Part 3: Galaxies and the Universe

Tuesday, March 22 — Reading: Chapter 12.1 — 12.3
- Our Galaxy = The Milky Way

Thursday, March 24 — Reading: Chapter 13.1 — 13.2
- Galaxies: types, properties, clusters of galaxies, dark matter

Tuesday, March 29 — Reading: Chapters 13.3, 15
- Galaxies: formation, evolution; distance scales; expansion of the Universe

Thursday, March 31 — Reading: Chapter 12.4, 14
- Galaxies: active galaxies and quasars; supermassive black holes

Monday, April 4 — TA's help session for HW3: 3 to 5 PM in WCH 1.120

Tuesday, April 5 — Reading: Chapter 15; HW 3 due
- Cosmology: Big Bang ➡ background radiation; formation of structure

Wednesday, April 6 — Help session: 4 to 6 PM in Welch 2.224

Thursday, April 7 — Exam 4

THE PRINCIPLE OF COSMIC HUMILITY

WE LIVE IN NO SPECIAL PLACE.

The existence of dark matter implies an ultimate point in the Principle of Cosmic Humility:

We and everything that we see around us are not even made of the main form of matter in the Universe.

We do not know what the main form of matter in the Universe is.

The mass of the individual particle of dark matter is unknown to 70 factors of 10.

Dark Matter is “Cold”

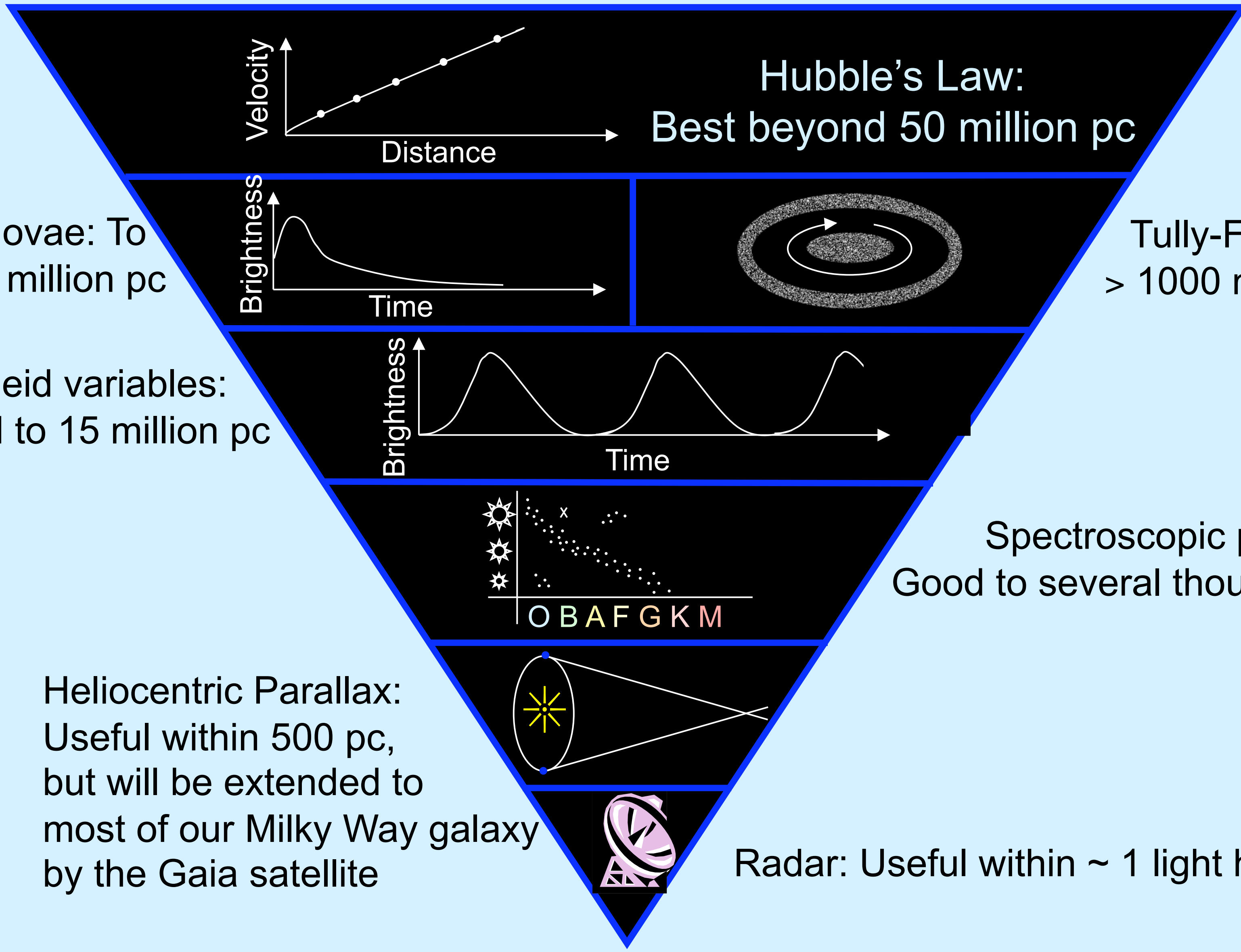
We do know two critically important things
about dark matter:

1 – Dark matter particles interact only via gravity.

2 – Dark matter particles are “cold” –
They move much more slowly than the speed of light.

We can calculate galaxy formation in astonishing detail!

Measuring Distances



Supernovae: To > 2000 million pc

Tully-Fisher: To > 1000 million pc

Cepheid variables: Good to 15 million pc

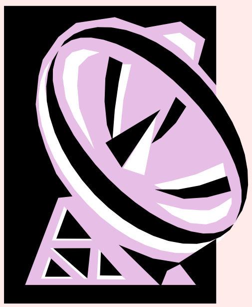
Spectroscopic parallax: Good to several thousand pc

Heliocentric Parallax: Useful within 500 pc, but will be extended to most of our Milky Way galaxy by the Gaia satellite

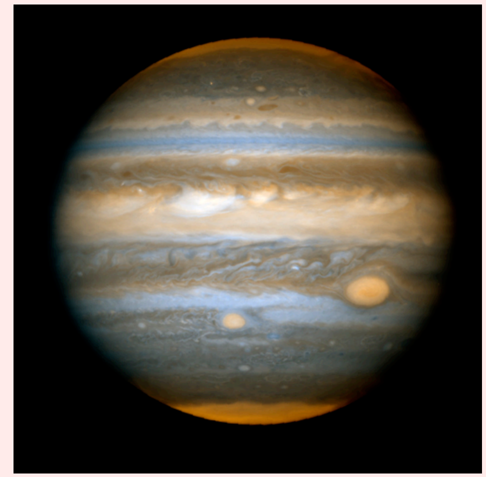
Radar: Useful within ~ 1 light hour

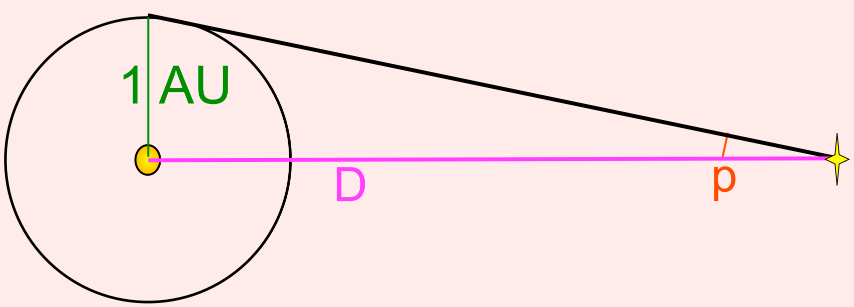
Calibrating the Distance Scale

In order to measure the distances to far away objects, we need to calibrate our measurement methods over a variety of distances.



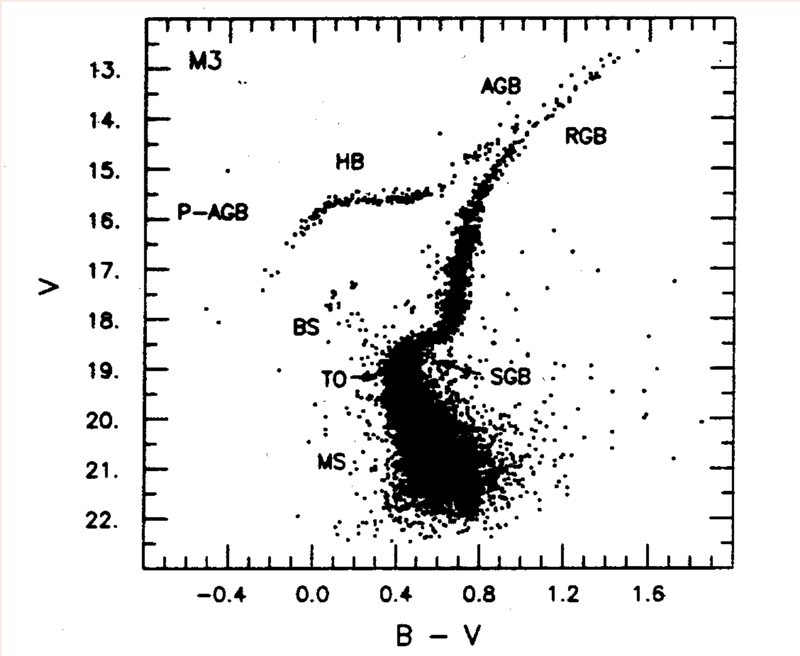
In the Solar System, we measure the distances to other planets using radar. This allows us to measure the radius of the Earth's orbit around the Sun very accurately.





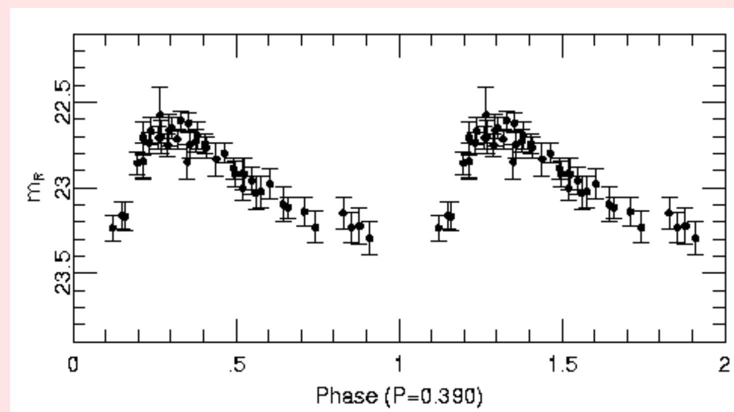
Once we know the size of the Earth's orbit we can use parallax to measure distances to nearby stars.

Calibrating the Distance Scale



Parallaxes tell us distances and therefore luminosities of main sequence stars as a function of spectral type. With this information, we can find the distances to more distant stars by measuring their spectral types and using HR diagrams. This technique is called spectroscopic parallax. (This is a very stupid name.)

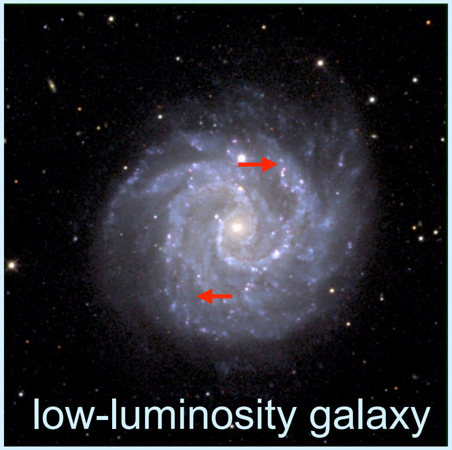
Cepheid and RR Lyrae variable stars satisfy a period-luminosity relation. All Cepheids of the same period have the same absolute luminosity. Using spectroscopic parallaxes, the luminosities of the nearest Cepheids are measured. Then Cepheids are used to measure distances to other galaxies by observing how long it takes for them to vary in brightness.

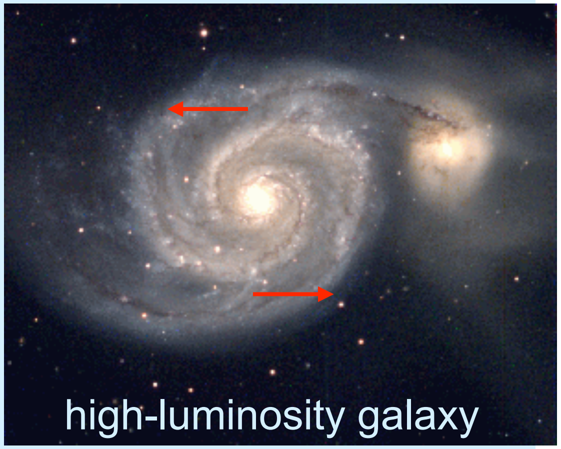


Calibrating the Distance Scale

The maximum luminosity of a **supernova** depends on the shape of its light curve. That is, supernovae are "standard candles" whose luminosities can be determined from how fast they vary in brightness. Their luminosities are calibrated by using Cepheids to measure the distances to nearby galaxies in which we have observed supernova. Because they are so bright, supernovae are used to measure distances out to at least 5 billion light years.

Tully & Fisher found that there is a relation between the luminosity of a spiral galaxy and how fast it rotates. More luminous galaxies spin faster. Calibration is provided by Cepheids.





The Expansion of the Universe

Hubble's Law

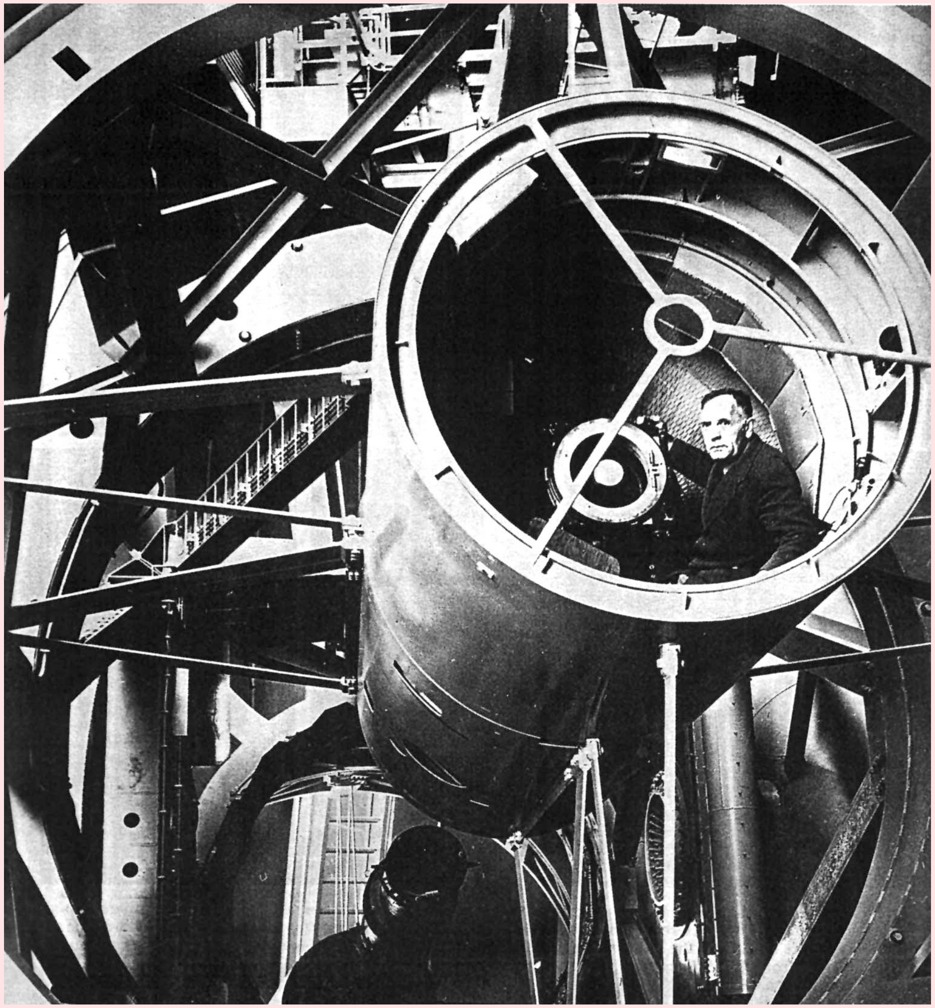
Even before we knew what galaxies are, people had noticed that most of them have Doppler shifts toward the red. Therefore they are moving away from us.

Hubble made systematic measurements of galaxy distances. When he plotted the recession velocity V of each galaxy against its distance D, he discovered that recession velocity is proportional to distance. In mathematical terms,

$$V = H_o D,$$

where H_o is the Hubble "constant". Current best measurements give

$$H_o \approx 70 \text{ km/sec/Mpc}.$$



Measuring Recession Velocities or Redshifts

The recession velocity of a galaxy is measured via the redshift of atomic lines in galaxy spectra.

Hubble's first derivations of the velocity-distance relation looked like this:

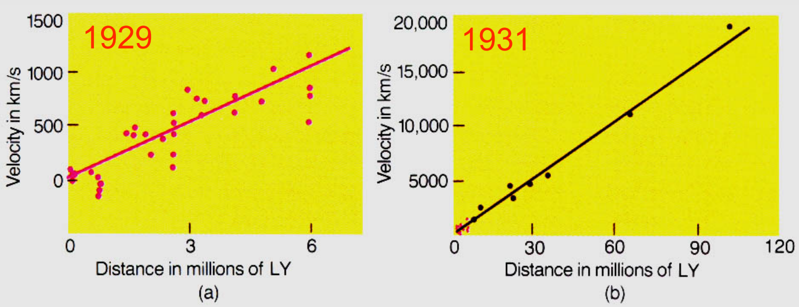
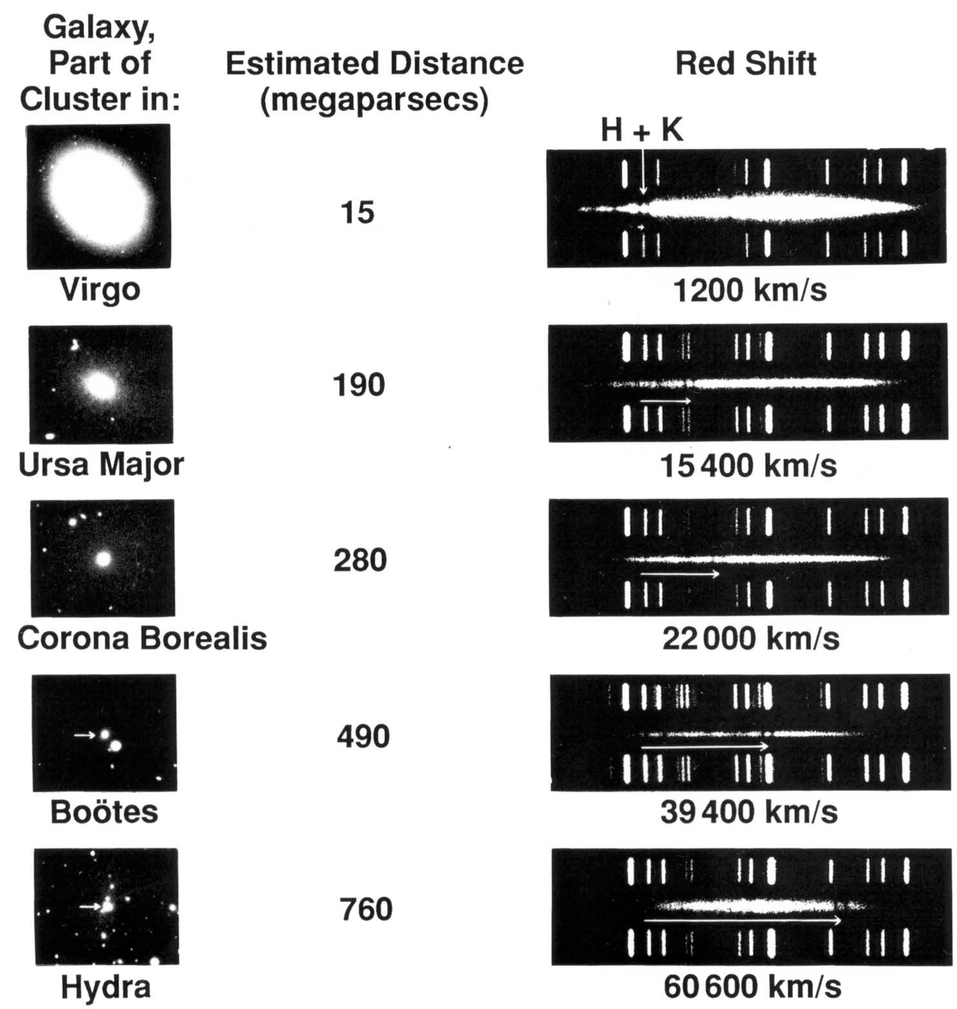


FIGURE 33.3 (a) Hubble's original velocity-distance relation, adapted from his 1929 paper in the *Proceedings of the National Academy of Sciences*. (b) Hubble and Humason's velocity-distance relation, adapted from their 1931 paper in *The Astrophysical Journal*. The red dots at the lower left are the points in the diagram in the 1929 paper (a). Comparison of the two graphs shows how rapidly the determination of distances and redshifts of galaxies progressed in the two years between these publications.

Relation Between Red Shift and Distance for Remote Galaxies



Correcting History

The expansion of the Universe was first discovered by Georges Lemaître (1927, Ann. Soc. Sci. Bruxelles, 47, 49) not Hubble (1929) !

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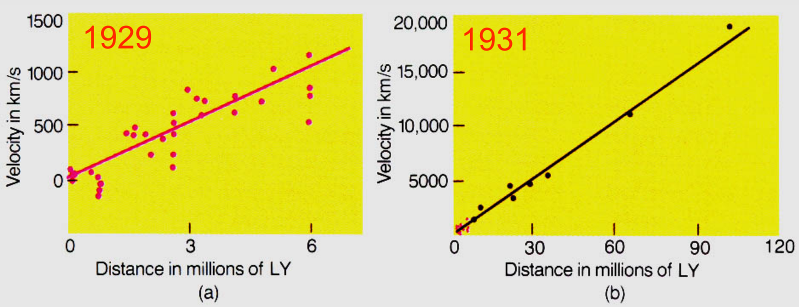

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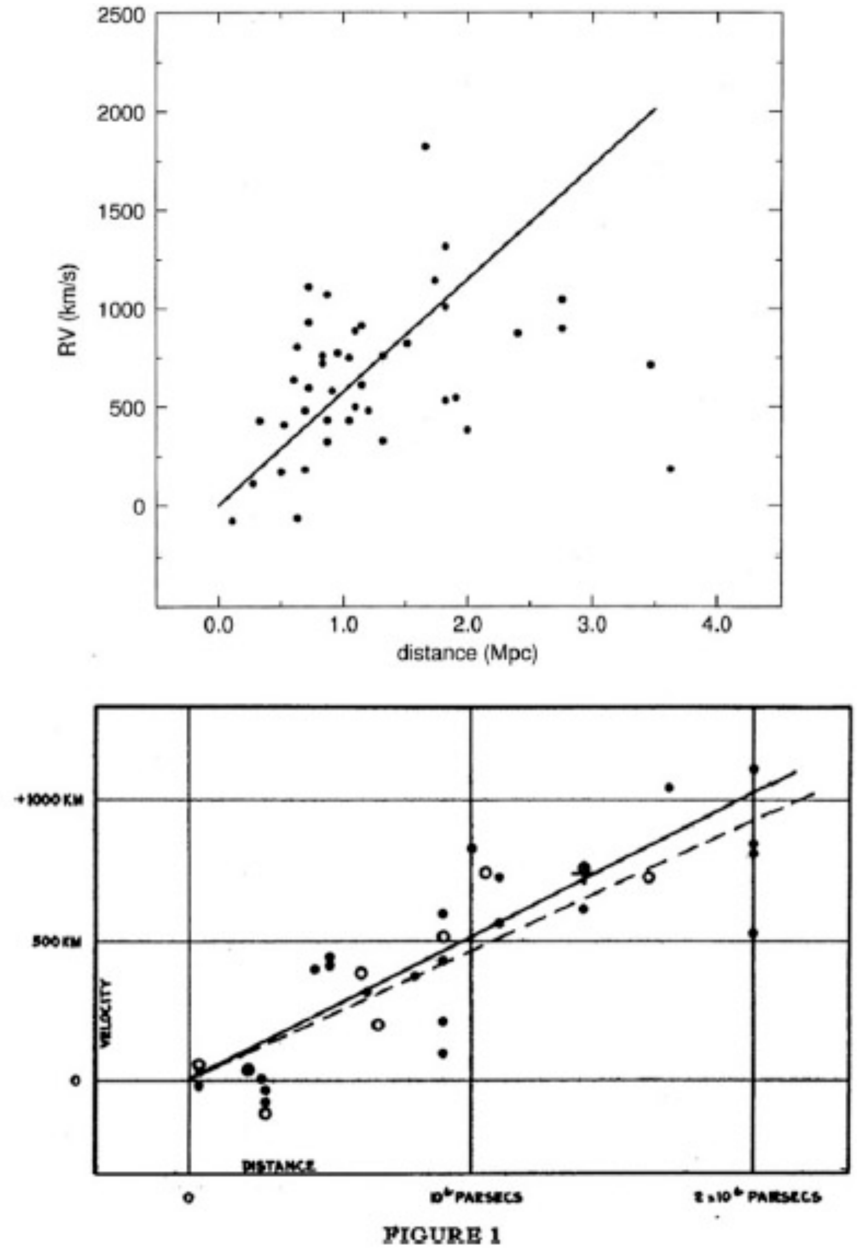
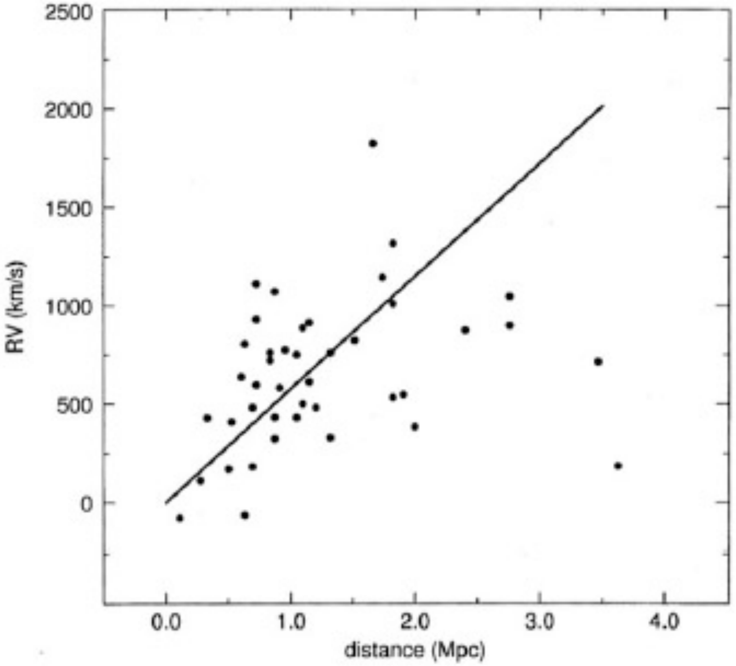


Fig. 1 *Upper panel*: The data used by Lemaître (1927) to yield the first empirical value of the rate of expansion of the Universe in which v/r is predicted to be constant (see Eq. 24 in Fig. 2). Lemaître derived values of 625 km s^{-1} Mpc^{-1} and 575 km s^{-1} Mpc^{-1}. The *solid line in the top panel* has a slope of 575 km s^{-1} Mpc^{-1} and is reconstructed by H. Duerbeck. *Lower panel*: the radial velocity–distance diagram published by Hubble, 2 years later, in 1929, with best slope of 530 km s^{-1} Mpc^{-1} (*Top panel*: Courtesy H. Duerbeck)

Correcting History

The expansion of the Universe was first discovered by Georges Lemaître, not by Edwin Hubble!



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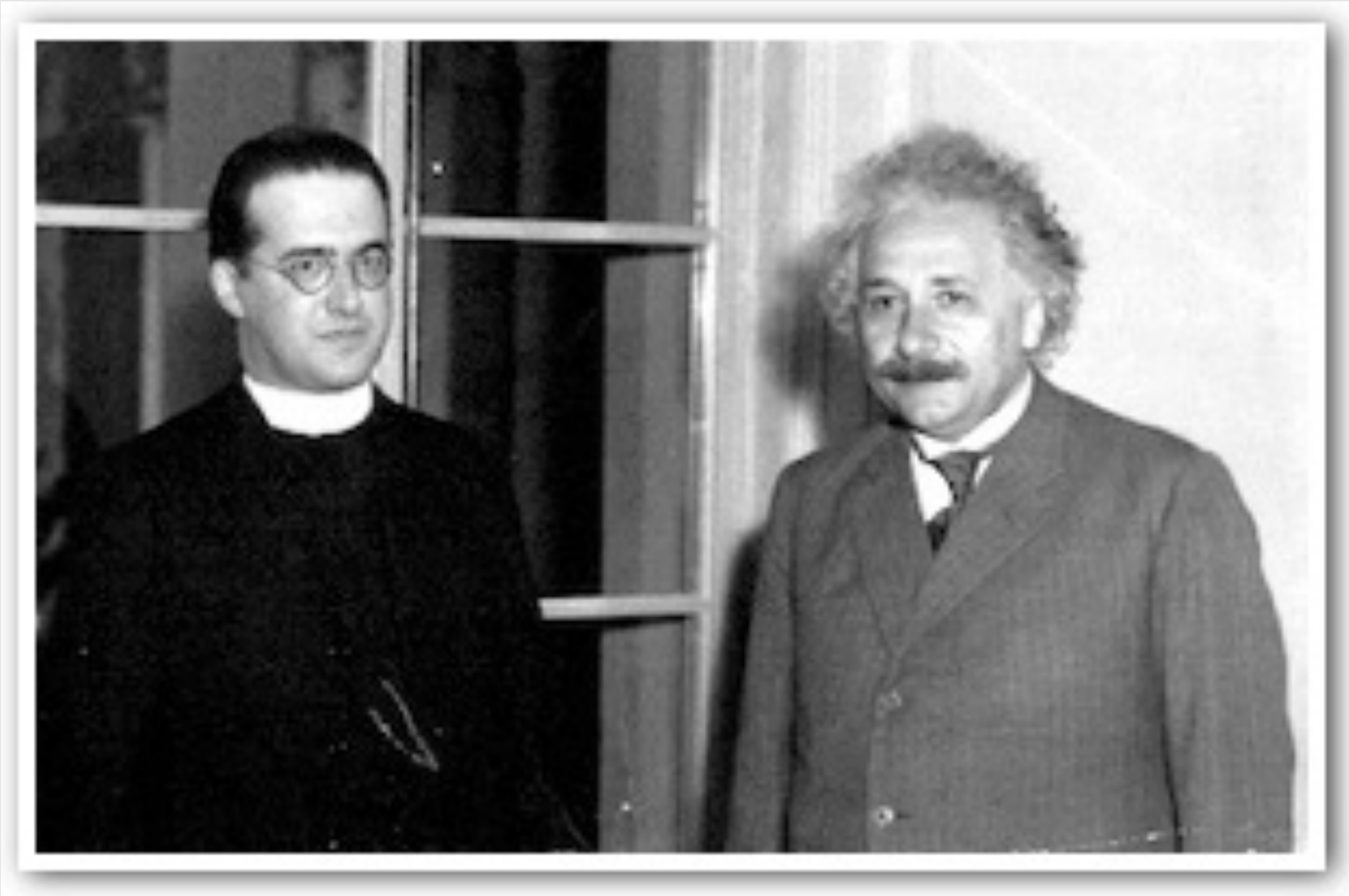
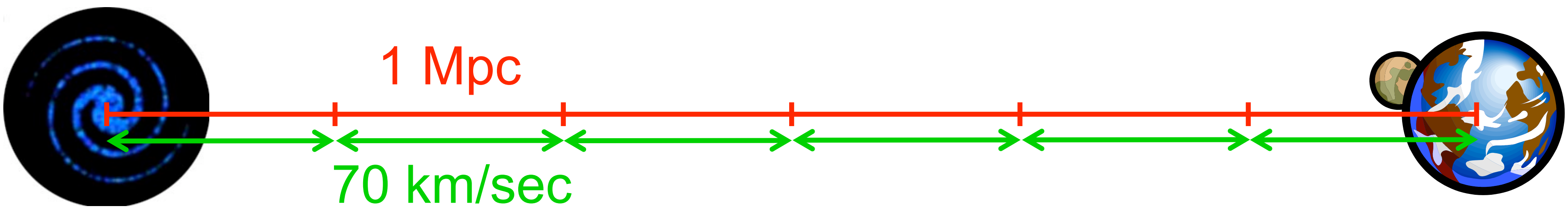


Measuring Distances Using Hubble's Law

Using the Tully-Fisher method and supernovae, we can reach great distances but not out to the most distant objects. For these, we use the observation that the Universe is expanding. Each Megaparsec (Mpc) of space between us and a distant galaxy is expanding at about 70 km/sec (to about ± 1 %).



This means that a galaxy that is 6 Mpc away is "moving" away from us at
6 Mpc × 70 km/sec/Mpc = 420 km/sec.

Alternatively, if we measure that a particular galaxy
is "moving" away from us at 108,000 km/sec,
then we deduce that its distance is
(105,000 km/sec) / (70 km/sec/Mpc) = 1500 Mpc = 4.9 billion ly.

Galaxy Formation

As the Universe ages,
gravity
organizes the material in it
into
larger and larger objects.

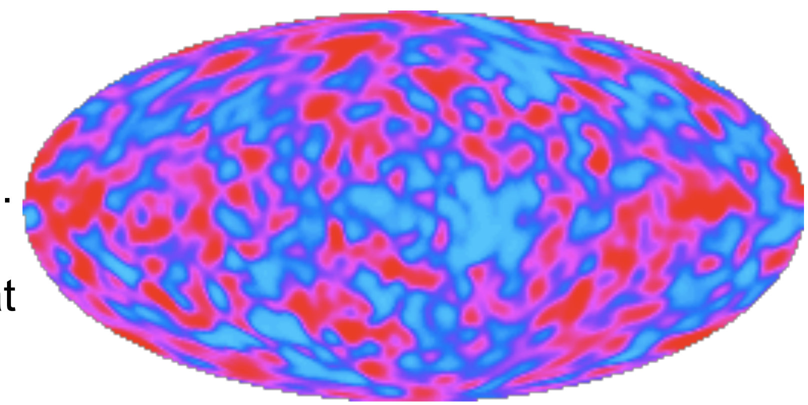
Galaxy Formation

Newton was the first to suggest that gravity transforms uniform-density matter into discrete objects. Details have evolved, but this idea is still correct for both galaxy and star formation.

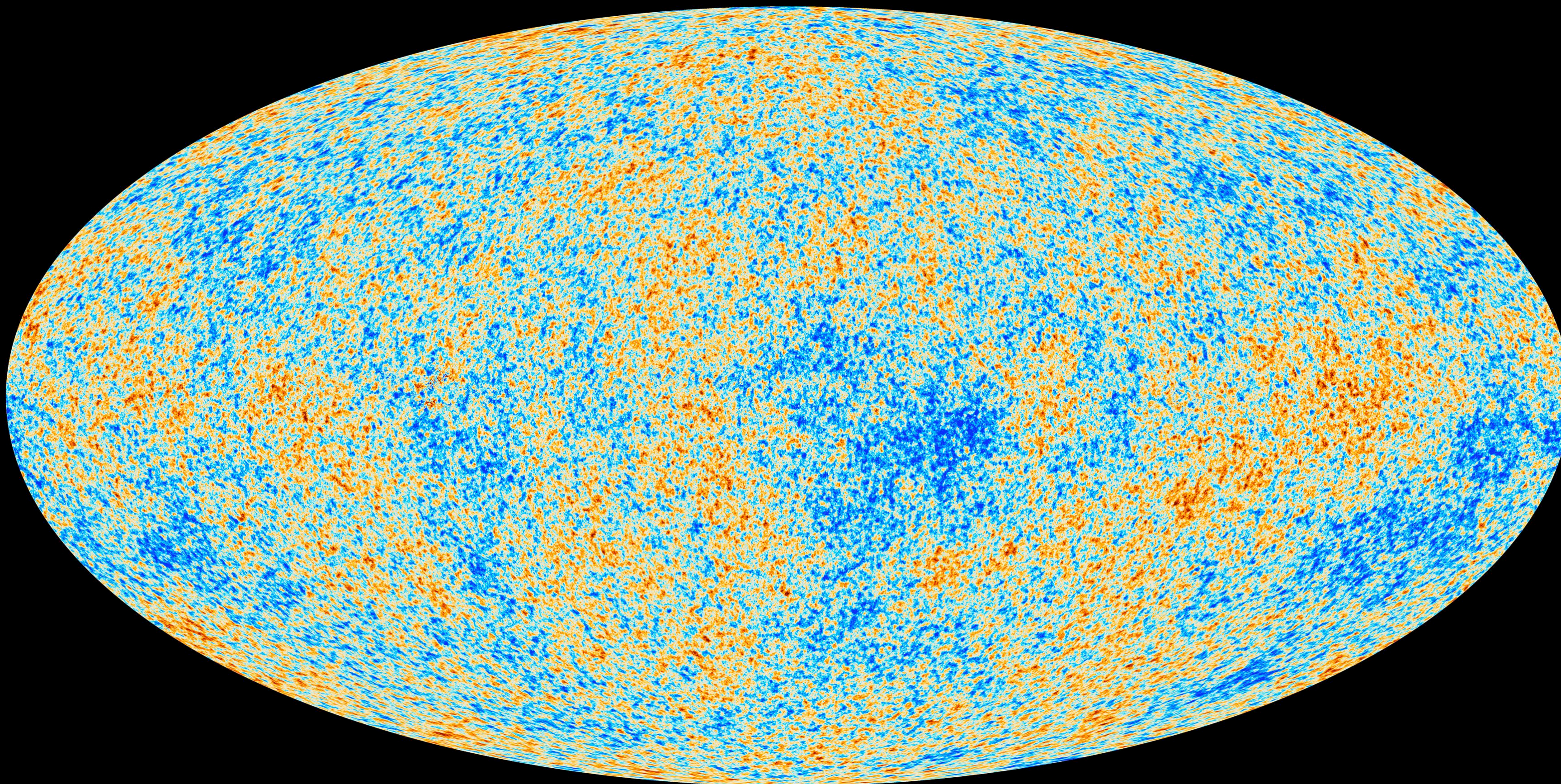
Gravitational Clustering

In the early Universe, there were no stars or galaxies. The density of matter was almost – but not quite – the same everywhere. Regions of higher than average density pulled gravitationally on their surroundings.   Matter streamed toward the regions of high density, increasing the density still more. The densest regions became gravitationally unstable and collapsed to make galaxies and clusters of galaxies. This is still happening now: galaxies fall into clusters and make them richer, and galaxies collide with each other, merge, and make bigger galaxies. This is called **hierarchical clustering**.

Gas Cooling: Gravity alone explains how dark matter forms galaxy halos, but it is not enough to explain the visible parts of galaxies. Gas inside the dark matter halos must cool before it can form stars. More massive protogalaxies take longer to cool. The galaxies that we see are the largest objects that have had time to cool since the Universe began.



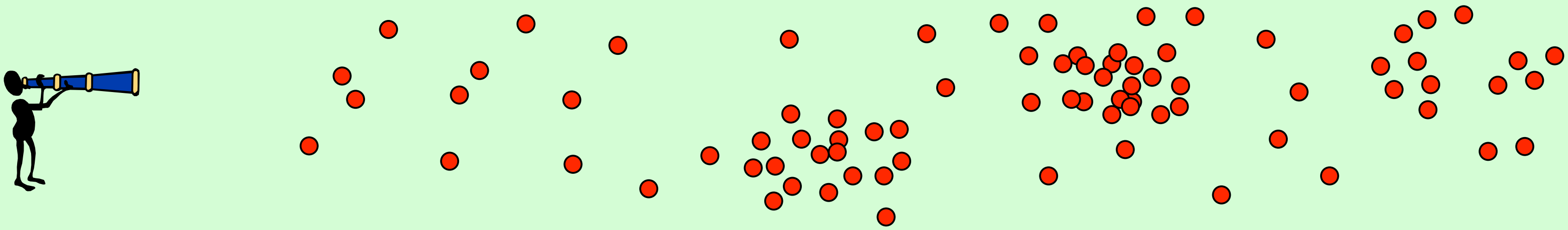
Fluctuations of ± 0.00002 K in the cosmic background radiation map density fluctuations when the Universe was only 380,000 years old.



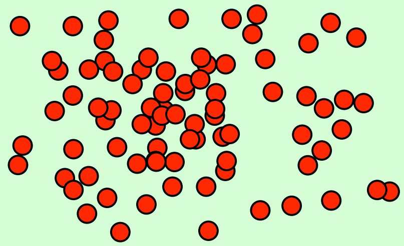
Observations from the Planck satellite give us the most detailed view of the (tiny!) density fluctuations that were present when the Universe was 380,000 years old. They tell us the initial conditions that we must use when we calculate galaxy evolution.

A cluster's density contrast is diluted by projection.

Even if the real density distribution is very clumpy, like this: ...



… what we see is much less clumpy:



Clusters don't stand out very well in projection.
It is not obvious when several clusters overlap in one clump
(although it helps that more distant galaxies are usually fainter).

The Solution

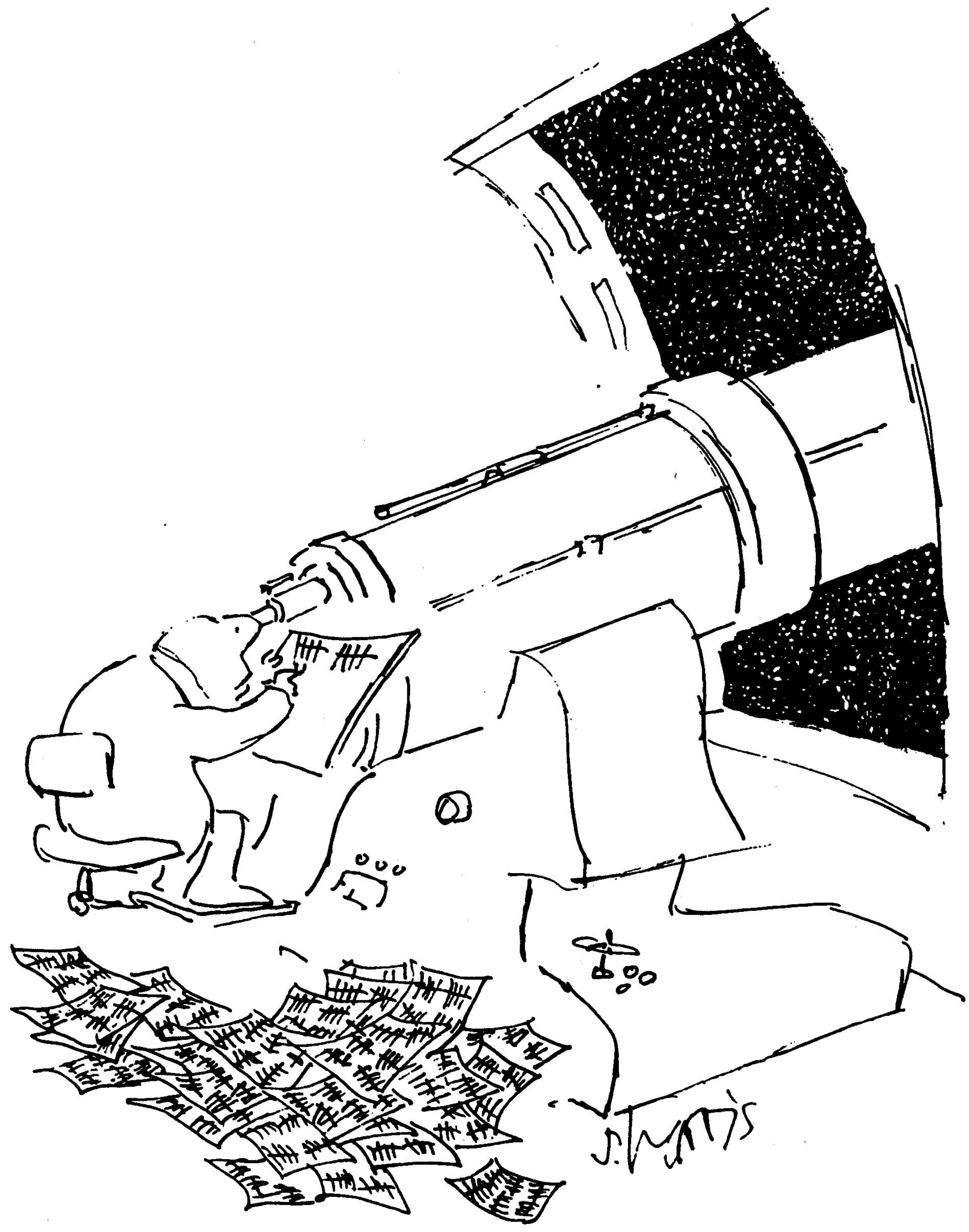
To see clusters clearly, we need to
measure the 3-dimensional distribution of galaxies in space.

Need: Distances

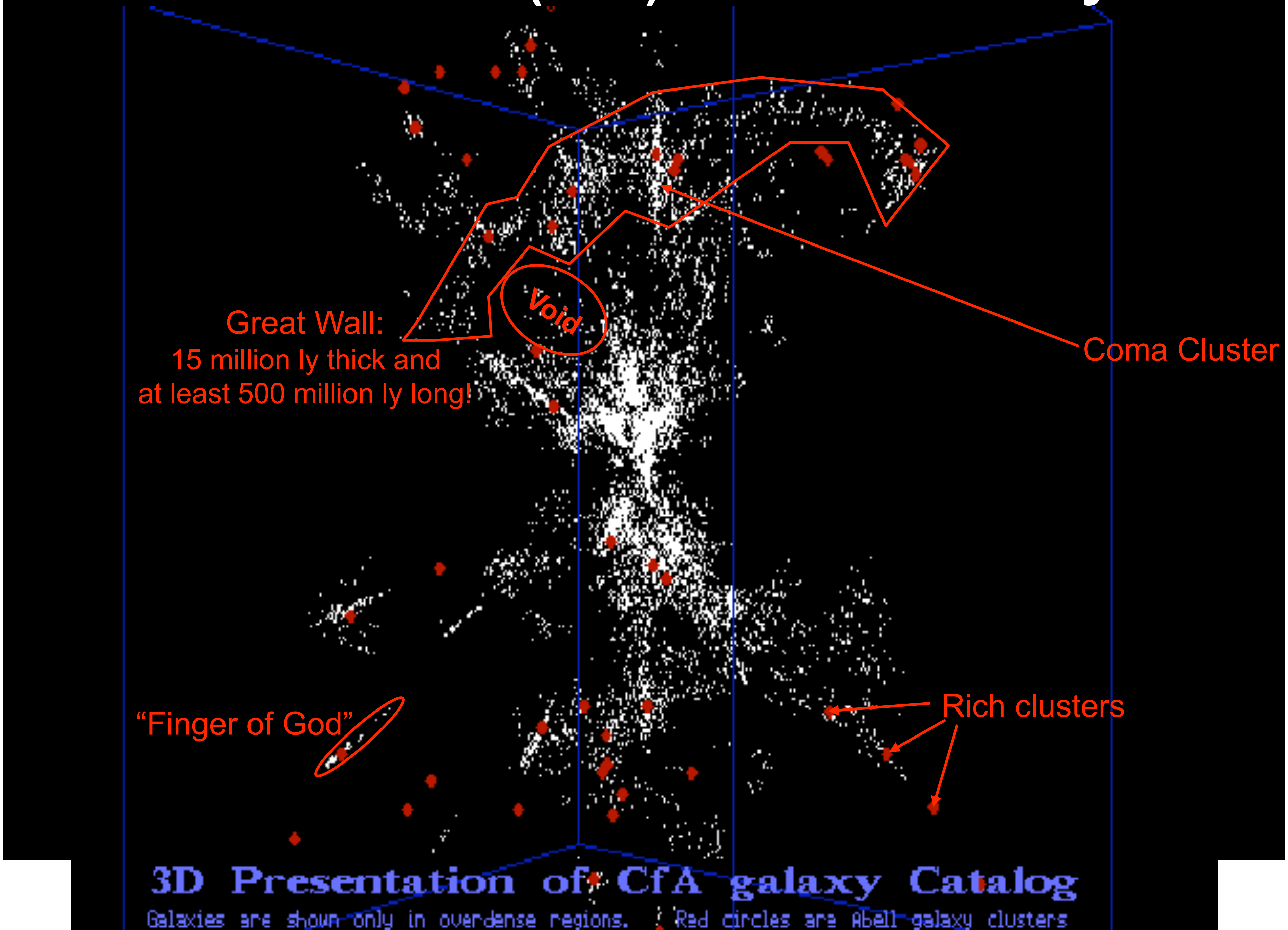
Method: Take spectra of lots of galaxies;
Use the Doppler shift to measure velocity V;
Then get distance D from $V = H_o D$,
where $H_0 \sim 70$ km / s / Mpc is the Hubble constant.

(1 Mpc = 3.26 million light years)

Many such surveys have now been made.
They show structure on very large scales:
— superclusters with sizes of several hundred Mpc;
— apparently empty voids several hundred Mpc across.



The Harvard (CfA) Redshift Survey

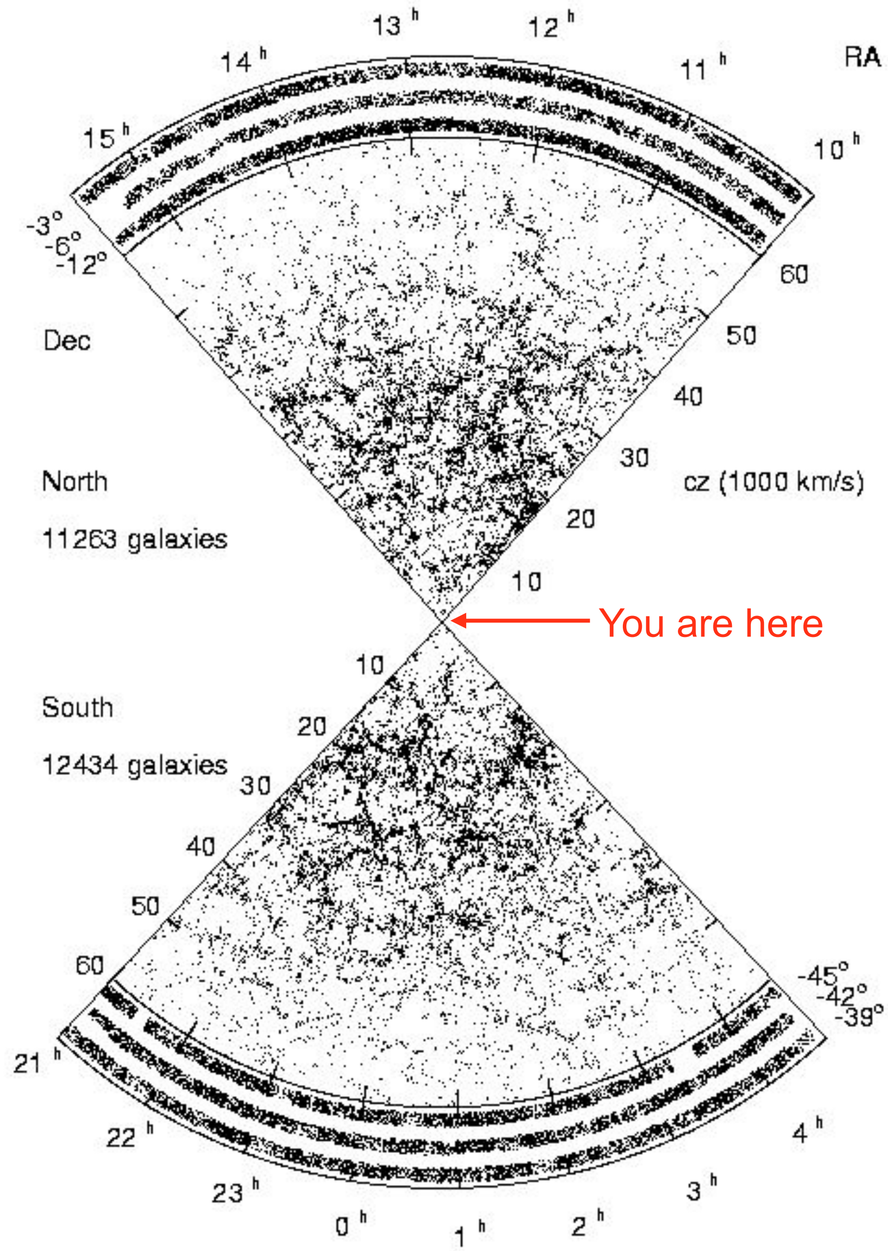


Observed Large-Scale Structure in the Universe

What do we need to explain?

Surveys of galaxies show that they are organized into clusters and clusters of clusters ("superclusters"). The largest superclusters discovered so far are about 250 million ly across.

The figure at right shows the distribution of individual galaxies (dots) in two slices of space with radii of ~ 3 billion light years. The structure is foamy — "empty" voids are surrounded by walls of galaxies. The density is highest where walls interesect; this is where clusters and superclusters are found. Figure 15-19 in the textbook is similar but shows a smaller volume.



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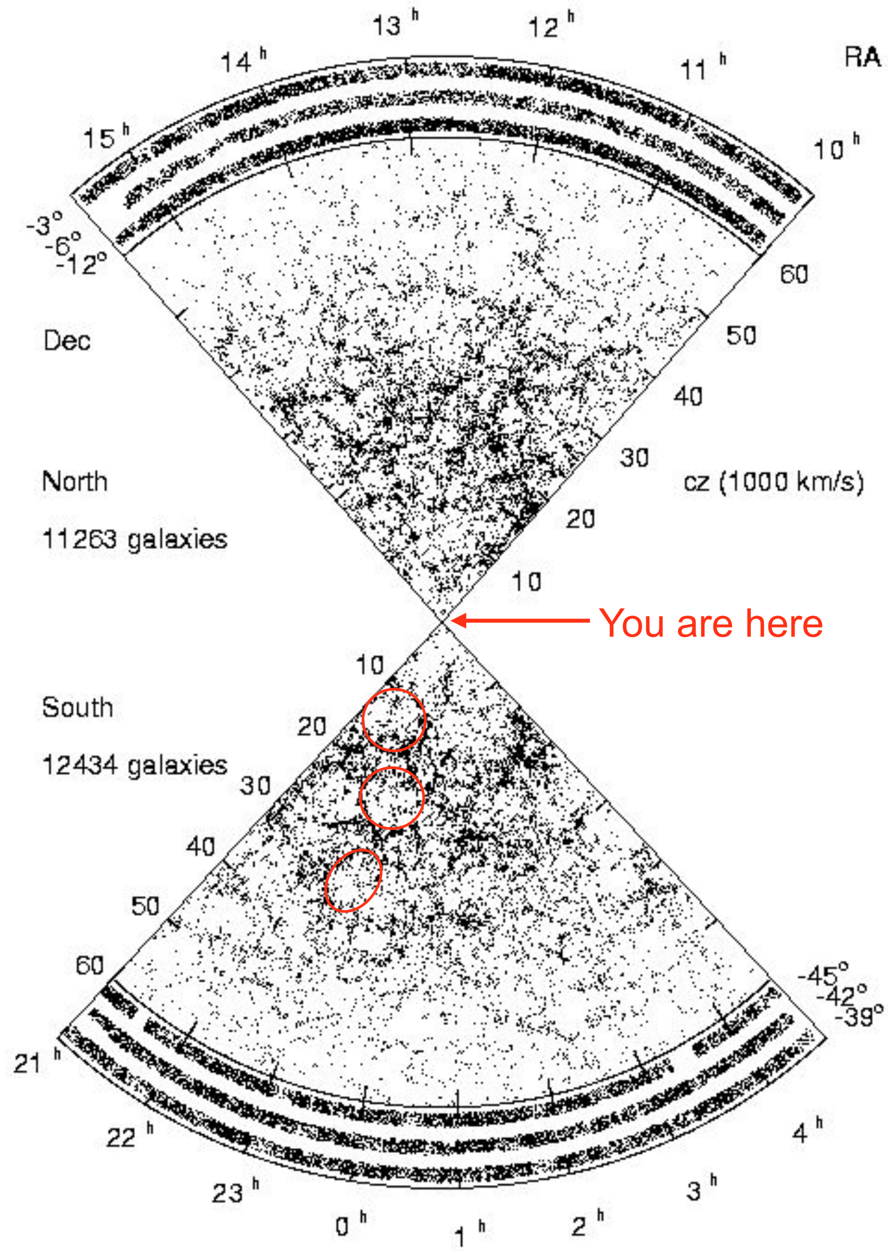
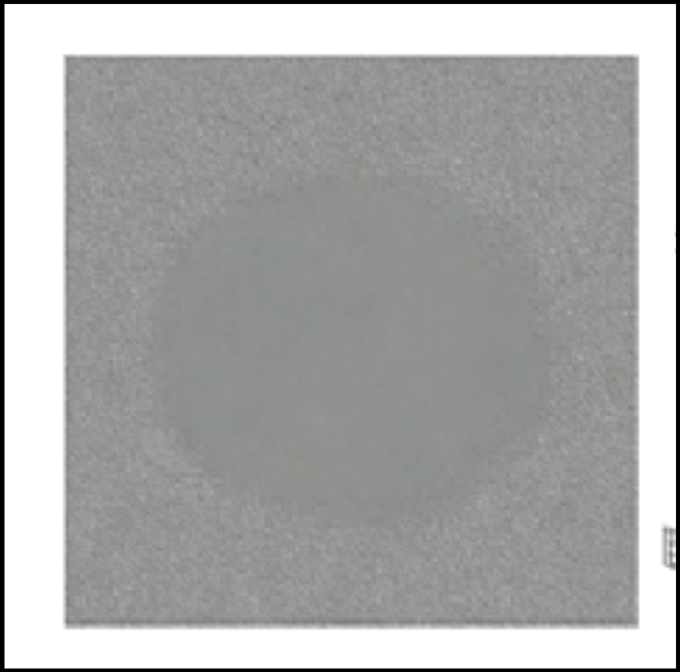
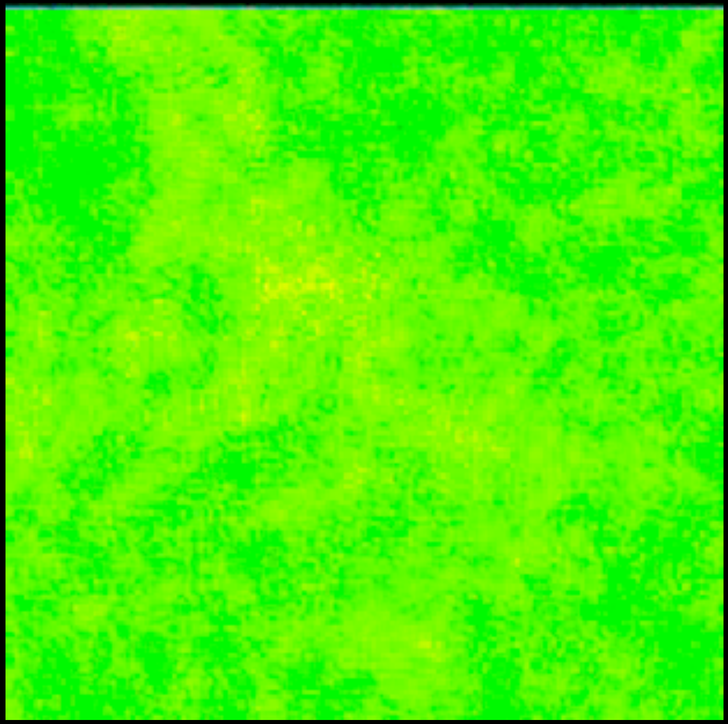
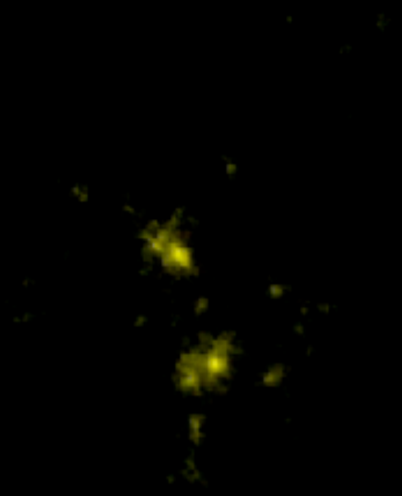
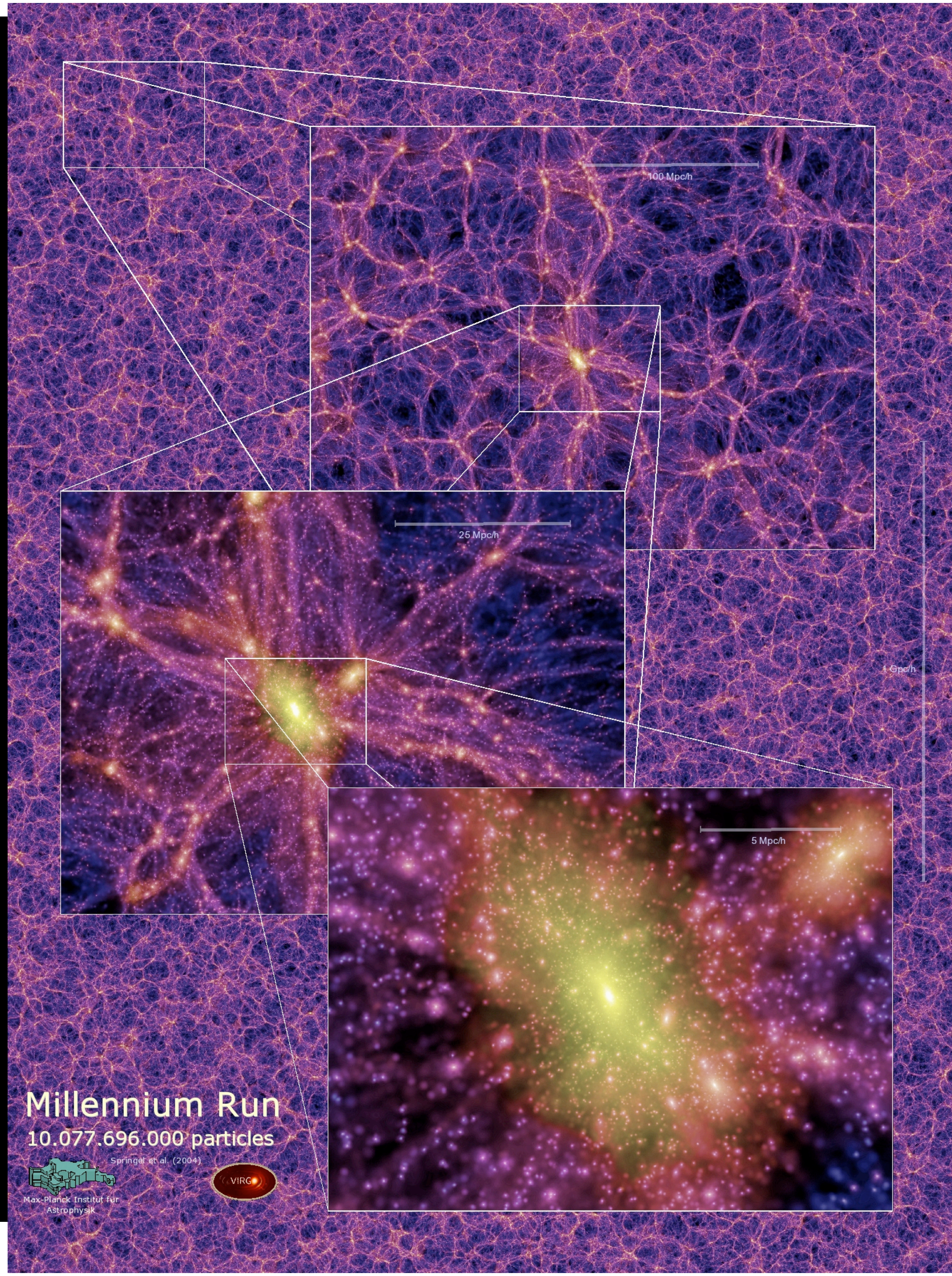


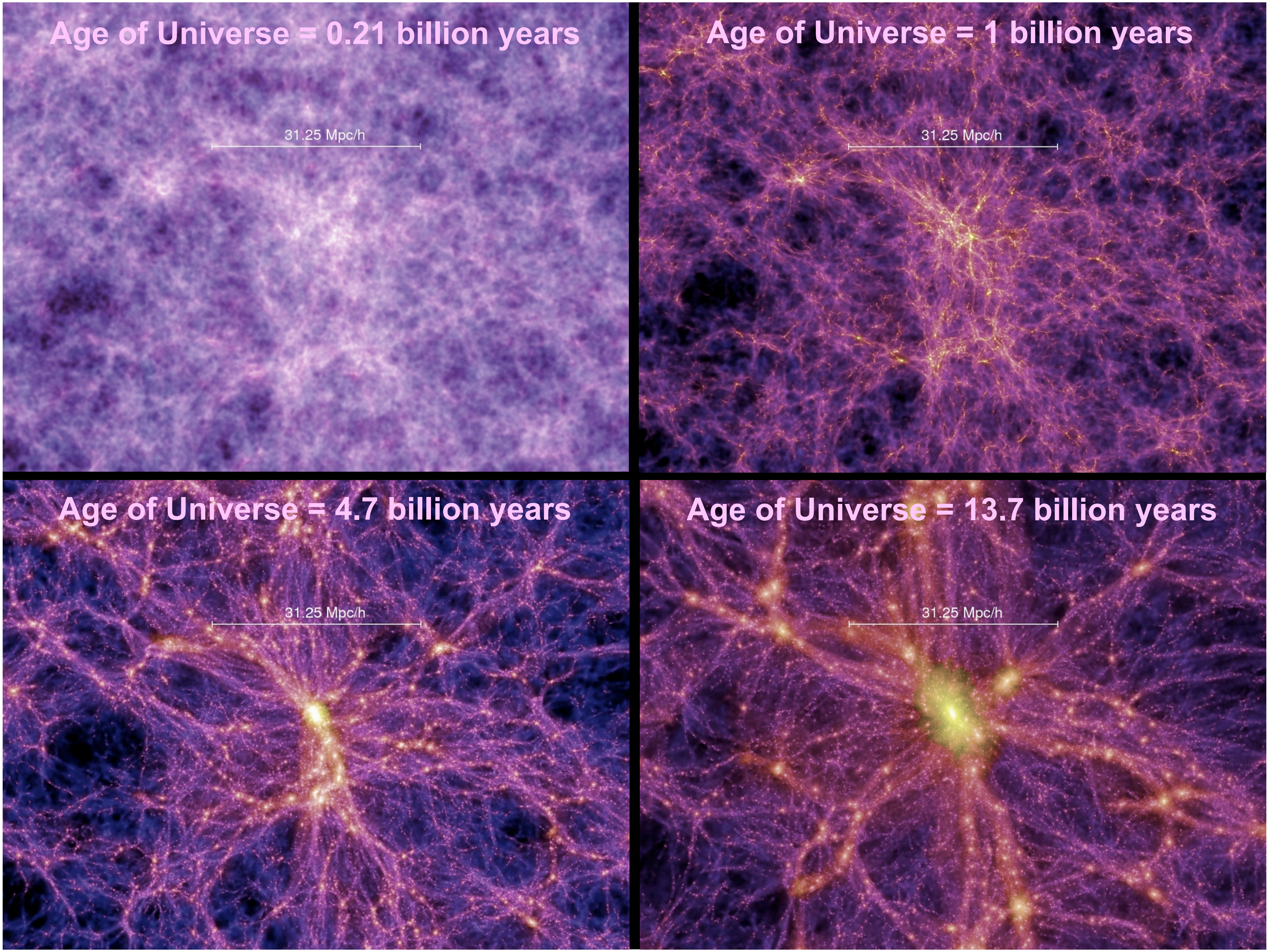


Formation of Large-Scale Structure By Hierarchical Clustering

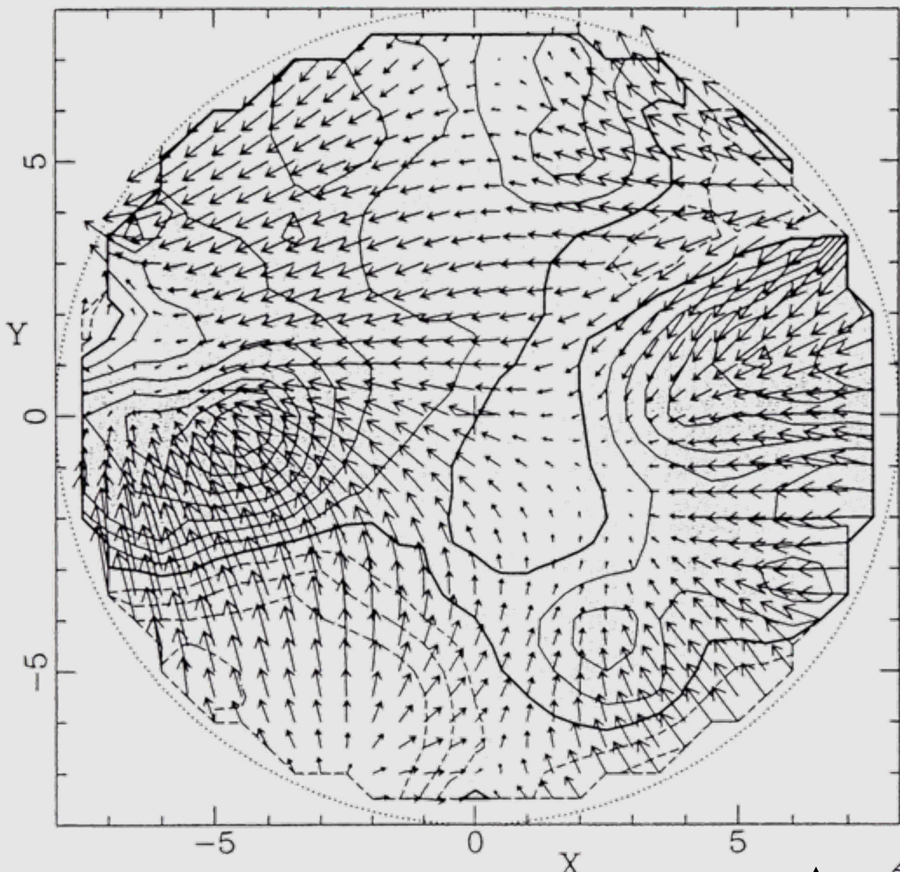


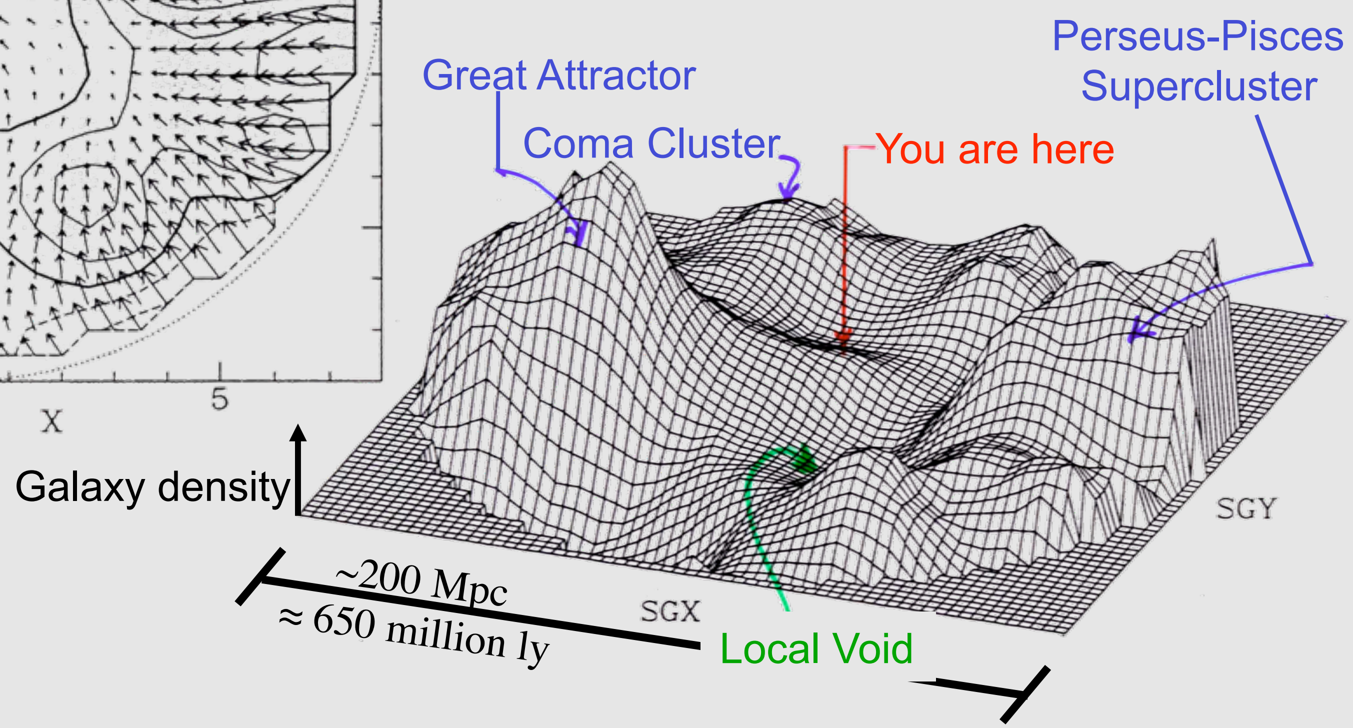



100 Mpc/h
25 Mpc/h
5 Mpc/h
1 Gpc/h
Millennium Run
10.077.696.000 particles
Springel et al. (2004)
Max-Planck Institut für
Astrophysik
VIRGO

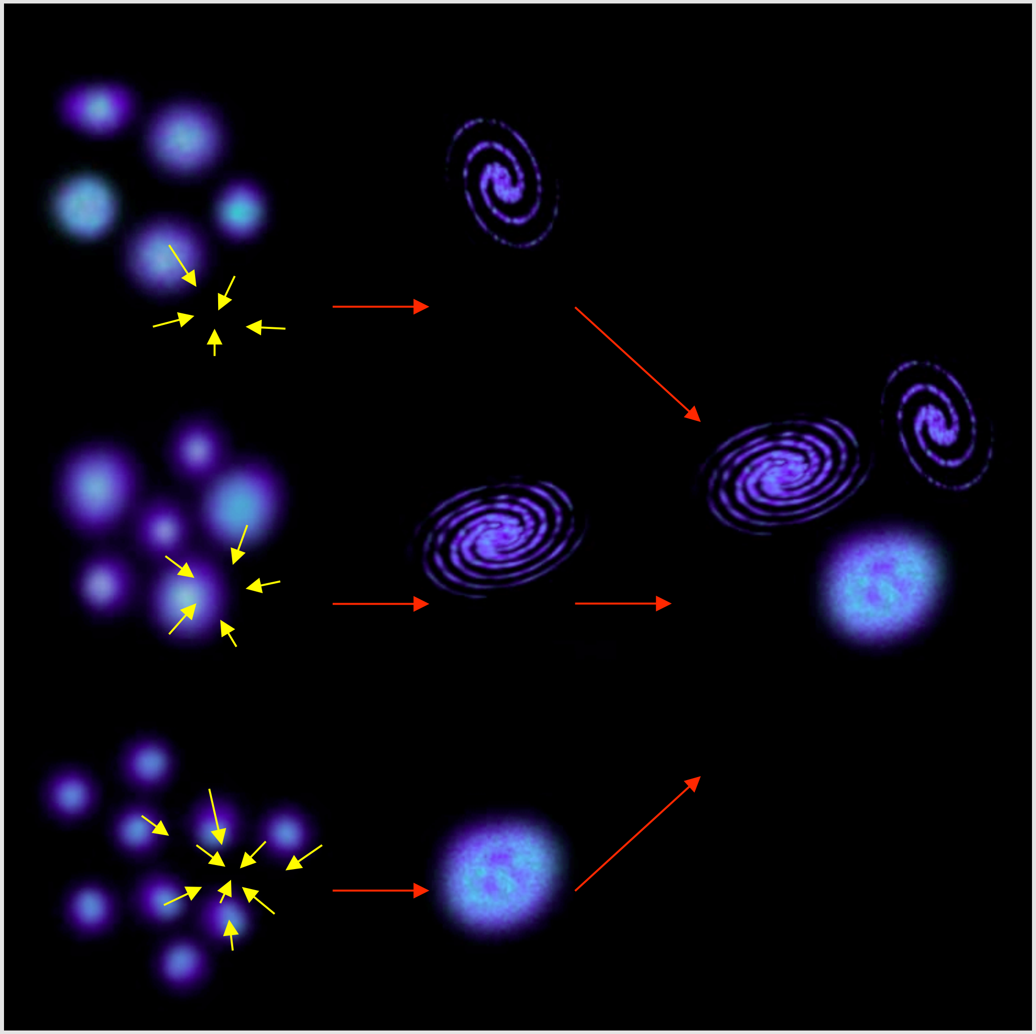

Age of Universe = 0.21 billion years
31.25 Mpc/h
Age of Universe = 1 billion years
31.25 Mpc/h
Age of Universe = 4.7 billion years
31.25 Mpc/h
Age of Universe = 13.7 billion years
31.25 Mpc/h

We live in the suburbs of the Virgo Cluster.
The Virgo Cluster is in the suburbs of the Great Attractor.





Bottom-Up Galaxy Formation



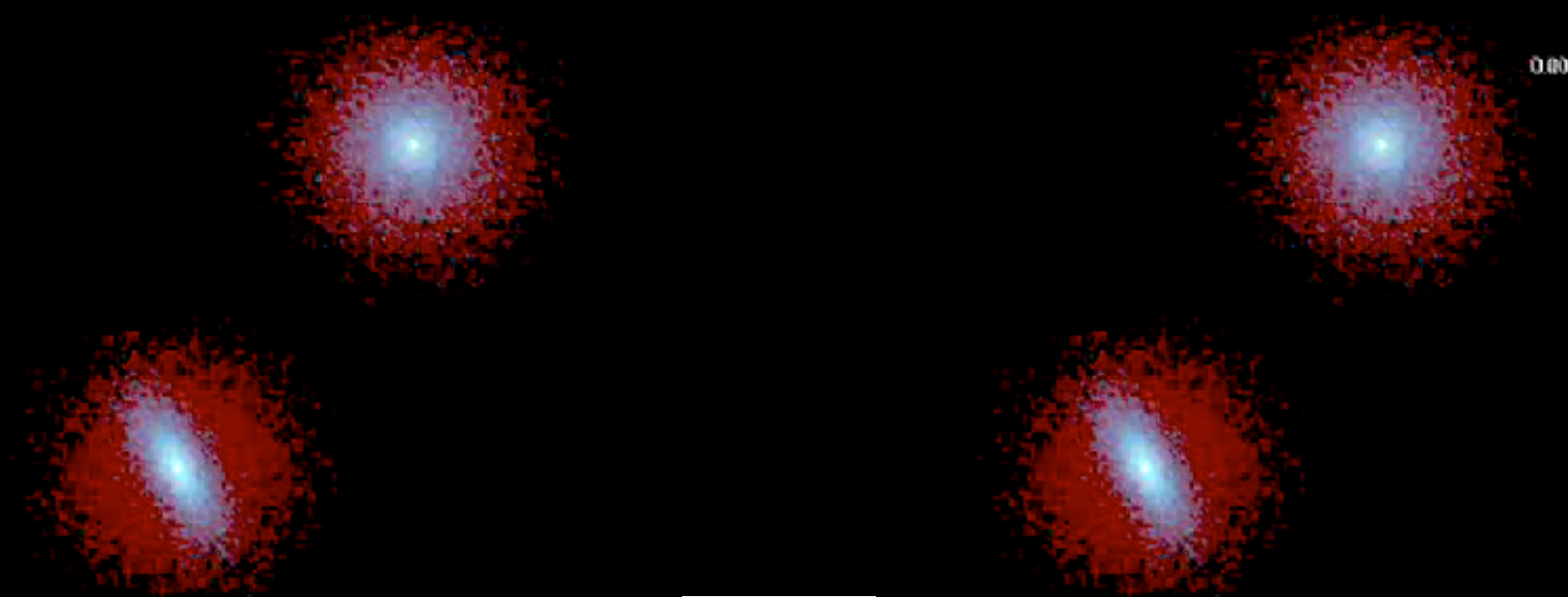
Small galaxies form first and then cluster together via gravity on larger and larger scales. Small galaxies merge to make big galaxies.

Josh Barnes

Colliding & *Merging*

Galaxies
Galaxies Galaxies
Galaxies

Galaxies evolve by colliding and merging to make bigger galaxies.



Colliding and Merging Galaxies

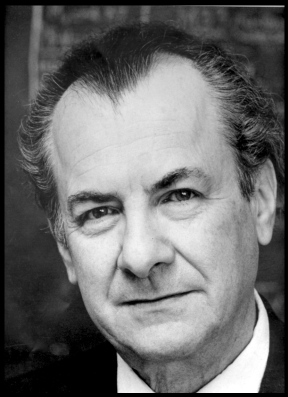
Colliding

&

Merging

Galaxies
Galaxies
Galaxies
Galaxies

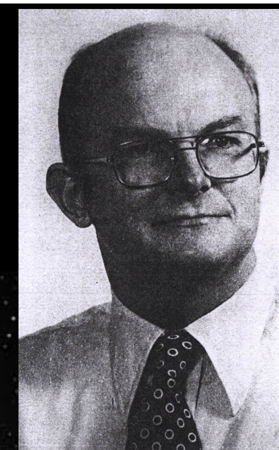
Most peculiar galaxies aren't.



After a collision, a car is a wreck, not a new type of car.

Gerard de Vaucouleurs

Tidal Interactions



Some galaxies do not fit into Hubble's classification. In the 1970s, Alar and Juri Toomre showed that such systems are pairs of once-normal galaxies that are interacting gravitationally. In fact, they are in the process of merging into one galaxy.

Bridges & Tails

The bridges and tails seen in many interacting systems are due to tidal forces acting on disk galaxies. The Moon produces a double-sided tide in the Earth's oceans. Similarly, each disk galaxy in an interacting pair develops two tidal tails that may stretch out to many times the diameters of the original galaxies.

Tidal spirals

Tidally-perturbed disk galaxies often develop striking spiral structure. Galaxies with symmetric two-armed spirals usually have close companions. The tidal effect of the companion combines with the galaxy's rotation to produce the spiral pattern.

Mergers

The most important effects of galactic collisions are due to gravity. When two galaxies pass through each other, few stars collide. Slow collisions are more damaging than fast collisions, because gravity has more time to distort the galaxies.

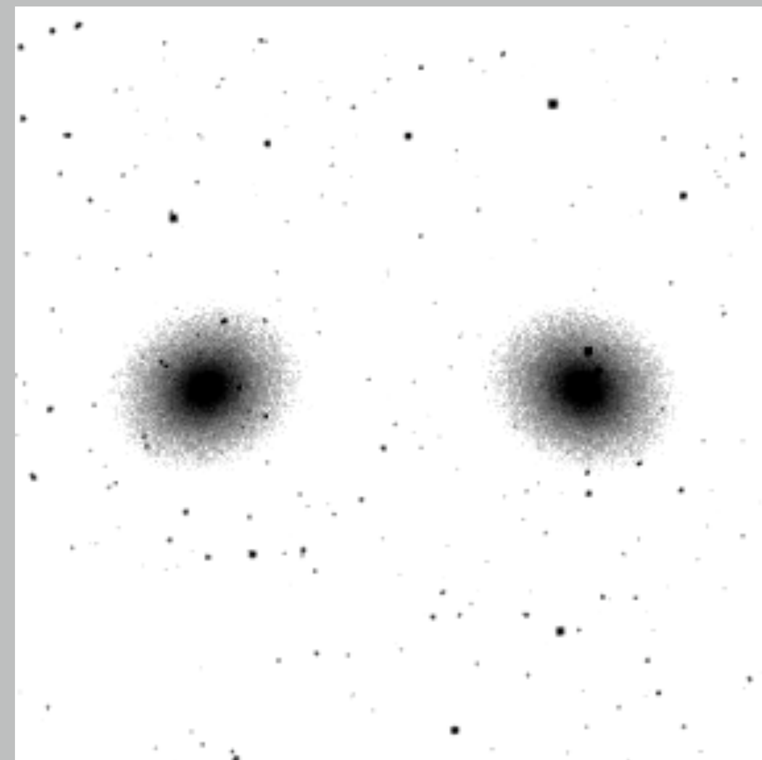
During a collision, the galaxies' dark halos are violently distorted by tidal forces. The energy required to create the distortions comes from the galaxies' relative motions. As a result, the galaxies slow down. They stay closer together after the collision than they were before.

After several collisions, the galaxies have lost so much orbital energy that they no longer separate. Instead, they merge into a single object.

During this process, rapidly changing gravitational fields fling disk stars into random orbits. If two disks were originally present, they get scrambled together to make a roughly spherical hulk of stars. Also, the remnant becomes smoother as stars spread out along their orbits. The end product is an elliptical galaxy.

Therefore, **a merger transforms two spiral galaxies into one elliptical.**

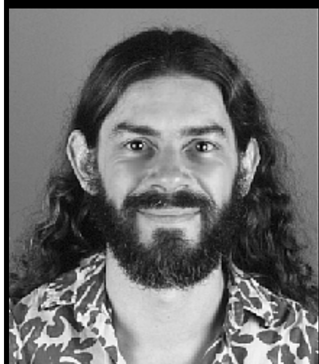
Making the Antennae

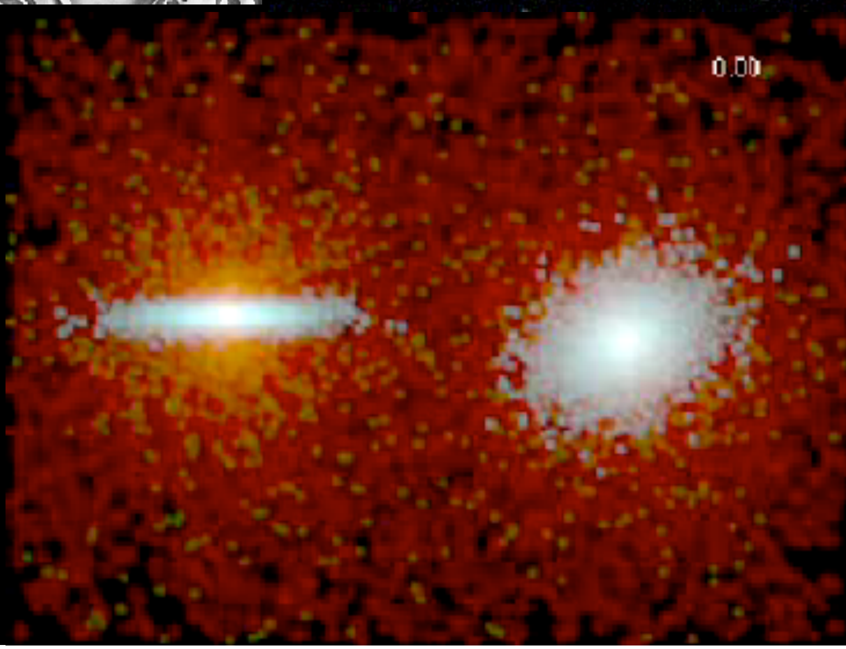


The Mice • Interacting Galaxies NGC 4676
Hubble Space Telescope • Advanced Camera for Surveys

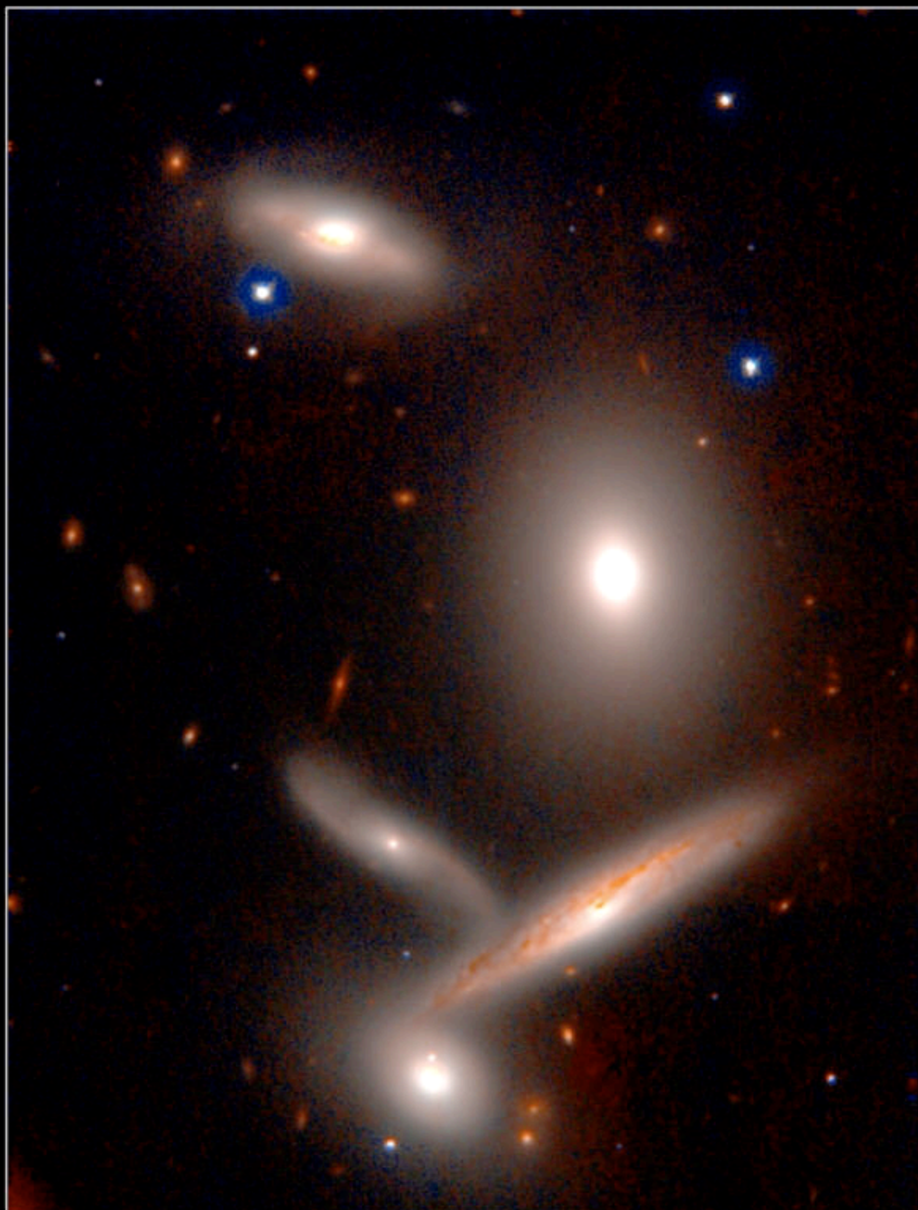
Making The Mice

Josh Barnes

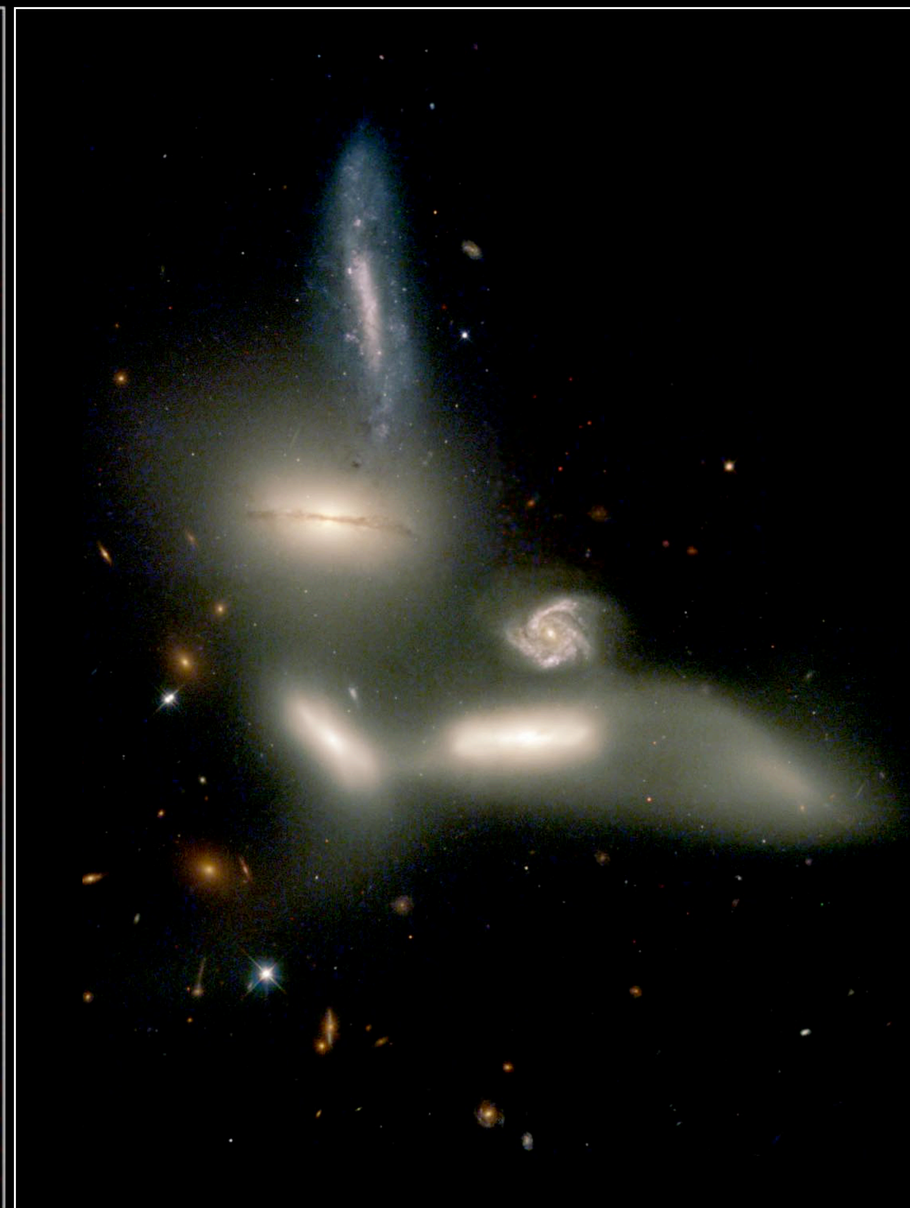




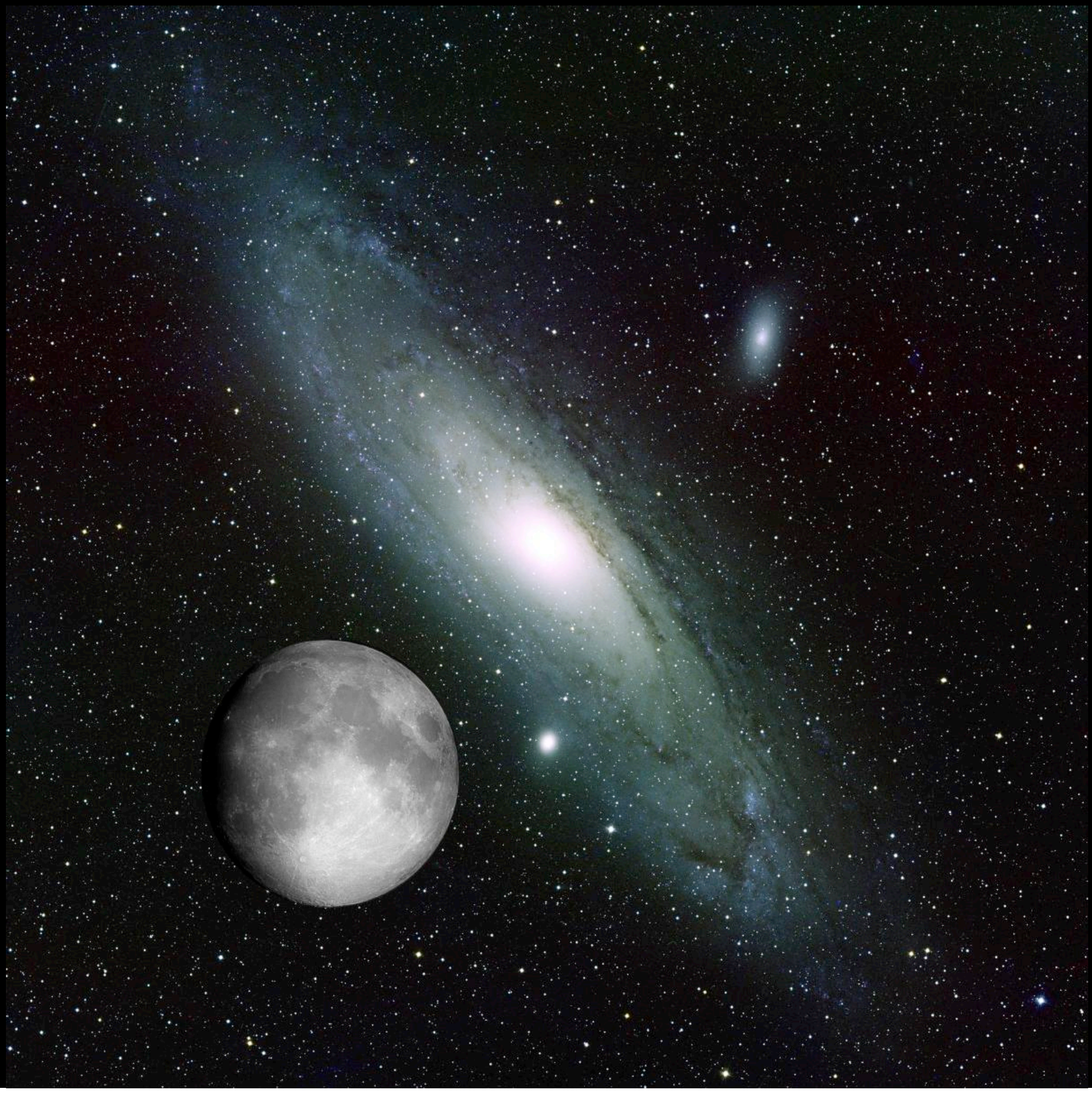
Two Future Mergers



Hickson Compact Group 40
Subaru Telescope, National Astronomical Observatory of Japan
CISCO (J & K′)
January 28, 1999



Our Galaxy and M 31 will merge in 3 — 4 billion years.



The Essential Difference Between the Formation of Bulges+Ellipticals and Disks

Ellipticals formed their stars before or during the collapse or merger that made the galaxy.

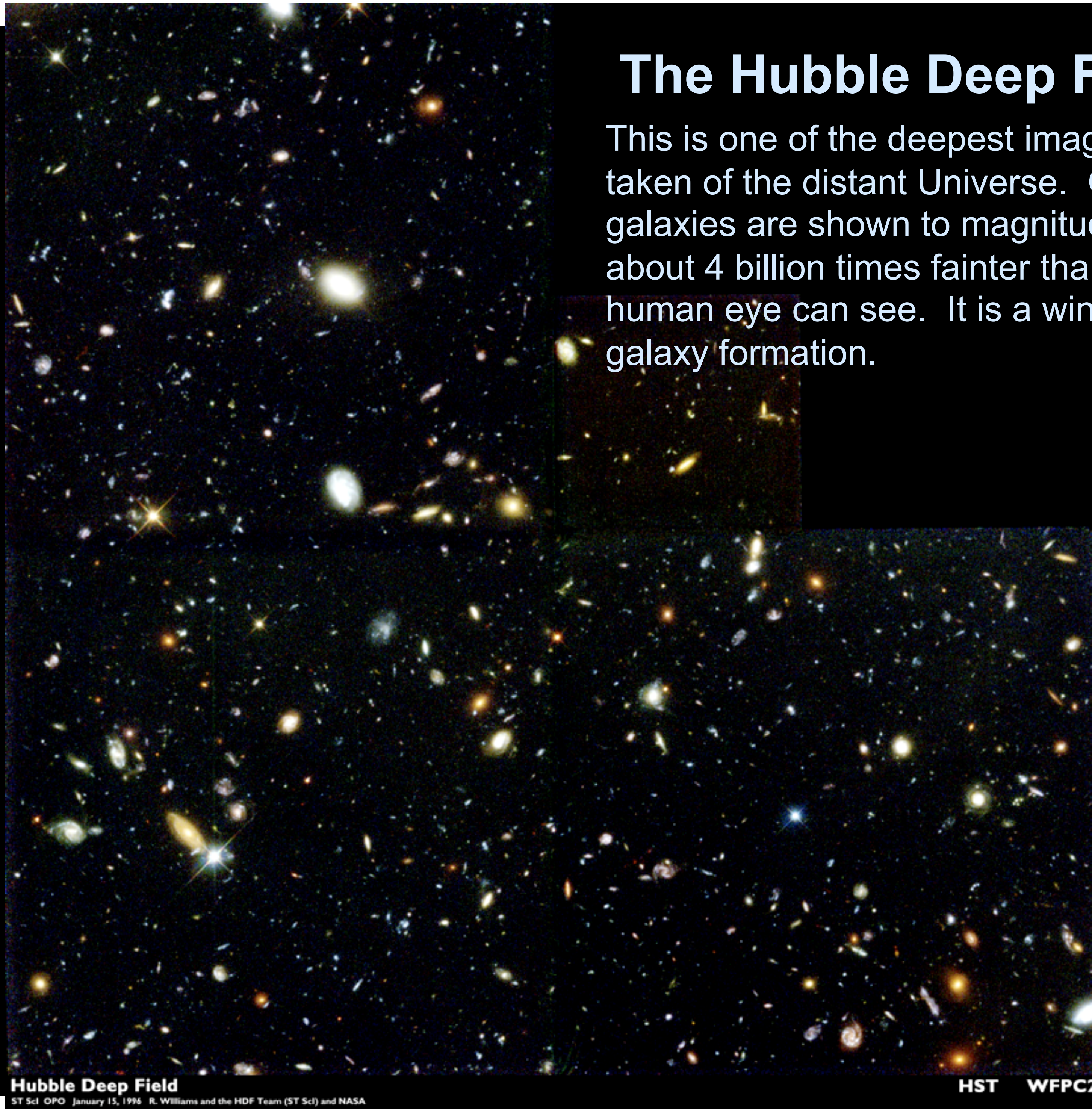
Disks formed their stars after the collapse that made the galaxy.

The material that made the disk had to be gas, not stars, when the disk formed. Only gas clouds can collide and dissipate their random velocities to settle into thin, rotating disks.

Disks are fragile. They must remain undisturbed by major mergers to stay thin. How this happens in the context of hierarchical clustering is a current mystery.

The Hubble Deep Field

This is one of the deepest images ever taken of the distant Universe. Over 1500 galaxies are shown to magnitude ~ 30, about 4 billion times fainter than the human eye can see. It is a window on galaxy formation.

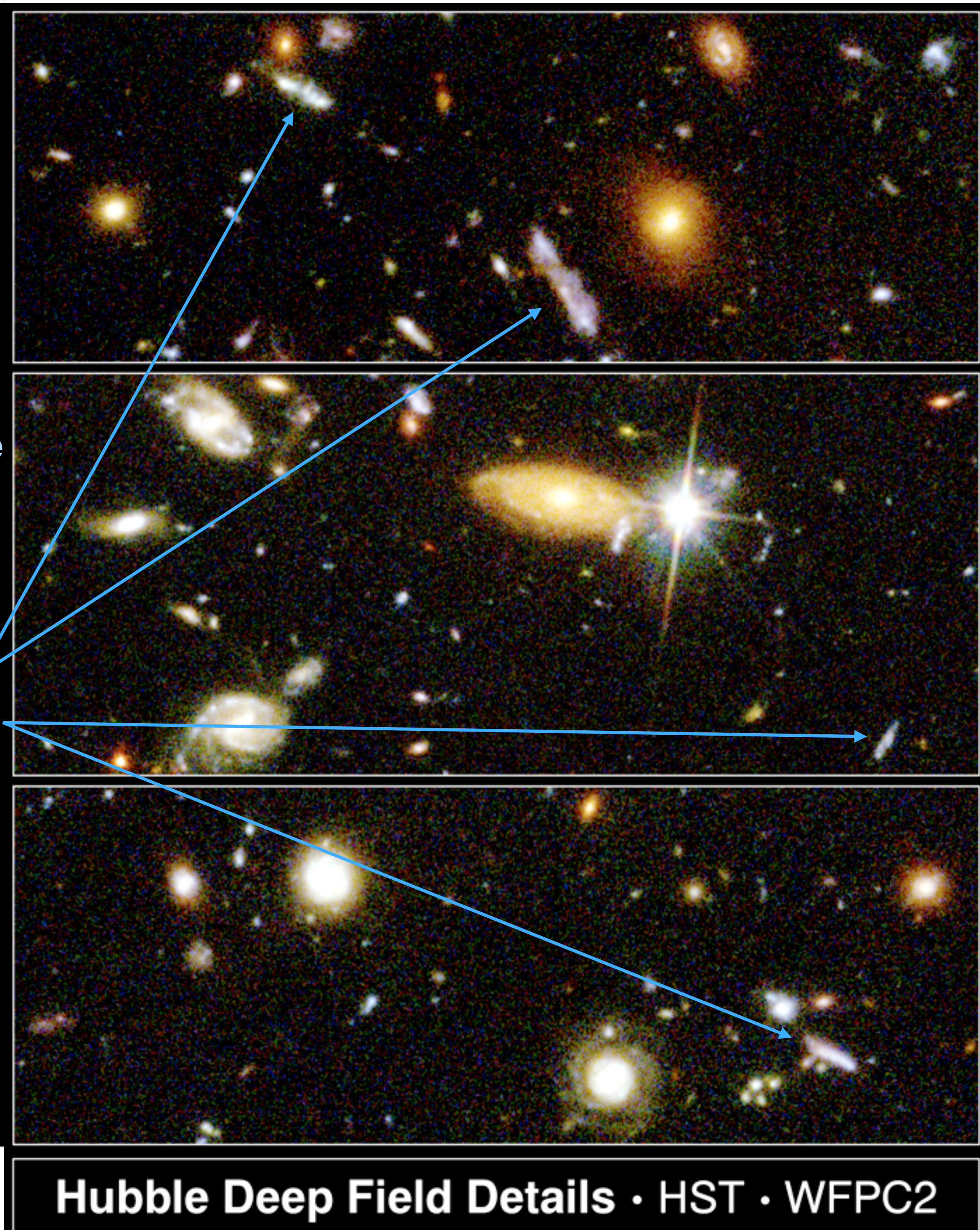


Hubble Deep Field

Hubble Space Telescope • WFPC2

Hubble Deep Field shows kinds of galaxies that we do not see in the nearby Universe.

Example: chain galaxies, i. e., long, thin, irregular, star-forming galaxies.



Also, when stellar ages are taken into account, there are more faint and fewer bright galaxies than we see now.

Astronomers believe that the HDF shows distant galaxy fragments that have since merged into present-day galaxies.