Lecture 37: Announcements

1) Final homework 8 due next Monday is posted on class website.

2) The list of topics to review for the exam is online.
   Go over this list and email me preferably by Sunday morning the topics you want me to review. The review session is on Monday in-class 12-1 and from 6-8 pm in RLM.

3) Exam is on Wed May 4. Bring a blue book

Understanding Galaxy Formation and Evolution

Understanding Galaxy Formation and Evolution

* Galaxies are the building blocks of the Universe.

* Today the Universe is 13.7 Gyr old and many massive mature galaxies (e.g., ellipticals, spirals) with well-defined components (e.g., disks, bars, bulges) are already in place.

* One of the main goals of astronomy is to answer questions such as :

  - When did galaxies first form?
  - How did they evolve into the types of galaxies we see today (ellipticals, spirals, dwarfs, Irr)?
  - How do these different galaxies relate to each other? Do some evolve into others ?
  - What was the role played by dark matter?

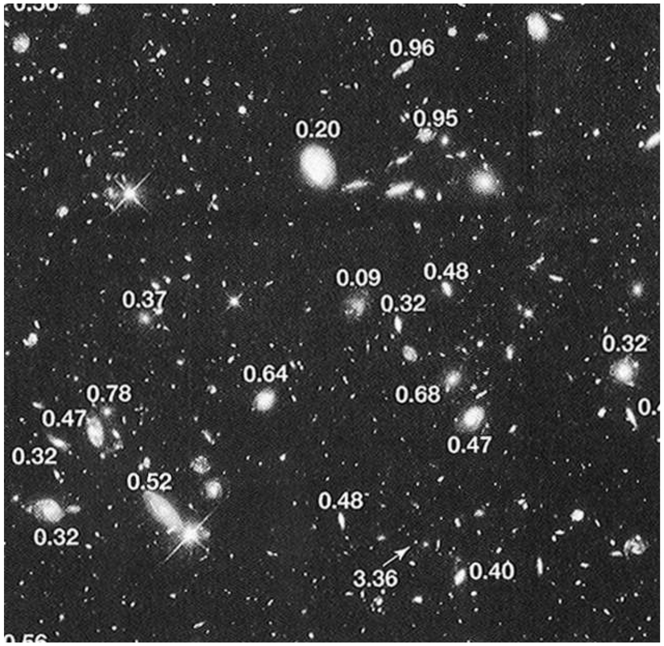
Understanding Galaxy Formation and Evolution

In order to map out the evolution of galaxies as a function of time

1) Need high resolution and sensitive images of galaxies found at different lookback times

à Why high resolution? To separate galaxies from each other and to separate the components of a galaxy (disk, bulge, bars, spiral arms) from each other. The angular size of a distant galaxy on the sky can be less than 0.5 arcsecond and hence we need Hubble Space Telescope images rather than ground-based images

à Why sensitive? To detect faint features, such as tidal tails, young disks



2) Need lookback time of each galaxy in the image

à We get lookback time t from distance d (d =c xt)

à We get distance d from Hubble's law if know recession speed v (v= Ho x d)

à We get recession speed by measuring Doppler redshift

3) Need to map galaxies distributed over larger areas in the sky

à Why large area? To get representative view of the Universe and capture its diversit

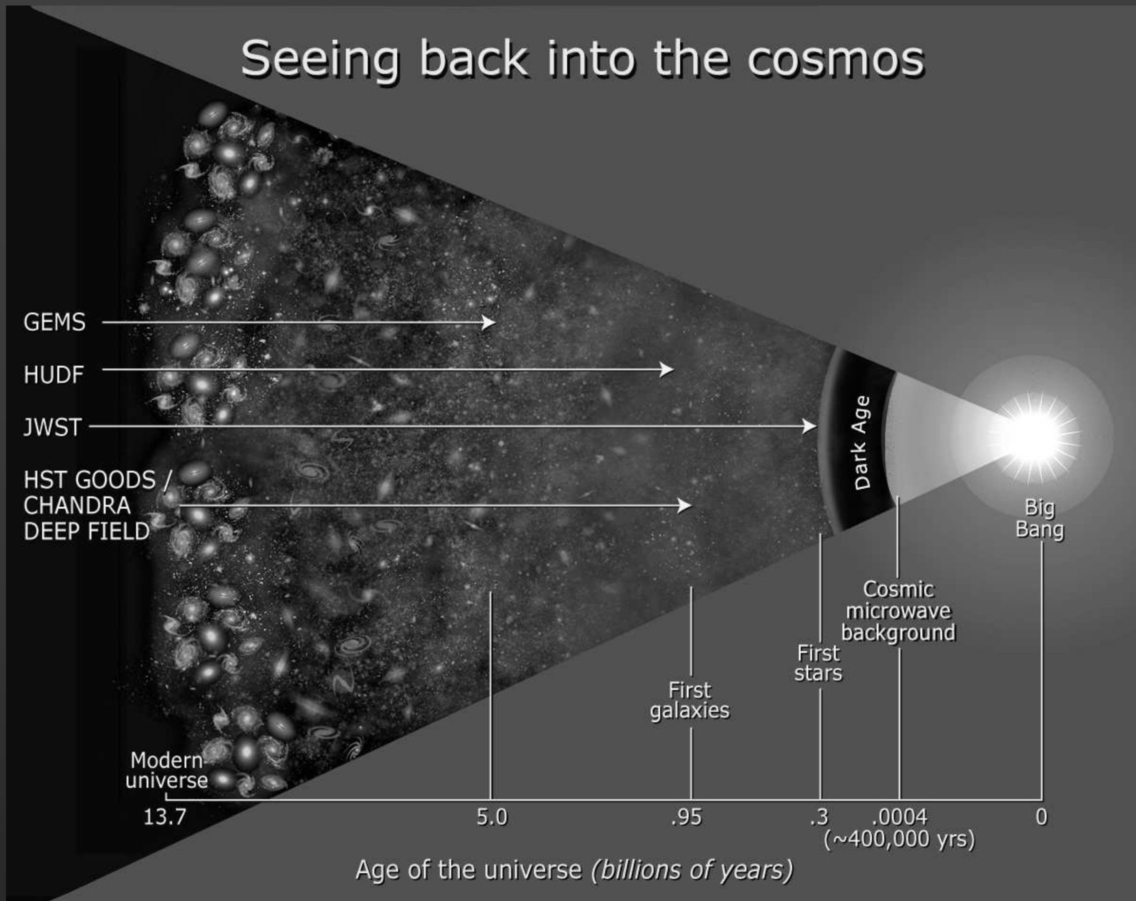
Understanding Galaxy Formation and Evolution

Early galaxy surveys,including the famous Hubble Deep Field (HDF) in 1996
used the old WFPC2 camera aboard HST .

The Advanced Camera for Surveys (ACS) installed in 2002 has a larger field of view ,
is more sensitive,and has higher spatial resolution than WFPC2 .

It has allowed several ground-breaking surveys in 2004

- à GEMS survey
- à HST Ultra Deep Field (HUDF)



Galaxy surveys trade off
<u>survey area vs survey depth</u>

à Larger area gives us a more representative view of the Universe
à Larger depth (exposure time) detects fainter distant galaxies and looks further back in time

GEMS = Galaxy Evolution from Morphology and SEDS . Widest area survey, looks back ~9 Gyr

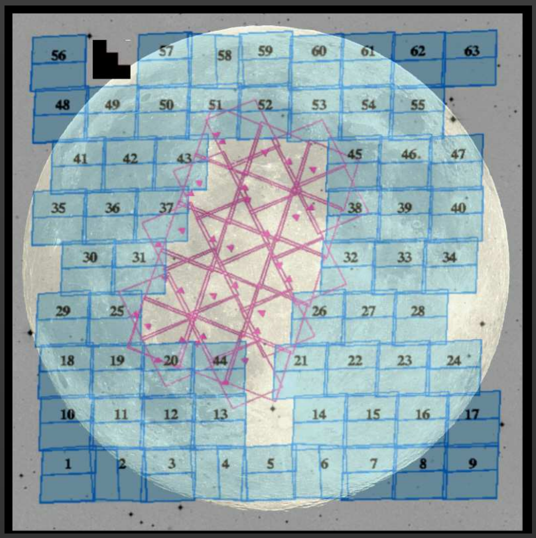
HUDF = HST Ultra Deep Field. Small-area but deepest survey. Looks back ~13 Gyr.

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 %

GEMS allows to look back up in time up to 9 Gyr ago. By covering a very large area, GEMS captures ~9,000 galaxies and gives us a representative view of the diverse galaxies present over this period

HUDF allows us to look back in time up to ~ 13.0 Gyr ago. But it covers a small area, 80 times smaller than that of GEMS

GEMS (Galaxy Evolution from Morphology and SEDS)



30’

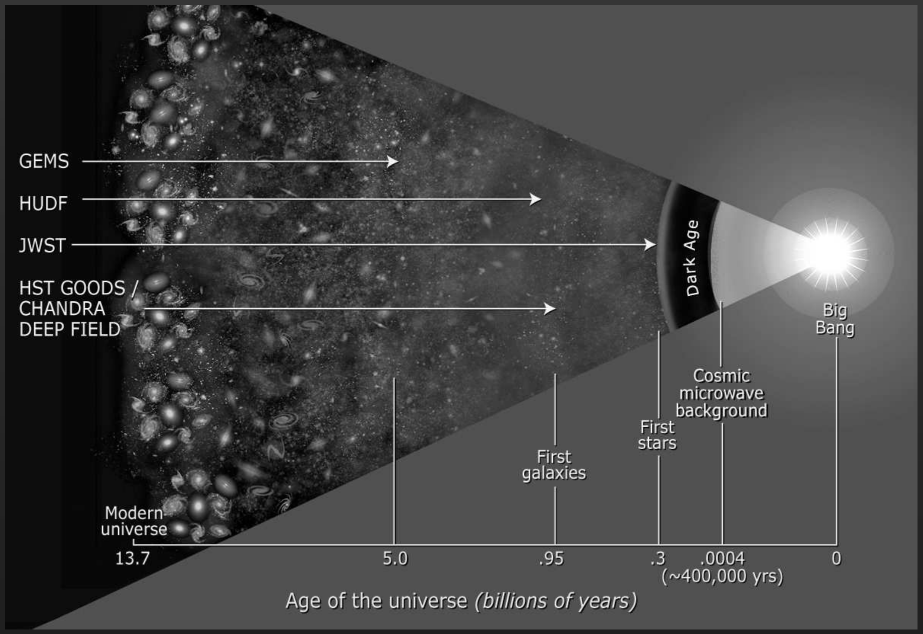
GEMS is largest area 2-filter imaging survey with HST

GEMS area = 30’x30’ or size of full moon on sky

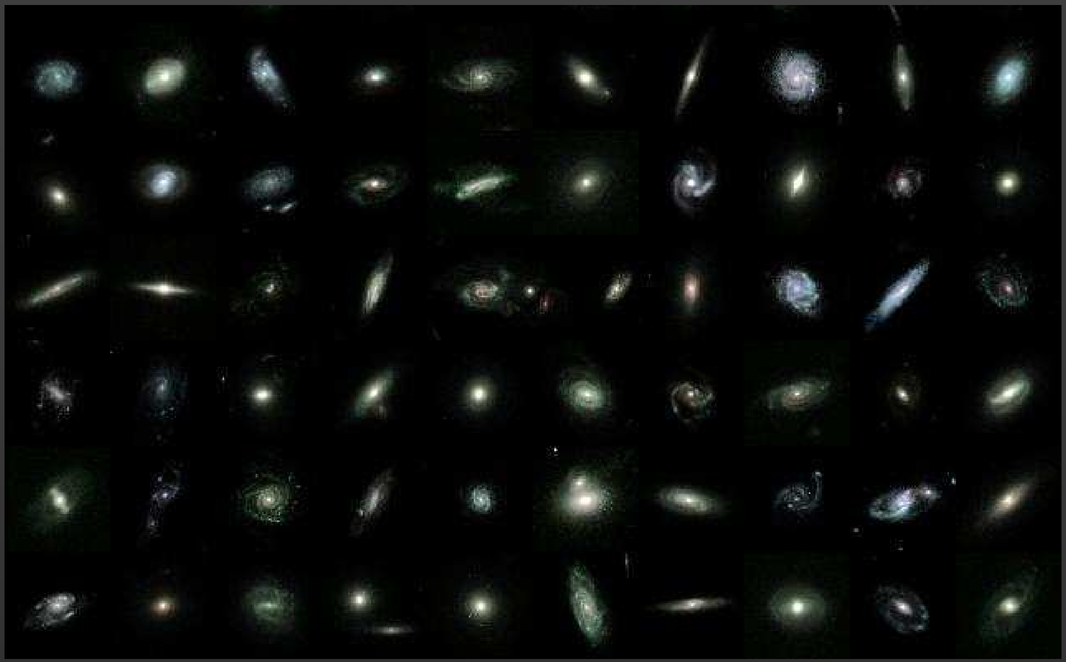
= 120 x area of Hubble Deep Field (HDF) carried out in 996

= 78 x area of Hubble Ultra Deep Field (HUDF) carried out in 2004

GEMS has accurate redshifts for ~9000 galaxies. This gives us distance and hence lookback time of each galaxy

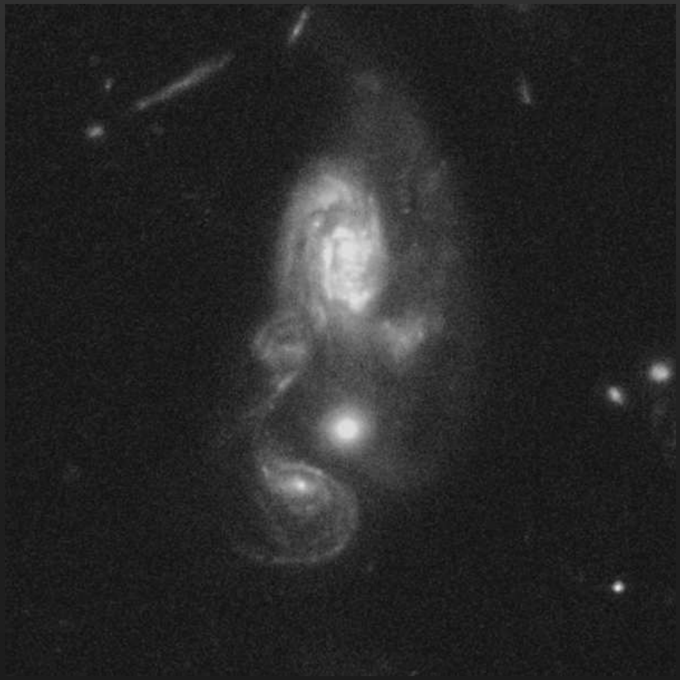


The GEMS survey maps 9000 galaxies over lookback times in the range 2-9 billion years, corresponding to epochs when the Universe was 11.7 to 4.7 Gyr old

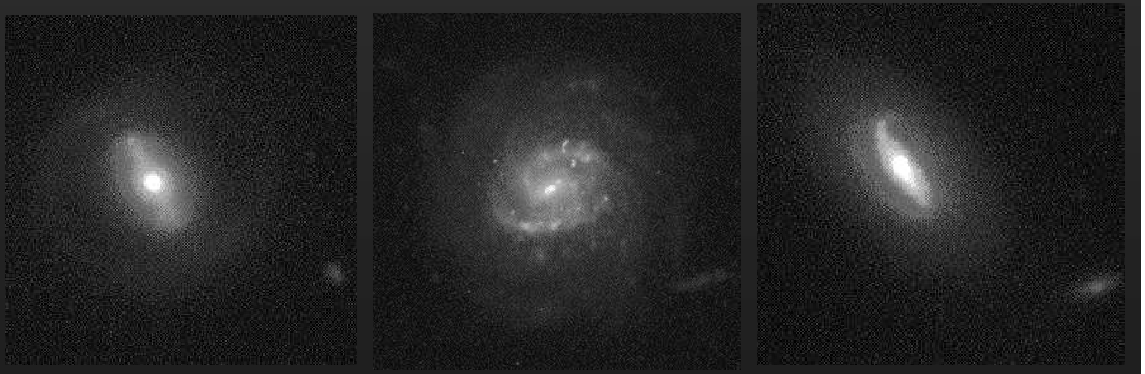


Excerpts from GEMS survey

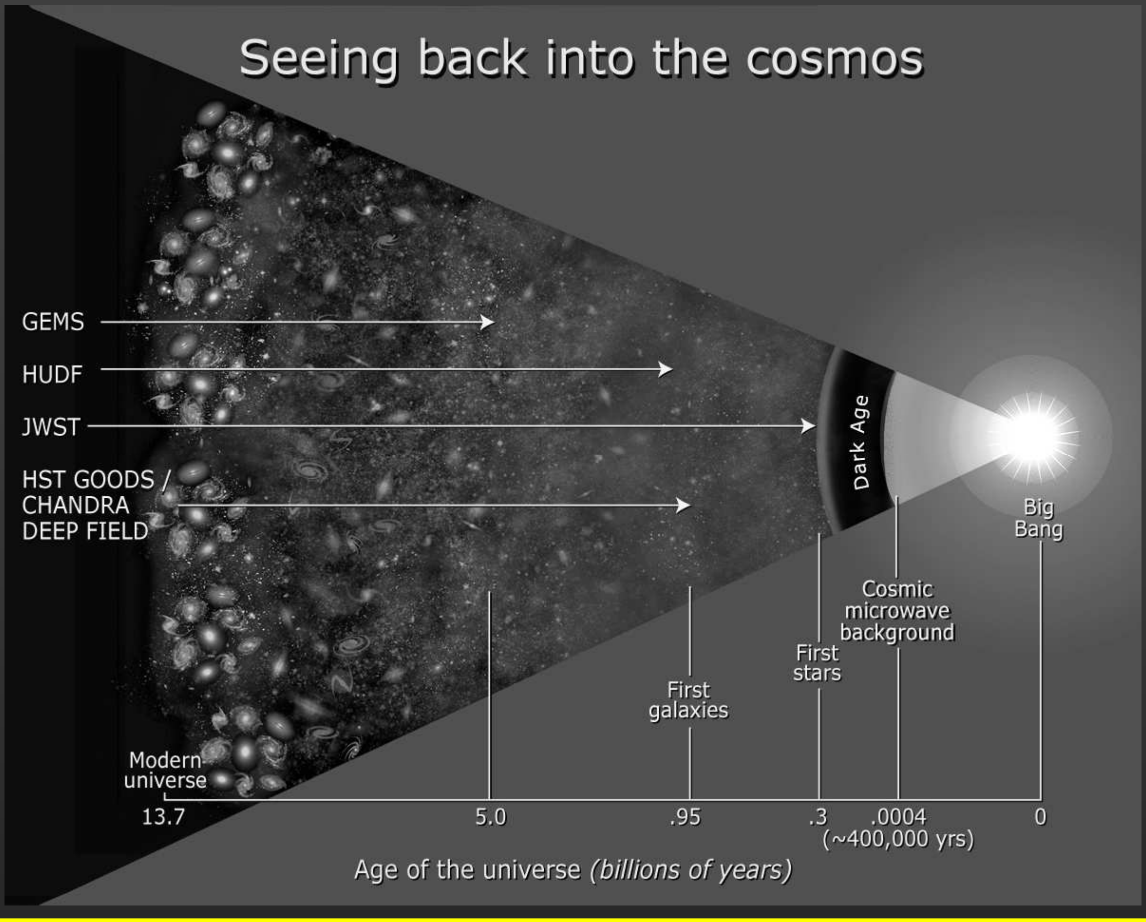
- à Album of galaxies in ‘their thirties’
- à Diversity of galaxies 9 Gyr ago, when Universe was only 30% of its present age!



Goals : Study impact of tidal interactions/mergers and bars on galaxy evolution



Interacting galaxies and barred spiral galaxies when the Universe was 1/2 to 1/3 of its present age (Jogee et al. 2004 and the GEMS collaboration)



What have we learnt from different galaxy surveys?

GEMS = Galaxy Evolution from Morphology and SEDS . Widest area survey, looks back ~9 Gyr

HUDF = HST Ultra Deep Field. Small-area but deepest survey. Looks back ~13 Gyr

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 Universe: How it all Began and Possible Fates

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
- 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

Unifying Fundamental Forces as Electroweak, GUT, and Superforces

Unifying Fundamental Forces as Electroweak, GUT, and Superforces

There are 4 fundamental forces in nature.
Force of gravity: acts on matter
Electromagnetic (EM) force: acts on charged and magnetised bodies
Weak force: acts on neutrinos
Strong force: glues protons and neutrons in nuclei together.

Unifying two or more forces means combining the forces into one single force

In the present-day, the four forces are decoupled (they act on different scales and make different predictions). Weak and strong forces only act on small scales comparable to nuclei, while EM and gravity act on long-ranges.

At earlier times, the Universe was much smaller, denser and hotter, such that all four forces are important and act on similarly small scales. To deal with the early Universe we therefore need theories that can unify as many of these four forces as possible.

Unifying Fundamental Forces as Electroweak, GUT, and Superforces

Can we unify these 4 fundamental forces?

Force of gravity   Electromagnetic (EM) force   Weak force   Strong force

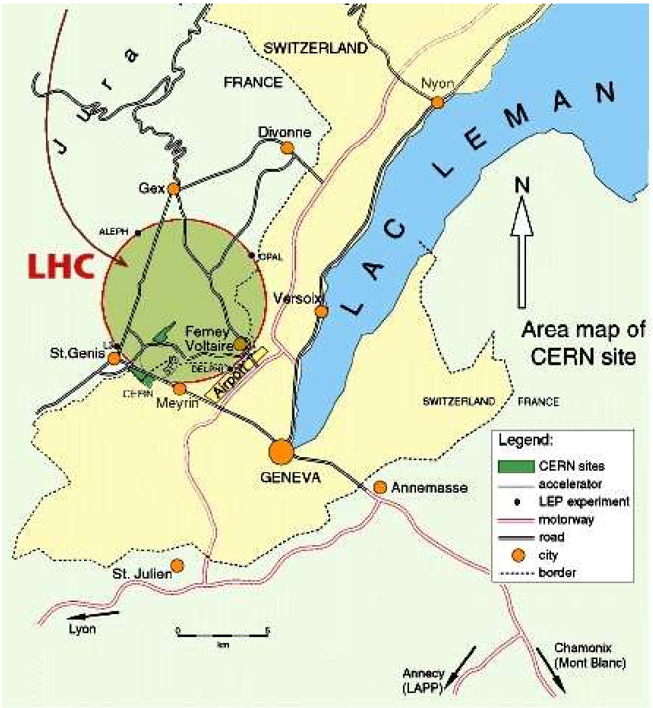
Electroweak theory (verified experimentally) unfiies the EM and weak force as the electroweak force.

Grand Unified Theories (GUTs) unify the strong and electroweak forces into a GUT force.

There is not yet a successful theory that can unify all the four forces, including gravity, to form a super force. One of the most fundamental goals in physics is to find such a super force

Experimental Tests of Electroweak and GUT theories?

The electroweak theory unifies the EM and weak forces as the electroweak force.   It was proposed by Glashow, Weinberg (at UT Austin) and Salam in 1960s. They got the Nobel Prize in Physics in 1979 after the theory was experimentally verified in 1970 and later at CERN in 1983. To test the theory (by detecting weak bosons), the CERN accelerator had to accelerate particles to huge energies (10^{11} ev or T ~ 10^{15} K), similar to those in Early Universe (at the end of the electroweak era, t=10^{-10} s) .



The CERN Large Hadron Collider (LHC), in 2007, will collides protons and ions at energies of (10^{12} eV or T ~ 10^{16} K) and probe slightly earlier epochs (middle of electroweak era). Its goal is to detect dark matter candidates called WIMPS.

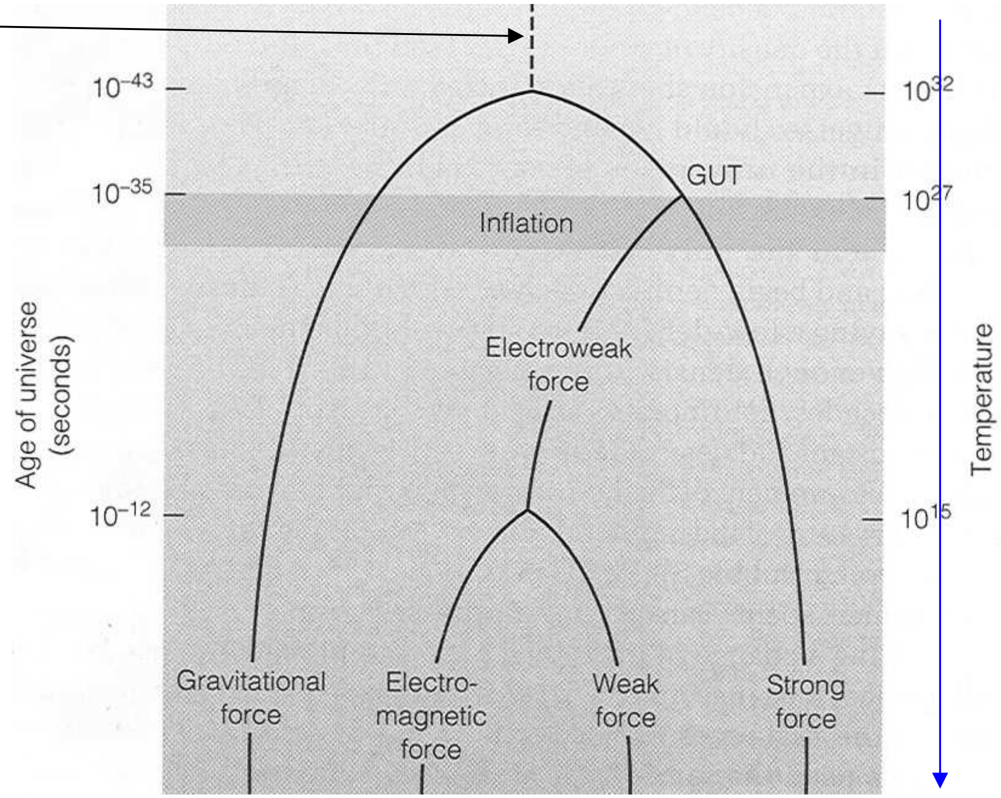
Grand Unified Theories (GUTs) claim to unify the strong and electroweak force . They cannot be verified experiementally any time soon as this requires huge energies (10^{24} eV or T ~ 10^{29} K)

The Beginning of Time: From 10^{-43} s to to the First Second

The Beginning of Time: From 10^{-43} s to to the First Second

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

Before 10^{-43} s (the Planck time), the laws of physics as we know them cannot be used to make any predictions. We need a theory or framework that unifies the four forces into one 'super force'.



TIME

Why do we need a super force only at early times $t < 10^{-43}$ s ?

à Whole Universe is compressed into very small scales like a black hole at early times

à General relativity (depends on gravity) says light cannot escape the Schwarzchild radius of the black hole

à But quantum mechanics (depends on other 3 forces) tells us a photon, when confined to very small scales comparale to the Planck length, can escape this energy barrier via quantum mechanical tunelling effects

à To avoid this contradiction need super force.

The Beginning of Time: From 10^{-43} s to to the First Second

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

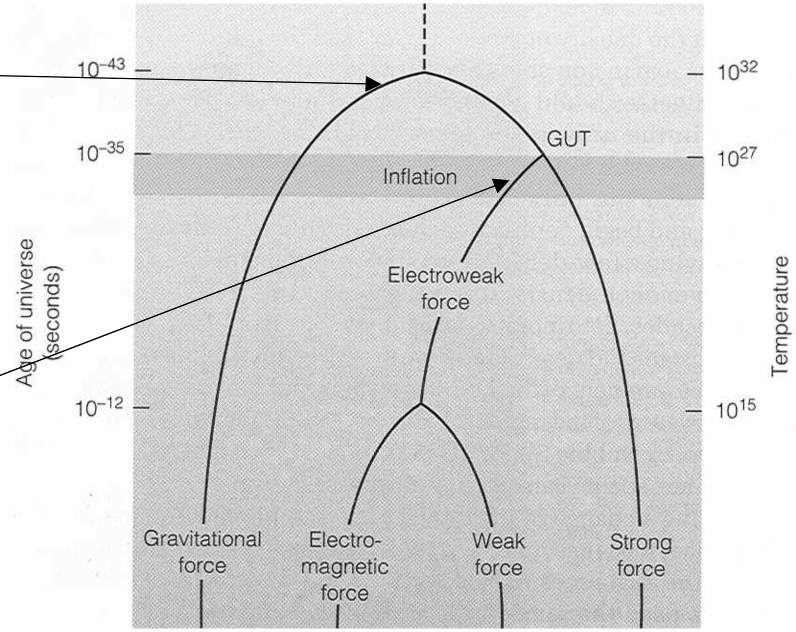
The force of gravity freezes out (decouples, separates) from the electroweak and strong forces which remain unified as a ‘GUT force

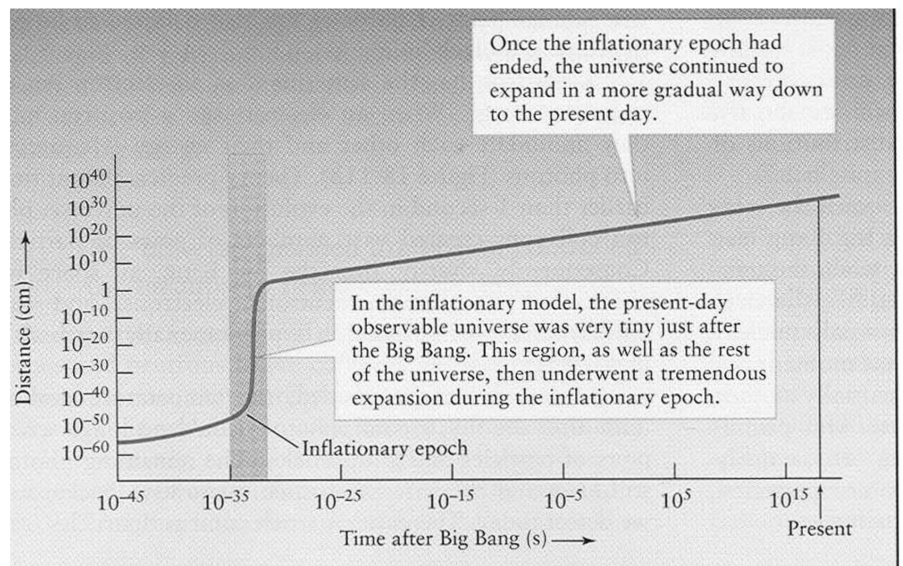
Electroweak era ($10^{-38}10^{-10}$ s)

The strong force freezes out from the electroweak forces which remain unified. This may have released lots of energy.

Inflation kicks in rom from 10^{-35} to 10^{-32} s and expands the Universe by a factor of $10^{25.}$ This would blow up a dot on this viewgraph to the size of the local group of galaxies (5 mlillion light years) !

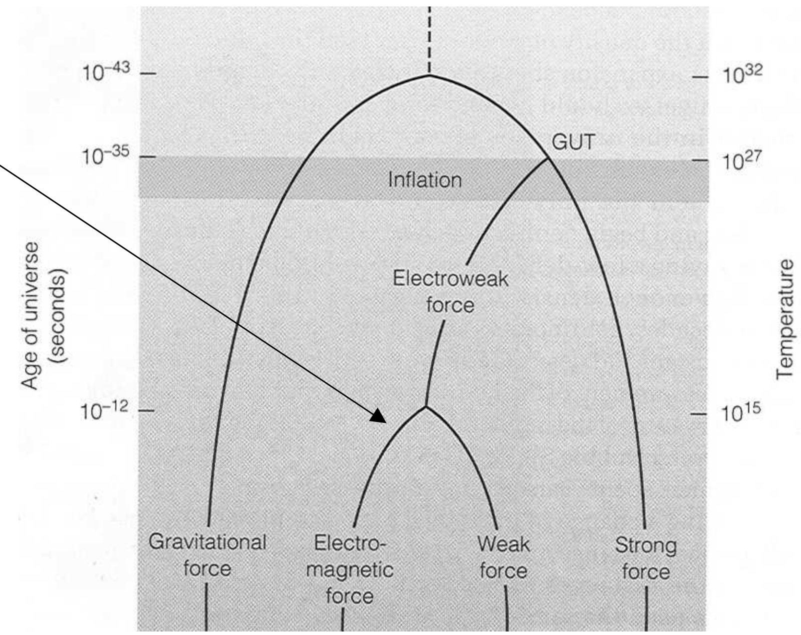
All four forces decouple at the end of the electroweak era.





Q: Do we have evidence for the electroweak era or for inflation ?

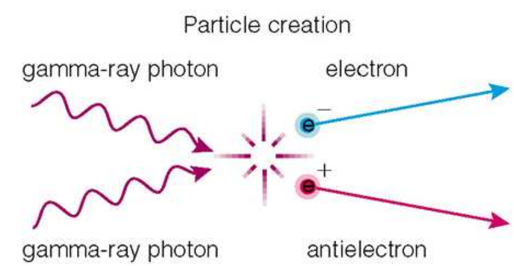
The Beginning of Time: From 10^{-43} s to to the First Second



Production of matter-antimatter pairs from radiation and the dominance of matter in our Universe (10^{-10}s - 1m) :

Einstein's principle,embodied in $E=mc^2$, states that energy and mass are equivalent. Thus, radiation can convert into mass and vice-versa.

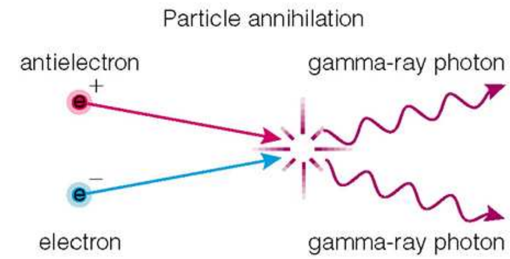
Early on, photons (radiation were hot enough that they can produce matter-antimatter pairs. Each pair has 2 particles that are made of matter and antimatter, and have opposite charges



The hotter/more energetic the photon, the more massive will be the matter-antimatter pair :

At $T>10^{13}$ K: photons à proton, anti-proton (p+,p-)
photons à neutron, anti-neutron

At $T>10^{9}$ K: photons à electron, anti-electron (e-,e+)

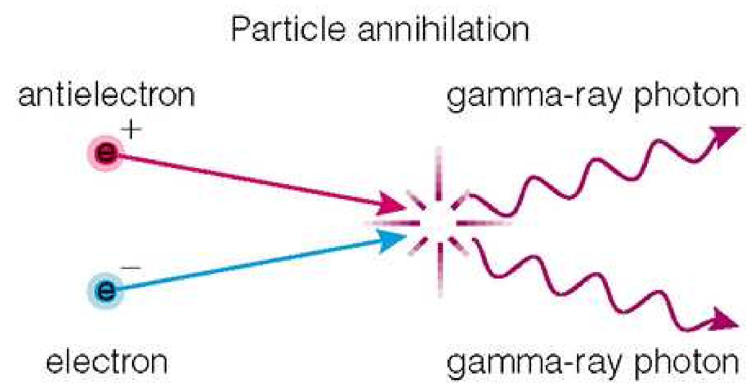


The matter-antimatter pair can anihilate each other to give back a photon.

The Beginning of Time: From 10^{-43} s to to the First Second

As the Universe expands, its temperature T drops, and photons no longer have enough energy to form new matter-antimatter pairs.

The existing matter-antimatter pairs anihilate to form photons. If the number of antimatter and matter particles had been exactly equal, then complete matter anihilation would have occurred by the time Universe was 1 minute old. The Universe would have contained only photons (radiation), but no matter particles, and none of us would have existed!



Due to symmetry-breaking in the early Universe

à there was a slight excess of matter over antimatter

à for every 10^9 matter-antimatter pairs that anihilated into 10^9 photons, there was one matter particle left over. We owe our existence to this symmetry breaking

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

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

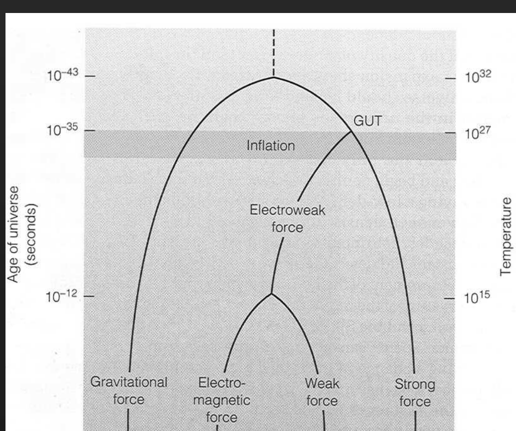
10^{-10} s - 1 s
Matter-antimatter pairs form from radiation and a net excess matter particles (n p e) emerge

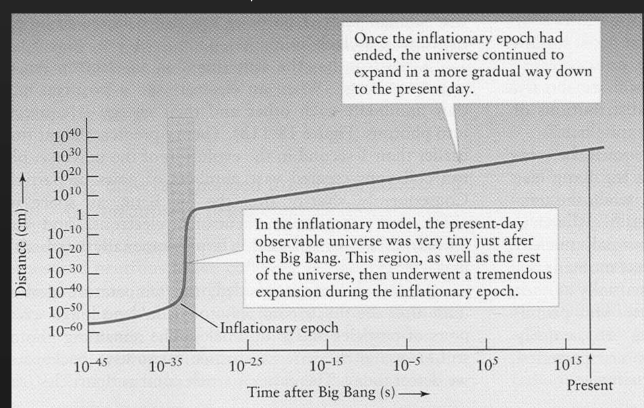
In GUT era, gravity freezes out while the strong and electroweak forces remain unified as a GUT force

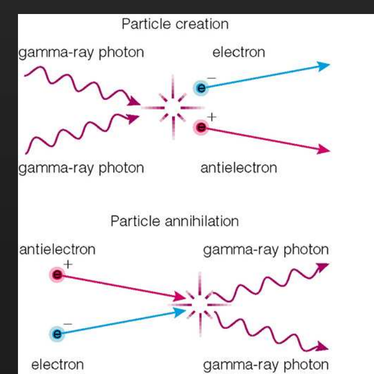
In the electroweak era, the strong force freezes out from electroweak forces. Inflation blows up the size of the Universe by a factor of 10^{25}

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







From The First Second to the First Billion Years

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

Proton (hydrogen nuclei) already existed at $t=10^{-6}$ s

Between t=1s and 3 min, protons and neutrons collide to form most of the helium nuclei and 10% of the lithium nuclei that exist today

After t =3 min, no more fusion occurs. Why?

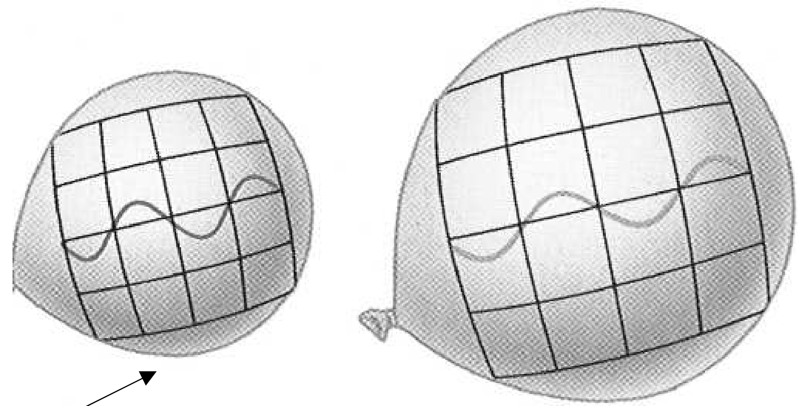
à Universe is expanding continually and temperaure T is dropping
à Beyond t=3 min, T is too low to allow fusion. The kinetic energy of the positively charged protons must be large in order for them to overcome their electric force of repulsion

- Where is the rest of the lithium and all of heavier elements like C O Ne S Mg SI Fe made?

Universe transitions from radiation-dominated to matter dominated

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

Photons (radiation) have larger energy density and exert larger gravitational forces than matter.



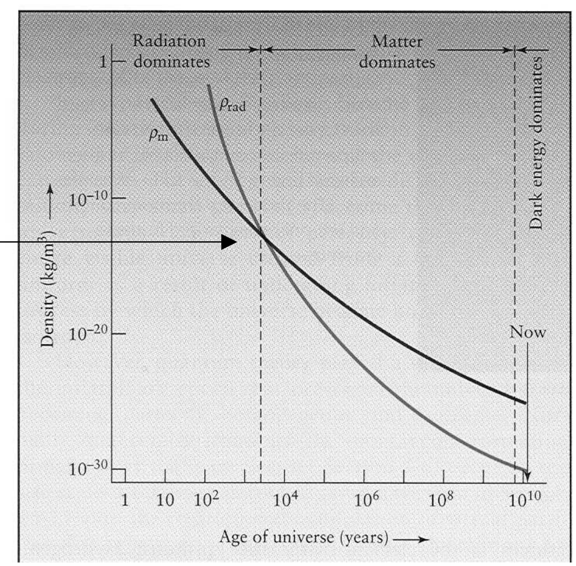
Transition to matter-dominated era ($t > 3x10^4$ yr)

As Universe expands, the energy in both photons and matter drops due to different reasons:

à photon λ stretches due to cosmological redshift 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; thus, soon the Universe transitions to being matter-dominated. Matter then has larger energy density and exert larger gravitational effects than photons (radiation)

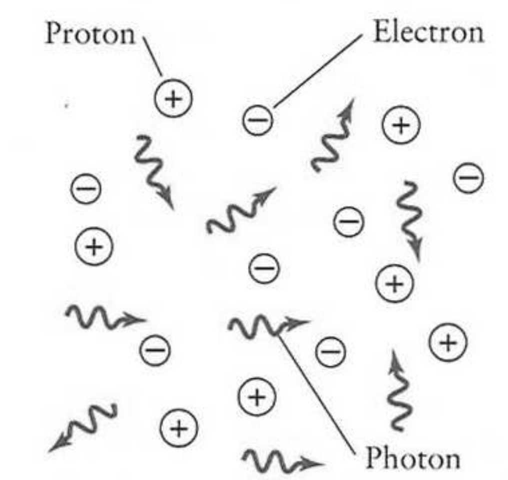


Matter/gas then responds to gravitational forces and forms clumps. These clumps are the seed from which larger structures such as stars and proto-galaxies wil come from

Recombination epoch: Universe transitions from opaque to transparent

Before recombination (t< 3x10^5 yr)

- Temperature high enough to ionize all neutral H atoms into protons and electron (p+,,e-).
- Photons collide frequently with e- and get trapped in the plasma. Therefore, the Universe is opaque.
- Matter and radiation are coupled and have the same temperature



After recombination (t > 3x10^5 yr)

- (p+,e-) combine into neutral H atoms as the temperature is too low to ionise neutral H
- Photons collide only rarely with neutral atoms, and they can now travel freely. The Universe becomes transparent for the first time.
- The photons released at recombination are the oldest photons we can ever see. They are emitted with $\lambda=10^{-6}$ m (T=3000 K) and get redshifted by today to form the CMB at $\lambda=10^{-3}$ m (T=2.7 K)
- Matter and radiation are decoupled and have different temperatures