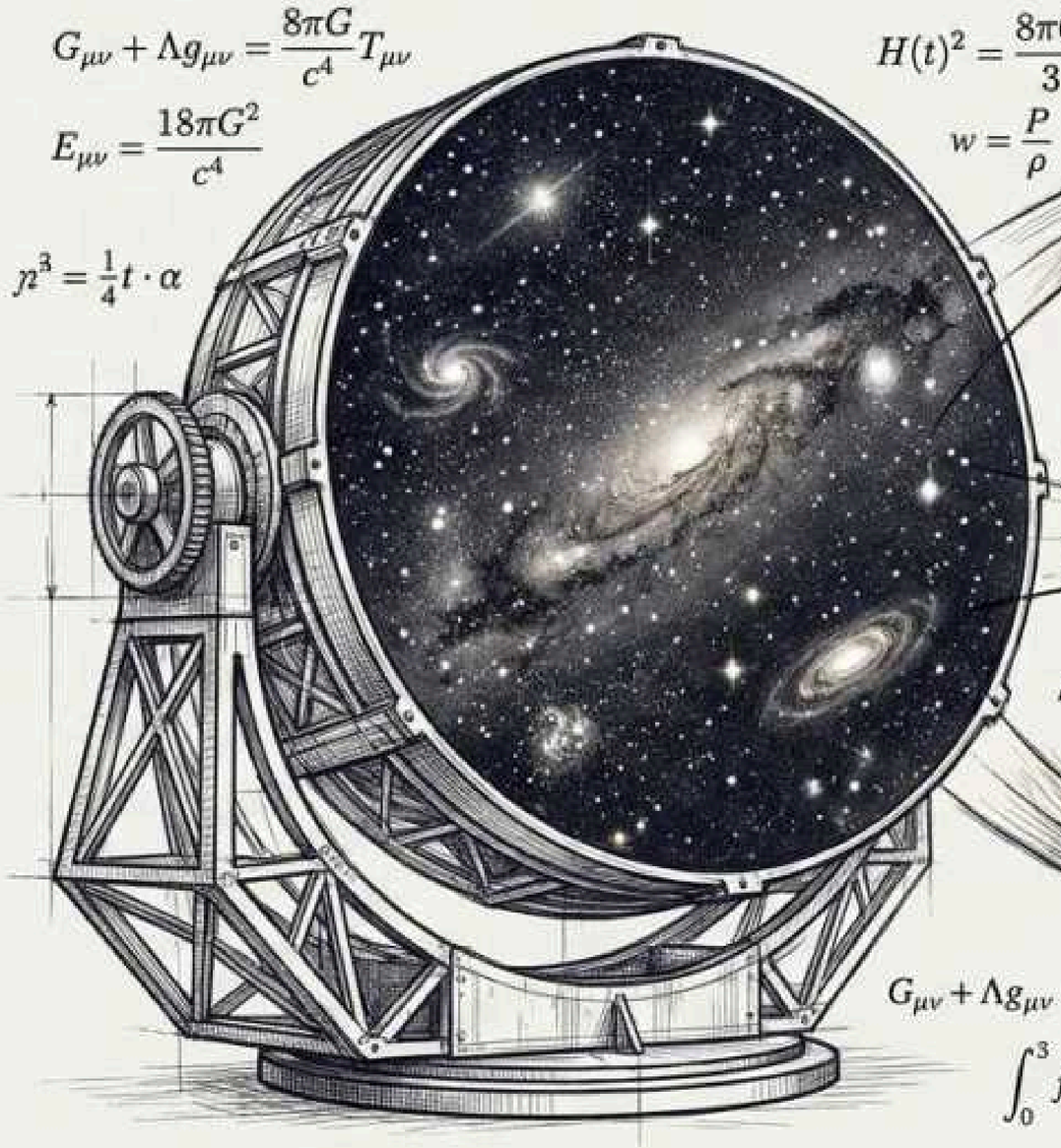
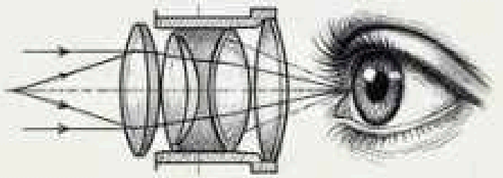
# Three Fundamental Questions of Cosmology

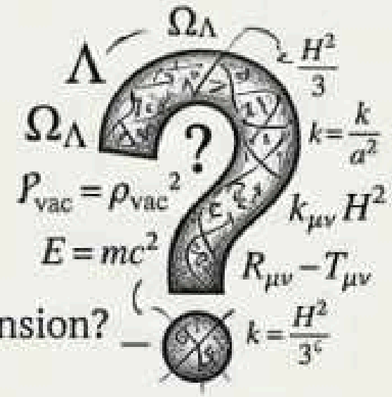


## The 1998 Discovery



What surprised astronomers?

## The Dark Energy Puzzle

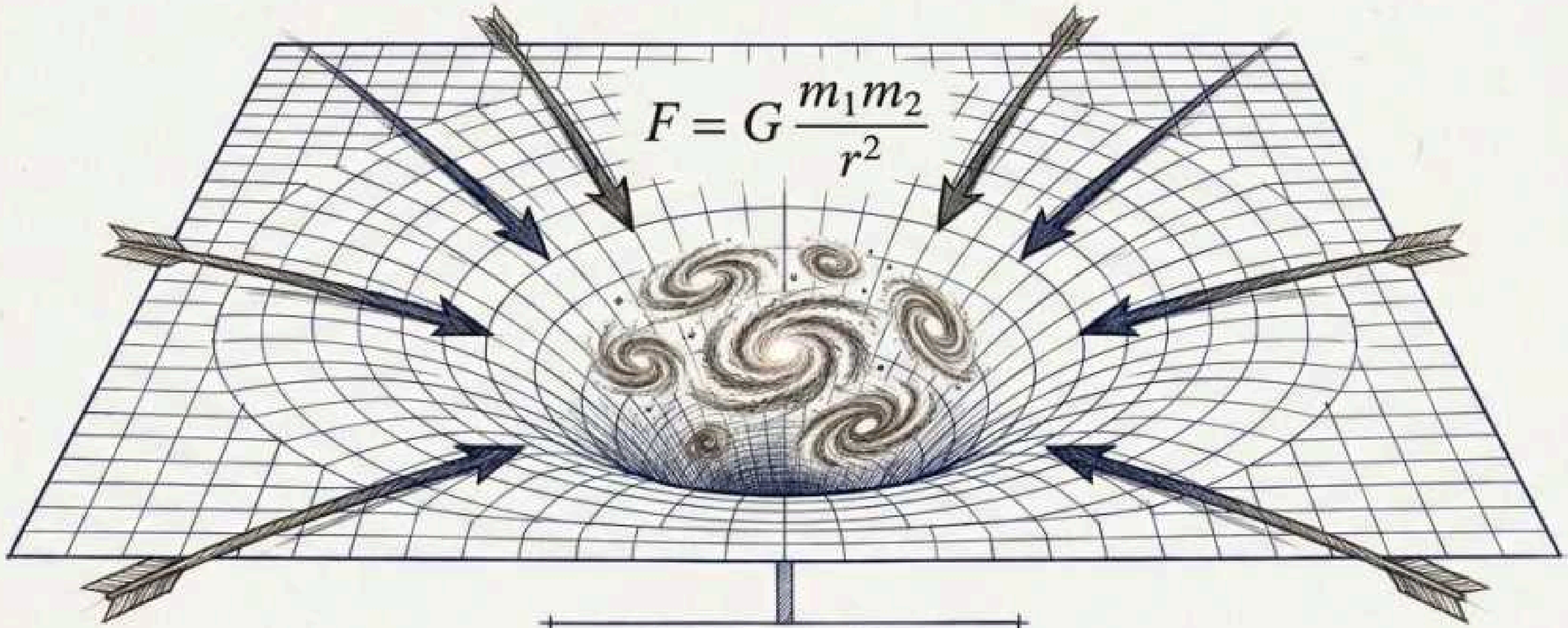


What is pushing the expansion?

## The Ultimate Fate



How might the universe end?




The Great Question:
By how much does gravity slow the expansion?

Scenario A:
Gravity is strong enough

Expansion stops and reverses.

Scenario B:
Gravity is too weak

Expansion slows forever but never completely stops.

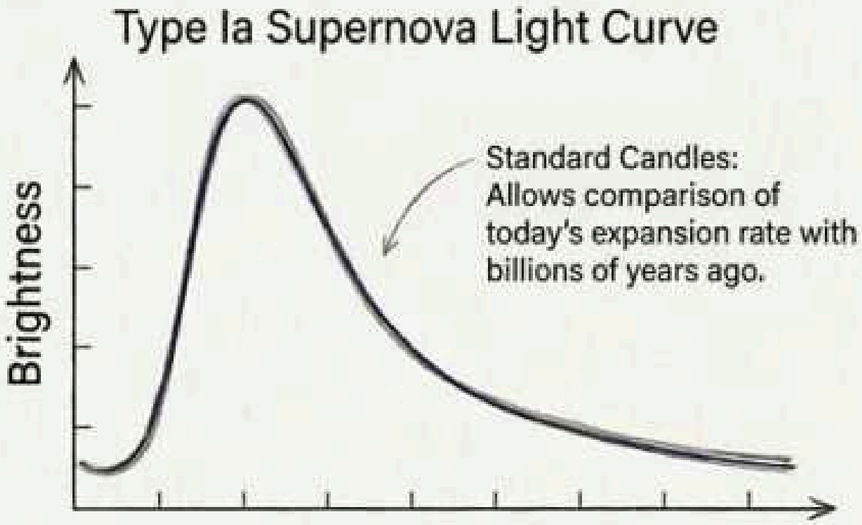
# Racing to Measure the Cosmic Slowdown

¶ 5.3

$$D_L = (1+z)\int \frac{dz'}{H(z')}$$

$$D_L = (1+z)\int \frac{dz'}{H(z')}$$

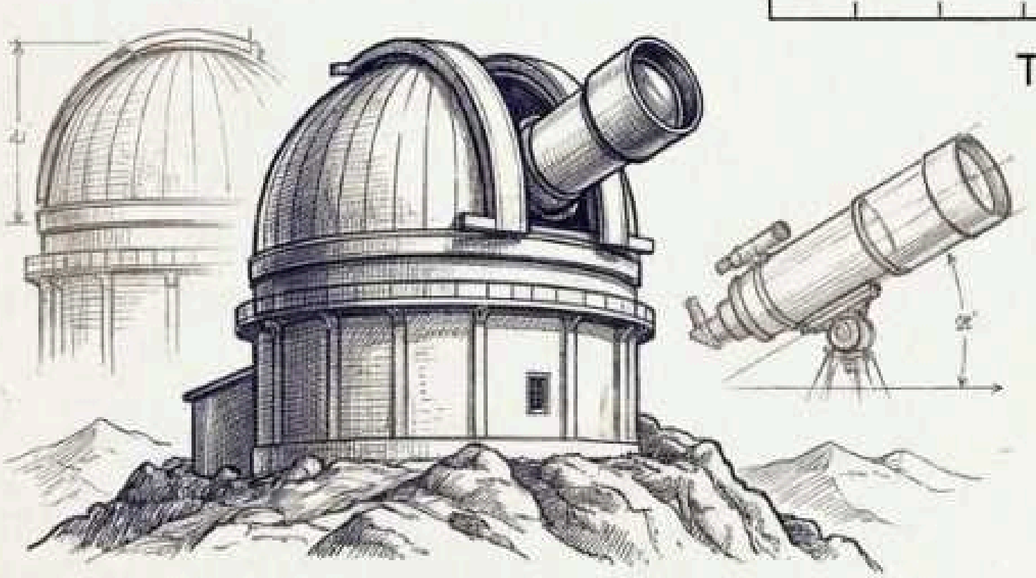
$$\therefore \sigma = \frac{\omega}{z}$$



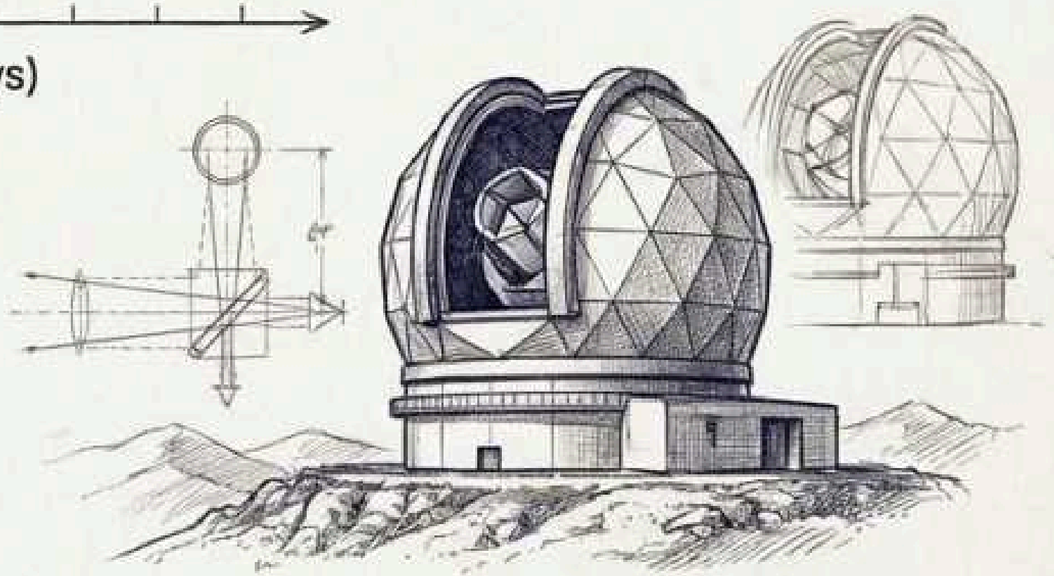

$$D_L = zzn\frac{d\omega}{Hz}$$

$$D_L = (1+z)\int \frac{dz'}{H(z')}$$

$$D_L = \frac{dz'}{H(z')}$$



Supernova Cosmology Project
Led by Saul Perlmutter

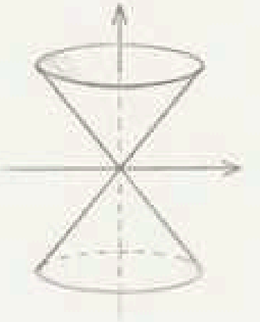


High-Z Supernova Search Team
Led by Brian Schmidt & Adam Riess

# The 1998 Discovery of Accelerating Expansion

$$D_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$



Actual Result:
Accelerating Expansion

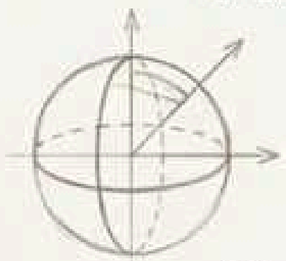
Distant supernovae were fainter than expected = farther away than a slowing universe allows.

Distance

Expected Slowing
(Gravity Dominant)

Redshift (Looking back in time)

$$D_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$



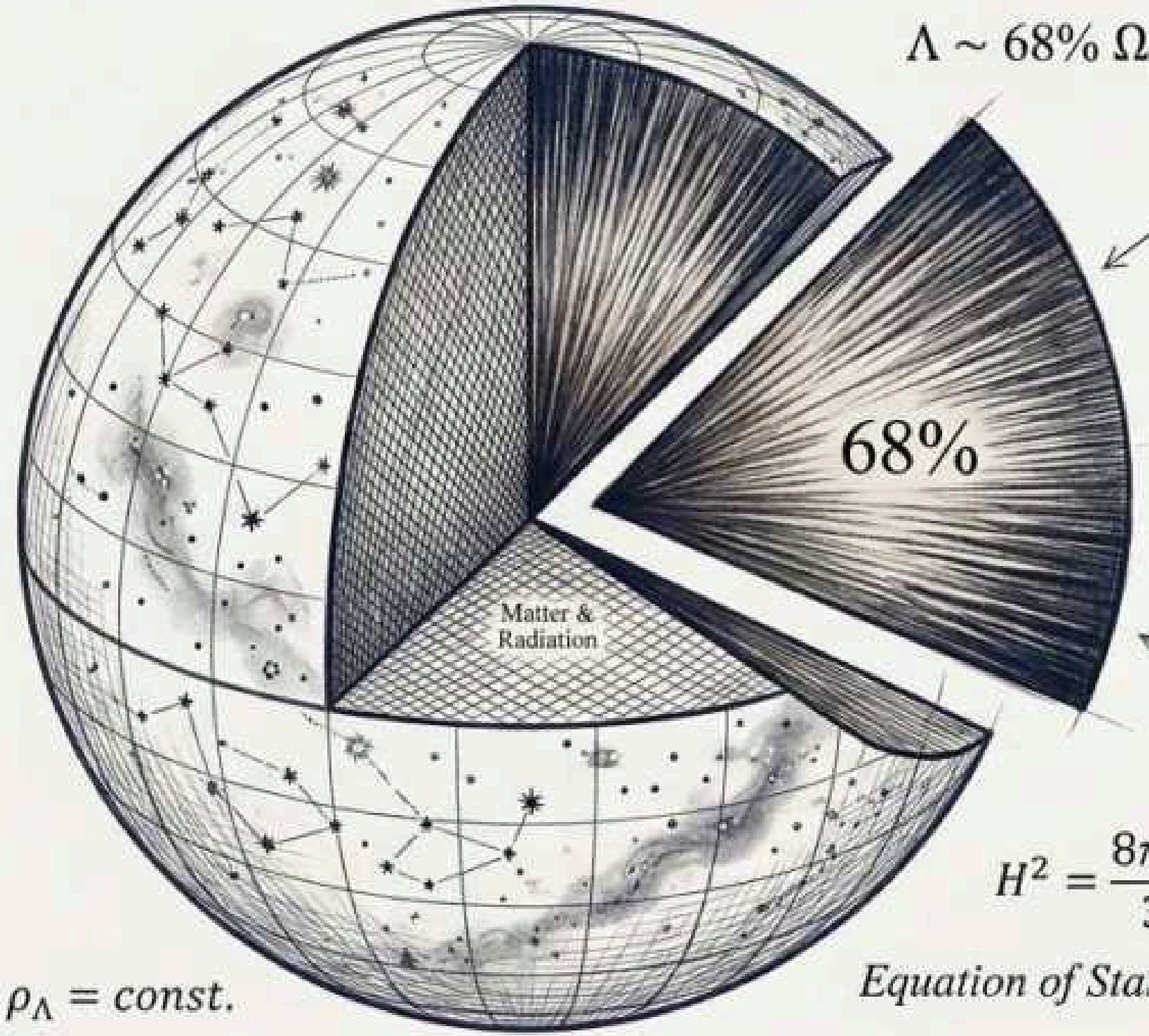
$$D_L(z) = \frac{1}{z}\int_0^z x\,\frac{dz'}{H(z')}$$

2011 Nobel Prize in Physics:
Perlmutter, Schmidt, and Riess.



# Identifying the Driver of Acceleration

¶ 5.5




$\rho_\Lambda = \text{const.}$

$$H^2 = \frac{8\pi G}{3}\rho_\Lambda$$

*Equation of State* $w = -1$

## Name: Dark Energy

The placeholder name for whatever is causing the cosmic acceleration.

## Nature: Property of Space

Belongs to the fabric of space itself, spreading evenly in all directions.

## Behavior: Constantly Replicating

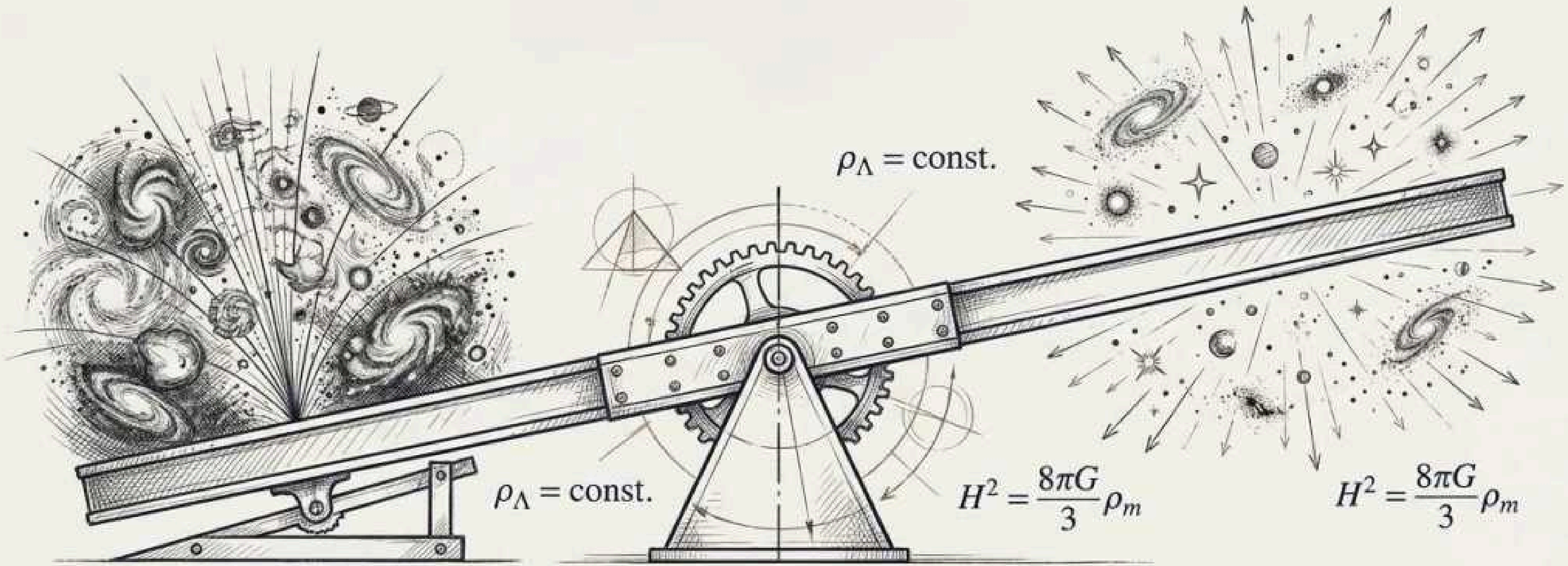
As the universe expands, more space is created, resulting in more dark energy.

# The Turning Point of Cosmic Dominance

¶ 5.6

Gravity Dominates

Dark Energy Dominates

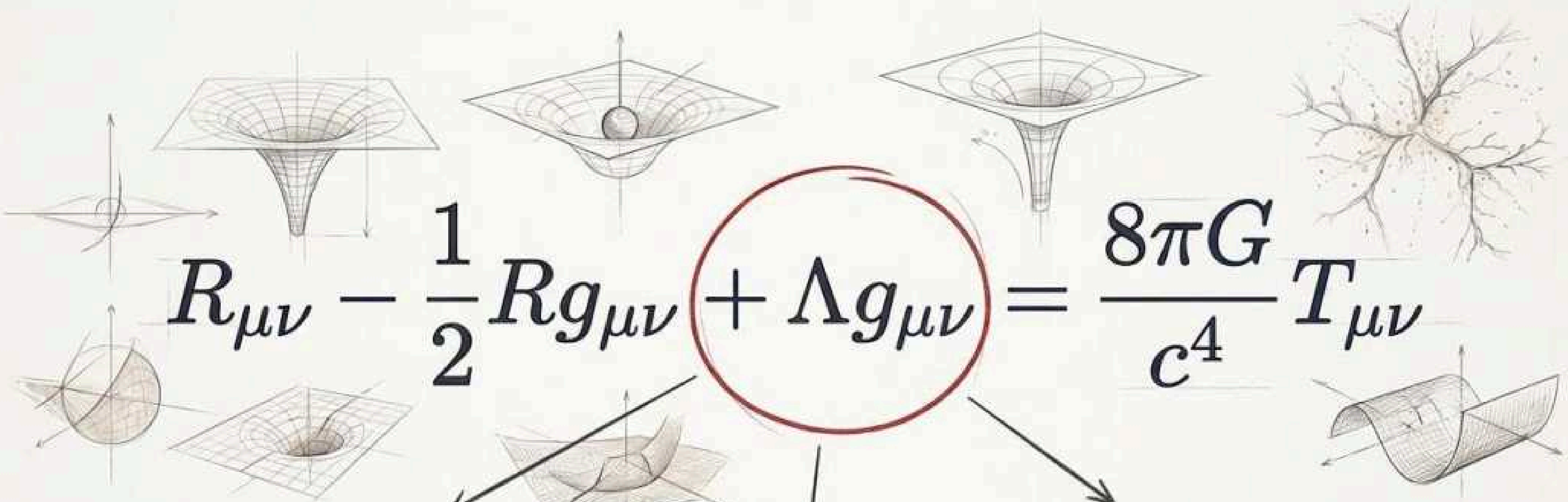



¶ Matter is densely packed. Gravity successfully slows expansion. ¶

5 Billion Years Ago ¶

¶ Matter thins out. Dark energy takes over. Expansion speeds up. ¶

# Resurrecting Einstein's Cosmological Constant



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

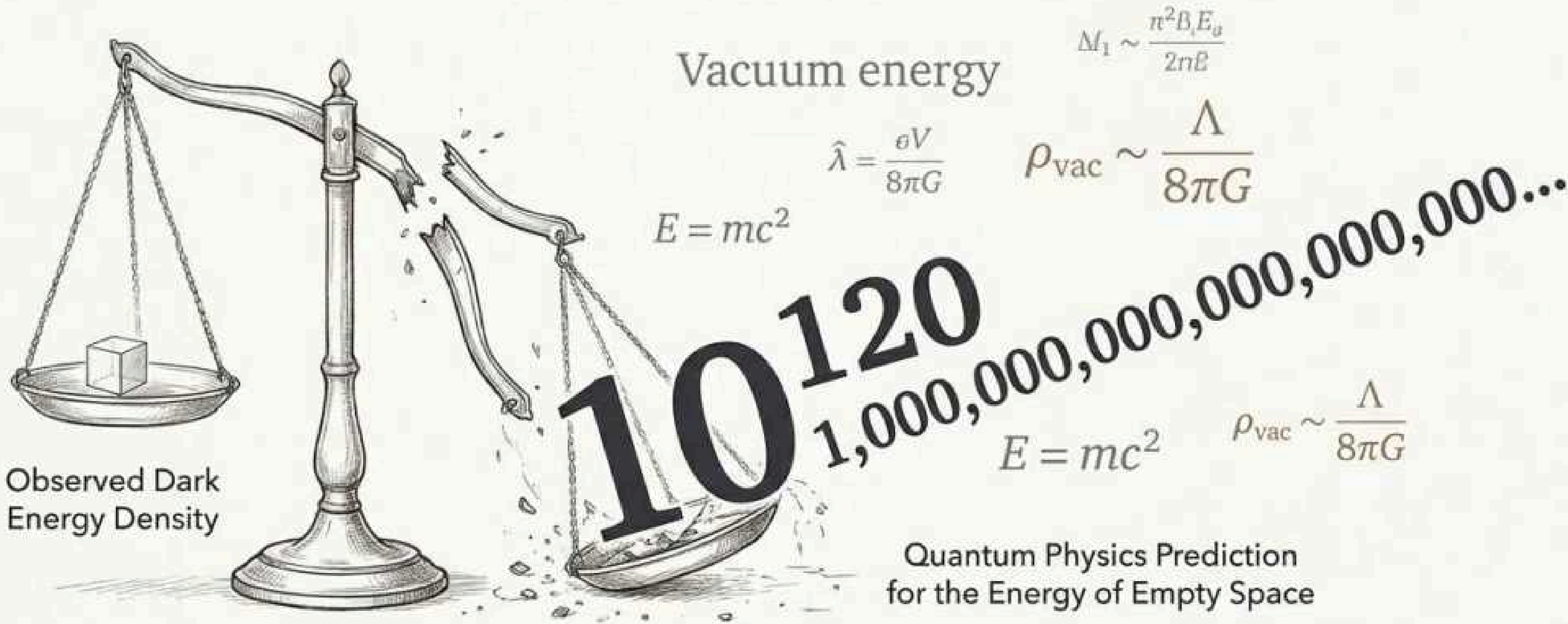
¶ Added in 1917, later abandoned by Einstein

¶ Added in 1917, later abandoned by Einstein as his "biggest blunder".

¶ Describes energy belonging to empty space itself (same density everywhere, at all times).

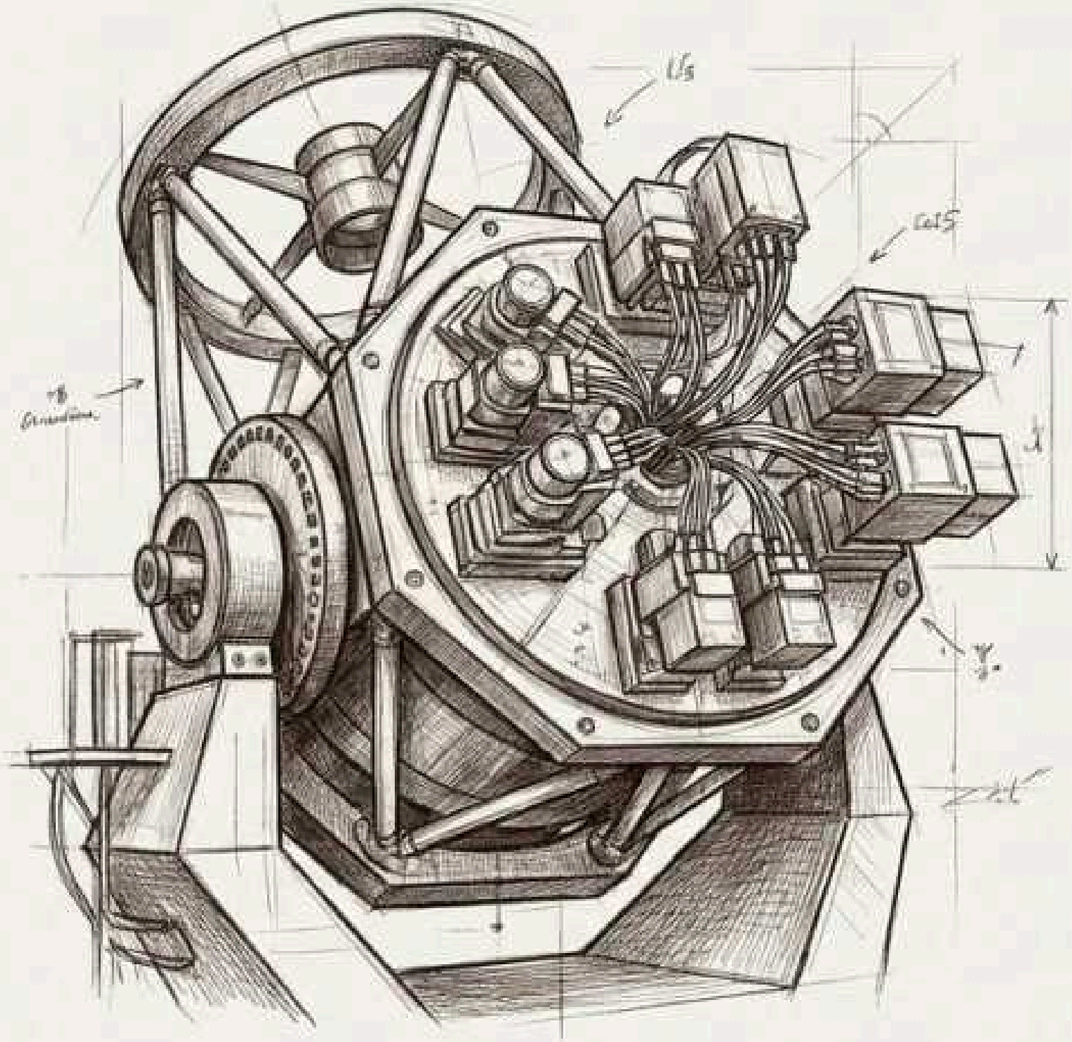
¶ Forms the Λ in ΛCDM (Lambda Cold Dark Matter), the standard model of cosmology.

# The Greatest Discrepancy in Theoretical Physics

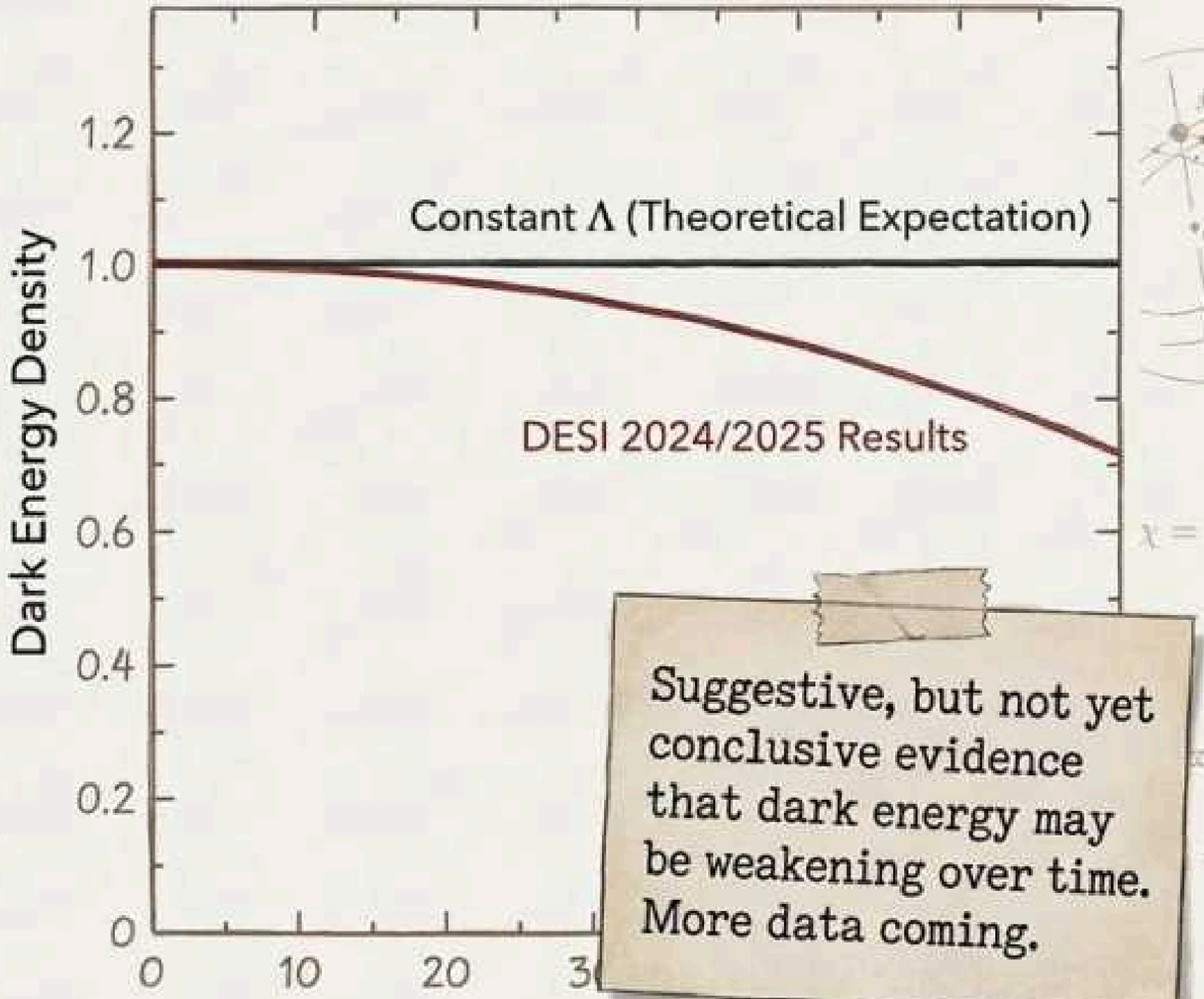

Vacuum energy
$\Delta M_1 \sim \frac{n^2 B_i E_a}{2\pi\ell}$
$\hat{\lambda} = \frac{\sigma V}{8\pi G}$
$\rho_{\text{vac}} \sim \frac{\Lambda}{8\pi G}$
$E = mc^2$
$10^{120}$
1,000,000,000

# Early Hints of a Dynamic Dark Energy

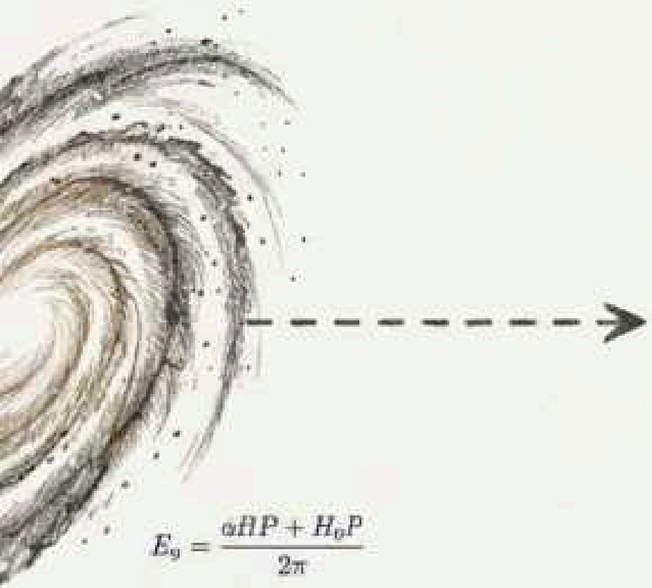
¶ 5.9



DESI (Arizona) - Mapping millions of galaxies



# Fate 1: The Big Freeze and Cosmic Heat Death



$$E_9 = \frac{aHP + H_0 P}{2\pi}$$

$$I = \tau \int^{\infty} \frac{d\Sigma E_m}{dt}$$

$$\omega = \frac{1}{n} \int_0 (\varpi l^3 + \epsilon_0 dx)$$



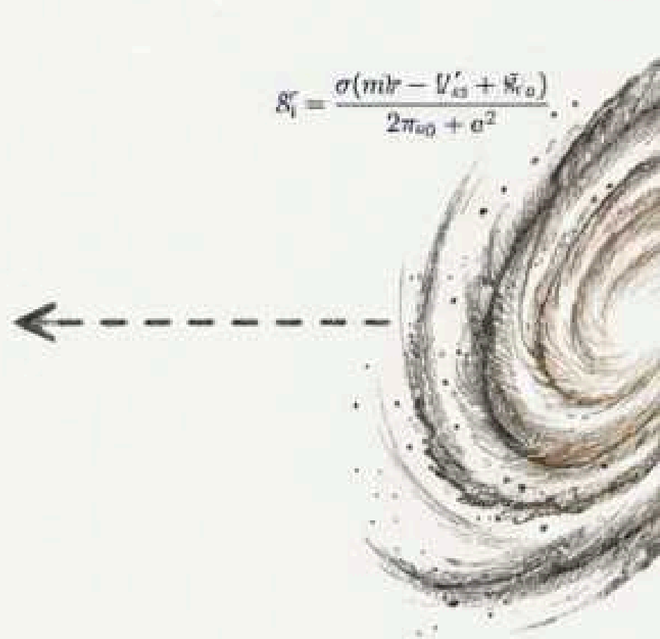
$$\Sigma(x) = \frac{\vec{a}^2}{U} + \frac{\omega m^2}{rt}$$

$$\varepsilon_0 = H(\sqrt{2}e^{-1.1})$$

$$H(x) = \frac{1}{n} \cdot \frac{db^2}{st} \cdot \frac{2\pi n}{r^3}$$

← Absolute Zero

$$g_i' = \frac{\sigma(m\dot{b}r - U_{ab}' + \bar{\varepsilon}_{\pi_0})}{2\pi_{\omega_0} + a^2}$$

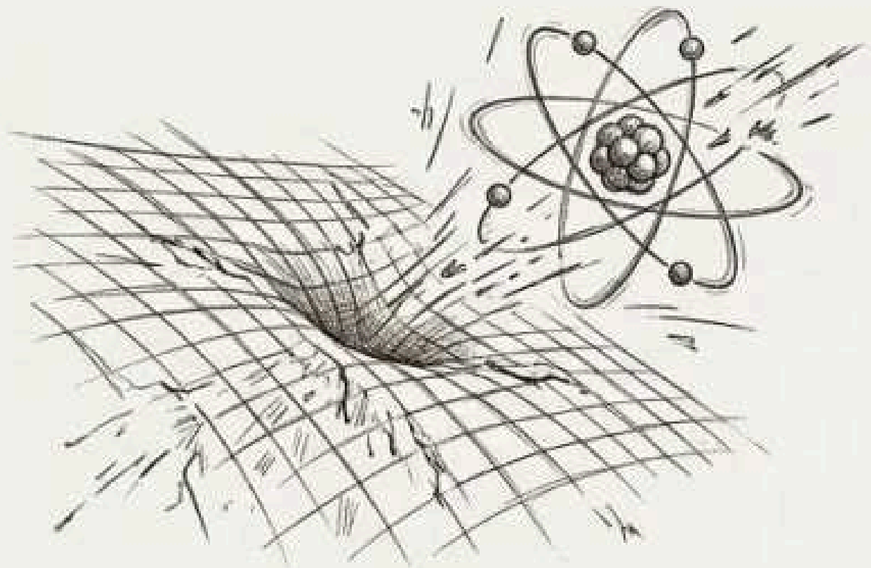


- Condition: Dark energy stays constant.
- Process: Continual acceleration leaves only our local merged galaxy group visible.
- Result: Over trillions of years, stars burn out, leaving a cold, dark universe.

# Alternative Extremes for the End of Time

## THE BIG RIP

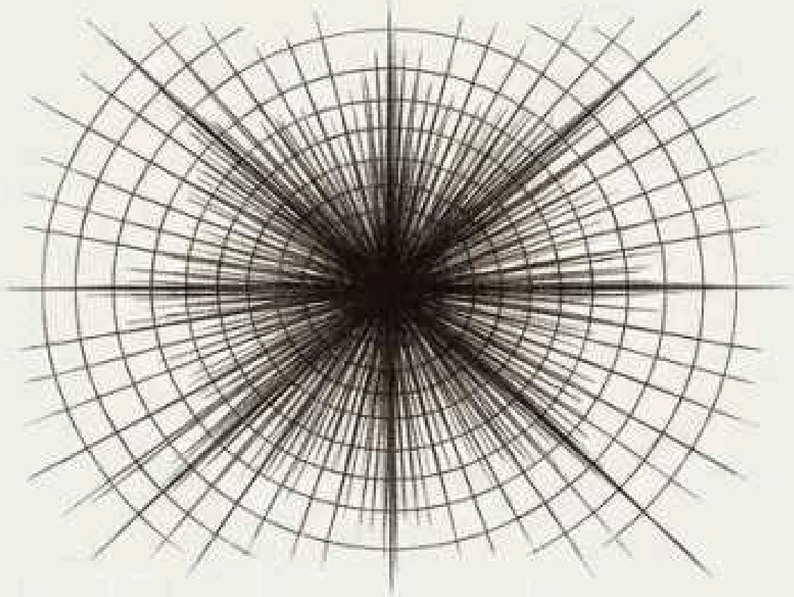
Condition: Dark Energy grows stronger



Outcome: Accelerated expansion aggressively tears apart galaxies, stars, planets, and atoms.

## THE BIG CRUNCH

Condition: Dark Energy weakens and reverses

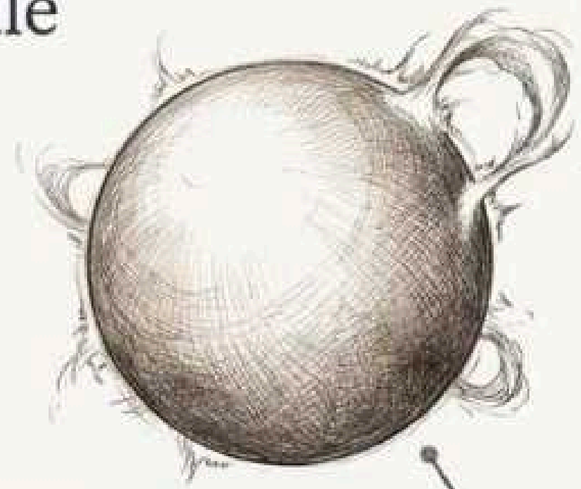


Outcome: Gravity wins, and the universe collapses inward on itself.

Note: Current data favour continued expansion (Big Freeze), but cannot rule out these alternative fates.

# Local Events on a Cosmic Timescale





5 Billion Years from now

The Sun swells into a Red Giant

4 to 5 Billion Years from now

Milky Way and Andromeda galaxies merge



Crucial Perspective: Even during this monumental merger, the individual stars are so far apart that few, if any, will actually collide.

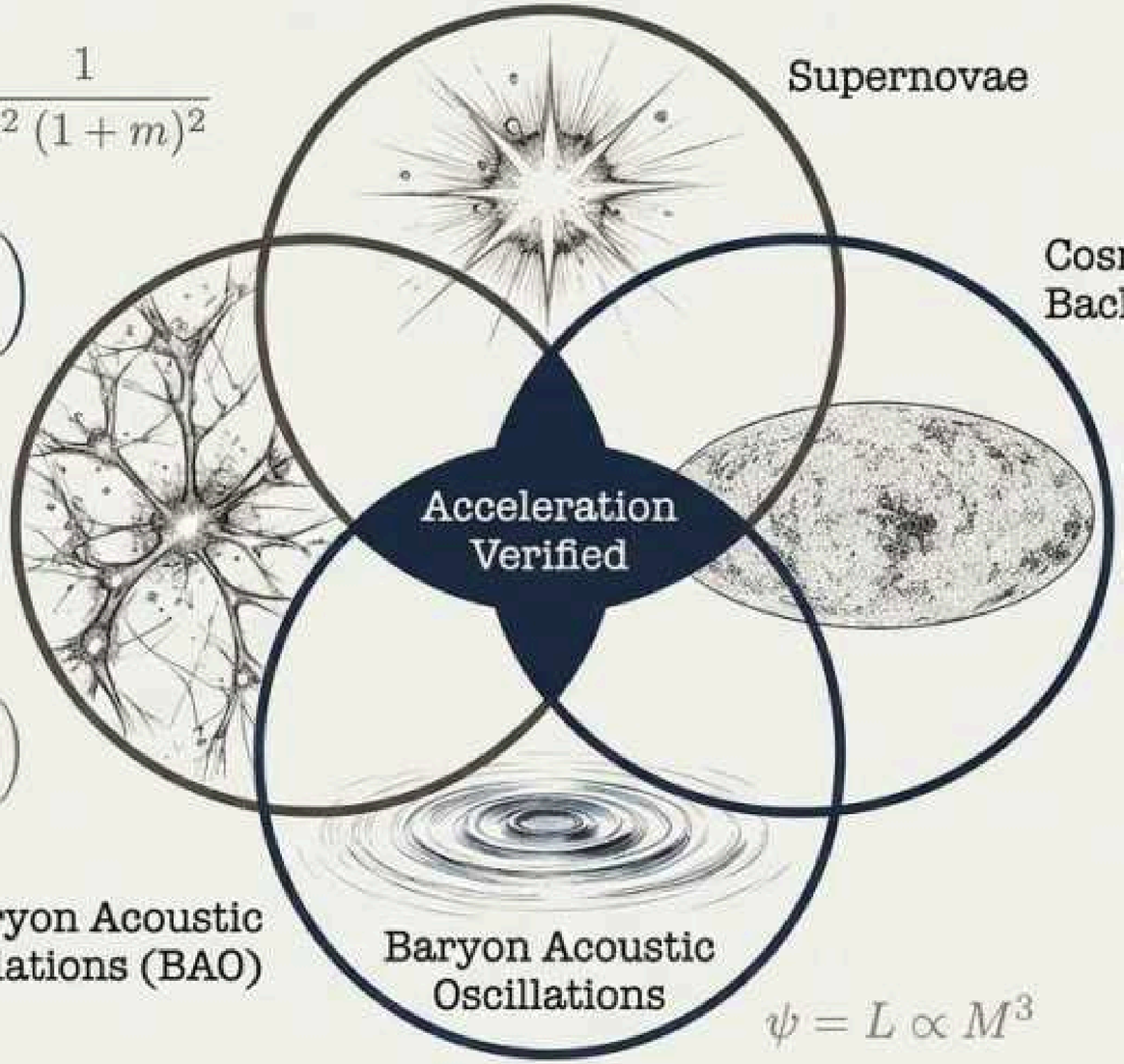
# Interlocking Evidence Strengthens the Model

$$\psi = G\frac{1}{m^2\,(1+m)^2}$$

$$P = \times \log\left(\frac{m_1 m_2}{4t}\right)$$

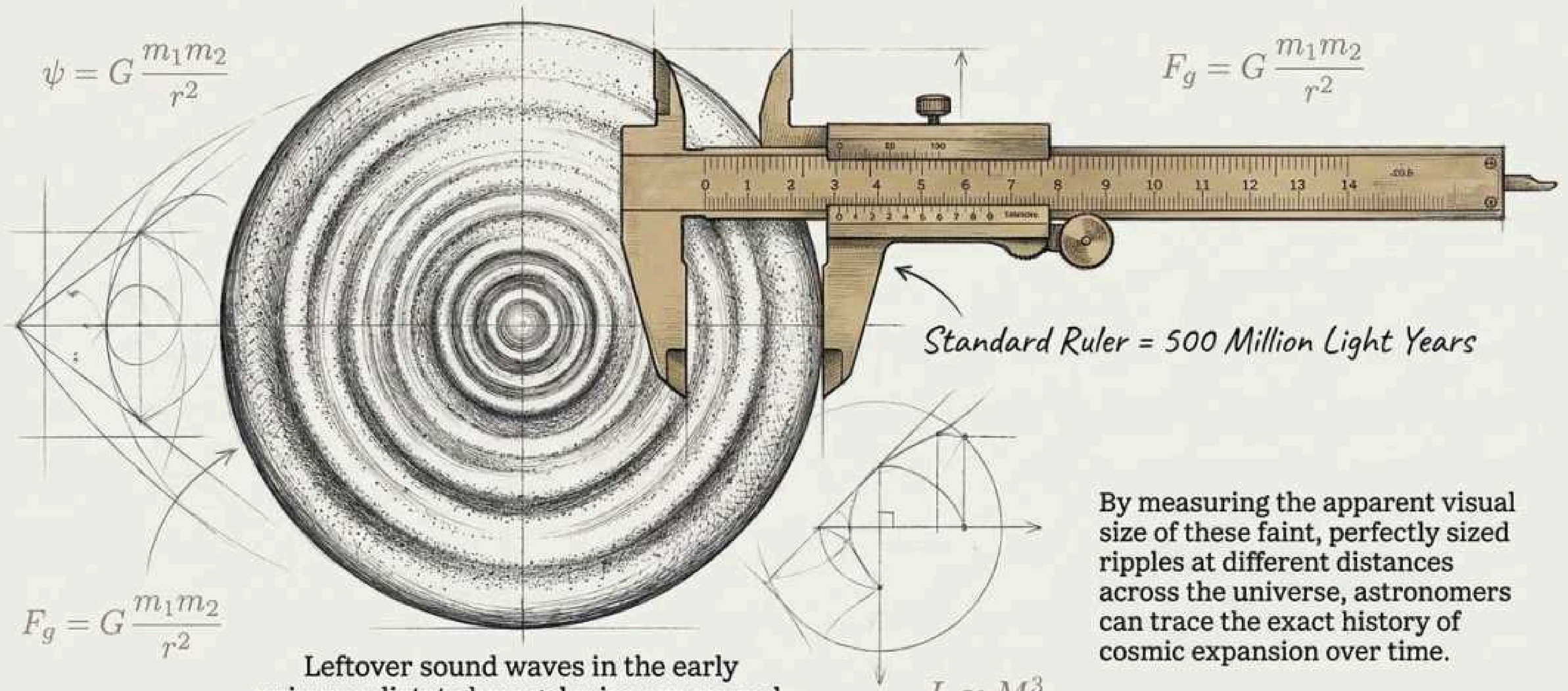
$$F_g = \log\left(\frac{m_1 m_2}{r^2}\right)$$

$$\psi = L \propto M^3$$




Each observational method has completely different potential weaknesses. The fact that they all converge on the exact same conclusion is immensely powerful evidence for Dark Energy.

# Baryon Acoustic Oscillations as a Standard Ruler




Leftover sound waves in the early universe dictate how galaxies are spaced.

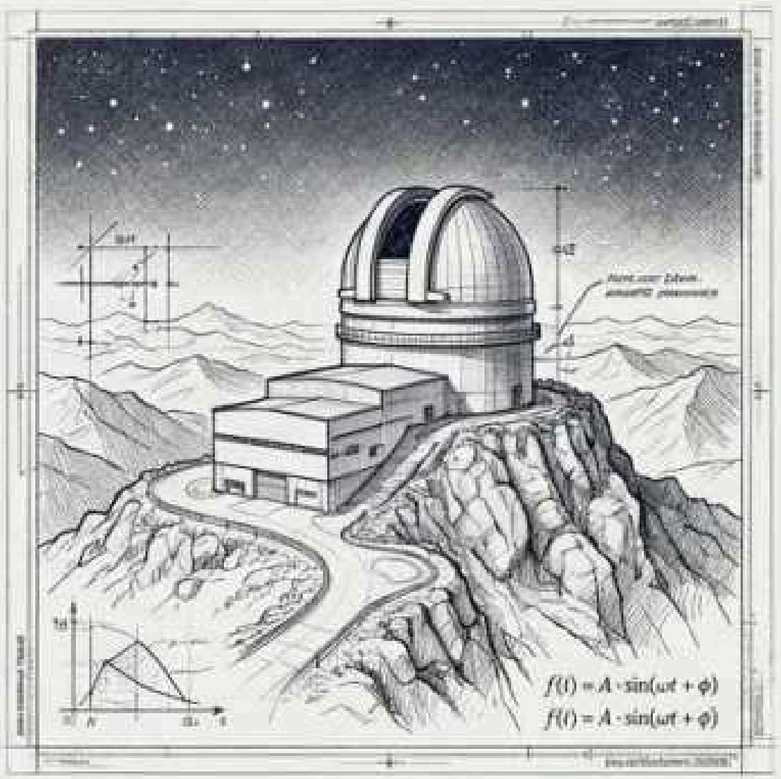
By measuring the apparent visual size of these faint, perfectly sized ripples at different distances across the universe, astronomers can trace the exact history of cosmic expansion over time.

# Next-Generation Instruments Mapping the Sky



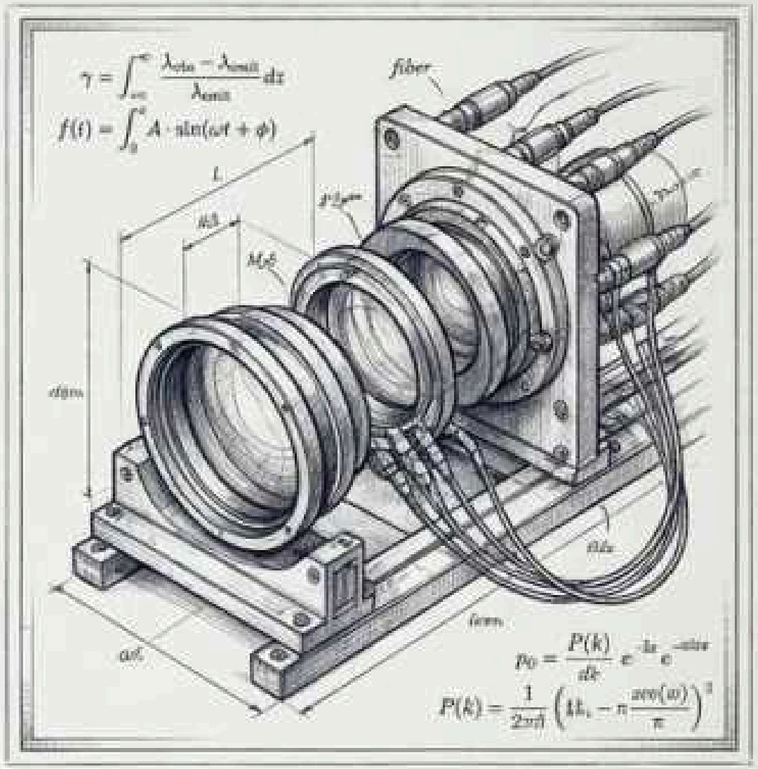
## Euclid Space Telescope

Launched 2023, mapping billions of galaxies.



## Vera C. Rubin Observatory

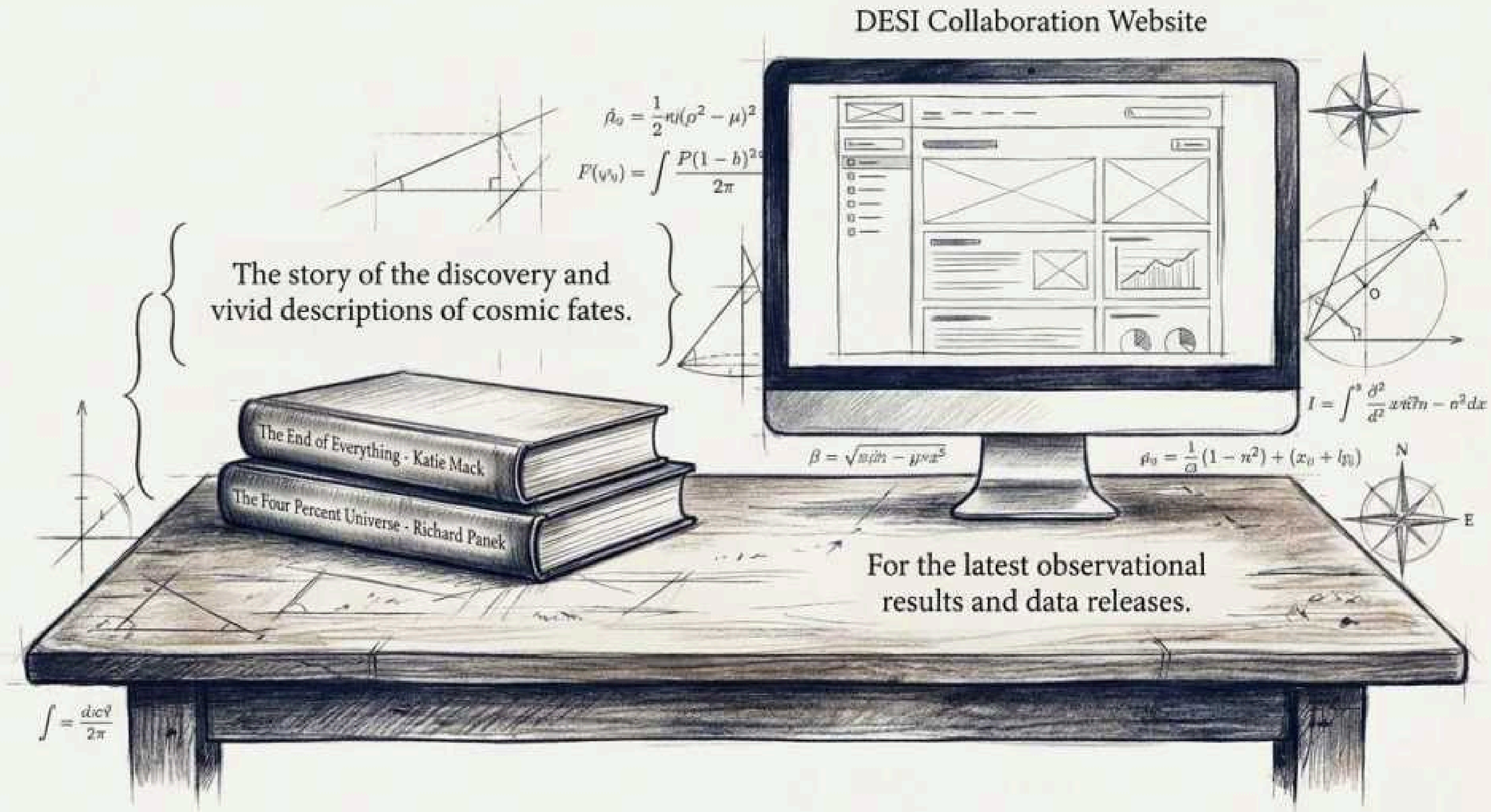
Began southern sky survey in 2025. Named after the dark matter pioneer.



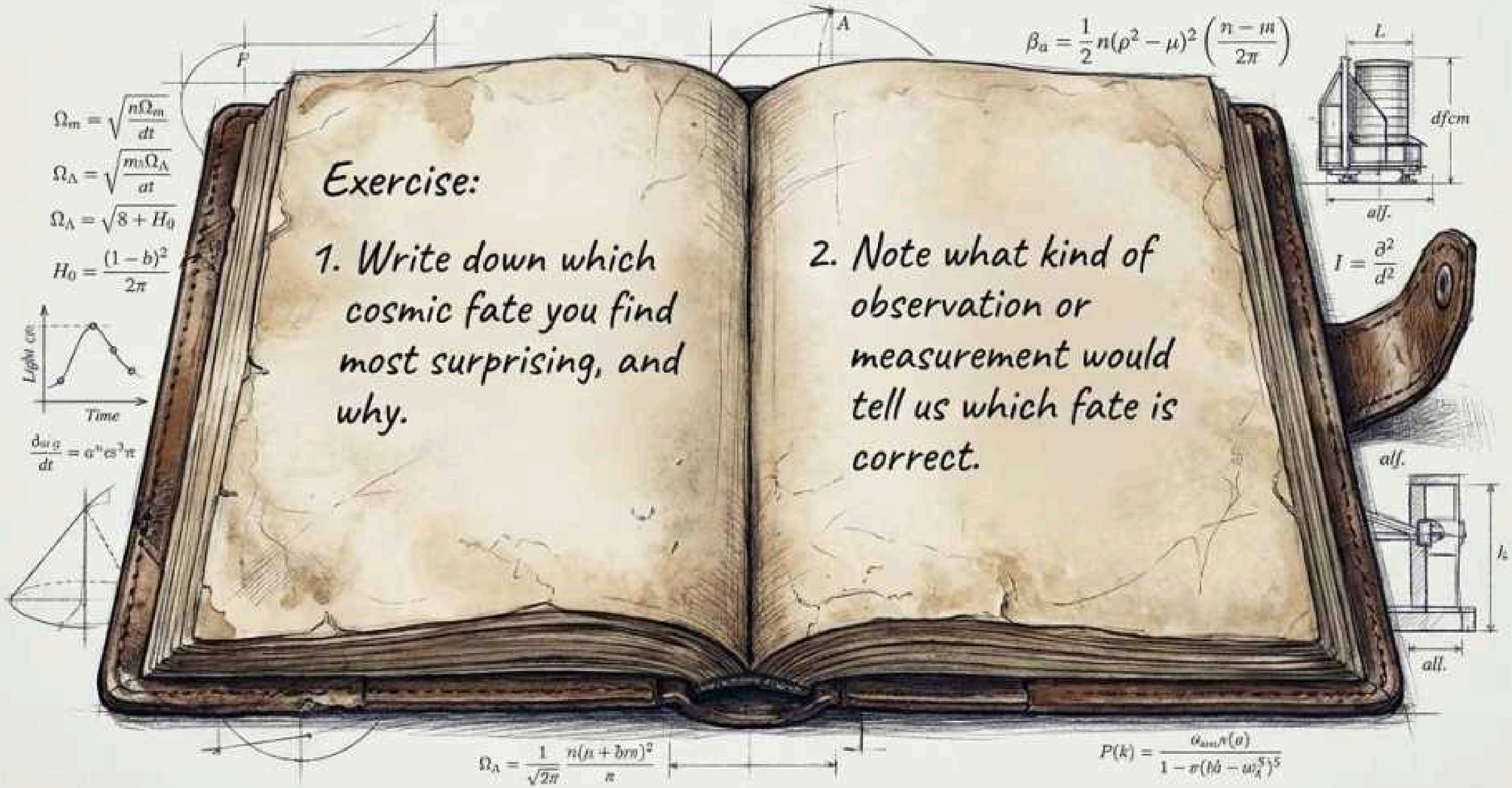
## DESI

Continuing spectral mapping from Arizona.

Together, these massive surveys aim to pin down whether dark energy is truly constant.


DESI Collaboration Website
The story of the discovery and vivid descriptions of cosmic fates.
The End of Everything - Katie Mack
The Four Percent Universe - Richard Panek
For the latest observational results and data releases.

# Observations Determine Our Final Fate




**Coming in Lecture 6: Inflation, the Multiverse, and the Biggest Open Questions.**