Station #6, "Cosmic Web"

Lecture 18: Clusters of Galaxies and Beyond

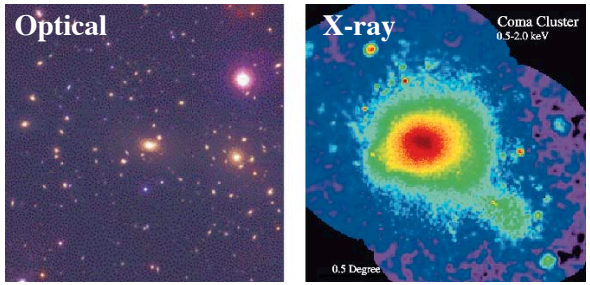
Lecture 19: Dark Matter and Dark Energy

Lecture 18
Clusters of Galaxies and Beyond

Reading: Chapter 22

Clusters of Galaxies

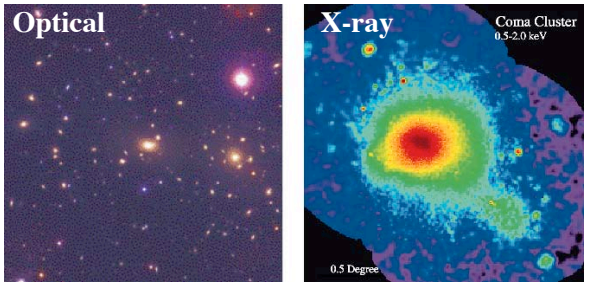
- The largest bound objects in the universe.
- A cluster typically contains 100-1000 galaxies.
  - Remember, EACH galaxy is also a bound object containing 100 billion stars.
  - Clusters are the upper hierarchy of galaxies.



Coma Cluster

Intracluster Medium (ICM)

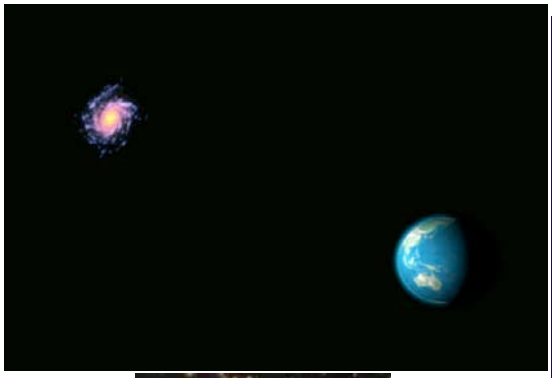
- What is out there between galaxies within a cluster?
  - A. The intracluster medium (ICM)
  - ICM contains hot gas emitting X-ray.
  - Gas was heated by gravitational potential energy. (Energy conservation again!)
  - Mass of a cluster is 100-1000 times the mass of galaxies --> Such large mass can heat the gas to 10 million to 100 million degrees.

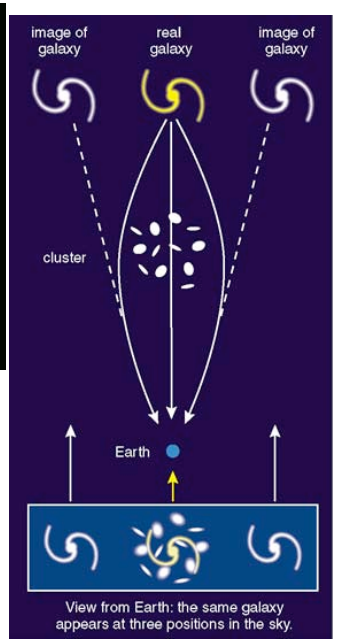


Coma Cluster

Clusters as a cosmic lens

- Large mass of clusters influences path of light.
  - That's **gravitational lensing**.
- Einstein's Theory of Relativity states that massive objects distort spacetime.
  - a massive cluster will bend the path of light which approaches it (like a lens)
  - the blue arcs are the lensed images of a galaxy which is behind the cluster



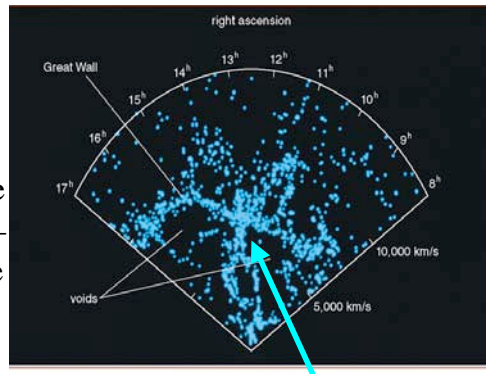


Clusters and Dark Matter

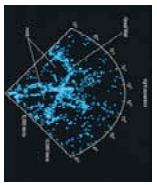
- The amount of gravitational lensing depends crucially on the mass inside a cluster.
- This property enables us to measure the mass in a cluster.
- It turns out that the mass of a cluster is much greater than what it appears – invisible form of matter must be there – "DARK MATTER".
- Remember that individual galaxies also contain nearly 10 times as much dark matter as visible matter.
- Clusters contain nearly 100 times as much dark!

Cosmic Web: Outside of Clusters

- Clusters of galaxies are merely "knots" of even larger scale structure.
- The largest scale structure looks like a spider's web -- Therefore, it's called the "**Cosmic Web**".
- There are "walls" and "voids".

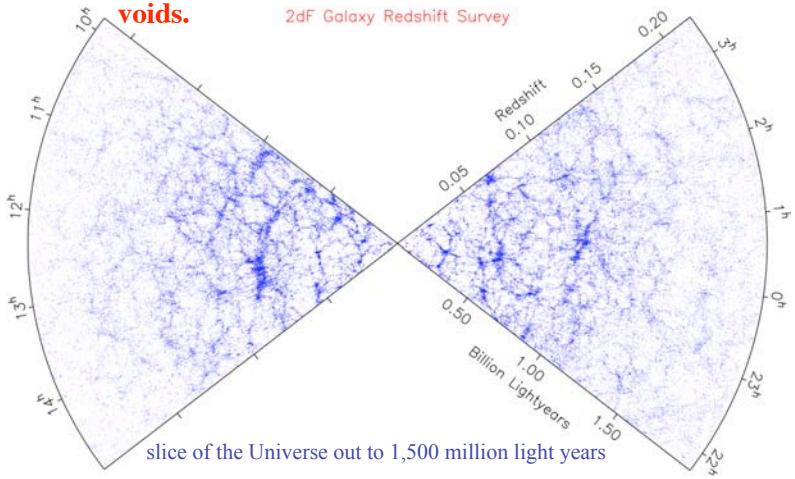


slice of the Universe out to 700 million light years



Cosmic Web Continues…

- **Universe is filled with Cosmic Web.**
- **There are many clusters at knots as well as voids.**



slice of the Universe out to 1,500 million light years

Powers of Ten Revisited

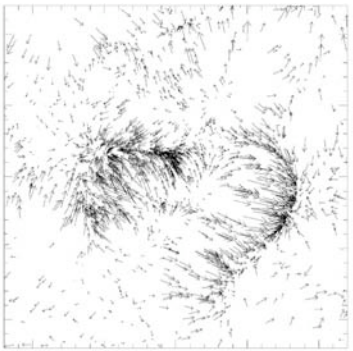
- Hierarchical Structure of the Universe
  - The largest scale: Uniform (10 billion light years)
  - Cosmic Web "Filaments & Voids" (1 billion light years)
  - Clusters of galaxies (100 million light years)
  - Local Group (10 million light years)
  - Galaxy Neighborhood (1 million light years)
  - Galaxy (Milky Way) (100,000 light years)
  - :
  - Nearest Star (4 light years)
  - :
  - Solar System (0.001 light years, or 70 AU)

The Origin of the Cosmic Web

- In the early universe, there was no web.
  - The universe is highly homogeneous.
- But, there were ***tiny irregularities*** in matter distribution.
- These irregularities are **amplified by gravity** to form galaxies, clusters of galaxies, and the web.
- It's gravity again!!
- Because gravity is all that matters here, and we understand laws of gravity, we can "simulate" development of the web using computer simulations.

The Growth of Structure

- At close range, gravitational attraction overcomes the Hubble expansion.
  - we see this in a galaxy's **peculiar velocity**
  - although the Universe as a whole expands, individual galaxies attract one another
  - peculiar velocity is a galaxy's deviation from the Hubble Law



Seeking for the "Right Answer"

- Besides gravity, we need to assume several things when simulating the cosmic web:
  - How fast the universe is expanding? (Hubble's constant)
  - How much dark matter does it exist?
  - How did the initial tiny irregularities look?
- By comparing simulated data with the observations of clumpiness, we can determine these key ***cosmological parameters***.
- Then, using the cosmological parameters determined from observations, we can calculate the age of the universe, and even predict the fate of the universe.

Even Larger Scales? Cosmic Horizon

- If the speed of light were infinite, then one would be able to see the entire Universe.
- However, since the speed of light if finite, AND the age of the universe is finite, there is the "cosmic horizon" beyond which one cannot see anything ***yet***.
- Will we see more of the universe as time goes by?
- **It depends**…
  - Cosmologists have believed for a long time that we will continue to see more of the universe as time goes by.
  - The recent discovery of "**Dark Energy**" has changed this picture completely --- in the future, we will see LESS of the universe!!
  - In other words, the cosmic horizon will become smaller.

Next Lecture: The Biggest Mystery!

- Dark Matter and Dark Energy
  - Reading: Chapter 22

- Quiz#5 Next Tuesday (Nov 9)
- Homework#5 also handed out on Nov 9