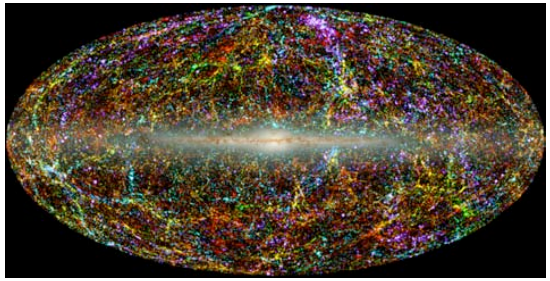
Lecture 15: Dark Matter and the Cosmic Web
(plus Gamma Ray Bursts)

Prof. Tom Megeath A2020

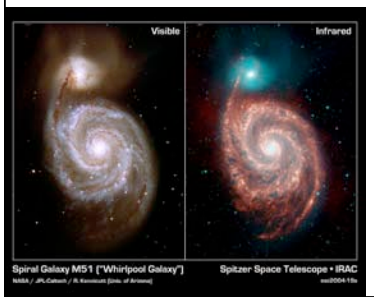


Disk Component:
stars of all ages,
many gas clouds

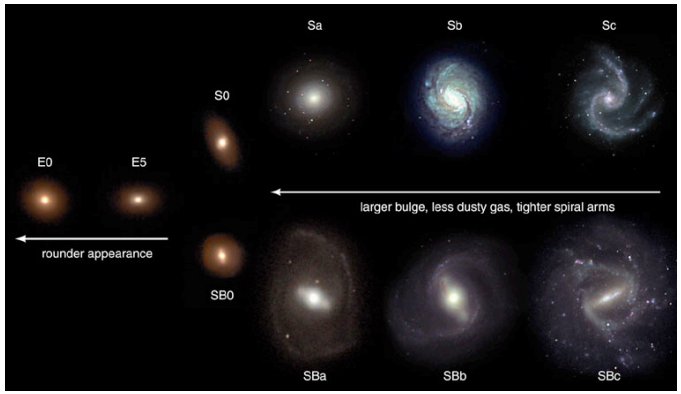
Review of Lecture 15

Spheroidal Component:
bulge & halo, old stars, few gas clouds

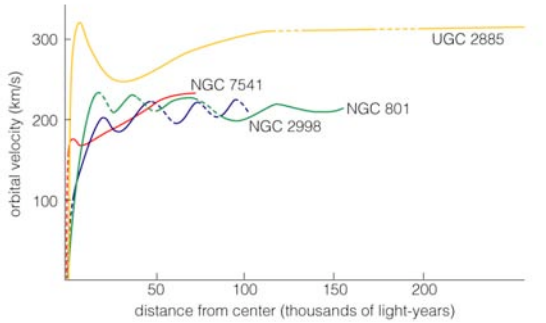
Review: Classifying Galaxies by their Morphologies (i.e. shapes)

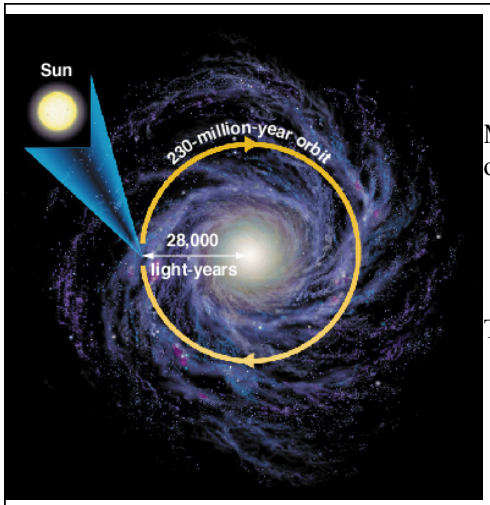


Review of Lecture 15



What is the evidence for dark matter in galaxies?





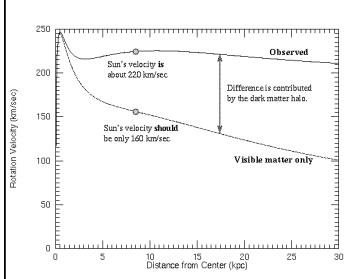
Mass within Sun's orbit:

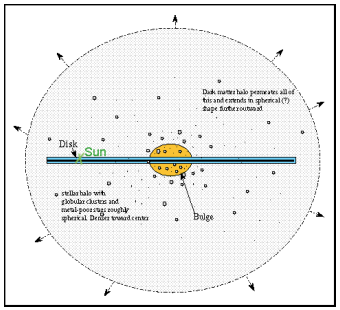
$1.0 \times 10^{11} M_{\text{Sun}}$

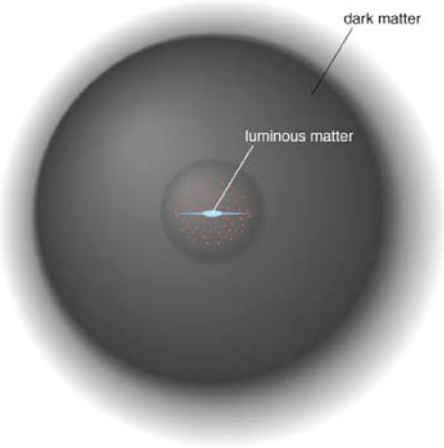
Total mass:

$\sim 10^{12} M_{\text{Sun}}$

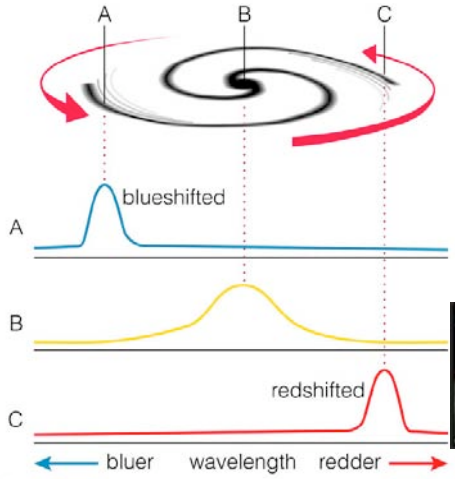
Dark Matter in Galaxy





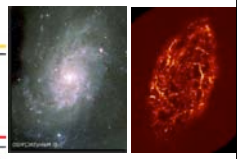


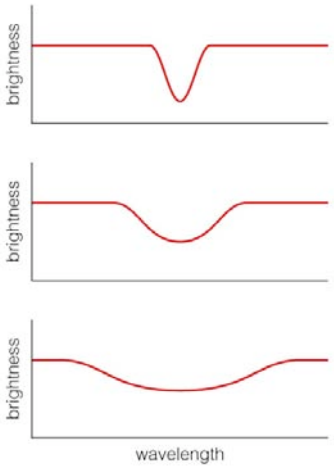
The visible portion of a galaxy lies deep in the heart of a large halo of dark matter



Dark Matter in Spiral Galaxies

In spiral galaxies we can measure rotation curves of other spiral galaxies using the Doppler shift of the 21-cm line of atomic H



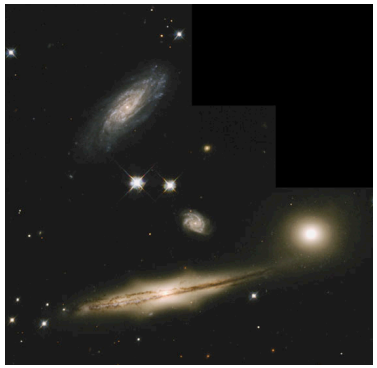


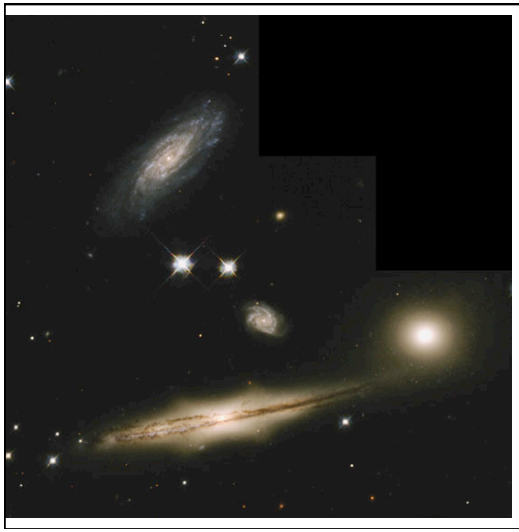
Dark Matter in Elliptical Galaxies

Broadening of spectral lines in elliptical galaxies tells us how fast the stars are orbiting

These galaxies also have dark matter

How are galaxies grouped together?





Spiral galaxies are often found in ***groups*** of galaxies

(up to a few dozen galaxies)

Elliptical galaxies are much more common in huge ***clusters*** of galaxies

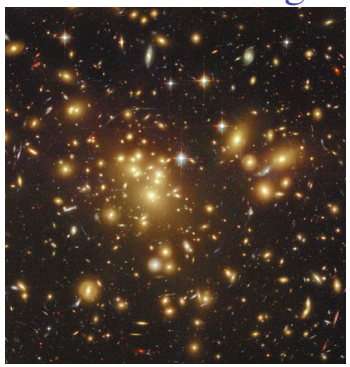
(hundreds to thousands of galaxies)

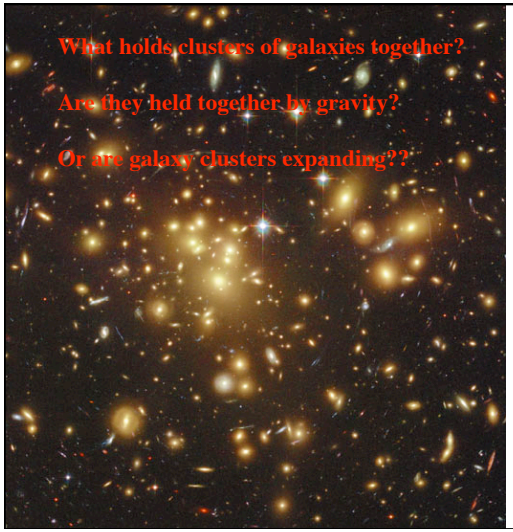
The cluster is thought to be held together by gravity.

There is not enough mass in the observed galaxies to bind the cluster by gravity.

Abell 1689

What is the evidence for dark matter in clusters of galaxies?



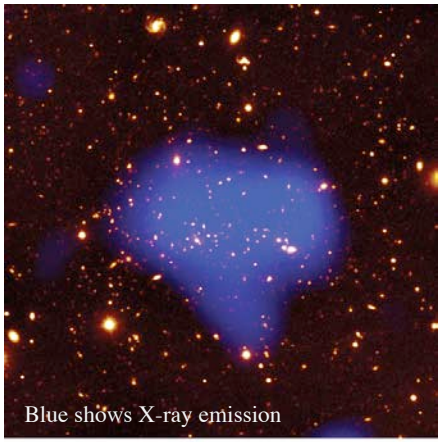


We can measure the velocities of galaxies in a cluster from their Doppler shifts

We can measure the number of stars by the brightness of the galaxies.

The mass we find from galaxy motions in a cluster is about ***50 times*** larger than the mass in stars!

10 million degree gas in galaxy clusters!



Clusters contain large amounts of X-ray emitting hot gas. We can estimate the ***mass of the hot gas*** from the X-ray emission.

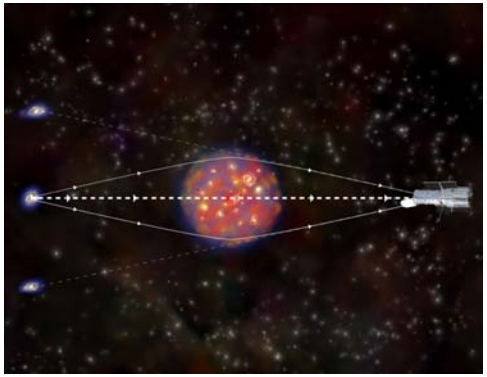
Plus, the temperature of the hot gas (particle motions) gives us an independent measure of the ***total*** cluster mass, *assuming the gas is bound by gravity to the cluster*:

2% stars
13% hot gas

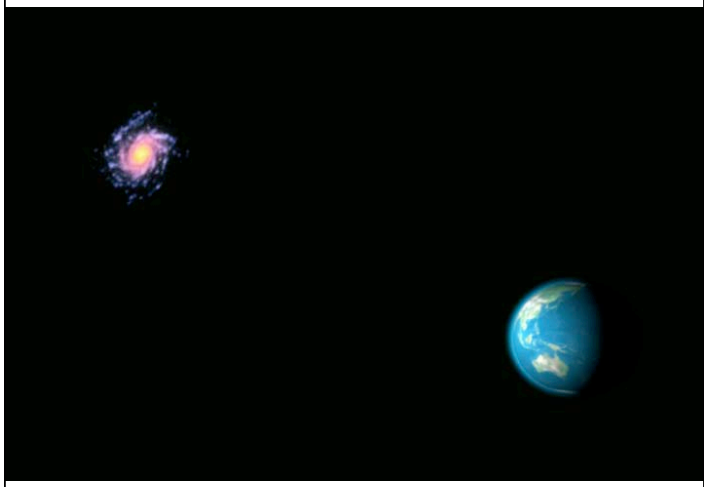
The remainder has to be something "else":

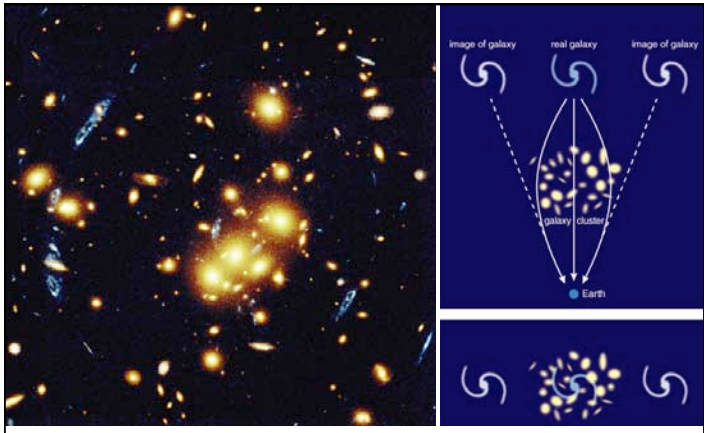
85% dark matter

Directly Measuring the Mass of Dark Matter in Clusters of Galaxies



Gravitational lensing provides an estimate of the total mass.





Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster's mass

Doppler shift, measurements of the X-ray emitting hot gas, and gravitational lensing indicate similar amounts of dark matter

Thought Question

What kind of measurement does not tell us the mass of a cluster of galaxies?

A. Measure velocities of cluster galaxies
B. Measure total mass of cluster's stars
C. Measure temperature of its hot gas
D. Measure distorted images of background galaxies

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Does dark matter really exist?

Our Options

1. Dark matter really exists, and we are observing the effects of its gravitational attraction

2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter

Our Options

1. Dark matter really exists, and we are observing the effects of its gravitational attraction

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Because gravity is so well tested, most astronomers prefer option #1

The Bullet Cluster

Visible Light | Visible Light + X-ray

Cluster appears to consist of two separate clusters.

X-ray emission shows 10 million degree gas.

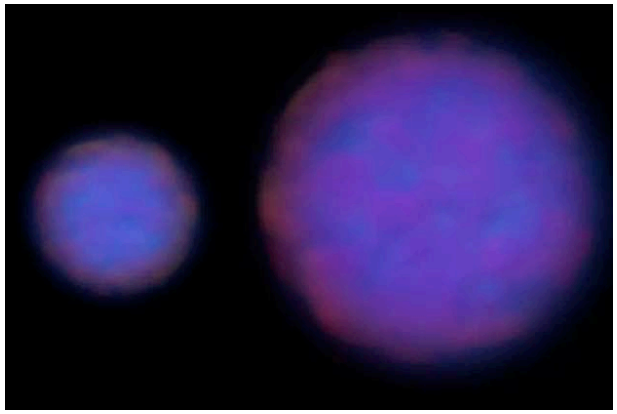
Dark Matter in the *Bullet* Cluster(s)

Blue shows the mass as measured by gravitational lensing

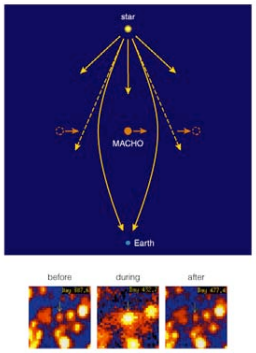
Dark Matter and X-ray Gas

Red shows X-ray emitting hot gas: why doesn't this trace the mass?

Collision of Two Galaxy Clusters



What might dark matter be made of?



Baryonic Matter

Baryons - protons and neutrons

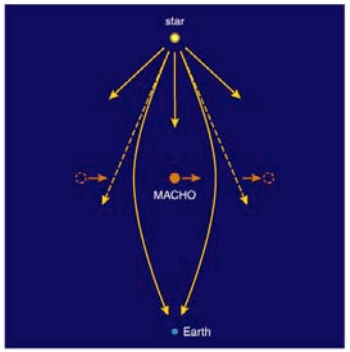
Baryonic Matter - all matter made from protons and neutrons.

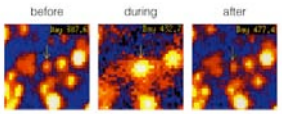
Everything we know of is made of baryonic matter.

Is dark matter made of Baryons?

Two Basic Options

- Ordinary Dark Matter (MACHOS)
  - Massive Compact Halo Objects:
    dead or failed stars in halos of galaxies (i.e brown dwarfs, white dwarfs, neutron stars or black holes collapsed from Baryonic structures such as stars).
- Extraordinary Dark Matter (WIMPS)
  - Weakly Interacting Massive Particles:
    mysterious neutrino-like particles





MACHO survey:

Monitor 8 million stars in bulge of our galaxy and LMC.

Look for brightening due to gravitational lensing by MACHOS

Approximately 50 events detected.

20% of the objects in the Halo of the Milky Way might be MACHOs

Density of MACHOs much too low to account for dark matter.

Two Basic Options

- Ordinary Dark Matter (MACHOS)
  - Massive Compact Halo Objects: dead or failed stars in halos of galaxies
- Extraordinary Dark Matter (WIMPS)
  - Weakly Interacting Massive Particles: mysterious neutrino-like particles

The Best Bet

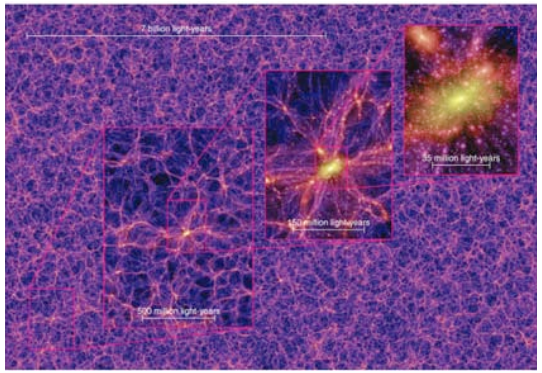
Why Believe in WIMPs?

- There's not enough ordinary matter
- WIMPs could be left over from Big Bang
- Models involving WIMPs explain how galaxy formation works

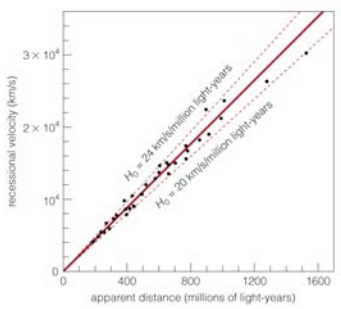
What have we learned?

- What is the evidence for dark matter in galaxies?
  - Rotation curves of galaxies are flat, indicating that most of their matter lies outside their visible regions
- What is the evidence for dark matter in clusters of galaxies?
  - Masses measured from galaxy motions, temperature of hot gas, and gravitational lensing all indicate that the vast majority of matter in clusters is dark
- Does dark matter really exist?
  - Either dark matter exists or our understanding of our gravity must be revised – *Bullet cluster provides strong evidence that dark matter exists*
- What might dark matter be made of?
  - There does not seem to be enough normal (baryonic) matter to account for all the dark matter, so most astronomers suspect that dark matter is made of (non-baryonic) particles that have not yet been discovered

What are the largest structures in the universe?



Review of Lecture 15

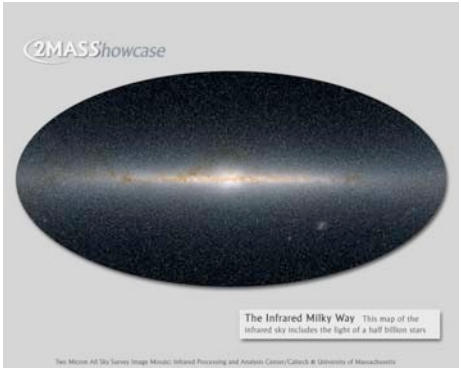


Hubble Ultra Deep Field

We can measure distances by the redshift of a galaxy.

By looking at a single patch of sky, we can see galaxies at many different distances

The Distribution of Galaxies



The stars in the sky are concentrated in the Milky Way.

Almost of all of these belong in our galaxy.

The exceptions are the stars in Magellenic Clouds, satellite galaxies to our own.

The Distribution of Galaxies

The color dots give the distribution of other Galaxies in the sky.

The Distribution of Galaxies are *isotropic*.

The Universe is Isotropic and Homogenous

Isotropic – it looks the same in all directions (the distribution of galaxies is basically the same in any direction in the sky).

Homogenous – it looks the same from any point in the Universe (i.e. the universe looks basically the same to us and aliens in another solar system in a very distant galaxy).

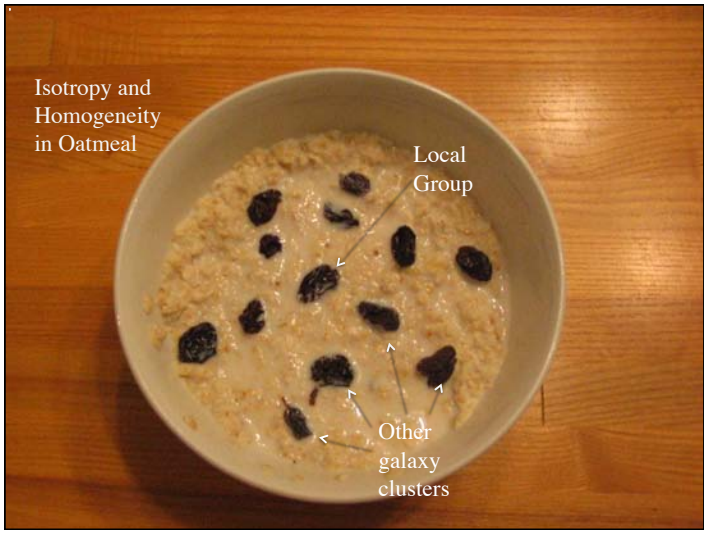
We know that the universe does not look exactly the same in every direction:

> We see the disk of our galaxy (i.e. the Milky Way)

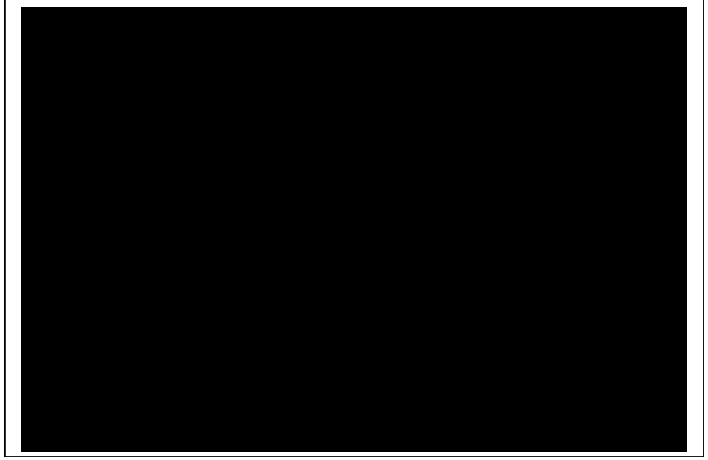
We know that the universe doesn't look exactly the same from every galaxy:

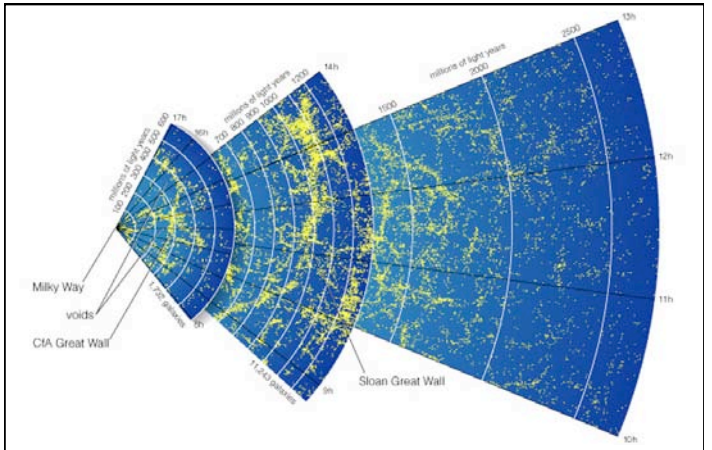
> For example, the the universe may look very different to an alien race in the middle of a galaxy cluster.

How do we think about this?



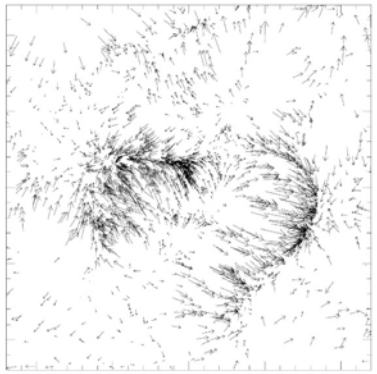
The Distribution of Galaxies by Redshift

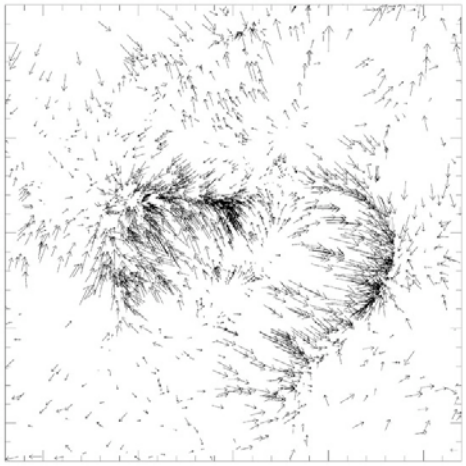




Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***

How does gravity and dark matter create the cosmic web



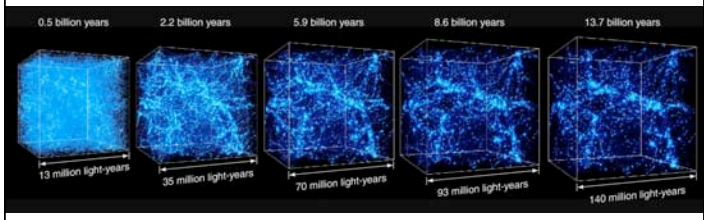


Dark matter is still pulling things together

After correcting for Hubble's Law, we can see that galaxies are flowing toward the densest regions of space

Time in billions of years

0.5 2.2 5.9 8.6 13.7

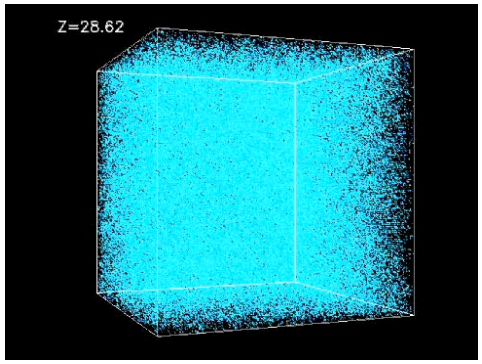


13 35 70 93 140

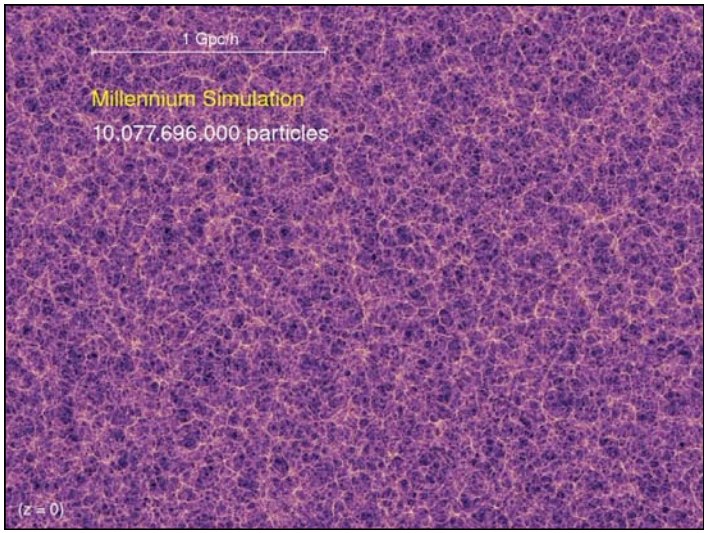
Size of expanding box in millions of lt-yrs

Models show that gravity of dark matter pulls mass into denser regions – universe grows lumpier with time

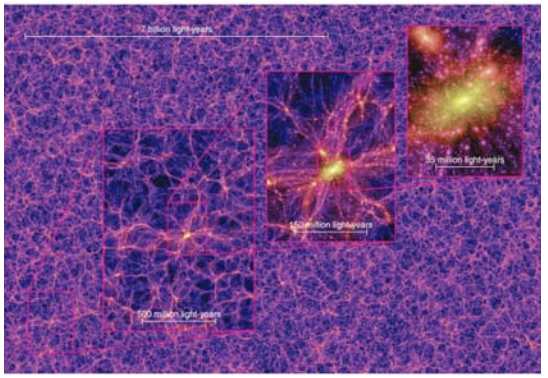
Formation of the Cosmic Web



http://cosmicweb.uchicago.edu/filaments.html

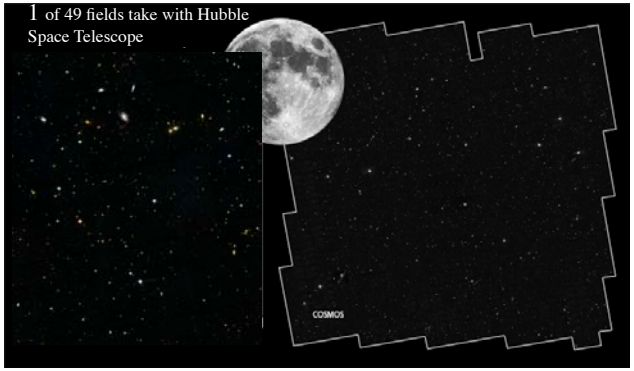


*All Matter (Baryonic and Dark Matter) is Organized into a **Cosmic Web***



Structures in galaxy maps look very similar to the ones found in models in which dark matter is WIMPs

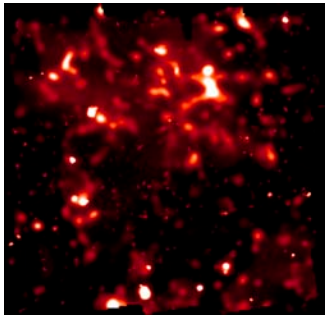
Can We Map Dark Matter in the Cosmic Web?



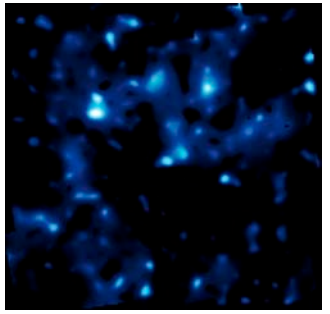
Goal: look at distortion of galaxy shapes by dark matter.

The Final Map

Baryonic Matter



Dark Matter

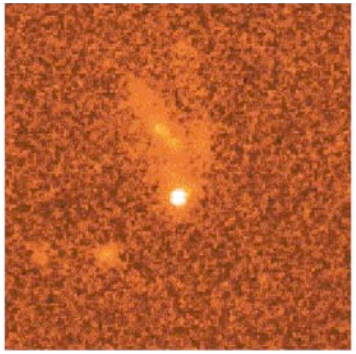


NASA, ESA, R Massey (Caltech)

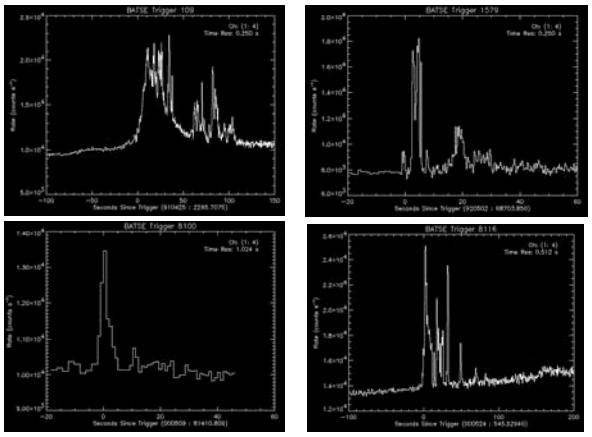
What have we learned?

- How is matter organized in the Universe?
  - On large scales, homogenous and isotropic.
  - The largest structures are clusters and chains of galaxies – these form the cosmic web.
  - The web is filled with voids – the voids are relatively empty of both baryonic and dark matter!
- What is the role of dark matter in the formation of the cosmic web?
  - Dark matter is dominant source of gravity. Gravity from dark matter pulled matter into the web as universe expanded.
  - Galaxies appear to be distributed in gigantic chains and sheets that surround great voids
- How do we map dark matter on large scales?
  - Using gravitational lensing.

Where do gamma-ray bursts come from?



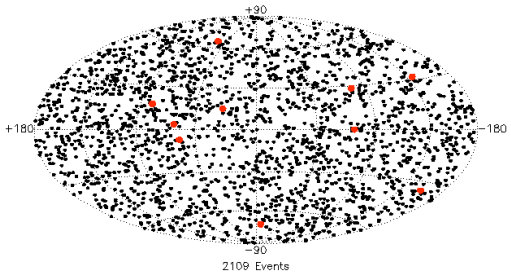
Gamma-Ray Bursts



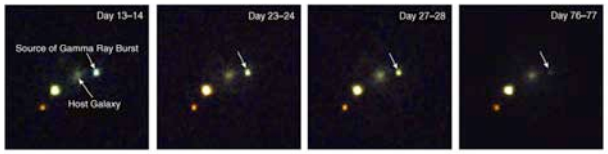
What are Gamma Ray Bursts

- In 1963 113 countries signed a treaty allowing only tests of nuclear weapons underground.
- Vela satellites built to look from Gamma-rays from nuclear weapons tests which defied the treaty.
- Vela satellites detected random bursts all over the sky, first detection of gamma ray bursts.
- At first, these were thought to be similar to X-ray bursts. X-ray bursts come from neutron stars in our galaxy.
- To test this, the Compton Satellite mapped the position of Gamma Ray Bursts in the sky.

Distribution of Gamma Ray Bursts



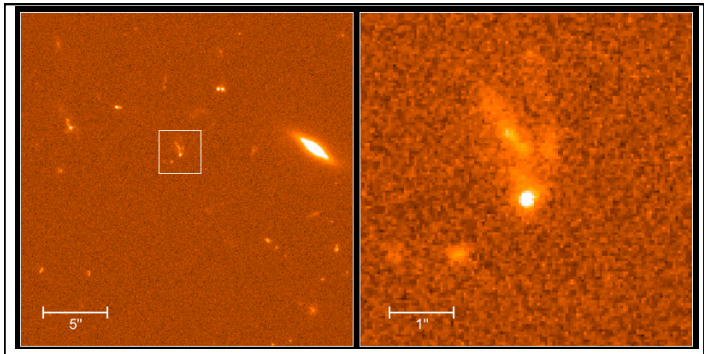
The Detection of Optical Transients



The angular resolution of the gamma ray observations are very limited (1 degree).

With this type of angular resolution, it was difficult to make a match between the gamma ray burst and a galaxy detected at visible wavelengths.

In 1997 came first detection of optical transient from gamma ray burst.



- Observations in the 1990s finally detected the glow of gamma ray bursts at visible wavelengths.
- These observations identified the host galaxies of gamma ray bursts.
- The distance can now be measured by the redshift of the galaxy.
- They must be among the most powerful explosions in the universe (10^{53} ergs - the amount of energy our sun would produce in 880 billion years)
- Most distant is at a Z=6.29 (13 billion light years away)

Supernovae and Gamma-Ray Bursts

http://www.nasa.gov/centers/goddard/news/topstory/2003/0618rosettaburst.html

- Observations show that at least some gamma-ray bursts are produced by supernova explosions.
- These supernova produce a black hole inside which destroy star through its jets and wind.
- Gamma ray emission produced in jet - may not be as luminous as thought.
- Some others may come from collisions between neutron stars

Gamma Ray Burst Jet

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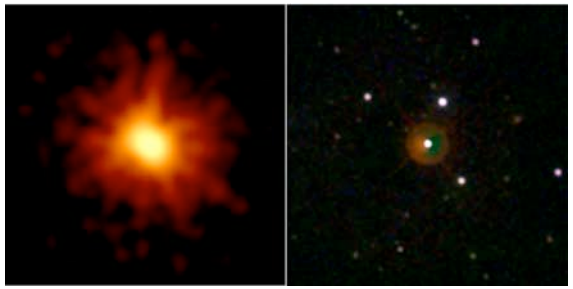
The Naked Eye Gamma Ray Burst



On March 19, NASA's SWIFT satellite detects a luminous GRB. It estimated that this GRB, was visible to the naked eye for 30 seconds. It is 7.5 billion light years away.

What have we learned?

- Where do gamma-ray bursts come from?
  - Most gamma-ray bursts come from distant galaxies
  - They must be among the most powerful explosions in the universe, probably signifying the formation of black holes
- What causes gamma-ray bursts?
  - At least some gamma-ray bursts come from supernova explosions