Announcements

- First to last quiz due tonight :-)
- Start working on problem sets if you haven't done so yet!
  → Due by end of semester, worth 10% of final grade
- Stargazing Blitz Week this week, Dec. 1-4: stargazing every night this week, 8-9 pm on 5th floor of Physics building
  → 1% bonus on final grade

Plan for Rest of Semester

Only 5 classes left before final!

- Today: Large Scale structure, age of universe
- Wednesday: Big Bang, Cosmology
- Friday: Life in the Universe
- Monday next week: ??? → Ideas?
  Behind the scenes of an observing run / More review / Other topics → Let me know
- Wednesday next week: Review for Final

More bonus opportunities: Math Problems

Back by popular demand

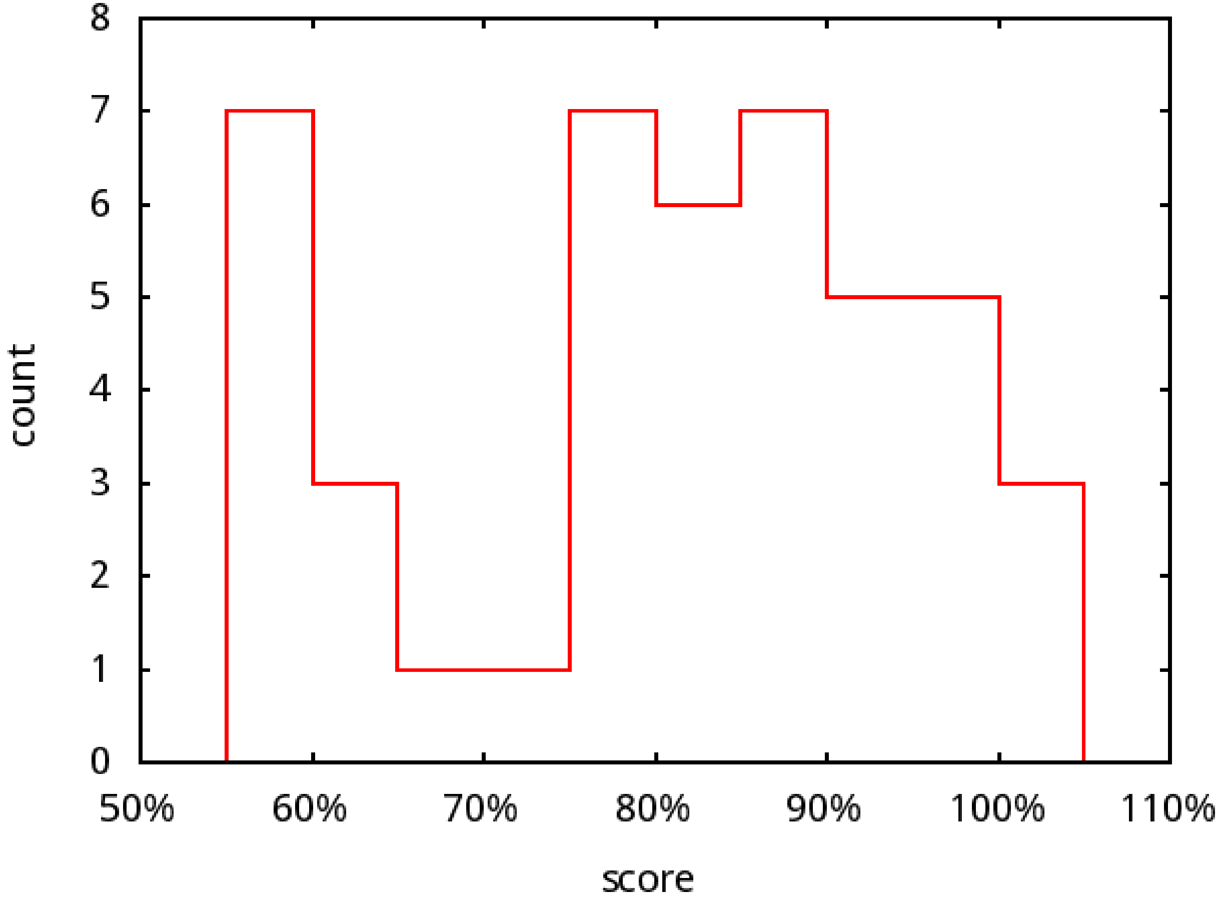
- available today until December 15th, 12 noon (day of final exam)
- 15 questions
- similar to questions involving math on previous quizzes
- 3 attempts allowed, 80% needed for credit (at least 12/15)
- will show which questions wrong, but correct answers won't be given
- +1% on final grade

More bonus opportunities: Short research paper on an astronomical topic

- Choose a topic that interests you
- Must be approved: email me or ask in class
- Write short paper (1 page minimum) about topic
- At least four sources required, must be given and used in text
- Acceptable sources:
  - Published books and magazines
  - Webpages from universities (.edu) and government organizations (e.g. NASA)
  - Wikipedia is not an acceptable source but is a great place to start – follow the references!
- Due by last day of classes, Wednesday December 10th
- +1% on final grade

Midterm #3 results

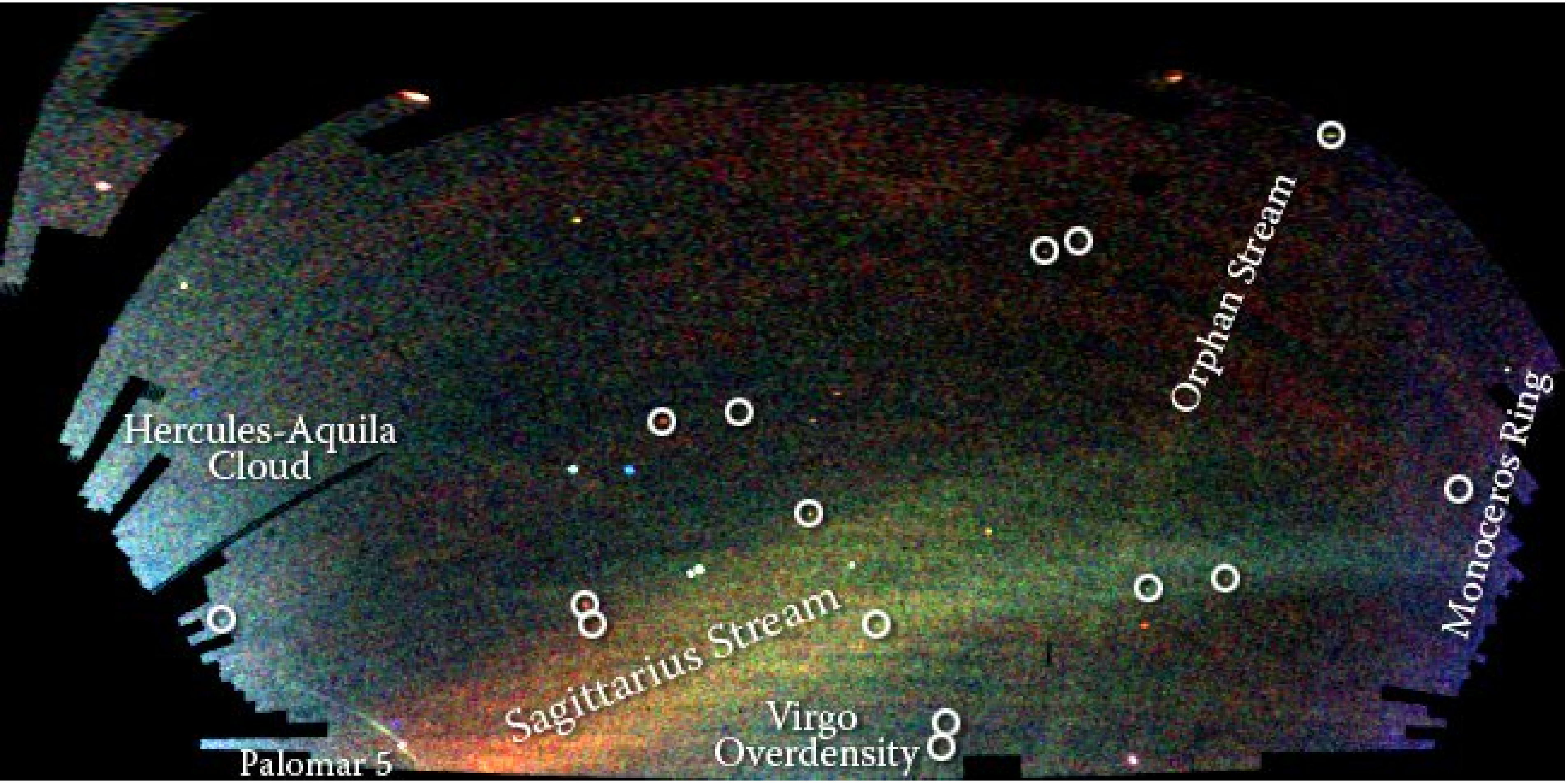
- Average: 78% (71% w/o bonus)
- Median: 84%
- >100%: 3
- <60%: 7



Review: Galaxy Evolution

- Galaxies in isolation do not change their Hubble classification
- **Galaxy mergers**: Can trigger starbursts and/or change Hubble classification
- Gravitational potential is dominated by dark matter → galaxies live in **Dark Matter Halos**
- Galaxies grow and evolve by accreting and/or merging with other galaxies
  → **Galactic cannibalism**

SDSS Evidence for the cannibalic past of the Milky Way



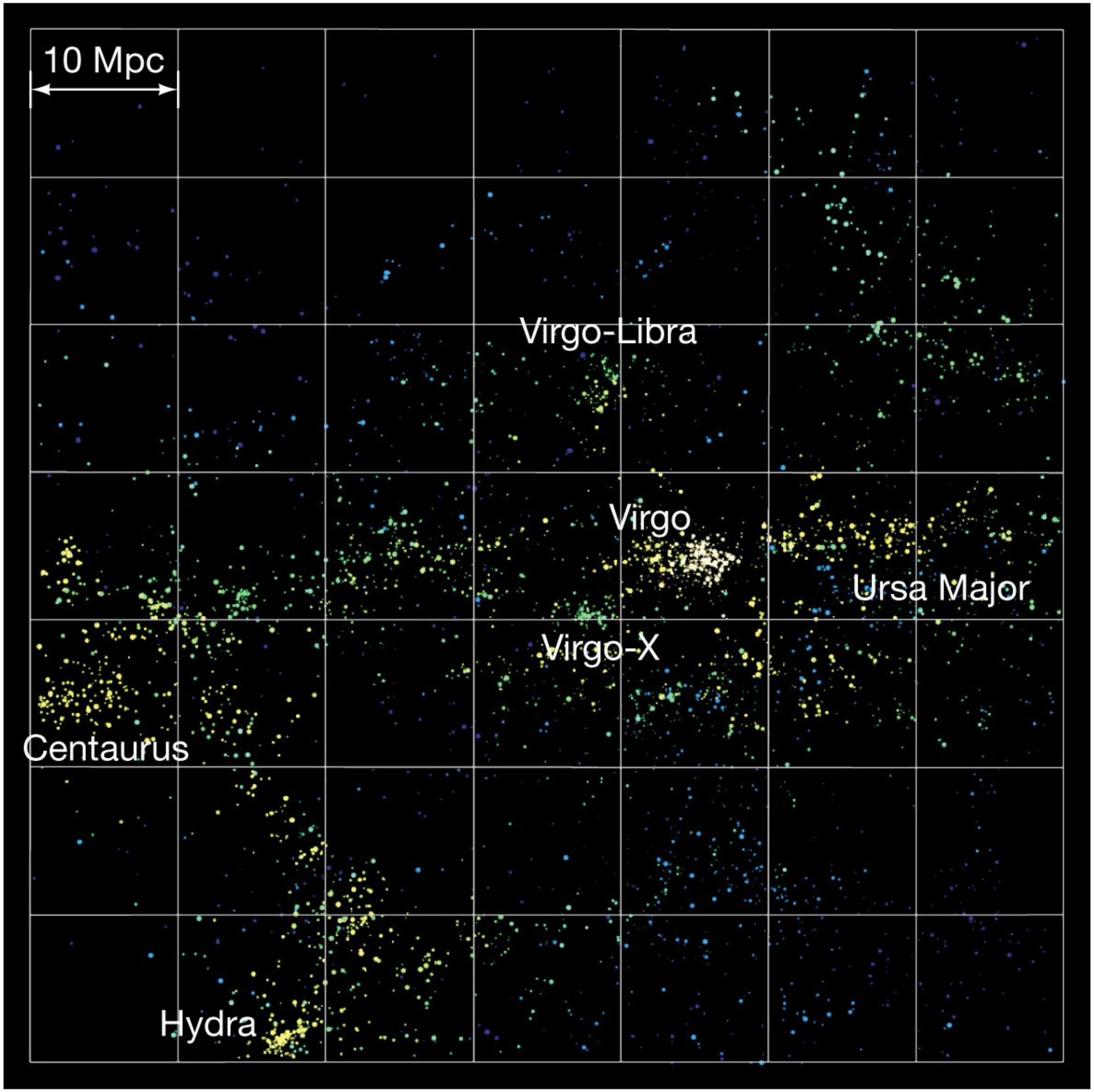
Large Scale Structure

- 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
- 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

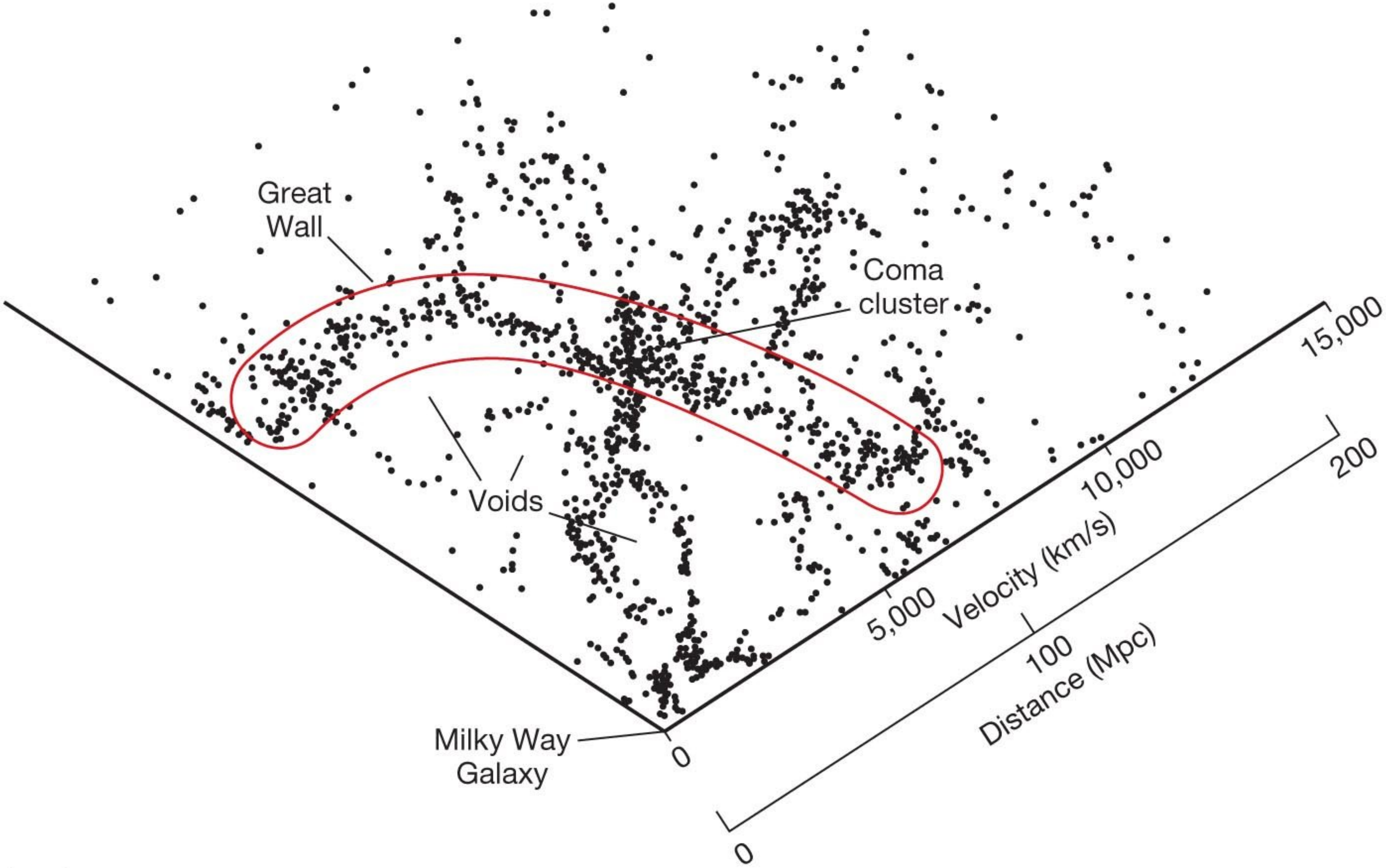
$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$

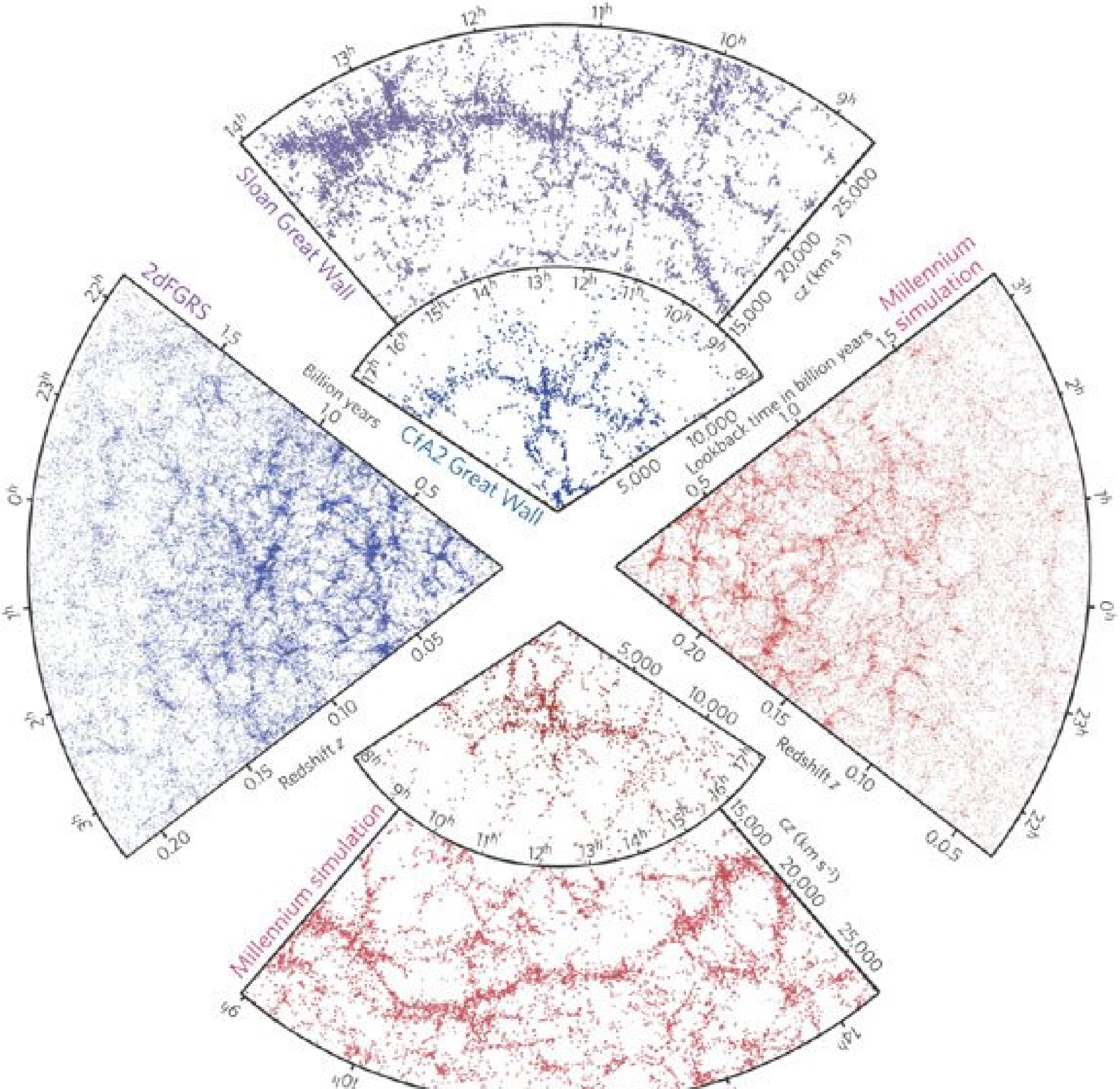
The redshift *z* is the difference between the observed and emitted wavelengths of a spectral line, divided by the emitted wavelength

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




Sloan Great Wall
CfA2 Great Wall
2dFGRS
Millennium simulation
Millennium simulation
Billion years
Lookback time in billion years
Redshift z
Redshift z
cz (km s⁻¹)
cz (km s⁻¹)
5,000
10,000
15,000
20,000
25,000
0.05
0.10
0.15
0.20
0.5
1.0
1.5
8h
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23h
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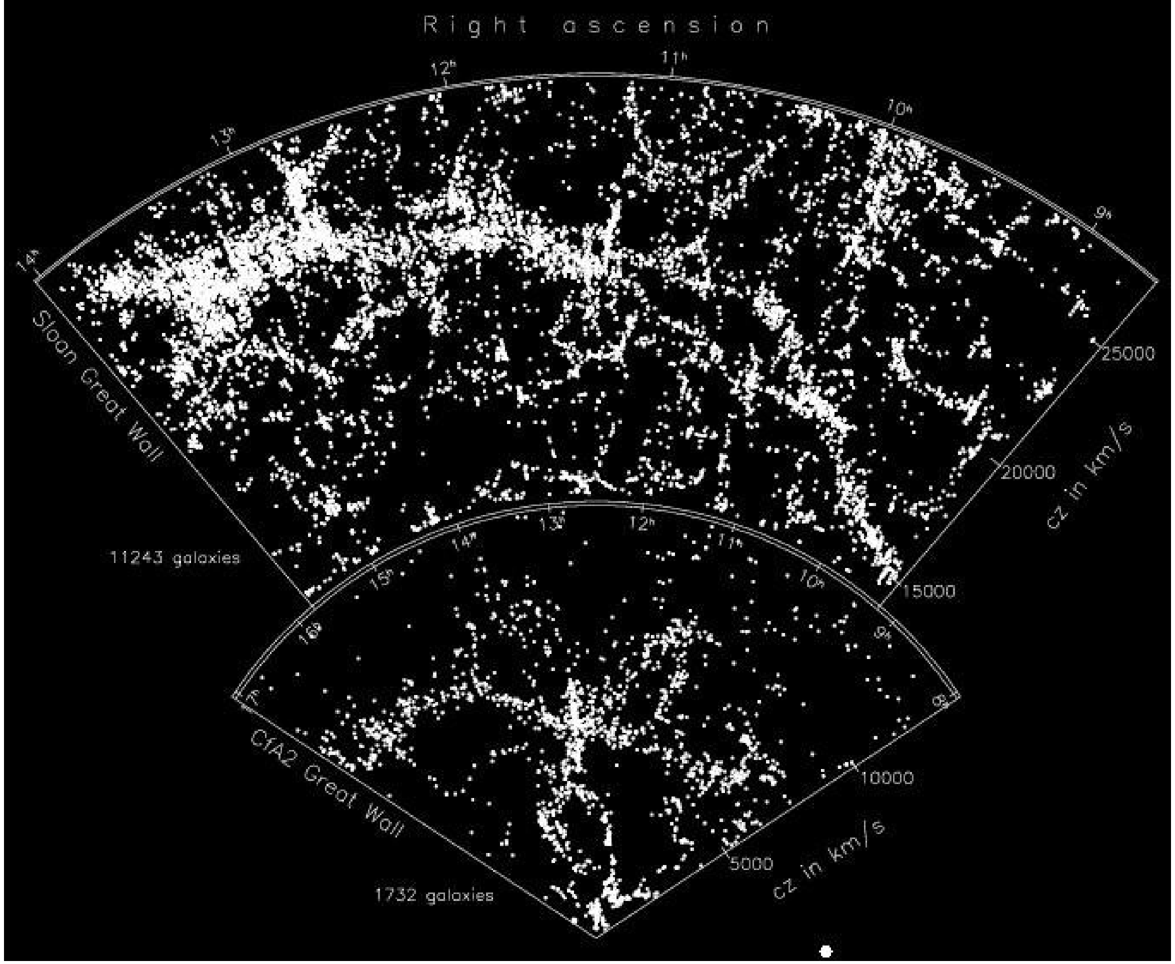
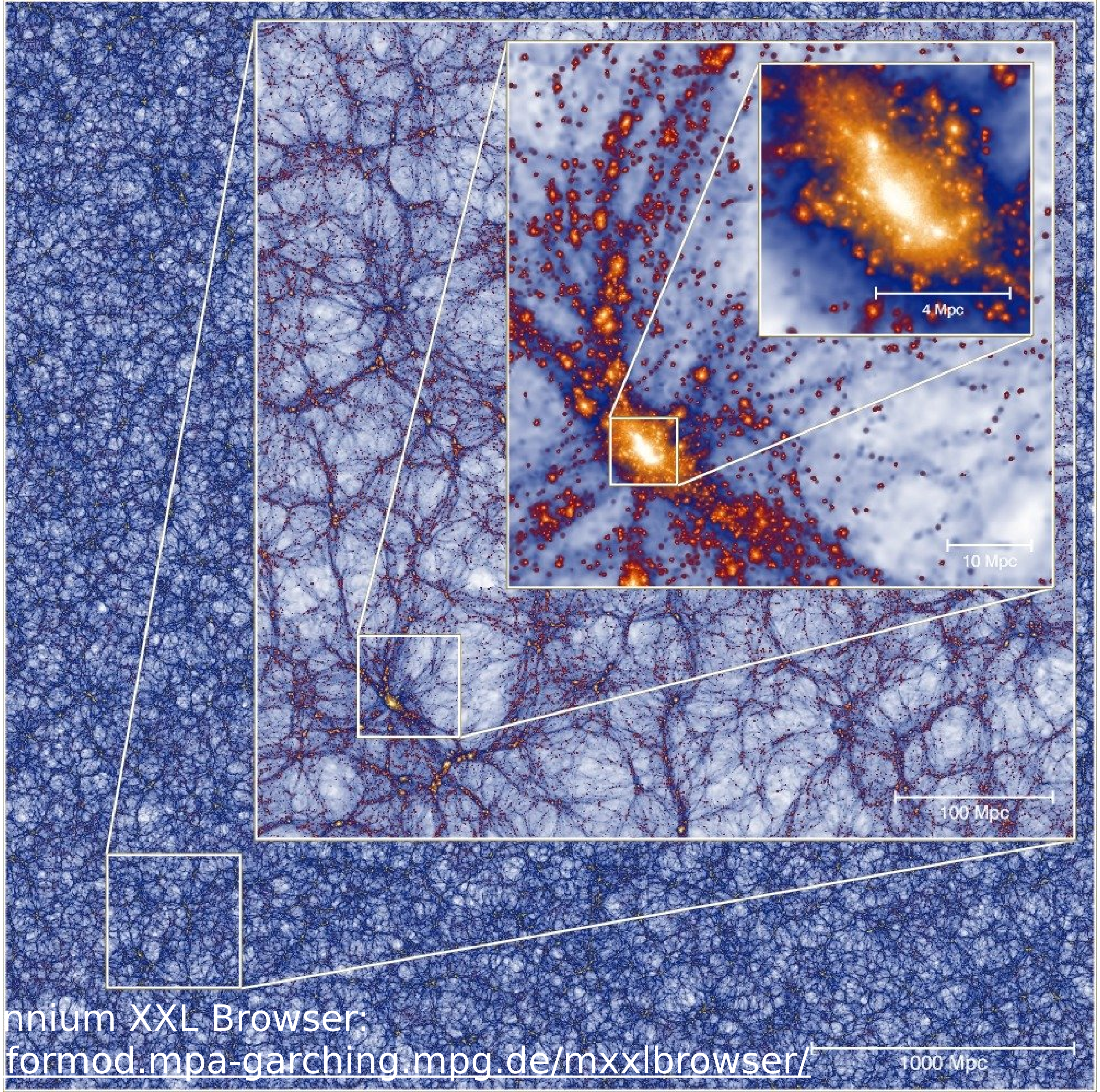


- The universe is organized into filaments on the largest scales, as revealed by these redshift surveys
- There are also large empty regions known as voids
- The biggest of these structures – filaments and voids – are around 200 Mpc

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



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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

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]

Astronomy 103

Cosmology

Please read chapter 17

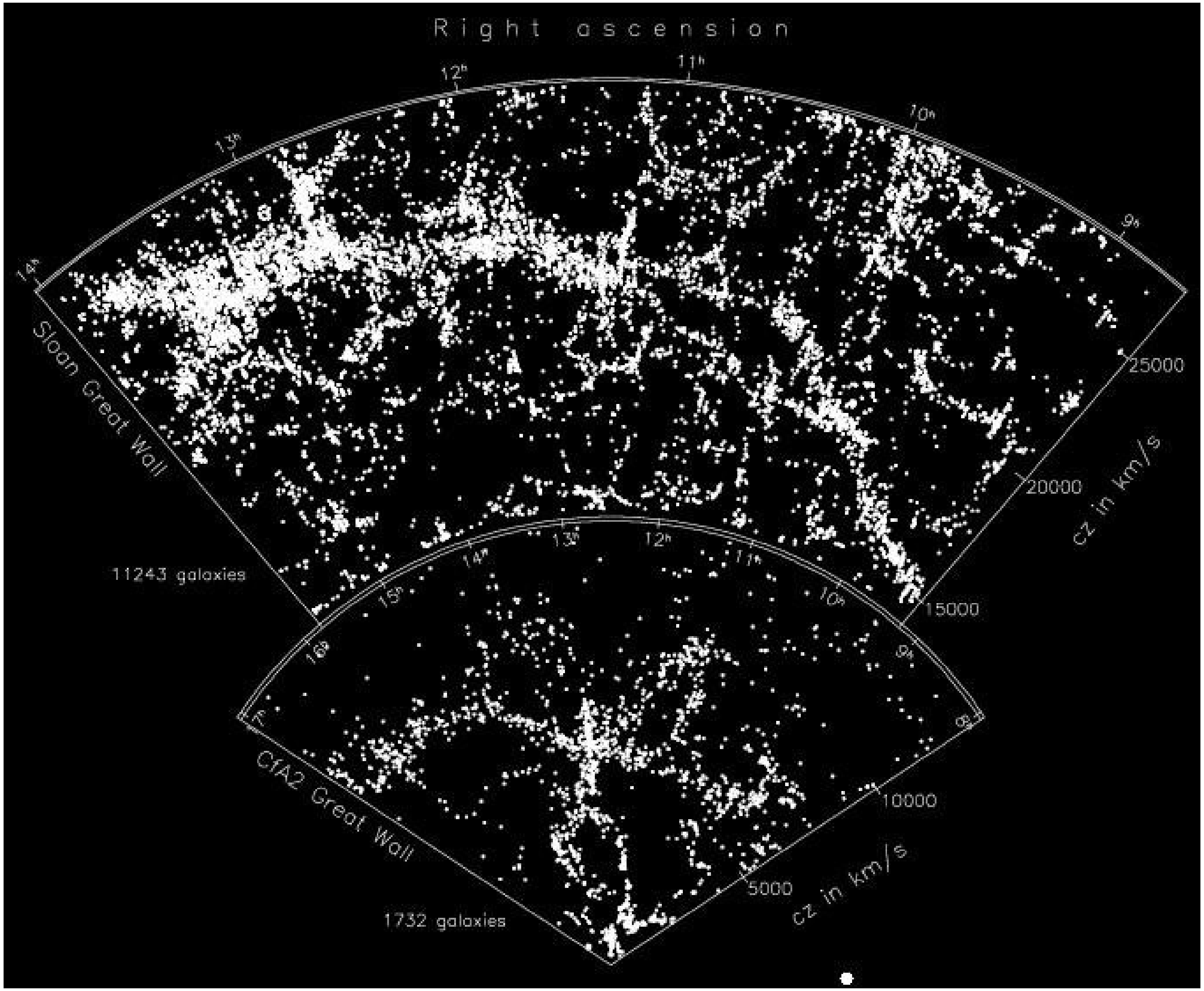
The Universe on Large Scales

When we look at our local part of the universe, it’s clumpy – matter is distributed in stars, galaxies, clusters, superclusters, and filaments, with empty voids between

But on the largest scales, the universe is more or less uniform – looks about the same everywhere

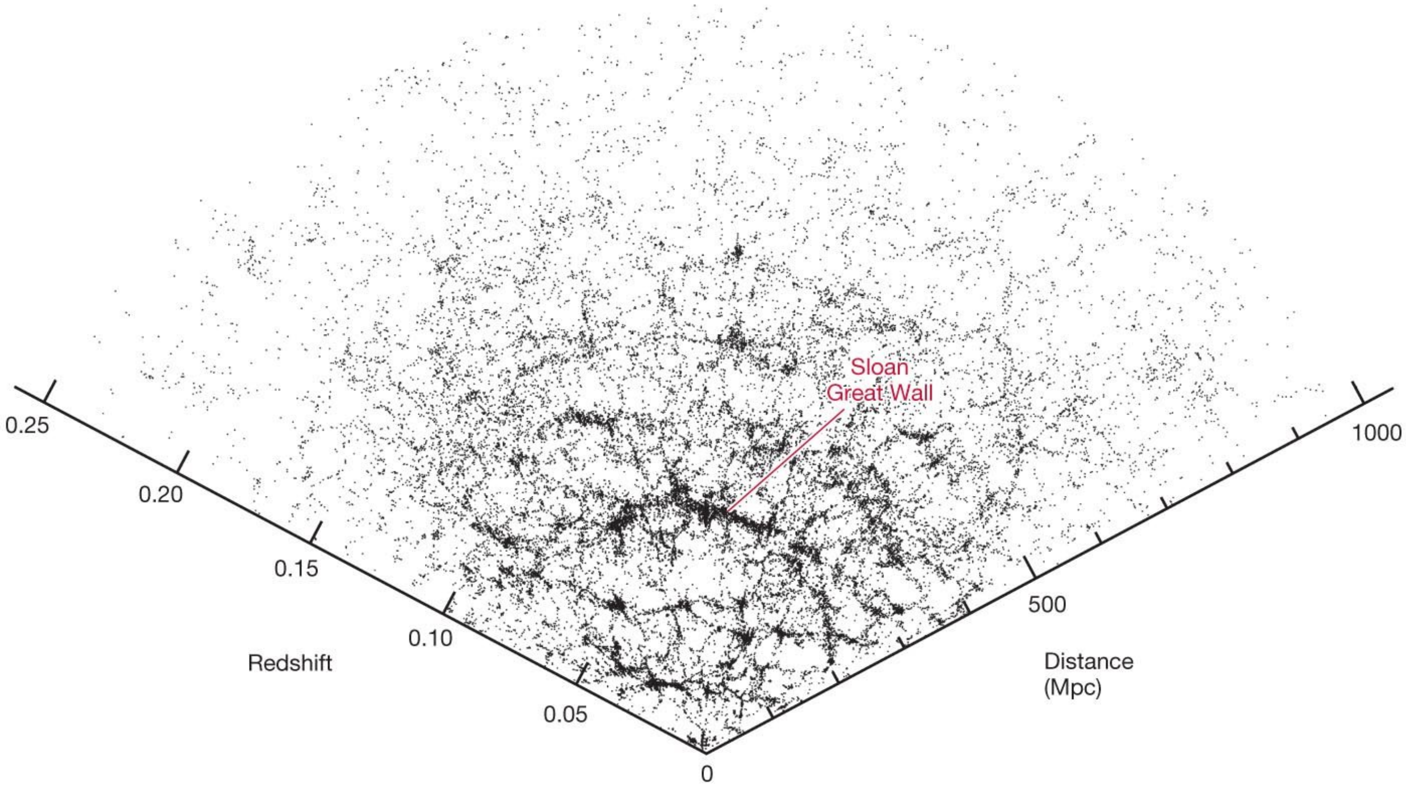
This happens on a scale around 200 megaparsecs: every 200 Mpc box looks about the same

The Universe on Large Scales



The Universe on the Largest Scales

This galaxy map shows the largest structure known in the universe, the Sloan Great Wall. No structure larger than 300 Mpc is seen.



The Universe on the Largest Scales

Therefore, the Universe is homogenous (any 200-Mpc-square block appears much like any other).

The universe also appears to be isotropic – the same in all directions.

The **cosmological principle** is the assumption that the Universe is isotropic and homogeneous.

Homogeneity means the universe has no edge: It looks the same everywhere

Isotropy means the universe has no center: it looks the same in every direction

The Universe on the Largest Scales

The **cosmological principle** is the assumption that the Universe is isotropic and homogeneous.

- **Homogeneity** means the universe has no edge: it looks the same everywhere
- **Isotropy** means the universe has no center: it looks the same in every direction

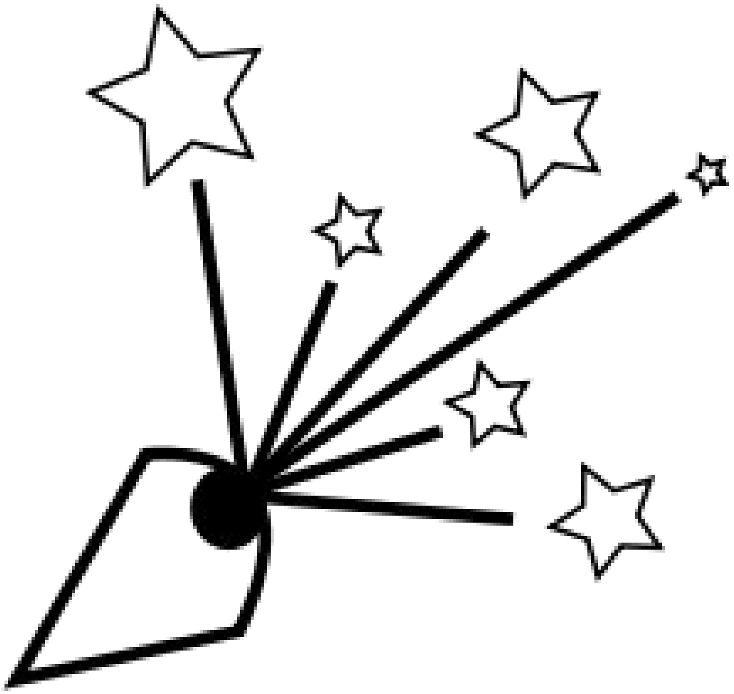
The cosmological principle is also called the **Copernican principle** – Copernicus showed that we aren’t at the center of the solar system, and the cosmological principle says we aren’t at the center of the universe. It has no center.

Olber’s Paradox

The main difference between night and day is that it is dark at night – but why?

If the universe is infinite and eternal, the sky can’t be dark at night – **Olber’s paradox**

In every direction we look, we’ll eventually see a star



The sky should be as bright as the surface of a star!

Olber’s Paradox

So why is the sky dark?

Because the universe hasn’t existed forever, and light from the greatest distances hasn’t had time to reach us yet.

Edgar Allen Poe in 1848: “Were the succession of stars endless, then the background of the sky would present us an [sic] uniform density ...since there could be absolutely no point, in all that background, at which would not exist a star. The only mode, therefore, in which, under such a state of affairs, we could comprehend the voids which our telescopes find in innumerable directions, would be by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all.”

Hubble’s Law Redux

Remember that Hubble’s law says that galaxies are moving away from us at a speed given by

$$V = H \times d$$

where H is Hubble’s constant.

So at a very early time in the universe, those galaxies must all have been in the same place

The Expanding Universe

If this expansion is extrapolated backward in time, all galaxies are seen to originate from a single point in an event called the Big Bang.

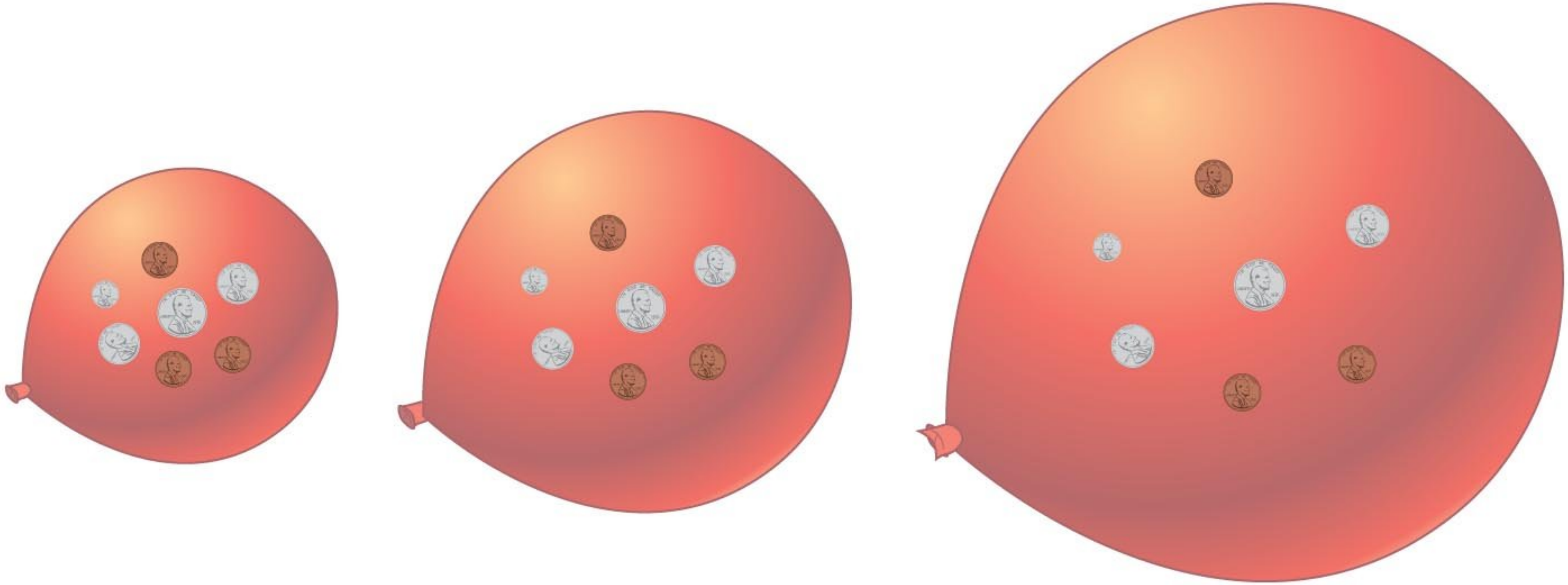
So, where was the Big Bang?

It was everywhere!

No matter where in the universe we are, we will measure the same relation between recessional velocity and distance, with the same Hubble constant.

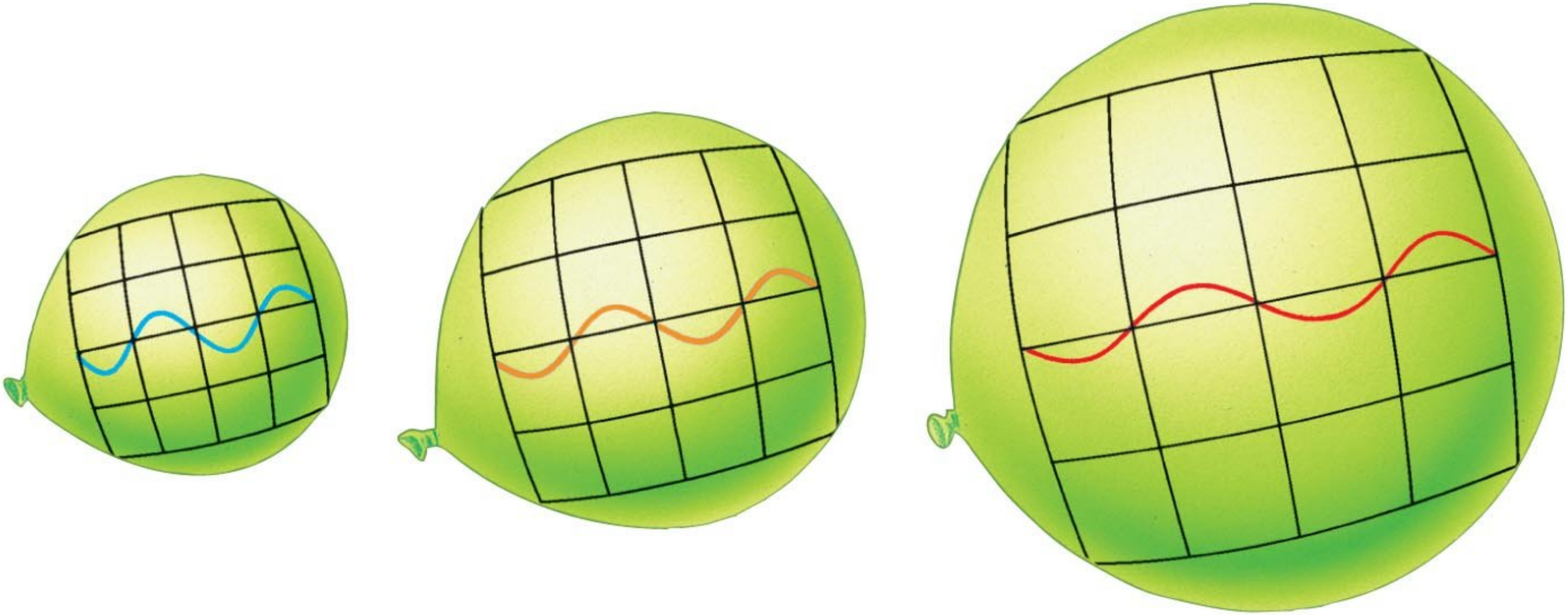
The Expanding Universe

The expanding universe in two dimensions: imagine a balloon with coins stuck to it. As we blow up the balloon, the coins all move farther and farther apart. There is, on the surface of the balloon, no “center” of expansion.



The Expanding Universe

The same analogy can be used to explain the cosmological redshift: the wavelength of light is stretched as the universe expands.



How old is the universe?

There are several ways of determining the time that the universe (at least the part of it we can see) began.

First, by using Hubble's law, we can find the time at which all the galaxies we see were at the same place.

We have already found that galaxies are moving away from us faster the farther away they are:

$$v = H \times d$$

So, how long did it take the galaxies to get to where they are now?

Using
H = 70 km/s/Mpc,
we find that this
time is about
14 billion years.

$$\text{time} = \frac{\text{distance}}{\text{velocity}} = \frac{\text{distance}}{H_0 \times \text{distance}} = \frac{1}{H_0}.$$

Note that Hubble's law is the same no matter who is making the measurements and where they are made.

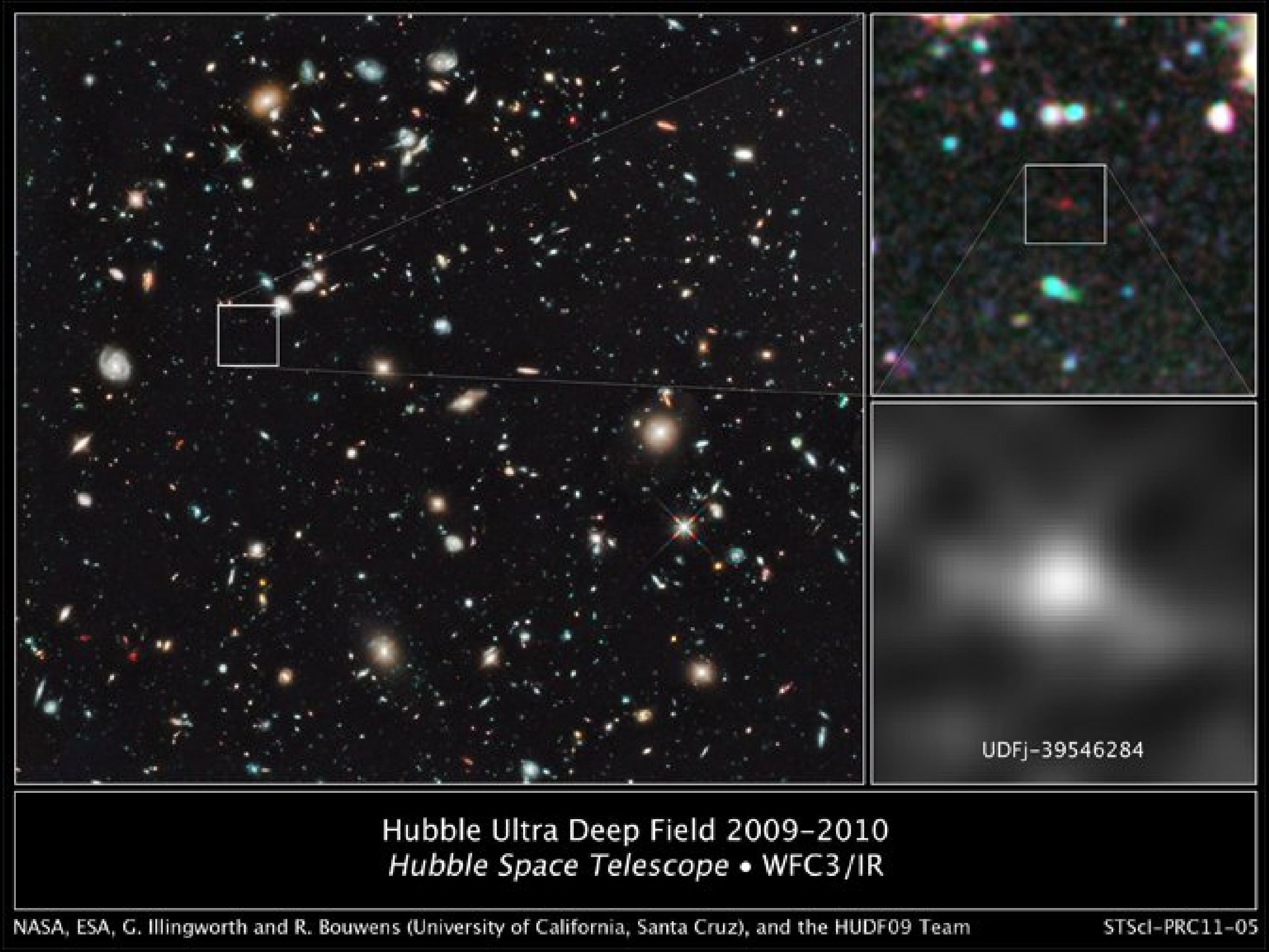
Age of the Universe

So the universe is about 14 billion years old

This agrees with other things we observe:

- The most distant galaxies we see are around 13 billion light years away
- The oldest stars we can find live in globular clusters, and are all younger than about 10-13 billion years

One of the most distant galaxies so far detected: A redshift of 8.6 and a distance of about **13 billion light years**

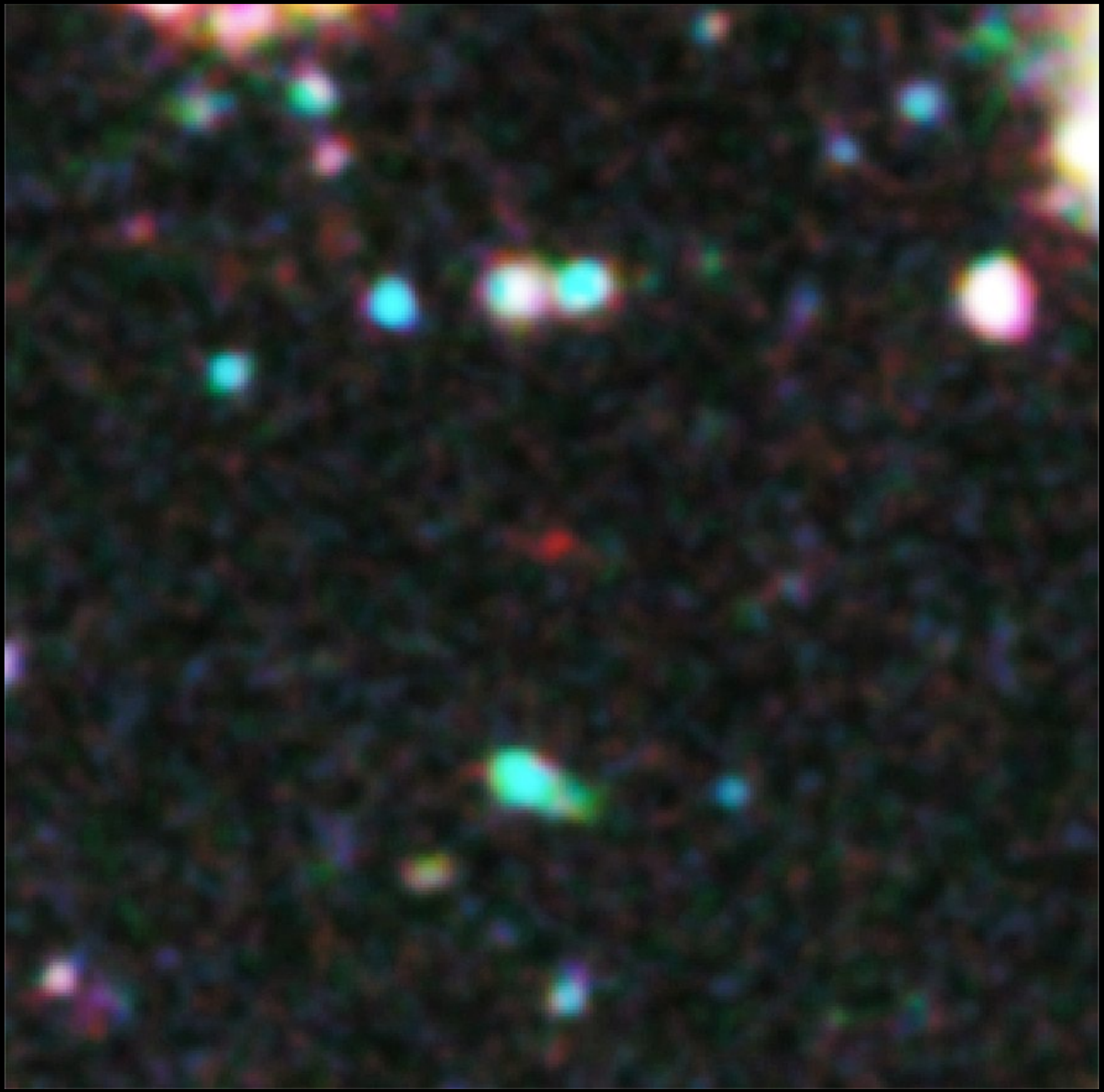


Hubble Ultra Deep Field 2009–2010
Hubble Space Telescope • WFC3/IR

NASA, ESA, G. Illingworth and R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team

STScI-PRC11-05

One of the most distant galaxies so far detected: A redshift of 8.6 and a distance of about **13 billion light years**



This picture was taken as part of the Hubble Ultra-deep Field: Hubble Space Telescope stared at a patch of sky for 1000000 seconds or about 11 days.

Finding the age of the Universe

Three independent ways of finding the age of the universe and of its oldest stars and galaxies:

- Dating the oldest globular clusters by using their H-R diagrams to see what stars have evolved off the main sequence: Today's best estimate: 11-13 billion years since first stars formed in globular clusters
- Using Hubble's law to deduce when the galaxies were all at a single point - when the Big Bang occurred: 14 billion years
- Finding the most distant objects and finding that they are about 13 billion light years away.