

Today's Topics

Wednesday, April 29, 2026 (Week 13, lecture 36) – Chapter 29.

0. Large scale galaxy distribution
1. Expanding universe.
2. Critical density.
3. Accelerating universe.

Final Exam is on Wednesday, May 6 at 9:00 am – noon, in this room

Course Evaluations

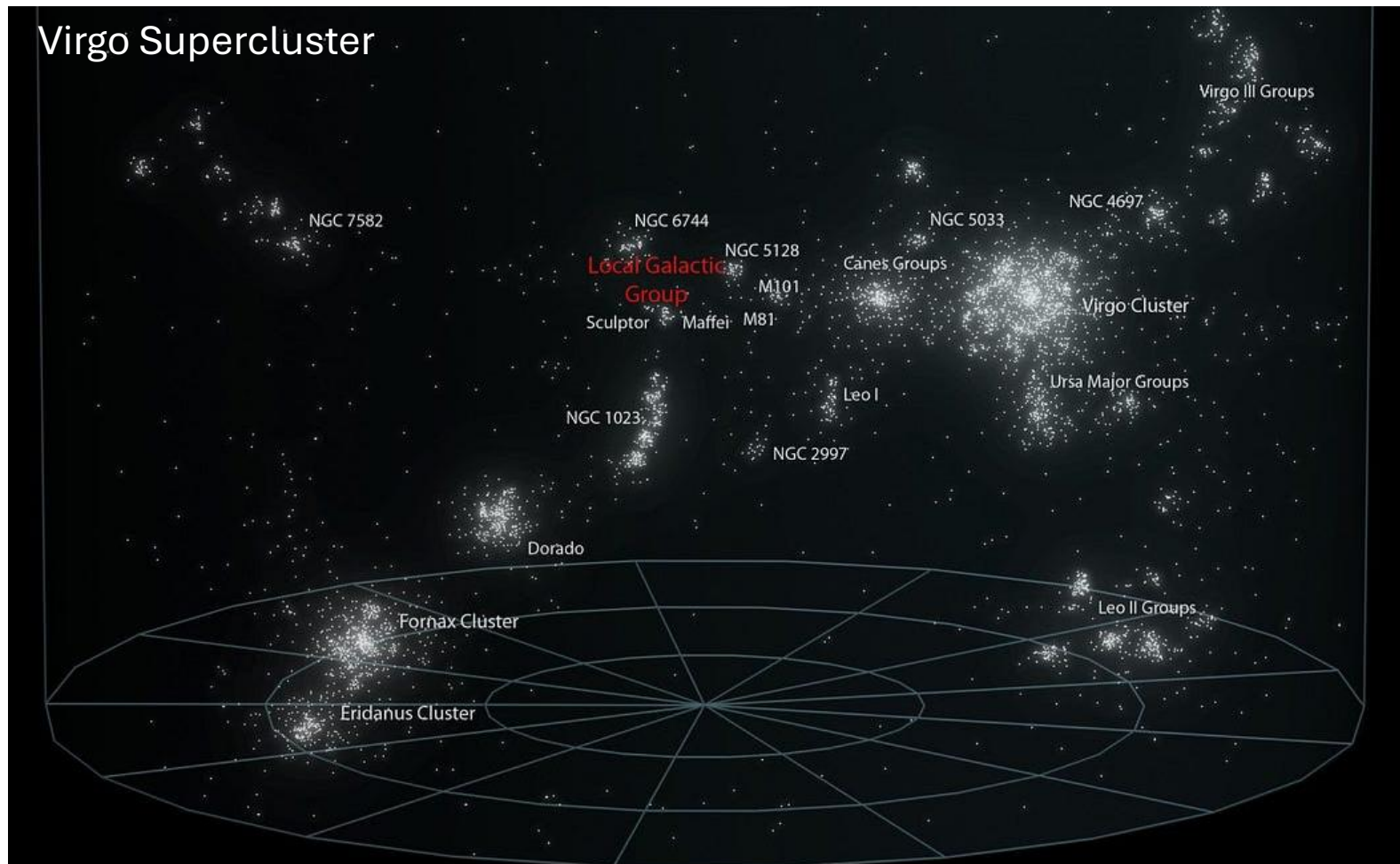
Please fill out.

Interested in the following info:

- Quality of textbook.
- Quality of ExpertTA & problems.
- Quality of Interlude 1 & 2 topics.
- Comments on Midterm tests.
- Comments on grading (essays and midterms)
- More quantitative vs less quantitative.
- More PowerPoint vs more handwritten notes.
- Comments on structure of lectures.
- Did you use the free tutoring (Thursdays 6-8 pm, Small Hall 122)?
- Comments on office hours.

Virgo Cluster & Supercluster

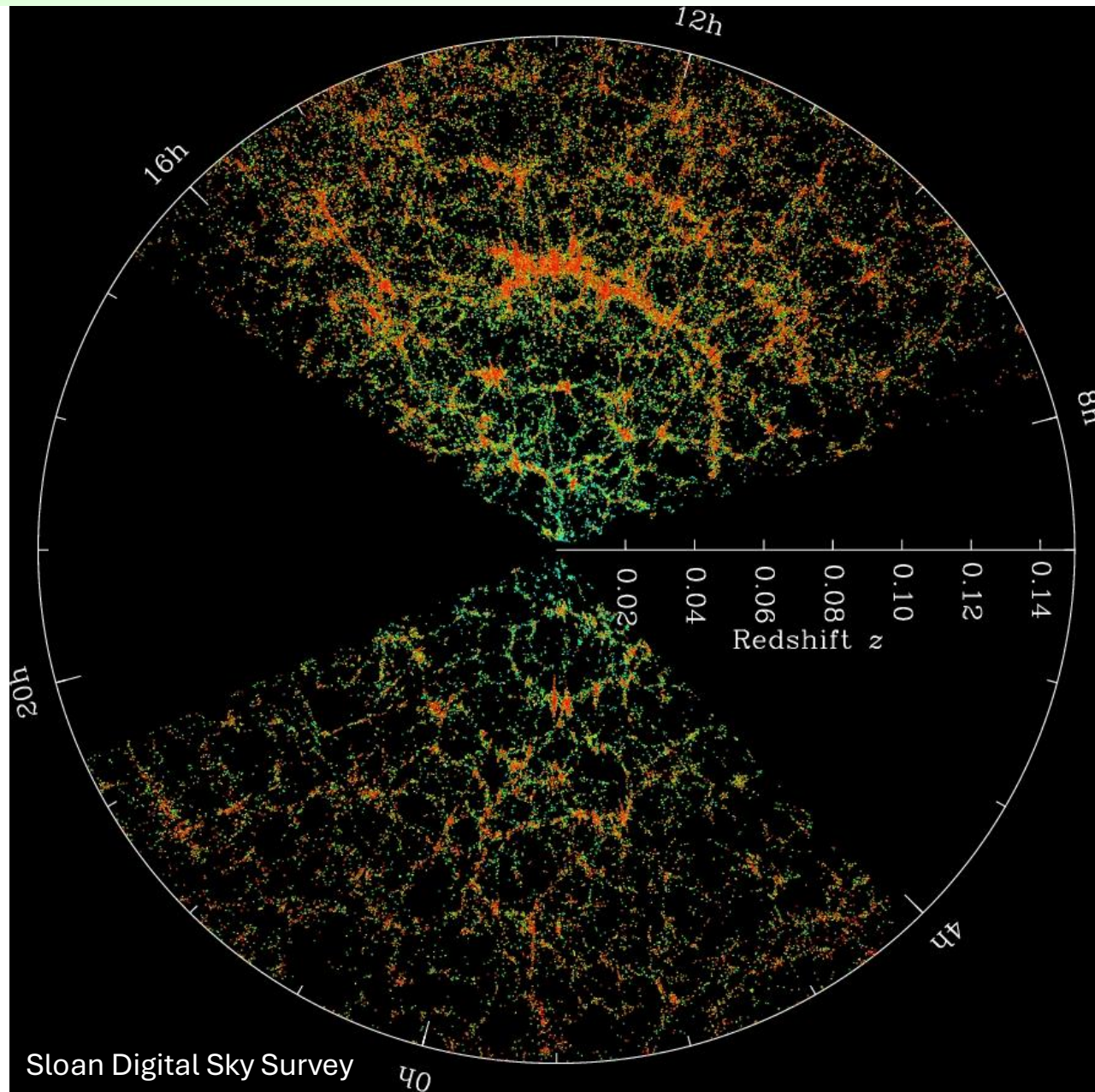
- Nearest cluster of galaxies is the Virgo cluster: about 2000 galaxies (distance: 50 Mly).
- The local group and the Virgo cluster are part of the Virgo Supercluster.
 - Consists of about 100 clusters and groups.



Large Scale Distribution of Galaxies

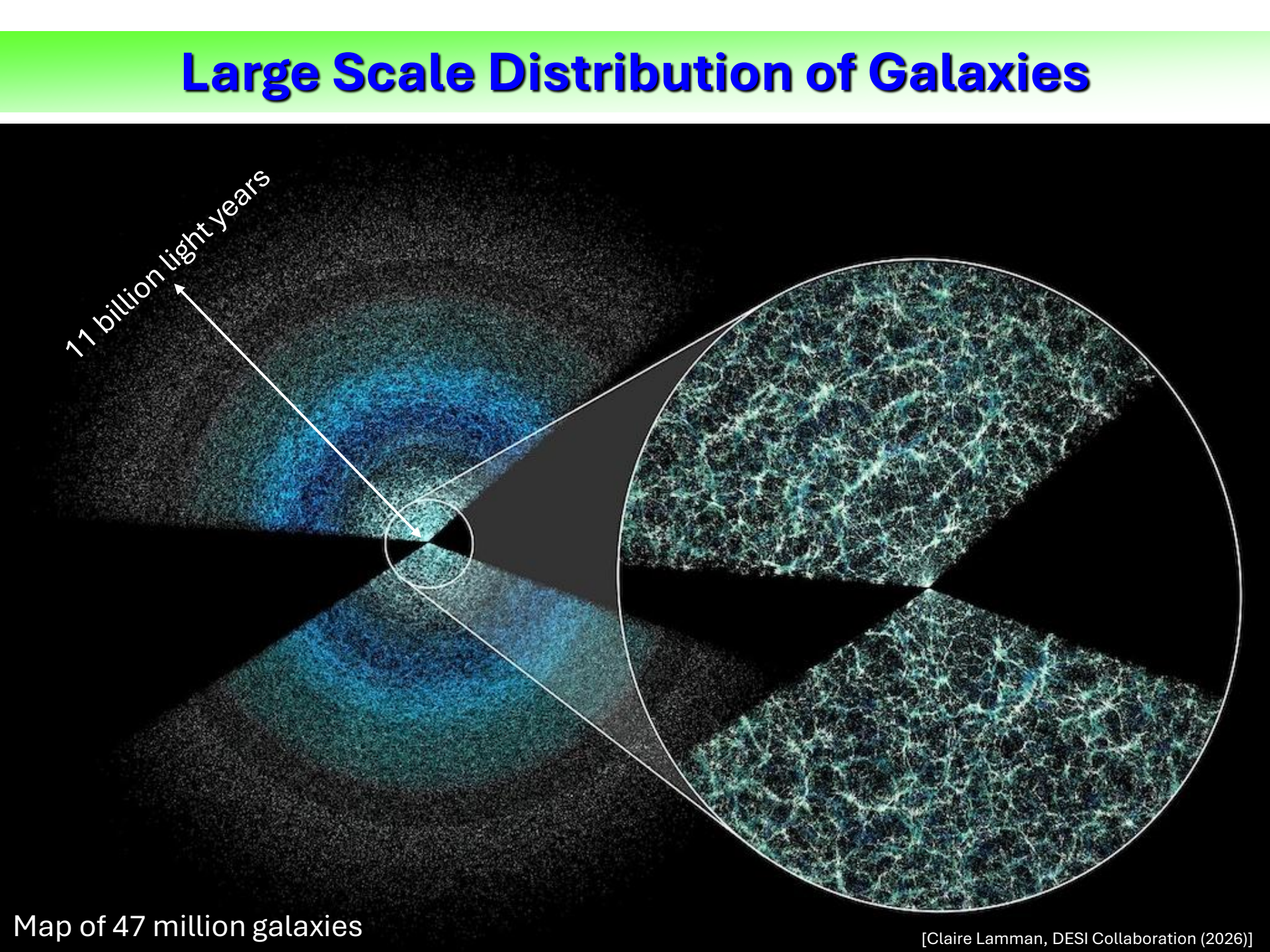
Sloan Digital Sky Survey

- 980,000 galaxies mapped.
→ Image: slice through sky
(black regions blocked by Milky Way dust)
- Distance from the center of the circle is redshift (*i.e.* distance from us).
- Circle is 2 billion light years in radius.
- Filamentary structure of superclusters (string-like or pancake like).
- Huge **Voids**.
- Overall structure is like a **sponge**, or **Swiss cheese**...



Large Scale Distribution of Galaxies

11 billion light years

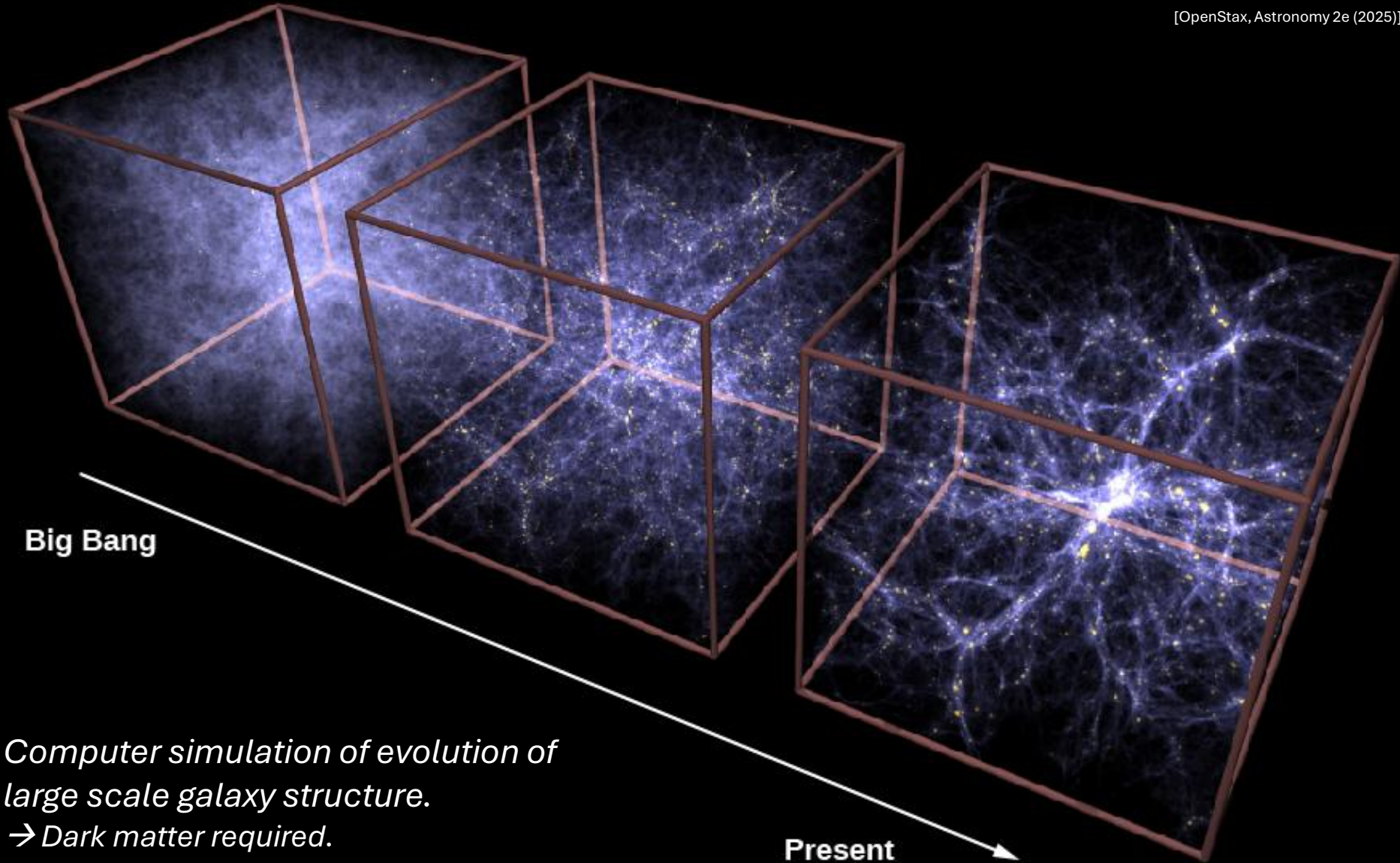


Map of 47 million galaxies

[Claire Lamman, DESI Collaboration (2026)]

Large Scale Distribution of Galaxies

[OpenStax, Astronomy 2e (2025)]



Big Bang

Computer simulation of evolution of large scale galaxy structure.

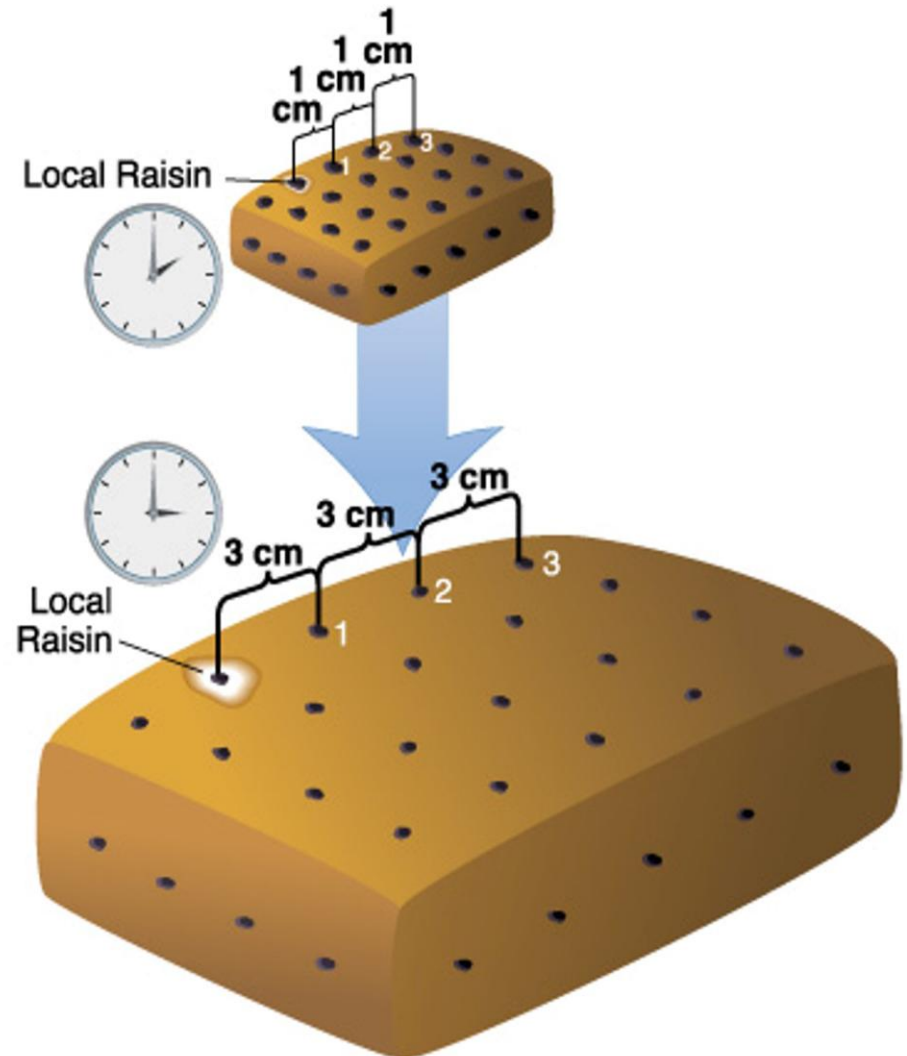
→ Dark matter required.

Present

Expansion of Universe: Space is stretching

Reminder (from Lectures 32-33)

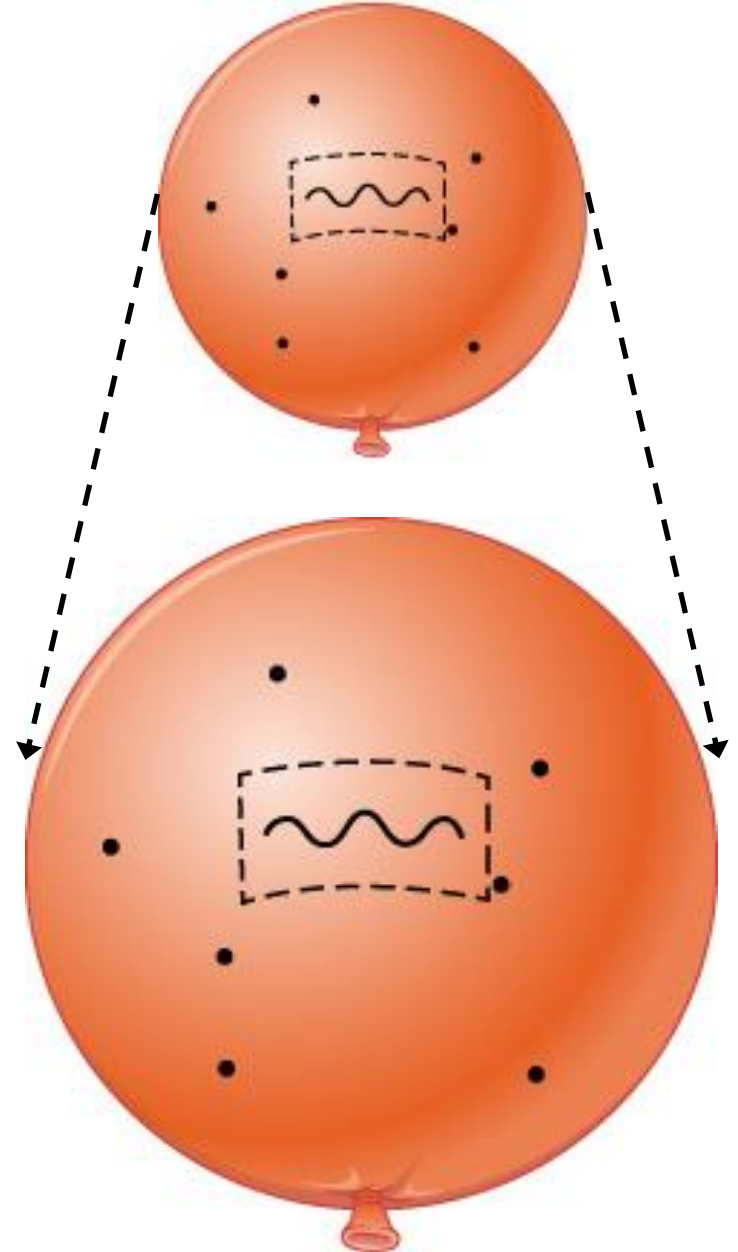
- From **Hubble's law**, we saw that the universe must be expanding.
- Over time, galaxy clusters will get further and **further apart**.
- **One view** is that the increasing distance is due to the **different velocities** of the galaxy clusters.
- **Another view** is that **space is actually expanding**,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

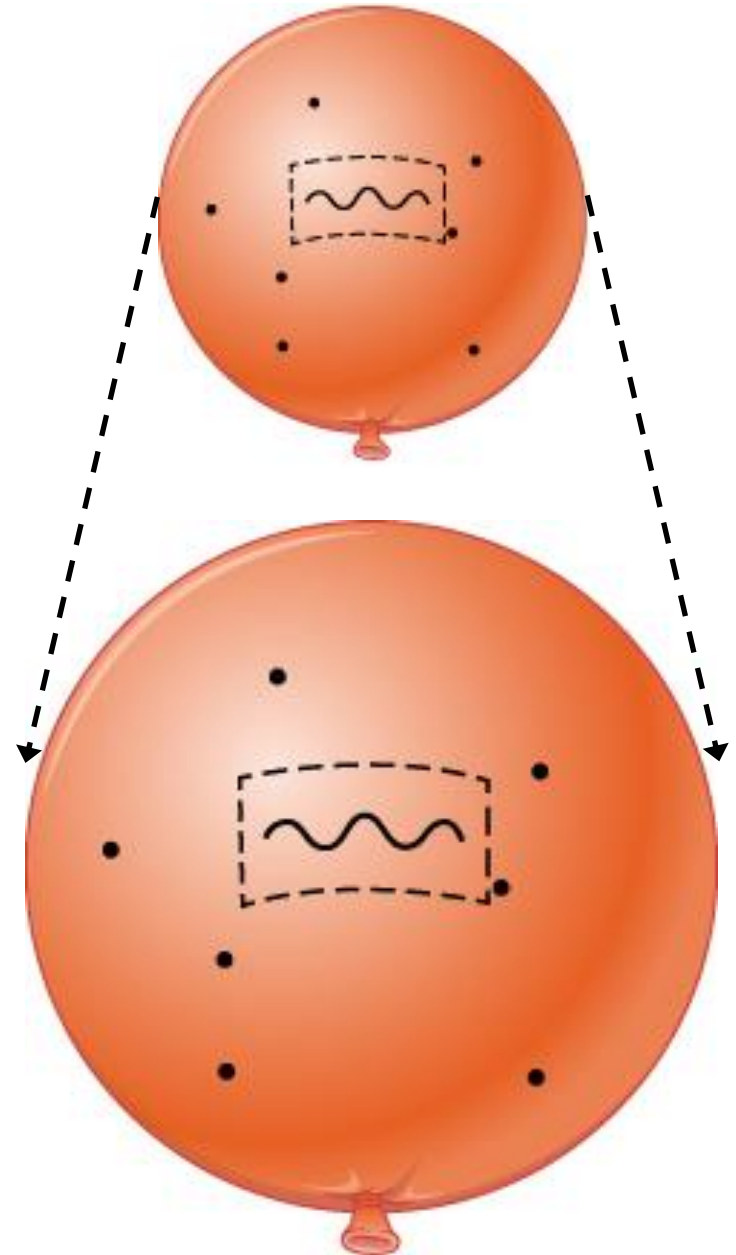


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Question 1: Will a house slowly get bigger over time, due to the expansion of space?



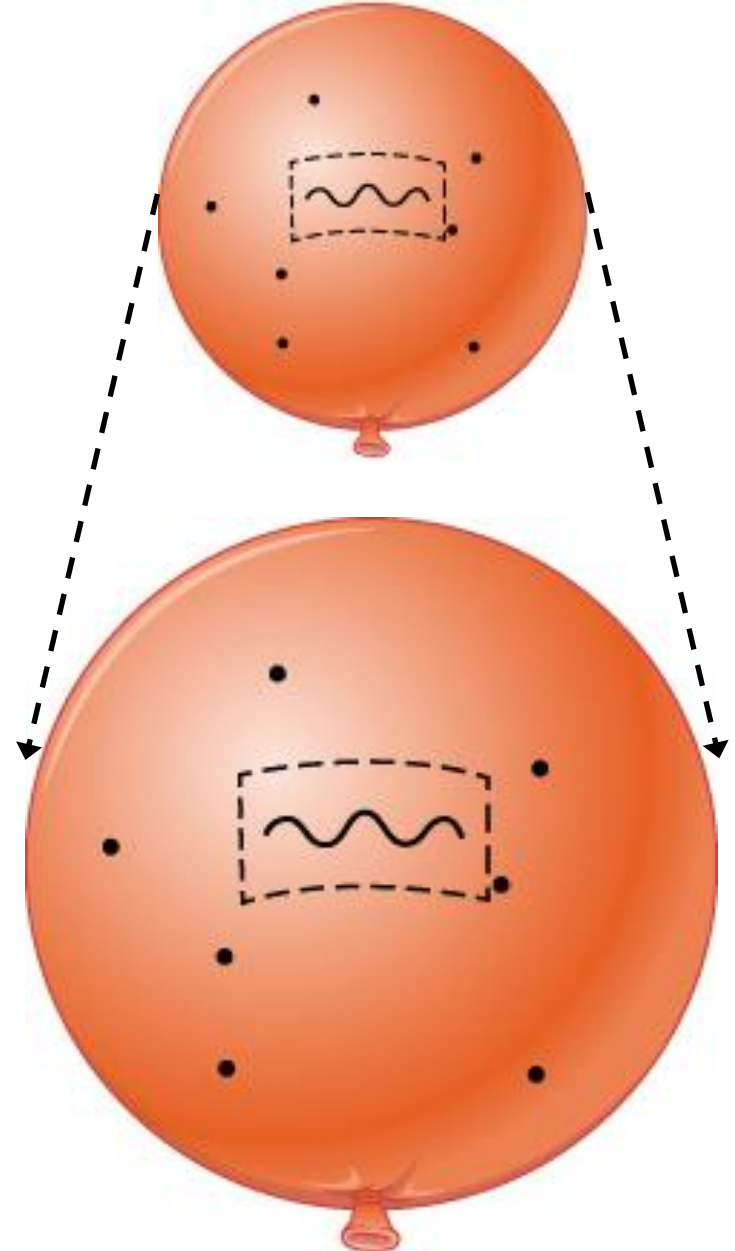
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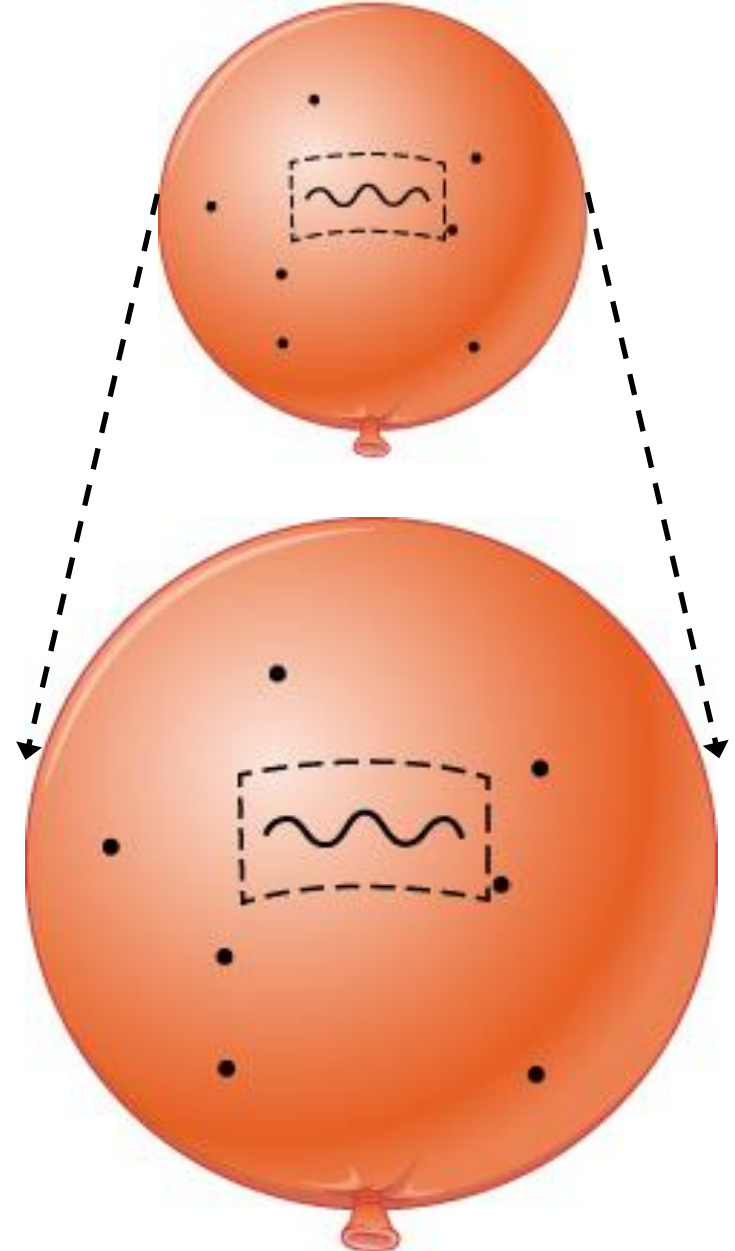
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Question 2: Will a galaxy get bigger over time, due to the expansion of space?



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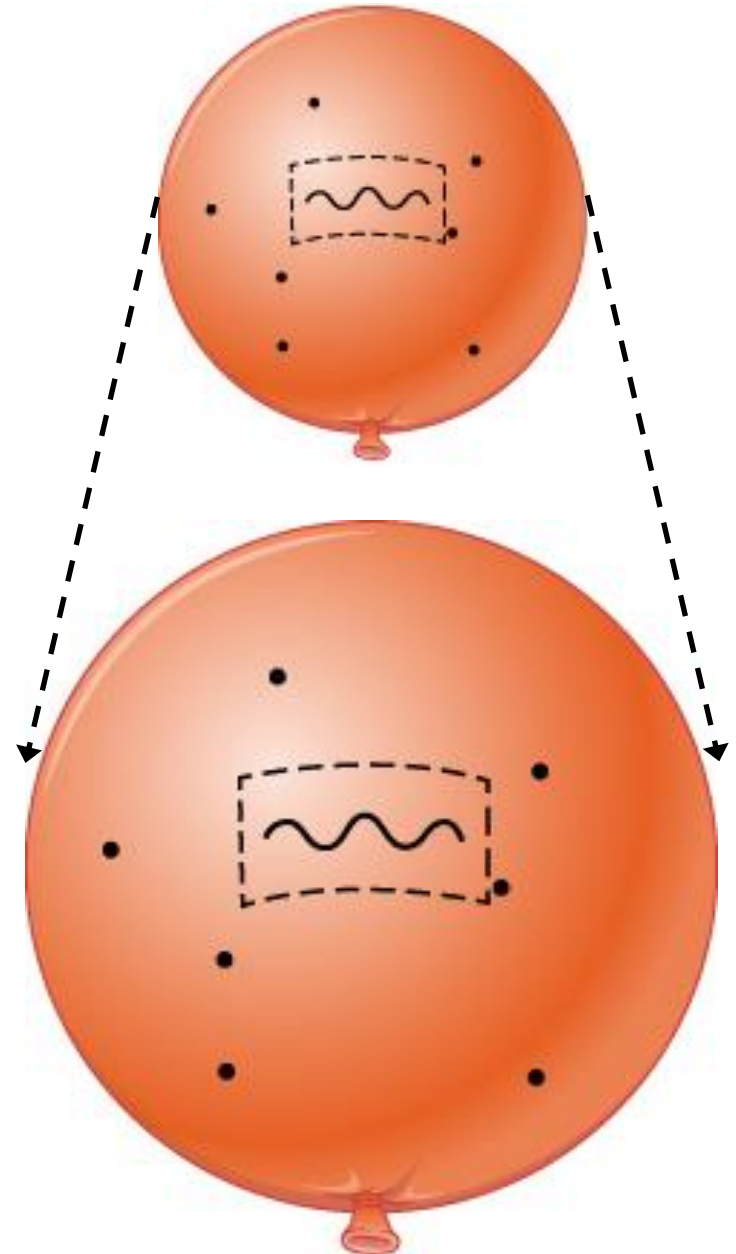
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Answer 1: No, the electromagnetic interaction (which binds matter together chemically) is strong enough to prevent your house from expanding.

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.

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

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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”

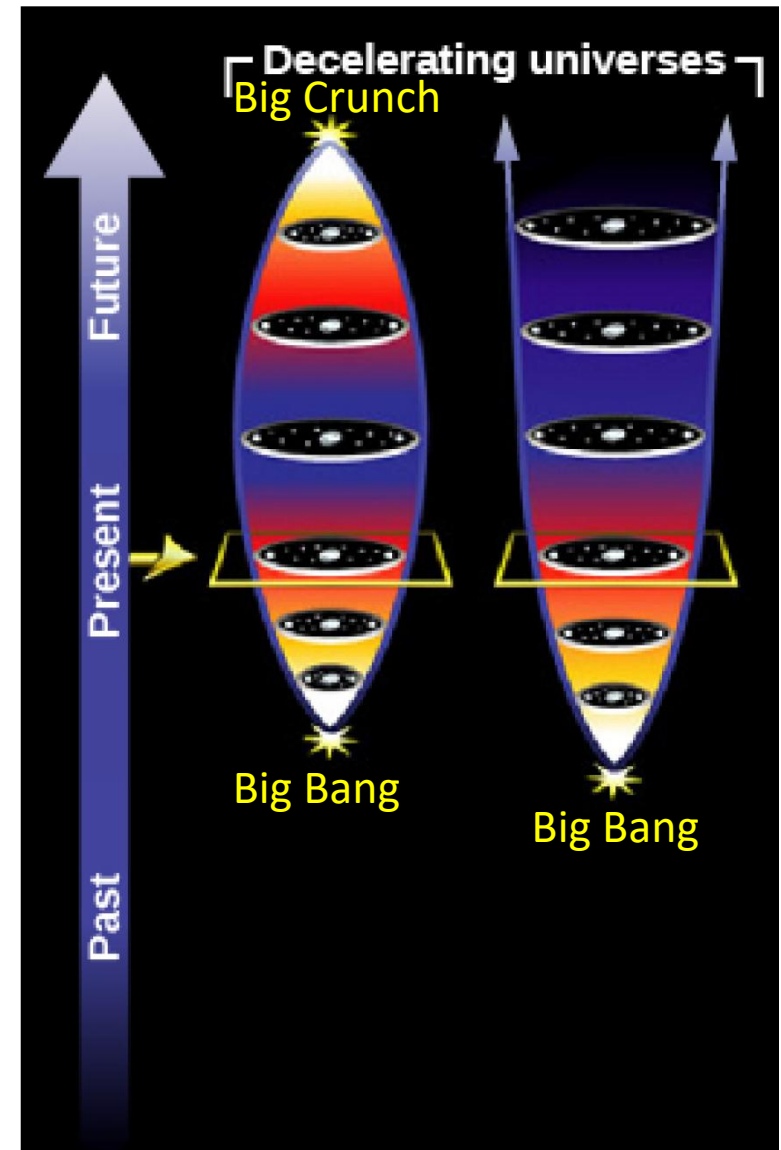
The universe has a lot of matter (including dark matter), and the universe’s gravitational self attraction is enough to slow, halt, and reverse the expansion of the universe (initiated by the big bang).

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

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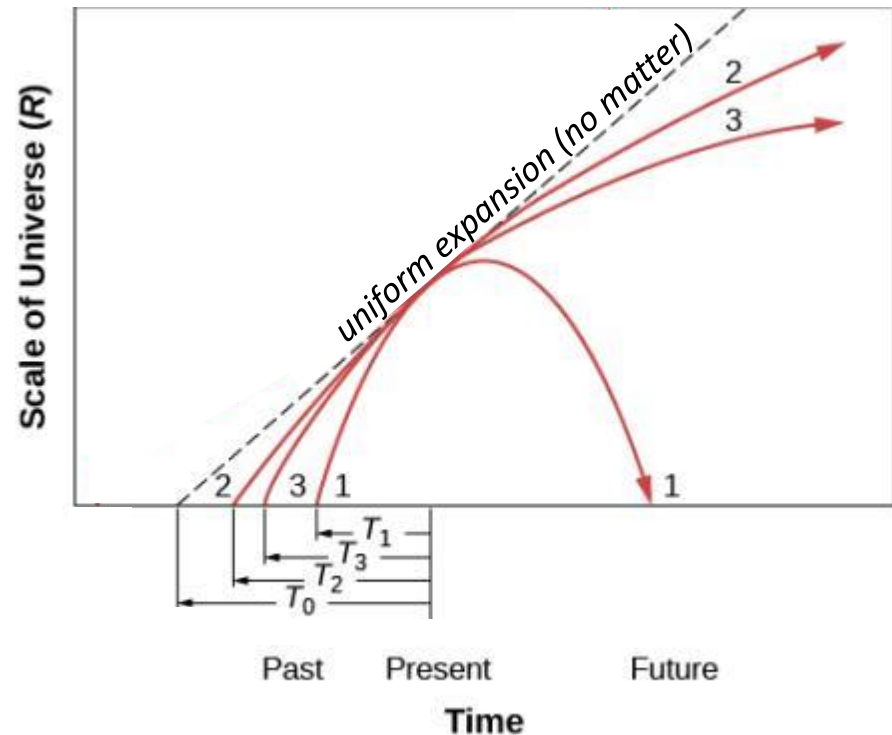
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Question: How much matter is required to bring the universe’s expansion to a stop at infinite time?

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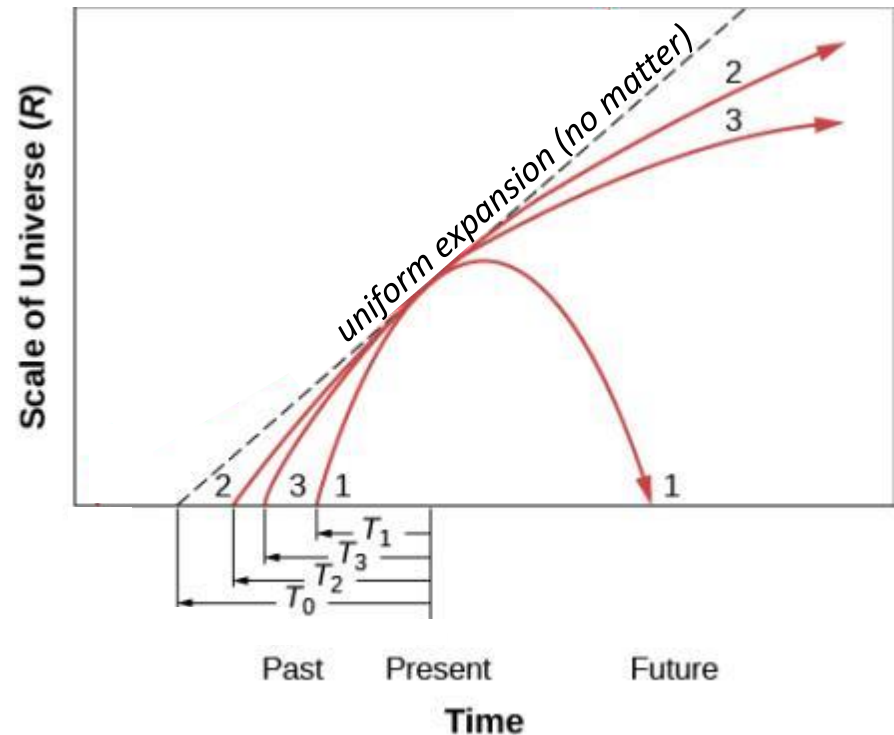
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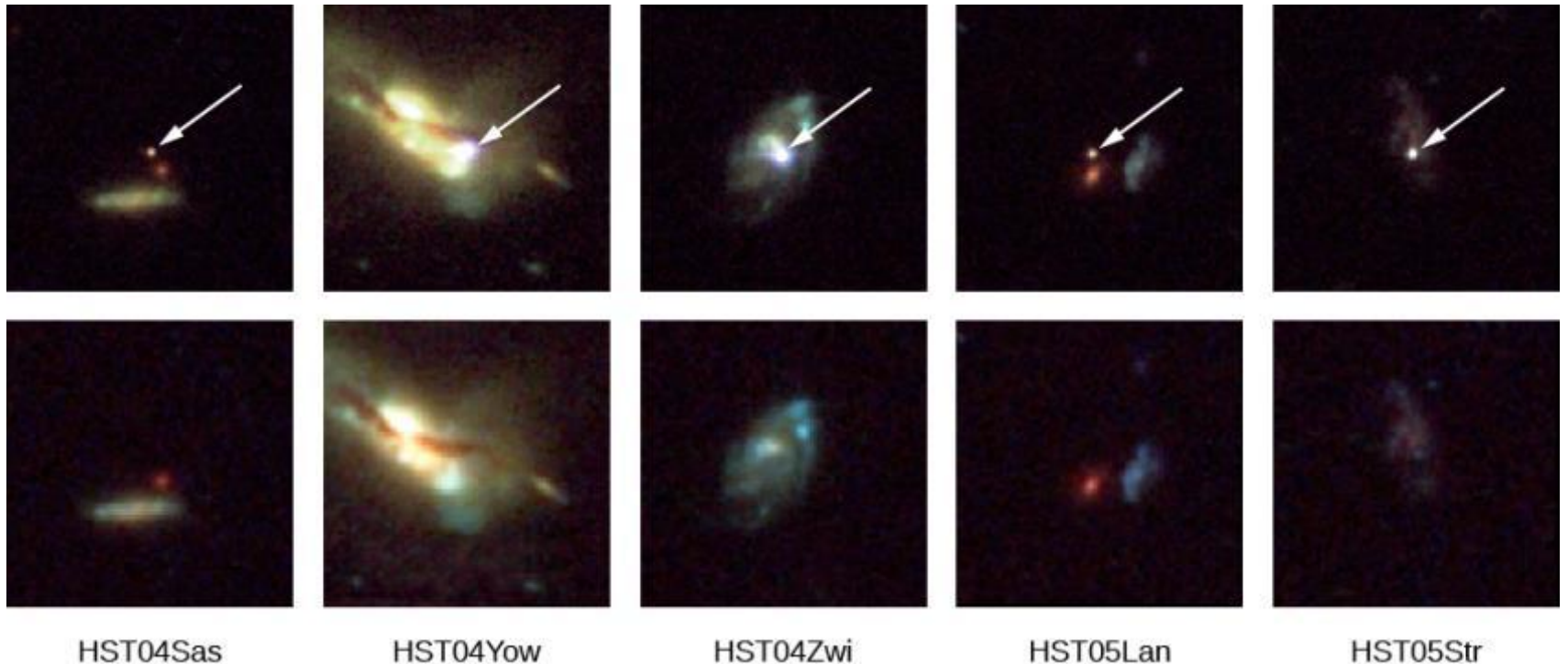


Question: How much matter is required to bring the universe’s expansion to a stop at infinite time?

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.



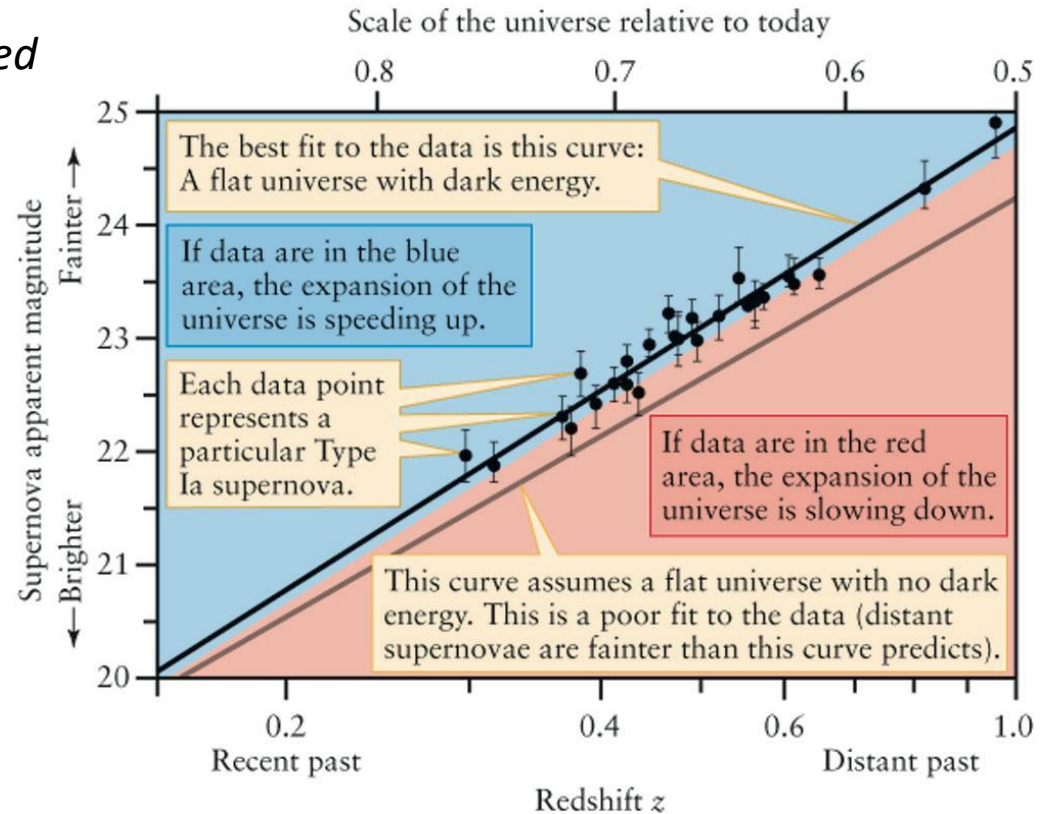
Five Supernovae and Their Host Galaxies. The top row shows each galaxy and its supernova (arrow). The bottom row shows the same galaxies either before or after the supernovae exploded.

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.



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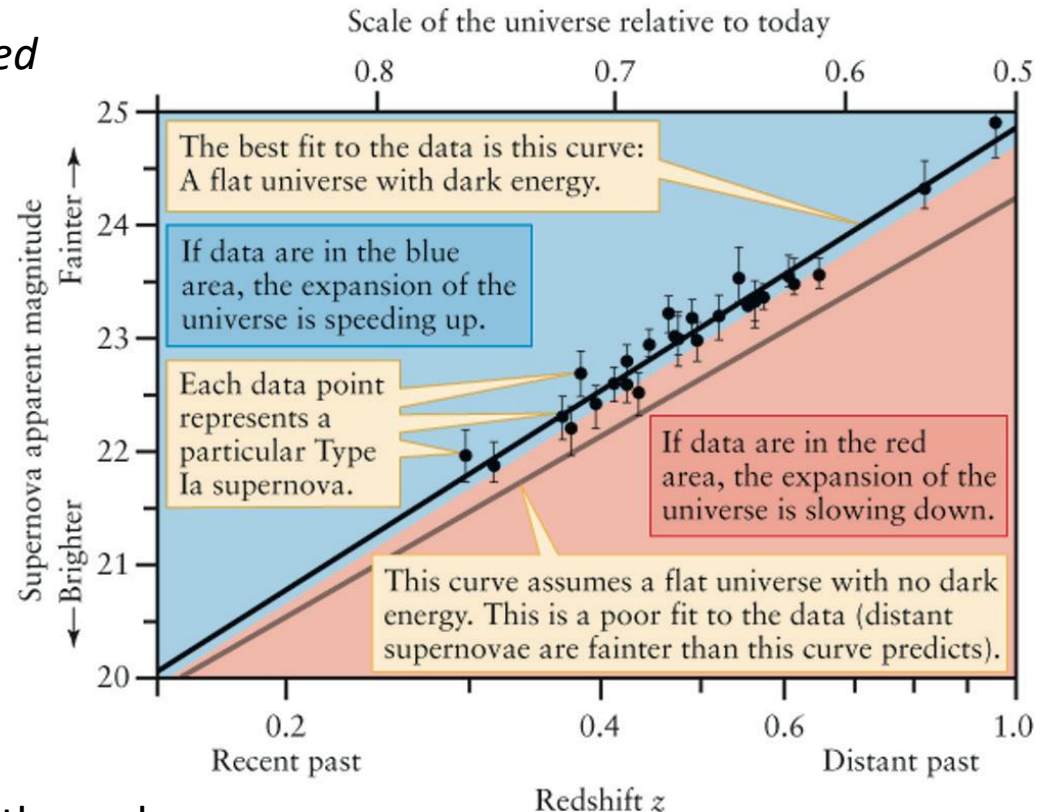
Distant supernova *fainter than predicted* using Hubble's law and the value of H from closer galaxies.

→ 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!

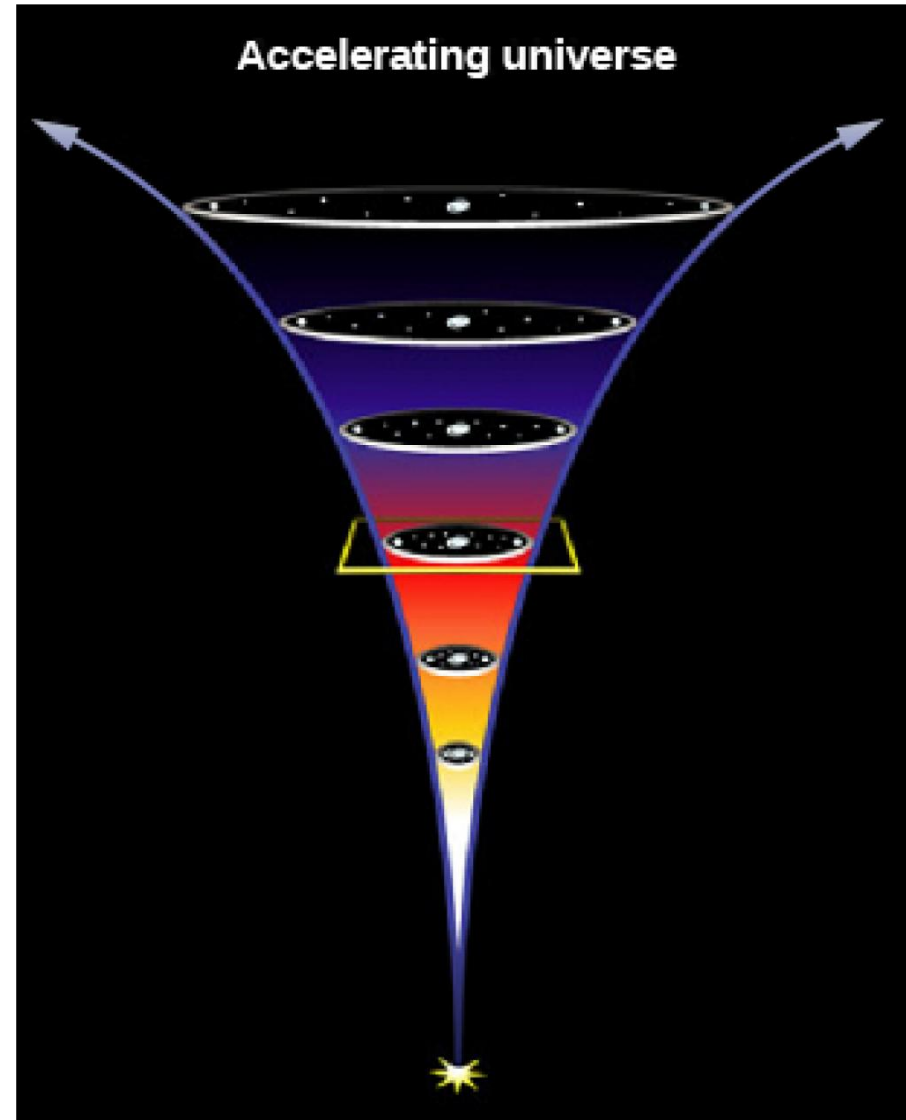
Since then, this has been confirmed with much more observational data.



*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 the expansion of the universe be accelerating?



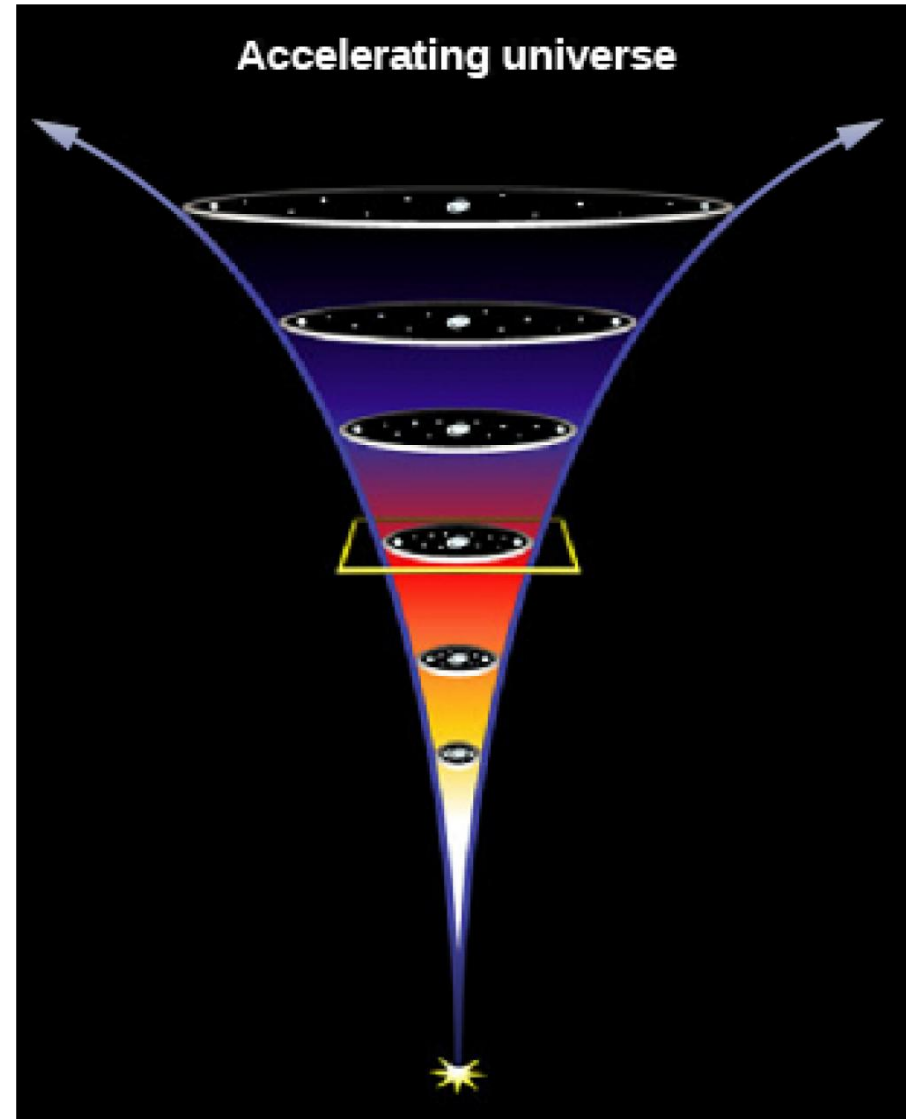
Accelerating Expansion: Dark Energy

Question: How can the 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.

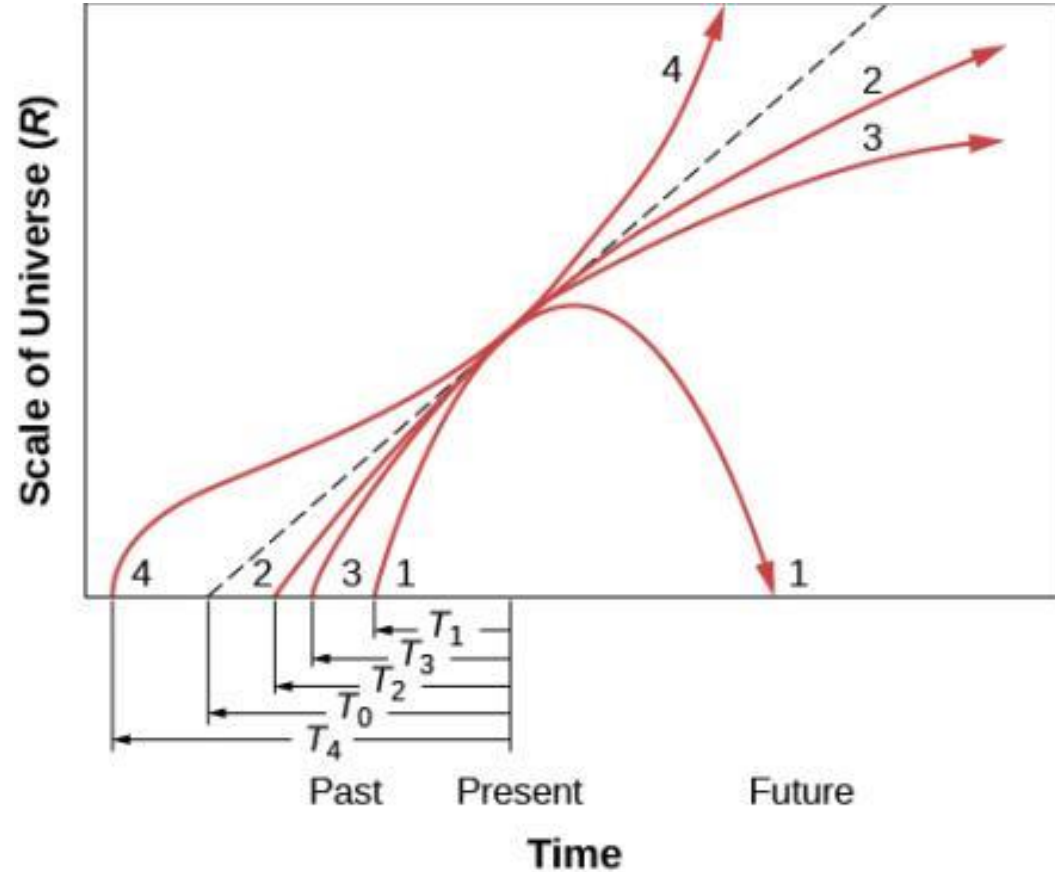


Scenario 4: Accelerating Expansion

*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.