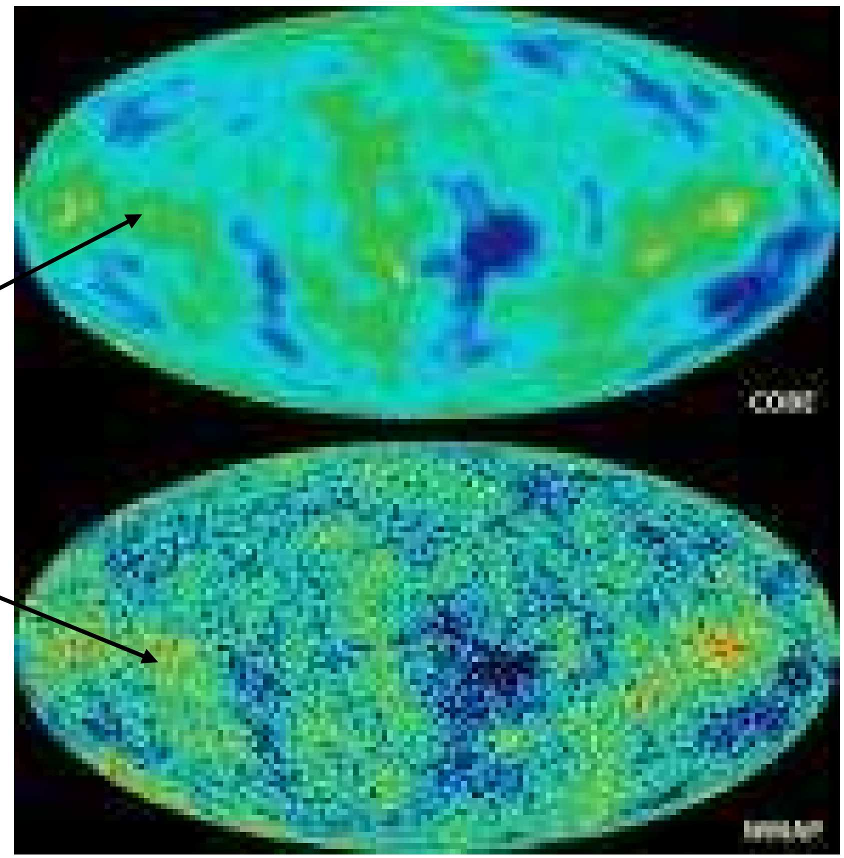
WMAP observations of the Cosmic Mircrowave Background

WMAP = Wilkinson Microwave
Anisotropy Map (2001-now)

COBE.

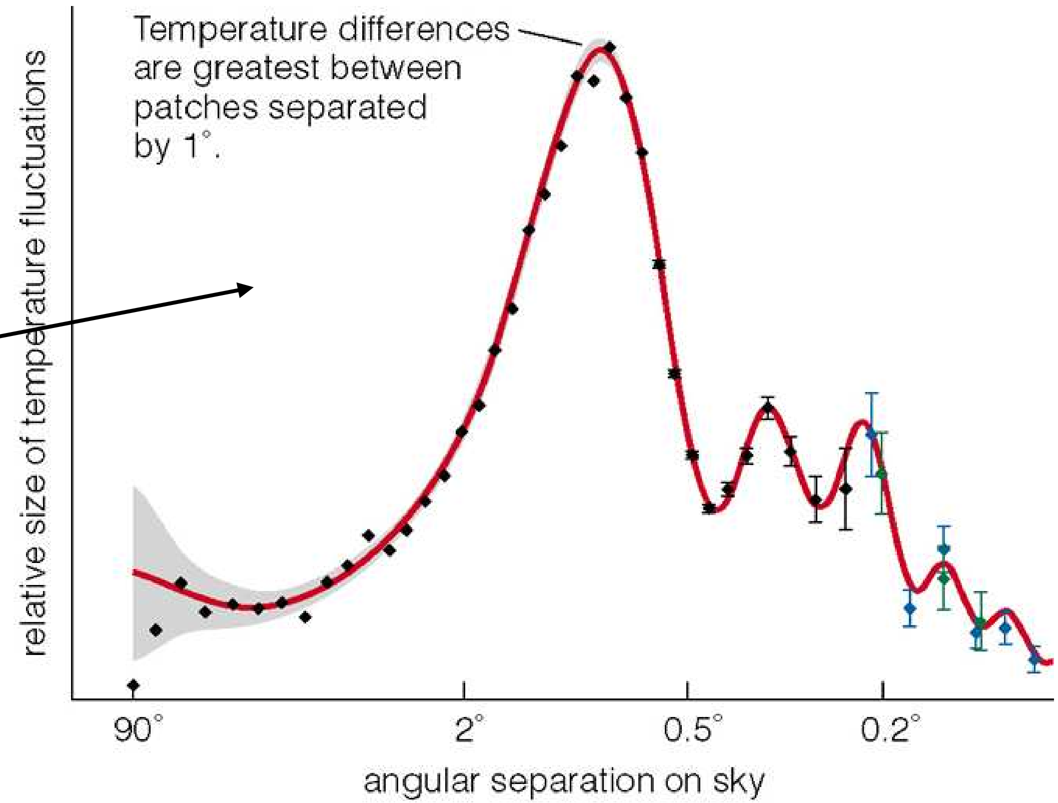
WMAP has 10 times better
angular resolution than COBE.

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

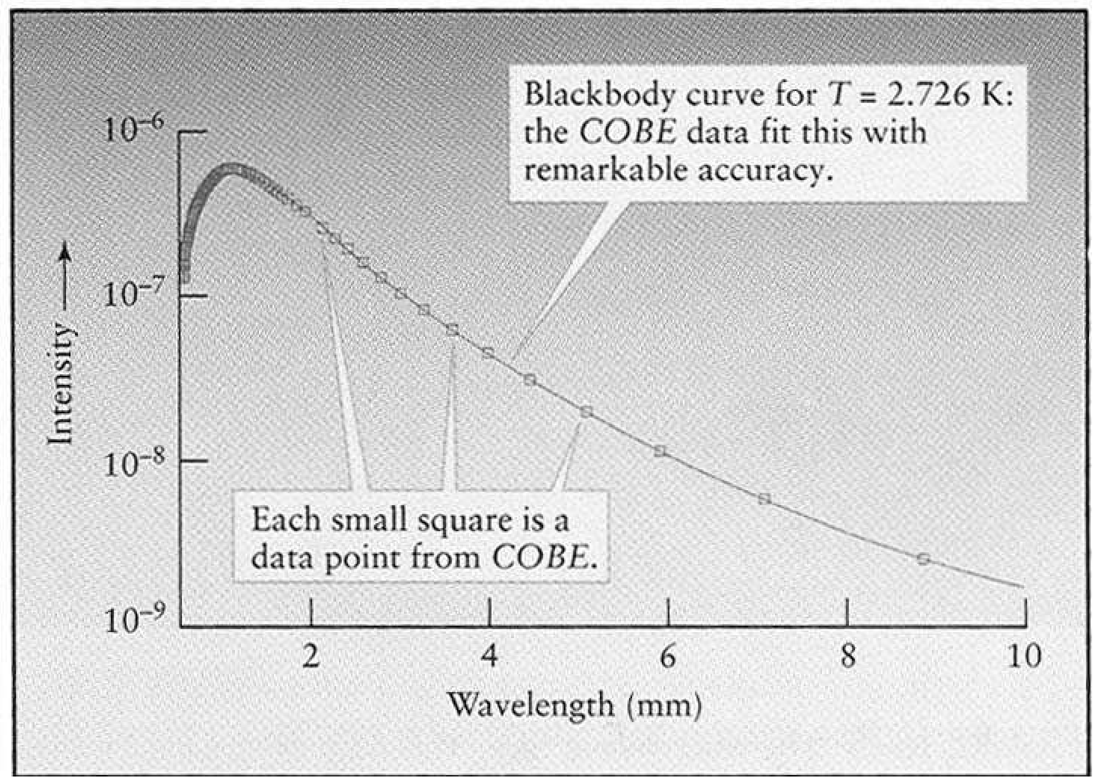
à constrain the nature of dark matter, favoring non-baryonic cold dark matter (WIMPS) over hot dark matter (neutrinos)

Why do need inflation in the Big Bang model?

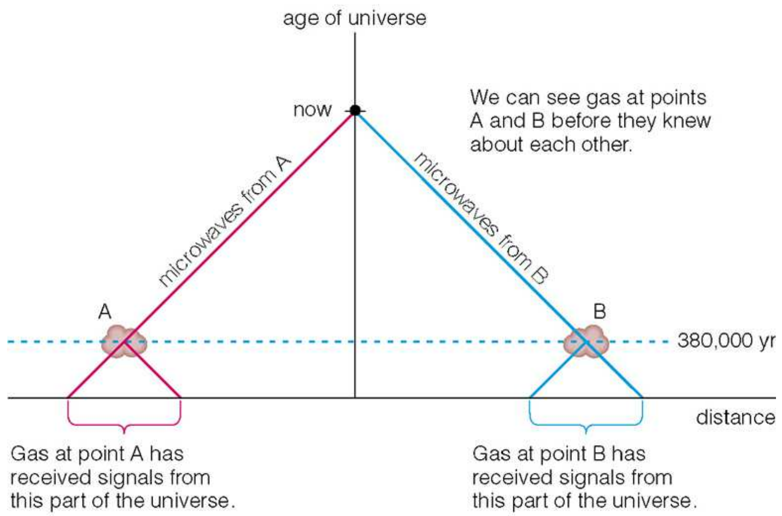
1) To account for the smoothness (uniformity) of the Cosmic Microwave Background

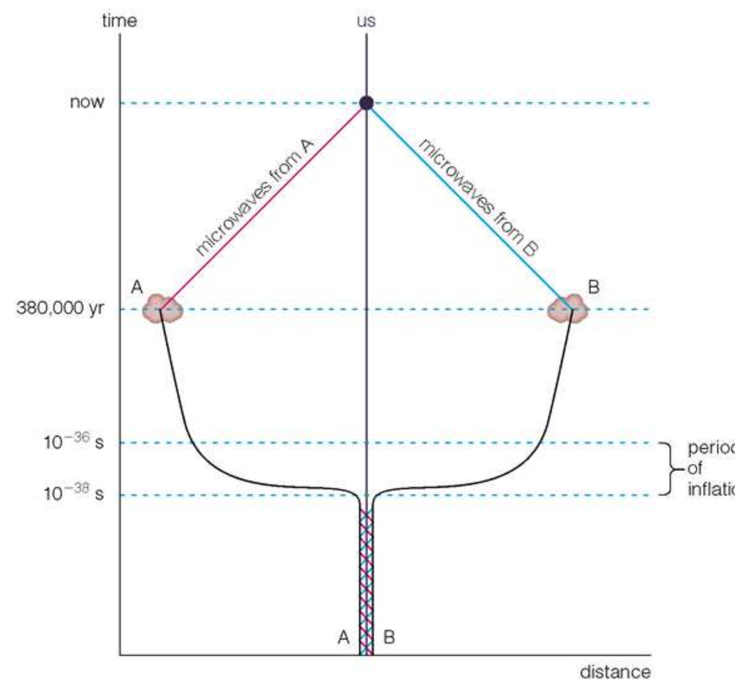
The observed CMB is very uniform: it looks almost identical all over the sky, with a temperature variation of less than 1 part in 10^5.

This 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.



Why do need inflation in the Big Bang model?





<u>In a Big Bang model without inflation</u>

à the Universe would **<u>always</u>** 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*.

<u>In a Big Bang model with inflation</u>

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

Why do need inflation in the Big Bang model?

2) To explain the origin of structure (stars, planets, galaxies)

Structure (stars, planets. galaxies) are believed to form as follows:

à   tiny clumps of gas and dark matter that exist during/before the recombination era grow with time into more dense and massive clumps until gravity makes the gas to collapse into stars and proto-galaxies.

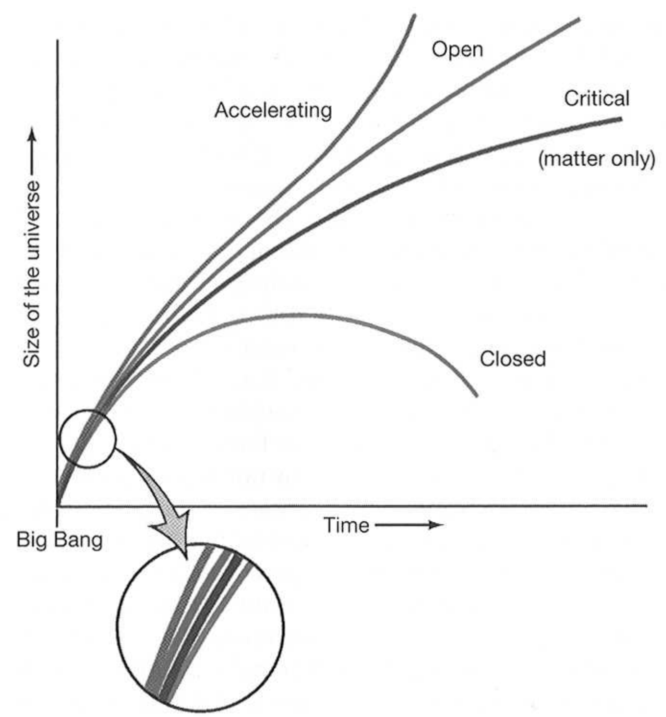
But where do these “tiny clumps of gas and dark matter “ come from?

Right after the Big Bang, and before the inflation era, there were only infinitesimal quantum mechanical (statistical) density fluctuations.

Inflation powerfully magnifies these infinitesimal quantum mechanical (statistical) density fluctuations into the tiny gas clumps that origin of structure (stars and galaxies) that later formed in the Universe.

Why do need inflation in the Big Bang model?

3) To explain why the total energy density is so close to the critical density (flatness problem)



▲ **FIGURE 27.9 Flatness Problem** If the universe deviates even slightly from critical density, that deviation grows rapidly in time. For the universe to be as close to critical as it is today, it must have differed from the critical density in the past by only a tiny amount.

Not important for this class

Fate of the Universe: Matter vs Dark Energy

Fate of the Universe : Matter vs Dark Energy

1) Matter (dark +luminous) exerts an attractive force of gravity that tries to make the Universe contract

2) Dark energy is a repulsive force or pressure that acts on large scales, is associated with a vacuum energy and tries to make the Universe expand.

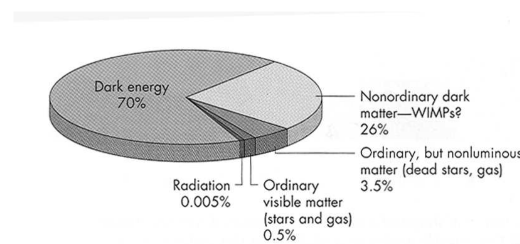
3) The competition between matter (both dark and luminous) versus dark energy determnes

- the geometry of space (close, flat, open)
- the ultimate fate of the Universe: whether it expands forever or eventually recollapse

4) Observations show (dark matter + visible matter + radiation) make up only 30% of the total energy density while dark energy makes up a whopping 70%

Radiation like CMB	0.005%
Visible matter :	0.5 %
Baryonic dark matter (e.g., MACHOS)	3.5 %
Non-baryonic cold dark matter (e.g., WIMPS)	26.5%

Total energy density in (dark matter+ luminous matter + radiation)	30.0 %
Total energy density in dark energy	70.0 %



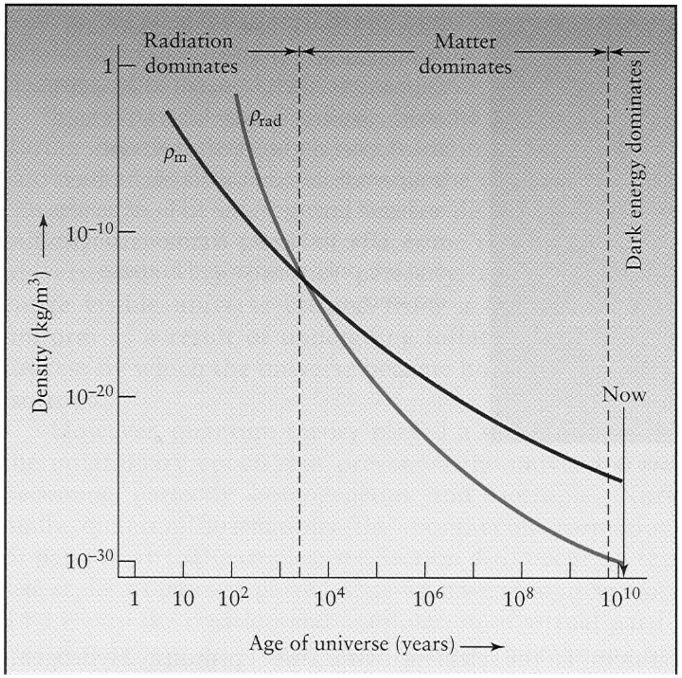
Fate of the Universe : Matter vs Dark Energy

Observations of white dwarf superovae (Type Ia supernovae; standard candles) out to large distances and early times, show that dark energy is accelerating the Universe outward (expanding it faster and faster)

Before t=30,000 yrs,
 à the Universe was radiation-dominated

At t=30,000 yrs,
 à the Universe became matter-dominated and structures (density enhancements, star,galaxies, clusters) started to grow,

At present times,
à the Universe is dominated by dark energy



Fate of the Universe : Matter vs Dark Energy

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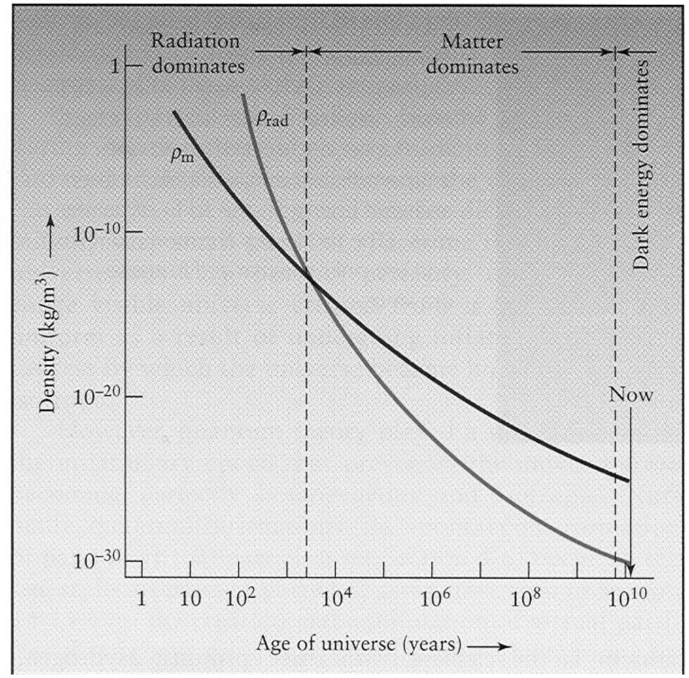


Yet we know practically nothing on the nature of dark energy

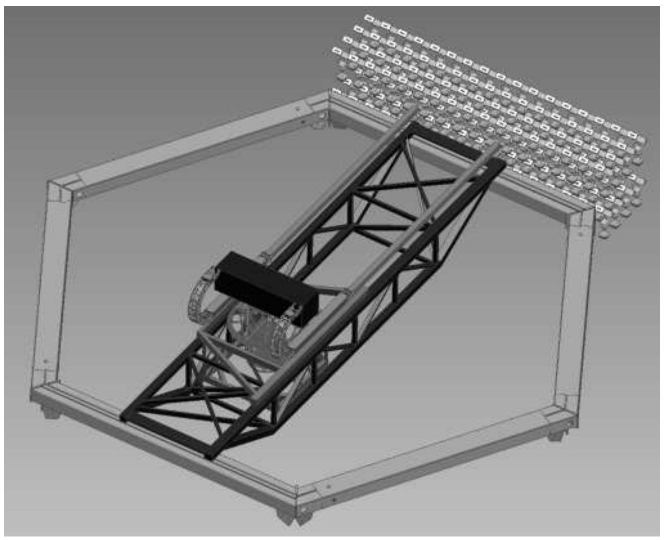
The National Academy of Science and the scientific community hold the view that the most important question that science has to answer is
the nature of dark energy

Nature of Dark Energy

HETDEX = Hobby Eberly Telescope Dark Energy Experiment at UT Austin

Will survey large scale structure of 1 million galaxies in a volume 10x that of the SDSS at $2 < z < 4$

These data will constrain the nature of dark energy in 8 years



VIRUS (instrument for HETDEX)

- VIRUS is an integral field spectrograph on the HET, that is 100 times more powerful than any in existence
- Will detect Ly-α emission from star forming galaxies