Einstein, relativity and the big bang

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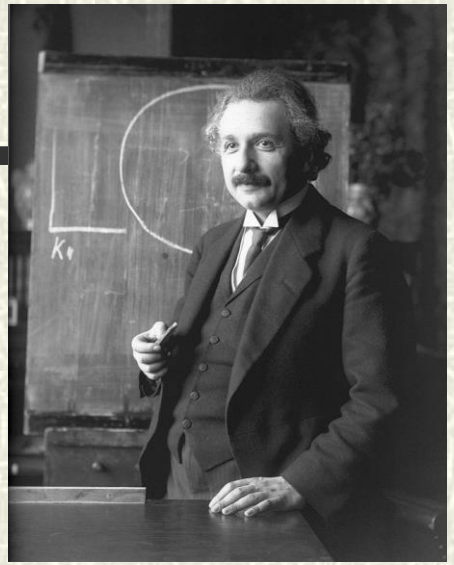
Overview

- **100 years of relativity**
  - *The special theory of relativity (1905)*
  - *The general theory of relativity (1915)*
- **Relativity and the universe**
  - *The static models of Einstein and de Sitter*
  - *The dynamic models of Friedman and Lemaître*
- **The expanding universe (1930)**
  - *The recession of the galaxies*
  - *Einstein's 'big bang' models of 1931 and 1932*
  - *New research into Einstein's models of 1931 and 1932*
  - *Einstein's steady-state model*
- **Conclusions: Einstein and the big bang**

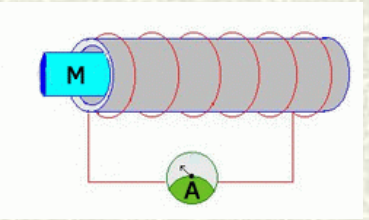


Einstein in California (1931)

The special theory of relativity (1905)

- **Two new principles for inertial observers**
  - *Invariance of laws of physics (including electromagnetism)*
  - *Invariance of the speed of light*

- **Implications for space and time**
  - *Space, time not absolute: distorted by motion*

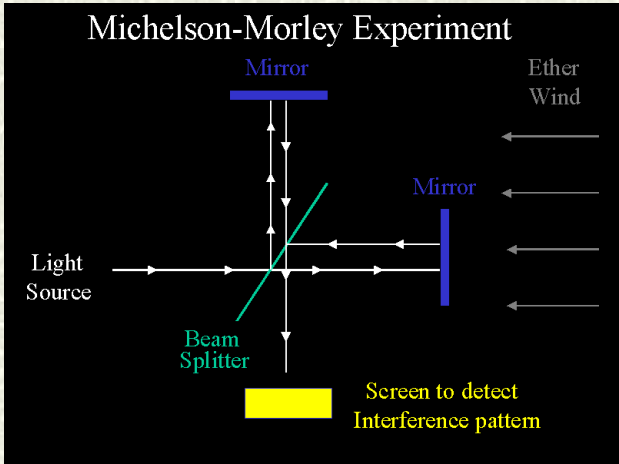


- **Predictions**
  - *Length contraction; time dilation*
  - *Mass increase; equivalence of mass and energy*

$$E = mc^2$$

- **Space-time**
  - *Space + time = space-time*
  - *4-dimensional entity*

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2$$

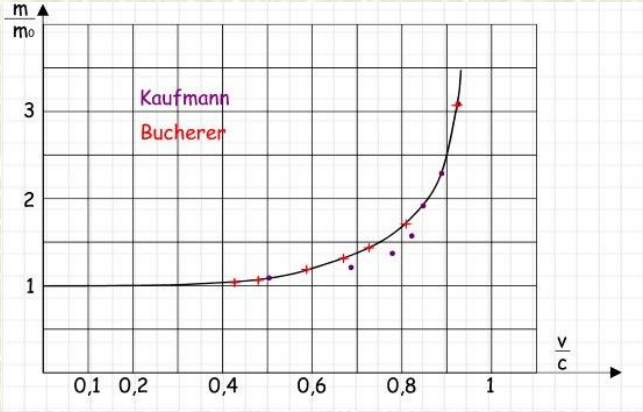


Evidence for special relativity

- **Mass increase**

  The experiments of Kaufmann and Bucherer

$$m' = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

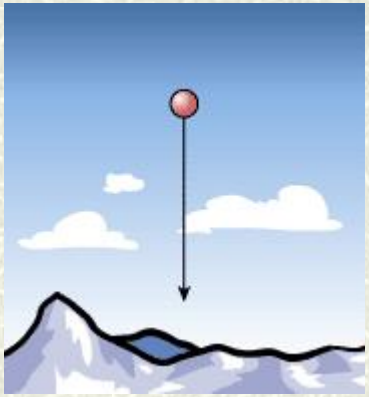


- **Time dilation**

  The long-lived muon

  2 μs → 22 μs

$$t' = \frac{t_0}{\sqrt{1 - v^2/c^2}}$$



- **Invariance of the speed of light**

  Many experiments to measure c

- **Particle experiments at the LHC**

  Maximum velocity = c

  Mass increase

  Particle creation

$$E = mc^2$$

General relativity (1915)

- **The general theory of relativity (1915)**

  Relativity and accelerated frames?

  Relativity and gravity?

Albert Einstein
1879-1955

- **Two new principles**

  Principle of equivalence

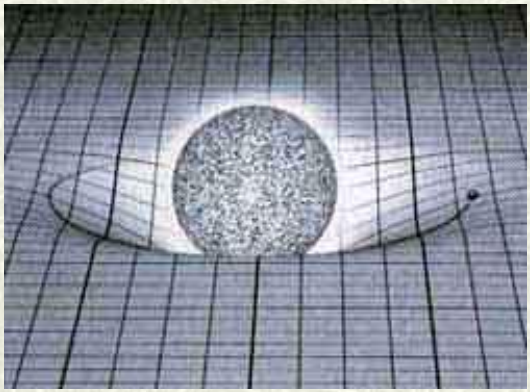
  Mach's principle

- **Predictions**

  Space-time distorted by mass

  Gravity = curvature of space-time

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



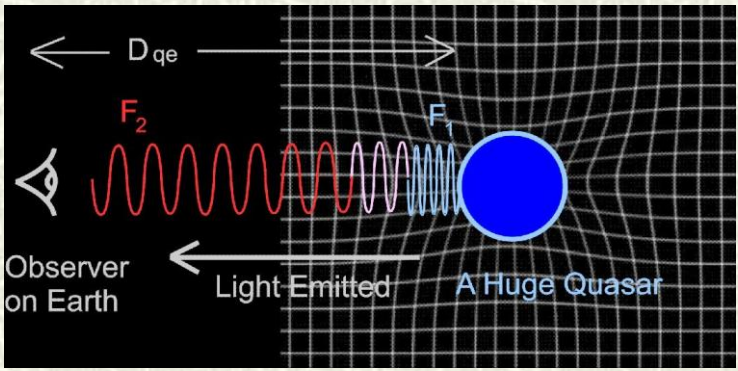
- **Empirical evidence**

  Orbit of Mercury: bending of starlight (Eddington, 1919)

Evidence for general relativity

- **Bending of distant light by stars**
  Gravitational lensing

- **Gravitational redshift**
  Shift in wavelength of light due to grav. field



- **Gravitational time dilation**
  GPS corrections

- **Black holes**
  Centre of galaxies

- **Gravitational waves**
  Hulse –Taylor binary system

II Relativity and the universe

- **Apply general relativity to the cosmos (1917)**

  Ultimate test for new theory of gravitation

Einstein's universe

- **Assumptions**

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

  Static universe

  Isotropic and homogeneous

  Null solution

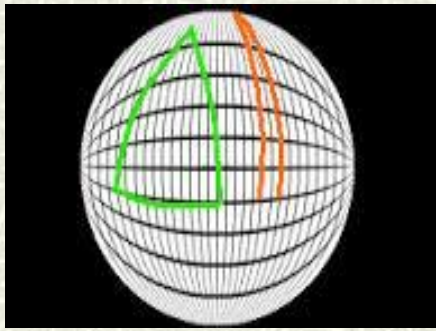
$$G_{\mu\nu} + \lambda g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

- **Cosmological constant λ**

  Add term to GFE for non-zero solution

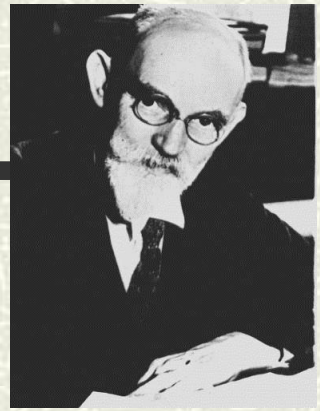
  Universe of closed curvature: no boundary problem

  Cosmic radius and matter density defined by λ



$$\lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2}$$

The de Sitter universe (1917)

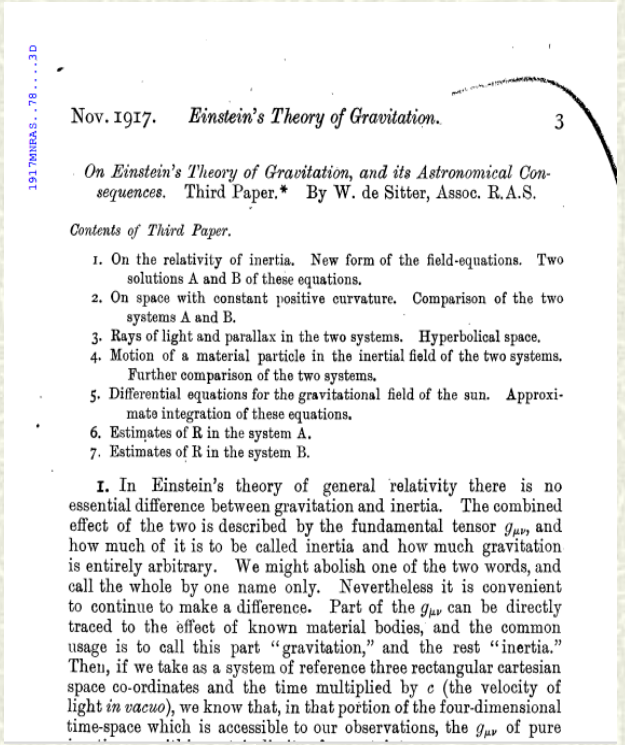


- **Apply general relativity to the cosmos**
  Include cosmological constant

- **'Empty' universe solution**
  Reasonable approximation
  $G_{\mu\nu} + \lambda g_{\mu\nu} = 0$
  Curvature of space proportional to cosmic constant

- **Disliked by Einstein**
  Conflict with Mach's principle
  Singularity problem?
  Beginning of Einstein's dislike for cosmic constant

- **Interest from astronomers**
  Radiation from matter redshifted – Slipher effect?
  Static or non-static model? (Weyl 1923, Lemaître 1925)



1917MNRAS..78...3D

Nov. 1917. *Einstein's Theory of Gravitation.* 3

On Einstein's Theory of Gravitation, and its Astronomical Consequences. Third Paper.* By W. de Sitter, Assoc. R.A.S.

Contents of Third Paper.

1. On the relativity of inertia. New form of the field-equations. Two solutions A and B of these equations.
2. On space with constant positive curvature. Comparison of the two systems A and B.
3. Rays of light and parallax in the two systems. Hyperbolical space.
4. Motion of a material particle in the inertial field of the two systems. Further comparison of the two systems.
5. Differential equations for the gravitational field of the sun. Approximate integration of these equations.
6. Estimates of R in the system A.
7. Estimates of R in the system B.

1. In Einstein's theory of general relativity there is no essential difference between gravitation and inertia. The combined effect of the two is described by the fundamental tensor $g_{\mu\nu}$, and how much of it is to be called inertia and how much gravitation is entirely arbitrary. We might abolish one of the two words, and call the whole by one name only. Nevertheless it is convenient to continue to make a difference. Part of the $g_{\mu\nu}$ can be directly traced to the effect of known material bodies, and the common usage is to call this part "gravitation," and the rest "inertia." Then, if we take as a system of reference three rectangular cartesian space co-ordinates and the time multiplied by c (the velocity of light *in vacuo*), we know that, in that portion of the four-dimensional time-space which is accessible to our observations, the $g_{\mu\nu}$ of pure

Friedman models of the cosmos

- **Time-varying solutions (1922)**
  - *Universe of time-varying radius*
  - *Assume positive spatial curvature*
  - *Two independent differential equations from GFE*

$$\frac{3R'^2}{R^2} + \frac{3c^2}{R^2} - \lambda = \kappa c^2 \rho,$$

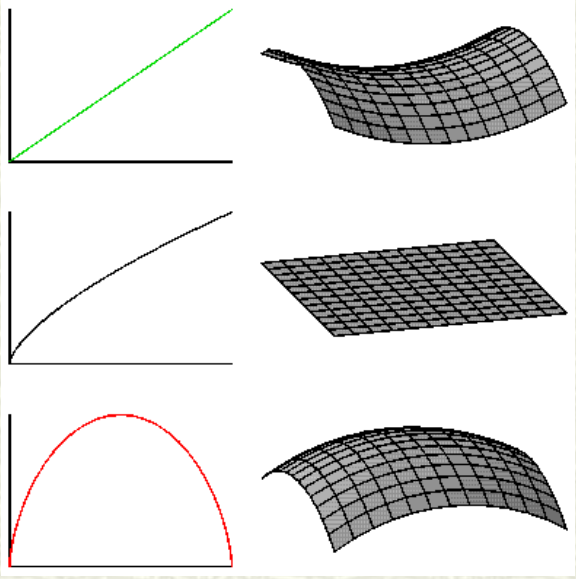
$$\frac{R'^2}{R^2} + \frac{2RR''}{R^2} + \frac{c^2}{R^2} - \lambda = 0.$$

Alexander Friedman (1888 -1925)

- **Expanding sphere**
  - *Density of matter decreases over time*

$$\frac{1}{c^2}\left(\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2 = \frac{A - R + \frac{\lambda}{3c^2}R^3}{R}$$

- **Ignored by community**
  - *Considered 'suspicious' by Einstein*
  - *Mathematical correction, later retracted*
  - *"To this a physical reality can hardly be ascribed"*



- **Negative spatial curvature (1924)**
  - *Cosmic evolution, geometry depends on matter content*

Lemaître's universe (1927)

Fr Georges Lemaître

- **Expanding model of the cosmos from GR**

  Similar to Friedman 1922 model

  Starts from static Einstein universe

$$3\frac{R'^2}{R^2}+\frac{3}{R^2}=\lambda+\kappa\rho$$

$$2\frac{R''}{R}+\frac{R'^2}{R^2}+\frac{1}{R^2}=\lambda-\kappa p$$

- **Redshifts of nebulae = expansion of space***?*

  Redshifts from Slipher, distances from Hubble

  $H = 585\ kms^{-1}Mpc^{-1}$

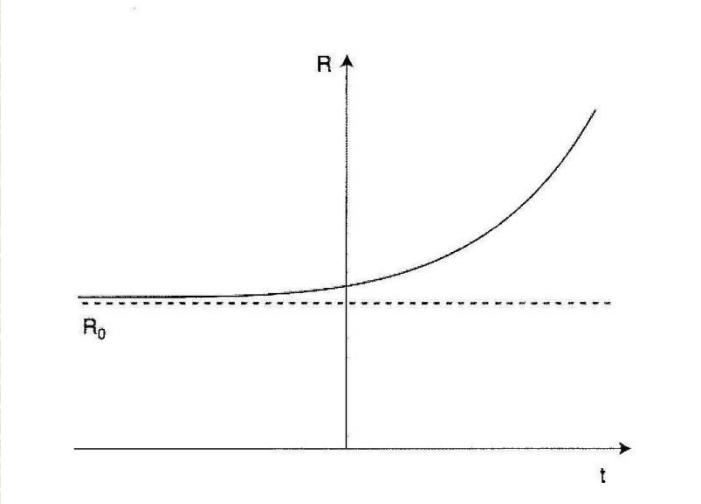
- **Ignored by community**

  Belgian journal (in French)

  Rejected by Einstein:"Votre physique est abominable"

  Lemaître informed of Friedman's solution

  Einstein not up-to-date with astronomy?



III Astronomy and the universe

- **The 'Great Debate' (1900-1920)**

  Spiral nebulae = clusters of stars ?

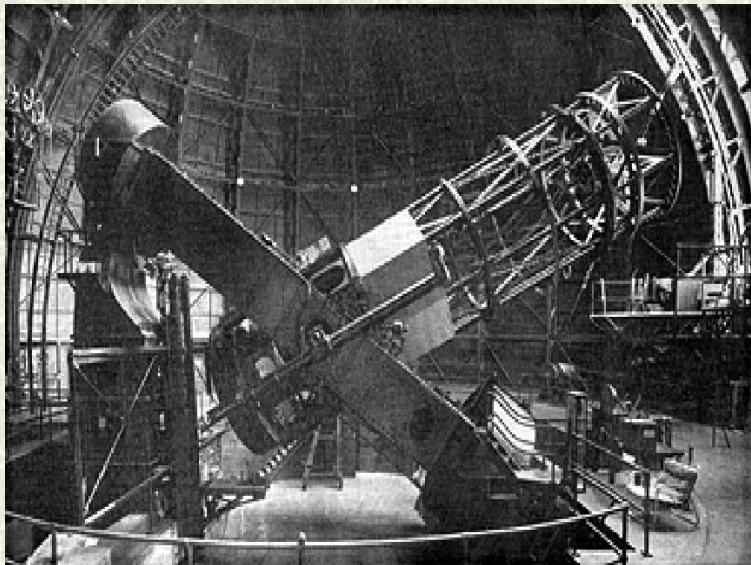
  Galaxies beyond Milky Way?

  Light from many spirals red-shifted (Slipher 1915, 1917)

- **The Hooker telescope (1917)**

  100-inch reflector

  Edwin Hubble (1921)



- **Distance of 2 spirals**

  Cepheid variables resolved in nebulae

  Leavitt's period-luminosity relation

- **Spirals far beyond Milky Way (1925)**

  A universe of galaxies

Motion of nebulae: redshift

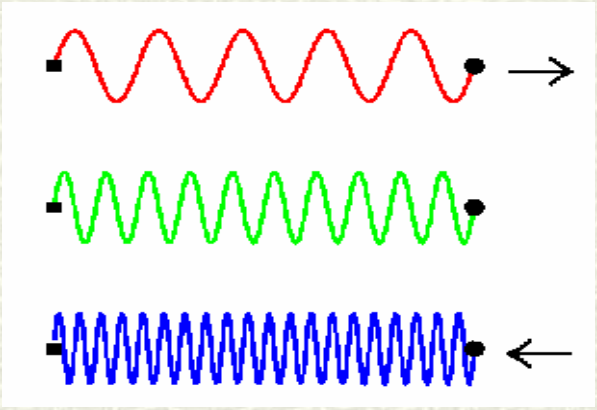
Vesto Slipher

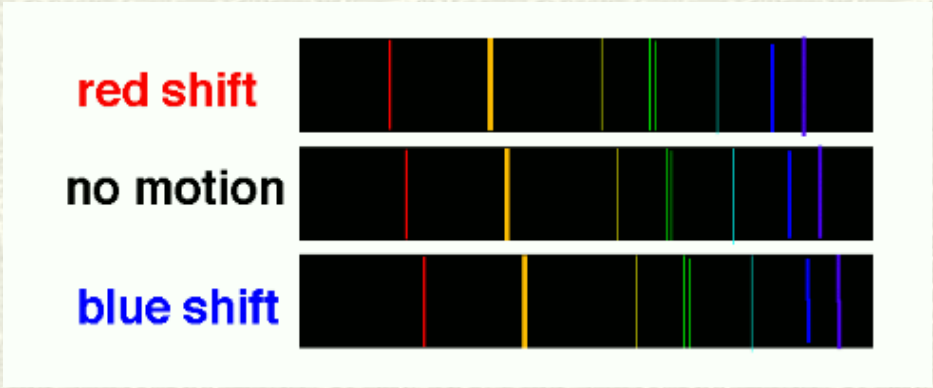
Frequency of light depends on motion of source relative to observer

Doppler Effect

Measure motion of nebulae by measuring light emitted

Light from most nebulae red shifted

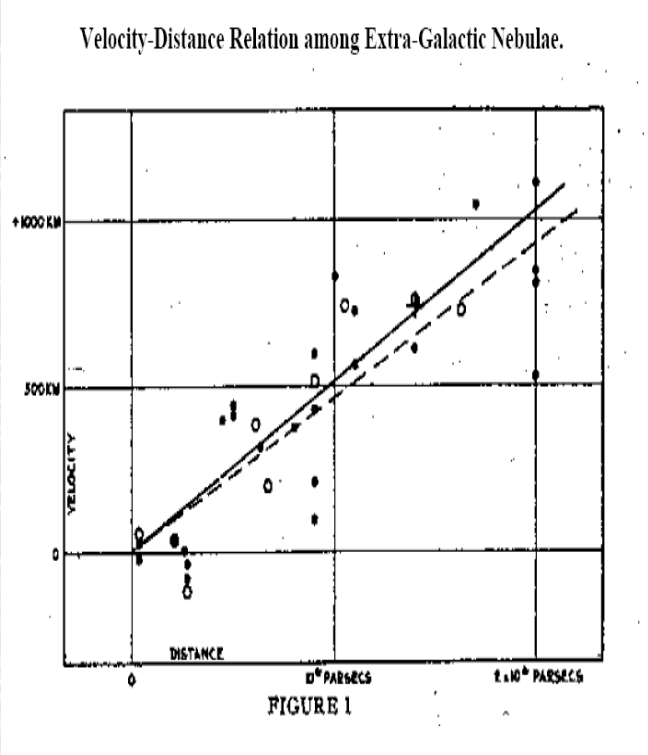




Hubble's law

Edwin Hubble (1889-1953)

- **A redshift/distance relation for the nebulae?**
  Motivation: establishing distances of all nebulae
- **Combined 24 distances with redshifts**
  Redshifts from Slipher: not acknowledged
- **Linear relation (Hubble, 1929)**
  $H = 500\ kms^{-1}Mpc^{-1}$: some errors
  Most important data point not shown
- **Landmark result in astronomy**
  Not cosmology



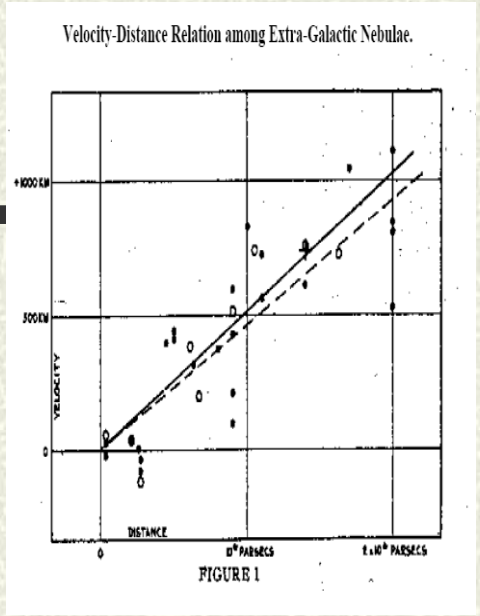
The expanding universe

- **RAS meeting (1930)**
  Eddington, de Sitter
  If redshifts are velocities, and if effect is non-local
  Static cosmic models don't match observations

- **Time-varying universe?**
  Hubble's law = expansion of space?

- **Lemaître expanding model**
  Eddington contacted by Lemaître
  1927 model republished in English (1931)

- **Friedman-Lemaître models circulated**
  Time-varying radius
  Time-varying density of matter
  Evolving universe



A Homogeneous Universe of Constant Mass and Increasing Radius accounting for the Radial Velocity of Extra-galactic Nebulæ. By Abbé G. Lemaître.

(Translated by permission from "Annales de la Société scientifique de Bruxelles," Tome XLVII, série A, première partie.)

1. *Introduction.*

According to the theory of relativity, a homogeneous universe may exist such that all positions in space are completely equivalent; there is no centre of gravity. The radius of space R is constant; space is elliptic, *i.e.* of uniform positive curvature $1/R^2$; straight lines starting from a point come back to their origin after having travelled a path of length πR; the volume of space has a finite value $\pi^2 R^3$; straight lines are closed lines going through the whole space without encountering any boundary.

Two solutions have been proposed. That of de Sitter ignores the existence of matter and supposes its density equal to zero. It leads to special difficulties of interpretation which will be referred to later, but it is of extreme interest as explaining quite naturally the observed receding velocities of extra-galactic nebulæ, as a simple consequence of the properties of the gravitational field without having to suppose that we are at a point of the universe distinguished by special properties.

The other solution is that of Einstein. It pays attention to the evident fact that the density of matter is not zero, and it leads to a relation between this density and the radius of the universe. This relation forecasted the existence of masses enormously greater than any known at the time. These have since been discovered, the distances

The expanding, evolving universe (1930 -)

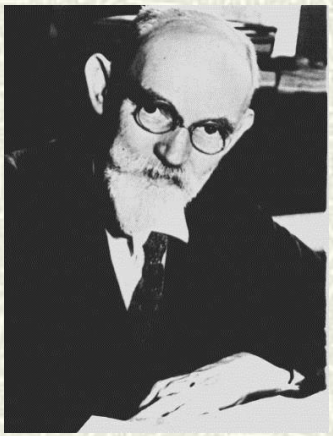
- **Eddington (1930, 31)**
  On the instability of the Einstein universe
  Expansion caused by condensation?

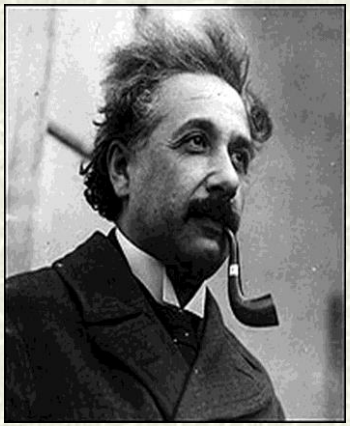
- **Tolman (1930, 31)**
  On the behaviour of non-static models
  Expansion caused by annihilation of matter ?

- **de Sitter (1930, 31)**
  Further remarks on the expanding universe
  Expanding universes of every flavour

- **Einstein (1931, 32)**
  Friedman-Einstein model $k = 1,\ \lambda = 0$
  Einstein-de Sitter model $k = 0,\ \lambda = 0$

Occam's razor?





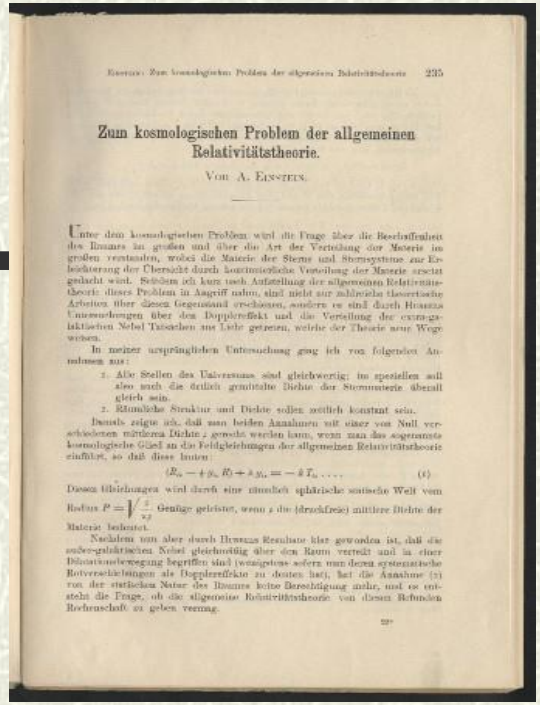
<u>If</u> redshifts represent expansion…
Evolving models

IV Einstein's 1931 model

- **Einstein's first dynamic model of the cosmos**

  Often cited, rarely read (not translated)

$$\frac{3P'^2}{P^2} + \frac{3c^2}{P^2} - \lambda = \kappa c^2 \rho \,.$$



Zum kosmologischen Problem der allgemeinen Relativitätstheorie.

Von A. Einstein.

- **Adopts Friedman 1922 model**

  Time-varying, closed universe: k =1

  Cosmic constant redundant: $\lambda g_{\mu\nu} = 0$

$$\frac{P'^2}{P^2} + \frac{2P''}{P} + \frac{c^2}{P^2} - \lambda = 0$$

$$\left(\frac{dP}{dt}\right)^2 = c^2 \frac{P_0 - P}{P}$$

- **Extraction of parameters!**

  Radius, density of matter

  $R \sim 10^8$ lyr, $\rho \sim 10^{-26}$ g/cm^3

$$D = \frac{1}{P}\frac{dP}{dt}\cdot\frac{1}{c}$$

$$D^2 = \frac{1}{P^2}\frac{P_0 - P}{P}$$

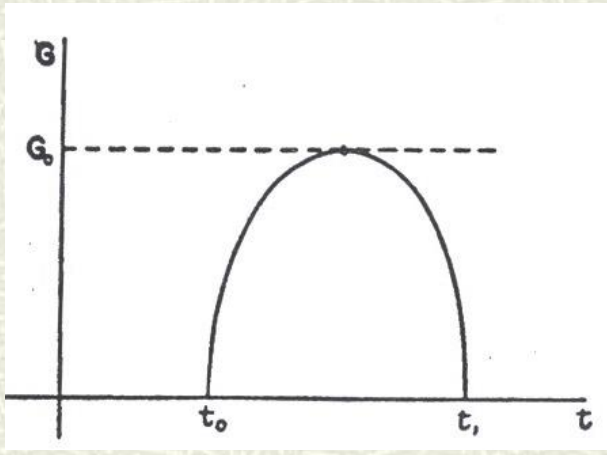
$$D^2 \sim \kappa\rho$$

$$P \sim \frac{1}{D}$$

- **Timespan problem**

  10^{10} yr: *conflict with astrophysics*

  Attributed to simplifying assumptions (homogeneity)



Einstein's 1931 model revisited

- **First translation into English**

  O'Raifeartaigh and McCann 2014

$$D = \frac{1}{P}\frac{dP}{dt}\cdot\frac{1}{c}$$

$$D^2 = \frac{1}{P^2}\frac{P_0 - P}{P}$$

$$P \sim \frac{1}{D}$$

- **Anomalies in calculations of radius and density**

  $P \sim 10^8$ lyr, $\rho \sim 10^{-26}$ g/cm^3

  Should be $P \sim 10^9$ lyr, $\rho \sim 10^{-28}$ g/cm^3

$$D^2 = \frac{1}{3}\kappa\rho\frac{P_0 - P}{P}$$

$$D^2 \sim \kappa\rho$$

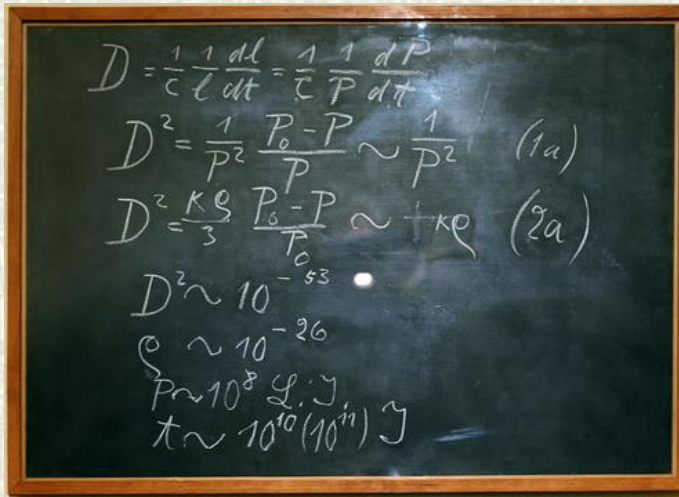
Oxford lecture (May 1931)

- **Source of error?**

  Oxford: $D^2 \sim 10^{-53}$ cm^{-2} (*should be* 10^{-55} cm^{-2})

  Time miscalculation $t \sim 10^{10}$ yr (*should be* 10^9 yr)

  Non-trivial error: misses conflict with radioactivity



- **<u>Not a cyclic model</u>**

  "Model fails at P = 0 "

  Contrary to what is often stated

Einstein-de Sitter model (1932)

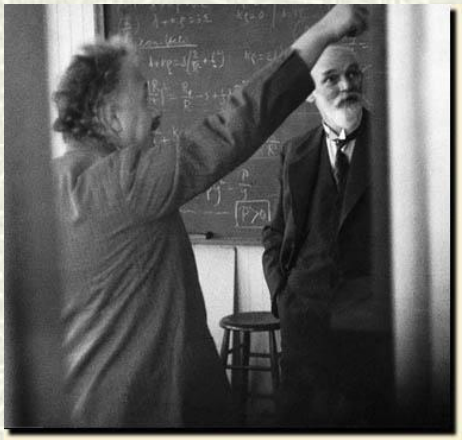
- **Curvature not a given in dynamic models**
  - *Not observed empirically*
  - *Remove spatial curvature (Occam's razor)*

$$ds^2 = -R^2(dx^2 + dy^2 + dz^2) + c^2dt^2$$

$$\frac{3R'^2}{R^2} + \frac{3c^2}{R^2} - \lambda = \kappa c^2 \rho,$$

$$\frac{1}{R^2}\left(\frac{dR}{cdt}\right)^2 = \frac{1}{3}\kappa\rho.$$

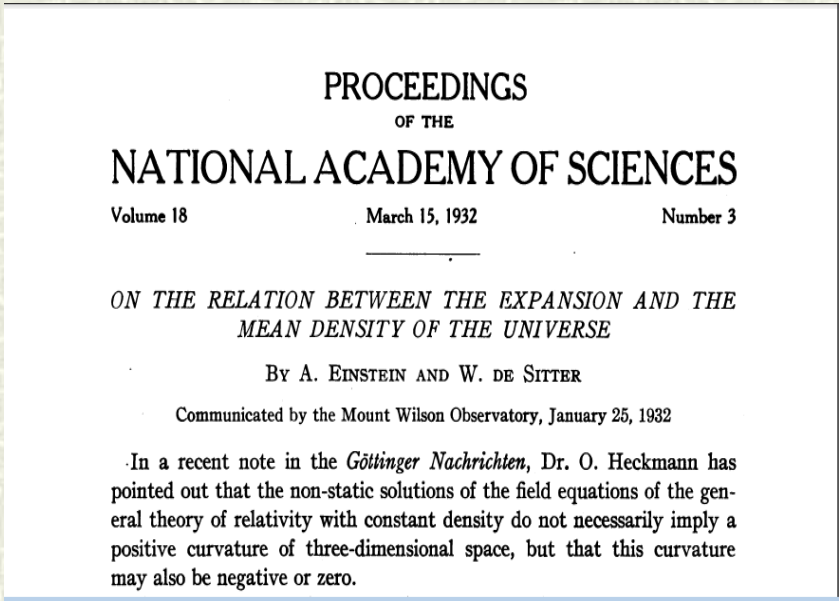
$$h^2 = \frac{1}{3}\kappa\rho$$



- **Simplest Friedman model**
  - *Time-varying universe with $\lambda = 0$, $k = 0$*
  - *Important hypothetical case: critical universe*
  - *Critical density : $\rho = 10^{-28}$ g/cm^3*

- **<u>Becomes standard model</u>**
  - *Despite high density of matter*
  - *Despite age problem*

<u>Time evolution not considered in paper – see title</u>



PROCEEDINGS
OF THE
NATIONAL ACADEMY OF SCIENCES

Volume 18 March 15, 1932 Number 3

ON THE RELATION BETWEEN THE EXPANSION AND THE MEAN DENSITY OF THE UNIVERSE

By A. Einstein and W. de Sitter

Communicated by the Mount Wilson Observatory, January 25, 1932

In a recent note in the *Göttinger Nachrichten*, Dr. O. Heckmann has pointed out that the non-static solutions of the field equations of the general theory of relativity with constant density do not necessarily imply a positive curvature of three-dimensional space, but that this curvature may also be negative or zero.

Einstein-de Sitter model revisited

- **Einstein's cosmology review of 1933**
  - *Review of dynamic models from first principles*
  - *Culminates in Einstein-de Sitter model*
  - *Cosmic constant banished*
  - *Possibility of flat geometry*

$$2A\frac{d^2A}{dt^2}+\left(\frac{dA}{dt}\right)^2=0$$

$$3\left(\frac{\frac{dA}{dt}}{A}\right)^2=\varkappa\rho c^2.$$

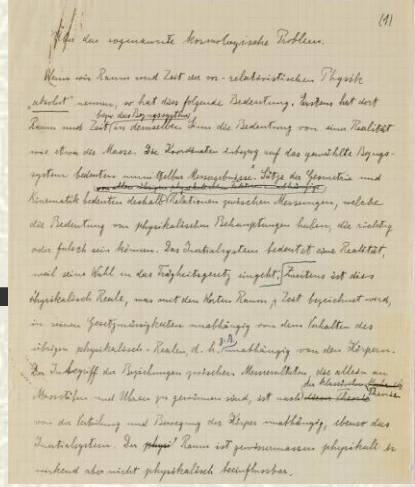
- **Parameters extracted**
  - *Critical density of 10^{-28} g/cm^3 : reasonable*
  - *Timespan of 10^{10} years: conflict with astrophysics*
  - *Attributed to simplifications (incorrect estimate)*

$$3h^2=\varkappa\rho c^2\ (=8\pi K\rho)$$

$$A=c(t-t_0)^{\frac{2}{3}}.$$

- **Published in 1933!**
  - *French book; small print run*
  - *Intended for scientific journal; not submitted*
  - *Significant paper*

$$t-t_0=\frac{2}{3h}.$$



SUR LA STRUCTURE COSMOLOGIQUE DE L'ESPACE [1]

Si nous appelons l'espace et le temps de la physique prérelativiste « absolus », il faut y voir la signification suivante. Tout d'abord l'espace et le temps et, par suite, le système de référence, y figurent dans le même sens comme réalité que, par exemple, la masse. Les coordonnées du système de référence choisi y correspondent immédiatement à des résultats de mesure [2]. Les propositions de géométrie et de cinématique signifient pour cette raison des relations entre des mesures ayant la valeur d'affirmations physiques, qui peuvent être vraies ou fausses. Le système d'inertie possède une réalité physique, parce que son choix entre dans la loi d'inertie. En second lieu, cette réalité physique, qui est désignée par les termes espace + temps, est, quant à ses lois, indépendante du comportement des autres réalités physiques, par exemple, des corps.

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Über das sogenannte kosmologische Problem.
by Einstein, Albert (Author)
Date: 1932-09-01
Archival Call Number: 1-115
Document Type: Autograph Draft of Document (ADDft)

DB Info

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.
by Einstein, Albert (Author)
Date: 1917-02-08
Archival Call Number: 90-9
Document Type: Printed Document (PD)

DB Info

Die Beantwortung Ihrer Frage, überhaupt kosmologischer Fragen
by Einstein, Albert (Author)
Date: 1929-09-20
Archival Call Number: 25-231
Document Type: Carbon/File Copy of Typed Letter (TLC)

DB Info

Das kosmologische Glied soll überholt sein.
by Hopf, Ludwig (Author)
Date: 1932-06-14
Archival Call Number: 13-306
Document Type: Autograph Letter Signed (ALS)

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Über das sogenannte kosmologische Problem.

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End Date:	1932-09-30
Main Author:	Einstein, Albert (Author)
Other Persons:	Mayer, Walther (Author)
Language:	German
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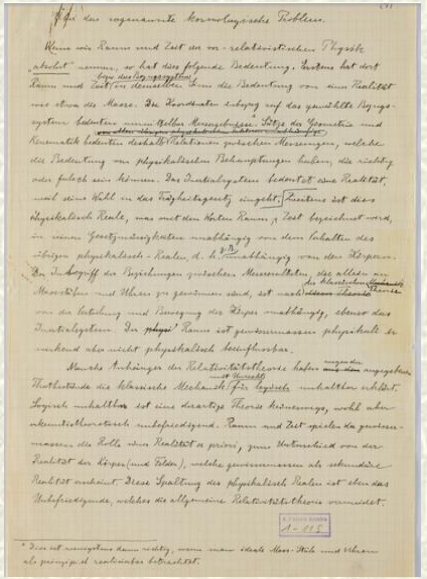


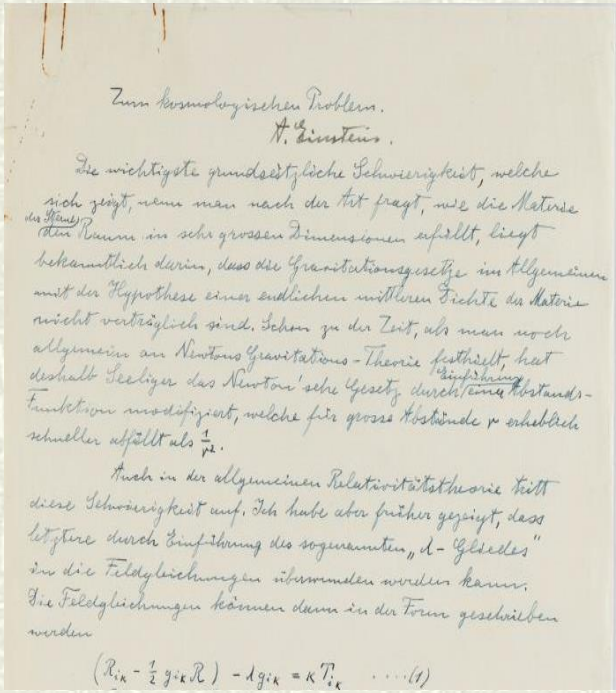
Bonus: Einstein's steady-state model

- **Unpublished manuscript**
  Archived as draft of F-E model (1931)
  Similar title, opening to F-E model

- **Something different**
  Cosmological constant
  "Constant matter density determines expansion"

- **Steady-state model**
  Continuous formation of matter from vacuum
  Fatal flaw; null solution
  Abandoned, not amended

Anticipates controversial theory (Hoyle)



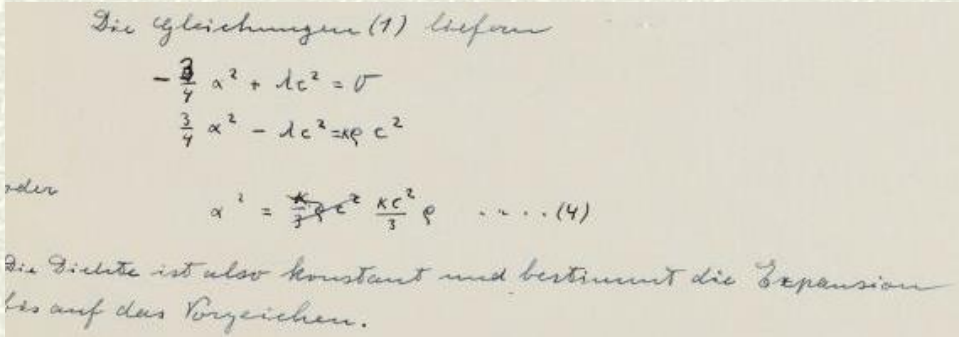
Zum kosmologischen Problem.

A. Einstein.

Die wichtigste grundsätzliche Schwierigkeit, welche sich zeigt, wenn man nach der Art fragt, wie die Materie den Raum in sehr grossen Dimensionen erfüllt, liegt bekanntlich darin, dass die Gravitationsgesetze im Allgemeinen mit der Hypothese einer endlichen mittleren Dichte der Materie nicht verträglich sind. Schon zu der Zeit, als man noch allgemein an Newtons Gravitations-Theorie festhielt, hat deshalb Seeliger das Newton'sche Gesetz durch eine Abstands-Funktion modifiziert, welche für grosse Abstände r erheblich schneller abfällt als $\frac{1}{r^2}$.

Auch in der allgemeinen Relativitätstheorie tritt diese Schwierigkeit auf. Ich habe aber früher gezeigt, dass letztere durch Einführung des sogenannten „λ-Gliedes" in die Feldgleichungen überwunden werden kann. Die Feldgleichungen können dann in der Form geschrieben werden

$$\left(R_{ik} - \tfrac{1}{2} g_{ik} R\right) - \lambda g_{ik} = \kappa T_{ik} \quad \ldots (1)$$



Die Gleichungen (1) liefern

$$-\frac{3}{4}\alpha^2 + \lambda c^2 = 0$$

$$\frac{3}{4}\alpha^2 - \lambda c^2 = \kappa\rho c^2$$

oder

$$\alpha^2 = \frac{\kappa}{3} c^2 \rho = \frac{\kappa c^2}{3}\rho \quad \ldots (4)$$

Die Dichte ist also konstant und bestimmt die Expansion bis auf das Vorzeichen.

Einstein's steady-state model (philosophy)

New solution

"In what follows, I wish to draw attention to a solution to equation (1) that can account for Hubbel's facts, and in which the density is constant over time"

Matter creation

"If one considers a physically bounded volume, particles of matter will be continually leaving it. For the density to remain constant, new particles of matter must be continually formed within that volume from space "

Dark energy

"The conservation law is preserved in that, by setting the λ-term, space itself is not empty of energy; its validity is well known to be guaranteed by equations (1)."

Abandoned model

- **de Sitter line element**

  Correct geometry

- **Simultaneous equations**

$$\alpha^2 = \frac{\kappa c^2}{3}\rho$$

  Error in derivation

  Null solution

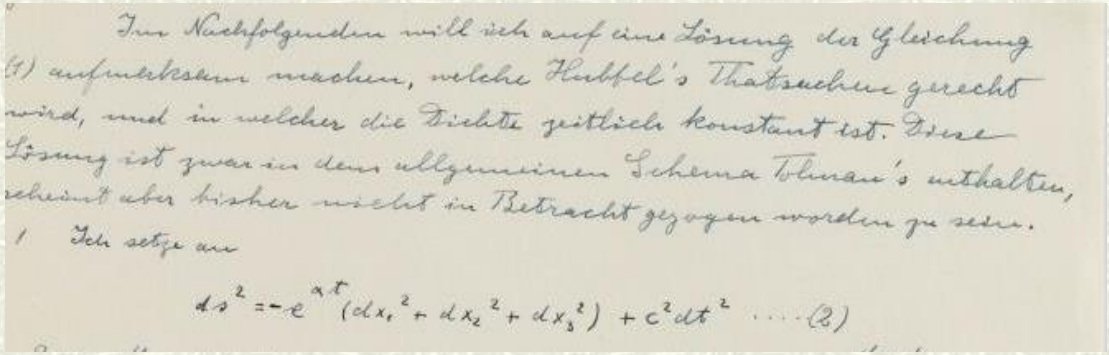
- **Einstein's crossroads**

  Realised problem on revision

  Declined to amend GFE

- **Evolving models**

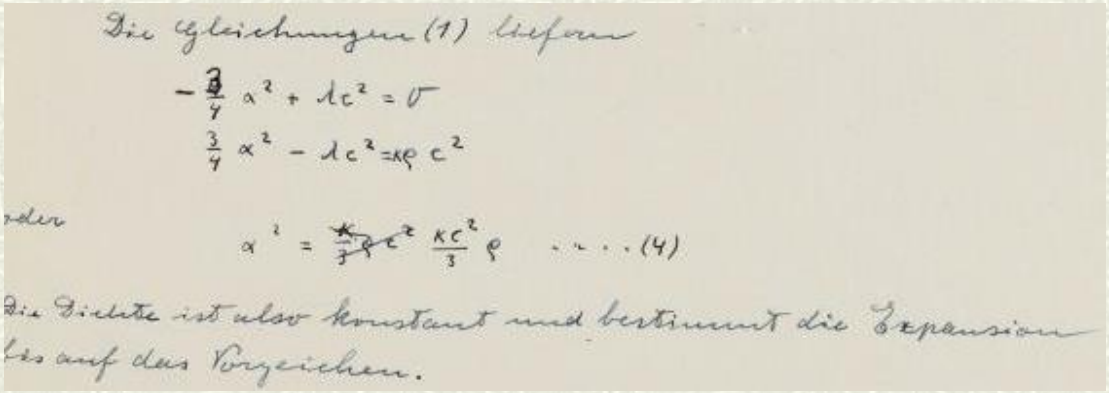
  Less contrived and set $\lambda = 0$



Im Nachfolgenden will ich auf eine Lösung der Gleichung (1) aufmerksam machen, welche Hubbel's Thatsachen gerecht wird, und in welcher die Dichte zeitlich konstant ist. Diese Lösung ist zwar in dem allgemeinen Schema Tolman's enthalten, scheint aber bisher nicht in Betracht gezogen worden zu sein.

Ich setze an

$$ds^2 = -e^{\alpha t}(dx_1^2 + dx_2^2 + dx_3^2) + c^2 dt^2 \quad \ldots (2)$$



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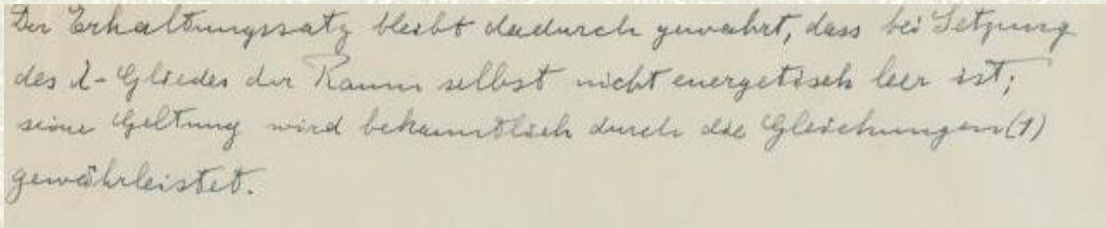
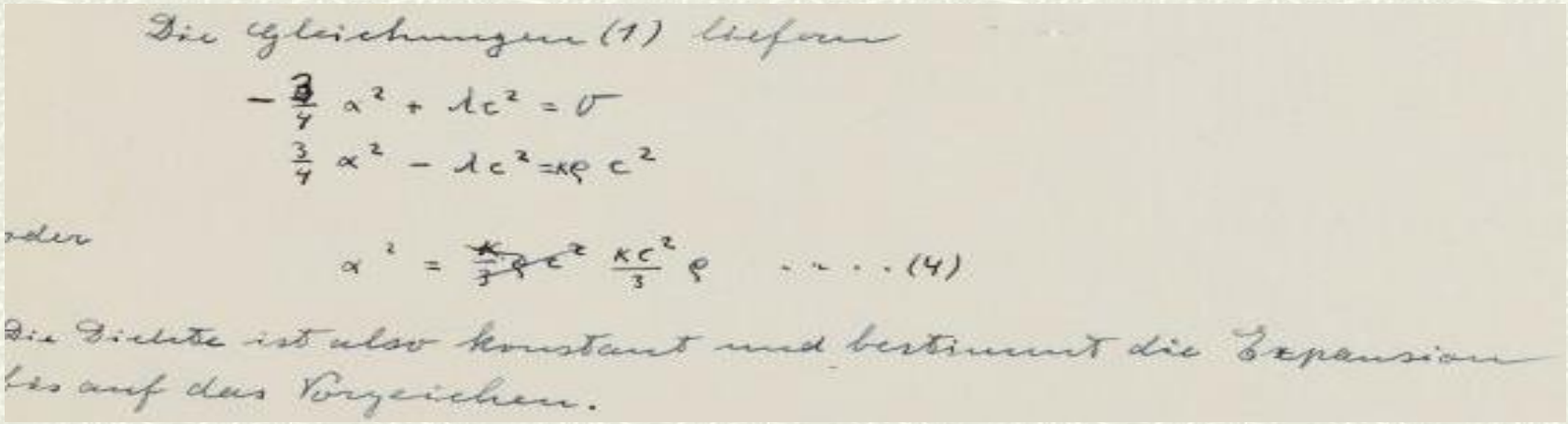


Der Erhaltungssatz bleibt dadurch gewahrt, dass bei Setzung des λ-Gliedes der Raum selbst nicht energetisch leer ist; seine Geltung wird bekanntlich durch die Gleichungen (1) gewährleistet.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$$\frac{3}{4}\alpha^2 - \lambda c^2 = \kappa\rho c^2$$

oder

$$\alpha^2 = \frac{\kappa c^2}{3}\rho \quad \ldots\ldots (4)$$

Die Dichte ist also konstant und bestimmt die Expansion bis auf das Vorzeichen.

Taking $T_{44} = \rho c^2$ (all other components zero) in the *time* component of equation (1) we obtain $\left(R_{44} - \frac{1}{2}g_{44}R\right) - \lambda g_{44} = \kappa\rho c^2$.
This gives on analysis - $3\alpha^2/4 + 3\alpha^2/2 - \lambda c^2 = \kappa\rho c^2$
the second of Einstein's simultaneous equations.

From the *spatial* component of equation (1), we obtain $\left(R_{ii} - \frac{1}{2}g_{ii}R\right) - \lambda g_{ii} = 0$.
This gives on analysis $3\alpha^2/4 - 3\alpha^2/2 + \lambda c^2 = 0$
for the first of the simultaneous equations.

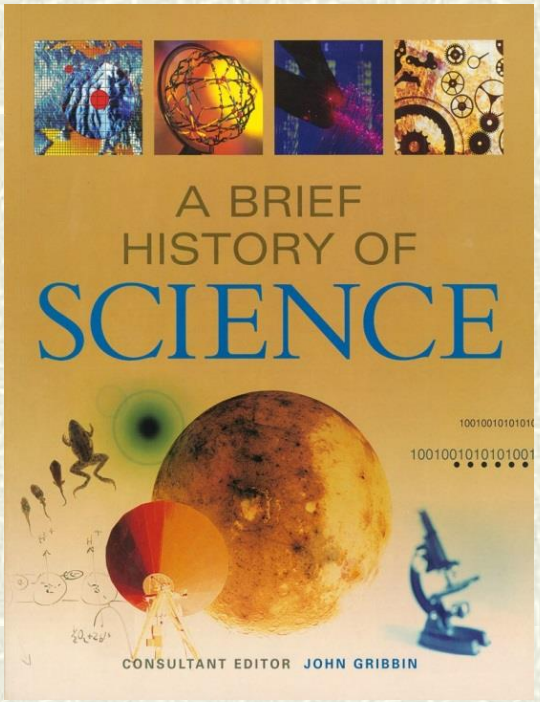
It is plausible that Einstein made a sign error here, initially getting $3\alpha^2/4 + 3\alpha^2/2 + \lambda c^2 = 0$ for this equation. (W. Nahm)

A significant find

- **New perspective on steady-state theory (1950s)**
  Logical possibility: not a crank theory

- **Insight into Einstein's philosophy**
  Discards model rather than introduce new term to GFE
  Occam's razor approach

- **Insight into scientific progress**
  Unsuccessful theories important
  Understanding the development of successful theories
  Not Kuhnian paradigm shift
  Slow dawning



Links with modern cosmology
Dark energy: creation energy and λ
Cosmic inflation: de Sitter metric

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Einstein's lost theory uncovered

Physicist explored the idea of a steady-state Universe in 1931.

Davide Castelvecchi

24 February 2014

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Einstein's Lost Theory Uncovered

The famous physicist explored the idea of a steady-state universe in 1931

nature

Feb 25, 2014 | By Davide Castelvecchi and Nature magazine

A manuscript that lay unnoticed by scientists for decades has revealed that Albert Einstein once dabbled with an

New Discovery Reveals Einstein Tried To Devise A Steady State Model Of The Universe

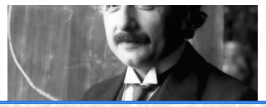
2 comments, 2 called-out + Comment Now + Follow Comments

Almost 20 years before the late Fred Hoyle and his colleagues devised the Steady State Theory, Albert Einstein toyed with a similar idea: that the universe was eternal, expanding outward with a consistent input of spontaneously generating matter.

An Irish physicist came across the paper last year and could hardly believe According to this week's article in Nature,

model of the universe very different to today's Big Bang Theory.

The manuscript, which hadn't been referred to by scientists for decades,



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THE IRISH TIMES **Science** Monday, March 10, 2014

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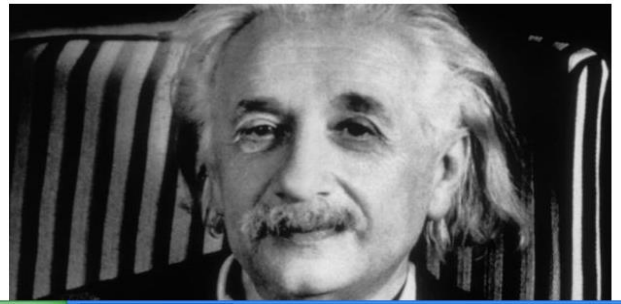
WIT researchers discover 'lost' Einstein model of universe

Scientists uncovered misfiled papers while searching Jerusalem university's online archive



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08:25 Flannery faces call from all parties to attend PAC

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The steady-state universe (1948)

- **Expanding but unchanging universe**

  Hoyle, Bondi and Gold (1948)

  Disliked speculation about physics of early epochs

  Perfect cosmological principle?

Bondi, Gold and Hoyle

- **Continuous creation of matter**

  Very little matter required

  No beginning, no age paradox

Hoyle and Narlikar (1962)

- **Replace λ with creation term** (Hoyle)

$$G_{\mu\nu} + C_{\mu\nu} = k T_{\mu\nu}$$

- **Improved version (1962)**

$$G_{\mu\nu} + \lambda g_{\mu\nu} = k T (C_{\mu} + C_{\nu})$$

Steady-state vs big bang

- **Optical astronomy (1950s)**

  Amended timescale of expansion (Baade, Sandage)

  Age problem removed

- **Radio-astronomy (1960s)**

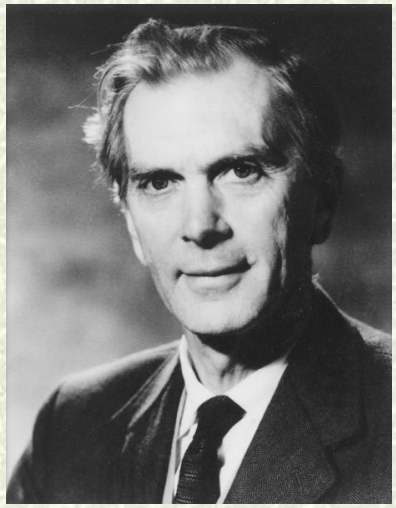
  Galaxy distributions at different epochs

  Cambridge 3C Survey (Ryle)

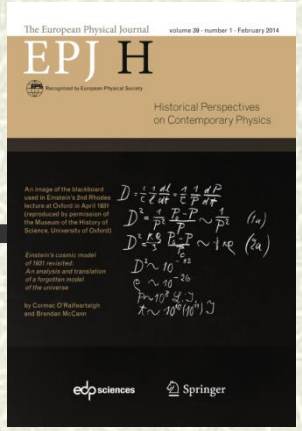
- **Cosmic microwave background**

  Low temperature, low frequency

  Remnant of early universe

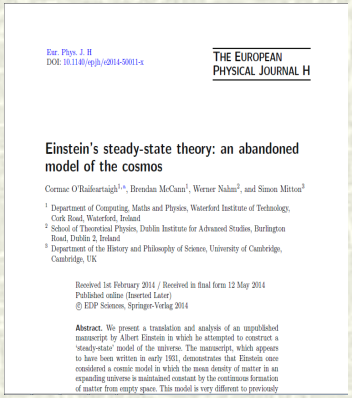


Results: publications



- **Einstein's 1931 model**

Einstein's cosmic model of 1931 revisited; an analysis and translation of a forgotten model of the universe. O'Raifeartaigh, C. and B. McCann. 2014 ***Eur. Phys. J (H)*** **39(1):63-85**

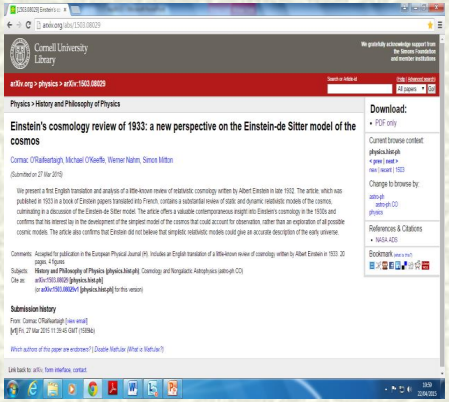


- **Einstein's steady-state manuscript**

Einstein's steady-state theory: an abandoned model of the cosmos. O'Raifeartaigh, C., B. McCann, W. Nahm and S. Mitton. 2014 ***Eur. Phys. J (H)*** **39(3):353-367**

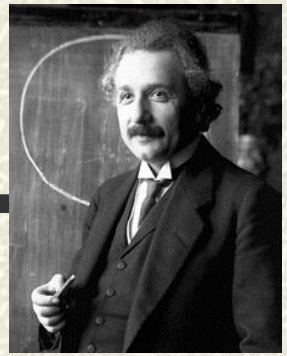
- **Einstein-de Sitter model**

Einstein's cosmology review of 1933: a new perspective on the Einstein-de Sitter model of the cosmos. O'Raifeartaigh, C., M.O'Keeffe, W. Nahm and S. Mitton. 2015. To be published in ***Eur. Phys. J (H)***



- **Review paper: conclusions**

Einstein's cosmology: conclusions



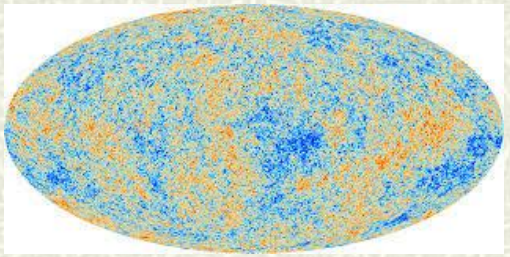
- **Major test for general relativity**
  Assumptions; space-time = space + time
  Homogeneous, isotropic and static universe

- **Embraces dynamic cosmology**
  New evidence – new models (JMK)
  Timespan of Friedman models puzzling
  Steady-state universe?

Hubble constant revised

- **Evolving models (less contrived)**
  Simplest models first
  Extraction of parameters; compatible with observation?
  Timespan puzzle attributed to simplifying assumptions
  No discussion of origins (wary of extrapolations)

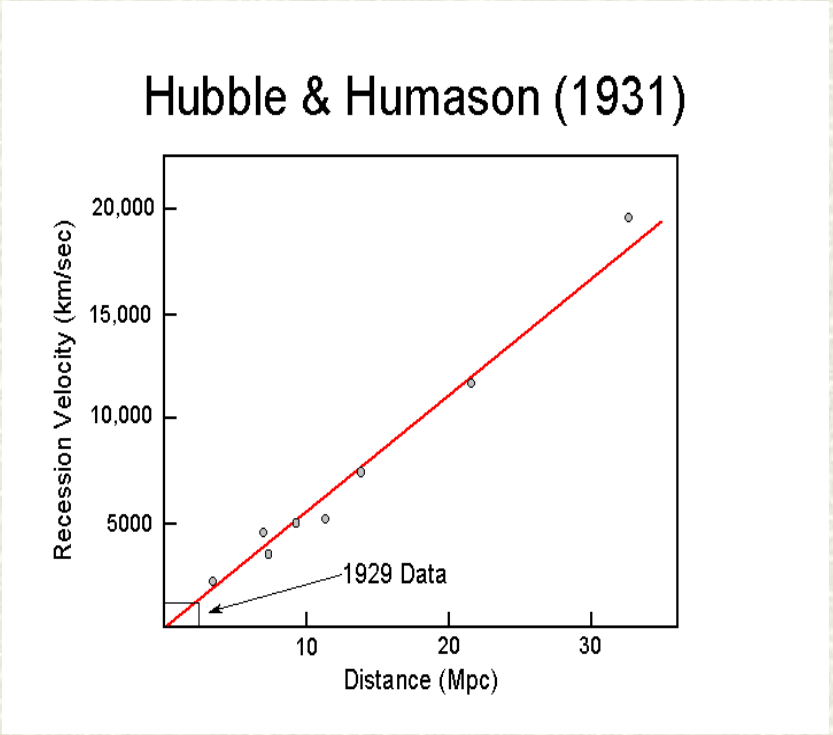
Verdict (1933, 1945): more data needed



Cosmic microwave background
Homogeneous, flat universe

Observational parameters needed (1930s)

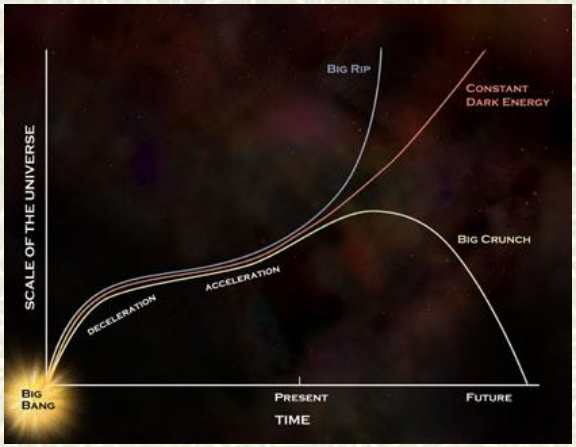
- **Spatial curvature** $k = -1,0,1?$
- **Cosmic constant** $\lambda = 0?$
- **Deacceleration** $q_0 = -\ \ddot{R}/\dot{R}^2$
- **Density of matter** $\rho < \rho_{crit}$?
- **Timespan** $\tau = 10^{10}\ yr?$
- **Hubble constant** $\dot{R}/R = 500\ kms^{-1}Mpc^{-1}?$



What do redshifts represent?
Is expansion a local effect?

Hubble and Tolman 1935

Einstein's steady-state model and cosmology today



- **Dark energy (1998)**

  Accelerated expansion (observation)

  Positive cosmological constant

- **Einstein's dark energy**

  "The conservation law is preserved in that, by setting the λ-term, space itself is not empty of energy; its validity is well known to be guaranteed by equations (1)."

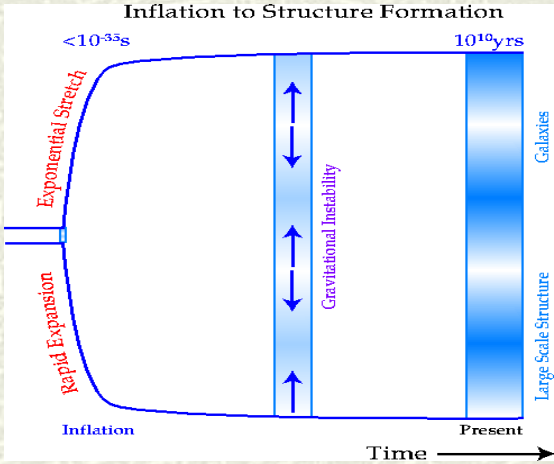
- **Cosmic inflation**

  Inflationary models use de Sitter metric

  Used in all steady-state models

  Flat curvature, constant rate of matter creation

  Different time-frame!



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THE EUROPEAN PHYSICAL JOURNAL H

Einstein's cosmic model of 1931 revisited: an analysis and translation of a forgotten model of the universe

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Received 21 September 2013 / Received in final form 20 December 2013
Published online 4 February 2014

Abstract. We present an analysis and translation of Einstein's 1931 paper "*Zum kosmologischen Problem der allgemeinen Relativitätstheorie*" or "*On the cosmological problem of the general theory of relativity*". In this little-known paper, Einstein proposes a cosmic model in which the universe undergoes an expansion followed by a contraction, quite different to the monotonically expanding Einstein-de Sitter model of 1932. The paper offers many insights into Einstein's cosmology in the light of the first evidence for an expanding universe and we consider his views of issues such as the curvature of space, the cosmological constant, the singularity and the timespan of the expansion. A number of original

The European Physical Journal volume 39 · number 1 · February 2014

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Historical Perspectives on Contemporary Physics

An image of the blackboard used in Einstein's 2nd Rhodes lecture at Oxford in April 1931 (reproduced by permission of the Museum of the History of Science, University of Oxford)

Einstein's cosmic model of 1931 revisited: An analysis and translation of a forgotten model of the universe

by Cormac O'Raifeartaigh and Brendan McCann

edp sciences Springer

Eur. Phys. J. H
DOI: 10.1140/epjh/e2014-50011-x

THE EUROPEAN PHYSICAL JOURNAL H

Einstein's steady-state theory: an abandoned model of the cosmos

Cormac O'Raifeartaigh[1,a], Brendan McCann[1], Werner Nahm[2], and Simon Mitton[3]

[1] Department of Computing, Maths and Physics, Waterford Institute of Technology, Cork Road, Waterford, Ireland
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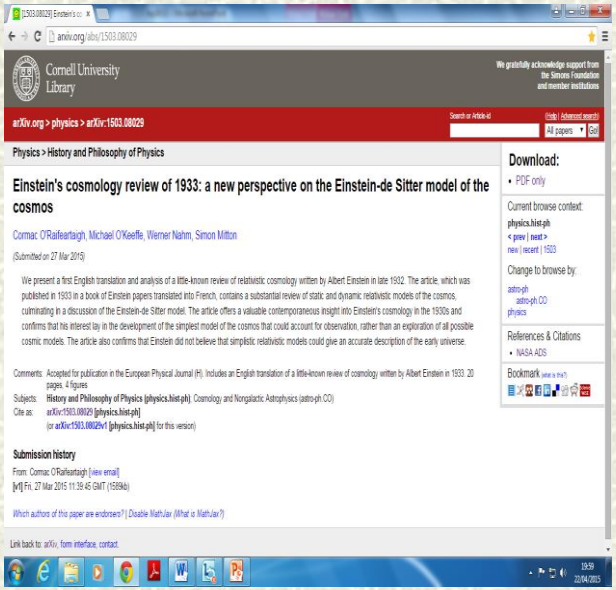
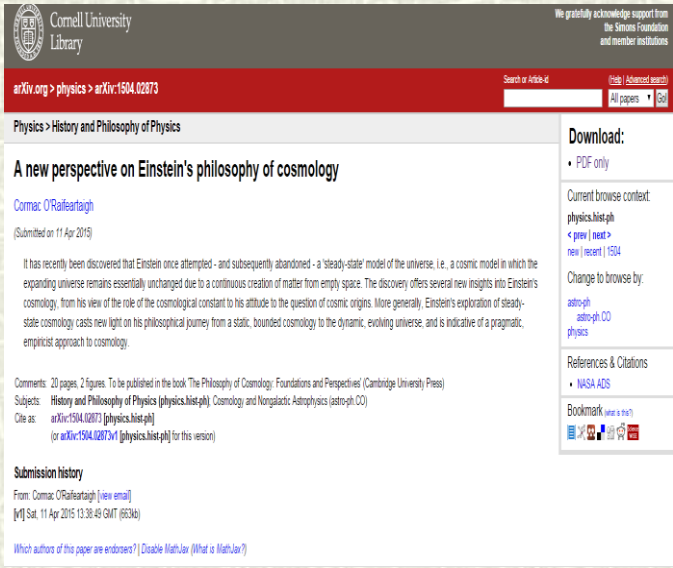
[3] Department of the History and Philosophy of Science, University of Cambridge, Cambridge, UK

Received 1st February 2014 / Received in final form 12 May 2014
Published online (Inserted Later)

Abstract. We present a translation and analysis of an unpublished manuscript by Albert Einstein in which he attempted to construct a 'steady-state' model of the universe. The manuscript, which appears to have been written in early 1931, demonstrates that Einstein once considered a cosmic model in which the mean density of matter in an expanding universe is maintained constant by the continuous formation of matter from empty space. This model is very different to previously

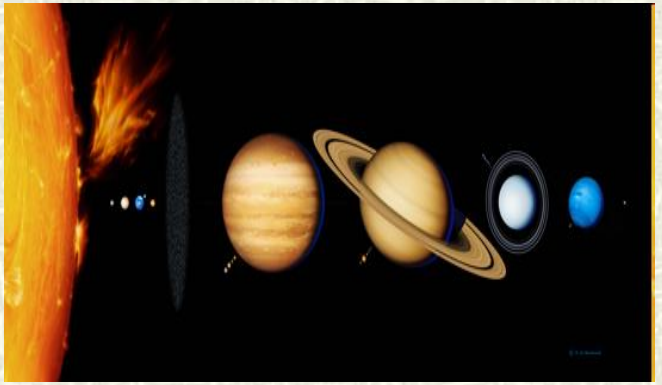




A cosmic puzzle

- **What is causing recession of the galaxies ?**
  If redshifts are velocities
  If effect is non-local

- **Newton's law of gravity**
  Gravity pulls in, not out
  No other long range force for neutral matter

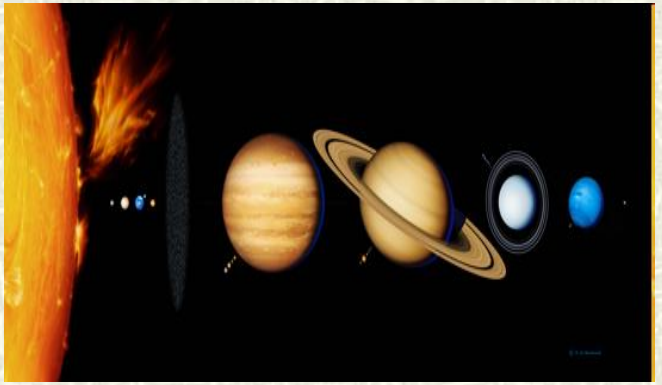


- **Space, time are fixed**
  Not affected by contents of universe
  Eternal, infinite universe

Conclusions

- **Cosmology – a testing ground for general relativity?**
  Assumptions; space-time = space + time
  Homogeneity and isotropy
  Static universe

- **Dynamic cosmology**
  Steady-state universe?
  Evolving models less contrived



- **Evolving models**
  Timespan problem: attributed to assumptions
  Origins puzzle: ignored

- **Verdict**
  More data needed

An origin for the universe? (1931)

Fr Georges Lemaître

- **Expanding *U* smaller in the past**
- **Rewind expanding model to early epochs**
- **Extremely dense, extremely hot**
- **Expanding and cooling ever since**
- **Explosive beginning at *R* = 0?**

Later called ***'The big bang'***

∞ density, ∞ temp at $t = 0$?

Einstein's steady-state model and cosmology today

- **Accelerated expansion (1998)**

  Supernova measurements

  Dark energy – positive cosmological constant

- **Einstein's dark energy**

  "The conservation law is preserved in that, by setting the λ-term, space itself is not empty of energy; its validity is well known to be guaranteed by equations (1)."

  Anticipates positive cosmological constant

- **De Sitter line element**

  $ds^2 = -e^{\alpha t}\,(dx_1^2 + dx_2^2 + dx_3^2) + c^2 dt^2$ ...

  Necessary for all steady-state models

  Identical to inflationary models (different time-frame)