A new perspective on Einstein’s cosmology

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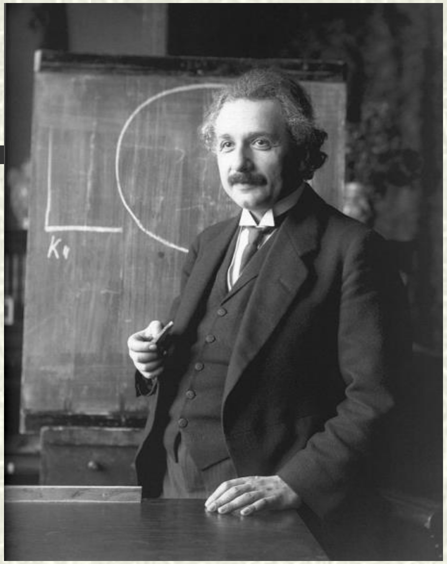
Overview

- **General relativity and the universe**
  The static models of Einstein and de Sitter
  The dynamic models of Alexander Friedman

- **Astronomy and the universe**
  The extra-galactic nebulae (1925)
  The recession of the nebulae (1929)

- **The expanding universe (1930)**
  The dynamic models of Lemaître, Eddington and de Sitter
  Einstein's dynamic models of 1931 and 1932

- **Original discoveries**
  Anomalies in Einstein's models of 1931 and 1932
  Einstein's steady-state model
  Conclusions



Einstein in California (1931)

General relativity (1915)

- **The special theory of relativity (1905)**

  Invariance of laws of physics and c (inertial frames)

  Space, time not absolute: affected by motion

  Space+ time = space-time

$E = mc^2$

$$ds^2 = -c^2 dt^2 + dx^2 + dy^2 + dz^2 = \eta_{\mu\nu} dx^\mu dx^\nu$$

Albert Einstein
1879-1955

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

  Invariance in accelerated frames

  Principle of equivalence , Mach's principle

  Space-time affected by mass

  Gravity = curvature of space-time

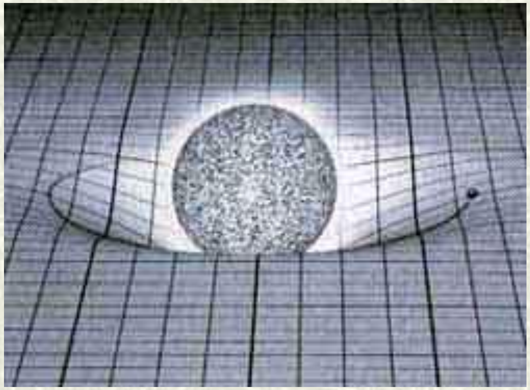
$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

- **Empirical evidence**

  Perihelion of Mercury (post-diction)

  Bending of starlight (Eddington, 1919)

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



Einstein's universe (1917)

- **Apply general relativity to the cosmos**

  Ultimate test for new theory of gravitation

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

- **Assumptions**

  Static universe

  Isotropic and homogeneous

  Metric tensor vanishes at infinity (Mach)

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

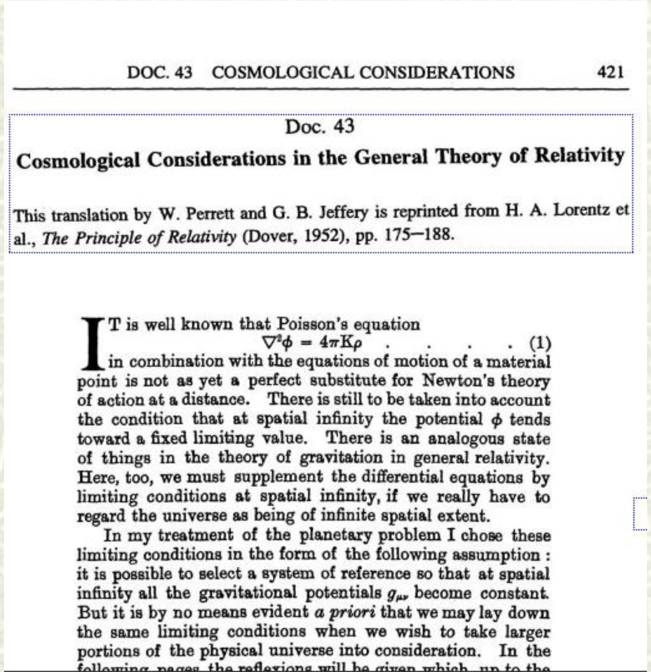
- **Introduce new term in GFE for non-zero solution**

  Preserves covariance

  Closed curvature: no boundary problem

  Matter density and radius defined by λ

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



DOC. 43 COSMOLOGICAL CONSIDERATIONS 421

Doc. 43

Cosmological Considerations in the General Theory of Relativity

This translation by W. Perrett and G. B. Jeffery is reprinted from H. A. Lorentz et al., *The Principle of Relativity* (Dover, 1952), pp. 175–188.

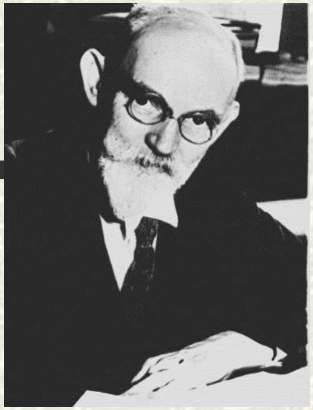
IT is well known that Poisson's equation

$$\nabla^2\phi = 4\pi K\rho \quad . \quad . \quad . \quad . \quad (1)$$

in combination with the equations of motion of a material point is not as yet a perfect substitute for Newton's theory of action at a distance. There is still to be taken into account the condition that at spatial infinity the potential ϕ tends toward a fixed limiting value. There is an analogous state of things in the theory of gravitation in general relativity. Here, too, we must supplement the differential equations by limiting conditions at spatial infinity, if we really have to regard the universe as being of infinite spatial extent.

In my treatment of the planetary problem I chose these limiting conditions in the form of the following assumption: it is possible to select a system of reference so that at spatial infinity all the gravitational potentials $g_{\mu\nu}$ become constant. But it is by no means evident *a priori* that we may lay down the same limiting conditions when we wish to take larger portions of the physical universe into consideration. In the

The de Sitter universe (1917)



- **Apply general relativity to the cosmos**

  Include cosmological constant

- **'Empty' universe solution**

  Reasonable approximation $\mathbf{G}_{\mu\nu} + \lambda g_{\mu\nu} = 0$

  Cosmic constant proportional to curvature of space

- **Disliked by Einstein**

  Conflict with Mach's principle

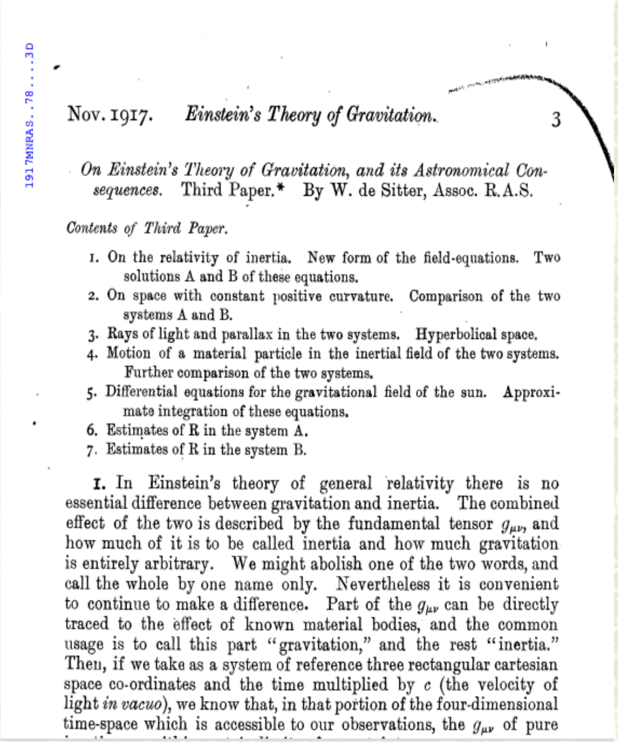
  Problems with singularities?

  Beginning of dislike for cosmic constant

- **Astronomical prediction**

  Radiation from matter redshifted – Slipher effect?

  Static or non-static model? (Weyl 1923, Lemaître 1925)



1917MNRAS..78....3D

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

Alexander Friedman
(1888 -1925)

- **Time-varying solutions (1922)**

  Universe of time-varying radius

  Assume positive spatial curvature

  Two independent differential equations from GFE

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

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

- **Evolving model (*Z. Ph.*)**

  Density of matter varies 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

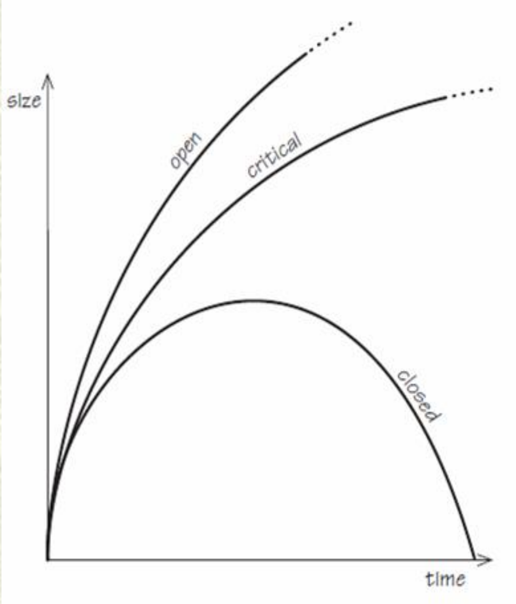
  Mathematical correction, later retracted

  "~~To this a physical reality can hardly be ascribed~~"

$$t=\frac{1}{c}\int_a^R\sqrt{\frac{x}{A-x+\frac{\lambda}{3c^2}x}}\,\mathrm{d}x+B$$

- **Negative spatial curvature (1924)**

  Cosmic evolution, geometry depends on matter



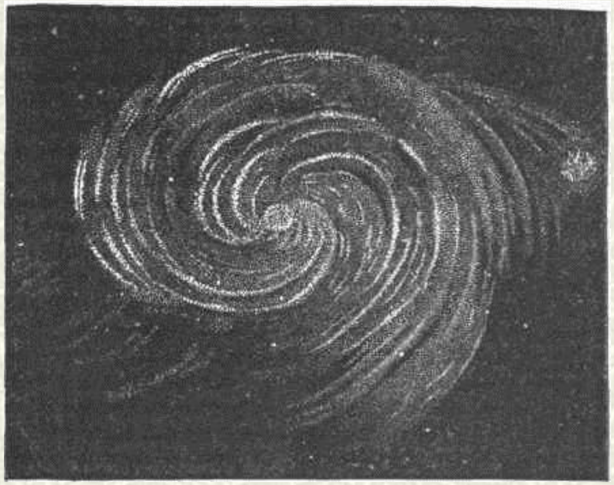
II Astronomy and the universe

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

  Spiral nebulae = clusters of stars ?

  Galaxies beyond Milky Way?

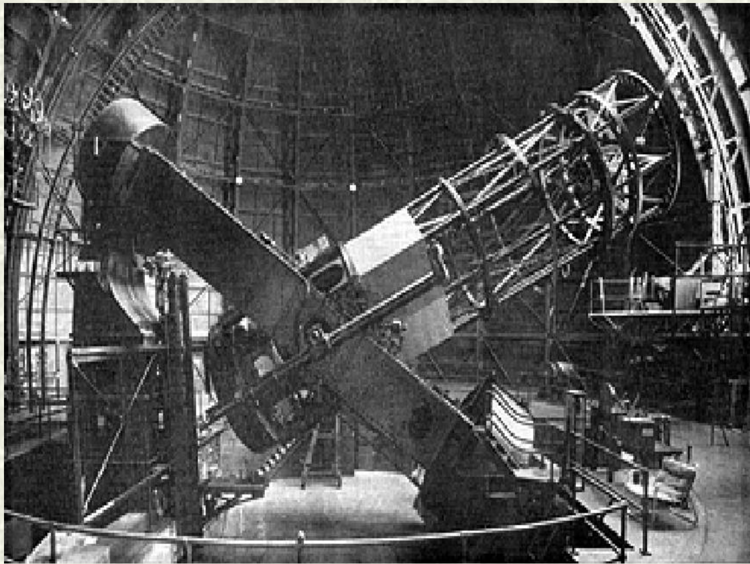
  Light from many spirals red-shifted (Slipher 1915, 1917)



- **The Hooker telescope (1917)**

  100-inch reflector

  Edwin Hubble (1921)



- **Distance of 3 spirals**

  Cepheid variables resolved in nebulae

  Leavitt's period-luminosity relation

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

  A universe of galaxies

Hubble's law

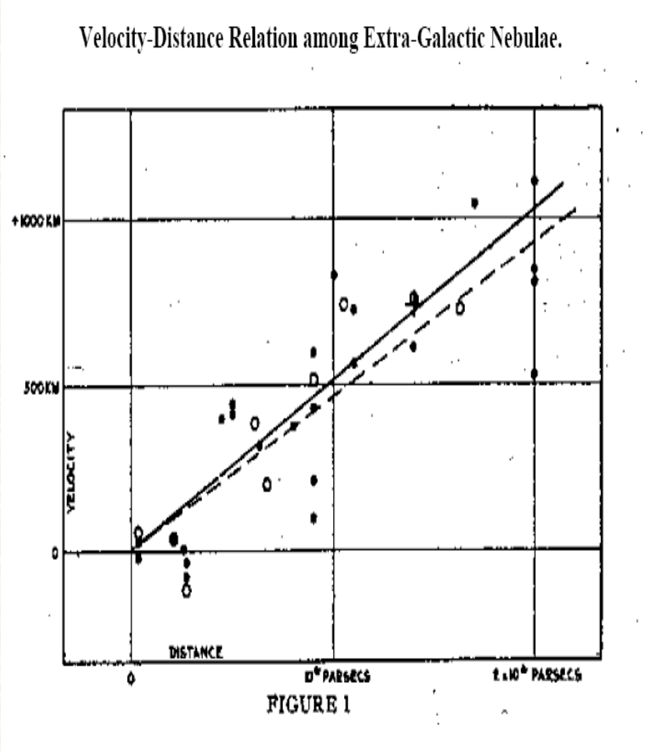
- **A redshift/distance relation for the nebulae?**
  Motivation: establishing distances of all nebulae

Edwin Hubble (1889-1953)

- **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



Lemaître’s universe (1927)

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

  Similar but not identical to Friedman 1922

  Starts from static Einstein universe

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

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

Fr Georges Lemaître

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

  Redshifts from Slipher, distances from Hubble

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

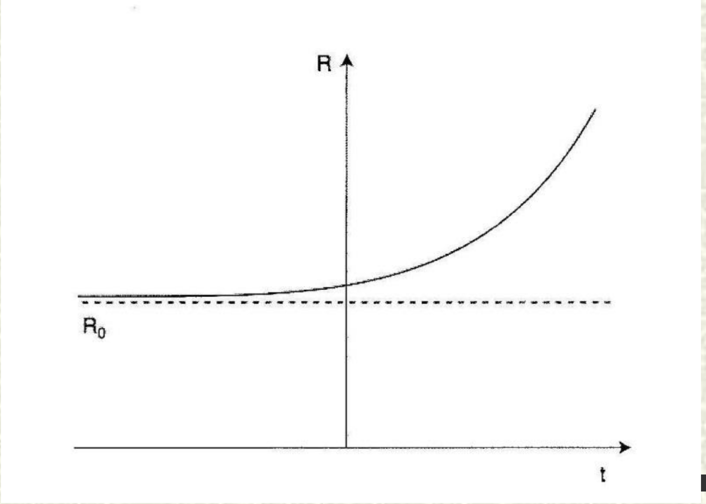
- **Ignored by community**

  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 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

- **Dynamic models?**
  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
  <u>Evolving universe</u>

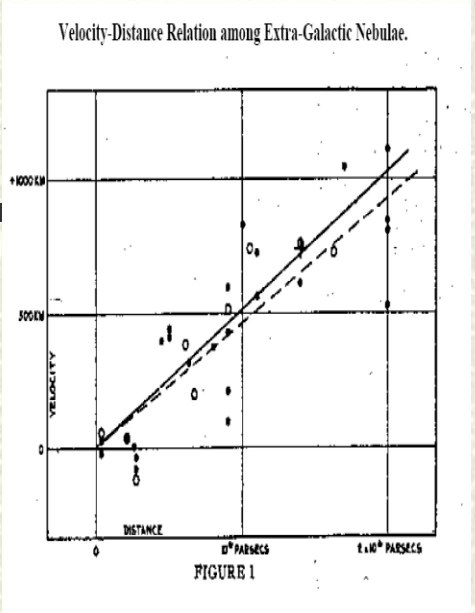
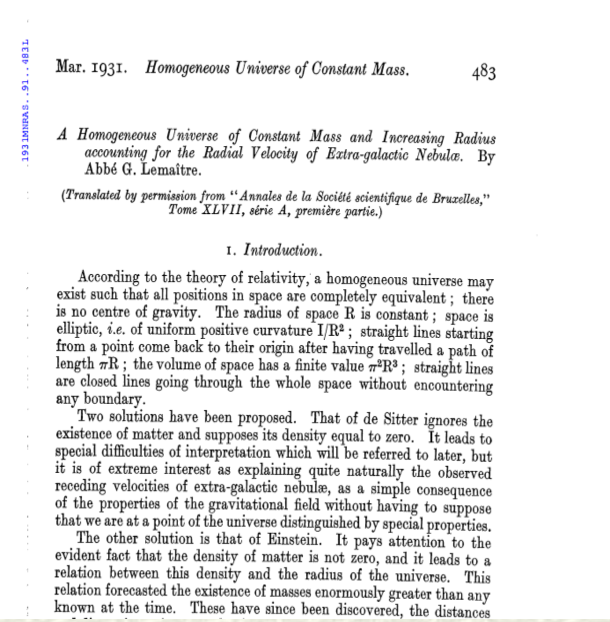


FIGURE 1



1931MNRAS..91..483L

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

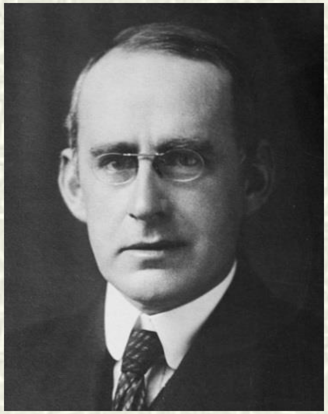
  Expanding universes of every flavour

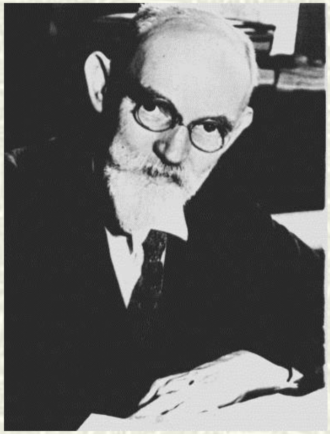
- **Einstein (1931, 32)**

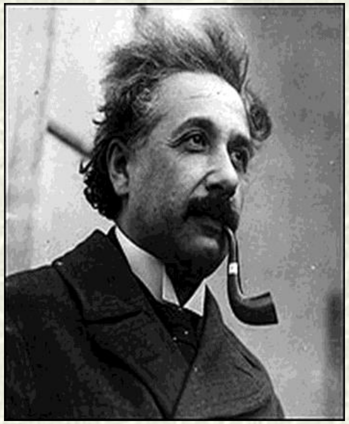
  Friedman-Einstein model $k = 1,\ \lambda = 0$

  Einstein-de Sitter model $k = 0,\ \lambda = 0$

Occam's razor?

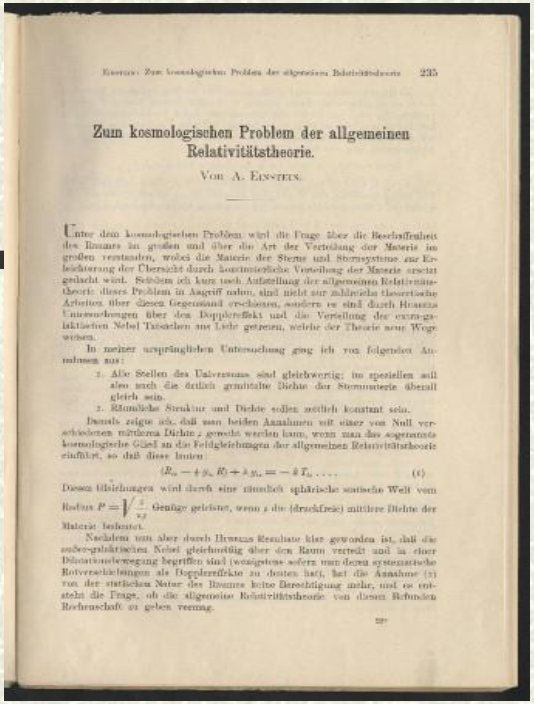






If redshifts represent expansion…
Evolving models

IV Einstein’s 1931 model



Zum kosmologischen Problem der allgemeinen Relativitätstheorie.

Von A. Einstein.

Unter dem kosmologischen Problem wird die Frage über die Beschaffenheit des Raumes im großen und über die Art der Verteilung der Materie im großen verstanden, wobei die Materie der Sterne und Sternsysteme zur Erleichterung der Übersicht durch kontinuierliche Verteilung der Materie ersetzt gedacht wird. Seitdem ich kurz nach Aufstellung der allgemeinen Relativitätstheorie dieses Problem in Angriff nahm, sind nicht nur zahlreiche theoretische Arbeiten über diesen Gegenstand erschienen, sondern es sind durch Hubbles Untersuchungen über den Dopplereffekt und die Verteilung der extra-galaktischen Nebel Tatsachen ans Licht getreten, welche der Theorie neue Wege weisen.

In meiner ursprünglichen Untersuchung ging ich von folgenden Annahmen aus:

1. Alle Stellen des Universums sind gleichwertig; im speziellen soll also auch die örtlich gemittelte Dichte der Sternmaterie überall gleich sein.
2. Räumliche Struktur und Dichte sollen zeitlich konstant sein.

Damals zeigte ich, daß man beiden Annahmen mit einer von Null verschiedenen mittleren Dichte ρ gerecht werden kann, wenn man das sogenannte kosmologische Glied an die Feldgleichungen der allgemeinen Relativitätstheorie einführt, so daß diese lauten:

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

Diesen Gleichungen wird durch eine räumlich sphärische statische Welt vom Radius $P = \sqrt{\frac{2}{\kappa\rho}}$ Genüge geleistet, wenn ρ die (druckfreie) mittlere Dichte der Materie bedeutet.

Nachdem nun aber durch Hubbles Resultate klar geworden ist, daß die außer-galaktischen Nebel gleichmäßig über den Raum verteilt und in einer Dilatationsbewegung begriffen sind (wenigstens sofern man deren systematische Rotverschiebungen als Dopplereffekte zu deuten hat), hat die Annahme (2) von der statischen Natur des Raumes keine Berechtigung mehr, und es entsteht die Frage, ob die allgemeine Relativitätstheorie von diesen Befunden Rechenschaft zu geben vermag.

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

  Often cited, rarely read (not translated)

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

- **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

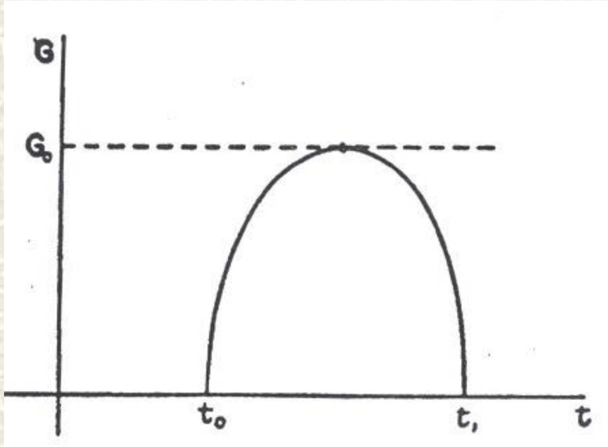
  $R \sim 10^8$ lyr, $\rho \sim 10^{-26}$ g/cm^3

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

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

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

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



- **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

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

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

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

- **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

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

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

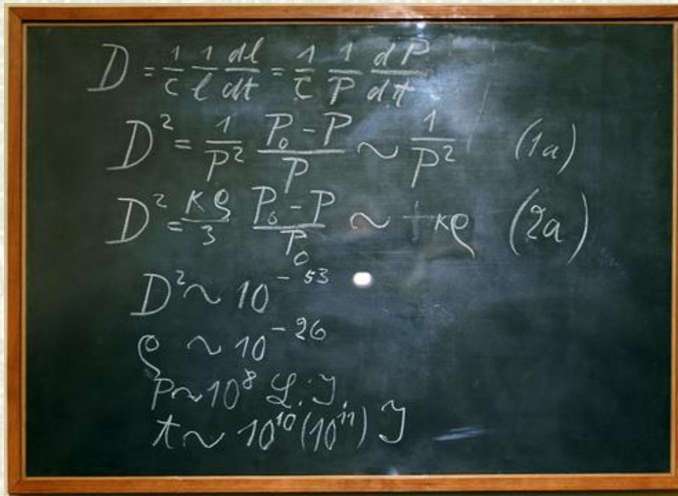
Oxford lecture (May 1931)

- **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)

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

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

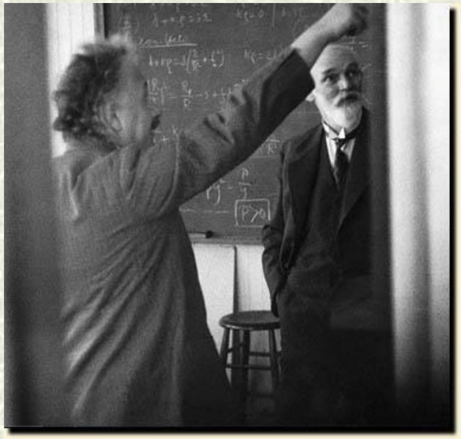
- **<u>Becomes standard model</u>**
  Despite high density of matter
  Despite age problem

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

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

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

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



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

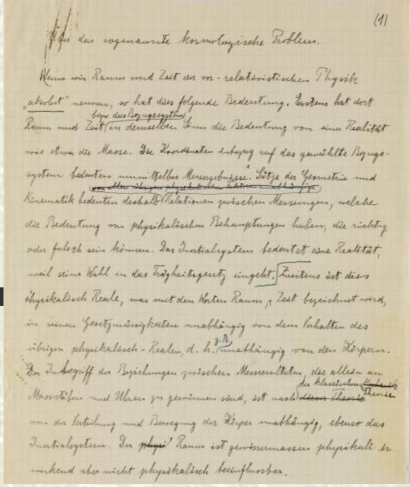
In a recent note in the *Göttinger Nachrichten*, Dr. O. Heckmann has pointed out that the non-static solutions of the field equations of the general theory of relativity with constant density do not necessarily imply a positive curvature of three-dimensional space, but that this curvature may also be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

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

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



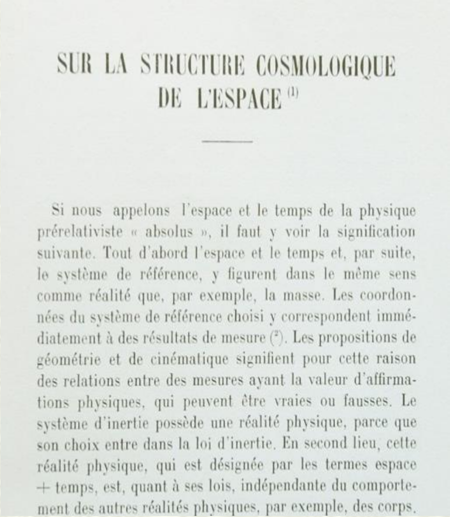
$$2A\frac{d^2A}{dt^2} + \left(\frac{dA}{dt}\right)^2 = 0$$

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

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

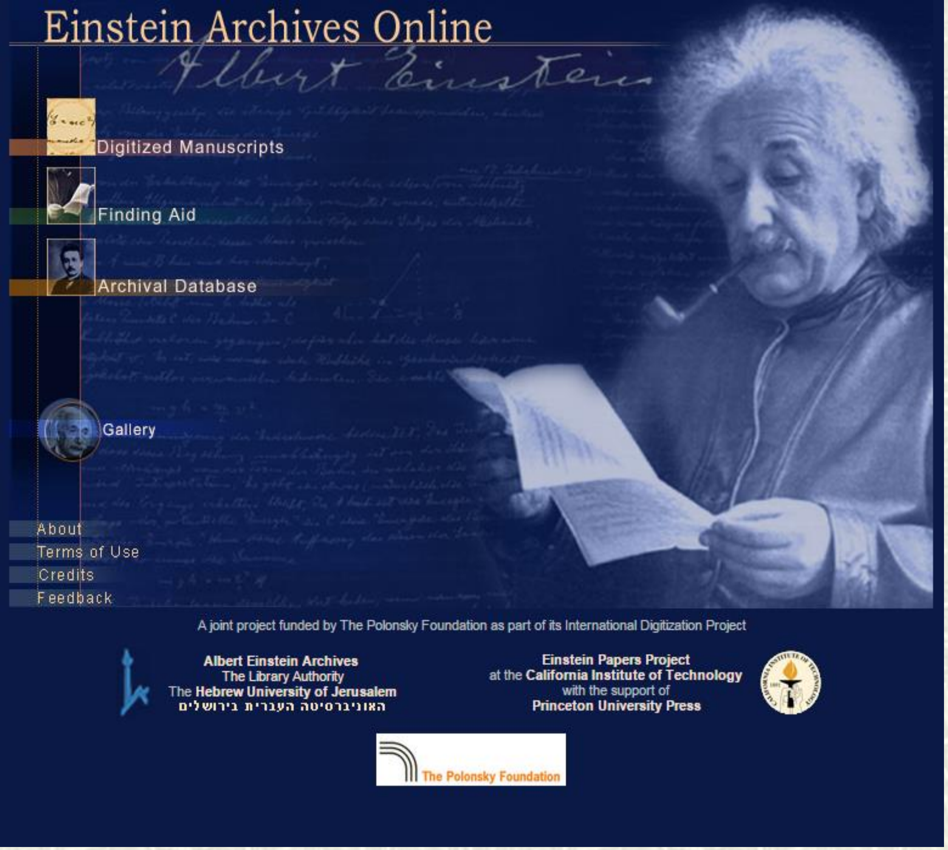
$$A = c\,(t - t_0)^{\frac{2}{3}}.$$

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



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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JPG
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
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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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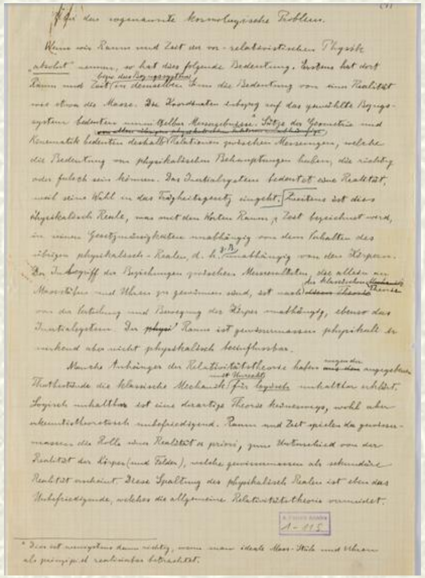


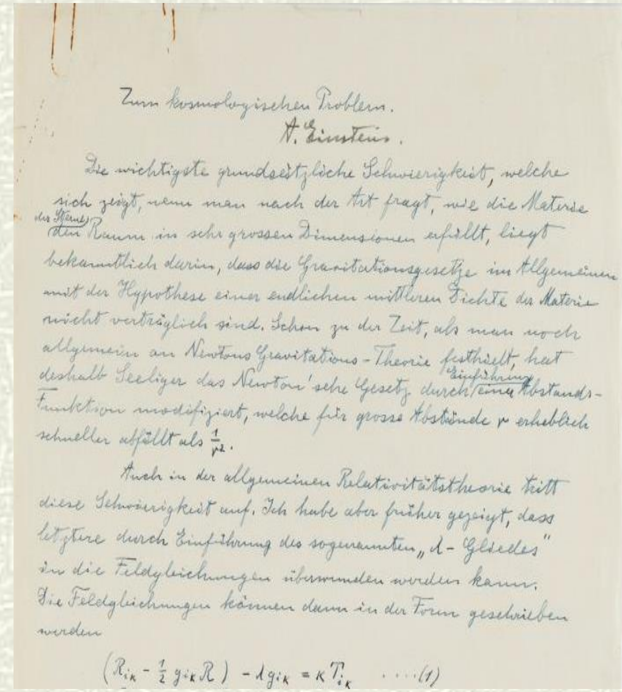
Bonus: Einstein's steady-state model

- **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*

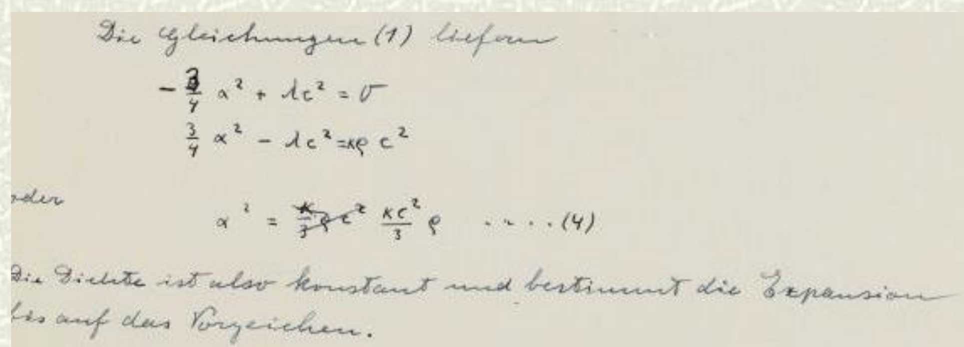
Anticipates controversial theory (Hoyle)


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 Einführung einer 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

$$-\tfrac{3}{4}\alpha^2 + \lambda c^2 = 0$$
$$\tfrac{3}{4}\alpha^2 - \lambda c^2 = \kappa\rho c^2$$

oder

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

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

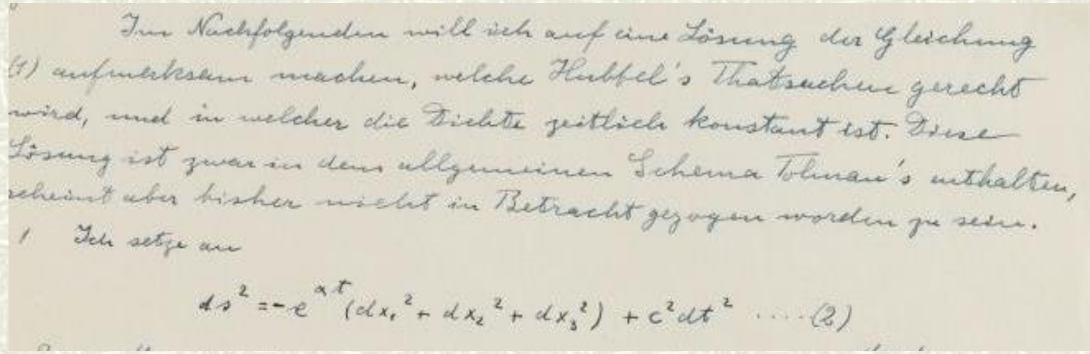
- **Einstein's crossroads**

  Realised problem on revision

  Declined to amend GFE

- **Evolving models**

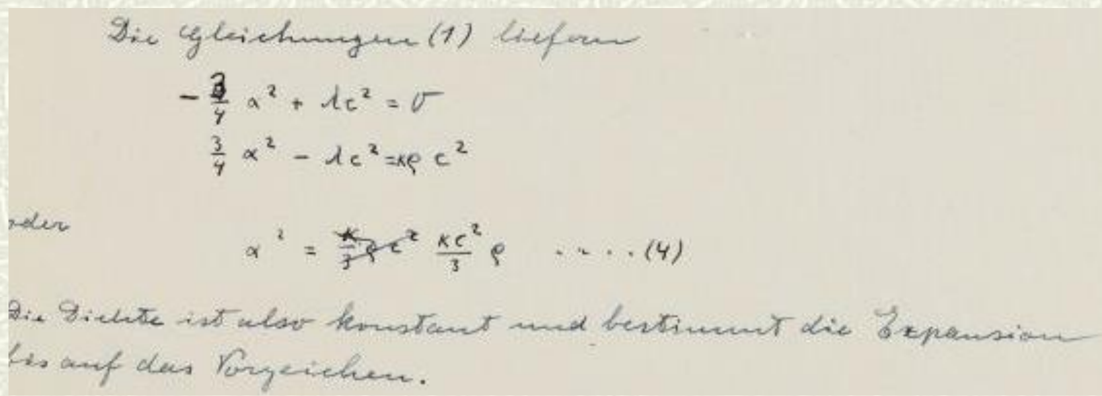
  Less contrived and set λ = 0



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

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



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oder

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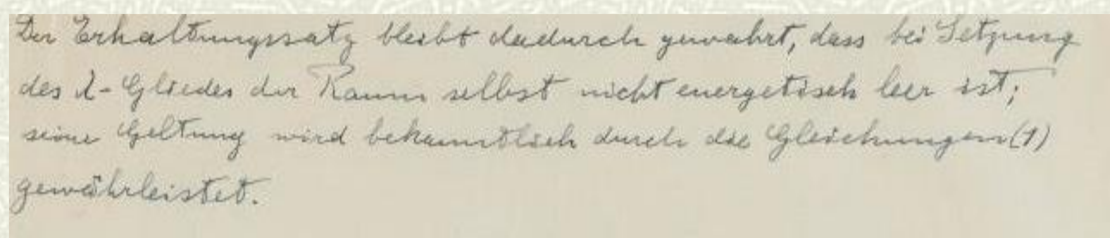
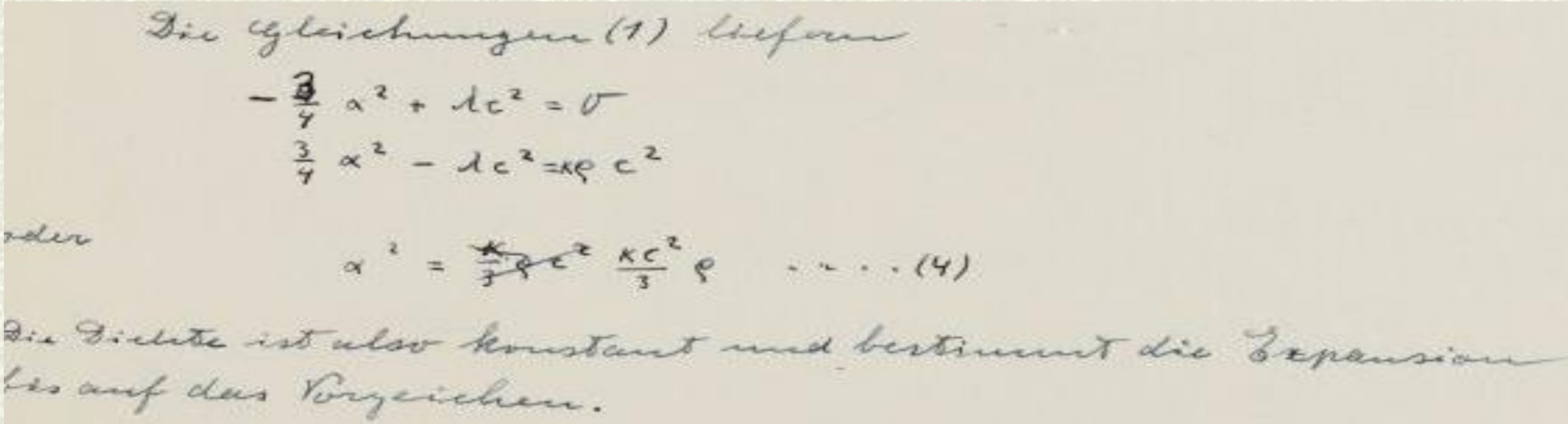


Der Erhaltungssatz bleibt dadurch gewahrt, dass bei Setzung des λ-Gliedes der Raum selbst nicht energetisch leer ist; seine Geltung wird bekanntlich durch die Gleichungen (1) gewährleistet.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$$\frac{3}{4}\alpha^2 - \lambda c^2 = \kappa\rho c^2$$

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.

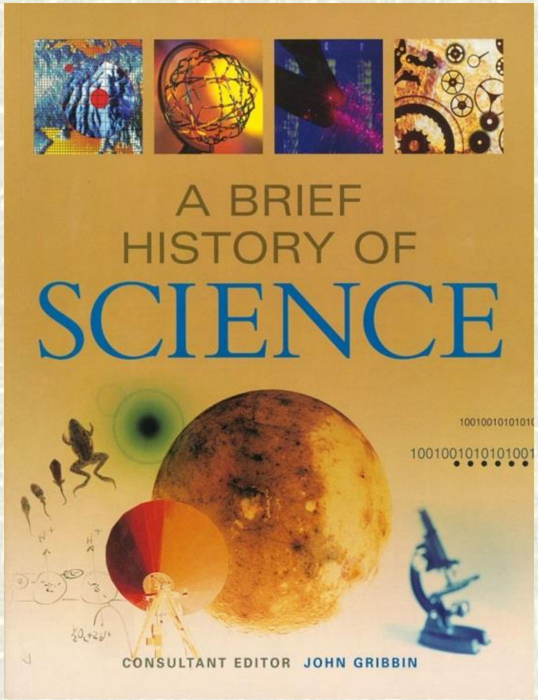
It is plausible that Einstein made a sign error here, initially getting $3\alpha^2/4 + 3\alpha^2/2 + \lambda c^2 = 0$ for this equation. (W. Nahm)

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

NATURE | NEWS

Einstein's lost theory uncovered

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

Davide Castelvecchi

24 February 2014

Top

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

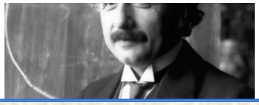
2 comments, 2 called-out + Comment Now + Follow Comments

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,



Rabobank The straight talking savings bank

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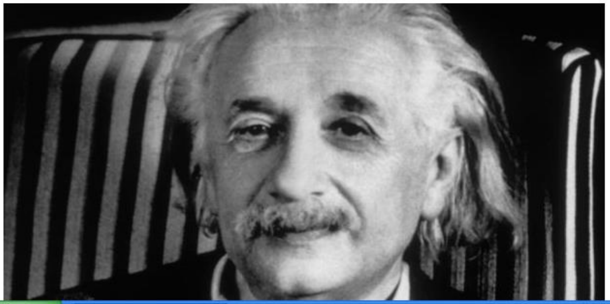
WIT researchers discover 'lost' Einstein model of universe

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



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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

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

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

- **Improved version (1962)**

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

Hoyle and Narlikar (1962)

Steady-state vs big bang

- **Optical astronomy (1950s)**

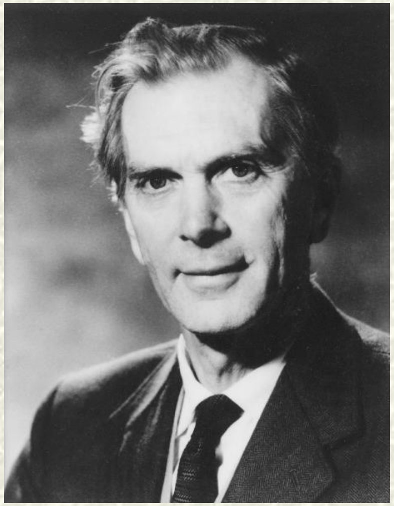
  Amended timescale of expansion (Baade, Sandage)

  Age problem removed

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

  Galaxy distributions at different epochs

  Cambridge 3C Survey (Ryle)

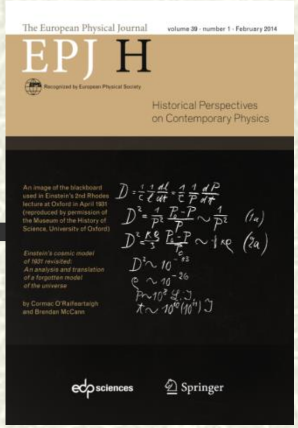


- **Cosmic microwave background**

  Low temperature, low frequency

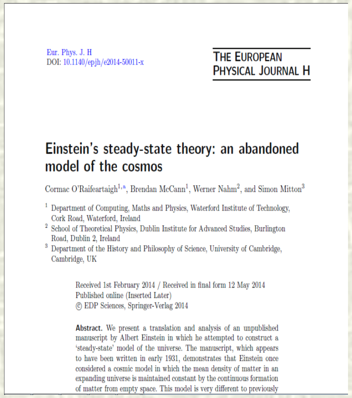
  Remnant of early universe

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**



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
[2] School of Theoretical Physics, Dublin Institute for Advanced Studies, Burlington Road, Dublin 2, Ireland
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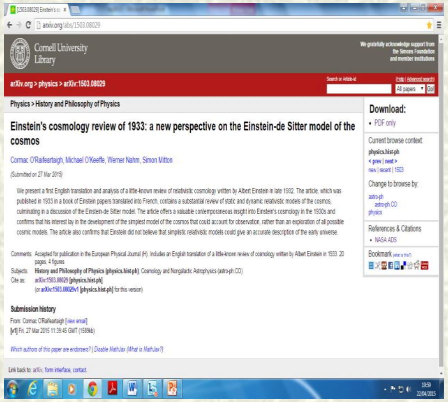
Abstract. We present a translation and analysis of an unpublished manuscript by Albert Einstein in which he attempted to construct a 'steady-state' model of the universe. The manuscript, which appears to have been written in early 1931, demonstrates that Einstein once considered a cosmic model in which 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

⌗ 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**

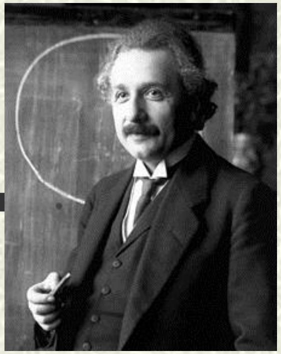
⌗ Einstein-de Sitter model

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

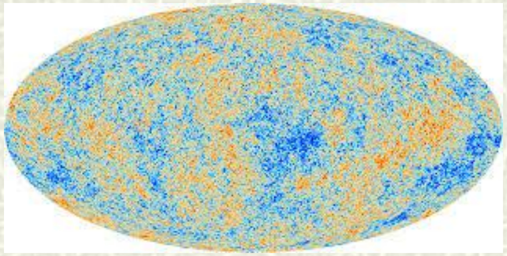
- **Embraces dynamic cosmology**

  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

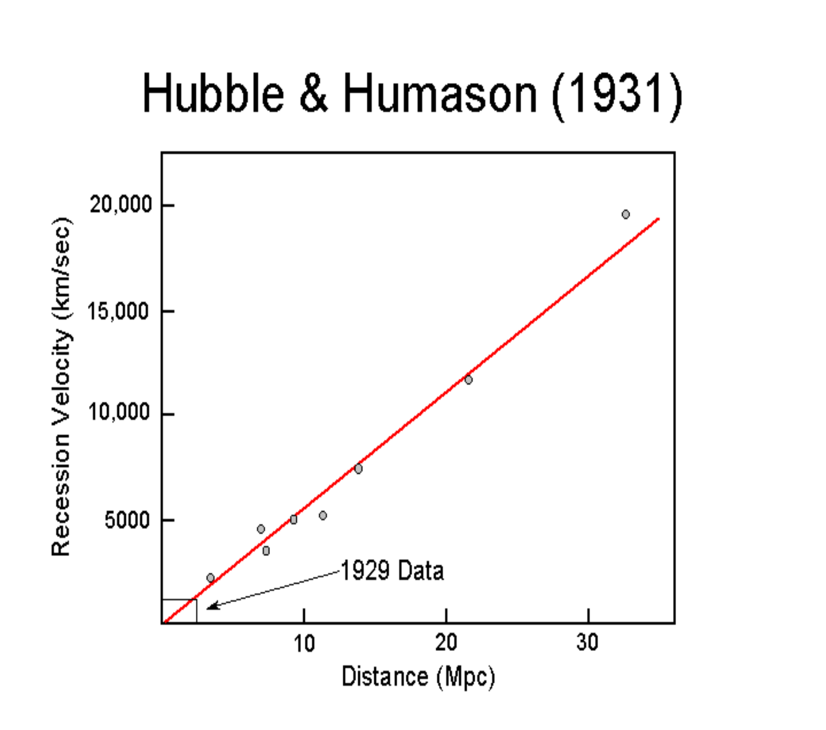
  No discussion of origins (wary of extrapolations)

Cosmic microwave background
Homogeneous, flat universe

Verdict (1933, 1945): more data needed

Observational parameters needed (1930s)

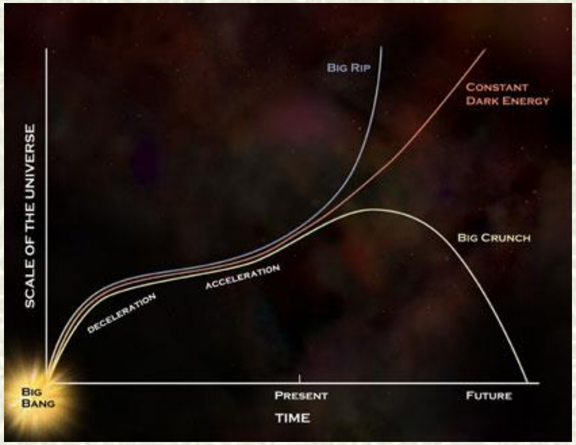
- **Spatial curvature** *k = -1,0,1?*
- **Cosmic constant** $\lambda = 0$?
- **Deacceleration** $q_0 = - \ddot{R}/\dot{R}^2$
- **Density of matter** $\rho < \rho_{crit}$?
- **Timespan** $\tau = 10^{10}$ yr?
- **Hubble constant** $\dot{R}/R = 500\ kms^{-1}Mpc^{-1}$?



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)."

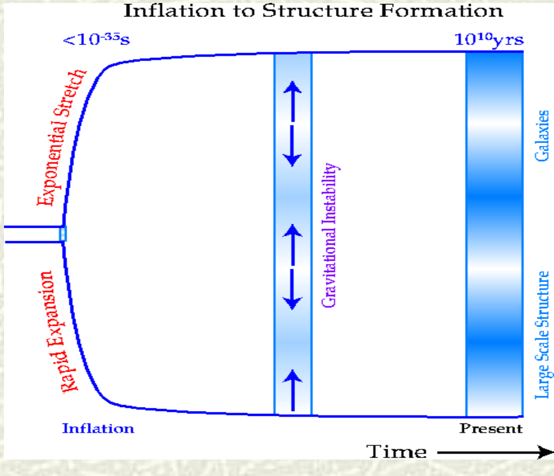
- **Cosmic inflation**

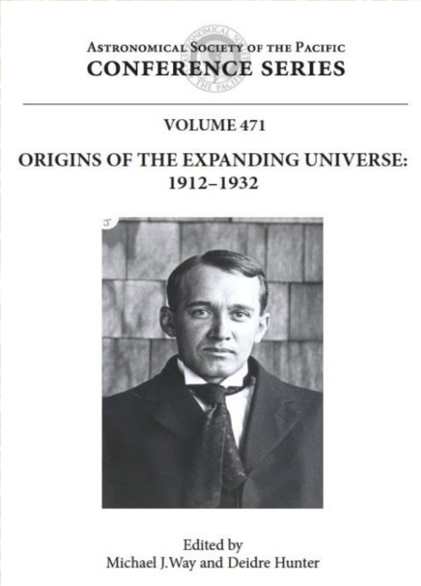
  Inflationary models use de Sitter metric

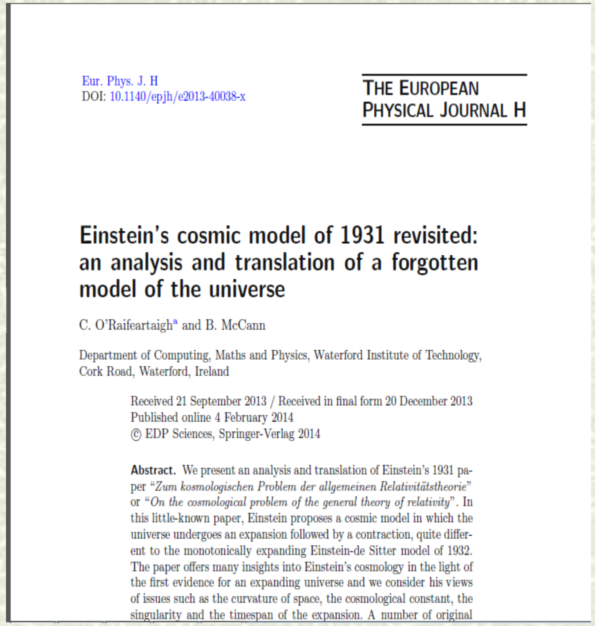
  Used in all steady-state models

  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

C. O'Raifeartaigh[a] and B. McCann

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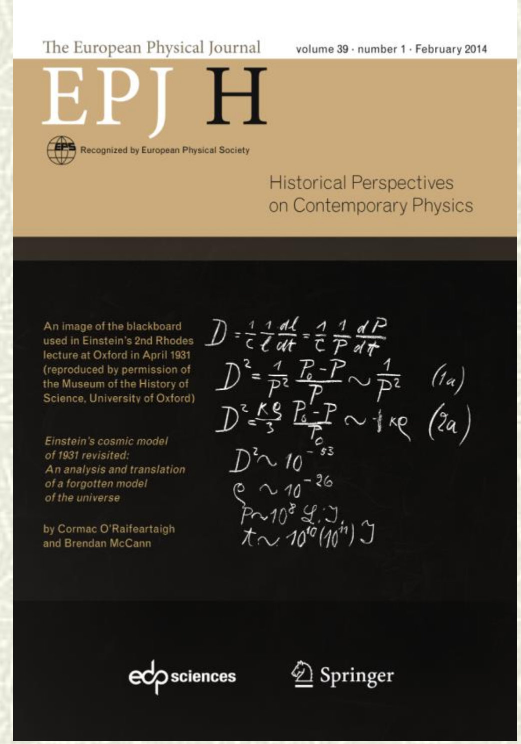
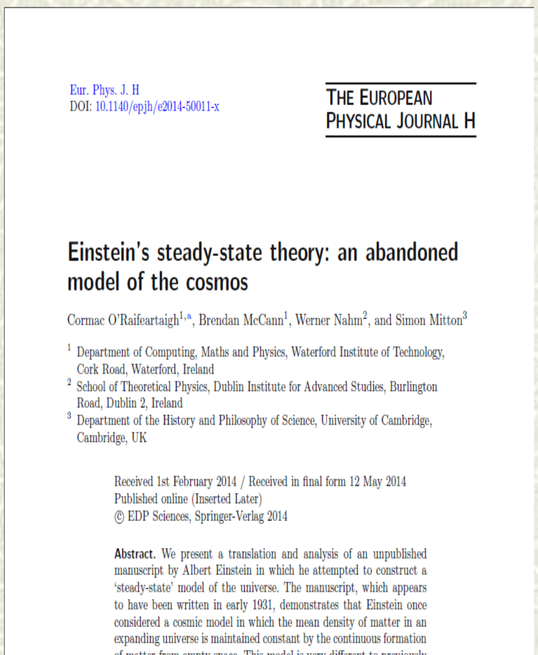
Abstract. We present an analysis and translation of Einstein's 1931 paper "*Zum kosmologischen Problem der allgemeinen Relativitätstheorie*" or "*On the cosmological problem of the general theory of relativity*". In this little-known paper, Einstein proposes a cosmic model in which the universe undergoes 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





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

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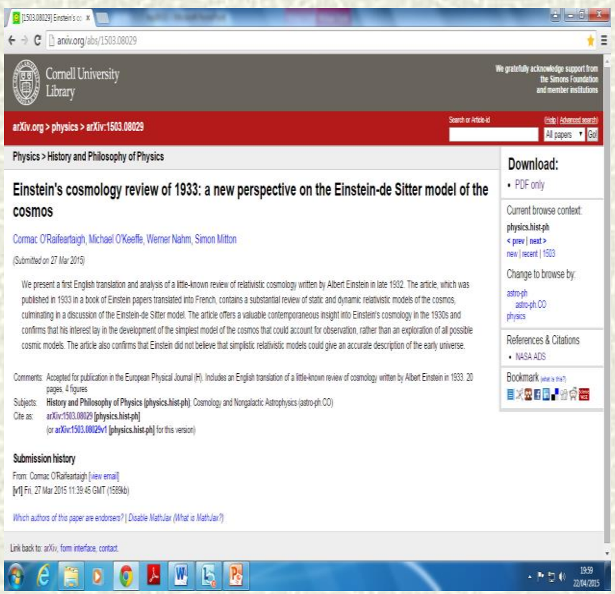


arXiv.org > physics > arXiv:1503.08029

Physics > History and Philosophy of Physics

Einstein's cosmology review of 1933: a new perspective on the Einstein-de Sitter model of the cosmos

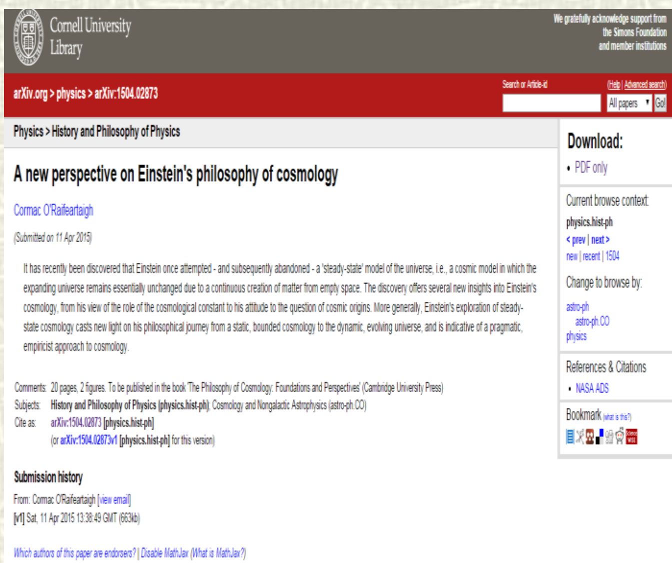
Cormac O'Raifeartaigh, Michael O'Keeffe, Werner Nahm, Simon Mitton

(Submitted on 27 Mar 2015)

We present a first English translation and analysis of a little-known review of relativistic cosmology written by Albert Einstein in late 1932. The article, which was published in 1933 in a book of Einstein papers translated into French, contains a substantial review of static and dynamic relativistic models of the cosmos, culminating in a discussion of the Einstein-de Sitter model. The article offers a valuable contemporaneous insight into Einstein's cosmology in the 1930s and confirms that his interest lay in the development of the simplest model of the cosmos that could account for observation, rather than an exploration of all possible cosmic models. The article also confirms that Einstein did not believe that simplistic relativistic models could give an accurate description of the early universe.

Comments: Accepted for publication in the European Physical Journal (H). Includes an English translation of a little-known review of cosmology written by Albert Einstein in 1933. 20 pages, 4 figures
Subjects: **History and Philosophy of Physics (physics.hist-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO)
Cite as: arXiv:1503.08029 **[physics.hist-ph]**
(or arXiv:1503.08029v1 **[physics.hist-ph]** for this version)

Submission history
From: Cormac O'Raifeartaigh [view email]
[v1] Fri, 27 Mar 2015 11:39:45 GMT (1589kb)



arXiv.org > physics > arXiv:1504.02873

Physics > History and Philosophy of Physics

A new perspective on Einstein's philosophy of cosmology

Cormac O'Raifeartaigh

(Submitted on 11 Apr 2015)

It has recently been discovered that Einstein once attempted - and subsequently abandoned - a 'steady-state' model of the universe, i.e., a cosmic model in which the expanding universe remains essentially unchanged due to a continuous creation of matter from empty space. The discovery offers several new insights into Einstein's cosmology, from his view of the role of the cosmological constant to his attitude to the question of cosmic origins. More generally, Einstein's exploration of steady-state cosmology casts new light on his philosophical journey from a static, bounded cosmology to the dynamic, evolving universe, and is indicative of a pragmatic, empiricist approach to cosmology.

Comments: 20 pages, 2 figures. To be published in the book 'The Philosophy of Cosmology: Foundations and Perspectives' (Cambridge University Press)
Subjects: **History and Philosophy of Physics (physics.hist-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO)
Cite as: arXiv:1504.02873 **[physics.hist-ph]**
(or arXiv:1504.02873v1 **[physics.hist-ph]** for this version)

Submission history
From: Cormac O'Raifeartaigh [view email]
[v1] Sat, 11 Apr 2015 13:38:49 GMT (663kb)

A cosmic puzzle

- **What is causing recession of the galaxies ?**

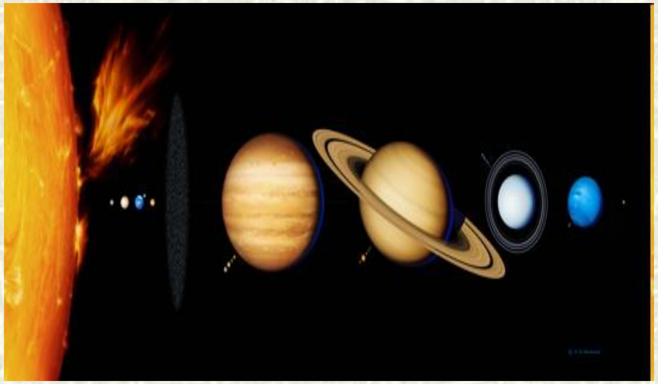
  If redshifts are velocities

  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

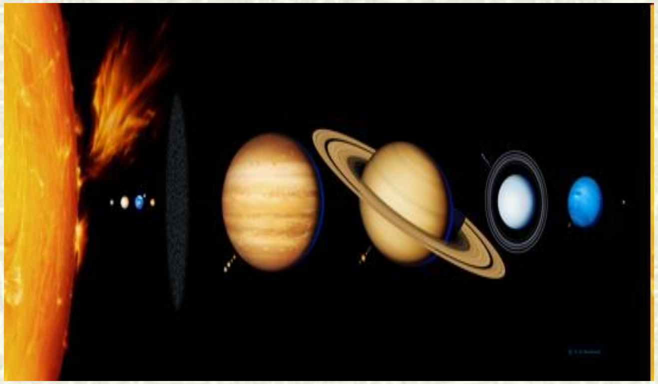
  Homogeneity and isotropy

  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 ***<u>'The big bang'</u>***

∞ 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**

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

  Necessary for all steady-state models

  Identical to inflationary models (different time-frame)