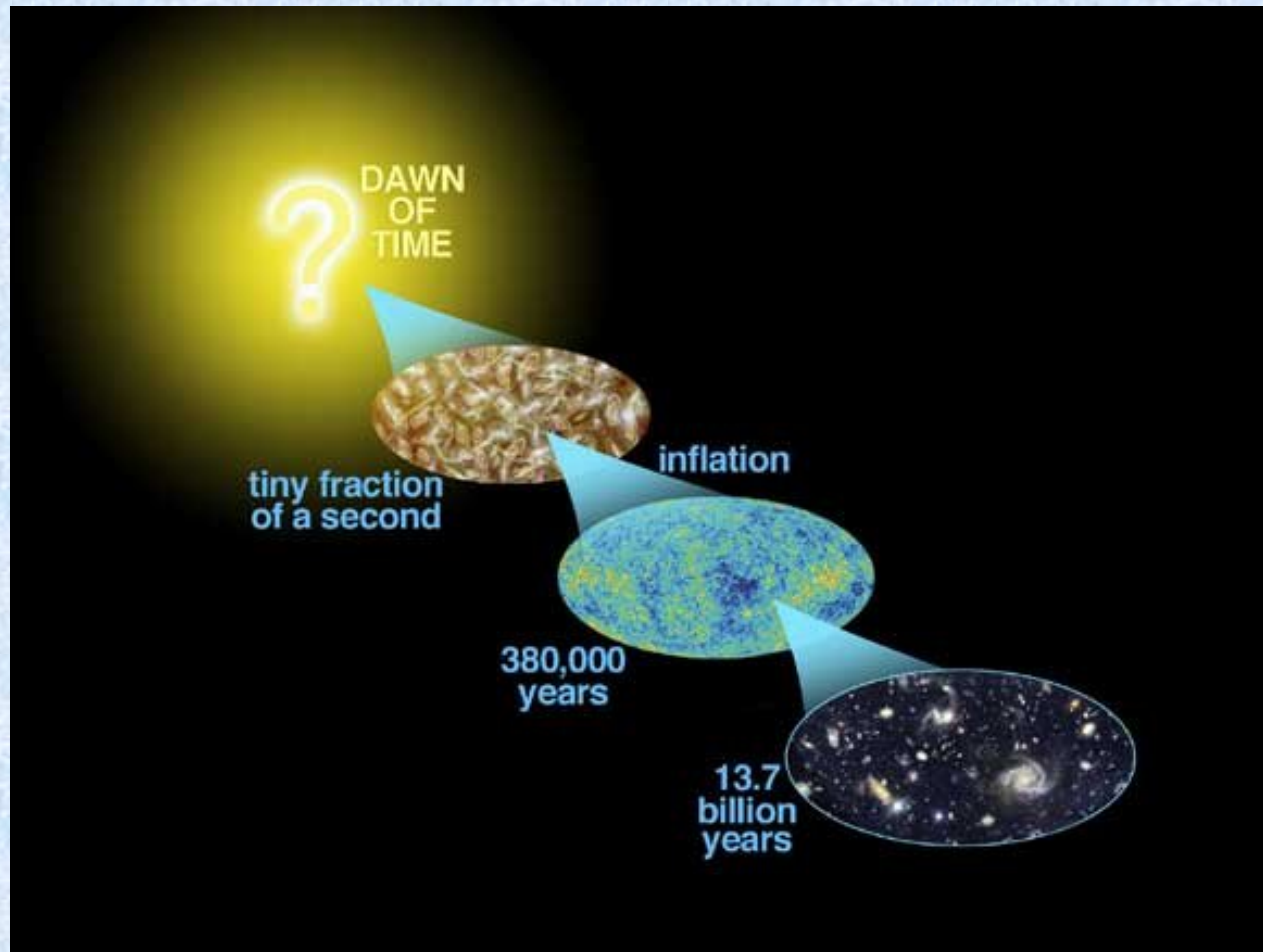


Astro-2: History of the Universe



Lecture 4; April 18 2013

Previously.. On Astro-2

- Galaxies appear to move away from us.
- The measured redshift is proportional to the measured distance through Hubble's Law.
- The constant of proportionality is known as the Hubble constant H_0
- Hubble's Law can be used to infer distances to every galaxy once we know the redshift that is "easy" to measure
- The Hubble constant is uncertain by $\sim 3\%$ and therefore astronomers use redshifts directly, which are much more precise

Previously.. On Astro-2

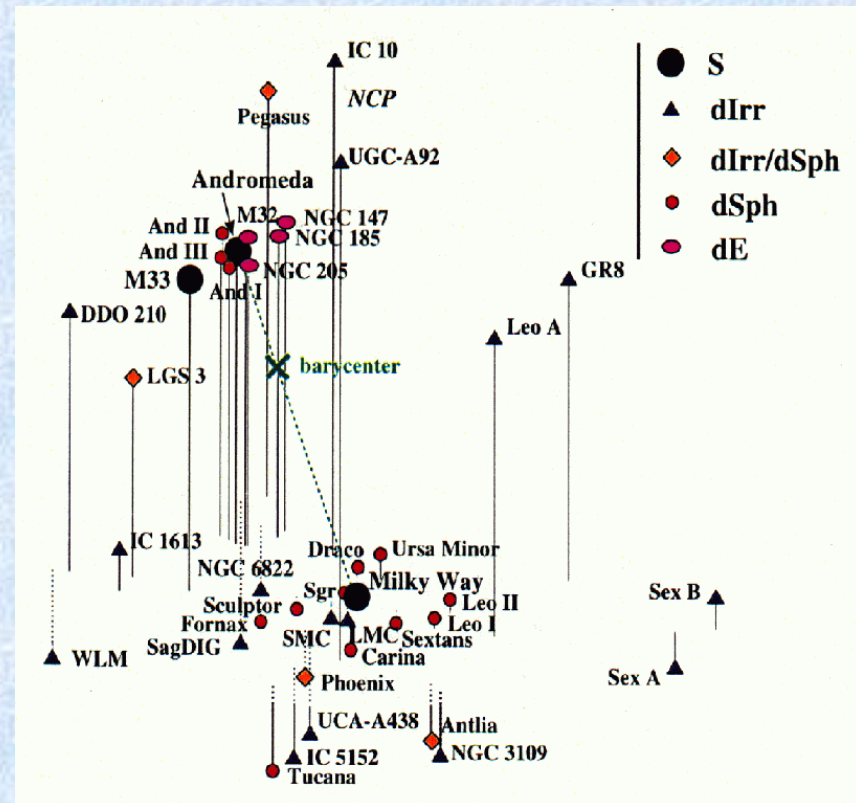
- Hubble's law is interpreted as evidence that the universe is expanding.
- The universe is not expanding into anything, space itself expands.
- The timescale for expansion is given by the inverse of the Hubble constant ~ 10 Gyrs
- The universe is approximately 10 Gyrs old.

Today.. On Astro-2

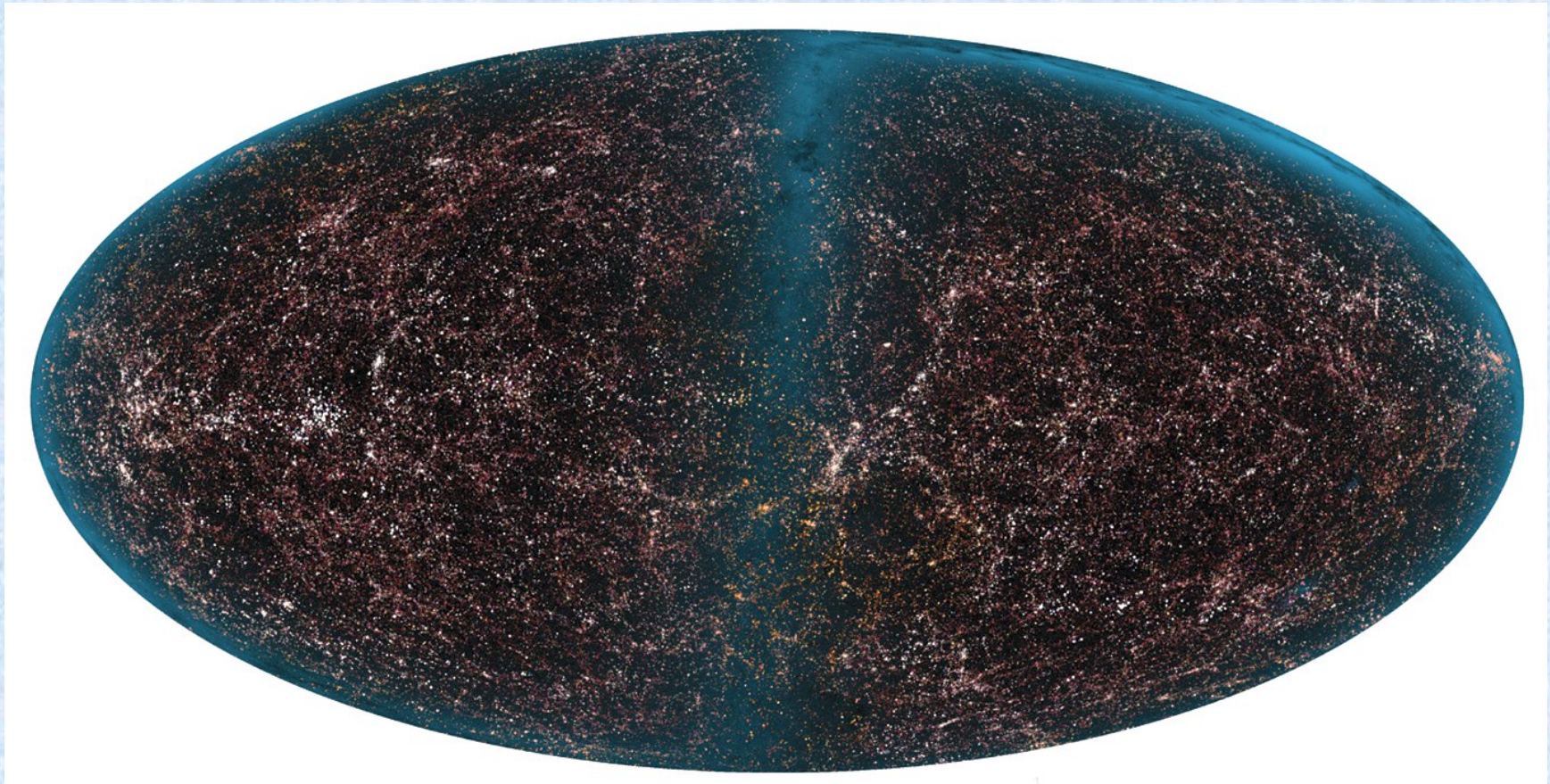
1. Are galaxies isolated? Clusters, groups and large scale structures
2. What happens when galaxies collide?
3. Dark matter

Are galaxies isolated?

- What do you guys think?
- Did we encounter an example of overdensity of galaxies in the first three lectures?
- The local group!



**Are galaxies isolated? Most galaxies
live in overdensities**



Are galaxies isolated?

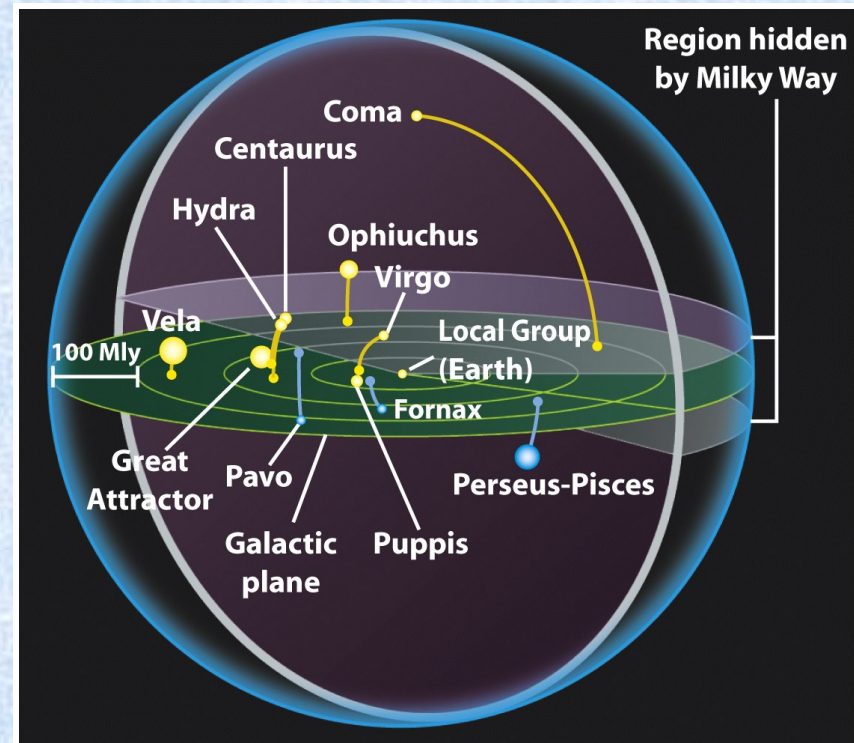
- Large overdensities are called clusters
- Small overdensities are called groups
- The Local Group is a group
- The nearest cluster of galaxies is called the Virgo Cluster and it is about 17 Mpc away



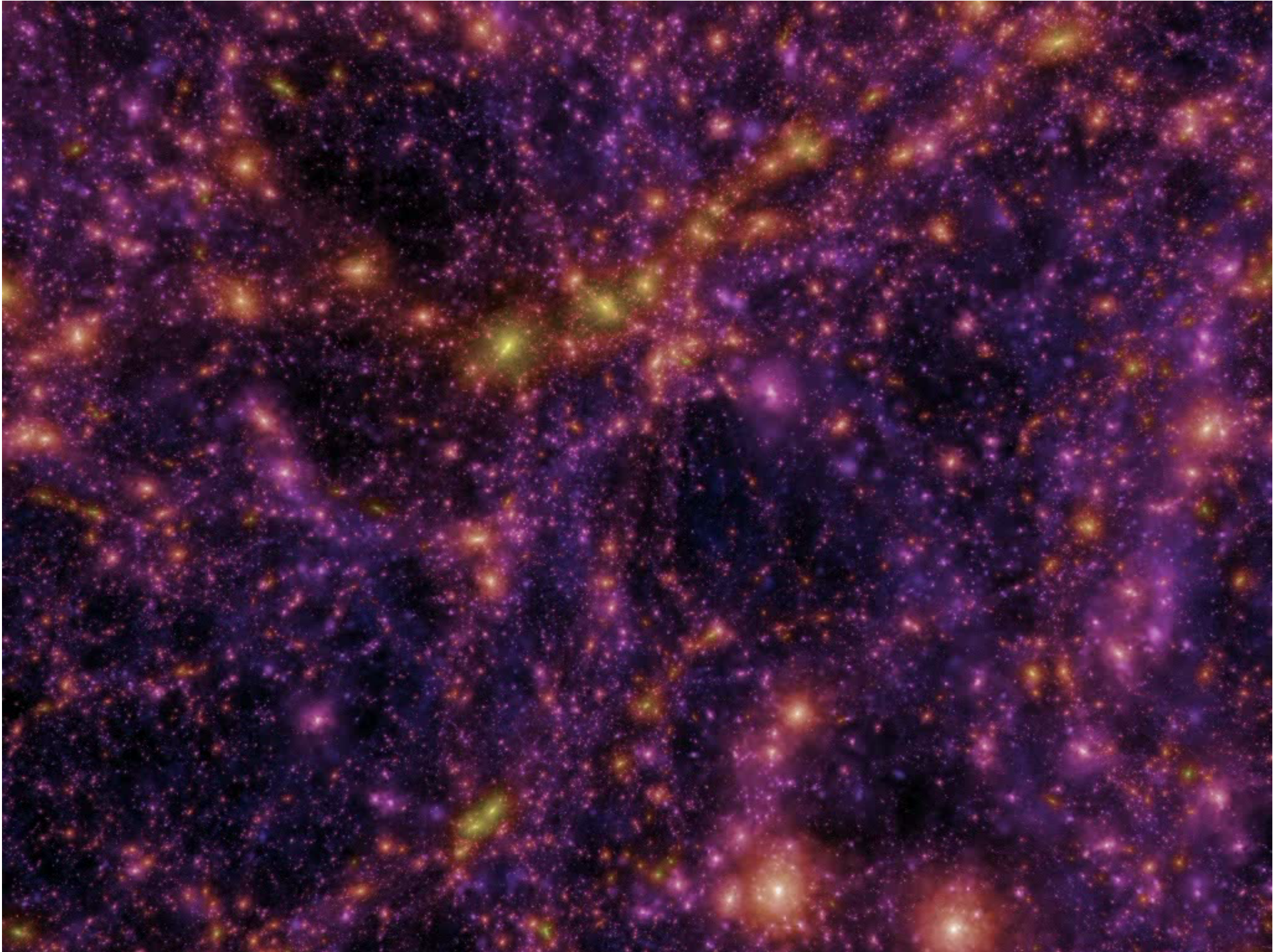
The center of the Virgo Cluster

Are galaxies isolated? Clusters of galaxies

- There are many clusters of galaxies, sometimes organized in even larger structures, called superclusters.
- This is called the large scale structure of the Universe
- MOVIE

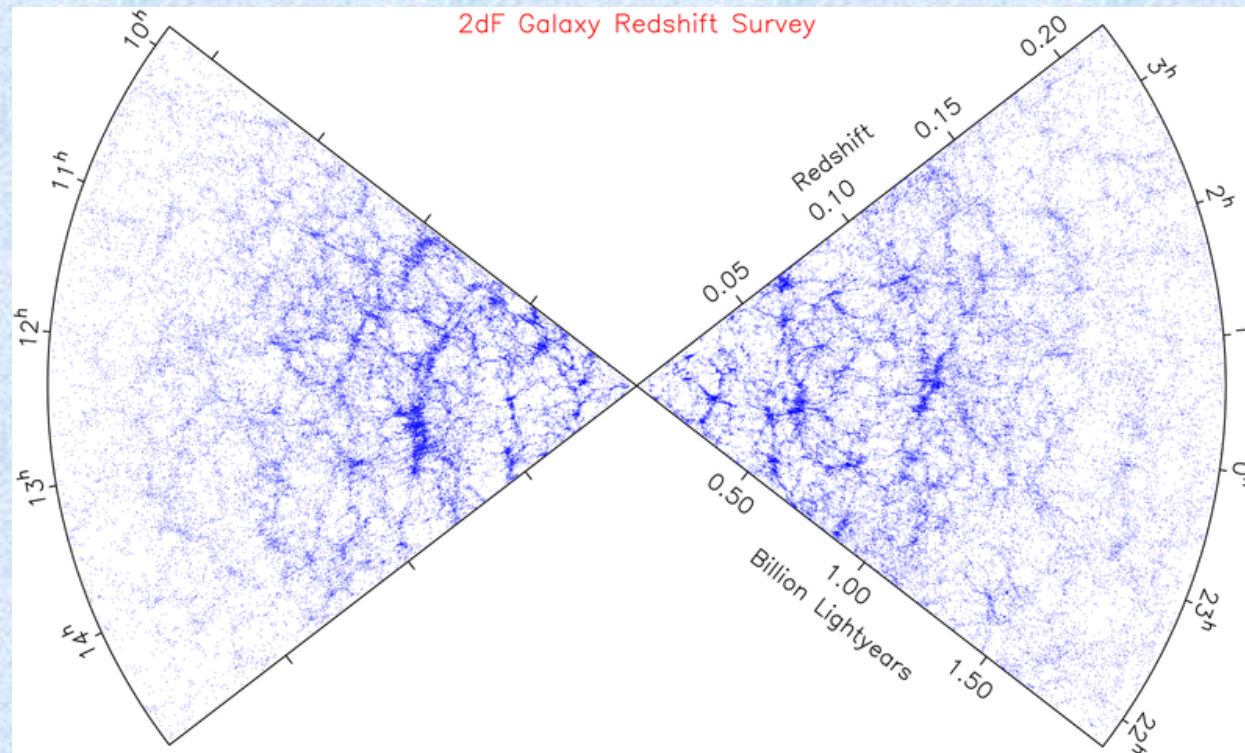


The region around the MW



Are galaxies isolated? Large scale structures

- Astronomers in the last 20 years mapped the local universe, providing a very detailed view of the LSS



Are galaxies isolated? Coma the nearest massive cluster



Are galaxies isolated? Other examples of clusters



Abell 2218



Abell 1689

Are galaxies isolated? Galaxies in clusters

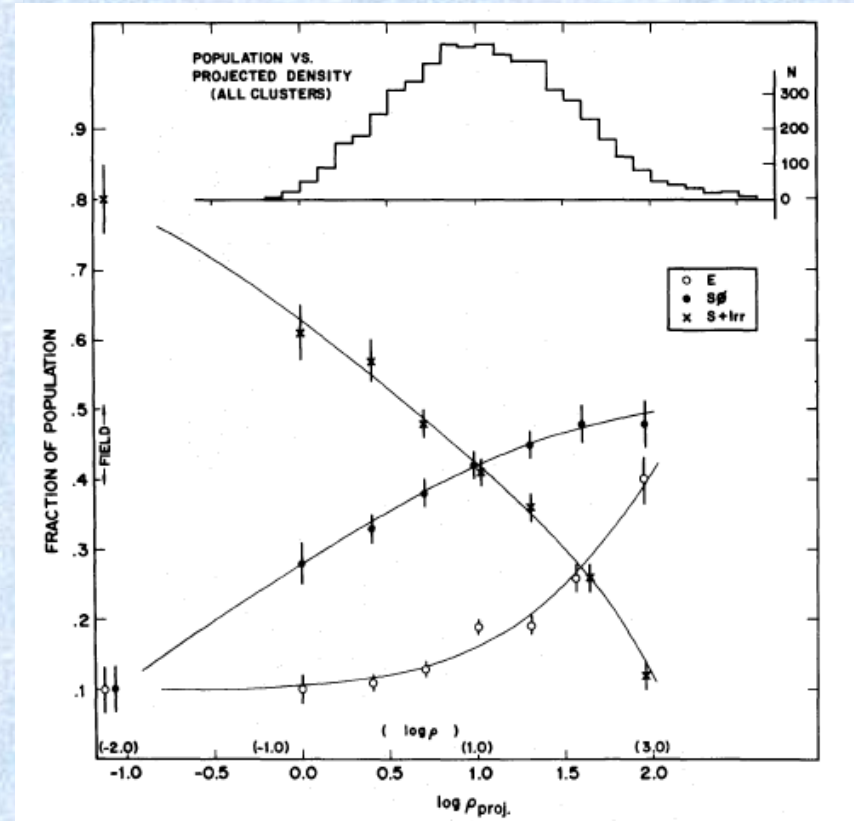
- Do you notice anything special about galaxies in clusters?
- What color/morphology are they?
- This is the so-called morphology density relation



Abell 1689

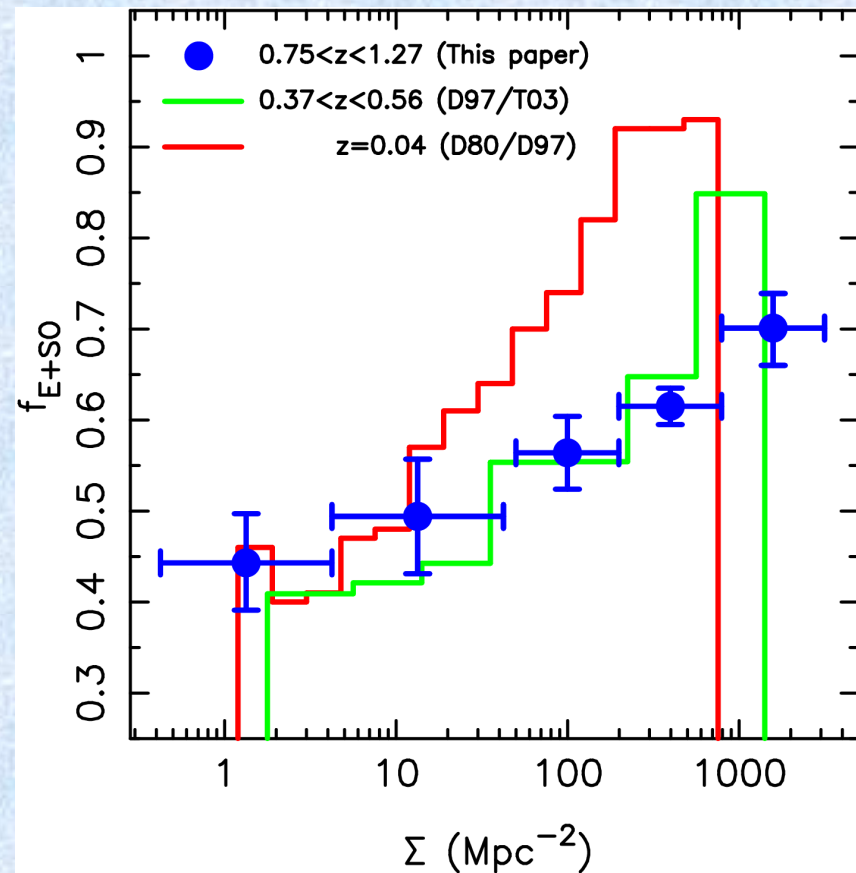
Are galaxies isolated? Morphology-Density relation

- The fraction of elliptical galaxies increases with local density of galaxies
- The fraction of spiral galaxies decreases with local density
- The fraction of lenticular galaxies more or less follows that of ellipticals
- This unsolved puzzle is thought to be connected to the formation of galaxies



Are galaxies isolated? Evolution of the Morphology-Density relation

- The fraction of elliptical and lenticular galaxies in dense regions is much lower at high redshift, back in time
- This suggests that galaxies are transformed from spirals to elliptical/lenticulars are relatively recent time



Are galaxies isolated? How massive are clusters?

- Clusters are gravitationally bound systems
- Like elliptical galaxies, they do not rotate, they are pressure supported
- Galaxies move very fast in clusters up to several thousands of km/s
- As for elliptical galaxies, we can measure their mass using the virial theorem
- $M = k \sigma^2 R / G$
- The most massive clusters are up to 1 million of billions of solar masses



Summary 1

- Galaxies do not live in isolation but in larger structures
- The structures are called groups (like the local group we live in)
- Clusters, like the Coma and Virgo Clusters
- Superclusters, that contain many clusters
- This is called the large scale structure of the universe
- The morphological mix depends on local density!

What happens when galaxies collide?



Antennae

What happens when galaxies collide? A galaxy merger

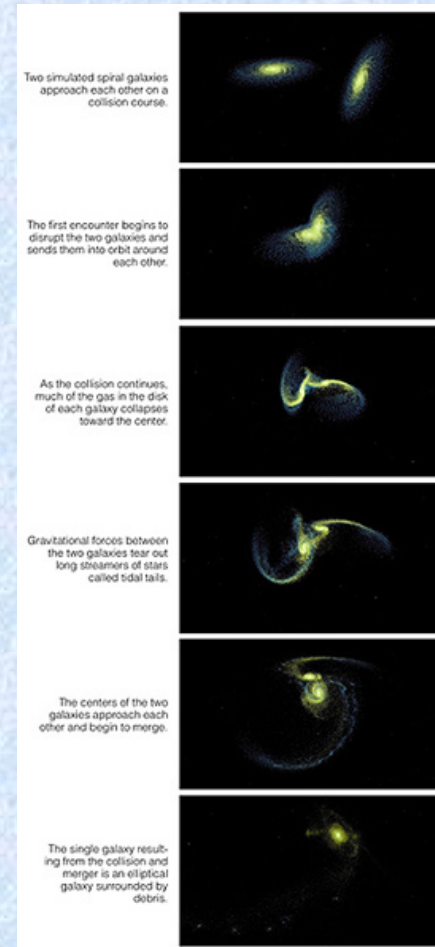
- Every now and then galaxies collide, especially in groups
- Mergers are devastating events, they change the morphology of galaxies as well as their stars

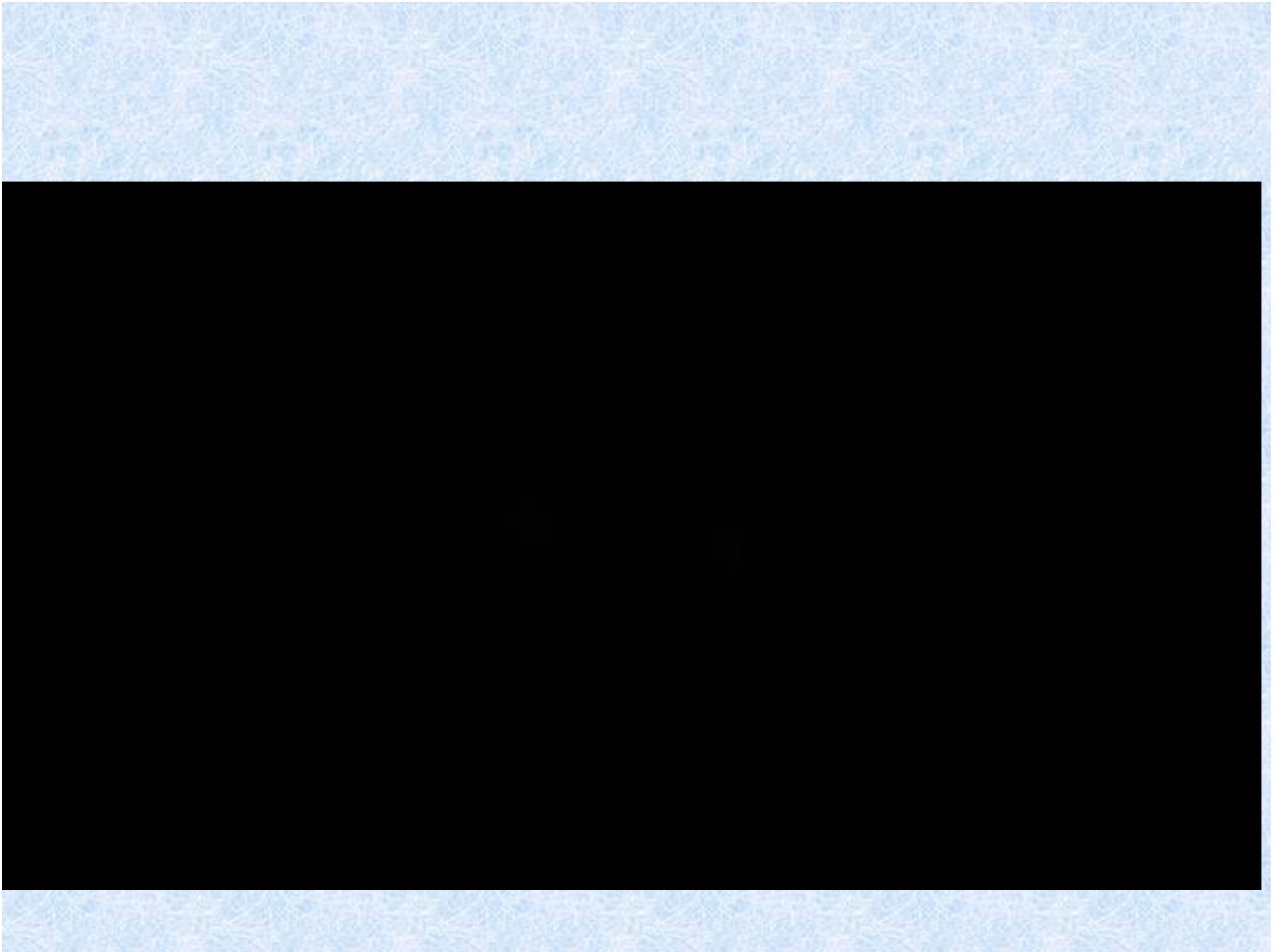


Mice

What happens when galaxies collide? A galaxy merger

- Mergers can transform two spirals into an elliptical galaxy or a bulge of a spiral
- In the standard cosmological model galaxies are always born as spirals, they transform into ellipticals only via subsequent mergers
- MOVIE





Galaxy mergers? Discussion

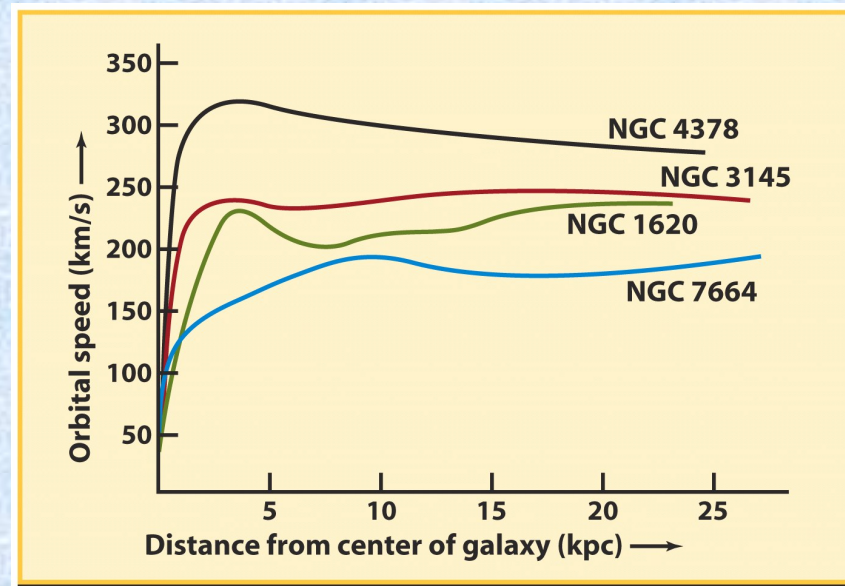
- Galaxies initially form as spirals
- Ellipticals form by mergers of spirals
- Which ones have the oldest stars?
- Ellipticals
- Why?

Summary 2

- Sometimes galaxy collide and merge
- Merging can induce bursts of star formation and changes in morphology
- One of the central assumption of the standard model of galaxy formation is that elliptical galaxies form by mergers of spirals

Dark matter. Galaxies

- Rotation curves
- If you count all mass than you can detect it is not nearly enough to produce the observed rotation curve.
- Two options:
 - 1) There is an extended halo of dark matter
 - 2) Gravity is wrong



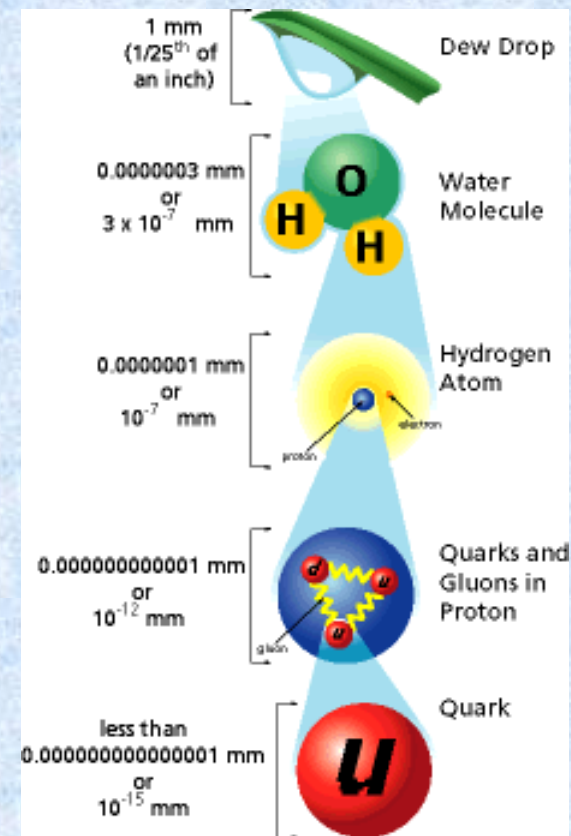
Dark matter. Clusters

- Back in the 30s a swiss astronomer named Zwicky measured the speed of galaxies in the Coma Cluster
- Using the virial theorem he found out that the its mass was much larger than he could account for with the observed mass.
- This has been confirmed many times in all clusters
- Again this is evidence for dark matter, or for a problem with gravity (will discuss this in the next lecture).



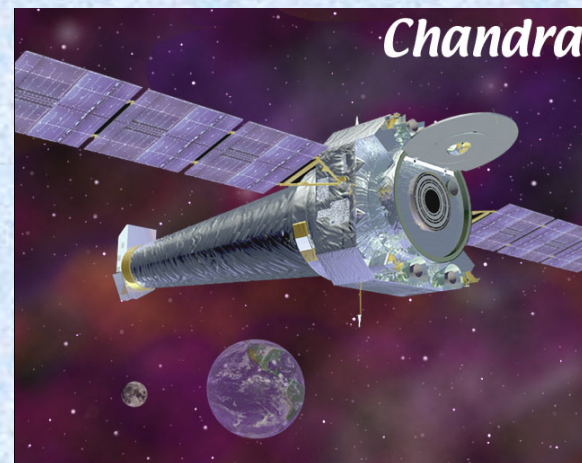
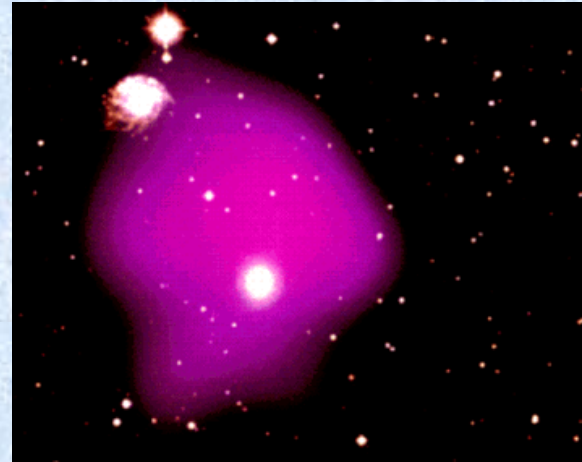
Dark matter. Brief excursion on particle physics. 1

- According to our understanding of particle physics, ordinary matter is constituted of baryons (from greek heavy) and leptons (from greek light).
- Baryons (protons and neutrons) are made of quarks and make up most of the mass of ordinary matter, like water



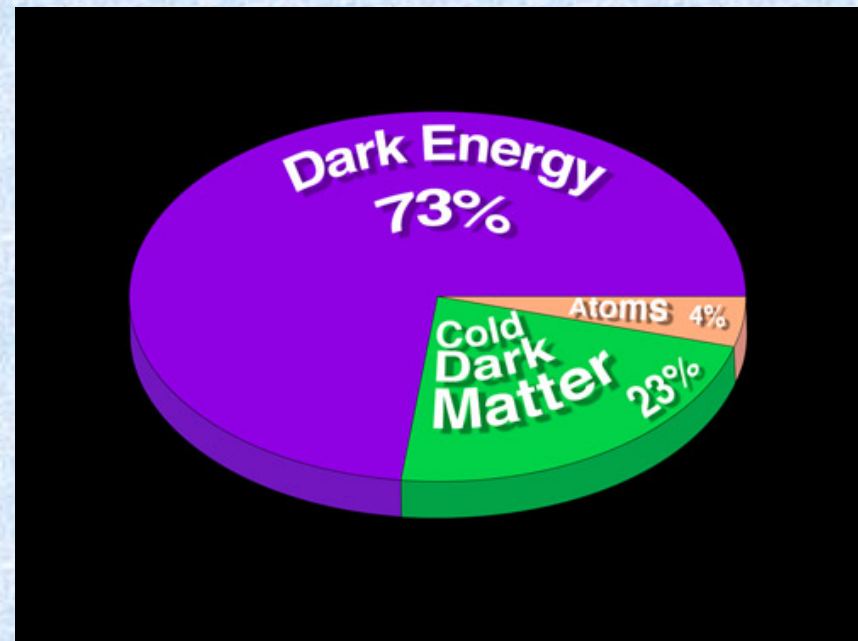
Dark matter. In clusters most of the “baryonic” mass is hot gas

- X-ray observations show that the majority of baryonic mass in clusters is in the form of hot gas (1,000,000 K). Much more than the mass in stars!
- The gas is too hot given the visible mass. Pressure support arguments applied to the cluster gas (like a balloon) imply that there is much more mass than meets the eye
- Even considering all the hot gas, we can account for only 10% of the mass of a cluster. The rest remains undetected, and is called dark matter
- Next time we will discuss whether dark matter is baryonic or not and alternatives to dark matter



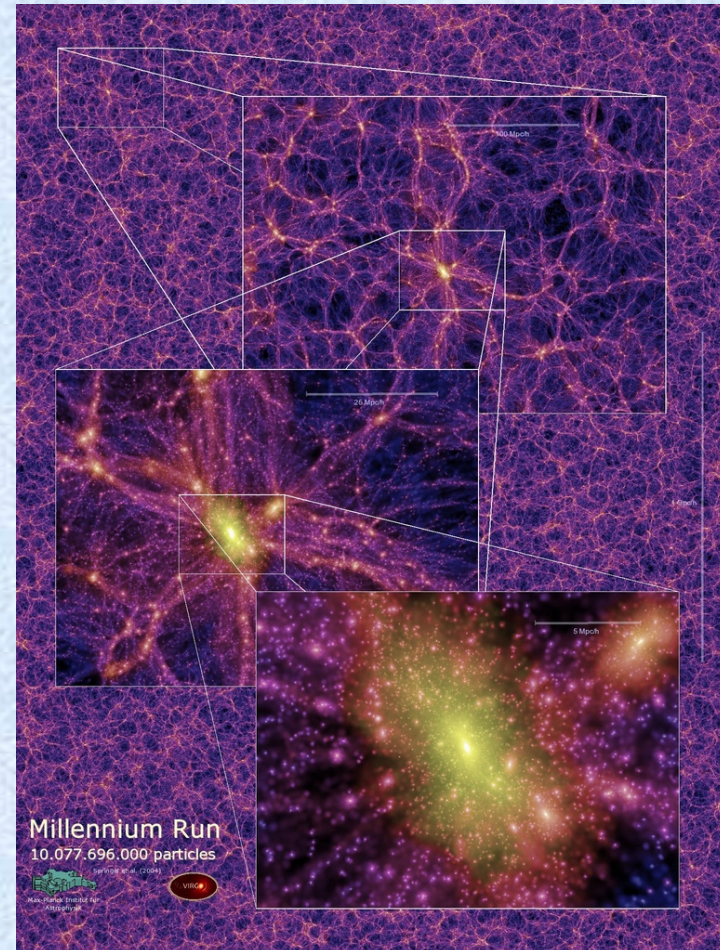
Most of the matter of the Universe is non-baryonic and dark

- According to this and other evidence, most of the mass in the universe is in the form of a mysterious entity called dark matter
- Atoms are only 1/6 of dark matter
- Baryons and dark matter are a minority of the energy of the universe.



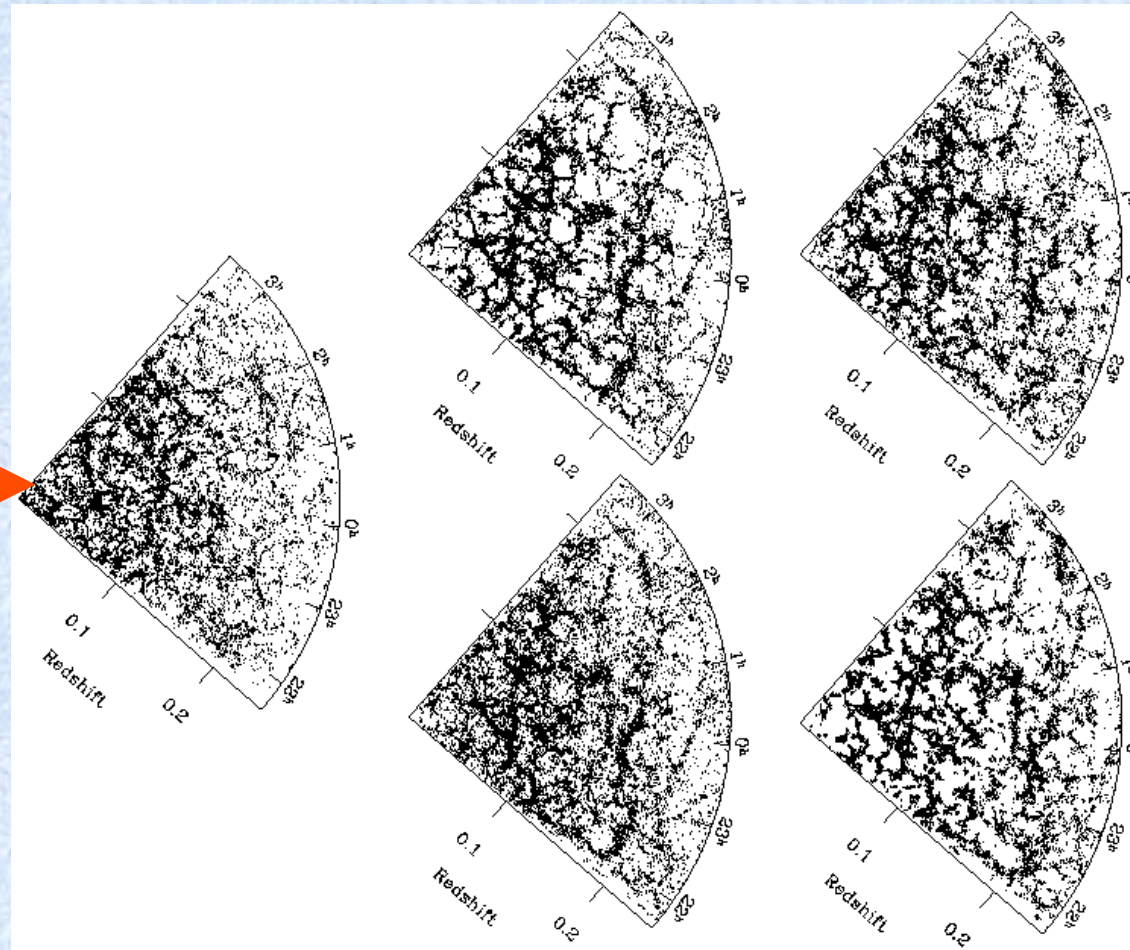
The standard model: galaxies live in dark matter halos

- Since most of the mass of the universe is in the form of dark matter, this dominates the dynamics of the universe
- Cosmological numerical simulations can reproduce from first principles the appearance of large scale structures of the universe based on dark matter



Comparison of 2dF data and model

Real data



The substructure “crises” of the standard model



A possible solution to the substructure “crises”

- Satellites are present also at galaxy scales, but they are not visible because they do not form stars efficiently
- How can we detect them if we do not see them? (next time..)



Summary 3a

- The motion of stars in galaxies and that of galaxies in clusters cannot be explained by the gravitational field of known matter
- This has been interpreted as evidence for exotic dark matter
- Dark matter makes up most of the mass of the Universe

Summary 3b

- In the current standard model galaxies and clusters live in dark matter halos
- This model successfully reproduces the properties of the universe on large scales
- There are problem on small scales, such as the substructure problem. Perhaps the model is not right...we shall see!

The End

See you on tuesday!