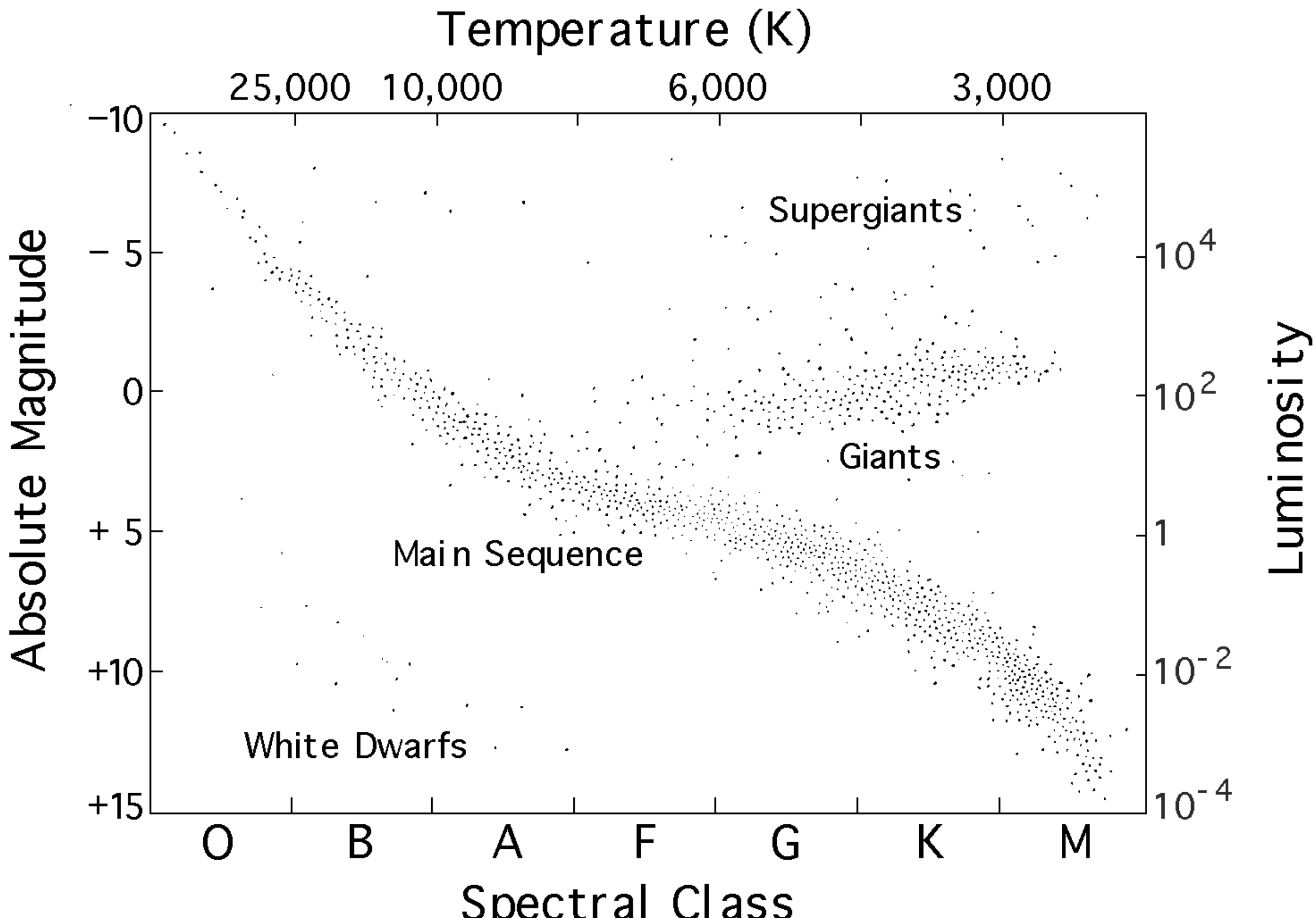
Announcements

- **Final exam is Wednesday, December 14, in LR 1 VAN at 9:45 am.**
- Office hours: Tuesday 9-11 am, 1–2 pm, and 3-4 pm or by appointment in 702 VAN
- There will be no Astronomy tutorial during finals week.
- There will be no homework #12.

Stars

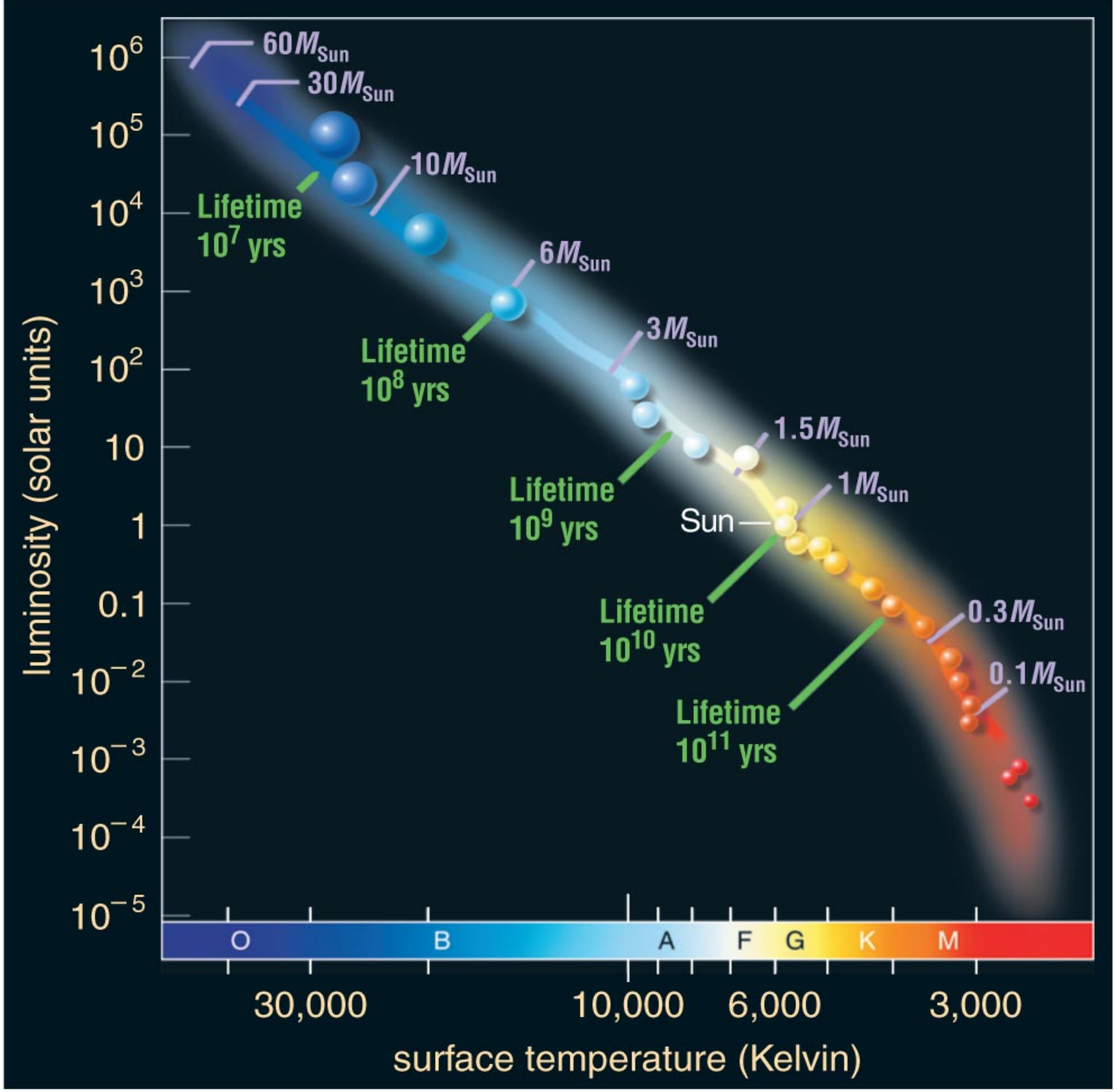
- The brightness of a star is described by its “apparent magnitude”, higher magnitude means dimmer.
- The luminosity of a star is described by its “absolute magnitude”.
- Spectral classification sorts stars according to their surface temperature/color. Sequence is: O B A F G K M. Type O is blue/hot (~25,000K), G is Sun-like (~6,000K), M is red/cool (~2500K).
- Spectral lines can be used to determine the chemical composition of a star.
- Stars are classified on the Hertzsprung-Russell diagram.
- “Vogt-Russell” theorem states there is only one way to make a star given a mass and chemical composition.
- A star's mass determines it other properties: surface temperature, luminosity, life time.

HR diagram


Temperature (K)
25,000
10,000
6,000
3,000
−10
− 5
0
+ 5
+10
+15
Absolute Magnitude
10^4
10^2
1
10^-2
10^-4
Luminosity
Supergiants
Giants
Main Sequence
White Dwarfs
O
B
A
F
G
K
M
Spectral Class

Main sequence

Main sequence is when a star is burning hydrogen in its core.
The luminosity and temperature of a main-sequence star are set by its mass.
More massive means brighter and hotter.



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Mass-Lifetime relation

- The lifetime of a star (on the main sequence) is longer if more fuel is available and shorter if that fuel is burned more rapidly
- The available fuel is (roughly) proportional to the mass of the star
- Luminosity is much higher for higher masses
- Therefore higher mass star live shorter lives

For main-sequence stars, the most massive stars:

A) have the shortest lives
B) are the hottest
C) are the most luminous
D) all of the above

Interstellar medium

- The space between the stars is full of gas and dust, features in the gas and dust are 'nebulae'.
- Emission-line nebulae are powered by UV light from nearby OB stars.
- Reflection nebulae reflect light from nearby stars.
- Dark nebula are so dense they absorb star light.

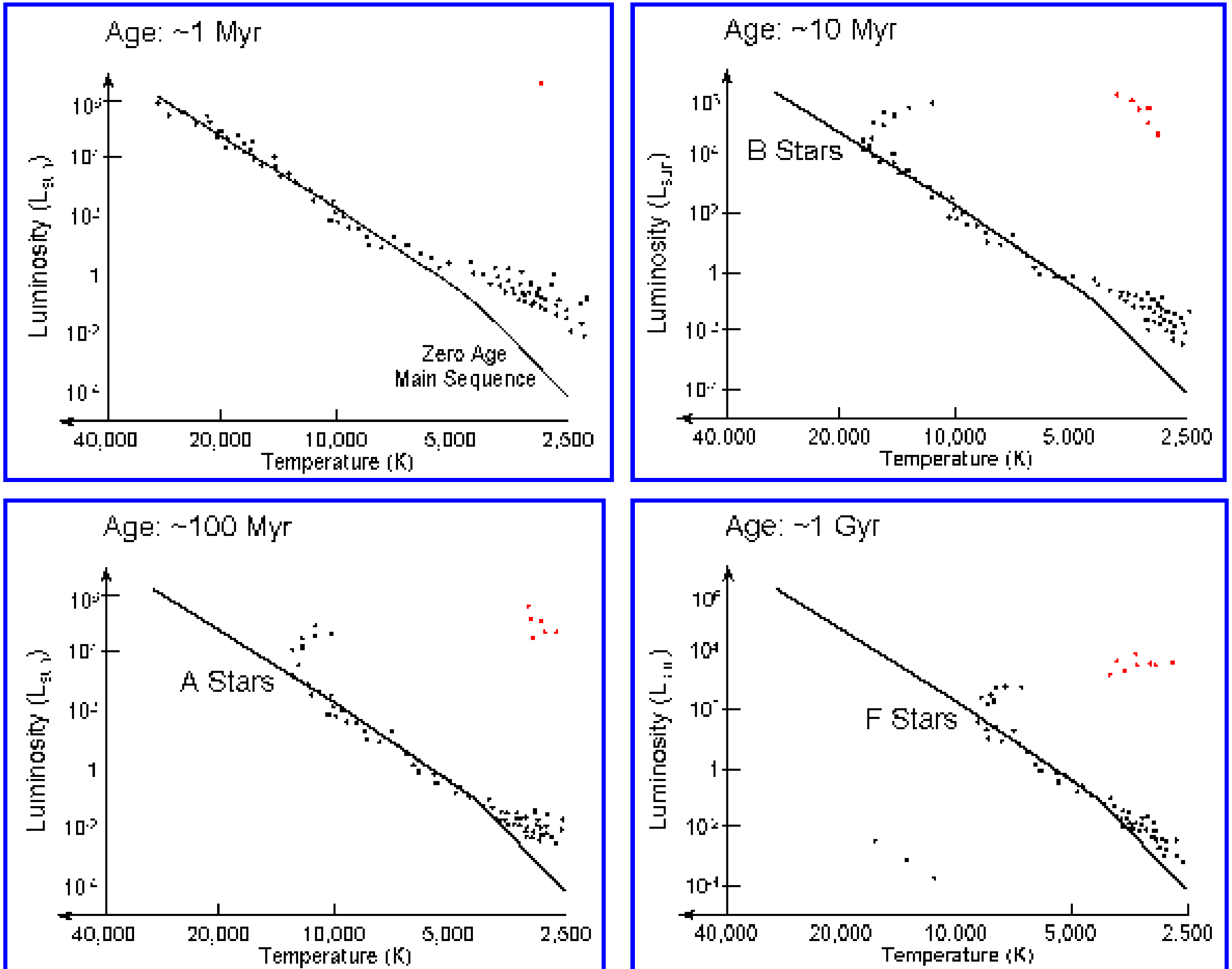
Star formation

- Stars form in the densest and coolest parts of the interstellar medium.
- Star formation begins when a dense region of a gas cloud starts pulling in more gas because the gravity of the dense region is stronger than that of the surroundings.
- This process feeds on itself as the dense region grows in mass.
- A protostar is powered by the gravitational energy released as the gas cloud contracts.
- The forming star can be tracked on the HR diagram. It starts cool and with low luminosity. The protostar remains cool until it becomes opaque and can trap the energy released.
- A protostar becomes a star when its core is dense and hot enough to start nuclear burning.
- Higher mass stars form faster.

Stellar evolution

- Stellar evolution is driven by the changing composition of the core and inner parts of a star as the ashes of nuclear burning accumulate.
- A star goes onto the giant branch when so much helium has built up in the core and so little hydrogen is left in the core that nuclear burning in the core stops. The core starts to collapse, hydrogen burning stars in a shell surrounding the core, and the outer surface of the star expands.
- The star then goes through some complicated motions on the HR diagram which represent nuclear burning (or not) of different elements in the core and surrounding shells.
- A solar-mass star ends up with an inert core of carbon and oxygen and ejects most of its outer layers into a “planetary nebula” surrounding a white dwarf.
- The white dwarf is the leftover core of carbon and oxygen. It starts off hot and then cools because it has no energy source.

Turn-off point of cluster reveals age



Death of high-mass stars

- Nuclear burning in high mass stars continues with higher mass nuclei up to iron. Burning stops at iron because iron is the most tightly bound nucleus and no further energy can be released.
- Eventually the iron core becomes massive enough that it collapses into a neutron star (which stops the collapse).
- The outer shells fall inwards, but then bounce off the neutron star surface and are flung out making a supernova explosion.
- Neutrinos were detected from a nearby supernova in 1987 supporting the idea that a neutron star formed.
- Most of the elements heavier than iron are formed in supernova explosions.
- Supernova can become the brightest objects in the night sky and can be see at very large distances.

Stellar remnants

- White dwarfs and neutron stars are made of "degenerate" matter in which pressure is caused by quantum mechanical motions and not by thermal motions like in normal matter.
- Objects made of degenerate matter have a weird relation between mass and size. More massive objects are smaller.
- There is a maximum possible mass, 1.4 solar masses, for a white dwarf set by when its size would shrink to zero. The similar limit for a neutron star is about 3 solar masses.
- When a star contracts to become a neutron star, its rotation speeds up and its magnetic field strength increases.
- Neutron stars have been detected as: radio pulsars which pulse in the radio as they spin, magnetars which make flashes of X and gamma-rays when star quakes rearrange their magnetic fields, X-ray pulsars which pulse in X-rays and matter falls onto their magnetic poles, and X-ray bursters in which matter falling onto the neutron star surface makes explosions due to nuclear burning.

Special Relativity

- The speed of light is a constant for all observers and is the maximum possible speed for any object (except maybe neutrinos). This is the basis of special relativity and has the consequences that
  - The length of an object decreases as its speed increases
  - Clocks passing by you run more slowly than do clocks at rest
- A spacetime diagram is drawn by sending out/receiving light rays at your current position in spacetime. It divides spacetime up into three regions: 1) your past light cone including all events which could have had an influence on you, 2) your future light cone including all events you can have an influence on, 3) events which cannot affect you nor can you affect them because light cannot travel between you and them
- Note that special relativity does not deal with gravity

General Relativity

- Is based on the equivalence principle, the idea that the effects of gravity cannot be distinguished from the effects of acceleration in the absence of gravity. This has the consequences that:
- Clocks deeper in a gravitation field run slower, e.g. a clock in the basement will run slower than a clock on the roof.
- Photons that climb out of a gravitational field are redshifted, e.g. if a photon is emitted from the basement and then detected on the roof, it will be observed on the roof to have lower energy and longer wavelength than it started with in the basement.
- The orbit of Mercury precesses.
- Gravity bends the path of light. This was first observed by Eddington during a solar eclipse.
- In general relativity, gravity is described as deformation of spacetime by massive objects. Objects then move on the shortest path, or "geodesic" on the curved spacetime.

Black Holes

- Black holes occur when the gravity of an object is so intense that light cannot escape from it, or equivalently when an object bends spacetime so strongly that there is no geodesic for light connecting the inside of the black hole to the outside.
- The event horizon of a black hole is a surface that divides the regions from which we can versus cannot see light. It has a radius equal to the Schwarzschild radius, $R_{Sch} = 3$ km (M/M_{Sun}).
- The center point of a black hole is a singularity where the density becomes extremely high.
- Three parameters completely described a black hole: mass, spin, and charge. Astrophysical black holes have zero charge.
- Rotating black holes drag spacetime around with them.
- Far away from a black hole, its gravitation field is the same as any object of the same mass.

Falling into a Black Hole

- An outside observed watching someone fall into a black hole sees signals from them become increasingly time dilated and redshifted.
- With a sufficiently large black hole, a freely falling observer would pass right through the event horizon in a finite time, would be not feel the event horizon.
- Falling into smaller black hole, the freely falling observer would be ripped apart by tidal effects because, assuming the observer is falling feet first, the gravity on his feet would be stronger than the gravity on his head, stretching him out and then ripping him apart.

Observing Black Holes

- In theory, black holes can evaporate via "Hawking radiation". This has never been observed.
- Matter falling towards a black hole forms an "accretion disk" around the black hole. The gravitational energy released by the infalling matter heats up the disk to very high temperatures, often hot enough to produce X-rays because a large amount of energy is radiated from a small surface area.
- Black holes are very efficient power generators. A non-rotating black hole converts 6% of the rest mass of infalling matter into energy. In a maximally rotating black hole, where the event horizon rotates at the speed of light, the event horizon and the inner edge of the accretion disk move inwards, and 42% of the rest mass of infalling matter into energy. Compare these numbers to $< 1\%$ efficiency for nuclear burning in the Sun.

Eddington Luminosity

- Matter falling toward a black hole experiences two forces: the force of gravity pulling it in and radiation pressure pushing out. If the accretion disk around a black hole becomes too bright, then radiation pressure will exceed gravitation force and matter will stop flowing in. This shuts down the power source for the black hole, thus places a limit on how bright an accreting black can become.
- This limit, the Eddington limit, is proportional to the black hole mass, M, and equals 30,000 L_{Sun} (M/M_{Sun}).
- If a black hole is observed to produce a particular luminosity, then it must have at least the mass calculated from the formula above.

A black hole is observed at a luminosity of 3,000,000 solar luminosities. The black hole mass must be

A) at least 100 solar masses
B) less than 100 solar masses
C) exactly 100 solar masses
D) at least 3,000,000 solar masses
E) less than 3,000,000 solar masses
F) exactly 3,000,000 solar masses

Quasars

- Quasi-stellar radio sources look like stars in visible light, but produce large amounts of radio emission.
- They are actually distant objects and must be very luminous to produce the observed radiation.
- Variations in the light from an object place an upper bound on the size of the object equal to the time for variation multiplied by the speed of light, e.g. if the flux of an object varies by 100% in 2 days, then the object must be less than 2 light-days across.
- Quasars vary on time scales of years. Thus, they must be less than light-years across.
- The requirement for high luminosity, or equivalently a very powerful energy generator, in a compact size suggests that quasars are supermassive black holes, 10^6-10^9 M_{sun}.
- Quasars produce jets that can extend 100,000 light years.

The luminosity of a quasar changes by a factor of 10 over 5 days. What does this tell us about the quasar?

A) It must be at least 10 light days in diameter.

B) It cannot be more than 10 light days in diameter.

C) It must be at least 5 light days in diameter.

D) It cannot be more than 5 light days in diameter.

Intermediate Mass Black Holes

- Black holes produced in supernova explosion, i.e. from a single star, cannot have a mass greater than their parent star. Thus, are limited to a maximum of around 30 M_{Sun}.
- Supermassive black holes, like those in quasars or found in the centers of most galaxies, have masses of 10^6-10^9 M_{Sun}.
- There are some X-ray sources that suggest they are black holes with masses in between, so called “intermediate mass” black holes with masses of 100-10,000 M_{Sun}.
- Research is currently going on to determine whether or not these objects are really intermediate mass black holes.

Distances and Pulsating Stars

- Certain stars, RR Lyrae and Cepheid variables, pulsate; their radius and surface temperature vary causing periodic changes in luminosity.
- This is useful for measuring distances because the pulsation period is related to the average luminosity of the star. If we can measure the pulsation period, then we can figure out how luminous the star is.
- After measuring the flux, we can then figure out the distance to the star using the luminosity/flux relation.
- Variable stars were important in measuring the size of the Milky Way galaxy, measuring the distance to the spiral nebula in Andromeda and proving that it is a separate galaxy outside the Milky Way, and in measuring the distances to other galaxies.

Distance Ladder

- The only direct way to measure astronomical distances is to use parallax. However, parallax only works for nearby objects, within about 500 pc.
- Astronomers construct a "distance ladder" to measure farther distances. For example, if we can find a close by variable star with an oscillation period of 1 day, then we can use parallax to measure its distance (step 1) and therefore its luminosity. If we find another variable star, also with an oscillation period of 1 day, then the luminosities of the two stars are equal. If the second star is in another galaxy, we can use the star to measure the distance to the galaxy (step 2). If a supernova goes off in that galaxy, we can figure out its true luminosity. Then if a supernova with the same properties goes off in another galaxy, we can figure out the distance to the second galaxy (step 3) since we know the luminosity of the supernova. Each step in the ladder depends on the previous one. There are many different and overlapping steps on the distance ladder. The first step is parallax.
- For a given distance, one must use an appropriate technique to measure it. Parallax works only for nearby objects. The best distance measurements at very large distances come from supernova.

Milky Way

- The Milky Way galaxy consists of a disk containing stars, gas, and dust (this is what we see as the Milky Way in the night sky), a halo containing globular clusters and old stars, and a bulge around the center containing mainly old stars.
- The size of the Milky Way was first measured using variable stars located in globular clusters. It is impossible to see to the center of the Milky Way in visible light because of dust in the disk. We can see globular clusters because they are in the halo, above the plane of the disk.
- We are about 8,000 pc from the center of the Milky Way. The disk is roughly 50,000 pc across.

Milky Way

- The Sun orbits around the center of the Milky Way.
- The orbital velocity of the Sun balances the gravitational pull of all the matter inside the Sun's orbit. We can estimate the mass of Galaxy by finding the gravitational force needed to balance the velocity of the Sun to keep it orbiting.
- The orbital velocity of the Sun is higher that what we would expect by calculating the gravitational force due to visible matter. Also, if we look at how the orbital velocity of other stars varies with distance from the Galactic center, the “rotation curve”, we find the rotation curve is approximately flat while it should be dropping at large distances if there is only visible matter.
- This is evidence for “dark matter” which does not produce any electromagnetic radiation.

Milky Way

- Dust dims and reddens star light. There is so much dust in the disk that we cannot see the center of the Milky Way galaxy in visible light.
- We can see the entire Galaxy in the infrared and radio.
- Hydrogen atoms emit radio waves with a wavelength of 21 cm.

- There is a supermassive black hole at the center of the Milky Way with a mass of about 4×10^6 M_{Sun}. We know because we can see stars (in the infrared) orbiting at very high speeds around the black hole.

Milky Way

- The spiral arms in the disk contain concentrations of young stars and molecular clouds and associated objects such as emission line nebula.
- The spiral arms are density waves, regions of increased density of gas and stars. The gravitational field of the density wave causes stars and gas to slow down near the arm. This compresses the interstellar clouds, triggering the formation of stars.
- Stars are formed in the arms, but do not stay in the arms. Young stars are found in the arms because they do not live long enough to move very far away.

How is the mass of the Galaxy estimated?

A) by observing the bending of light from distant galaxies as it passes near the Milky Way center

B) by observing its movement toward neighboring galaxies because of gravitational attraction

C) by counting stars and assuming an average stellar mass

D) by applying the laws of gravity to the motion of the Sun and other stars

If the galactic center is now thought to contain a supermassive black hole, why is the Sun not falling into it under the black hole's extreme gravity?

A) The inward force exerted on the Sun from the black hole is offset by the force exerted outward by the hidden “dark” matter beyond the Sun's orbit.

B) Its mass is so small that even this extreme mass concentration at the galactic center will not exert a significant force upon it.

C) The Sun has sufficient velocity that it can orbit the galactic center in a circle.

D) The mutual gravitational forces of local stars in the Orion spiral arm are sufficient to overcome the strong inward force and keep the Sun moving in its orbit.

Galaxies

- Hubble showed that the Andromeda nebula was actually an entire galaxy, like the Milky Way but outside of it, by measuring its distance and showing it was much larger than the size of the Milky Way.
- Galaxies come in different types:
- Spiral galaxies have a disk, bulge, and halo. There is gas in the disk and stars are currently forming there. Stars in the disk orbit in the same direction. There are old stars in the bulge and halo and they orbit in random directions.
- Elliptical galaxies do not have a disk and have very little gas and therefore little or no star formation. Most of the stars formed when the galaxy formed. The stars orbit in random directions.
- Irregular galaxies have no clear structure. They have lots of gas and lots of star formation. They are often interacting with other galaxies.

Galaxies

- Galaxies interact. The Milky Way is current consuming its nearby neighbor and there are many examples of interacting galaxies.
- Interactions tend to trigger star formation.
- Close interactions can disrupt the galaxies.
- The large elliptical galaxies found in the centers of clusters are thought to be formed by the merging of several galaxies. The mergers destroy the disks and randomize the stellar orbits.

- Early in the Universe, galaxies were closer together and interacted more frequently. If we look back in time, we see more spirals and irregular galaxies and fewer ellipticals.

Clusters and Large Scale Structure

- Galaxies can be found in small groups of just a few galaxies, like the Local group which contains Andromeda and the Milky Way, and cluster of various sizes. The largest clusters contain hundreds of galaxies.
- Rich clusters contain hot gas between the galaxies. The gas emits in the X-rays and has more mass than all the stars in all the galaxies in the cluster.
- It is possible to measure the total mass in clusters using gravitational lensing and also by looking at the orbital motions of galaxies within a cluster. Both of these techniques confirm the need for dark matter in clusters.

- Clusters of galaxies are organized on irregular sheets with voids between them. On scales much larger than 100 Mpc, the distribution of galaxies appears to be roughly uniform.

As we look deeper and deeper into space (and thus farther and farther back in time) the composition of rich clusters of galaxies

A) is about the same mix of ellipticals and spirals that we find in the Virgo cluster and other nearby rich clusters.

B) increases in the ratio of ellipticals to spirals.

C) increases in the ratio of spirals to ellipticals.

D) contains increasing numbers of large irregular galaxies, replacing spirals and ellipticals altogether.

Cosmology

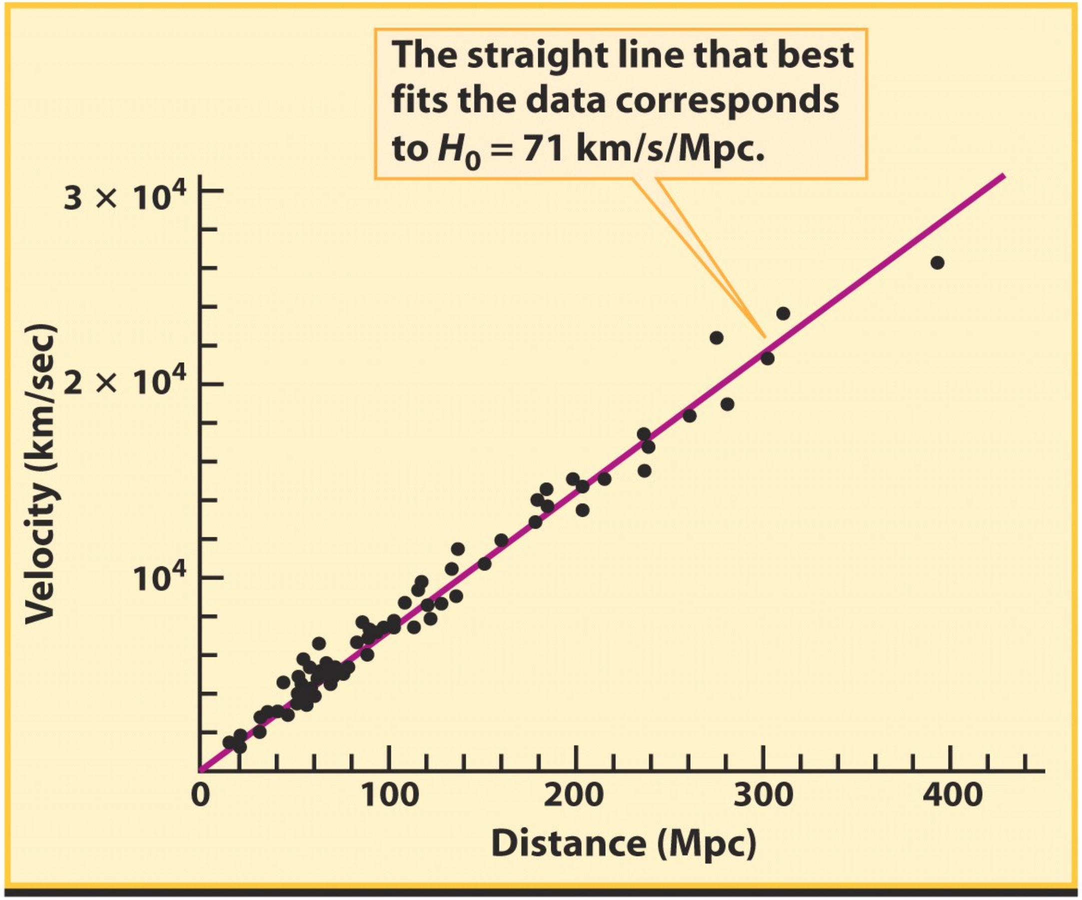
- The Copernican principle underlies out study of the Universe and states: we do not occupy a special place, there are no special places, the universe is homogeneous if viewed at sufficiently large scales, the laws of physics are the same everywhere.
- The Copernican principle can be tested by seeing if the Universe appears uniform in all direction and if the spectral lines from distant galaxies match those measured on Earth.

- In a static universe that is infinite (in time and space) and full of Sun-like stars, the night sky should be as bright as the Sun. This is "Olber's Paradox". The fact that the night sky is dark implies at least one of these assumptions is false.

Cosmology

- Hubble measured the distance to and recession velocity (via the red shift) of galaxies and found that the velocity is proportional to the distance.
- This particular form of the law means that if we run the expansion in reverse then all galaxies will be at the same point in space at some time in the past.
- Therefore the expansion started at a specific time in the past and we can calculate that time.

Hubble expansion $v = H_0 d$



Time = distance/velocity

$= d/H_0 d$

$= 1/H_0$

= 1/(71 km/s/Mpc)

= 13.8 Gyr

What does Hubble's law give for the age of the universe? (H_0 = Hubble's constant, v is the recessional velocity of objects in the universe, and d = distance to objects in Mpc.)

A) age = v/H_0

B) age = H_0

C) age = d/H_0

D) age = $1/H_0$

Cosmology

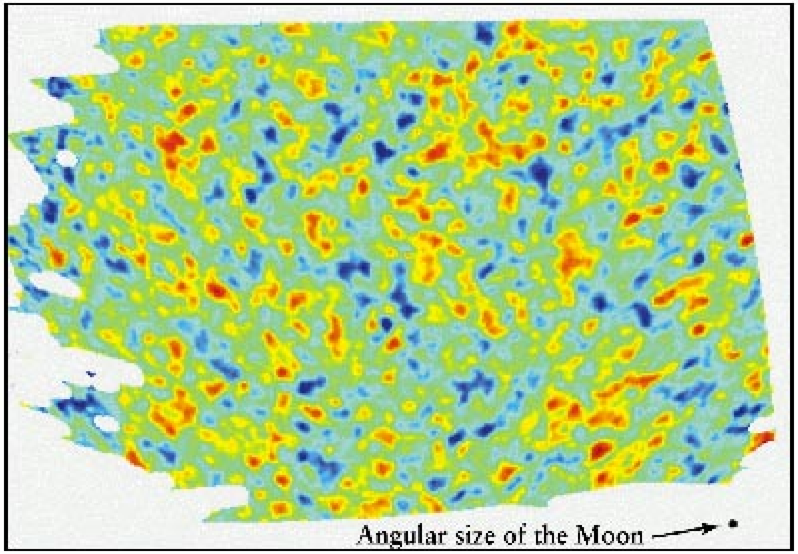
- The fact that the Universe is now expanding means that it used to be more compact and therefore denser and hotter. The hot and dense starting state of the Universe is the “Big Bang”.
- When temperatures were very high, there were no atoms, no nuclei, and even no protons and neutrons. As the Universe cooled, protons and neutrons formed at about 1 second after the Big Bang, helium nuclei formed at about 100 seconds.
- The ratio of helium to hydrogen for pristine gas (not affected by star formation) matches that predicted in models of the Big Bang.

Cosmology

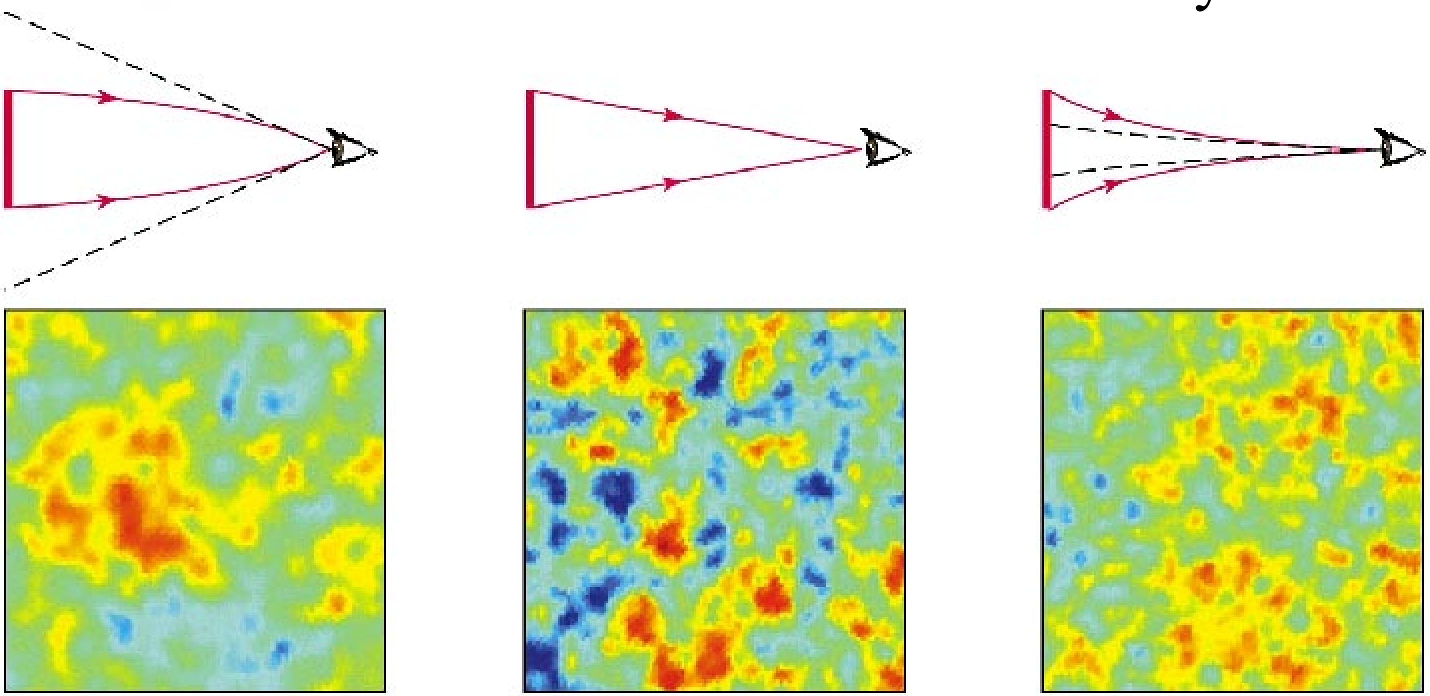
- For the next several 100,000 years, the Universe was an opaque hot gas. Photons were continually emitted and then rapidly absorbed by the gas. At about 400,000 years, electrons combined with nuclei to form atoms and the Universe became transparent. The photons present were then able to travel the length of the Universe without being absorbed.
- The cosmic microwave background is photons from when the Universe became transparent. The photons were originally emitted with a blackbody spectrum at a temperature of 3000 K, but have been redshifted down to 2.7 K.
- Discovery of the cosmic microwave background in the 1960s was important evidence in favor the Big Bang.

Cosmology

- The overall geometry of the spacetime of the Universe can be curved. Three possibilities:
- Flat: the geometry you are used to, sum of angles in a triangle = 180º, circumference of a circle = $\pi \times$ diameter, total density of matter and energy = critical density which balances Hubble expansion.
- Positive curvature: sum of angles in a triangle > 180º, circumference of a circle < $\pi \times$ diameter, total density of matter and energy > critical density which balances Hubble expansion.
- Negative curvature: sum of angles in a triangle < 180º, circumference of a circle > $\pi \times$ diameter, total density of matter and energy < critical density which balances Hubble expansion.



The physical size of hot/cold regions in the cosmic microwave background can be calculated and measured. They match, indicating the Universe is flat and therefore the density of matter and energy is close to the critical density.



a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

In a positively curved Universe, galaxies at very large distances would appear

A) smaller than they really are

B) the angular size calculated from the small angle formula

C) larger than they really are

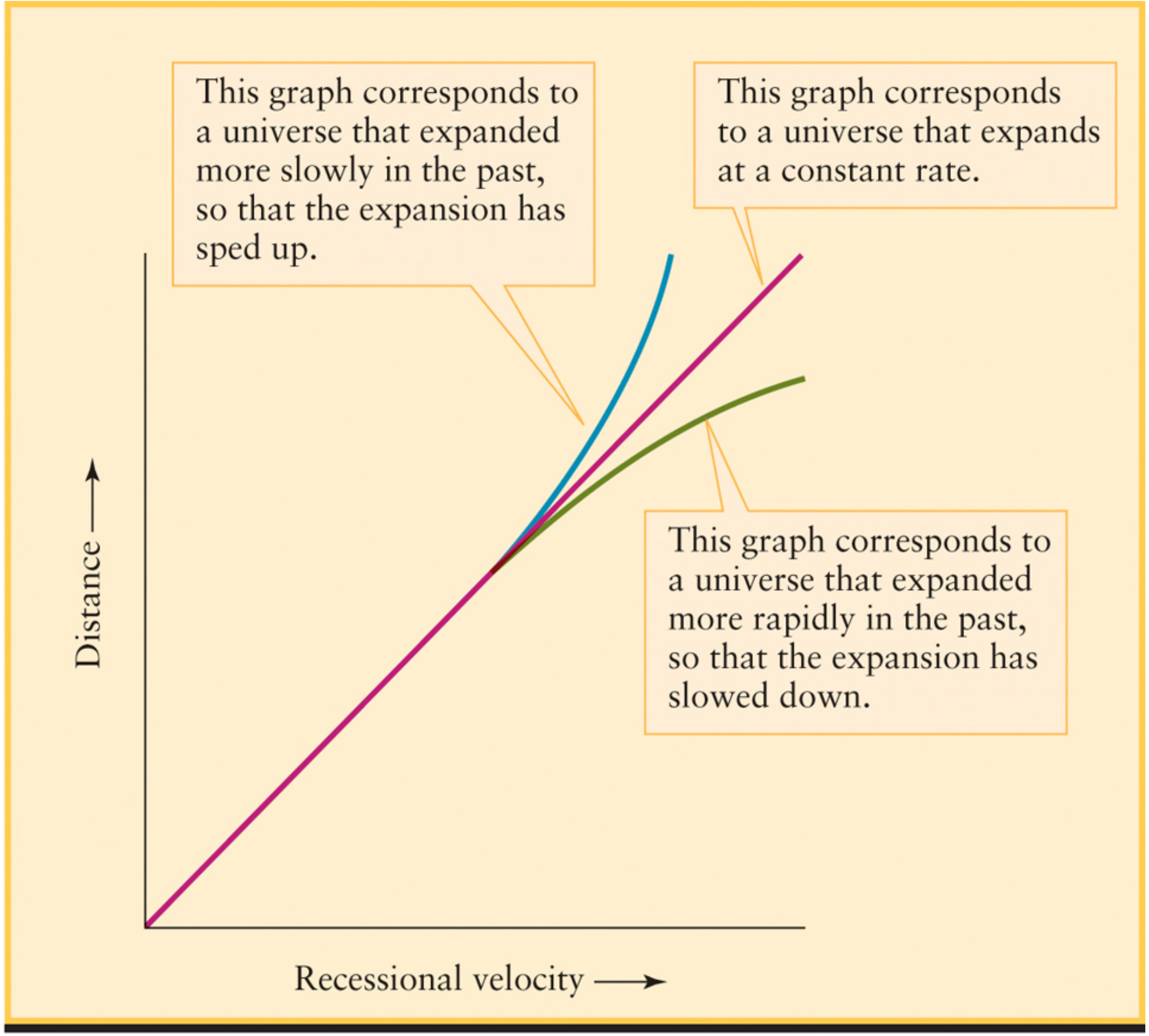
D) bent

Expansion of the Universe

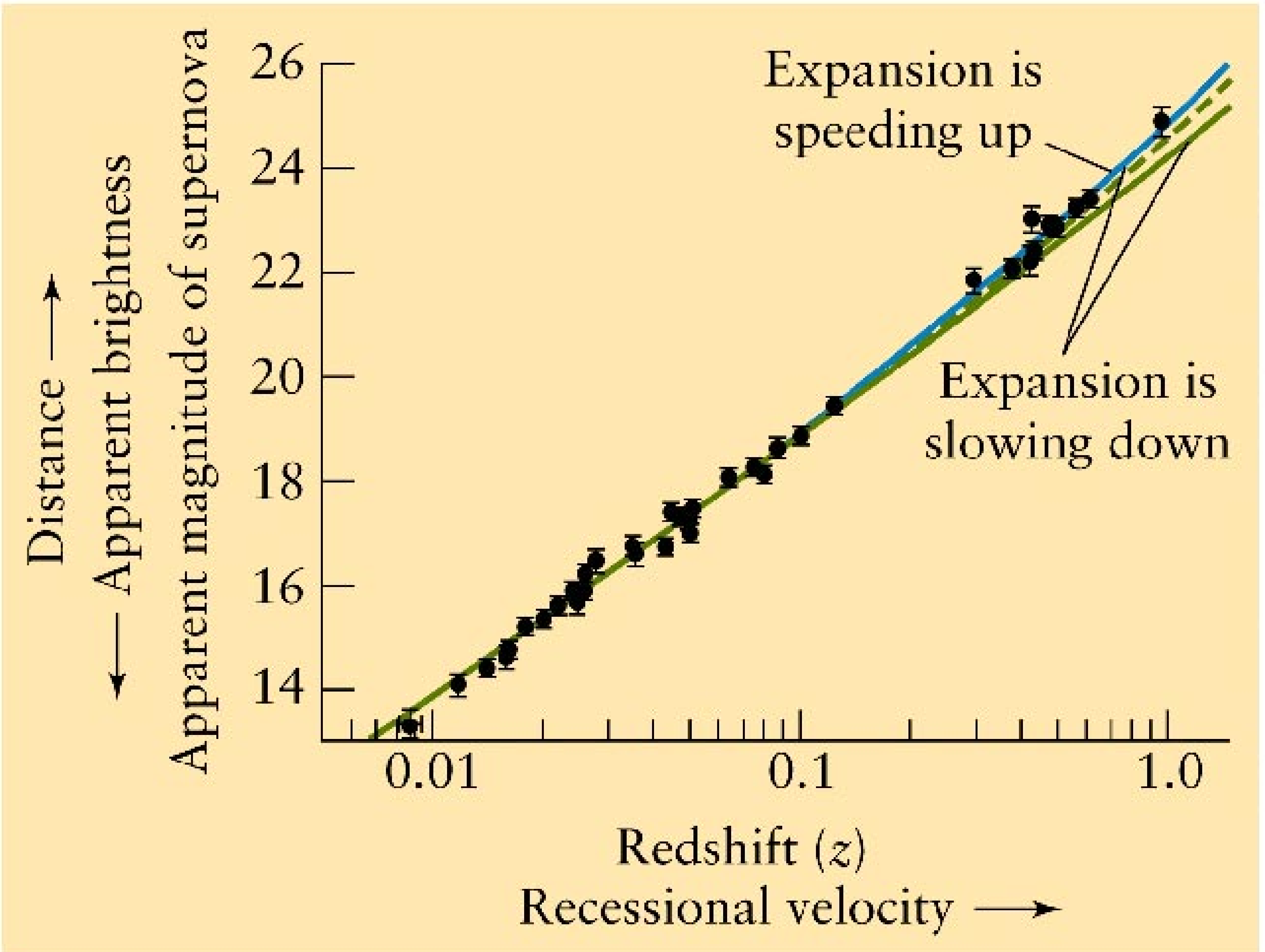
Larger distance means we are looking further into the past.

Decelerating Universe:
If the rate of expansion of the universe was faster in the past, we should see larger velocities for larger distances.

Accelerating Universe:
If the expansion rate was slower in the distant past, we should see lower velocities for large distances.

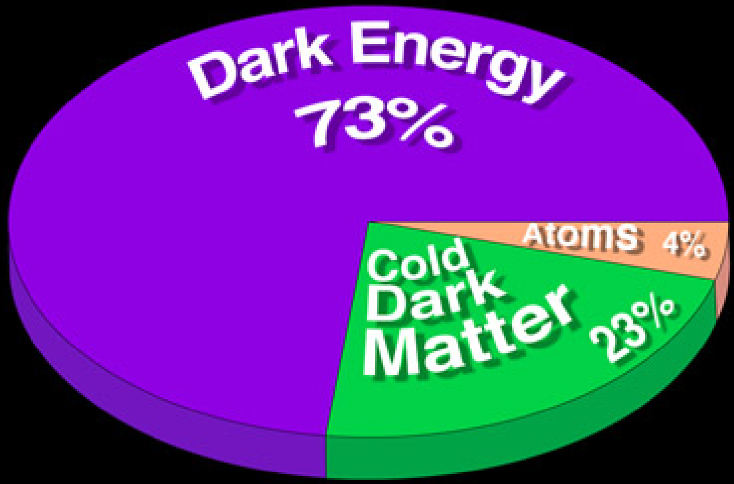


(b) Possible expansion histories of the universe



Expansion is speeding up
Expansion is slowing down
26
24
22
20
18
16
14
0.01
0.1
1.0
Redshift (z)
Recessional velocity →
Distance →
← Apparent brightness
Apparent magnitude of supernova

Contents of the Universe



Total density of matter and energy equals the critical density which balances the Hubble expansion. Normal matter, the stuff we are made of, is only 4% of the total.