Astro 301/ Fall 2005

(48310)

Introduction to Astronomy

Instructor: Professor Shardha Jogee

TAs: David Fisher, Donghui Jeong, and Miranda Nordhaus

Lecture 25 = Tu Nov 29
Lecture 26 = Th Dec 1

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

Lecture 25: Announcements

1) Exam 2

- If you did not pick up Exam 2 on Tue, please pick it up from TA Donghui
- Final score from part 1 and part 2 is online… well done !
  A : 46 % B: 25% C:19% D:6% F:2%

2) The current total score including [exams + homeworks + quiz] is

A: 40% B: 28% C:23% D:6% F:4%

Still upcoming: homeworks 5+6; Quiz 6; Exam 3

3) Will there be a make-up quiz ?

Rather than give a make-up quiz to a few of you, I will give all of you a chance to improve your quiz grade

Iniital quiz policy: 6 quizzes are given and we drop the worst one

New quiz policy : 6 quizzes are given and we drop the two worst ones .
No make-up quiz

Lecture 25: Announcements

-- Schedule for next week

Th Dec 1: Homework 5 is due back. We will give out homework 6

Quiz 6:   Based on lectures 22 to 27 (last) + on Chap 23. On Tu Dec 6 or Th Dec 8

Exam 3: Based on lectures 22 to 27 (last) + on Chapter 23. On Th Dec 8.
Format = only written questions, no multiple choice

-- Help/Review Session for Exam 3 and Hwk 6:

- on Tue Dec 6 in class
- on Tue De 6: from 5 to 6 pm   or 6 to 7 pm --- which one?

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

<u>Galaxies: An Amazing Diversity</u>

(also covered in Lec 2+3)

Galaxy: Collection of few times (10^8 to 10^{12}) stars orbiting a common center and bound by gravity. Made of gas, stars, dust, dark matter.

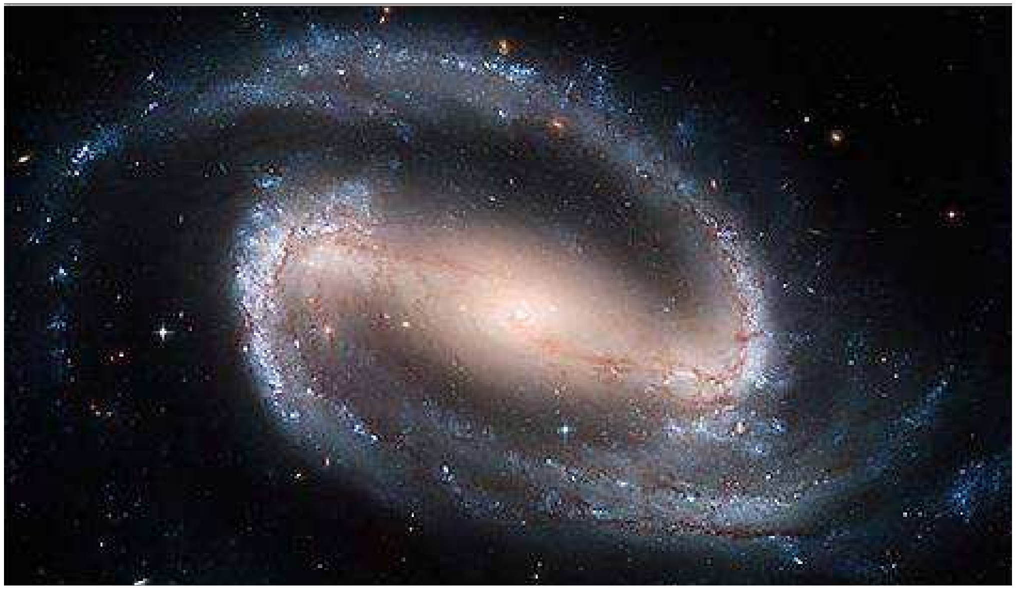
There are many types of galaxies and they can be classfiied according to different criteria. If we classify them according to their structure, sizes, total amounts of gas and star formation, we get the following types:

- à Spiral galaxies, Elliptical galaxies,
- à Irregular galaxies, Dwarf galaxies,
- à Peculiar/Interacting galalxies

Spiral Galaxies

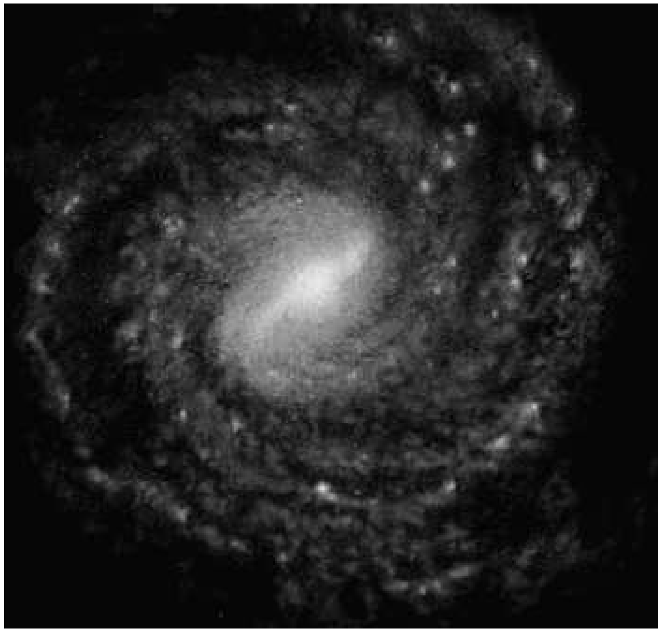
1) They have a disk component (shaped like a saucer). In the center of the disk, there is sometimes a spheroidal bulge (a melon-shaped component).
2) They contain up to 10^{12} stars and lots of gas, dust, ongoing star formation .
3) Most spiral galaxies are barred, meaning that their disk contains an elongated stellar feature called a bar. Bars carry gas from the disk to the center of a spiral galaxy, thus influencing its evolution. Our Milky Way is a barred spiral.

Unbarred spiral (SAab) NGC 4622



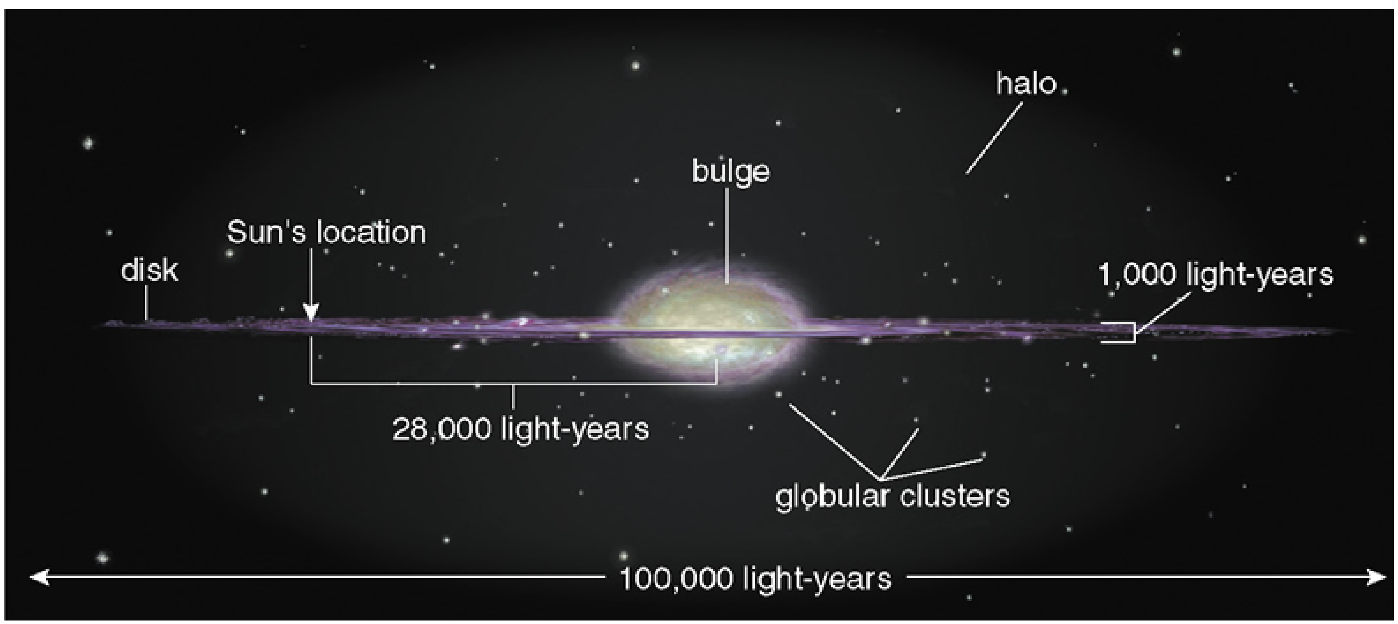
Strongly Barred spiral (SBbc) NGC 1300

Milky Way = a barred spiral galaxy, hosting our Sun and Solar system



Face-on view
(Artist's conception)

Edge-on view :
Actual infrared image
from COBE satellite



Edge-on view
(Artist's conception)

Elliptical Galaxies

1) They are spheroidal systems (shaped like a water melon) and do not have extended disk components. Contain up to up to 10^{12} stars.
2) They have a smooth appearance as they are mostly made of old stars, and have little gas, dust, and recent star formation

Giant elliptical M87

Irregular Galaxies

1) They have irregular, peculiar morphologies in terms of gas, dust and star formation.
2) They are low mass gas-rich systems.Typically contain up to a few x 10^9 stars
3) Two of the three closest galaxy neighbors of the Milky Way, the LMC and SMC, are Irr galaxies

LMC; Irr; 30,000 ly across

SMC; Irr ;18,000 ly across

Dwarf Galaxies

1) They are much smaller than spirals or ellipticals, but may be comparable to Irr galaxies. Their optical radius is typically less than 15,000 lyr while that of spirals is greater than 50,000 lyr.

2) They typically contain up to a few x 10^{8} stars

3) They come in two types : dwarf ellipticals and dwarf irregulars

Leo I, dwarf elliptical

Galaxy Interactions and Cosmic Fireworks!

(also covered in Lec 4+5)

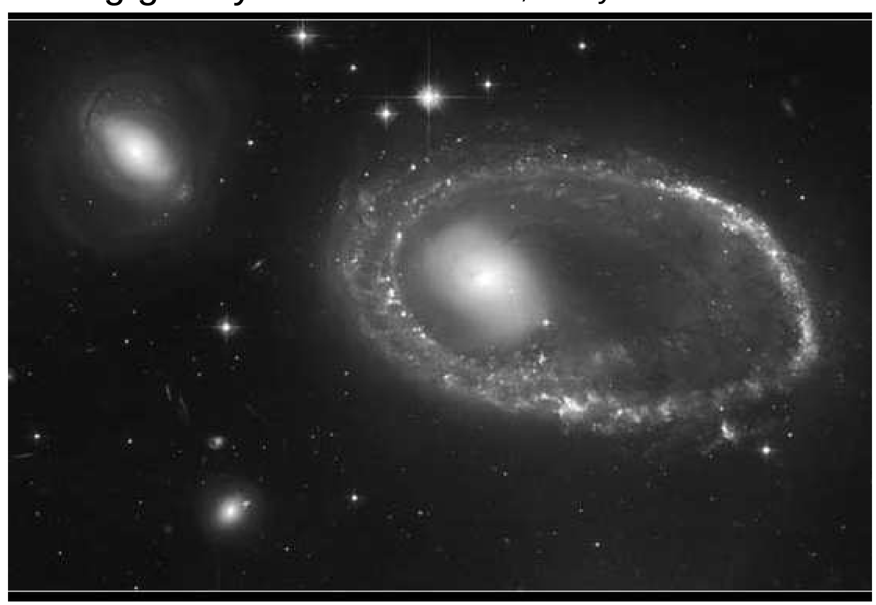
Peculiar/Interacting Galaxies

Galaxies which look peculiar and distorted. These distortions are often caused by interactions with other galaxies.

Polar ring galaxyNGC 4650

Cartwheel galaxy
Head-on collision

Ring galaxy AM 0644-741 50,000 ly across

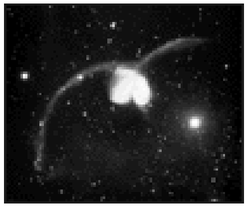


Major vs Minor Mergers

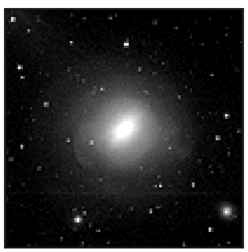
See in-class notes

The Toomre Sequence


Credit: Vera Rubin (CIW/DTM)
NGC 5426/5427


Credit: Francois Schweizer (CIW/DTM)
NGC 4038/4039


Credit: Francois Schweizer (CIW/DTM)
NGC 7252


Credit: Francois Schweizer (CIW/DTM)
NGC 3610


Credit: Digitized Sky Survey (AURA, Inc.)

When 2 spirals of similar mass merge:

1) Gravitational forces fling out gas and stars into two extended tails. The similar length of the two tails ‘reflects’ the rotation of the two disk galaxies of similar masses.

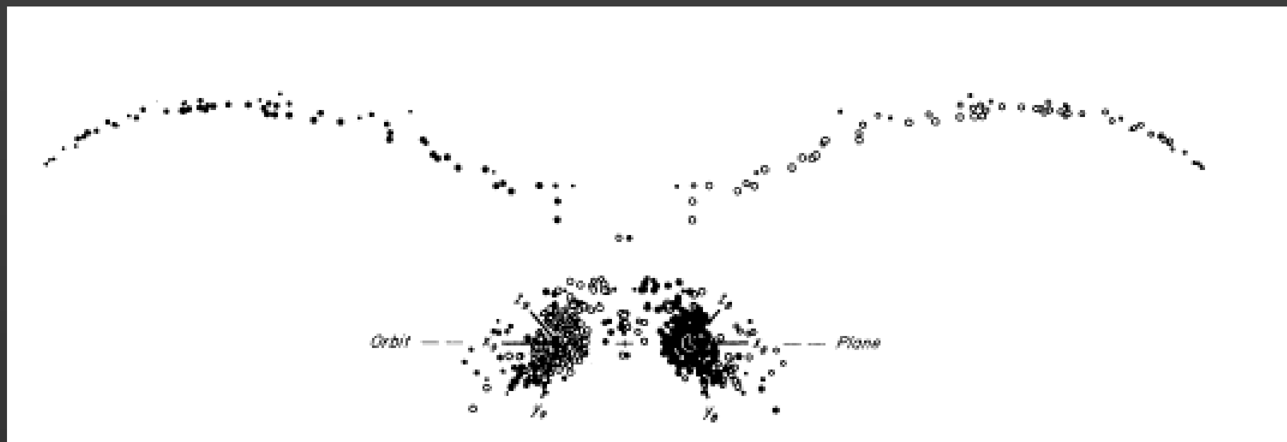
2) The stars in the tails fade away, while gas in the tails falls back into the galaxies to form stars.

3) The disks are destroyed via a process called violent relaxation. The stars in the two spirals “lose memory” of their disk distributions and redistribute into a spheroidal (water-melon) configuration

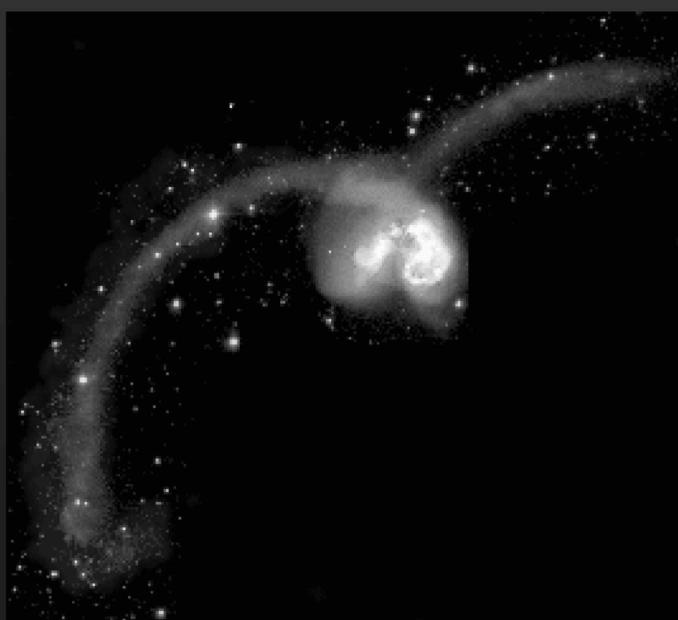
4) End-product is an elliptical galaxy

What is the Toomre sequence? See in-class notes

Major Merger of 2 spirals

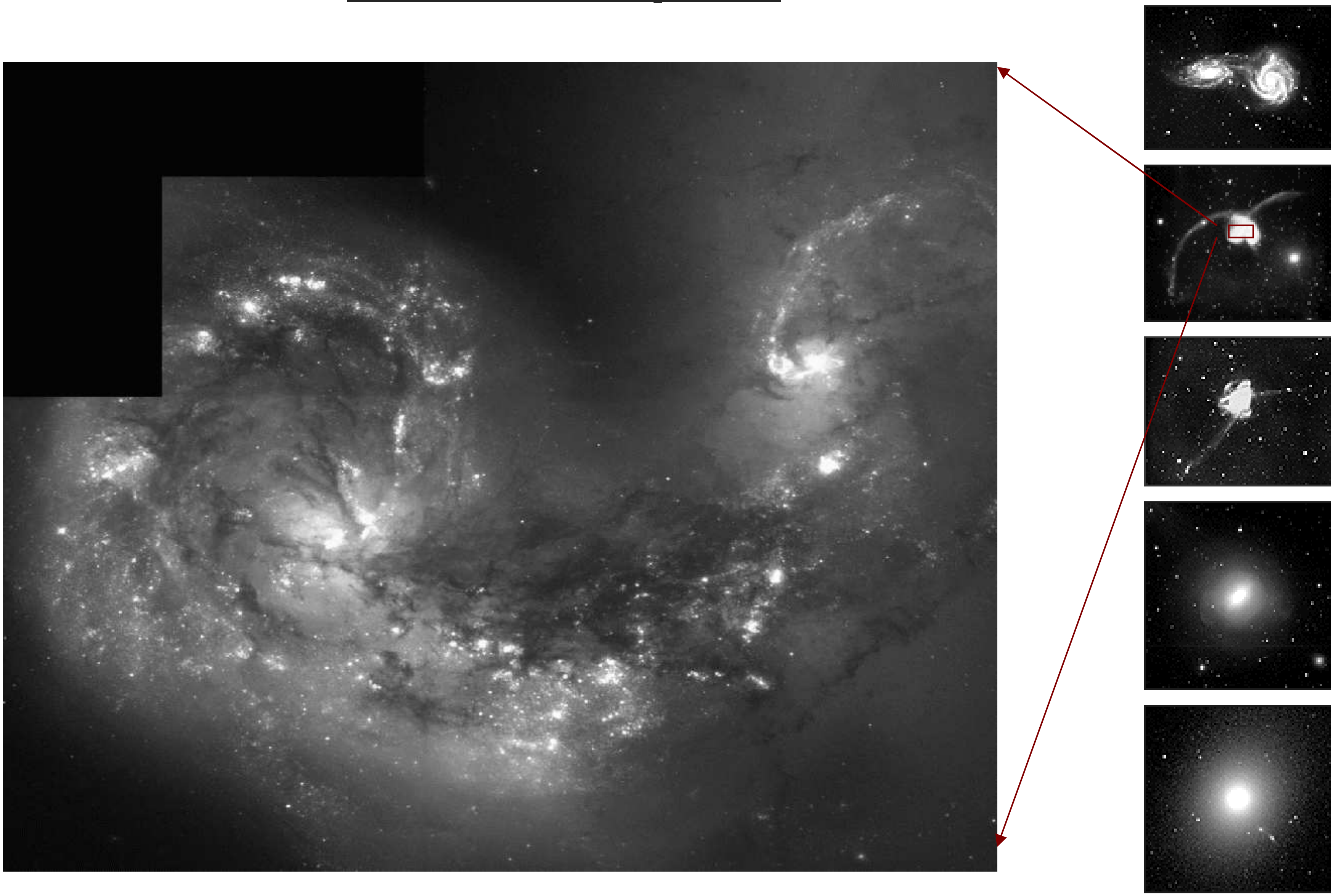


Computer simulation of 'Galactic bridges and tail' by Toomre & Toomre 1972



Observation of stars (green) and HI gas (blue) in NGC 4038/39 called The Antennae galaxy.
(J. Hibbard)

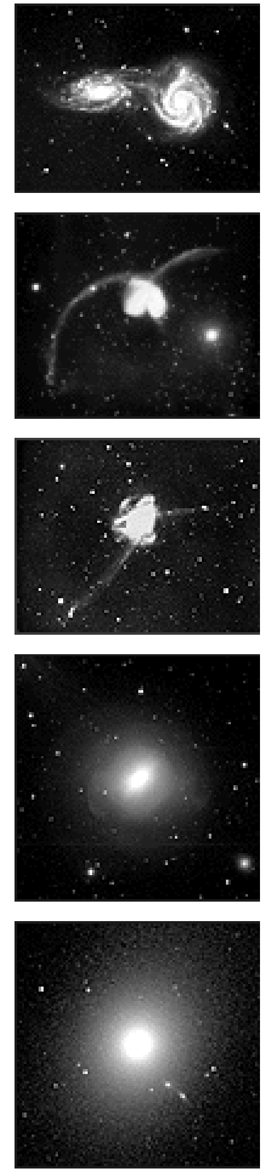
The Toomre Sequence



The Antennae system is part of the Toomre sequence on RHS

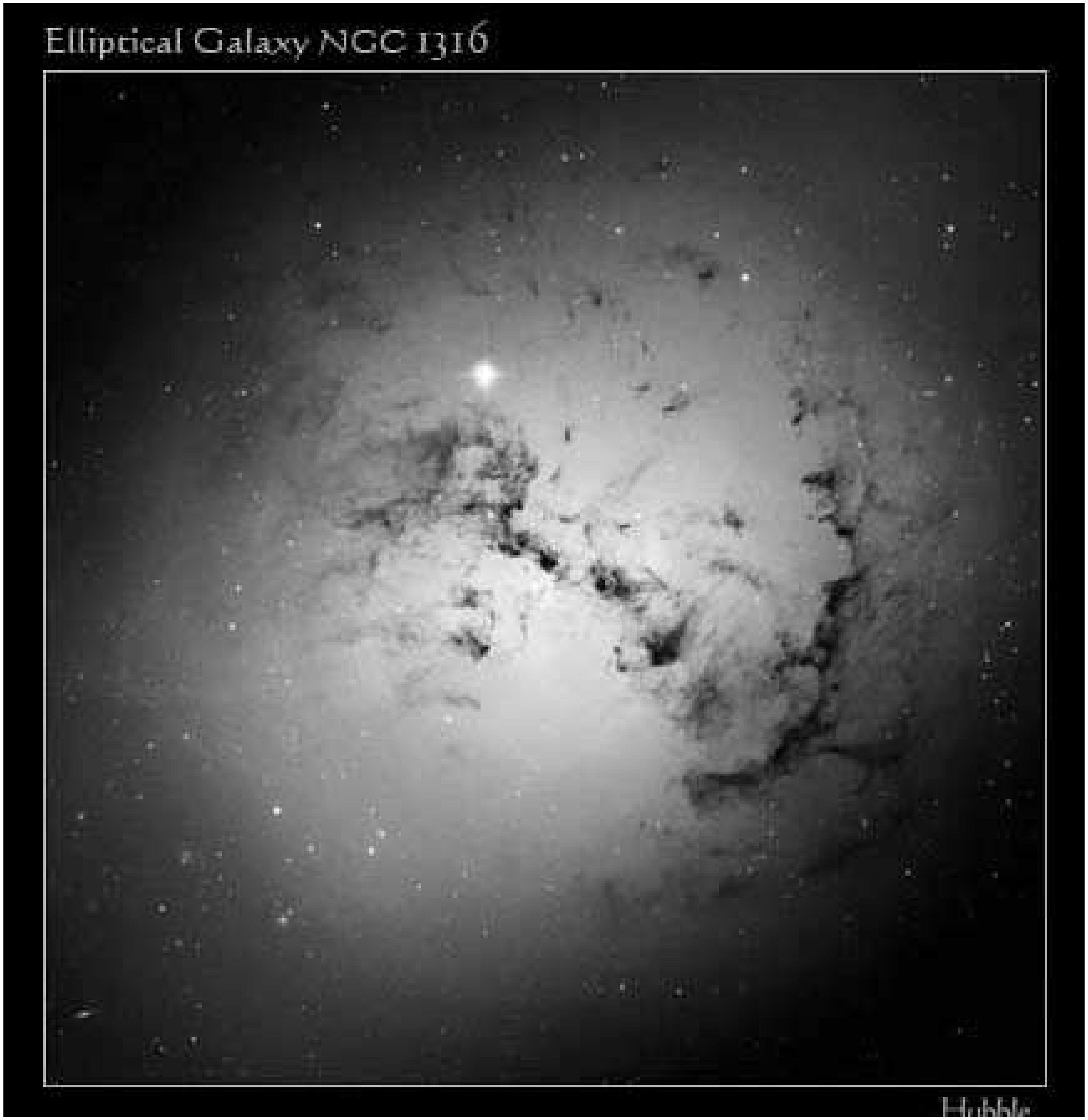
The HST image shows the central region only: it confirms the presence of 2 disks with gas stripped out

Simulation of Major Mergers



Merger of 2 spirals of similar mass destroys the disks and produces an elliptical galaxy!

Minor mergers



The elliptical galaxy (NGC 1316) has recently cannibalized smaller spiral galaxies which are 1/10 to 1/100 its mass, and have lots of gas and dust

NGC 2782: What type of merger is this?

The visible light image shows
- a relatively undisturbed disk
- a 20,000 pc tail to the left

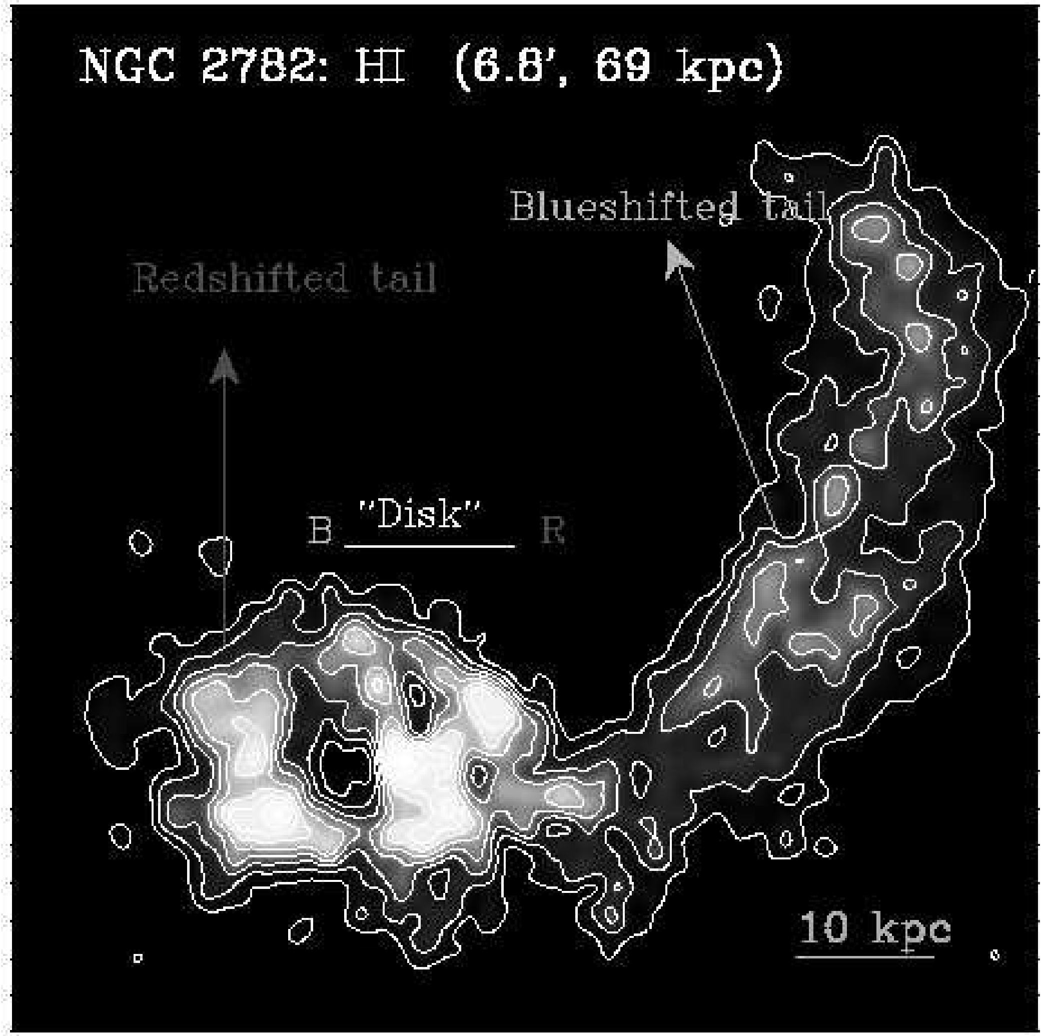


Image at 21 cm (atomic H) shows the disk and a HUGE 50,000 pc tail to the right

Is our own Galaxy Interacting?

(also covered in Lec 4+5)

Is our own Galaxy Interacting?

- The Milky Way, is part of the Local Group, a set of ~40 galaxies that are bound by gravity. (Includes 3 massive spirals, 4E/dEs, 17 dwarfs dSph, 12 dIrr/Irr).

- 90% of the luminosity of the local group come from 3 massive spirals
  M31 (Andromeda SAb), Milky Way (SBbc), M33(SAcd)

- Closest neighbors of the Milky Way are Sagittarius (dwarf), LMC (Irr), and SMC (Irr)
  Sagittarius (dE): 0.08 x 10^6 lyr ; LMC (Irr) : 0.16 x 10^6 lyr SMC (Irr) , distance = 0.19 x 10^6 lyr

LMC; Irr; 30,000 ly across

SMC; Irr ;18,000 ly across

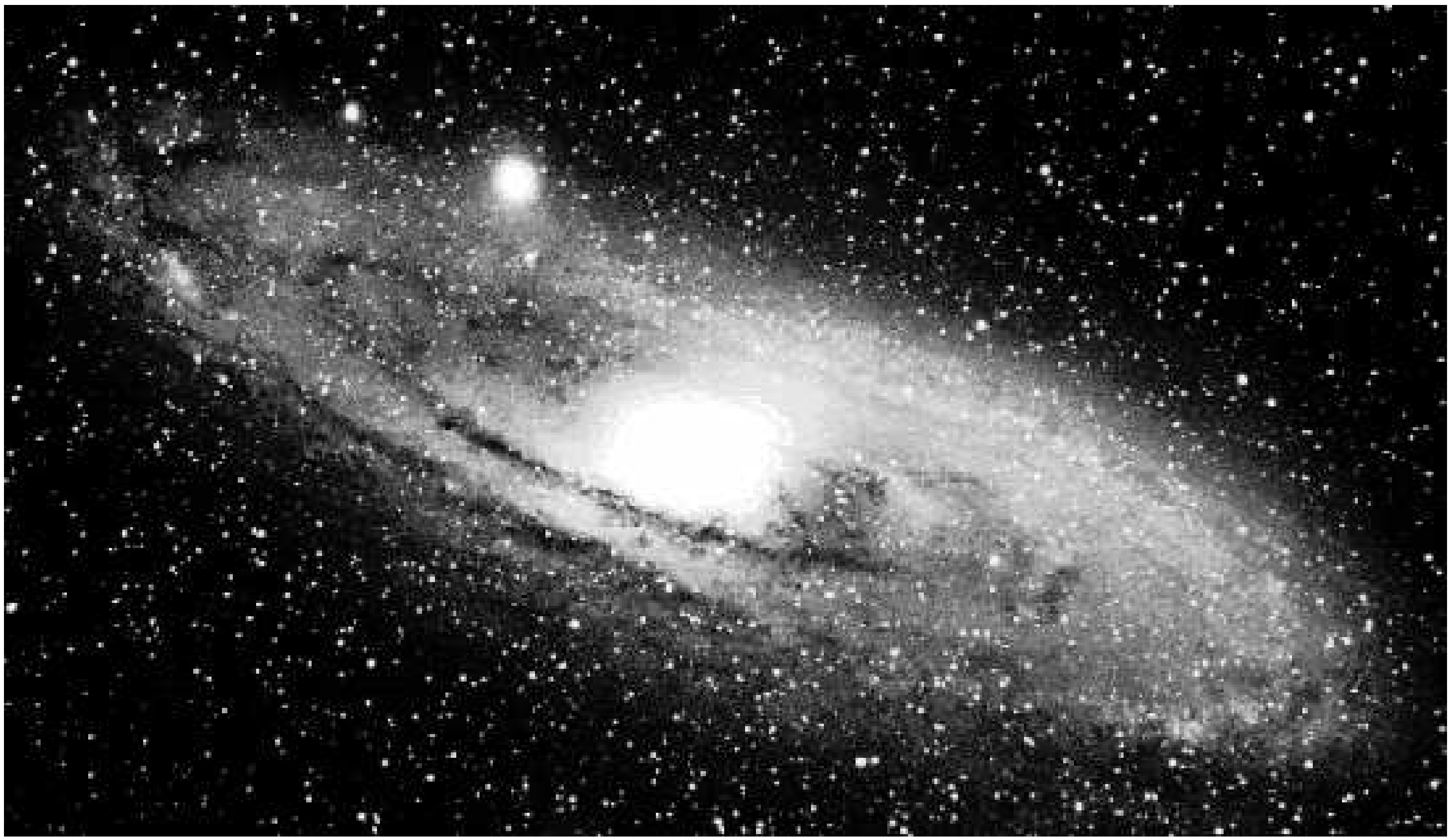
The Milky Way (an SBbc galaxy) is currently undergoing several interactions

à It is presently 'digesting' the Sagittarius (dwarf elliptical) galaxy_.

à It is interacting with SMC (Irr) and LMC (Irr) producing the Magellanic bridge of atomic H

à It has a warp and this may be due to a past accretion of a satellite

In the future, there is at least one more coming …..



à The Milky Way is moving at 83 km/s toward M31 (Spiral SAb) located 2.5 million ly away.

à See Lect 4 + hwk 6: what type of merger will this be? When will it occur?

How Did Galaxies Form and Evolve 0ver the last 13 Gyr

Studying the Formation and Evolution of Galaxies

* 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 and how did proto-galaxies – the precursors of galaxies-- first form?
- How did these proto-galaxies evolve over the last 13 Gyr into galaxies that we see today? How much of the stars that we see today were formed over that time?

- When did barred spiral galaxies like our own Milky Way come into existence?

- How will the Milky Way and other galaxies evolve in the future?

- What was the role played by dark matter?

To answer these questions

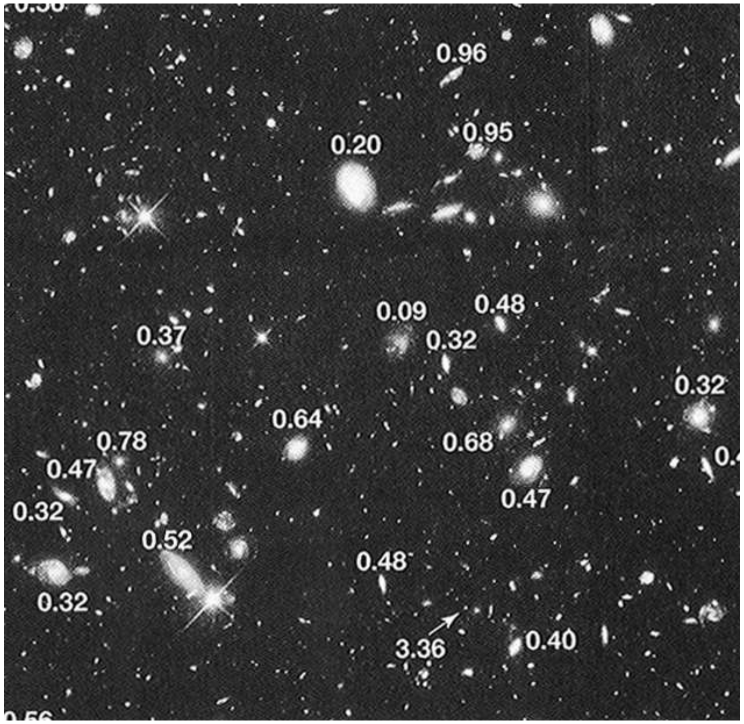
-à we need to **observe galaxies at different cosmic epochs**

How to effectively survey distant galaxies at different lookback times?

Astronomers look back in time and map galaxies at different lookback times by conductiing galaxy surveys which

- take images of galaxies located at different distances,.
- take spectra of galaxies in order to compute their redshifts and hence, distances

What are the 4 criteria that a galaxy survey should satisfy in order to be effective, and why? See in-class notes



Cutting-Edge Galaxy Surveys: GEMS & HUDF

Early galaxy surveys,including the famous Hubble Deep Field (HDF) in 1996 used the old WFPC2 camera aboard HST . WFPC2 ad a very small field of view

The Advanced Camera for Surveys (ACS) installed in 2002 is 10 times more powerful than WFPC2

à has a larger field of view (60 times larger)
à more sensitive
à higher angular resolution

It has allowed several groud breaking surveys of galaxy evolution in 2004

à the GEMS survey
à the GOODS survey
à the HST Ultra Deep Field (HUDF)

-- See in-class notes

Lecture 26: Announcements

-- Schedule for next week

Th Dec 1: Homework 5 is due back. We will give out homework 6

Quiz 6: Based on lectures 22 to 27 (last) + on Chap 23. On Tu Dec 6

Exam 3: Based on lectures 22 to 27 (last) + on Chapter 23. On Th Dec 8.
Format = only written questions, no multiple choice

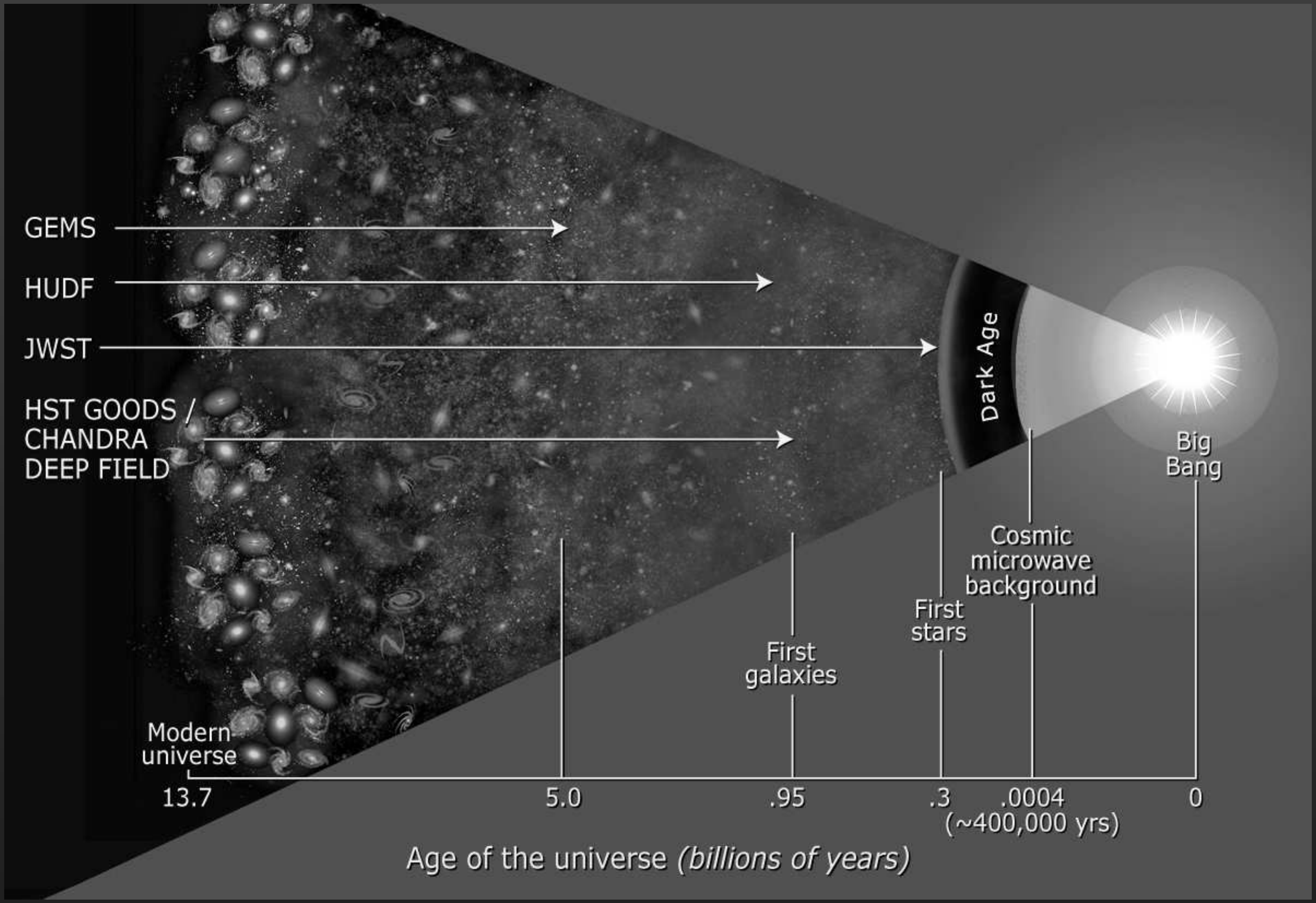
-- Help/Review Session for Exam 3 and Hwk 6:

- on Tue Dec 6 in class
- on Tue De 6: from 5 -6 & 6- 7 pm in WRW 102 (W. R. Woolrich Labs) (Corner of 24th/Speedway)

- Can I request 3 volunteers to coordinatethe class evaluations on Tue in class?

The Hubble Ultra Deep Field (HUDF) survey

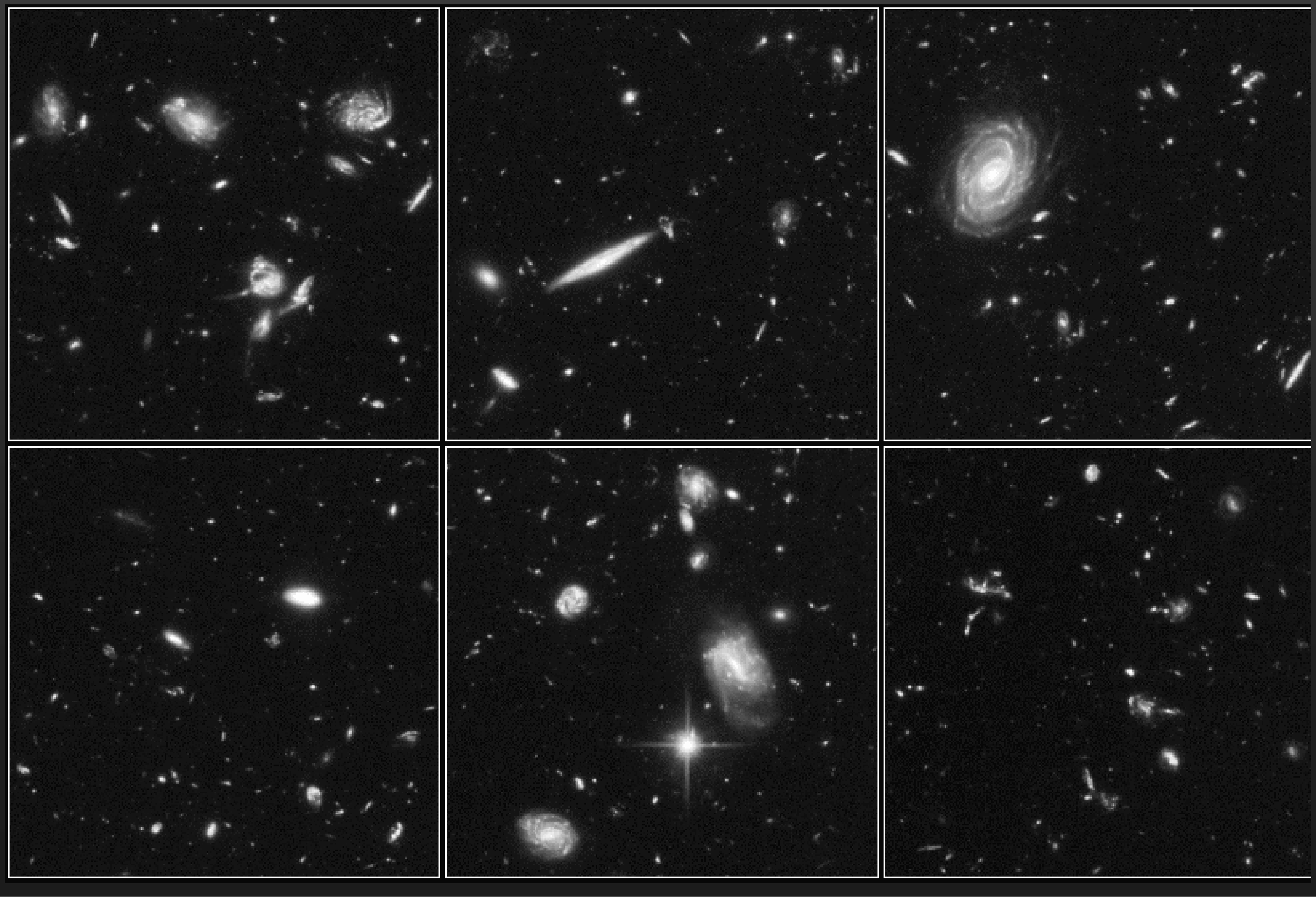
Probing Early Cosmic Epochs with GEMS and HUDF



GEMS surveys galaxies out to lookback times of 9 Gyr, when Univ was 4.7 Gyr old
HUDF surveys galaxies out to lookback times of 13 Gyr , when Univ was 0.7 Gyr old

HUDF survey: Looking back in time 13 billions years

The Hubble Ultra Deep Field (HUDF) is the deepest visible-light image of the Universe. It consists of a million s exposure taken with the ACS camera aboard HST in 2004 by the HUDF team. It probes lookback times of 13 Gyr , when Univ was a mere 0.7 Gyr old.



Some HUDF results

At very early epochs, when the Universe was ~ 0.7 Gyr old (i.e 5% of its present age, corresponding to lookback times of 13 Gyr):

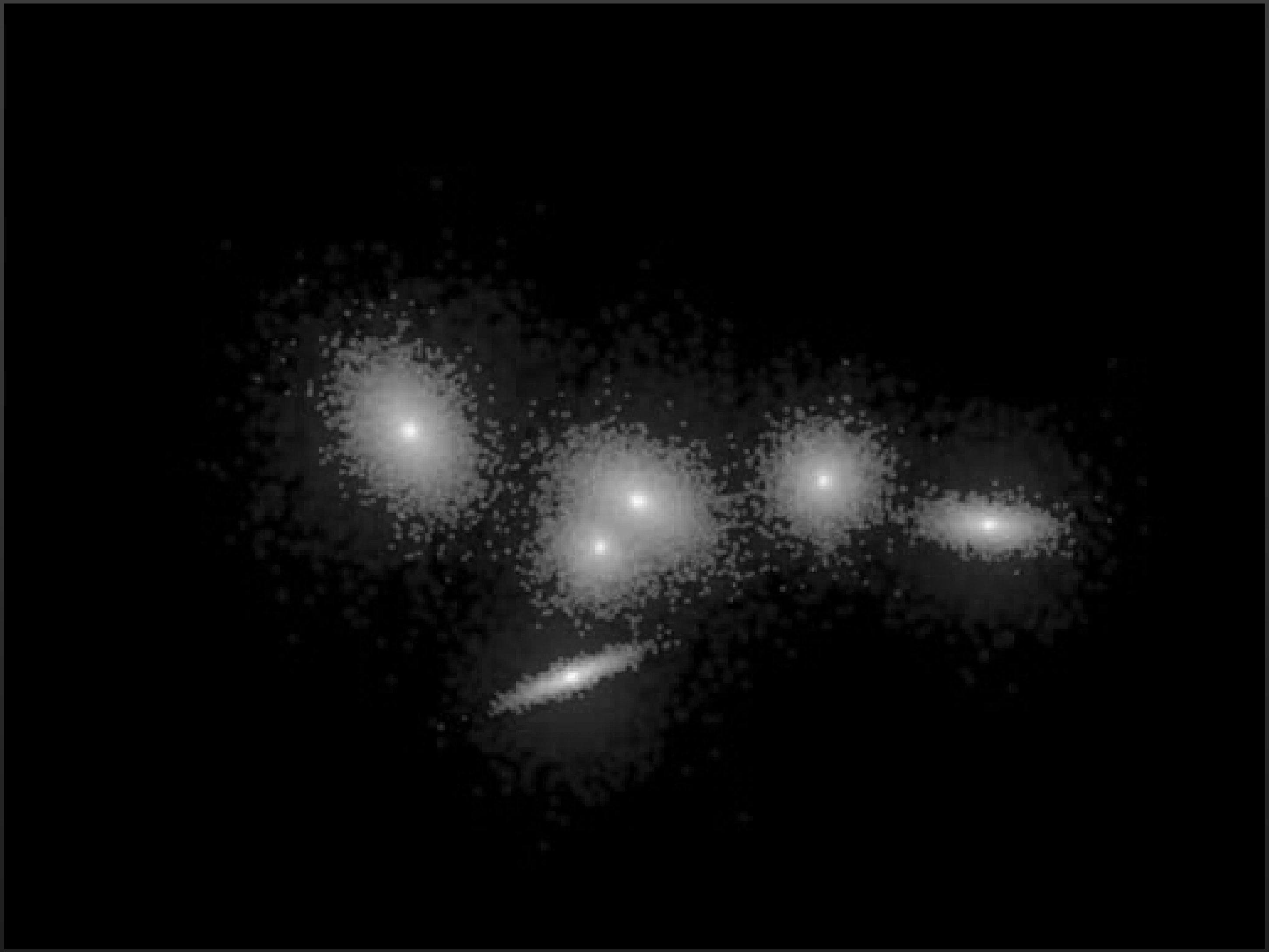
à first proto-galaxies, made of gas and dark matter were forming. They were similar to dwarf galaxies and much smaller than present-day spirals.

à the Universe was a violent place, dominated by very frequent mergers which assemble the proto-galaxies into larger blocks

As the Universe aged from 0.7 to 3 Gyr old (corresponding to lookback times of 10.7 Gyr):

à Mergers of proto-galaxies build bulges of spirals, disks of spirals, and some ellipticals. These galaxies are however not yet as massive as present-day systems and have to grow further by accretion and minor/major mergers

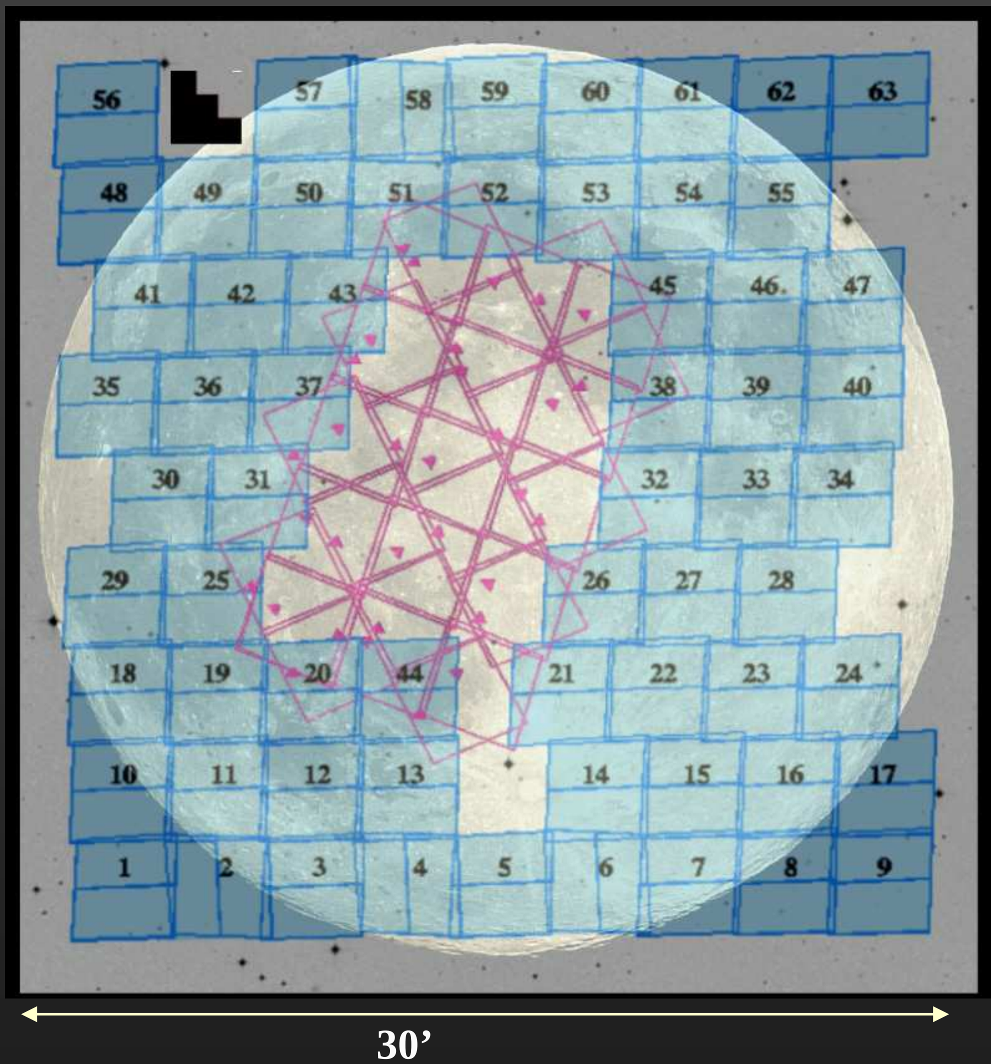
Mergers of multiple galaxies in dense regions and at early epochs



Credit : Joshua Barnes (University of Hawaii)

The GEMS survey

The GEMS survey



GEMS is largest-area imaging survey conducted using 2 filters on the ACS camera aboard HST

GEMS survey area

= 77 ACS pointings patched together

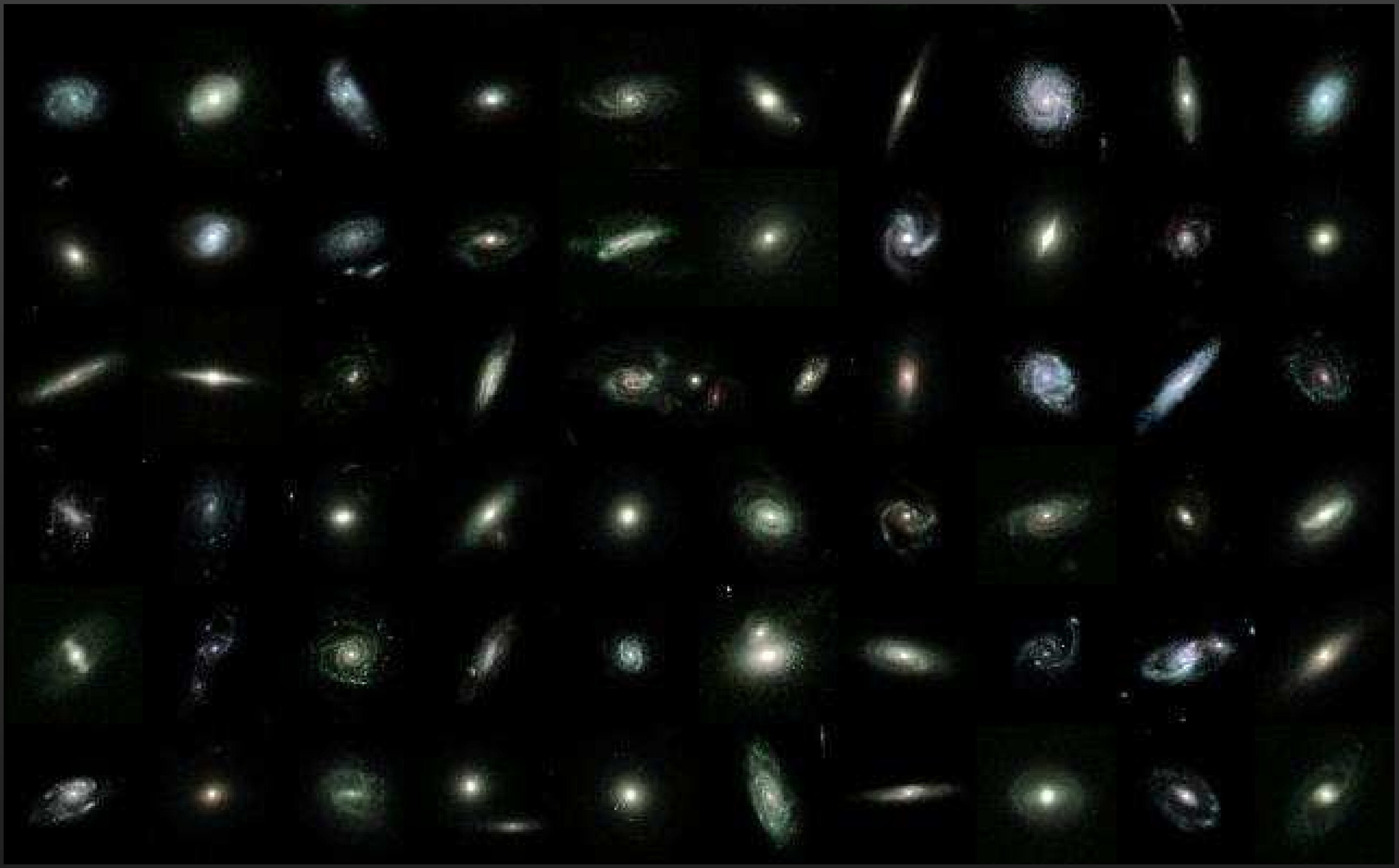
= 30’x30’= size of full moon on sky

= 120 x area of Hubble Deep Field (HDF) conducted with WFPC2 in 1995

= 72 x area of Hubble Ultra Deep Field (HUDF)

GEMS also has galaxy spectra which provide accurate redshifts for ~9000 galaxies. The redshifts are used to derive the lookback times, which lie in the range 2 to 9 Gyr

GEMS results



Provides family album of how galaxies looked like in their youth ('thirties')
Shows diverse galaxies were in place 9 Gyr ago, when Universe was only 30% of its present age!

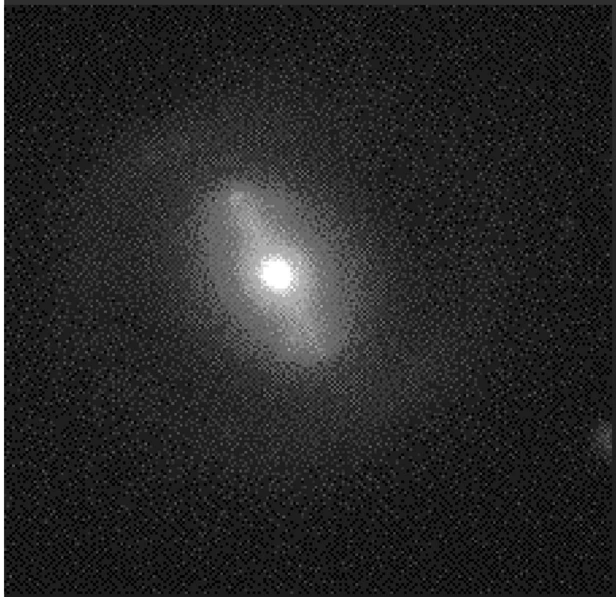
GEMS results

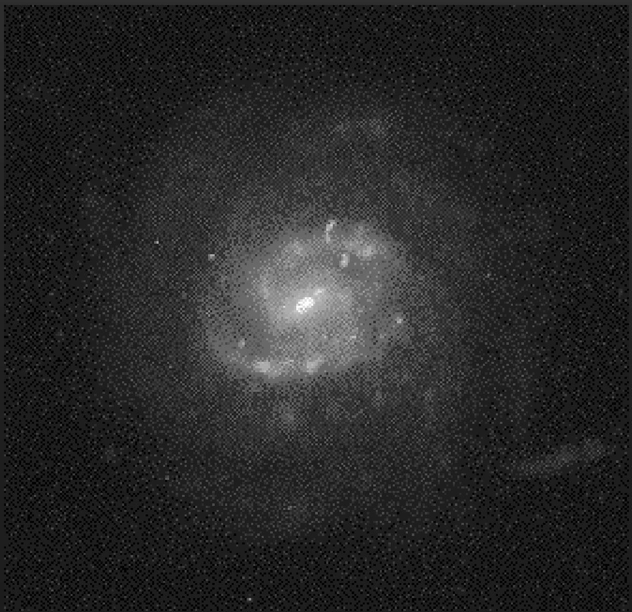
Early studies (1999) based on the HDF survey claimed that barred spirals similar to our Milky Way were ~ absent 9 Gyr ago and only formed very recently. This claim contradicted our best models of how barred spirals form !

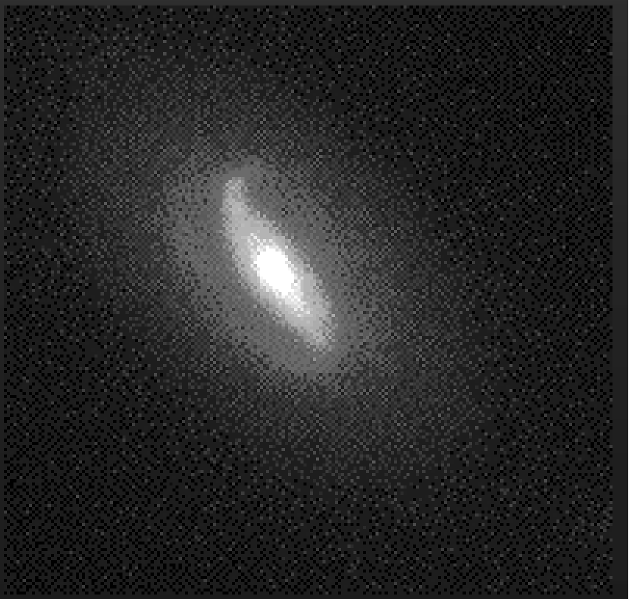
GEMS result (Jogee and GEMS team, 2004, The Astrophysical Journal)

à We conclusively demonstrated that barred spiral galaxies similar to our Milky Way are abundant at lookback times of 5 to 8 Gyr

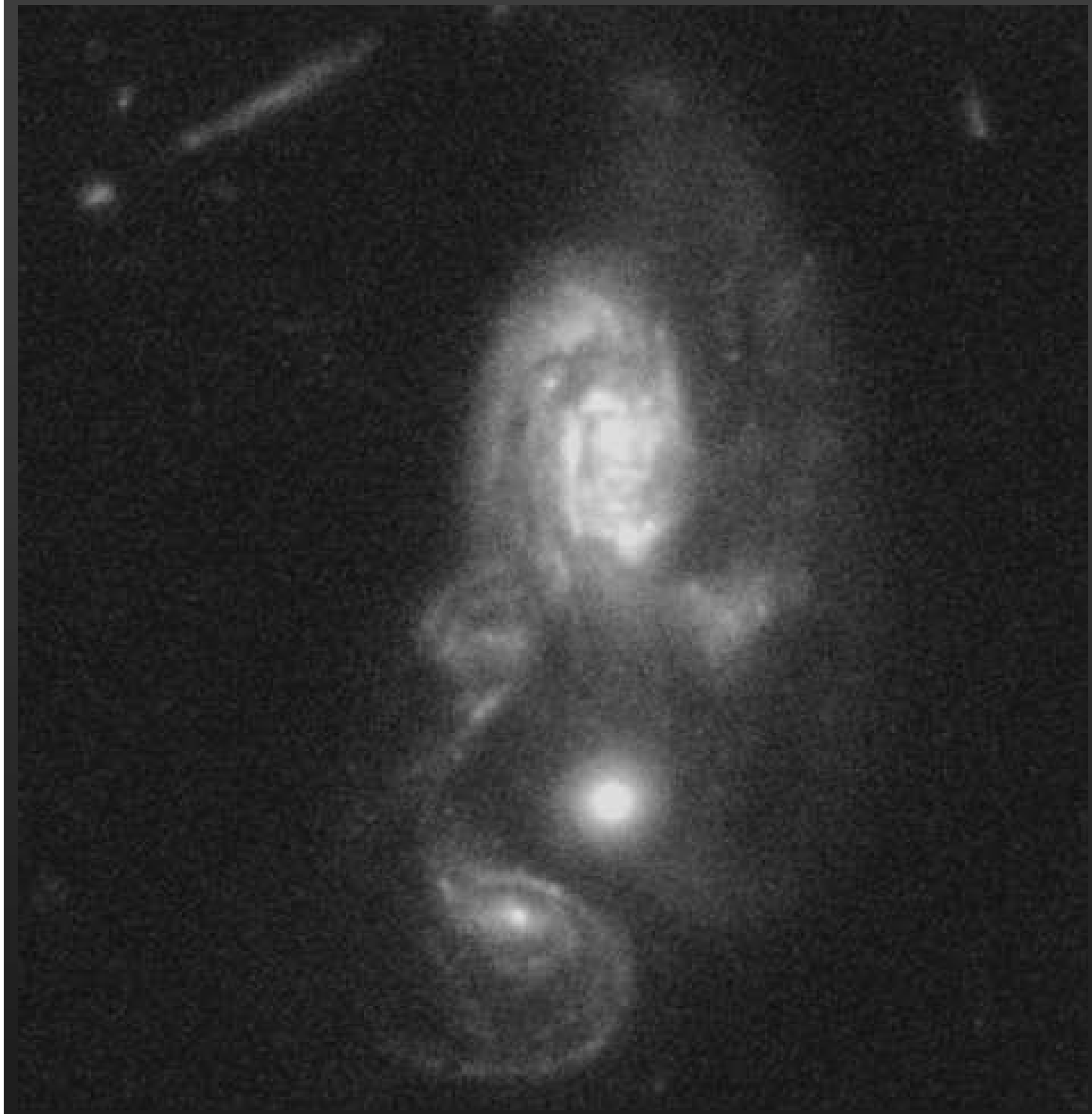
à We showed that bars are long-lived and strongly influence the dark matter







GEMS results



Interacting galaxies in GEMS

Over last 9 billion years ,

à The Universe transitions from a violent evolution to a more quiescent evolution

à the frequency of major mergers drops. Galaxies, instead, mainly undergo minor mergers and keep growing in mass slowly.

à HALF of the stars in elliptical galaxies are built over his period

<u>Mapping the Dark Matter in Galaxies and in the Universe</u>
<u>(Read Chapter 22)</u>

What is Dark Matter? How is it Measured?

Dark matter is mass that does not emit any radiation and is not visible at electromagnetic wavelengths

We detect dark matter through the force of gravity that any mass(be it dark or visible) exerts on a surrounding mass.

The mass of dark matter is measured via the steps below

à We estimate the total mass of a system (e.g, a galaxy or cluster of galaxies) by measuring the force of gravity that it exerts.

à We estimate the total luminous of the galaxy, based on its total luminosity L

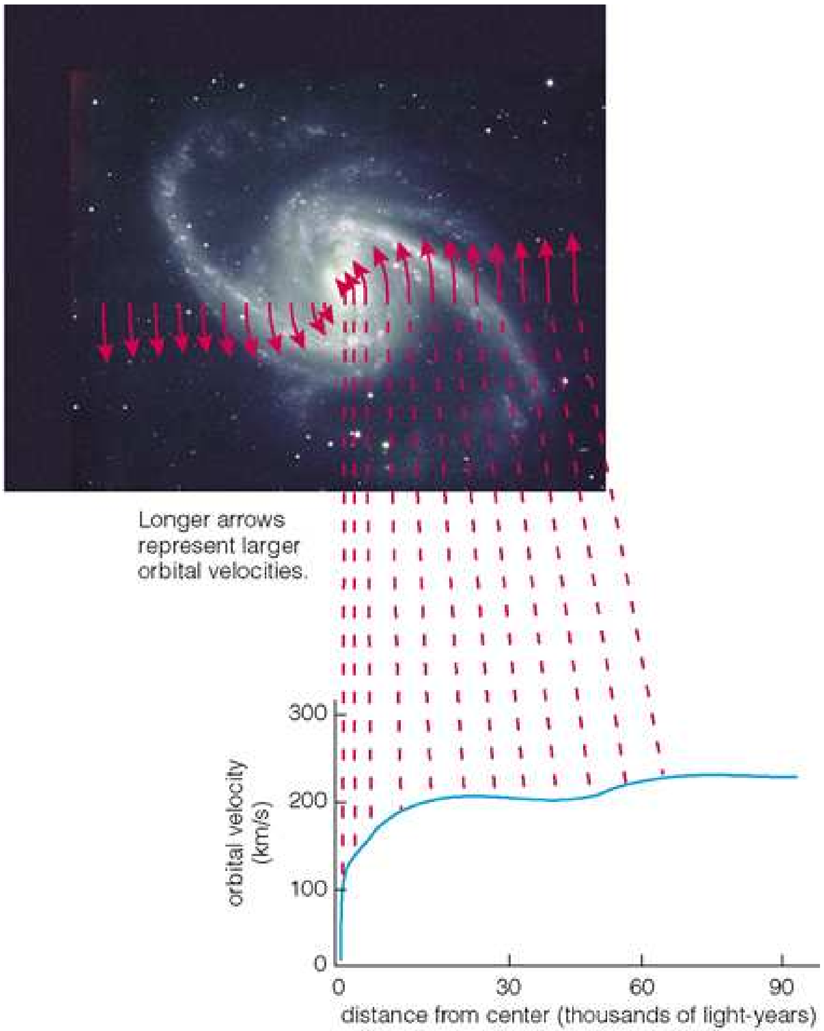
à The mass of dark matter = Total Mass - Luminous Mass

We find that dark matter makes up a very large fraction of the total mass:

à Spirals/ Ellipticals: 90% of total mass within R = 150,000 ly is dark

à Cluster of galaxies: 90% of total mass within the cluster is dark

Hot To Measure The Total Mass of A Spiral Galaxy?



Measure speed v of a gas cloud that is orbiting at radius R in the disk of the galaxy.

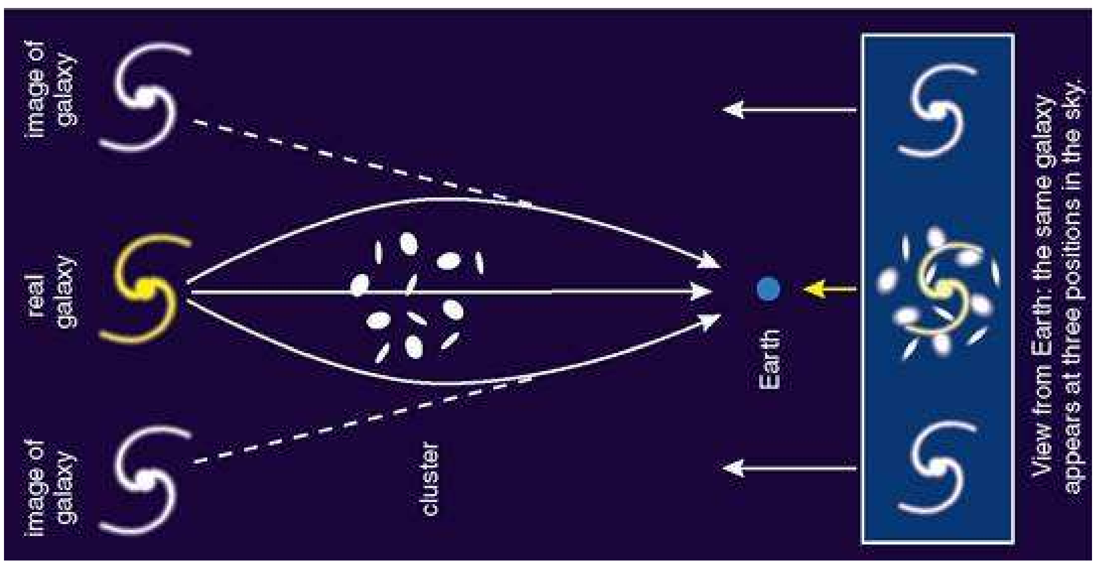
Using the quantities v and R, we can estimate the force of gravity exerted by the total mass inside the radius R.

See Hwk2/Q3, where you estimated the total mass inside a radius R=8.5 x 10^3 pc, and estimated the amount of dark matter

How To Measure The Total Mass of A Cluster of Galaxies

If light from a distant background galaxy passes near a foreground cluster on its way to Earth, the light will be bent by the force of gravity exerted by the total mass of the cluster.

This makes us see multiple images of the background galaxy, forming arcs (Einstein's rings)
This is called gravitational lensing: the cluster acts as a lens for the light of background galaxy



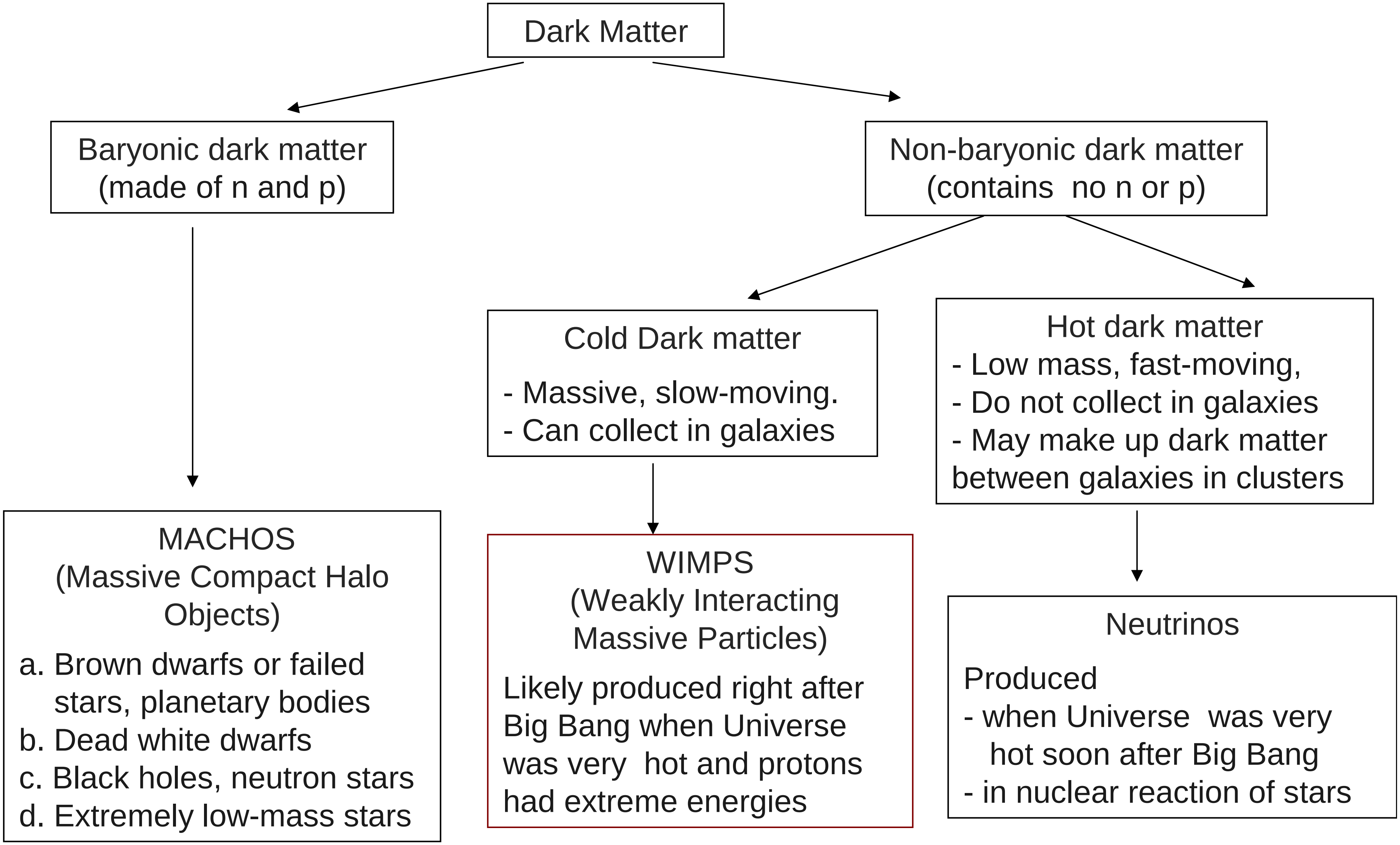
Candidates for Dark Matter

We find that dark matter makes up a very large fraction of the total mass:
à Spirals/ Ellipticals: 90% of total mass within R = 150,000 ly is dark
à Cluster of galaxies: 90% of total mass within the cluster is dark

<u>Can rule OUT options below for dark matter candidates</u>:

- high and intermediate mass stars: emits UV, optical light
- low mass stars : emit near-IR light
- hot gas : emits X-ray light
- warm gas and dust: emit mid-IR light
- cold gas : emits radio light

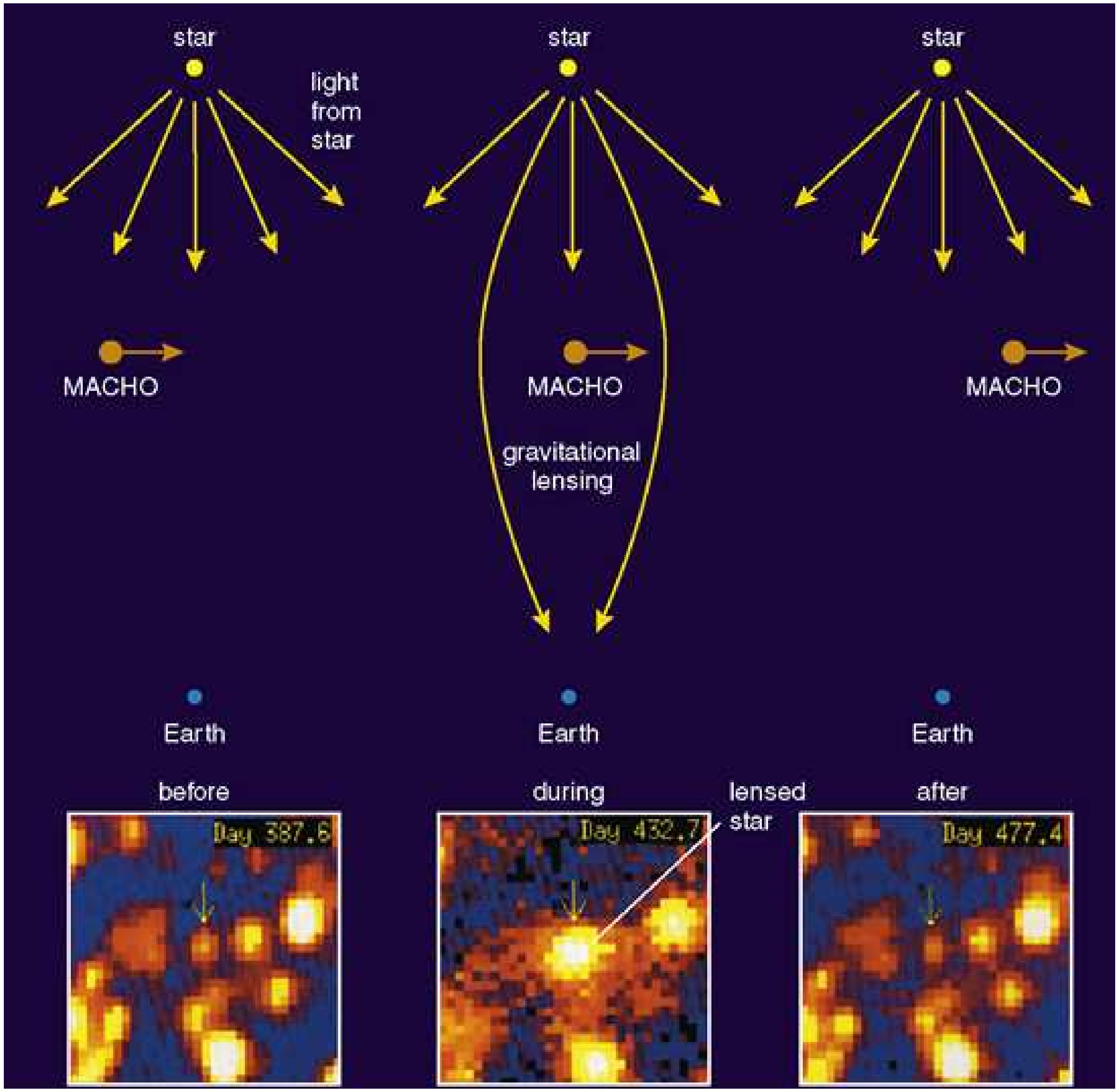
Candidates for Dark Matter



Leading candidate = Cold dark matter = WIMPS

How Do We Test/Detect Different Dark Matter Candidates?

Detecting MACHOS in our Galaxy via Microlensing



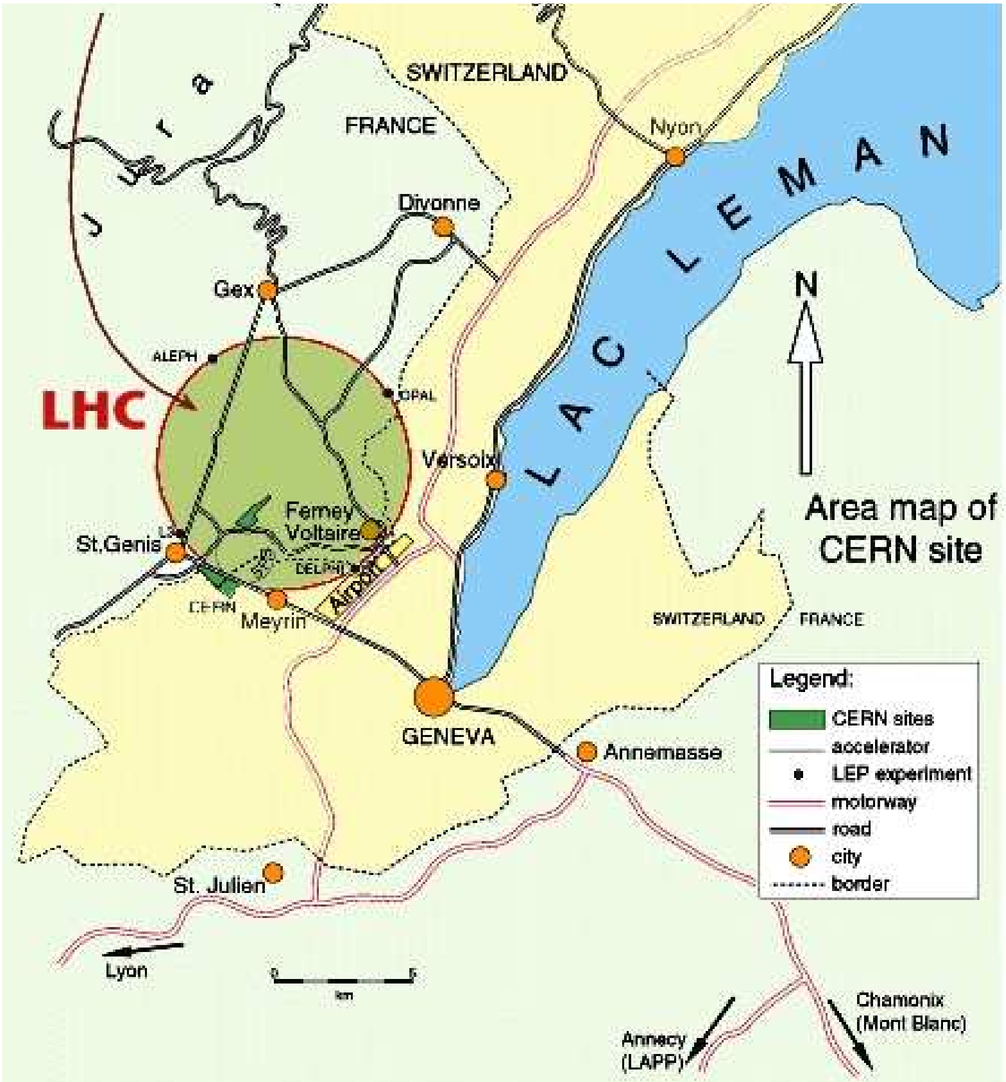
As light from a bulge star or halo star travels to us, it can be bent by the force of gravity from a passing MACHO if the latter crosses the light's path.

The light gets focused and the apparent brightness of the star increases for a short period until the MACHO moves away.

.

Results to date: MACHOS make up only a small fraction of the dark matter in Milky Way.

Characterizing WIMPS with Large Hadron Collider



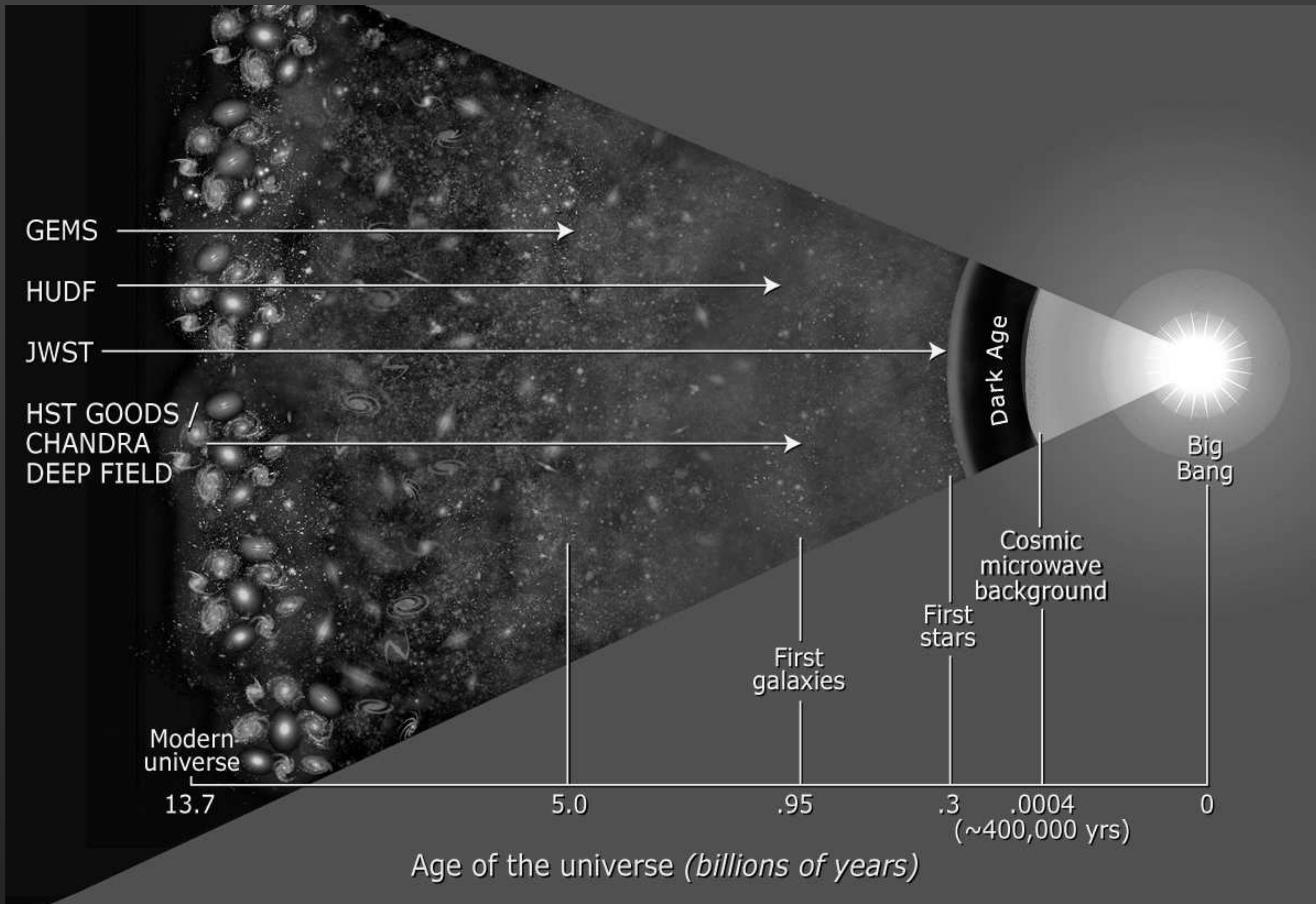
Large Hadron Collider (LHC) will be online in 2007 at CERN , at Franco-Swiss border

LHC is an acelerator that will collide protons and ions head-on <u>at energies (E=10^{12} eV) and temperatures (T = 10^{16-17} K) higher than ever achieved before.</u> These conditions <u>recreate the conditions just after the "Big Bang".</u>

It wil characterize WIMPS

<u>WIMPS are leading candidates for dark matter</u>

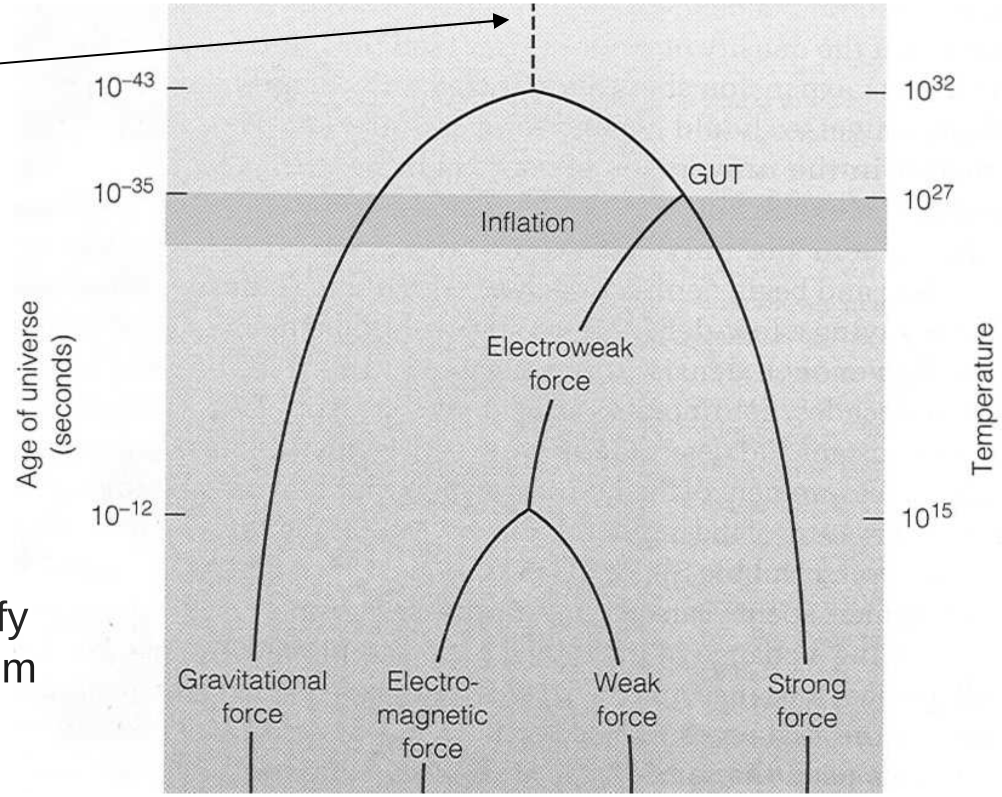
The Beginning of Time In the Big Bang Model : From the Planck Time (10^{-43} s) to the First Second



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.
Next we focus on the very first billion years….from time t= 10^{-43} s to 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

- the 4 fundamental forces (strong, weak , EM, and gravity) act on same scales
- current laws of phyiscs cannot make any prediction. We need a theory that can unify the 4 fundamental forces (i.e, unify quantum mechanics and general relativity)

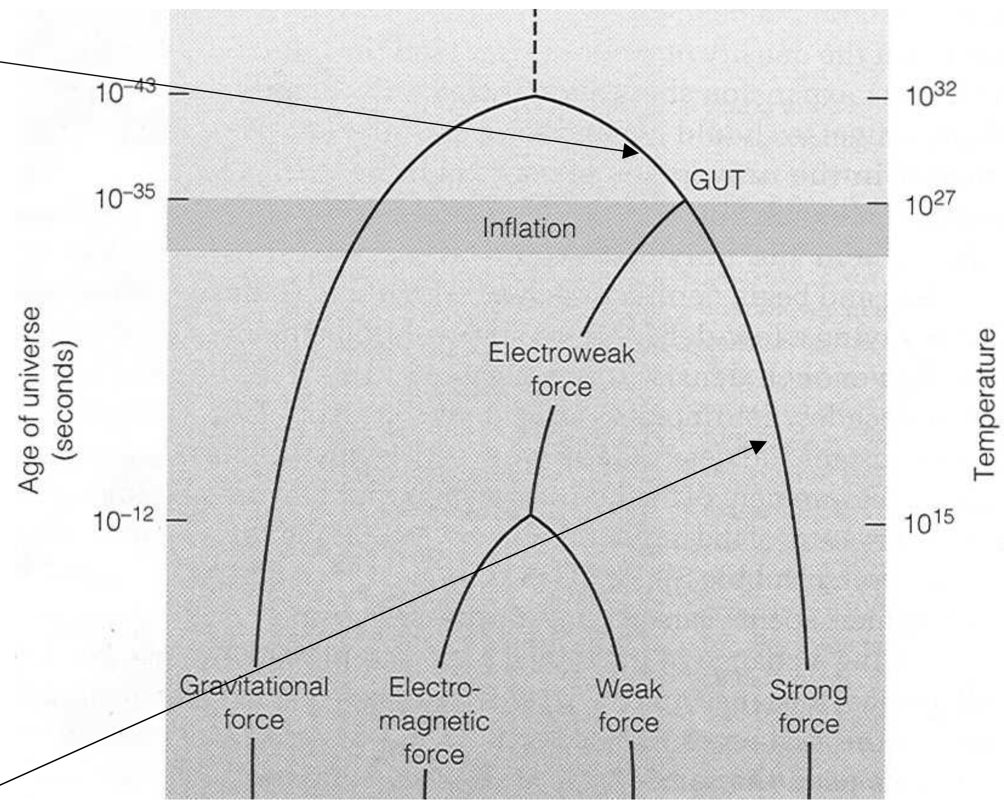
To find this theory (superstring, supergravity) is a key goal of modern physcis

"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 Era (t = 10^{-43} to 10^{-38} s)

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

GUT era

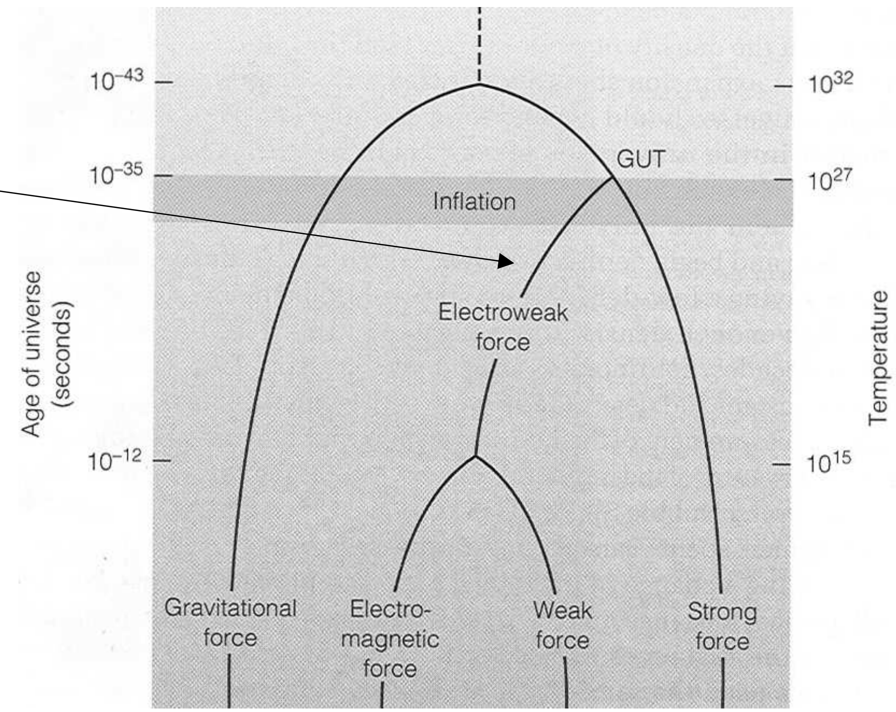


Several theories describing the GUT force exist , but they are not yet verified experimentally as the energies and temperatures to test them are too high (E=10^{24} eV, T= 10^{29} K) to be currently achievable.

Even CERN LHC collider In 2007 will only reach T= 10^{17} K…. which is only comparable to the middle of electroweak era.

The Electroweak era (t=10^{-38} to 10^{-10}s)

In the electroweak era, the EM and weak force remain unified as the electroweak force, while the strong force freezes out.

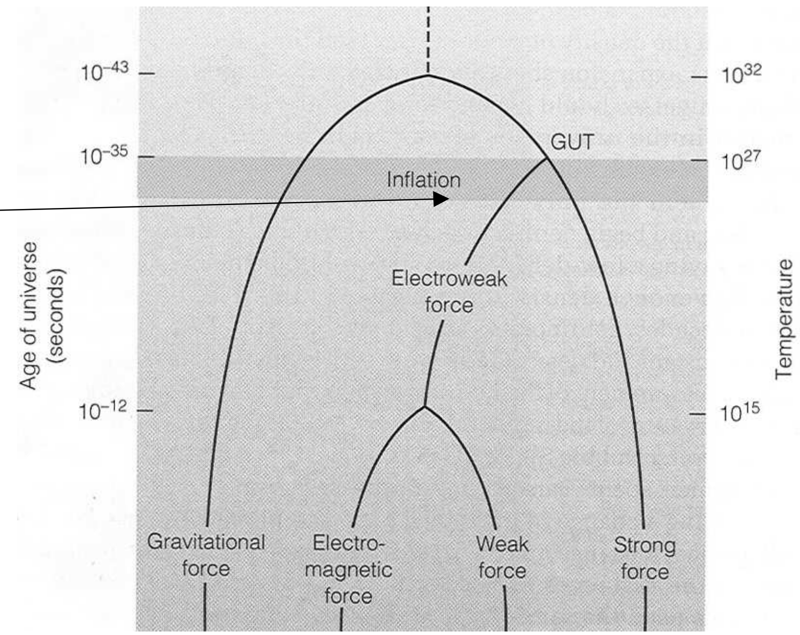


Glashow, Weinberg (at UT Austin) and Salam developed the electroweak theory. Were awarded Physics Nobel Prize in 1979 after the electroweak theory were verified experimentally in 1970 at CERN

At CERN, in 1970+1983 where particles were accelerated to energies and temperatures matching those at end of electroweak era (E=10^{11} eV, T= 10^{15} K)

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

Inflation kicks in during the very early part of the electroweak era (t=10^{-35} to 10^{-32} s).

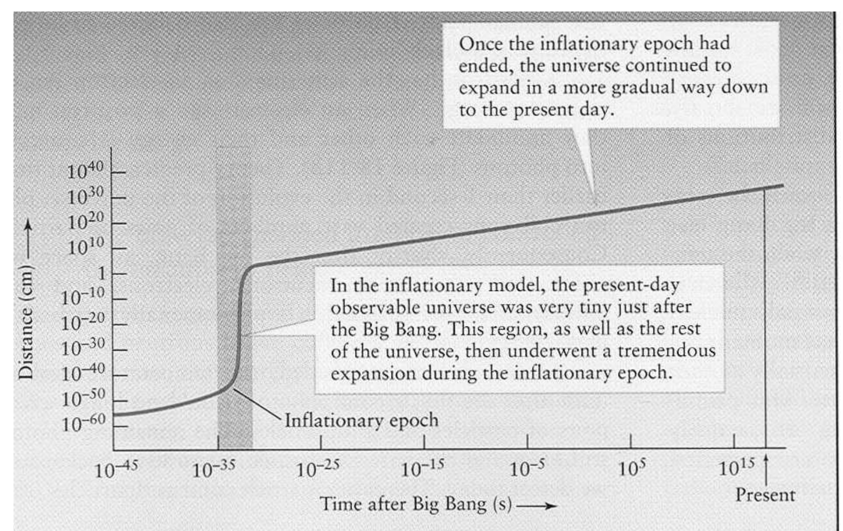


Inflation

- 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).

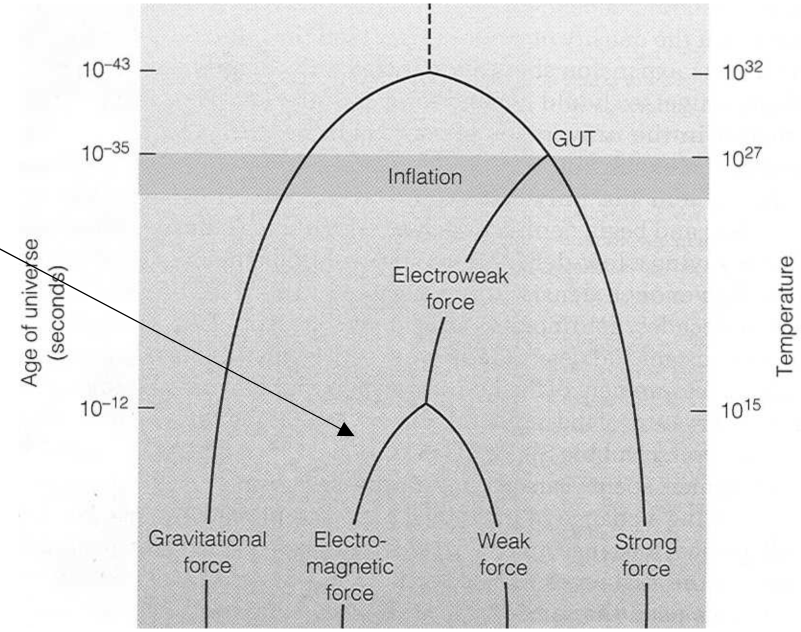
- causes an extremely rapid expansion of the Universe, a few trillion (10^{12}) times faster than the expansion , which we see today and describe with Hubble's law



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

Production of Matter-Antimatter Pair + Formation of n,p,e (t=10^{-10} s to 1 s)

At end of electroweak era, all 4 forces decouple. .



Universe keeps expanding and cooling .

Early on, photons (radiation) were hot enough that they can produce matter-antimatter pair. The hotter the photon, the more massive the matter-antimatter pair

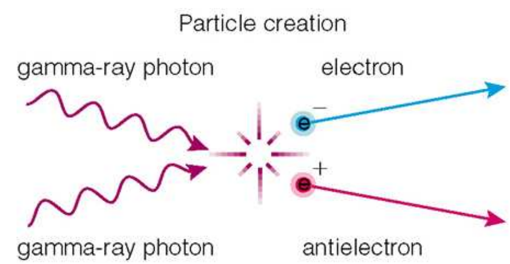
At T>10^{13} K:

photons à proton, anti-proton (p+,p-)

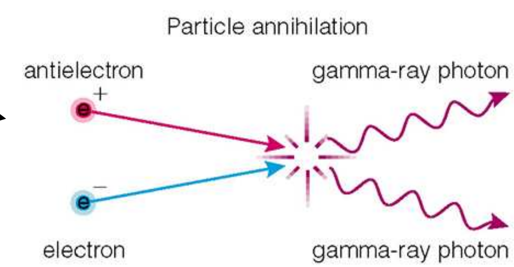
photons à neutron, anti-neutron

At T>10^{9} K:

photons à electron, anti-electron (e-,e+)



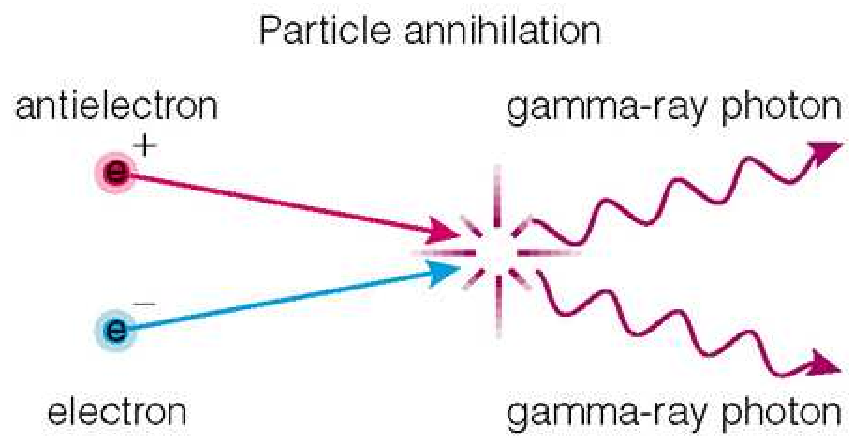
A matter-antimatter pairs has 2 particles, that are made of matter and antimatter, and have opposite charges The 2 particles can annihilate each other to give back a photon.



Production of matter-antimatter & dominance of matter ($t=10^{-10}$ s to 1 s)

As the Universe keeps expanding, its temp. keeps dropping, and soon photons do not have enough energy to form new matter and antimatter pairs.

Existing matter-antimatter pairs annihilate to form photons. If the number of of matter and anti-matter particles had been exactly equal, then complete annihilation of matter would have occurred and none of us would be here today



Luckily for us, due to symmetry breaking, there was a slight excess of matter over anti-matter, (1 excess matter particle for every billion matter-antimatter pairs) . Thus, matter particles neutrons and protons (H nuclei) form by $t< 10^{-6}$ s and electrons by t = s.

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

We owe our existence to this symmetry-breaking

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