Lecture 36: 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.

Galaxy Formation and Evolution.

Several topics for galaxy evolution have already been covered in Lectures 2, 3, 4,14,15,16. you should refer to your in-class notes for these topics which include:

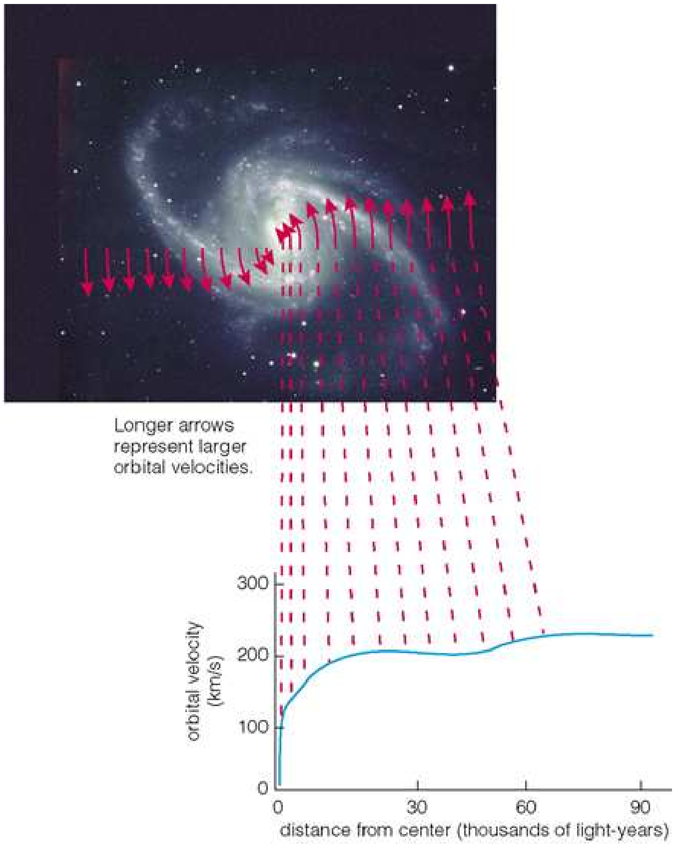
- Types of galaxies (barred spiral, unbarred spirals, ellipticals, irregulars)
- The Local Group of Galaxies, The Virgo and Coma Cluster of galaxies
- How images of distant galaxies allow us to look back in time
- The Hubble Ultra Deep Field (HUDF)
- The Doppler blueshift (Lectures 15-16)
- Tracing stars, dust, gas via observations at different wavelengths (Lecture15-16).

In next lectures, we will cover

- Galaxy Classification. The Hubble Sequence
- Mapping the Distance of Galaxies
- Mapping the Visible Constituents of Galaxies: Stars, Gas, Dust
- Mapping the Dark Matter in Galaxies and in the Universe
- Galaxy Interactions: Nearby Galaxies, the Milky Way, Distant Galaxies
- Understanding Galaxy Formation and Evolution

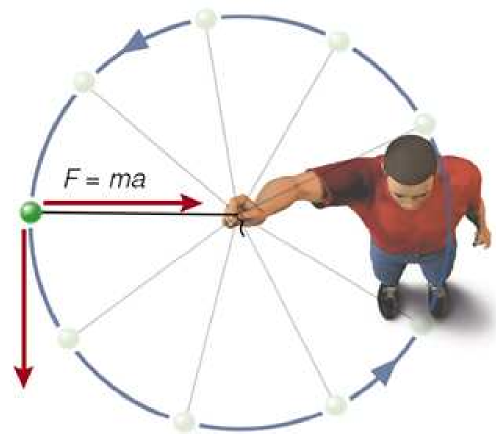
Mapping the Dark Matter in Galaxies and in the Universe

Dark Matter in Spiral Galalxies



Rotation curve of a spiral galaxy = plot of the velocity v of gas or stars against the radius R of their orbits. Atomic HI gas can be mapped further out than stars in spirals

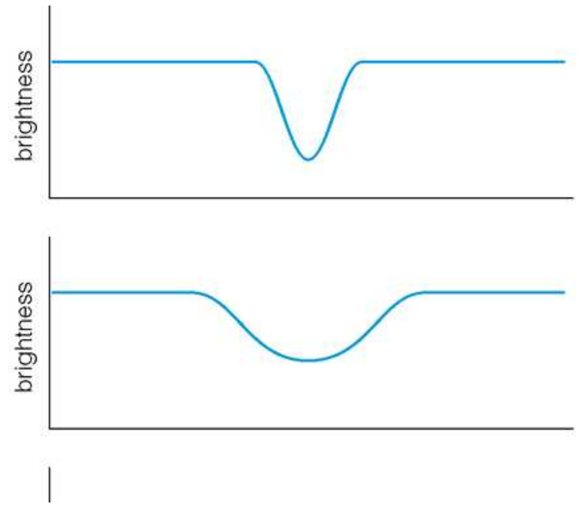
The speed v at each radius is a measure of the total mass M enclosed within that radius, because it is the pull of gravity from this mass that cause the star or gas particles to orbit the galaxy .



à Only 10% of total mass M comes from stars that emit at visible wavelengths

à 90 % of the total mass comes from dark matter , a form of matter that has mass, exerts a force of gravity, but does not emit visible light.

Dark Matter in Elliptical Galalxies



In elliptical galaxies, stars do not have ordered motion in circular orbits like those in spiral galaxies. Instead, stars have disordered motions, called velocity dispersion σ

The value of σ for a star at a given radius R measures the total mass M which is enclosed within that radius and exerts a pull of gravity on the star. By measuring σ from the width and profile of stellar absorption lines, can estimate M .

There is little gas in ellipticals, so can only use stars. Cannot trace M at large radii

à Only 10% of total mass M comes from stars that emit at visible wavelengths
à 90 % of the total mass comes from dark matter

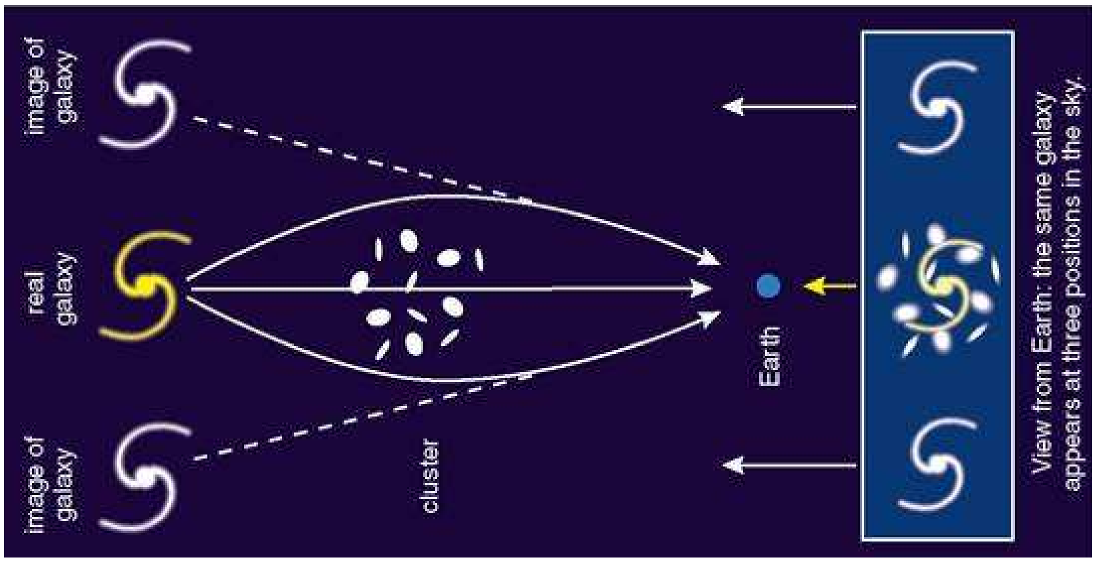
Dark Matter in Clusters of Galaxies

A cluster of galaxies is a collection of galaxies bound together by the force of gravity.

Method 1 : A galaxy at a distance R from the center of the cluster orbits the cluster with a speed v that depends on the total mass of the cluster inside radius R. By mapping the average orbital speed of galaxies at different distances from the center of the cluster can get the total mass of the cluster.

Dark Matter in Clusters of Galaxies

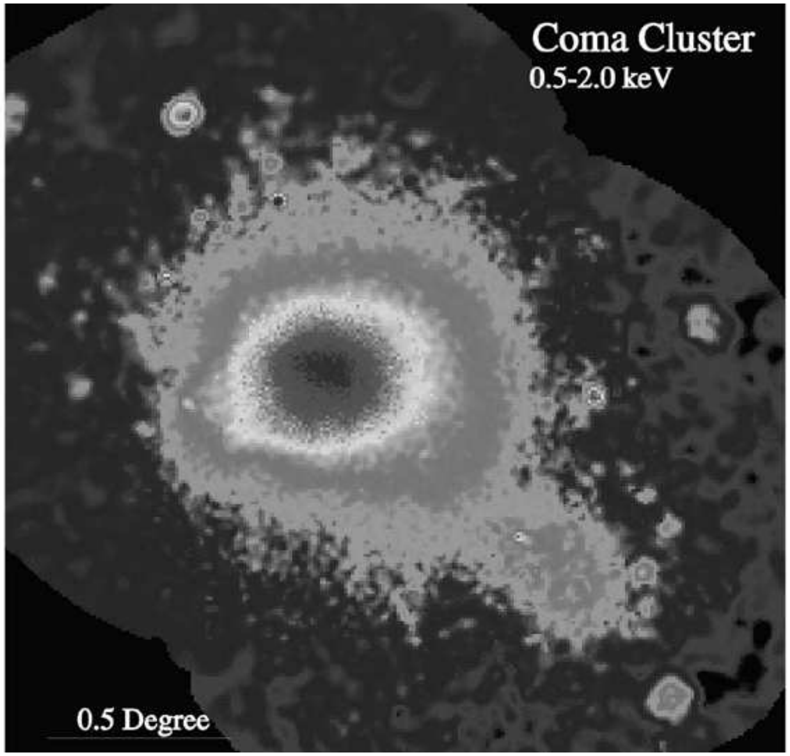
Method 2: If light from a distant background galaxy passes near a forgeround cluster on its way to Earth, the light will be bent by the force of gravity exerted by the total mass of the cluster. This distorts the image of the background galaxy and can produce several images of the galaxy. This phenomenon is called gravitational lensing and the cluster acts as a lens.



By analyzing the distortions induced in the images with Einstein's general theory of relativity, can infer the total mass M of the cluster

Question: force of gravity acts on mass… how can it bend light?

Dark Matter in Clusters of Galaxies



Method 3: X-ray observations reveal hot (10^7 to 10^8 K) gas between galaxies in a cluster.

The hot gas is in gravitational equilibrium : its outward pressure (caused by thermal kinetic energy of its hot particles) balances the force of gravity from the total mass of the cluster.

By mapping the temperature of the gas from X-ray data

- à can infer the thermal K.E of the hot particles
- à can compute the total mass of the clusters.

Results

1) All three methods, based on different techniques (average orbital speeds of galaxies, gravitational lensing, and temperature of hot X-ray emitting gas), show that
   - à visible matter (stars) make up only 10% of total mass in clusters of galaxies
   - à dark matter makes up 90% of the total mass
2) The hot gas revealed by X-rays can make up at most 40% of the dark matter in clusters.

Candidates for Dark Matter

There are two types of dark matter: baryonic and non-baryonic.

Baryonic dark matter is made of neutrons and protons

MACHOS = Massive Compact Halo Objects

MACHOS are candidates for baryonic dark matter. Examples of MACHOS include

a) Brown dwarfs or failed stars (M<0.08 Msun), Jupiter-mass (0.001 Msun) objects, and other non-luminous debris left over from formation of our solar system and galaxy. These objects failed to ignite hydrogen fusion and hence do not produce any luminosity

b) Low-mass red stars which emit no visible light

c) Solar mass black holes, and neutron stars formed from the imploding core of a dying high-mass star

Candidates for Dark Matter

How to detect MACHOS ?

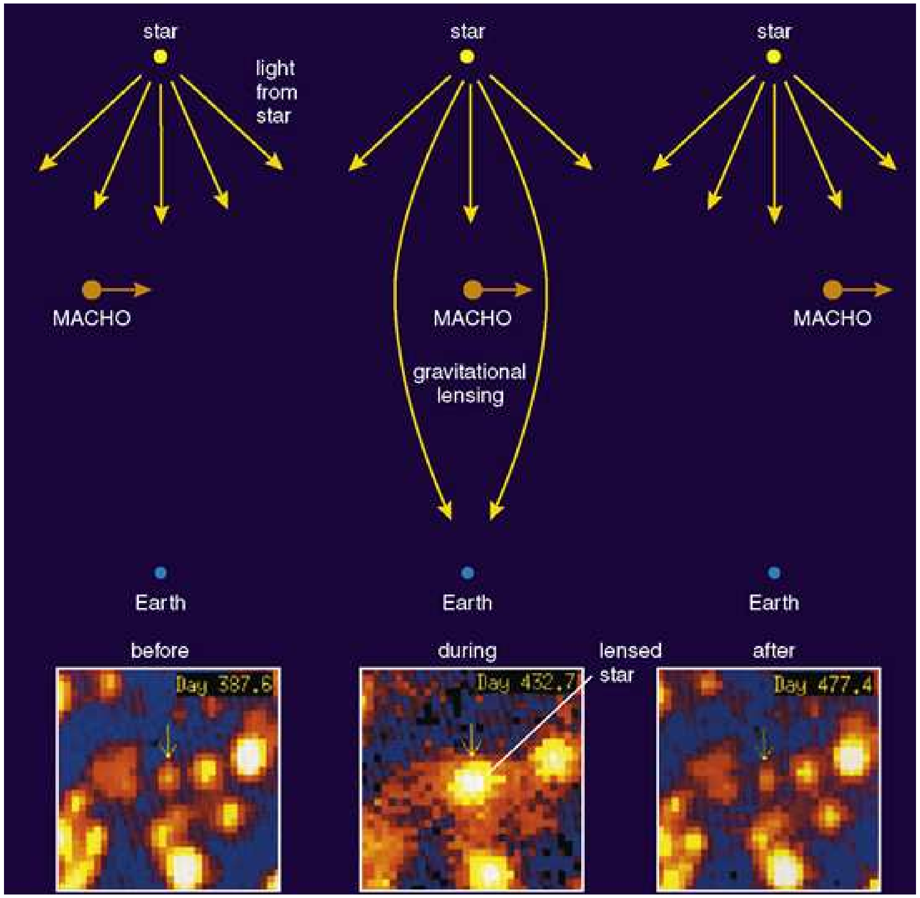
à As light from a bulge or halo star travels to us, it can be bent by a passing MACHO if the latter crosses the light's path.

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

à This phenomenon is called microlensing and the duration allows us to infer the mass of the intervening MACHO.

à Microlensing needs chance superposition and only happens to ~1 star in a million each year! Need to microlens several millions of stars in bulge/halo of our galaxy for years to get good statistics.

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



Candidates for Dark Matter

WIMPS = Weakly Interacting Massive Particles (also termed cold dark matter)

Non-baryonic dark matter contains neither neutrons or protons. WIMPS are candidates for non-baryonic dark matter and have the following properties

1) They have no charge. Hence they experience no electromagnetic force and emit no electromagnetic radiation (at any wavelength).
2) They have no neutron or protons and hence do not experience the strong force
3) They experience the force of gravity (as they have mass).
4) They experience the weak force, which acts only at short ranges, inside atomic nuclei.
5) They are massive and slow-moving and can collect in galaxies.

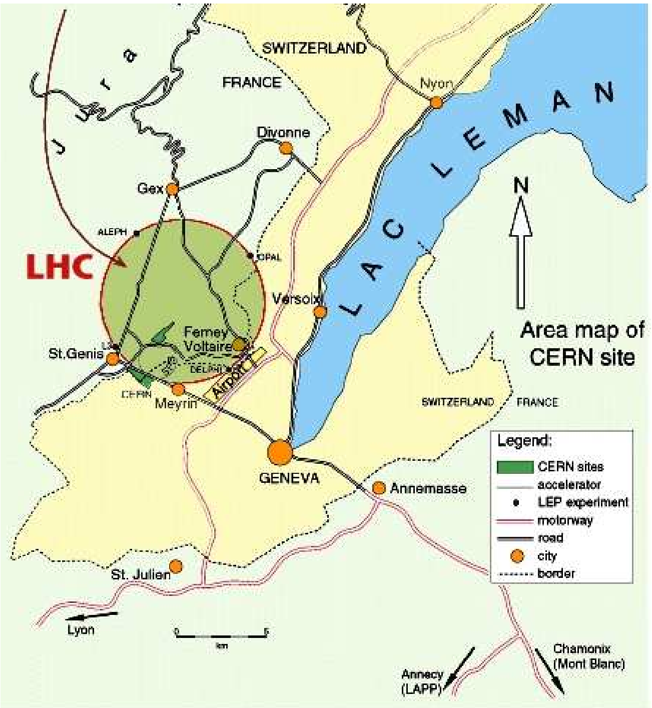
WIMPS are leading contender for dark matter

How to detect WIMPS ?

Large Hadron Collider (LHC) online in 2007 in CERN (Centre Europeen de Recherche Nucleaire).

à accelerator which collides protons and ions head-on at higher energies (Tev) than ever achieved before. Recreate the conditions just after the "Big Bang".

à One of its goals is to characterize WIMPS.



Candidates for Dark Matter

Hot Dark Matter

Hot dark matter are candidates for non-baryonic dark matter. Examples are neutrinos

Hot dark matter share properties 1) to 4) above for WIMPS, but they are very low mass and move very fast such that they do not collect in galaxies. They are dark matter candidates outside galaxies, and between galaxies in clusters

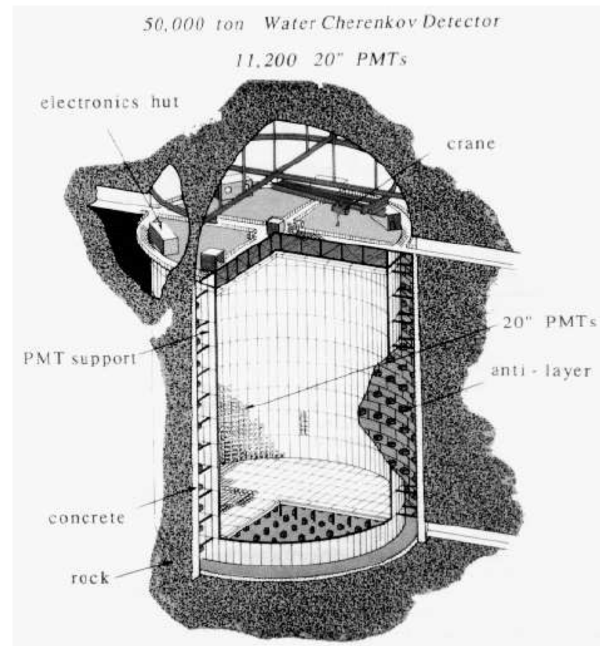
How to detect neutrinos?

Neutrinos are produced in many circumstances

- when the universe was very hot, just after the Big Bang
- when a star explodes as a supernova,
- in nuclear reactions in the core of the sun.
- when cosmic rays interact with O or N nuclei in earth's atmosphere

Super-Kamiokande experiment in Japan

à has detected neutrinos and is characterising their properties



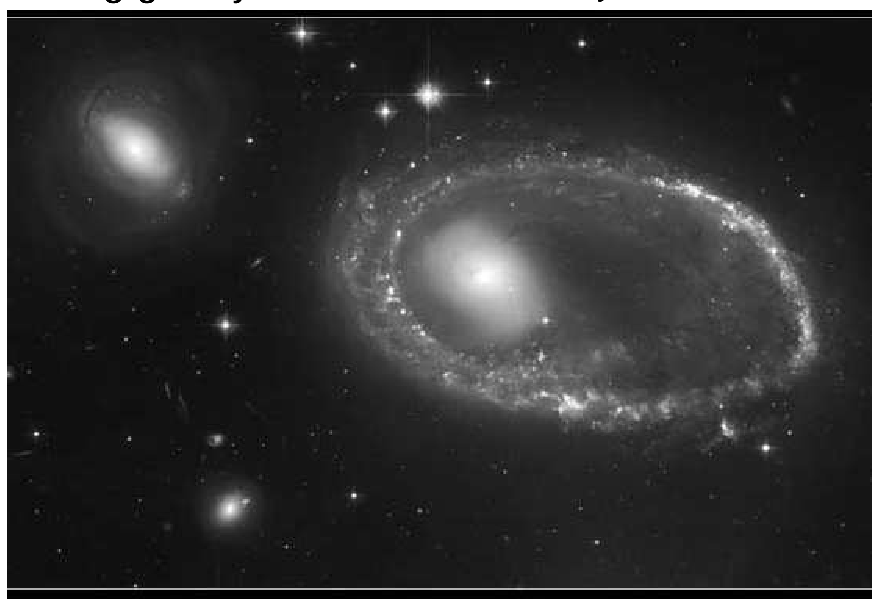
Galaxy Interactions:
Applications to the Milky Way and to Distant Galaxies

Interactions between galaxies can induce dramatic changes in morphology.

Polar ring galaxy
NGC 4650

Cartwheel galaxy
Head-on collision

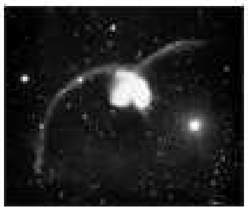
Ring galaxy AM 0644-741 50,000 ly across



Major Merger of 2 spirals and the Toomre Sequence

What is the Toomre sequence? See in-class notes

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:

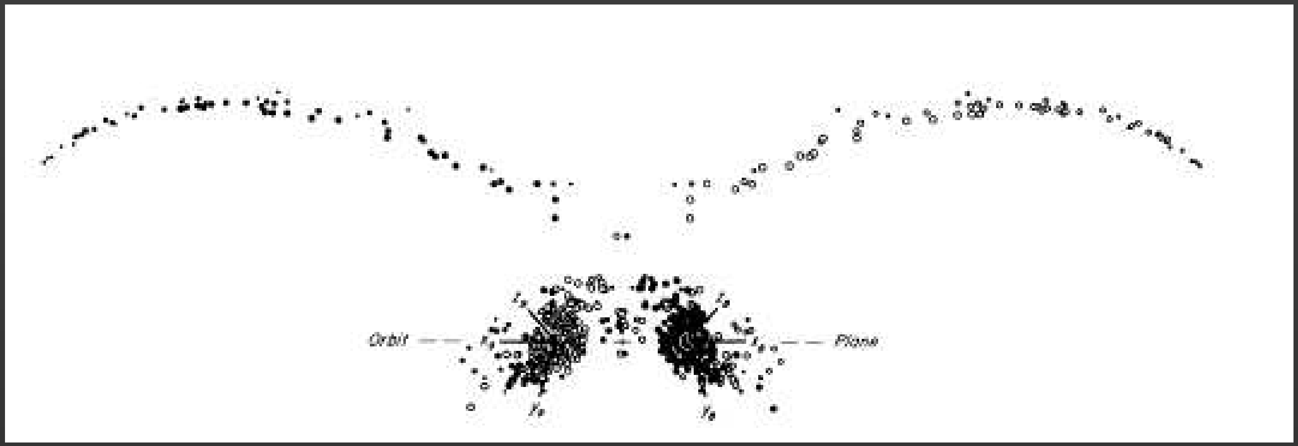
1) Gravitational forces fling out gas and stars into two extended tails. The similar length of the two tails ‘reflect’ the rotation of the two disk galaxies of similar masses.

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

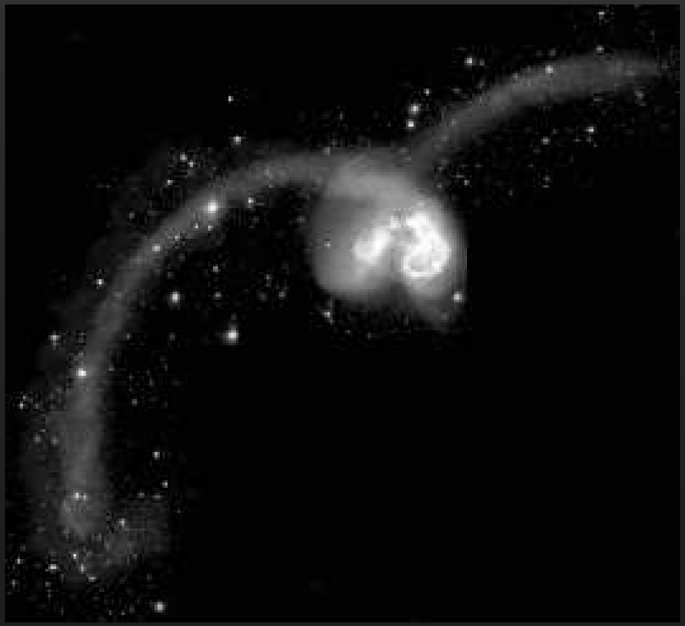
3) The disks are destroyed via a process called violent relaxation. The stars in the two spirals “lose memory” of their disk distributions and redistribute into a spheroidal (water-melon) configuration

4) Thus, get an elliptical galaxy

Major Merger of 2 spirals and the Toomre Sequence

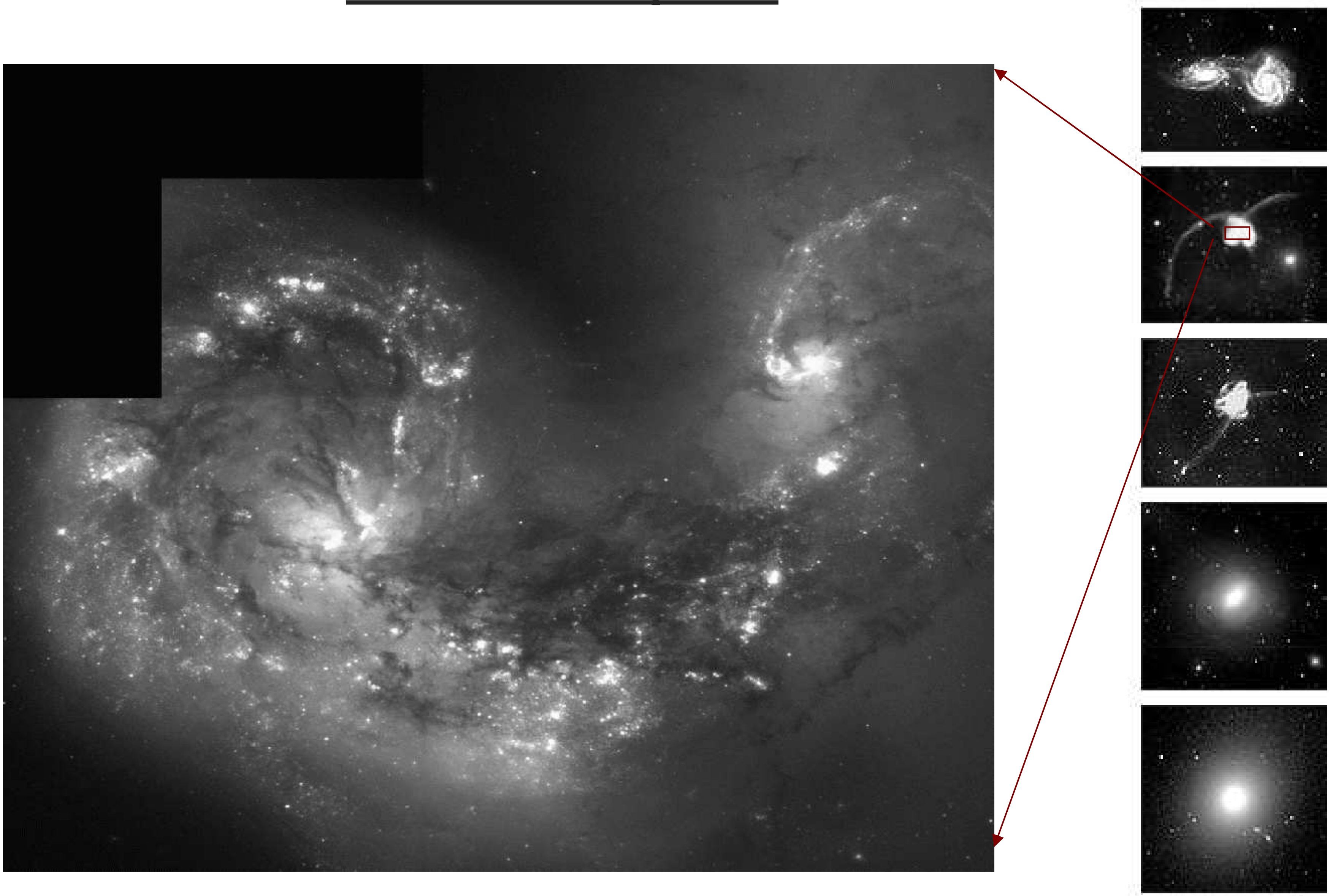


Computer simulation of 'Galactic bridges and tail' by Toomre & Toomre 1972



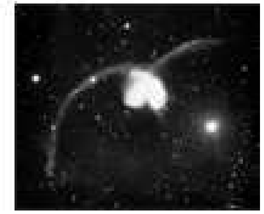
Observation of stars (green) and HI gas (blue) in NGC 4038/39 called The Antennae galaxy.
(J. Hibbard)

The Toomre Sequence



The Antennae system is part of the Toomre sequence (left) of galaxies. It is likely made of 2 spirals of similar masses that have collided. The HST image shows the central region only.

Simulation of Major Mergers

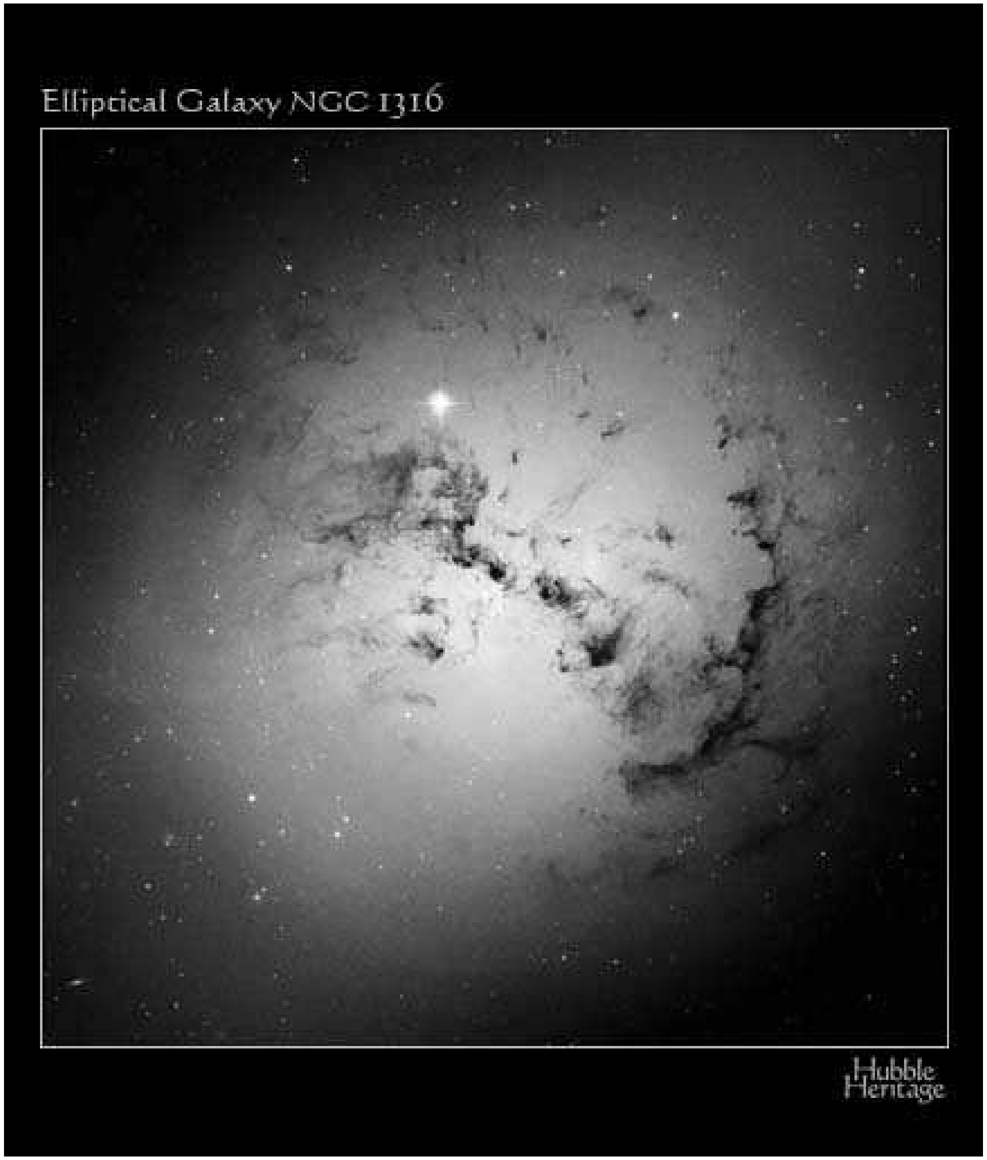


Merger of 2 spirals can produce a dramaticallly different system-à an elliptical galaxy!

Minor Mergers and Cannibalism

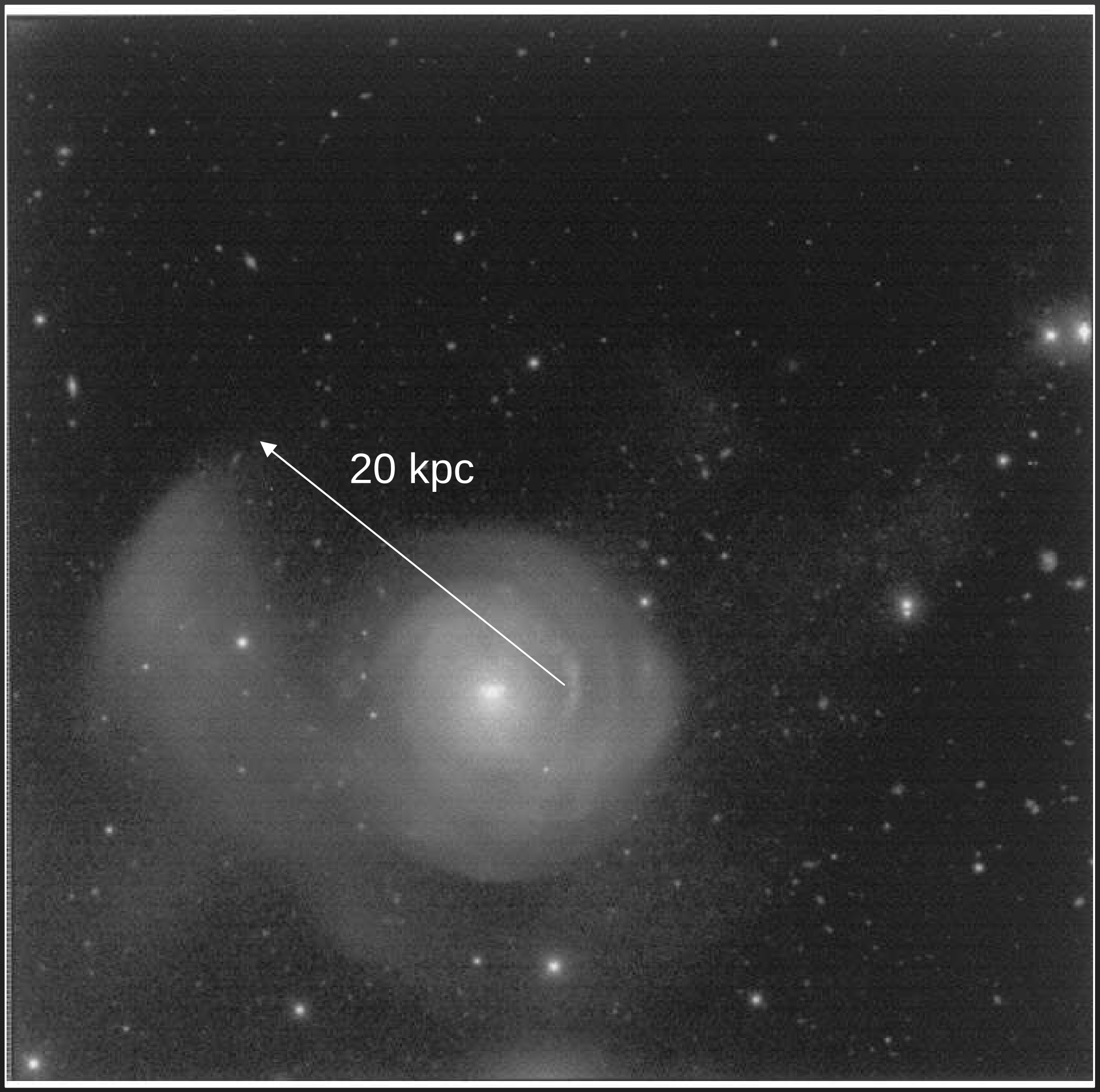
See in-class notes

Minor mergers



An elliptical galaxy (NGC 1316) which has recently cannibalized one or more smaller gas-rich, dust-rich spiral galaxies.

Intermediate mergers



NGC 2782 is the result of a the merger of a spiral galaxy with a smaller disk galaxy, having one quarter of its mass (1:4)

The smaller galaxy moved from right to left and its disk got tidally ripped apart and forms the left hand tail.

The disk of the bigger galaxy survives with a few ripples and disturbances

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, and Irr galaxies LMC, SMC
  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

What's our own Galaxy up to?

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

à It is presenlty 'digesting' the dwarf elliptical Sagittarius.
It has 8 other dE satellites which it may eat up

à It is interacting with the Irr galaxies SMC & LMC, producing the Magellanic stream, a bridge of HI seen in atomic gas gas

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 …..

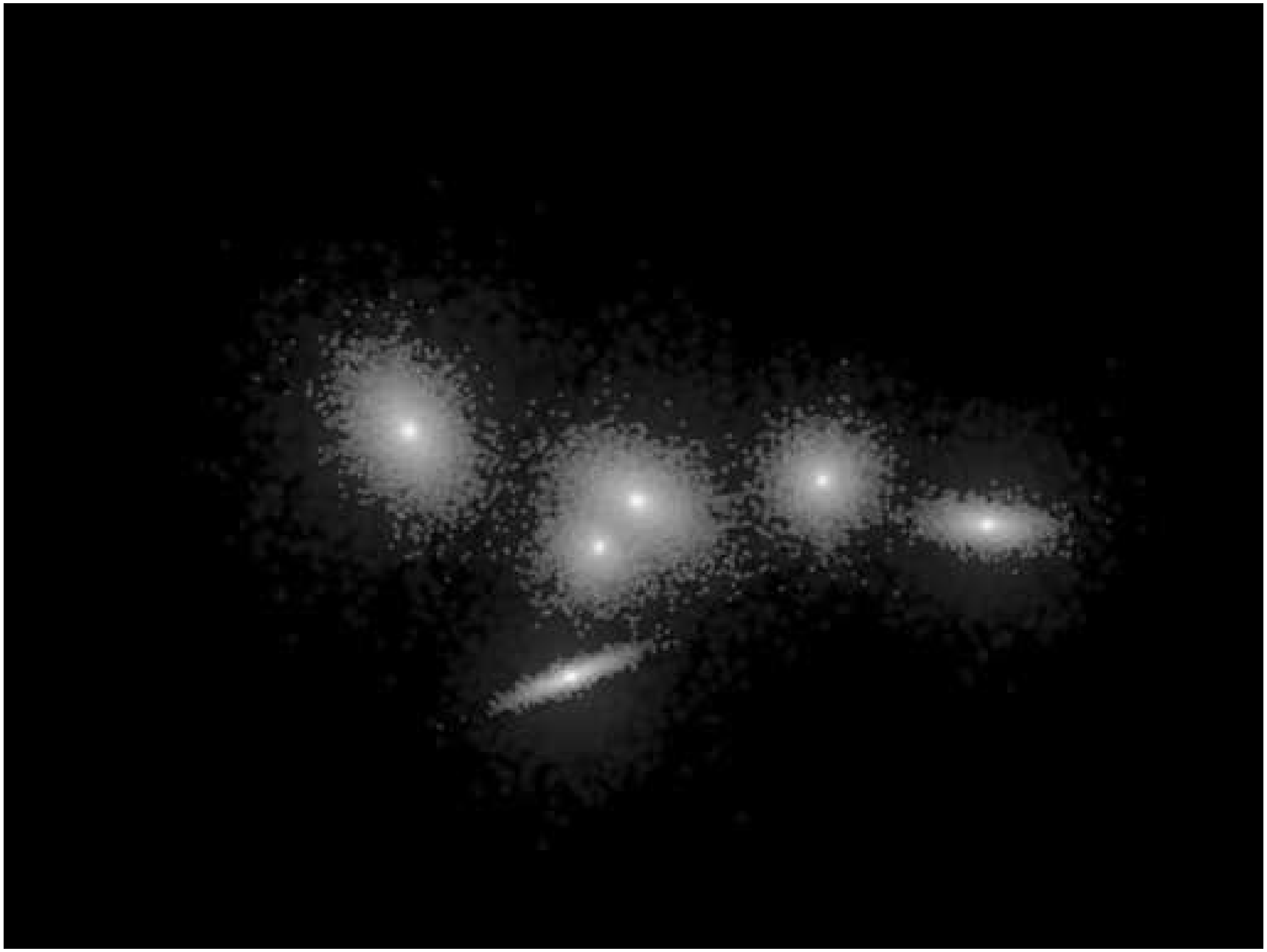
à The Milky Way is moving at 83 km/s toward the M31 (SAb galaxy) 2.5 million ly away.

à It will likely merge in how many Gyr ?.

à What type of merger will this be: major, minor or intermediate?

à What wil be the outcome?
See homework 8, Q3

Multiple Galaxy Collisions in Dense Clusters or Early Universe



Credit : Joshua Barnes (University of Hawaii)