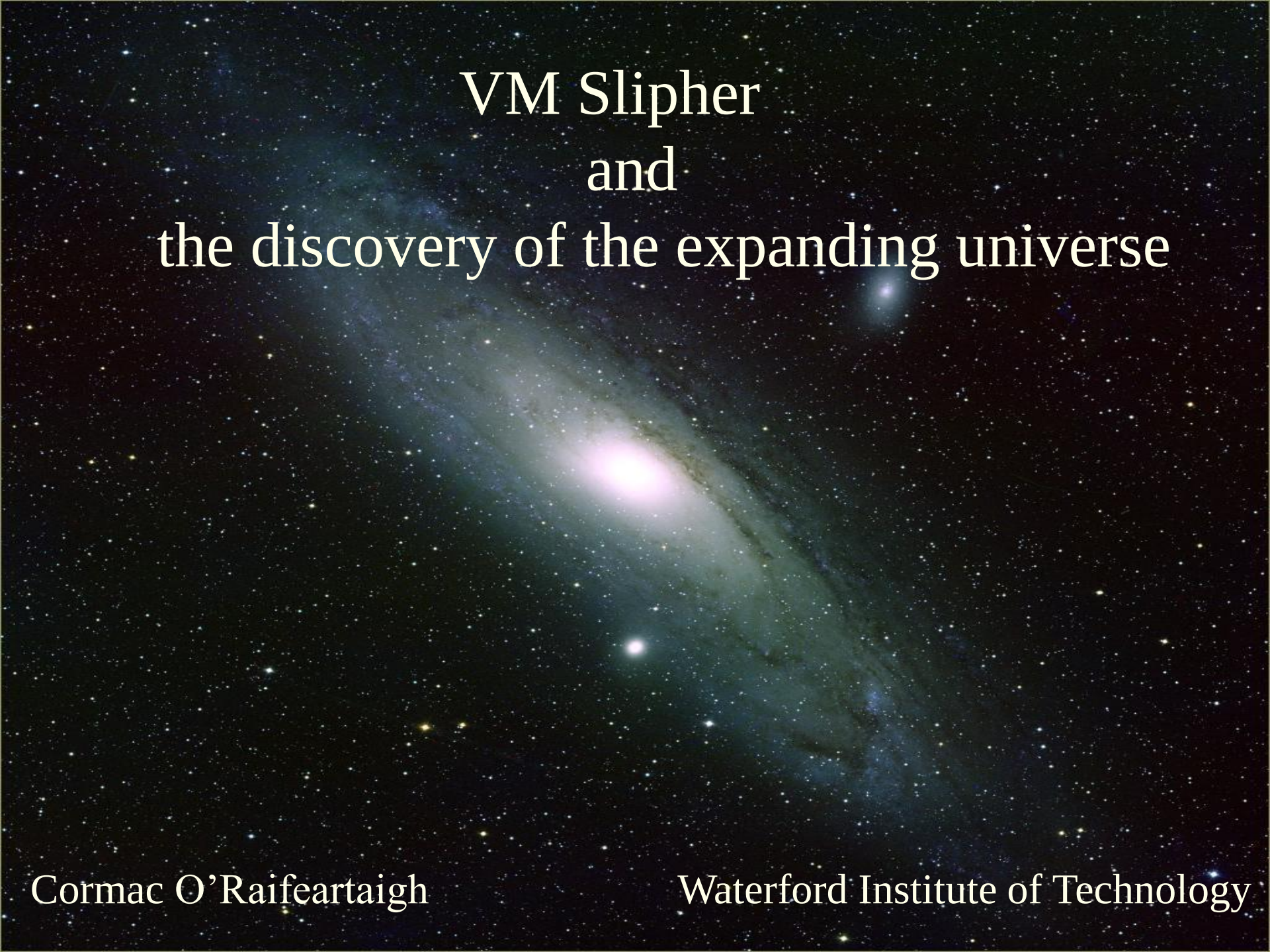


VM Slipher and the discovery of the expanding universe

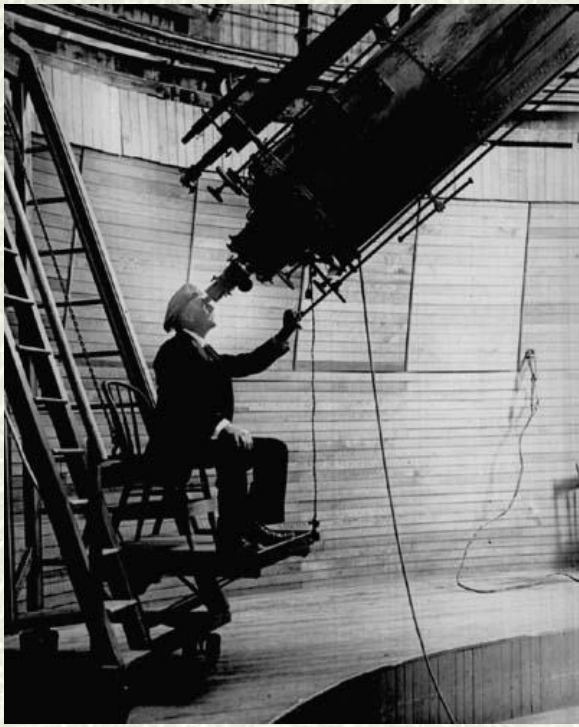
Cormac O'Raifeartaigh

Waterford Institute of Technology

Overview

Vesto Slipher 1875-1969

- **A brief history of experiment (1912-1931)**
  - *The redshifts of the nebulae (Slipher)*
  - *The distances to the nebulae (Hubble)*
  - *The Hubble-Slipher graph*
- **A brief history of theory (1915-1931)**
  - *The static universes of Einstein and de Sitter*
  - *The dynamic universes of Friedman and Lemaitre*
- **The expanding universe (1931)**
- **On the naming of laws and equations**



I The nebulae

- Observed by Marius (1614), Halley, Messier

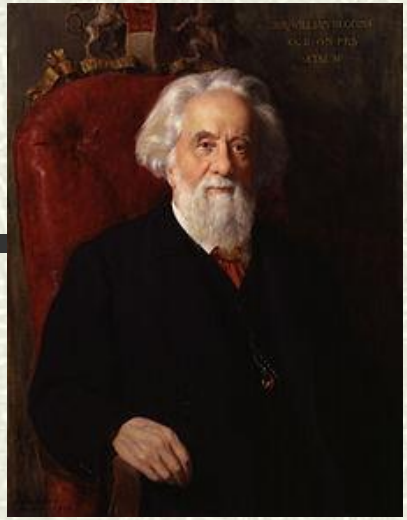
- ‘Island universes’: Kant, Laplace (1755-96)
  Collections of stars at immense distance?
  Are stars born in the nebulae?

- Wilhem Herschel
  36-inch reflecting telescope
  Catalogue of a thousand (1786)

- Earl of Rosse
- 72-inch reflecting telescope (1845)
- Some nebulae have spiral structure, stars

Problem of resolution, distance

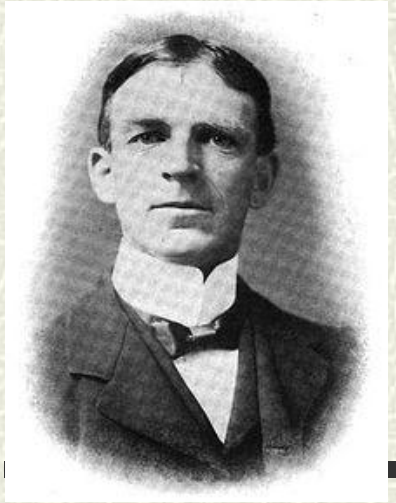
The spectra of the nebulae



Sir **William Huggins** (1824 – 1910)

- Photography and spectroscopy (19th cent)
  Emission and absorption lines of celestial objects
- Composition of the stars and planetary nebulae
  William Huggins
- Radial motion of the stars
  Doppler effect
  William Campbell
- Spectroscopy of spiral nebulae?
  Information on evolution of solar system
- Difficult to resolve

William Campbell (1862 – 1938)



The Lowell observatory

- Founded by Percival Lowell (1894)
  Eccentric astronomer
- 24-inch refracting telescope
  Flagstaff, Arizona
- Controversial
  Canals on Mars
- Employed VM Slipher (1901)
  Brashear spectrograph
- Spectroscopy of planetary atmospheres

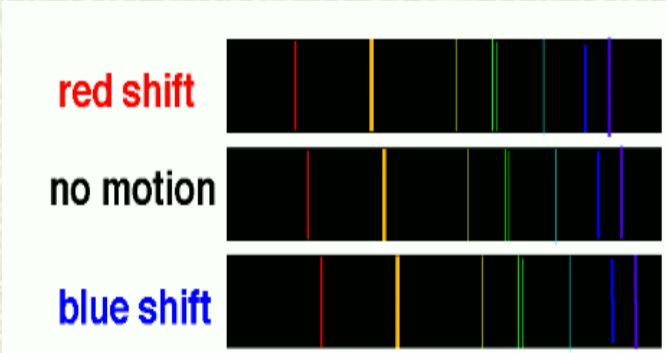
Percival Lowell (1855 – 1916)

Spectra of the spiral nebulae

- **Analyse light of the spiral nebulae? (1909)**
  Evolving solar system? Lowell
- **Slipher reluctant**
  Larger telescopes failed
- **Experiments with spectrograph camera**
  Good results with fast camera lens
- **Clear spectrum for Andromeda nebula (1912)**
  Significantly blue-shifted
  Approaching at 300 km/s
- **Many spiral nebulae red-shifted (1917)**

Vesto Slipher

$\Delta\lambda/\lambda = v/c$



Redshifts of the spiral nebulae

- **Spectra of 25 spirals (1917)**
  Large outward velocities
  Some receding at 1000 km/s
- **Much faster than stars**
  Gravitationally bound by MW?
- **Island universe debate**

"Island universe hypothesis gains favour"

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

The great debate revisited (1920)

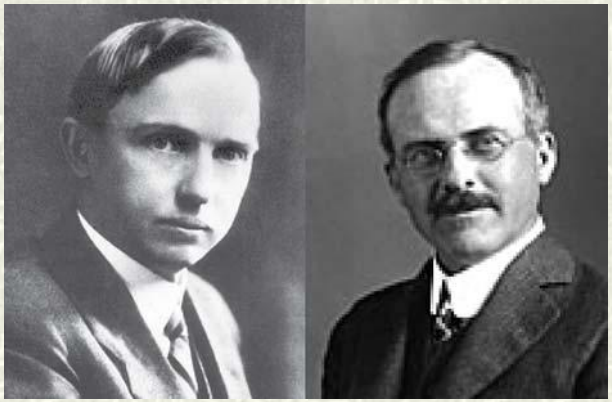
Distinct galaxies

- Stellar structure of spiral nebulae
- Redshifts – not gravitationally bound?
- Many faint novae – great distance?

OR

- Big galaxy model (*300,000 Lyr)*
- Rotation data *(Van Maanen)*
- Andromeda nova/supernova

Harlow Shapley vs Heber Curtis



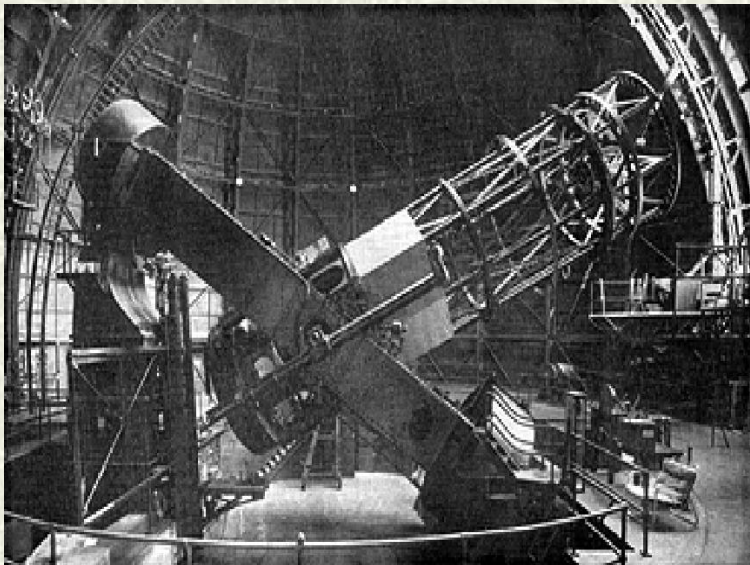
A clear resolution (1925)

- Hooker telescope (Mt Wilson, 1917)
- 100-inch reflector

- Edwin Hubble (1921)
- Ambitious astronomer

Edwin Hubble (1889-1953)

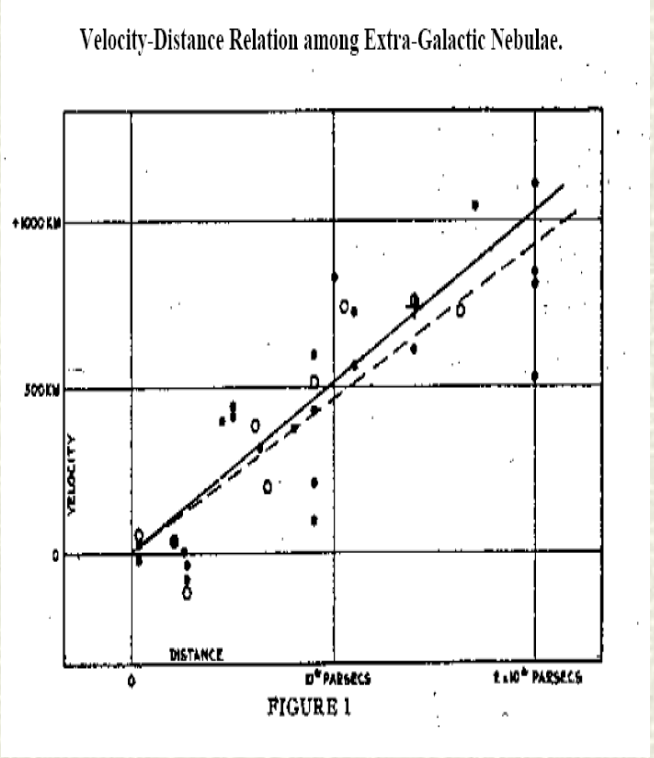
- Resolved Cepheid stars in nebulae
- Leavitt's period-luminosity relation
- Spirals beyond Milky Way! (1925)



A velocity/distance relation

- What do the redshifts of the galaxies mean?
- Is there a relation between ***v*** and ***r*** ?
- Combine redshifts with 24 distances
- Approx linear relation (Hubble, 1929)

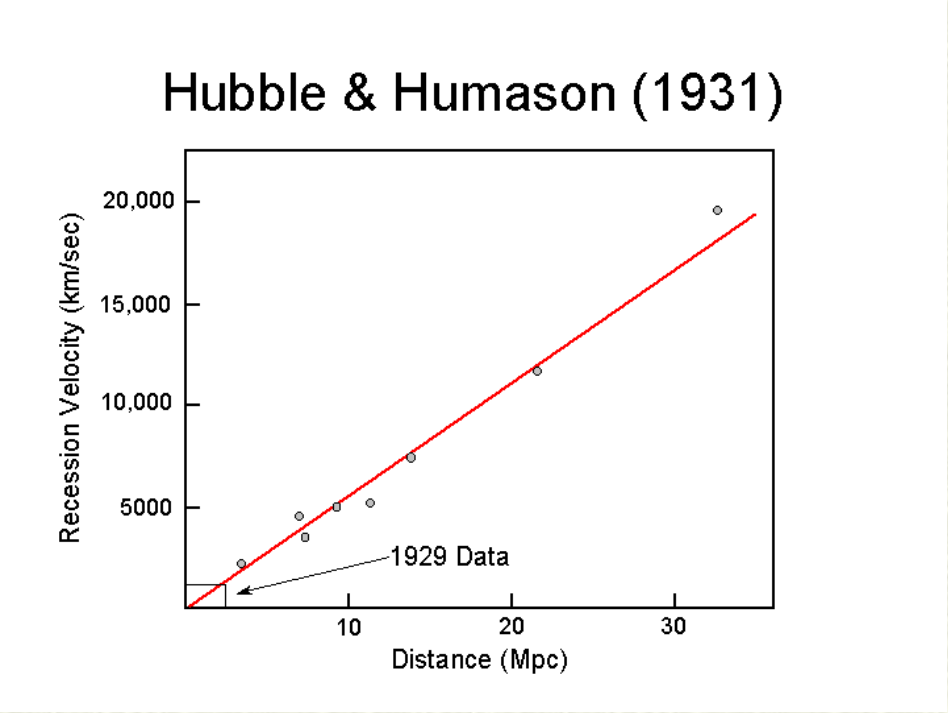
Slipher data not acknowledged
Becomes known as Hubble's law



m = 585 km/s/Mpc

Hubble-Humason graph (1931)

- Distance measurements for 40 nebulae/galaxies
- Corresponding redshifts by Humason
- Reduced scatter - linear
- Justification
- Explanation?



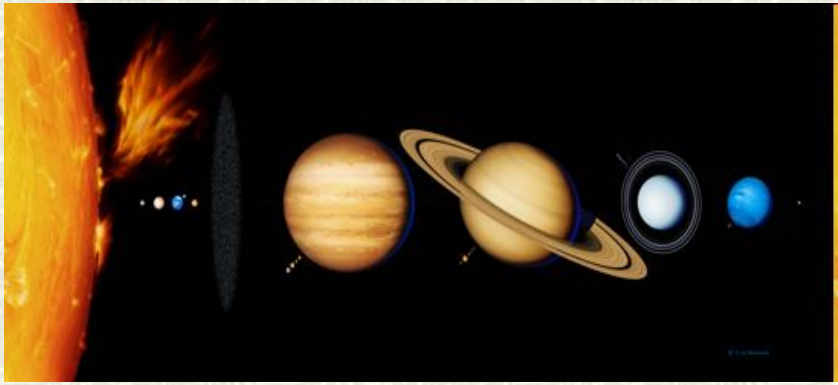
Hubble did not discover the expanding universe

II The expanding universe

Isaac Newton

- What do the redshifts represent?
- Recession velocities for distant galaxies?
- If so, why?
- Newtonian gravity pulls in
- What is pushing out?

Space, time fixed



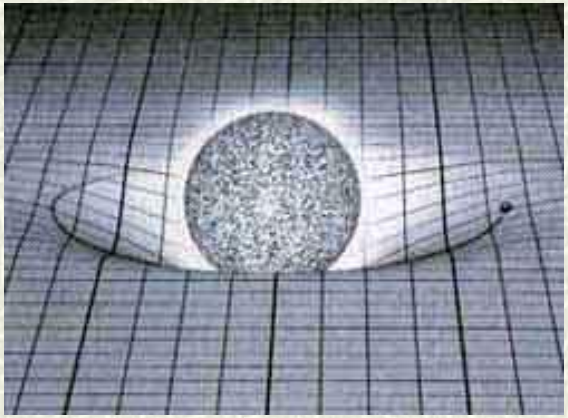
General relativity (1915)

- Space+time = space-time
- Space-time dynamic
- Distorted by motion, mass
- Causes other mass to move

Gravity = curvature of space-time

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Eddington experiment (1919)

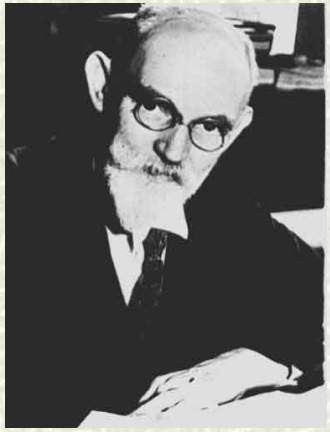


Two models of the cosmos

Einstein (1917)

- Assume uniform density of matter
- Equations predict dynamic universe
- No evidence for such a universe
- Add cosmic constant – ‘static’
- Closed curvature, finite radius

$$G_{\mu\nu} + \lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



De Sitter (1918)

- Assume empty universe
- Apparently static (co-ordinate system)
- Redshifts due to time dilation/matter

Explanation for redshifts of the galaxies?

De Sitter effect and astronomy

- **Silberstein** (1923)

  $\Delta\lambda/\lambda = +/- r/R$ (global clusters)

- **Carl von Wirtz** (1924)

  Redshifts for nebulae different to clusters

  Time dilation effect?

- **Lundmark** (1924)

  'The determination of the curvature of spacetime in de Sitter's world' Stars and globular clusters

- **Stromberg** (1925)

  Vel/dist relation for globular clusters?

Friedman universes

Alexander Friedman 1888 -1925

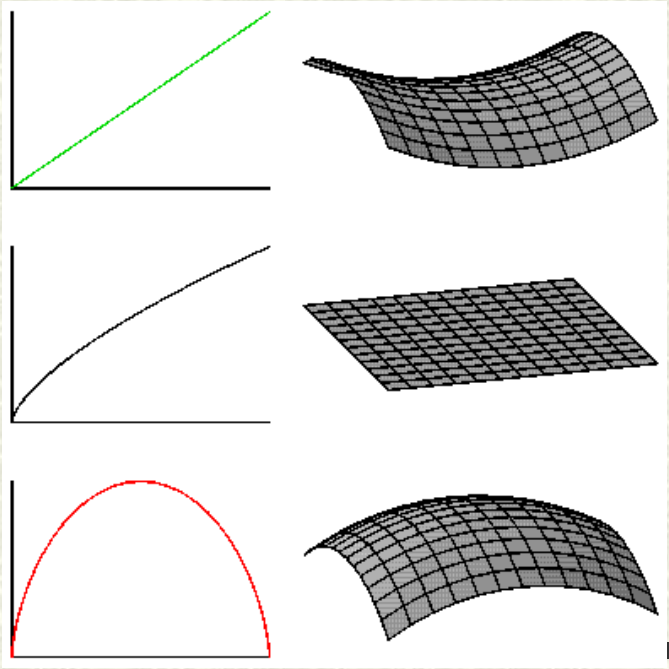
- General solutions (1922, 24)
- Time-varying radius
- Expanding or contracting

- Positive or negative curvature
- Depends on matter $\Omega = d/d_c$

Hypothetical models (ZfPh)

All possible universes (to be decided by astronomy)

Disliked by Einstein ('suspicious')



Lemaitre's expanding universe

- De Sitter model is not static (1925)
- New solution combining best of *E* and *deS*
- Matter-filled universe of increasing radius (1927)

Fr Georges Lemaitre

- Connection with astronomy
- Redshifts = expansion of space-time metric?
- Rate of expansion from average measurements of distance and redshift *H = 585 km/s/Mpc*

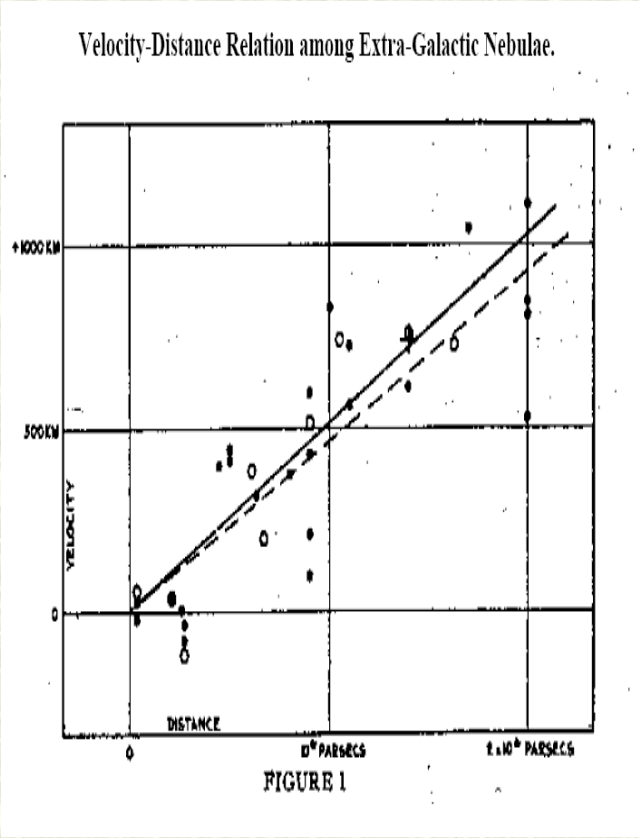
Obscure journal

Rejected by Einstein

Weyl (1925)
Lanczos (1923)
Robertson (1928)

III The expanding universe (1931)

- Hubble-Slipher graph (1929)
- Einstein, de Sitter models don't fit
- Lemaitre reminds Eddington of his paper
- Paper translated (MNAS, 1931)



- Satisfactory explanation
- Space is expanding (relativists)
- Astronomers sceptical (Hubble)

Expansion of space

Who discovered the expanding universe?

- Friedman *Evolving universe*
- Lemaitre *Expanding U and experiment*
- Hubble/Slipher *Empirical evidence*

All of them!

FLRW metric, but nothing for Slipher

‘Hubble graph’ should be Hubble-Slipher graph

‘Hubble expansion ‘should be Hubble-Lemaitre expansion

P.S. On paradigm shifts

Slow emergence of theory and evidence

- Experiment: Rosse, Huggins, Leavitt, Shapely , Slipher, Hubble
- Theory: Einstein, de Sitter, Weyl, Lanzcos, Friedman, Lemaitre, Robertson, Walker

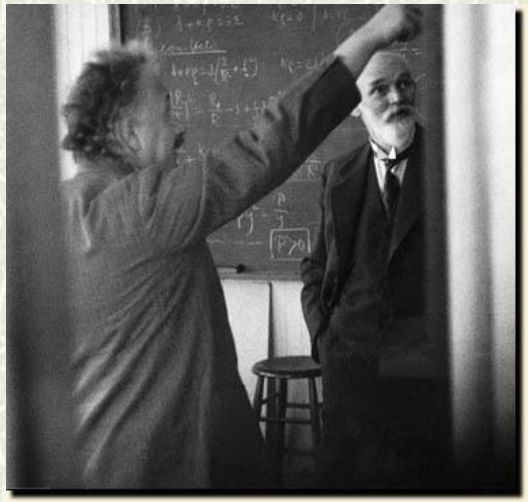
Slow acceptance by community

- Many astronomers doubt relativistic universe
- No upsurge of interest in cosmology until 1965

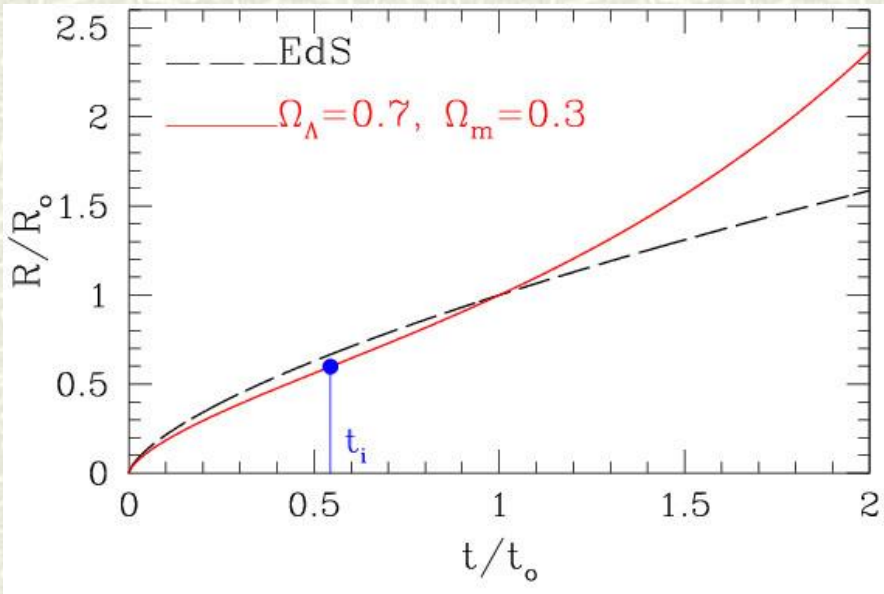
Thomas Kuhn

Slow dawning, not incommensurate paradigm shift

Einstein-deSitter universe (1932)

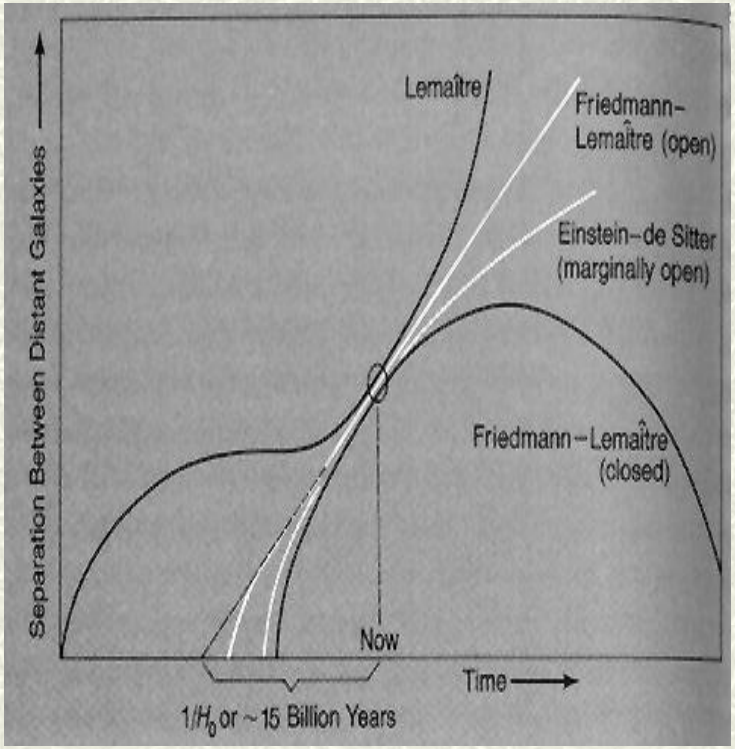


- Einstein rejects static universe (1931)
- Removes cosmic constant (Λ=0)
- U of Flat geometry
- Critical mass density
- Standard model ***(age problem)***



Lemaitre's universe (1934)

- Positive cosmic constant
- Accelerated expansion
- Expansion from radioactive decay
- Stagnation period



No age problem

Λ = Energy of vacuum

$p = -\rho_0 c^2$, $\rho_0 = \lambda c^2/8\pi G$

Cyclic universe?