Astronomy 350L

(Fall 2006)

The History and Philosophy of Astronomy

(Lecture 22: Hubble II)

Instructor: Volker Bromm
TA: Jarrett Johnson

The University of Texas at Austin

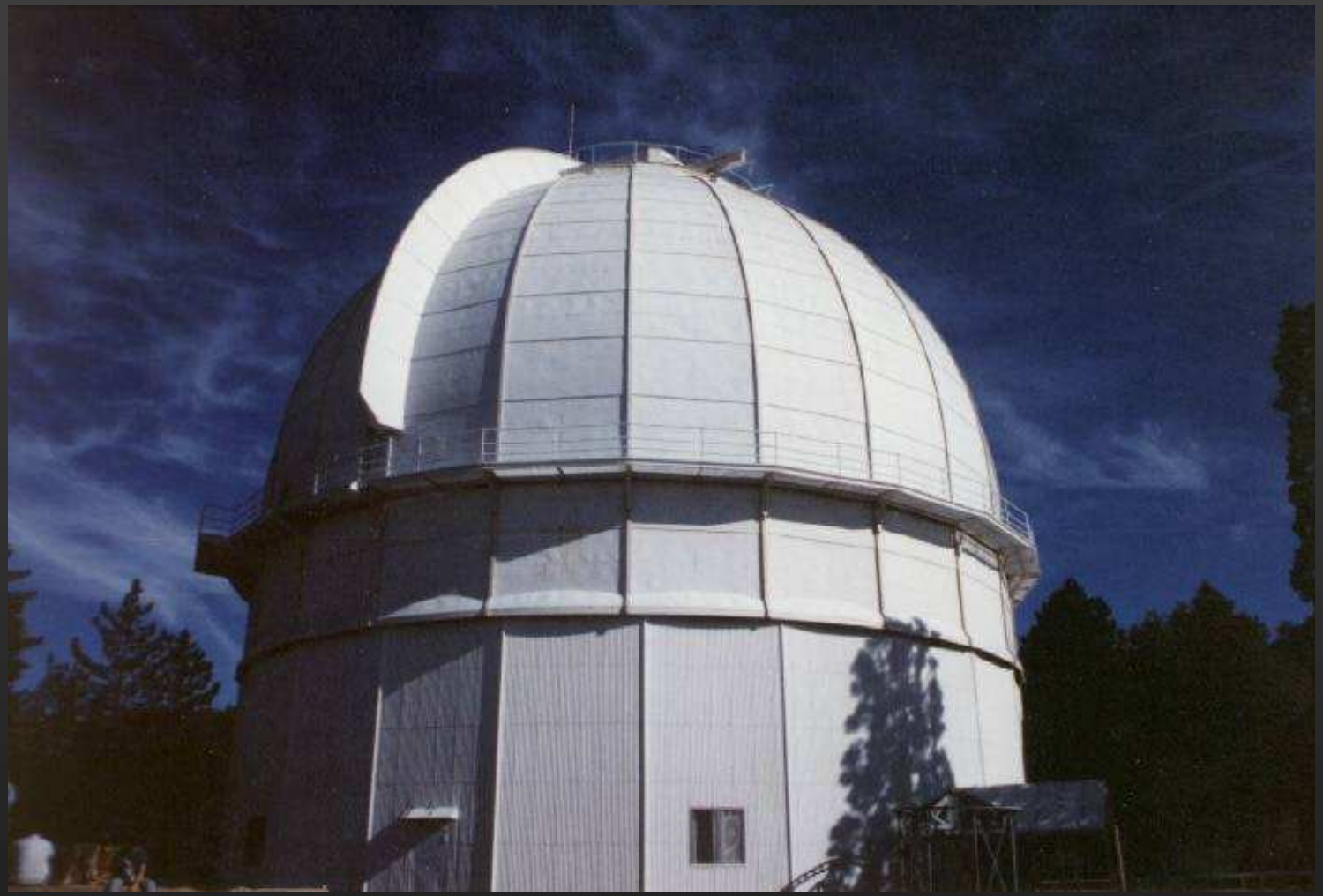
Edwin P. Hubble: Mariner of the Nebulae

- 1889 (Missouri) – 1953 (Pasadena)

- leading observational astronomer of 20th century:
  - discovers galaxies (1924):
    - à Milky Way but one of innumerable “island universe”
  - expansion of the universe (1929):
    - à Hubble’s Law:

$$v = H_0 \times d$$

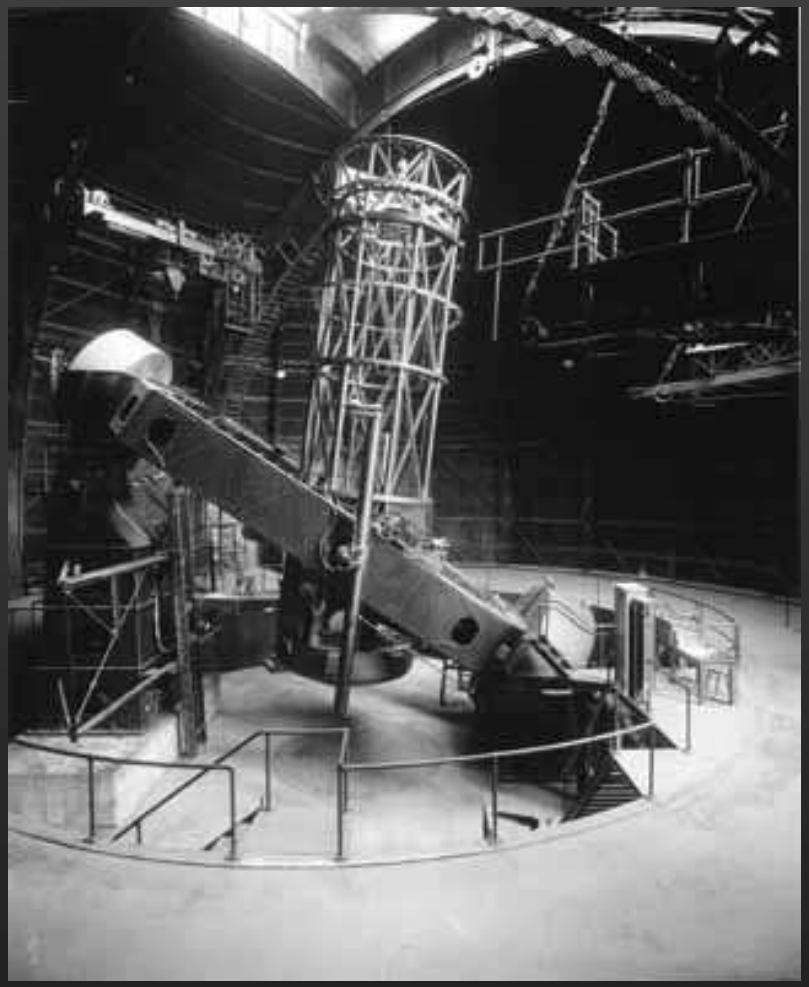
Mount Wilson Observatory



- 1919 onwards: world’s largest telescope

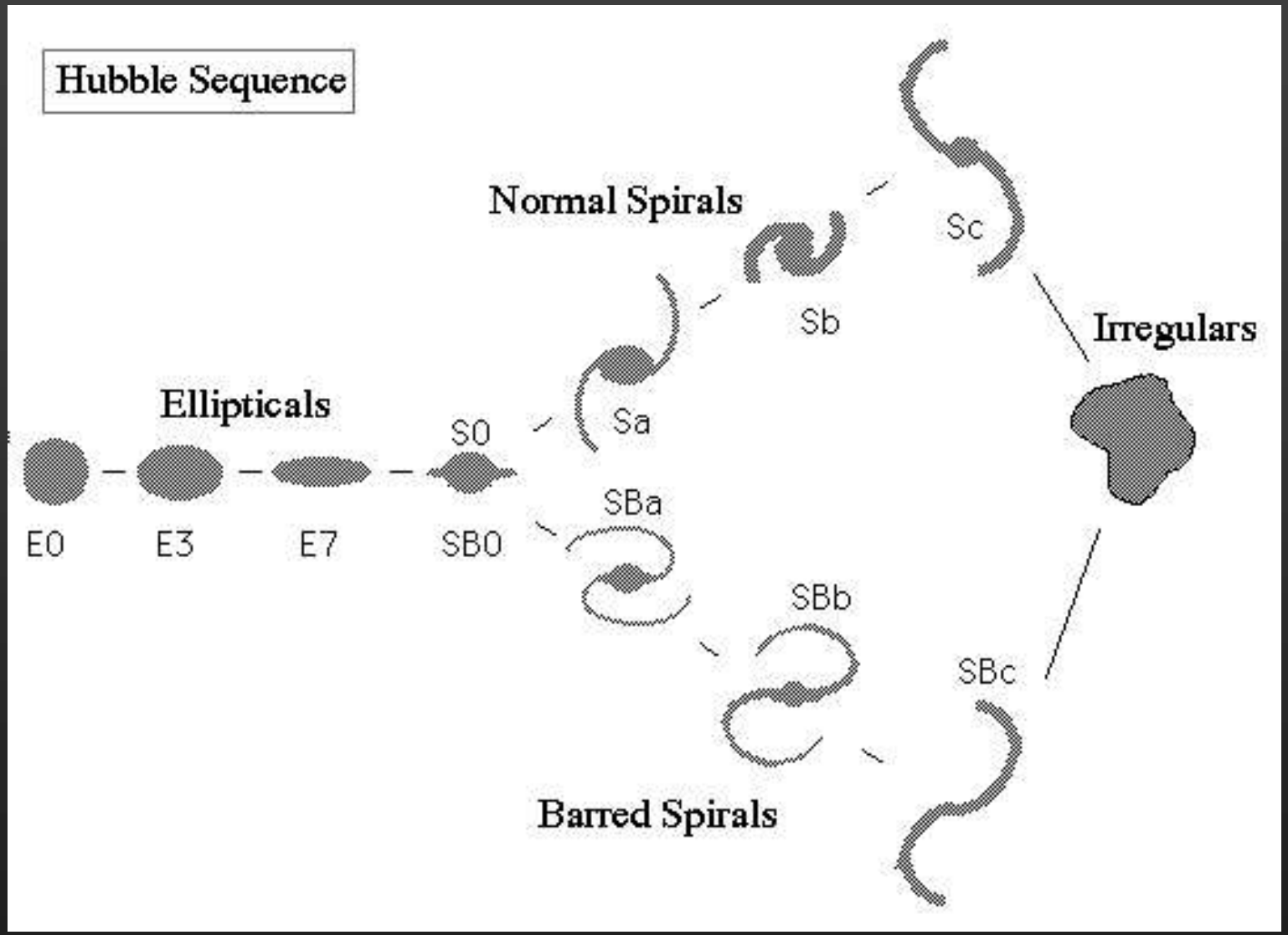
Mount Wilson Observatory

George Hale (1868-1938)



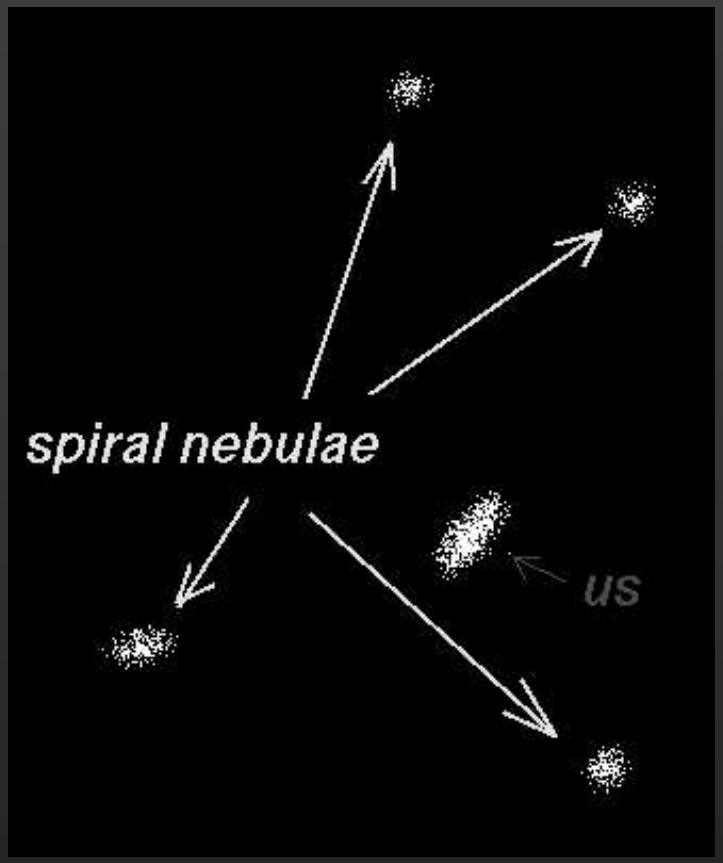
100-inch Hooker Telescope

Classification of Nebulae (=galaxies)



- 1923: Tuning-fork diagram

Big Q: How do the Spiral Nebulae Move?

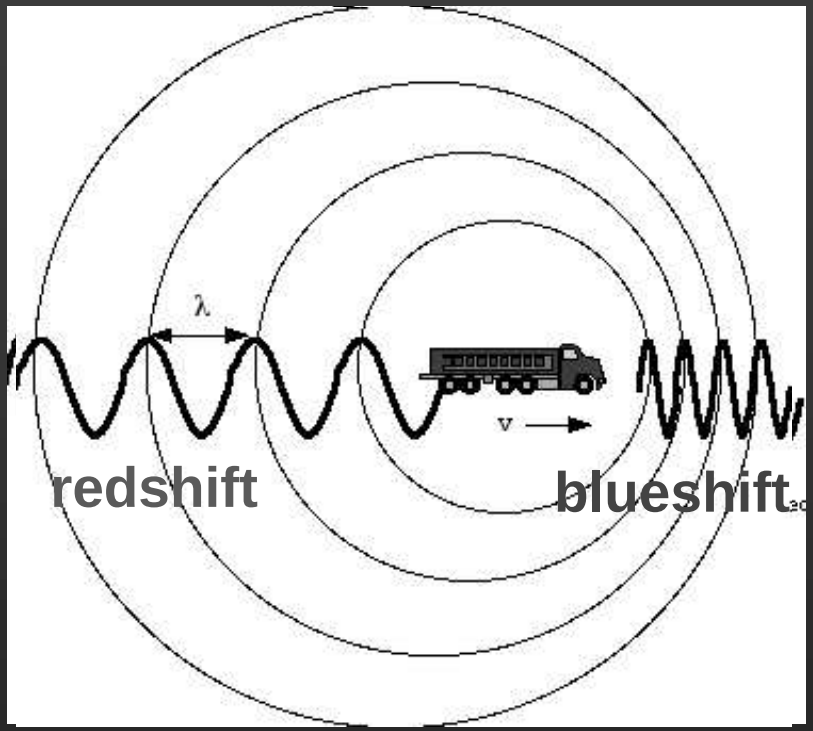


- figure out radial velocities by taking spectra, and measure the shift of spectral lines

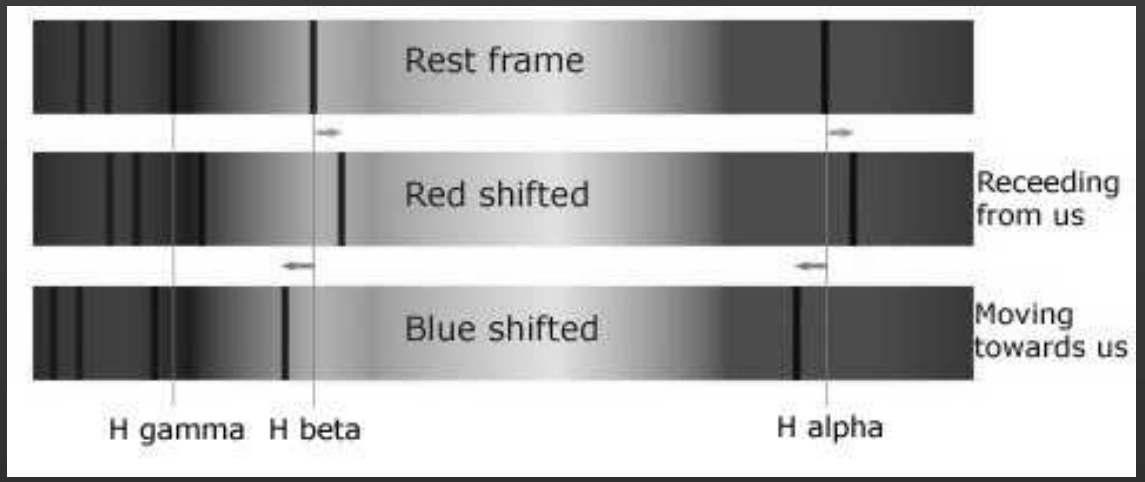
à Doppler effect!

The Doppler Effect (1842)

Christian Doppler (1803-53)



The Doppler Effect for Spectral Lines



- Calculate radial speed:

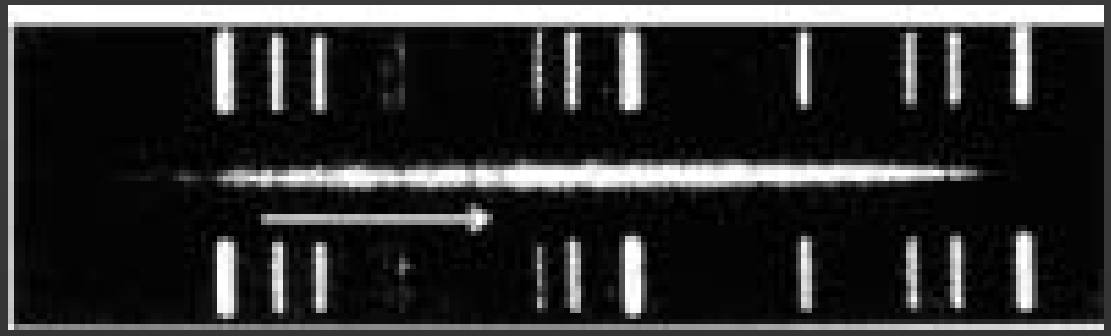
$$\frac{\text{wavelength shift}}{\text{rest wavelength}} = \frac{\text{speed in line-of-sight}}{\text{speed of wave}}$$

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

- By measuring the shift in wavelength of spectral lines, one can figure out radial velocity of source with high precision!

The Flight of the Spiral Nebulae (1912)

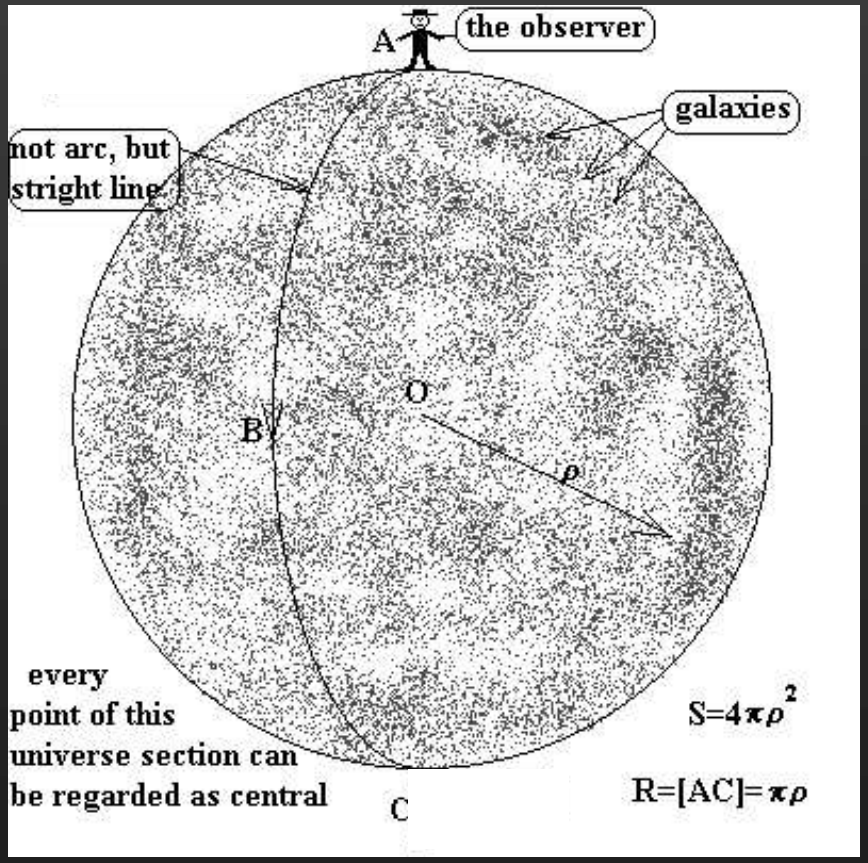
Vesto M. Slipher (1875-1969)



- Important discovery: most spiral nebulae display redshifts in their spectra!
- From Doppler effect: Do spiral nebulae move away from us???

Solving Einstein's Equations of GR

- 1917: Einstein constructs model of the universe that is eternal and static

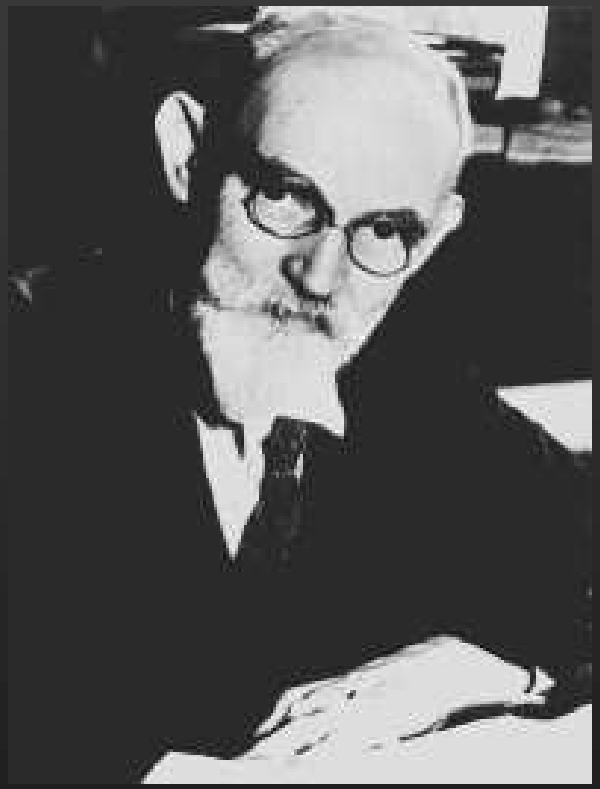


- balance between attractive gravity and repulsive cosmological constant ("anti-gravity")

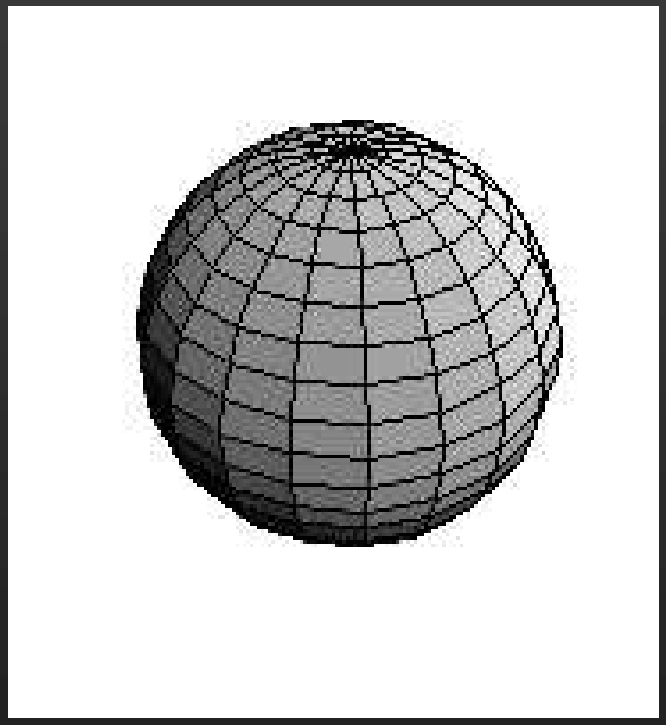
- finite but without boundary (spatially closed)

Solving Einstein's Equations of GR

- 1917: de Sitter constructs a model of the universe that contains no matter, but predicts motion!



Willem de Sitter
(1872-1934)



- an empty universe!

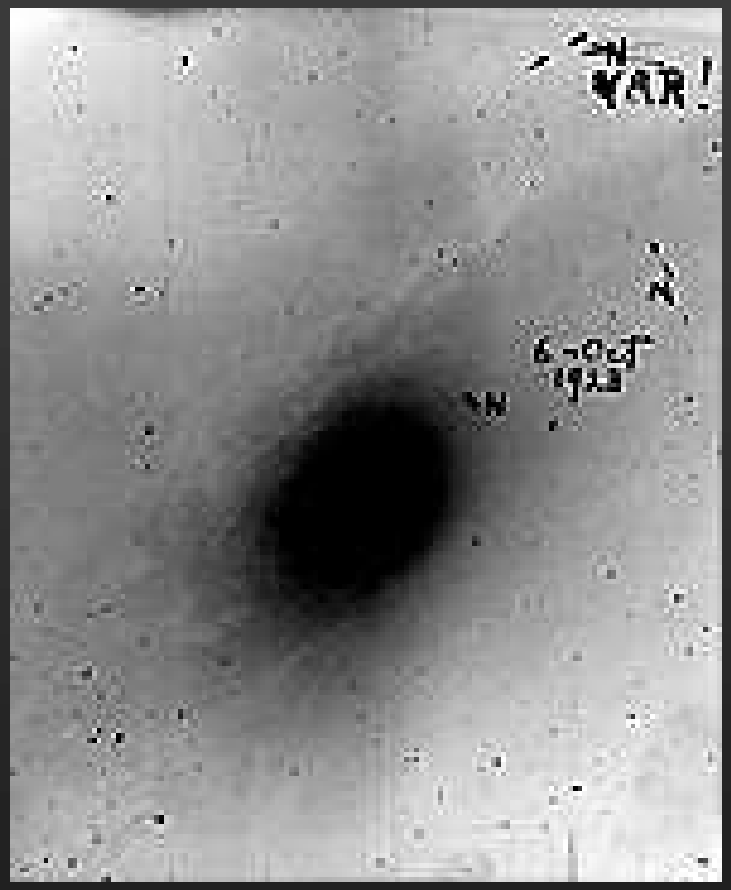
Solving Einstein's Equations of GR

- 1917: de Sitter constructs a model of the universe that contains no matter, but predicts motion!

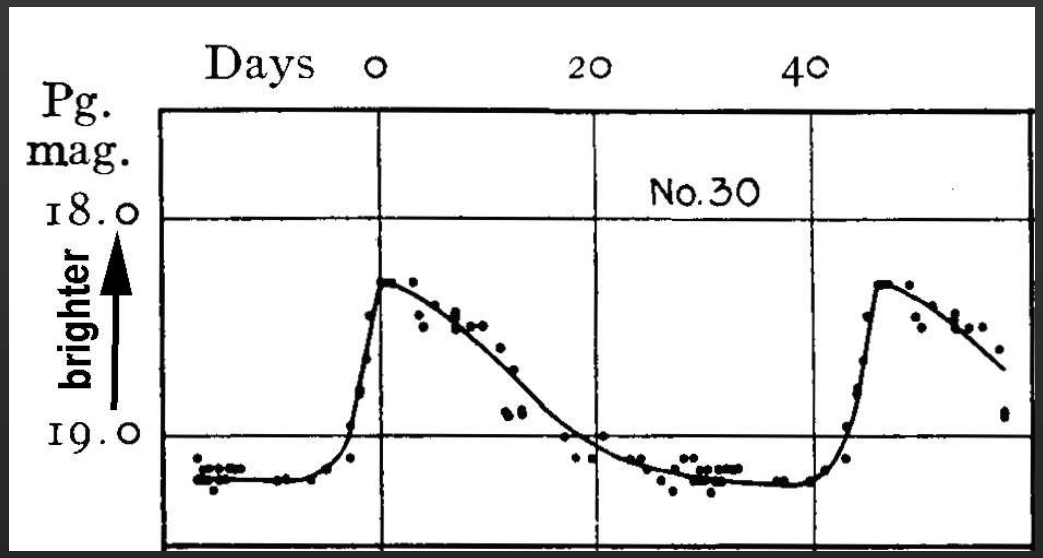
- particles are "scattered away" from origin ("de Sitter effect")
  -- the larger the distance, the larger the apparent speed!

Hubble and the Distance to Andromeda (M31)

- October 1923: He obtains photograph of M31



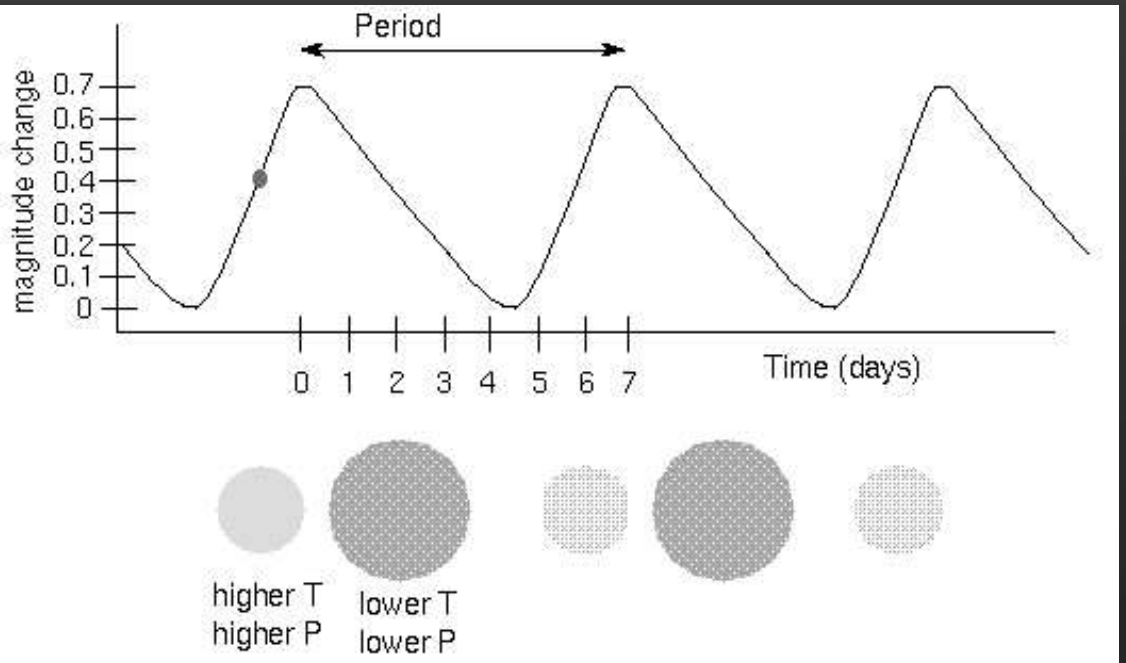
Brightness vs time



- Hubble discovers a Cepheid variable in Andromeda!

What are the Cepheids?

- A: Pulsating stars (periods of ~ few days)



Cepheid variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**.
RR-Lyrae variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.

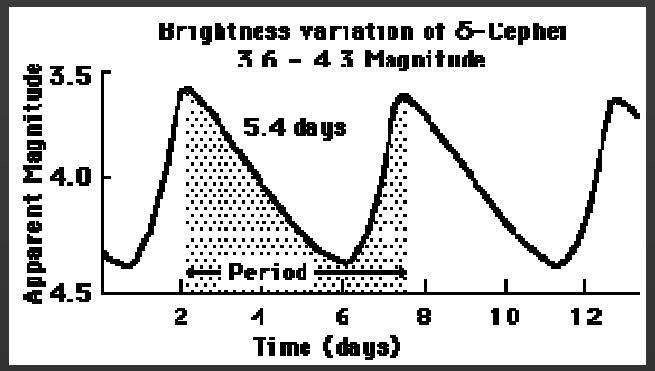
Cepheids as Standard Candles

Standard Candle

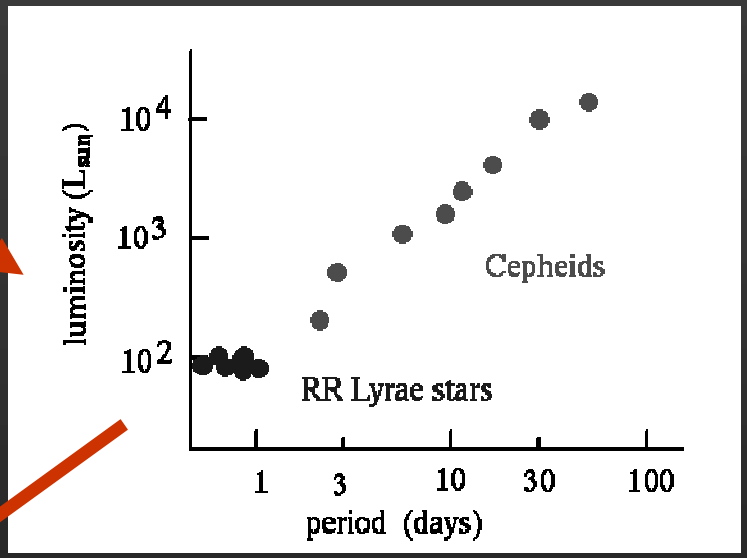
As a car approaches on a highway, its lights appear to get brighter. However, the amount of light or energy produced by the lights is constant. The apparent brightness of the headlights is a function of how far away the car is. The closer the car, the brighter the headlights. Astronomical objects that produce specific amounts of energy can be used to determine the distance to that object if the apparent brightness is measured. These objects are known as Standard Candles.

Cepheids as Standard Candles

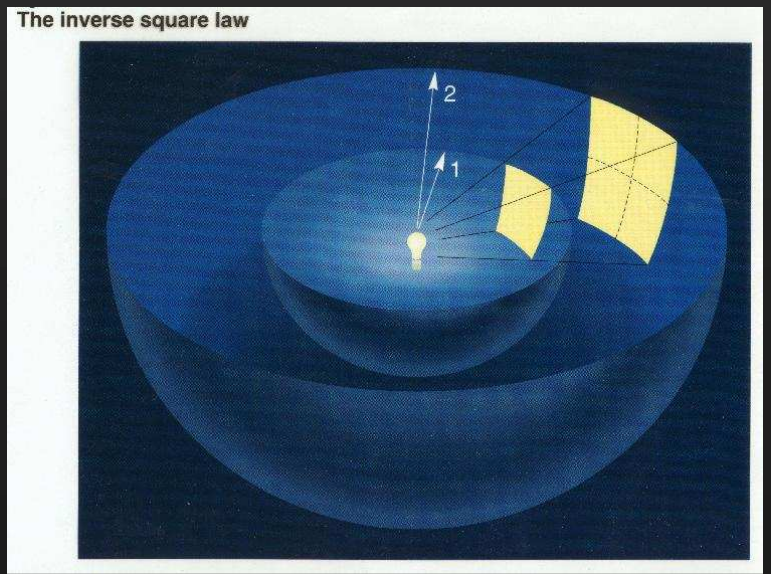
1) Measure Period



2) Calculate luminosity



3) Calculate distance



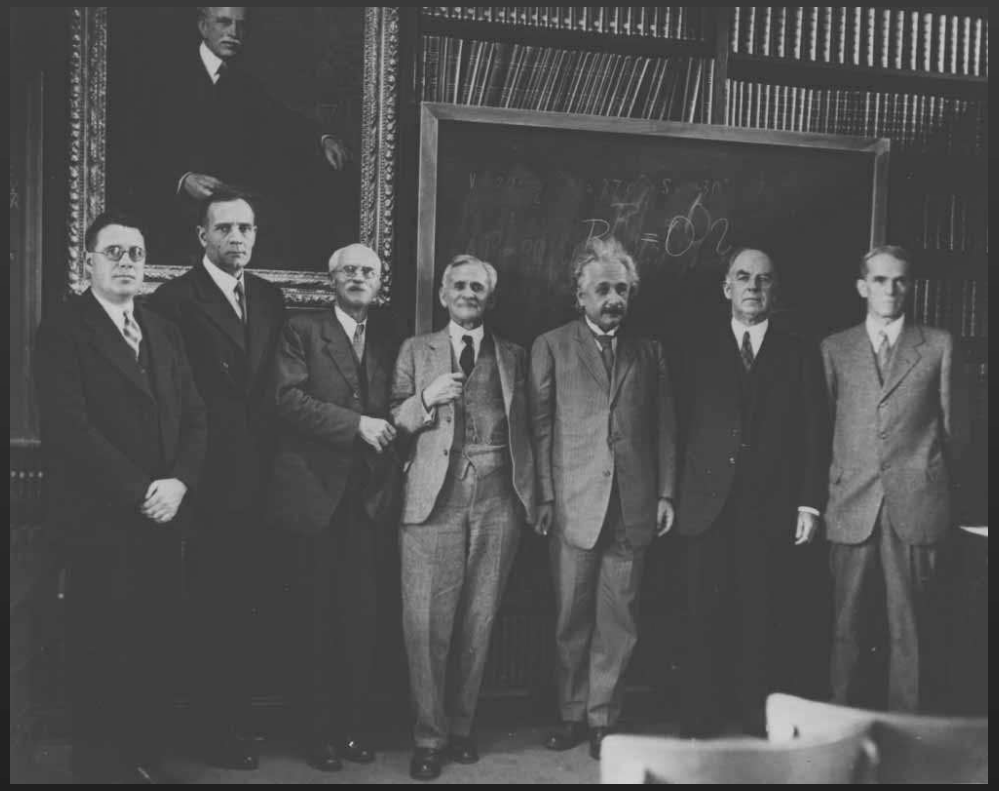
- inverse-square law:
  flux=luminosity/distance^2

measure

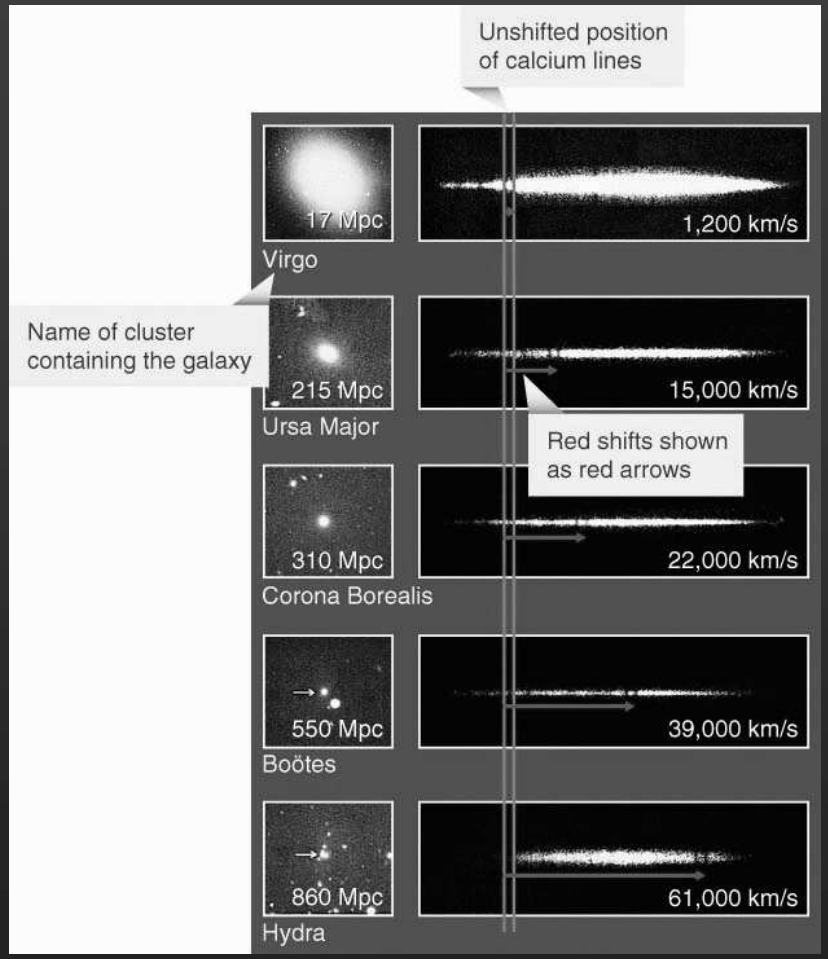
Hubble teams up with Humason

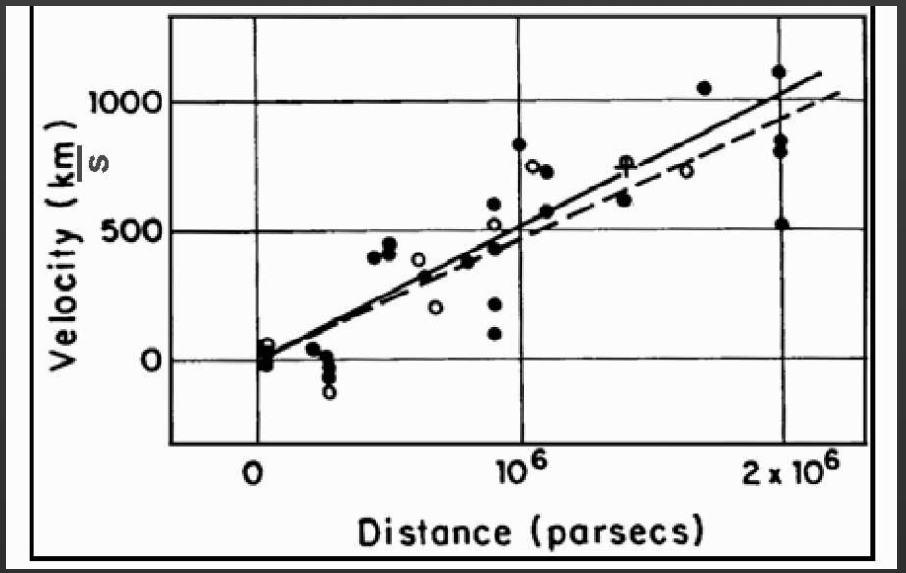
- Hubble and Humason become partners in nebular reserach

Milton L. Humason
(1891-1972)



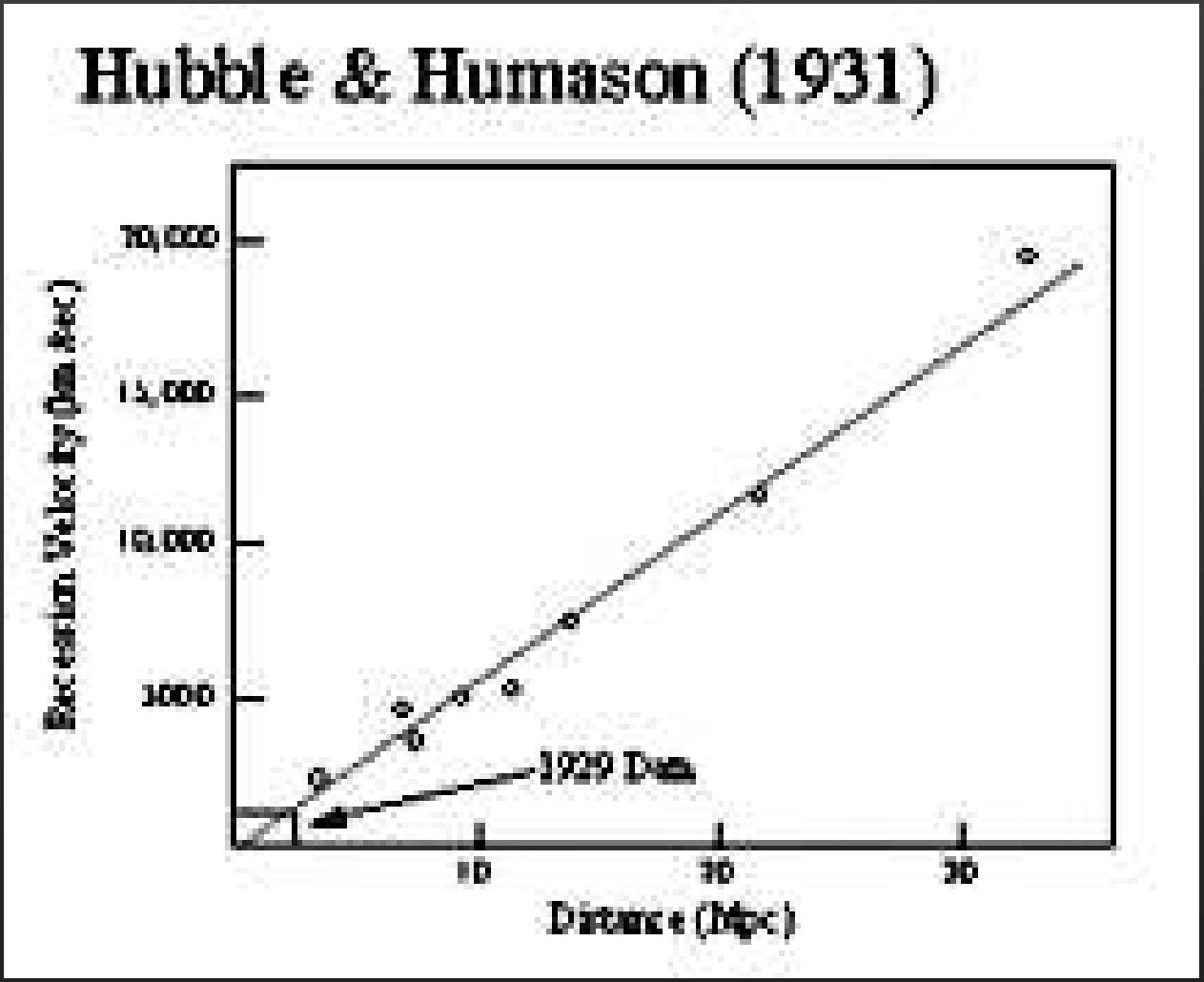
Discovery of the Hubble Law (1929)





- Great Discovery: Redshift is proportional to distance ("Hubble Law")

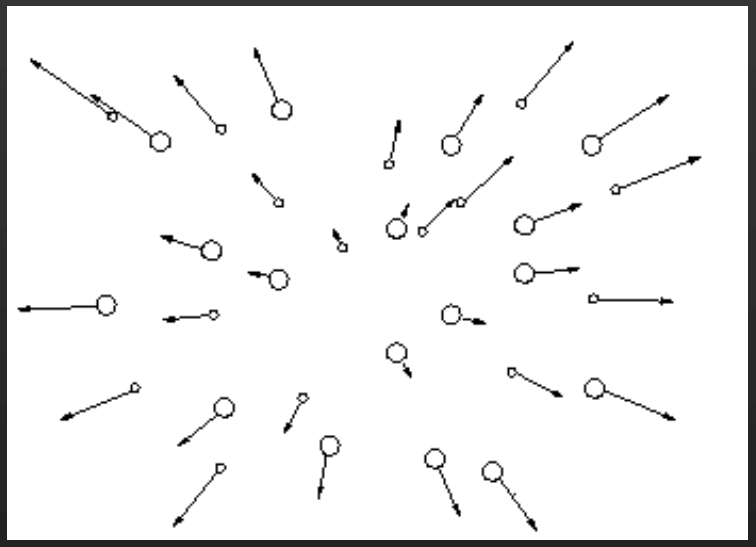
Discovery of the Hubble Law



- greatly improve accuracy by reaching larger distances!

Meaning of the Hubble Law

- recession speed = (Hubble) constant x distance
- $v = H_0 \times d$
- (H_0=500 km s^{-1} Mpc^{-1})

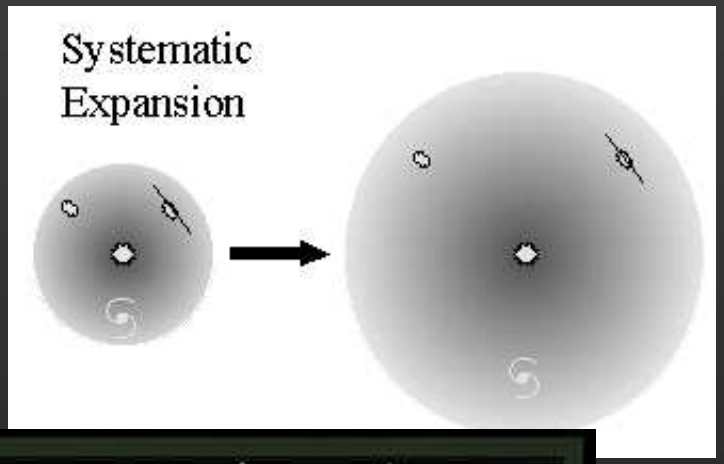


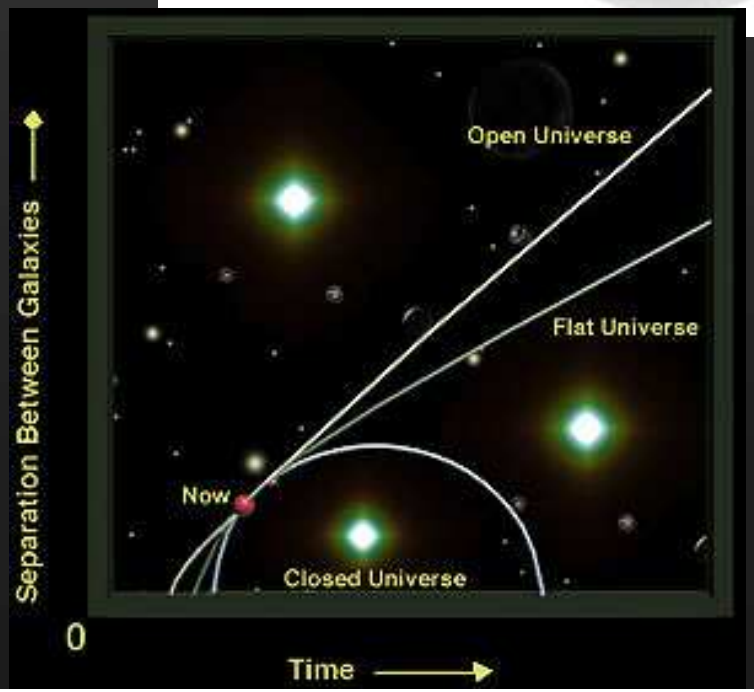
- Hubble initially did not interpret his law as implying an expanding universe! (He only referred to “de Sitter effect”)

Solving Einstein's Equations of GR

- 1922: an expanding universe (GR without cosmological constant)

Alexander Friedmann
(1888-1925)

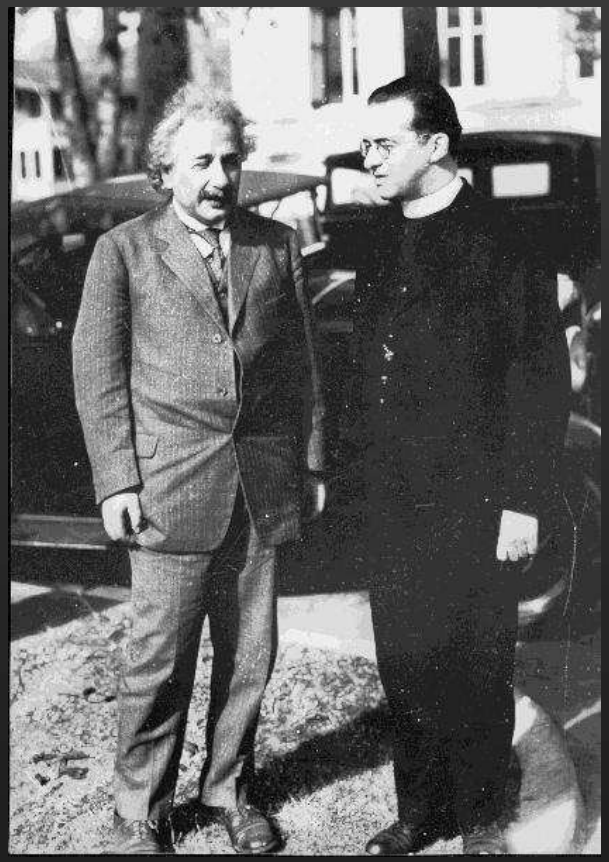




Solving Einstein's Equations of GR

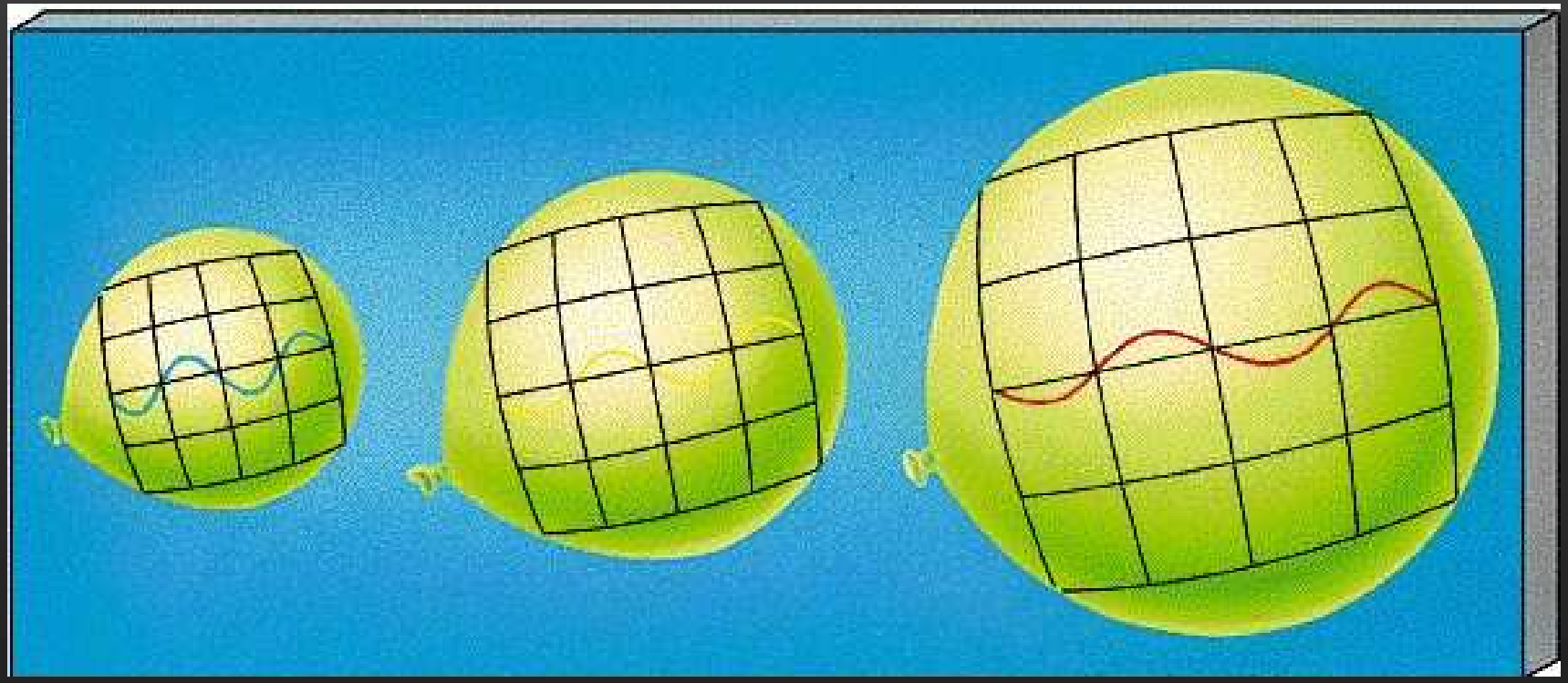
- 1927: Lemaitre independently (re-) discovers the expanding-universe solutions of GR

Georges Lemaitre (1894-1966)



The Expanding Universe (early 1930s)

- Lemaitre interprets Hubble's Law as indicating that space itself expands!



- redshifts due to stretching of expanding space!

The Expanding Universe (early 1930s)

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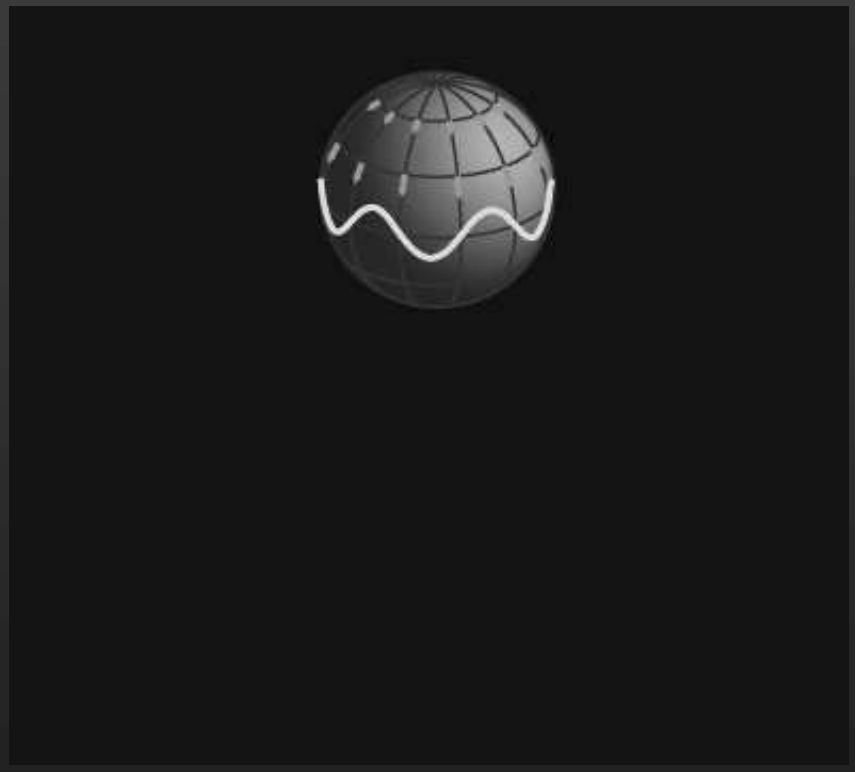
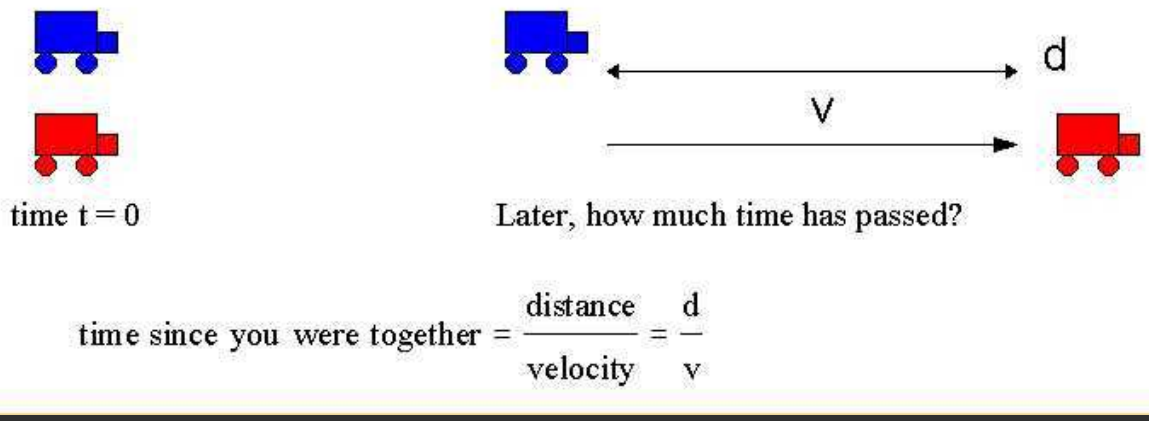


- redshifts due to stretching of expanding space!

The Age of the Expanding Universe

- Estimate expansion age of the universe:

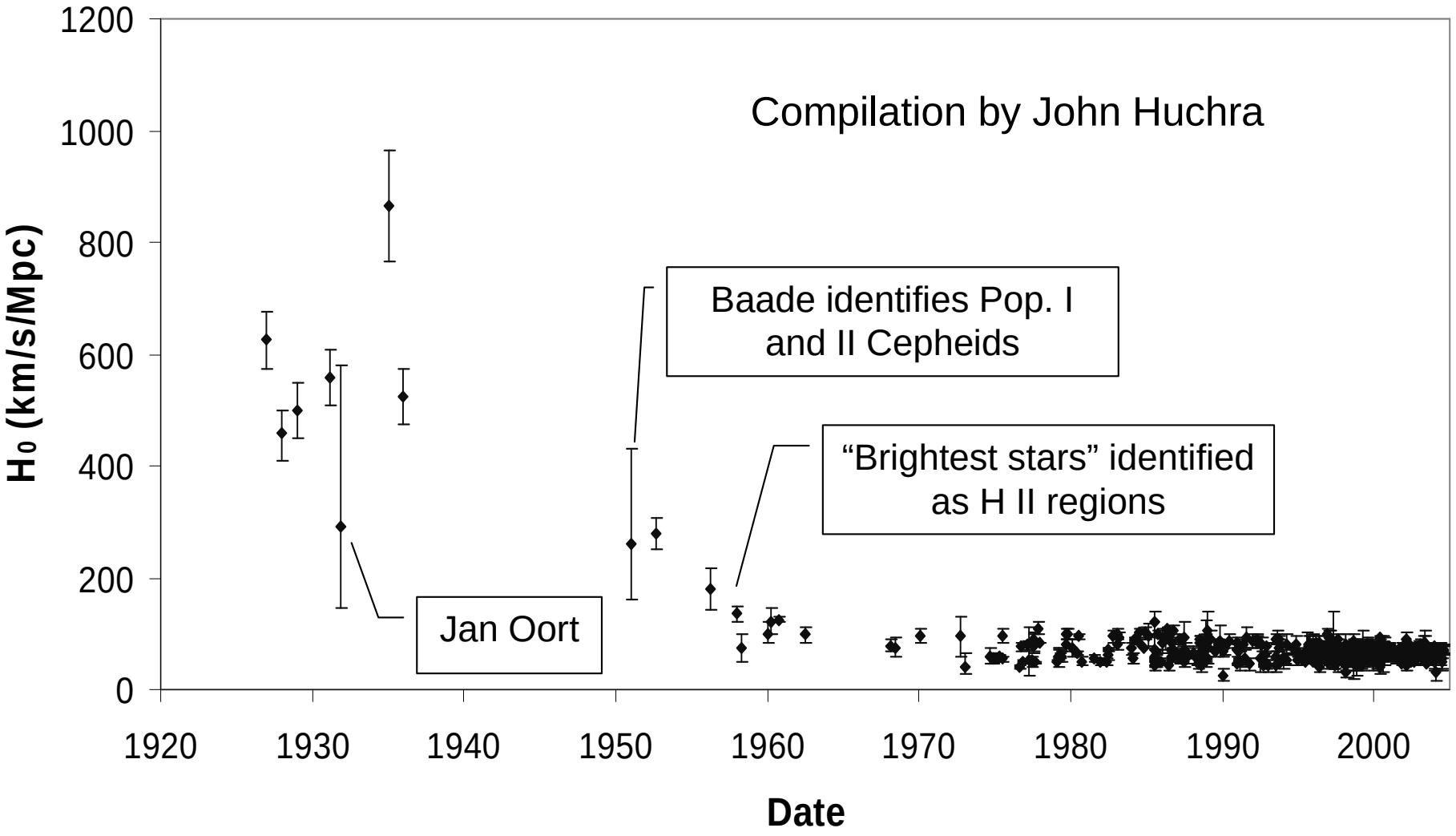


$$\text{time since you were together} = \frac{\text{distance}}{\text{velocity}} = \frac{d}{v}$$

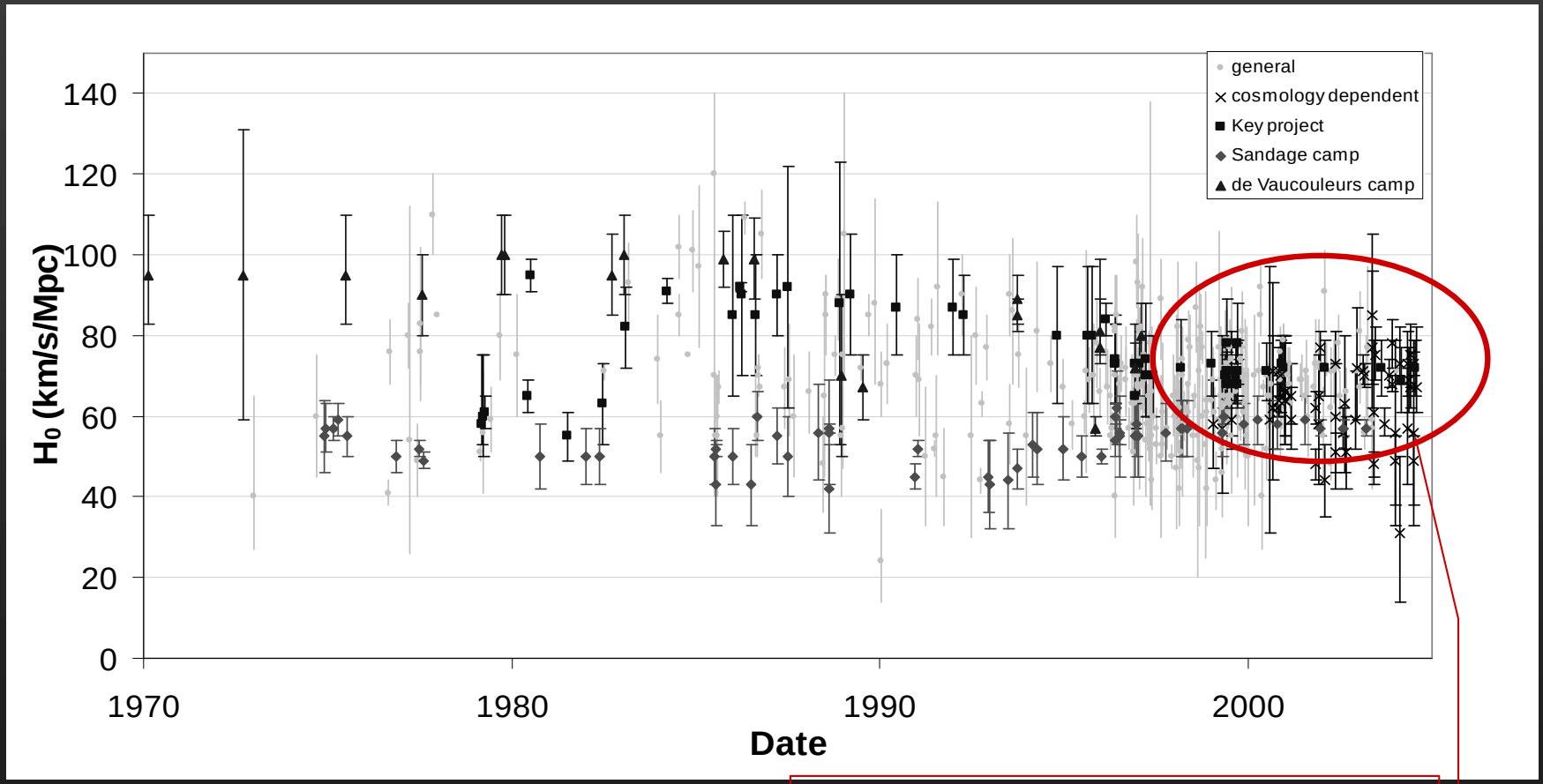
$$\text{time} = \frac{\text{distance to a given galaxy}}{\text{its velocity of recession}} = \text{age of the universe}$$

$$\text{age of the universe} = \frac{1}{H_0}$$

History of H_0

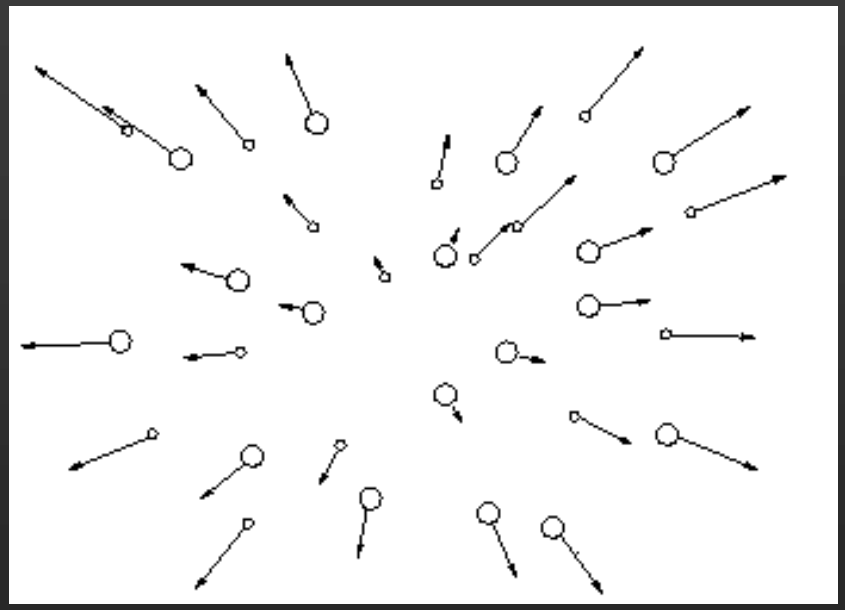


Hubble Wars



reasonable convergence only in last decade – see later

Big Q: What happened in the past, when all the galaxies where close together???



- an initial “Big Bang”???

Hubble (part 2)

- Discovery of Recession of Spiral Nebulae (1929-31)
  - already known: most spirals show redshifts in their spectra
  - Hubble and Humason use Cepheids and other standard candles to determine distances to spiral nebulae
  - "Hubble's Law": $v = H_0 \times d$
  - Initial estimate of "Hubble's constant": $H_0 = 500$ km s^{-1} Mpc^{-1}

- Interpretation of Hubble's Law (1930s)
  - Lemaitre (rediscovering Friedmann's work) proposes solutions to Einstein's General Relativity for an expanding universe!
  - Naturally explains "Hubble's Law" ($v = H_0 \times d$) with expansion of space itself!