

The Big Bang

a state of the universe report

Motion of the Spiral Nebulae

- 1912: Vesto M. Slipher discovered "Doppler" shifts in spectra of spiral nebulae
- Of 41 nebulae, 36 exhibited redshifts
- Found some receding in excess of 2 million mph!



Sir Isaac's Little Secret

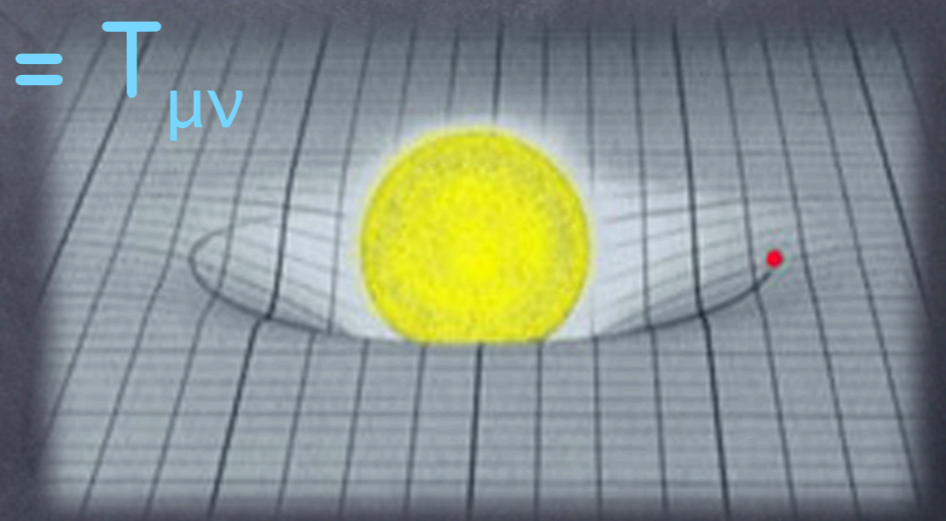
"...Thus I have explained the phenomena of the heavens and of our sea by the force of gravity, but I have not yet assigned a cause to gravity...I have not as yet been able to deduce from phenomena the reason for these properties of gravity, and I do not feign hypotheses."

— Isaac Newton

General Relativity and the Expanding Universe

- Space and time dynamically linked by General Theory of Relativity in 1915
- Gravity described as curvature of spacetime due to presence of mass

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} R = T_{\mu\nu}$$



General Relativity and the Expanding Universe

- 👁️ 1917: Einstein formulated model universe filled with matter and radiation
 - 👁️ **Isotropic** — looks the same from every location
 - 👁️ **Homogeneous** — looks the same in every direction
- 👁️ The model had **NO** steady-state solution. The universe was either expanding or contracting!

His Greatest Blunder

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} R + \Lambda g_{\mu\nu} = kT_{\mu\nu}$$

"...we admittedly had to introduce an extension of the field equation of gravitation which is not justified by our actual knowledge of gravitation... That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars."

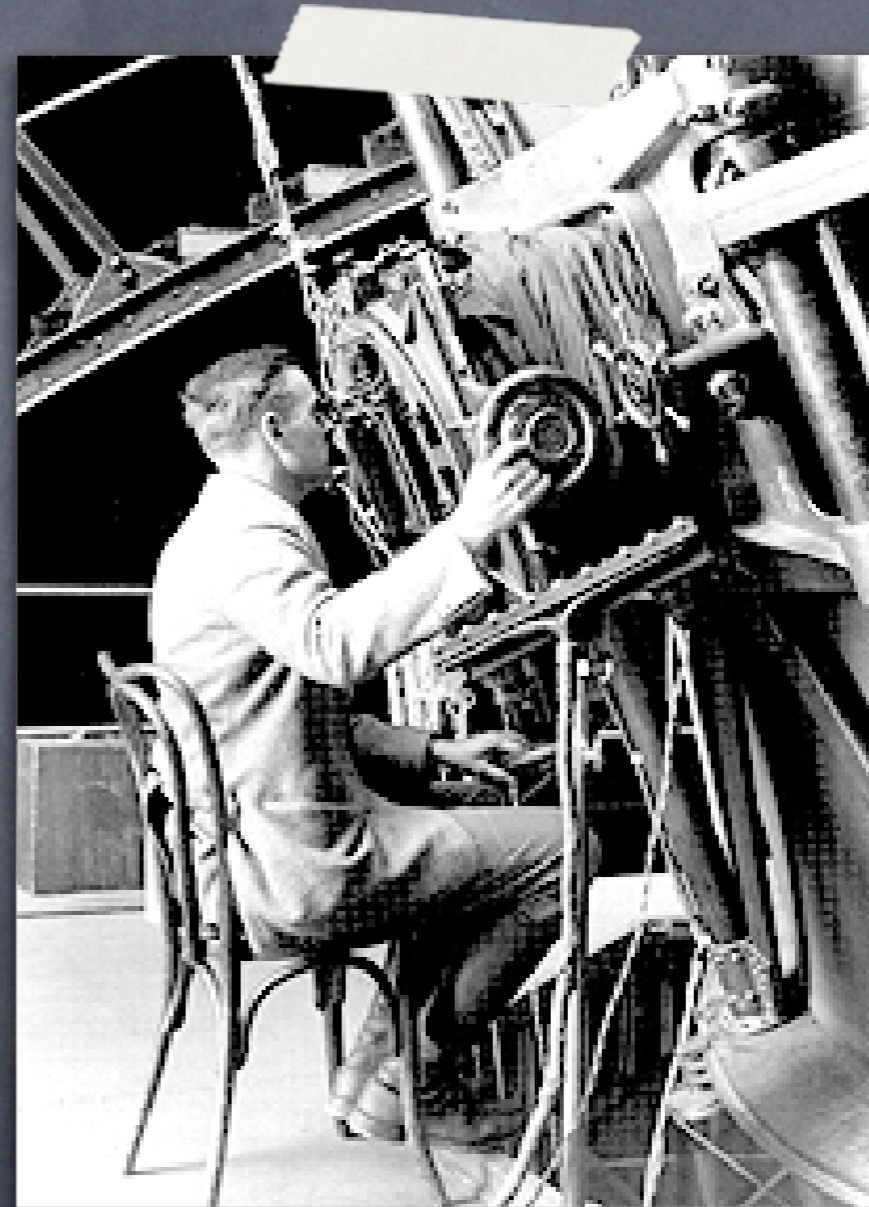
*Cosmological Considerations on
the General Theory of Relativity*
— Albert Einstein, 1917

The Contrarians

- 👁️ 1917: Willem de Sitter's solution to the equations of general relativity could account for Slipher's redshifts
- 👁️ 1922: Alexandr Friedmann found a solution in which the universe could be filled with matter AND expanding!
- 👁️ Contrary to Einstein's model, de Sitter and Friedmann universes **changed over time**

Edwin Hubble and the Realm of the Nebulae

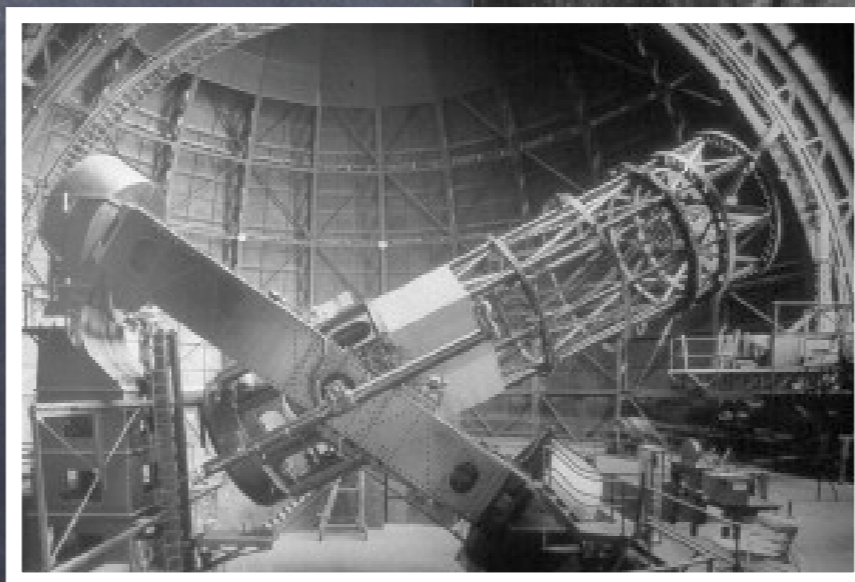
- 1923: Discovered Cepheid variables in M31 and other nearby nebulae—confirmed existence of galaxies
- Calculated recession velocities of galaxies from redshifts



Edwin Hubble and the Realm of the Nebulae

- 1929: Established law relating redshift velocity to distance

- $$v = H_0 r$$



Abbe Georges Lemaître's "Day Without Yesterday"

- 1927: Unaware of Friedmann's work, wrote that field equations of General Relativity indicated an expanding universe
- 1933: Incorporating quantum theory, wrote that universe began as hot "Primeval Atom"



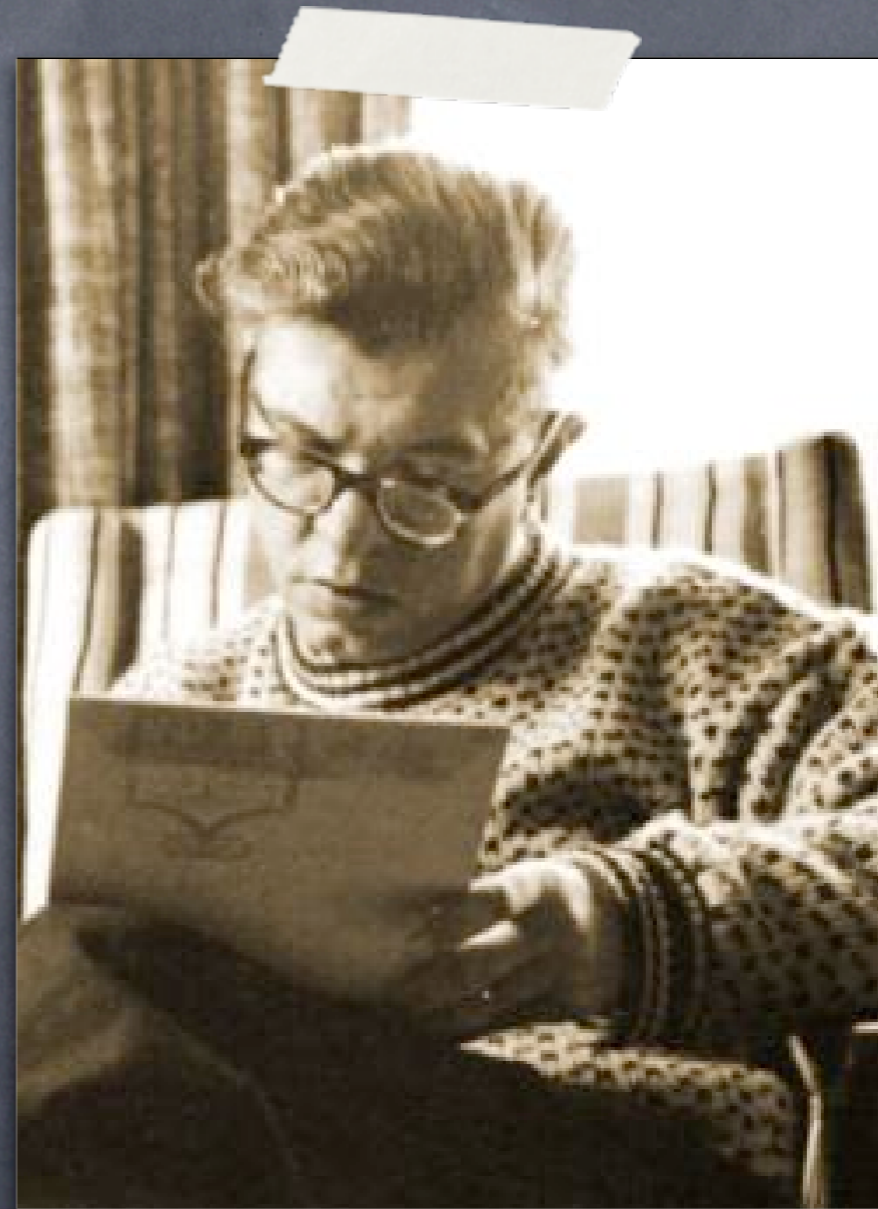
The Primeval Atom

“Standing on a well-chilled cinder we see the fading of the suns, and try to recall the vanished brilliance of the origin of the worlds.”

— Abbé Georges Lemaître

Sir Fred Hoyle and the Big Bang

- 1940s: Argued physical laws in expanding universe would change
- Championed "steady state" universe that continually created matter
- 1949: Derided that "Big Bang" idea



George Gamow and Nucleosynthesis

- ① 1948: Theorized hot early universe could produce elements in observed abundances
- ① Predicted radiation from expanding, cooling universe should be detectable at 5 K



Maybe it's the pigeons...

- 👁️ 1964: Penzias and Wilson detect faint microwave "hiss" filling entire sky at 3.7 K
- 👁️ Bell Labs antenna had accidentally detected redshifted radiation from Big Bang!



Last Scattering

- At 365,000 years after Big Bang, expanding universe cooled to 3,000 K and hydrogen atoms formed
- Free electrons scatter photons efficiently; neutral atoms do not
- Matter and radiation “decoupled” and universe became transparent

What is It?

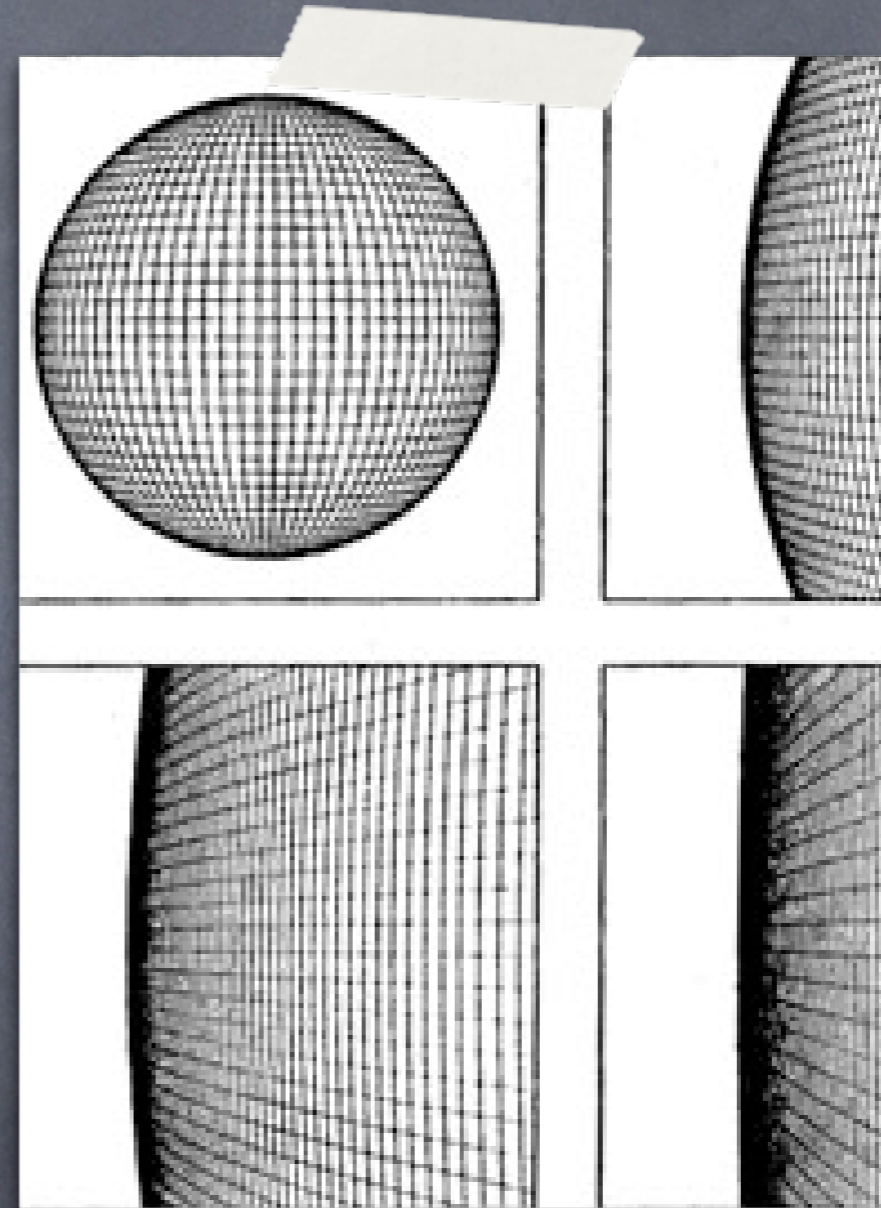
- ① The Big Bang is properly described as the expansion of spacetime, with matter **carried along by the expansion**, rather than as an explosion hurling matter into pre-existing space
- ① In a very real sense, spacetime began with the Big Bang

The Big Bang doesn't explain:

- The "flatness" of spacetime
- The extreme uniformity of the 3K cosmic microwave background (CMB) radiation
- How the early universe evolved from very smooth to the "lumpy" galaxy-filled universe of today

Inflation to the Rescue

About 10^{-32} sec ABB (After the Beginning of Time), a tiny part of the universe expanded exponentially by 40 orders of magnitude (that's 10^{40} times!)

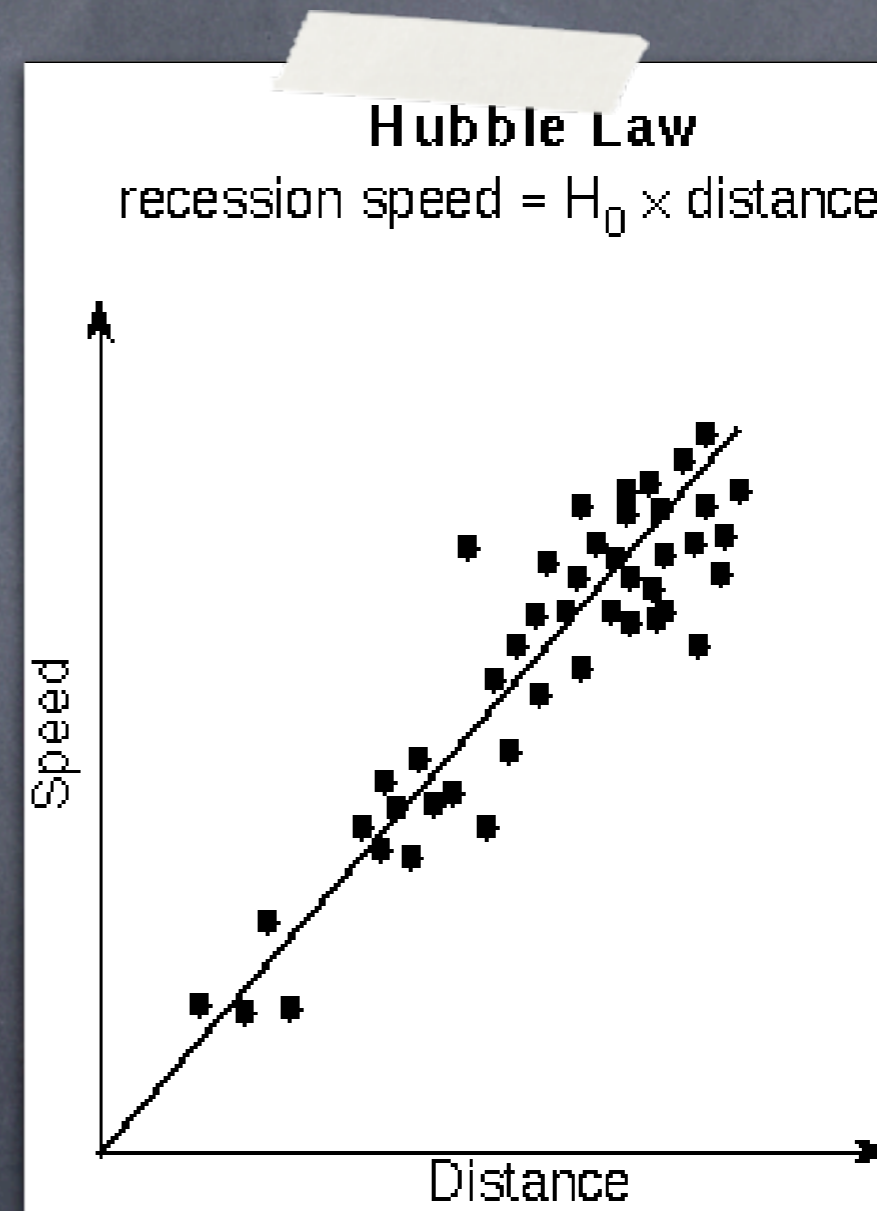


What Inflation Solves

- Potential energy from this era gave rise to enormous heat of the Big Bang
- During inflation, quantum fluctuations were stretched to astronomical sizes
- Further expansion and cooling gave rise to the CMB radiation

The Hubble Parameter Sets the Scale of the Universe

- Time back to the Big Bang (13.7 billion yrs)
- Size of visible portion of the universe
- $H_0 = 72 \pm 7.2 \text{ km/s/Mpc}$

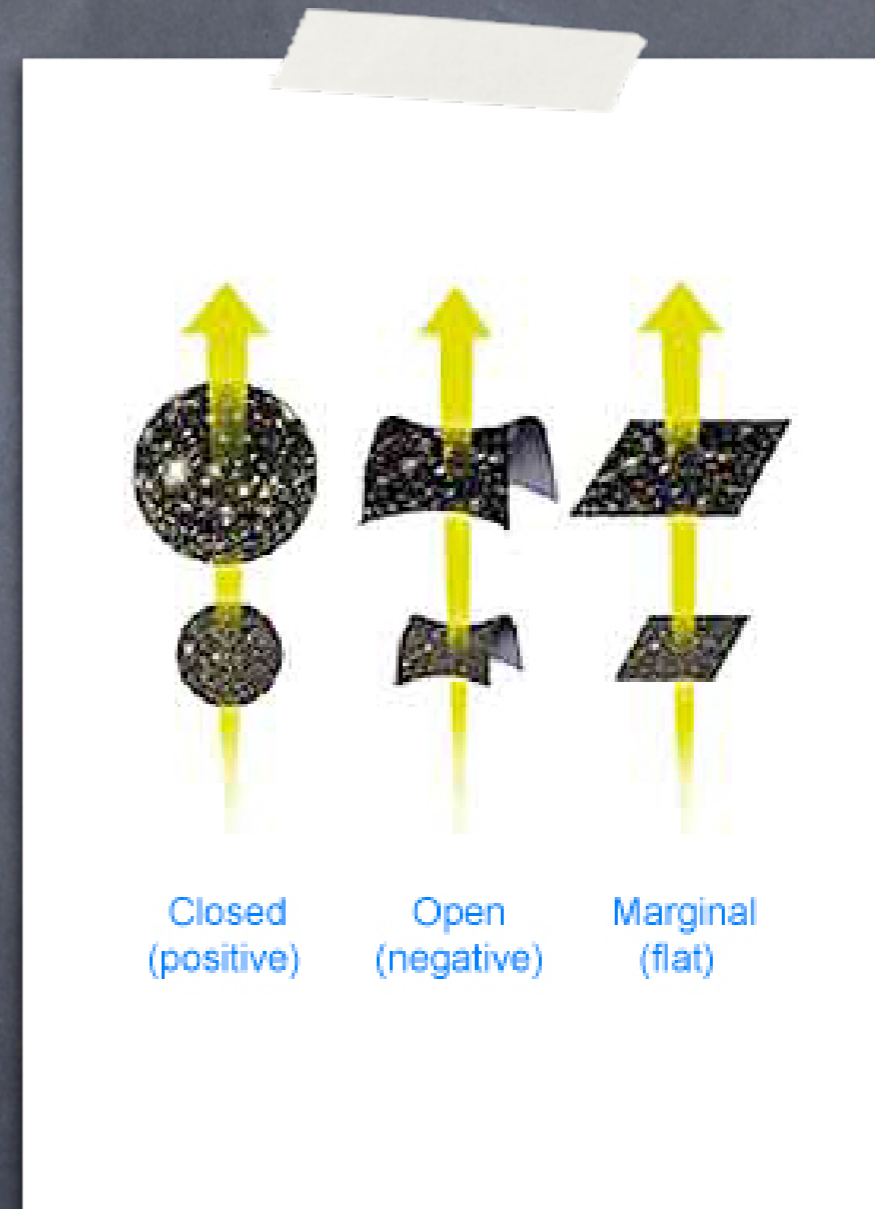


The Fine Print

- ① Actual time back to Big Bang depends upon how fast universe is expanding and on expansion rate in the past
- ① Just as gravity slows ball thrown up, cosmologists believed expansion was slowing down.
- ① By measuring deceleration, fate of universe could be determined

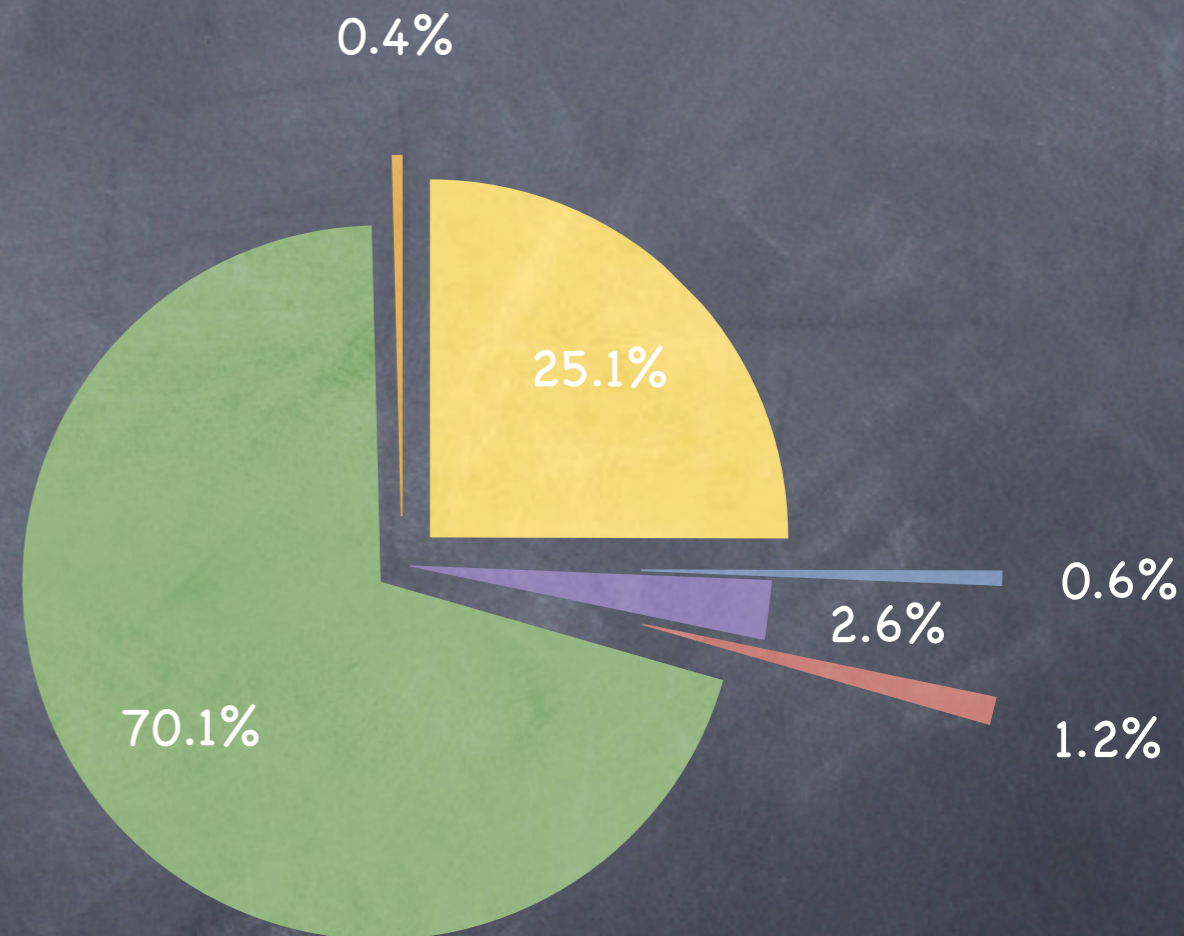
Ah, Houston, problem here...

- 1997: Measured Hubble constant resulted in calculation of universe's age as 9 billion years
- Others estimated oldest globular clusters to be 13 billion years old
- Oops



It's what?

- 1998: Survey of Type Ia supernovae found most distant ones fainter than they should be
- Expansion appears to be speeding up and we don't know why!



- Non-Baryonic Dark Matter
- Warm/Hot Intergalactic Medium
- Dark Energy

- All Visible Matter
- Cold Intergalactic Medium
- Hot Gas in Galaxy Clusters