Chapter 16
Galaxies and Dark Matter

Units of Chapter 16

Dark Matter in the Universe

Galaxy Collisions

Galaxy Formation and Evolution

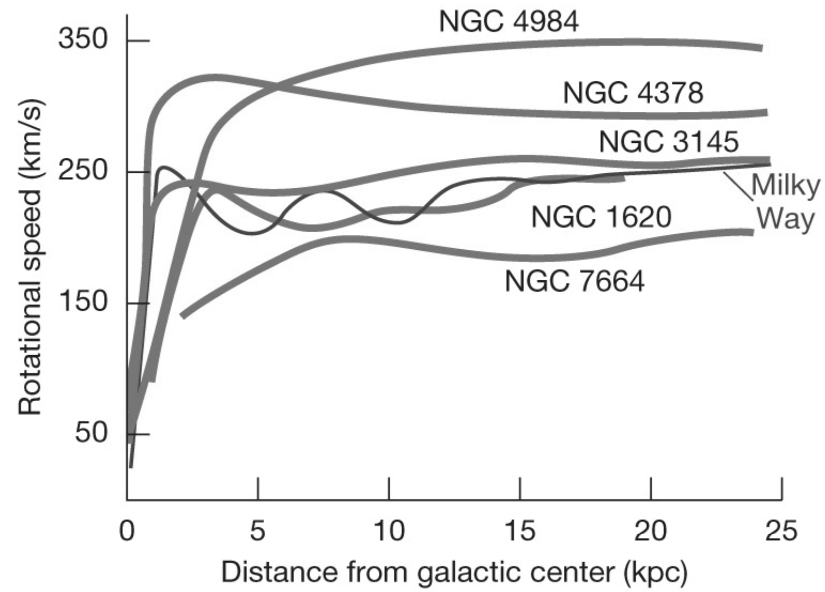
Black Holes and Active Galaxies

The Universe on Very Large Scales

16.1 Dark Matter in the Universe

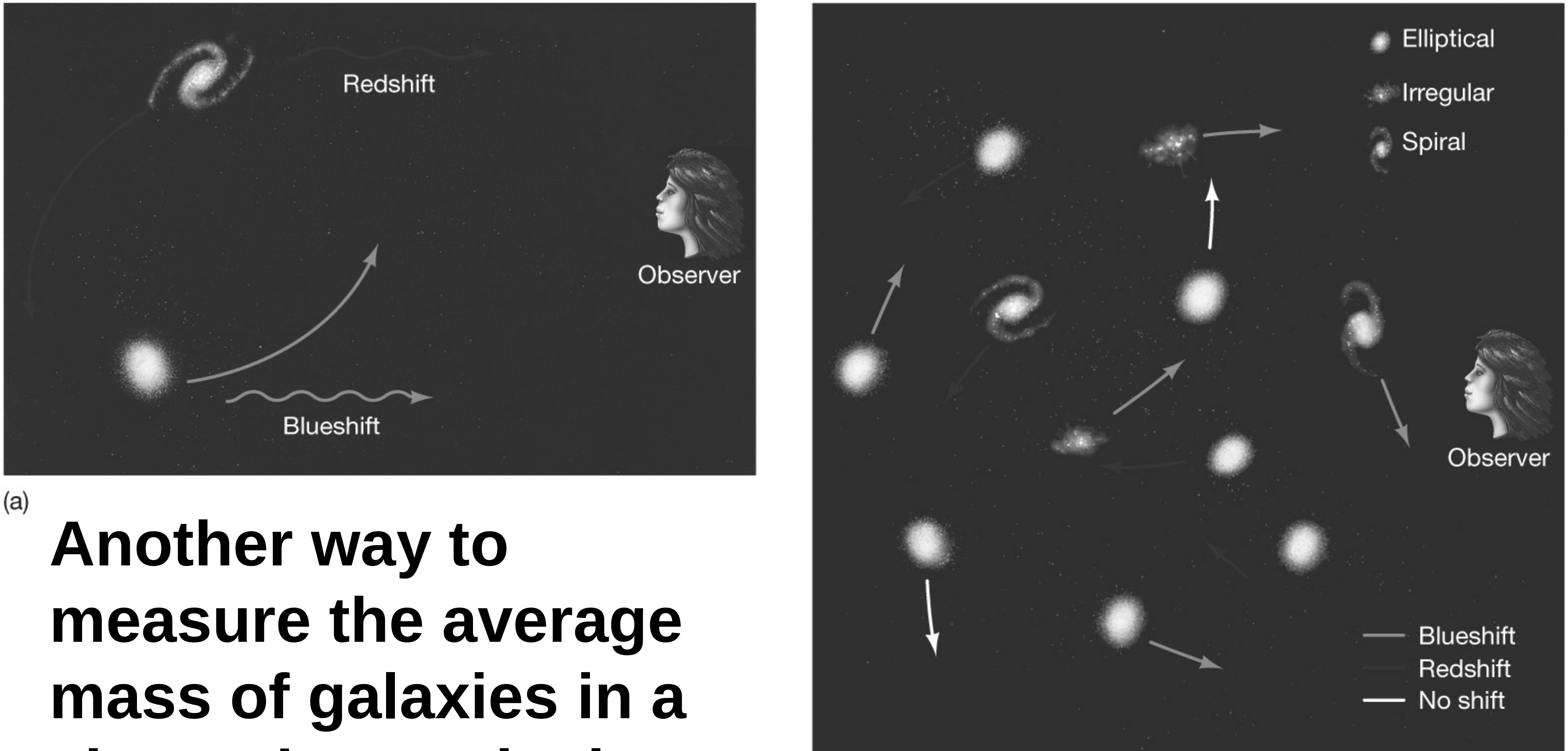
Other galaxies have rotation curves similar to ours, allowing measurement of their mass:

(a)



(b)

16.1 Dark Matter in the Universe



(a)

(b)

Another way to measure the average mass of galaxies in a cluster is to calculate how much mass is required to keep the cluster gravitationally bound.

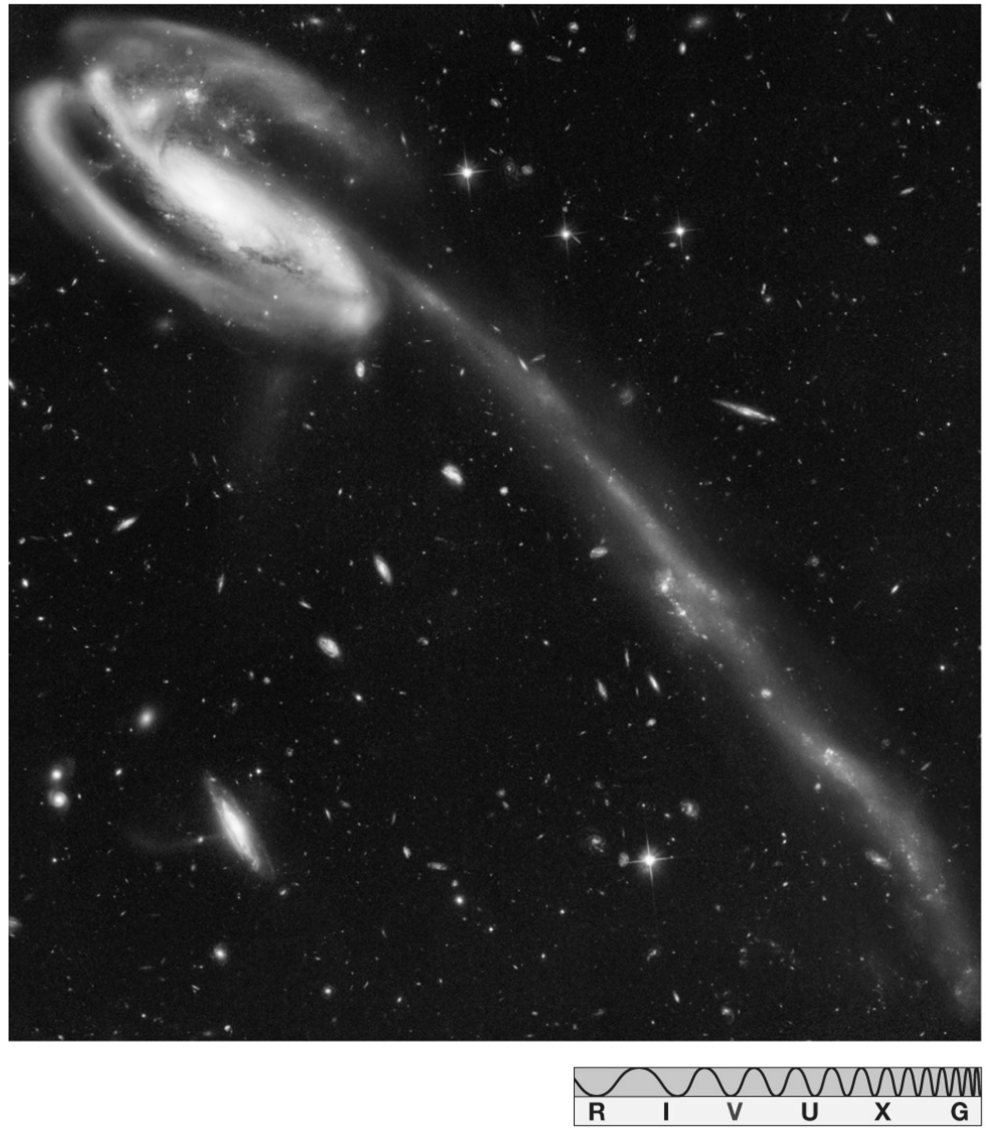
16.1 Dark Matter in the Universe

Galaxy mass measurements show that galaxies need between 3 and 10 times more mass than can be observed to explain their rotation curves.

The discrepancy is even larger in galaxy clusters, which need 10 to 100 times more mass. The total needed is more than the sum of the dark matter associated with each galaxy.

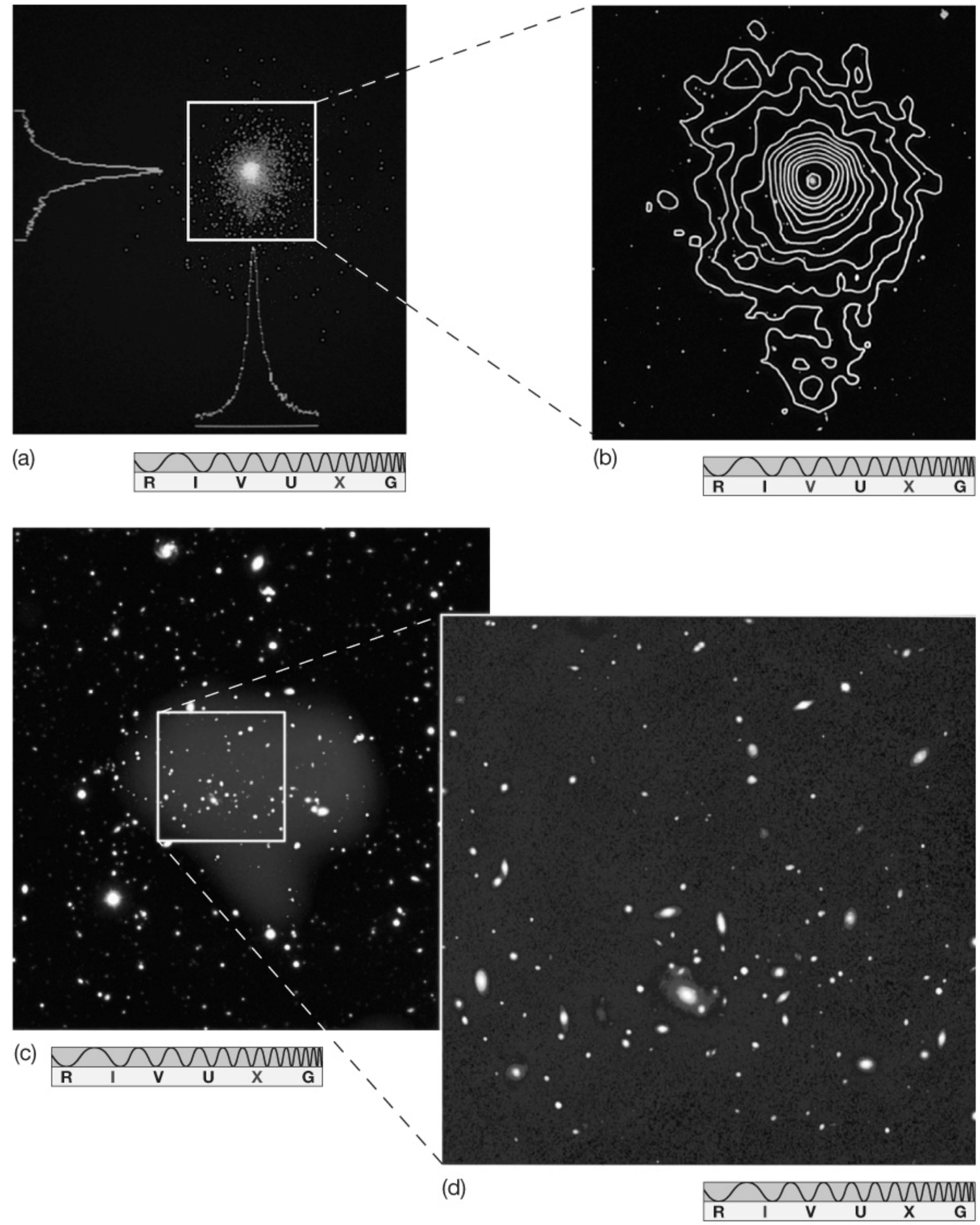
16.1 Dark Matter in the Universe

This image may show a galaxy interacting with an unseen neighbor – a "dark galaxy".



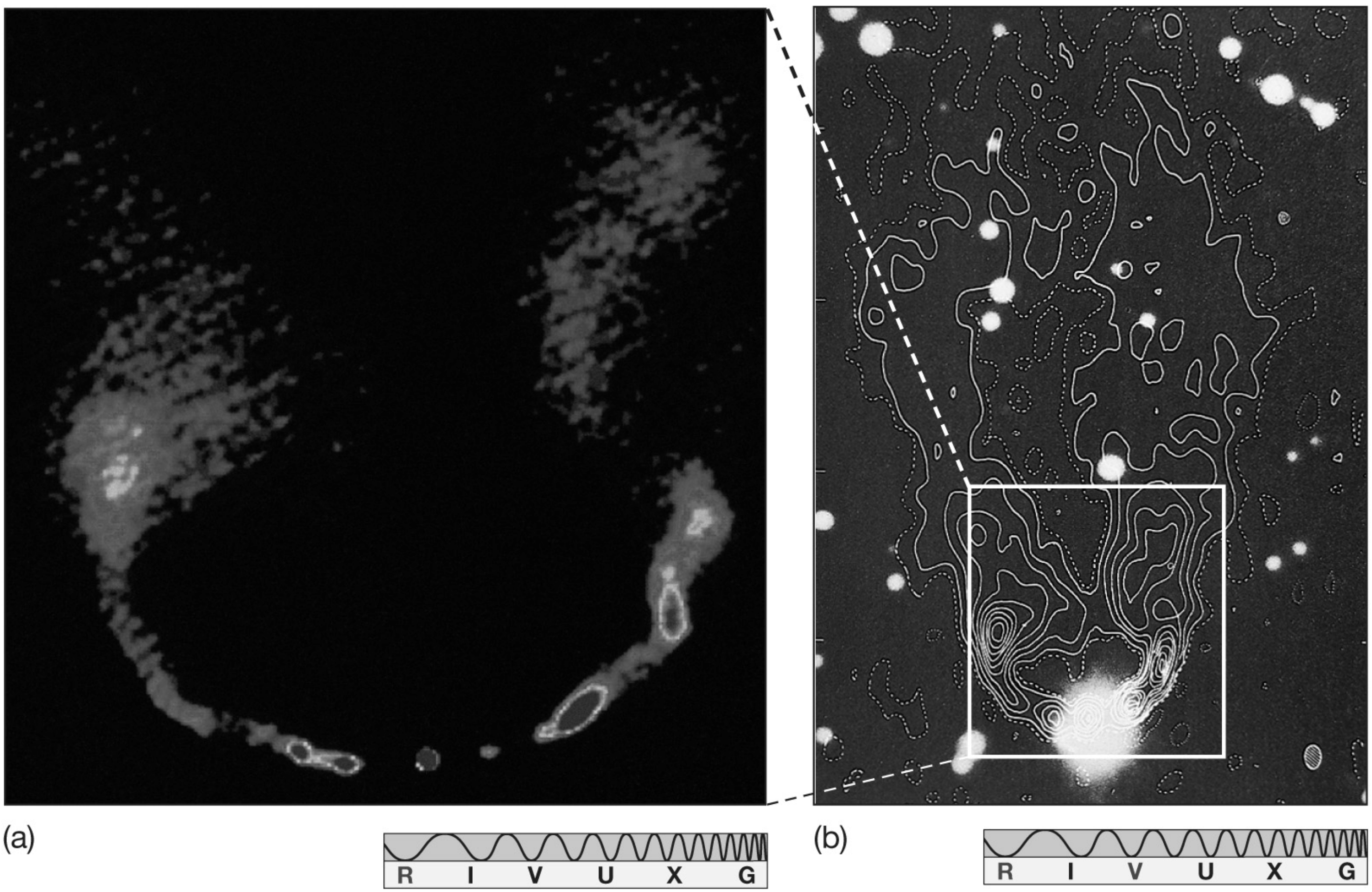
16.1 Dark Matter in the Universe

There is evidence for intracluster superhot gas (about 10 million K) throughout clusters, densest in the center:



16.1 Dark Matter in the Universe

This head-tail radio galaxy's lobes are being swept back, probably because of collisions with intracluster gas:



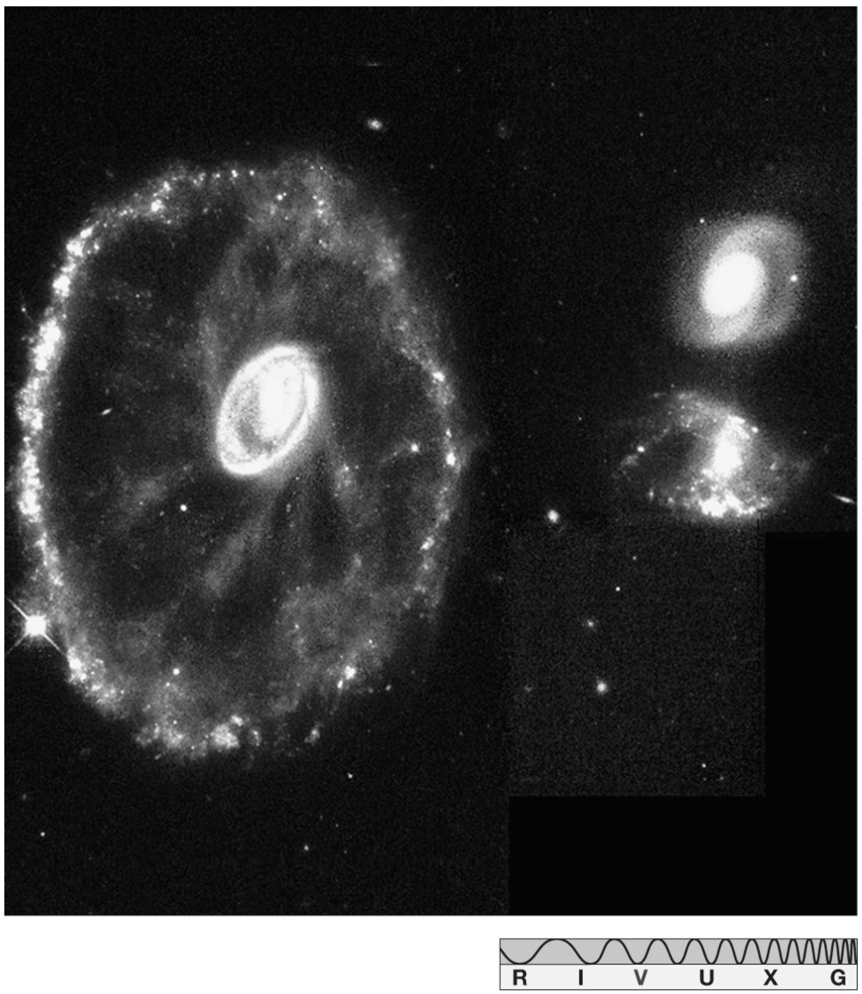
16.1 Dark Matter in the Universe

It is believed this gas is primordial – dating from the very early days of the Universe.

There is not nearly enough of it to be the needed dark matter in galaxy clusters.

16.2 Galaxy Collisions

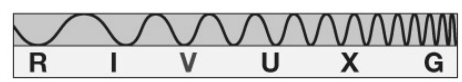
The separation between galaxies is usually not large compared to the size of the galaxies themselves, and galactic collisions are frequent.



The "cartwheel" galaxy on the left appears to be the result of a head-on collision with another galaxy, perhaps one of those on the right.

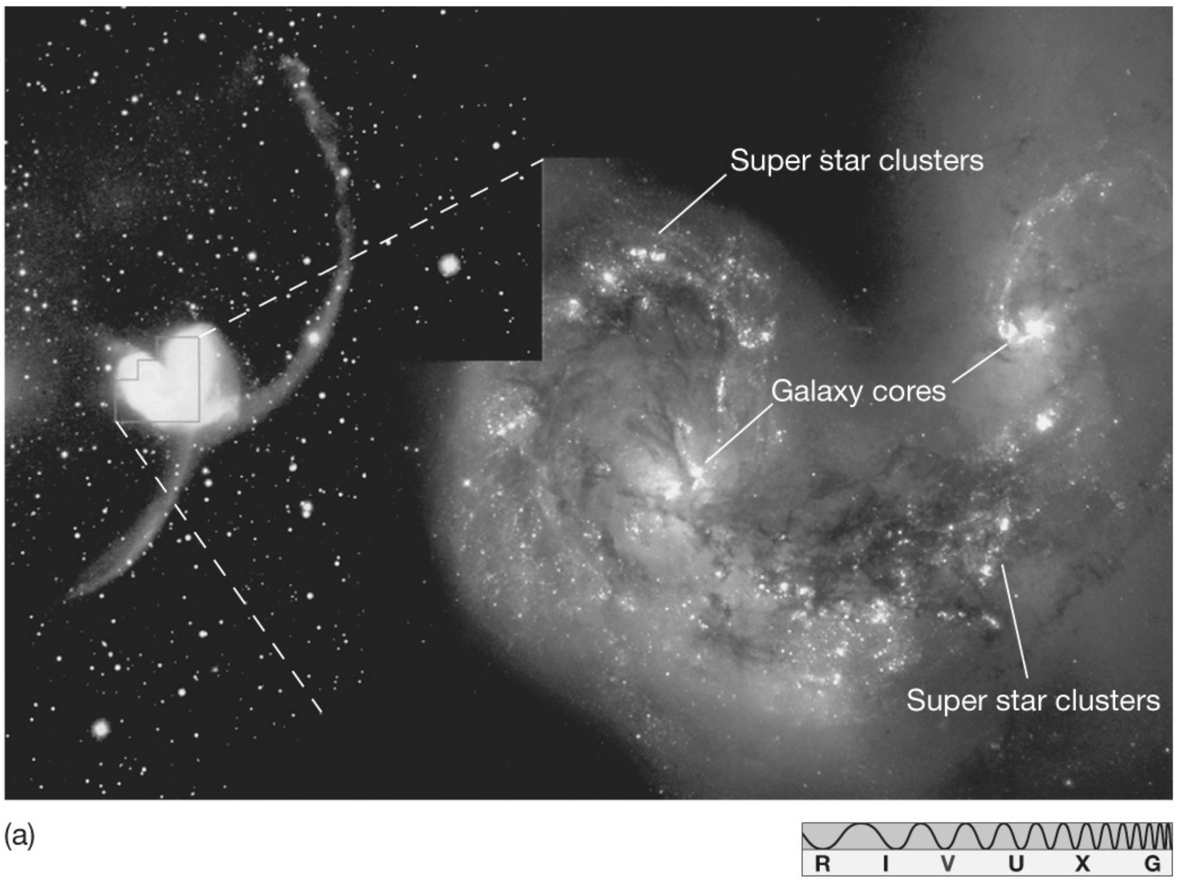
16.2 Galaxy Collisions

This galaxy collision has led to bursts of star formation in both galaxies; ultimately they will probably merge.

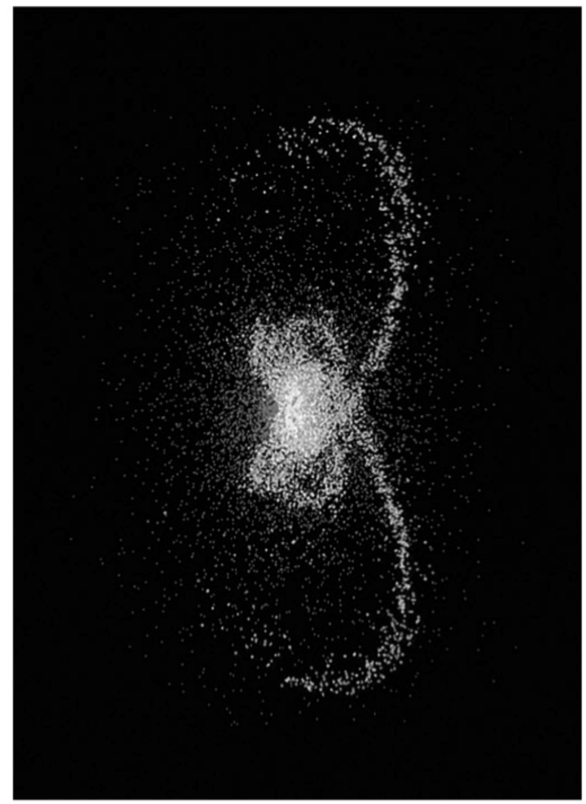


16.2 Galaxy Collisions

The Antennae galaxies collided fairly recently, sparking stellar formation. The plot on the right is the result of a computer simulation of this kind of collision.



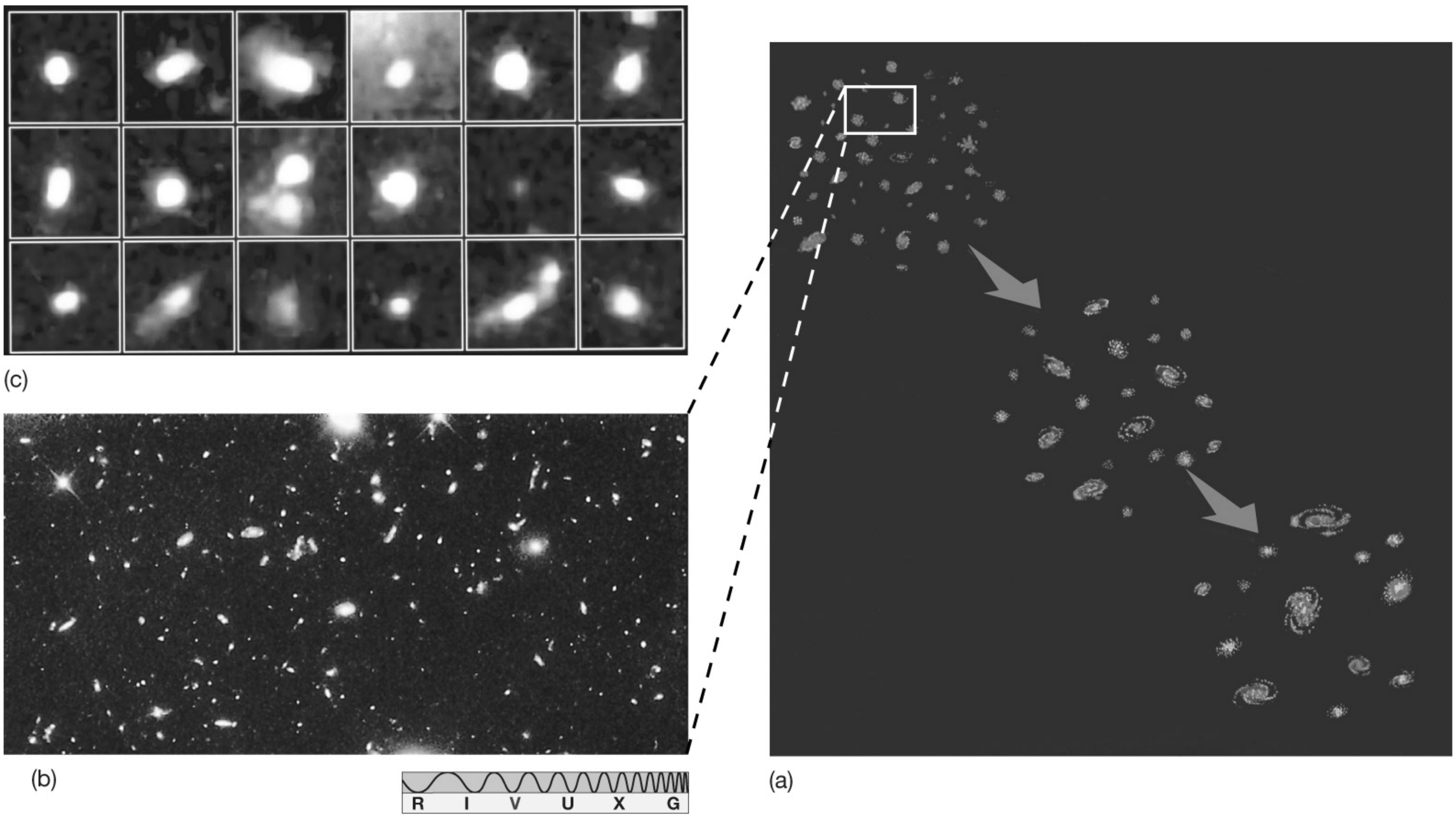
(a)



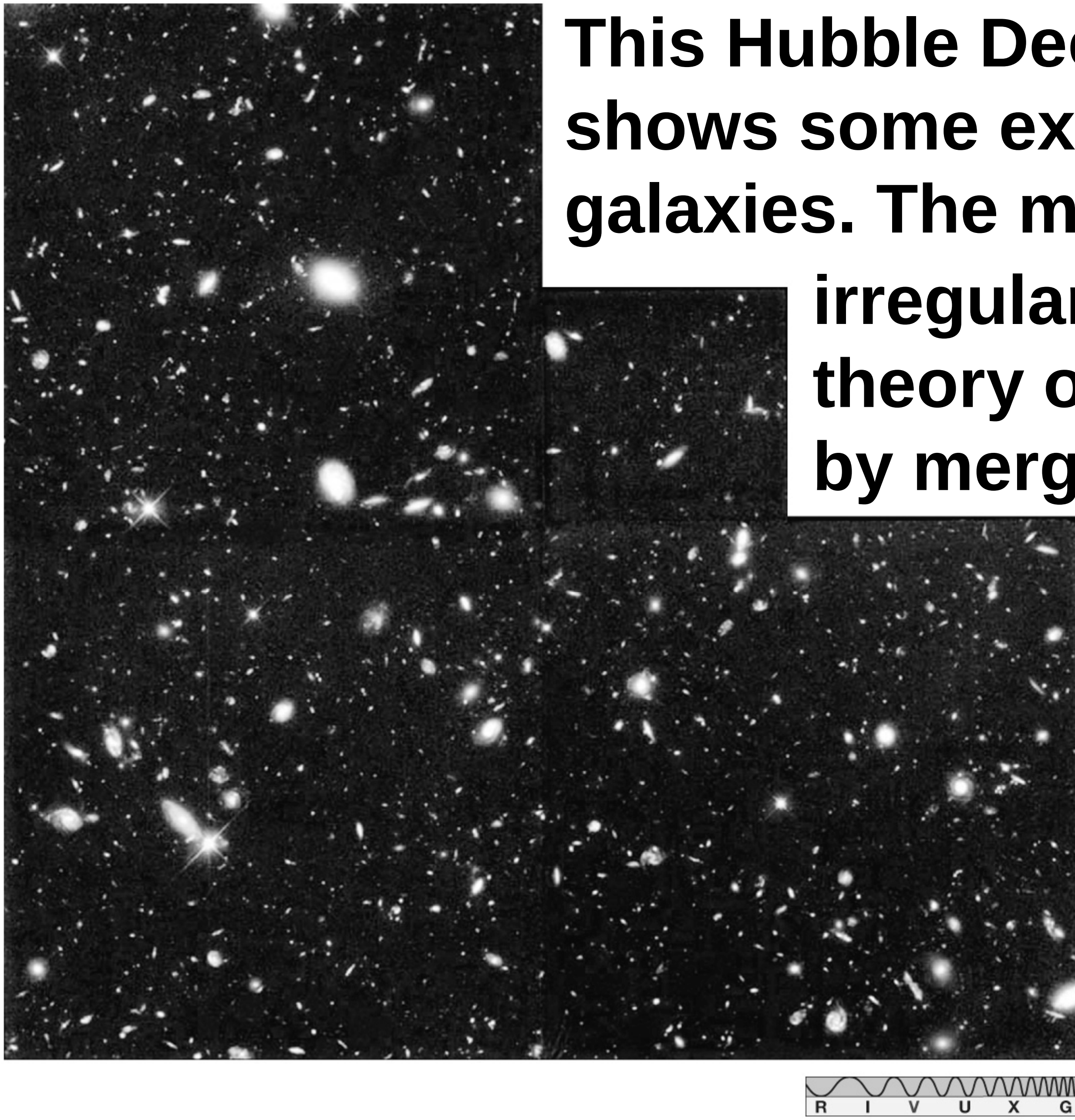
(b)

16.3 Galaxy Formation and Evolution

Galaxies are believed to have formed from mergers of smaller galaxies and star clusters. Image (c) shows large star clusters found some 5000 Mpc away. They may be precursors to a galaxy.



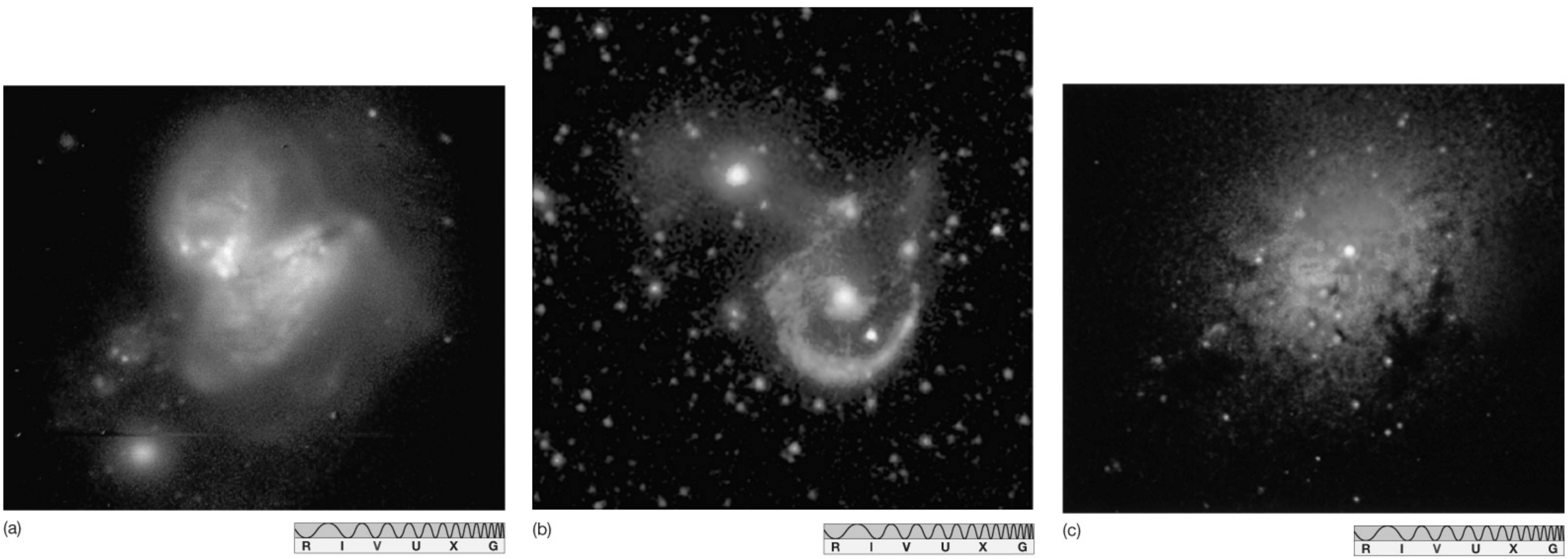
16.3 Galaxy Formation and Evolution



This Hubble Deep Field view shows some extremely distant galaxies. The most distant appear irregular, supporting the theory of galaxy formation by merger.

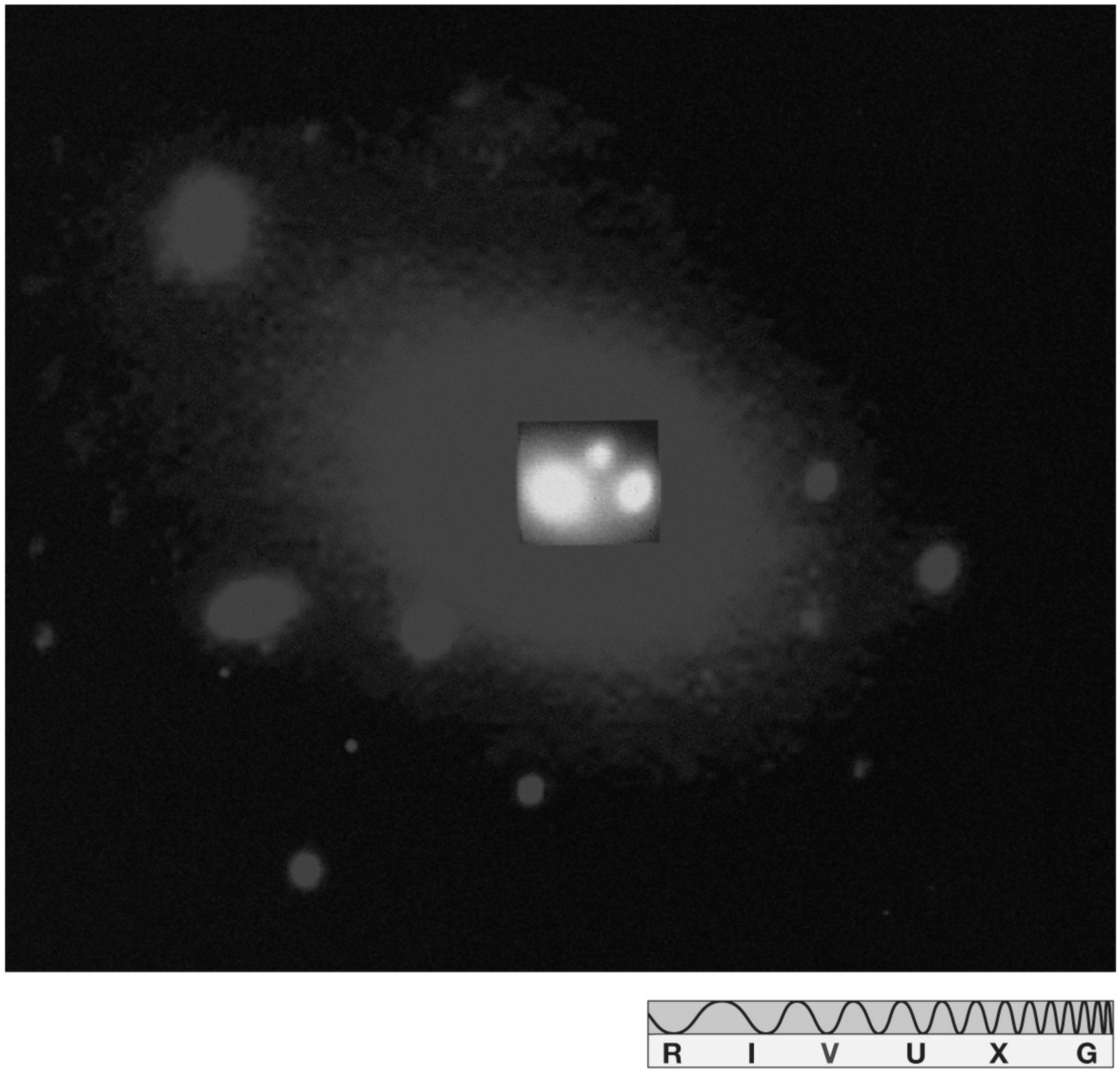
16.3 Galaxy Formation and Evolution

Each of these starburst galaxies exhibits massive star formation in the wake of a galactic collision. In images (a) and (b), the two colliding galaxies can be clearly seen.



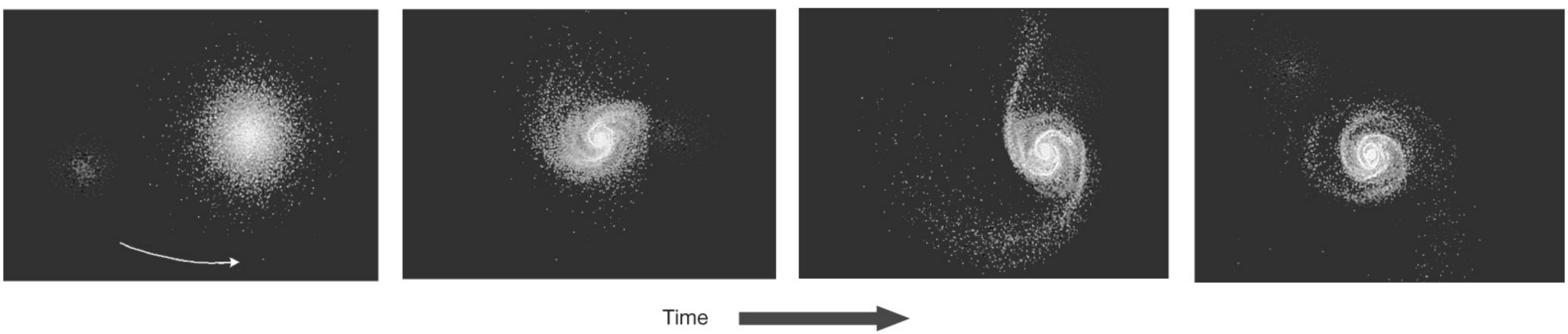
16.3 Galaxy Formation and Evolution

This appears to be an instance of galactic cannibalism – the large galaxy has three cores.



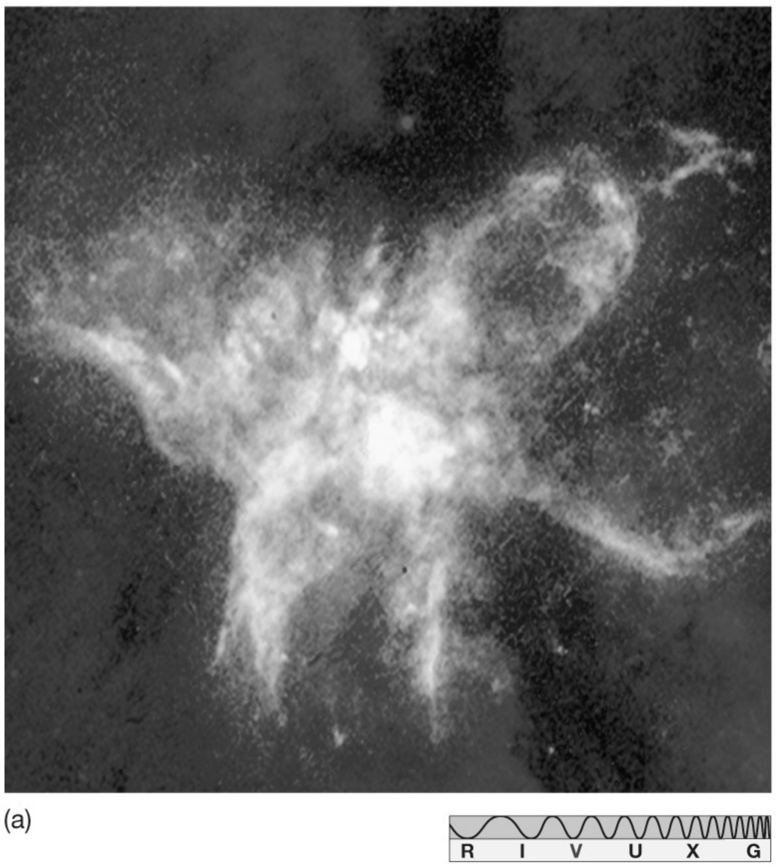
16.3 Galaxy Formation and Evolution

This simulation shows how interaction with a smaller galaxy could turn a larger one into a spiral.

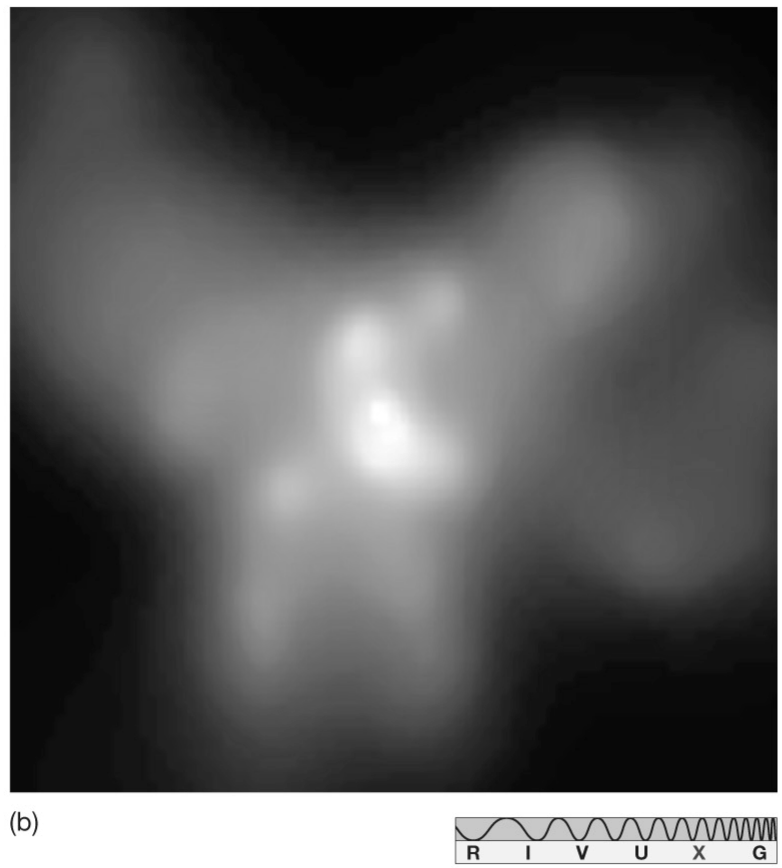


16.4 Black Holes and Active Galaxies

These visible and X-ray images show two supermassive black holes orbiting each other at a distance of about 1 kpc. They are expected to merge in about 400 million years.



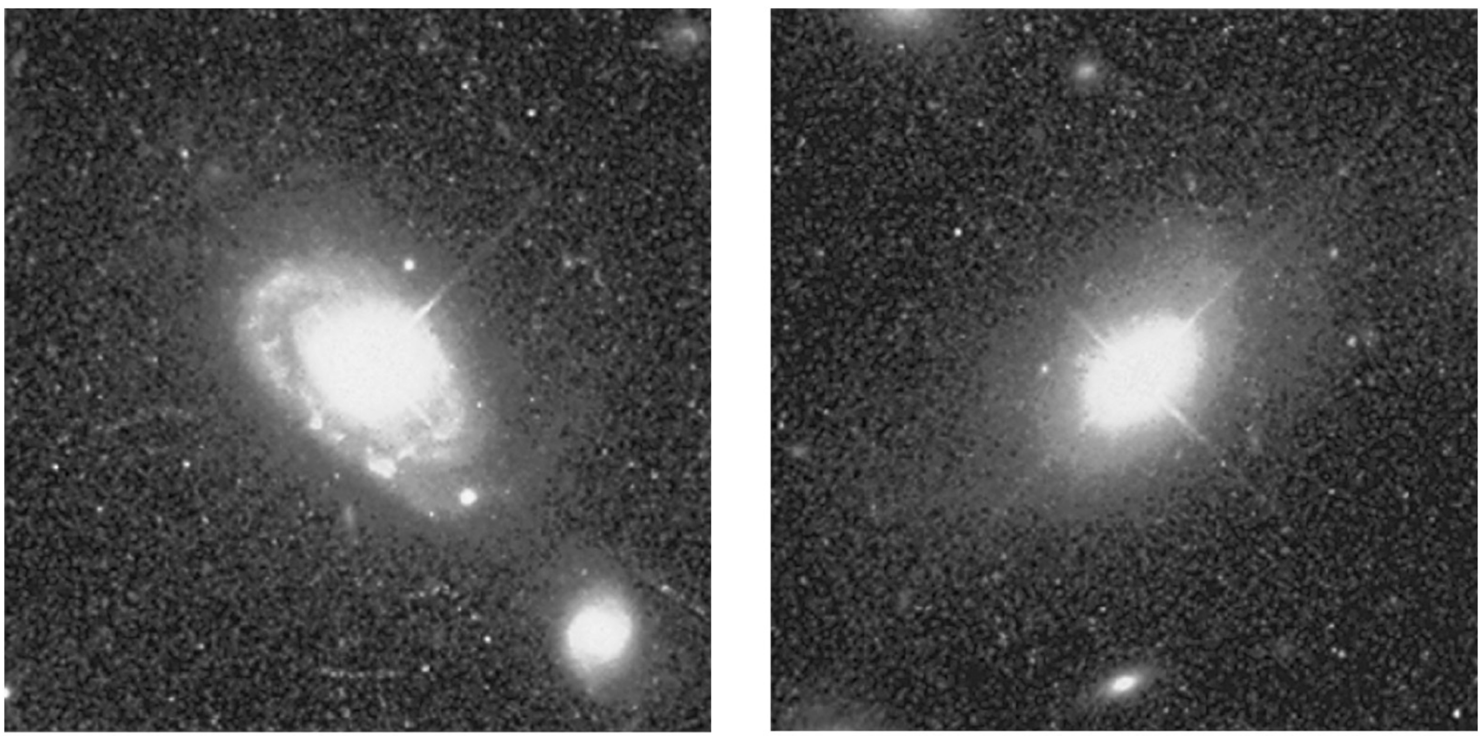
(a)

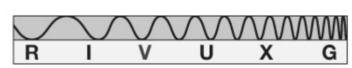


(b)

16.4 Black Holes and Active Galaxies

The quasars we see are very distant, meaning they existed a long time ago. Therefore, they may represent an early stage in galaxy development. The quasars in this image are shown with their host galaxies.



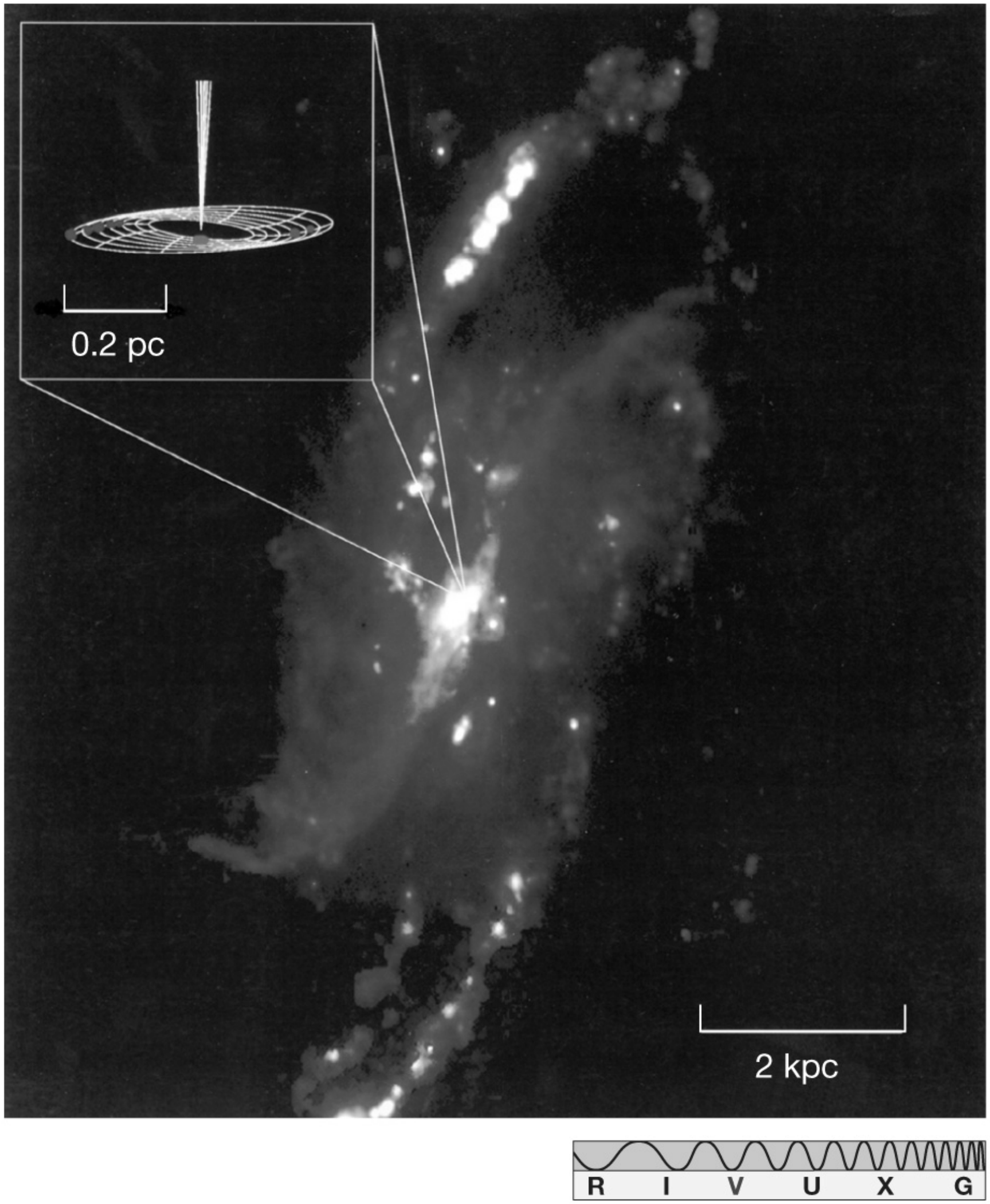


16.4 Black Holes and Active Galaxies

The end of the quasar epoch seems to have been about 10 billion years ago; all the quasars we have seen are older than that.

The black holes powering the quasars do not go away; it is believed that many, if not most, galaxies have a supermassive black hole at their centers.

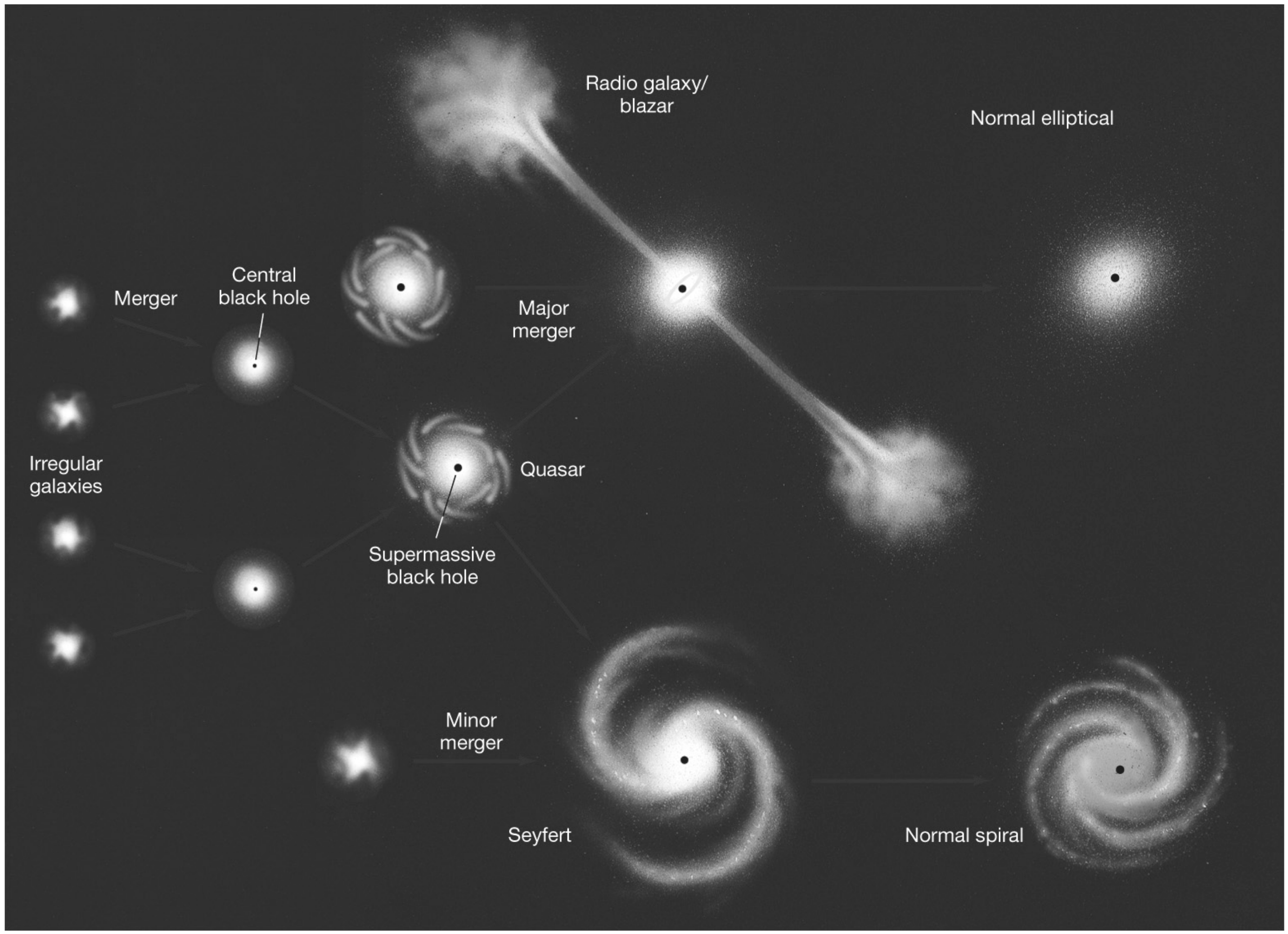
16.4 Black Holes and Active Galaxies



This galaxy is viewed in the radio spectrum, mostly from 21-cm radiation. Doppler shifts of emissions from the core show enormous speeds very close to a massive object – a black hole.

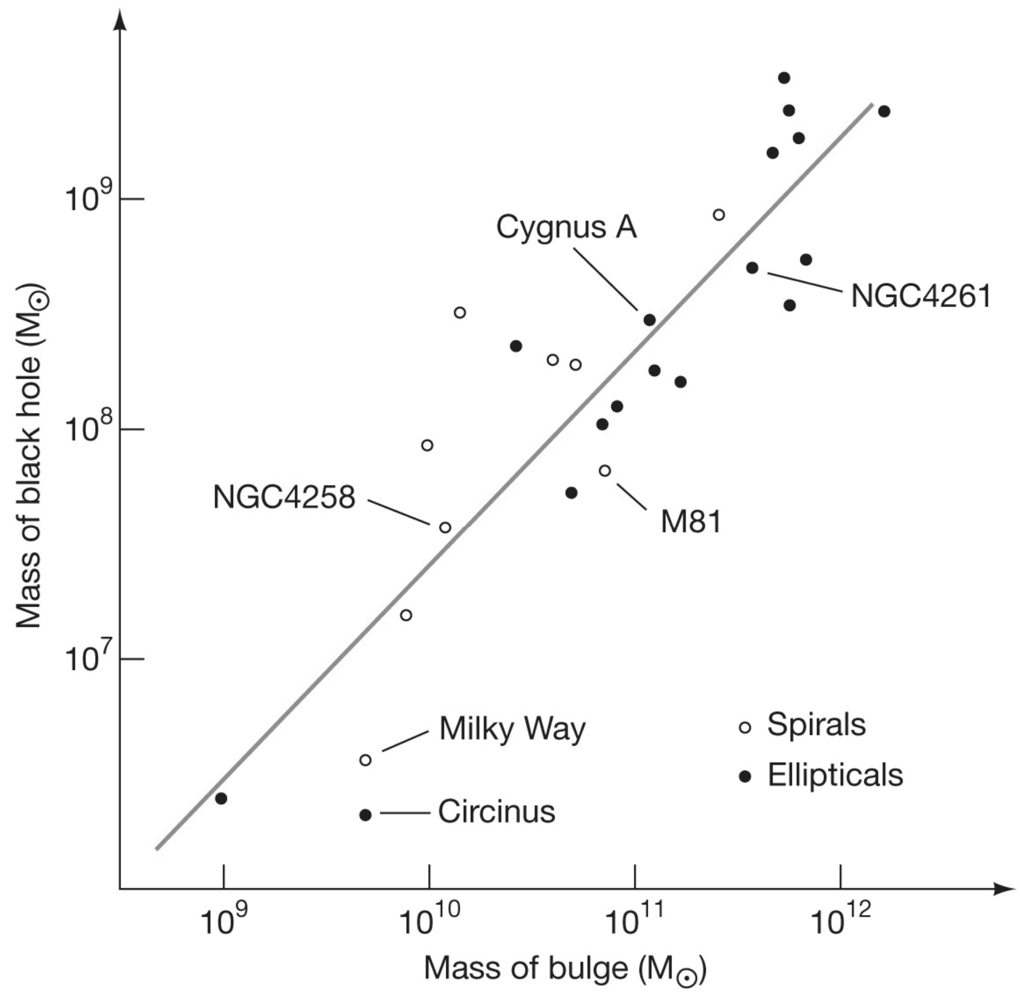
16.4 Black Holes and Active Galaxies

This figure shows how galaxies may have evolved, from early irregulars through active galaxies, to the normal ellipticals and spirals we see today.

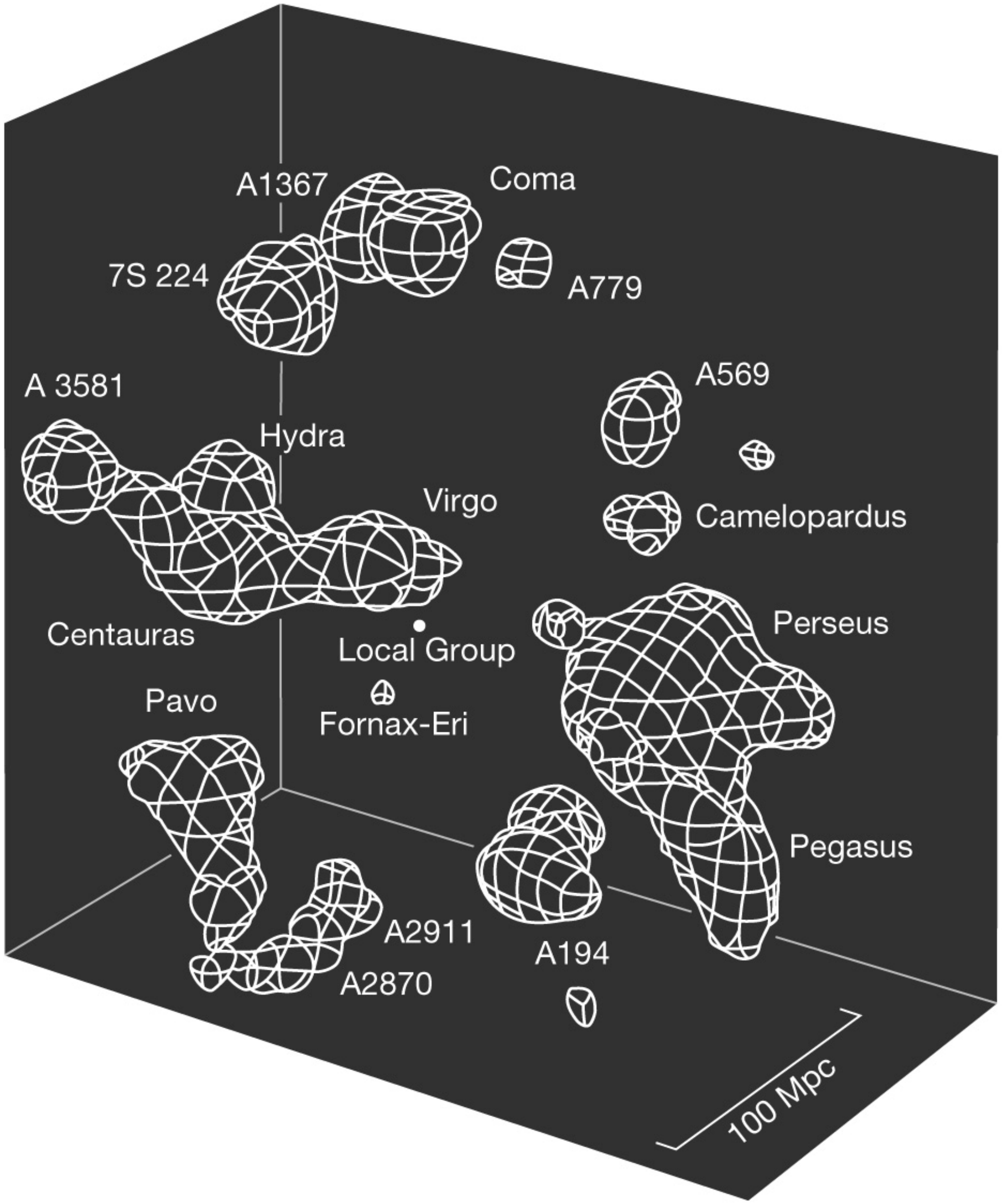


16.4 Black Holes and Active Galaxies

Careful measurements show that the mass of the central black hole is correlated with the size of the galactic core.



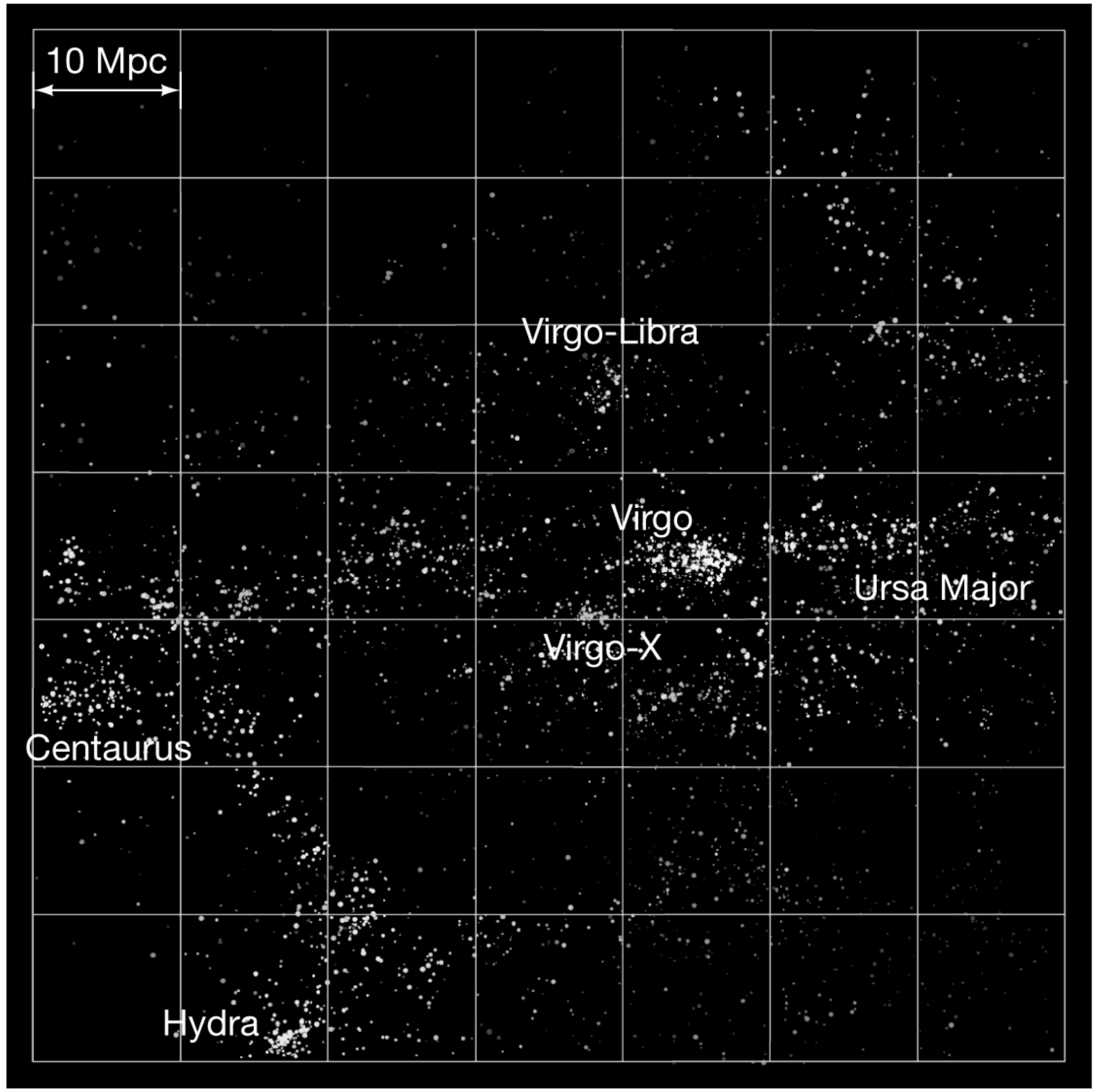
16.5 The Universe on Very Large Scales



Galaxy clusters join in larger groupings, called superclusters. This is a 3-D map of the superclusters nearest us; we are part of the Virgo supercluster.

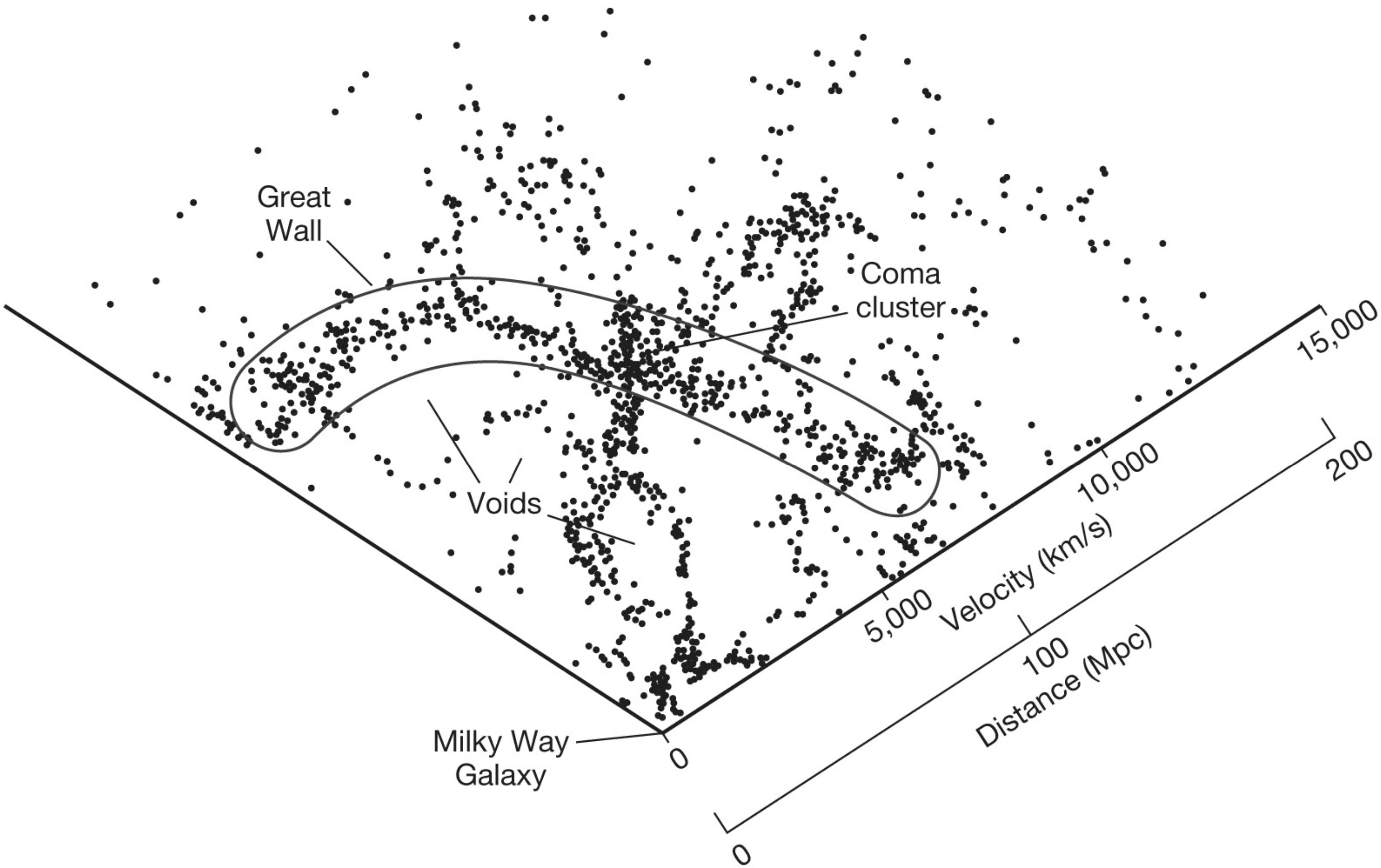
16.5 The Universe on Very Large Scales

This plot shows the locations of individual galaxies within the Virgo Supercluster.

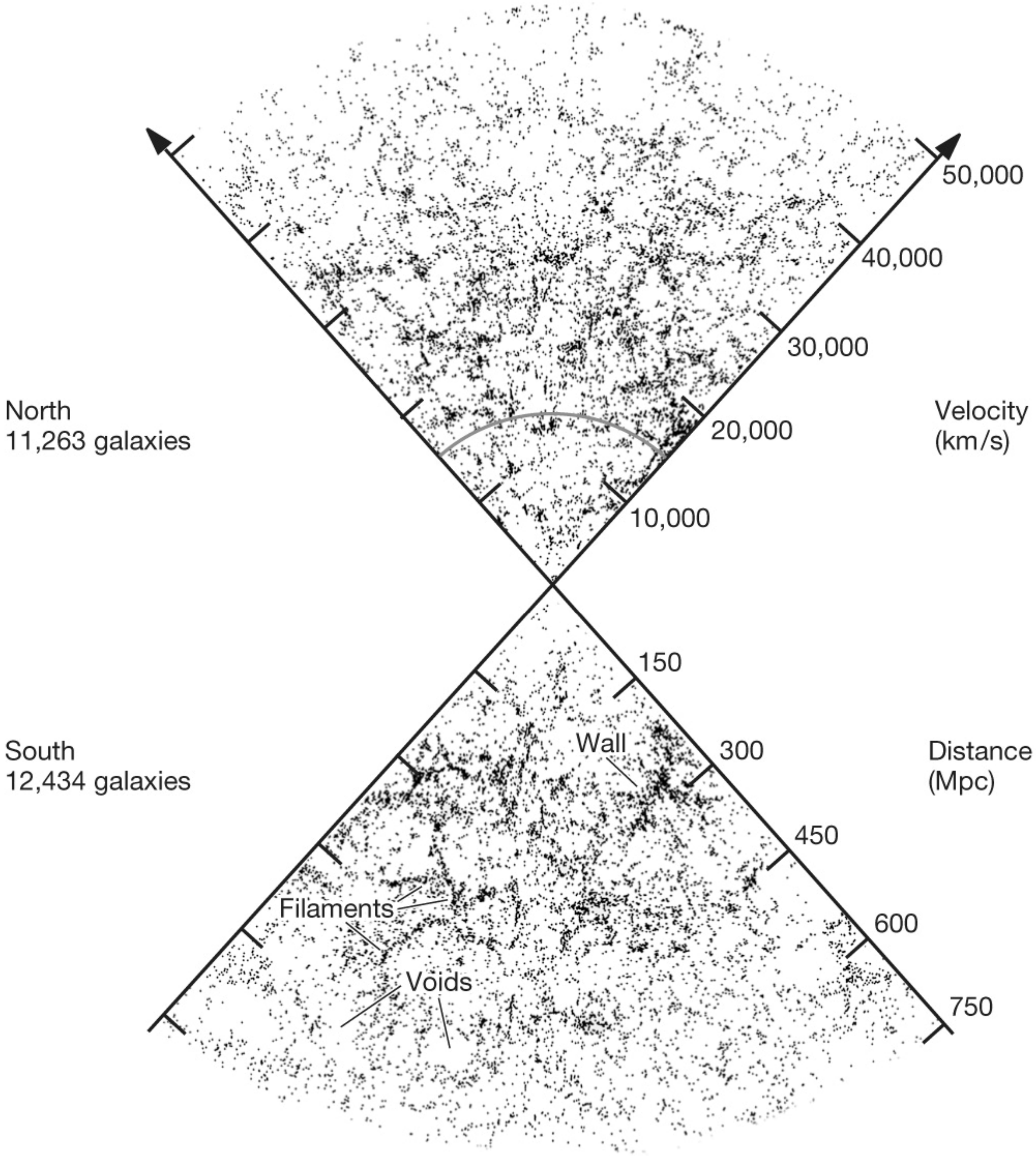


16.5 The Universe on Very Large Scales

This slice of a larger galactic survey shows that, on the scale of 100-200 Mpc, there is structure in the Universe – walls and voids.



16.5 The Universe on Very Large Scales



This survey, extending out even farther, shows structure on the scale of 100-200 Mpc, but no sign of structure on a larger scale than that.

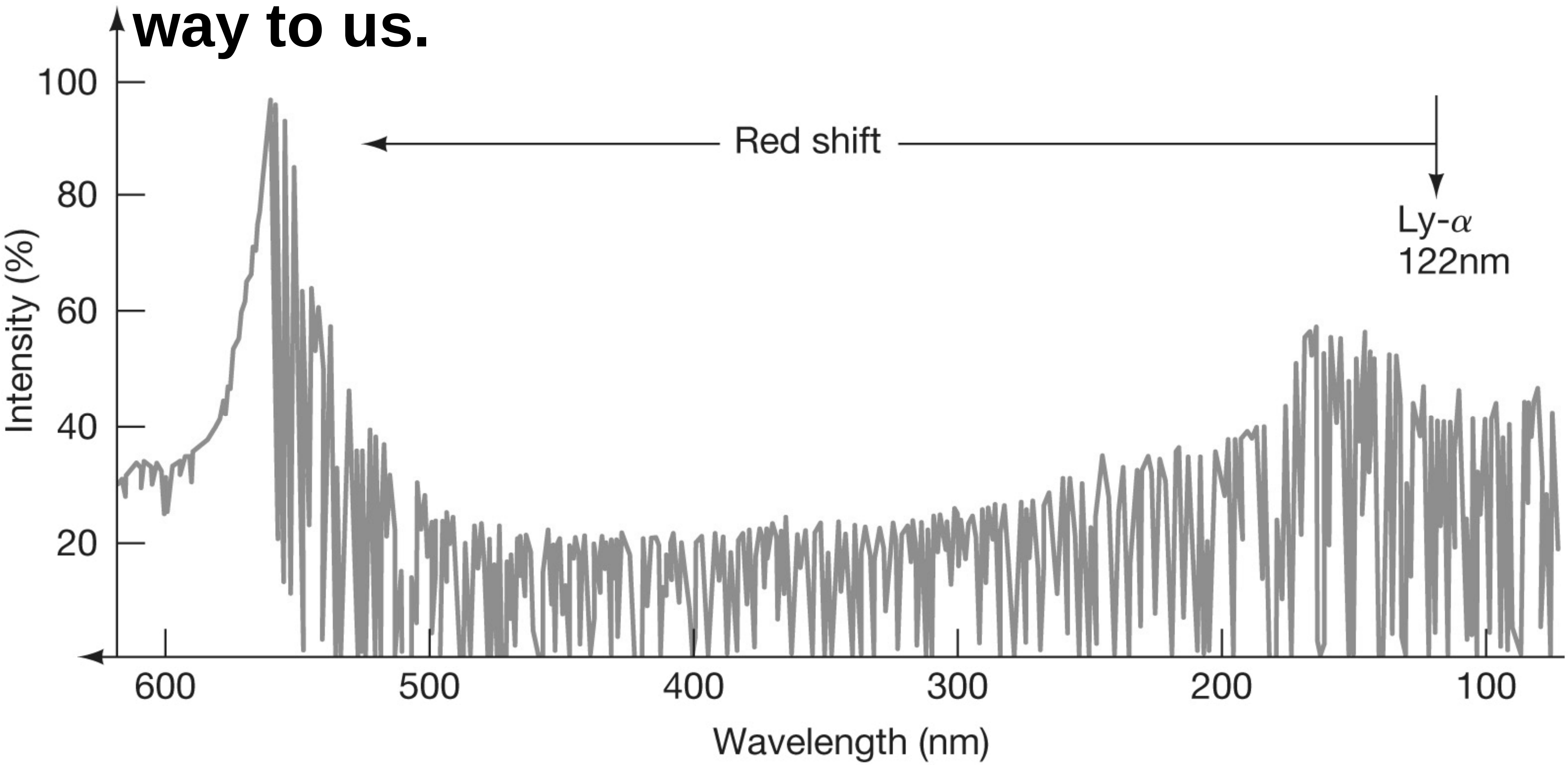
The decreasing density of galaxies at the farthest distances is due to the difficulty of observing them.

16.5 The Universe on Very Large Scales

Quasars are all very distant, and the light coming to us from them has probably gone through many interesting regions. We can learn about the intervening space by careful study of quasar spectra.

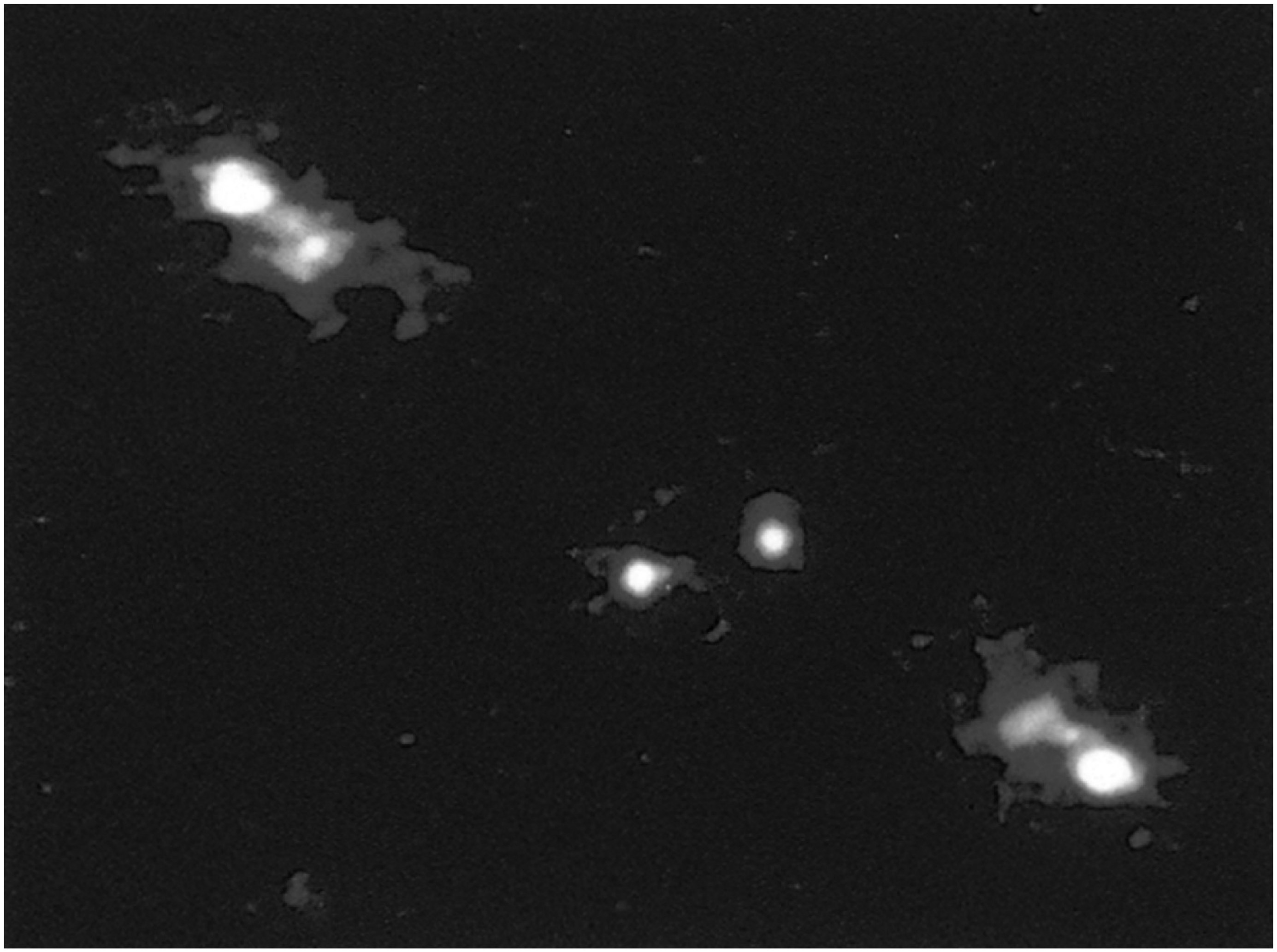
16.5 The Universe on Very Large Scales

This "Lyman-alpha forest" is the result of quasar light passing through hundreds of gas clouds, each with a different redshift, on its way to us.

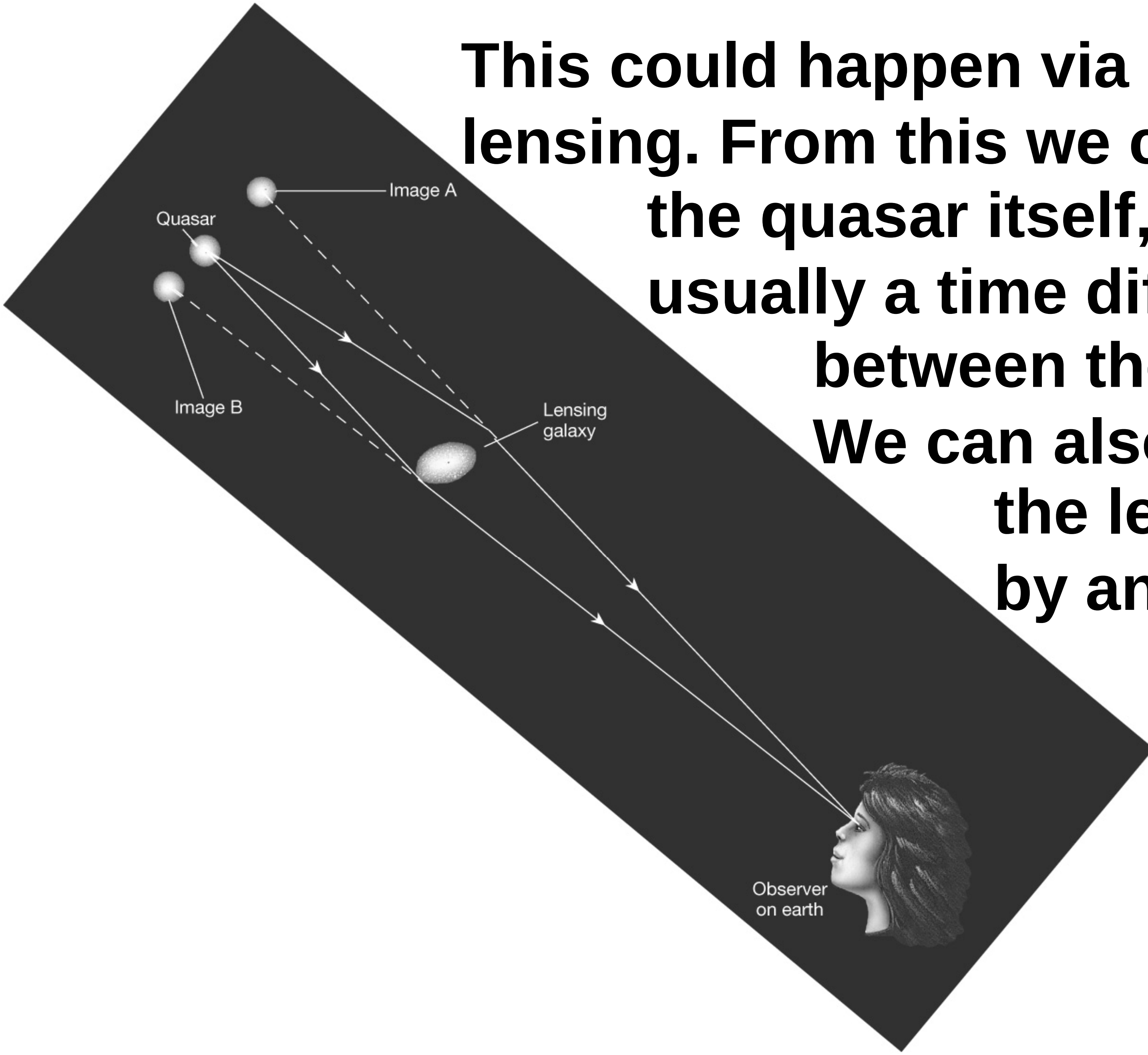


16.5 The Universe on Very Large Scales

This appeared at first to be a double quasar, but on closer inspection the two quasars turned out to be not just similar, but identical – down to their luminosity variations. This is not two quasars at all – it is two images of the same quasar.



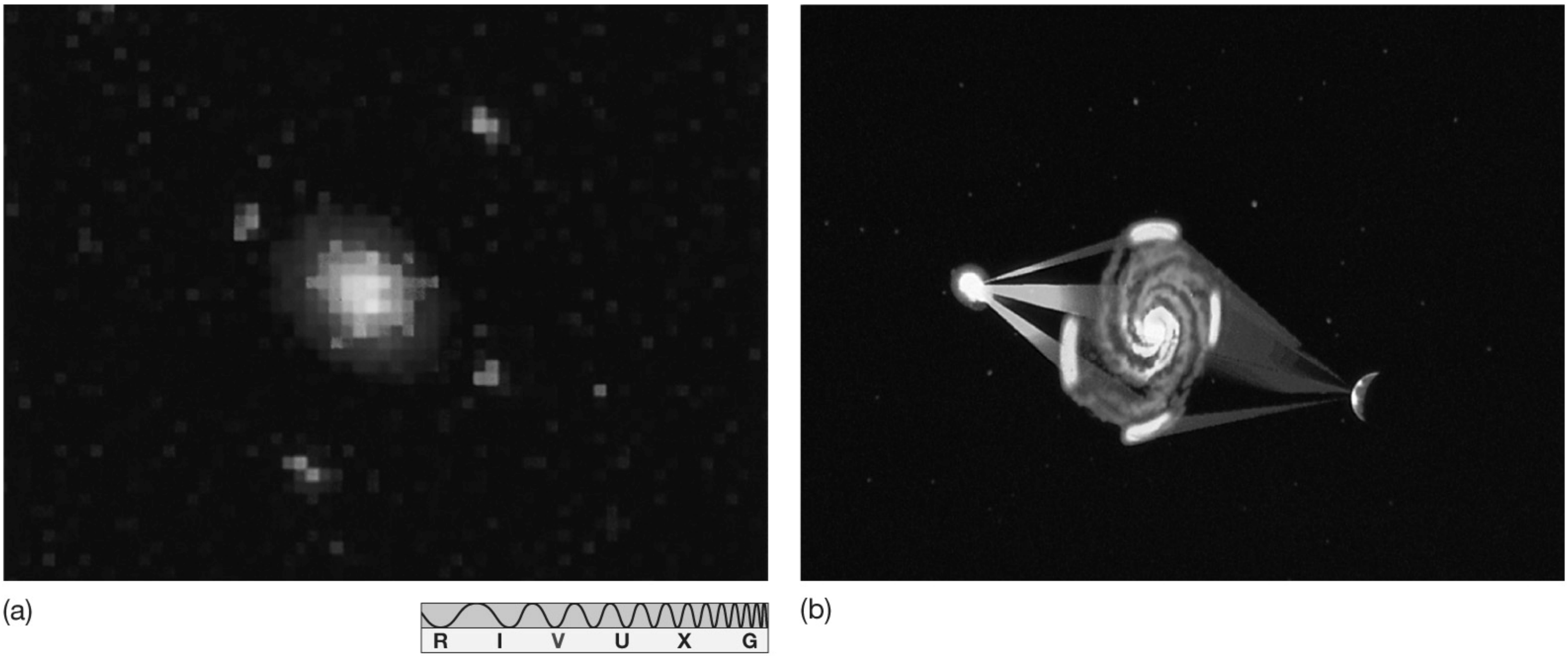
16.5 The Universe on Very Large Scales



This could happen via gravitational lensing. From this we can learn about the quasar itself, as there is usually a time difference between the two paths. We can also learn about the lensing galaxy by analyzing the bending of the light.

16.5 The Universe on Very Large Scales

Here, the intervening galaxy has made four images of the distant quasar.

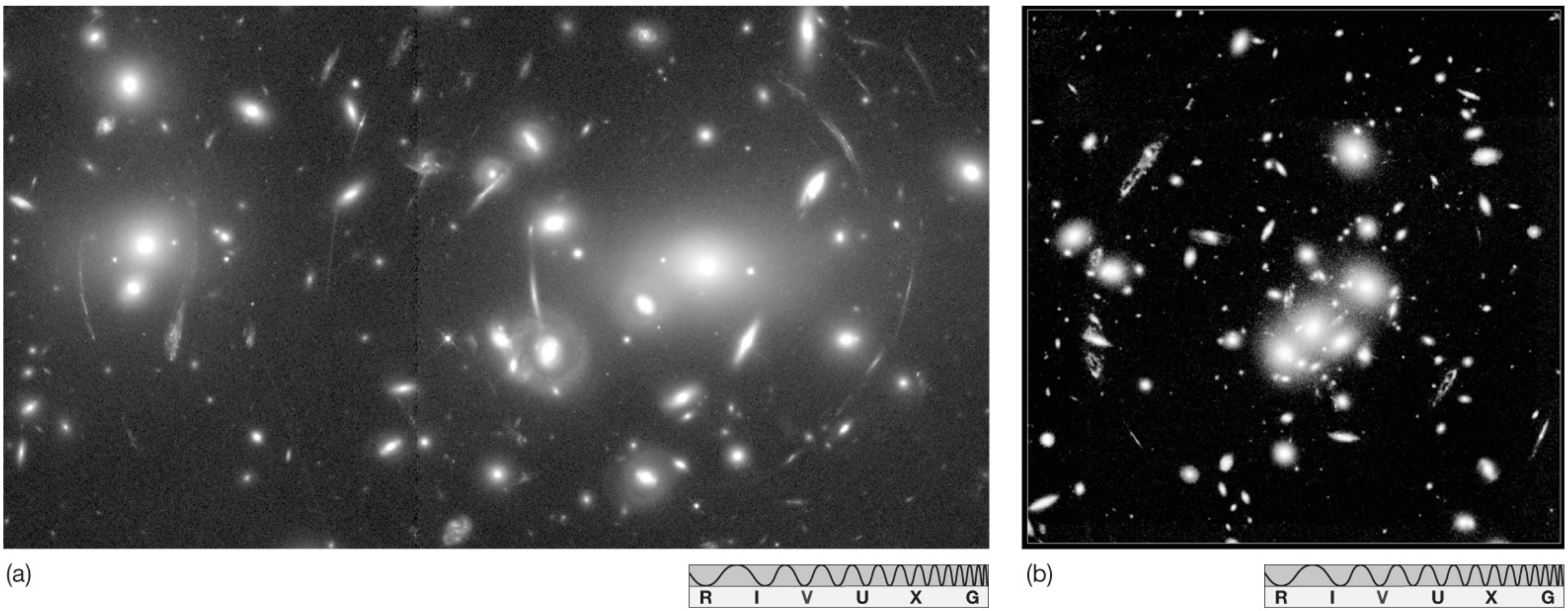


16.5 The Universe on Very Large Scales

These are two spectacular images of gravitational lensing.

On the left are distant galaxies being imaged by a whole cluster.

On the right is a cluster with images of what is probably a single galaxy.

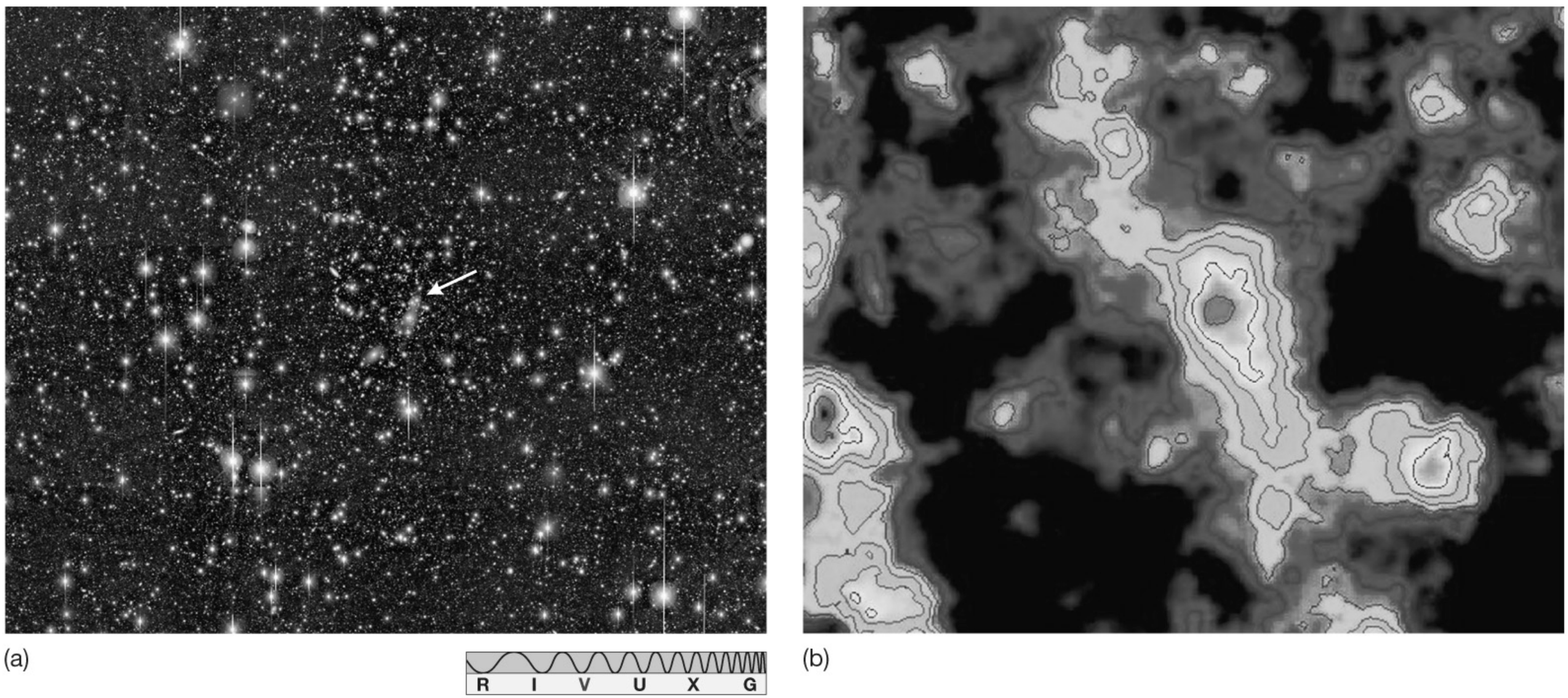


(a) (b)

16.5 The Universe on Very Large Scales

On the left is a visible image of a cluster of galaxies.

On the right, to the same scale, is the dark matter distribution inferred from galaxy motion.



(a) (b)

Summary of Chapter 16

- Galaxy masses can be determined by rotation curves and galaxy clusters
- All measures show that a large amount of dark matter must exist
- Large galaxies probably formed from the merger of smaller ones
- Collisions are also important
- Merger of spiral galaxies probably results in an elliptical

Summary of Chapter 16

- **Quasars, active galaxies, and normal galaxies may represent an evolutionary sequence**
- **Galaxy clusters are gravitationally bound into superclusters**
- **The Universe has structure up to 100-200 Mpc; beyond that, there is no sign of it**
- **Quasars can be used as probes of intervening space, especially if there is galactic lensing**