Who discovered the expanding universe?

An open-bus tour

Cormac O'Raifeartaigh

Waterford Institute of Technology

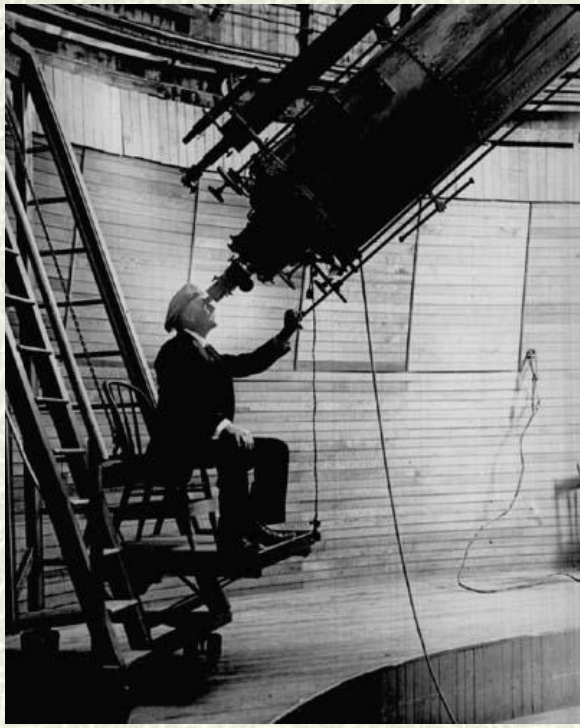
Three major discoveries

Vesto Slipher 1875-1969

- The galaxies (-1925)
  Redshifts and the great debate

- The expanding universe (1930, 31)
  Redshifts and Lemaitre's relativity

- An origin for the universe (1931-)
  Redshifts and the big bang



On the nature of discovery

- Hypothesis, observation and discovery
  (Copernicus, Kepler, de Brahe, Newton)
- Theory vs experiment
- Discovery vs justification
- Retrospective view/credit in science
- Re-discovery
- The importance of scientific context

The unimportance of social context

Francis Bacon

Kuhn, Feyerabend, Latour

I The puzzle of 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)
- <u>Some</u> nebulae have spiral structure, stars

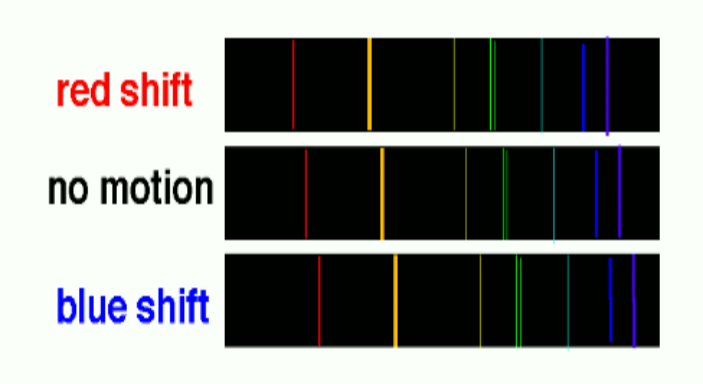
Problem of resolution, distance

1912: Doppler shifts of the spiral nebulae

- Analyse light of the nebulae? Lowell/Slipher
- Camera speed, exposure time, not telescope size
- Andromeda nebula blue-shifted (1912)
  Interpret as radial velocity $\Delta\lambda/\lambda = v/c$
  Approaching at 300 km/s
- Many spiral nebulae red-shifted (1915,17)
  Some receding at 1000 km/s

Much faster than stars
Outside Milky Way?

Vesto Slipher

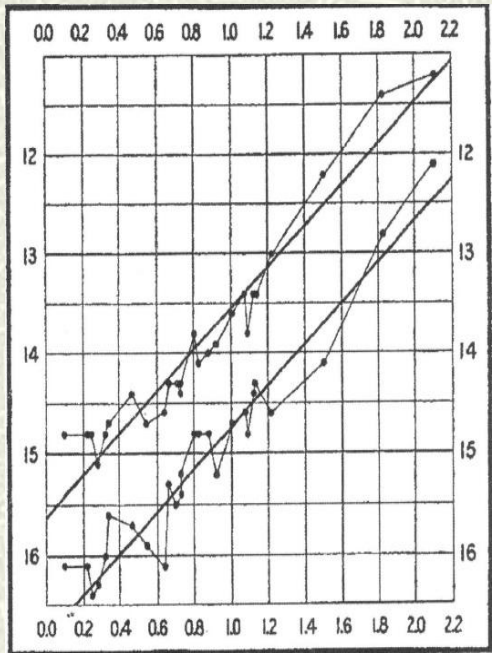


1912: The distance to the stars

Henrietta Leavitt

- Henrietta Swan Leavitt (1908, 12)
- Period-luminosity relationship for Cepheids
- Measure intrinsic luminosity from period
- Calculate distance
- **Standard candles**

Leavitt's law



The great debate revisited (1920)

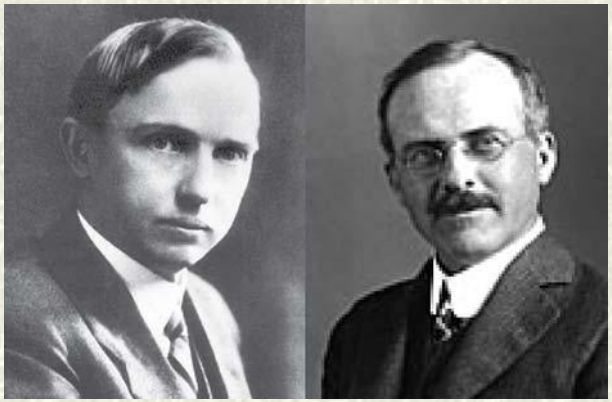
- Stellar structure of spiral nebulae
- Redshifts – not gravitationally bound?
- Many faint novae – great distance?

Distinct galaxies

OR

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

Harlow Shapley vs Heber Curtis



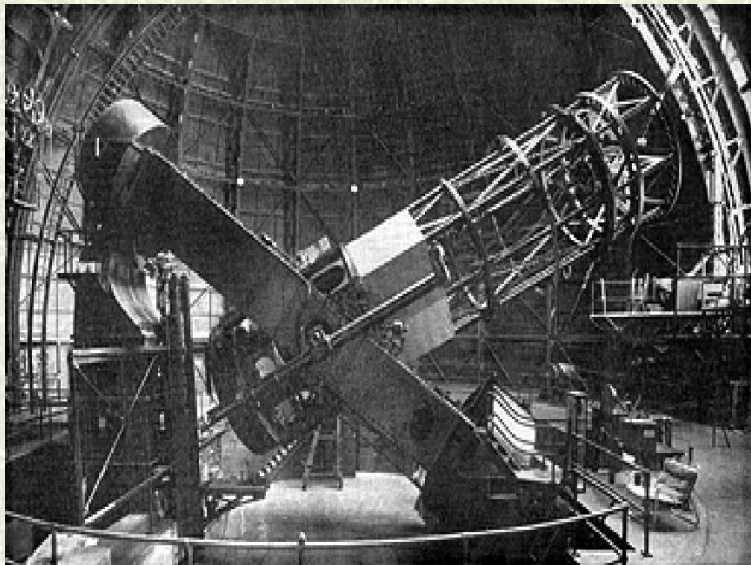
A clear resolution (1923-5)

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

- Edwin Hubble (1921)
- Ambitious astronomer

- Resolved Cepheid stars in nebulae
- Applied Leavitt's law
- Nebulae at huge distance! (1923-25)

Edwin Hubble (1889-1953)

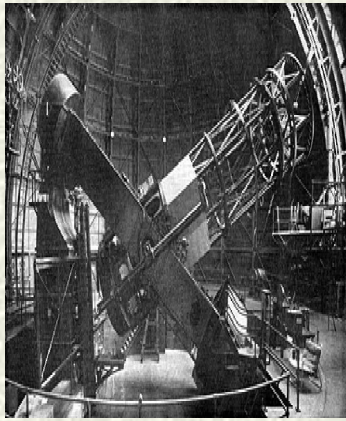


Discovery of the galaxies

- Spiral nebulae are distinct galaxies
- Verdict quickly accepted
- Universe very large
- Kuhnian paradigm shift? NO

Slow accumulation of evidence

What do galaxy redshifts represent?

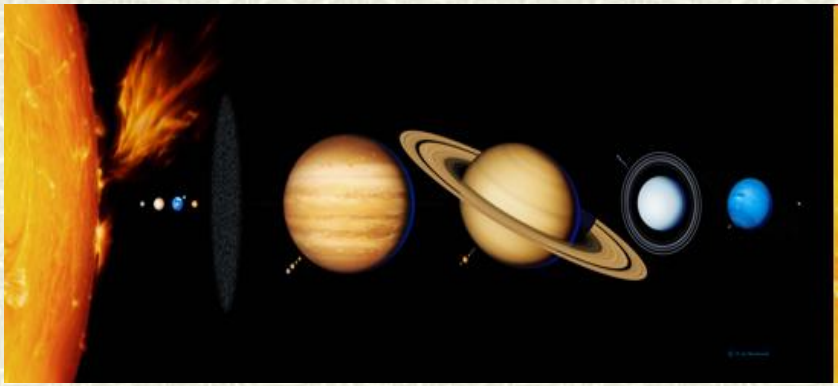


II The expanding universe

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

Space, time fixed

Isaac Newton

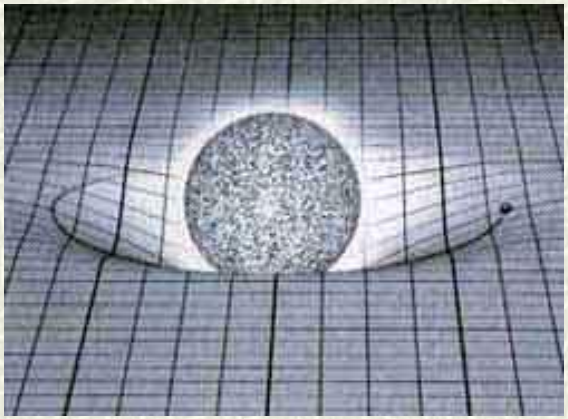


General relativity (1915)

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

Gravity = curvature of space-time

$$\boldsymbol{G}_{\mu\nu} = \frac{8\pi G}{c^4}\boldsymbol{T}_{\mu\nu}$$



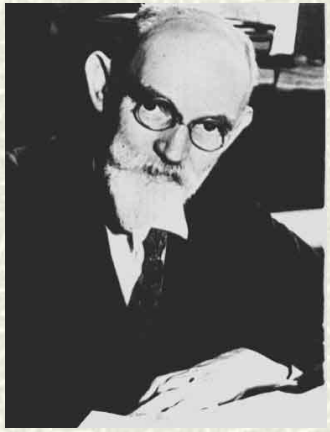
- Eddington experiment (1919)

Two models of the cosmos

Einstein (1917)

- Cosmological principle
- Dynamic universe (matter)
- No evidence for such a universe
- Add cosmic constant – 'static'
- Closed curvature, finite radius

$$\boldsymbol{G}_{\mu\nu} + \lambda g_{\mu\nu} = \frac{8\pi G}{c^4}\boldsymbol{T}_{\mu\nu}$$



De Sitter (1918)

- Empty universe
- Apparently static (co-ordinate system)
- <u>Redshifts</u> due to matter/time dilation

Explanation for redshifts of the galaxies?

De Sitter redshifts 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)

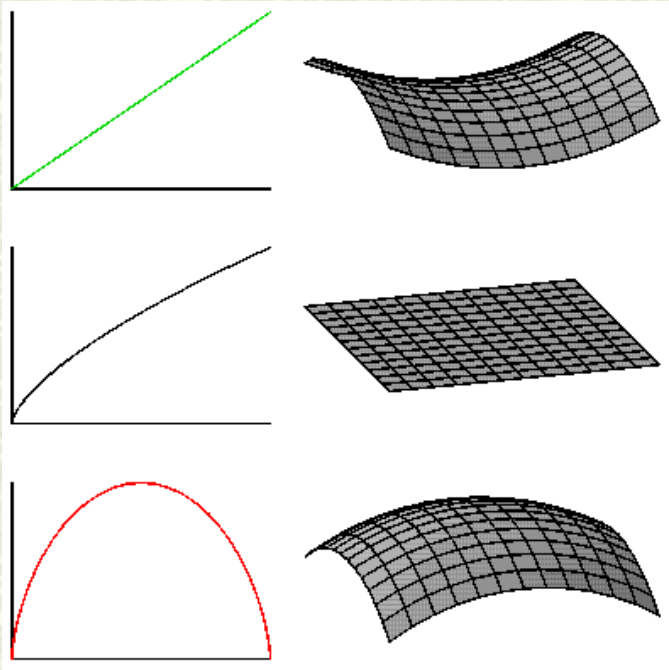
  Vel/dist relation for globular clusters?

Friedmann universes

Alexander Friedmann 1888 -1925

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

  Expansion of metric
- Three possible curvatures
- Depends on matter $\Omega = d/d_c$
- Periodic solutions



Hypothetical models (ZfPh)

All possible universes (to be decided by astronomy)

Disliked by Einstein ('suspicious')

Lemaitre's universe (1925,27)

- De Sitter model expanding
- New solution combining best of *E* and *deS*
- <u>Matter-filled universe of increasing radius (1927)</u>

- Connection with astronomy
- Predicts redshifts = expansion of <u>space</u>
- Rate of expansion from average measurements of distance and redshift *H = 585 km/s/Mpc*

Fr Georges Lemaitre

Obscure journal

Rejected by Einstein

Weyl (1925)
Robertson (1928)

Hubble and the redshifts (1929)

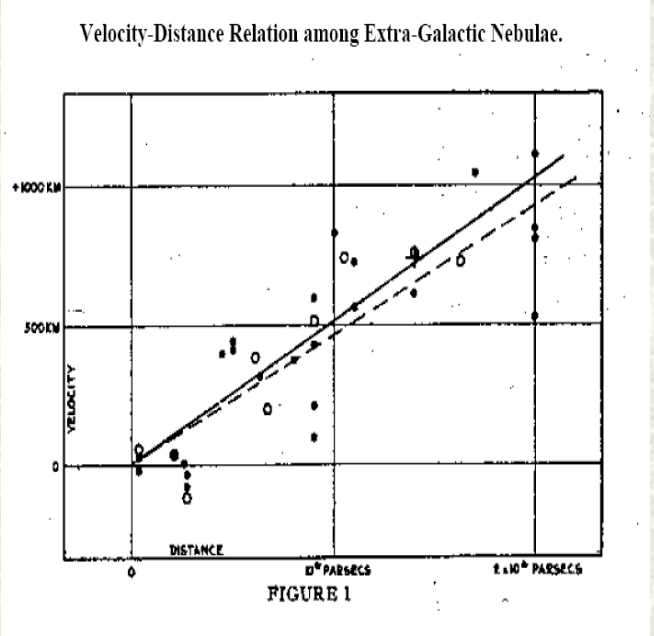
- Redshift/distance relation for the nebulae?
- Natural next step

  New distance measure?
- Combine distance measurements with

  Slipher redshifts (24 galaxies)

Not cited

- Approx linear relation (1929)
- Empirical relation

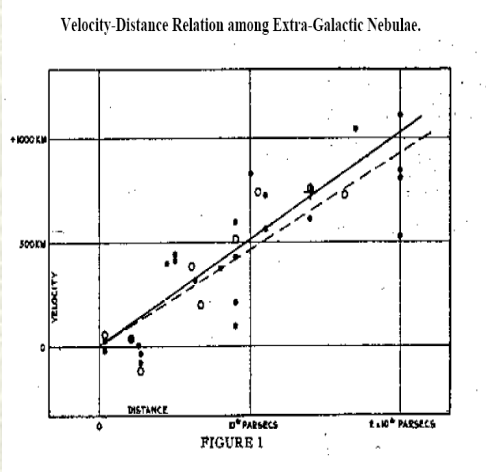


Rapid acceptance (except Shapely)

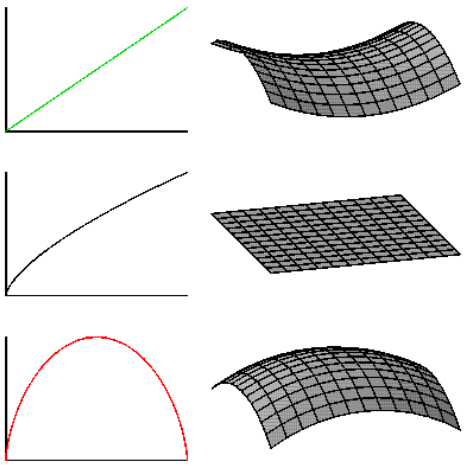
New model of the universe required (Eddington)

$$v = kr$$

The expanding universe (1930,31)



- Lemaitre's intervention
- Eddington, de Sitter convinced
- Translated theory (1931)

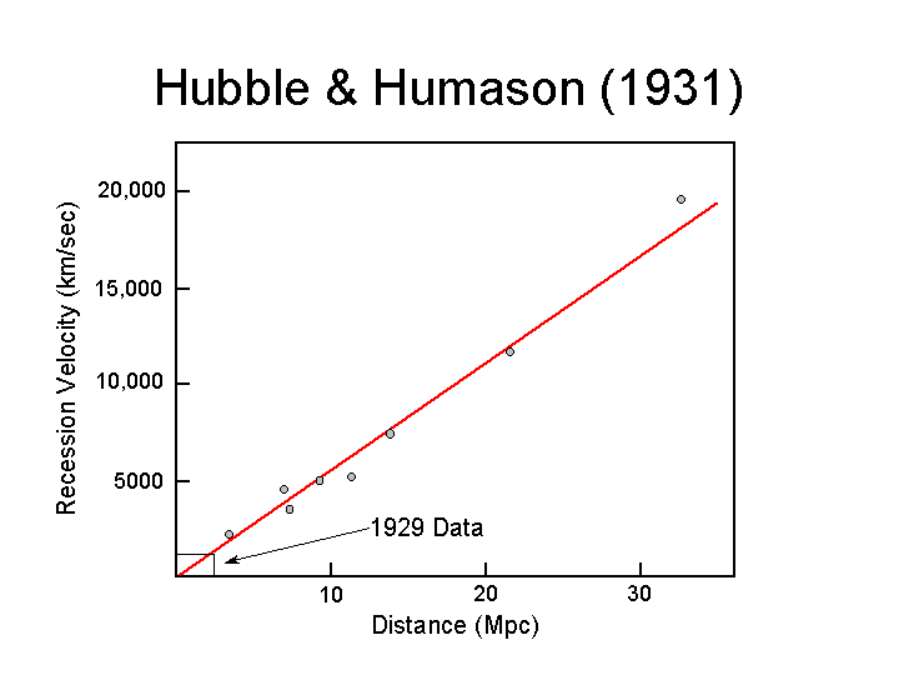


- Hubble graph + explanation
- Space is expanding (relativists)
- <u>Astronomers sceptical (Hubble)</u>

Keep measuring

Hubble-Humason graph (1931)

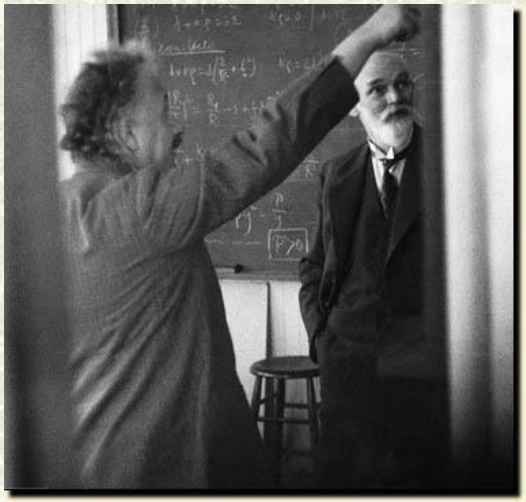
- Distance measurements for 40 nebulae/galaxies
- Corresponding redshifts by Humason
- Reduced scatter - <u>linear</u>
- Empirical relation



Leave theory to theorists

Justification

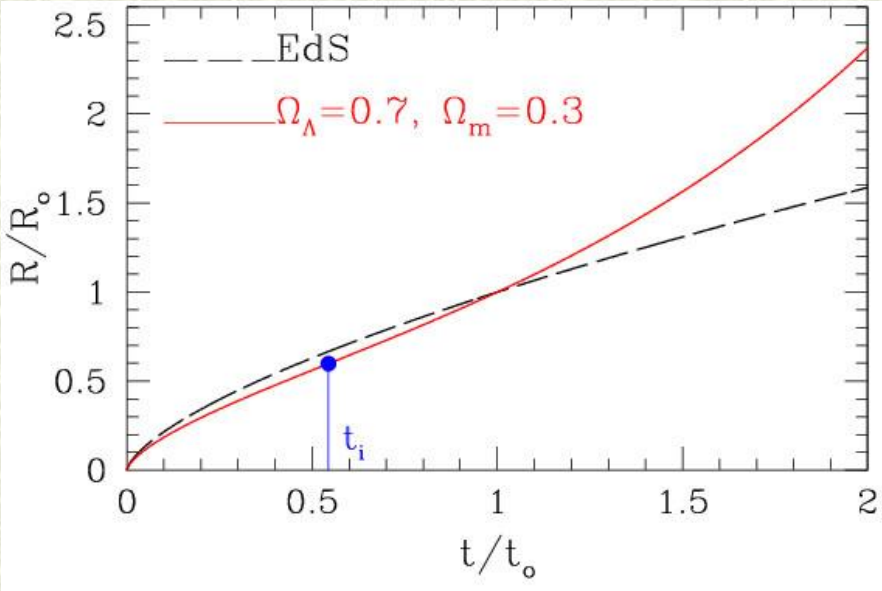
Einstein-deSitter universe (1932)



- Remove cosmic const (Λ=0)
- Flat geometry
- Critical mass density
- <u>Standard model</u>

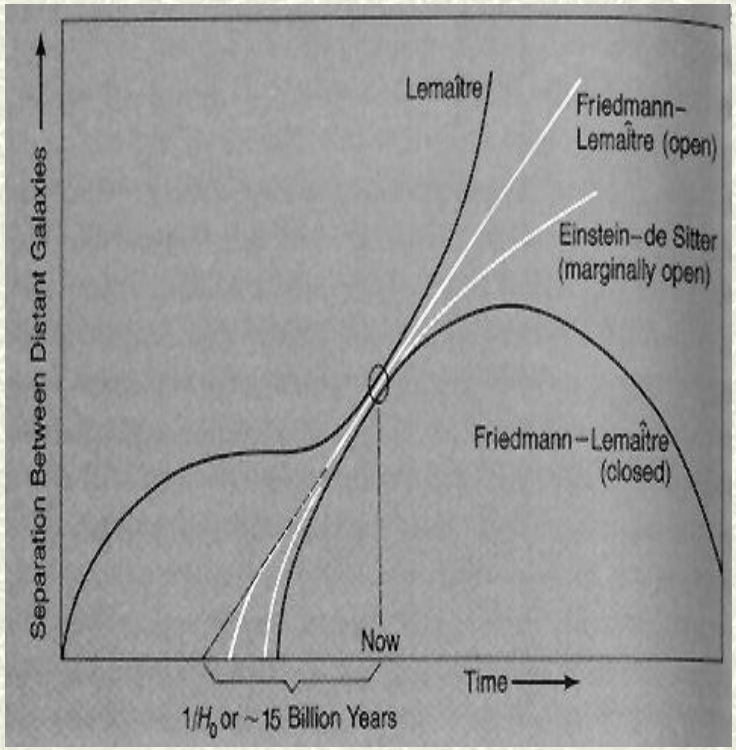
Problem of age

Problem of matter density



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?

Who discovered the expanding universe?

- Lemaitre *Theory and experiment*
- Friedmann *Time-varying solutions*
- Hubble/Slipher *Empirical law*

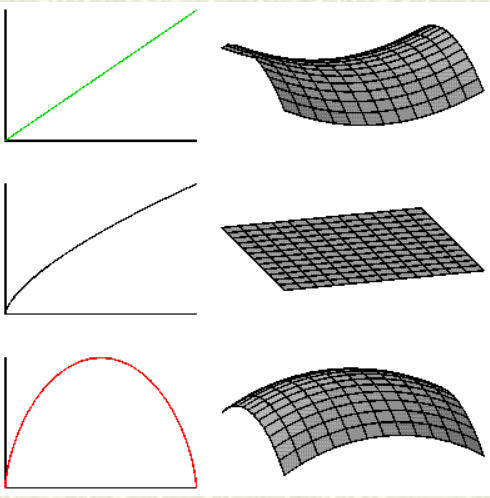
<u>FLRW metric, but nothing for Slipher</u>

Ross, Huggins, Leavitt, Shapely ,Einstein, deSitter,

Weyl, Lanzcos , Silberstein,Wirtz, Lundmark, Stromberg..

Slow accumulation of theory and evidence

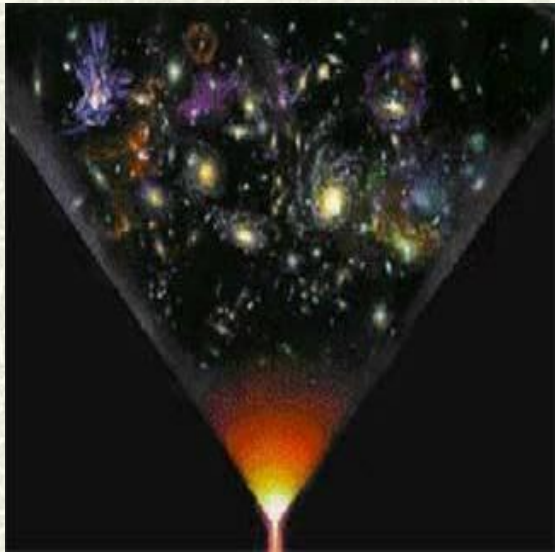
III An origin for the universe



- Expanding U implies beginning

  Lemaitre (1931)

The beginning of the world according to quantum theory



- Giant primeval atom?
- Decays to today's matter

Reception: not accepted

- Unpopular with astronomers

  (Not with a Bang!)
- Rarely cited by theorists

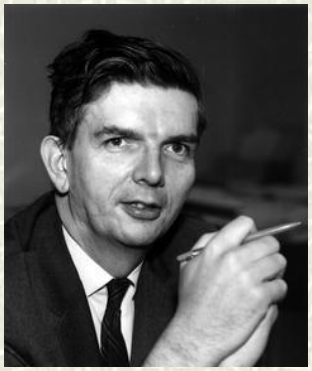
- Creation theory? (Einstein)
- Radioactive mechanism wrong
- Far ahead of its time

Nucleosynthesis, radio-galaxy counts, cosmic microwave background

Who discovered the big bang?

- Lemaitre (primeval atom)
- Gamov, Alpher and Herman (nucleosynthesis)
- Alpher and Herman (prediction of cmb)

- Penzias and Wilson (cmb)
- Dicke and Peebles (explanation)
- Martin Ryle (radio counts)

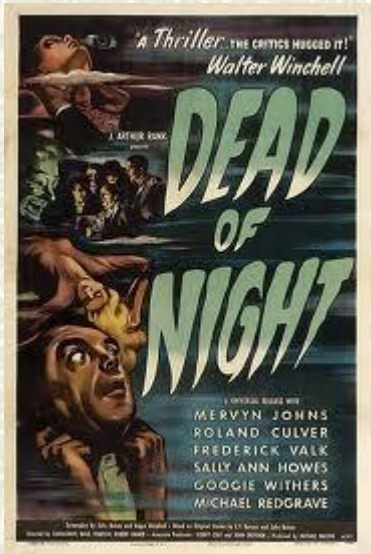


- COBE experiment
- WMAP experiment

Slow dawning, accumulation of theory and evidence

Steady-state model (1950s)

Fred Hoyle



- Rival model
- Expanding universe

BUT

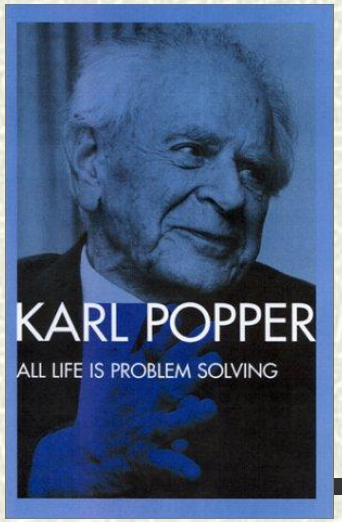
- Matter continuously created
- No beginning

Steady-State vs Big Bang

- *U* unchanging, eternal ?
- Density of matter constant ?
- Continuous creation?

Falsification possible

<u>Young universe different to today ?</u>



Radio-astronomy (1960s)

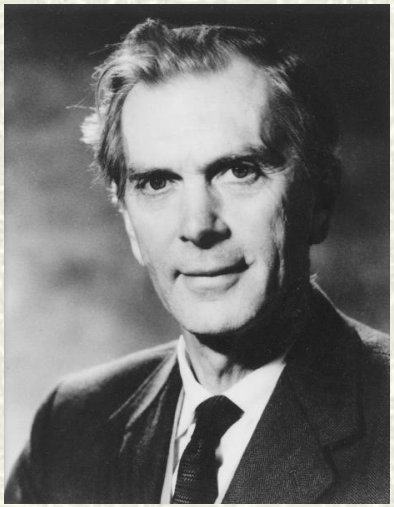
- Study most distant galaxies

  Look back in time
- Compare with local galaxies

- Density the same at all times? (SS)
- Or different? (BB)

Answer: <u>different</u>

End of steady-state model



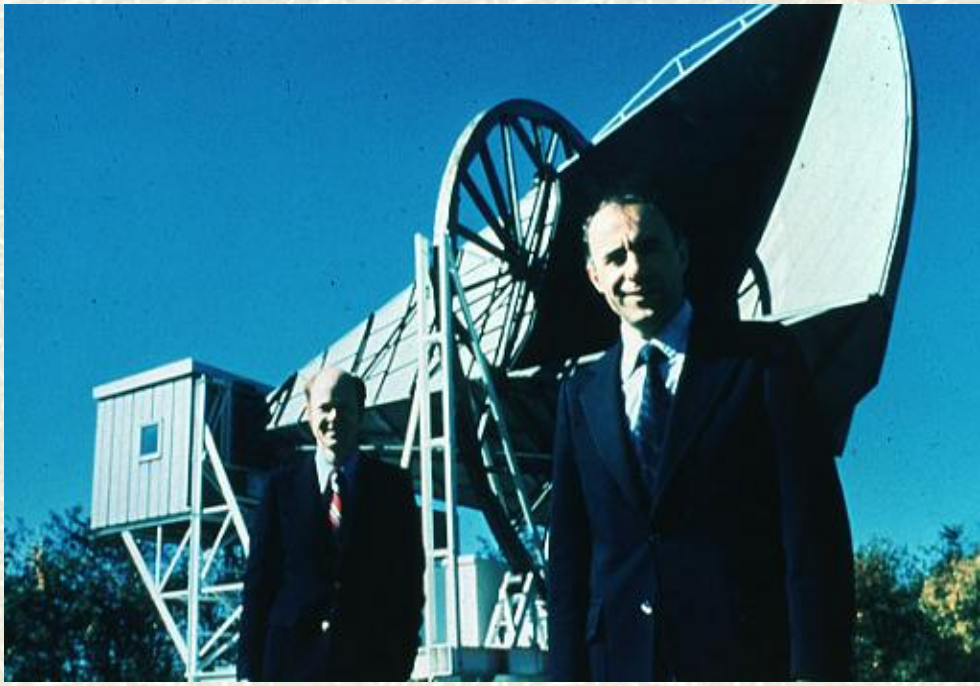
Martin Ryle

Cambridge
3C survey

Bonus: cosmic radiation (1965)

CMB discovered accidentally

- Universal signal
- Low frequency (microwave)
- Low temperature (3K)

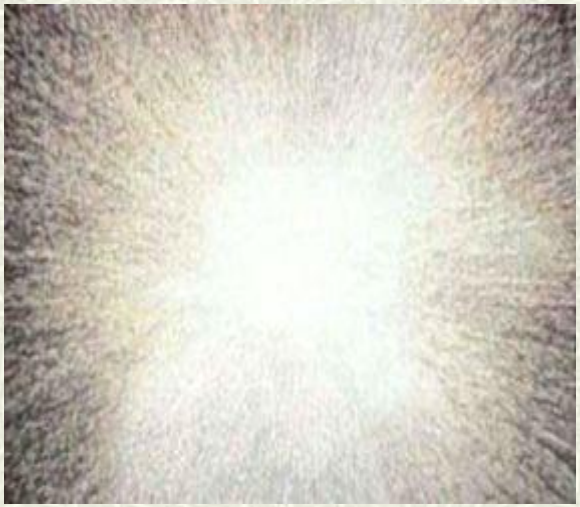


Penzias and Wilson

Echo of Big Bang!

BB model goes mainstream

The big bang – is it true?



Superhot, superdense

Expanding and cooling

√ ***1.*** The expansion of the *U*

√ ***2.*** The abundance of H and He

√ ***3.*** The evolution of galaxies

√ ***4***. The cosmic background radiation

How did it start?

The singularity: a cyclic universe?

- Breakdown at time zero
- No model of bang itself

- Multiple bangs?
- Colliding branes
- Prediction of string theory

- Cyclic universe
- Eternal universe

Cyclic universe

Tests?