Announcements

- Midterm grades next week
- **Quiz 12** on Chapter 16 due Monday
- Today: Chapter 16
- Monday: start Chapter 17, Cosmology
- Next week will be Chapter 17
- **Quiz 13** on Ch 17 due Monday May 5 – last regular quiz
- Monday May 5: Ch 18, Life in the Universe
  - **Extra credit quiz** on Ch 18 on D2L, available May 1
- **Additional extra credit quiz**: math problems
- Wednesday May 7, review for final
- Final exam Monday May 12

Based on galactic rotation curves and motions of galaxies in clusters, **dark matter**

- **A** makes up about 90% of the matter in the universe
- **B** is best detected by the largest optical telescopes
- **C** makes up about 10% of the matter in clusters of galaxies
- **D** exists but has no observable effects on galaxies

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The rapid variation of brightness in quasars indicates that

A — the source of energy is very small

B — energy is coming from matter and antimatter

C — the energy source is rotating rapidly

D — there are many separate sources of energy in the core

Astronomy 103

Galaxies and Dark Matter

Please read chapter 16

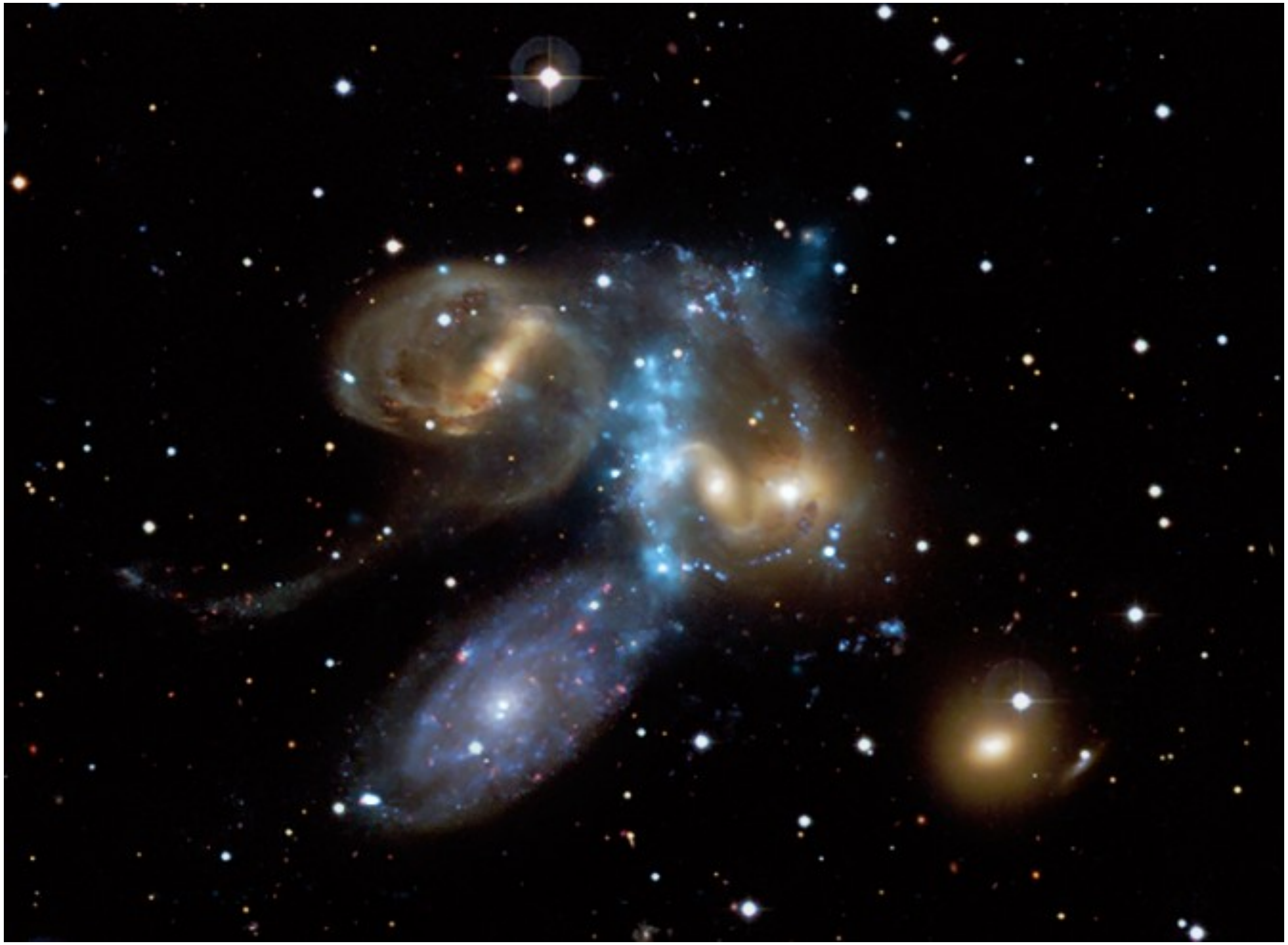
Galaxy Evolution

- As we've discussed, galaxies in isolation evolve slowly and don't change types
- But sometimes more dramatic things happen, like **galaxy collisions**

Galaxy Collisions

On average, a galaxy will collide with another galaxy at least once during its lifetime

When Galaxies Collide…



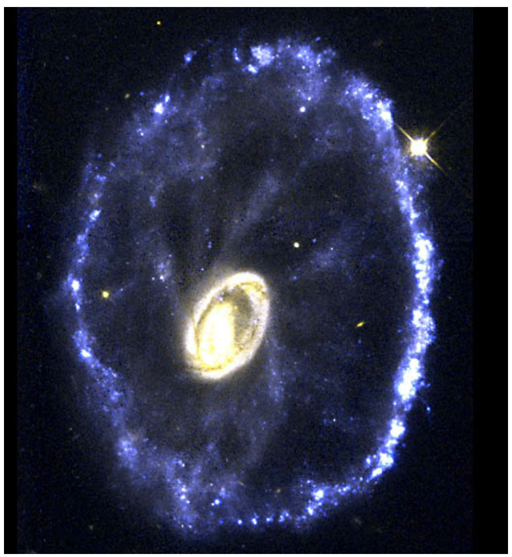
- The stars themselves do not collide, because the space between them is very large
- **Gas does collide**, and this can trigger new star formation

Galaxy Collisions

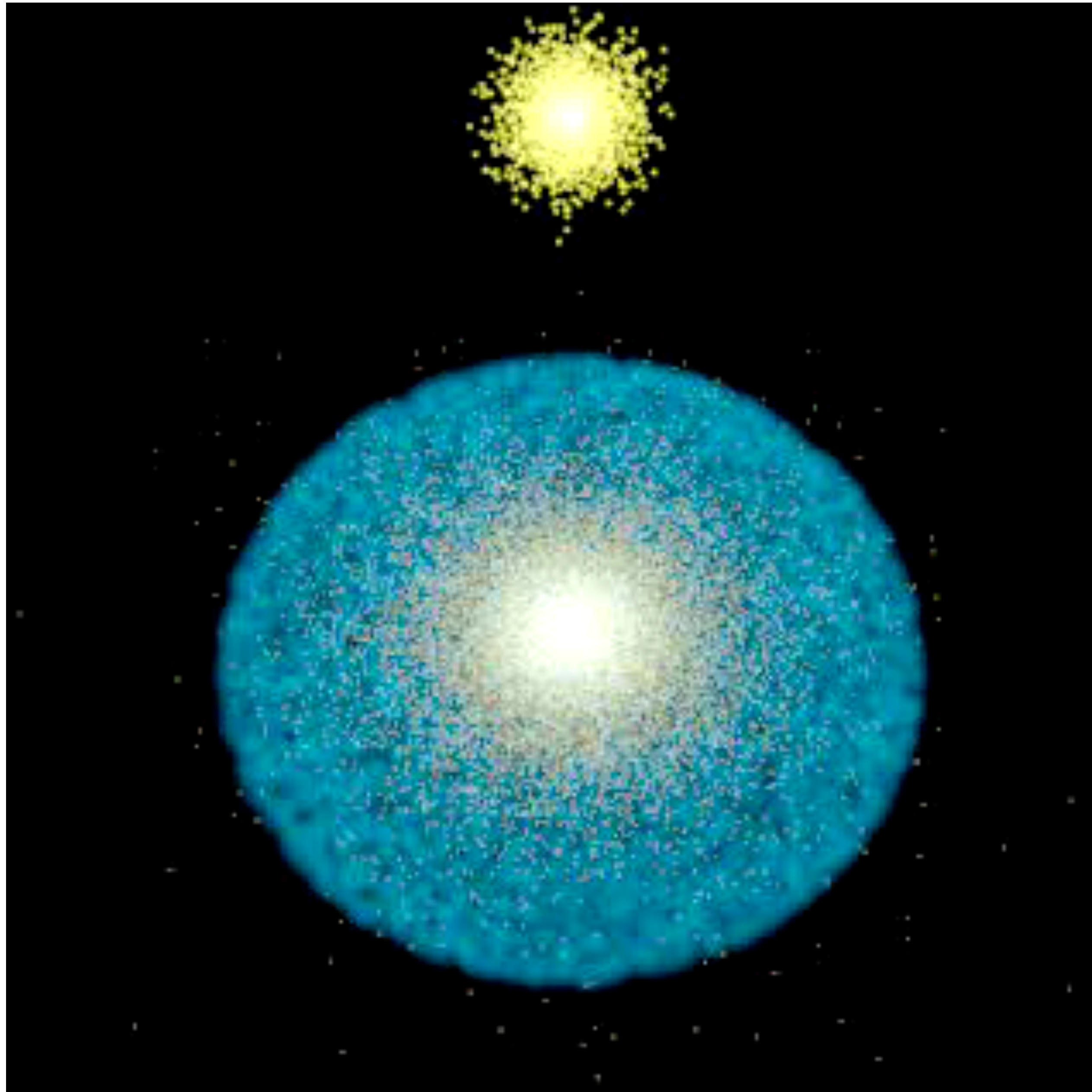
The outer rim and spokes of the Cartwheel Galaxy are thought to be the result of a collision through the center by a smaller galaxy

Galaxy Collisions

Here is a computer simulation of this process in action.



Cartwheel Galaxy

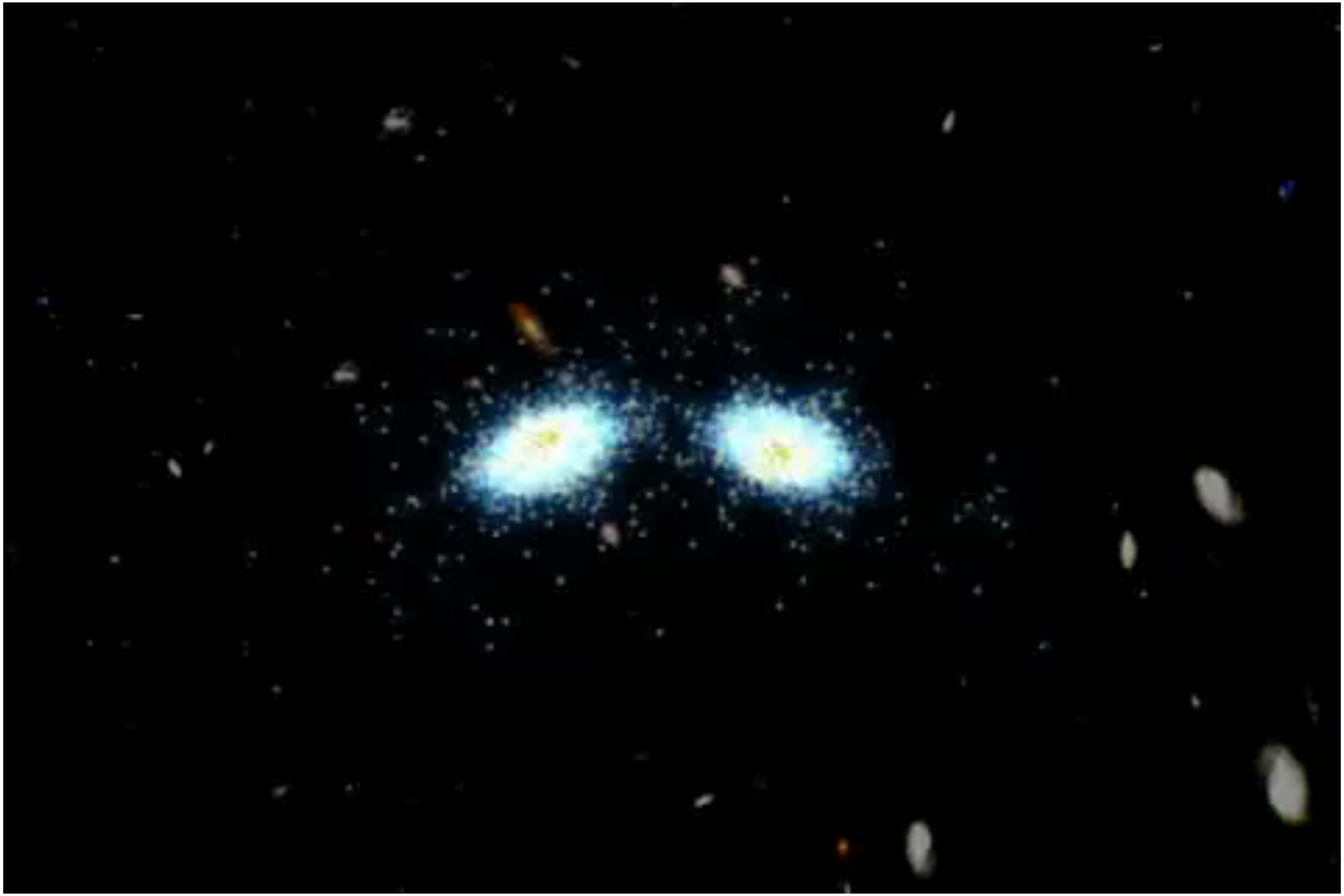


Galaxy Collisions

This pair of interacting galaxies is called the Antennae

Galaxy Collisions

A computer simulation of how to produce such a galaxy:



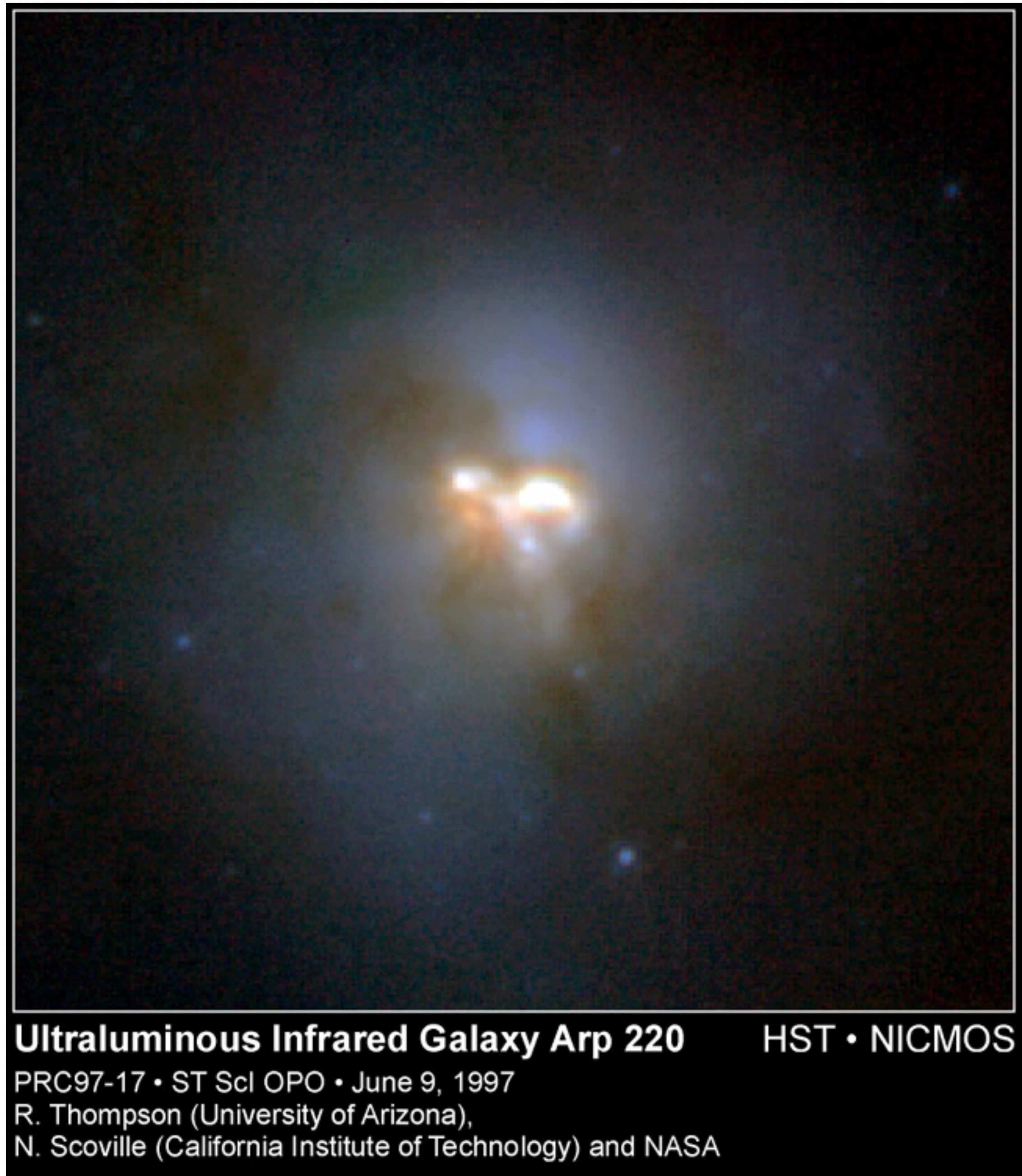
Galaxy Collisions

Collisions cause galaxies to change their shape, and also can induce very rapid star formation.

In the Antennae Galaxy, we see the formation of massive star clusters – **superstar clusters** – with the mass of about 10 million solar masses. This is a huge amount of star formation.

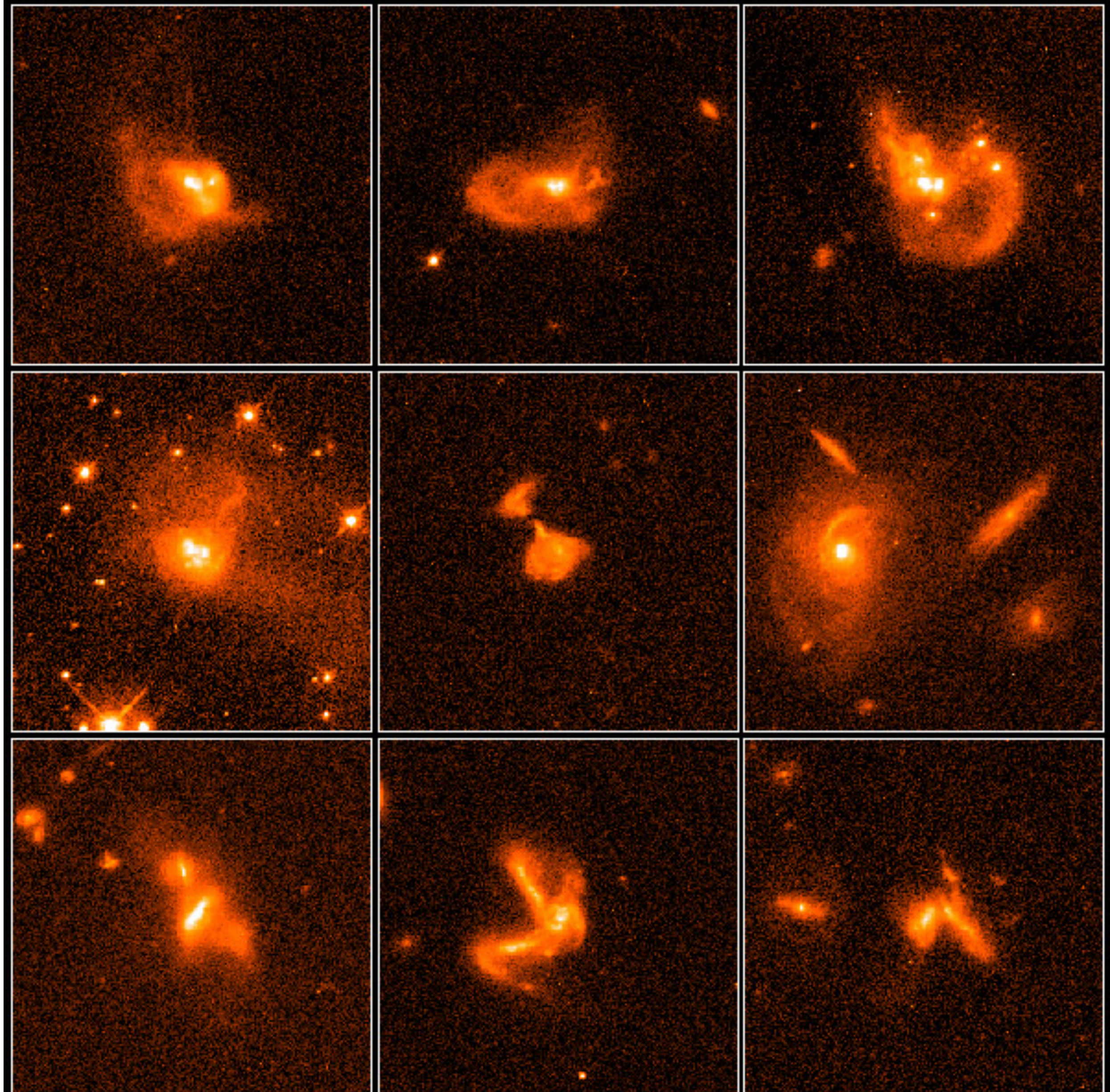
Galaxy Collisions

The most rapidly star-forming galaxies in the Universe (at least unless we go back to the very early Universe when galaxies were more active) look like collisions. These are called **ultraluminous infrared galaxies**, because they are very dusty and forming stars very fast. Star formation heats the dust, which radiates in the infrared.



Here is a collage of images of these **ultraluminous infrared galaxies** from the Hubble Space Telescope.

They look like collisions!



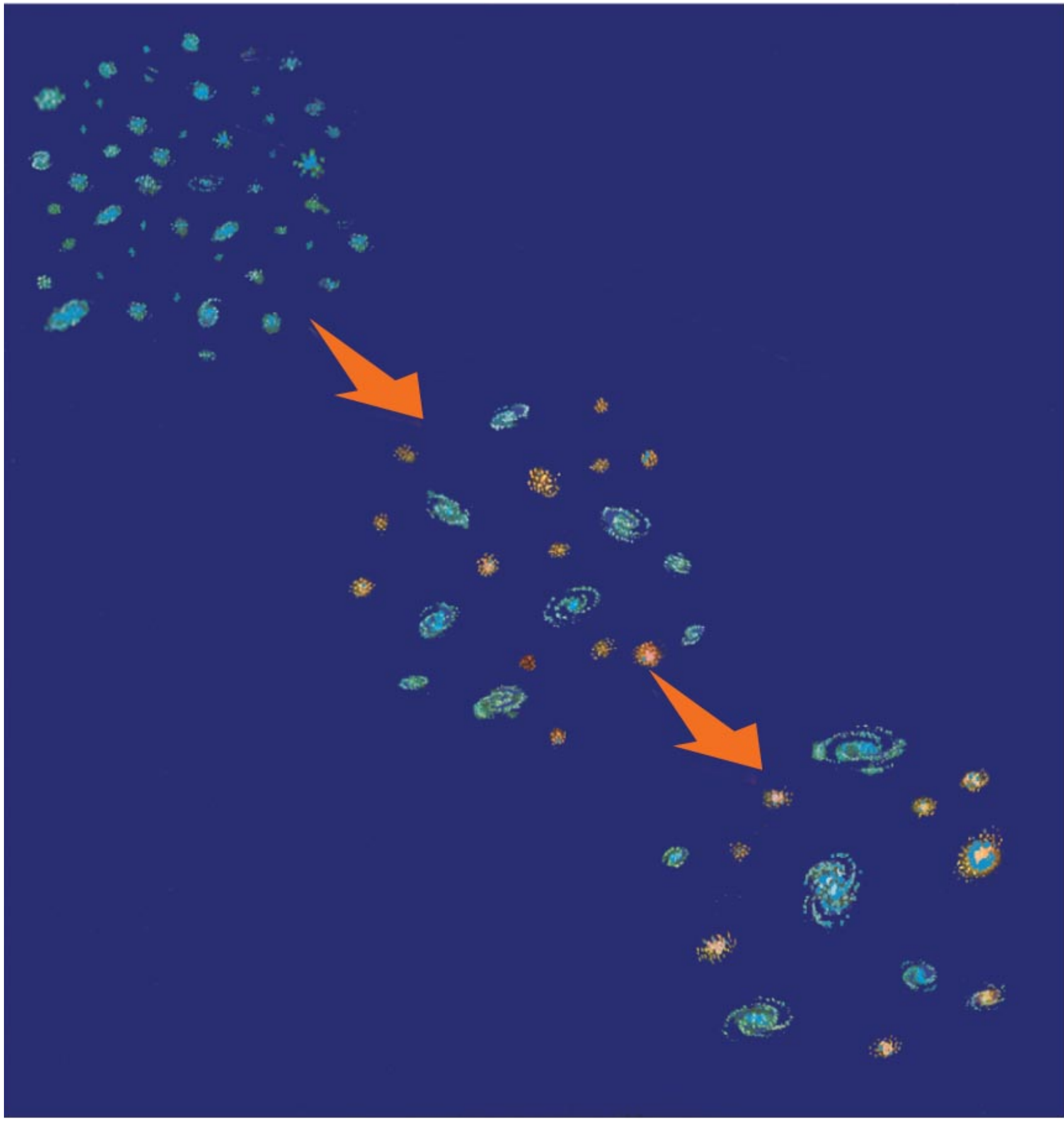
Ultraluminous Infrared Galaxies HST • WFPC2
NASA and K. Borne (Raytheon ITSS and NASA Goddard Space Flight Center), H. Bushouse (STScI), L. Colina (Instituto de Fisica de Cantabria, Spain) and R. Lucas (STScI)

Galaxy Formation

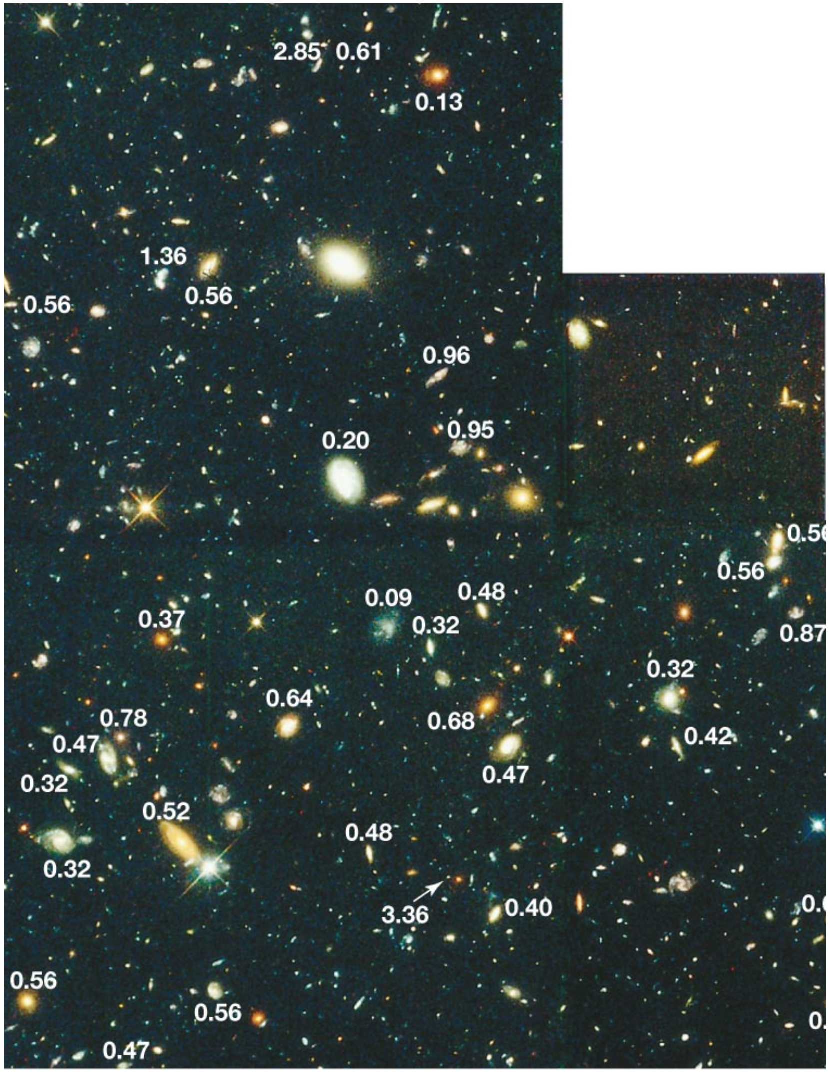
Galaxy collisions can cause galaxies to evolve.

It is generally thought that galaxies form by the merging of many smaller galaxies.

This is called **hierarchical merging** or, more generally, **hierarchical galaxy formation.**



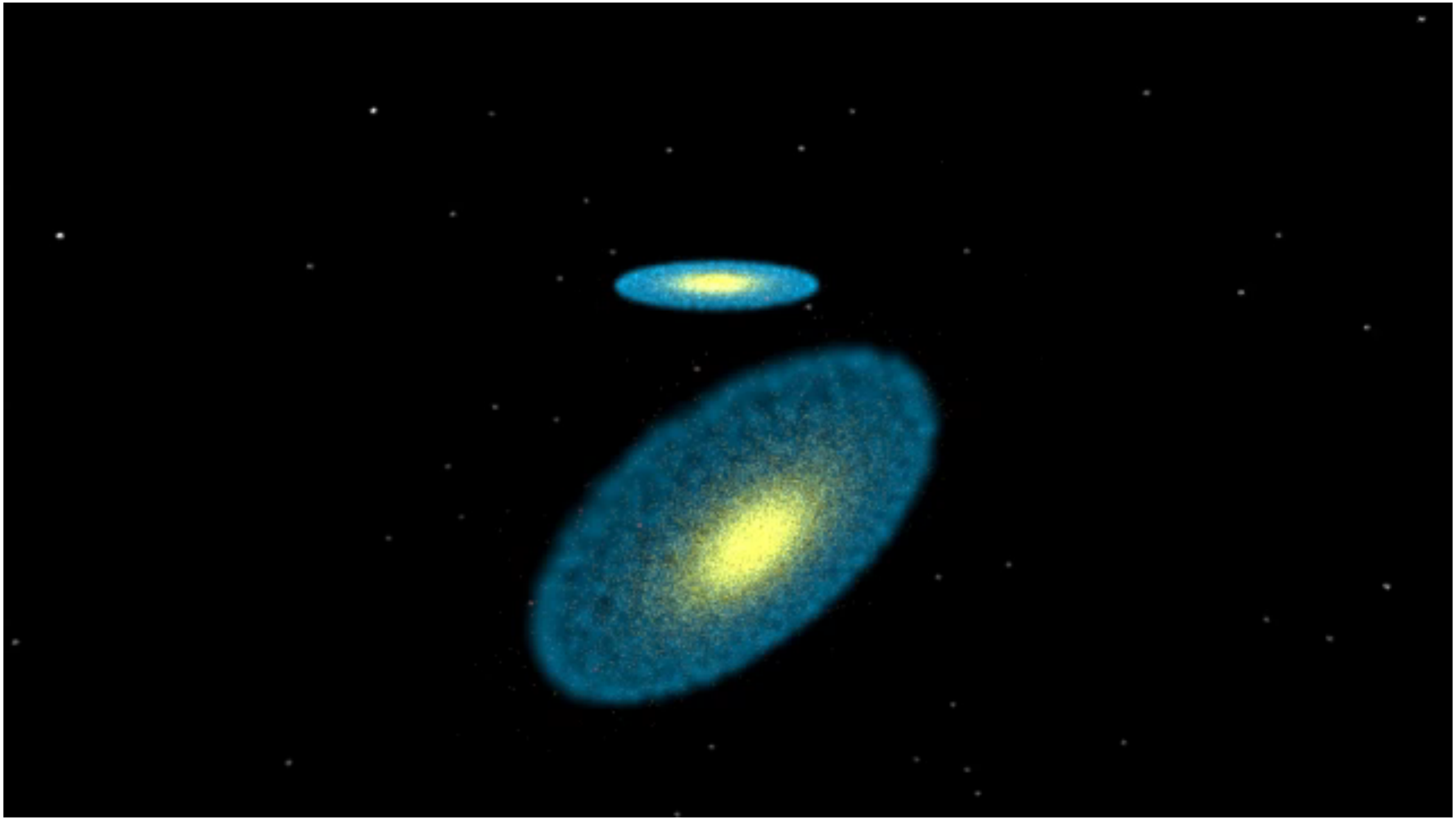
Galaxy Formation



- Galaxy formation is a complex subject that is not fully understood!
- Lines of evidence for hierarchical merging:
  - Pictures of the early universe show large numbers of young lower-mass irregular galaxies
  - Computer simulations of the formation of galaxies usually show elliptical galaxies being formed in mergers

Galaxy Formation

A collision between two spiral galaxies will probably produce an elliptical galaxy. This is a simulation of the predicted collision of the Milky Way and Andromeda.



Galaxy Formation

- The collision between the Milky Way and Andromeda – both spirals – will probably produce an elliptical galaxy

- The collision destroys the disks and mixes up the orbits of the stars, producing a ball of stars – an elliptical

- In fact it is generally thought that elliptical galaxies are formed by the collisions of spirals, although this may not always be the case

- Collisions between two galaxies of comparable mass are called major mergers -- collisions between a big galaxy and a smaller galaxy are called minor mergers

Galaxy Formation

The Whirlpool Galaxy is an example of a minor merger

Galaxy Formation and Black Holes

- Galaxy collisions not only fuel star formation, but can send huge amounts of gas to the center to fuel the central supermassive black hole

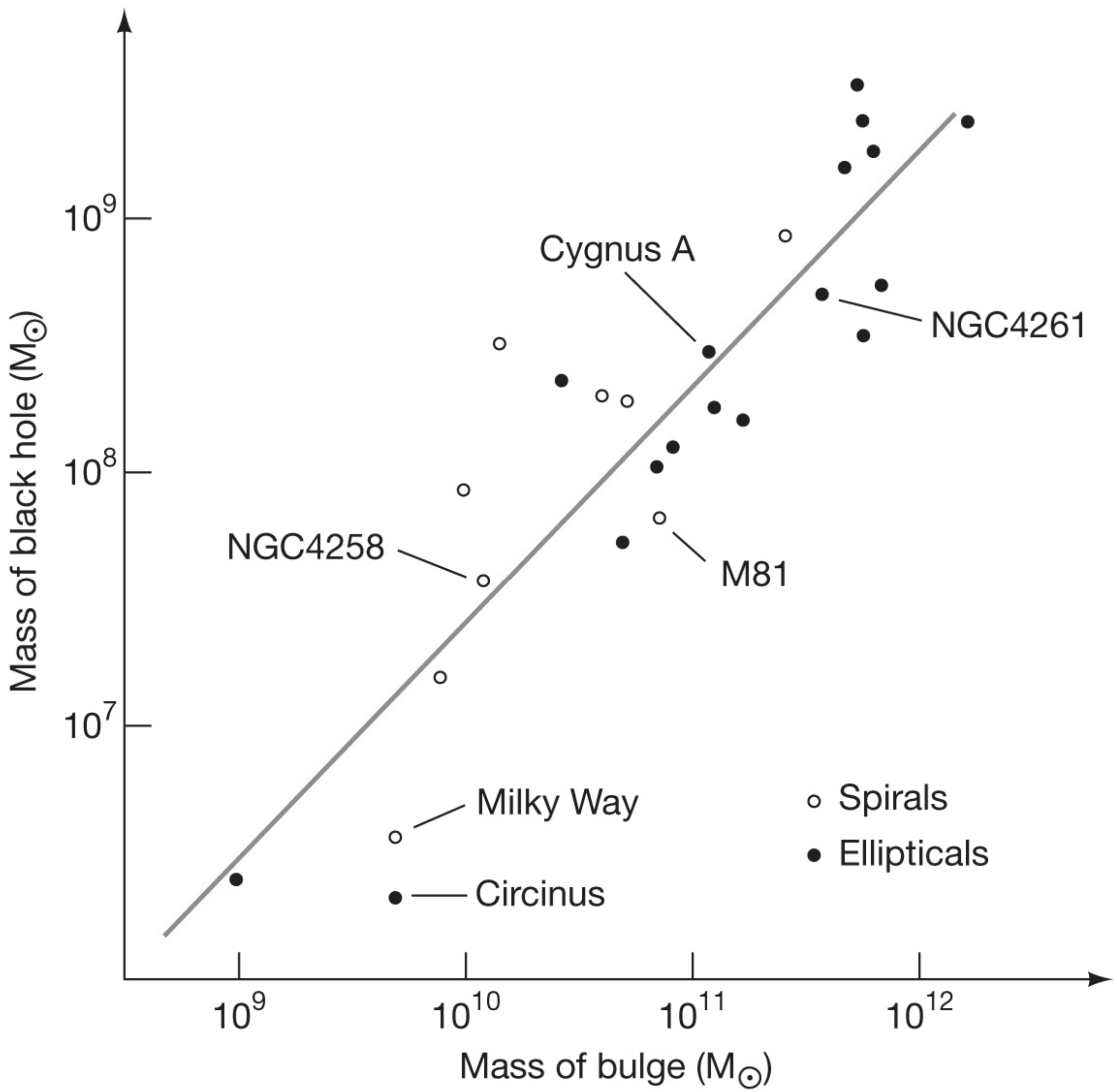
- The energy emitted by this accreting supermassive black hole can blow the gas out of a galaxy

- This is known as **feedback**

Galaxy Formation and Black Holes

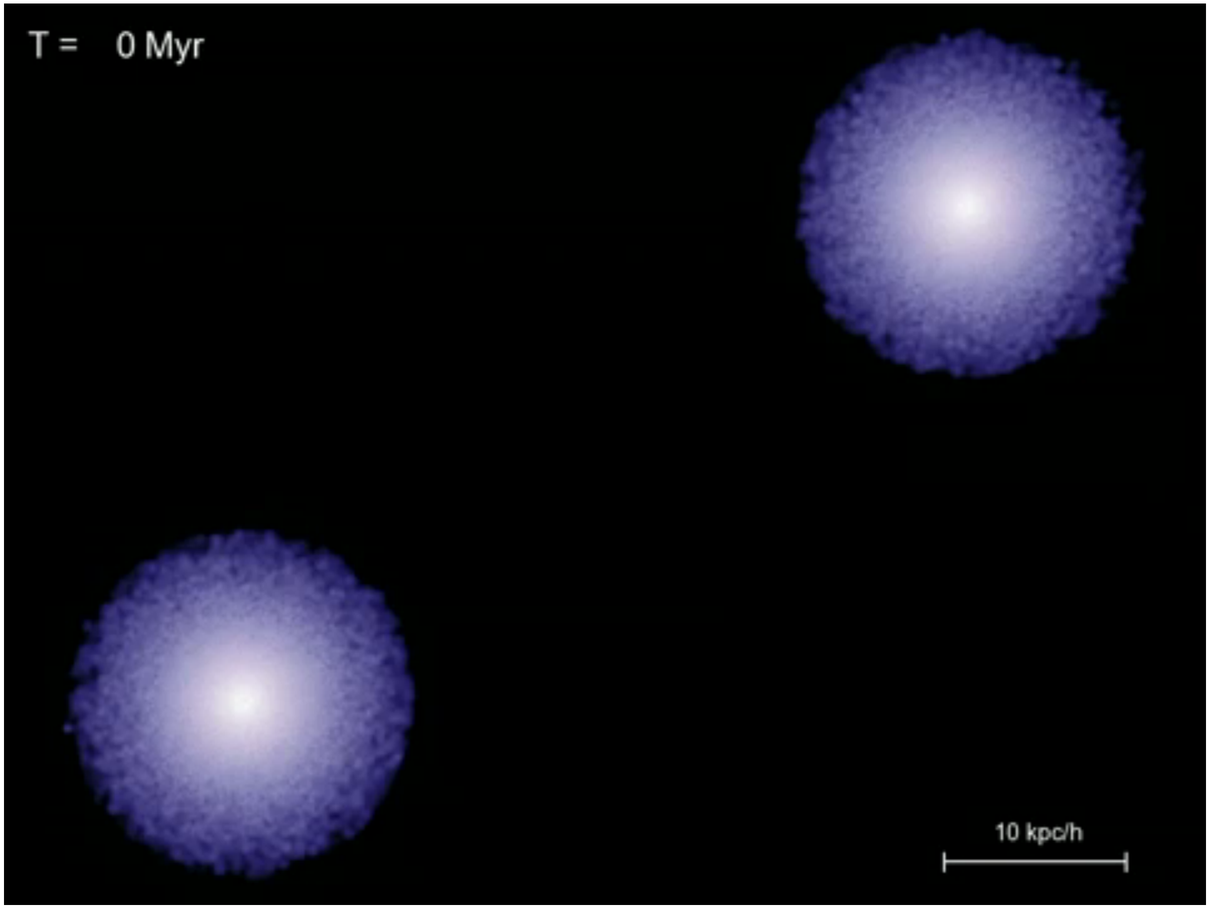
One line of evidence for feedback comes from the close relationship between the mass of the black hole and the mass of the galactic bulge.

How does a black hole know about the mass of the bulge, which is 1000 times more massive?



Galaxy Formation and Black Holes

How do black holes know about the mass of the galaxy?

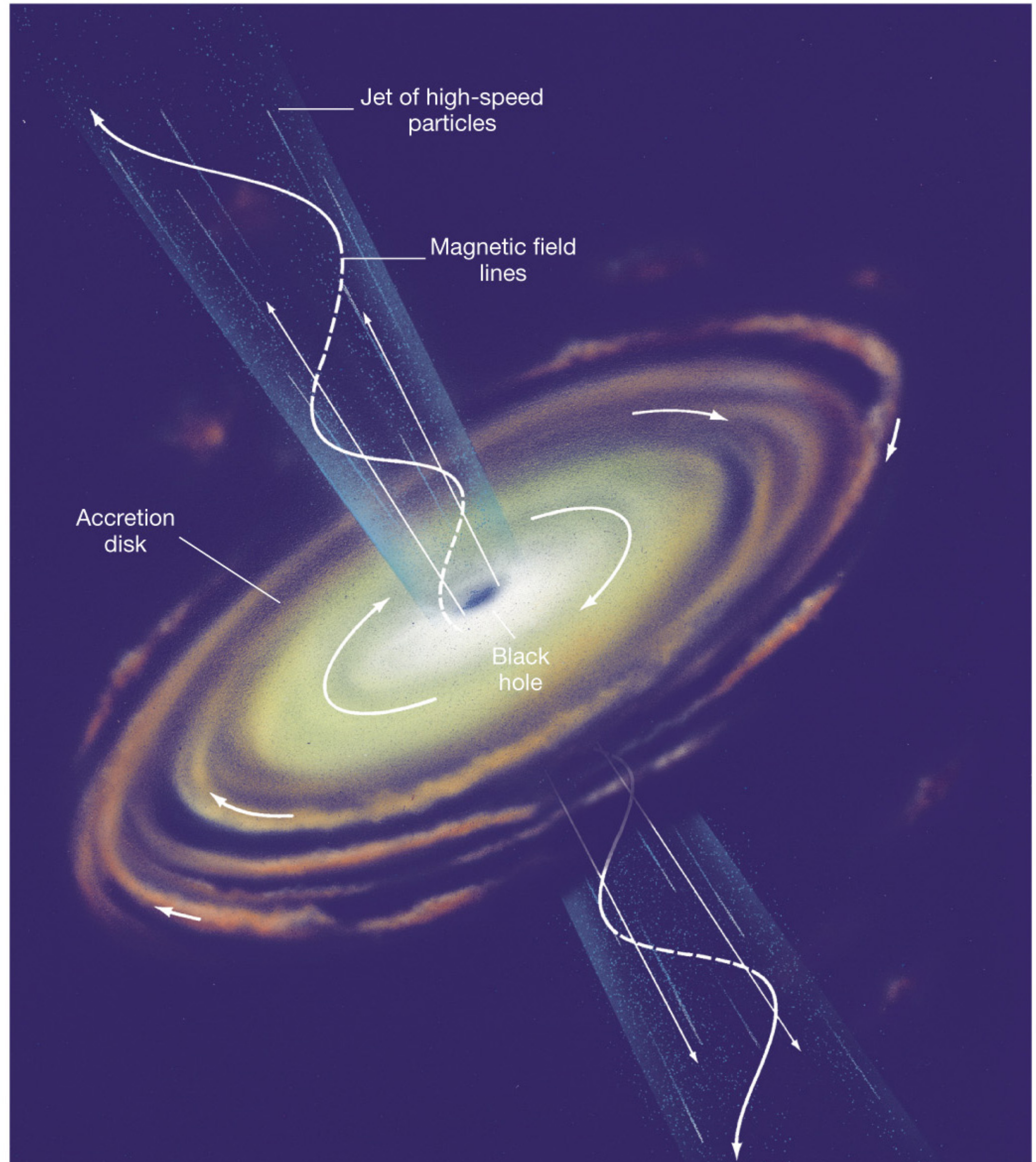


The collision of galaxies drives so much gas to the center that the black hole grows. When it gets big enough, it blows the gas away, stopping its growth and the growth of the galaxy.

Galaxy Formation and Black Holes

- As the black hole is accreting gas, it shines brightly as a quasar – which we encountered in the last chapter.

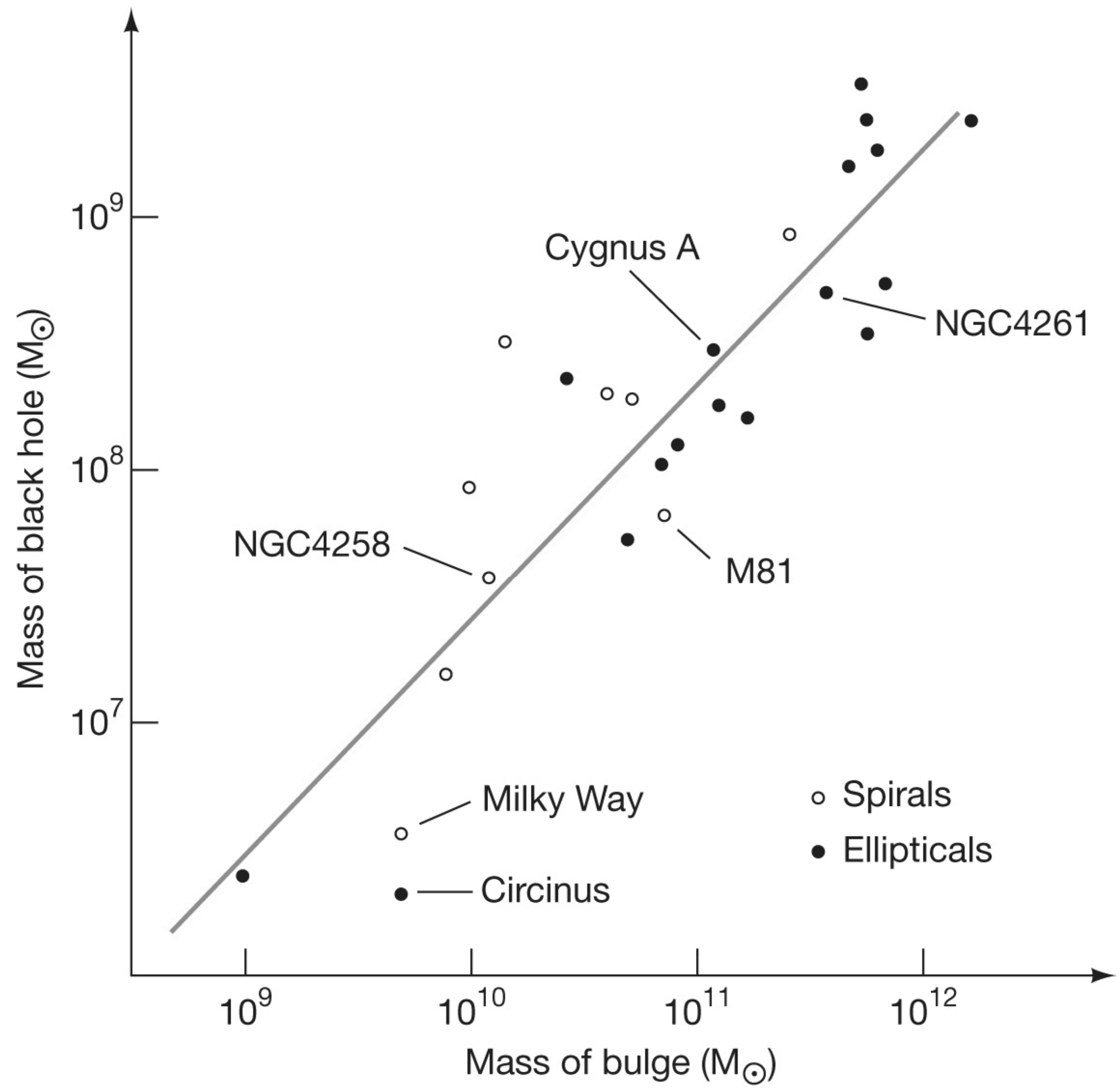
- Recall that the friction of gas falling into a black hole cause the gas to shine brightly!



Galaxy Formation and Black Holes

- Because every galaxy seems to have this close relationship with its black hole – every galaxy may have been a quasar at some point in its history!

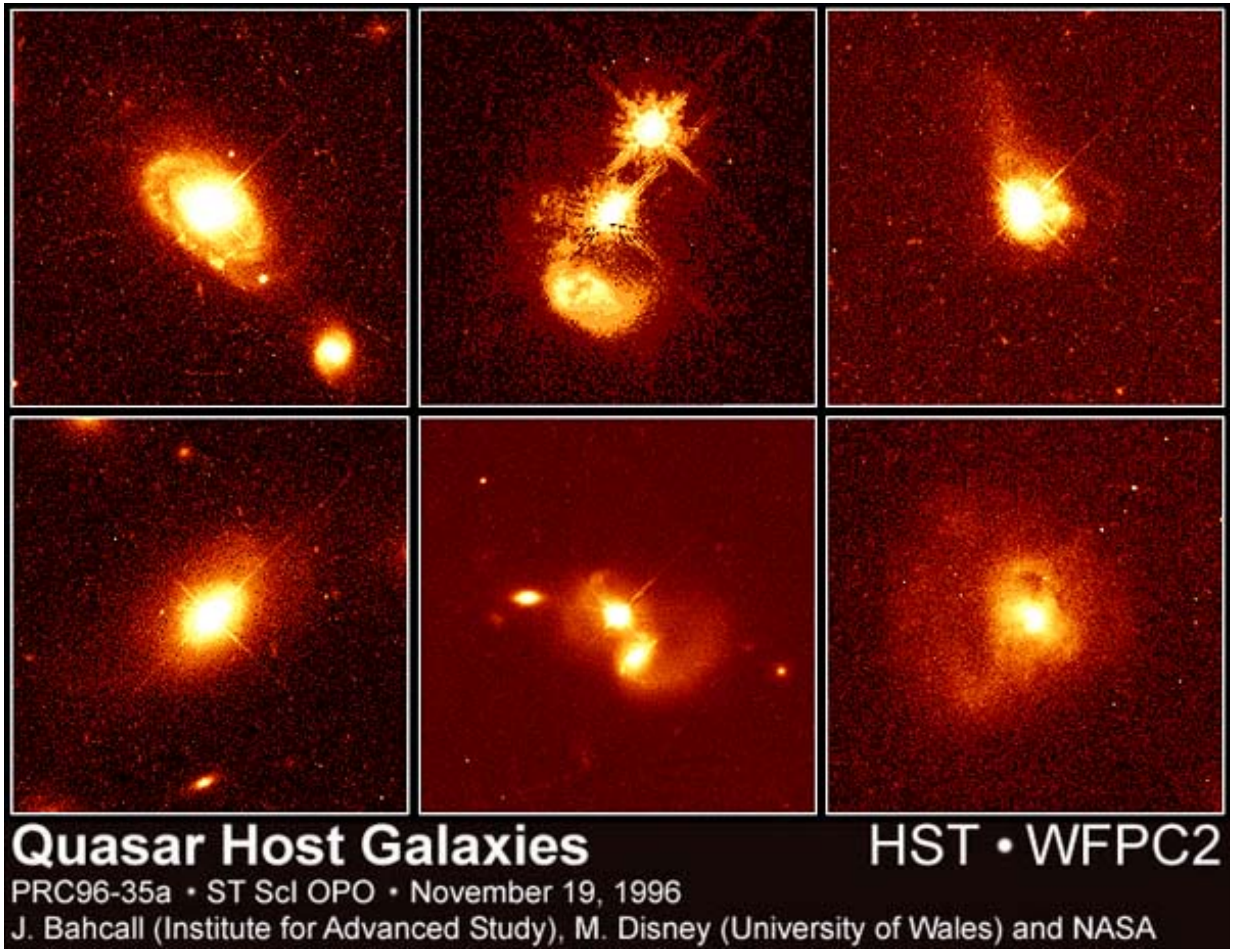
- Every galaxy had its quasar phase



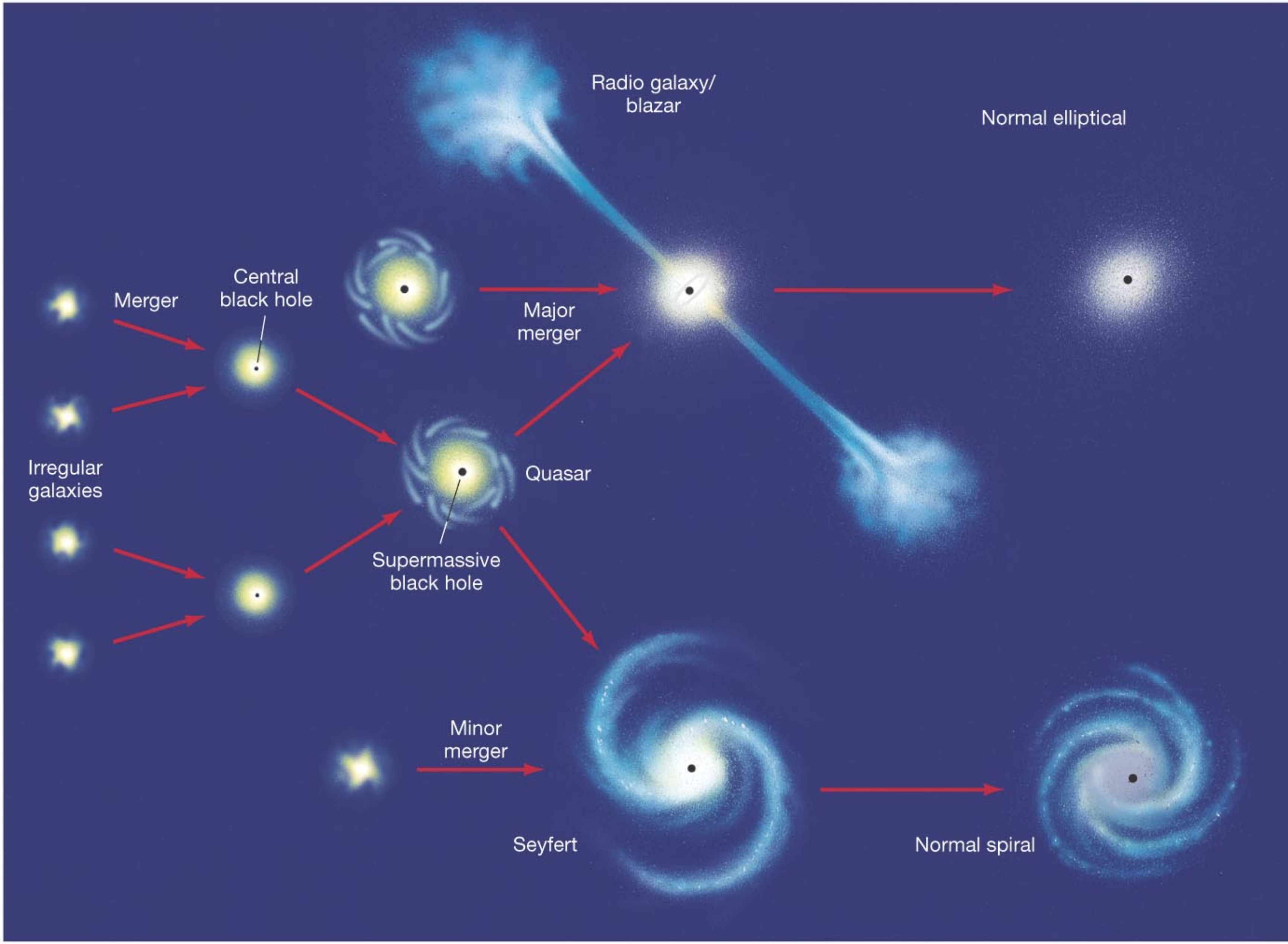
The Quasar Phase

- The quasar phase happens soon after galaxies collide – so quasar hosts should look like collisions

- This seems to be the case, as this collage from Hubble shows



Galaxy Formation and Evolution



Galaxy Formation and Evolution

- The sequence of galaxy formation and evolution on the previous slide can be understood as follows:
  - Galaxies form from the merging of many smaller galaxies – hierarchical merging
  - Major mergers produce starburst galaxies, quasars, and (typically) elliptical galaxies
  - Minor merger can fuel Seyfert galaxies (a smaller version of a quasar) and leave the disk intact so we have a spiral galaxy

Large Scale Structure

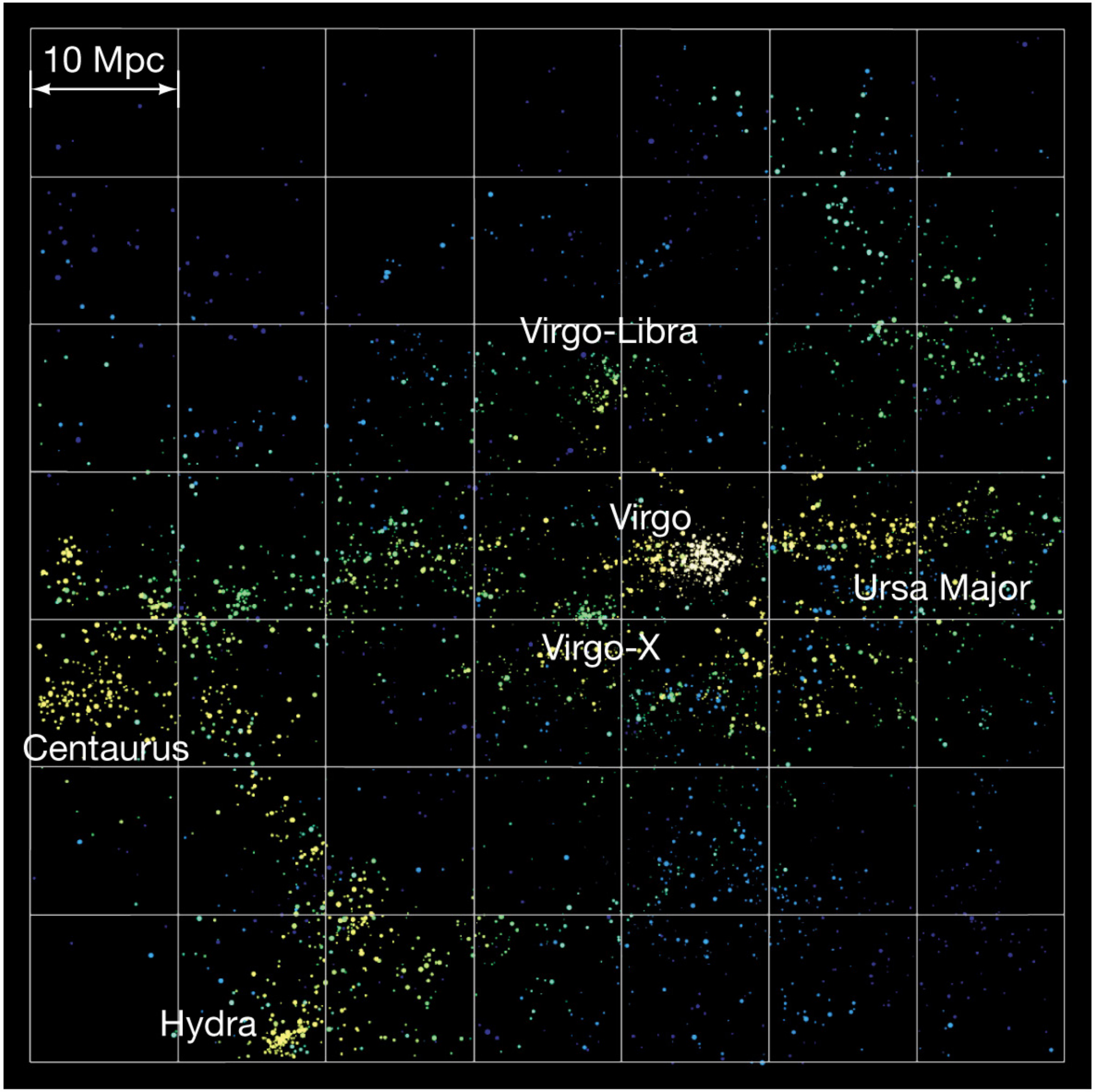
- The universe is organized on the largest scales

- Stars are organized into galaxies, galaxies into clusters, clusters into even larger structures called superclusters

Our Galactic Neighborhood

- The Milky Way, Andromeda, and several other smaller galaxies form the **Local Group**, a small **galaxy cluster**
  - Galaxy clusters consist of a collection of galaxies orbiting one another, bound together by their own gravity
- The nearest large galaxy cluster to the Local Group is the Virgo Cluster
- Galaxy clusters themselves tend to clump together into **superclusters**. The Virgo Cluster, the Local Group, and several other nearby clusters form the Local Supercluster.

Local Supercluster



Large Scale Structure

- From the map of the local supercluster, you can see that the galaxies are lined up in lines or **filaments**
- This is true also on even larger scales
- We can see this using large surveys of galaxies called redshift surveys

Redshift Surveys

- We point the telescope in a particular direction, and measure the **redshifts** of as many galaxies there as we can
  - By looking at the galaxies' spectral lines, we can tell how fast they are receding from us
  - Using Hubble's Law v = H x d, we can then figure out the distance from measuring the velocity
  - For the most distant galaxies, we don't usually bother converting the velocity to a distance – we just measure the **redshift** *z*

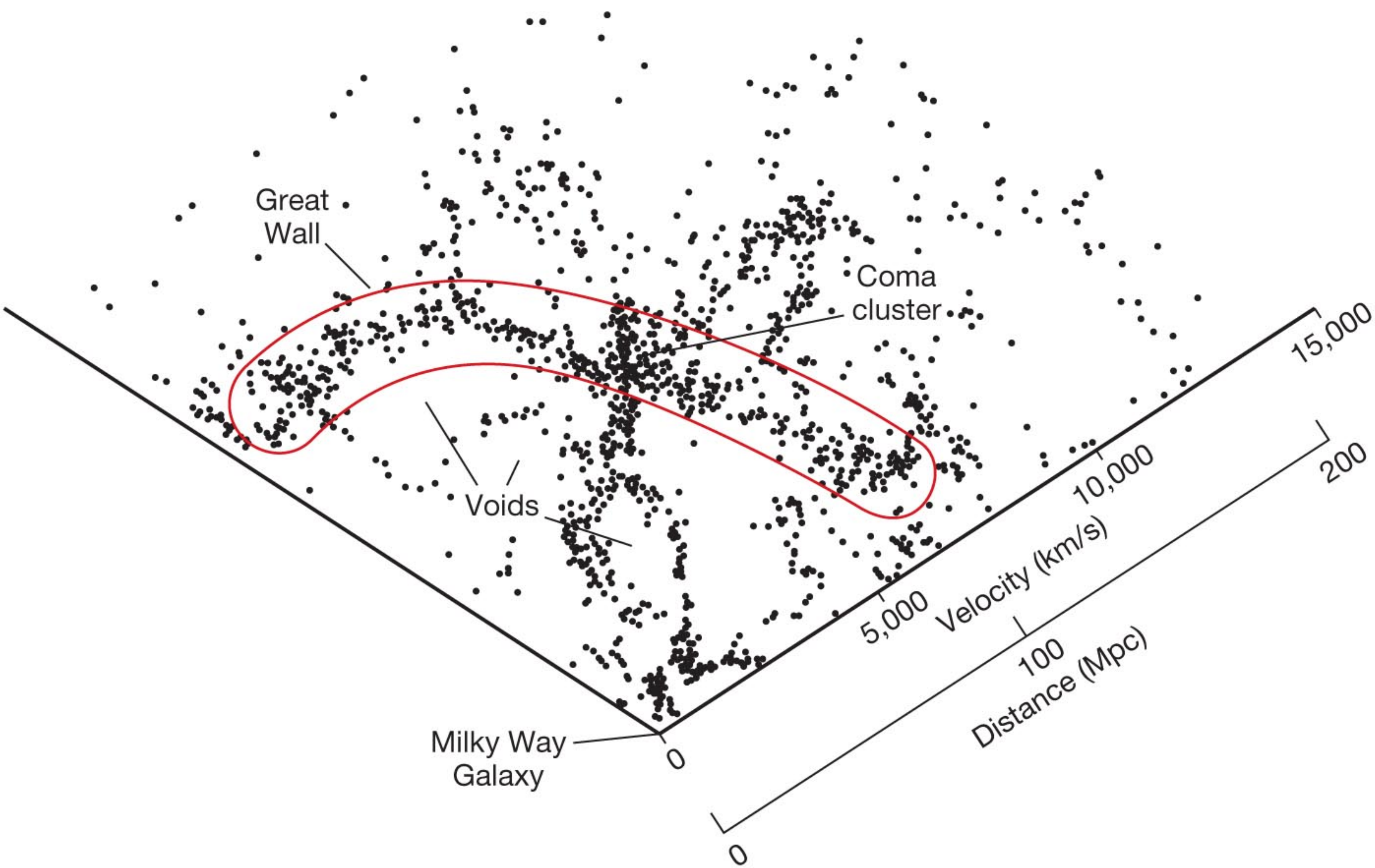
$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$

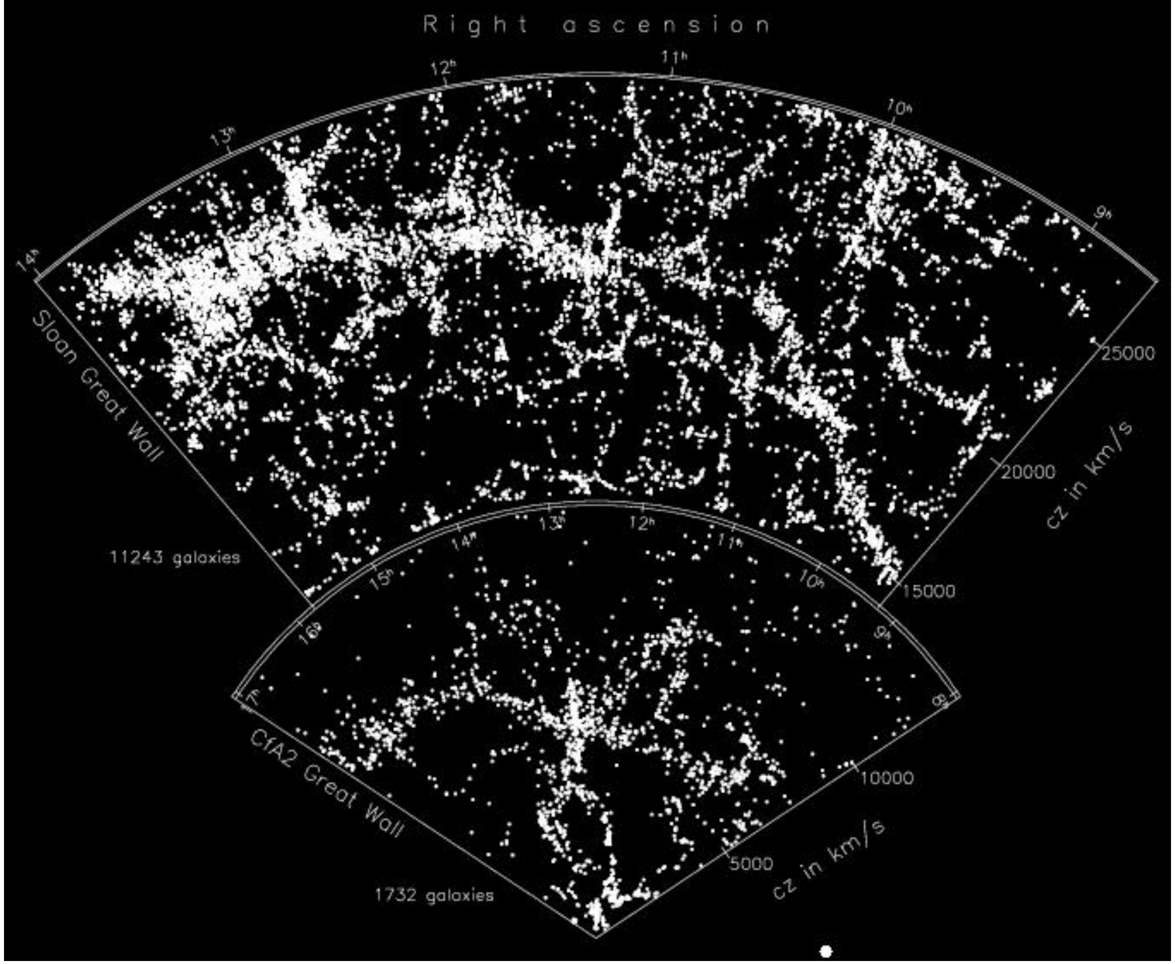
The redshift *z* is the difference between the observed and emitted wavelengths of a spectral line, divided by the emitted wavelength

Redshift Surveys

- One example of a redshift survey is the Sloan Digital Sky Survey or SDSS
- It has measured the spectra of about 1 million galaxies and 120,000 quasars
- The biggest dataset in astronomy (so far!)

Large Scale Structure



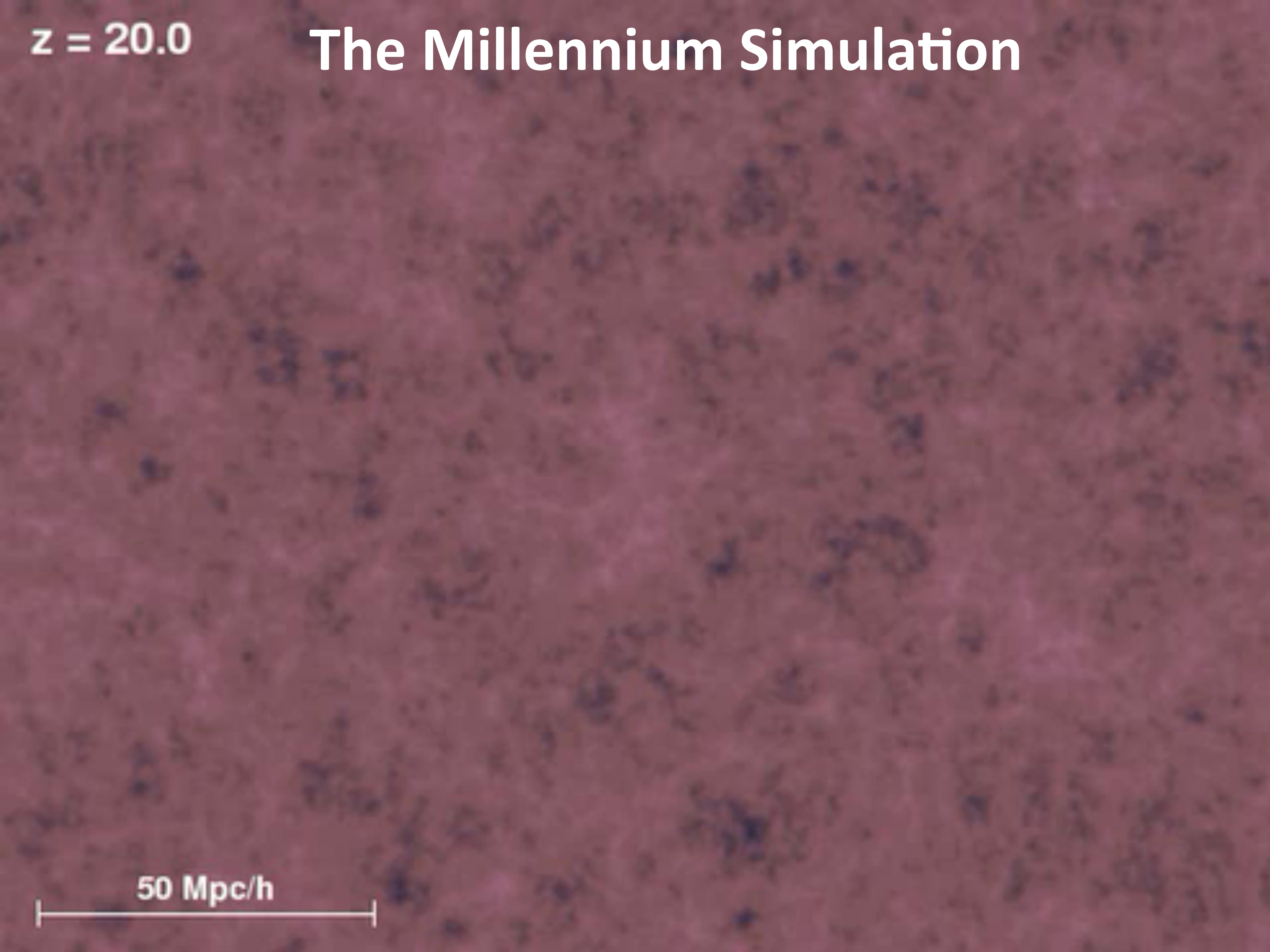


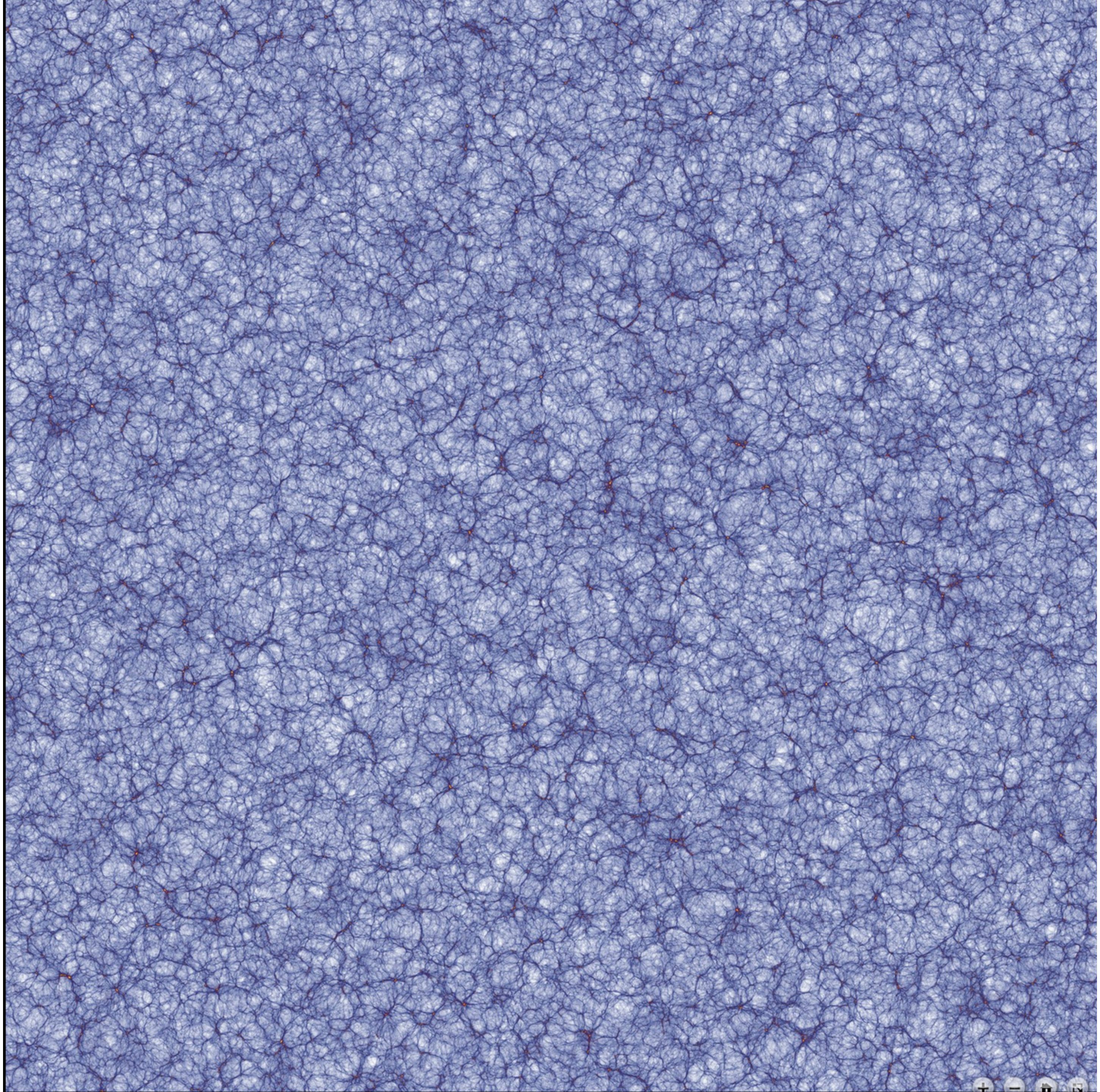
- The universe is organized into filaments on the largest scales, as revealed by these redshift surveys
- There are also large empty regions known as voids
- The biggest of these structures – filaments and voids – are around 200 Mpc

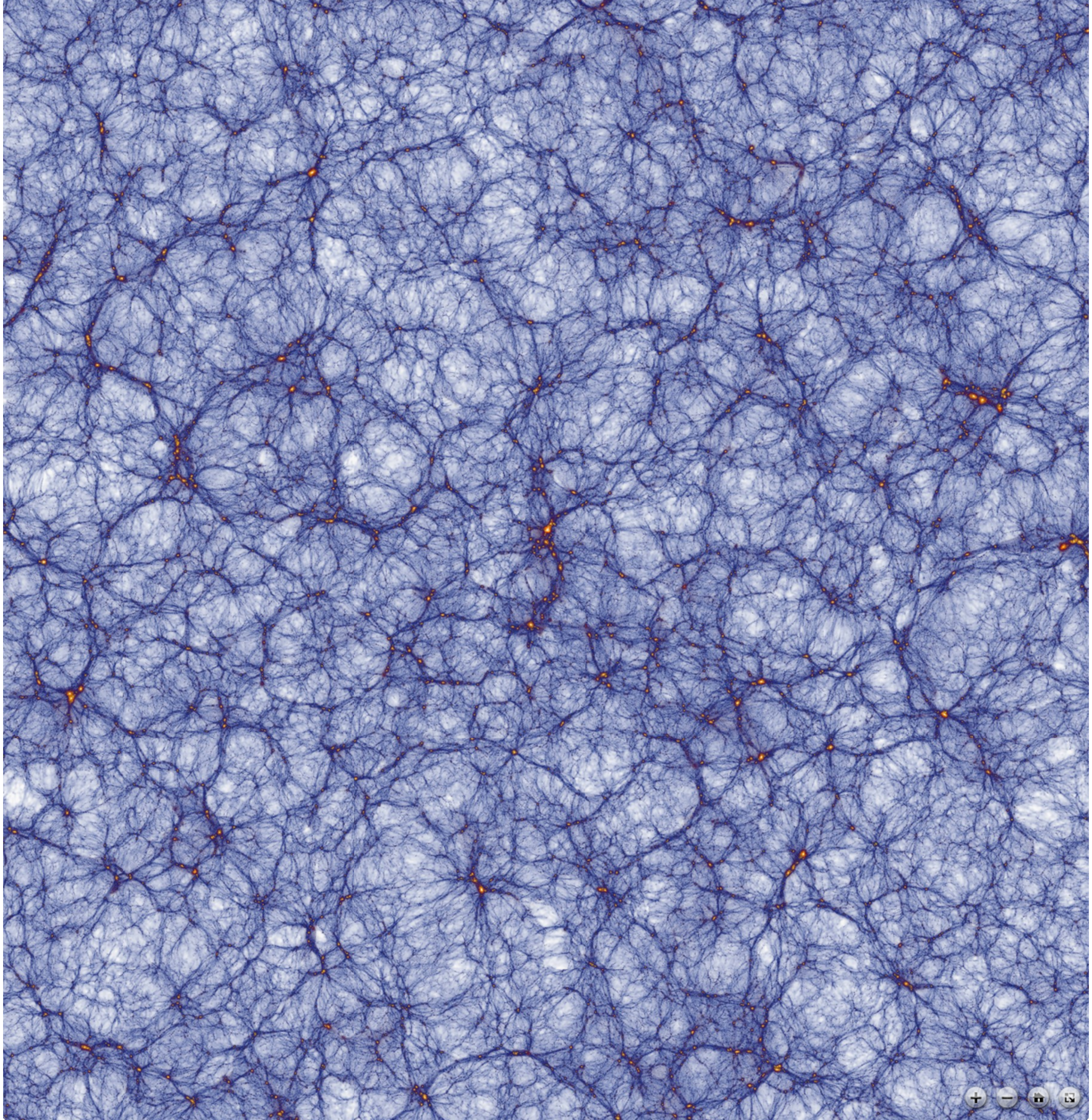
Dark Matter on Large Scales

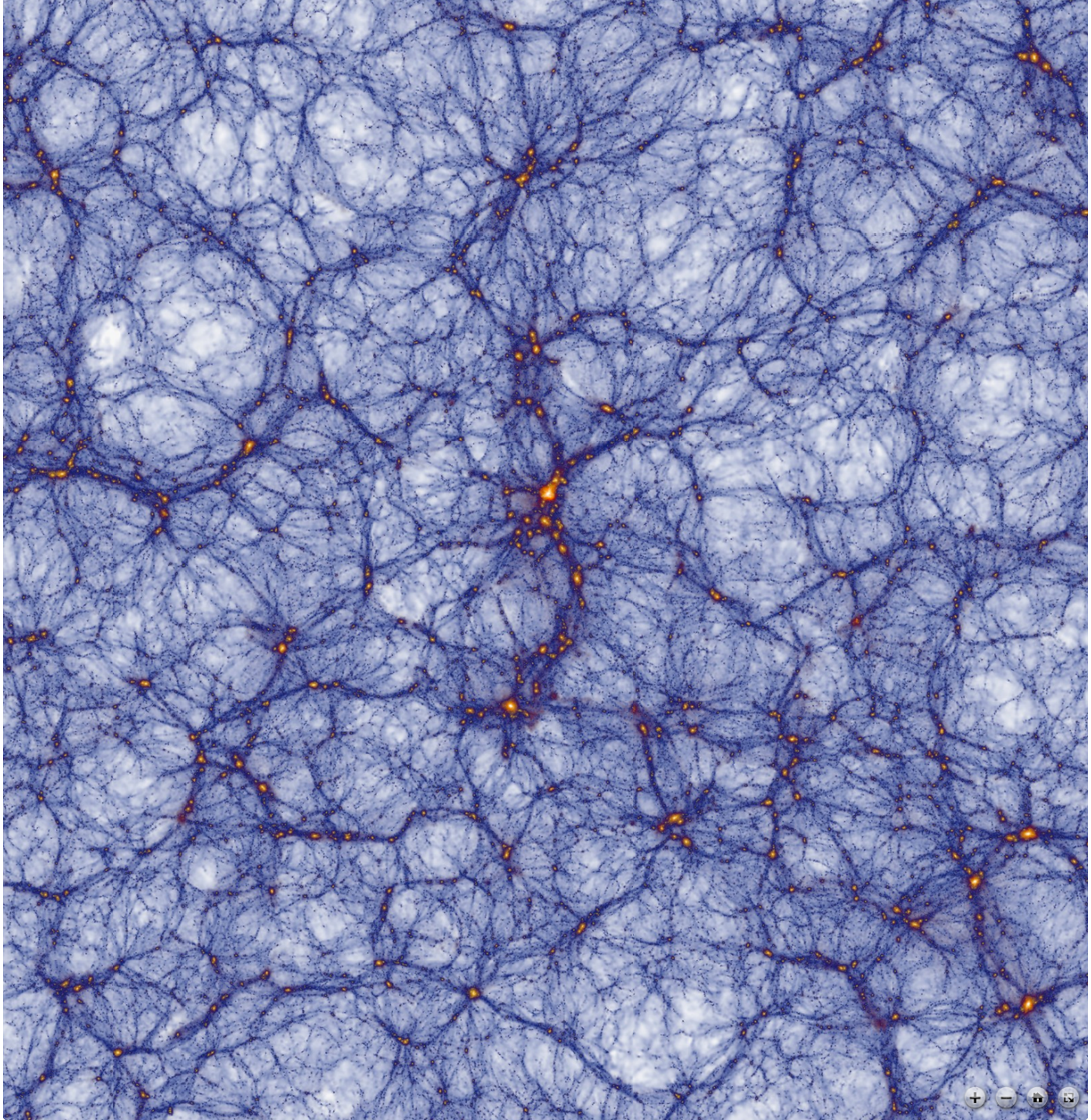
- The clumpiness of the universe on these large scales is explained by dark matter
- Dark matter only interacts via gravity, and gravity causes things to clump up: massive, dense regions attract more matter because of their gravity
- Computer simulations of dark matter naturally produce such a **cosmic web** – strong evidence that the universe is filled with dark matter

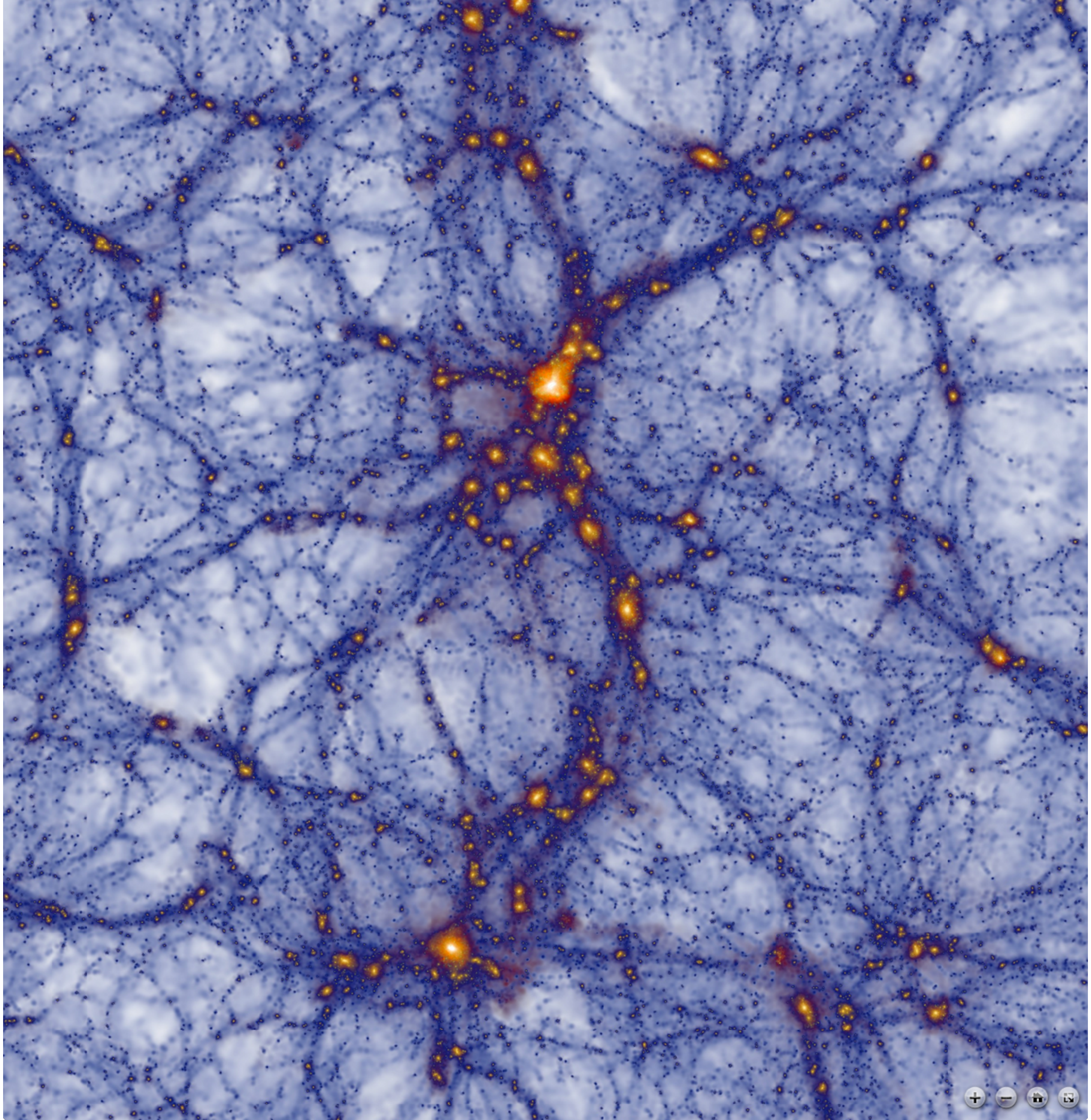
The Millennium Simulation

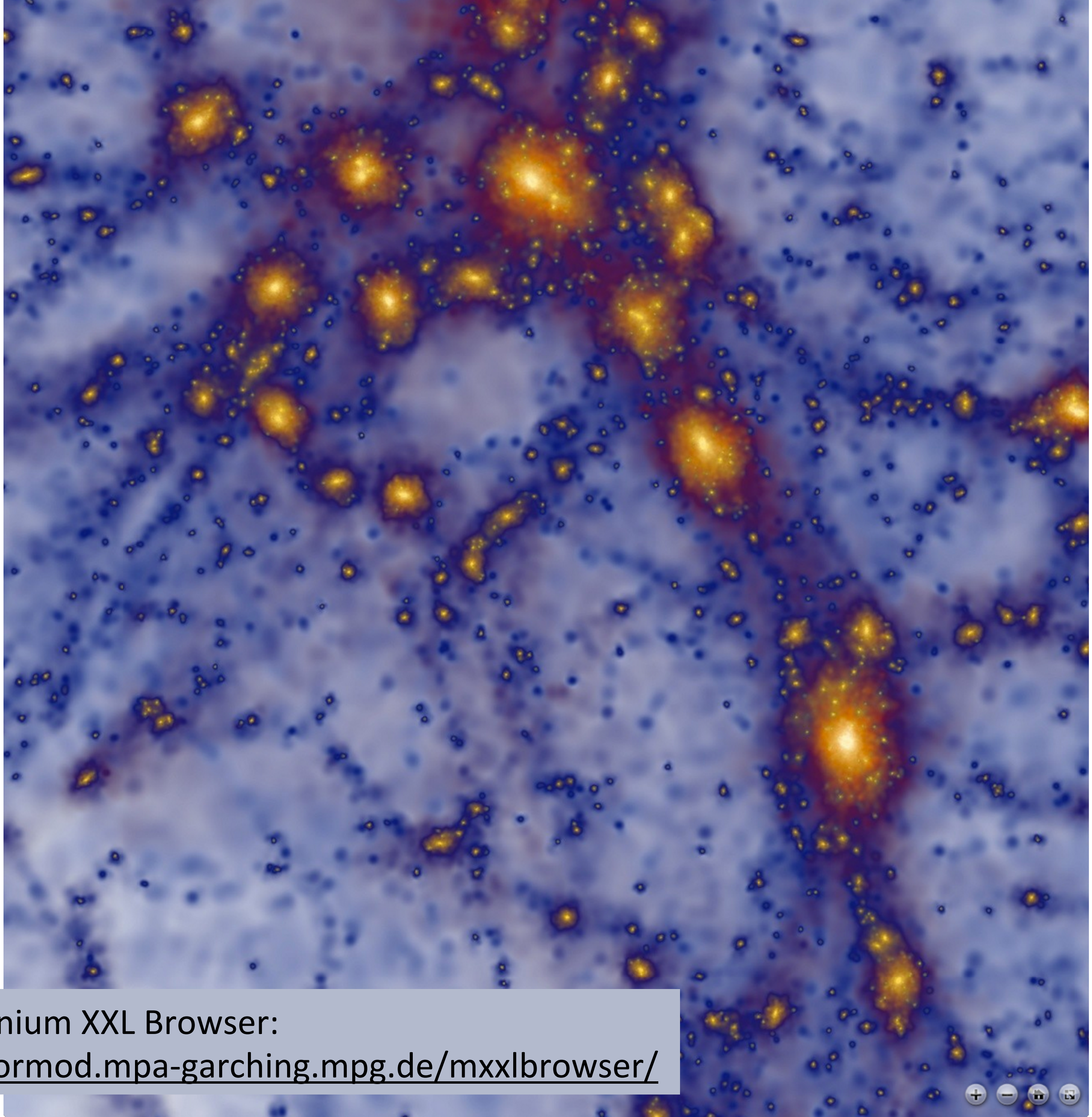












The Millennium XXL Browser:
http://galformod.mpa-garching.mpg.de/mxxlbrowser/

Dark Matter on Large Scales

- Notice how dark matter tends to clump and combine in the simulation
- Galaxies live in dark matter halos! So galaxies that follow the dark matter haloes would combine with each other as a result
- Galaxy collisions are a natural result of dark matter in the universe
- **Dark matter clumps together because of gravity, and carries galaxies along so that they collide with one another**

The large-scale distribution of galaxies in the universe reveals

A — a smooth, continuous and homogeneous arrangement of clusters

B — a large supercluster at the center of the universe

C — a central void with walls of galaxies at the edge of the universe

D — large voids, with most of the galaxies lying in filaments and sheets

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Dark Matter and Gravitational Lensing

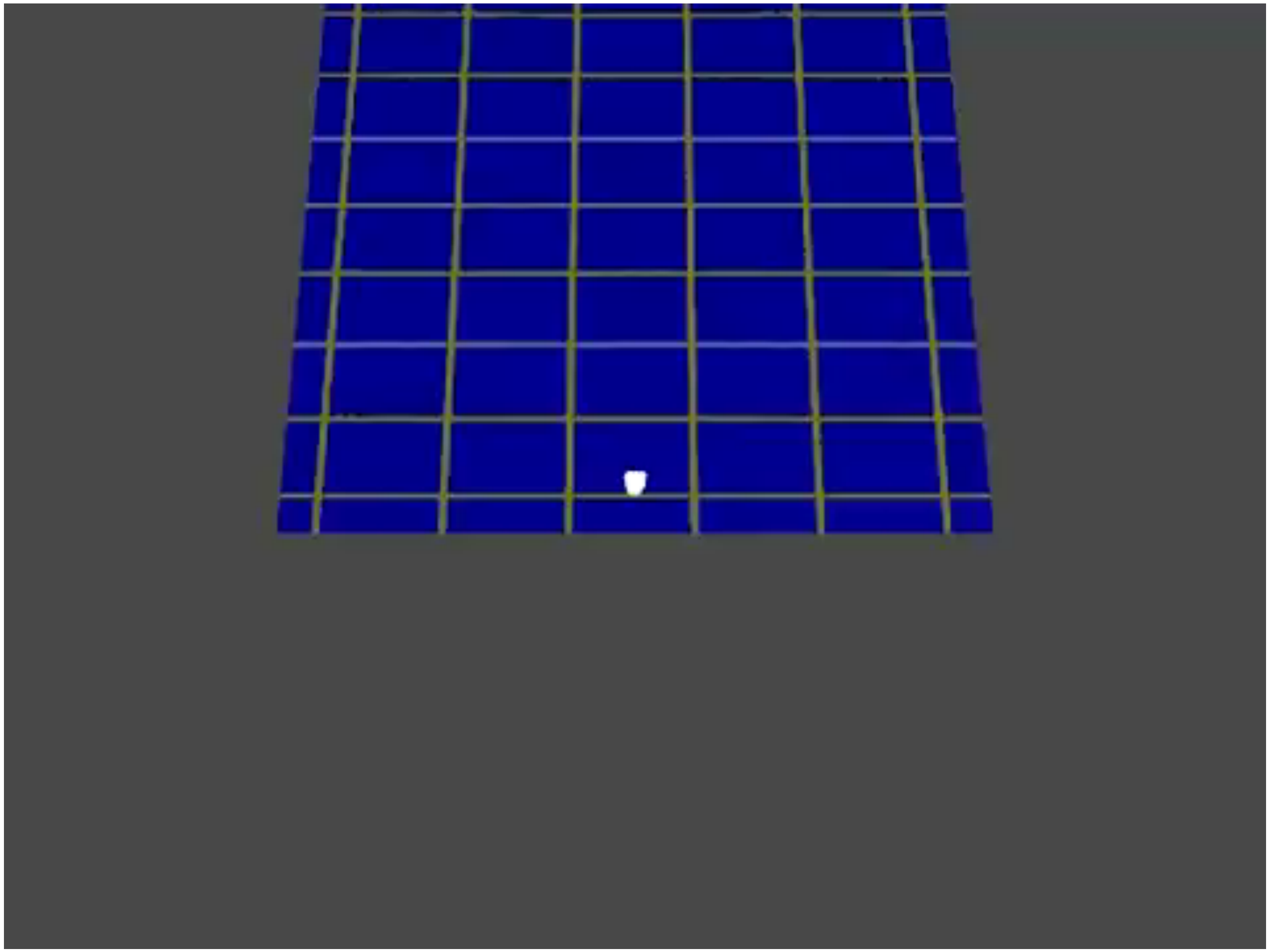
- Because we see the effects of dark matter via its gravity, we can see this gravity distort light

- 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



A massive object bends the path of light

Gravitational Lensing

Gravitational lensing is seen around clusters of galaxies.

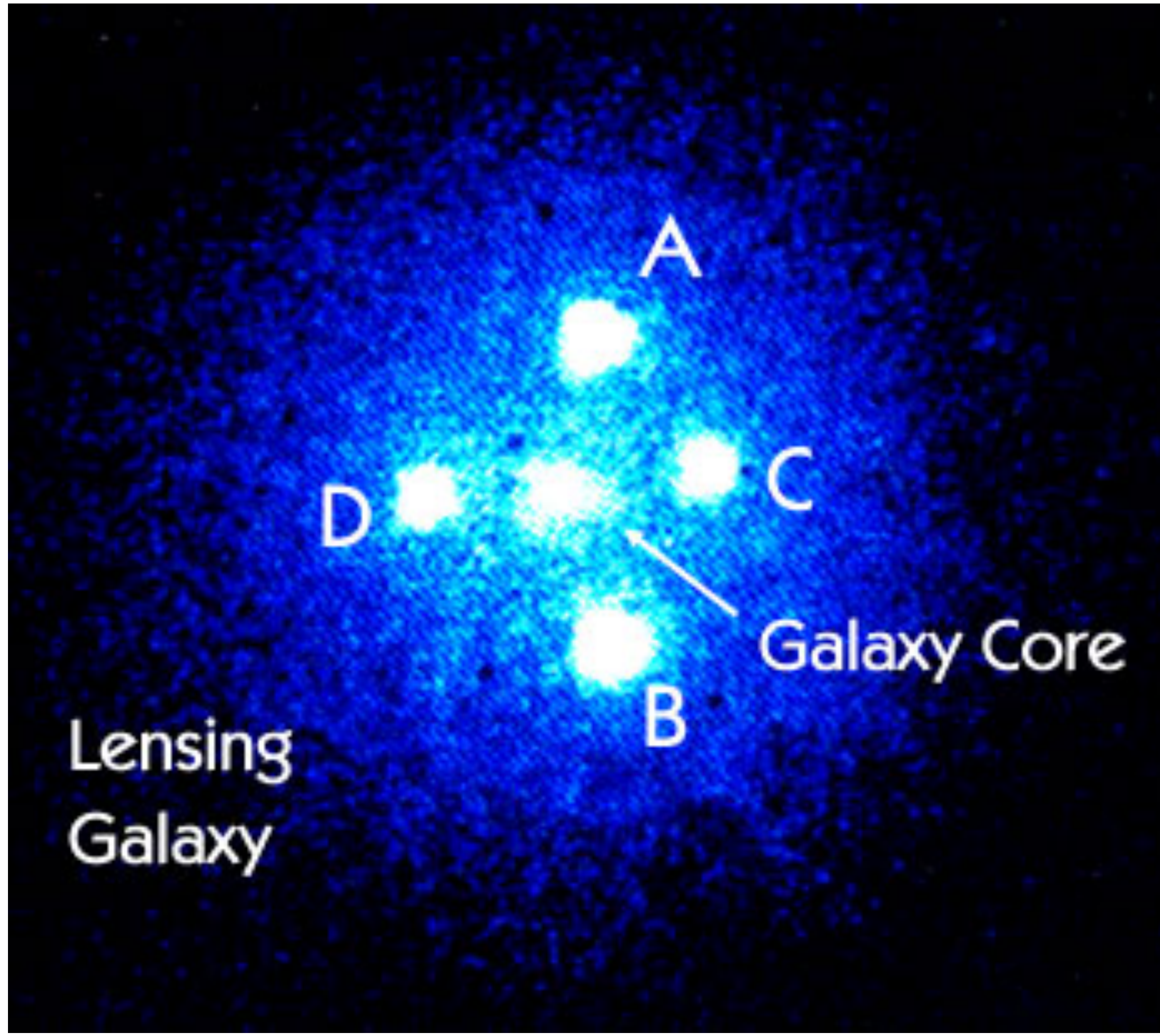
Background galaxies are seen as stretched objects.

Lensed galaxies

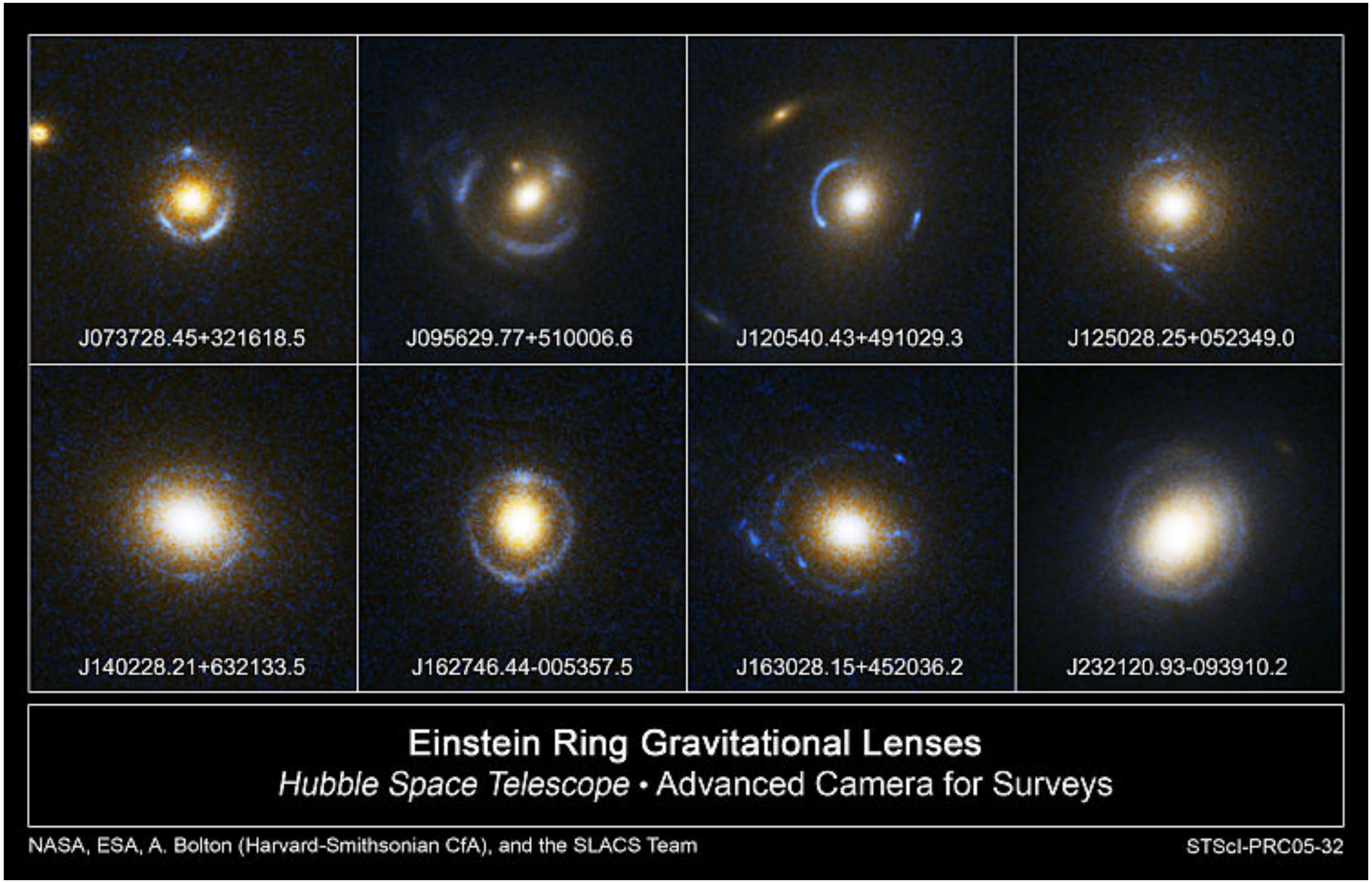
Gravitational Lensing

- 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

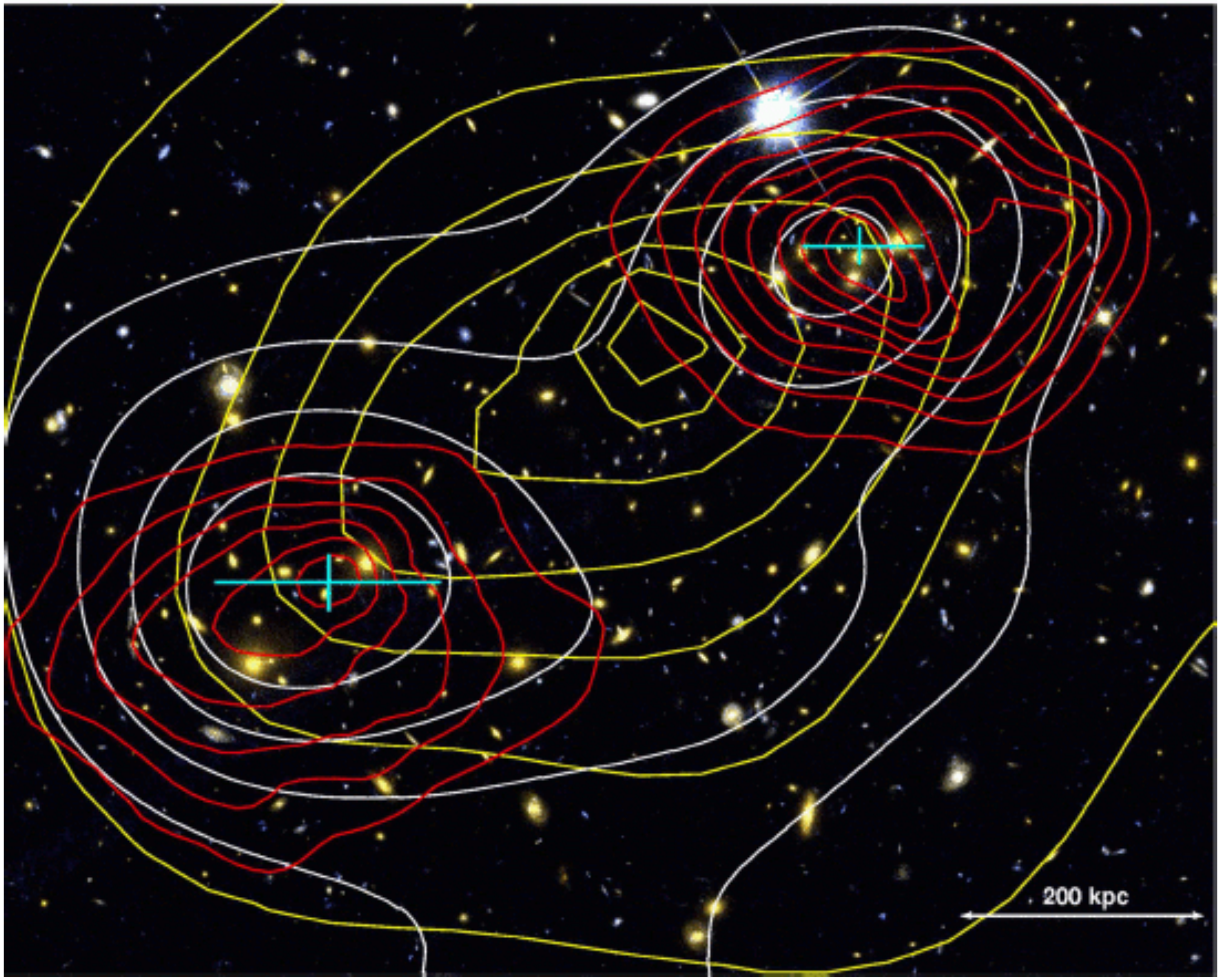
- So gravitational lensing can tell us how much dark matter there is and how it is distributed!

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.



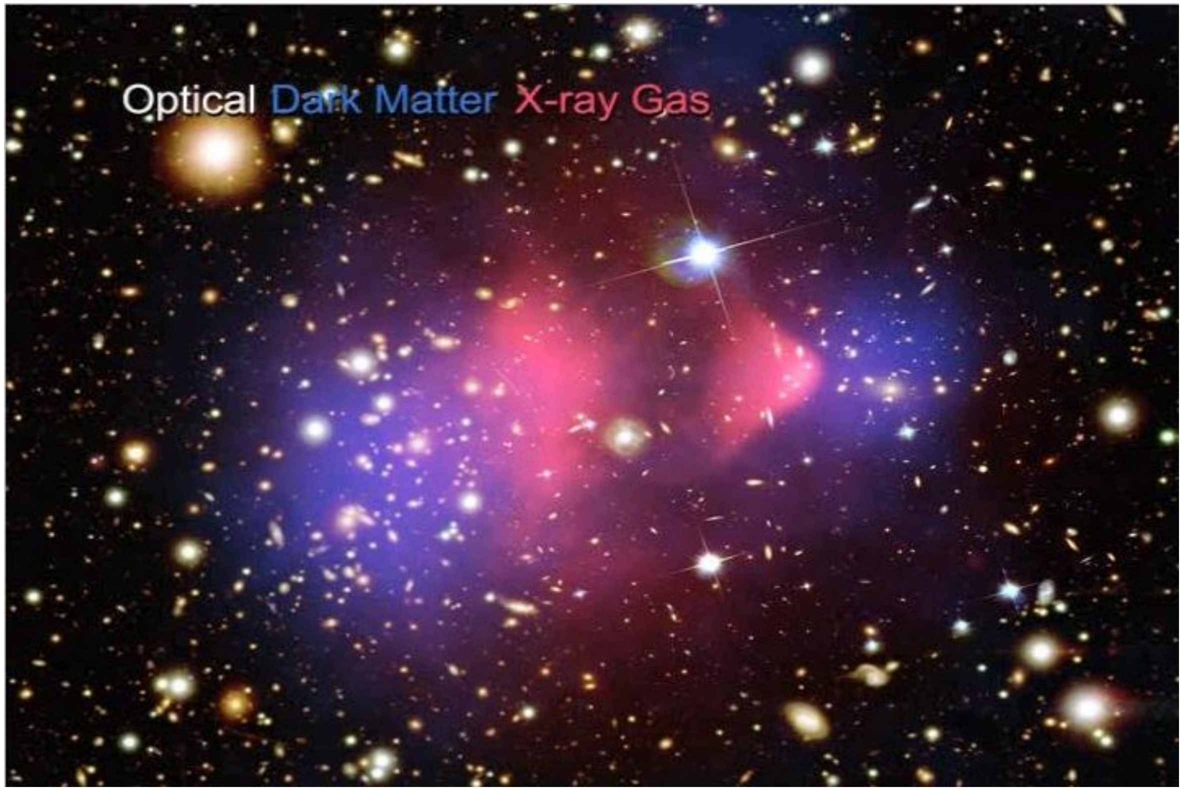
Bullet Cluster

- 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