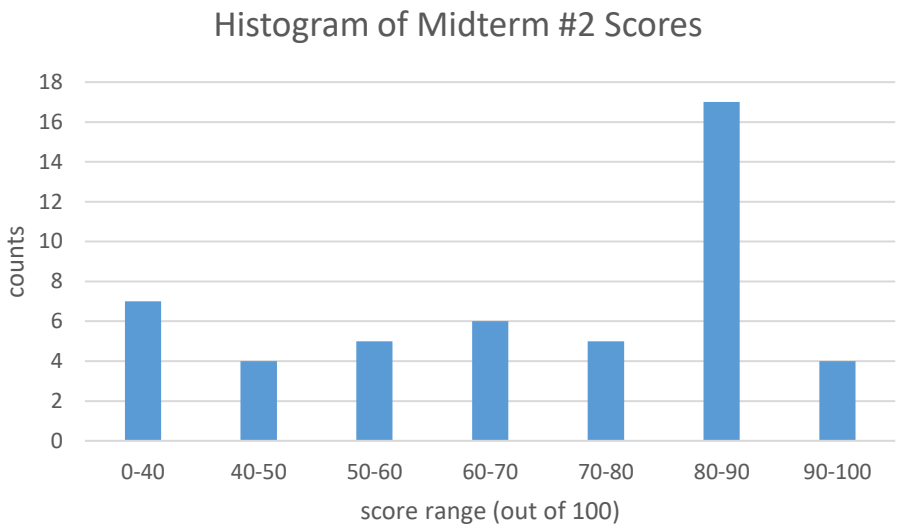
# Midterm #2 Results

Average score = 67.3 /100

Median = 72.5/100

High score = 95 /100




| | Problem #1 | Problem #2 | Problem #3 | Problem #4 |
|---|---|---|---|---|
| average = | 19.0 /25 | 14.6 /25 | 16.8 /25 | 16.9 /25 |

# Today's Topics

Wednesday, April 30, 2025 (Week 13, lecture 35) – Chapter 29.

1. Expanding universe.

2. Critical density.

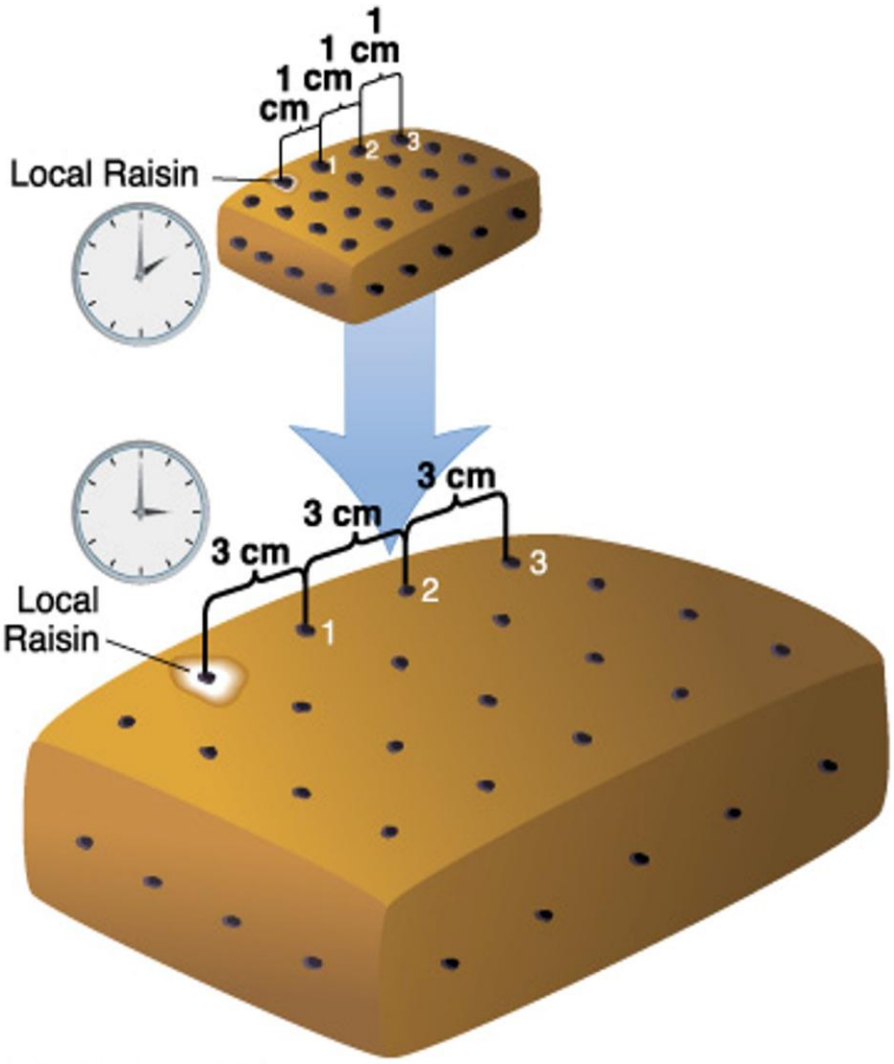
3. Accelerating universe.

**Final Exam** is on Thursday, May 8 at 9:00 am – noon, in this room

# Expansion of Universe: Space is stretching

**Reminder** (from Lecture 31)

- From **Hubble's law**, we saw that the universe must be expanding.
- Over time, galaxy clusters will get further and **further apart**.
- **One view** is that the increasing distance is due to the **different velocities** of the galaxy clusters.
- **Another view** is that **space is actually expanding**, i.e. stretching out.

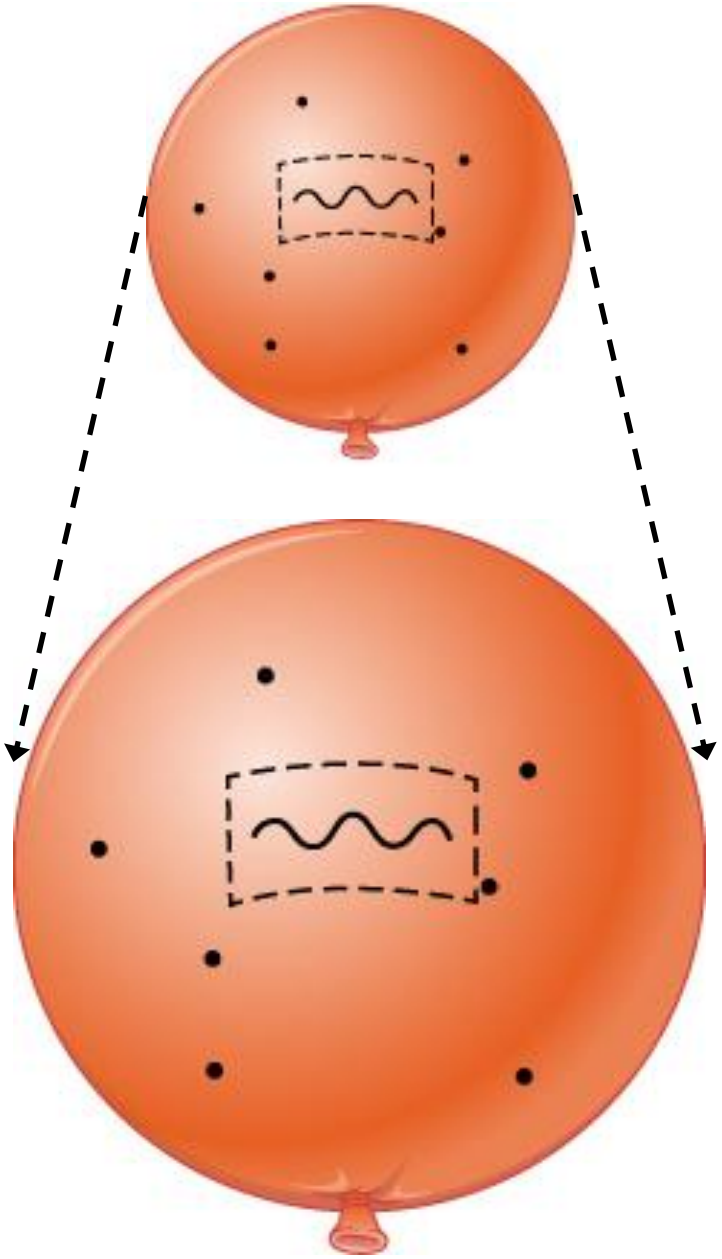


# Expansion of Universe – Redshift

The **redshift of light** can be thought of as due to the expansion of space (instead of the receding velocity of the emitter).

→ The light waves get stretched out as space stretches out.

→ Over time, the wavelength gets longer and longer as space stretches.



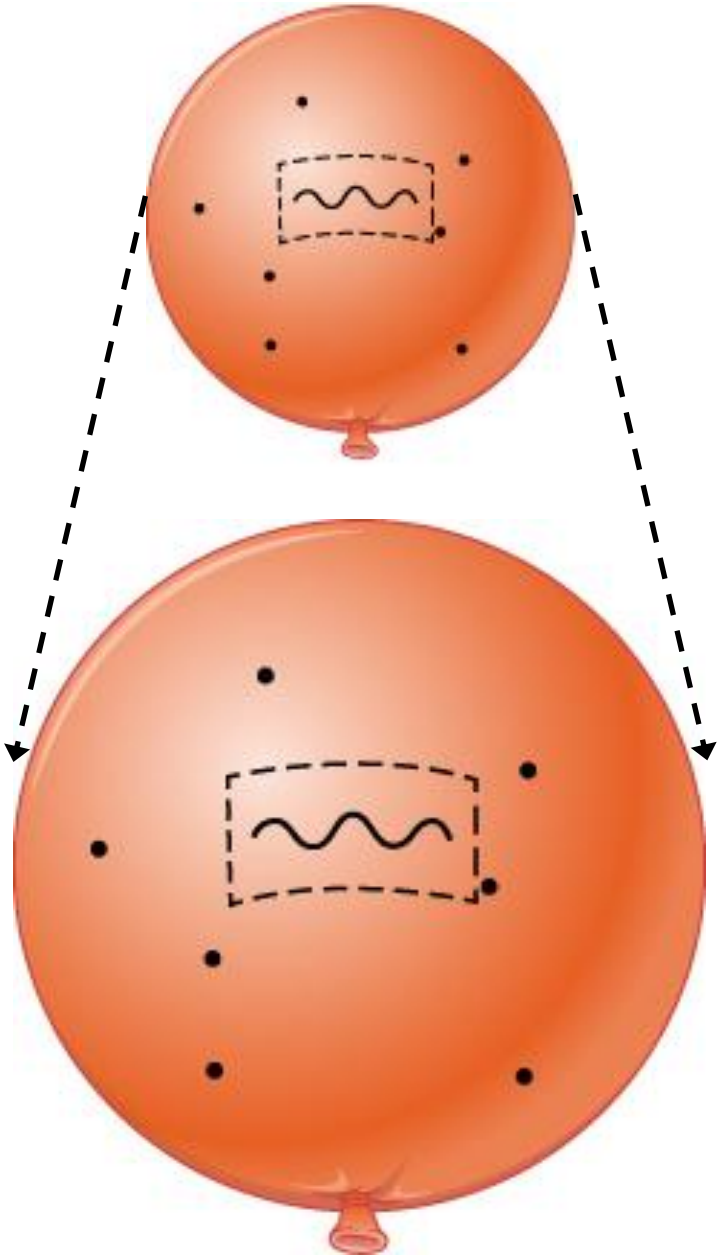
# Expansion of Universe – Redshift

The **redshift of light** can be thought of as due to the expansion of space (instead of the receding velocity of the emitter).

→ The light waves get stretched out as space stretches out.

→ Over time, the wavelength gets longer and longer as space stretches.

**Question 1:** Will a house slowly get bigger over time, due to the expansion of space?



# Expansion of Universe – Redshift

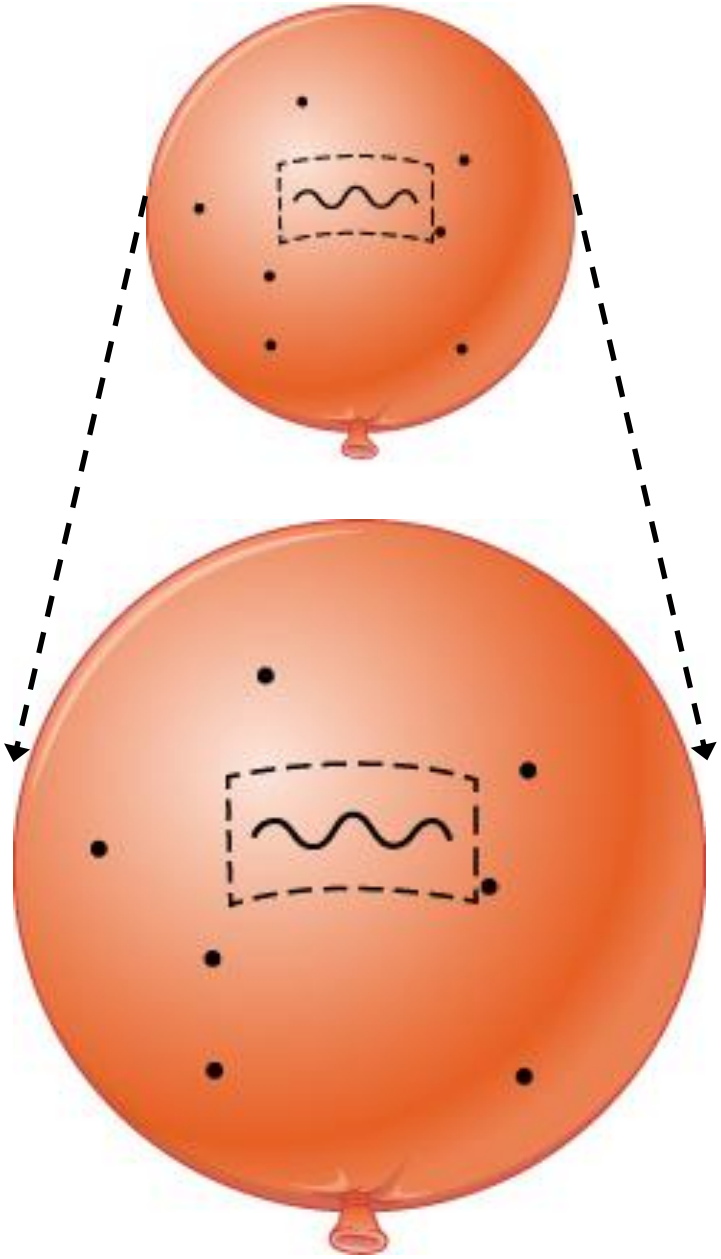
The **redshift of light** can be thought of as due to the expansion of space (instead of the receding velocity of the emitter).

→ The light waves get stretched out as space stretches out.

→ Over time, the wavelength gets longer and longer as space stretches.

**Question 1:** Will a house slowly get bigger over time, due to the expansion of space?

**Answer 1:** No, the electromagnetic interaction (which binds matter together chemically) is strong enough to prevent the house from expanding.



# Expansion of Universe – Redshift

The **redshift of light** can be thought of as due to the expansion of space (instead of the receding velocity of the emitter).

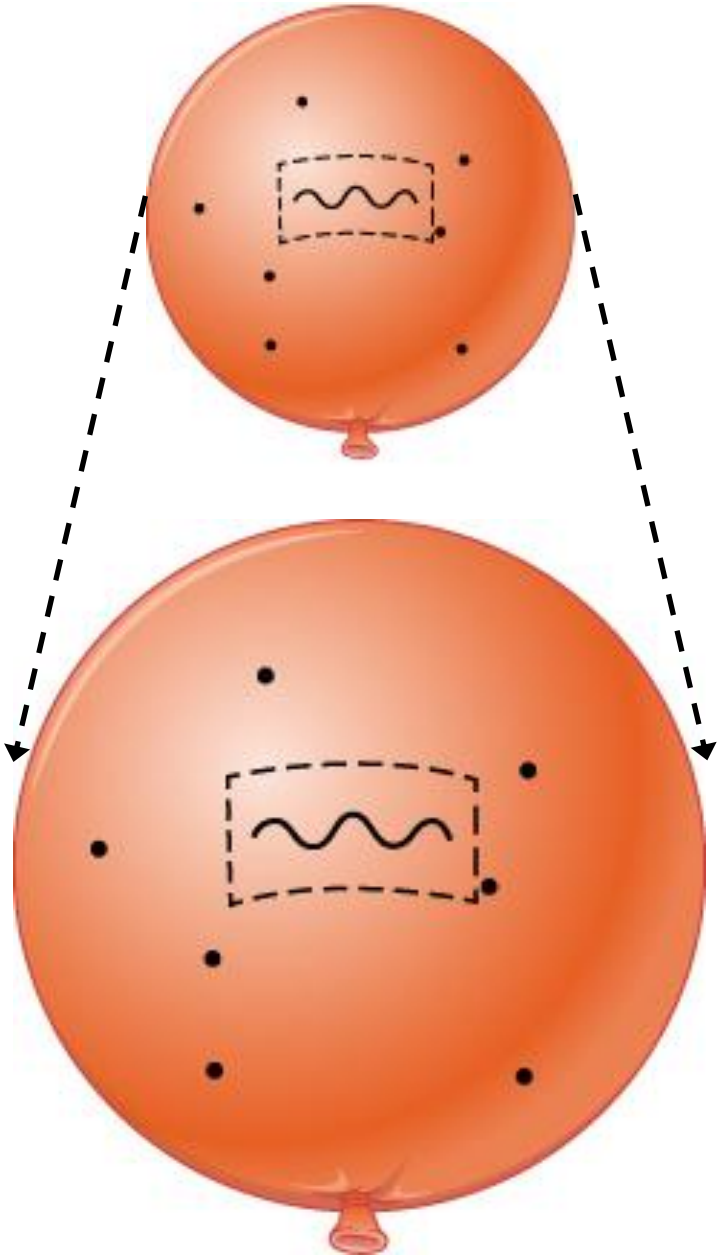
→ The light waves get stretched out as space stretches out.

→ Over time, the wavelength gets longer and longer as space stretches.

**Question 1:** Will a house slowly get bigger over time, due to the expansion of space?

**Answer 1:** No, the electromagnetic interaction (which binds matter together chemically) is strong enough to prevent the house from expanding.

**Question 2:** Will a galaxy get bigger over time, due to the expansion of space?

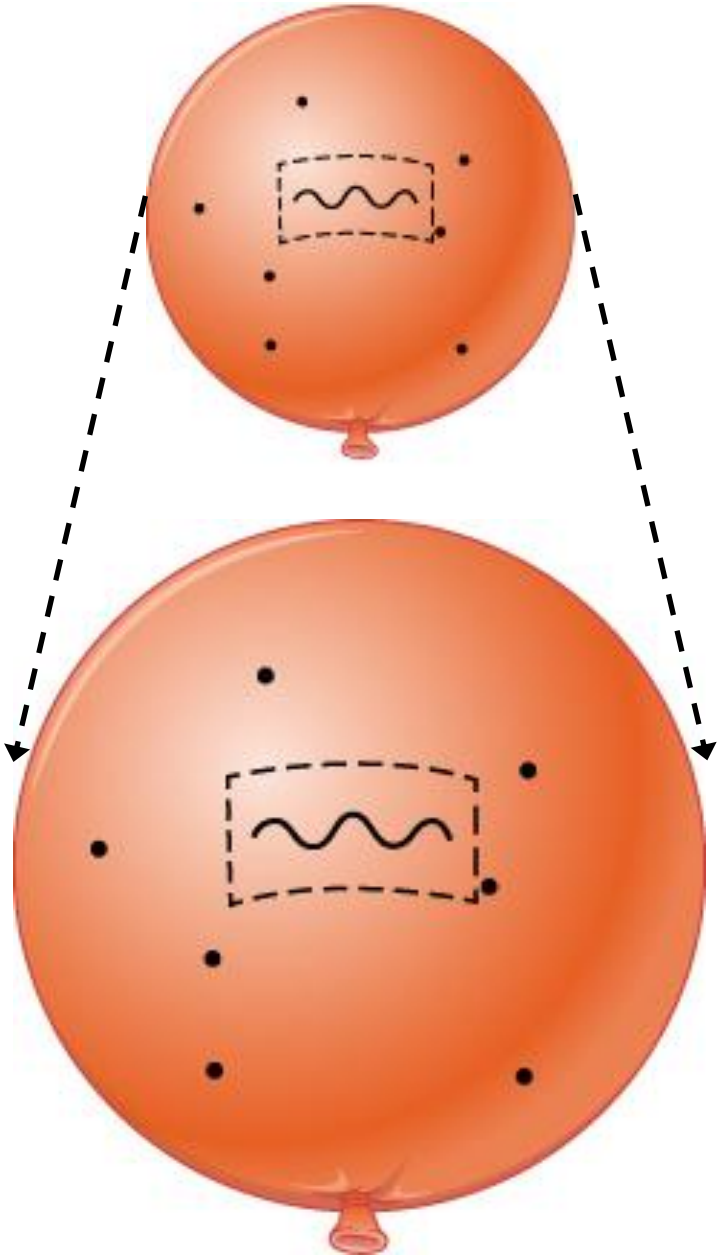


# Expansion of Universe – Redshift

The **redshift of light** can be thought of as due to the expansion of space (instead of the receding velocity of the emitter).

→ The light waves get stretched out as space stretches out.

→ Over time, the wavelength gets longer and longer as space stretches.



**Question 1:** Will a house slowly get bigger over time, due to the expansion of space.

**Answer 1:** No, the electromagnetic interaction (which binds matter together chemically) is strong enough to prevent your house from expanding.

**Question 2:** Will a galaxy get bigger over time, due to the expansion of space?

**Answer 2:** No, the gravitational attraction between nearby stars is strong enough to prevent the galaxy from expanding.

# Closed universe?

**Question 3:** Will a galaxy supercluster get bigger over time, due to the expansion of space?

**Answer 3:** No, the gravitational attraction between nearby galaxies (dark matter included) is still strong enough to prevent the supercluster from expanding.

# Closed universe?

**Question 3:** Will a galaxy supercluster get bigger over time, due to the expansion of space?

**Answer 3:** No, the gravitational attraction between nearby galaxies (dark matter included) is still strong enough to prevent the supercluster from expanding.

**Question 4:** Could the gravity of the whole universe be enough to prevent its expansion?

… Well, the universe is expanding, so it seems like the answer is no.

# Closed universe?

**Question 3:** Will a galaxy supercluster get bigger over time, due to the expansion of space?

**Answer 3:** No, the gravitational attraction between nearby galaxies (dark matter included) is still strong enough to prevent the supercluster from expanding.

**Question 4:** Could the gravity of the whole universe be enough to prevent its expansion?

… Well, the universe is expanding, so it seems like the answer is no.

**Question 4 -- rephrased:** Could the gravity of the whole universe be enough to slow down and stop the expansion of the universe?

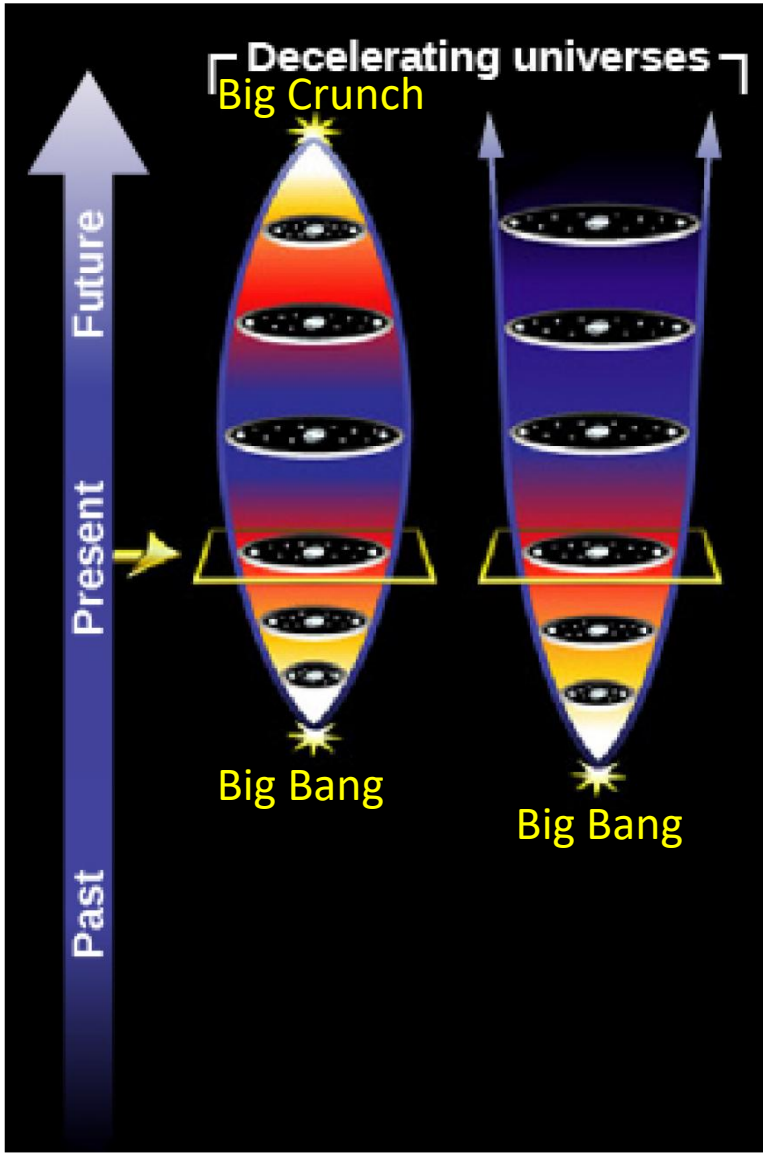
**Answer 4:** If the universe has enough matter in it (including dark matter), then this gravitational self-attraction could slow down and stop the expansion of the universe … and possibly lead to its contraction, i.e. a closed universe.

# Closed Universe vs Open Universe

**Scenario 1: "Big Crunch"**
The universe has a lot of matter (including dark matter), and the universe's gravitational self attraction is enough to slow, halt, and reverse the expansion of the universe (initiated by the big bang).

**Scenario 2: Continued expansion, but slowing down**
The gravity from the matter in the universe slows down the expansion of the universe but not sufficiently to stop it.

**Scenario 3: Expansion stops at infinite time**
There is just enough matter in the universe to slow down the expansion of the universe and bring to a halt at infinite time.

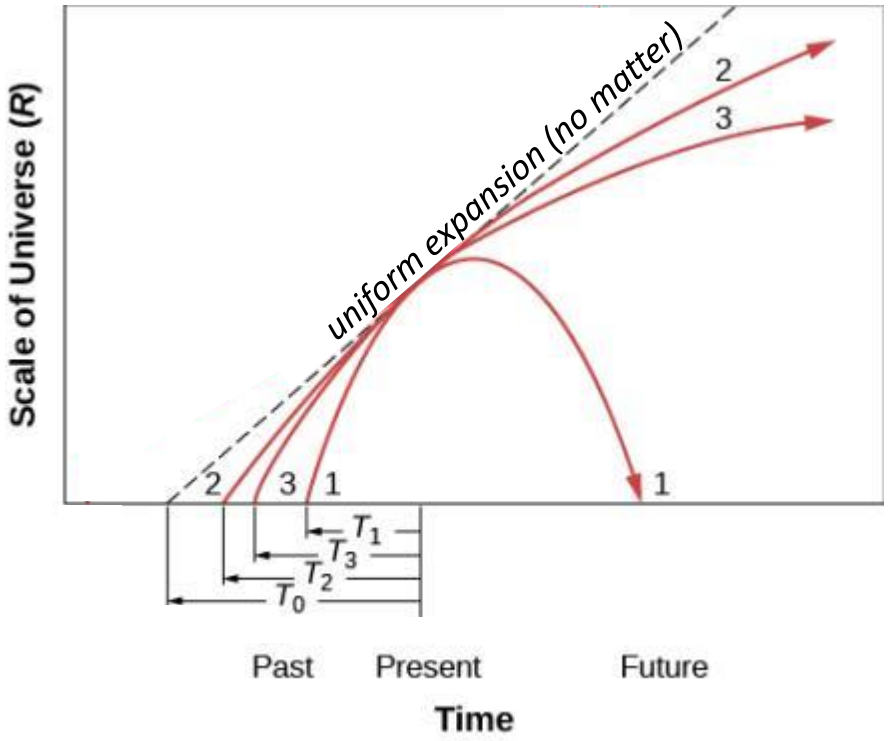


# Closed Universe vs Open Universe

**Scenario 1: "Big Crunch"**
The universe has a lot of matter (including dark matter), and the universe's gravitational self attraction is enough to slow, halt, and reverse the expansion of the universe (initiated by the big bang).

**Scenario 2: Continued expansion, but slowing down**
The gravity from the matter in the universe slows down the expansion of the universe but not sufficiently to stop it.

**Scenario 3: Expansion stops at infinite time**
There is just enough matter in the universe to slow down the expansion of the universe and bring to a halt at infinite time.



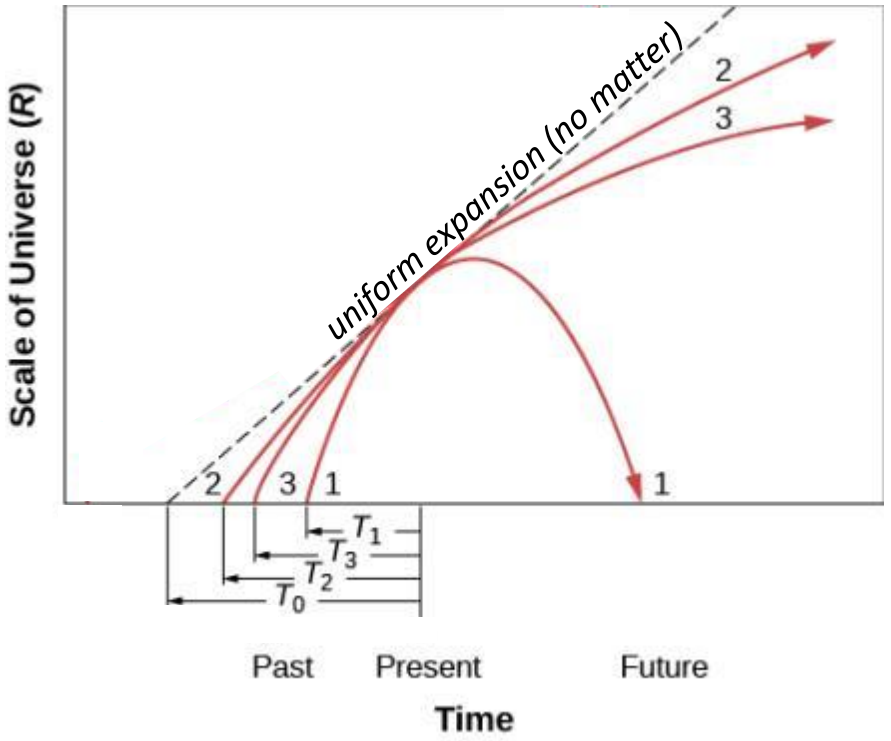

**Question:** How much matter is required to bring the universe's expansion to a stop at infinite time?

# Closed Universe vs Open Universe

**Scenario 1: "Big Crunch"**
The universe has a lot of matter (including dark matter), and the universe's gravitational self attraction is enough to slow, halt, and reverse the expansion of the universe (initiated by the big bang).

**Scenario 2: Continued expansion, but slowing down**
The gravity from the matter in the universe slows down the expansion of the universe but not sufficiently to stop it.

**Scenario 3: Expansion stops at infinite time**
There is just enough matter in the universe to slow down the expansion of the universe and bring to a halt at infinite time.

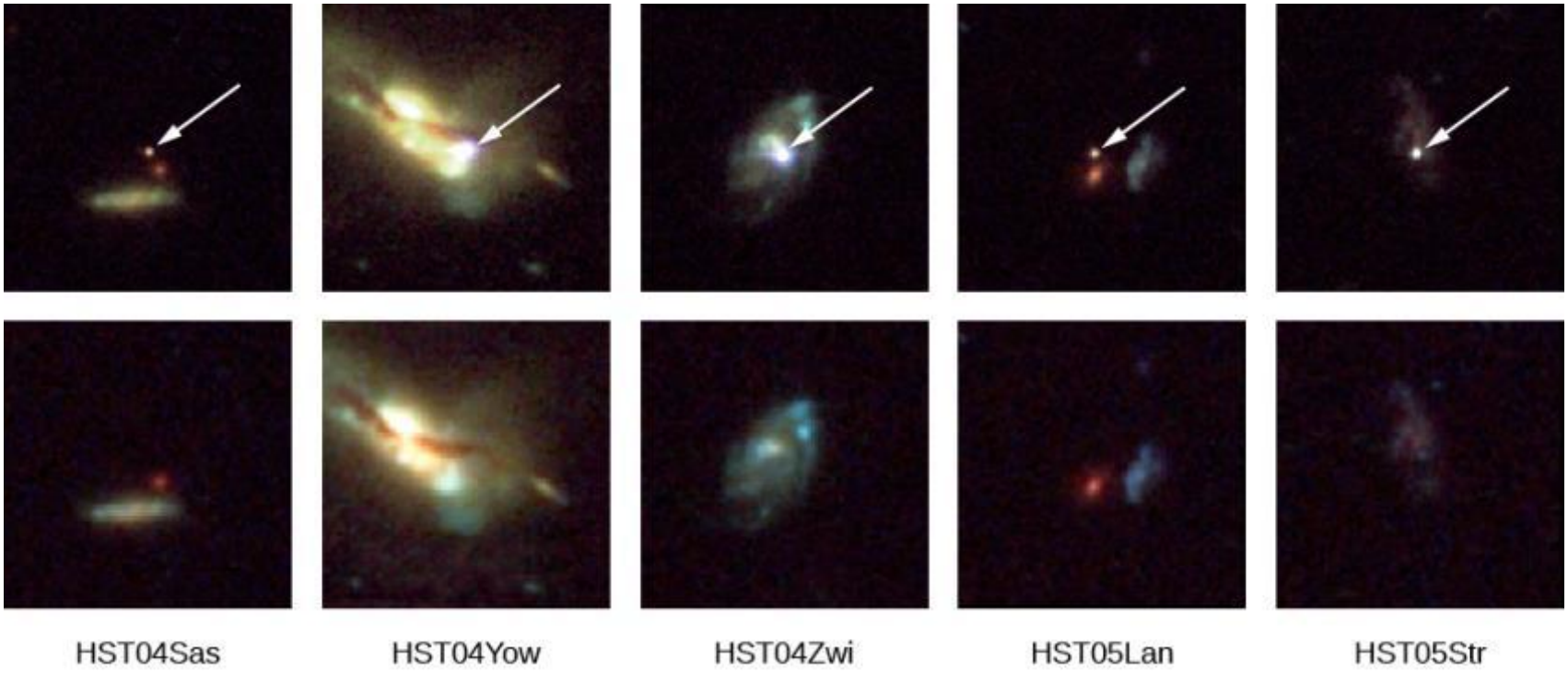



**Question:** How much matter is required to bring the universe's expansion to a stop at infinite time?

**Question -- rephrased:** What is the average density (kg/m$^3$) of matter required to bring the universe's expansion to a stop at infinite time?

# The Revolution of 1998

Two research teams measured the distance to very far galaxies using type 1a supernovae as standard candles.




**Five Supernovae and Their Host Galaxies.** The top row shows each galaxy and its supernova (arrow). The bottom row shows the same galaxies either before or after the supernovae exploded.

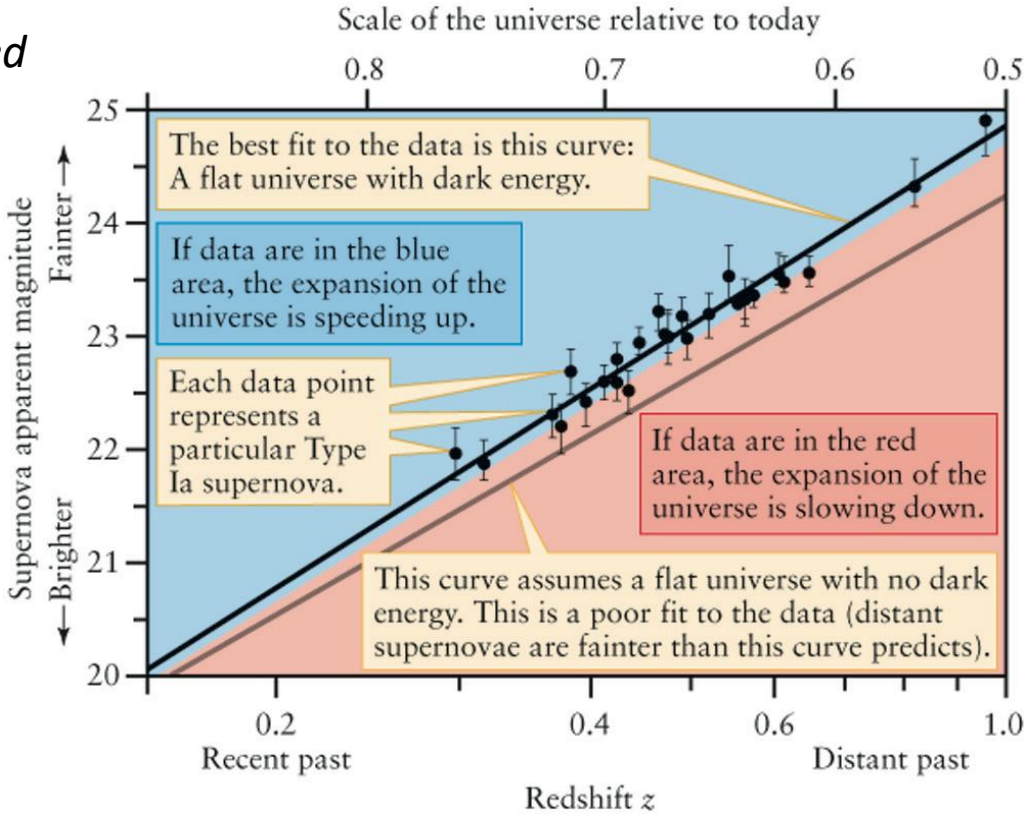
[credit: modification of work by NASA, ESA, and A. Riess (STScI)]

# Hubble constant NOT constant !!

**1998:** Measurements using type 1a supernovae reveal that the expansion of the universe is slowly accelerating.

Distant supernova *fainter than predicted* using Hubble's law and the value of H from closer galaxies.

→ Distant galaxies are further than expected from Hubble's law.



# Hubble constant NOT constant !!

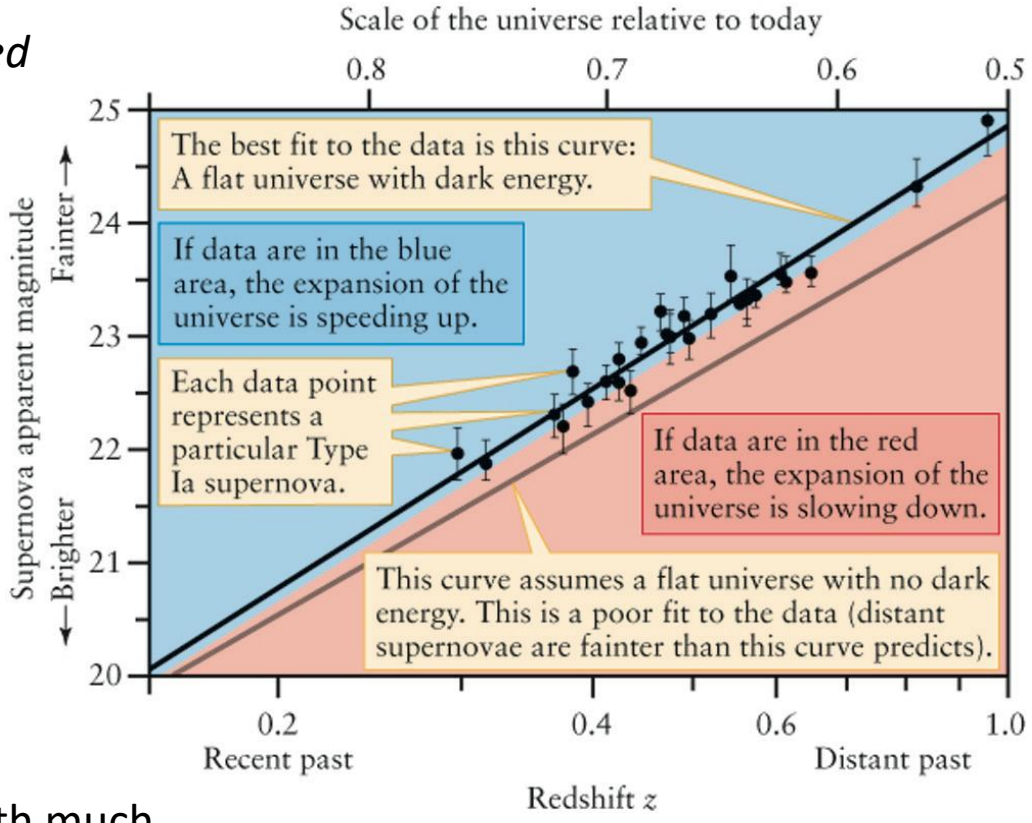
**1998:** Measurements using type 1a supernovae reveal that the expansion of the universe is slowly accelerating.

Distant supernova *fainter than predicted* using Hubble's law and the value of H from closer galaxies.

→ Distant galaxies are further than expected from Hubble's law.

Solution: The Hubble constant is ***not*** a constant*.

→ The expansion of the universe is accelerating!

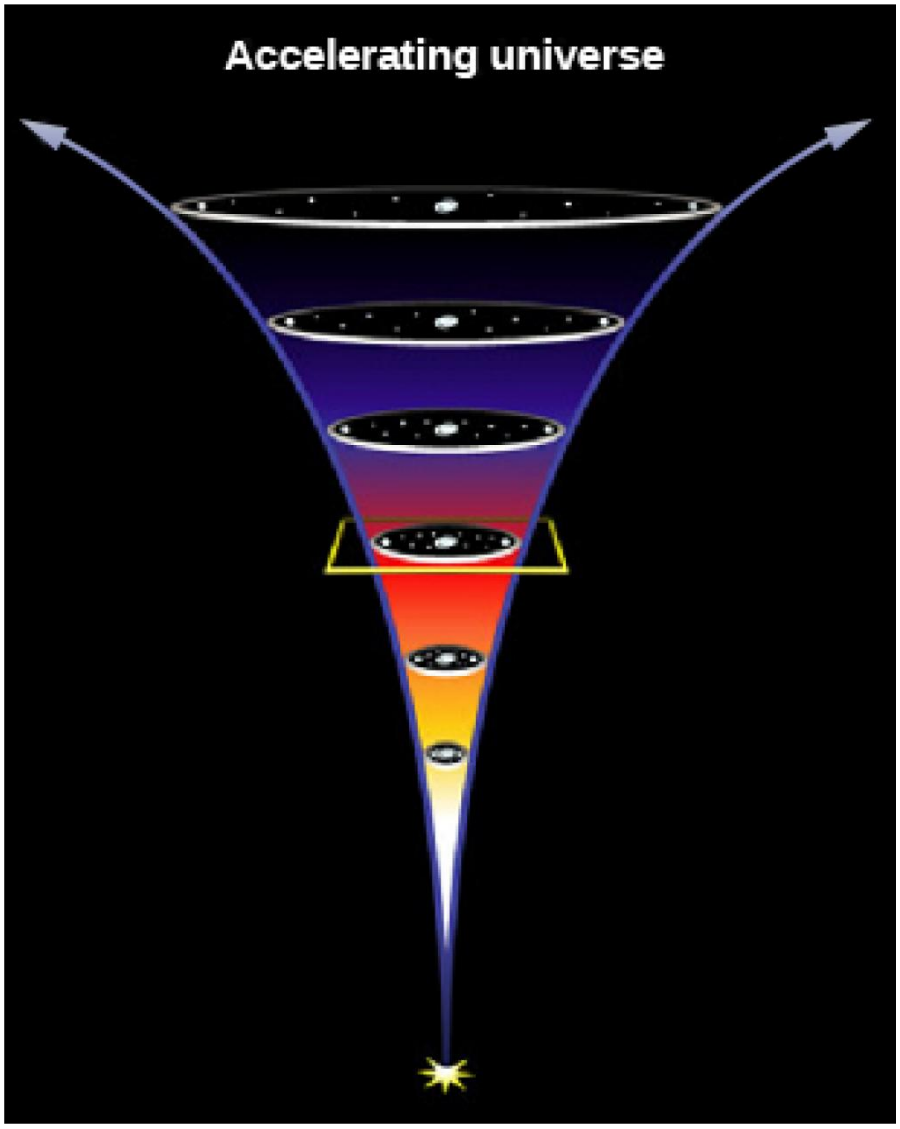



Since then, this has been confirmed with much more observational data.

**Note: The value we now quote for Hubble's constant H is the value at the present time.*

# Accelerating Expansion: Dark Energy

**Question:** How can they expansion of the universe be accelerating?



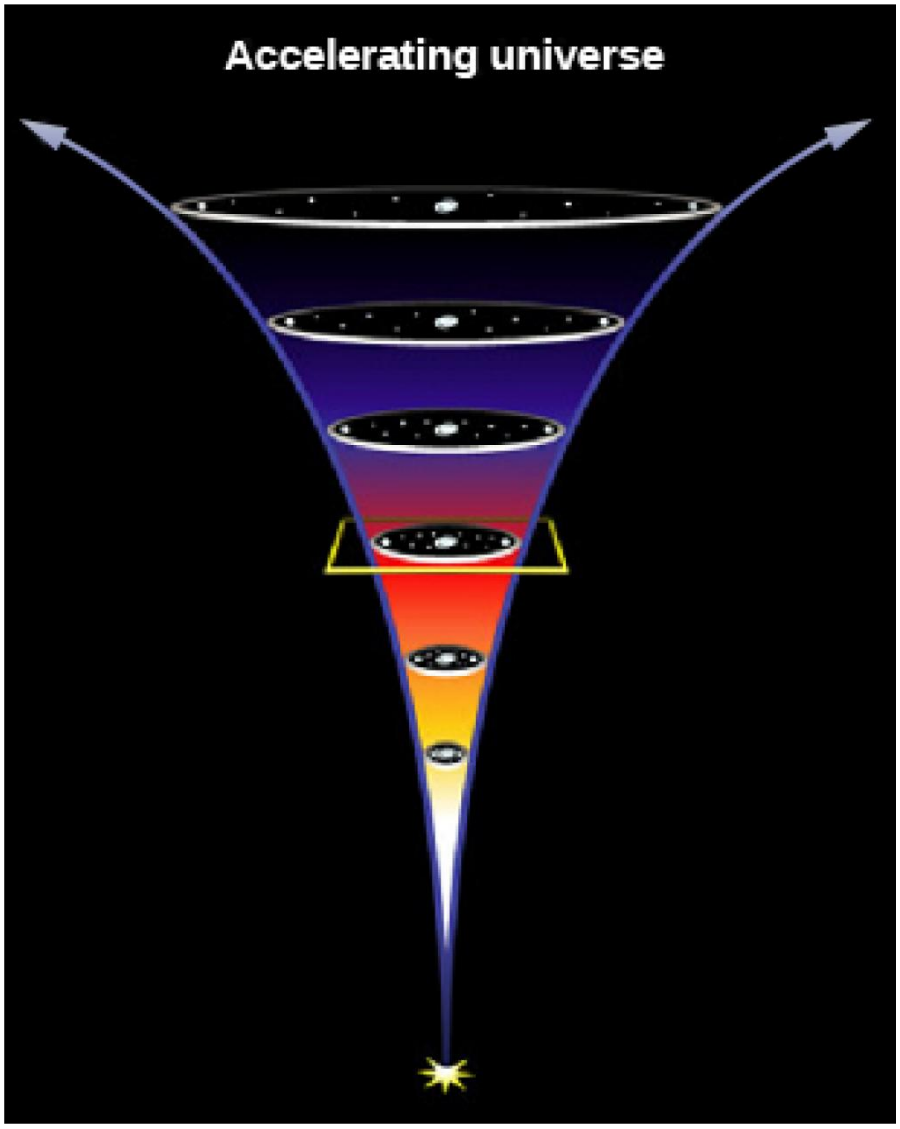
# Accelerating Expansion: Dark Energy

**Question:** How can they expansion of the universe be accelerating?

**Answer:** Something ***other*** than gravity must be acting.

We call it **Dark Energy**.

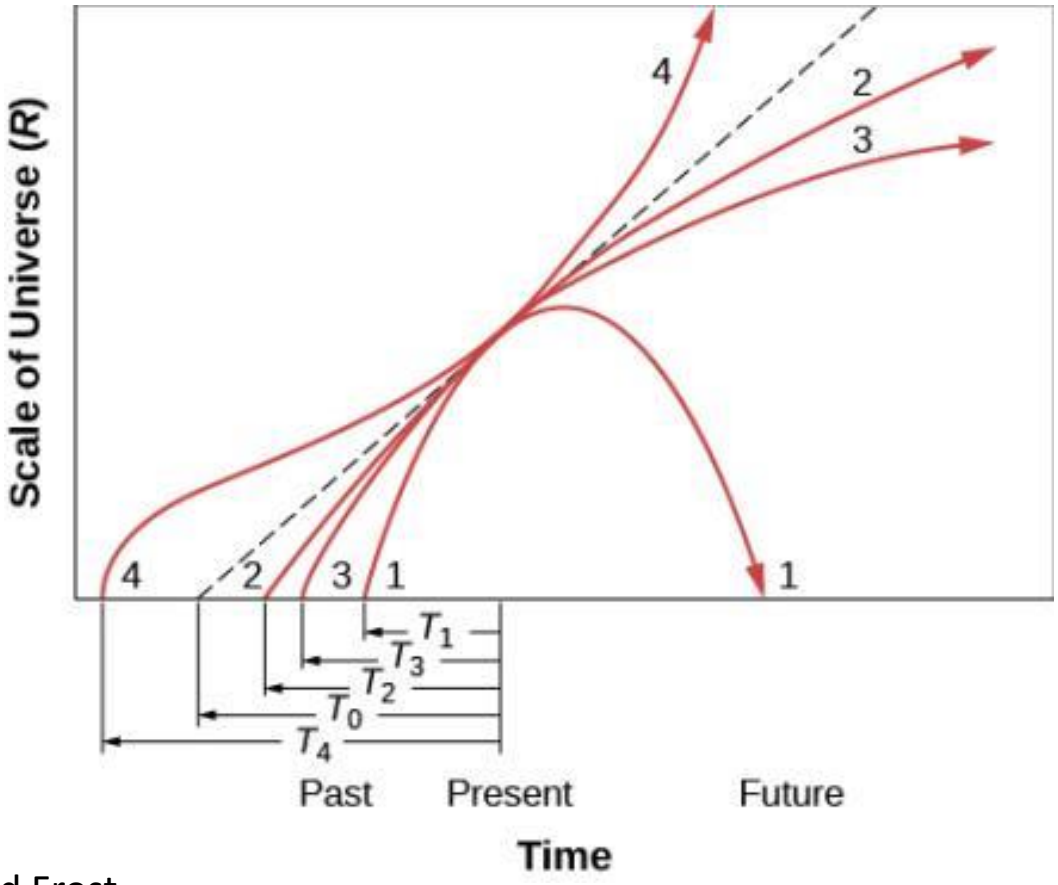
→ It causes some sort of repulsive force: like a **pressure** in empty space.



# Scenario 4: Accelerating Expansion

*Some say the world will end in fire,*
*Some say in ice.*
*From what I've tasted of desire*
*I hold with those who favor fire.*
*But if it had to perish twice,*
*I think I know enough of hate*
*To say that for destruction ice*
*Is also great*
*And would suffice.*

Fire and Ice, Robert Frost (1920)




Note: Harlow Shapley claimed to have inspired Frost after a conversation about an astronomer's view of the fate of the world.

→ Current evidence is pointing to an icy end to the universe.