Key Concepts of Monday

- How can we search for the center of the cosmos?
- Charting the universe
  - Finding distances (our tool: Standard Candles)
  - Finding speeds (our tool: Doppler Shift, z)
  - Relationship between z and speed (low/high speeds)
  - Correlating distances and speeds (Hubble Diagram)

Speed of recession,
(speed = c*z)

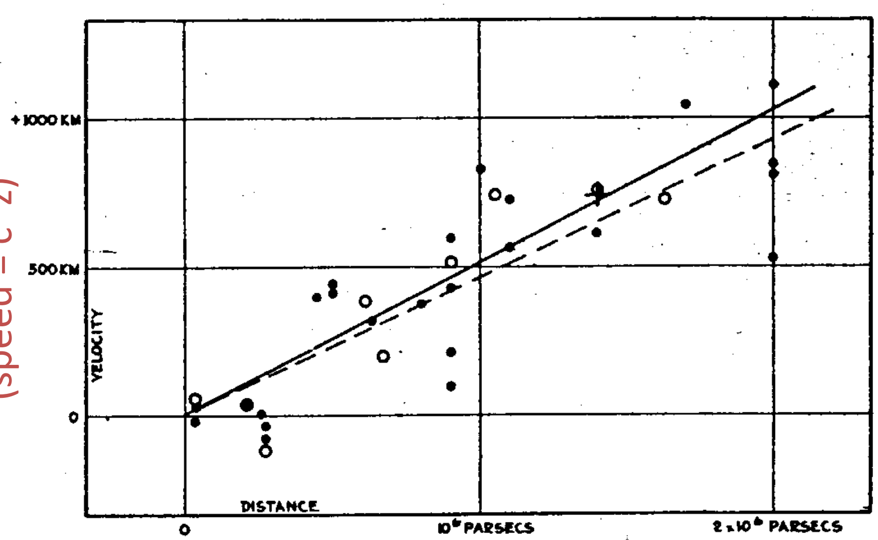


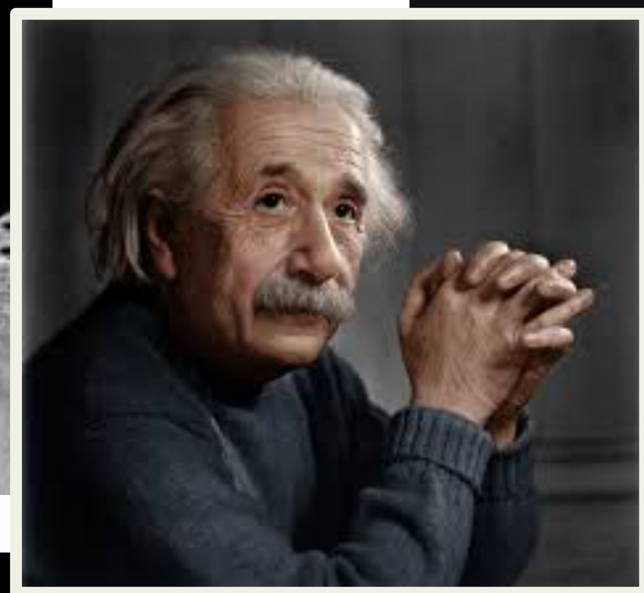
FIGURE 1

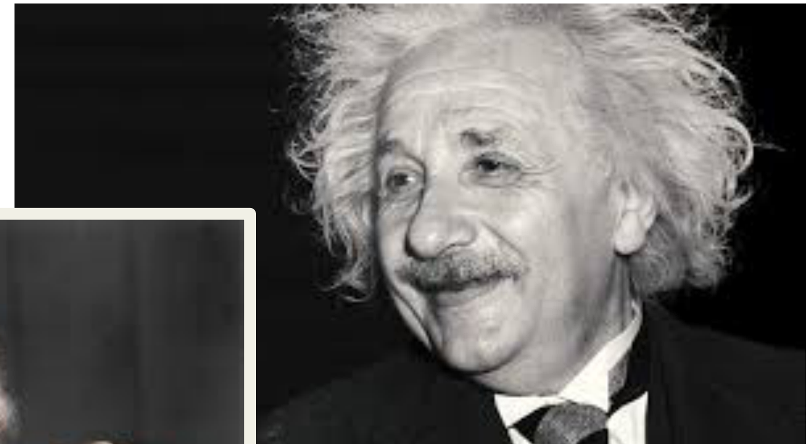
Distance from Milky Way

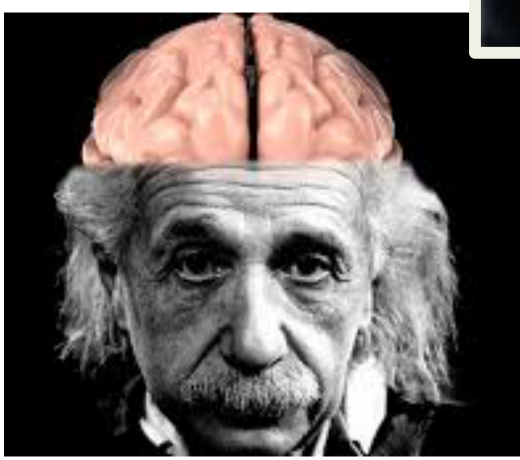
Coming soon
(Homework 3)
Does the Hubble
Diagram require
that we are at the
cosmic center?

Enter Einstein 1905+
The Shape of Space

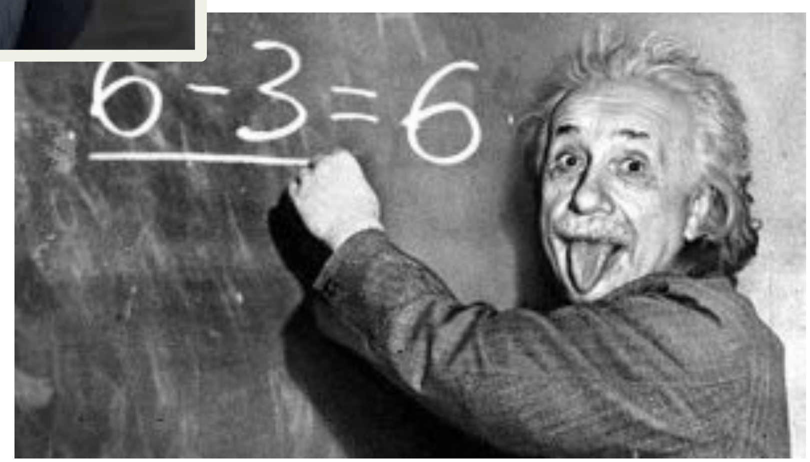
Highlights of Text Chapter 1







14 March 1879
– 18 April 1955



Einstein and a radical new view of space and time

Einstein's ANNUS MIRABILIS papers (1905-06)

(https://en.wikipedia.org/wiki/Annus_Mirabilis_papers)

Four Revolutionary Papers:

(Measurement of the sizes of molecules)

1. **Brownian motion (heated atoms migrate throughout a containing vessel)**
2. **Photoelectric effect (introduction of "photons") , Nobel Prize, 1922**
3. **Special Relativity (meaning of "simultaneity" and inertial reference frames)**
4. **Mass-energy equivalence ($E_{rest} = mc^2$)**

Principles of special relativity

- **the laws of physics remain the same for any "inertial" (non-accelerating) frame of reference**
- **the speed of light has the same value in all inertial frames of reference, independent of the state of motion of the emitting body**
- **there is no absolute frame of reference**

Principles of general relativity

- **experiment cannot distinguish causes of acceleration (springs, gravity, etc)**
- **the paths of light are influenced by gravity (globally and near masses)**

Einstein Sets the Stage

$$E = mc^2$$

Mass and energy are equivalent

Let’s look under the hood.

Energy of Motion: Classical Physics

$$\mathrm{KE} = \frac{1}{2}mv^2$$

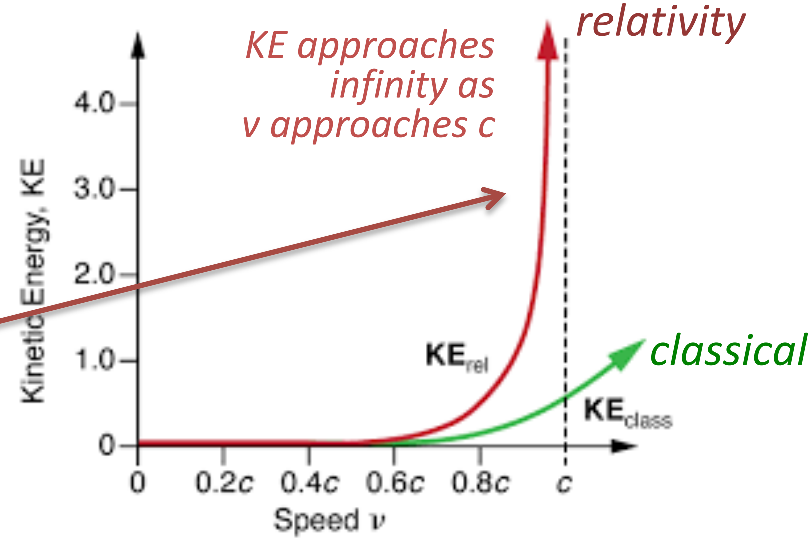
Kinetic energy is energy of motion

Energy of Motion: Relativity (1906)

$$\text{total energy E} = \text{“rest energy”} + \mathrm{KE}$$

$$E_{rest} = m\ c^2$$

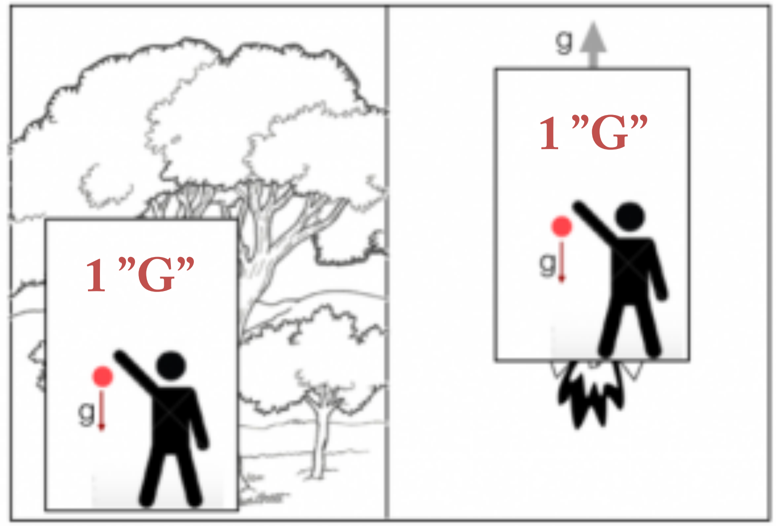
$$KE = \frac{mc^2}{\sqrt{1 - v^2/c^2}}$$



This is why mass can't be accelerated to the speed of light: Requires infinite energy!

Scales measure force

Equivalence Principle

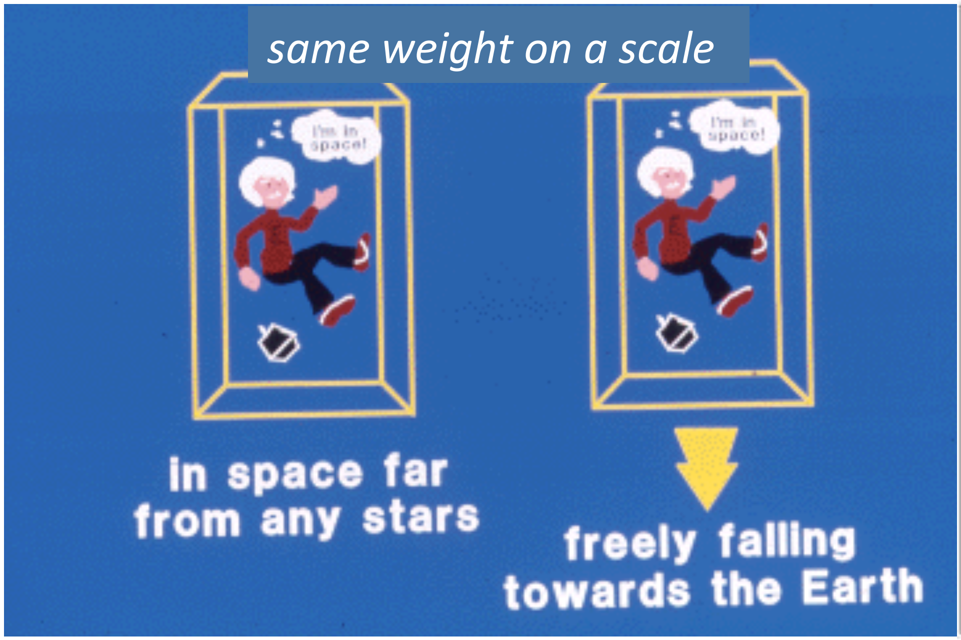


Scales respond equivalently in gravity or an accelerating reference frame.

Weight and acceleration are the same.

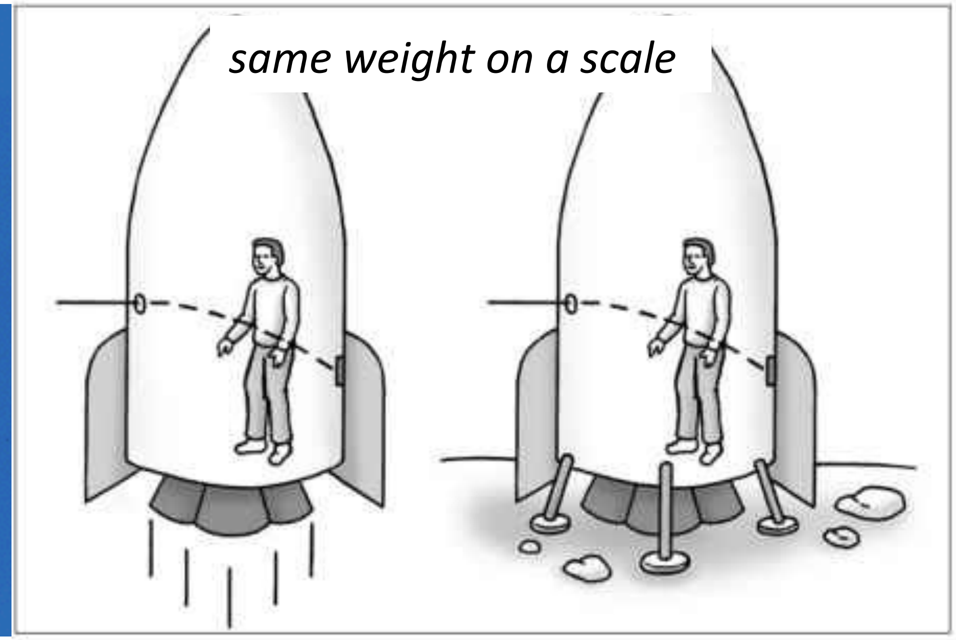
Einstein’s Equivalence Principles

You can’t tell the difference



weightlessness

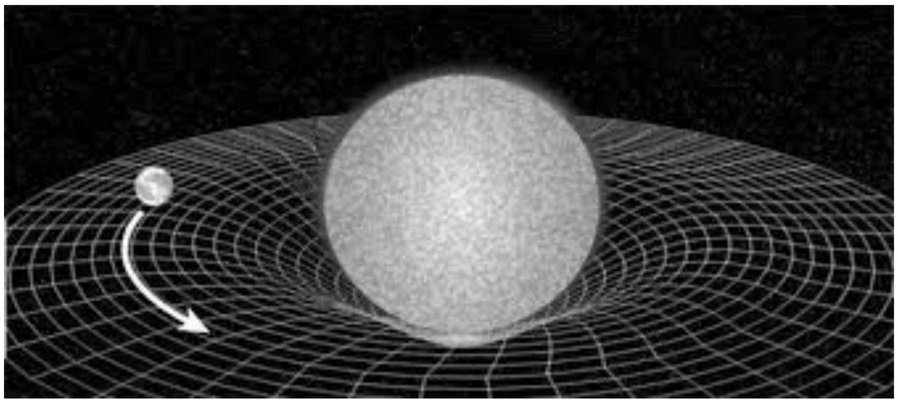
Weightlessness is possible with or without gravity. *You can’t tell if you’re in an empty universe or a free-falling elevator.*



weight and curvature

Light traversing an accelerating rocket **OR** under the influence of gravity follows a curved path. *You can’t tell the difference.*

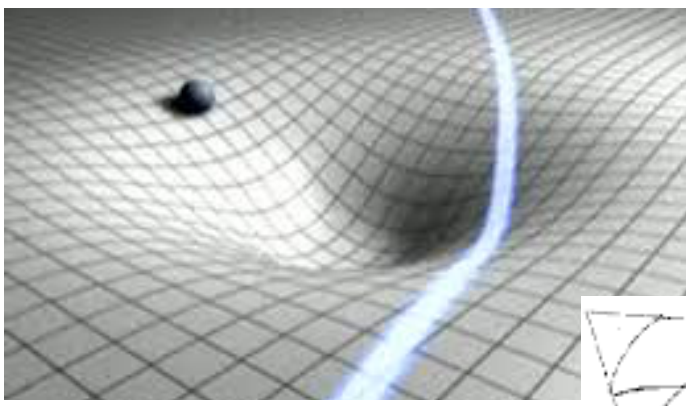
The Curvature of Space

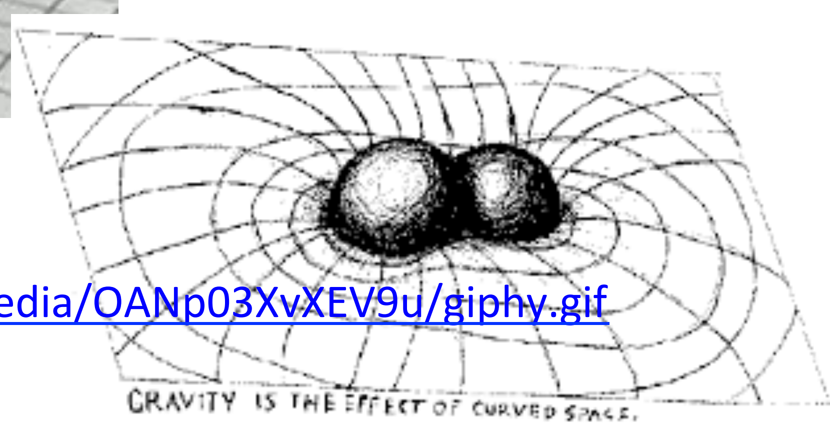


Masses bend space locally.

Gravity and the curvature of space are equivalent.

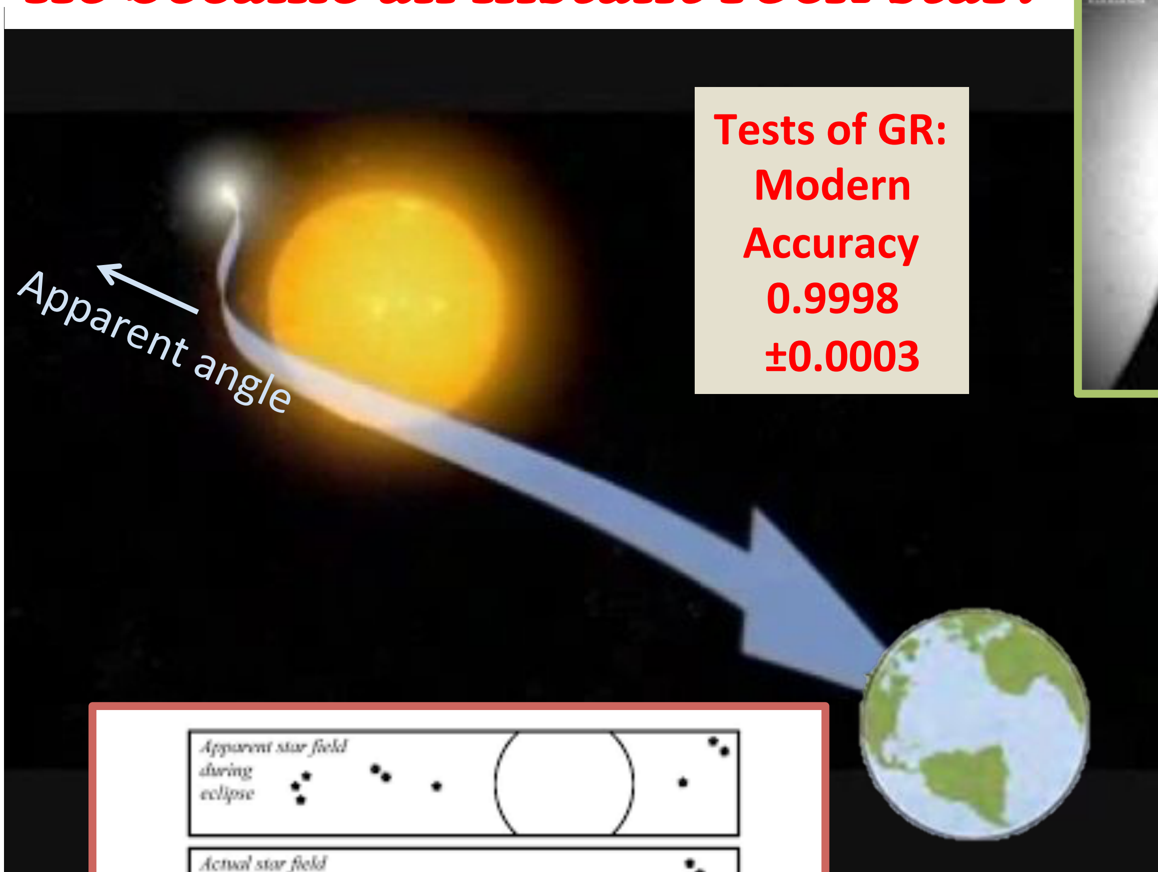
Since space is curved, all paths through space (including light rays) are also curved.



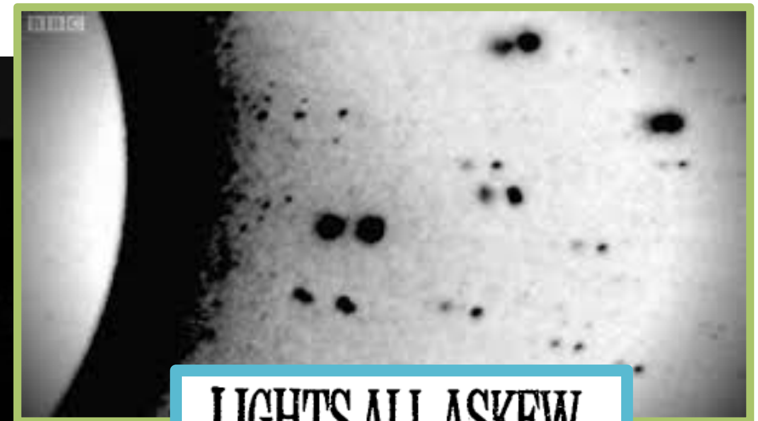


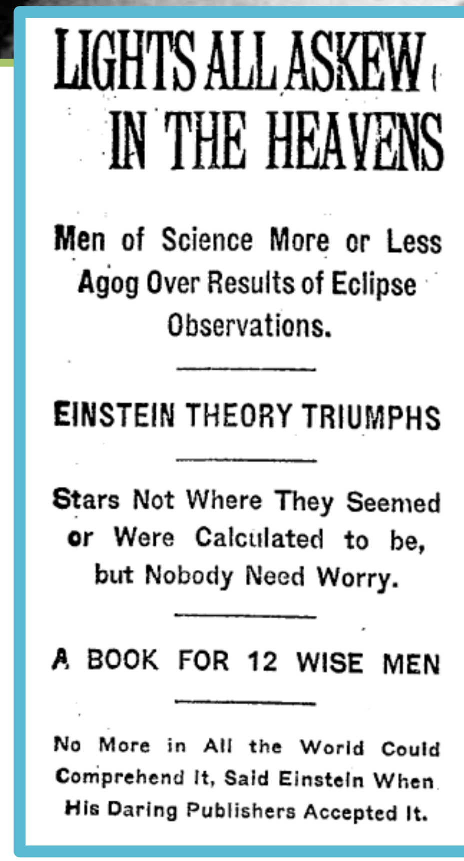
Black Holes merging
https://media.giphy.com/media/OANp03XvXEV9u/giphy.gif

Einstein's famous prediction was verified.
He became an instant rock star!



Tests of GR:
Modern
Accuracy
0.9998
±0.0003




LIGHTS ALL ASKEW IN THE HEAVENS

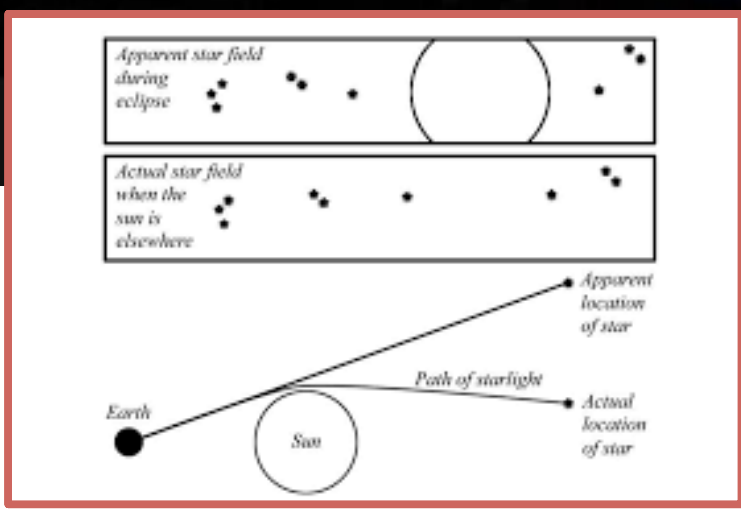
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

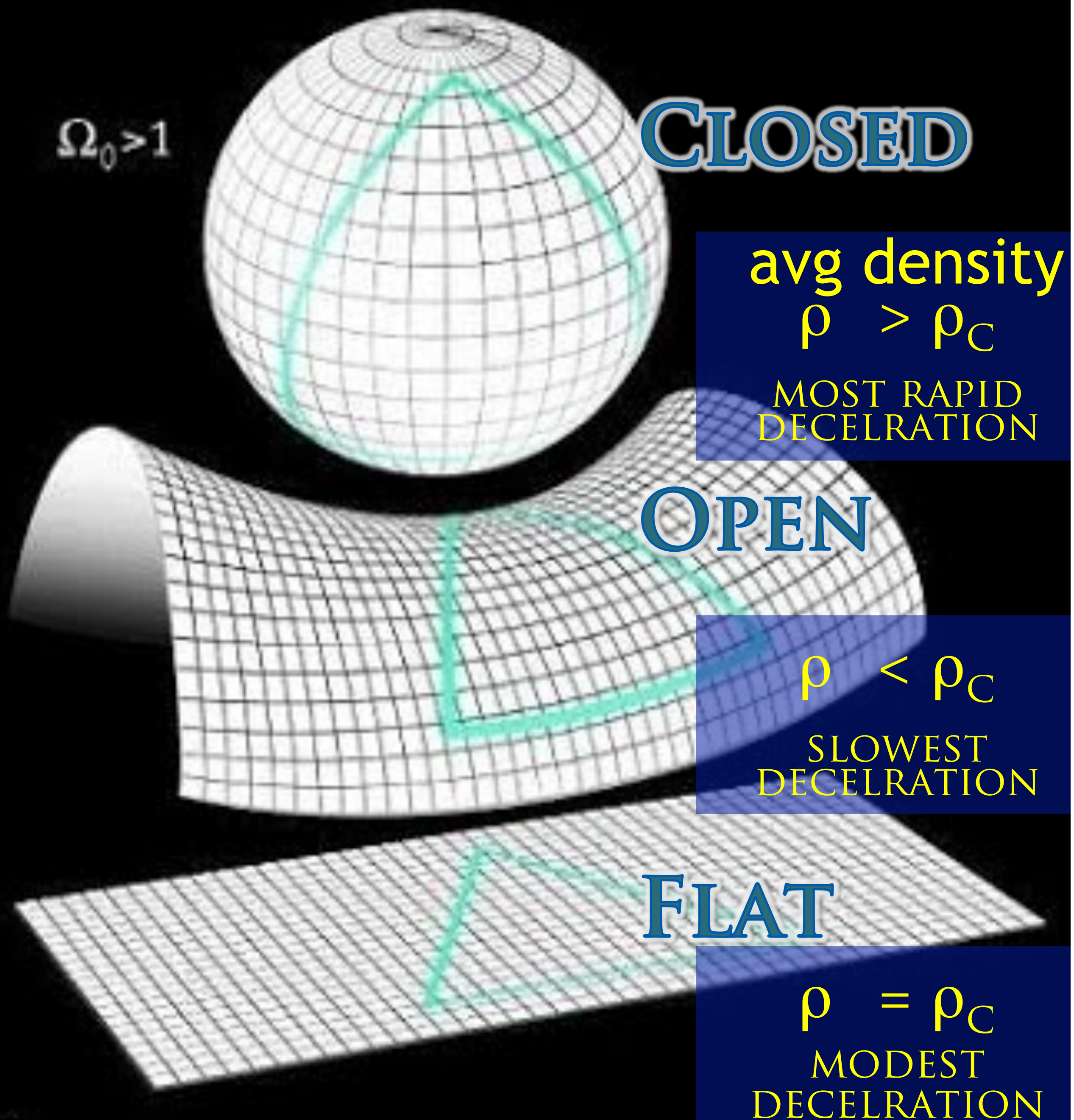
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.



Einstein: Possible Shapes of Space



1917: General Relativity:
The Field Equation(Cosmic & Local)

"A gravitational field acts on matter telling it how to move. . . matter generates gravitational fields in space-time, telling it how to curve"

Text, middle of page 40

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

Left side: the shape of space
Used to derive the shortest path between points ***x*** and ***y*** (light must take it)

Right side: The directional "stresses" on space imposed by gravity

Note: cause and effect are not distinguished: mass bends space; the bending of space causes acceleration (deviations from uniform motion); accelerations and bending of space are equivalent

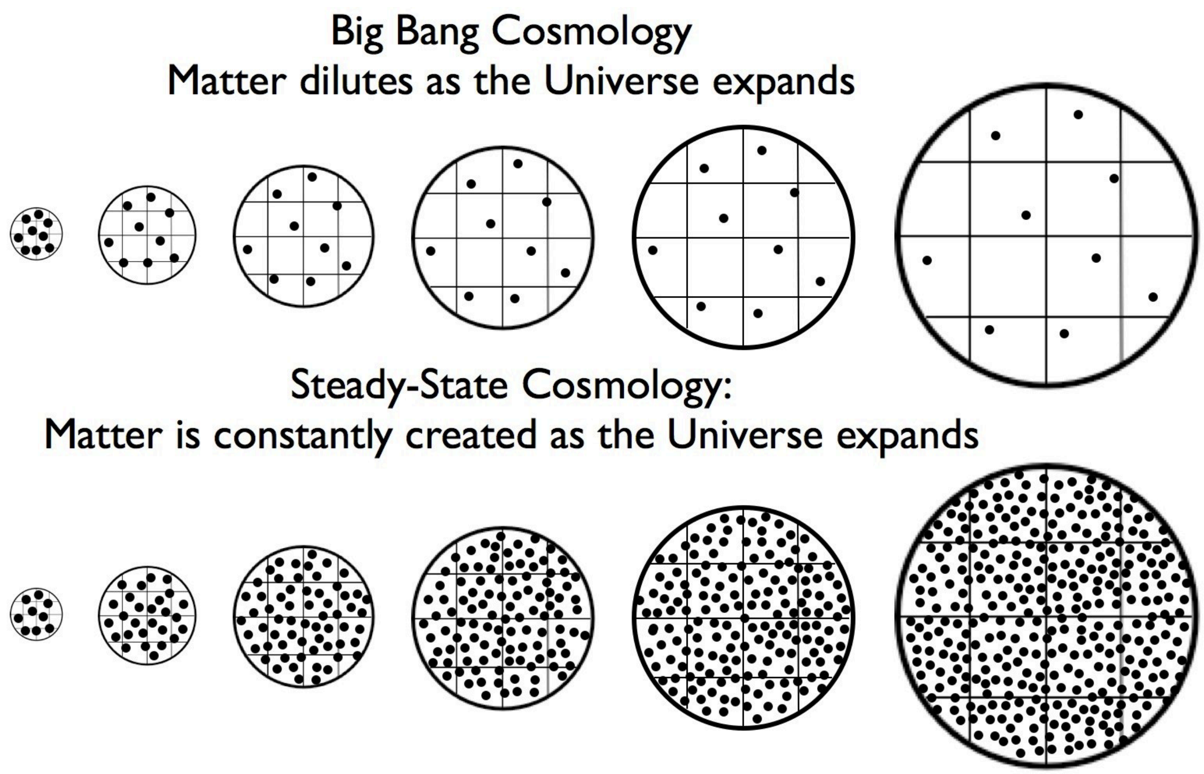
Expanding for sure! Even so, does the Universe actually change???

Big Bang

Uniformity required, but evolution of the gross properties of the Universe is OK.

Steady State

Uniformity required, and no evolution of the gross properties of the Universe



SS: If cosmic density is really constant and its volume increases then new matter must constantly be created <u>in situ</u>!

Early Theoretical Cosmology

A Universe that can't sit still: from Einstein to LeMaitre

Everyone had long believed in a static Universe

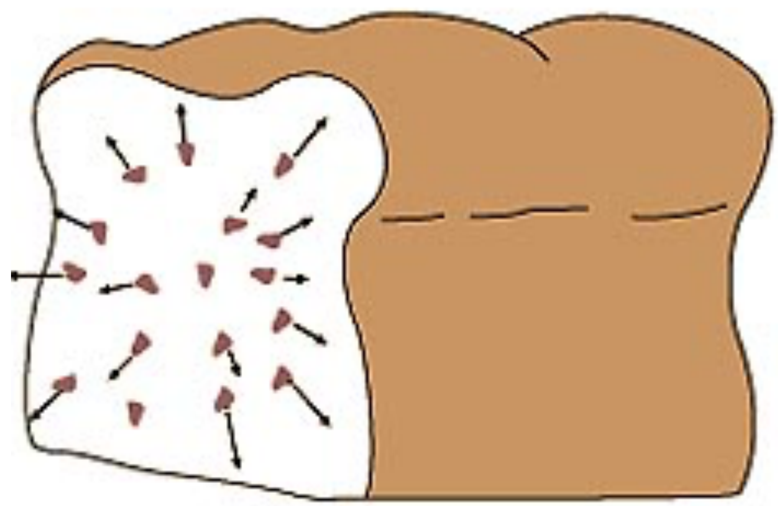
- When he derived General Relativity Einstein realized that his equations had the same problem as Newton's falling sky:

  imminent gravitational collapse!
- DeSitter showed that an empty universe with matter was stable if it expanded fast enough. Friedman (others) . . .
- In 1927 Lemaitre proposed that Hubble's observations of increasing galaxy-distances was the result of the expansion of space itself (raisin cake, balloon, and trampoline analogies)
  - *Nothing can move through space faster than light,*
  - ***but this restriction doesn't apply to space itself!***
  - *Galaxies don't move **THROUGH** space, they move **WITH** it.*

Important!

Expanding Space or Flying Galaxies: They aren’t equivalent.

Einstein-de Sitter



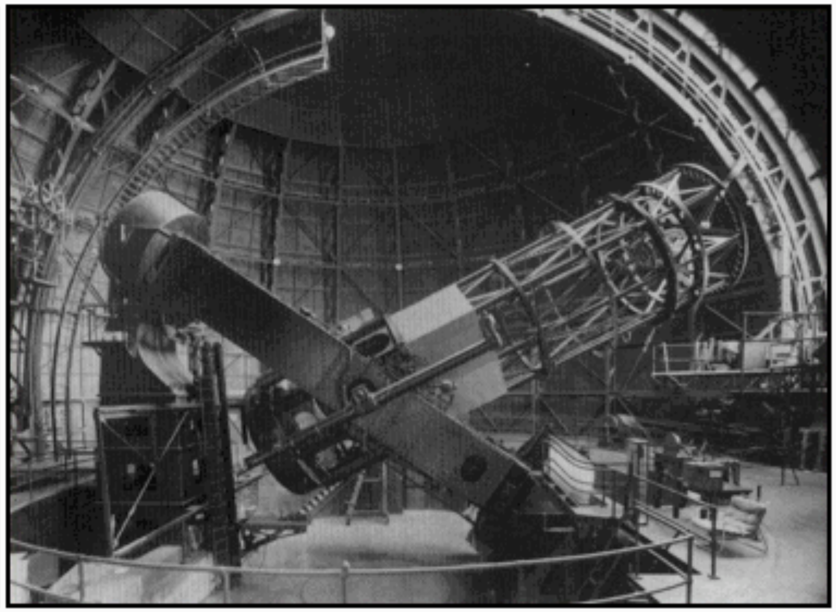
Lemaitre

How can we rule one (or both) out?

The Restless Universe
Hubble (and colleagues)

Highlights of Text Chapter 2

Edwin Hubble
1889 – 1953



100 inch Mt Wilson Telescope

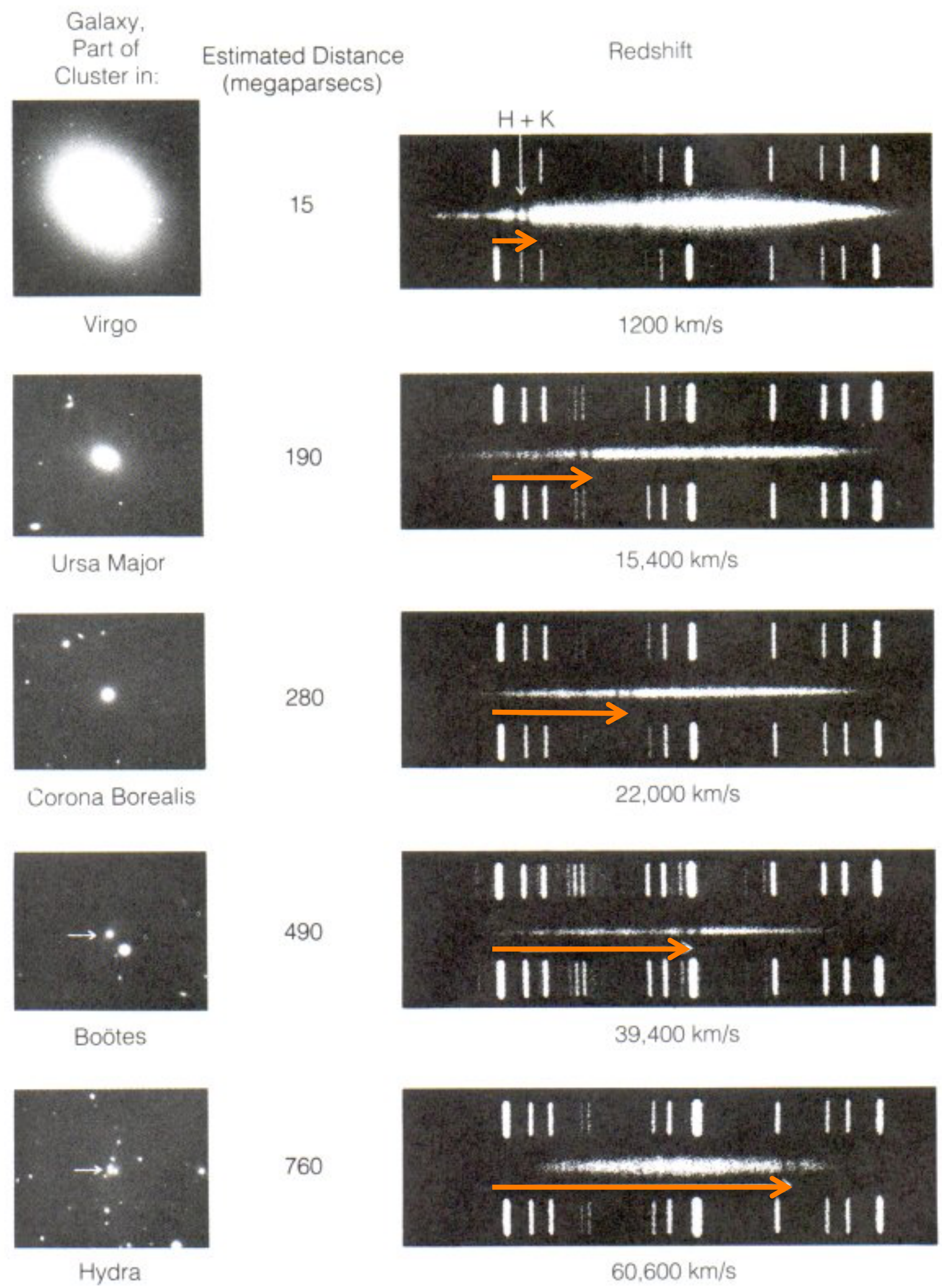
Milton Humason
1891 – 1972

Vesto Slipher
1875 – 1969

Fritz Zwicki 1898 – 1974

Allan Sandage 1926 – 2010

1920s: Slipher and his spectra



1920s: Hubble and his first diagram

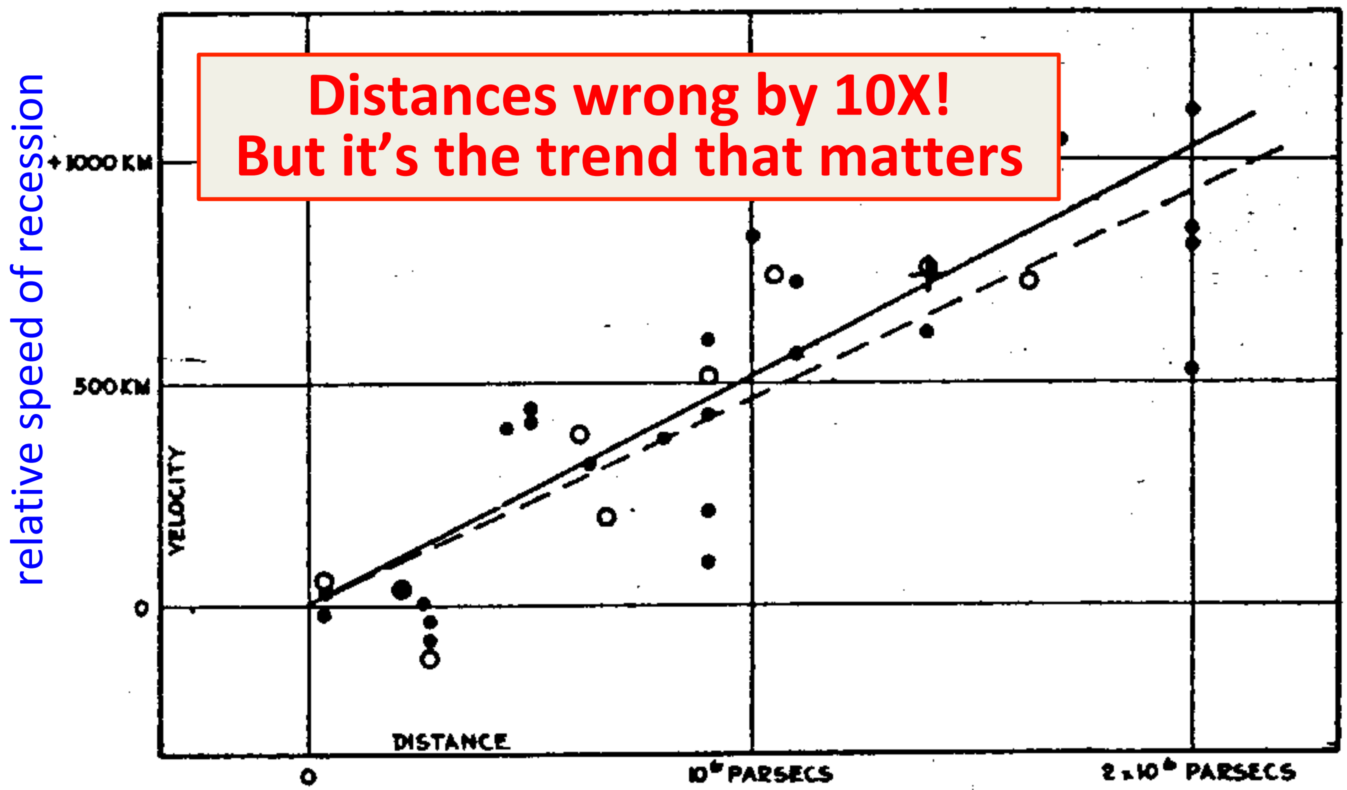


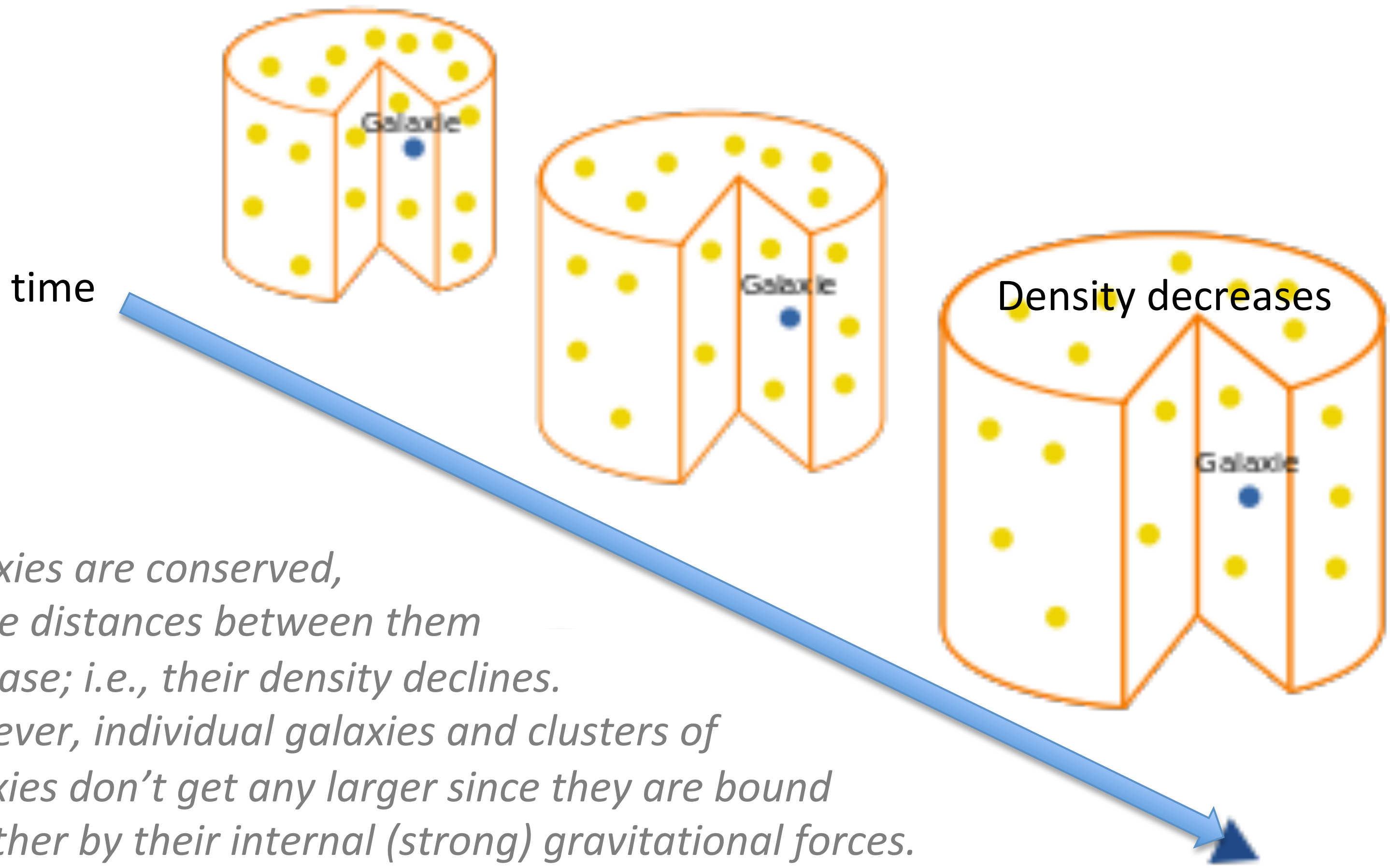
FIGURE 1

Distance from Milky Way

Hubble correlated the Doppler shifts and distances of galaxies

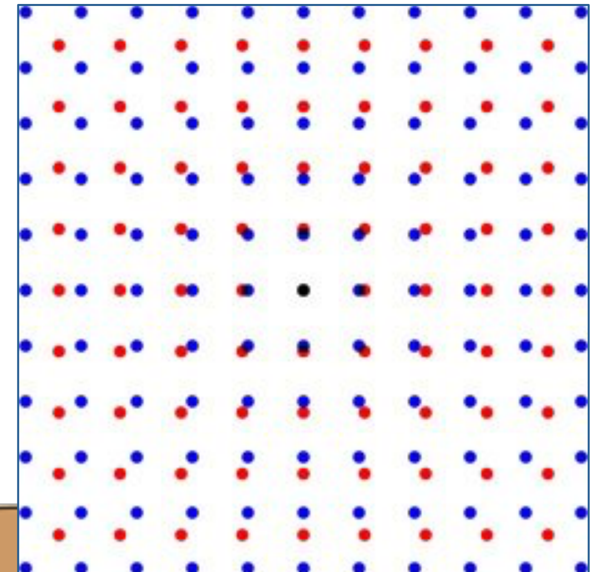
Hubble's distances,
Slipher's Doppler shifts,
Humason's observing skills
Hubble presents the "Hubble Diagram"

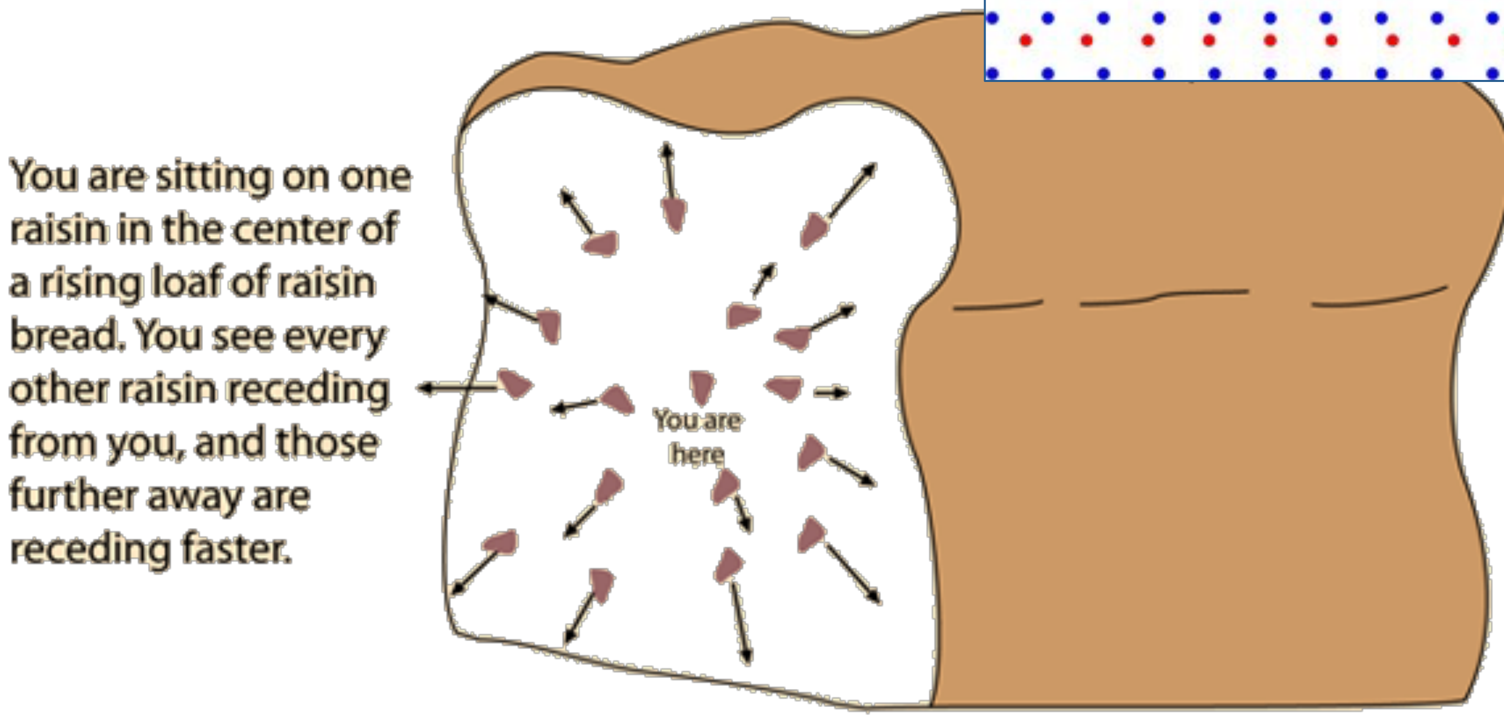
If our view is universal then the entire Universe is expanding (with no center)!

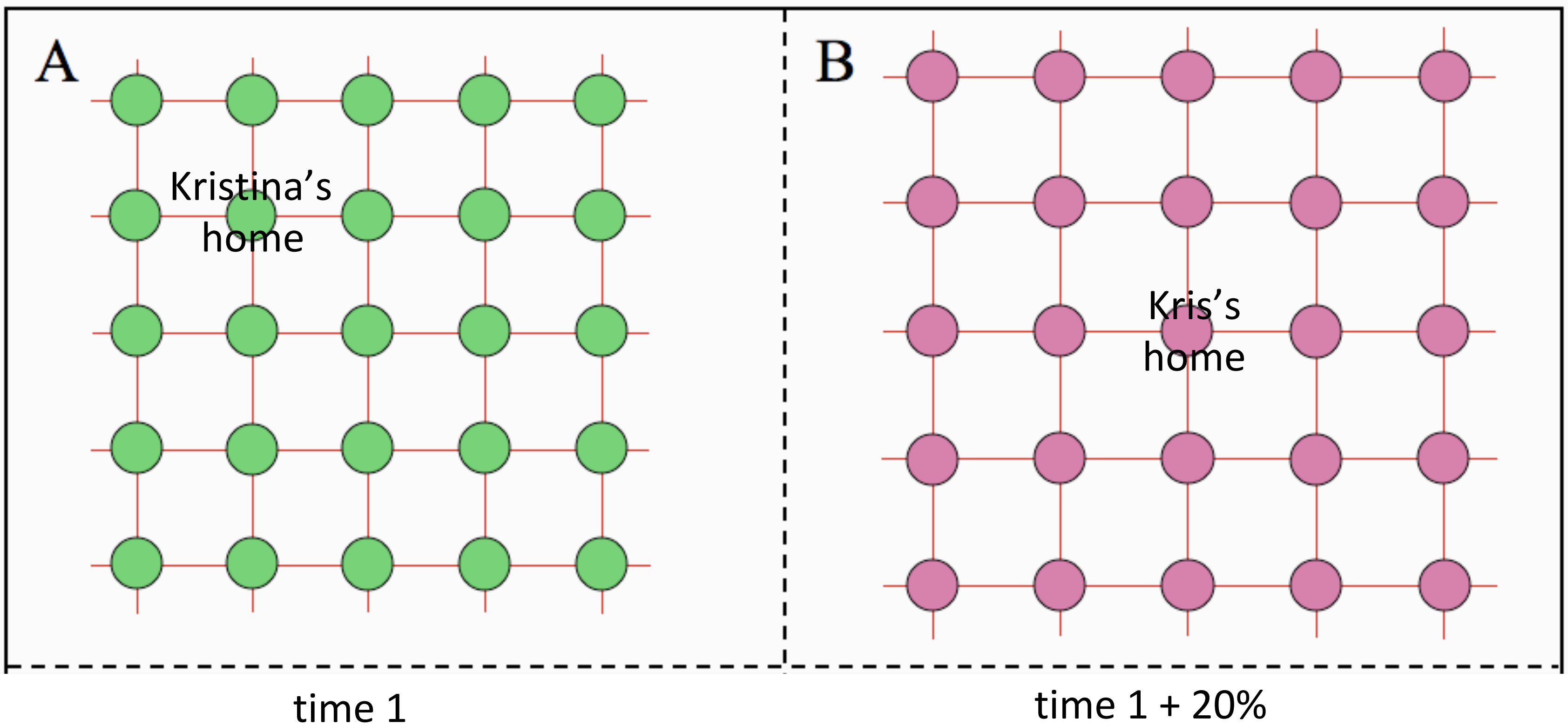


Galaxies are conserved, so the distances between them increase; i.e., their density declines. However, individual galaxies and clusters of galaxies don't get any larger since they are bound together by their internal (strong) gravitational forces.

Examples of things in an expanding space

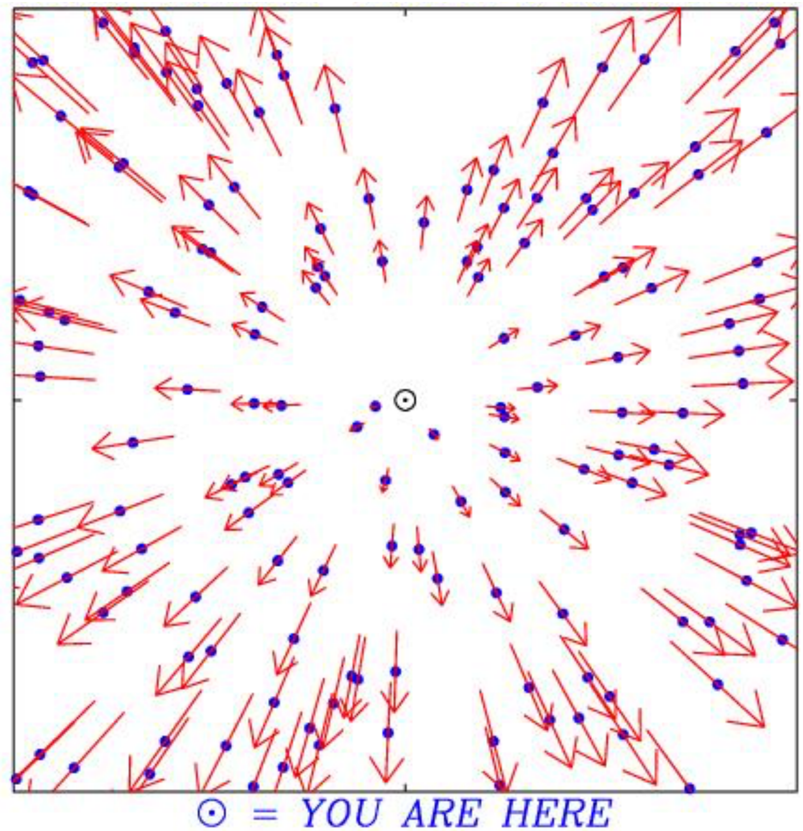






Does expansion define the center of space?

Hubble estimates the age of the Universe



Play it backwards!

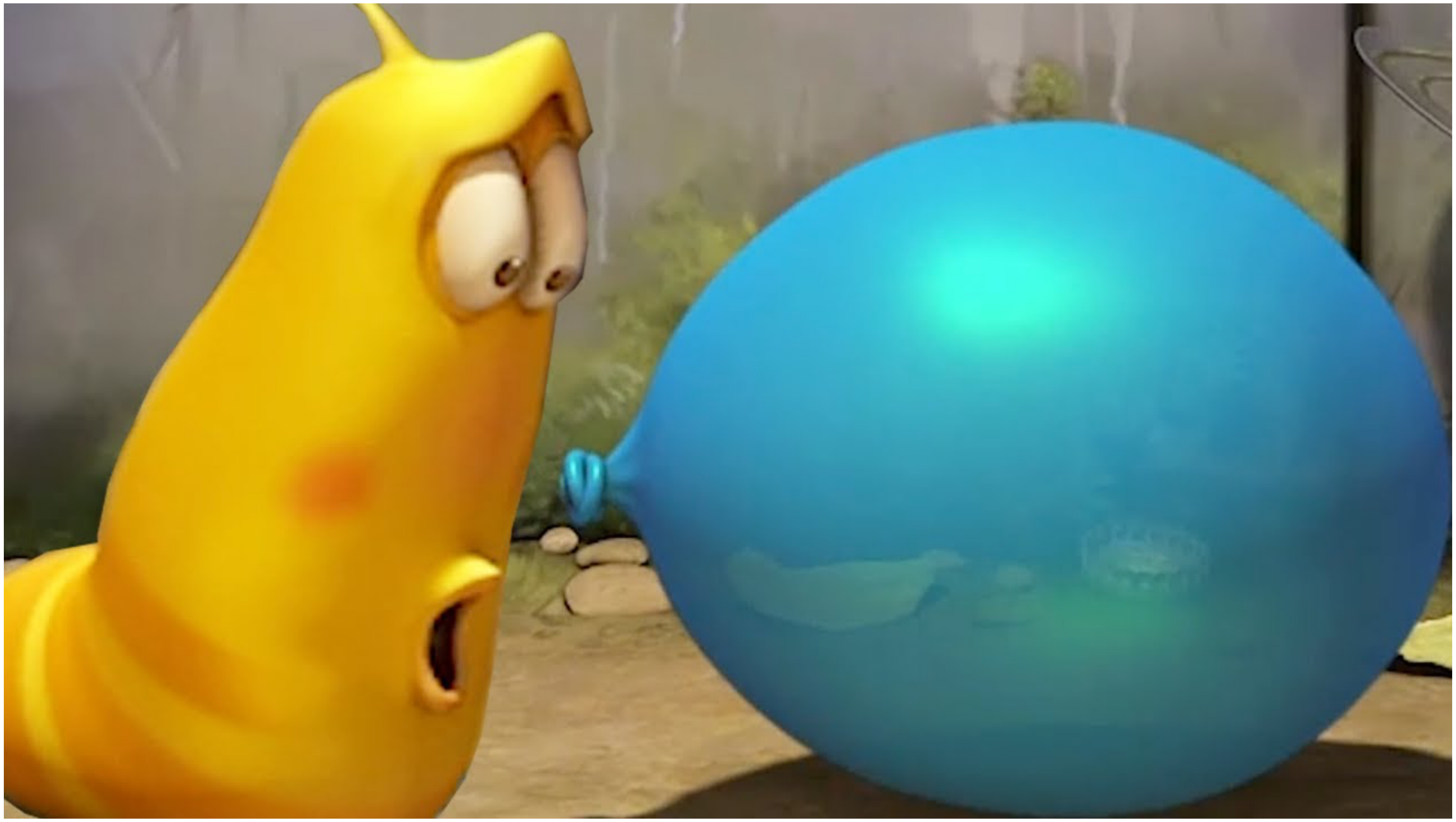
Any (every) pair of galaxies collide at time (separation)/(recession speed)

All pairs or galaxies collide at a universal “Hubble time” = X Gy ago

Roadmap

- Density is Destiny: How can the density be measured?
- Sandage searches for signs of early gravitational deceleration. No luck.
- Measuring Galaxy Masses: it’s Easy!
  – (if you know the distance)
- What's the Matter? We can feel it, but we can’t see it.
  – Skip ahead to Chapter 6: DARK MATTER — esp. page 193-201
- Dark Matter in the Milky Way and other galaxies
- Observational ‘Proof’ of Dark Matter: Gravitational Lenses

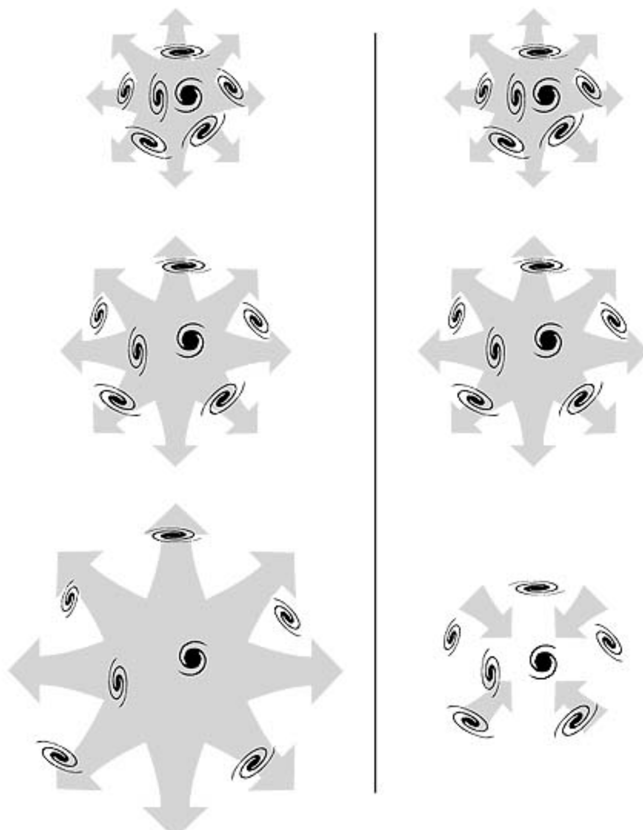
Cosmic Expansion:Can Gravity Slow it Down?



What is the fate of the cosmos ?

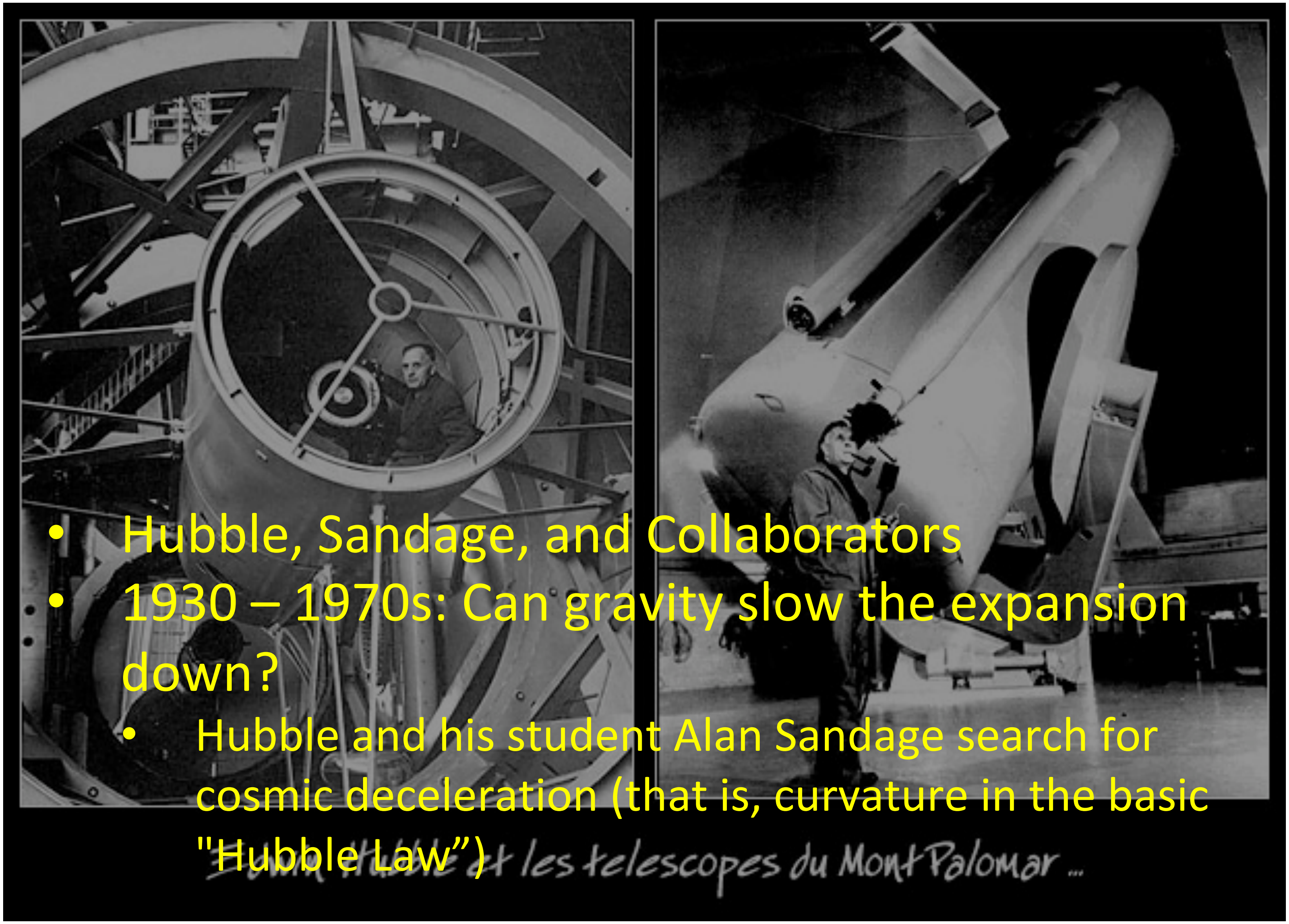
Its gravity ***(aka mass density)*** *determines the gravitational fate of the Universe*

Low density: expands forever



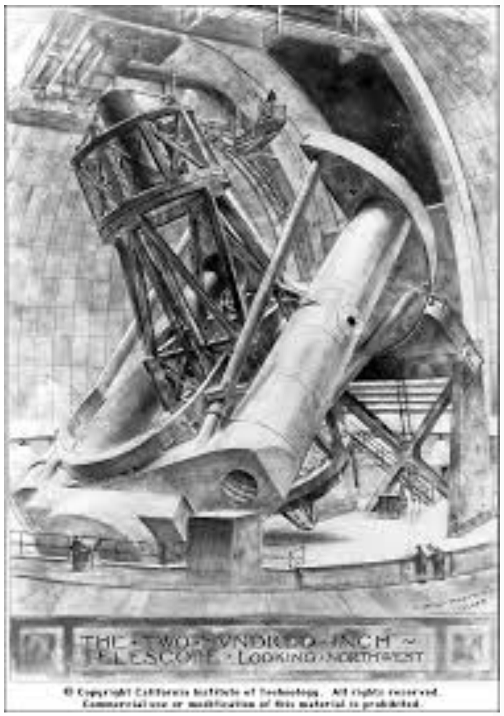
High density: ultimate collapse

No theory predicts the mass density.



- Hubble, Sandage, and Collaborators
- 1930 – 1970s: Can gravity slow the expansion down?
  - Hubble and his student Alan Sandage search for cosmic deceleration (that is, curvature in the basic "Hubble Law")

1950s to 1980s
Sandage and others use the 200-inch telescope to extend Hubble's correlation plot to thousands of faint galaxies



Palomar 200-inch Telescope