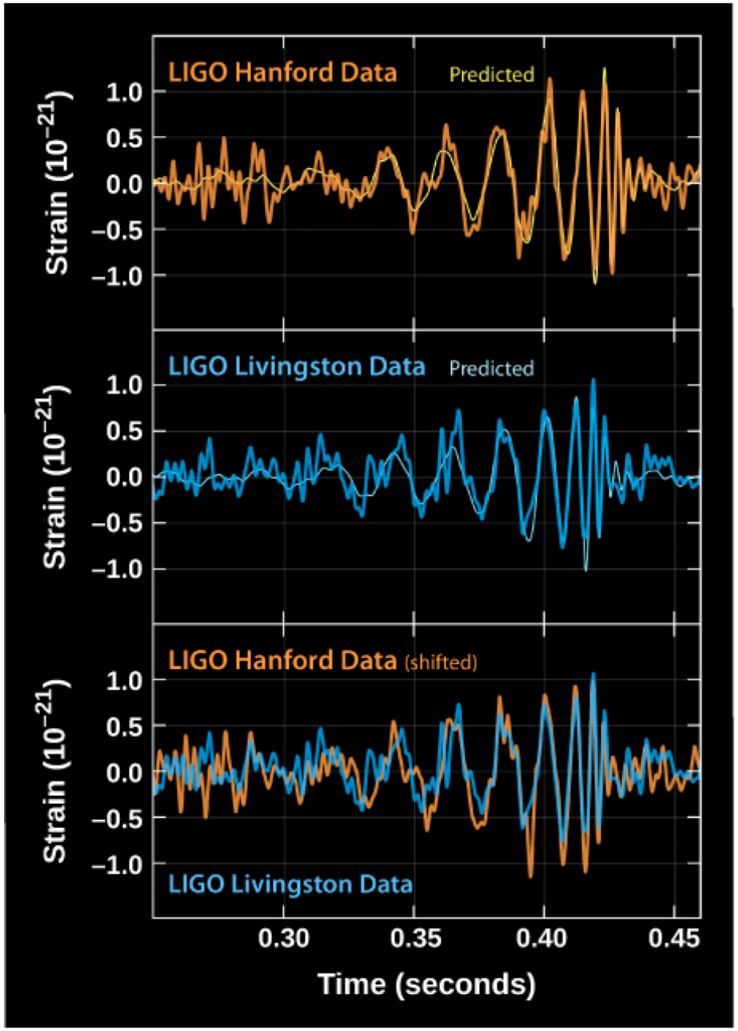
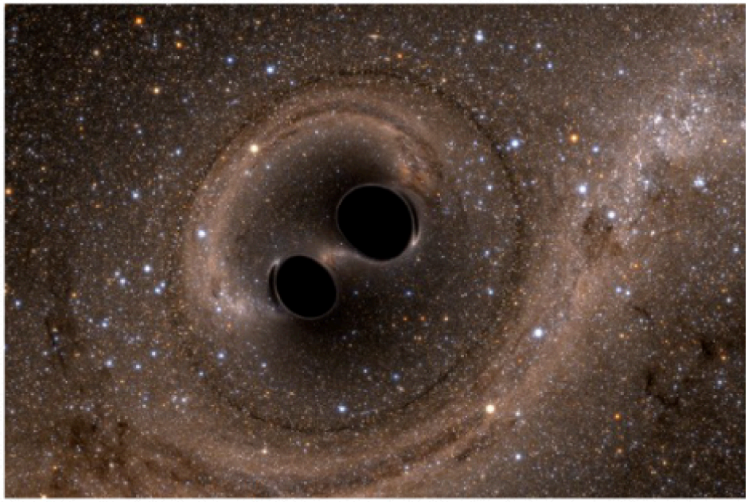
# Gravitational waves: LIGO detected merger of two stellar-mass black holes!



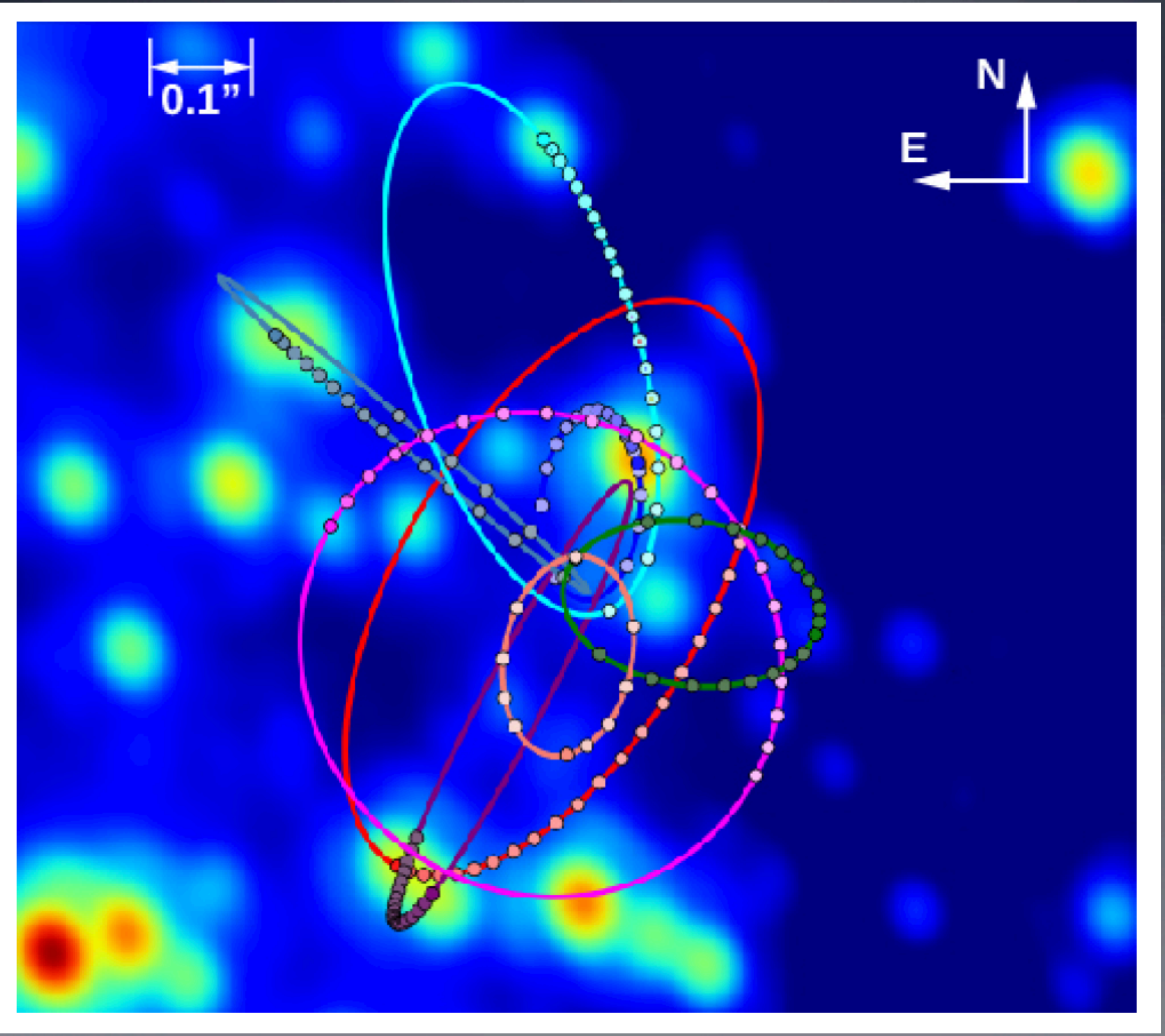
# Black holes: event horizon defines radius where light can no longer escape

(a)

(b)

**Figure 24.14 Light Paths near a Massive Object.** Suppose a person could stand on the surface of a normal star with a flashlight. The light leaving the flashlight travels in a straight line no matter where the flashlight is pointed. Now consider what happens if the star collapses so that it is just a little larger than a black hole. All the light paths, except the one straight up, curve back to the surface. When the star shrinks inside the event horizon and becomes a black hole, even a beam directed straight up returns.

# Galactic center orbits



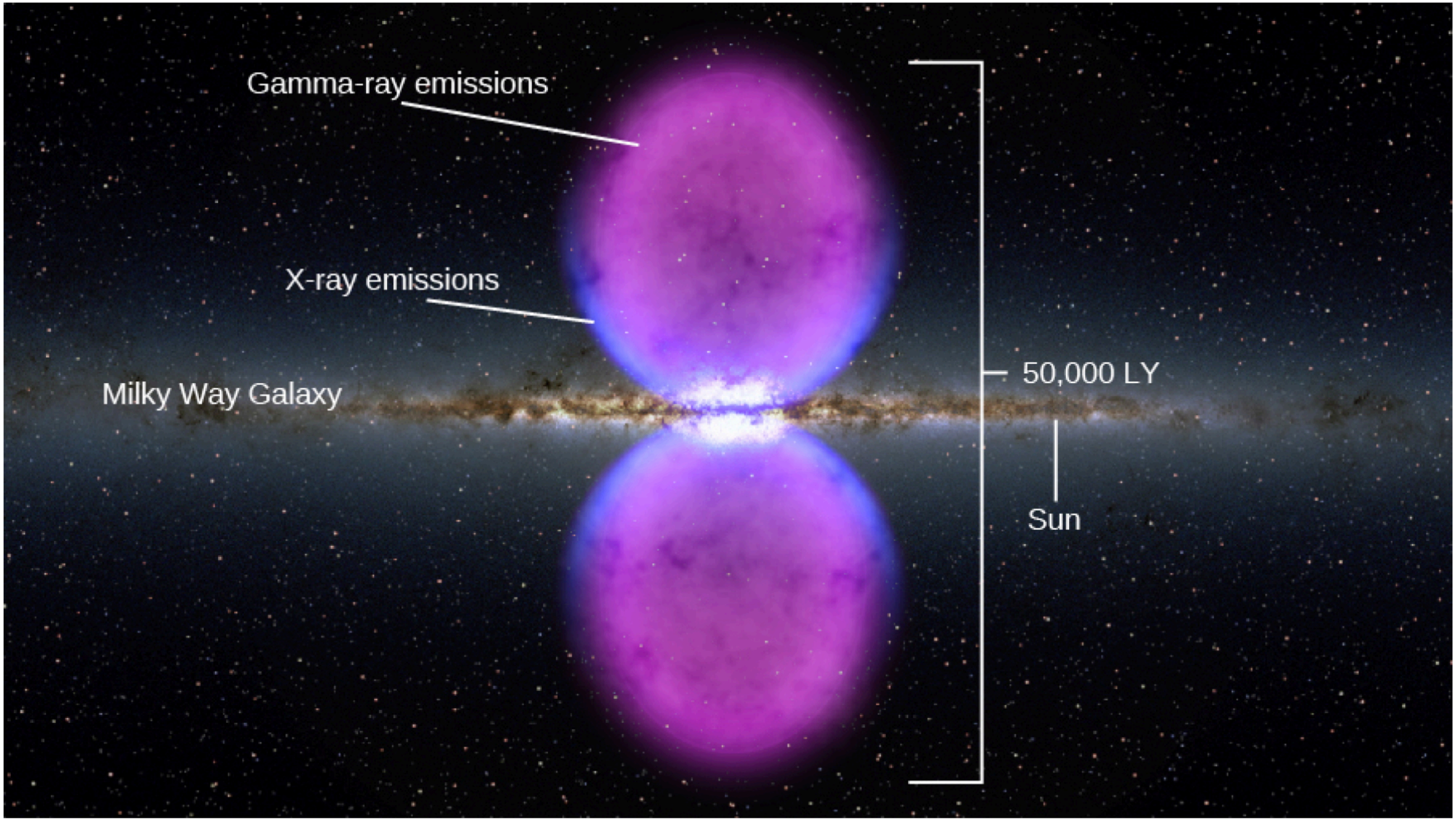
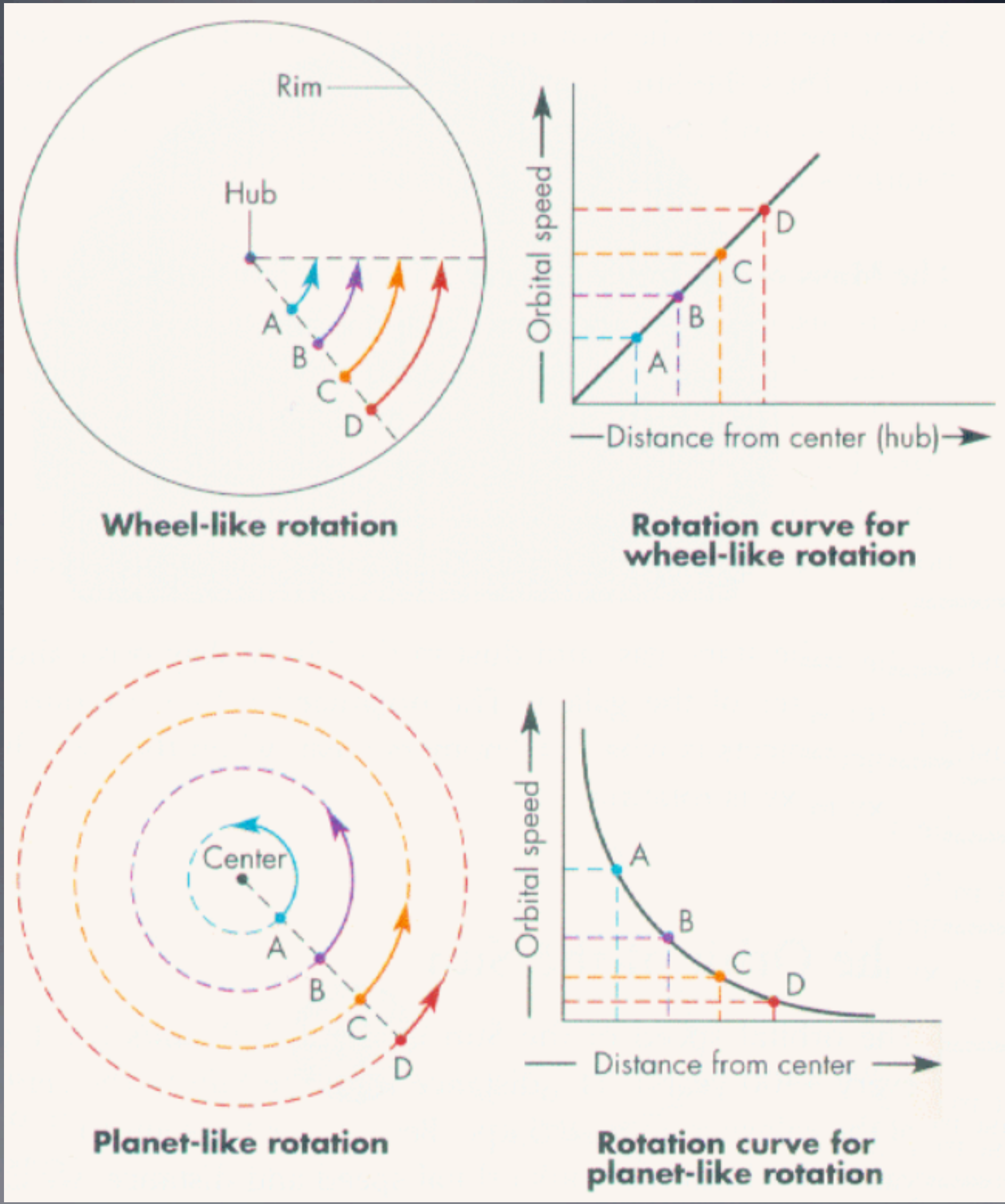
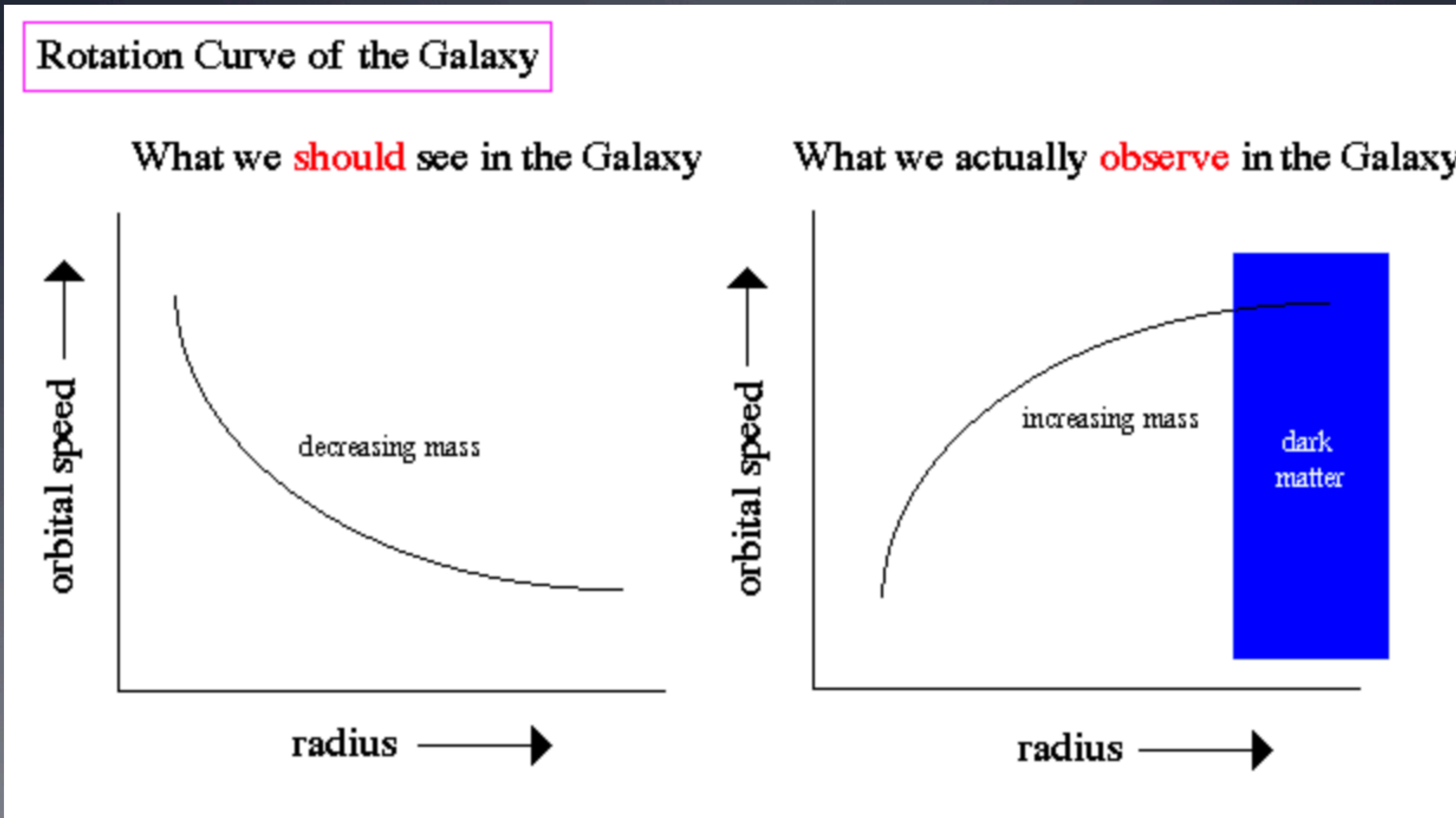



**Figure 27.11 Fermi Bubbles in the Galaxy.** Giant bubbles shining in gamma-ray light lie above and below the center of the Milky Way Galaxy, as seen by the Fermi satellite. (The gamma-ray and X-ray image is superimposed on a visible-light image of the inner parts of our Galaxy.) The bubbles may be evidence that the supermassive black hole at the center of our Galaxy was a quasar a few million years ago. (credit: modification of work by NASA's Goddard Space Flight Center)

- How to measure the mass of the galaxy?

  Kepler’s laws!




Rotation Curve of the Galaxy
What we should see in the Galaxy
orbital speed
decreasing mass
radius
What we actually observe in the Galaxy
orbital speed
increasing mass
dark
matter
radius

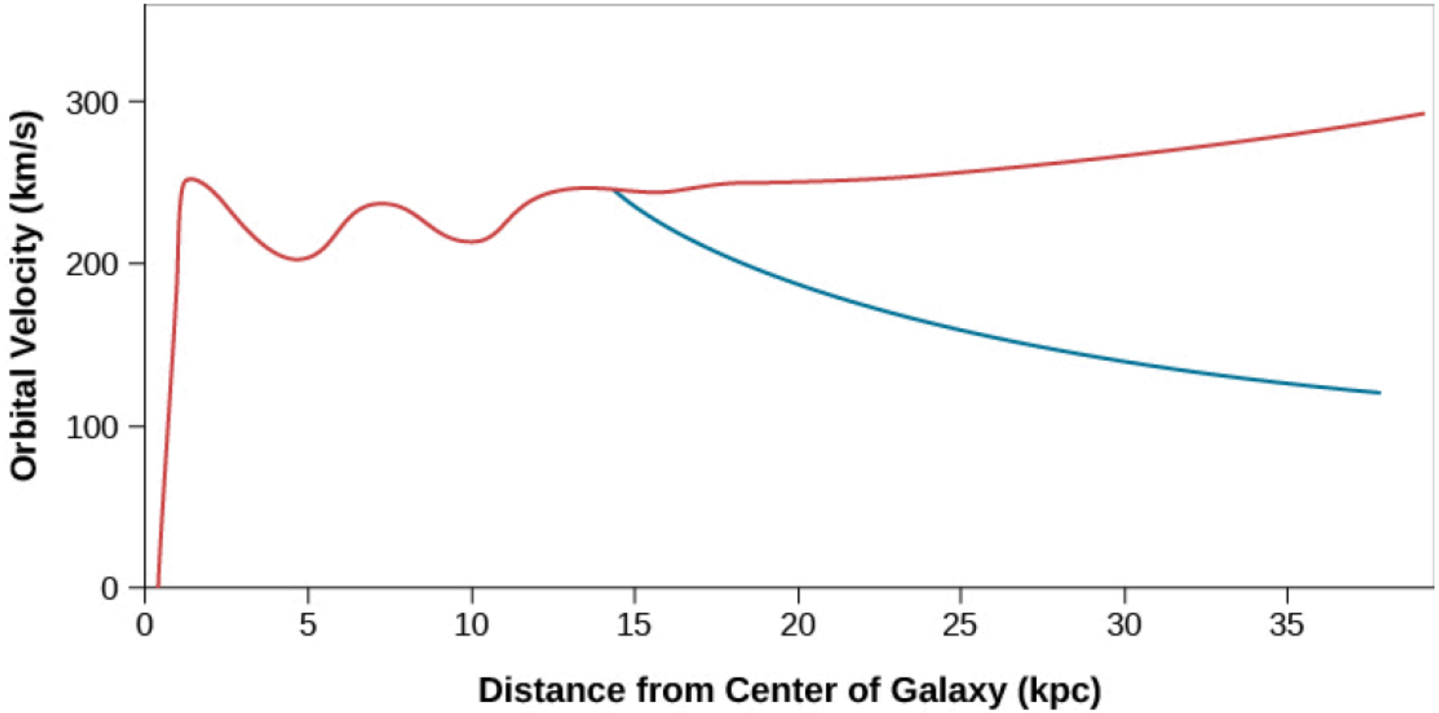
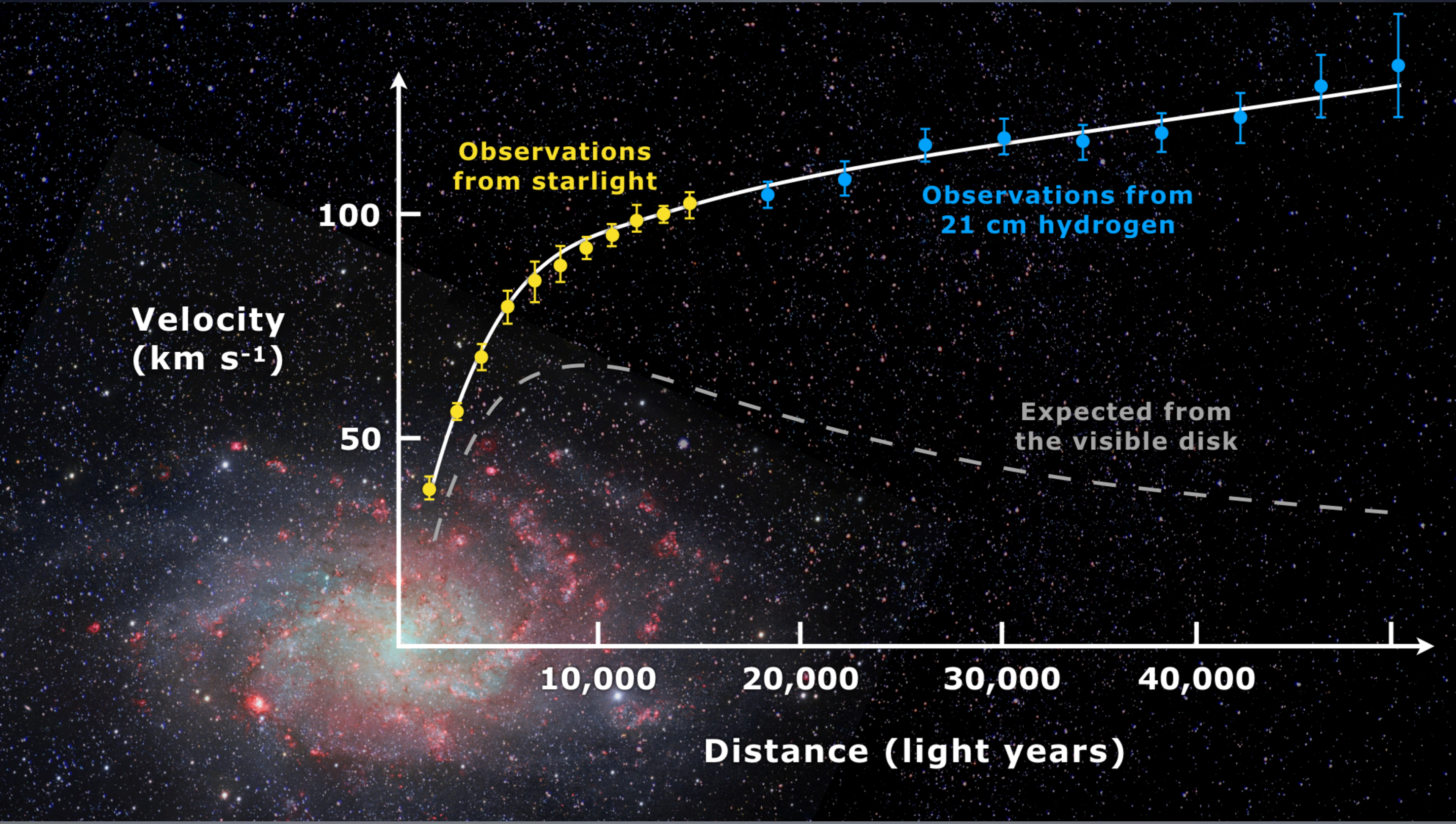



**Figure 25.13 Rotation Curve of the Galaxy.** The orbital speed of carbon monoxide (CO) and hydrogen (H) gas at different distances from the center of the Milky Way Galaxy is shown in red. The blue curve shows what the rotation curve would look like if all the matter in the Galaxy were located inside a radius of 50,000 light-years. Instead of going down, the speed of gas clouds farther out remains high, indicating a great deal of mass beyond the Sun’s orbit. The horizontal axis shows the distance from the galactic center in kiloparsecs (where a kiloparsec equals 3,260 light-years).



Observations
from starlight
Observations from
21 cm hydrogen
100
50
Velocity
(km s$^{-1}$)
Expected from
the visible disk
10,000
20,000
30,000
40,000
Distance (light years)

# Dark Matter!

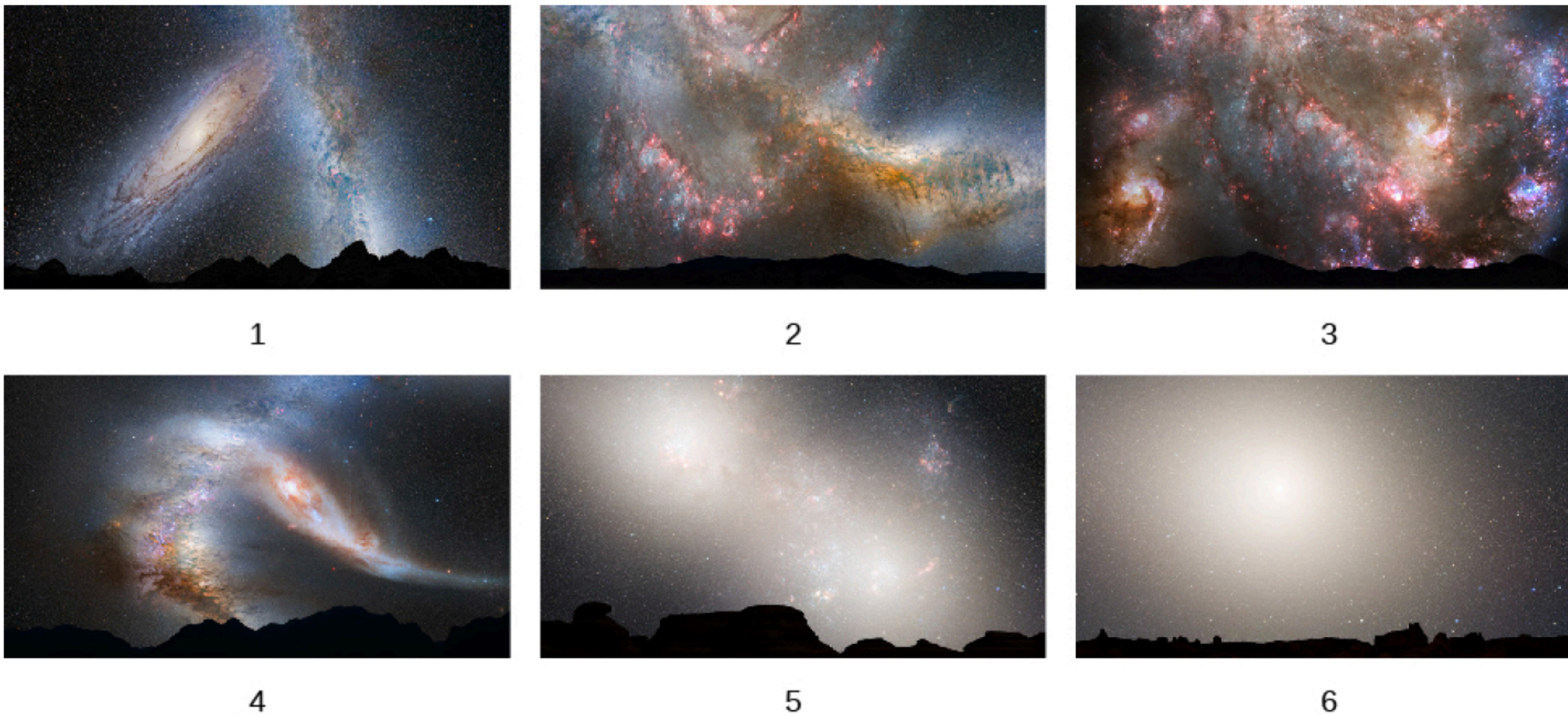
- We can measure accurately the mass of the galaxy through Kepler's Laws/gravity
- We can measure the mass of stars+gas
- Mass of stars = 0.2 x mass of galaxy

Rule out: black holes, brown dwarfs/ planets,interstellar gas

Dark matter: exotic, non-interacting particle

Dark=not interacting; 80% of mass!

# The future: it’s coming right at us!



# The future: it’s coming right at us!

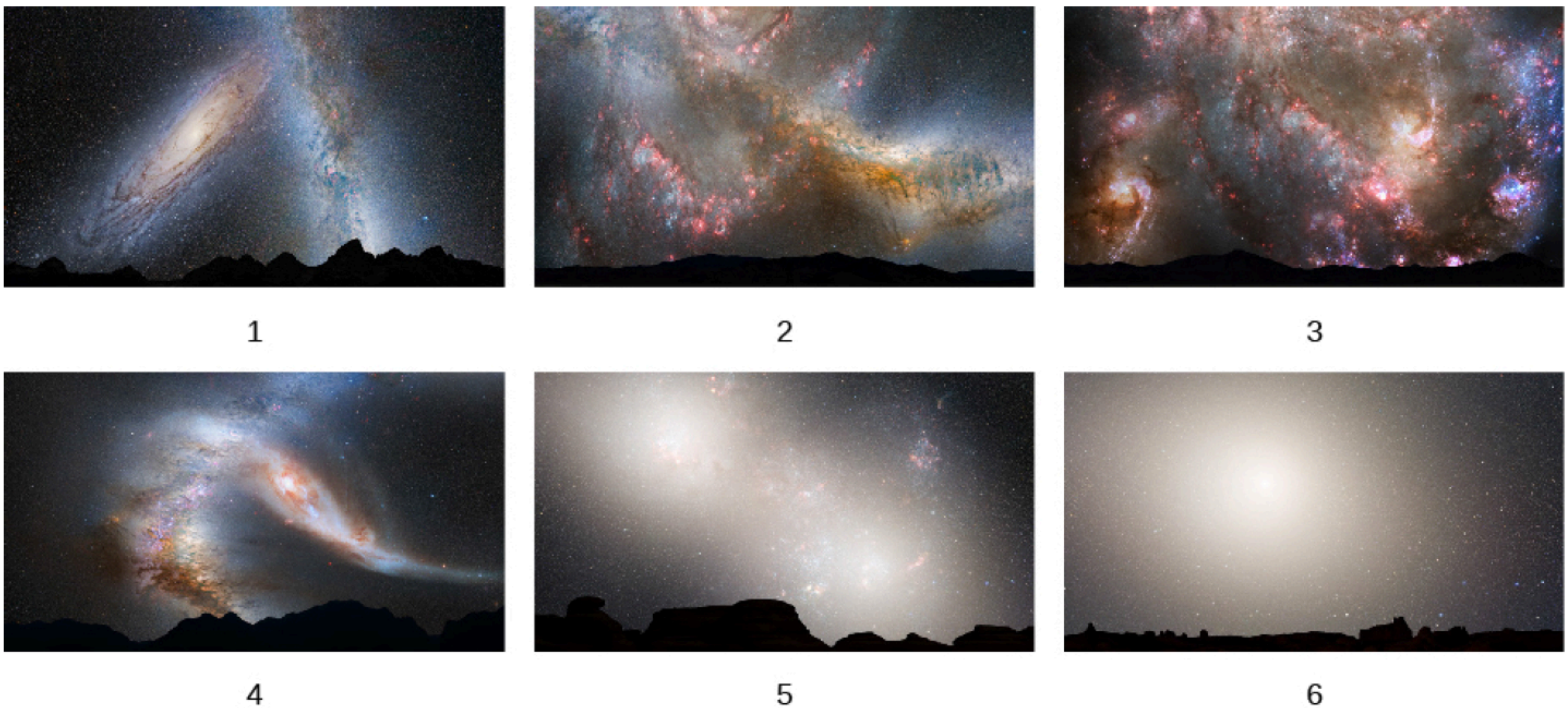
4

5

6

# The future: it’s coming right at us!

## Collision with Andromeda galaxy: 3 billion years



# Next lectures: galaxies, supermassive black holes, and Big Bang/cosmology