A Uniform Expansion

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

d Distance to object now

Δd Change in distance to object during time Δt

t_H Expansion timescale

$t_H =$ age of the Universe *if the expansion rate has always been constant*

Today's best value : $t_H = 13.8 \pm 0.6$ Gyr

(Spergel et al., 2006, astro-ph/0603449)

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

A Universe right now has expansion timescale t_H = 13.8 Gyr. Assume the expansion rate has always been constant.

Galaxy A is twice as far away as Galaxy B. How will t_H as measured for Galaxy A compare to t_H as measured from for Galaxy B? (Assume that Galaxy A is no more than, say, a hundred million light-years away.)

A $t_H(A) = \frac{1}{4} t_H(B)$

B $t_H(A) = \frac{1}{2} t_H(B)$

C $t_H(A) = t_H(B)$

D $t_H(A) = 2\, t_H(B)$

E $t_H(A) = 4\, t_H(B)$

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

A Universe right now has expansion timescale t_H = 13.8 Gyr. Assume the expansion rate has always been constant. A certain galaxy is 100 Mpc away. How long has it been since that galaxy was 50 Mpc away?

A 3.45 Gyr

B 6.90 Gyr

C 13.8 Gyr

D 27.6 Gyr

E 55.2 Gyr

The expansion rate of the Universe is currently accelerating– that is, it is getting faster. It has been accelerating for something like the last 7 billion years.

Right now, we have t_H=13.6 Gyr. (Remember that Gyr=gigayears=billion years.) 3.6 billion years ago, was the expansion timescale:

A <10.0 Gyr,

B Exactly 10.0 Gyr,

C between 10 Gyr and 13.6 Gyr,

D exactly 13.6 Gyr, or

E >13.6 Gyr?

C. I have no basis for this answer, but C is said to be most often right on multiple choice exams. I have no idea if this is correct, but I'm just going to follow my instincts.

t_H=13.8 Gyr right now. If the expansion rate of the Universe has been constant, what was t_H 3.8 Gyr ago?

- A t_H<10.0 Gyr
- B t_H=10.0 Gyr
- C 10.0Gyr<t_H<13.8Gyr
- D t_H=13.8Gyr
- E t_H>13.8Gyr

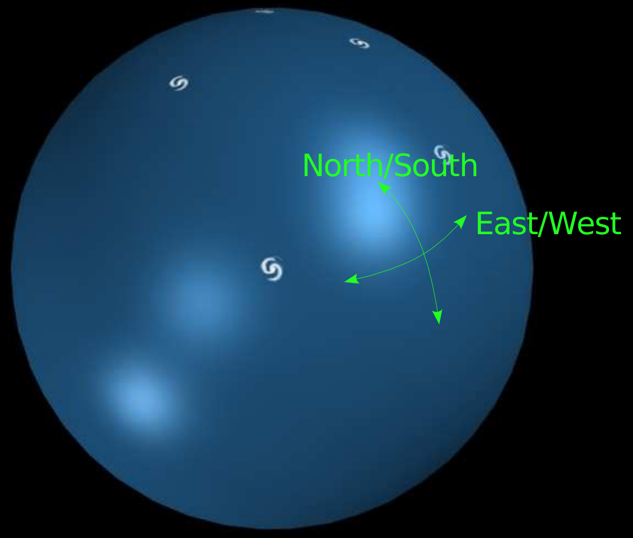
Does a *slower expansion rate* mean a *lower* t_H or a *higher* t_H?

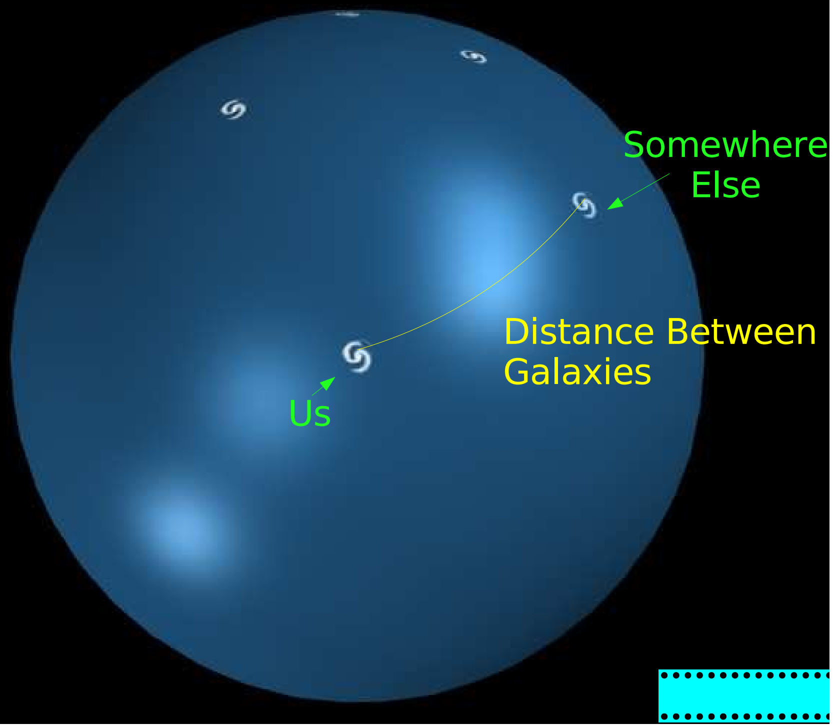
- A Lower
- B Higher

If the expansion of the Universe is accelerating, what was t_H 3.8 Gyr ago?

- A t_H<10.0 Gyr
- B t_H=10.0 Gyr
- C 10.0Gyr<t_H<13.8Gyr
- D t_H=13.8Gyr
- E t_H>13.8Gyr

A model 2-d closed Universe: the ***surface*** of a sphere





Redshift

$$z = \frac{\lambda_{\rm obs} - \lambda_{\rm emit}}{\lambda_{\rm emit}} = \frac{\Delta\lambda}{\lambda}$$

This is the *definition* of observed redshift; whatever causes it, it is redshift.

$$1+z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}}$$

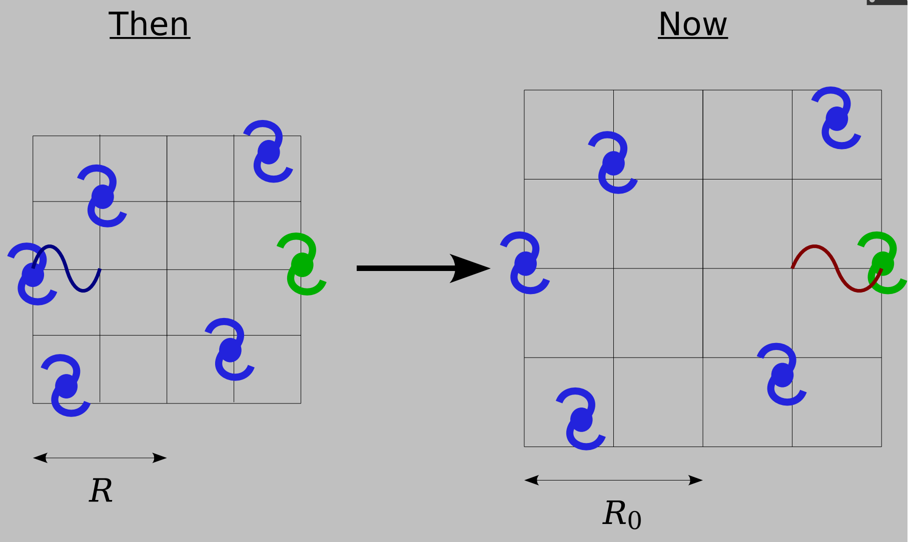
One possible source of redshift : the Doppler Shift

$$z = \frac{v}{c} \quad \text{for } v \ll c$$

$$1+z = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}$$ for any v, but I'll never make you use that

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

$$1+z = \frac{d_0}{d}$$

$$z = \frac{d_0}{d} - 1 = \frac{d_0}{d} - \frac{d}{d}$$

$$z = \frac{d_0 - d}{d} = \frac{\Delta d}{d}$$

The cosmological redshift is a direct measurement of how much the Universe has expanded!!

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

We can also measure Δt – it's lookback time!

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

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

Can Measure (with a spectrum)

Can Measure (dimmer std. candle = bigger d)

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

Expanding Universe Equation (only works for z ≪ 1)

Know

From previous measurements, today we know this = 13.8 Gyr