Lecture 38: Announcements

The Universe: How it all Began and Possible Fates

-- Unifying Fundamental Forces as Electroweak, GUT, and ‘Super’ forces

-- The Beginning of Time: From 10-43 s to to the First Second
 - The Planck era , GUT era , and Electroweak era.
 - Inflation.
 - Production of matter-antimatter pairs from radiation : emergence of matter

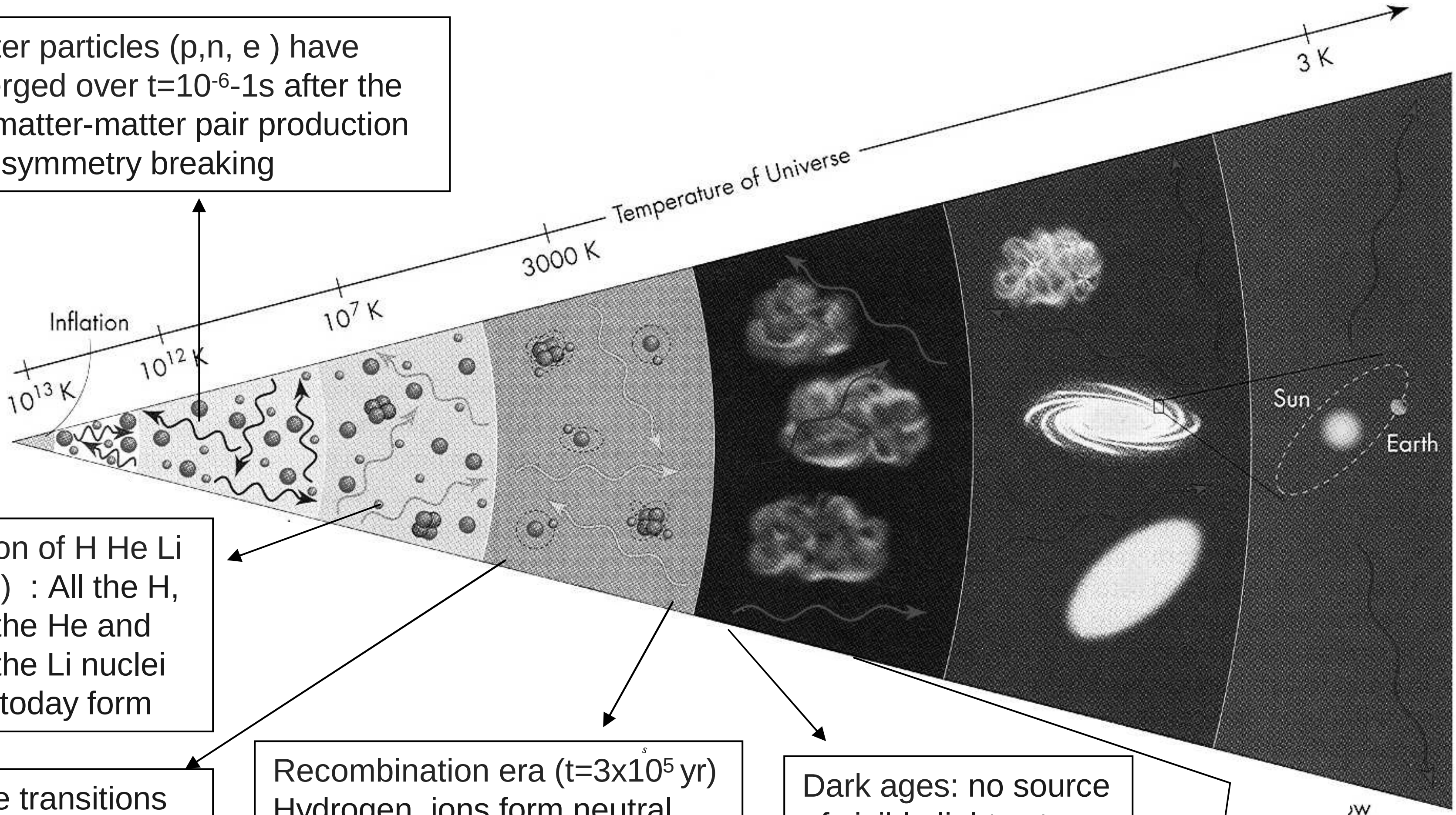
-- From the first second to the first billion years
 - The formation of basic elements: (H, He, Li) nuclei
 - Universe transitions from radiation-dominated to matter dominated
 - Recombination epoch : Universe transitions from opaque to transparent
 - The dark ages ß
 - The formation of the first luminous objects: stars and proto-galaxies,
 - The reionization era

-- The cosmic microwave background : Its importance and how it is observed
-- Evidence for the Big Bang model and for Inflation.
-- The critical density of the Universe and its fates

-- Perspectives: Our civilization

Overview: From the first second to the first billion years

Matter particles (p,n, e) have emerged over t=10^{-6}-1s after the antimatter-matter pair production and symmetry breaking



Formation of H He Li (t=3 min) : All the H, 90% of the He and 10% of the Li nuclei present today form

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

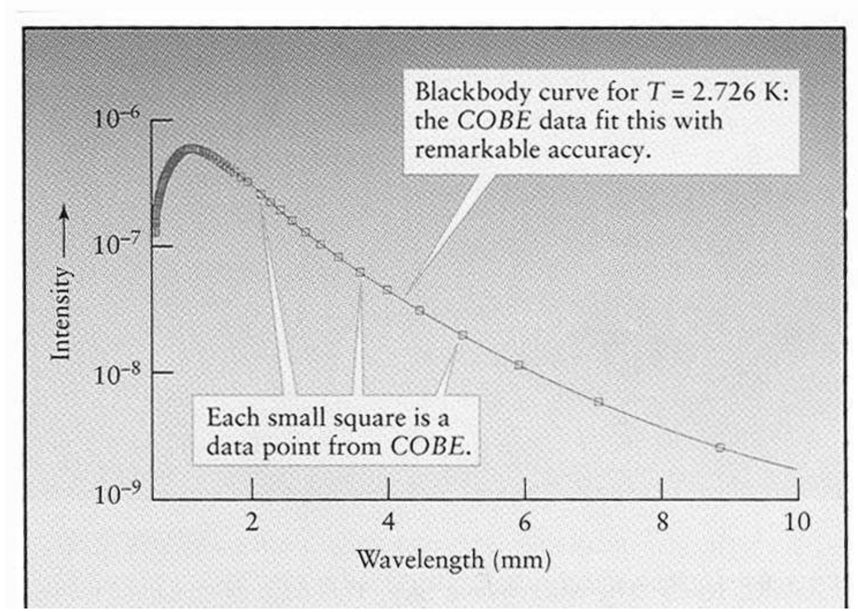
Recombination era (t=$3x10^{5}$ yr) Hydrogen ions form neutral atoms, and Universe changes from opaque to transparent. The photons released are the oldest ones we see and get redshifted to form the CMB at mm wavelengths and T=2.7 K

Dark ages: no source of visible light yet.

First luminous objects form: stars at t=1-2 $x10^{8}$ yr), then proto-galaxies (t=3-$7x10^{8}$yr) These end the dark ages and their UV light also reionized neutral H back to protons and electrons (reionizaion era) .

Importance of The Cosmic Microwave Background (CMB)

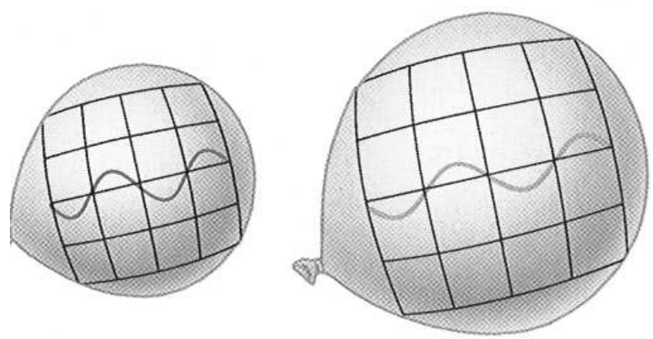
The Cosmic Microwave Background (CMB) is uniform radiation that is detected at mm wavelengths from all over the sky .



The CMB spectrum peaks at 1.1 mm and is extremely well fitted with an almost perfect blackbody curve at 2.73 K. The deviation in the temperature of the CMB is less than 1 part in 10^5 K, irrespective of where we observe it in the sky.

The CMB contains the oldest photons that we can observe in the Universe.These photons originated from the recombination era (t=300,000 yr), when hydrogen changed from ionized to neutral, causing the Universe to became transparent for the first time.

When the photons were emitted, their spectrum peaked at 10^{-6} m, corresponding to a blackbody temperature T=3000K. Due to the expansion of the Universe, they got redshifted such that today their spectrum peaks at 1.1×10^{-3} m, corresponding to T=2.73 K



Importance of The Cosmic Microwave Background (CMB)

The CMB is one of the strongest piece of evidence in support of the Big Bang and inflationary model of the Universe

Furthermore, the CMB tell us about conditions present in the early Universe and can constrain the nature of dark matter, favoring cold dark matter (WIMPS) over hot dark matter (neutrinos)

à The fact that the CMB only shows small deviations in temperature tells us that at the recombination era, there were small density enhancements in the otherwise smooth distribution of matter

à These density enhancements, along with extra density ehnancement added by dark matter, grew to form stars and galaxies later on.

à The epoch where the first galaxies form will be very different depending on whether the dark matter is made up of WIMPS (cold dark matter) as opposed to neutrinos (hot dark matter)

à Observations showing that galaxies are already forming by ~ 1 Gyr, strongly favor WIMPS (cold dar matter) as the leading candiate for dark matter, and rules out hot dark matter….. (the ‘cold’ war is over)

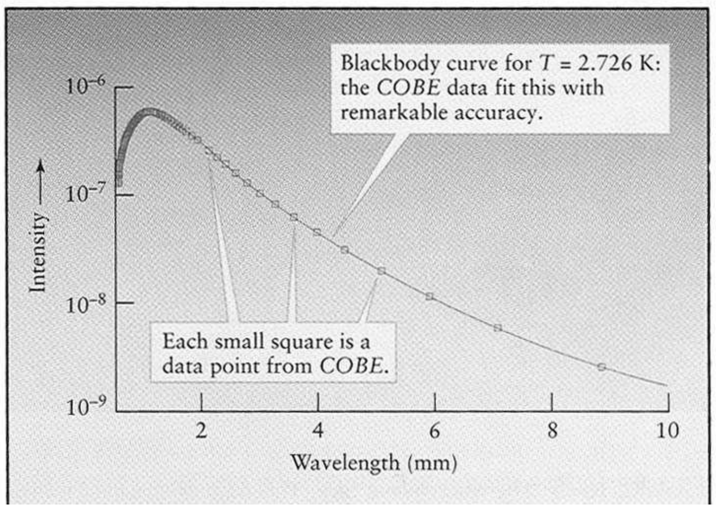
Observing the Cosmic Microwave Background (CMB)

Bell Labs Horn Antenna (1965)

à   CMB predicted by Gamow and Alpher in 1940s

à   Dicke, Peebles and Wilkinson at Princeton started to design a microwave radio telescope in 1960s

à They were scooped by Arno Penzias and Robert Wilson who detected CMB with Bell Labs Horn Antenna in1965.
- They were relaying telephone calls to Earth-orbiting satellites and found a *persistent and annoying noise all over the sky*, which they could not get rid of! Eventually realised it was the CMB. Awarded the 1978 Nobel Prize in Physics.



Cosmic Microwave Background Explorer (COBE; 1990)

First precise measurement of CMB by COBE; 1989-1994)

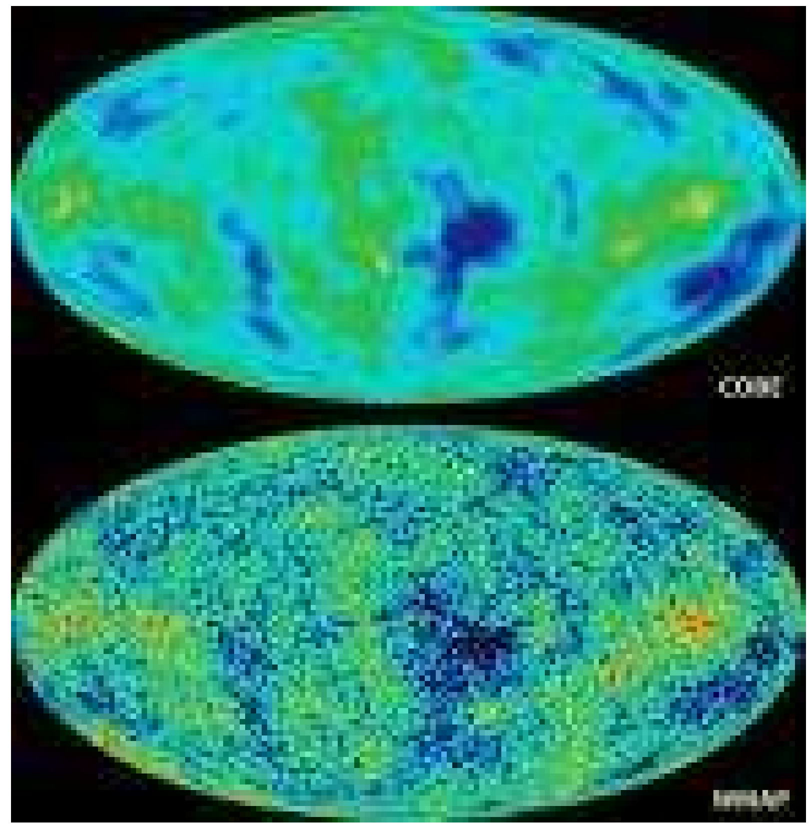
This showed the spectrum could be fit by an almost perfect black body spectrum with T=2.73 K

Observing the Cosmic Microwave Background (CMB)

Boomerang Telescope

Boomerang telescope carried by a balloon, travelled over Antartica for 10 days in 2002

Wilkinson Microwave Anisotropy Map (WMAP; 2001-now)



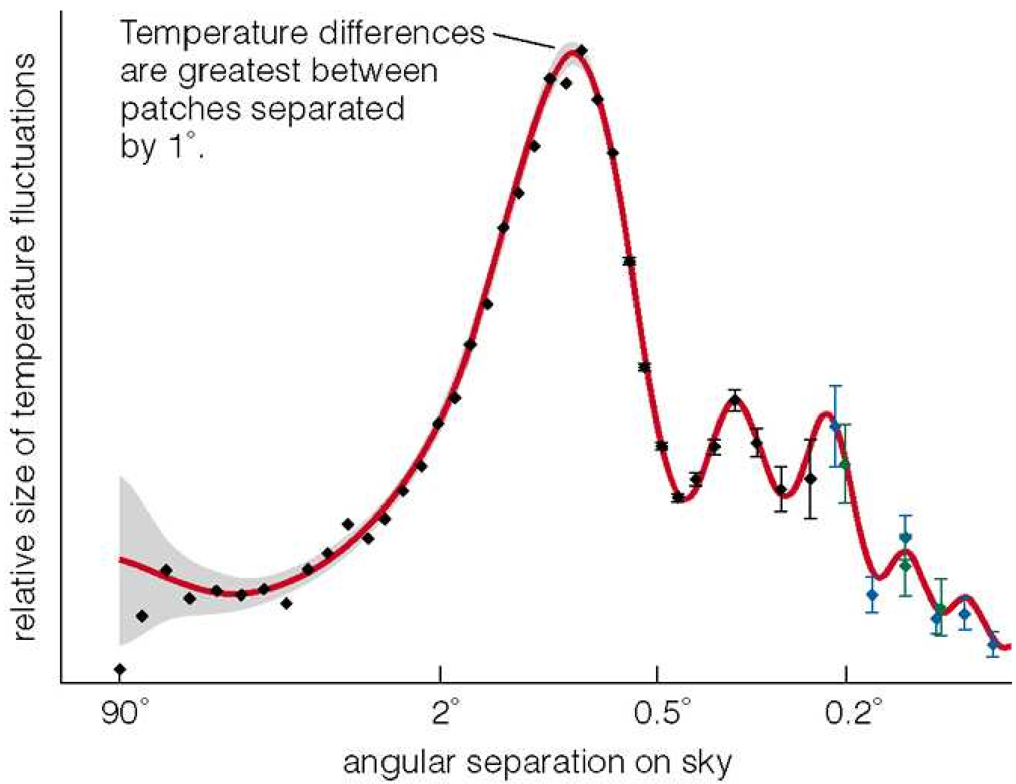
WMAP has 10 x better resolution than COBE

Observing the Cosmic Microwave Background (CMB)

WMAP observations provide the best measurements to date of CMB . They set constraints not only on the Big Bang model of the Universe, but also

à directly test inflation

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



Evidence for the Big Bang inflationary model of the Universe

1) The Cosmic Microwave Background (CMB)

The properties of the CMB, (its quasi black-body spectrum at 2.73 K, its shape, and its isotropic and homoegeneous nature over different locations in the sky) match the properties predicted by the Big Bang inflationary model for radiation produced at the recombination era.

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) Hubble's law showing the expansion of the Universe

Hubble's law showing that all galaxies are receding from each other with a speed that is directly proportional to their separation shows that the Universe is expanding, and must therefore have been much smaller in the past.

Why do need inflation in the Big Bang model?

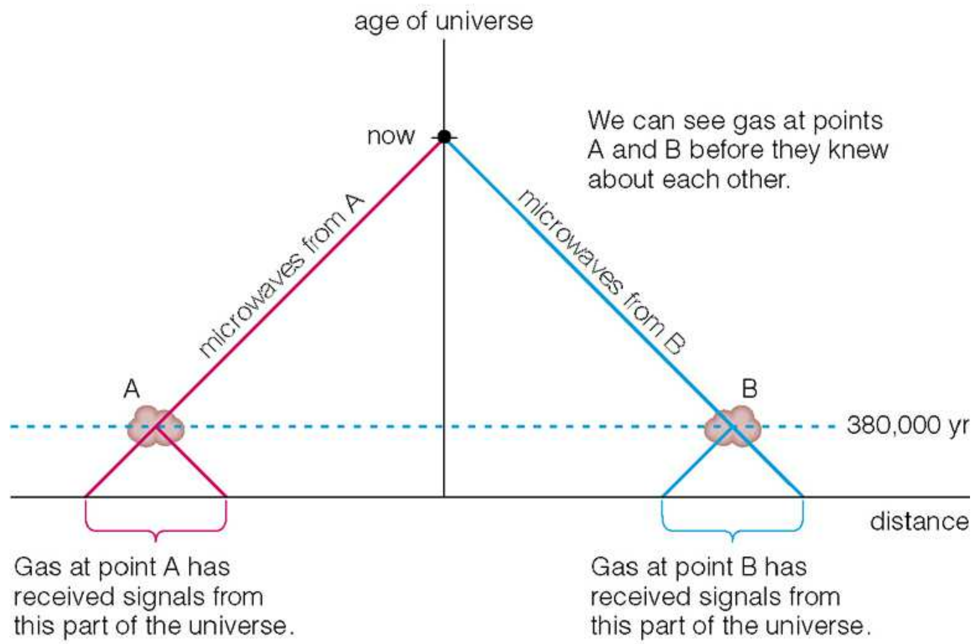
A Big Bang model without inflation is unable resolve 3 fundamental problems

1) The smoothness problem (or problem of synchronization over large scales)

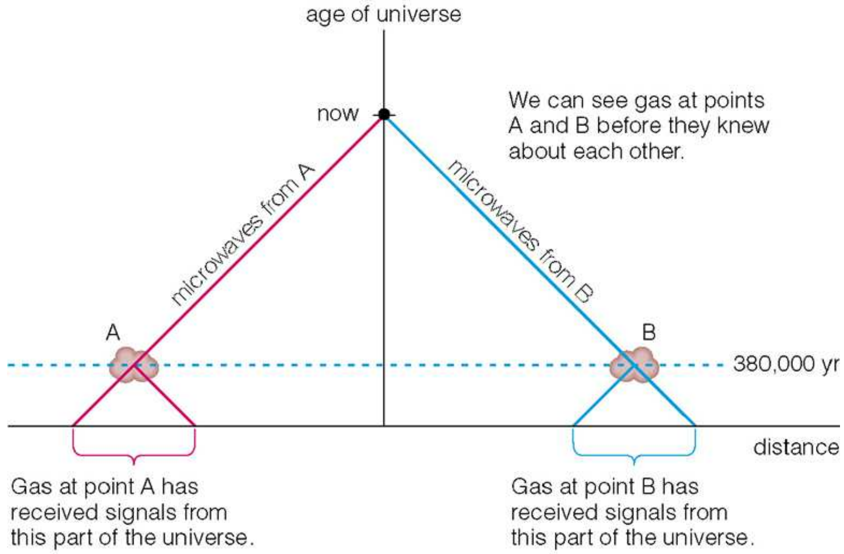
The CMB is remarkably similar today at points that are located at very large distances over the sky. This implies that these different points must have communicated with each other at or before the recombination era in order for them to synchronize their temperature, densities, and CMB emission ('get their act together')

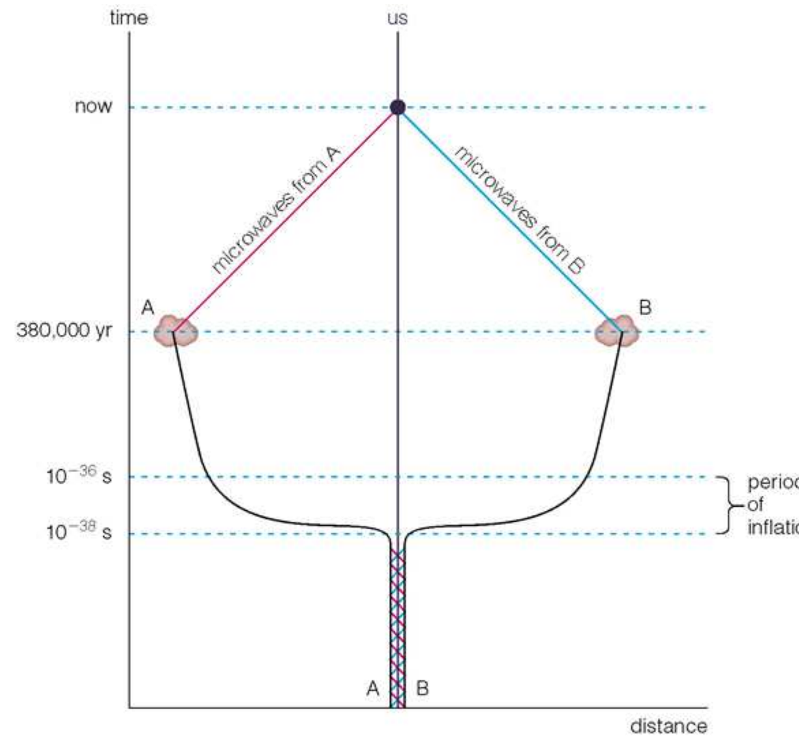
The fastest way to transmit information between 2 points is via the speed of light. Yet, one can show that 2 points on the sky today, were still so far apart at recombination era that even light would not have had time to travel from one to the other at that time.

So how did they synchronze their emission?



Why do need inflation in the Big Bang model?





Inflation which kicks in from from 10^{-35} to 10^{-32} s and expands the Universe by a humongous factor of 10^{25} solves this problem. In the inflationary model,

à before inflation the observable Universe would have been the size of 10^{-38} light seconds

à before inflation, light could have travelled across different points of this tiny Universe, synchronzing their temperature and densities.

à Once inflation kicks in, it would inflate the Universe by 10^{25}, resulting in the large separations we see at recombination (t=300,000 yr) and later

Why do need inflation in the Big Bang model?

2) The structure problem

The CMB is remarkably homogeneous and the deviation in its temperature is less than 1 part in 10^5 K, irrespective of where we observe it in the sky.

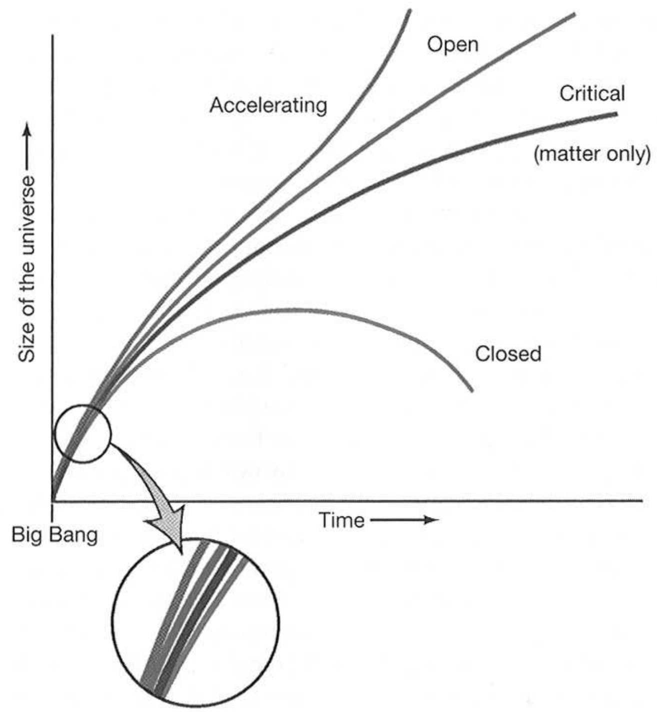
While this deviation is small, it is significant and tells us that at the recombination era there were small density enhancements in the otherwise smooth matter distribution

These tiny density enhancements, as well as any extra enhancement produced by dark matter, grew later on to form the stars and galaxies we see today. But where did this density enhancements come from in the first place?

Inflation provides a natural explanation for the origin of the density enhancements present at the recombination era, and hence for the origin of structure (stars and galaxies) that later formed in the Universe. Quantum mechanical (statistical) density fluctuations present in the very early Universe before 10^{-35} s can easily be amplified to the required size when inflation kicks in from 10^{-35} to 10^{-32} s.

Why do need inflation in the Big Bang model?

3) The flatness problem (or why density is so close to critical density)



▲ **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

Dark Energy (do not confuse with dark matter)

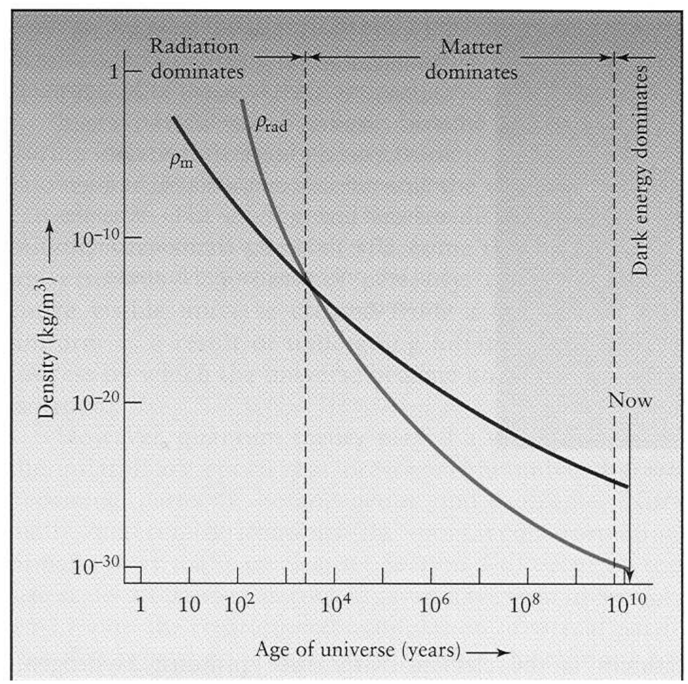
Dark energy is a <u>repulsive force</u> that acts on large scales and is associated with a vacuum energy. Obervational evidence for it exist since 1990s. Its exact nature and origin is not yet poorly understood.

Energy density in matter and radiation (ρ-matter)
à produces an attractive gravitational force and energy (-ve),
and tries to collapse the Universe
Energy density in dark energy matter (ρ-dark-energy)
à produces an repulsive force and energy (+ve),
and tries to expand the Universe

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,

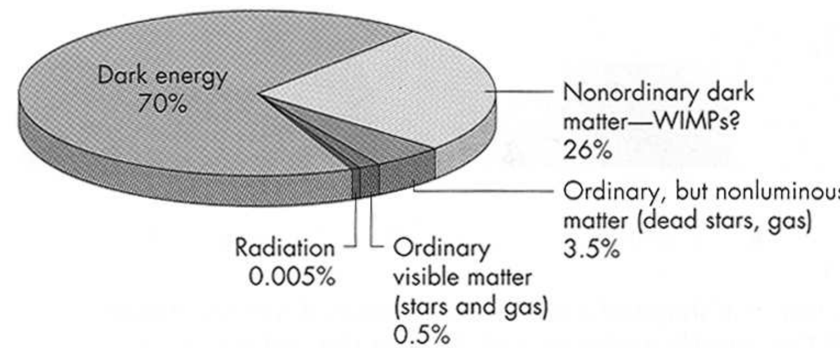
At present times,
à the Universe is dominated by dark energy



Dark Energy (do not confuse with dark matter)

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)

Observations show that matter (both dark and visible) and radiation only make up 30% of the energy density or mass density of the Universe, while dark energy makes up a whopping 70%!

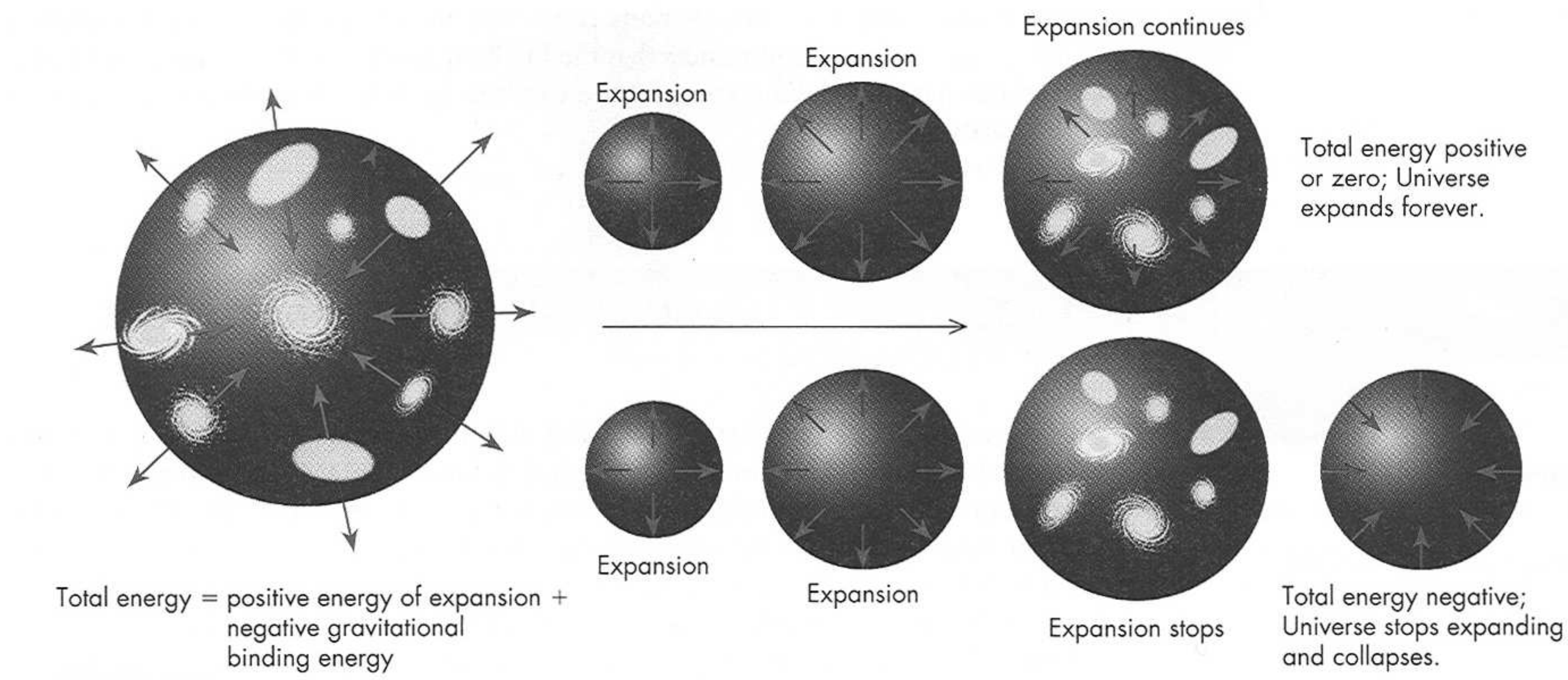


Radiation like CMB	0.005%
Visible matter :	0.5 %
Baryonic dark matter (e.g., MACHOS)	3.5 %
Non-baryonic cold dark matter (e.g., WIMPS)	26.5%

Total energy or mass density in matter+radiation	30.0 %
Total energy or mass density in dark energy	70.0 %

Fate of Universe

The average density of matter compared to that of dark energy determines will determine
- the geometry of space (close, flat, open)
- the ultimate fate of the Universe: whether it expands forever or eventually recollapses



Current indications are that the Universe will expand forever.

<u>Perspectives: Our Privileged Civilization</u>

Overview: The Beginning of Time - 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

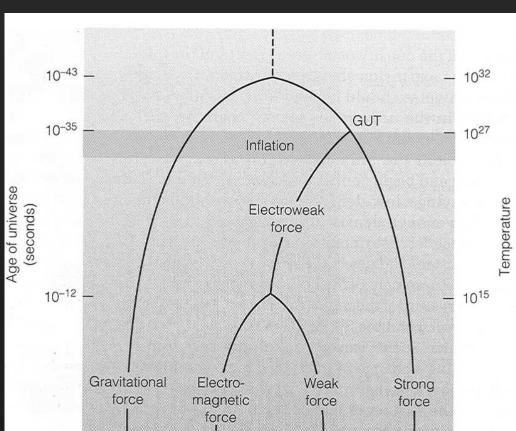
10^{-10} s - 1 s
Matter-antimatter pairs form from radiation and a net excess matter particles (n p e) emerge

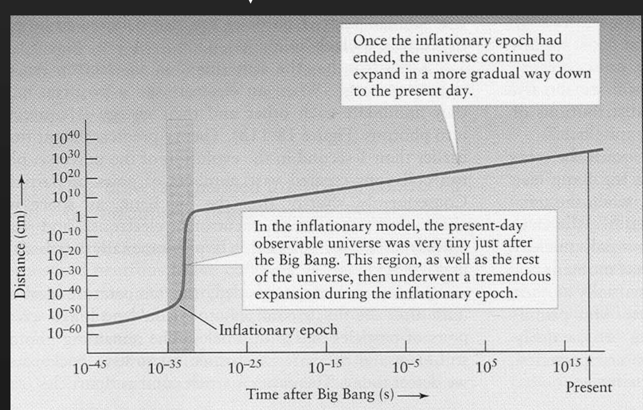
In GUT era, gravity freezes out while the strong and electroweak forces remain unified as a GUT force

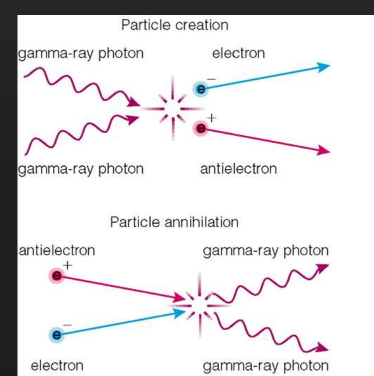
In the electroweak era, the strong force freezes out from electroweak forces. Inflation blows up the size of the Universe by a factor of 10^{25}

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

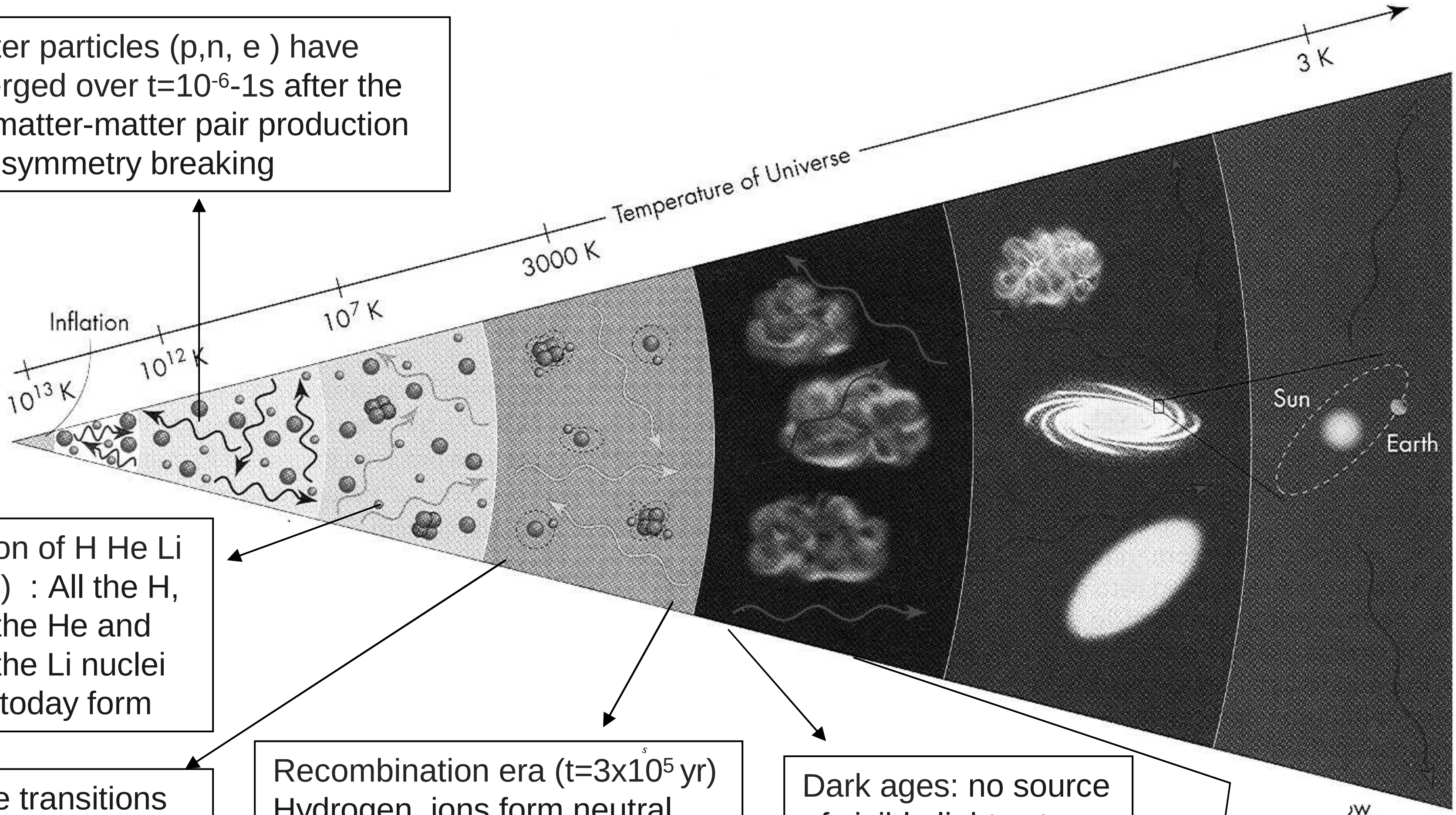






Overview: From the first second to the first billion years

Matter particles (p,n, e) have emerged over t=10^{-6}-1s after the antimatter-matter pair production and symmetry breaking



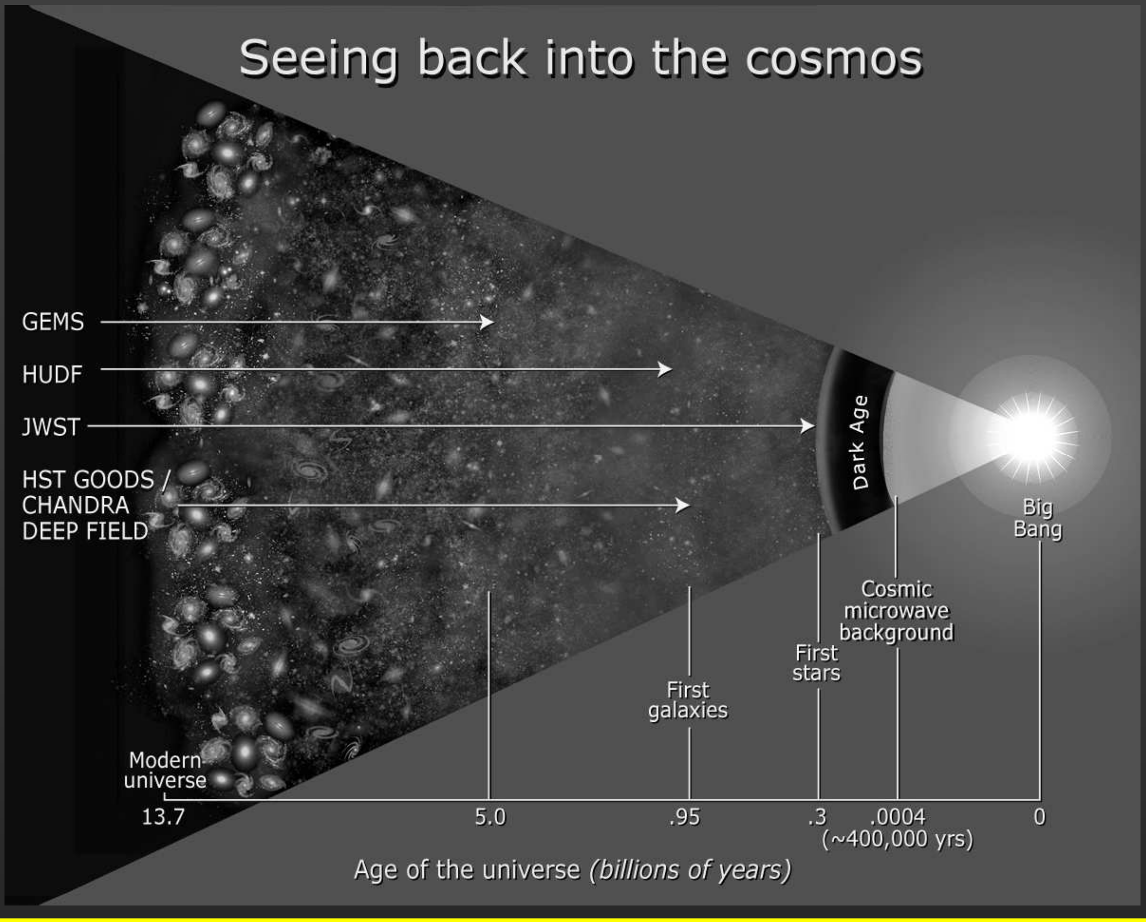
Formation of H He Li (t=3 min) : All the H, 90% of the He and 10% of the Li nuclei present today form

Universe transitions from radiation-dominated to matter-dominated (t=3×10^{4} yr)

Recombination era (t=3×10^{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 at mm wavelengths and T=2.7 K

Dark ages: no source of visible light yet.

First luminous objects form: stars at t=1-2 $\times10^{8}$ yr), then proto-galaxies (t=3-7$\times10^{8}$yr) These end the dark ages and their UV light also reionized neutral H back to protons and electrons (reionizaion era) .



From the First Billion years to 13.7 Billion years (today): Galalxies Evolve and Grow

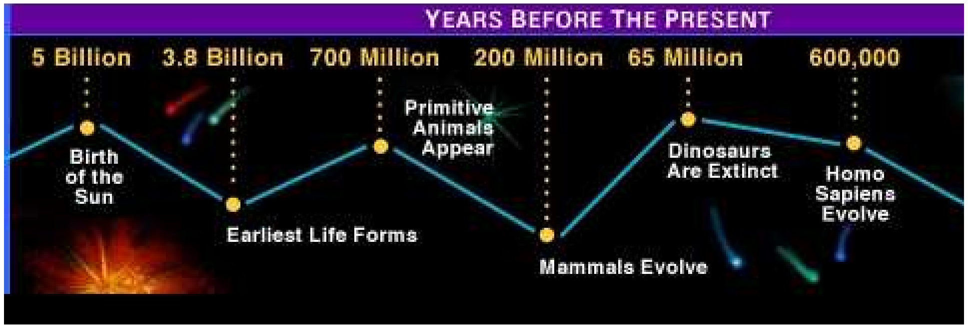
0.0	9	13.0	13.7	Lookback Time in Gyr
13.7 (100%)	4.7 (35%)	0.7 (5%)	0 (0%)	Age of Universe in Gyr and %

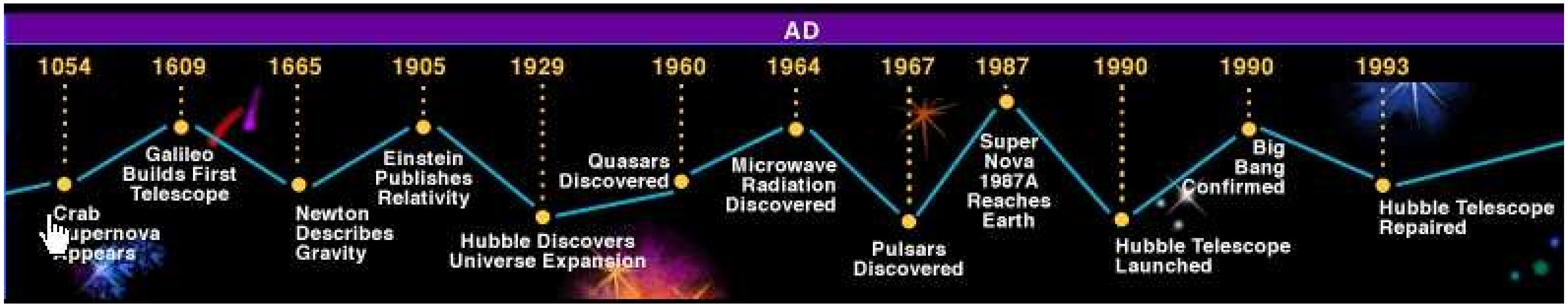
Today, mature galaxies on the Hubble sequence are in place

Over last 11 Gyr, the mass and structures (disks, bars, bulges) of galaxies grow. Gradually the frequency of major mergers drops and galaxies evolve more quietly

Chaotic period ~ 13.0 Gyr ago where first proto-galactic disks structures form and merge. The Universe is dominated by violent major mergers at early times.

The last Century





If we make an analogy where the age of our Universe (13.7 billion years) is represented by one year from Jan 1 to Dec 31, then humans only appeared in last hour of Dec 31 (600, 000 yrs ago), a mere blink of an eye away.

What you need to know for the exam from last section of course

-- Unifying Fundamental Forces as Electroweak, GUT, and 'Super' forces

-- The Beginning of Time: From 10-43 s to to the First Second
- The Planck era , GUT era , and Electroweak era.
- Inflation. (**)
- Production of matter-antimatter pairs from radiation : emergence of matter (**)

-- From the first second to the first billion years
- The formation of basic elements: (H, He, Li) nuclei (**)
- Universe transitions from radiation-dominated to matter dominated
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- The dark ages
- The formation of the first luminous objects: stars and proto-galaxies
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-- The cosmic microwave background : Its importance and how it is observed (**)
-- Evidence for the Big Bang model and for Inflation.
-- The critical density of the Universe and its fates

-- Perspectives: Our civilization

Lecture 38: Exam-Related Announcements

1) Exam is on Wed May 4. Bring a blue book
   The list of topics to review is online. Make sure you the in-class notes listed.

2) Review session is on Mon May 2 (today) from 6-8 pm in RLM 15.216. I will also review the solution to homework 8. Those who cannot attend can come to my office tomorrow (Tue) to review the solution set or ask questions.

NB: I will not accept any hwk 8, even for partial credit, after the review session tonight.

3) Extra credit (EC) based on class participation and telescope observing will be added to your exam grade. If your exam grade then exceeds 100 %, we will add the excess EC to your second worst homework. I will post the list of those w/ EC on the class website.

4) To get EC for telescope observing, I need your certification slip by Mon Apr 16.

5) No lecture on Friday May 6. Have a good end of semester and summer!

Lecture 38: Feedback Forms

1) Please fill in the 3 feedback forms for the Professor and two TAs. You have 15 min.

Professor = Shardha Jogee
Teaching assistant = Nick Sterling   Course id =46690
Teaching assistant = Nairn Baliber

Please fill in the forms for both TAS. If you have not interacted with a TA and therefore cannot fill in the multiple choice questions, then please indicate so in the comment section.

2) When you are done, please return the form under the appropriate grouping on the table. Do not leave the lecture room.

3) 2 student volunteers will monitor the reviews, put the feedback forms in the relevant envelopes, and call me back in after 15 min.

4) After the reviews: Hwk 7, Solution set for Hwk 7, Exam-related announcements