Announcements

- Quiz due tonight
- several Bonus point opprtunities on D2L
- Third Midterm one week from today
  - same rules as Midterms 1 & 2
  - 50 questions, including 5 bonus questions
- Review for midterm this Friday

Galaxies and Active Galaxies: Review

- The Hubble sequence organizes galaxies according to their shapes
- Galaxy types include spiral, barred spiral, elliptical, and irregular
- Objects of relatively uniform luminosities are called **“standard candles”**; examples include Cepheid variable stars and Type I supernovae. We use them to find distances to other galaxies.
- The Milky Way lies within a small cluster of galaxies called the Local Group
- Other galaxy clusters may contain thousands of galaxies

Galaxies and Active Galaxies: Review

- **Hubble's law**: Galaxies are receding from us, and the farther away they are the faster they recede
- **Active galaxies** are far more luminous than normal galaxies, and their radiation is nonstellar
- Seyfert galaxies, radio galaxies, and quasars all have very small cores; many emit high-speed jets.
- Active galaxies are thought to contain **supermassive black holes** in their centers; infalling matter is converted to energy, powering the galaxy
- Most normal galaxies probably contain black holes, but they aren't accreting enough gas to be brighter than the stars in the galaxy

Astronomy 103

Galaxies and Dark Matter

Please read chapter 16

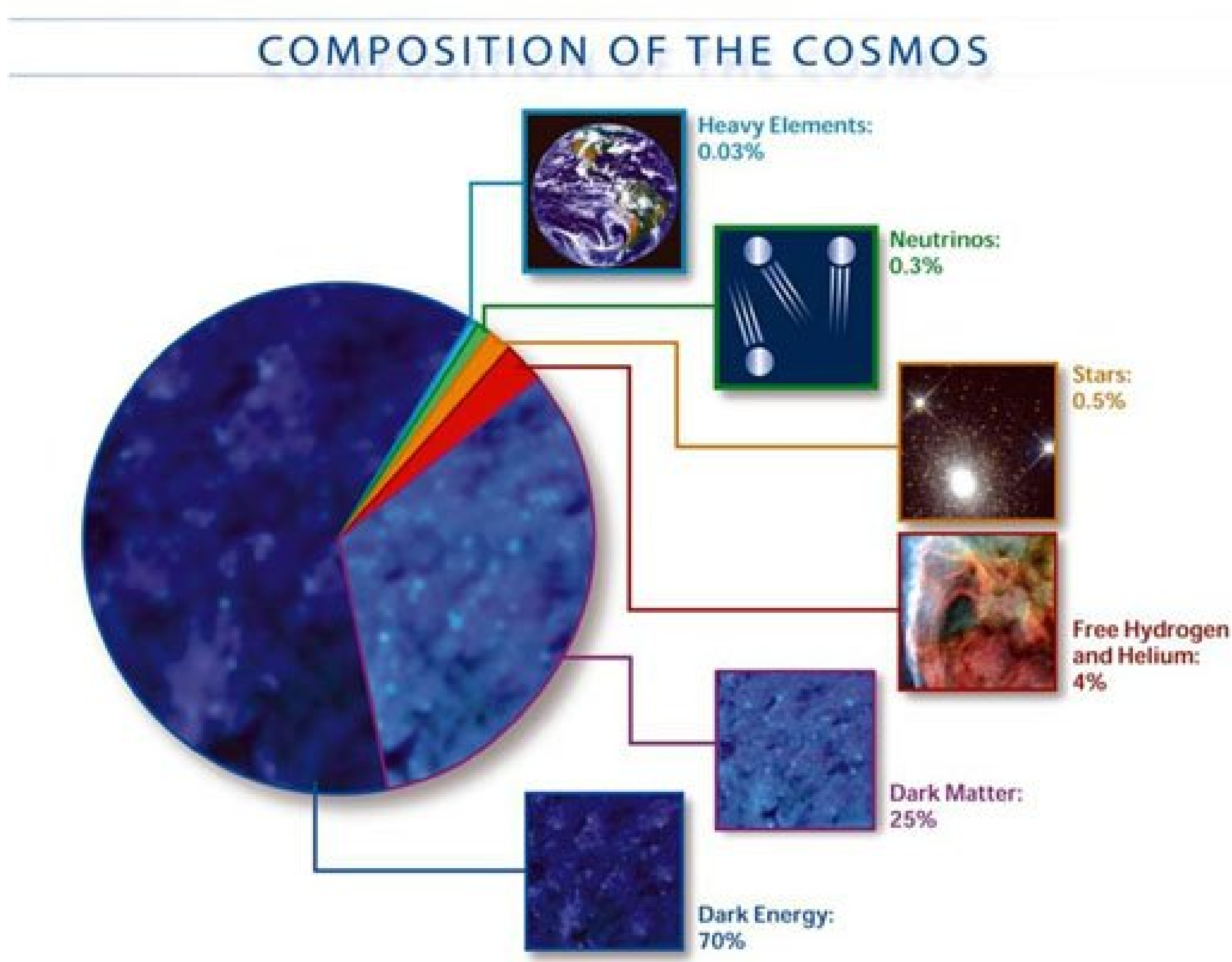
The Makeup of the Universe

Up to now, we have talked about stars, planets, galaxies, black holes . . . .

But this makes up about 1-2% of the universe.

The stuff that shines doesn't even contain most of the atoms in the universe – most of the atoms are still gas.

The Makeup of the Universe



In fact about 95% of the universe is invisible!
And 23% of it is **dark matter**.

Dark matter

- We don’t know what dark matter is – unlike anything else we experience.
- Ordinary matter interacts with other ordinary matter and with light.
- Dark matter doesn’t – only interaction is through gravity.

Dark matter

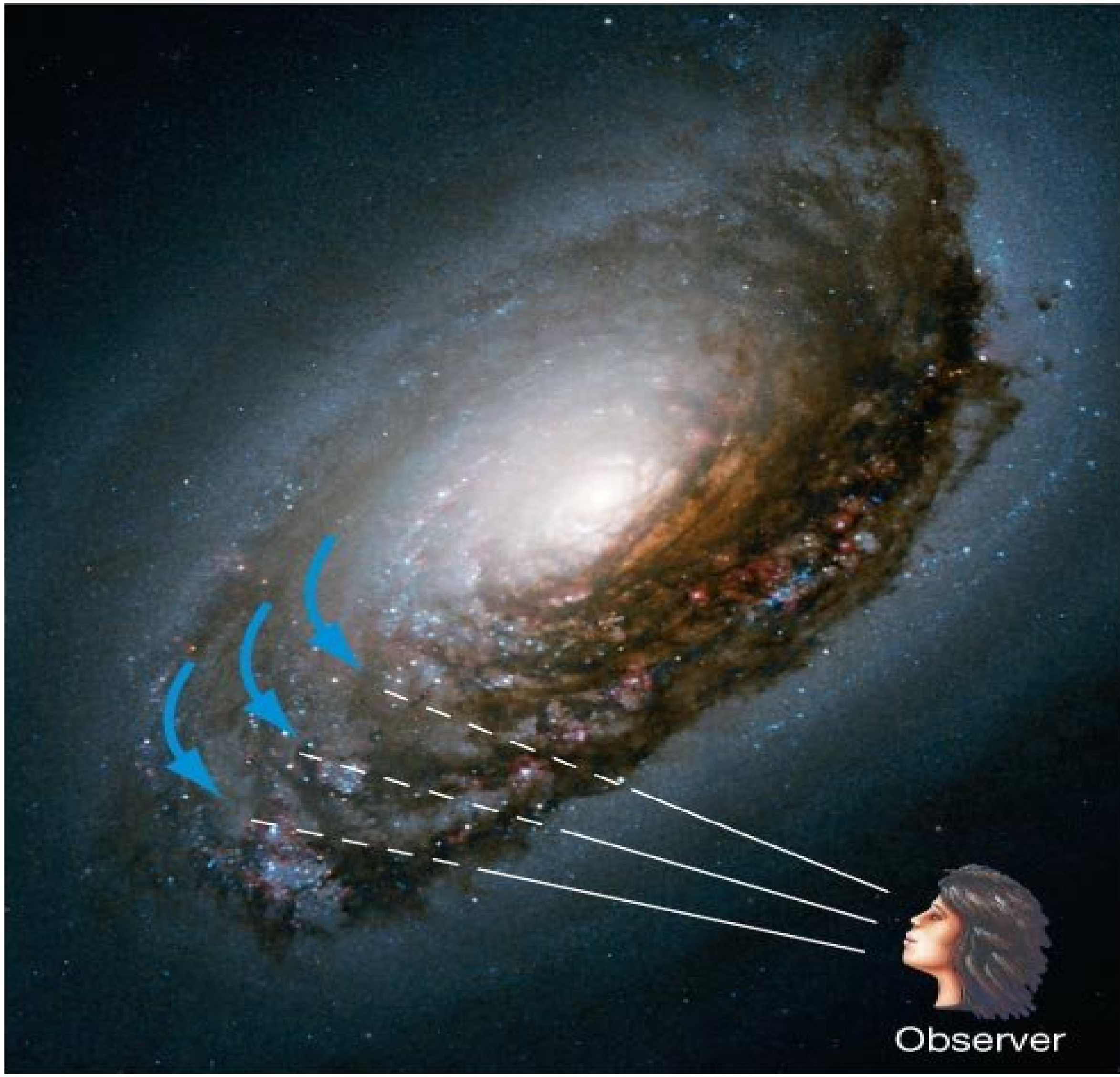
Right now, dark matter can only be observed via its gravity.

So we have to look at its effect on the biggest objects in the universe – galaxies and galaxy clusters.

Rotation Curves of Galaxies

We can measure the mass of a galaxy by looking at how fast gas and stars rotate around it

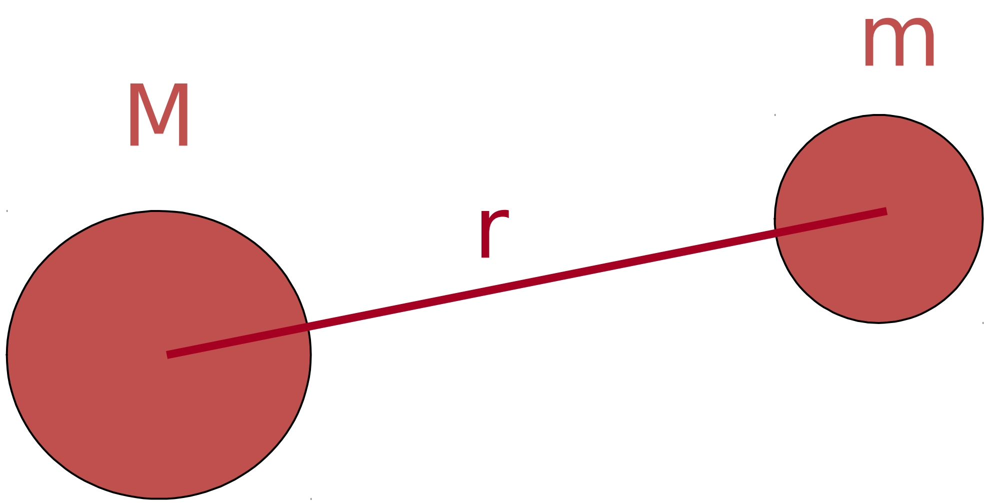
By looking at the Doppler shift of stars and gas, we can tell **how fast they are moving toward us at different points in a galaxy**



Newton's law of gravity

Newton's law of gravity: Any two objects in the universe attract each other with a force given by

$$F = G\frac{Mm}{r^2},$$



With
r in meters
m in kg

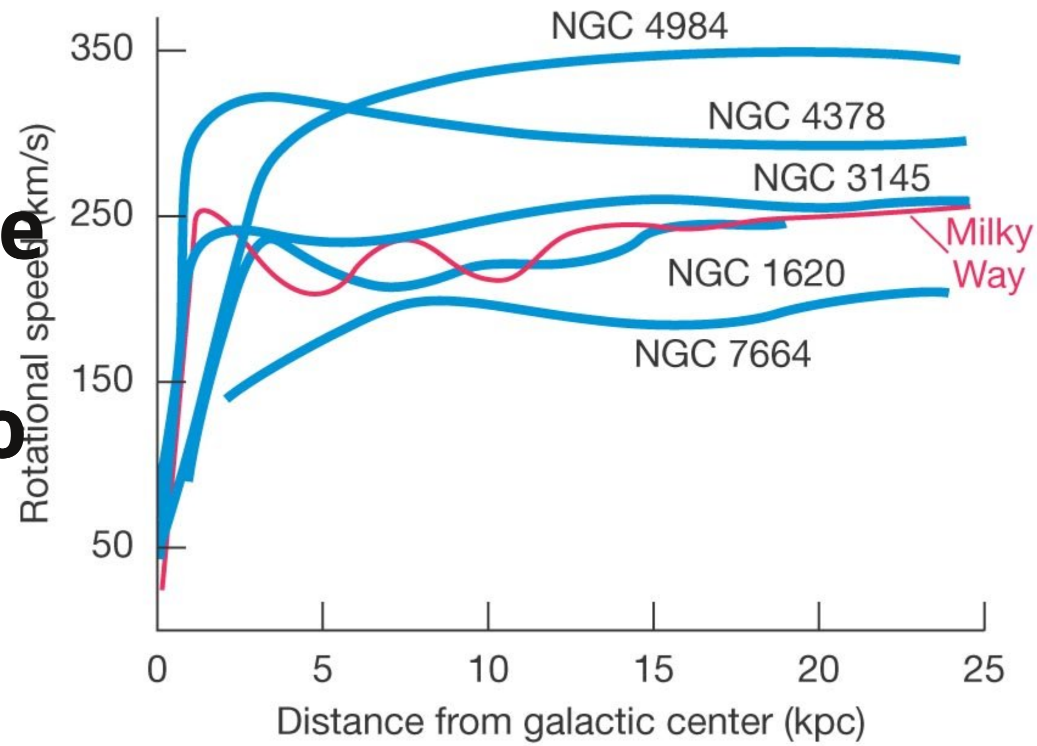
F in Newtons, where
1 Newton = 4.5 lb

$G = 7x10^{-11}$

Rotation Curves of Galaxies

What we find is that as we move away from the center of a galaxy, the rotational speed tends to flatten to a constant speed

This means that **the mass of the galaxy continues to increase even in areas where there are very few to no stars**



(b)

Rotation Curves of Galaxies

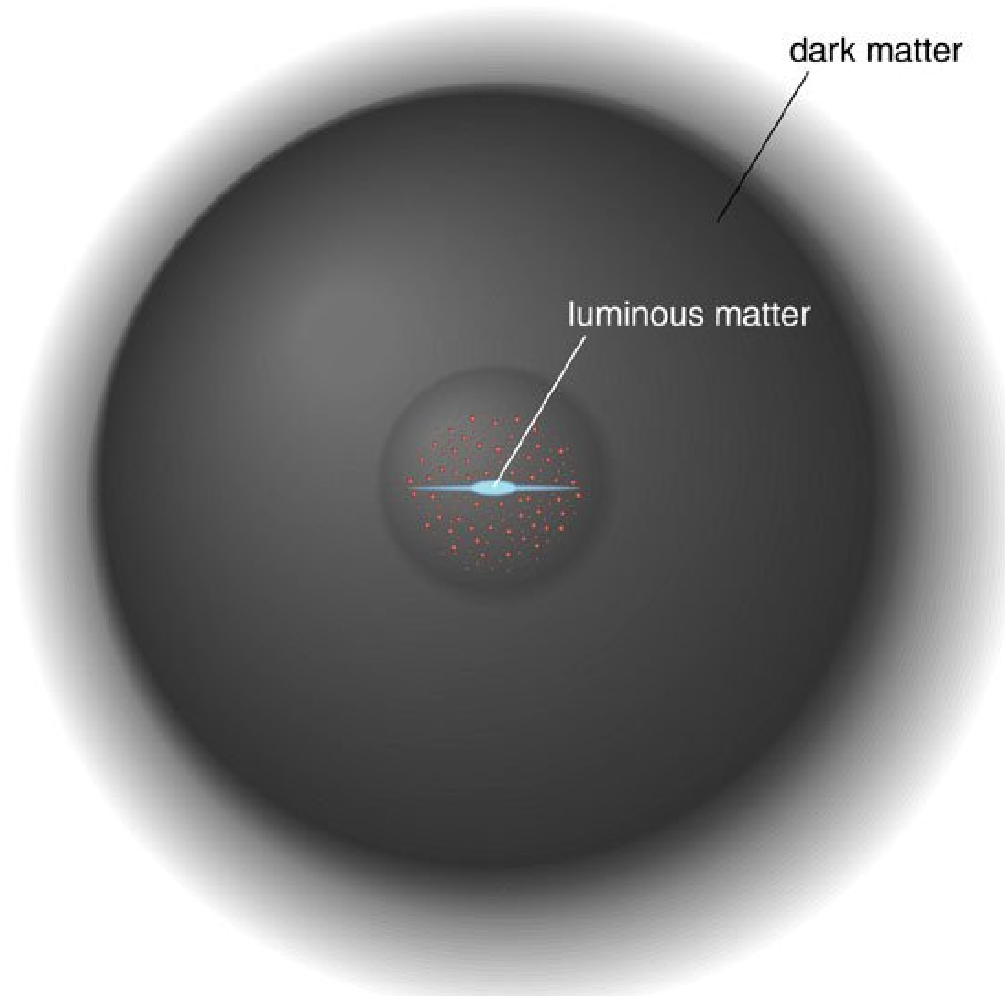
Here is one example. There is apparently more mass beyond the outer regions of this spiral galaxy that there is in the inner parts we can actually see

So there is some hidden matter or “dark” matter that is adding to the gravity of the galaxy

Dark Matter

Galaxies and galaxy clusters sit in the middle of a collection of dark matter known as a dark matter halo.

The dark matter halo extends for a distance at least 10x bigger than the visible galaxy.



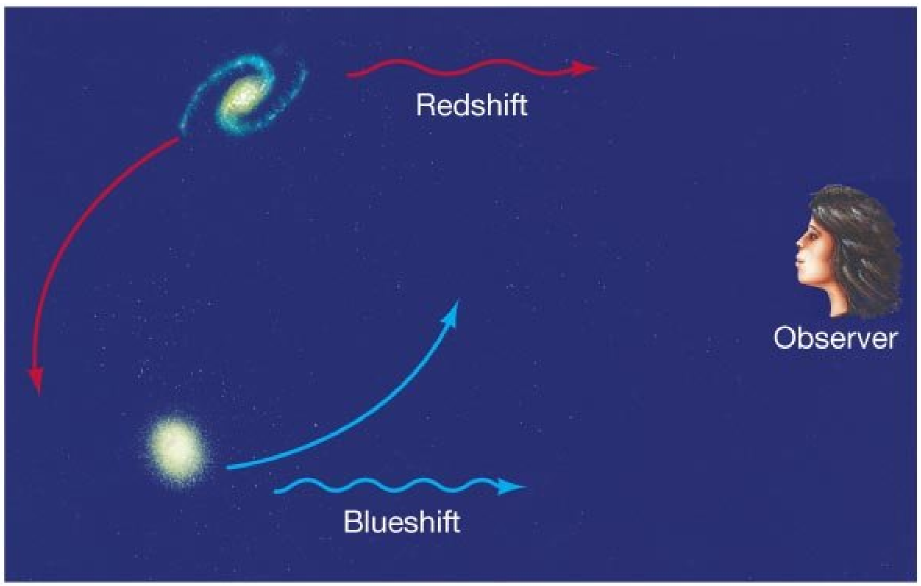
Galaxy clusters

We can also use individual galaxies and their orbitals speeds to infer the masses of galaxy clusters – the most massive gravitationally bound structures in the universe

Large galaxy clusters contain thousands of galaxies, many of them as big or bigger than the Milky Way

Galaxy clusters

By looking at the redshifts and blueshifts of many galaxies in the cluster, we can figure out how fast they are moving on average



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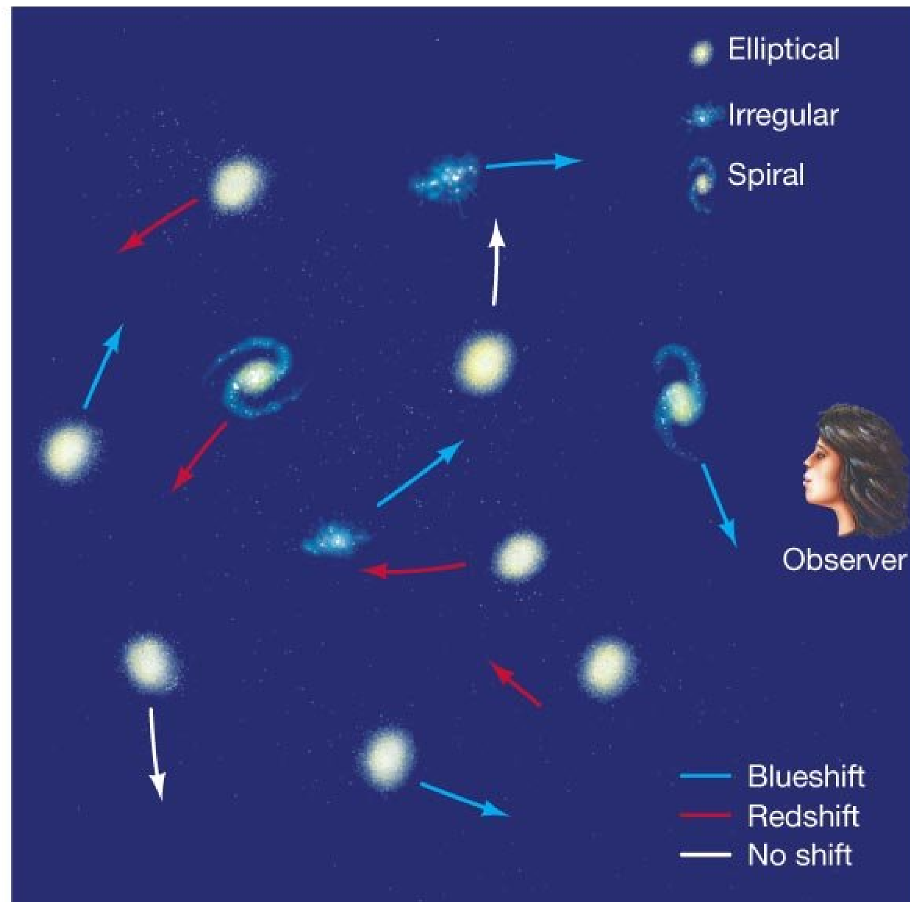
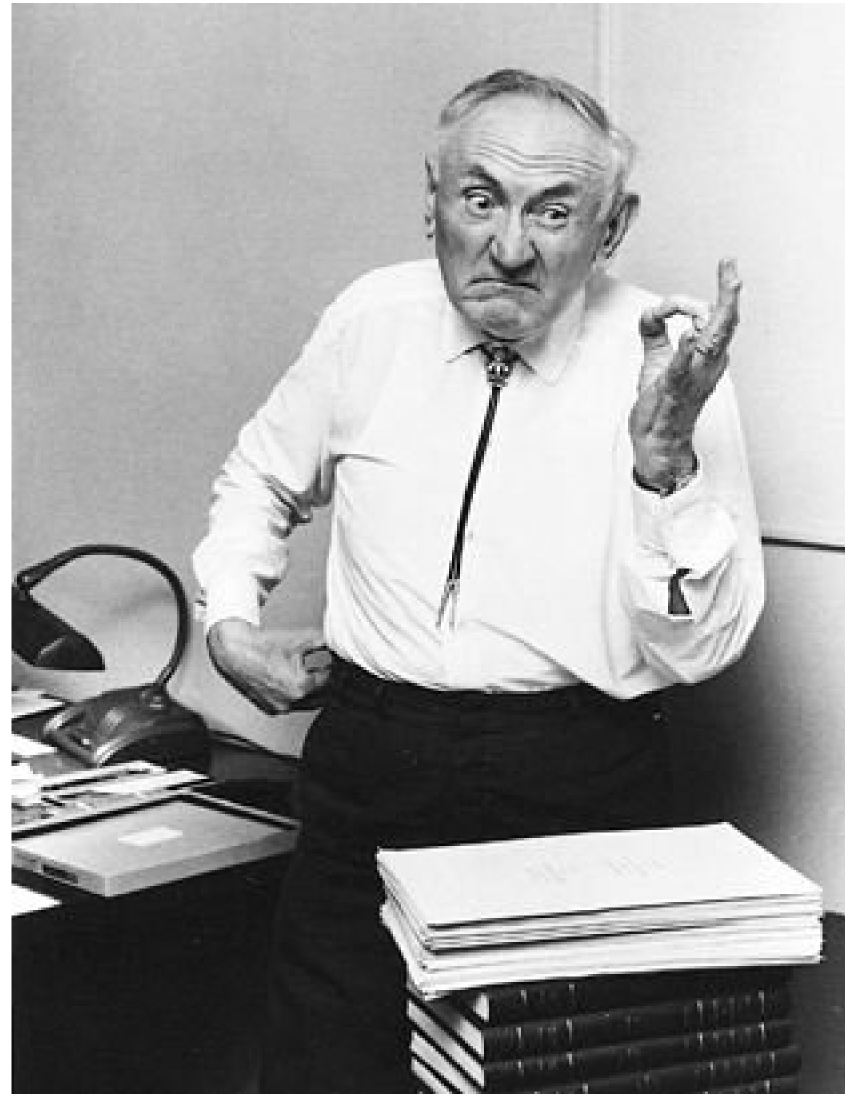


Galaxy clusters

One of the first people to do this was **Fritz Zwicky** – you may remember him as one of the two astronomers who predicted the existence of neutron stars shortly after the discovery of the neutron and 30 years before they were observed



Galaxy clusters

Zwicky looked at the Coma Cluster, the next closest large cluster of galaxies after the Virgo Cluster

Galaxy clusters

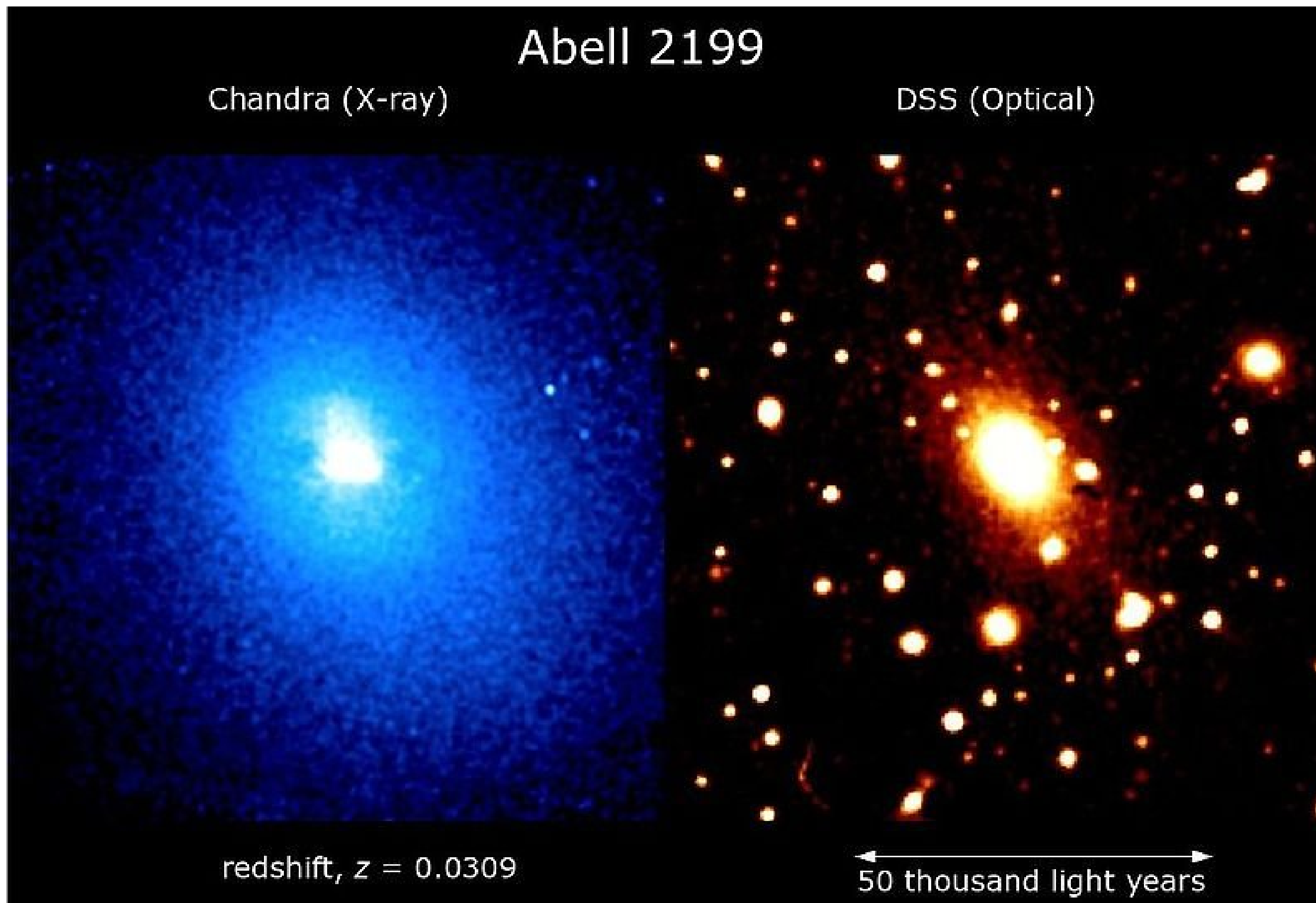
He used the speeds of the galaxies to calculate the mass of the cluster, and found that it was 100 times larger than the mass of all the visible galaxies.

Galaxy clusters

As we have discussed, most of the ordinary matter is not in galaxies in galaxy clusters. Rather it is in gas – intracluster gas – which is extremely hot (up to 4×10^7 K)

But this is not enough.

There is still more matter than the intracluster gas can account for.



Dark Matter

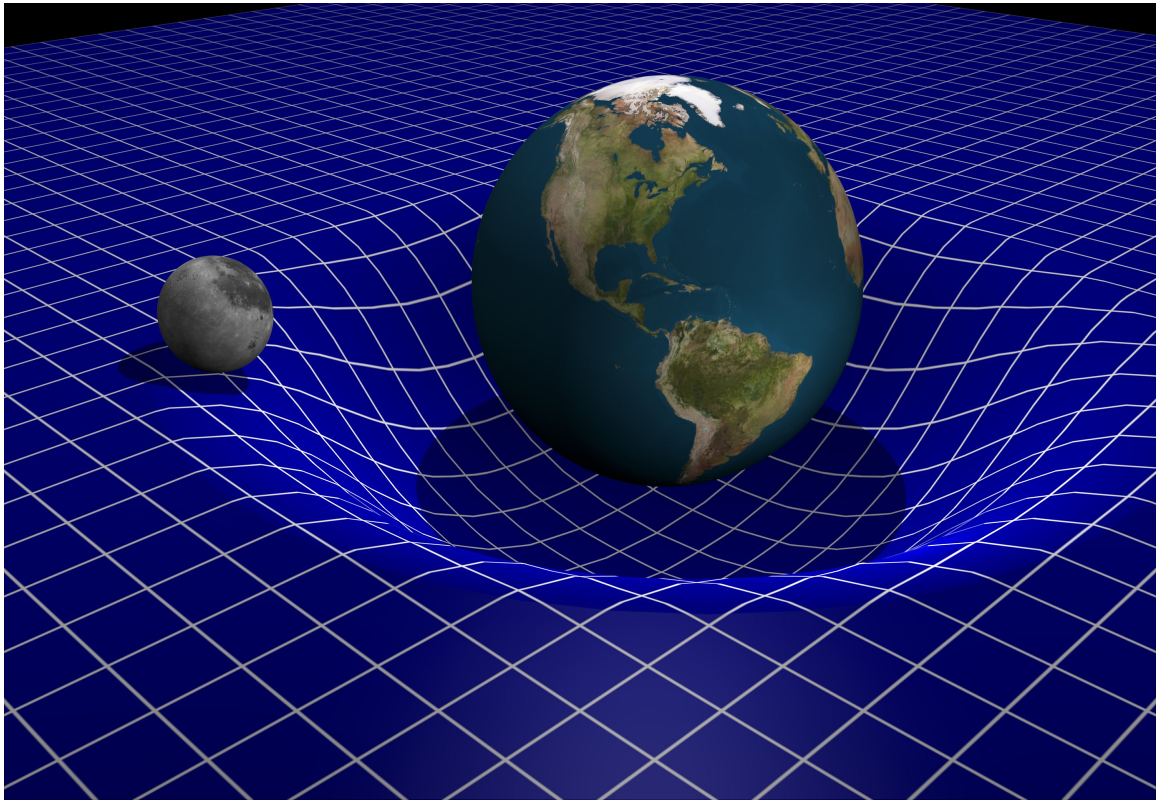
So the combination of all these measurements means that there is a lot more **gravitating** mass than visible mass in the universe.

- Flat rotation curve of galaxies
- Orbital speed of galaxies in clusters
- Gravitational lensing

This matter is known collectively as **dark matter**.

It is generally though to be a particle that doesn't interact with ordinary matter, but even this is not known – could be several particles.

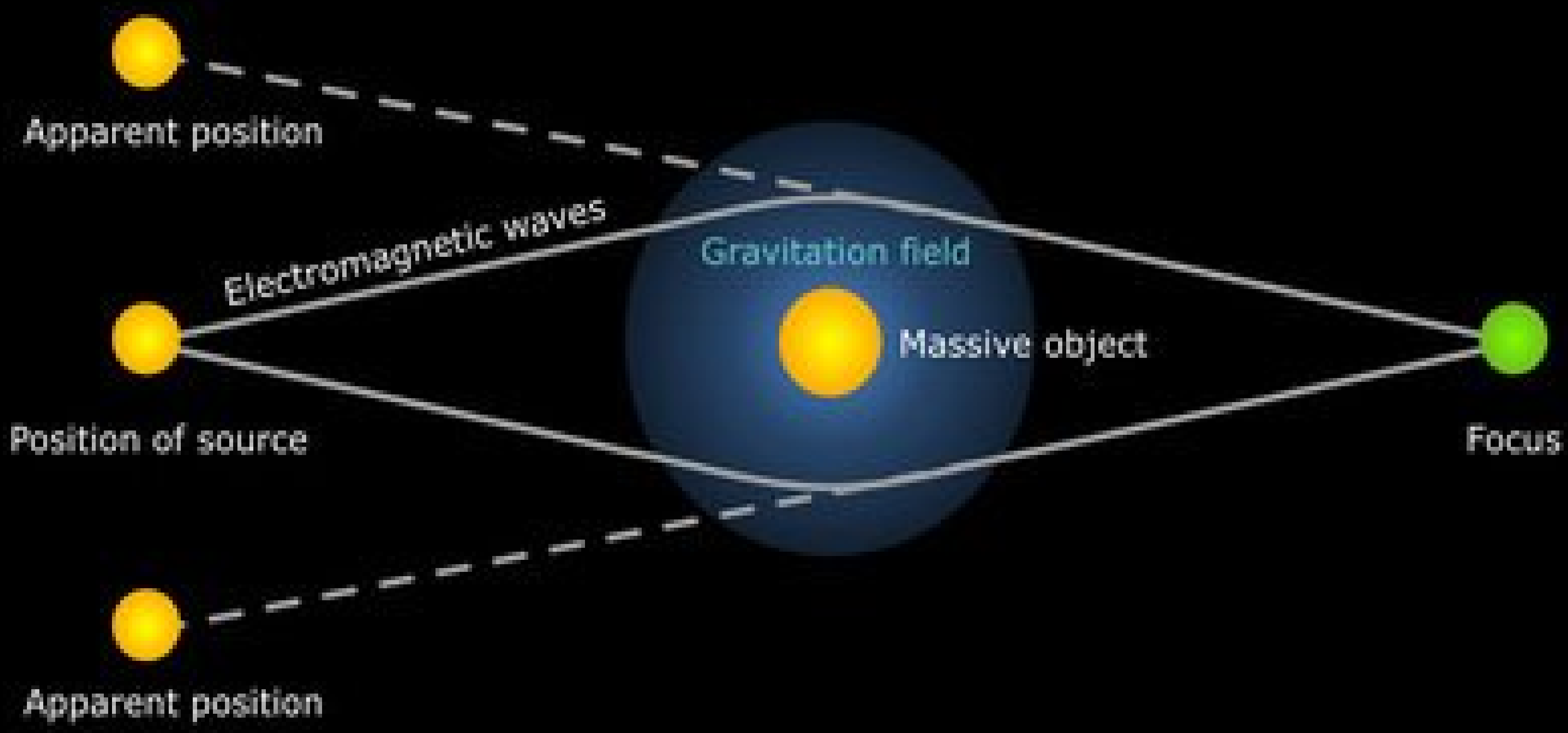
Gravitational Lensing and curved space



Einstein's Theory
of General Relativity:

Space is curved, and the curvature depends on the amount of mass. Since light has energy – and energy means mass ($E=mc^2$) – light also gets bent by gravity.

Gravitational Lensing



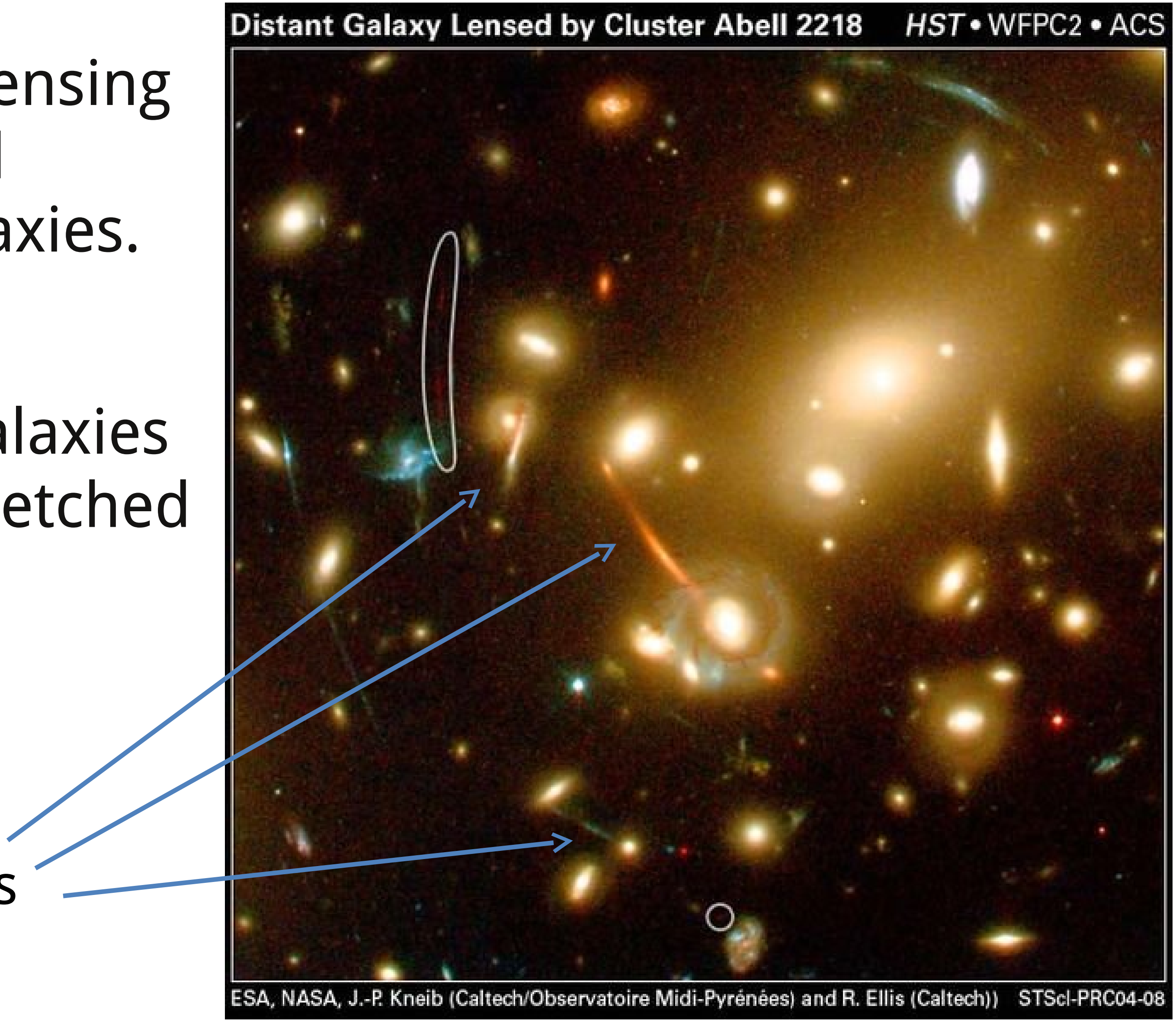
Dark Matter and Gravitational Lensing

- Because we see the effects of dark matter via its gravity, we can see this gravity distort light
- Recall Einstein's theory of general relativity: a gravitating mass bends the path of light
- So massive objects can act like a lens, focusing distant light to us
- This is gravitational lensing

Gravitational Lensing

Gravitational lensing is seen around clusters of galaxies.

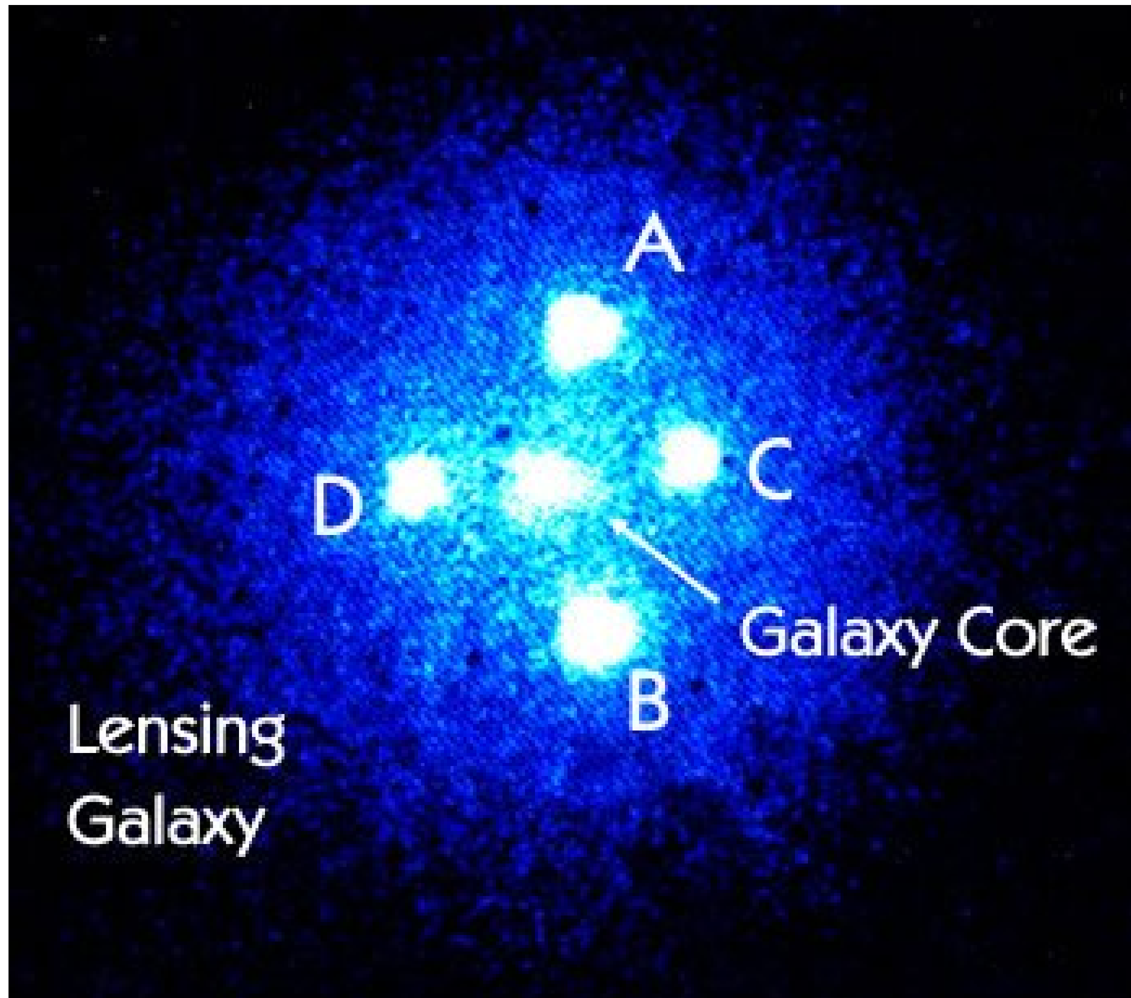
Background galaxies are seen as stretched objects.



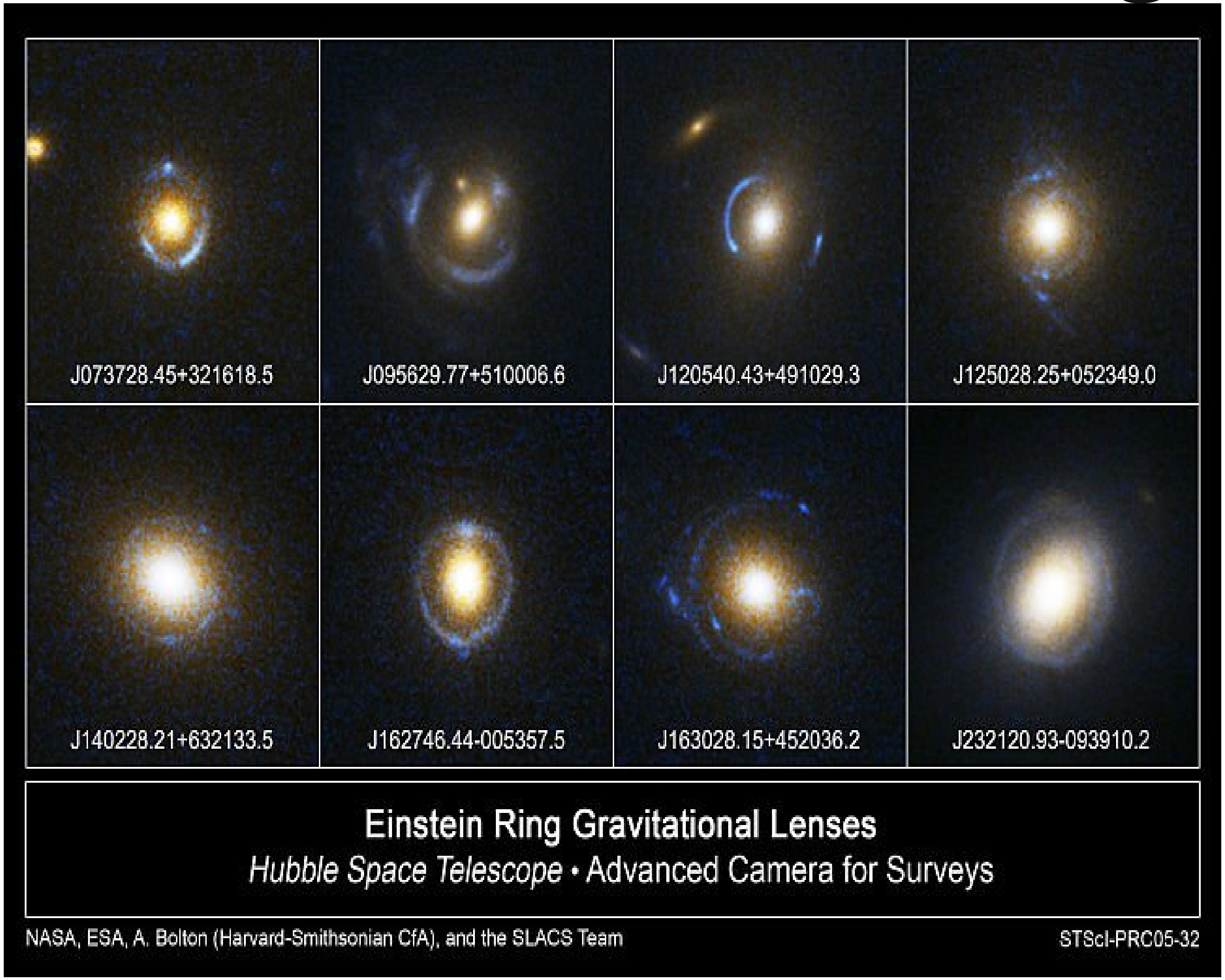
Gravitational Lensing

This is another famous lens, the **Einstein Cross**

A background quasar is lensed into 4 different images by a foreground galaxy



Gravitational Lensing



Here are a few other examples of lenses – these are **Einstein rings**. The blue lensed galaxies are almost directly behind the red lensing galaxies, so their images are lensed to a ring.

Gravitational Lensing

The previous slides were examples of **strong gravitational lensing** – strong because it is quite obvious

By measuring the distortion of the background galaxy, we can map the dark matter

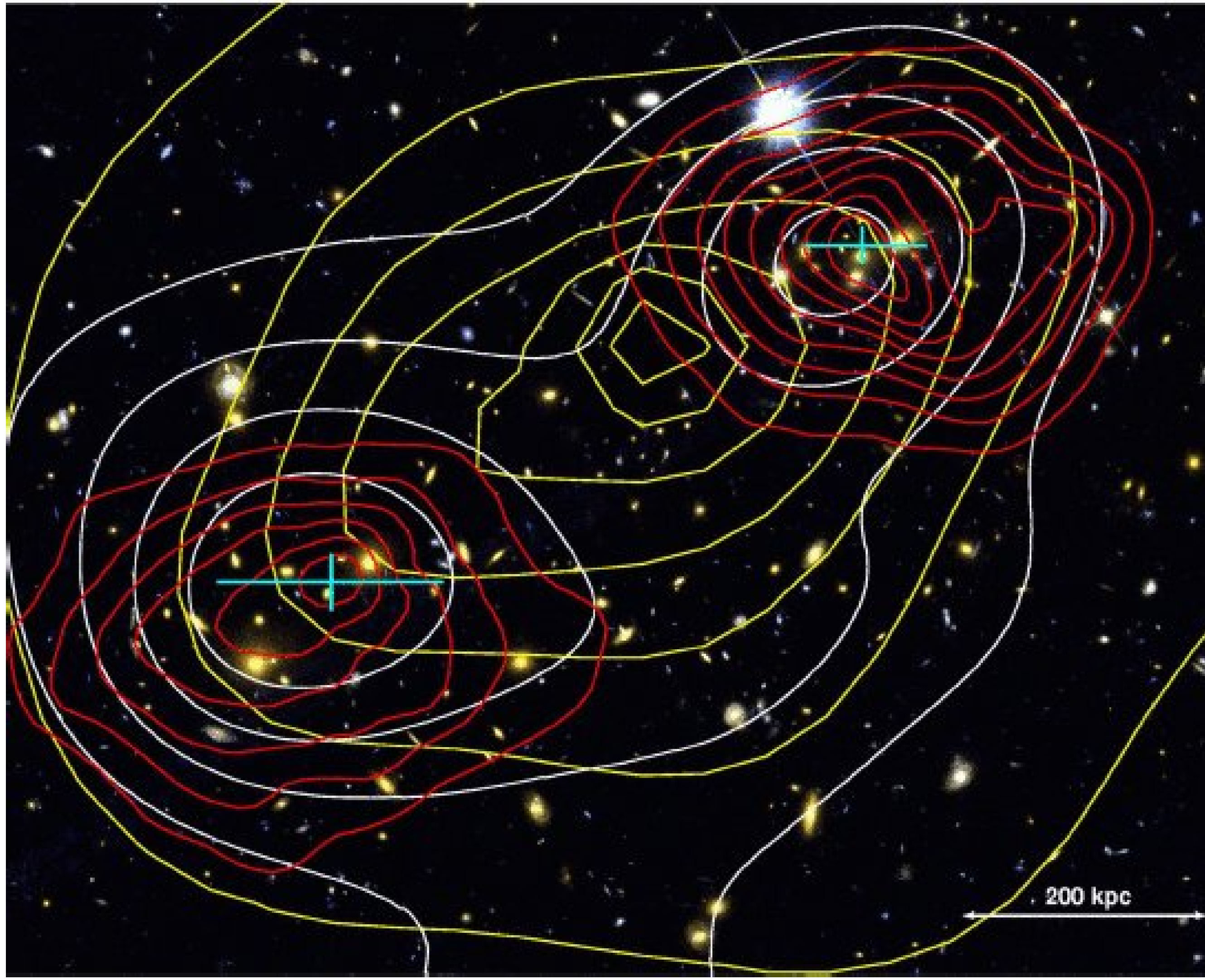
So gravitational lensing can tell us how much dark matter there is and how it is distributed!

Gravitational Lensing

Here is one such map of a cluster known as the Bullet cluster.

It is the merger of two clusters.

Red contours show where the dark matter is.



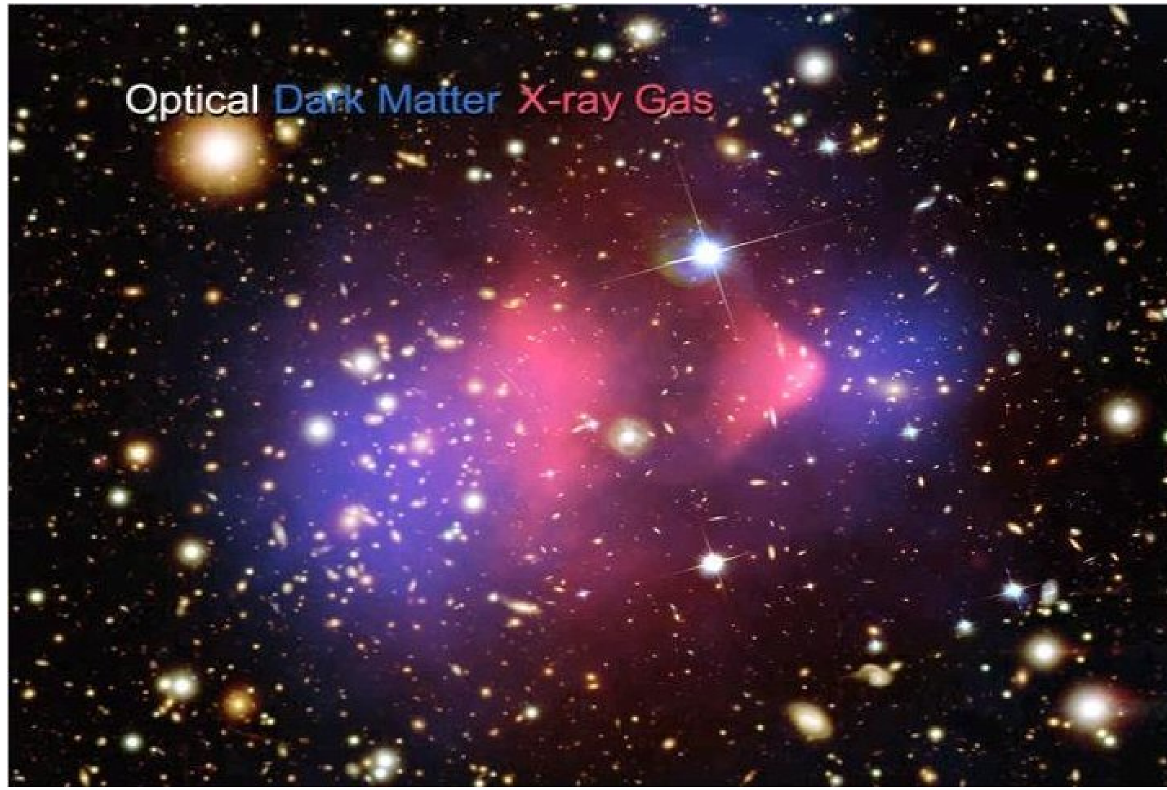
Bullet Cluster

The Bullet cluster is important because we can tell where the **dark matter** is with gravitational lensing, and we can use x-rays to tell where most of the **intracluster gas** is – remember that most of the ordinary matter in galaxy clusters is hot intracluster gas

We have a map of this: ordinary matter in red, dark matter in blue

The Bullet Cluster

Bullet Cluster



The gas and the dark matter aren't in the same place!

Gas was affected by the collision of the two clusters, dark matter was not

So most of the matter in the cluster is NOT ordinary matter, but rather dark matter that doesn't interact with ordinary matter

Very strong evidence for the existence of dark matter!

Gravitational Lensing

Strong gravitational lensing: strong because it is quite obvious, with multiple and/or strongly distorted images of background objects

However, most galaxies are not lensed so strongly – instead they are only slightly distorted by matter (particularly dark matter) in the foreground

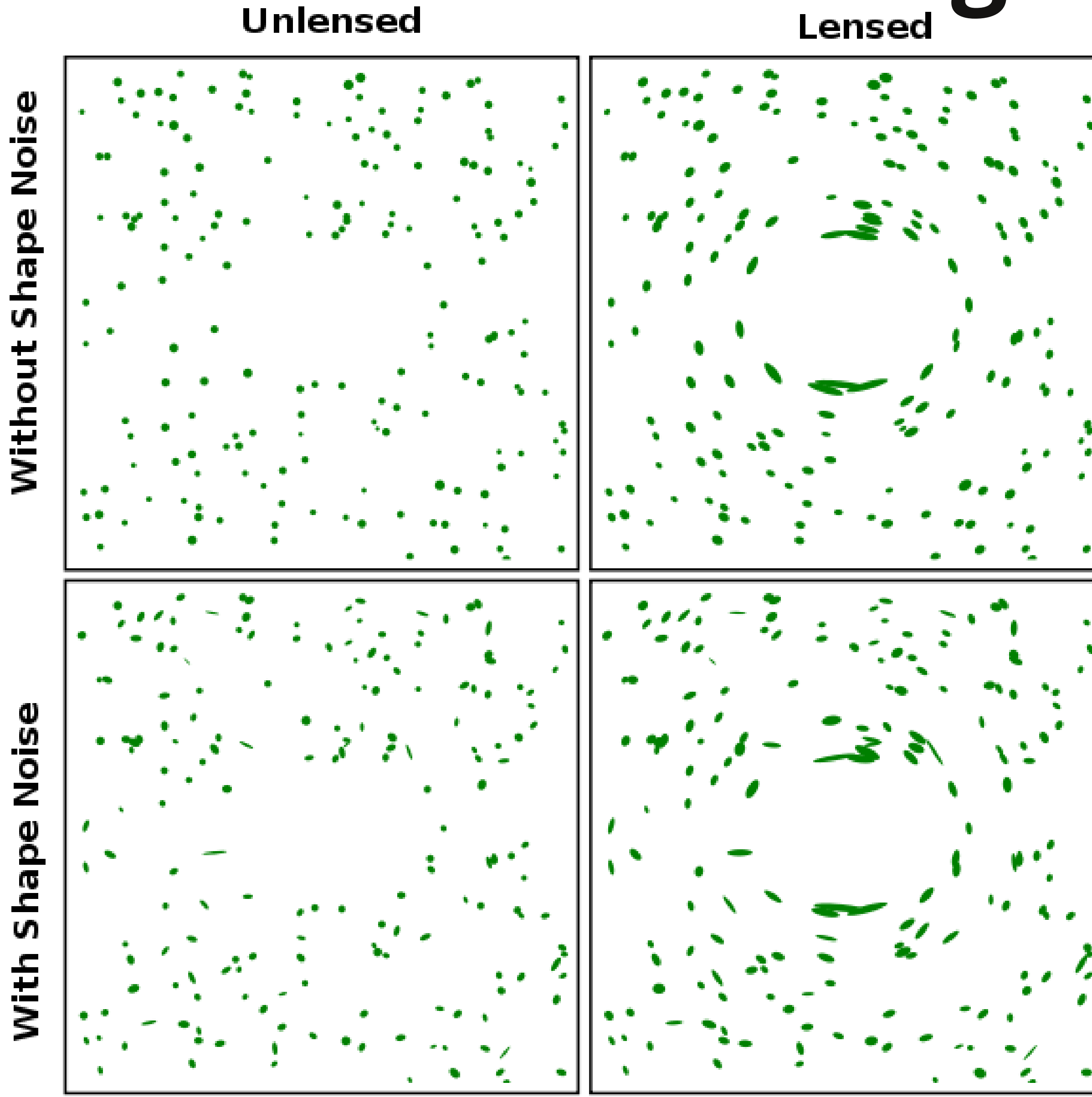
If we can measure this very slight distortion, we can map the dark matter

This slight distortion is called **weak lensing**

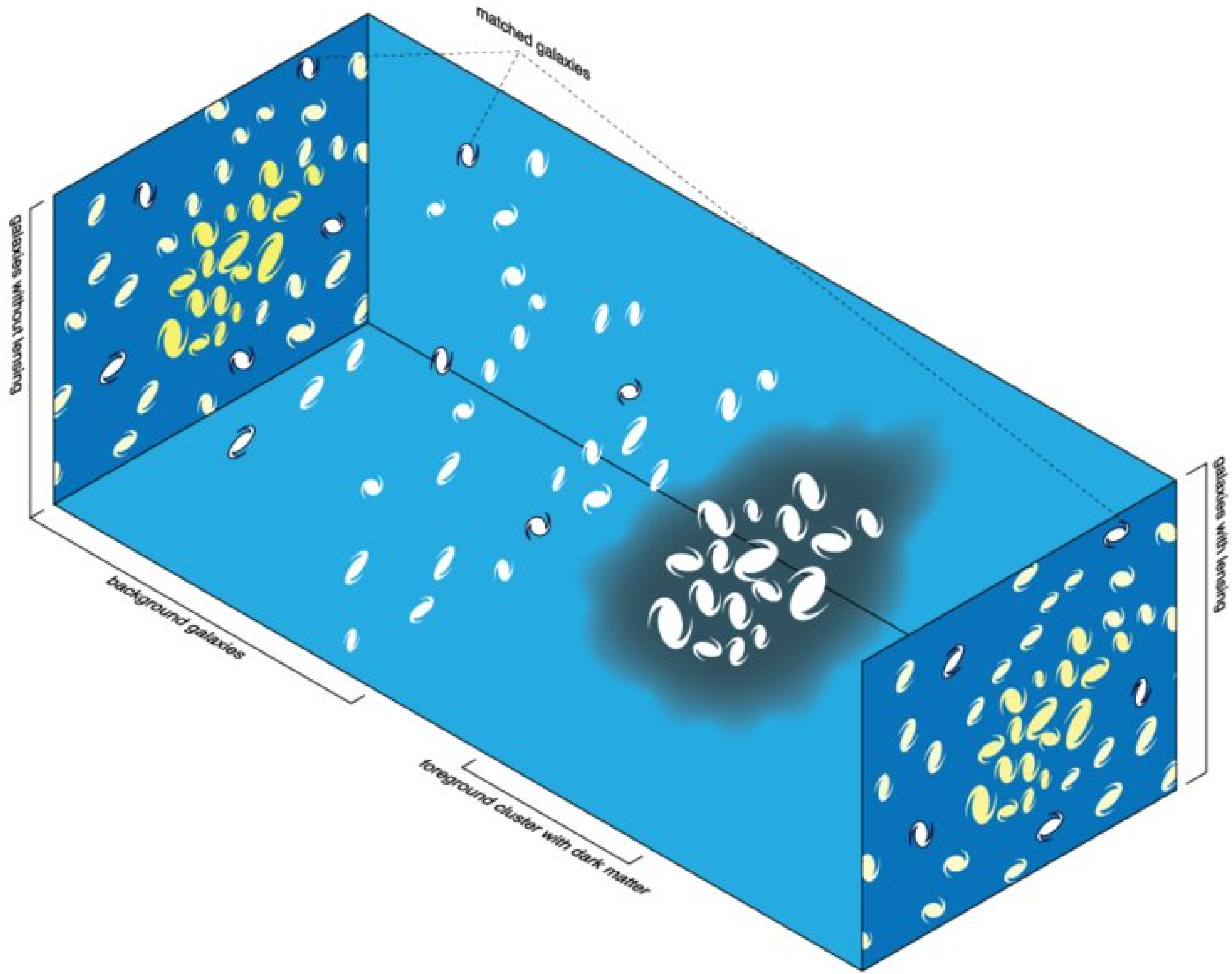
Weak Gravitational Lensing

The distortion changes the shape of galaxies, so that they “wrap” around the foreground dark matter

This picture is exaggerated!



Weak Gravitational Lensing



Weak Gravitational Lensing

Problem: we don’t know what shape the galaxies were before they were distorted!

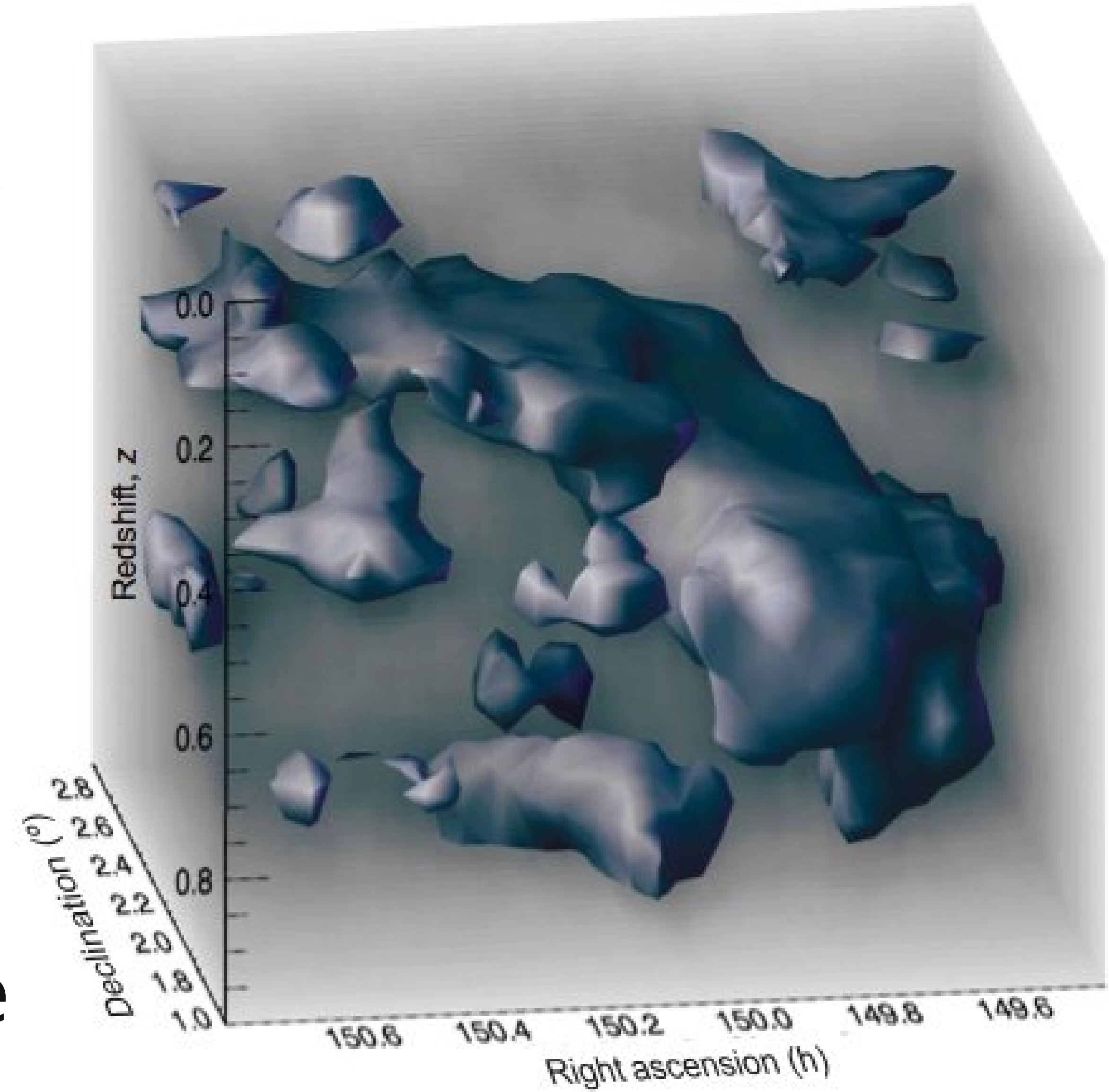
So, to measure the distortion, we need to measure a lot of galaxies and assume that they are randomly oriented

This turns out to be extremely hard! Some progress, but still highly uncertain

Weak Gravitational Lensing

By looking at galaxies and their distortion at different redshifts, we can make a 3-d map of the dark matter.

Here is one example from the COSMOS survey



Dark Matter: Summary

- Galaxy masses can be determined by rotation curves, and galaxy cluster masses from measuring velocities of galaxies
- All measures show that a large amount of dark matter must exist
- Gravitational lensing can be used to map the distribution of dark matter