Today's Topics

Monday, April 21, 2025 (Week 12, Lecture 31) – 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 25, 2025, by 9:00 AM

Interlude 2 essay is due on Gradescope on Monday, April 28, 2025 by 9:00 AM

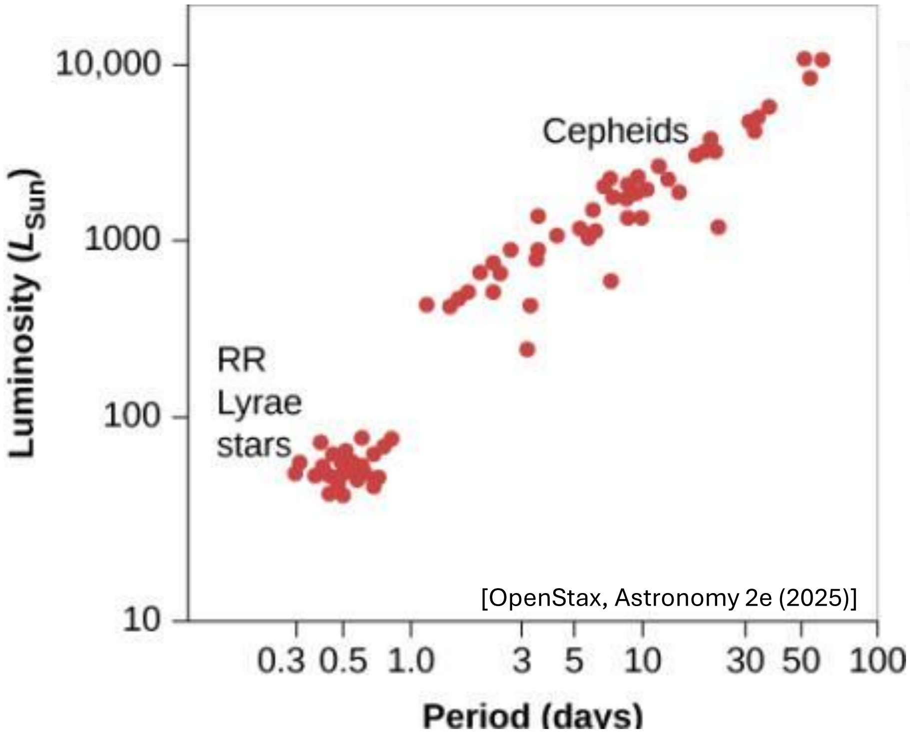
The Distance Ladder

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

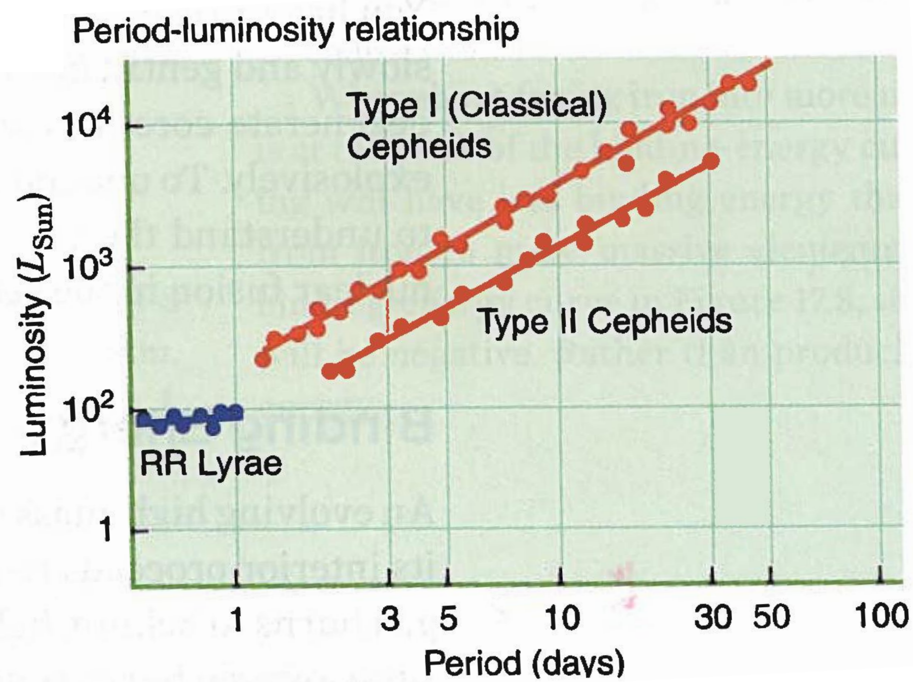
0. **Solar system distances:** Radar
1. **4 to 1000 light years:** Parallax
2. **to 300,000 light years:** RR Lyrae variable stars
3. **to 1 million light years:** H-R diagram - comparing same types of stars
4. **to 60 million light years:** Cepheid variable stars
5. **to 300 million light years:** **Tully-Fisher 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



[OpenStax, Astronomy 2e (2025)]

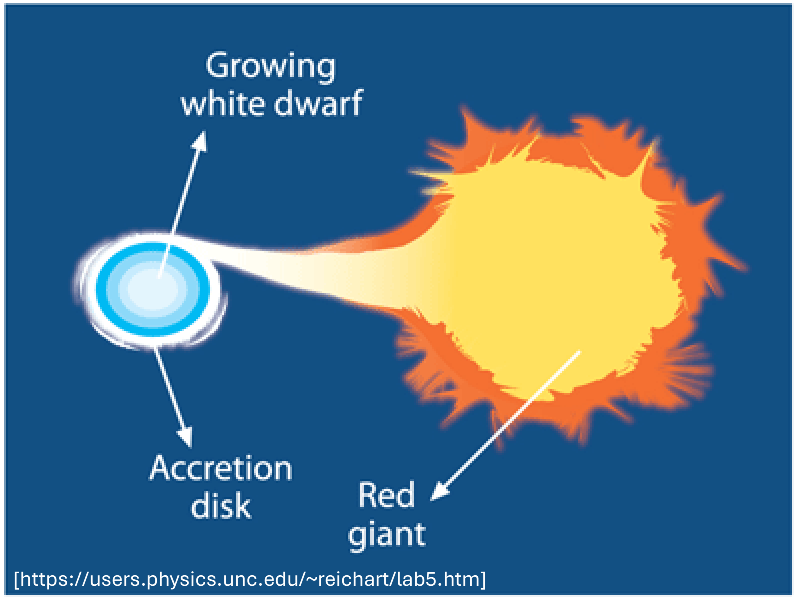


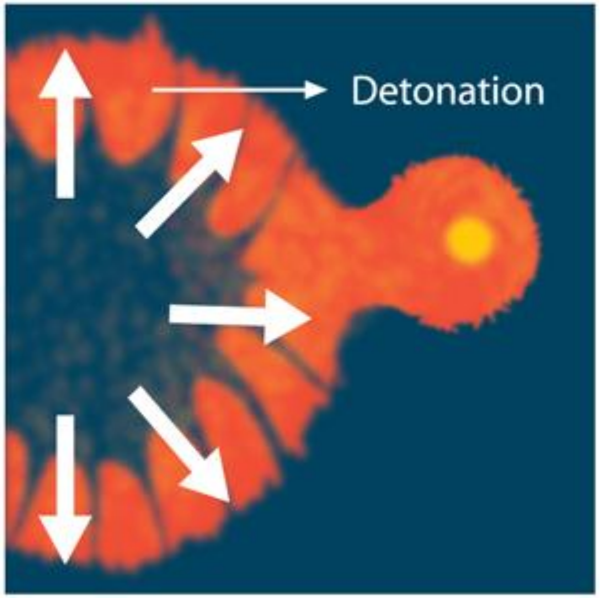
[*21st century Astronomy*, 5th ed., by L. Kay, S. Palen, and G. Blumenthal (Norton, 2016)]

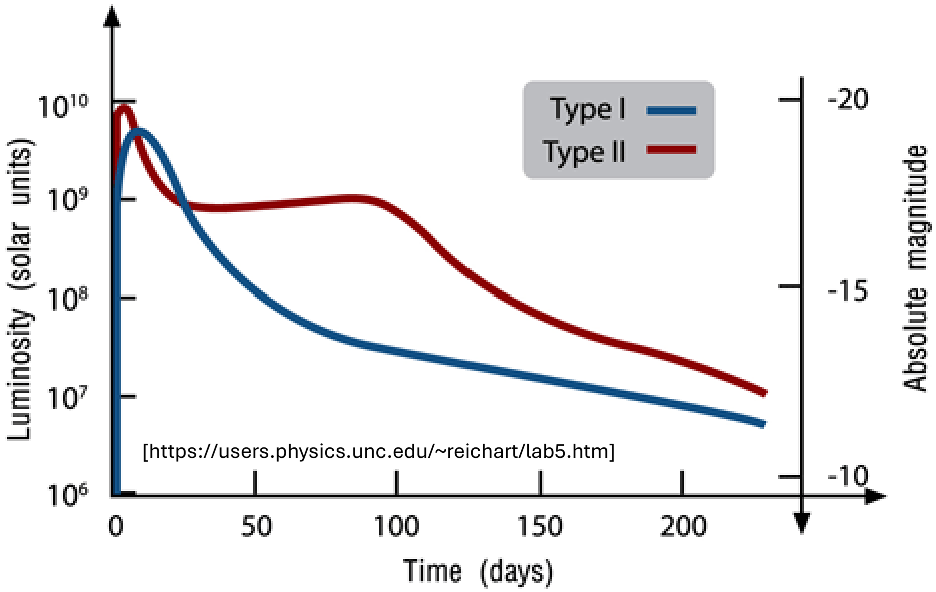
Period-Luminosity Relation for Cepheid Variables

- 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

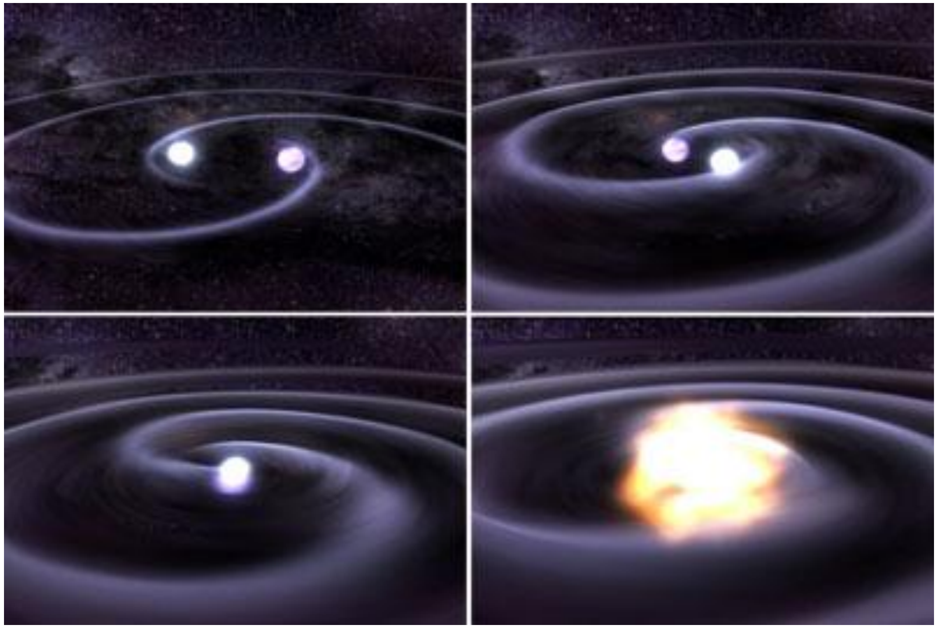






All type 1a supernovae have an effective maximum luminosity of about $5 \times 10^9\ L_{Sun}$.

Type 1a Supernovae – a standard candle

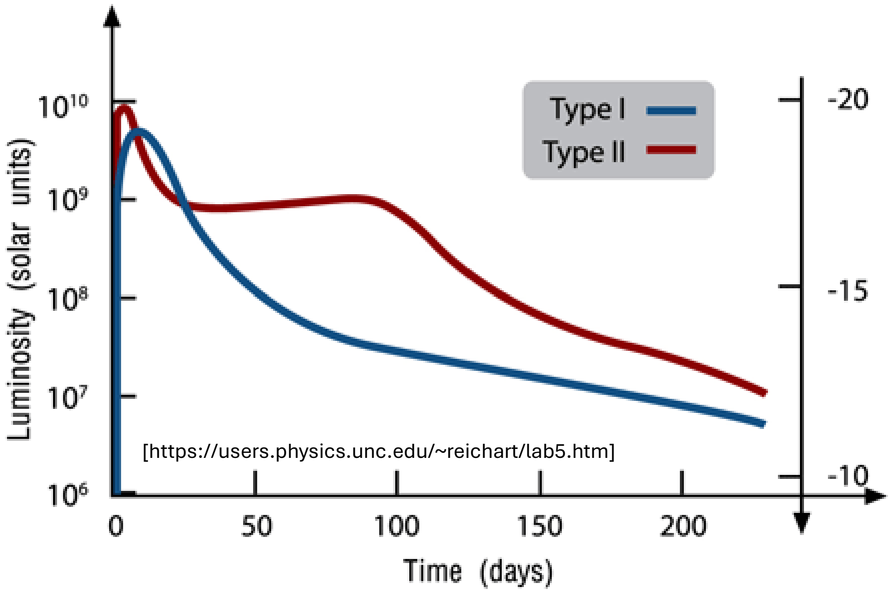


Alternate scenario:

- 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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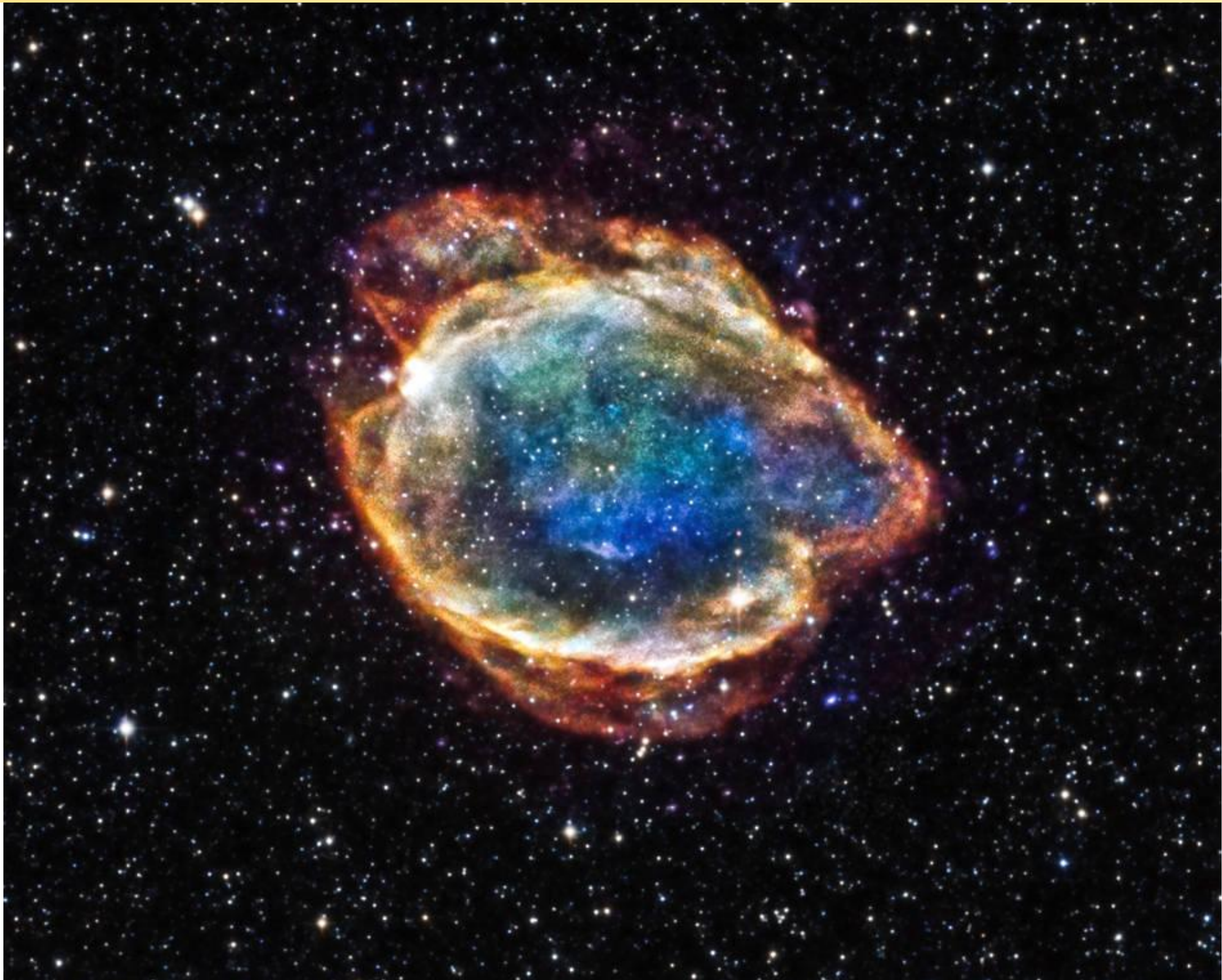
Type 1a Supernovae – a standard candle

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.

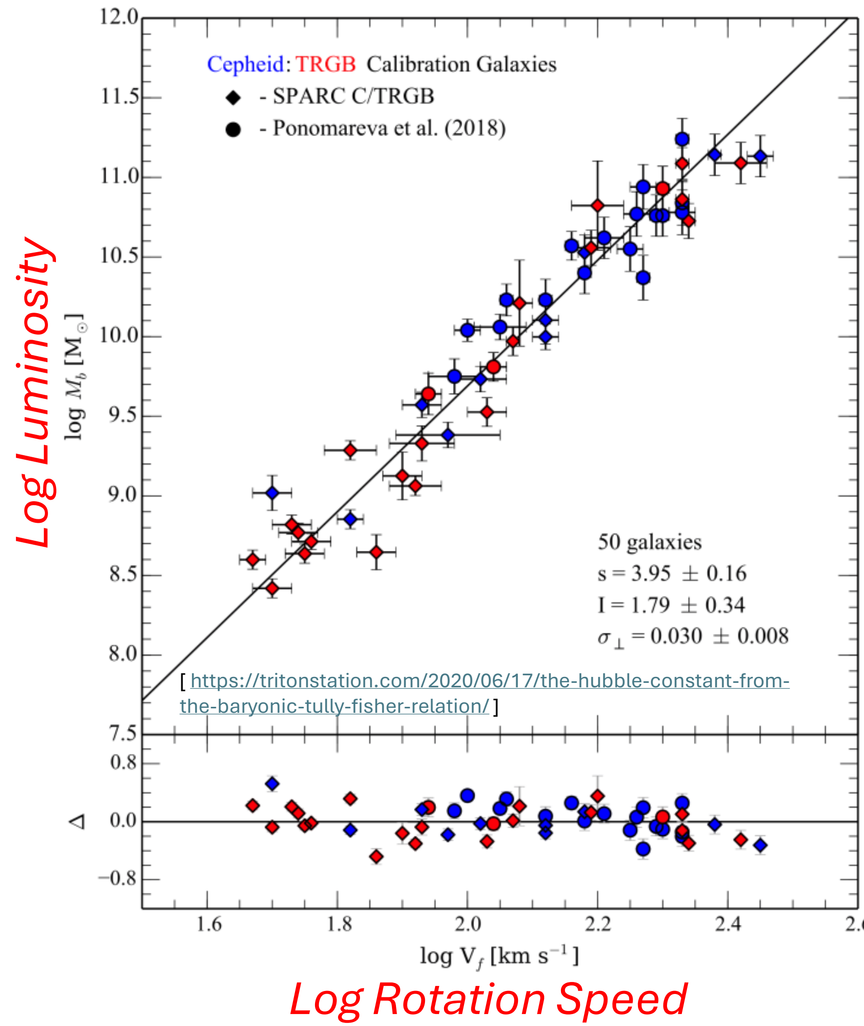
Elements produced:
- **Up to nickel**, which then decays to **iron**.
- Significant amounts of **silicon**.



G299 supernova type 1a remnant
[NASA/CXC/U.Texas]

Tully-Fischer Relation

Tully and Fisher discovered, for <u>spiral galaxies</u>, a simple **empirical** relationship between the **total luminosity** of the galaxy and its **rotational speed**.



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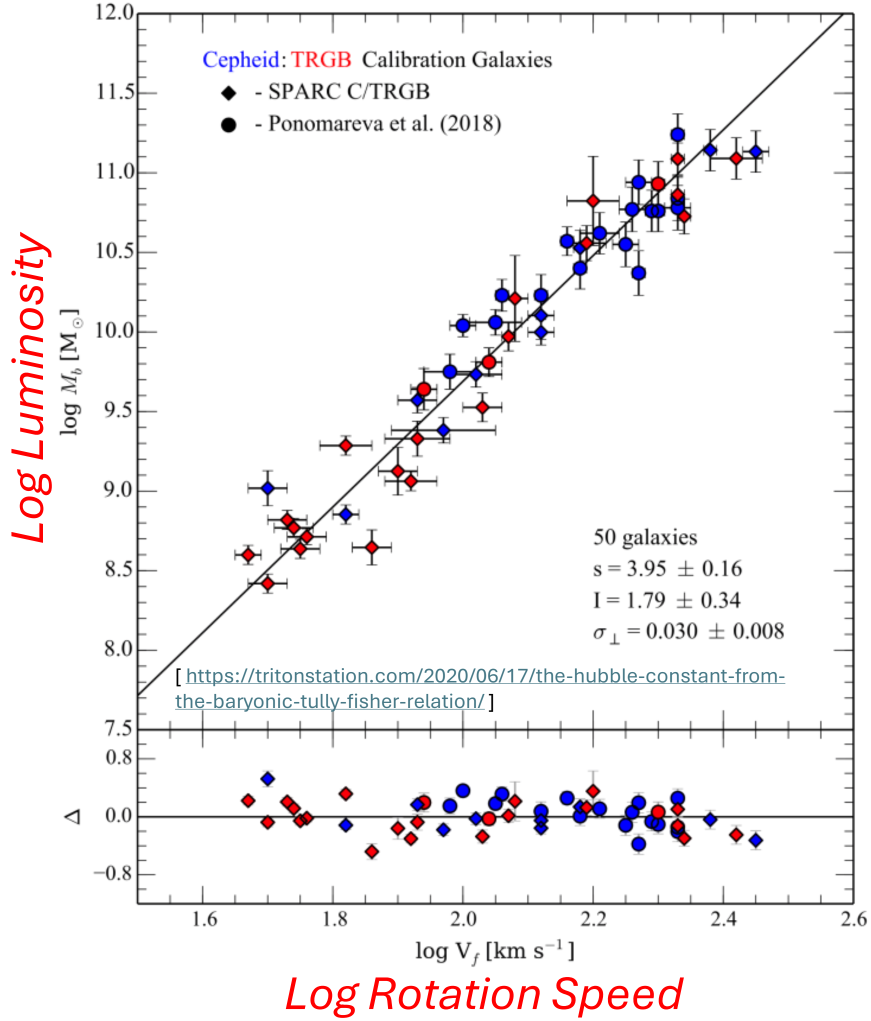

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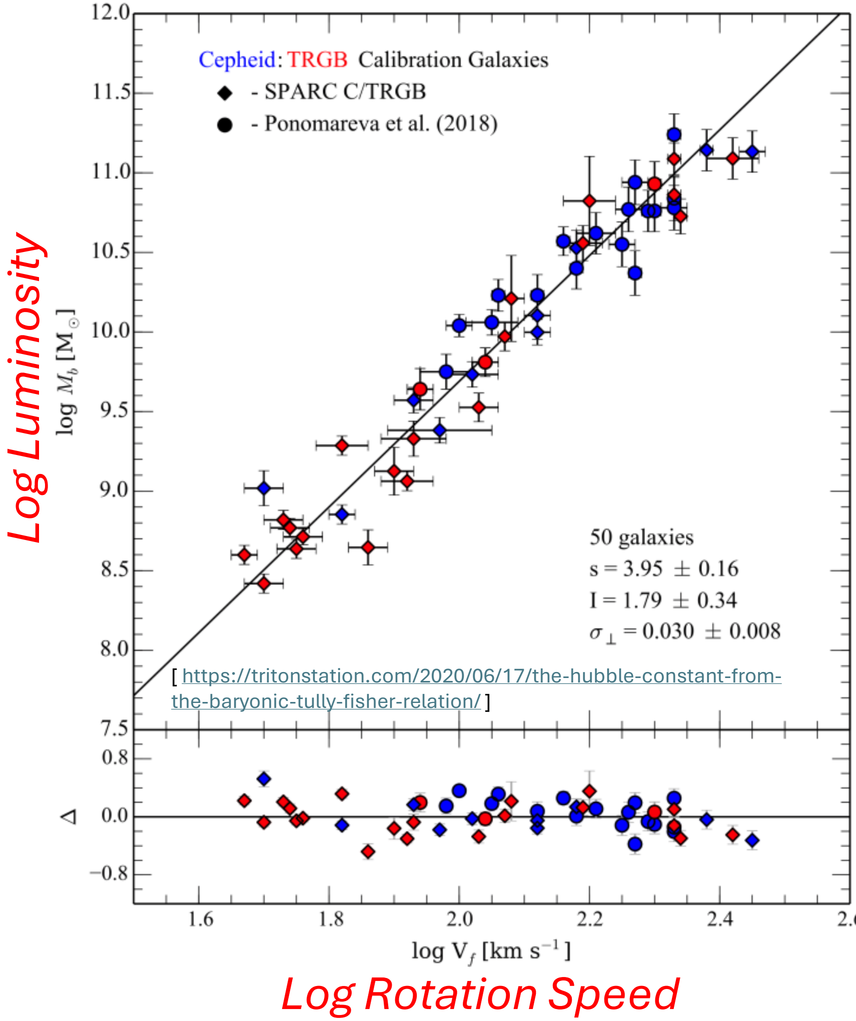
Intuitive idea

- **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).
- **Empirically**, it seems to work.



[https://tritonstation.com/2020/06/17/the-hubble-constant-from-the-baryonic-tully-fisher-relation/]

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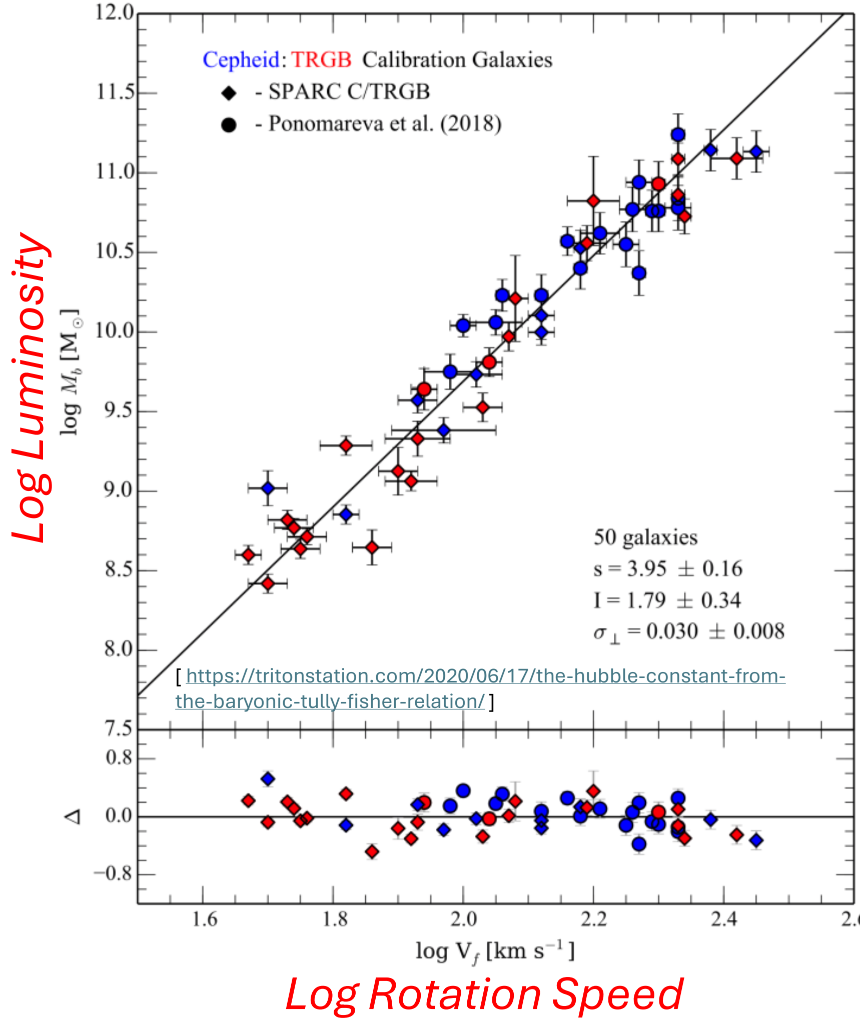
"Standard candle" to get distance

- Get luminosity from rotation speed

- Get distance from the apparent brightness ("magnitude") and $1/d^2$.



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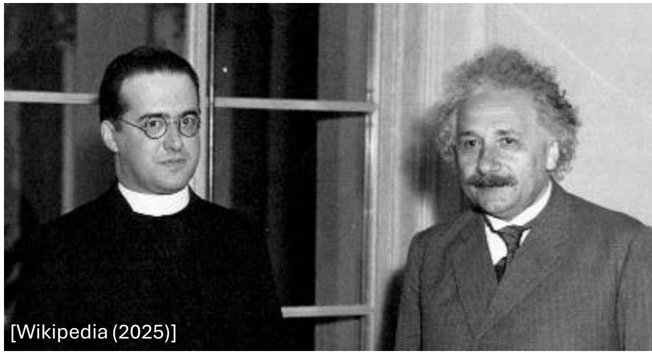
1927: Georges Lemaître solved Einstein's General Relativity equations and found a solution with an expanding universe.

- 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.)



[Wikipedia (2025)]

Lemaître and Einstein (CalTech 1933)

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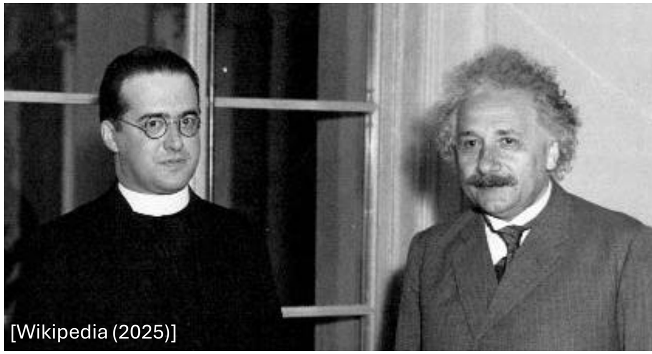
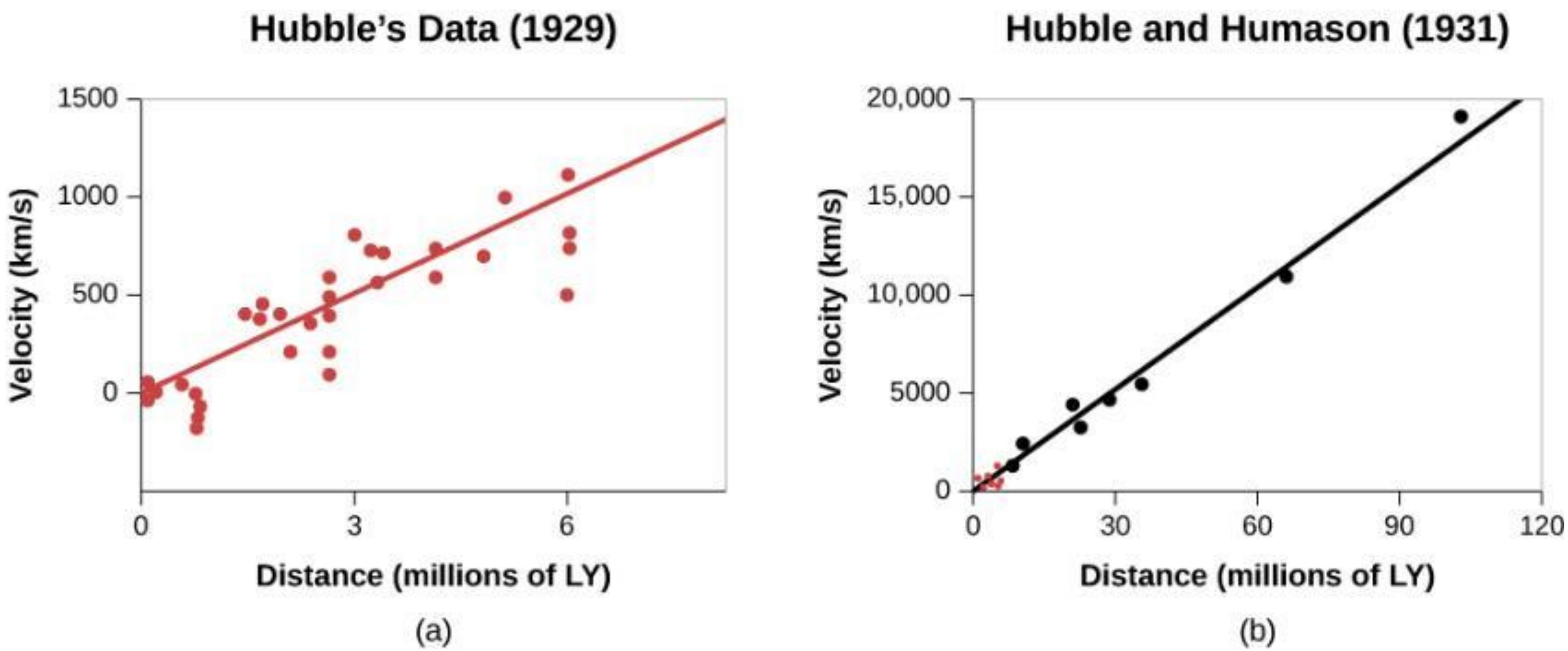


[Wikipedia (2025)]

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 Law: $V = H \times d$

V = recession velocity

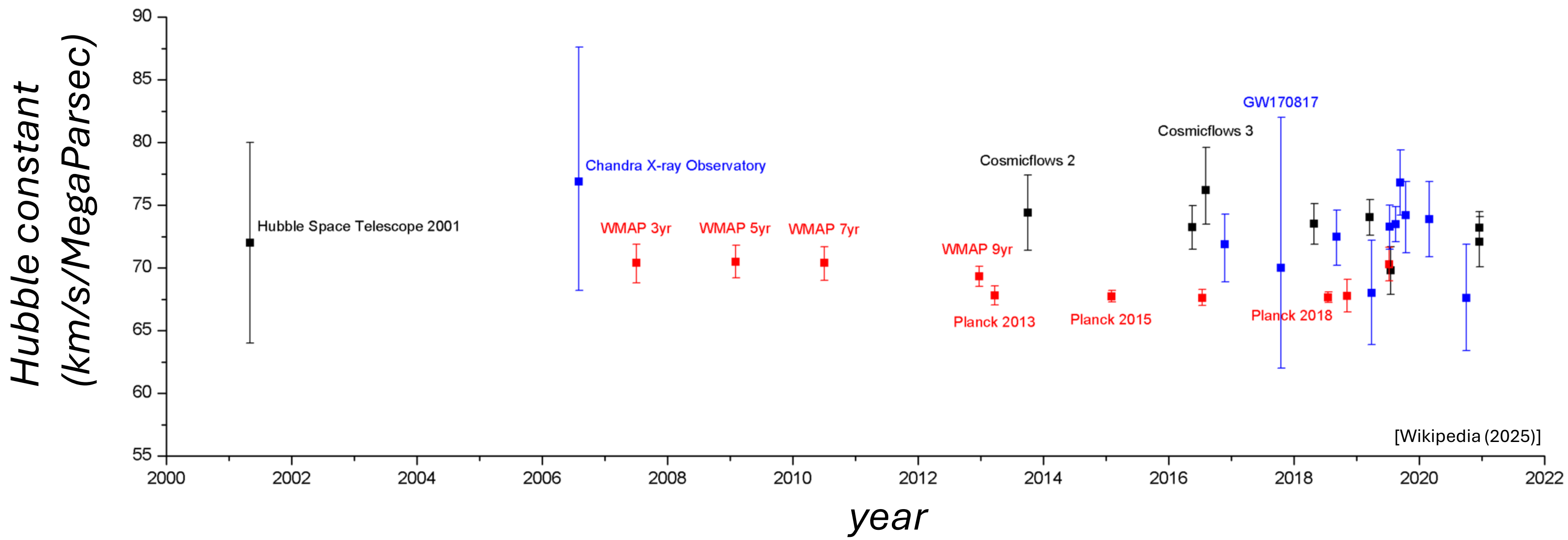
D = distance from Earth

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 <u>the distance between all points is getting larger</u>.

→ That's all.

Hubble's Law: The Expansion of the Universe

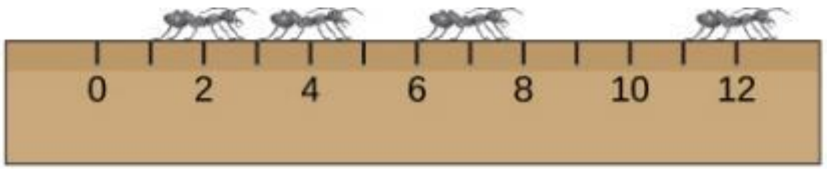
- The fact that we (on Earth) see all the galaxies moving away from us, and the farther away they are, the faster they are receding, does ***not*** mean that we are in some special location (an anthropocentric view).

- 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.

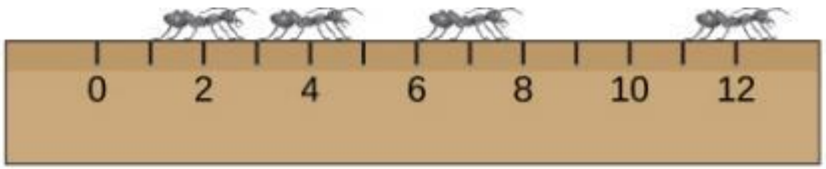
- ***Huh?***

1D model of Expanding of the Universe



Ants at rest on stretchable ruler.

1D model of Expanding of the Universe



Ants at rest on stretchable ruler.

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

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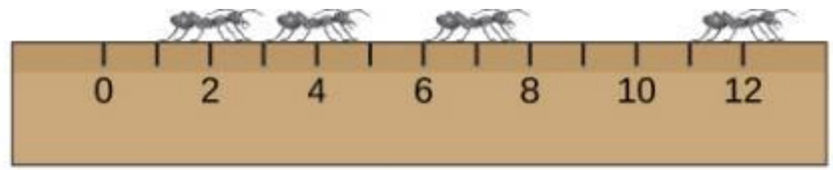

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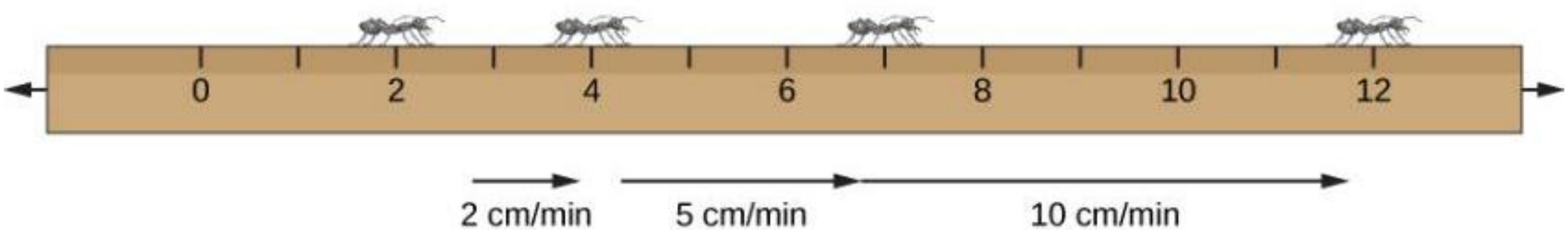

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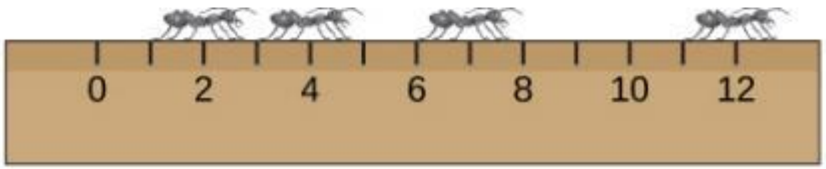

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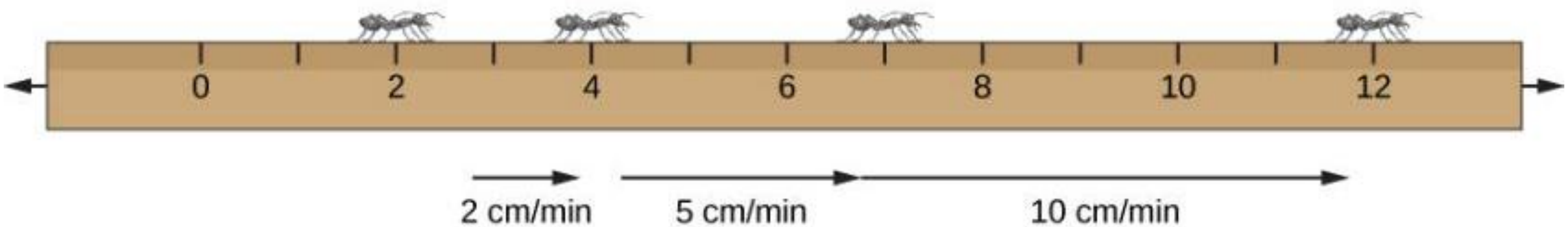
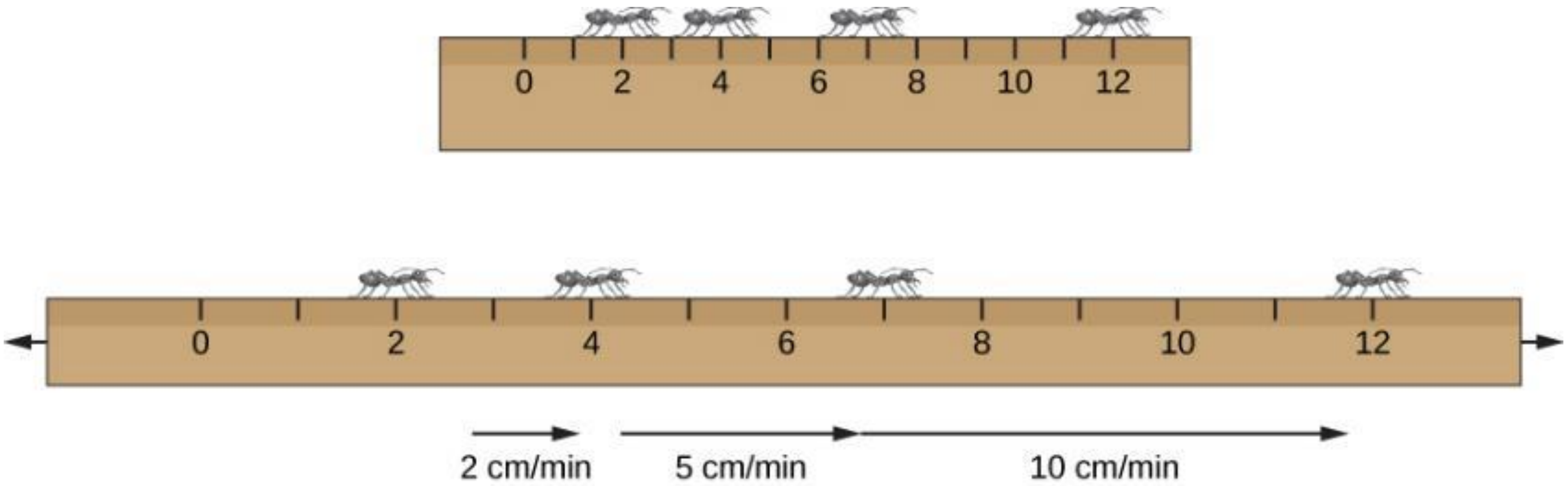


- The farther away ant B was from ant A originally, the farther it has moved from ant A.
- The larger the initial separation, the larger the stretched separation (proportionally).

→ *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).

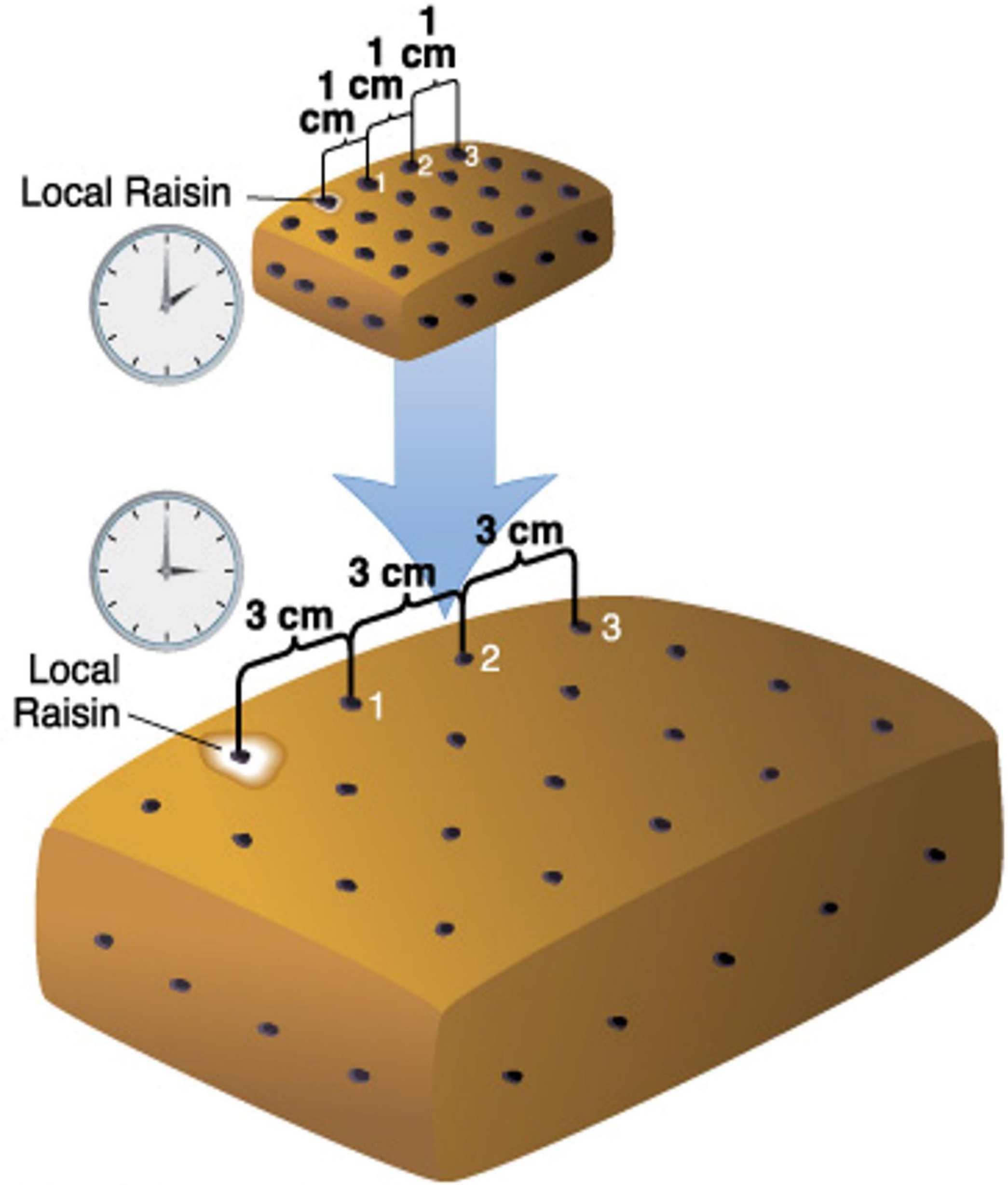
→ An expanding universe doesn't have to expand ***into*** anything!

→ 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

- Insert raisin bread loaf in oven.
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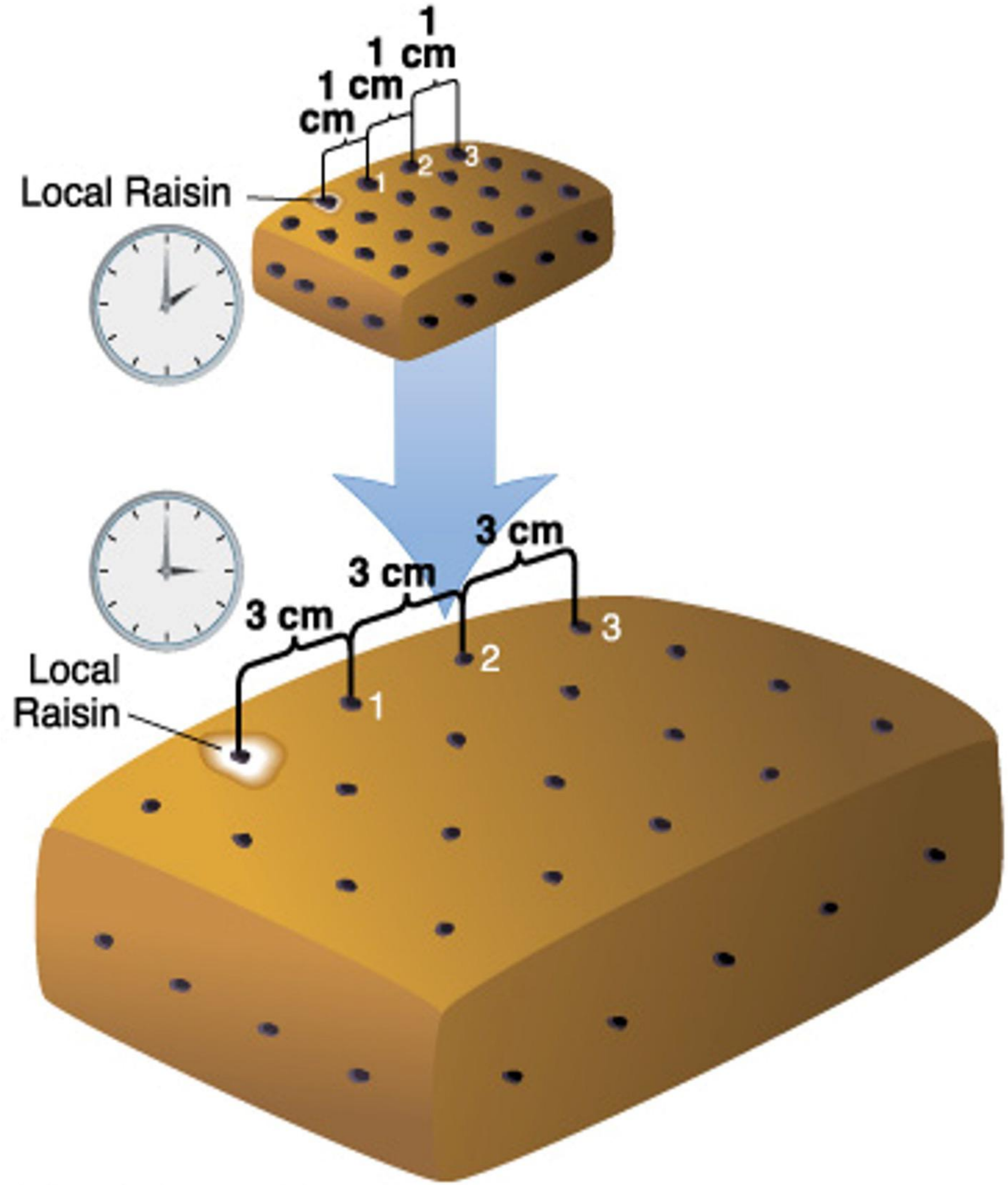
- The **relative velocity** of raisins <u>increases with distance</u>.
- Now imagine an infinite loaf …
  … The same thing happens.



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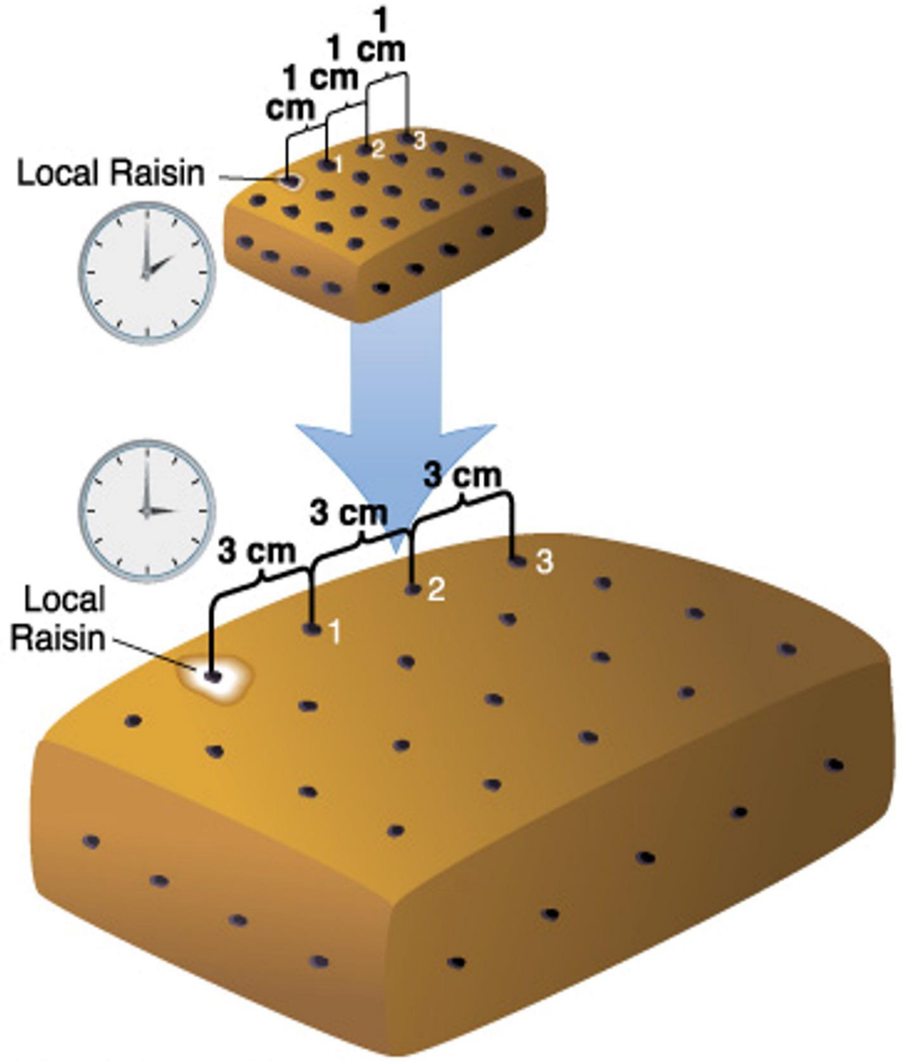
Note: a raisin itself does not expand. Think of the raisins as galaxies.



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