

# Today's Topics

Monday, April 20, 2026 (Week 12, Lecture 32) – Chapter 19.3-4, 26.

1. Distance Ladder
2. Tully-Fisher Relation
3. Hubble's Law

**Problem Set #10** is due on ExpertTA on Friday, April 24, 2026, by 9:00 AM

**Interlude 2 essay** is due on Gradescope on Monday, April 27, 2026 by 9:00 AM

# The Distance Ladder

How do we measure **distance** to stars and galaxies?

0. **Solar system distances:** Radar

1. 4 to 1000 light years: **Parallax**

2. to 300,000 light years: RR Lyrae **variable stars**

3. to 1 million light years: H-R diagram - comparing same types of stars

4. to 60 million light years: Cepheid **variable stars**

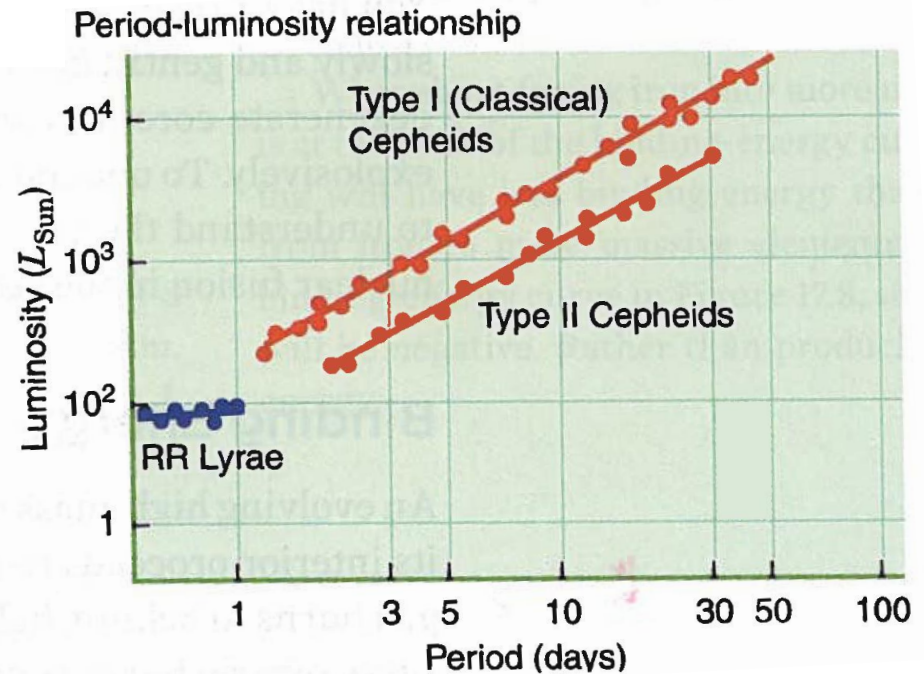
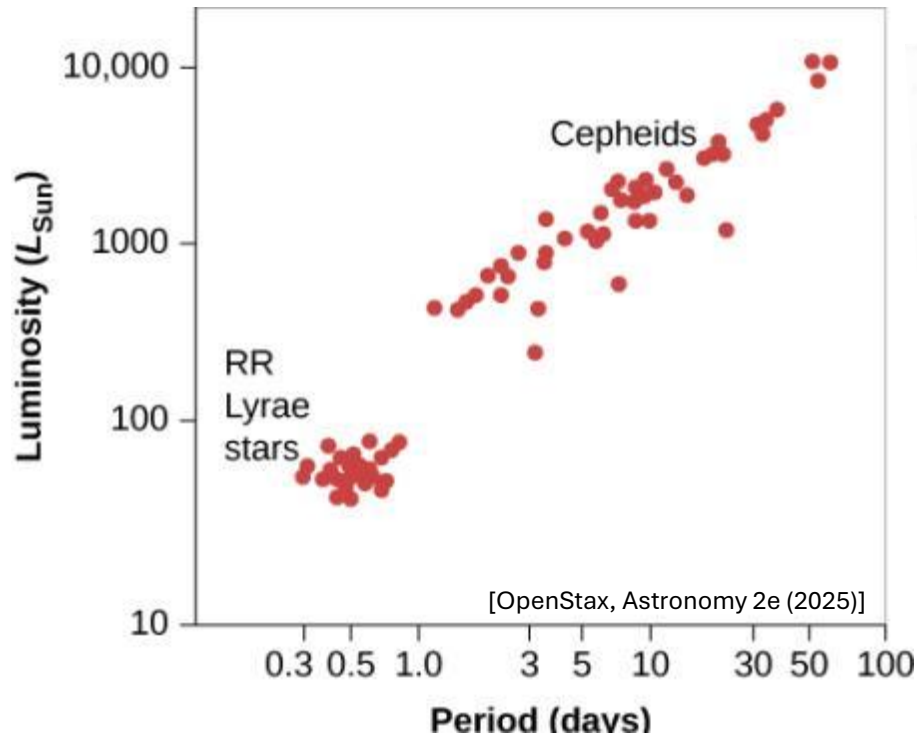
5. to 300 million light years: **Tully-Fisher law** (for spiral galaxies)

6. to 11,000 million light years: Type 1A **Supernovae**

7. To 13,000 million light years: **Red shift** and **Hubble's Law\*** (\* caveat)

**Main idea:** if we can find some sort of “**standard candle**”, *i.e.*, a star where we know (from some other property) what its Luminosity is, then its Apparent Brightness tells us its Distance.

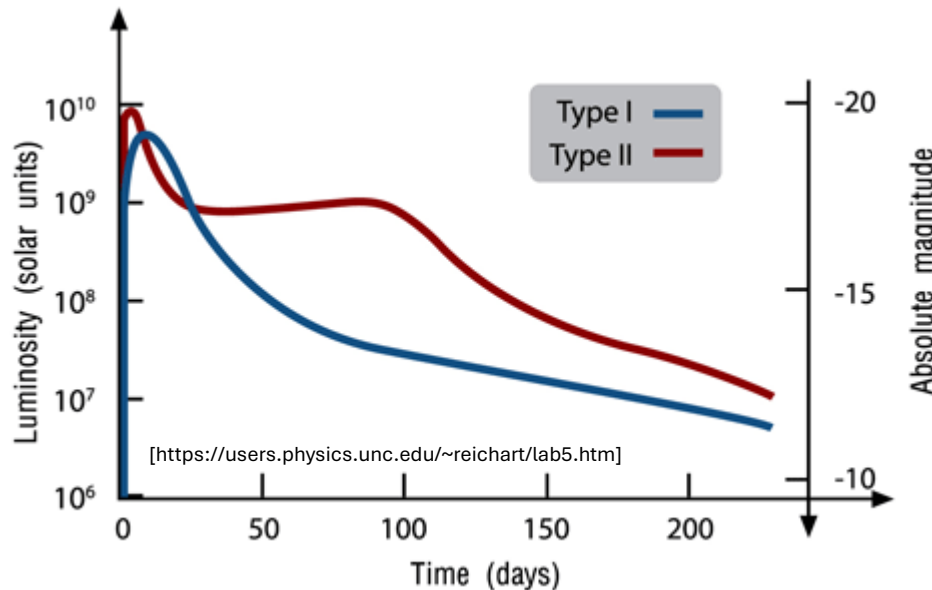
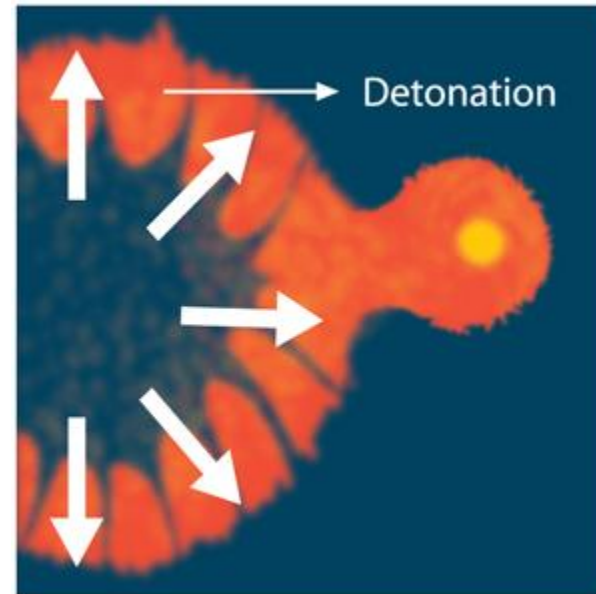
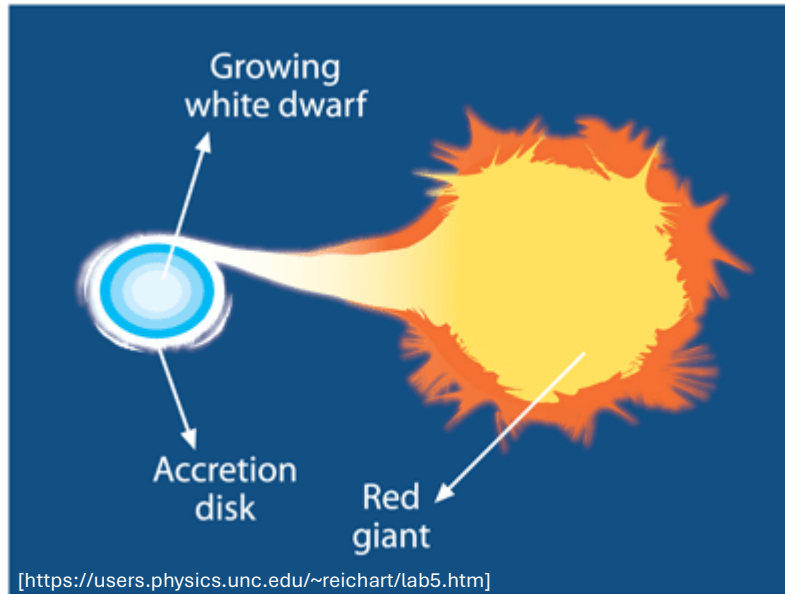
# Cepheid Variable Stars – a standard candle



## Period-Luminosity Relation for Cepheid Variables

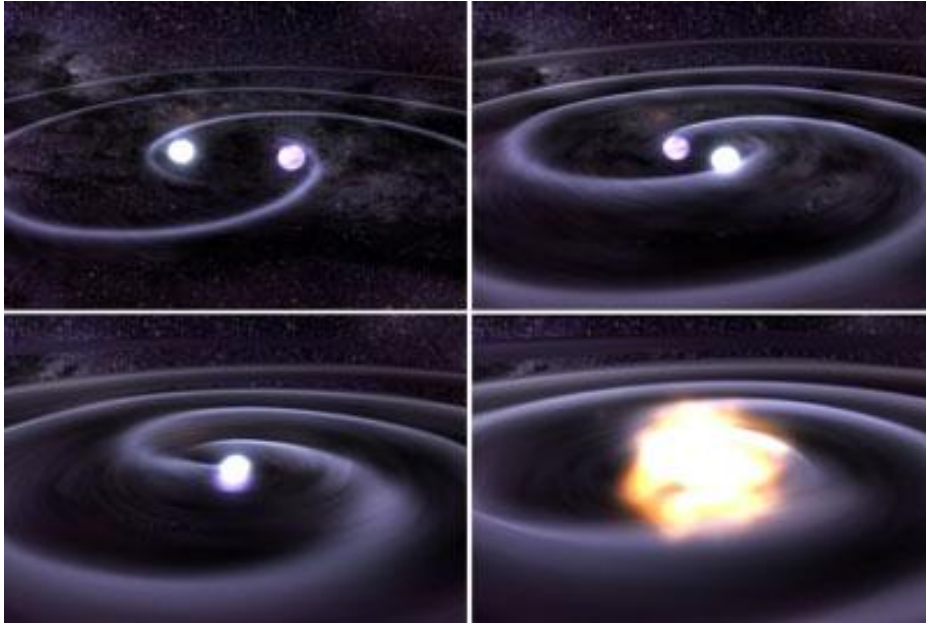
- The time the star takes to go through a cycle of luminosity changes is related to the average luminosity of the star.
- RR Lyrae stars have a comparable behavior.

# Type 1a Supernovae – a standard candle



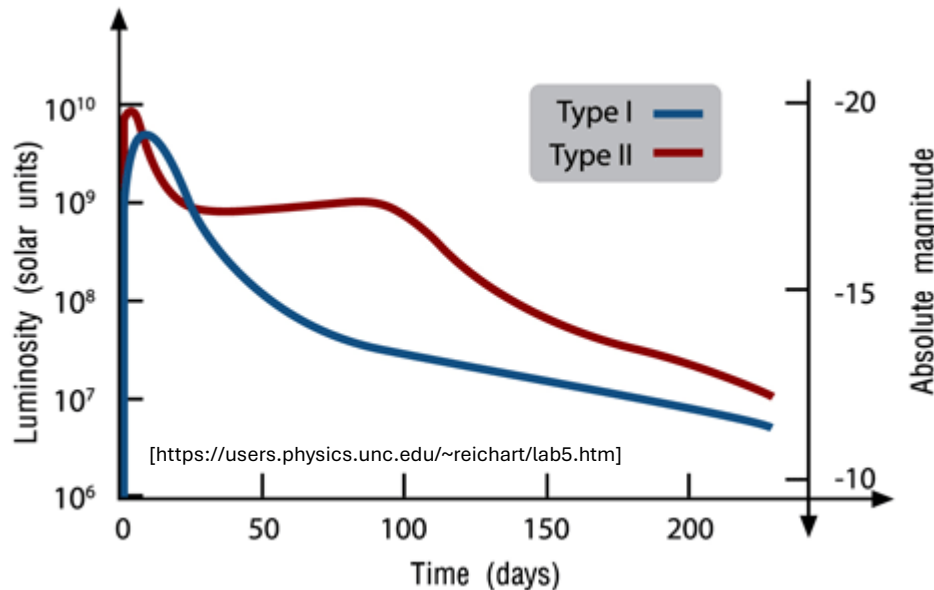
All type 1a supernovae have an effective maximum luminosity of about  $5 \times 10^9 L_{Sun}$ .

# Type 1a Supernovae – a standard candle



## Alternate scenario:

- Two orbiting **white dwarfs** (composition: carbon-oxygen) merge.
- The merger results in **explosive fusion** to higher elements.
- Both white dwarfs are **blasted apart** in the merger (no compact remnant).



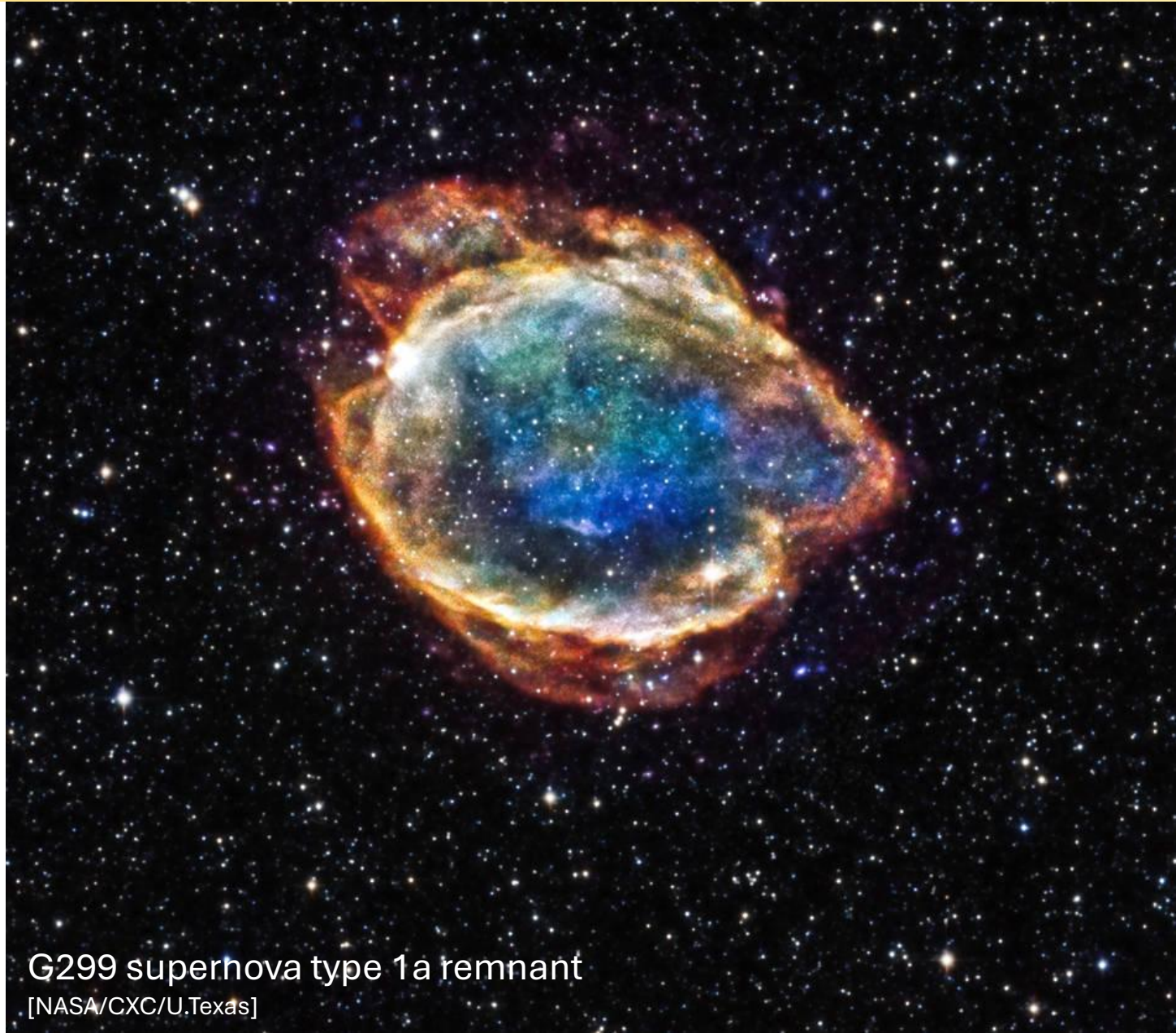
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# Type 1a Supernovae – a standard candle

This type of supernova does **NOT leave a compact remnant** (e.g., white dwarf, neutron star, or black hole).

The progenitor white dwarf is **destroyed** in the explosion.

Elements produced:  
- **Up to nickel**, which then decays to **iron**.  
- Significant amounts of **silicon**.

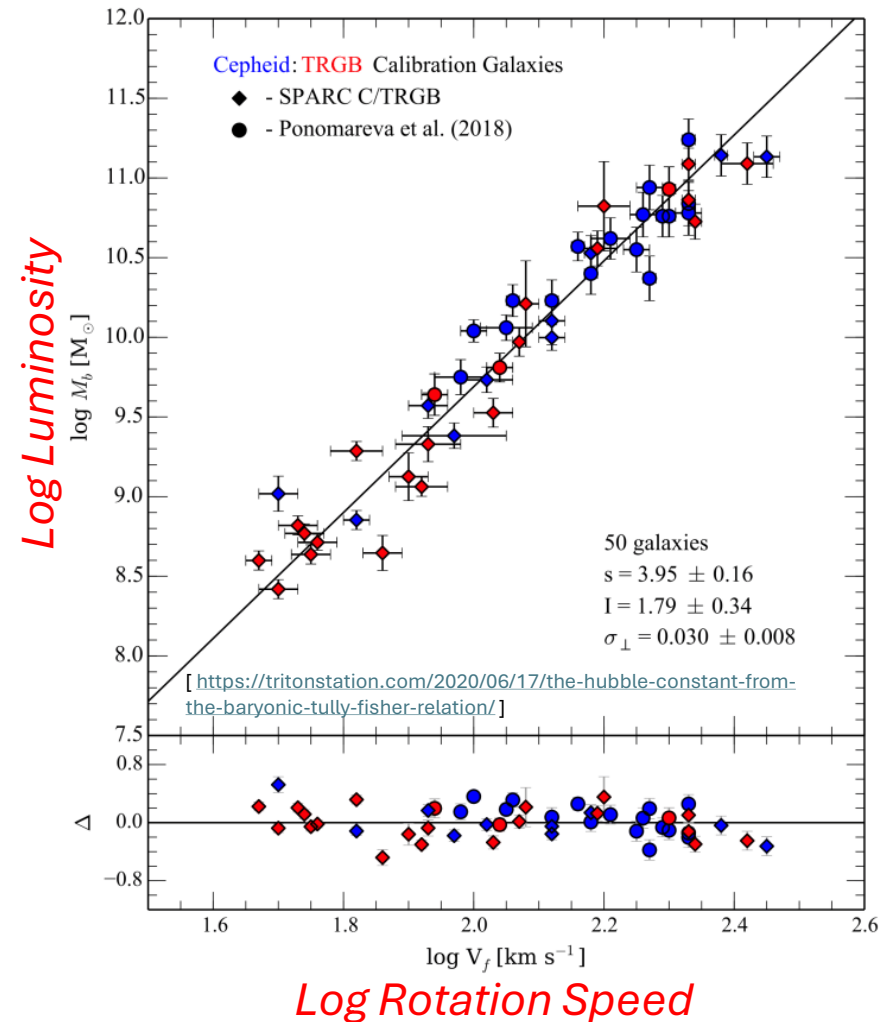


G299 supernova type 1a remnant

[NASA/CXC/U.Texas]

# Tully-Fischer Relation

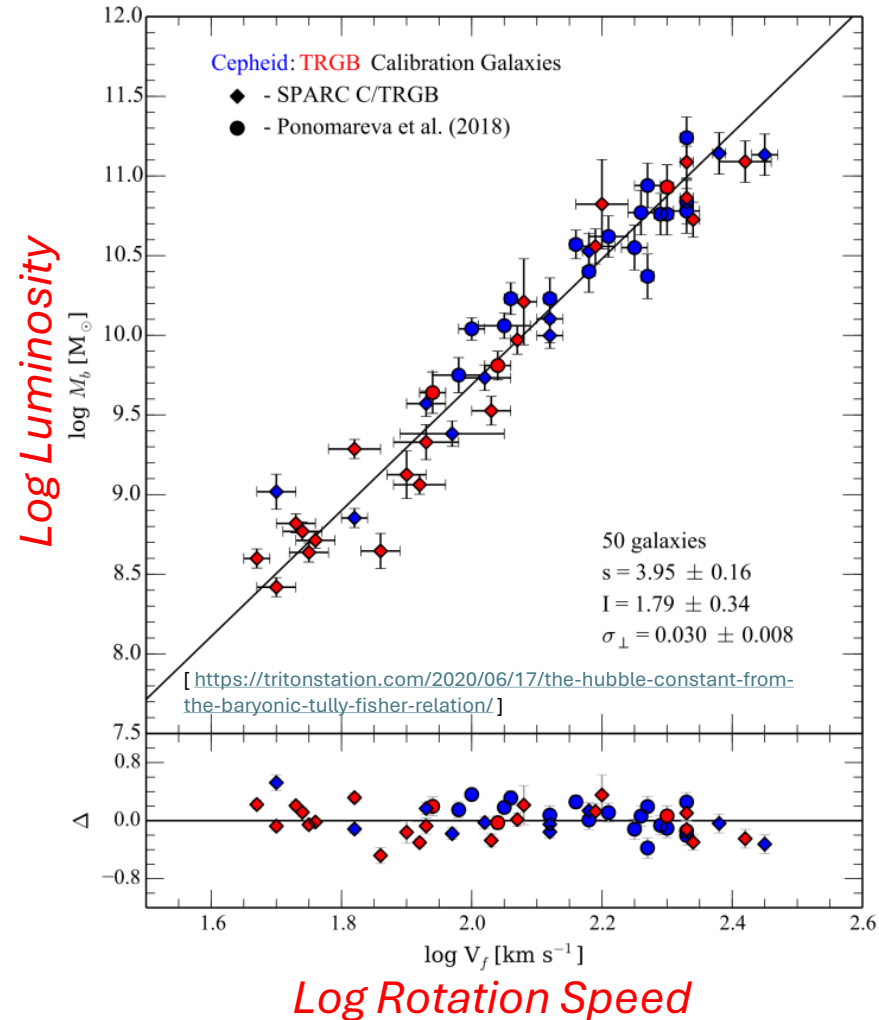
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- The average **rotational speed** can be measured from the **Doppler broadening** in absorption lines in the visible spectrum or of the 21 cm hydrogen line.



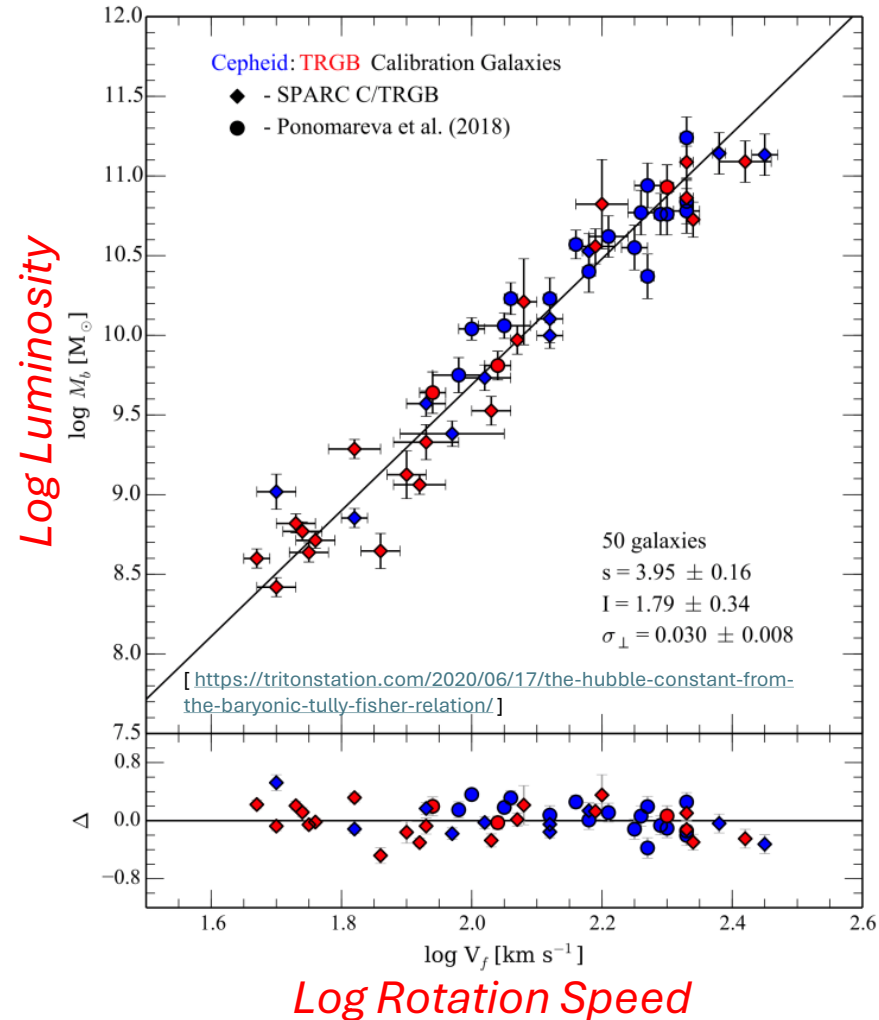
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## *Intuitive idea*

- **Luminosity** depends on the total **mass** of the galaxy (number of stars)
- **Mass** and **rotational rate** are related by Kepler's 3rd law (as long as dark matter fraction is similar for all galaxies).
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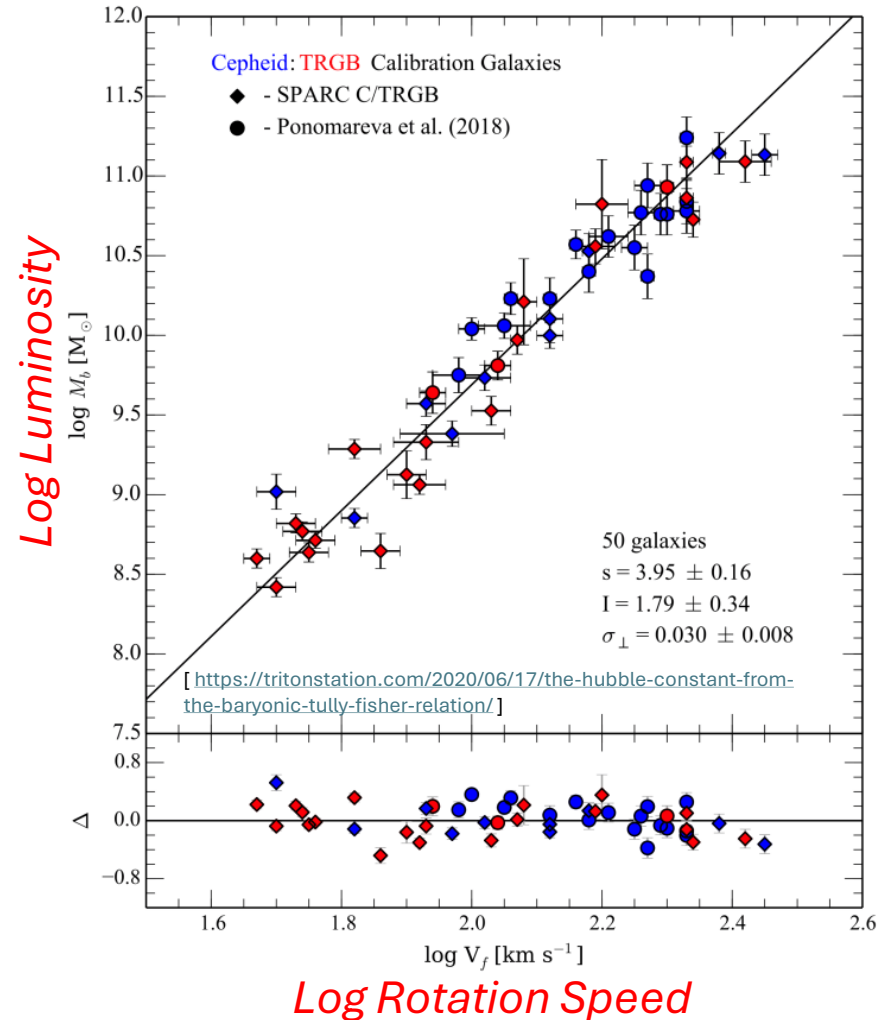
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## “Standard candle” to get distance

- Get luminosity from rotation speed
- Get distance from the apparent brightness (“magnitude”) and  $1/d^2$ .



# Red Shifts & Expanding Universe

**1914: Vesto Slipher** measured Doppler shifts of light from 40 nearby galaxies.

- Almost every one showed a large **redshift**.
- Almost all were receding from Milky Way.
- Exceptions were 3 close galaxies (including Andromeda).



[National Academies of Science]

*Vesto Slipher*  
1875-1969

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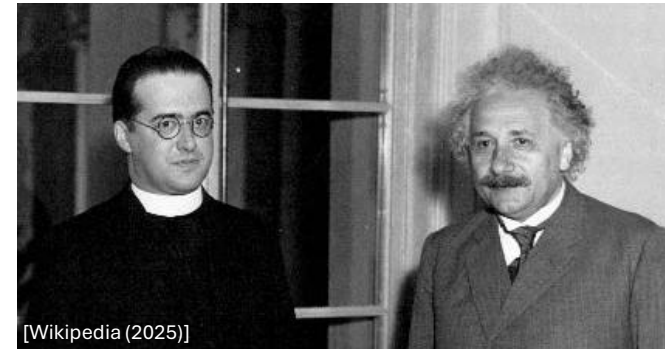
**1927: Georges Lemaître** solved Einstein's General Relativity equations and found a solution with an expanding universe.

- Alexander Friedmann did this independently in 1922.
- Lemaître proposed that the universe was expanding and argued that Slipher's data supported this.
- Einstein apparently commented: "*Vos calculs sont corrects, mais votre physique est abominable*" ("Your calculation is correct, but your physics is abominable" ... Initially, Einstein did not accept the idea of a non-static universe.)



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[Wikipedia (2025)]

*Lemaître and Einstein (CalTech 1933)*

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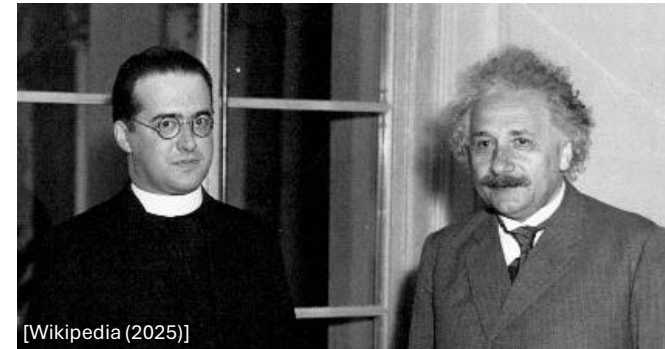


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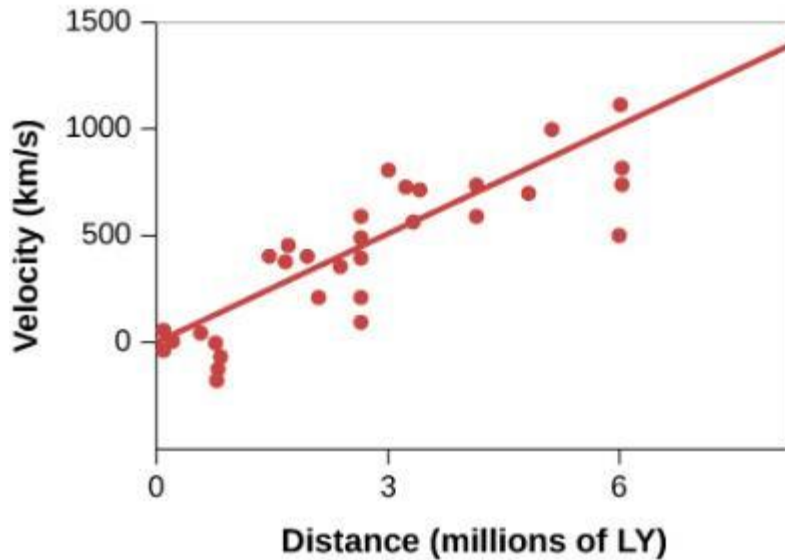
[Wikipedia (2025)]

Lemaître and Einstein (CalTech 1933)

**1931: Edwin Hubble and Milton Humason** extended Slipher's measurements to much more distant galaxies.

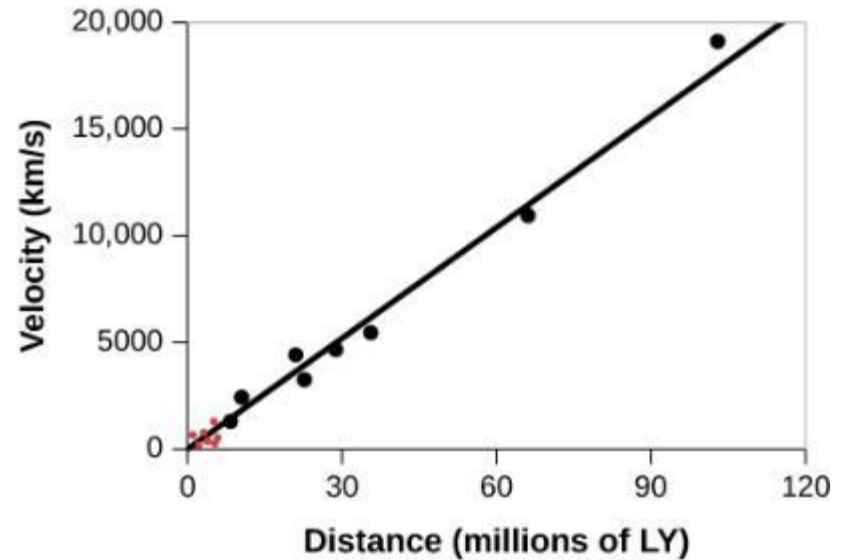
# Red Shifts & Hubble's Law

Hubble's Data (1929)



(a)

Hubble and Humason (1931)



(b)

$$\text{Hubble's Law: } V = H \times d$$

$V$  = recession velocity

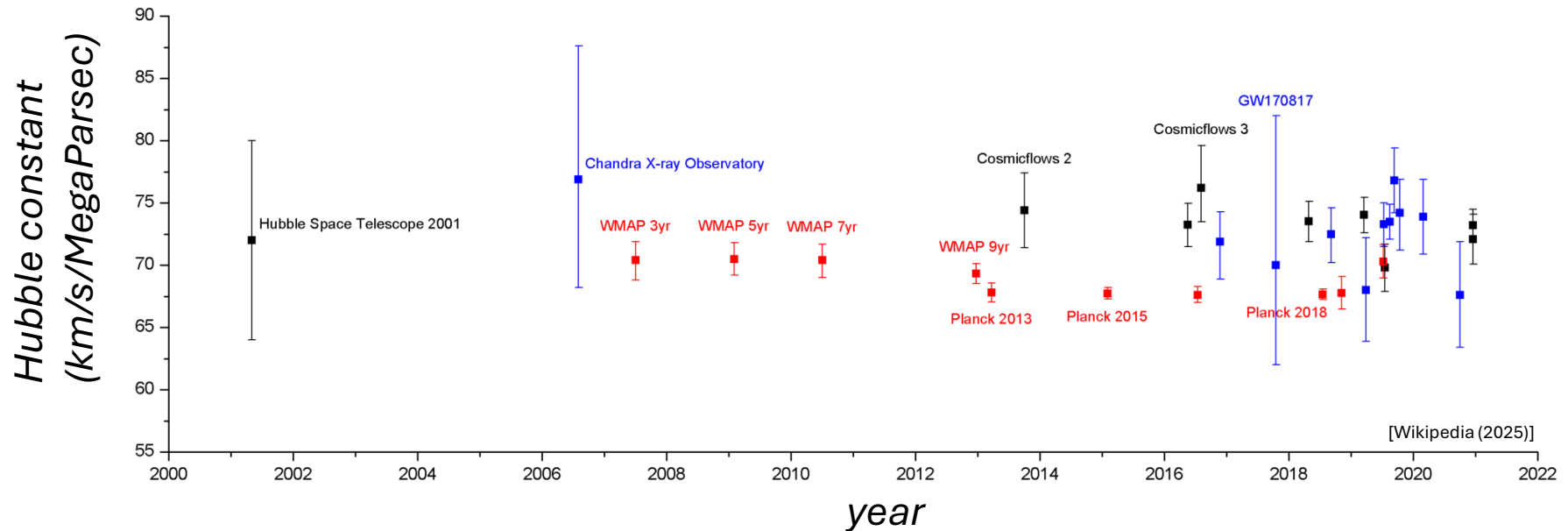
$d$  = distance from Earth

$H$  = Hubble constant [modern value]

= 22 (km/s)/million-light-years

= slope of the above lines

# Hubble Constant



- Recent measurements of the **Hubble constant** H, plotted versus date.
- Some disagreement based on measurement technique.
  - This matters because it affects our value for the age of the universe.

# Hubble's Law: The Expansion of the Universe

Hubble's law is interpreted to mean that the **universe is expanding.**

## *What does this mean?*

- It does NOT mean the universe is expanding from a point.
- It does NOT mean the universe is expanding into something else.
- It does NOT mean that the universe started as a single point-like "cosmic atom".

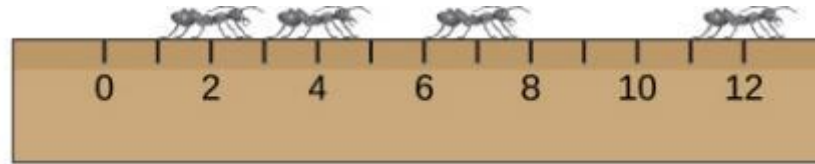
→ It just means that the distance between all points is getting larger.

→ That's all.

# Hubble's Law: The Expansion of the Universe

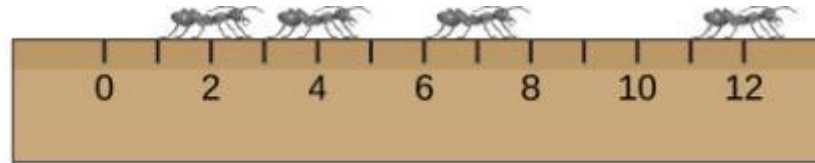
- The fact that we (on Earth) see all the galaxies moving away from us, and the farther away they are, the faster they are receding, does **not** mean that we are in some special location (an anthropocentric view ).
- On the contrary – someone located in a distant galaxy would see **exactly the same thing!** Everything (including us) is rushing away from them.
  - The farther away, the faster the recession.
- **Huh?**

# 1D model of Expanding of the Universe



Ants at rest on stretchable ruler.

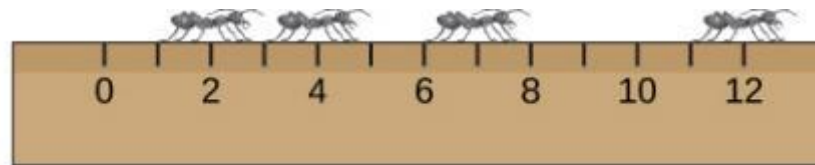
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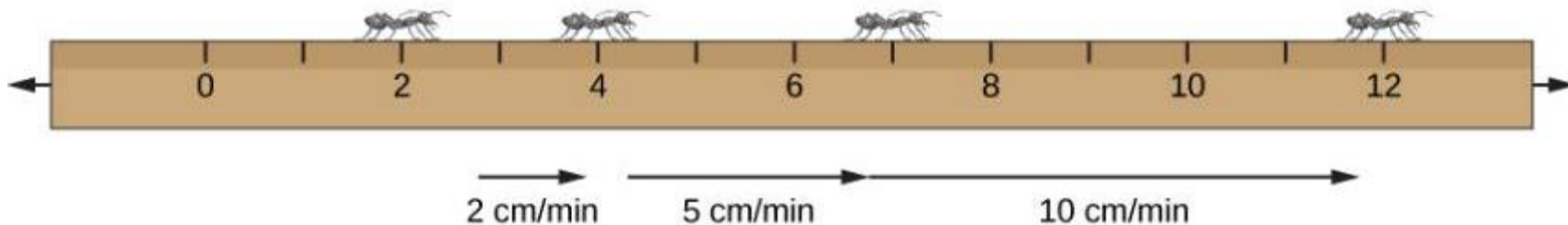
- Ruler is stretched.
- Each ant sees each other ant having moved farther away.

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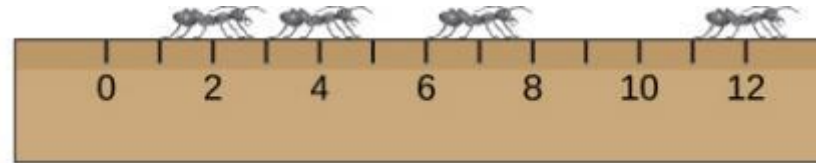


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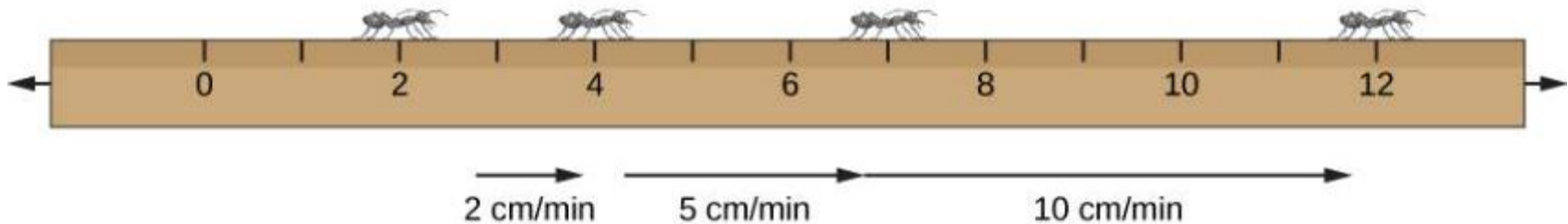


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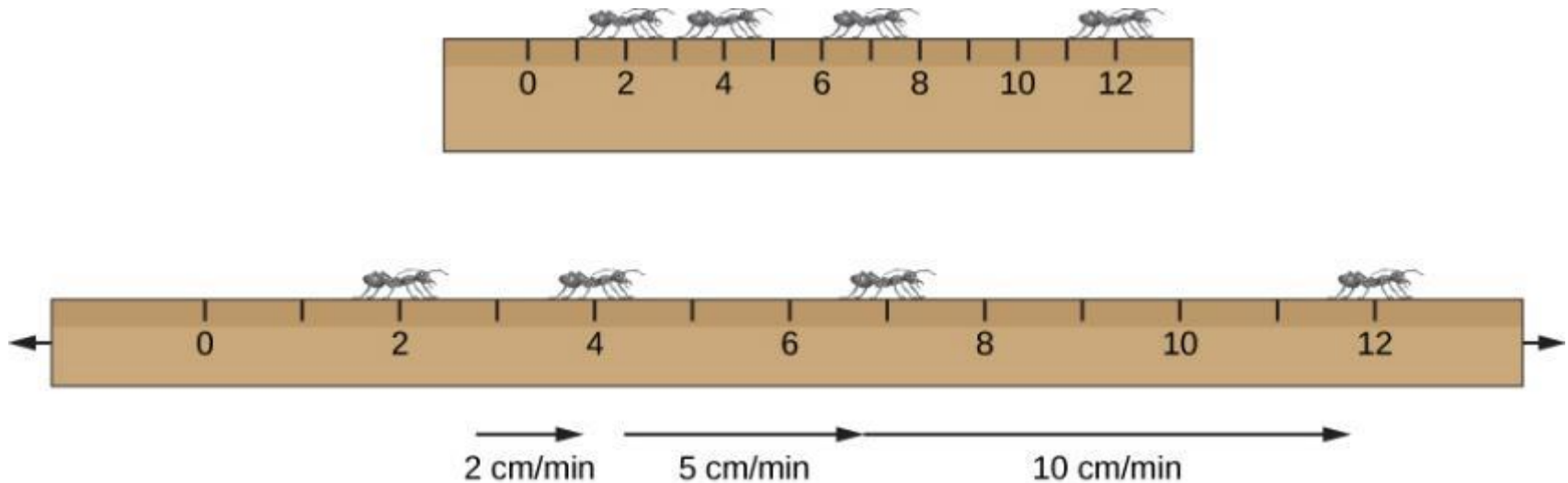
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- The farther away ant B was from ant A originally, the farther it has moved from ant A.
- The larger the initial separation, the larger the stretched separation (proportionally).  
→ *Larger the separation = higher recession velocity (i.e., higher redshift).*

# 1D model of Expanding of the Universe



**Note:** everything stays the same if the ruler is infinitely long (no boundaries or edges to this 1D universe).

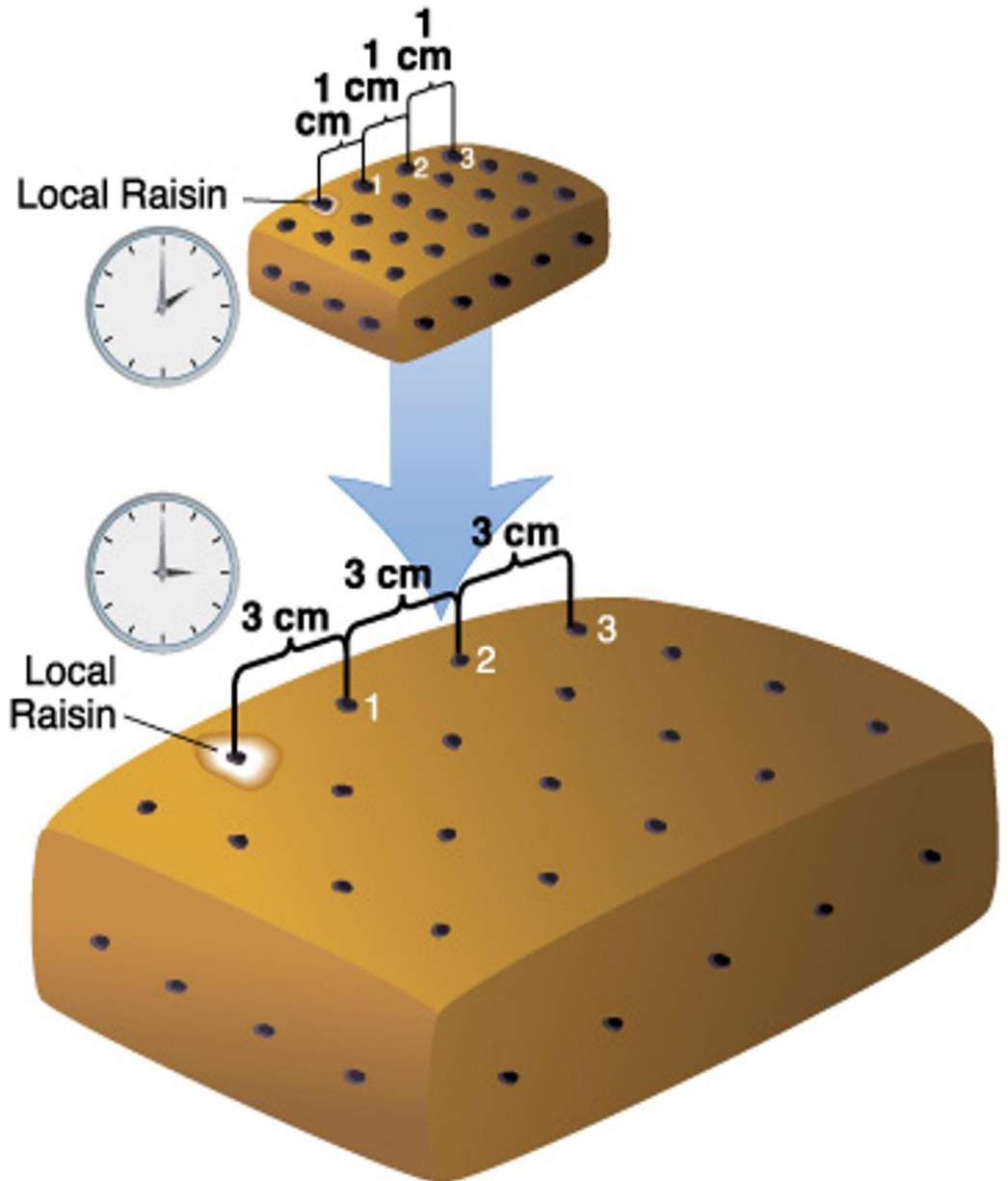
→ An expanding universe doesn't have to expand *into* anything!

→ It also has **no center**.

Think of the ruler as like the number line in math, which, of course, is infinite...

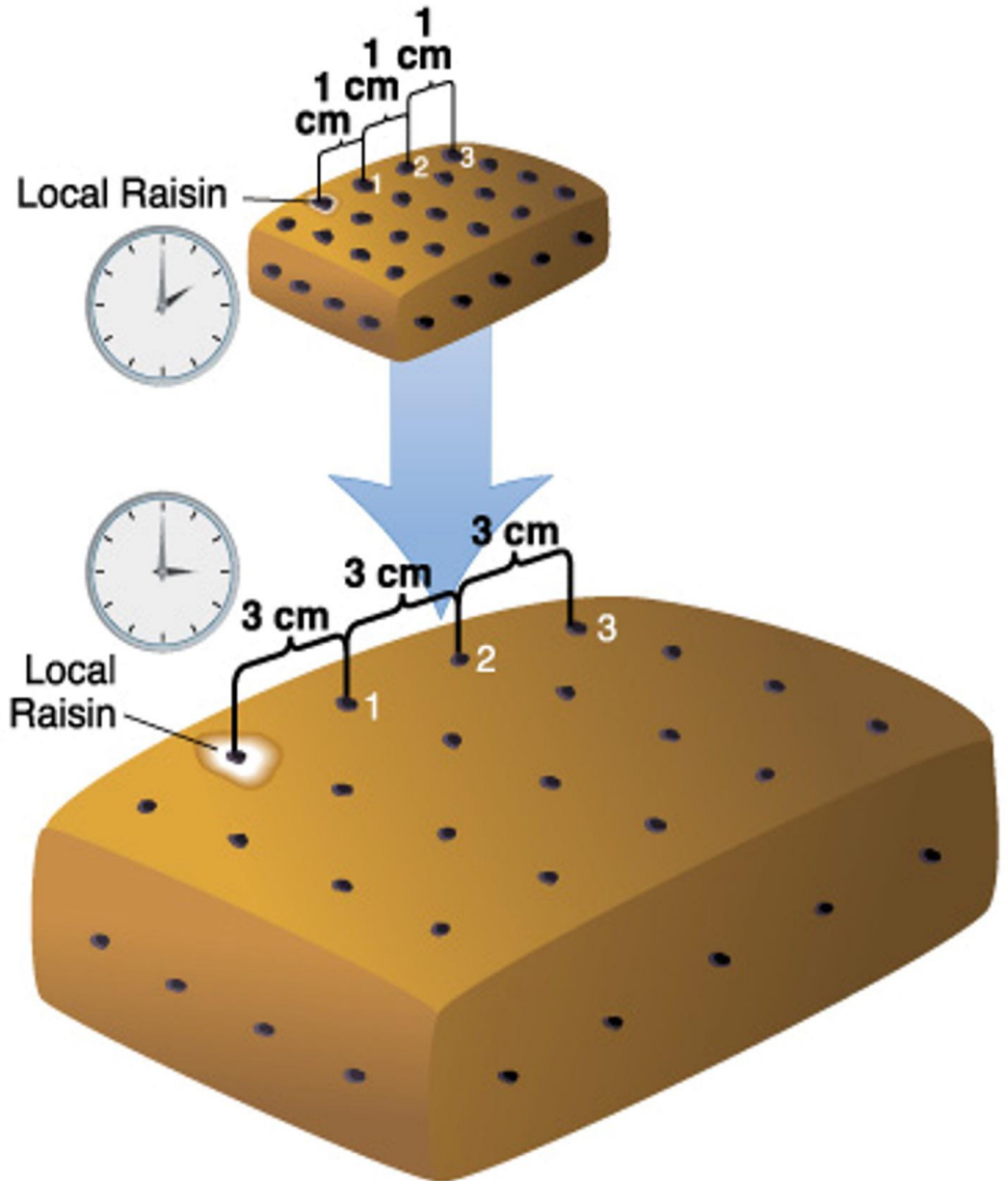
# Expanding of the Universe: 3D Analogy

- Insert raisin bread loaf in oven.
- Loaf expands.
- Every raisin gets farther away from every other raisin.



# Expanding of the Universe: 3D Analogy

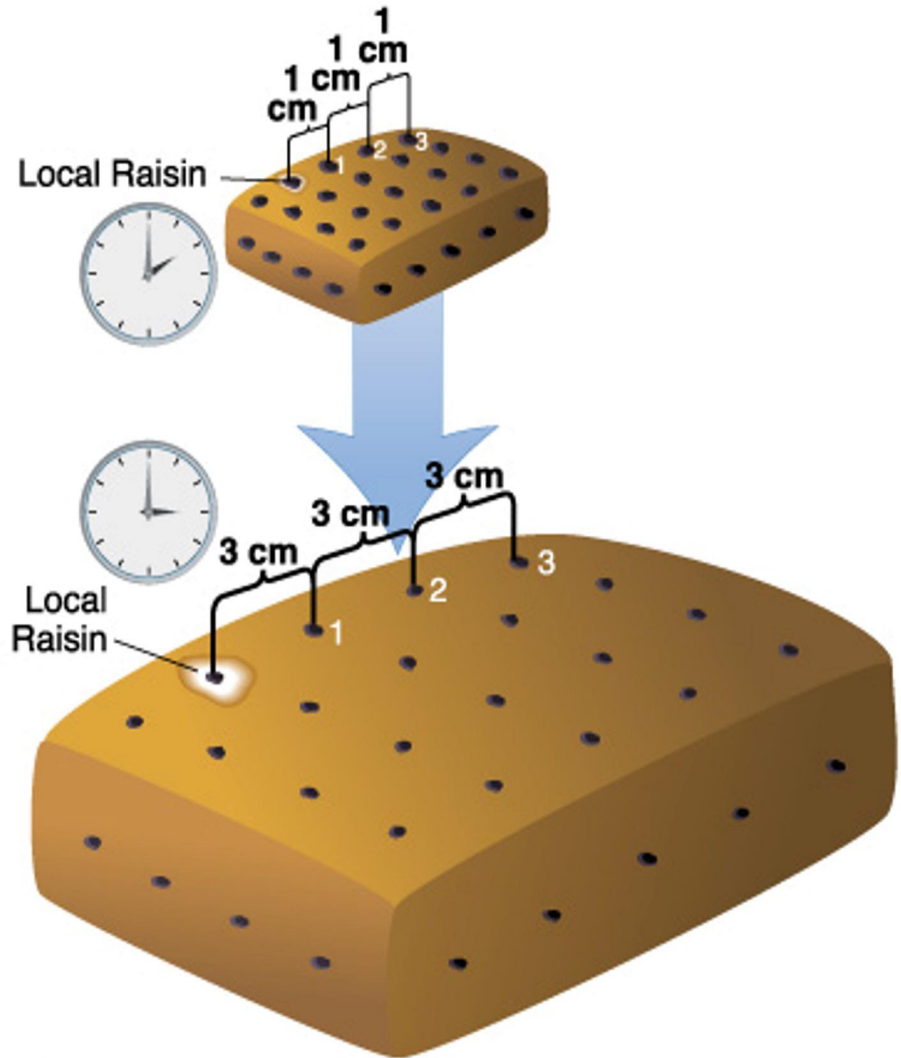
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- Now imagine an infinite loaf ...  
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- Now imagine an infinite loaf ...  
... The same thing happens.

**Note:** a raisin itself does not expand.  
Think of the raisins as galaxies.



**Gravity** holds galaxies and clusters of galaxies together, and they get farther away from each other—without themselves changing in size—as the universe expands.

# Expanding of the Universe: Another Visualization

