The Expanding Universe
Core Concepts for Astronomy 102

- Lookback Time
- a Uniform Expansion
- Cosmological Redshift
- $d = z\,/\,c\;t_H$ (and variants)
- Hubble Time / Expansion Timescale
- The Hubble Diagram : plotting size vs. time
- Dark Matter & Dark Energy
- The Big Bang Theory

Lookback Time

Light takes time to travel.

If you see light from an object that is distance d away, then it took time $t = d/c$ to reach you.

Speed of Light $= c = 1\,\frac{\text{light-year}}{\text{year}} = 3\times10^{8}\,\frac{\text{m}}{\text{s}}$

This form is often the most useful for distances and lookback times!!!

1 pc = 3.26 lyr   1 Mpc = 10^6 pc = 1,000,000 pc

A Uniform Expansion

Every point is moving uniformly away from every other point.

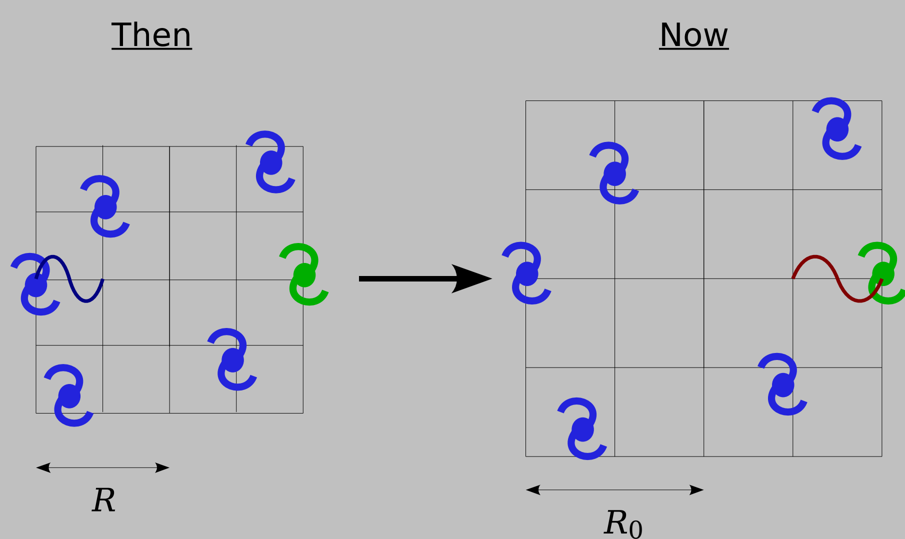
Examples:

- An explosion in space. (Bits of shrapnel fly away from the explosion point, not slowed by air resistance.)
- Paper clips on a stretching rubber band
- Pennies on a balloon.
- Raisins in rising bread
- The expansion of the Universe after the Big Bang

Some uniform expansions have a center from which they are expanding; *some do not*!

Cosmological Redshift

As the Universe expands, the wavelength of light expands *at exactly the same rate*.



Cosmological Redshift

As the Universe expands, the wavelength of light expands *at exactly the same rate.*

$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} = 1+z = \frac{R_0}{R}$$

- R = "size of Universe" at emission (average distance between galaxies, or distance to a given galaxy)
- R_0 = "size of Universe" now
- λ_{emit} = emitted wavelength
- λ_{obs} = observed (redshifted) wavelength

The Expanding Universe Equation

The Universe expands by $\Delta d = d_0 - d$ in time $\Delta t = d/c$

Δt = time for light to go distance d (time=distance/speed)
d = initial distance to galaxy = the distance the light goes
d_0 = distance now

$$\frac{\Delta d}{d} = \frac{\Delta t}{t_H} \qquad z = \frac{\Delta t}{t_H}$$

$$z = \frac{d}{c\, t_H}$$

- z: Can Measure (with a spectrum)
- d: Can Measure (dimmer std. candle = bigger d)
- c: Know
- t_H: From previous measurements, today we know this = 13.8 Gyr

Expanding Universe Equation (only works for $z \ll 1$)

The Hubble Time : t_H

***t_H* is how old the Universe would be if the expansion rate had always been constant.**

"The Expansion Timescale"

Looking to the future...

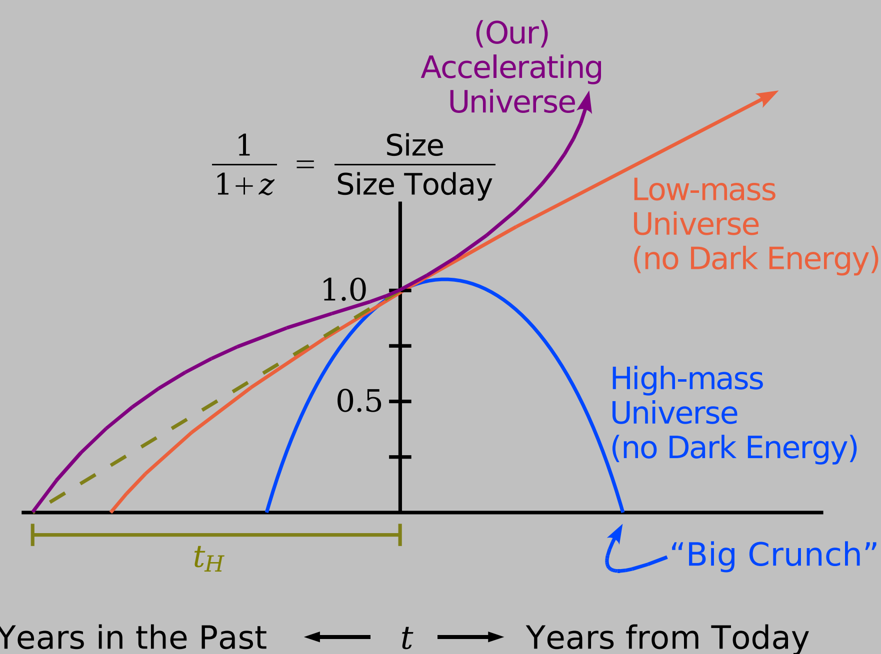
$$\frac{\Delta d}{d} = \frac{\Delta t}{t_H}$$

If an object is at distance d right now, its distance will change by Δd in time Δt (as long as t_H stays constant during Δt)

Looking to the past...

$$\frac{\Delta d}{d} = z = \frac{t_{\text{lookback}}}{t_H} = \frac{(d/c)}{t_H} = \frac{d}{c\, t_H}$$

The Hubble Diagram



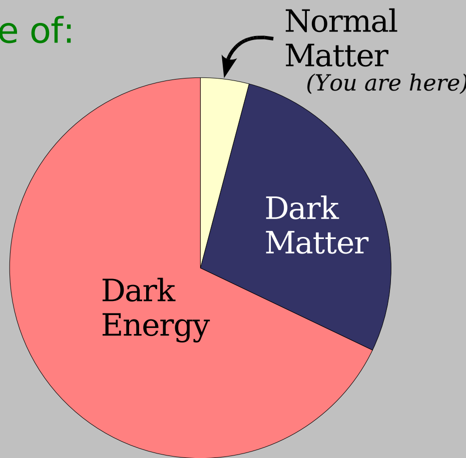
Dark Matter and Dark Energy

What the Universe is made of:

Ω_M Fraction of the Universe that is matter (normal + dark matter) = 0.3

Ω_Λ Fraction of the Universe that is dark energy = 0.7

Ω_b Fraction of the Universe that is "baryonic" (i.e. normal matter) = 0.05



Dark Matter has a normal gravitational effect, but we can't see it directly. We've seen its effects on dynamics (rotation curves of galaxies need more mass than is seen) and through gravitational lensing (which measures mass regardless of type)

Dark Energy has a *negative* (repulsive) gravitational effect. It is what is causing the expansion of the Universe to accelerate; the acceleration is the most direct evidence for Dark Energy

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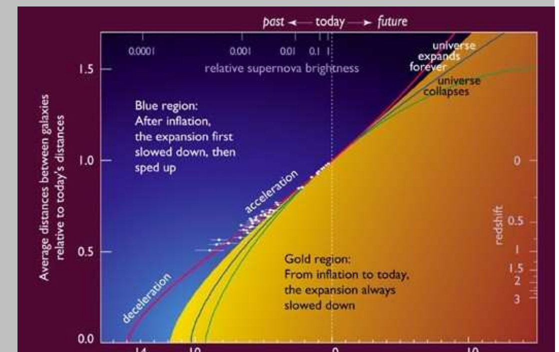


(Bigger Image on 2006/11/08)

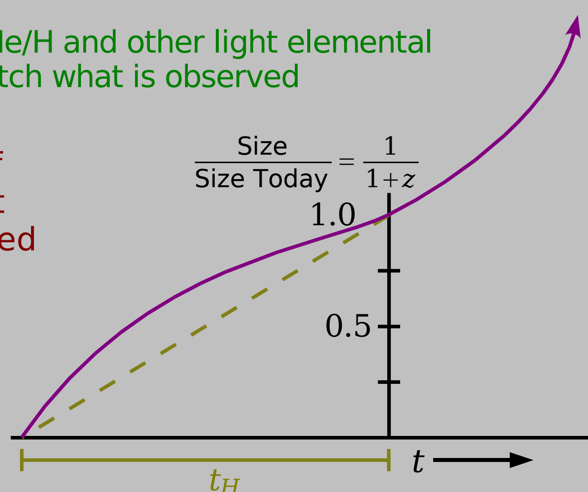
The Big Bang Theory

Evidence :

- expanding Universe & cosmological redshift
- the Cosmic Microwave Background (the "afterglow of creation")
- calculations of He/H and other light elemental abundances match what is observed

In the Big Bang Theory, the shape of the size vs. time plot is completely specified by t_H, Ω_M, and Ω_Λ.

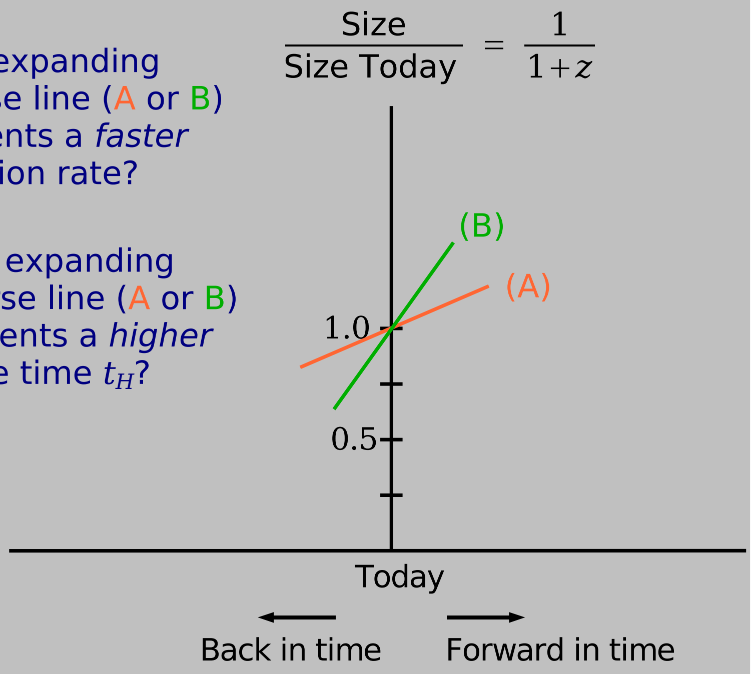
From this, we have determined the Universe's age to be **13.7±0.2 Gyr**

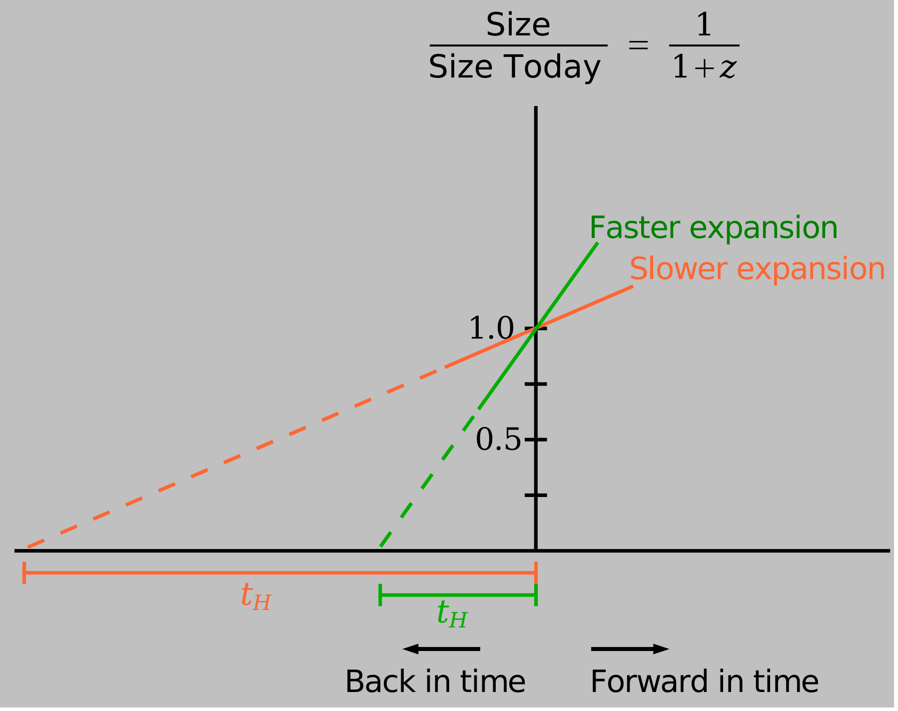


A few questions...

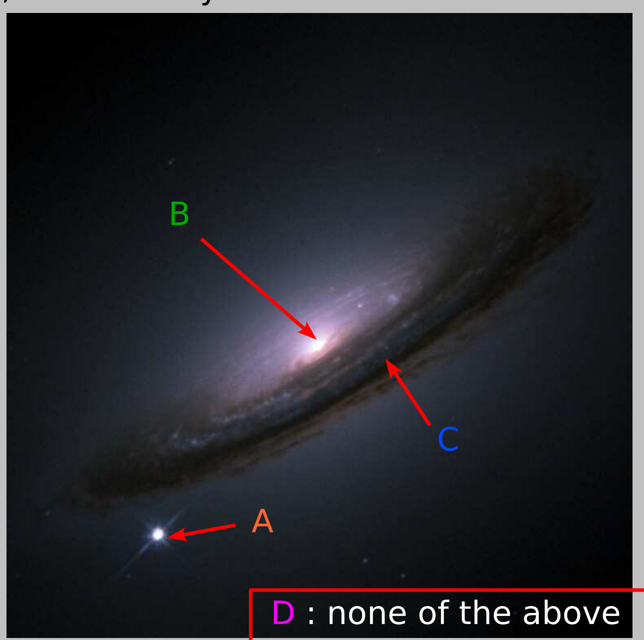
Q1 Which expanding Universe line (A or B) represents a *faster* expansion rate?

Q2 Which expanding Universe line (A or B) represents a *higher* Hubble time t_H?





In this image of the Sombrero Galaxy and Supernova 1994D, where can you see the Dark Matter?



Which of the following are evidence for the existence of Dark Energy?

A Gravitational lensing by the Bullet Cluster shows most of the mass is in a different place from the luminous mass.

B Observations of distant supernovae showed that the expansion of the Universe is accelerating.

C The rotation speeds of spiral galaxies farther from the center are too fast given the amount of luminous matter.

D Galaxies within galaxy clusters have speeds that should make the clusters fly apart given only the gravity from the matter we can see.

E All of the above.

A, C, and D are evidence for *Dark Matter*.

In the expanding universe equation, which of the following is a correct statement about the Hubble Time t_H?

$$z = \frac{d}{c\, t_H}$$

A A higher t_H means an older Universe, and thus an accelerating expansion.

B A higher t_H means an older Universe, and thus a decelerating expansion.

C A higher t_H means a bigger d for a given amount of expansion z, and thus is a faster current expansion.

D A higher t_H means a greater lookback time d/c for a given amount of expansion z, and thus is a slower current expansion.

E A higher t_H means it's taking more and more time for a given amount of expansion for given lookback time d/c, and thus a decelerating expansion.

Which of the following statements about a uniform expansion is true?

A At one point in time, you will measure *the same* expansion timescale t_H everywhere within the expansion.

B At one point in time, you will measure a *larger* expansion timescale t_H for points farther from the center.

C At one point in time, you will measure a *smaller* expansion timescale t_H for points farther from the center.

D The expansion timescale t_H goes up over time at exactly the same rate as the age of the expansion.

E You will measure the same expansion timescale t_H at any time as long as the expansion is going.

The Cosmic Microwave Background was emitted over 13 billion years ago when the Universe made a transition from being opaque to being transparent. Where was the closest CMB photon emitted back then?

A Right here

B About 13 million light-years away (13 billion divided by z_{CMB}≃1000.)

C About 13 billion light-years away.

D About 13 trillion light-years away (13 billion times z_{CMB}≃1000.)

The CMB was emitted *everywhere*. The photons emitted here are now billions of light-years away. We see the ones just now reaching us.

We observe a quasar. The light we observe was emitted when the Universe was 1/3 its current size. What is the redshift z of the quasar?

A z=0.33

B z=0.5

C z=1

D z=2

E z=3

$$1+z = \frac{\text{Size Now}}{\text{Size Then}}$$

$$1+z = \frac{3}{1} = 3$$

$$z = 2$$

What is a typical lookback time for a Milky Way globular cluster?

- A Close to 0 on astronomical timescales
- B Tens to hundreds of years.
- C Thousands to tens of thousands of years.
- D 12-13 billion years – just a little less than the age of the Universe.
- E Older than our best estimate for the age of the Universe.

Globular clusters in our Galaxy have an *age* of up to 12-13 billion years. They are, however, within our galaxy – 10's of parsecs away – and distance is what determines the lookback time.

A thermonuclear (Type Ia) supernova is discovered in a galaxy with a redshift of z=0.86. What can you say from this information?

- A The galaxy is moving away from us at 86% of the speed of light.
- B The supernova exploded 86% of the age of the Universe ago (or about 11.9 billion years ago).
- C The Universe is 1.86 times the size it was when the supernova exploded.
- D This supernova must have been intrinsically *bluer* than ones nearby to still be a standard candle.
- E All of the above.

You observe two galaxies. Galaxy A has a distance of d_A=100 Mpc, and Galaxy B has a distance of d_B=200 Mpc. Which of the following can you say?

- A Both galaxies have the same redshift because of the uniformity of the expansion.
- B Galaxy B is flying away from us at twice the speed of Galaxy A.
- C Galaxy A is flying away from us at twice the speed of Galaxy B.
- D Galaxy A has a bigger redshift because light took longer to reach us from Galaxy B, and the Universe was smaller back then.
- E Galaxy B has a bigger redshift because light took longer to reach us from Galaxy B, and the Universe expanded more in that time.

Look at the expanding universe equation to the right. If I tell you that d_A=100 Mpc and d_B=200 Mpc, which will be bigger, z_A or z_B?

$$z = \frac{d}{c\, t_H}$$

Is your answer consistent with your answer to the previous question?

- A $z_A > z_B$
- B $z_B > z_A$
- C $z_A = z_B$
- D There is not enough information to answer the question.

Your answer had better be consistent with that of the previous question; they're basically the same question! The equation is another way of expressing the concept....

How old is the Universe? How do we know?

A At least 4.5 billion years, because radioactive dating (based on the very well-supported theory of Quantum Mechanics) gives us that age for the Solar System.

B At least 12-13 billion years, because that is the age we need to match the H-R diagram of globular clusters using the very well-supported theory of Stellar Evolution.

C 13.7 billion years, because that's what we calculate given the measured expansion rate, dark matter density, and dark energy density using the very well-supported Big Bang theory.

D All of A, B, and C.

E Billions of years, as part of the scientific conspiracy to destroy the moral fabric of American society.