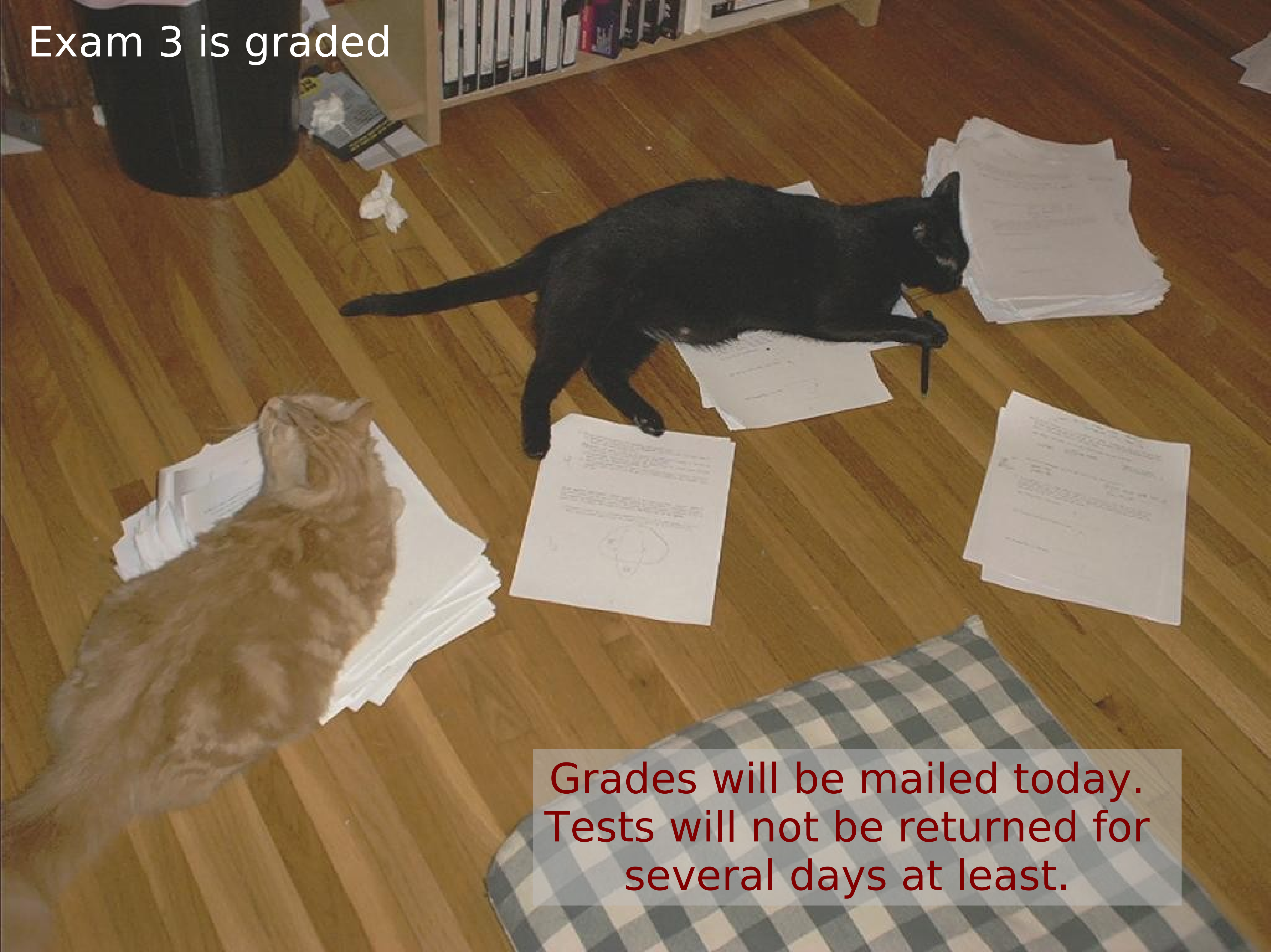
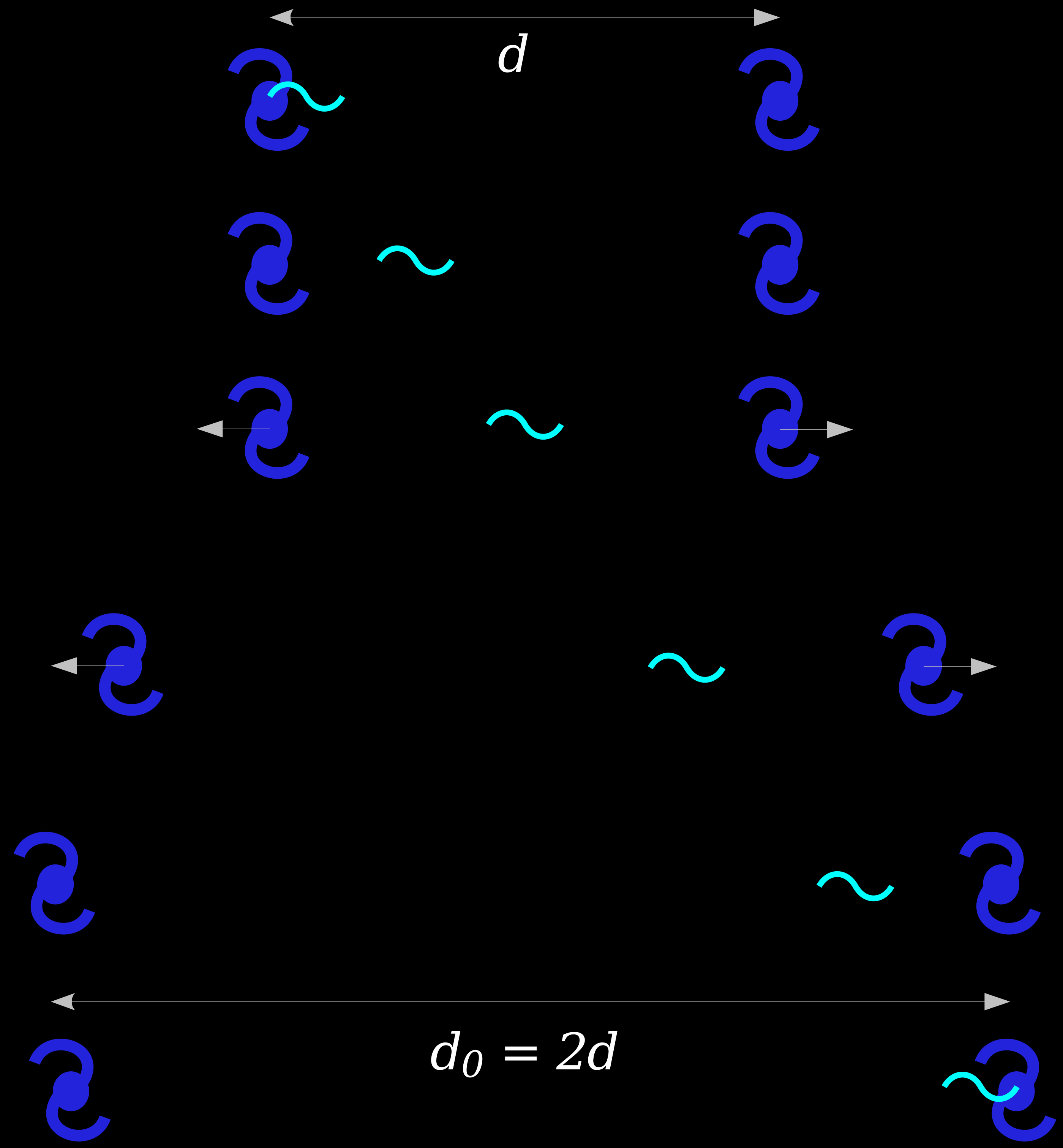
Exam 3 is graded



Grades will be mailed today.
Tests will not be returned for several days at least.


d
$d_0 = 2d$

The expanding Universe equation : (“Hubble's Law”)

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

The Meaning of the Variables

d = distance the light traveled (= distance to the galaxy for $z \ll 1$)

c = speed of light

t_H = Hubble time

z = cosmological redshift

$$z = \frac{\text{Change in Size}}{\text{Size}}$$

“Size” of the Universe, or something proportional to it (avg. dist. bet. galaxies, dist. to a given distant galaxy)

$$1 + z = \frac{\text{Size Now}}{\text{Size When Light Emitted}}$$

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

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

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

$$z = 2$$

The top rung of the cosmic distance ladder...

Redshift

The Universe has always been expanding....

...thus, greater distance = larger lookback time = more total expansion since emission = bigger z

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

Redshift is almost always easier (though expensive in telescope time) to measure than distance... but using it as a stand-in for distance requires knowing t_H (and, actually, a few other things).

Warning : this equation should only be used for $z \ll 1$.
For larger z, the interpretation of d gets complicated.

Example : Prof. Knop's favorite galaxy is VV114. VV114 has a redshift z=0.020. How far away is VV114?

$$d = c\, t_H\, z$$

$$d = \left(1\ \frac{\text{light-year}}{\text{year}}\right)(13.8\times10^{9}\ \text{years})\,(0.020)$$

$$d = 2.76\times10^{8}\ \text{light-years} = 278\ \text{Mlyr}$$

$$d = (2.76\times10^{8}\ \text{lyr})\left(\frac{1\ \text{pc}}{3.26\ \text{lyr}}\right) = 8.47\times10^{7}\ \text{pc} = 84.7\ \text{Mpc}$$

What is Prof. Knop's Favorite Galaxy?

- A ~~The Milky Way~~ — *Annoying people live there!*
- B ~~The Andromeda Galaxy~~ — *It's so close!!!*
- C **VV114** — *So pretty!!! And, anyway, it's always C.*
- D ~~M87~~
- E ~~M81~~

People get them mixed up!!!
(Although I did win $0.05 on a bet with a seminar speaker on which was which...)

The Quasar 3C273 is the closest quasar to the Milky Way. (There are closer objects that are similar to quasars, but not as luminous.) It has a measured redshift of z=0.158. How far away is it in Mpc? (For a sense of scale, recall that the Andromeda Galaxy is about 0.8 Mpc away, and the Virgo Cluster is about 20 Mpc away.)

Hubble's Law : $z = \frac{d}{c \ t_H}$ *(Note: works for $z \ll 1$)*

$$d = z \, c \, t_H$$

$$d = 0.158 \ \left(3\times10^8 \frac{\text{m}}{\text{s}}\right) \ \left(13.8\times10^9 \text{yrs}\right)$$

$$d = 0.158 \ \left(3\times10^8 \frac{\text{m}}{\text{s}}\right) \ \left(13.8\times10^9 \text{yrs}\right) \ \left(\frac{3.16\times10^7 \text{s}}{\text{yr}}\right) \ \left(\frac{1 \text{Mpc}}{3.086\times10^{22} \text{m}}\right)$$

$$d = 670 \text{ Mpc}$$

An easier way to do it (fewer unit conversions):

Hubble's Law : $z = \frac{d}{c \;\; t_H}$ *(Note: works for $z \ll 1$)*

$$d = z \, c \, t_H$$

$$d = 0.158 \left(1 \frac{\text{lyr}}{\text{yr}}\right) \left(13.8 \times 10^9 \, \text{yrs}\right)$$

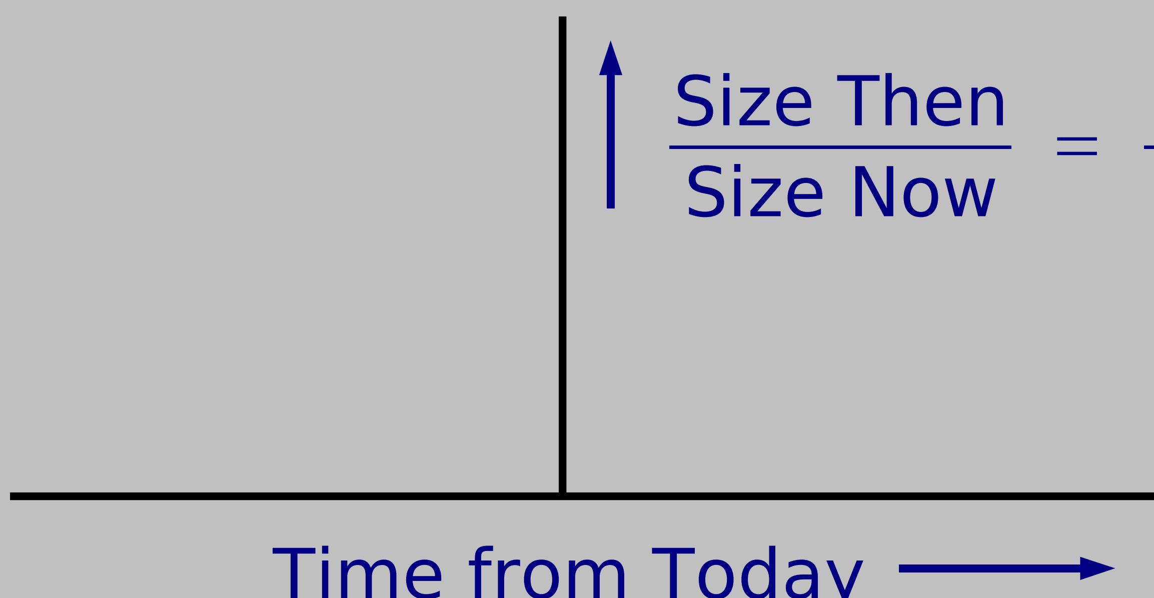
$$d = 2.2 \, \text{billion light years}$$

$$d = \left(2.2 \times 10^9 \, \text{lyr}\right) \left(\frac{1 \, \text{Mpc}}{3.26 \times 10^6 \, \text{lyr}}\right) = 670 \;\; \text{Mpc}$$

Measuring the Expansion of the Universe:

1. Measure the distance to figure out the lookback time (farther away = light was traveling longer to reach us).

2. Measure the redshift to find out how much the Universe expanded during that time.

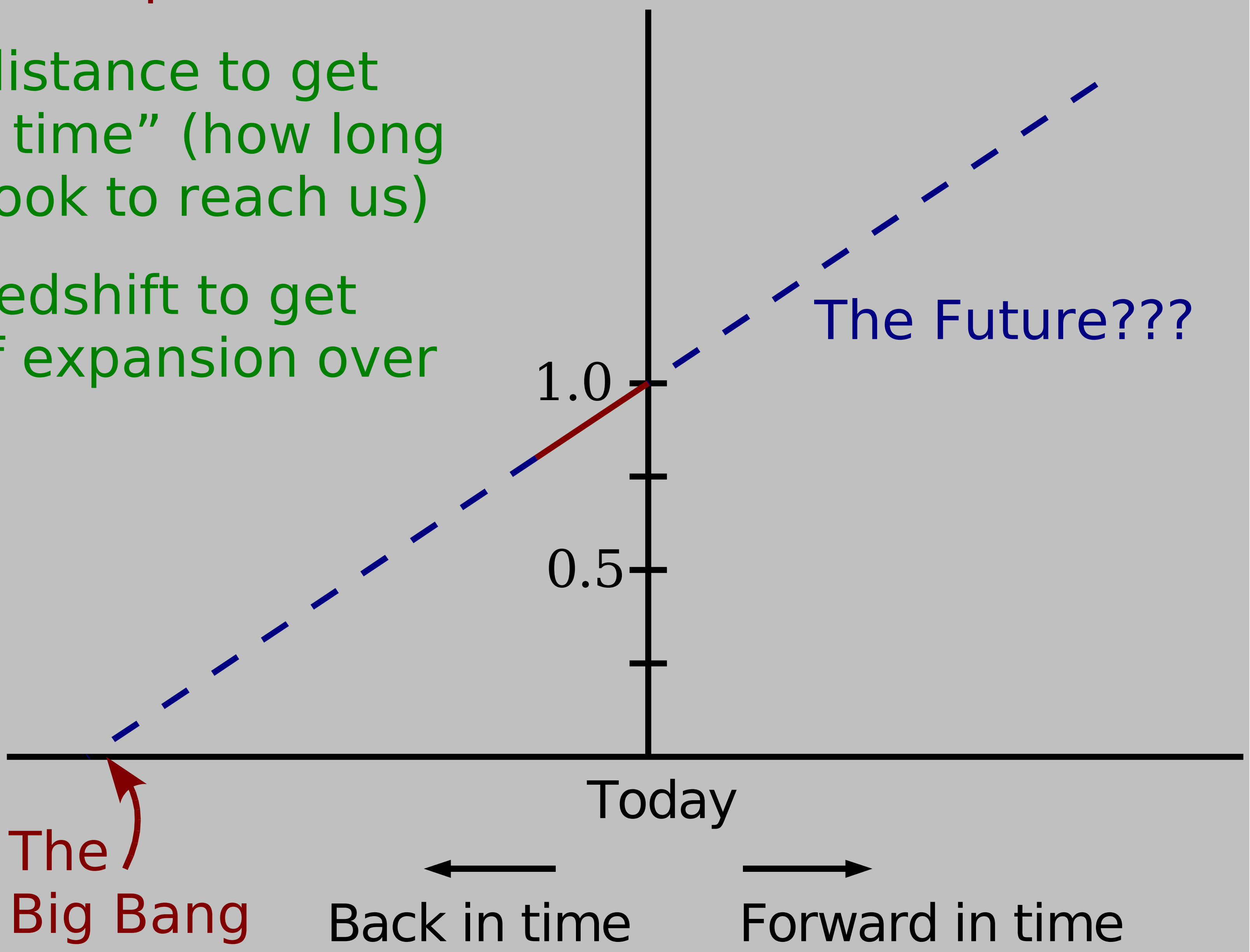


$$\frac{\text{Size Then}}{\text{Size Now}} = \frac{1}{1+z}$$

Measuring the Expansion

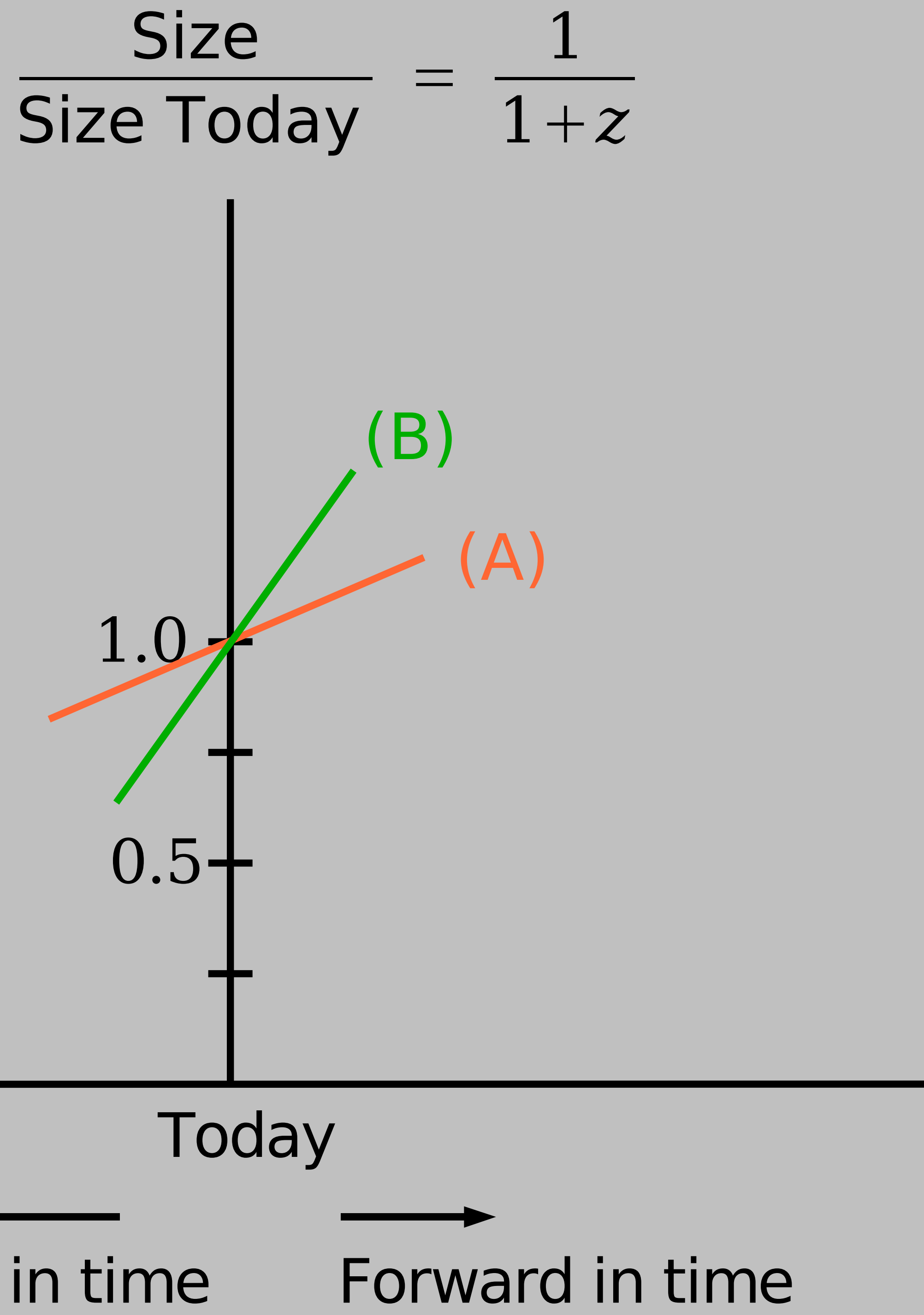
- Measure distance to get "lookback time" (how long the light took to reach us)
- Measure redshift to get amount of expansion over that time.

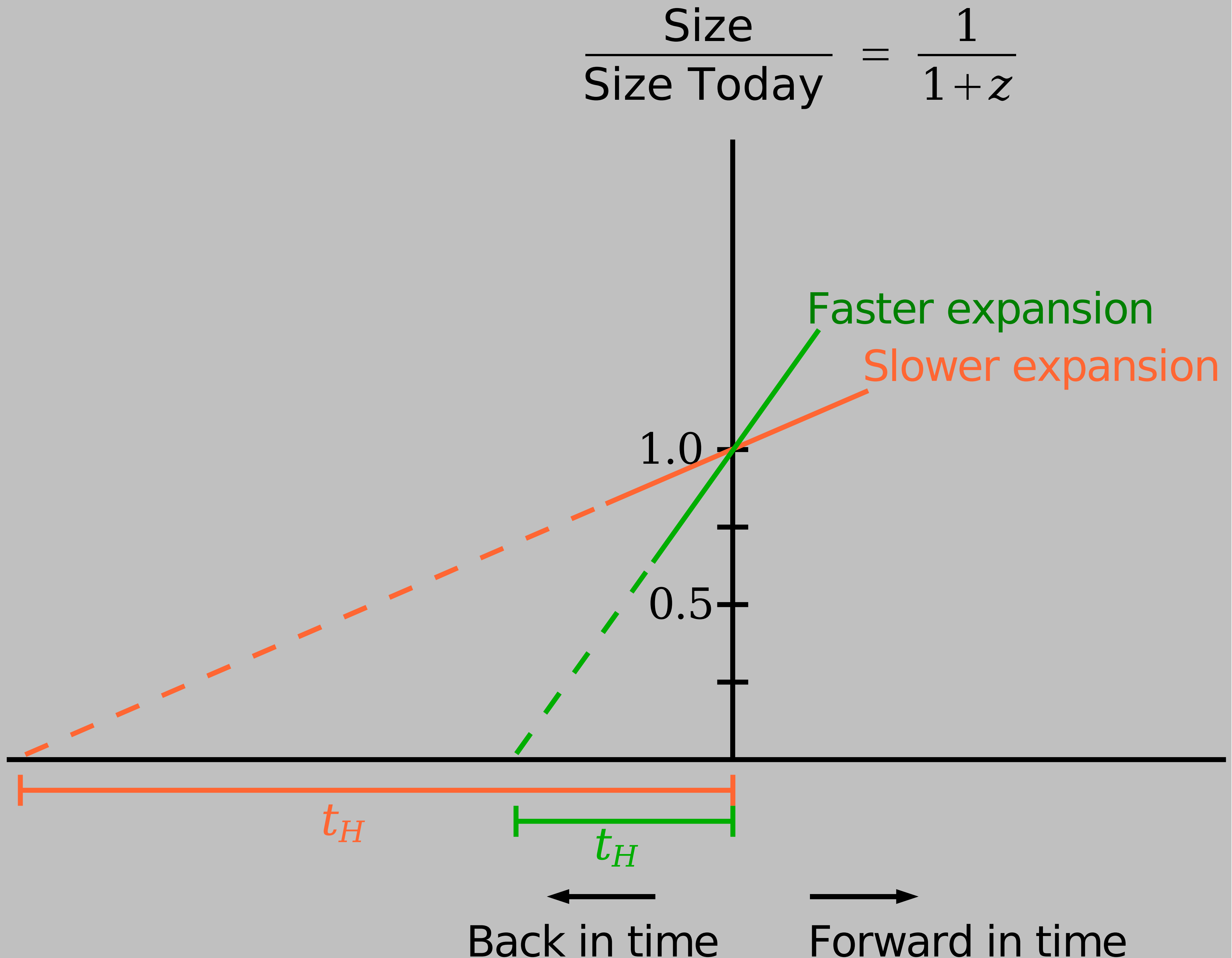
$$\frac{\text{Size}}{\text{Size Today}} = \frac{1}{1+z}$$



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?





$\frac{\text{Size}}{\text{Size Today}} = \frac{1}{1+z}$
Faster expansion
Slower expansion
1.0
0.5
t_H
t_H
Back in time
Forward in time

The meaning of the Hubble Time t_H

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

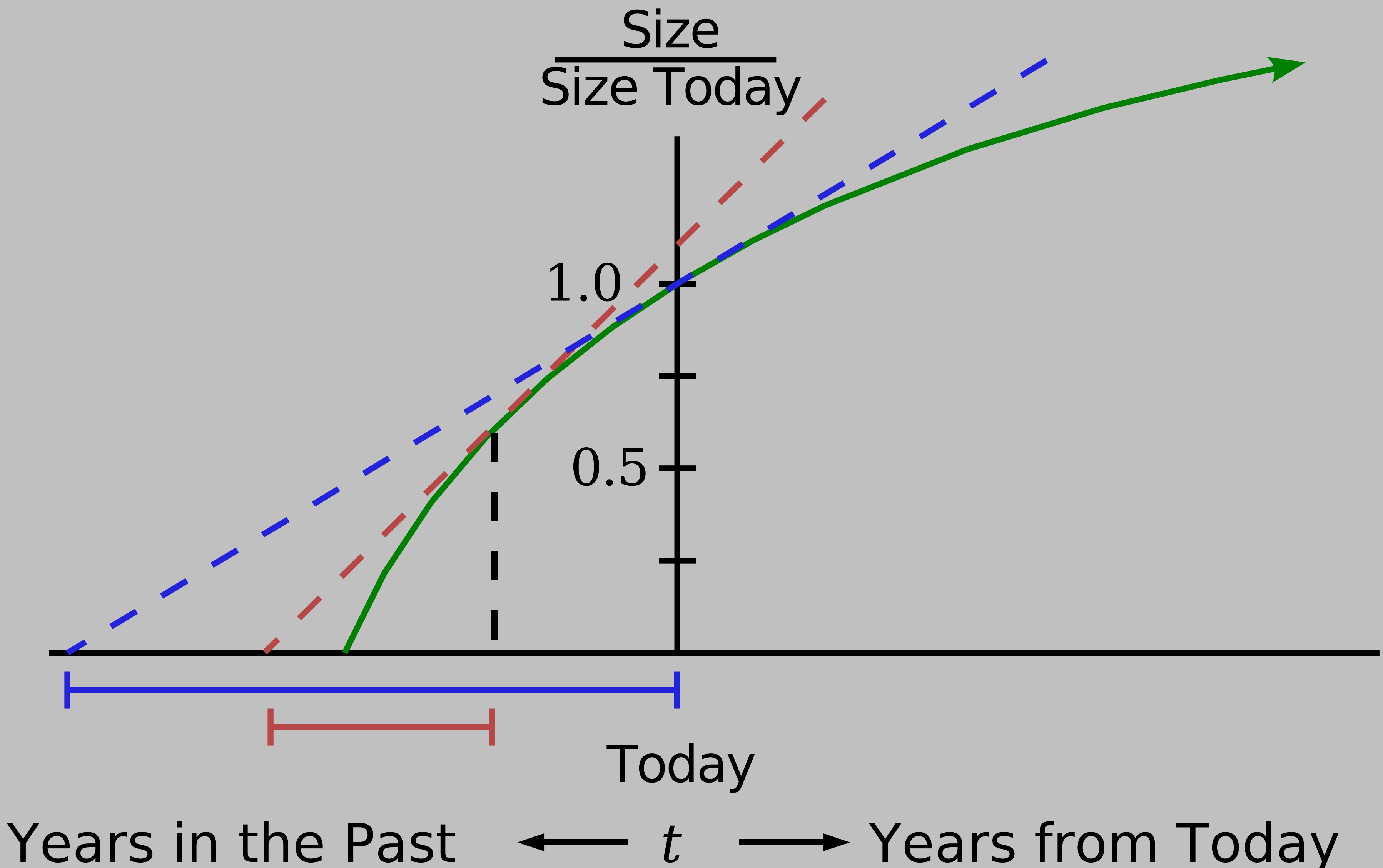
t_H gives you the expansion rate of the Universe:
Higher t_H = slower expansion

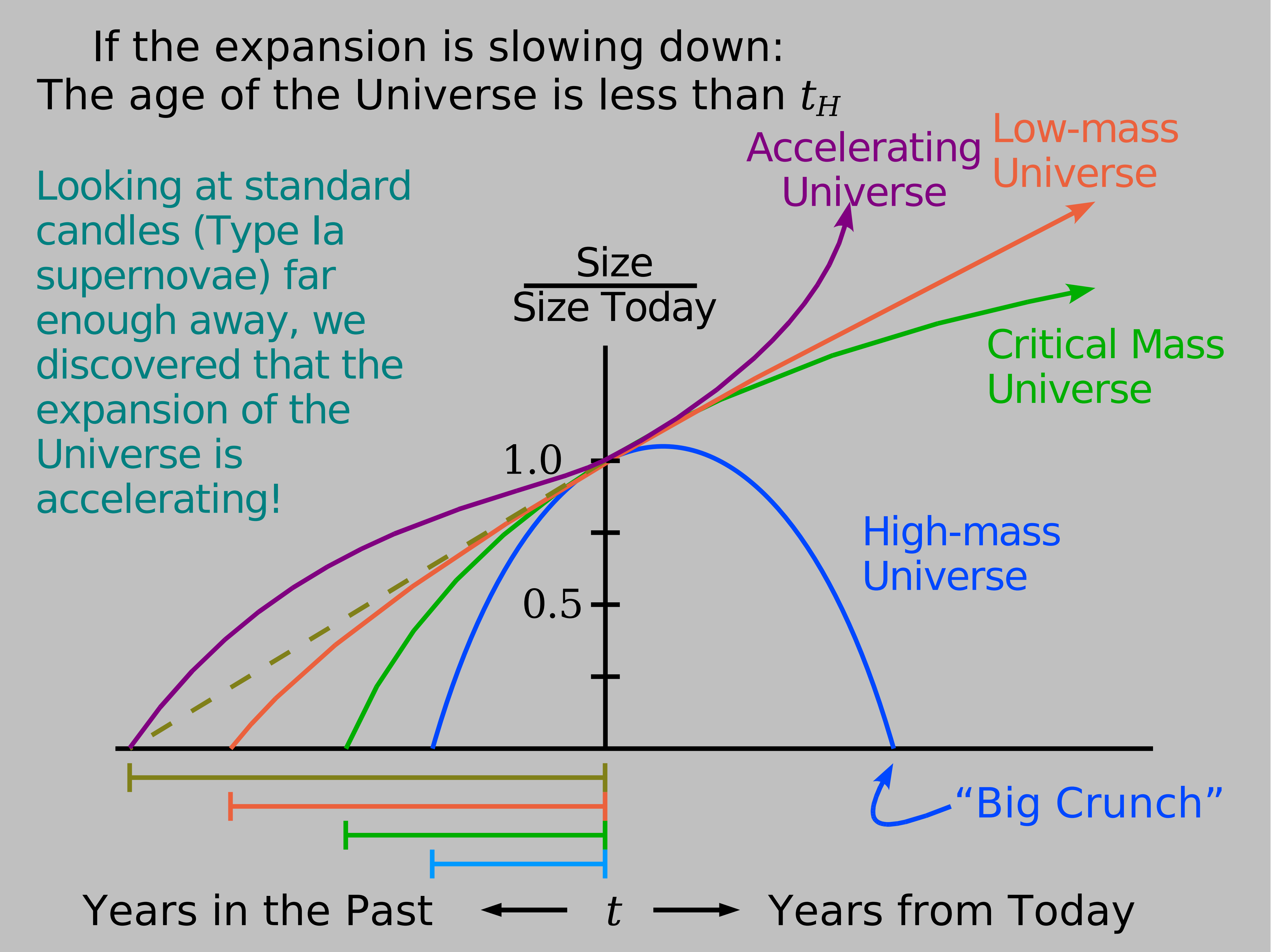
t_H is the "doubling time" – how long it will take the size of the Universe to double from right now iif the expansion rate remains constant.

t_H is the age of the Universe *if* the expansion rate has always been constant and equal to the current expansion rate.

If the expansion is slowing down:

expansion rate was higher in the past than it is today




If the expansion is slowing down:
The age of the Universe is less than t_H
Looking at standard candles (Type Ia supernovae) far enough away, we discovered that the expansion of the Universe is accelerating!
Accelerating Universe
Low-mass Universe
Critical Mass Universe
High-mass Universe
Size / Size Today
1.0
0.5
"Big Crunch"
Years in the Past
t
Years from Today