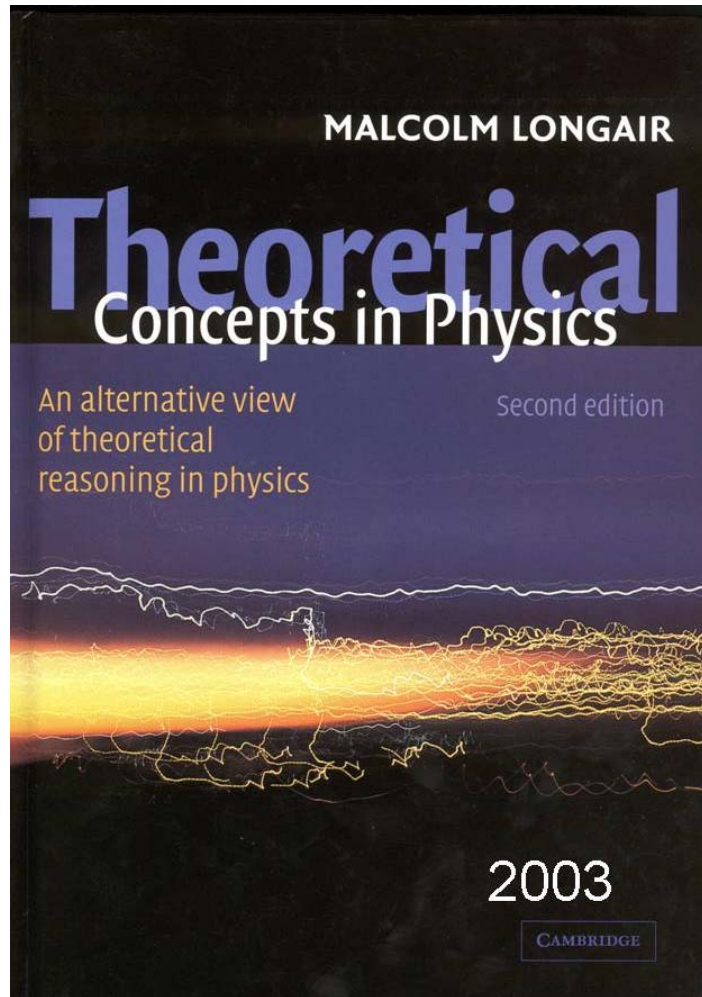# Three Lectures
on Astrophysics and Cosmology

- A Brief History of Cosmology

- The Most Luminous Radio Galaxies

- Galaxy Formation and Fluctuations in the Cosmic Microwave Background Radiation – What You Really Need to Know
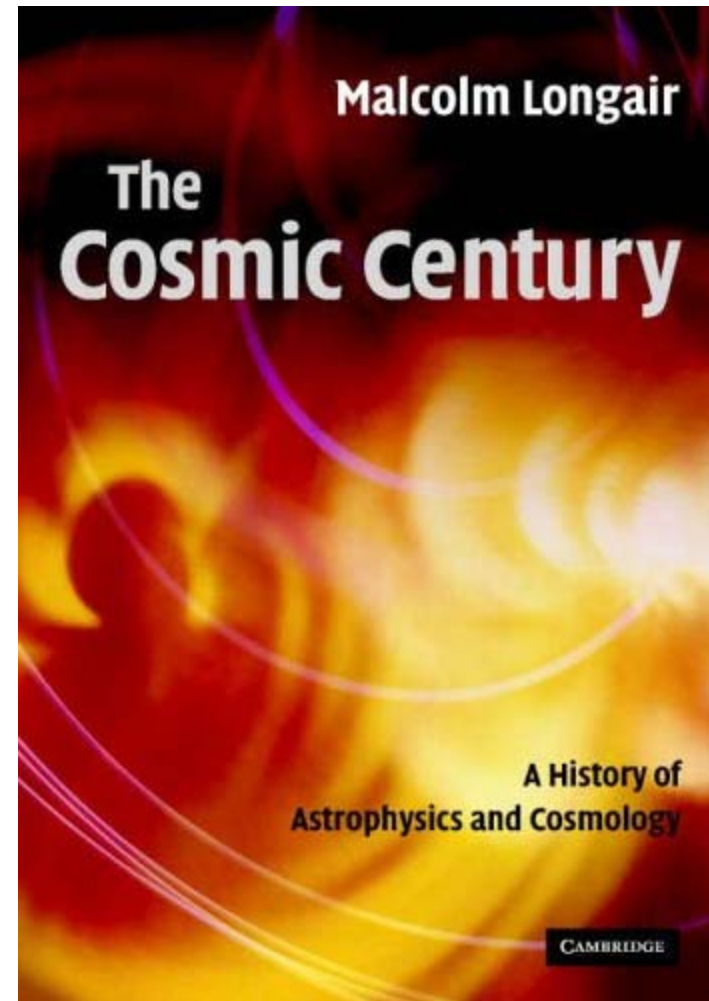
A Brief History of Cosmology

- Observational Cosmology to 1926

- Theoretical Cosmology to 1939

- Post-War Observational and Theoretical Cosmology to the 1990s

- Where we are now

The Books of the Lecture

MALCOLM LONGAIR

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Concepts in Physics

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Chapter 19 includes many
useful derivations and results

Malcolm Longair

The
Cosmic Century

A History of
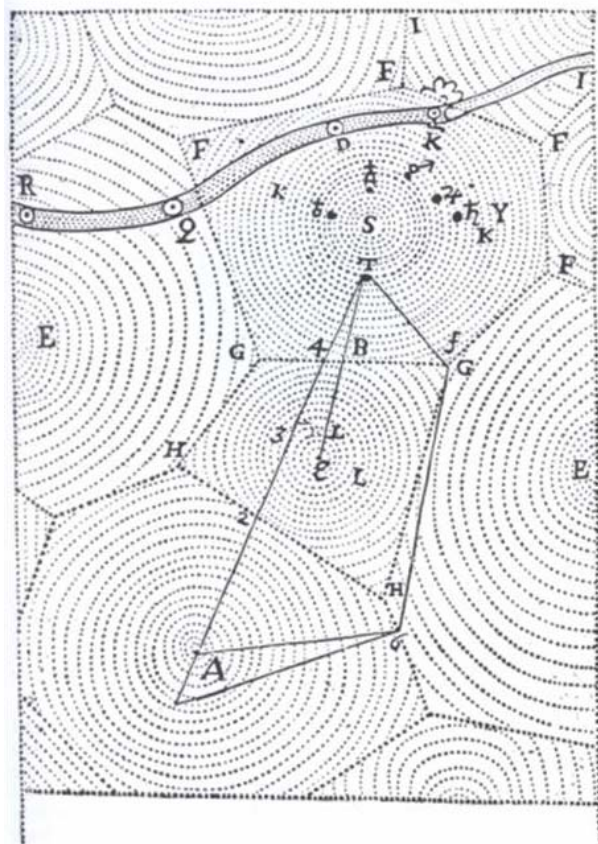Astrophysics and Cosmology

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To appear in March 2006.
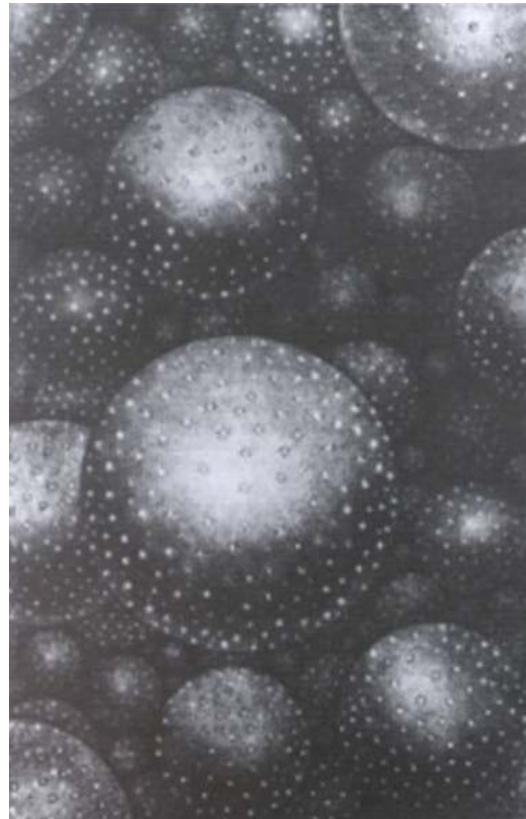
1. Observational Cosmology to 1926

Early Speculations
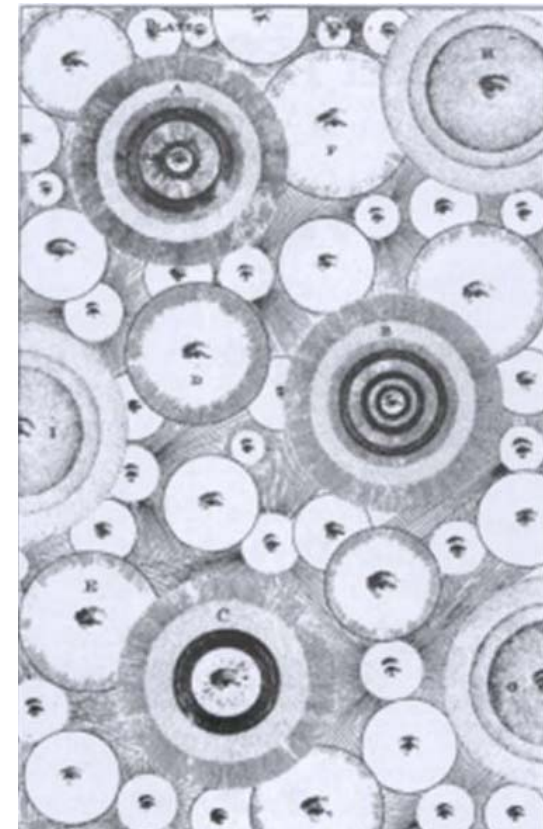
The earliest cosmologies were speculative cosmologies.

René Descartes *The World (1636)*

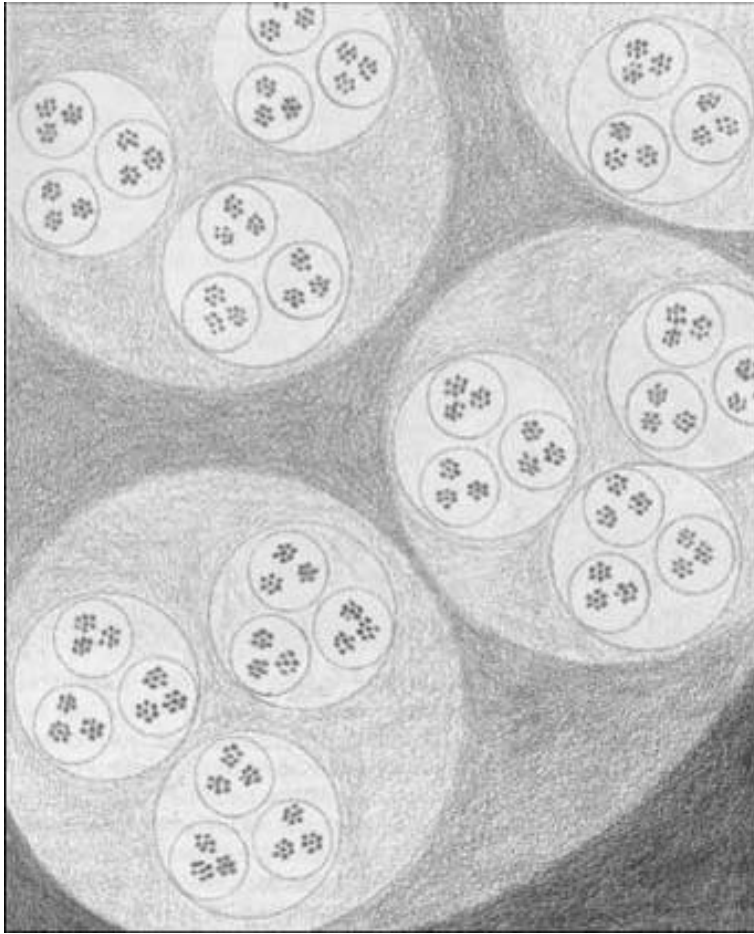Thomas Wright *An Original Theory of the Universe (1750)*

Thomas Wright *An Original Theory of the Universe (1750)*

Early Speculations

The hierarchical (fractal) Universe
of Kant (1755) and Lambert (1761)

Immanuel Kant had speculated that the flattening of celestial objects was due to their rotation.

The early cosmologies were speculative ideas without quantitative support of observation. The first quantitative estimates of the scale and structure of the Universe were made by William Herschel.

William Herschel

Herschel's star counts provided the first quantitative evidence for the island Universe picture of Wright, Kant, Swedenborg, and Laplace.
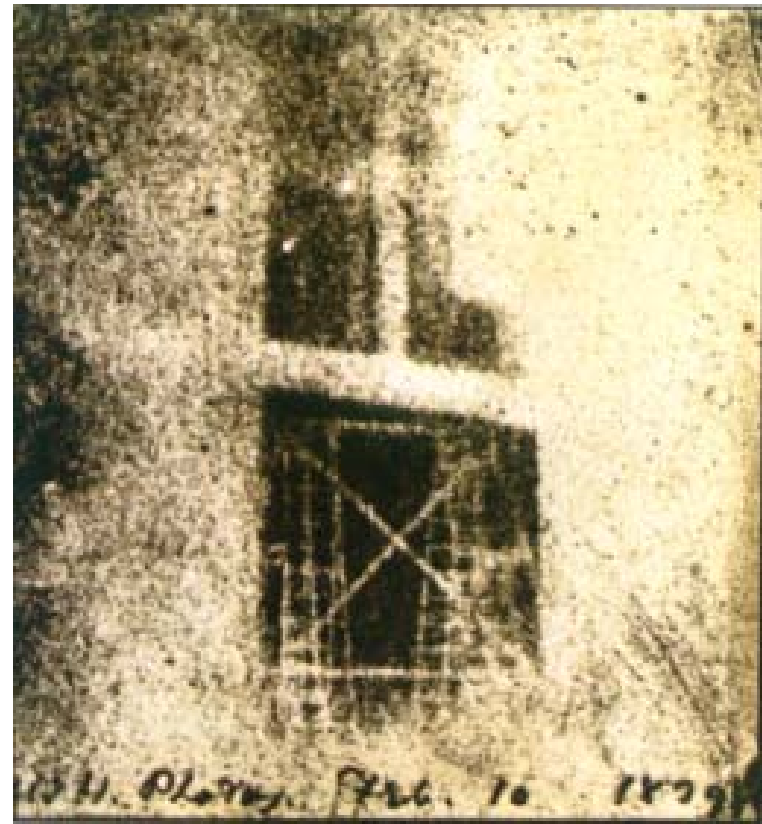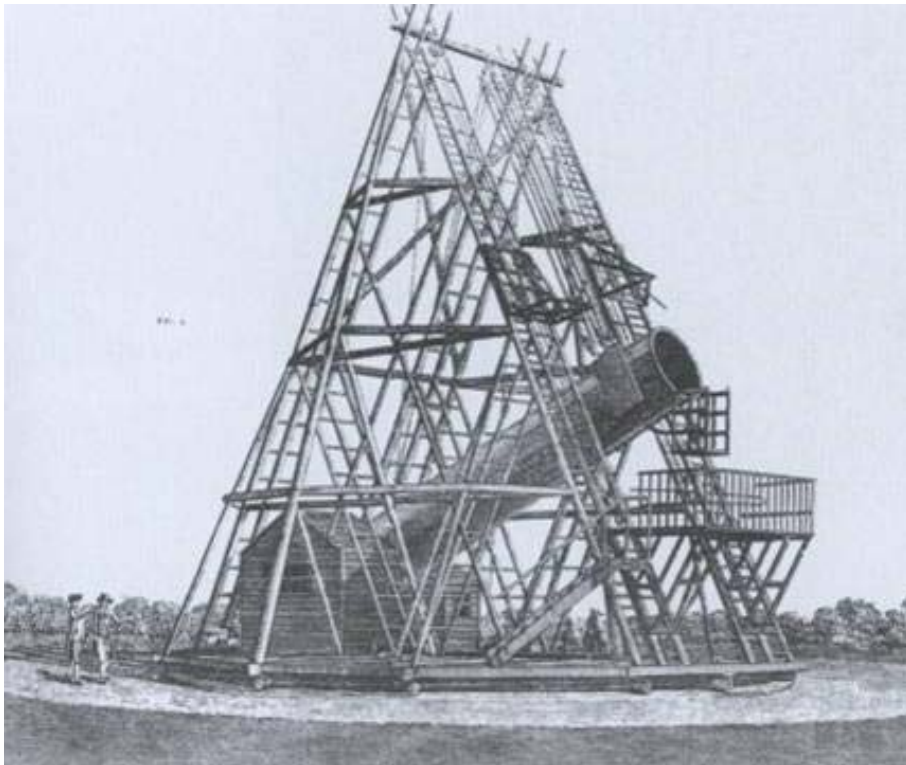
Herschel's 40-foot Telescope at Slough

THE FORTY-FOOT TELESCOPE AT SLOUGH.

Photographed by Sir JOHN F. W. HERSCHEL.

In 1839 Sir John Herschel, wishing to ascertain more fully how far organic matter is indispensable to the decomposition of the salts of silver by light, used glass plates to receive, under water, a deposit of "muriate" (chloride) of silver from a mixed solution of the nitrate with common salt. His MS record of this crucial experiment in photography goes on to say:

'After 48 hours (the chloride) 'had formed a film firm 'enough to bear draining the 'water off very slowly by a 'siphon. Having dried it I 'found that it was very little 'affected by light; but by washing 'with nitrate of silver, weak, and 'drying it, it became highly sensible. 'In this state I took a camera picture of 'the telescope on it.'

He exposed it 'with the glass towards the incident 'light', and fixed the image with hyposulphite of soda, the solvent action of which on chloride of silver he had announced 20 years earlier. The 'negatives' (as he called them) thus taken were the first obtained on glass, and from them he printed a few 'positives', now lost. The negative of this is exhibited in the South Kensington Science Museum, and now, after more than half a century, 25 copies have been printed from it by projection, true to it in size.

The 40-foot tube had been lowered for the last time before this was taken, and the whole structure was dismantled in Dec. 1839.

See Phil. Trans, 1840, 20th February, paragraphs 35 and 36, and MS of chemical experiments, vol. iii, page 397, Experiment 1075.

Presented to Capt Abney, by W. J. Herschel a J Herschel } August 1890.

This photograph was taken by John Herschel within months of the announcement of the discovery of the photographic process by Daguerre and Fox-Talbot in 1839.

Herschel's Model of the Galaxy

Herschel assumed that all stars have the same absolute luminosities. The importance of interstellar extinction had yet to be appreciated.

John Michell and William Herschel

- In 1767, Michell had already shown that Herschel's assumption of the constancy of the absolute luminosities of stars was incorrect from observations of bright star clusters. This was the introduction of statistical concepts into stellar statistics. He pointed this out before Herschel created his map of the Galaxy. Herschel ignored the problem

- 1802: Herschel measured the magnitudes of visual binary stars - he then agreed with Michell.

- The 40-foot telescope showed that the stellar system was unbounded.

- Herschel lost faith in his model of the Galaxy.

William Parsons 3rd Earl of Rosse

Lord Rosse's restored 72-inch telescope at Birr Castle, Ireland

Sketch of M51 by Lord Rosse from observations with the 72-inch Telescope at Birr.

James Keeler and the Crossley Reflector at the Lick Observatory

The Crossley reflector at the Lick Observatory on Mount Hamilton.
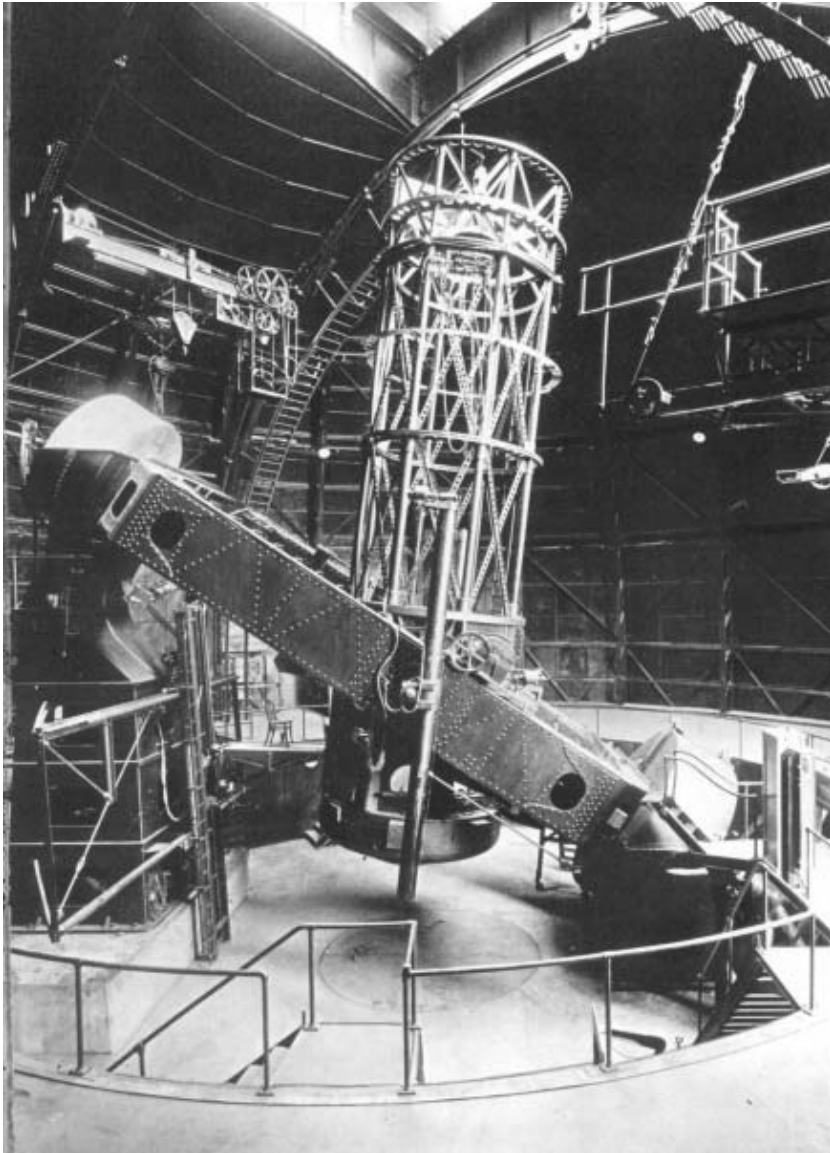

Keeler's image of M51 of 1900. While commissioning the Crossley reflector, Keeler obtained spectacular images of faint spiral galaxies.

The 100-inch Hooker Telescope at Mount Wilson

The Telescope weighed 100 tonnes and was completed in 1918. This instrument dominated observational cosmology until the commissioning of the Palomar 200-inch telescope in 1948.

The "Great Debate"

What is commonly referred to as "The Great Debate" revolved around two issues:

(1) What is the size of our Galaxy? (2) Are the spiral nebulae Galactic or extragalactic objects?
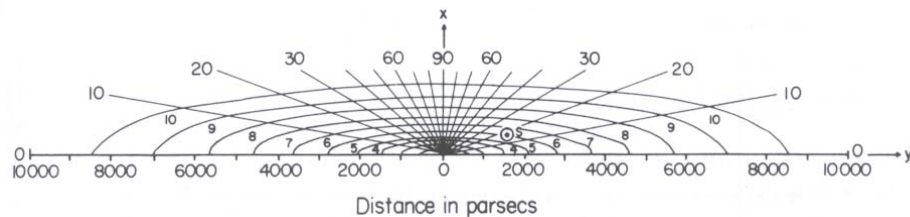
The structure of the Galaxy from Star Counts by Johannes Kapteyn (1921).

Distribution of Globular Clusters in the Galaxy due to Shapley (1918).

Aspects of the "Great Debate"

- J. Scheiner (1899) obtained a spectrogram of M31 and stated that the spectrum suggested a cluster of Sun-like stars.

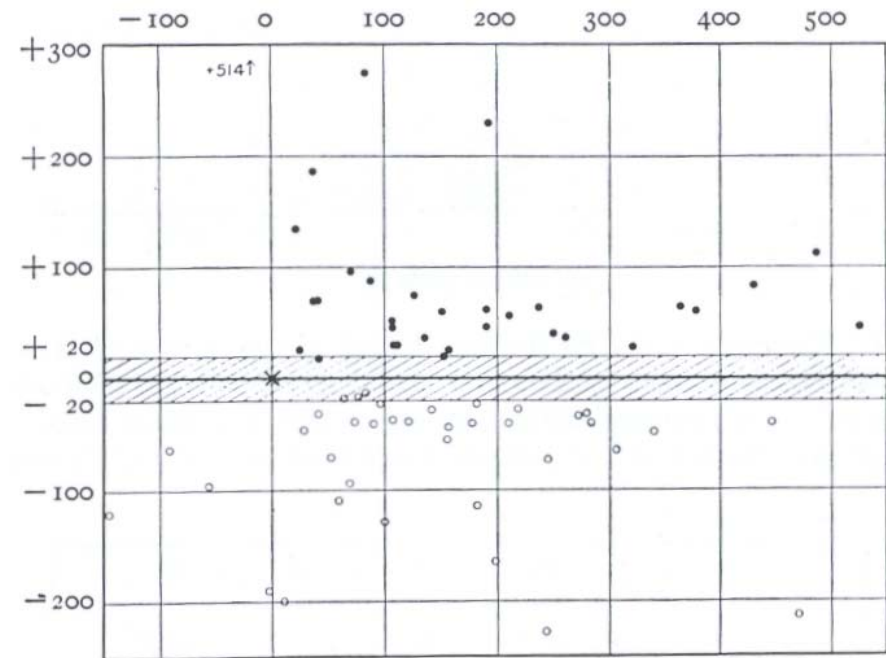- The central role of van Maanen's measurements of the proper motions of spiral arms from 1916 onwards. If the spiral nebulae were extragalactic, the motions of the arms would approach or exceed the speed of light. The observations were only definitively refuted by Edwin Hubble in 1933.

- Variable stars in spiral nebulae were discovered by Duncan in 1922. This led to a flurry of activity.

- Henrietta Leavitt had used observations with the 24-inch Bruce telescope at Arequita to discover the period luminosity relation for Cepheids in the Magellanic Clouds.

The Characteristic Light Curve of a Cepheid Variable
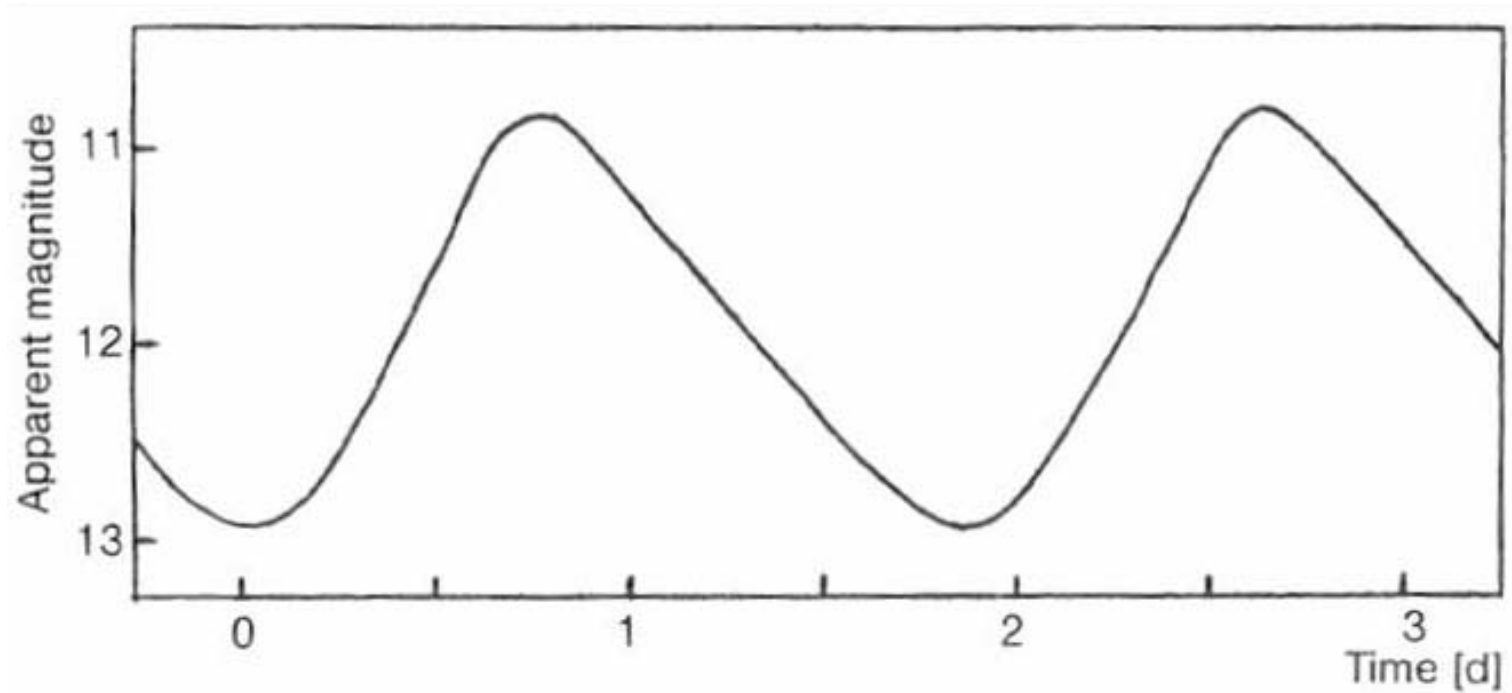
The Cepheid variable stars are characterised by a rapid rise in brightness followed by a slower decline.

Henrietta Leavitt and the Cepheid Variable Stars in the Magellanic Clouds (1912)

Henrietta Leavitt, like Annie Cannon, was profoundly deaf. Her major contribution was the determination of the magnitude scale of stars in the North Polar Sequence from m = 2 to 21.

Henrietta Leavitt
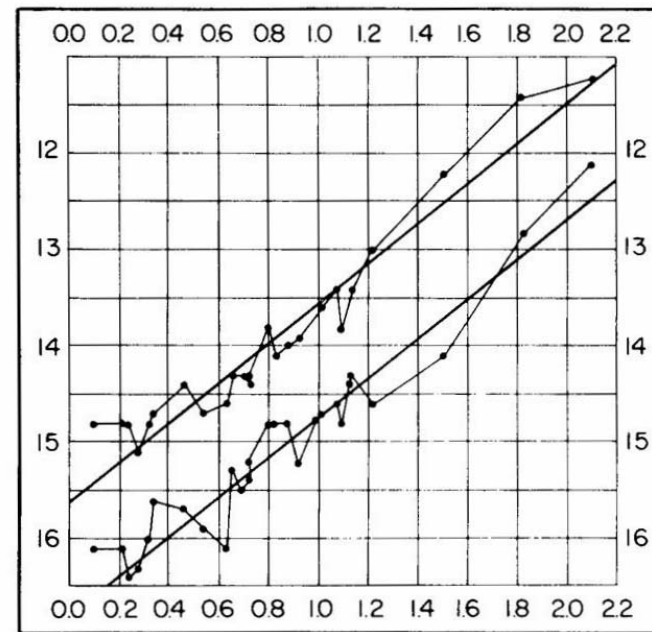
Henrietta Leavitt's period-luminosity relation for Cepheid variables in the Magellanic Clouds.

The Extragalactic Nature of the Spiral Nebulae

Edwin Hubble

In 1925, Hubble used Cepheid variables to show that M31 is outside our own Galaxy. In 1926, he presented a complete description of galaxies as extragalactic systems.

Hubble (1926)

This paper was the pioneering description of galaxies as extragalactic systems.

- Morphological classification of galaxies.

- Numbers of different types.

- Estimates of mass-to-luminosity ratios

- Mean mass density of the Universe and comparison with Einstein's static model.

He noted that the 100-inch telescope could observe typical galaxies to about 1/600 of the radius of the Einstein Universe and that "... with reasonable increases in the speed of plates and sizes of telescopes it may become possible to observe an appreciable fraction of the Einstein Universe."

In 1928 George Ellery Hale began his campaign to raise funds for construction of the Palomar 200-inch telescope. He obtained a grant of $6,000,000 from the Rockefeller Foundation for the telescope before the year was out.

2. Theoretical Cosmology to 1939

Nikolai Lobachevsky and Janos Bolyai

Working independently in Kazan in Russia and Transylvania in the period 1825–1830, Lobachevsky and Bolyai solved the problem of the existence of geometries which violated Euclid's fifth axiom. These were the first self-consistent hyperbolic (non-Euclidean) geometries and led to Riemann's introduction of quadratic differential forms and his discovery of spaces of positive (spherical) curvature.

In his great text On the Principles of Geometry, Lobachevsky worked out the minimum parallax of any star in hyperbolic geometry $\theta = \arctan(a/R)$ where a is the radius of the Earths orbit and R the radius of curvature of the geometry. In his textbook, he found a minimum value of $R \geq 1.66 \times 10^5$ AU. This was 8 years before Bessel's announcement of the first successful parallax measurement of 61-Cygni.

In his papers of 1829–30, Lobachevsky remarked,

'There is no means other than astronomical observations for judging the exactness which attaches to the calculations of ordinary geometry.'

The Route to General Relativity

Unlike Einstein's other great discoveries, the route to General Relativity was to prove to be long and tortuous. Four ideas were important in the development of the theory:

- The influence of gravity on light.
- The principle of equivalence.
- Riemannian space-time.
- The principle of covariance.

The key technical developments were the mathematics of quadratic differential forms and the absolute differential calculus.

Einstein and Grossmann

Towards the end of 1912, he realised that what was needed was non-Euclidean geometry. Einstein consulted his old school friend, Marcel Grossmann, about the most general forms of transformation between frames of reference for metrics of the form

$$\mathrm{d}s^2 = g_{\mu\nu}\,\mathrm{d}x^\mu\mathrm{d}x^\nu.$$

He came back with the answer that the most general transformation formulae were the Riemannian geometries, but that they had the 'bad feature' that they are non-linear. Einstein recognised that, on the contrary, this was a great advantage since any satisfactory theory of relativisitic gravity must be non-linear.

Einstein's Universe

Once General Relativity was formulated, Einstein realised in 1917 that he had the tools with which to derive the first fully self-consistent model of the whole Universe. At that time, the expansion of the Universe had not been discovered. To create a static Universe, he had to introduce the cosmological constant Λ.

When the cosmological constant is introduced, the equation which describes the variation of the scale factor R with cosmic epoch becomes

$$\frac{\mathrm{d}^2 R}{\mathrm{d}t^2} = -\frac{4\pi G \rho_0}{3R^2} + \frac{1}{3}\Lambda R.$$

The first term on the right-hand side describes the deceleration due to gravity.

The second term describes what Zeldovich called 'the repulsive effect of the vacuum'. The significance of the Λ-term was unknown at the time.

Einstein on the Introduction of the Cosmological Constant

Einstein believed that he had incorporated Mach's Principle into General Relativity. In his words,

> "The inertial structure of space-time was to be exhaustively conditioned and determined by the distribution of material throughout the Universe."

The extension of the field equations was "not justified by our actual knowledge of gravitation", but was "logically consistent". (1917)

The cosmological term was "necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of stars". (1934)

The de Sitter Solution

Almost immediately, a major spanner was thrown in the works by Willem de Sitter, who showed that there existed solutions of Einstein's cosmological field equations, even if there were no matter present in the Universe.

$$\mathrm{d}s^2 = \mathrm{d}r^2 - R^2 \sin^2\left(\frac{r}{R}\right)(\mathrm{d}\phi^2 + \cos^2\phi\,\mathrm{d}\theta^2) + \cos^2\left(\frac{r}{R}\right)c^2\,\mathrm{d}t^2.$$

The interpretation of the result was the subject of controversy, but it did show a redshift effect with distance which became known as the de Sitter effect.

In 1919, Einstein showed that the cosmological constant appears naturally as a constant of integration in the development of General Relativity and is set to zero in the standard development. Many cosmologists argued that rather it should be determined observationally whether or not it is zero.

Lanczos (1922)

In 1922, Cornelius Lanczos showed that, by a simple change of coordinates, the de Sitter solution could be interpreted as an expansion of the system of coordinates in hyperbolic space.

$$ds^2 = -dt^2 + \cosh^2 t [d\phi^2 + \cos^2 \phi (d\psi^2 + \cos^2 \psi \, d\chi^2)].$$

Lanczos remarked that:

"It is interesting to observe how one and the same geometry can appear with quite different physical interpretations according to the interpretations placed upon the particular coordinates."

The Friedman World Models

The standard world models used by all cosmologists today were discovered in 1922 and 1924 by the Soviet meteorologist Aleksander Aleksandrovich Friedman. The key realisation was that isotropic world models had to have isotropic curvature everywhere.
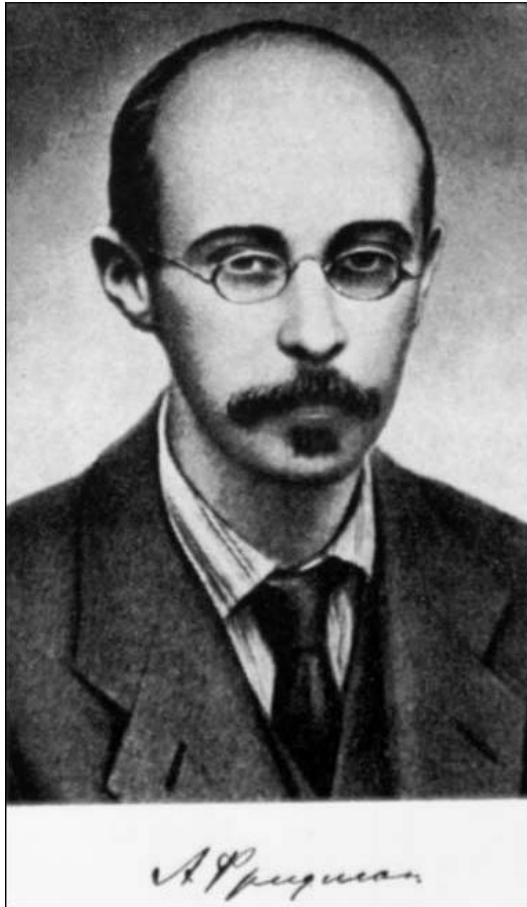
Aleksander Aleksandrovich Friedman

Friedman (1922)

$$\left(\frac{\dot{R}}{R}\right)^2 + \left(\frac{2R\ddot{R}}{R^2}\right) + \frac{c^2}{R^2} - \lambda = 0.$$

Friedman (1924)

$$\left(\frac{\dot{R}}{R}\right)^2 + \left(\frac{2R\ddot{R}}{R^2}\right) - \frac{c^2}{R^2} - \lambda = 0.$$

In both cases,

$$\frac{3\dot{R}^2}{R^2} + \frac{3c^2}{R^2} - \lambda + \kappa c^2 \varrho.$$

Lemaître and Robertson (1927-8)

They rediscovered the Friedman solutions independently .

- Lemaître: He derived the 'apparent Doppler effect where the receding velocities of extragalactic nebulae are a cosmical effect of the expansion of the Universe.'

- Robertson: found $v = cl/R$, where l = distance. From nearby galaxies he found the equivalent of a Hubble constant of 500 km s^{-1} Mpc^{-1}.

Vesto M. Slipher

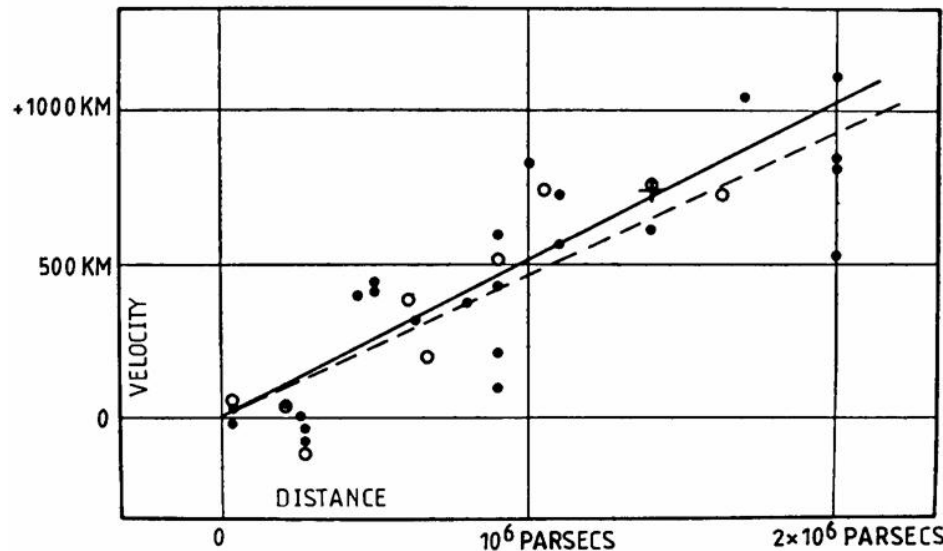One of the heroes of modern cosmology is Vesto Slipher. He obtained the spectra of the spiral nebulae in very long integrations with small telescopes. He realised that, for the spectroscopy of low surface brightness objects such as the spiral nebulae, the crucial factor was the f-ratio of the spectrograph camera, not the size of the telescope.

Of the 44 redshifts used on Hubble's famous 1929 paper, 39 were measured by Slipher.

Hubble's Velocity-Distance Relation of 1929

In 1921, Carl Wilhelm Wirtz almost discovered this relation.

In Hubble's diagram there are only 24 galaxies. The distances were estimated as follows:

- The first seven objects within 500 kpc had Cepheid distances
- The distances of the next 13 were found assuming the brightest stars all had the same absolute magnitude.
- The last four in the Virgo cluster were estimated on the basis of the mean luminosities of nebulae in the cluster.

Humason and Hubble's Velocity-Distance Relation of 1934 and the Isotropy of the Univevrse
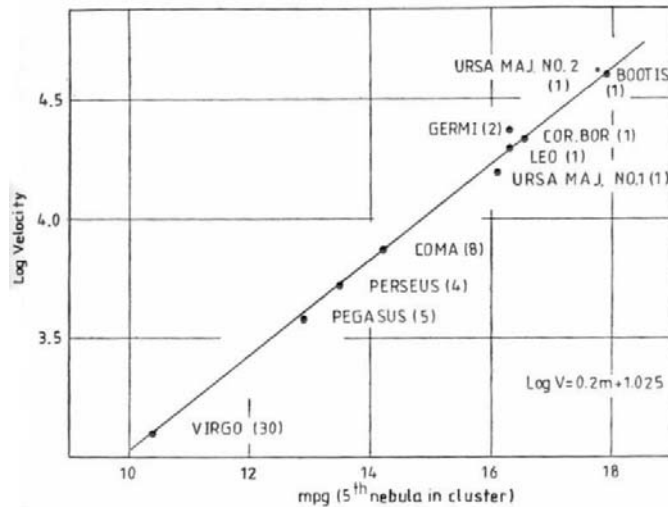
By 1934, Hubble and Milton Humason had extended the velocity-distance relation to 7% of the speed of light.
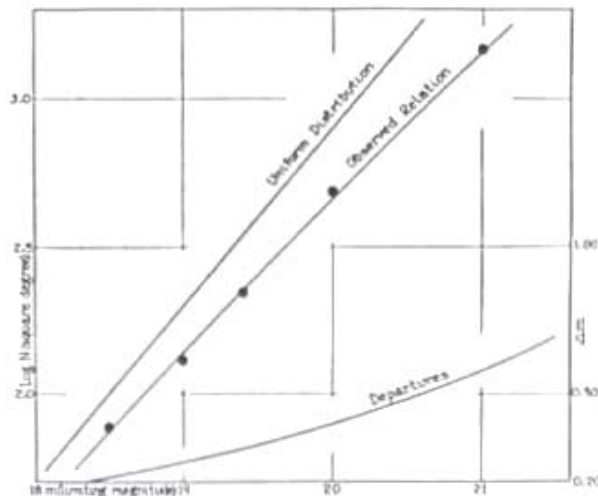
By counting the numbers of faint galaxies, Hubble established that they are uniformly distributed in space.

The Robertson-Walker Metric

In 1929, Robertson published the paper which is the basis of modern cosmology for isotropic, homogeneous world models. The key features are:

- The separation of space and time coordinates.

- Space-time is spatially isotropic and homogeneous.

He and Arthur Walker independently showed that such world models had to have a metric of the form

$$\mathrm{d}s^2 = \mathrm{d}t^2 - \exp(2f)\, h_{\mu\nu}\, \mathrm{d}x^\mu\, \mathrm{d}x^\nu,$$

where f is an arbitrary real function and $h_{\mu\nu}$ are the spatial coefficients of the metric.

The Einstein-de Sitter Model

In 1932, Einstein and de Sitter emphasised the unique nature of the Einstein-de Sitter or critical model.

$$\Lambda = 0 \qquad \kappa = 0 \qquad R \propto t^{2/3}.$$

The critical density was $\varrho_0 = 4 \times 10^{-25}$ kg m^{-3}.

This was very much greater than Hubble's estimate of the mass density in galaxies, but they argued that there might well be considerable amounts of 'dark matter' in the Universe.

Evidence was not long in coming. In 1933, Fritz Zwicky made the first dynamical estimates of the masses of clusters of galaxies and found a mass-to-light ratio of 500 for the cluster as a whole, compared with values of about 3 in our own Galaxy. All subsequent studies have confirmed Zwicky's key result.

The Standard Models of the Universe Milne and McCrea (1934)
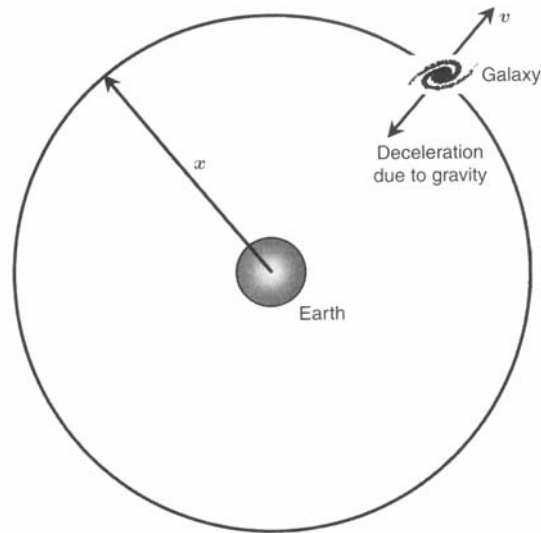
We can find exactly the correct answers if we replace the whole Universe by a uniformly expanding sphere - every piece of Universe is just as good as any other bit.

We can understand the behaviour of these models in terms of the concept of escape velocity - is the Universe expanding fast enough to escape from its own gravity?
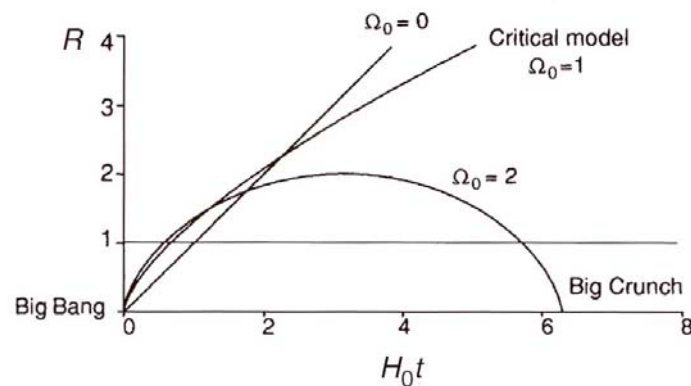
The behaviour depends upon the average density of matter in the Universe. There is a critical density which separates the models which expand forever from those which eventually collapse to a Big Crunch.

The Age of the Universe

In the standard models with $\Lambda = 0$, the empty model has the greatest age, $T_0 = 1/H_0$, because the Universe has not been decelerated.

Hubble's estimate of Hubbles constant in 1935 was 500 km s^{-1} Mpc^{-1} corresponding to $T_0 = 1/H_0 = 2$ billion years. It was known that the age of the Earth was about 4.6 billion years.

Arthur Eddington and George Lemaître realised that the time-scale problem could be resolved if they included the cosmological constant into the world models. In Eddington's words, the Universe would have a "logarithmic infinity" to fall back on.

In these Eddington-Lemaître models, the effect of the cosmological constant is to counteract the attractive force of gravity and so the cosmological time-scale can be stretched out. By a suitable choice of Λ, the age of the Universe can become greater than $1/H_0$. Distant objects are fainter than in the standard models.

Origin of the Chemical Elements

Two arguments favoured a primordial origin for the chemical elements:

- The uniformity of the chemical abundances of the elements in stars.

- The cores of stars were not hot enough to synthesise the elements.

In 1931, Georges Lemaître proposed that the initial state of the Friedman models consisted of a primaeval atom. Following the discovery of the neutron in 1932, this was identified with a sea of neutrons.

The Basic Problem of Galaxy Formation

The first discussion of the inevitability of gravitational collapse took place between Isaac Newton and Richard Bentley in 1692 as Bentley prepared the first series of Boyle lectures "to combat atheism". They agreed that the Universe had to be infinite because otherwise it would collapse to the centre under the attractive force of gravity.

In addition, however, they noted that, even in such a Universe, the system is gravitationally unstable. As expressed by Edward Harrison,

> "(Newton) agreed with Bentley that providence had designed a Universe of infinite extent in which uniformly distributed stars stand poised in unstable equilibrium like needles on their points."

Jeans (1902)

In 1902, James Jeans first derived the instability criterion for perturbations in a static medium under gravity. The dispersion relation is

$$\omega^2 = c_\mathsf{s}^2 k^2 - 4\pi G \varrho_0$$

where c_s is the speed of sound in the medium. The corresponding equation for the electrostatic case, which results in plasma oscillations, was only discovered in the 1920s by Langmuir and Tonks.

$$\omega^2 = c_\mathsf{s}^2 k^2 + \frac{N_\mathsf{e} e^2}{m_\mathsf{e} \epsilon_0}$$

The instability occurs when the gravitational term on the right-hand side is dominant gravity overwhelms pressure support. The critical Jeans wavelength is

$$\lambda_\mathsf{J} = \frac{2\pi}{k_\mathsf{J}} = c_\mathsf{s} \left(\frac{\pi}{G \varrho_0} \right)^{1/2}.$$

Note the well known technical difficulty with the derivation of this result - there is not a stable background solution about which to perturb the medium.

Lemaître (1933) and Tolman (1934)
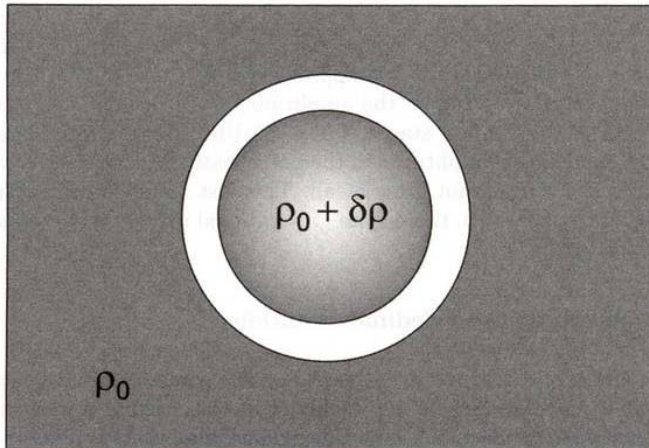
Lemaître and Tolman carried out the first analyses of the development of spherical perturbations in an expanding medium. This has the great advantage of removing the technical problem of the lack of a stable background model.
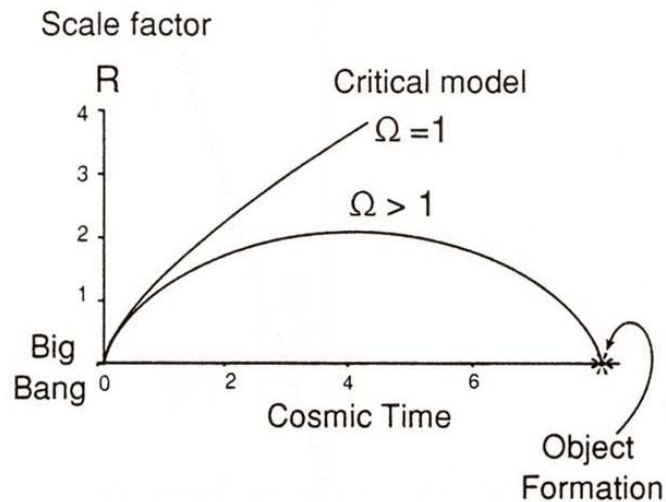
Gravitational Instability
in the Expanding Universe

They found the key result that the density perturbations grow only algebraically with scale factor rather than exponentially as in a static medium. The general relativistic version of the problem was carried out by Lifshitz in 1946 with the same result:

$$\frac{\delta\varrho}{\varrho} \propto R \qquad \text{provided} \qquad \Omega_0 z \geq 1.$$

These authors inferred that the large-scale structure of the Universe could not have developed from infinitesimal perturbations and so galaxies could not have formed by gravitational collapse.

3. Post-War Observational and Theoretical Cosmology to the 1990s

Origin of the Chemical Elements

In 1946, George Gamow found that the time-scale of the early expansion of the Universe was too short for the equilibrium abundances to the established.

- Alpher, Bethe and Gamow paper - stationary Universe, sea of free neutrons, synthesis starts at $kT = 0.1$ MeV.

- Alpher and Herman (1950) determined the thermal history of the Universe, predicting a background radiation temperature of 5 K.

- Fermi and Turkevich (1950) showed that the heavy elements were created in miniscule quantities because there are no stable elements with mass numbers 5 and 8.

Alternative Theories

Immediately after the Second World War, many different cosmological theories were in the air.

- Milne's kinematic cosmology

- Dirac's theory of large number coincidences leading to a variable gravitational constant

- Eddington's Fundamental Theory

- Steady State Theory

The Origin of Steady State Cosmology

From the reminiscences of Fred Hoyle:

'In a sense, the steady-state theory may be said to have begun on the night that Bondi, Gold and I patronised one of the cinemas in Cambridge. The picture, if I remember rightly, was called *The Dead of Night*. It was a sequence of four ghost stories, seemingly disconnected as told by the several characters in the film, but with the interesting property that the end of the fourth story connected unexpectedly with the beginning of the first, thereby setting-up the potential for a never-ending cycle. When the three of us returned that evening to Bondi's rooms in Trinity College Gold suddenly said: "What if the Universe is like that?" '

The Case of Steady State Cosmology

According to the Perfect Cosmological Principle, the Universe presented the same appearance at all epochs. This provided an immediate solution of the time-scale problem. Consequently,

- The density of the Universe is a constant

- The spatial geometry is flat

- The scale-factor varies as $\exp H_0(t - t_0)$

- There must be the continuous creation of matter out of the vaccuum.

Hoyle attributed these properties to the action of the creation field C.

William McCrea (1951)

McCrea realised that there was a quite different interpretation of what Hoyle had done.

"The single admission that the zero of absolute stress may be set elsewhere than is currently assumed on somewhat arbitrary grounds permits all of Hoyle's results to be derived within the system of General Relativity theory. Also, this derivation gives the results an intellectual physical coherence."

He wrote the physics of the Steady State picture in terms of a negative pressure equation of state $p = -\varrho c^2$. This is exactly the same physics as the simplest interpretation of the nature of the cosmological constant Λ.

The Palomar 200-inch Telescope and Revisions of Hubble's Constant

The telescope was designed by Hale in the 1930s and commissioned by Hubble in the late 1940s. The 200-inch Telescope dominated extragalactic research until the 1970s.

After the Second World War, successive revisions took place to the value of Hubble's constant. In 1955, Walter Baade reduced it to 250 km s^{-1} Mpc^{-1} and then Sandage reduced it further to 180 km s^{-1} Mpc^{-1}.

By the 1970s, the value was reduced to between 50 and 100 km s^{-1} Mpc^{-1}. The precise value became a subject of considerable controversy. These values correspond to: $T_0 = H_0^{-1} = 20$ and 10 billion years.

Testing the Steady State Picture

The perfect cosmological principle made the Steady State model unique and highly testable. Martin Ryle had the genius to understand how to use the principles of aperture synthesis to obtain high angular resolution and sensitivity in radio astronomy.
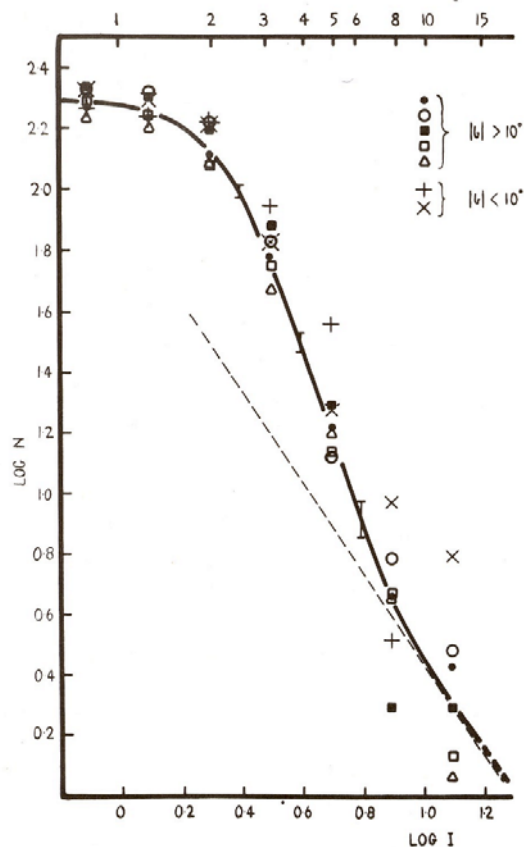
The 2C Radio Survey of extragalactic radio sources of 1955 found a very large excess of faint radio sources, relative to the expectations of uniform world models. In his Halley Lecture of 1955, Ryle concluded:

"This is a most remarkable and important result, but if we accept the conclusion that most of the radio stars are external to the Galaxy, and this conclusion seems hard to avoid, then there seems no way in which the observations can be explained in terms of a steady state theory"

Testing the Steady State Picture

This was a surprise to the astronomical community since the physical nature of the sources was not understood and only 20 of them were identified with relatively near galaxies.

The Sydney Astronomers led by Bernard Mills used the Mills Cross Radio Telescope, which had better angular resolution, to survey bright sources in the southern sky and found a source counts $N(\geq S) \propto S^{-1.65}$ which they argued was consistent with a uniform distribution $N(\geq S) \propto S^{-1.5}$. In 1957, Mills and Slee wrote:

"We therefore conclude that discrepancies, in the main, reflect errors in the Cambridge catalogue, and accordingly deductions of cosmological interest derived from its analysis are without foundation."

Peter Scheuer and the Problem of Source Confusion

The effects of source confusion were poorly understood and led to a serious overestimate of the numbers of faint sources. The hero of this part of the story was undoubtedly Peter Scheuer who showed in a brilliant analysis how the true slope of the counts could be found directly from the interferometer records and eliminated the need to identify individual radio sources.

Scheuer found exactly the correct answer, $N(\geq S) \propto S^{-1.8}$. His statistical analysis was somewhat forbidding and not immediately understood. I remember him telling me that nobody believed him – Ryle because he did not find $N(\geq S) \propto S^{-3}$ and Mills because he did not find $N(\geq S) \propto S^{-1.5}$.

The direct measurement of the steep source count slope came with the 3CR and 4C surveys.

The Problem of the Cosmic Helium Abundance

In the early 1960s, it was realised that the percentage by mass of helium, wherever it could be measured in the Universe was always at least 23%. This is much greater than can be created by stellar nucleosynthesis. In 1964, Fred Hoyle and Roger Tayler showed that such a percentage of helium is synthesised in the early stages of the Big Bang and is remarkably independent of the cosmological model.

As the Universe cooled down from a very high temperature in its early phases, nuclear reactions took place between the protons and neutrons which resulted in the formation of helium.

In subsequent computations with William Fowler and Robert Wagoner, traces of deuterium, helium-3 and lithium-7 were also found to be created as by-products of the nuclear reactions. The light elements, ^{4}He, ^{3}He, D, ^{7}Li, are very difficult to account for by nucleosynthesis inside stars. The predicted Big Bang abundances turn out to agree well with the observations.

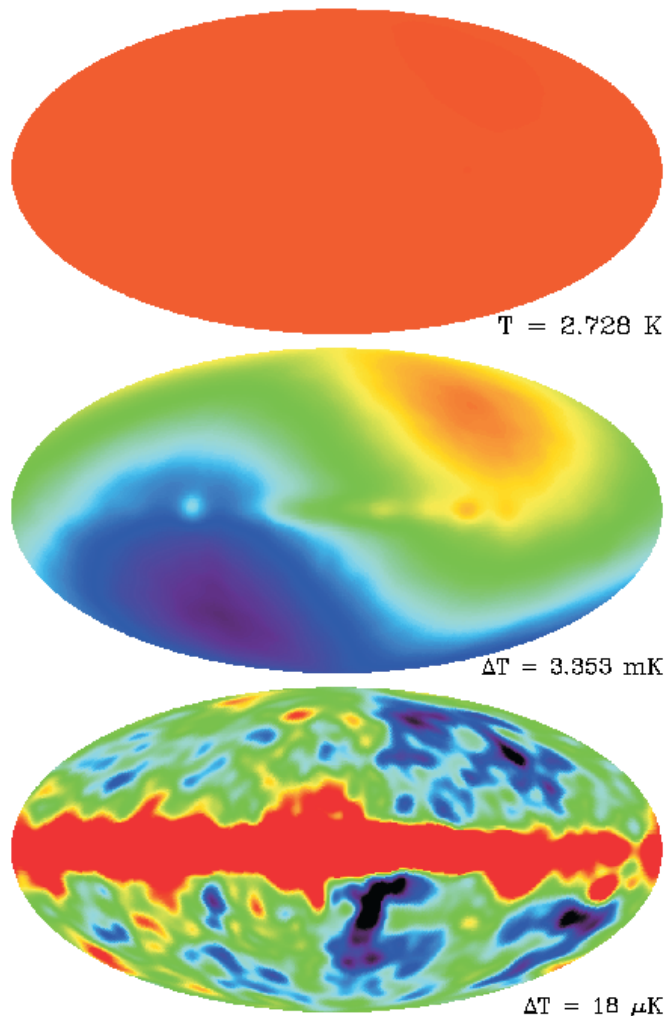# The Discovery of the Cosmic Microwave Background Radiation (1965)

Contributions to the total measured radio signal in Penzias and Wilson's experiments at 4.08 GHz (7.35 cm).

The Bell Laboratories 20-foot horn antennae was designed for satellite communication at centimetre wavelengths. Arno Penzias and Robert Wilson built a 7.3 cm cooled maser receiver, with which they planned to undertake radio astronomical observations. They discovered an excess of about 3K radiation wherever they pointed the telescope on the sky.

Signal	Noise (T/K)
Total zenith noise temperature	6.7 ± 0.3
Atmospheric emission	2.3 ± 0.3
Ohmic losses	0.8 ± 0.4
Backlobe response	≤ 0.1
Cosmic Background Radiation	3.5 ± 1.0

COBE Observations of the Cosmic Microwave Background Radiation (1990s)

T = 2.728 K

ΔT = 3.353 mK

ΔT = 18 μK

These studies culminated in the observations of the Cosmic Microwave Background Radiation by the COBE satellite in the early 1990s.

- The spectrum is very precisely that of a perfect black-body at a radiation temperature of 2.726 K.

- A perfect dipole component is detected, corresponding to the motion of the Earth through the frame in which the radiation would be perfectly isotropic.

- Away from the Galactic plane, the radiation is isotropic to better than one part in 10^5. At this level, significant temperature fluctuations $\Delta T/T \approx 10^{-5}$ were detected on scales $\theta \geq 10°$.

The Problem of Galaxy Formation Revisited

The slow rate of growth of density perturbations was a real difficulty and other ideas came into play.

- Hoyle, Lyttleton and Bondi's theory of accretion wakes as a means of forming galaxies in the Steady-State picture

- George Field's analysis of thermal instabilities in the expanding Universe.

These ideas would find application in quite different contexts in the theory of structure formation. Other authors adopted the solution of including finite amplitude density perturbations into the initial conditions and then working out how they evolved with cosmic epoch.

- Moscow School led by Yakov Zeldovich: his students/post-docs included Igor Novikov, Andrei Doroshkevich and Rashid Sunyaev.

- Princeton School: James Peebles.

Origin of the Standard Model

- In 1964, Novikov showed that, to form structure on the scale of galaxies and clusters of galaxies, the amplitudes of the perturbations had to be $\sim 10^{-4}$ when they entered the horizon.

- The thermal history of the Universe could be determined precisely. Ray Weymann (1966) described the coupling of matter and radiation during the radiation-dominated phases. Sunyaev and Zeldovich (1969) used the Kompaneets equation to solve the detailed coupling of matter and radiation throughout the history of the Universe.

- Joseph Silk (1968) demonstrated the importance of photon diffusion in wiping out small scale structures in the adiabatic picture of structure formation.

The Discovery of Sakharov or Acoustic Oscillations.

In 1965, before the discovery of the microwave back-ground radiation, Sakharov predicted the existence of preferred mass scales in the formation of galaxies. These calculations were repeated for the standard Hot Big Bang model by Zeldovich and Sunyaev (1969).
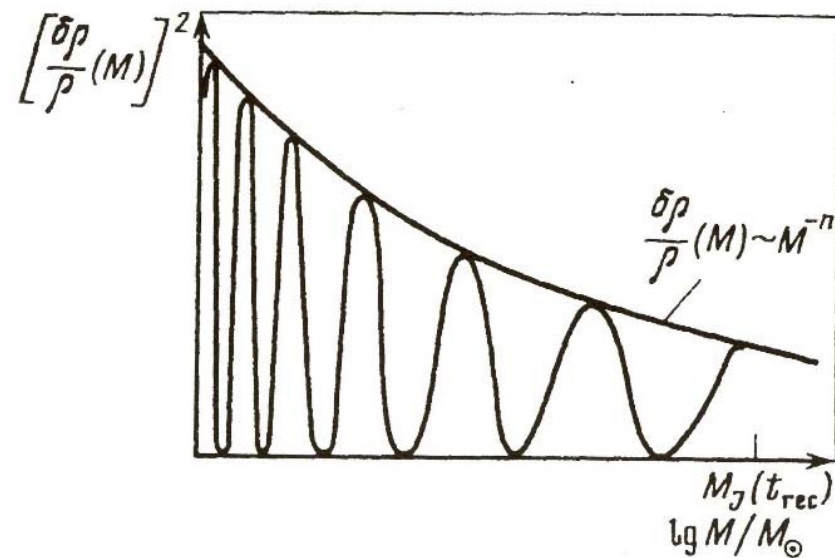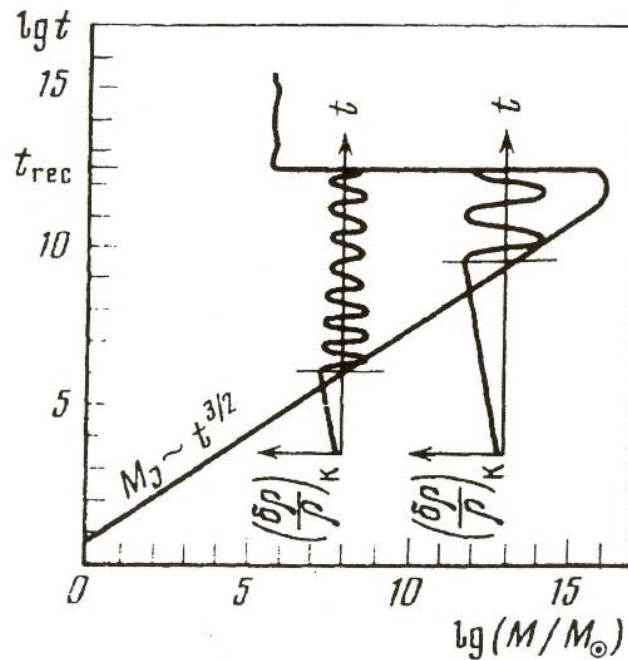
The Large-scale Distribution of Galaxies

- In the 1950 and 1960s, Jerzy Neyman and Elisabeth Scott devoted a large effort to understanding the statistical distribution of galaxies.

- In the 1960s George Abell and Fritz Zwicky presented evidence for the existence of superclusters from their studies of clusters of galaxies.

- Kihara and Totsuji (1969) applied power-spectrum techniques to the large-scale distribution of galaxies.

- James Peebles and his colleagues published a long series of important papers analysing in detail the distribution of galaxies throughout the 1970s.

The Harrison-Zeldovich Spectrum

In the early 1970s, Edward Harrison (1970) and Zeldovich (1972) argued from a variety of different perspectives that the initial power spectrum of perturbations should have the form

$$\frac{\delta\varrho}{\varrho} \propto M^{-2/3} \qquad \text{corresponding to} \qquad |\Delta_k|^2 \propto k^n \qquad \text{with} \qquad n = 1.$$

Problems gradually accumulated for the standard Baryonic Model. Silk, Peebles, Zeldovich and Sunyaev has shown that there must be temperature fluctuations in the microwave background radiation in the various versions of the standard model. By 1980, the predictions were exceeding the observational limits to the perturbations and something was needed to patch up the models.

Neutrino Fluctuations and Cold Dark Matter

In 1980, Valentin Lyubimov claimed to have measured a rest mass of 30 eV for the electron neutrino. This led Zeldovich and his colleagues to develop a neutrino-dominated model which avoided the problems with the perturbations in the microwave background radiation. The result was a closed model in which structure on all small scales was washed out by neutrinos streaming freely out of the perturbations.
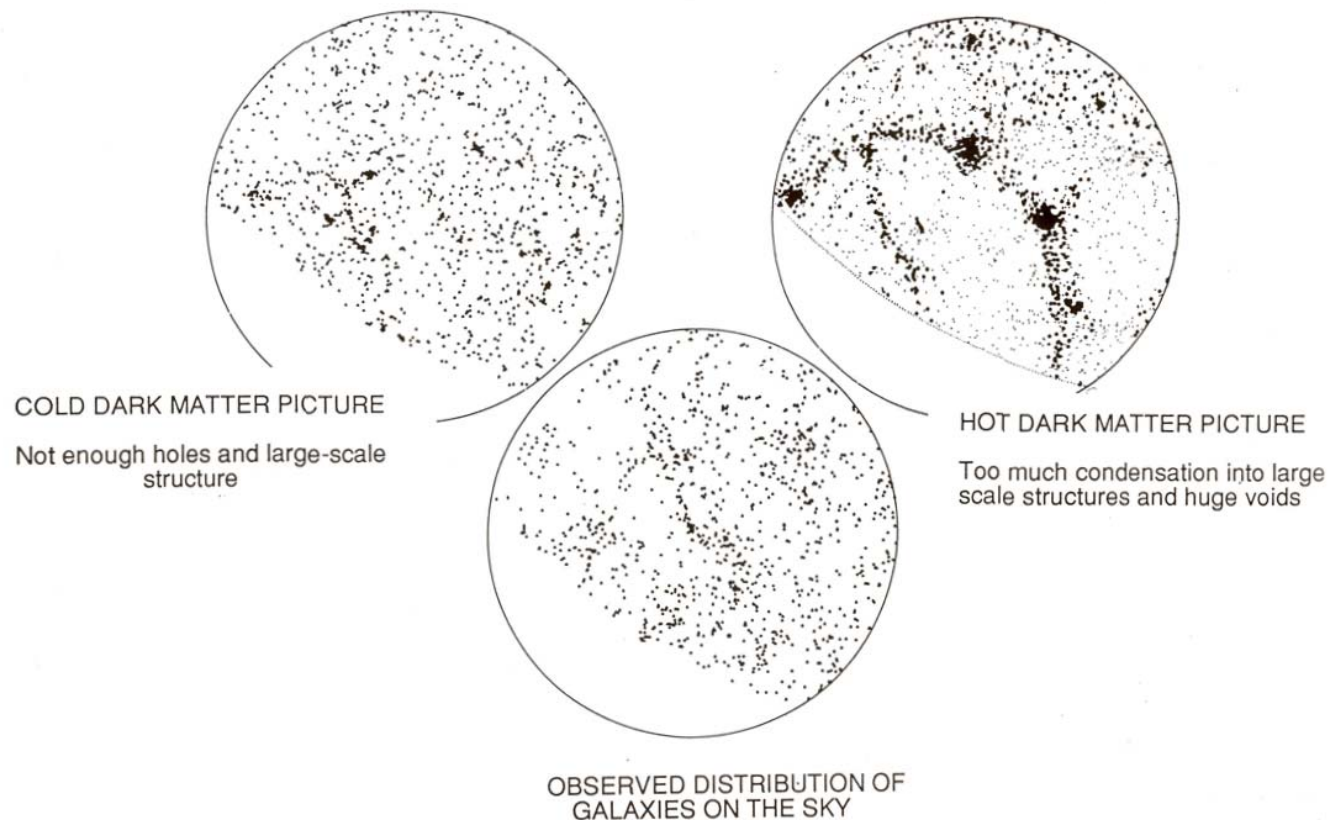
The neutrino model did not survive long because the neutrino mass estimates turned out to be incorrect. The concept of avoiding the excess temperature perturbations by allowing dark matter with very small interaction cross-section with baryonic matter to dominate the dynamics of the Universe was proposed by Peebles, Bond and others.

This Cold Dark Matter picture was to become the preferred model for the formation of structure.

Cold Dark Matter Scenarios

This model proved remarkably successful in accounting for many features of the large-scale structure of the Universe, but it needed patching up to be consistent with all the observations. The most important subsequent results concerned the detection of perturbations in the cosmic microwave background radiation by COBE, which were at a level consistent with the theories of the origin of large-scale structure.

COLD DARK MATTER PICTURE

Not enough holes and large-scale structure

HOT DARK MATTER PICTURE

Too much condensation into large scale structures and huge voids

OBSERVED DISTRIBUTION OF GALAXIES ON THE SKY

Inflation

A key innovation of the early 1980s was the introduction of the concept of the inflationary Universe by Alan Guth.

- The concept of the very early exponential expansion of the Universe could resolve the horizon and flatness problems without a physical realisation of the theory.

- By 1982, the theory had suggested an origin for the scale-invariant spectrum of primordial perturbations in terms of quantum processes on the horizon scale.

Liddle and Lyth remark in their book *Cosmological Inflation and Large-Scale Structure*:

"Although introduced to resolve problems associated with the initial conditions needed for the Big Bang cosmology, inflation's lasting prominence is owed to a property discovered soon after its introduction: it provides a possible explanation for the initial inhomogeneities in the Universe that are believed to have led to all the structures we see, from the earliest objects formed to the clustering of galaxies to the observed irregularities in the microwave background."

4. Where we are now

The Revolution in Modern Cosmology

The first fruits of the era of precision cosmology are now appearing – it is no longer history but contemporary research.

- Supernovae of Type 1A

- Fluctuation spectrum and polarisation of the Cosmic Microwave Background Radiation

- The power spectrum of galaxies from the Sloan Digital Sky Survey and the AAO 2dF galaxy survey.

- Mass density of the Universe from the infall velocities of galaxies into large scale structures.

- The formation of the light elements.

- Nucleocosmochronology.

- The value of Hubble's constant from the HST Key Project.

The Concordance Model

This set of parameters is consistent with all observations listed above:

- Hubble's constant $H_0 = 72$ km s^{-1} Mpc^{-1}

- Baryonic density parameter $\Omega_B = 0.047$

- Cold Dark Matter density parameter $\Omega_D = 0.233$

- Total Matter density parameter $\Omega_0 = \Omega_B + \Omega_D = 0.28$

- Density Parameter in Vacuum Fields $\Omega_\Lambda = 0.72$

- Optical Depth for Thomson Scattering on Reheating $\tau = 0.17$

- Curvature of Space $\Omega_\Lambda + \Omega_0 = 1$; $\kappa = 0$.