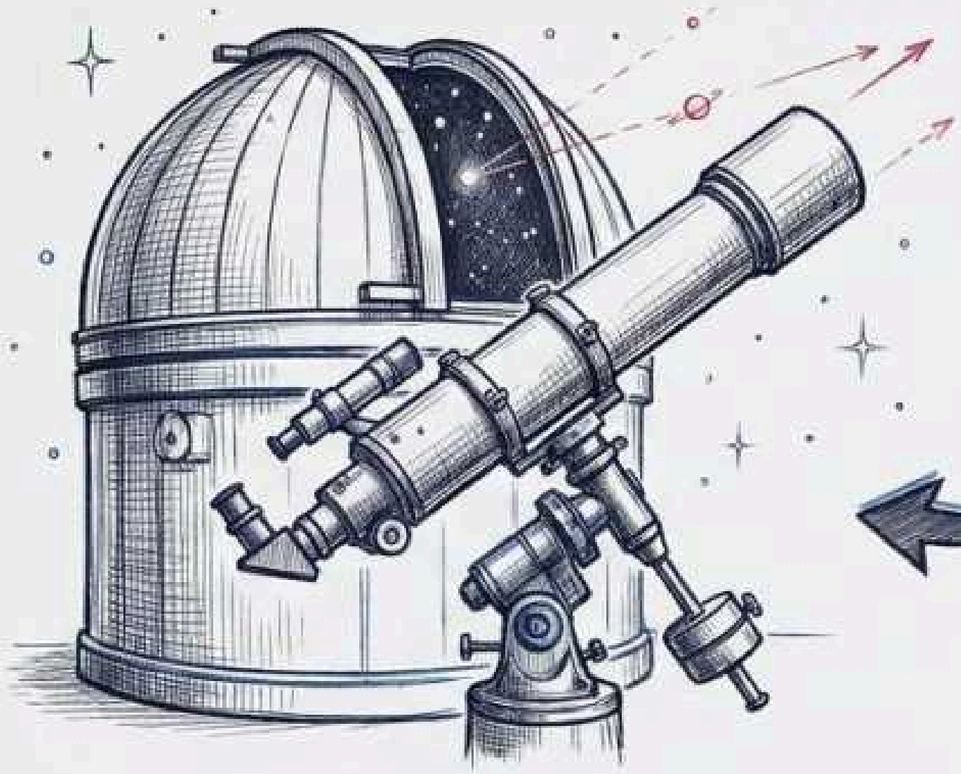
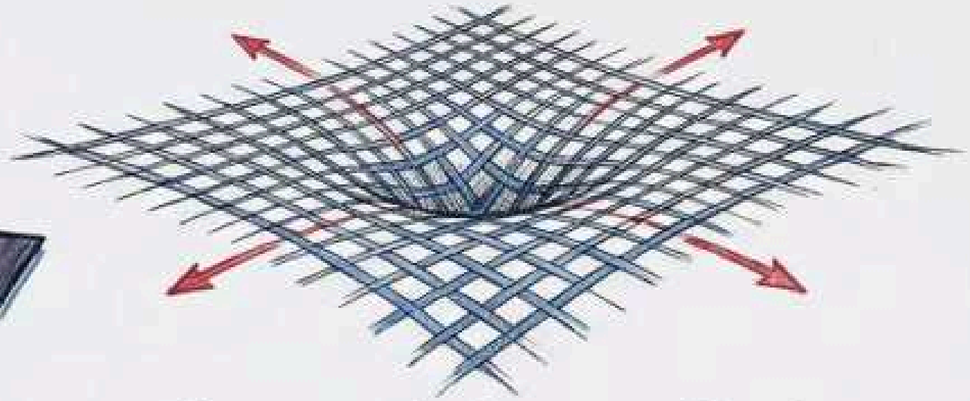
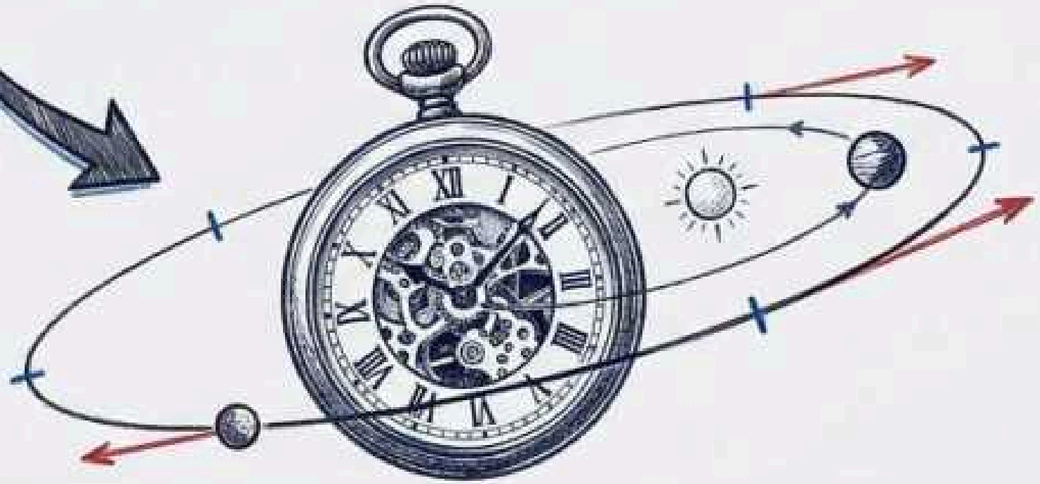
Three pillars of cosmic inquiry.



How do we know the universe is expanding?



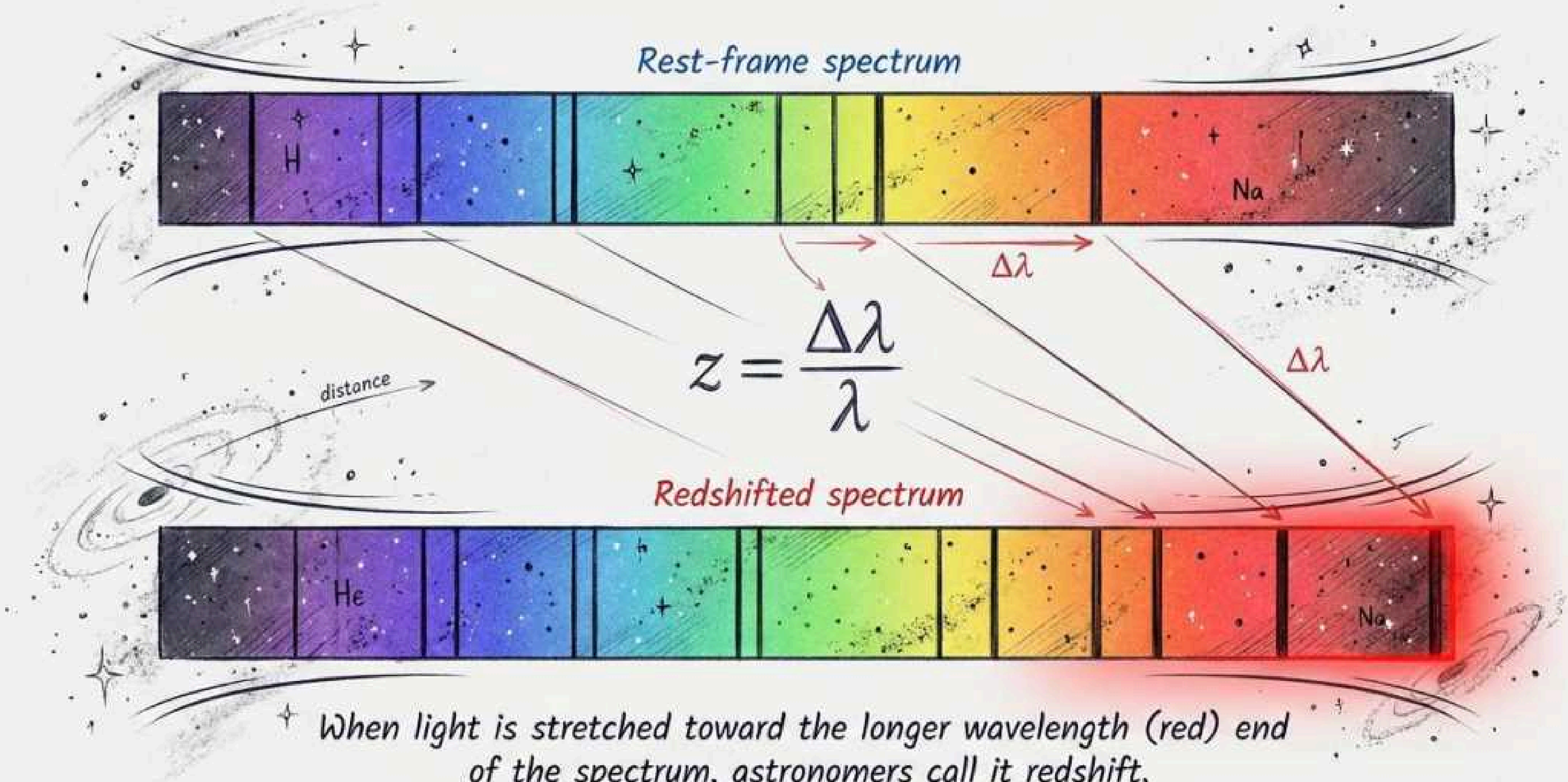
What exactly is expanding?



How does the expansion rate tell us the universe's age?

Redshift reveals the stretching of light.

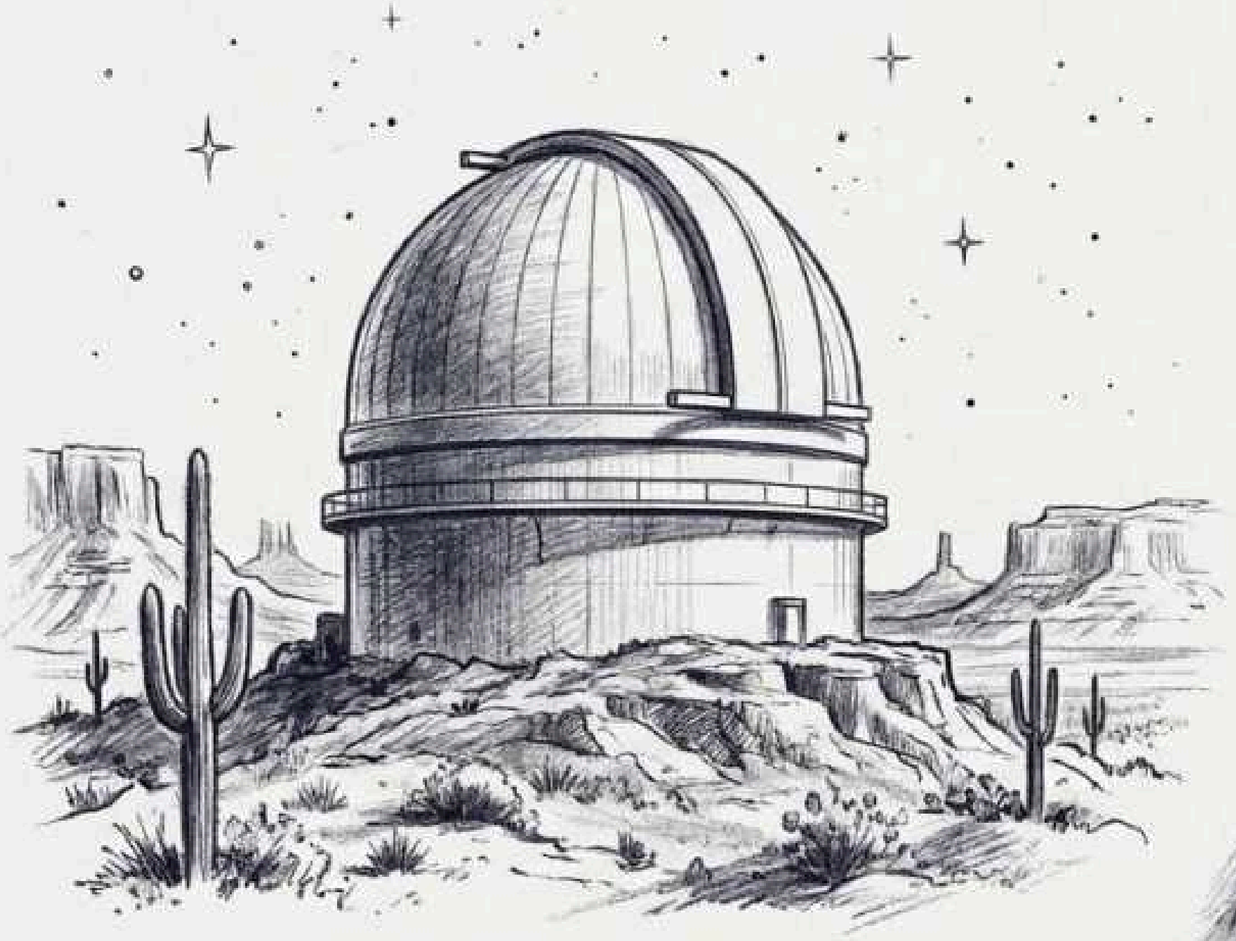
¶ 2.2



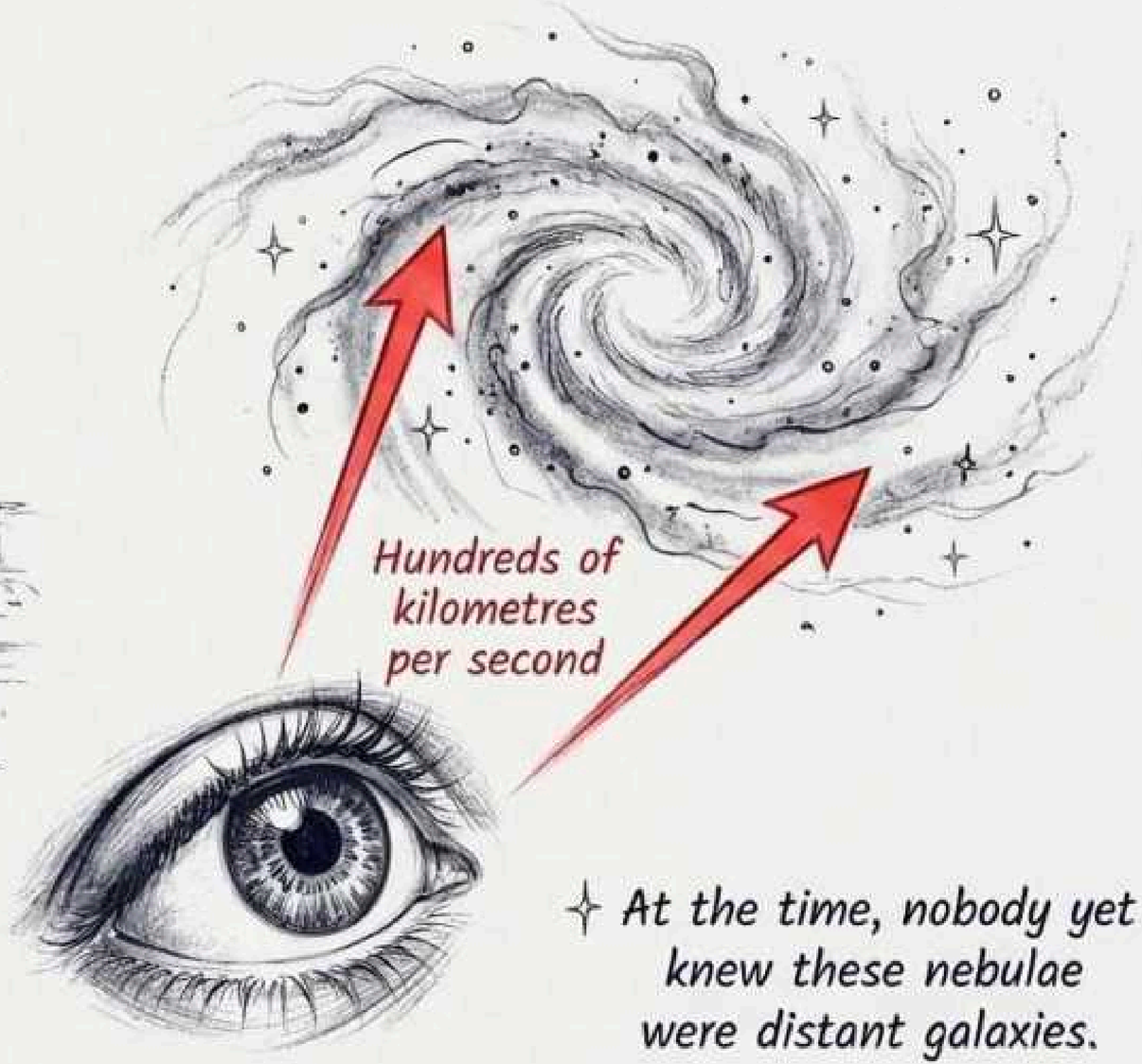
When light is stretched toward the longer wavelength (red) end of the spectrum, astronomers call it redshift.

Slipher's early clues at Lowell Observatory.

¶ 2.3



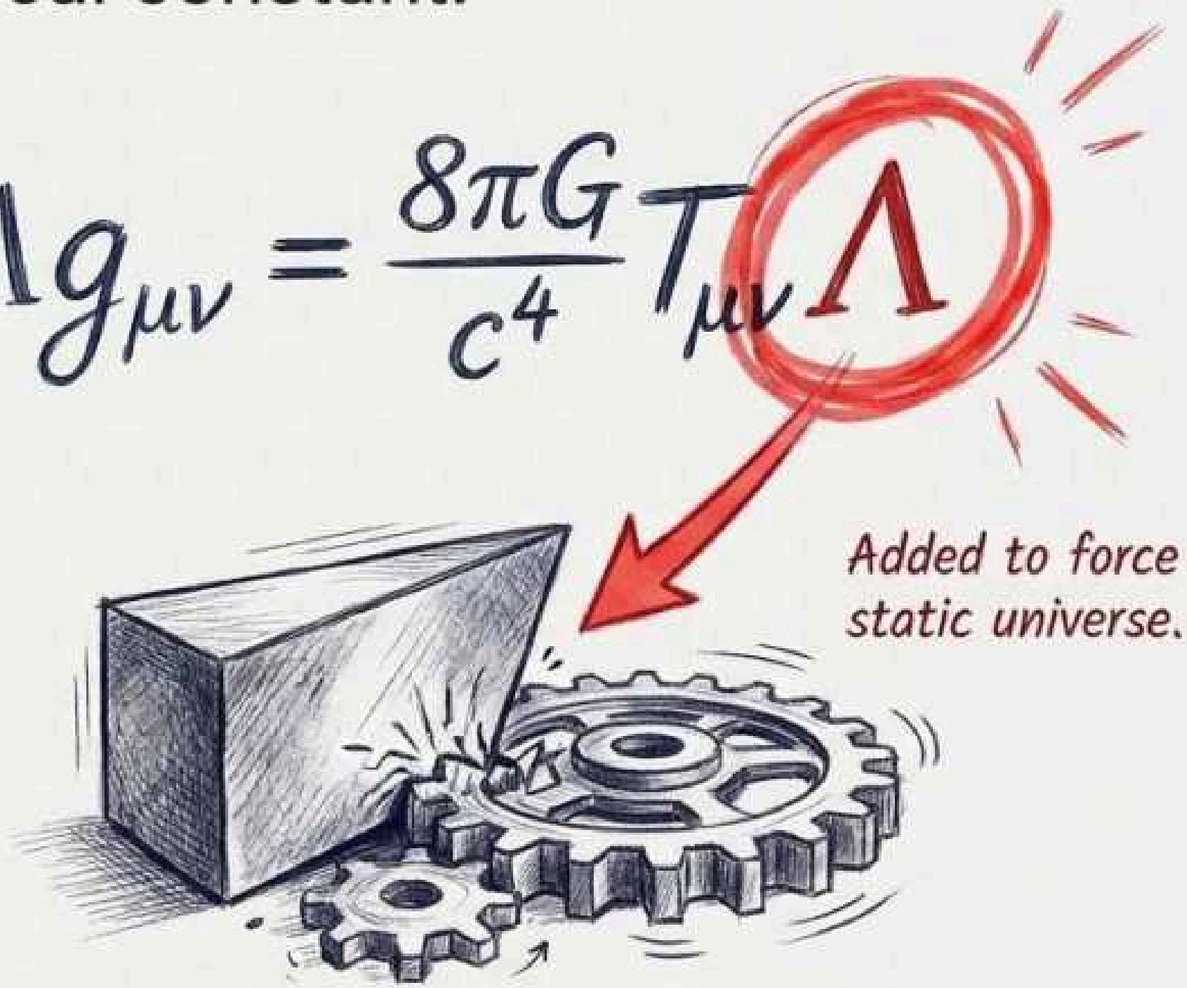
1912–1917



✦ At the time, nobody yet knew these nebulae were distant galaxies.

Einstein's restless universe and the cosmological constant.

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

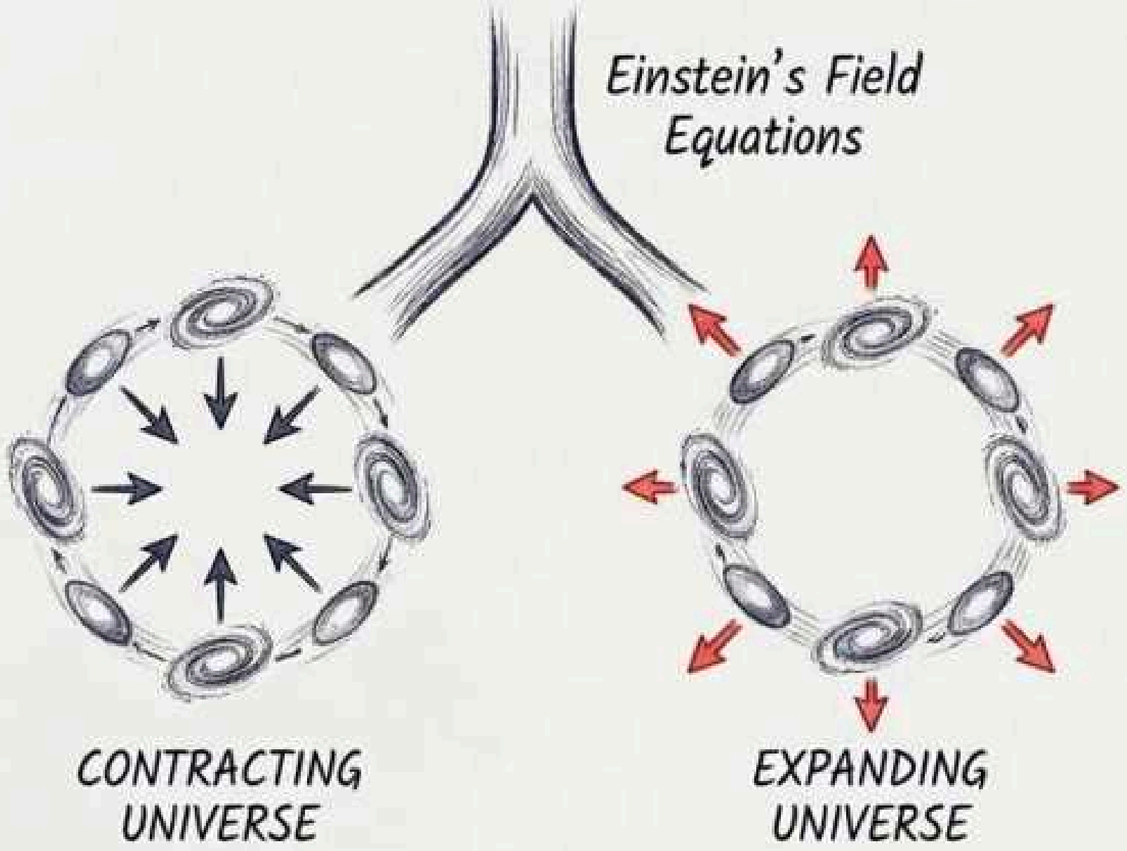


Gravity curves space and time. The raw equations showed a universe that refused to stay still.

The theorists embrace the expanding equations.

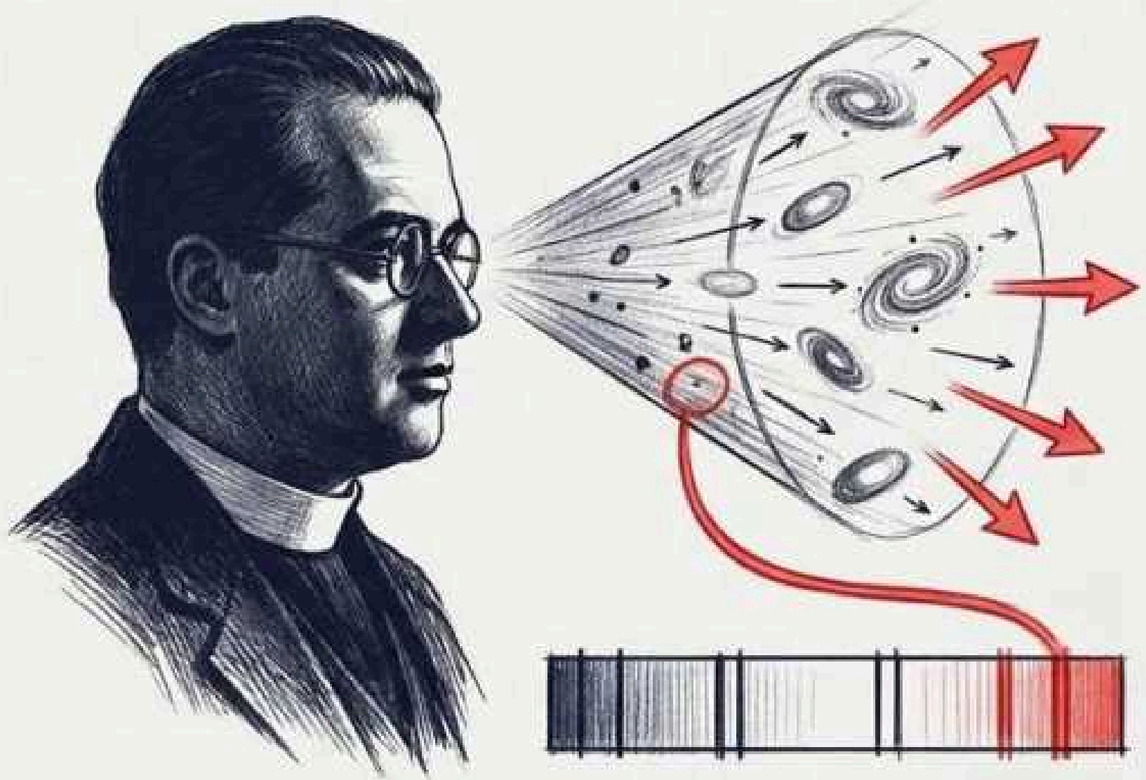
¶ 2.5

Alexander Friedmann (1922)



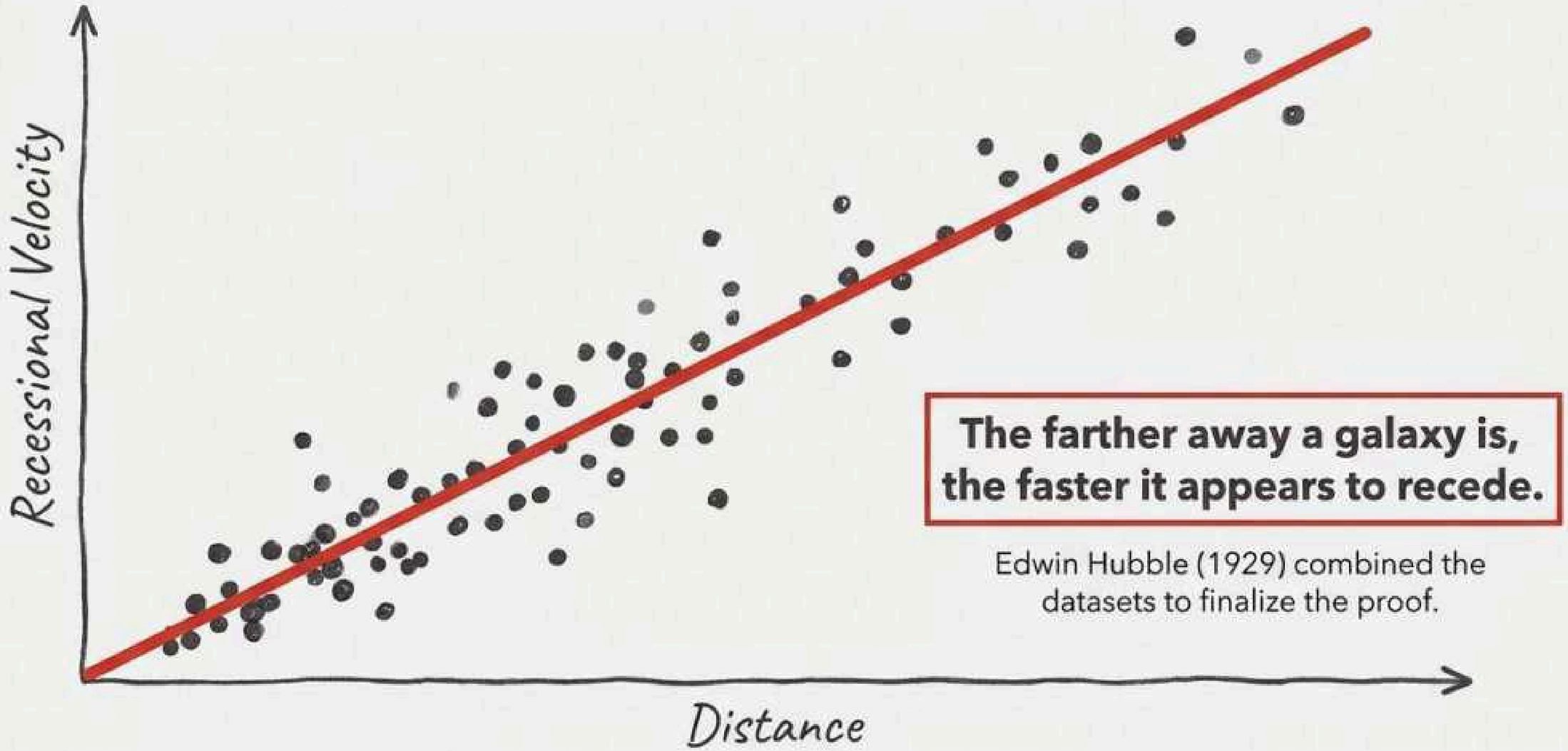
General relativity allows both states.

Georges Lemaître (1927)



Independently derived an expanding universe explicitly linked to the observable redshifts of galaxies.

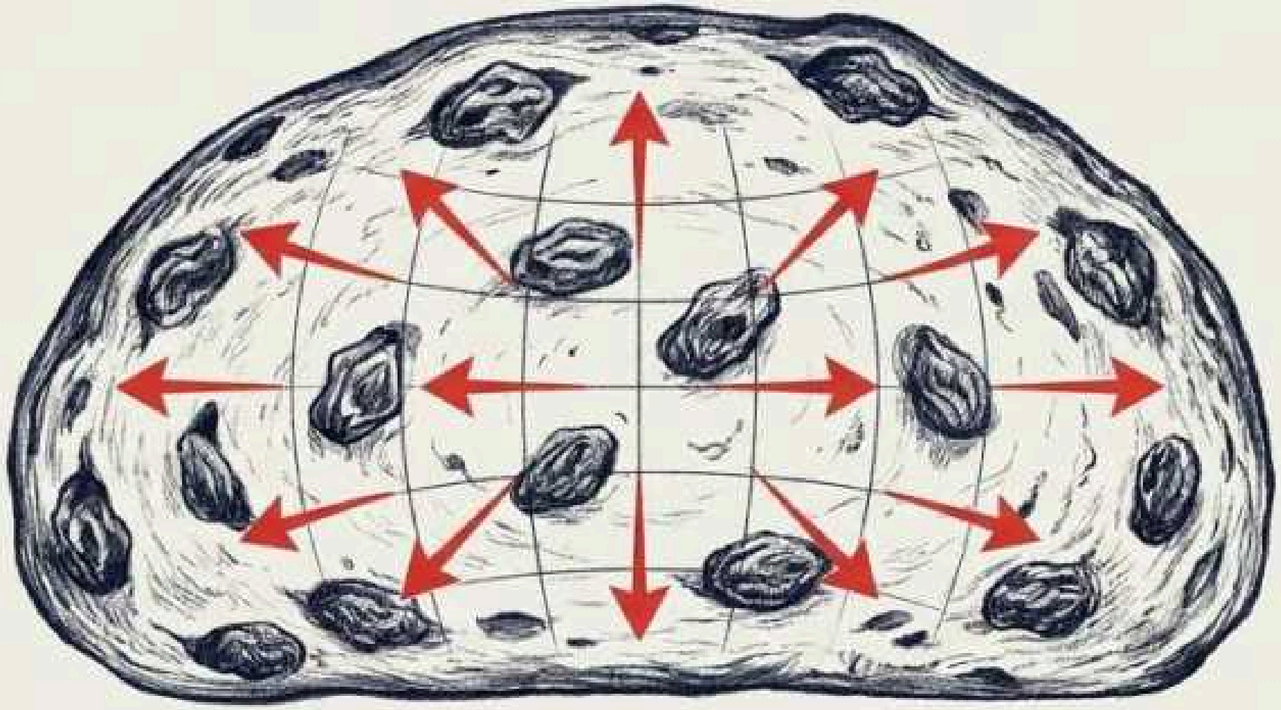
The Hubble-Lemaître law proves the pattern.



The farther away a galaxy is, the faster it appears to recede.

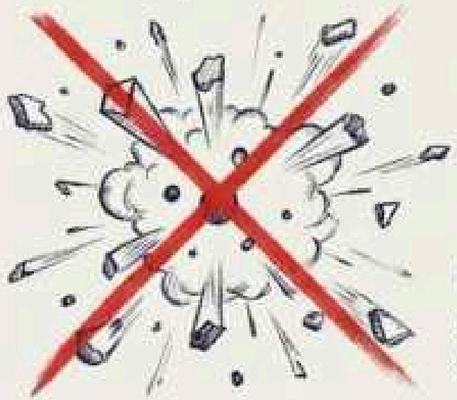
Edwin Hubble (1929) combined the datasets to finalize the proof.

Space itself is stretching.



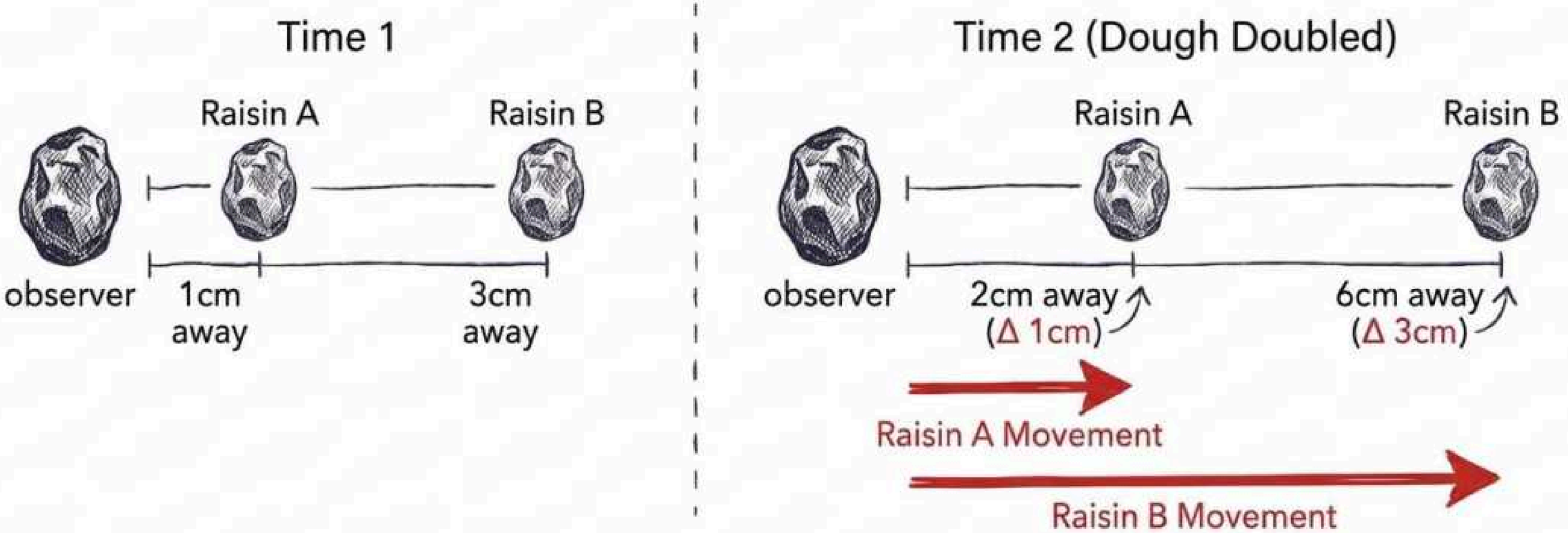
Every raisin moves away from every other,
and no raisin is at the centre.

Anti-Metaphor



It is not an explosion of
galaxies flying through
space from a central point.

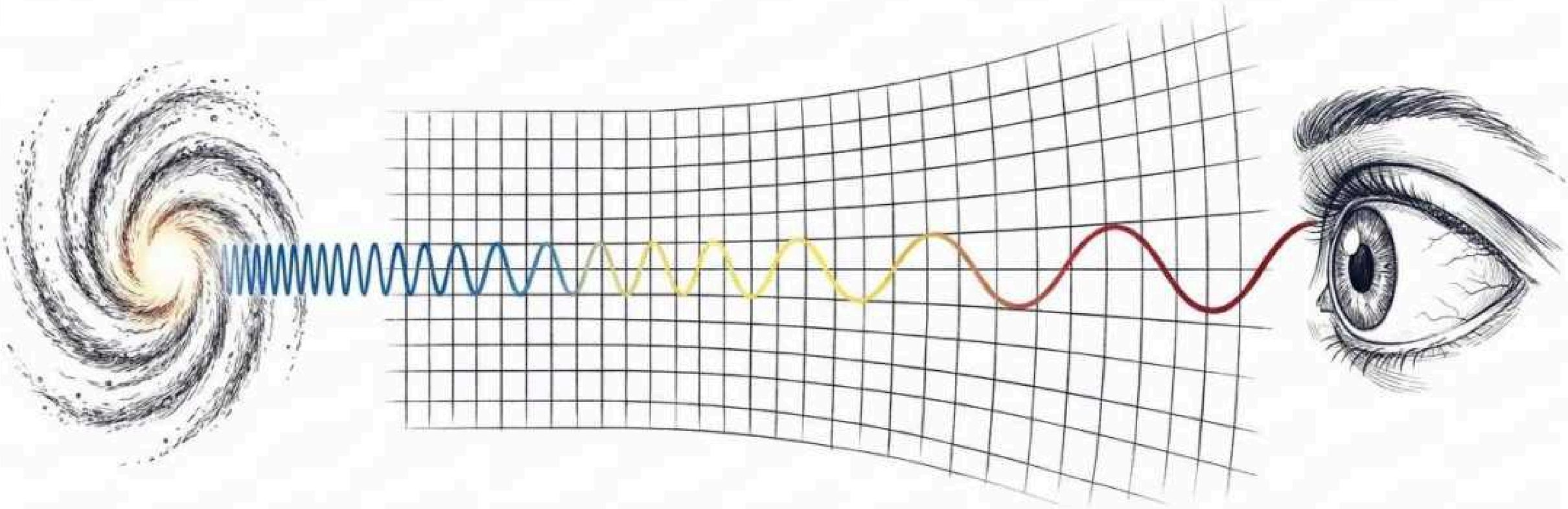
The mathematics of the dough.



Because the distant raisin moved farther in the exact same amount of time, it appears to move faster. Every raisin sees this identical pattern.

Stretching the light.

¶ 2.9



As light travels through stretching space, its wavelength stretches with it. The longer the journey, the more the stretch.

Measuring the rate of expansion.

¶ 2.10

$$H_0 \approx 70 \ km/s/Mpc$$



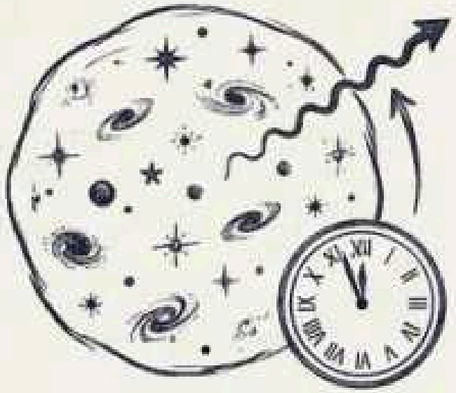
The Hubble constant is the current measurement of the expansion rate, linking physical distance directly to recessional speed.

Correcting the cosmic yardstick.

Hubble's Initial Estimate (1920s)

$$H_0 \approx 500$$

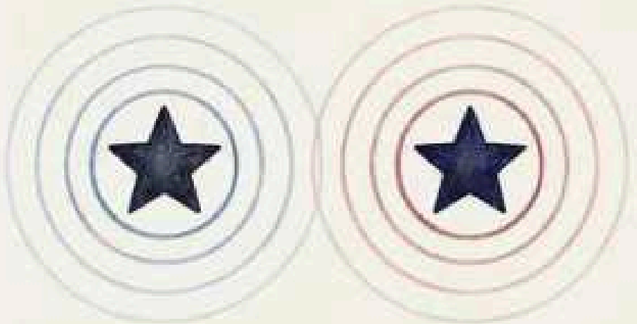
Seven times too large



Young Age

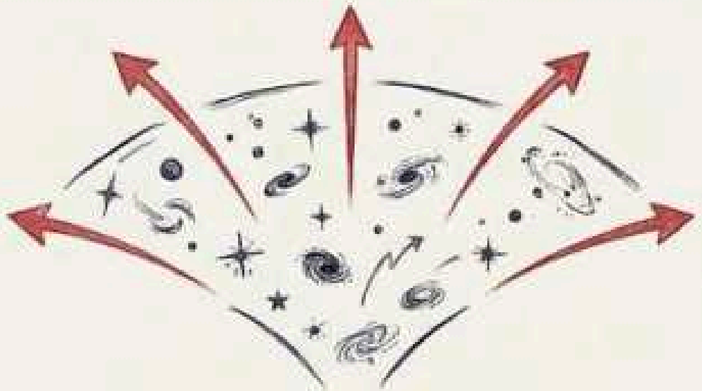
Reason: Distances were vastly underestimated.

Walter Baade's Correction (1950s)



Discovery of two types of Cepheid variables

$$H_0 \searrow$$

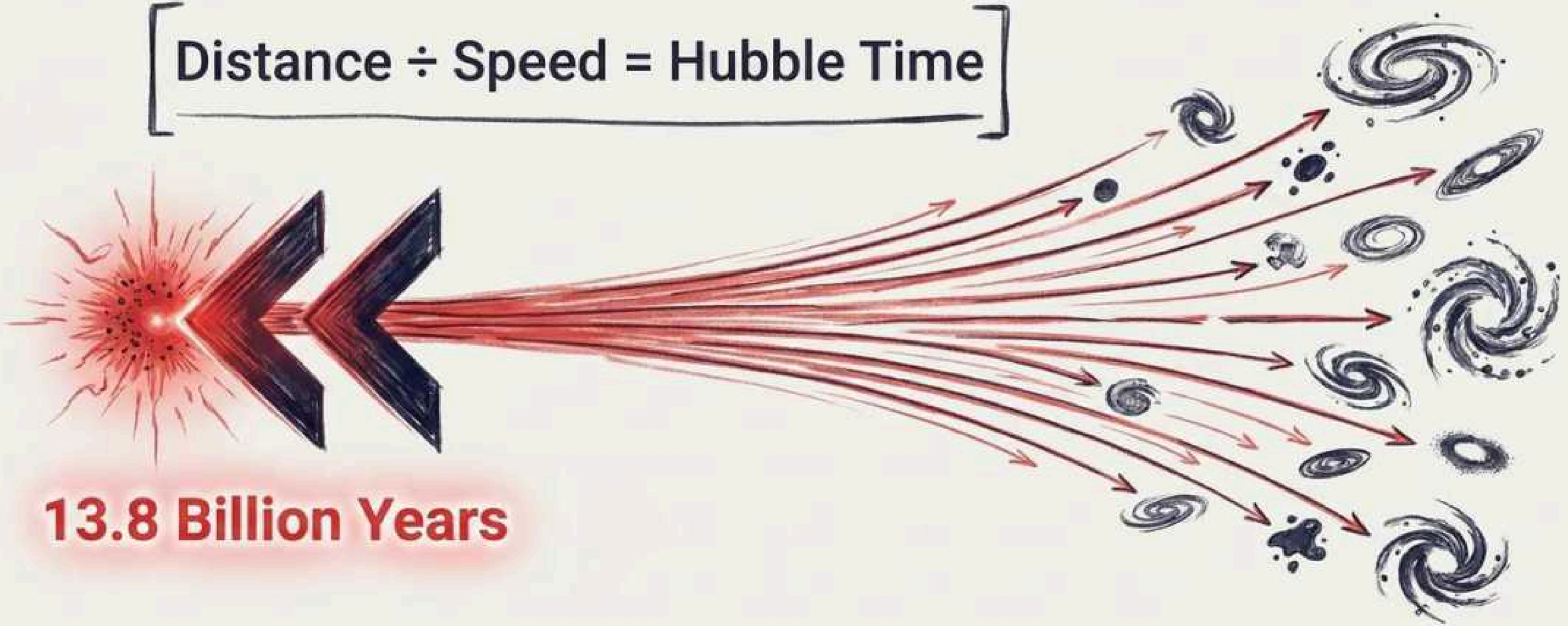


Massively expanding scale

The universe grew bigger and older with each correction.

Rewinding the clock to the beginning.

Distance ÷ Speed = Hubble Time



13.8 Billion Years

Accounting for how expansion rates have changed refines the rough calculation to exactly 13.8 billion years.

Einstein's biggest blunder.

¶ 2.13



> "The cosmological constant was my biggest blunder."

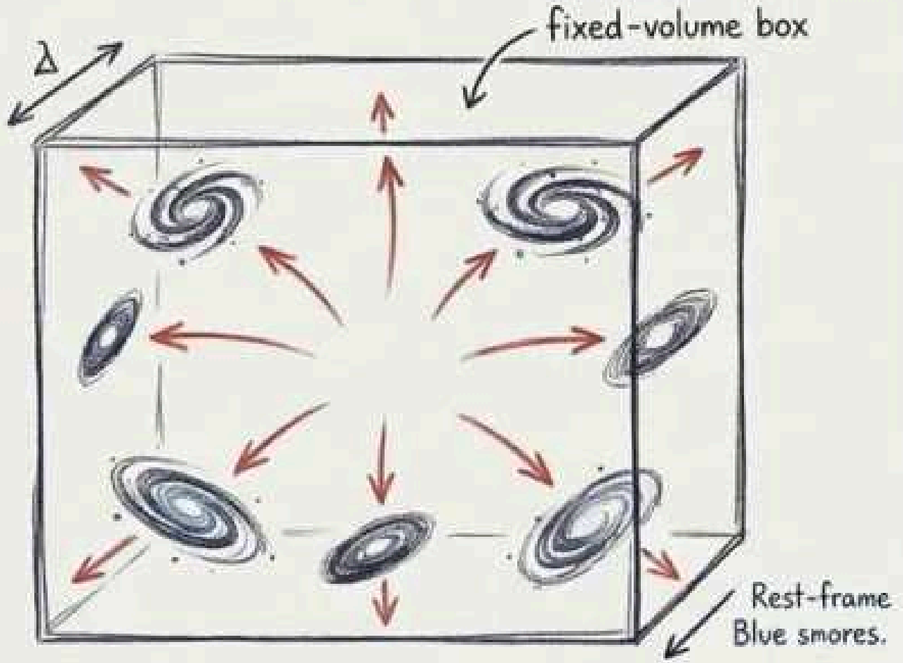
— Attributed to Einstein by physicist George Gamow, acknowledging it blinded him to the reality of the expanding universe.

To be continued in Lecture 5... the constant returns.

The Steady State rival (1948).

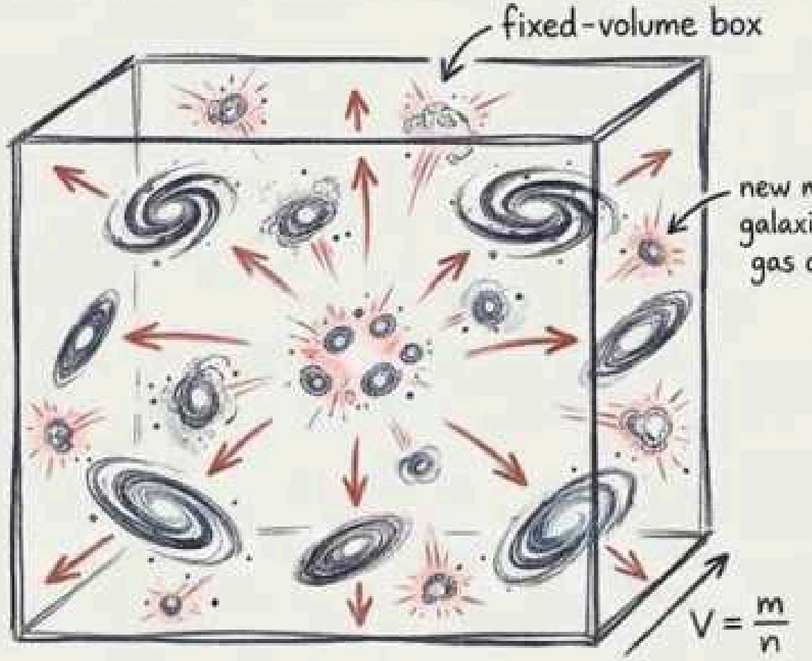
¶ 2.14

The Big Bang Paradigm



Density drops over time.
Universe had a beginning.

Steady State Theory

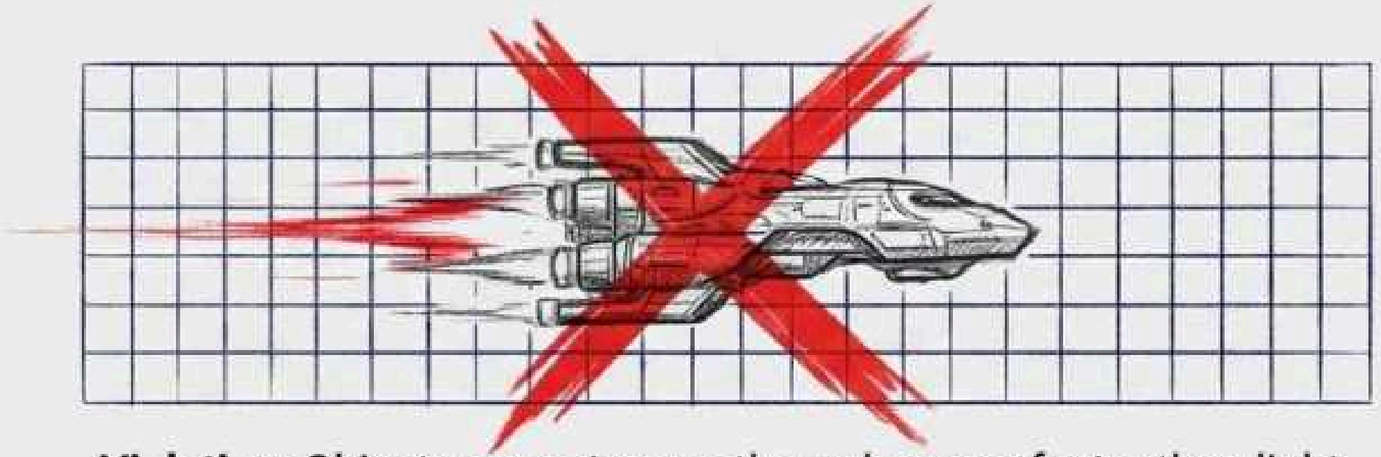


New matter continuously created.
Density remains constant. No beginning.

Proposed by Hoyle, Bondi, and Gold, this remained a serious rival to the Big Bang for two decades.

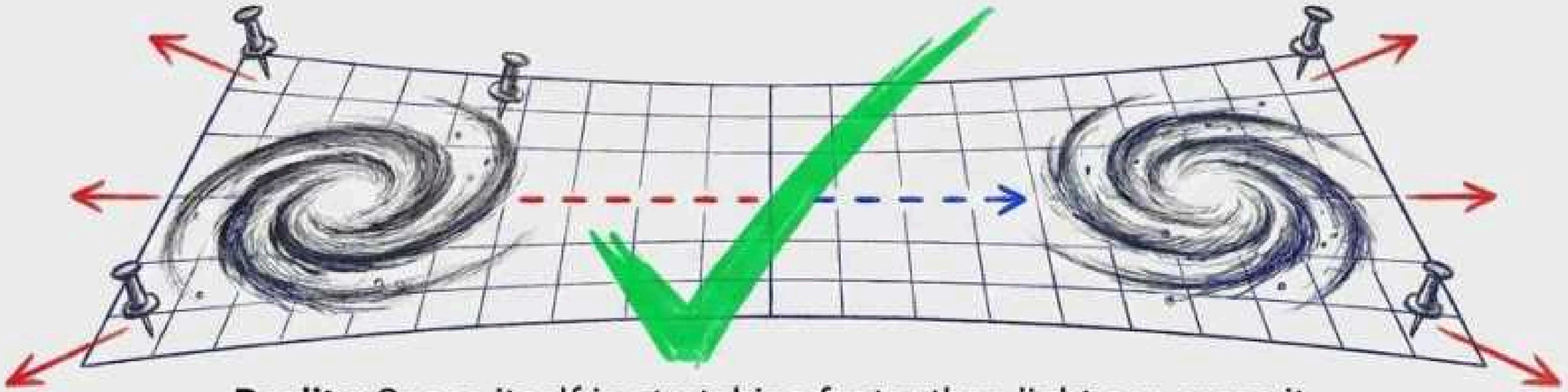
The faster-than-light paradox.

Scenario A:
Objects cannot move through space faster than light.



Violation: Objects cannot move through space faster than light.

Scenario B:
Space itself is stretching faster than light can cross it.



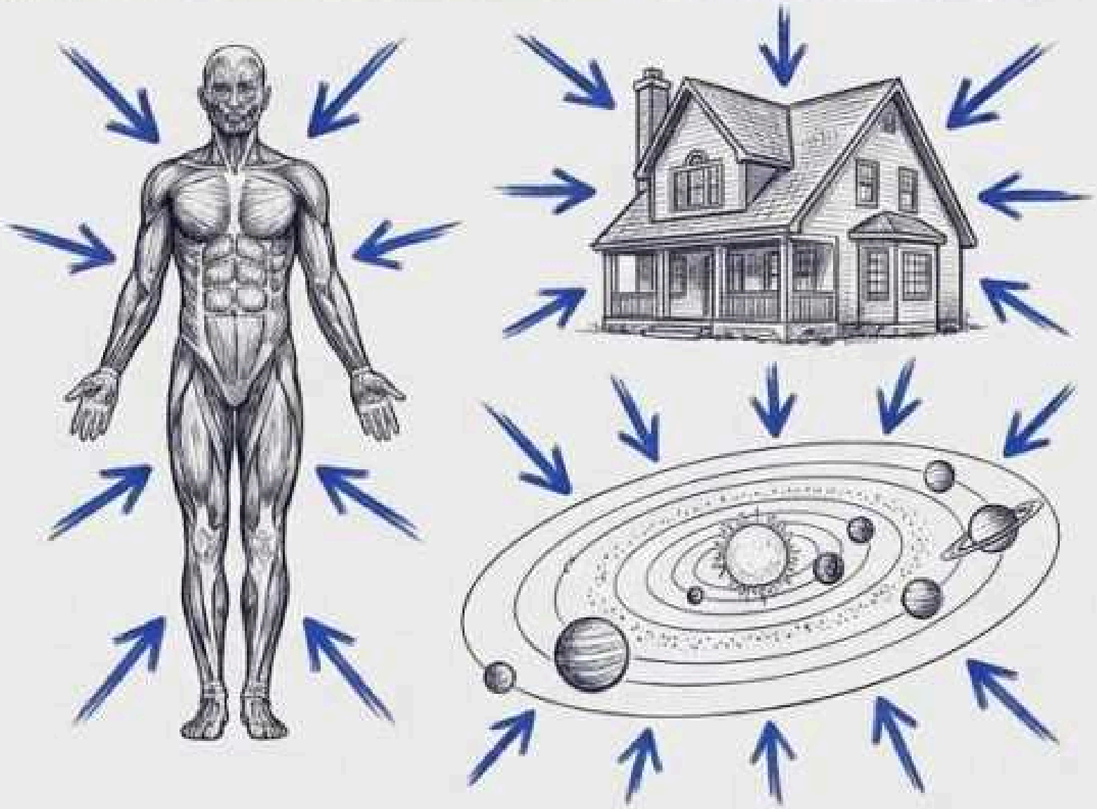
Reality: Space itself is stretching faster than light can cross it.

Very distant galaxies recede faster than light, but nothing is breaking Einstein's rule.
Nothing is moving through space; space itself is stretching.

The limits of expansion.

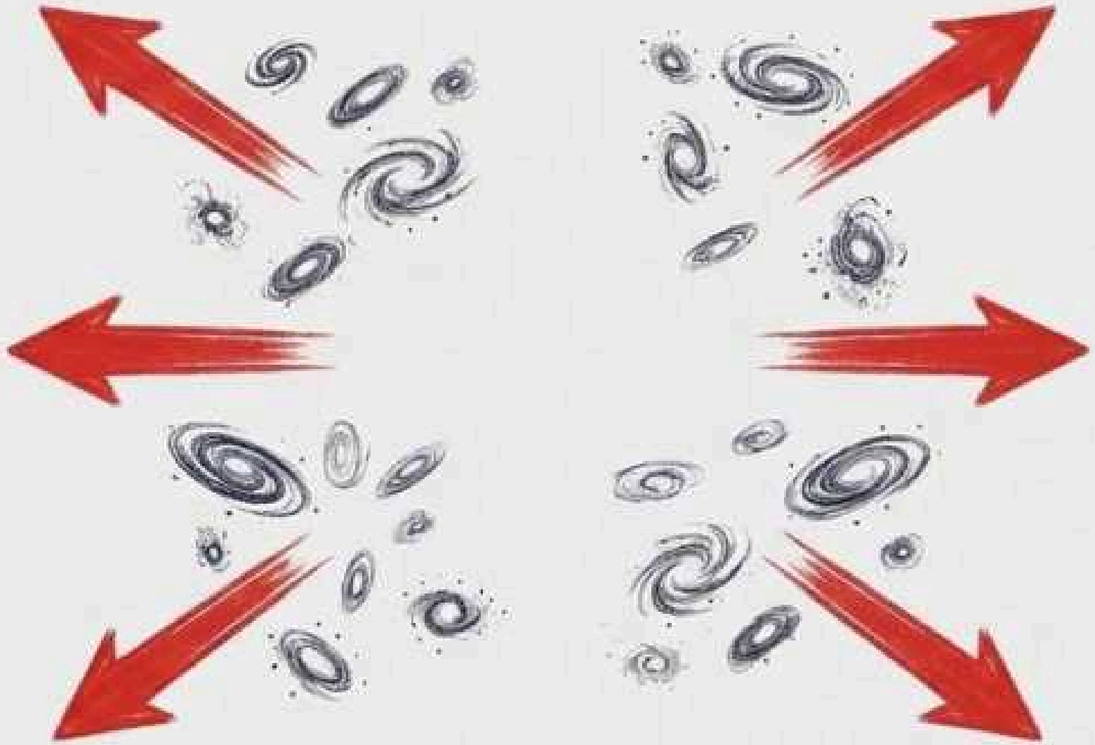
¶ 2.16

Gravity & Local Forces Win



Matter is held together firmly.
Your house is not growing.

Expansion Wins

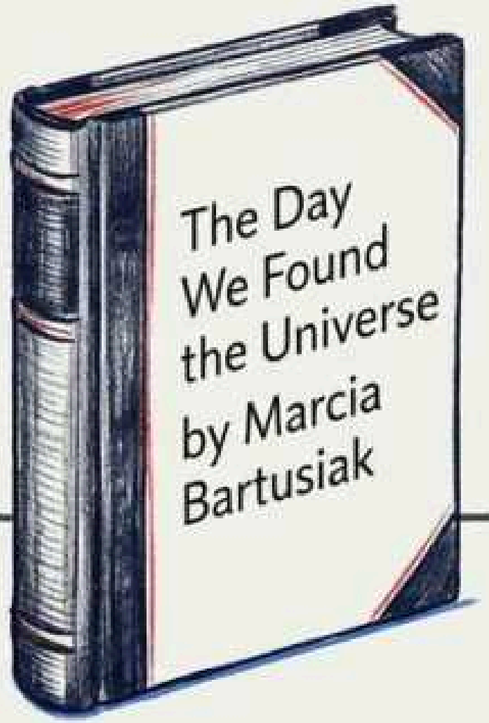


Expansion only shows up on the scale of the space between groups of galaxies, where gravity is too weak to resist.

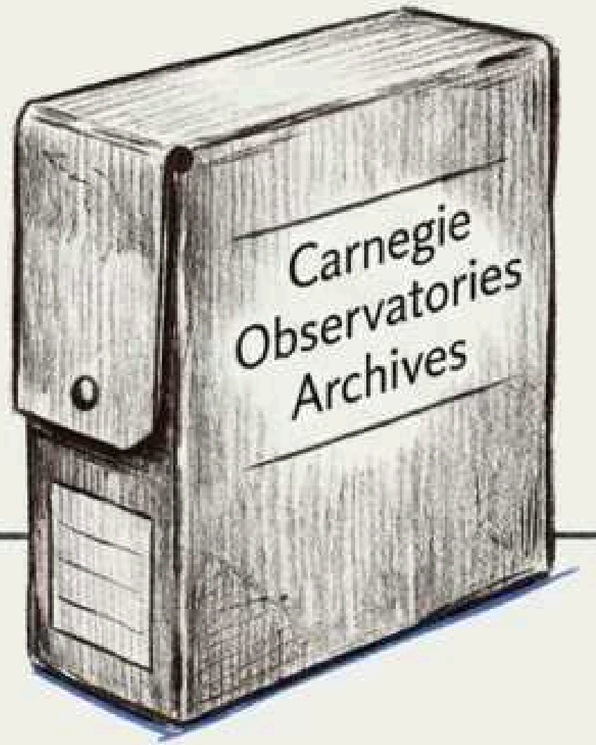
Where to go next.



The story of the discovery in lively detail.



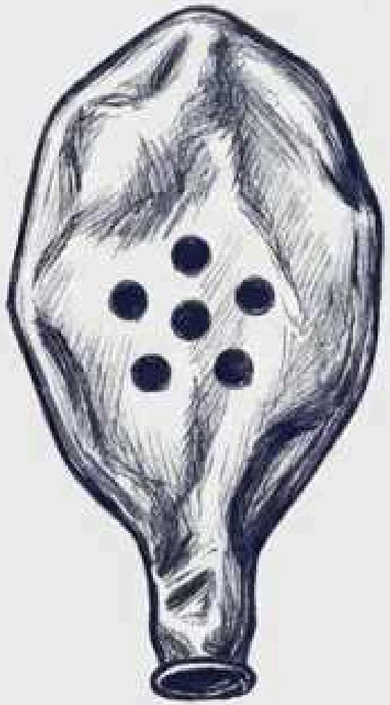
Focuses on the critical 1920s.



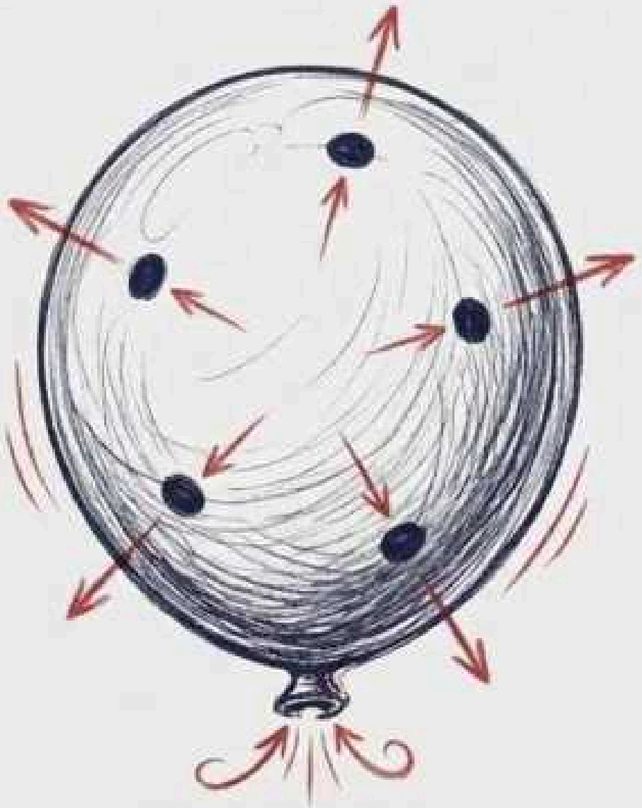
Covers the foundational work at Mount Wilson.

Closing exercise: The balloon universe.

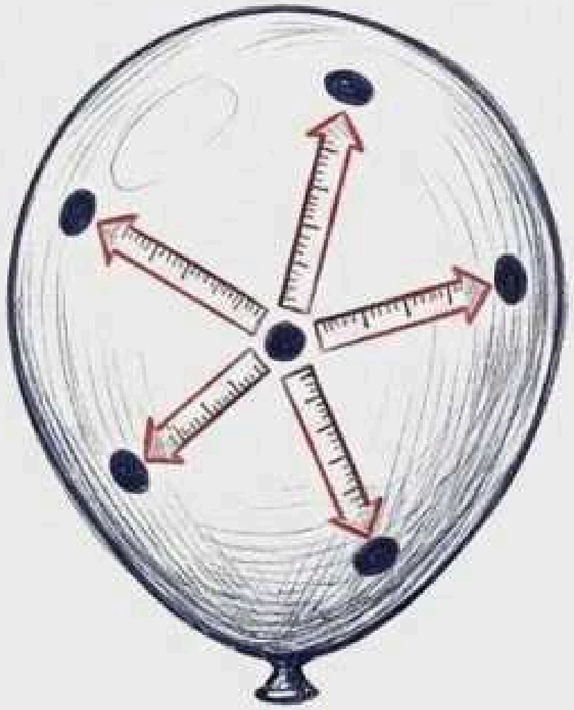
¶ 2.18



Draw 5 dots on a deflated balloon.



Inflate the balloon.



Measure distances from any single dot.

Notice that more distant dots move farther, and this holds true whichever dot you choose as the center.

In Lecture 3, we turn to the Big Bang and its afterglow.