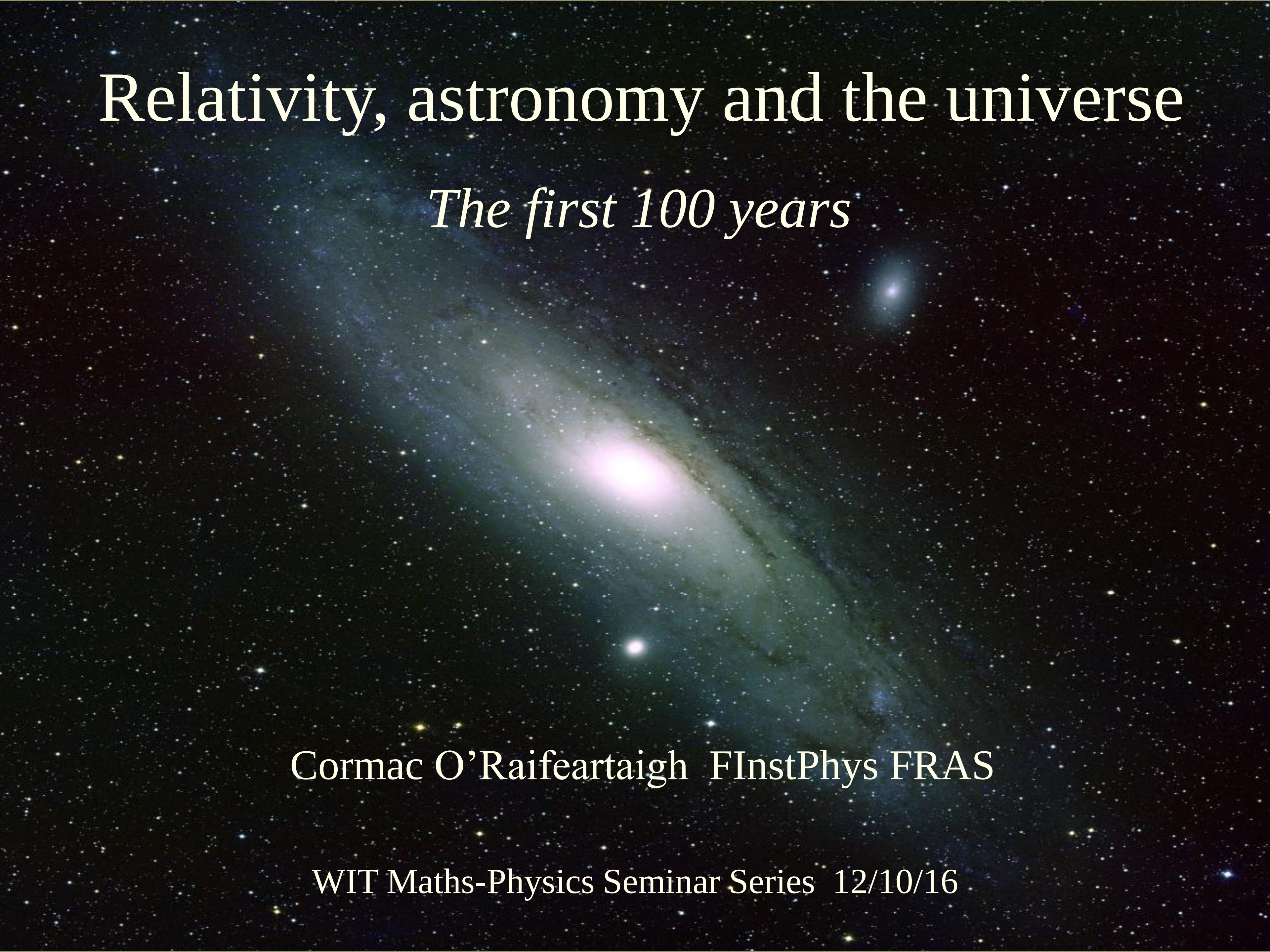
Relativity, astronomy and the universe

The first 100 years



Cormac O'Raifeartaigh FInstPhys FRAS

WIT Maths-Physics Seminar Series 12/10/16

Overview

- **Introduction to relativity**

  The special theory of relativity

  The general theory of relativity

- **Three astronomical tests**

  The perihelion of Mercury; the bending of starlight

  The gravitational redshift

Einstein in Berlin (1916)

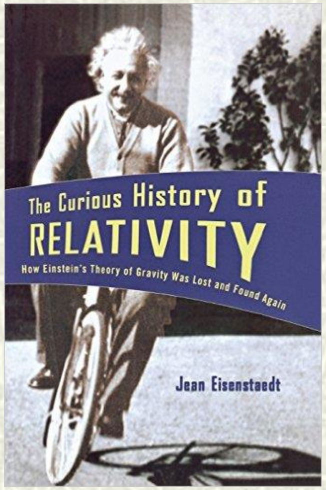
- **Relativity and the universe**

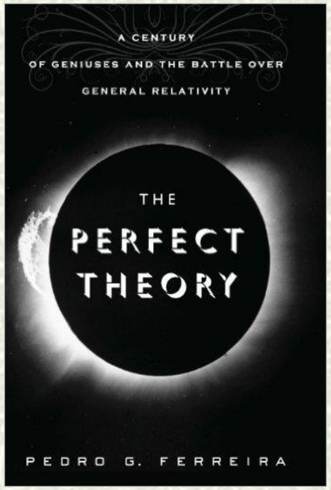
  A static or a dynamic universe?

  Hubble's law and the big bang

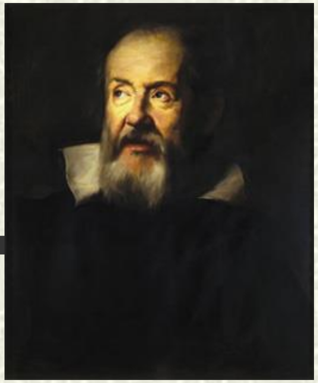
- **The renaissance of relativity**

  Astronomy and the universe (1960 -)





Relativity

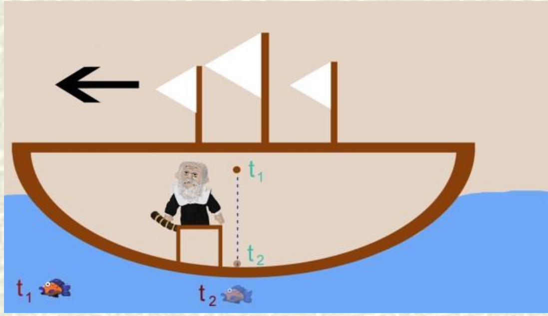


Galileo (1564-1642)

- **The principle of relativity**

  Relativity of motion

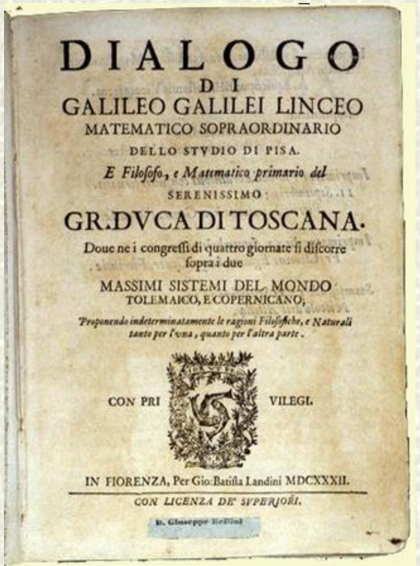
  Buridan, Oresme, Bruno, Copernicus



- **Galileo’s galleon (1632)**

  Motion of objects in closed cabin of ship

  Impossible to detect motion of ship by experiments in cabin



DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filoſofo, e Matematico primario del
SERENISSIMO
GR.DVCA DI TOSCANA.
Doue ne i congreſſi di quattro giornate ſi diſcorre ſopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filoſofiche, e Naturali tanto per l'vna, quanto per l'altra parte.
CON PRI VILEGI.
IN FIORENZA, Per Gio:Batiſta Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

- **Implications for cosmology**

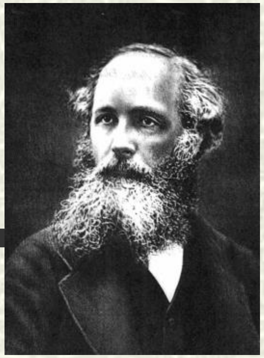
  Motion of earth undetectable to passengers

- **Implications for mechanics**

  Anticipates Newton’s law of inertia

Relativity in the 19th century

Michael Faraday



JC Maxwell

- **Electromagnetism**

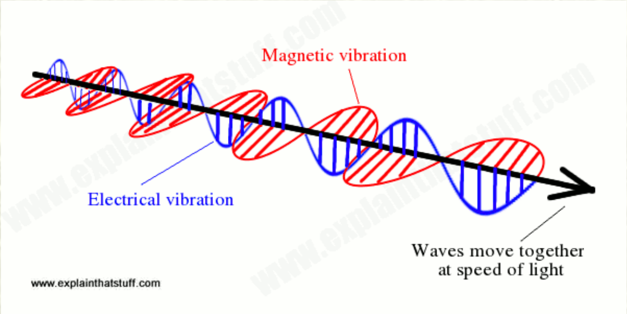
  Electricity and magnetism = electromagnetism

  Speed of electromagnetic wave = speed of light in vac

- **Light = an electromagnetic wave**

  Changing electric and magnetic fields

  The electromagnetic spectrum

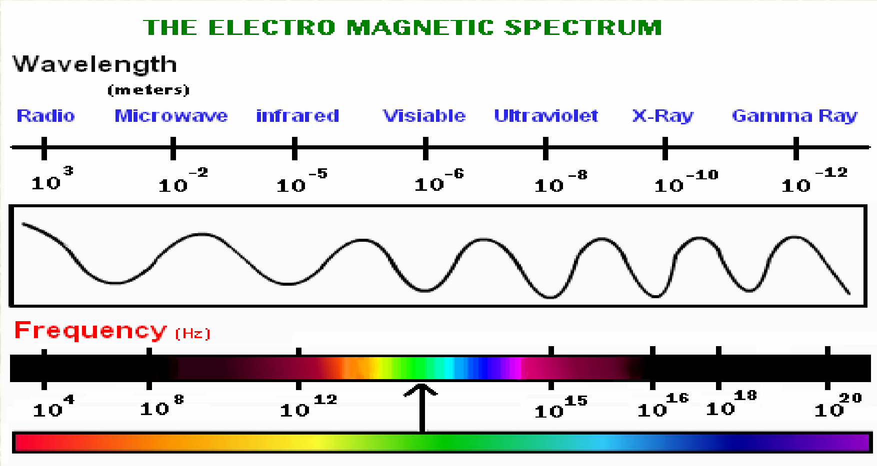


- **Speed relative to what?**

  The concept of the ether

- **The search for the ether**

  Michelson-Morley experiment

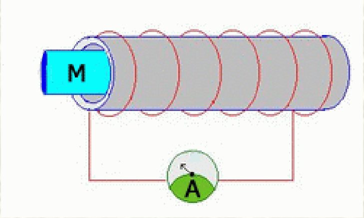


The special theory of relativity (1905)

- **Two principles**

  *Laws of **all** physics identical for observers in relative uniform motion*

  Speed of light in vacuum identical for observers in relative uniform motion



- **Implications**

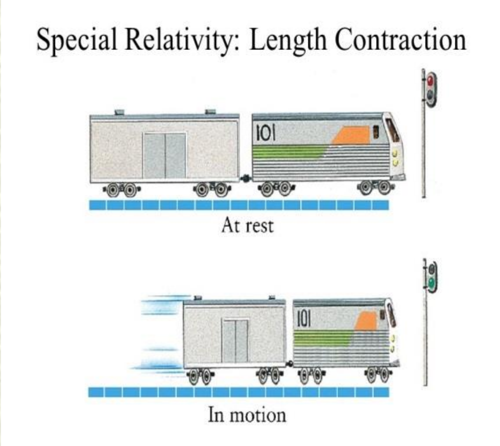
  Intervals in distance and time not universal

  Experienced differently by bodies in relative uniform motion

- **Predictions (high-speed bodies)**

  Length contraction : time dilation

  Mass increase; mass-energy equivalence



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

- **Minkowski space-time (1908)**

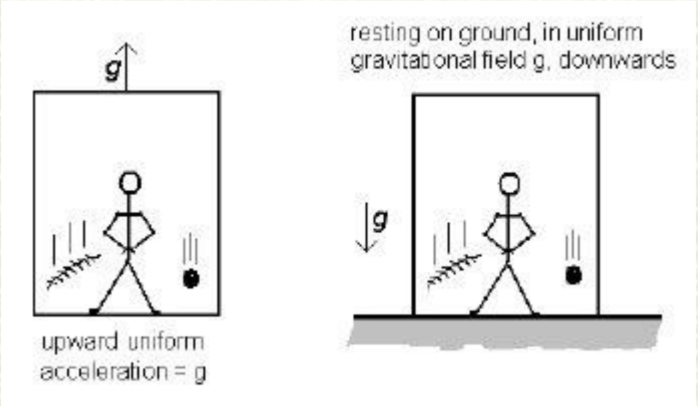
  Space-time invariant for observers in relative uniform motion

The general theory of relativity (1916)

- **Extending the special theory (1907-)**

  Relativity and accelerated motion?

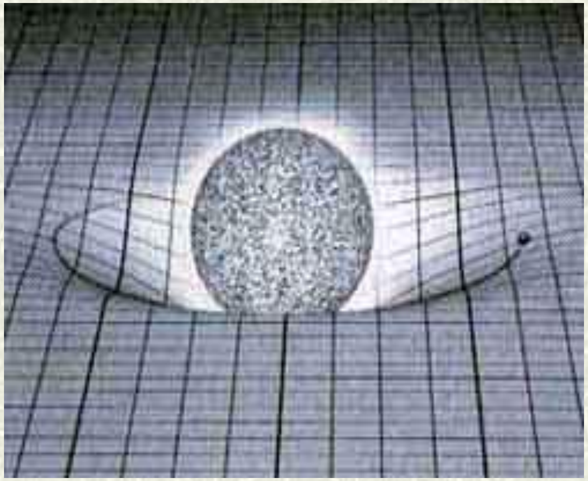
  Relativity and gravity?



- **<u>The principle of equivalence</u>**

  Equivalence of gravity and acceleration

  Extension of Galileo's principle



- **<u>The principle of Mach</u>**

  Inertial mass defined relative to matter

- **A long road (1907-1915)**

  Space-time determined by matter

  Gravity = curvature of space-time

The field equations of GR (1915)

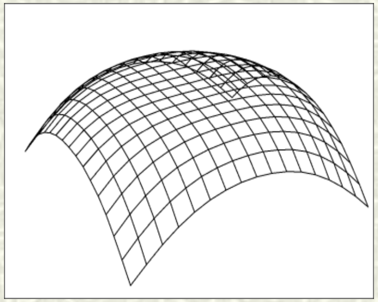
$$G_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

10 non-linear differential equations that relate the geometry of space-time to the density and flow of mass-energy

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

$$ds^2 = \sum_{\mu,\nu=1}^{4} n_{\mu\nu} dx^\mu dx^\nu$$

$$n_{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$



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

$$ds^2 = \sum_{\mu,\nu=1}^{4} g_{\mu\nu} dx^\mu dx^\nu$$

$g_{\mu\nu}$: *variables determined by matter*

Three astronomical tests (Einstein, 1916)

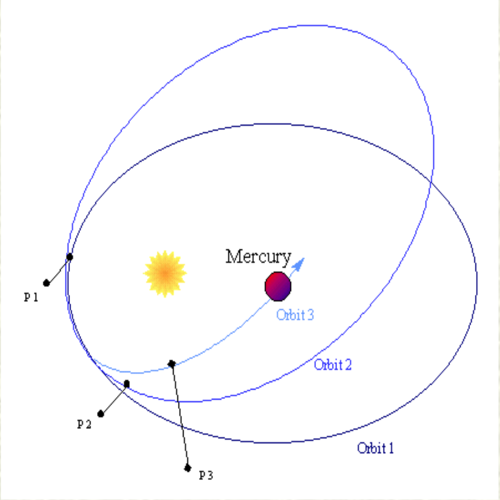
- **Different in principle from Newton's gravity**

  Small deviations in practice (weak scale)

- **The perihelion of Mercury**

  Well-known anomaly in Mercury's orbit (43" per century)

  Postdicted by GR (1916)



- **The bending of starlight by the sun** (1.7")

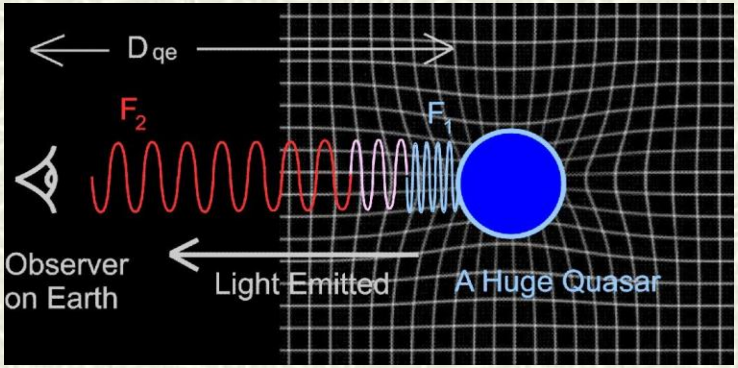
  Eclipse expeditions of Eddington and Dyson (1919)

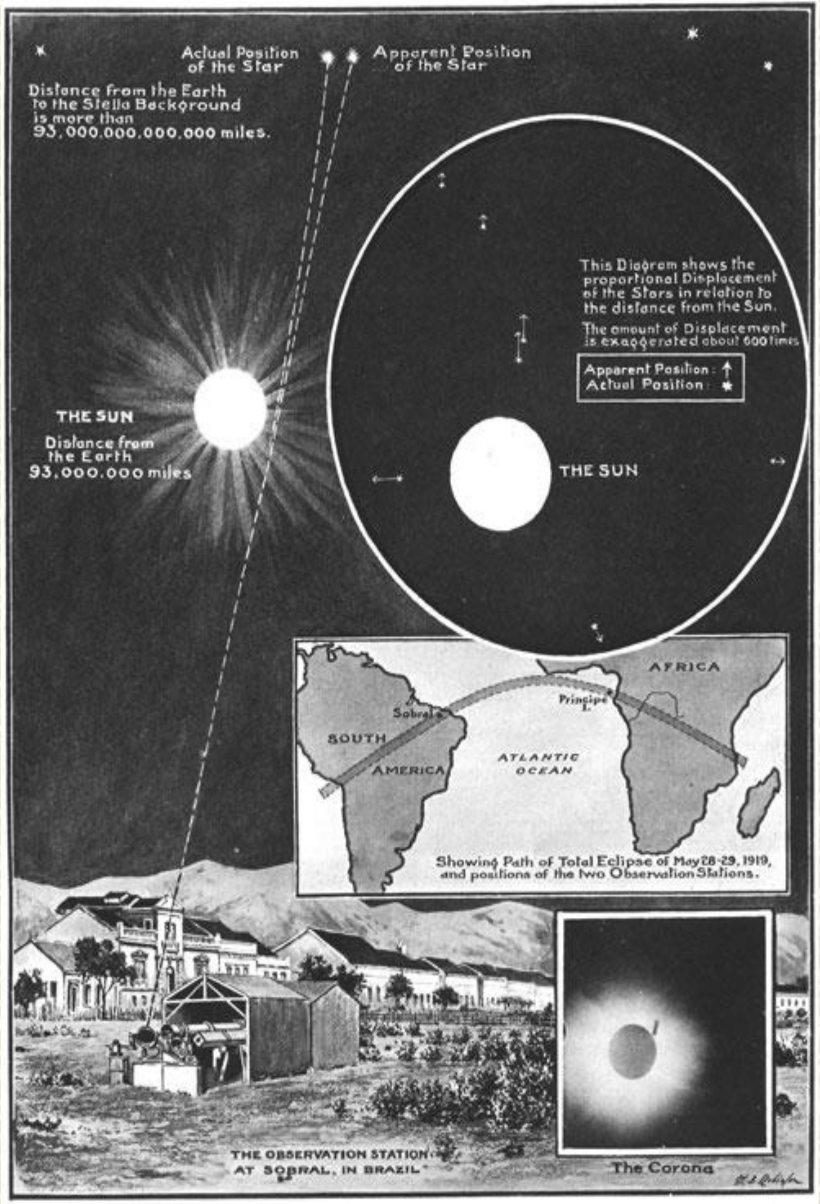
  Successful measurement (large error margin)

- **Gravitational redshift**

  Time dilation in strong gravitational field

  Light from a star redshifted by stellar mass?





Eclipse Results (1919)

Sobral: 1.98" +/- 0.16
Principe: 1.7" +/- 0.4

Einstein famous (1919)

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Asymmetric controversy (Collins and Pinch 1970s)

Claim of bias; rebutted by astronomers (RAS)

Einstein’s reaction to eclipse result

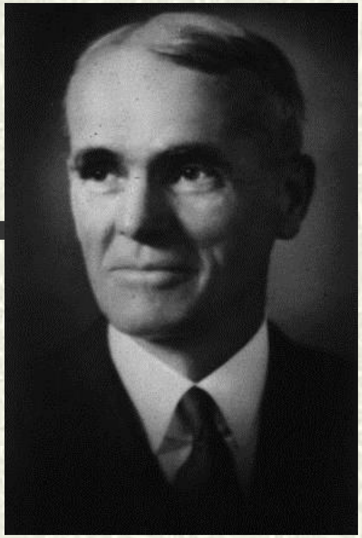
Albert Einstein, The Times (Nov 28th 1919)

The new theory of gravitation diverges considerably, as regards principles, from Newton’s theory. But its practical results agree so nearly with those of Newton’s theory that it is difficult to find criteria for distinguishing them which are accessible to experience. Such have been discovered so far:

1. In the revolution of the ellipses of the planetary orbits round the sun (confirmed in the case of Mercury).
2. In the curving of light rays by the action of gravitational fields (confirmed by the English photographs of eclipses).
3. In a displacement of the spectral lines toward the red end of the spectrum in the case of light transmitted to us from stars of considerable magnitude (unconfirmed so far).*

Let no one suppose, however, that the mighty work of Newton can really be superseded by this or any other theory. His great and lucid ideas will retain their unique significance for all time as the foundation of our whole modern conceptual structure in the sphere of natural philosophy.

Gravitational redshift



Walter Adams (1876–1956)

- **Sirius B**

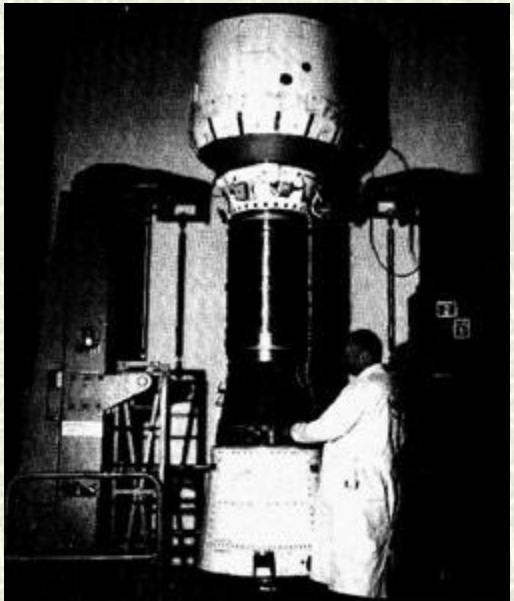
  Walter Adams 1925: redshift of spectrum

  False result; contamination by Sirius A

- **Harvard Tower experiment**

  Pound, Rebka and Snyder (1952)

  Redshift of gamma rays (Mossbauer effect)



- **Gravity probe A**

  NASA (1976): maser clock 10,000 km above earth

  Changes in clock's rate in agreement with GR

- **GPS**

  Clocks in GPS satellites adjusted for weak gravitational field

Relativity and the universe

- **Einstein: apply GR to the Universe (1917)**

  Ultimate test for new theory of gravitation

- **Assumptions**

  Uniform, static distribution of matter

  Mach's principle: metric tensor to vanish at infinity

- **Boundary problem!**

  Assume cosmos of closed curvature

  Snag…no consistent solution from GFE

- **New term needed in field equations!**

  Cosmic constant – allowed by theory

  Anti-gravity effect?

  Radius and density defined by λ

Doc. 43

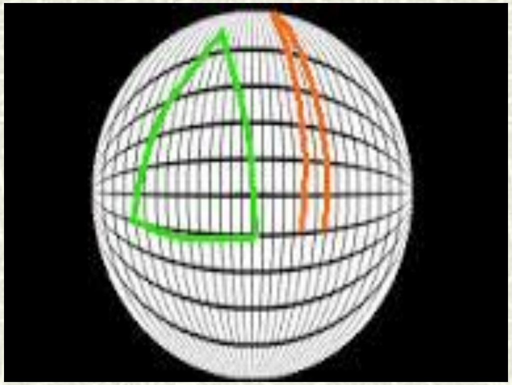
Cosmological Considerations in the General Theory of Relativity

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

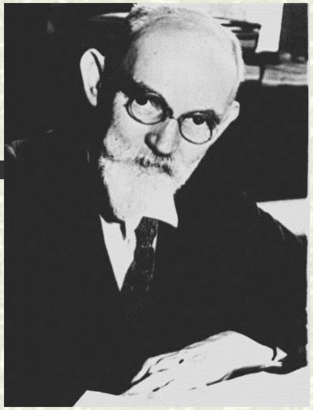


$$G_{\mu\nu} = -\kappa T_{\mu\nu}$$

$$G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu}$$

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

De Sitter's universe



- **Alternative cosmic solution for the GFE**
  A universe empty of matter (1917)

- **Solution B**
  Cosmic constant proportional to curvature of space

$$\lambda = 3/R$$

- **Disliked by Einstein**
  Conflict with Mach's principle
  Problems with singularities? (1918)

- **The de Sitter confusion**
  Static or non-static - a matter of co-ordinates?
  Weyl , Lanczos, Klein, Lemaître

[p. 270] 5. "Critical Comment on a Solution of the Gravitational Field Equations Given by Mr. De Sitter"

[Einstein 1918c]

SUBMITTED 7 March 1918
PUBLISHED 21 March 1918

IN: *Königlich Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* (1918): 270–272.

[1] Herr De Sitter, to whom we owe deeply probing investigations into the field of the general theory of relativity, has recently given a solution for the equations of gravitation[1] which, in his opinion, could possibly represent the metric structure of the universe. However, it appears to me that one can raise a grave argument against the admissibility of this solution, which shall be presented in the following.

The De Sitter solution of the field equations

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa T_{\mu\nu} + \frac{1}{2} g_{\mu\nu} \kappa T \qquad (1)$$

is

Prediction of redshifts – astronomical interest

The dynamic universe (theory)

Alexander Friedman
(1888 -1925)

Georges Lemaître
(1894-1966)

- **Alexander Friedman (1922)**

  Allow time-varying solutions for the cosmos

  Two differential equations for R

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

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

- **Evolving universe**

  Time-varying radius and density of matter

  Considered 'suspicious' by Einstein

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

- **Georges Lemaître (1927)**

  Theoretical universe of time-varying radius

  Expanding universe in agreement with emerging astronomical data

  Also rejected by Einstein

"Vôtre physique est abominable"

Astronomy and the universe

Edwin Hubble (1889-1953)

- **Hubble's law (1929)**

  A redshift/distance relation for the galaxies

  Linear relation: h = 500 kms^{-1}Mpc^{-1}

- **Evidence of cosmic expansion?**

  RAS meeting (1930): Eddington, de Sitter

- **Friedman-Lemaître models circulated**

  Time-varying radius and density of matter

- **Einstein apprised**

  Sojourn at Cambridge (June 1930)

  Sojourn at Caltech (Spring 1931)

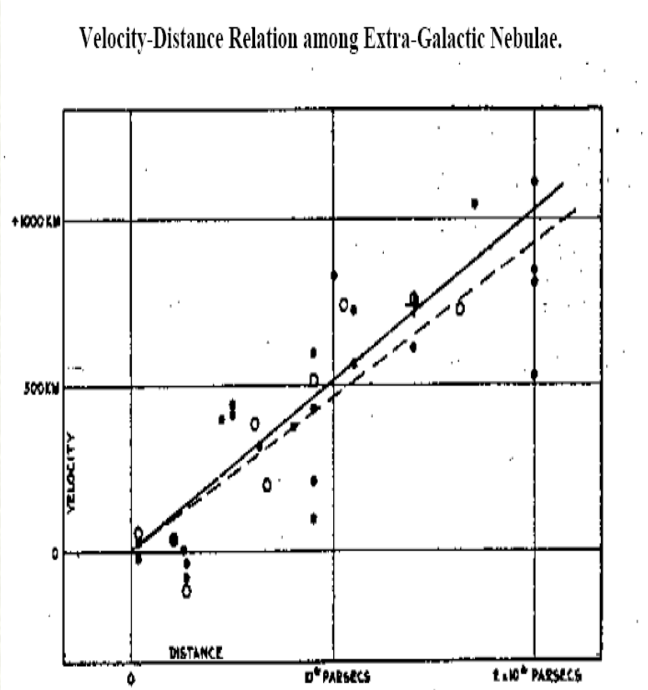


FIGURE 1

The expanding universe (1930 -)

- **Eddington (1930, 31)**

  On the instability of the Einstein universe
  Expansion caused by condensation?

- **Tolman (1930, 31)**

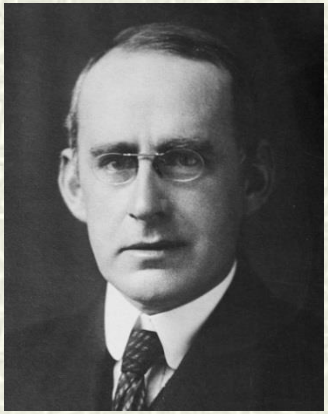
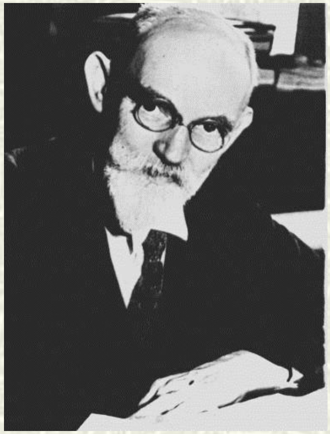
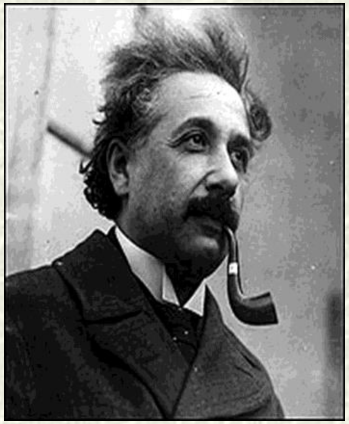
  On the behaviour of non-static models
  Expansion caused by annihilation of matter ?

- **de Sitter (1930, 31)**

  Further remarks on the expanding universe
  Expanding universes of every flavour

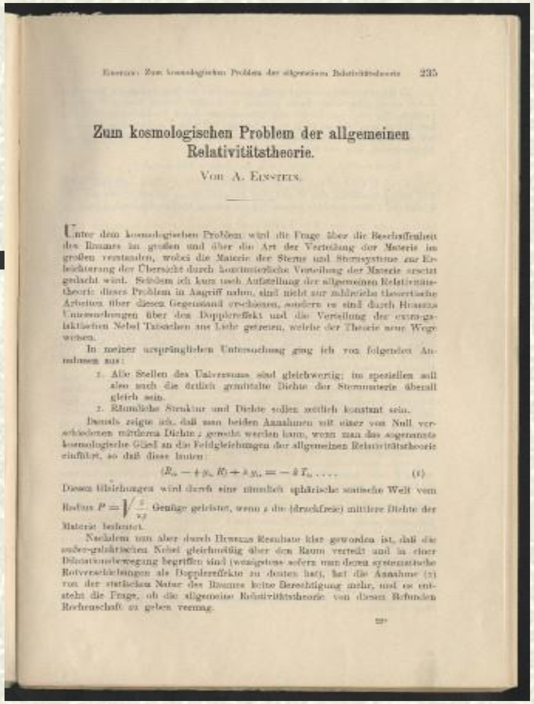
- **Einstein (1931, 32)**

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

Expanding models
No mention of origins

Einstein's 1931 model (*F-E*)



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:

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

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 expanding model**

  Rarely cited (not translated)

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

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

- **Adopts Friedman 1922 model**

  Instability of static solution

  Hubble's observations

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

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

- **Sets cosmic constant to zero**

  Redundant

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

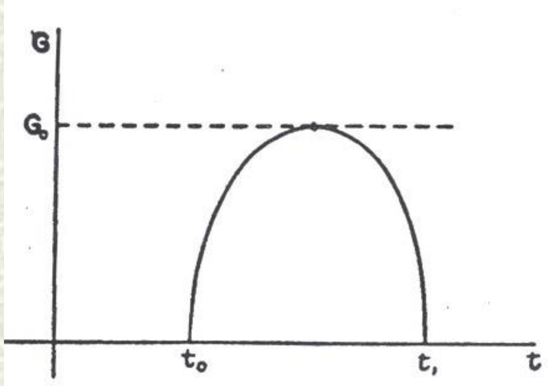
- **Extraction of cosmic parameters**

  P ~ 10^8 lyr : *ρ* ~ 10^{-26} g/cm³

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

  Attributed to simplifying assumptions (homogeneity)

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



Einstein's 1931 model revisited

- **First translation into English**

  O'Raifeartaigh and McCann 2014

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

- **Not a cyclic model**

  "Model fails at P = 0 "

  Contrary to what is usually stated

$$P \sim \frac{1}{D} \qquad D^2 \sim \kappa\rho$$

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

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

  We get: $P \sim 10^9$ lyr, $\rho \sim 10^{-28}$ g/cm^3, $t \sim 10^9$ yr

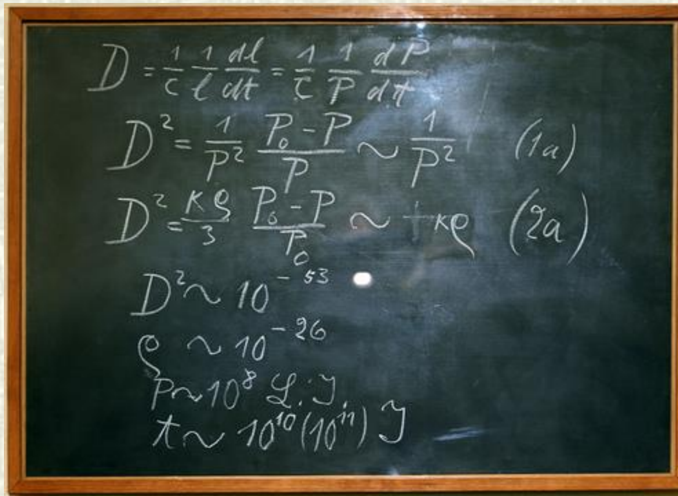
- **Source of error?**

  Oxford blackboard: $D^2 \sim 10^{-53}$ 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

Oxford lecture (May 1931)



Einstein-de Sitter model (1932)

- **Curvature not a given in dynamic models**

  Not observed empirically

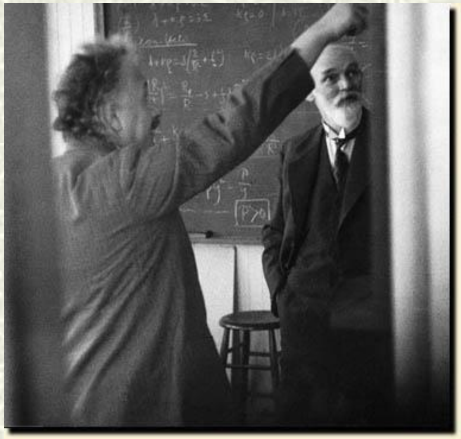
  Remove spatial curvature (Occam's razor)

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

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

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

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



- **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

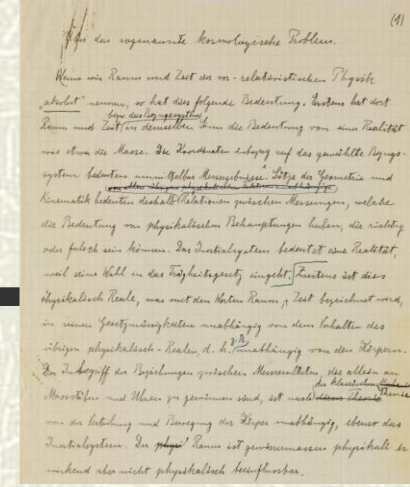
ON THE RELATION BETWEEN THE EXPANSION AND THE MEAN DENSITY OF THE UNIVERSE

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



(1)

Zu dem sogenannten kosmologischen Problem.

Wenn wir Raum und Zeit der vor-relativistischen Physik „absolut" nennen, so hat dies folgende Bedeutung. Erstens hat dort Raum und Zeit (bzw. das Bezugssystem) in demselben Sinne die Bedeutung von einer Realität wie etwa die Masse. Die Koordinaten inbezug auf das gewählte Bezugssystem bedeuten unmittelbare Messergebnisse. Sätze der Geometrie und Kinematik bedeuten deshalb Relationen zwischen Messungen, welche die Bedeutung von physikalischen Behauptungen haben, die richtig oder falsch sein können. Das Inertialsystem bedeutet eine Realität, weil seine Wahl in das Trägheitsgesetz eingeht. Zweitens ist dies physikalisch Reale, was mit den Worten Raum + Zeit bezeichnet wird, in seinen Gesetzmässigkeiten unabhängig von dem Verhalten des übrigen physikalisch-Realen, d. h. z.B. unabhängig von den Körpern. Der Inbegriff der Beziehungen zwischen Messresultaten, die allein an Massstäben und Uhren zu gewinnen sind, ist nach der klassischen Theorie von der Verteilung und Bewegung der Körper unabhängig, ebenso das Inertialsystem. Der Raum ist gewissermassen physikalisch wirkend aber nicht physikalisch beeinflussbar.

- **Einstein's cosmology review of 1933**

  Review of dynamic models from first principles

  Cosmic constant banished

  *Curved **<u>or</u>** 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

  <u>Timespan of 10^{10} years</u>: conflict with astrophysics

  Attributed to simplifications (incorrect estimate)

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

- **Published in 1933!**

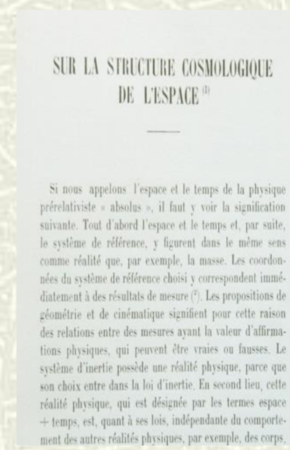
  French book; small print run

  Intended for scientific journal; not submitted

  Significant paper

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

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



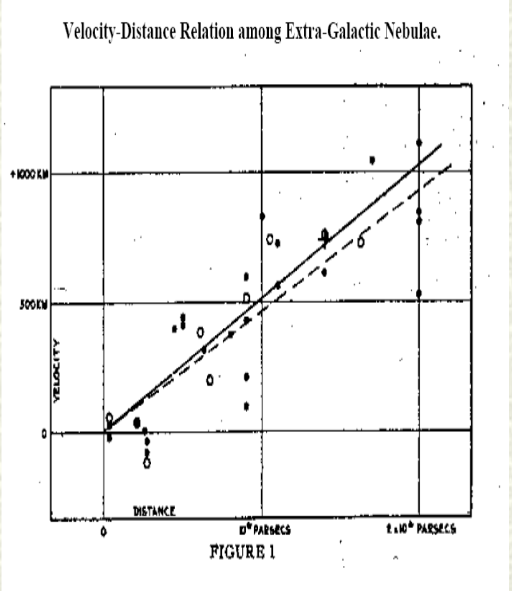
SUR LA STRUCTURE COSMOLOGIQUE DE L'ESPACE (1)

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.

Cosmic prediction: the big bang

- **Lemaître 1931**: expanding *U* smaller in the past
- Extrapolate to very early epochs
- Extremely dense, extremely hot
- Expanding and cooling ever since
- ‘Fireworks beginning’ at *R* = 0?

Fr Georges Lemaître



Not endorsed by community (1930-60)

Simplified models: timescale problem

Later called ***‘The big bang’***

A new line of evidence

- **Gamow and nuclear physics (1940s)**

  Student of Friedman

- **How were the chemical elements formed?**

  Problems with stellar nucleosynthesis

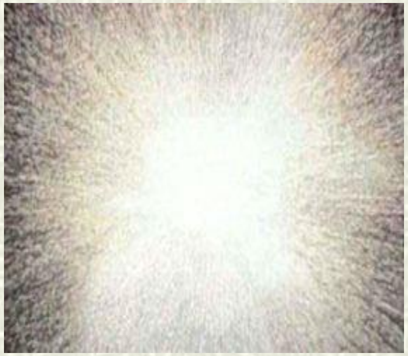
- **Elements formed in the infant hot universe?**

  Theory predicts U = 75% Hydrogen, 25% Helium

- **Agreement with observation**

  Support for big bang model?

Georges Gamow



Heavier atoms formed in stars

Bonus: a curious prediction

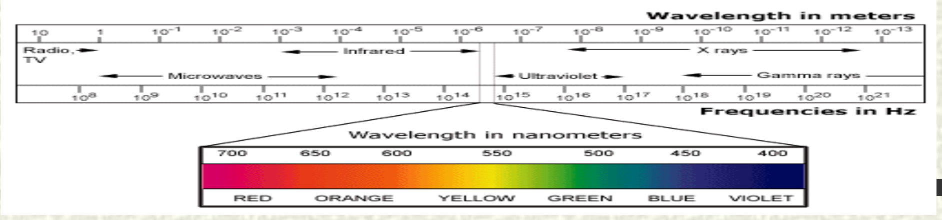
- **Infant universe very hot**
- **Dominated by radiation**
- **Radiation still observable today?**

  Low temp, microwave frequency
- **A fossil from the early universe!**

  Released when atoms formed (300,000 yr)

Alpher, Gamow and Herman

<u>No-one looked</u>



The steady-state universe (1948)

- **Expanding but unchanging universe**

  Time independent

  No extrapolation to early epochs necessary

  No beginning, no timescale paradox

Hoyle, Bondi, Gold (1948)

- **Requires continuous creation of matter**

  Very little matter required

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

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

- **Other steady-state models**

Arrhenius, Thomson and Einstein

Hoyle and Narlikar (1962)

Bonus: Einstein’s steady-state model

- **Unpublished manuscript**

  Archived as draft of Friedman-Einstein model

  Similar title, opening

- **Something different**

  Cosmological constant ***λ***

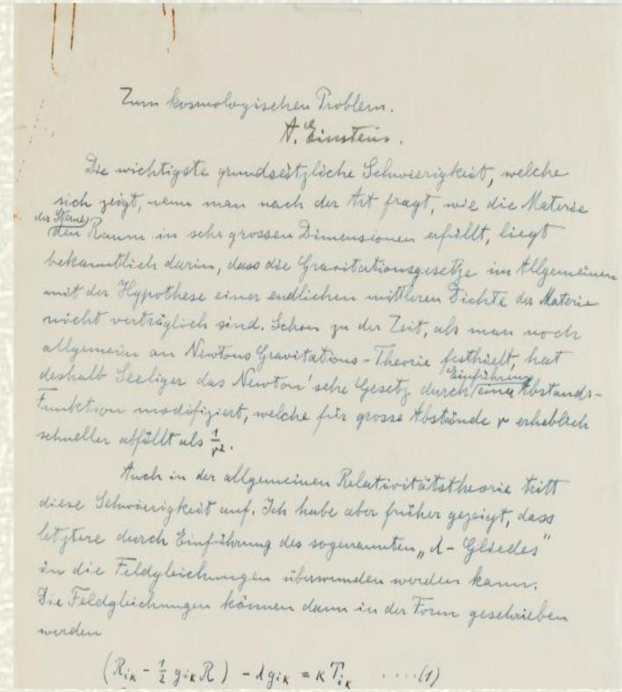
  “The density is constant and determines the expansion”

- **Steady-state model**

  Continuous formation of matter from vacuum

  Anticipates Hoyle’s model

  Fatal flaw: abandoned



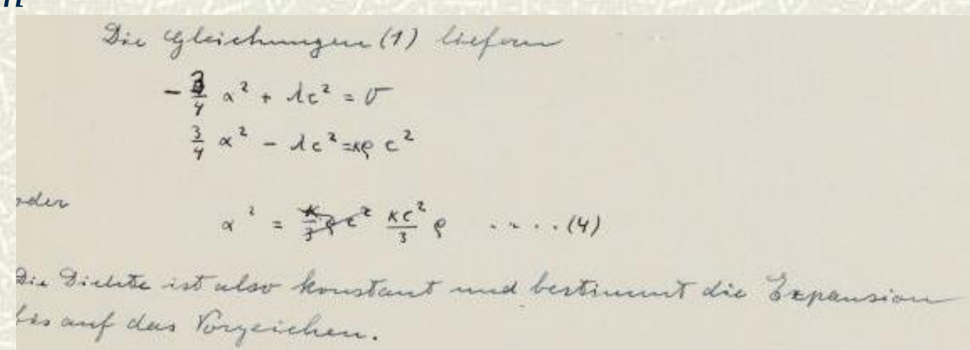
Zum kosmologischen Problem.

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

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



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

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

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

Steady-state vs big bang (1950-70)

- **Nucleosynthesis of light elements**

  Alpher, Hermann and Gamow (1948)

- **Optical astronomy (1950s)**

  Revised distances to the nebulae (Baade, Sandage)

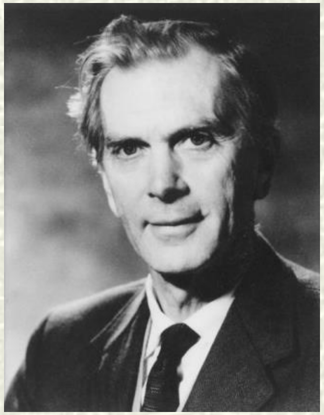
  Timescale problem resolved

Allen Sandage

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

  Galaxy distributions at different epochs

  Cambridge 3C Survey (Ryle)



- **Cosmic microwave background (1965)**

  Microwave frequencies

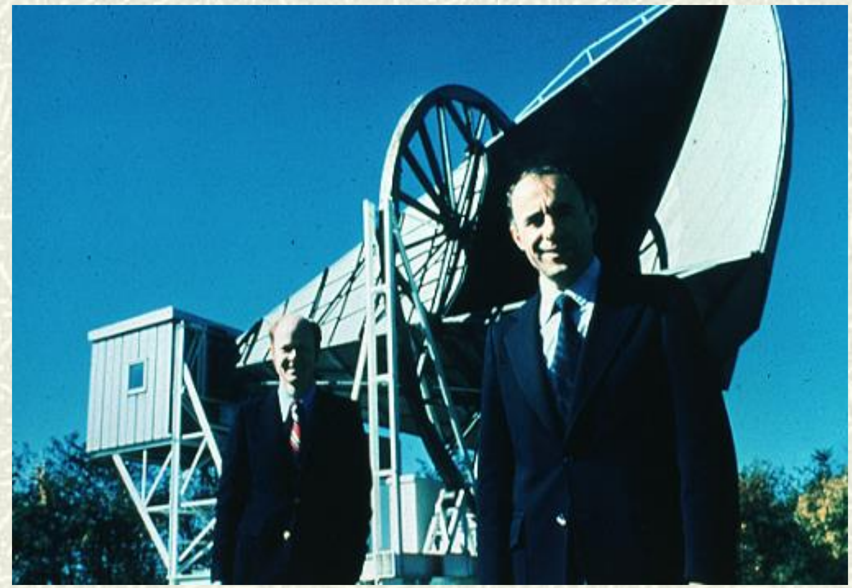
  Remnant of young, hot universe

Martin Ryle

Cosmic background radiation (1965)

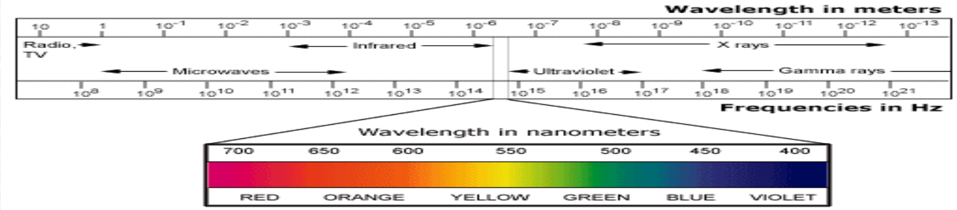
CMB discovered accidentally

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



Penzias and Wilson (1965)

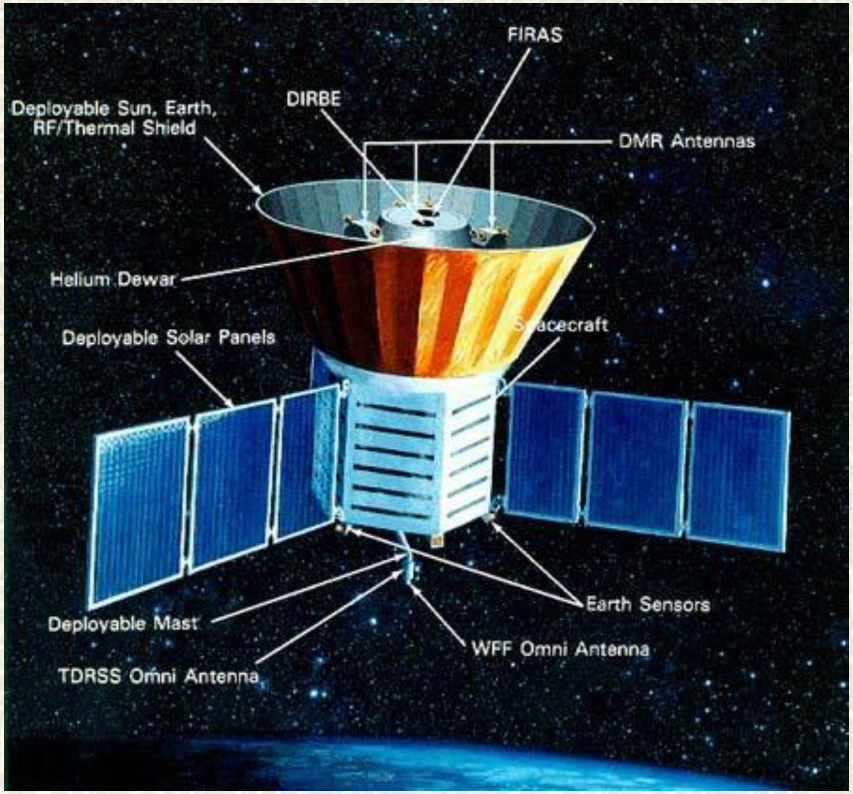
Echo of Big Bang!



Modern measurements of the CMB

- Details of background radiation
- Full spectrum
- Comparison with theory
- Perturbations?

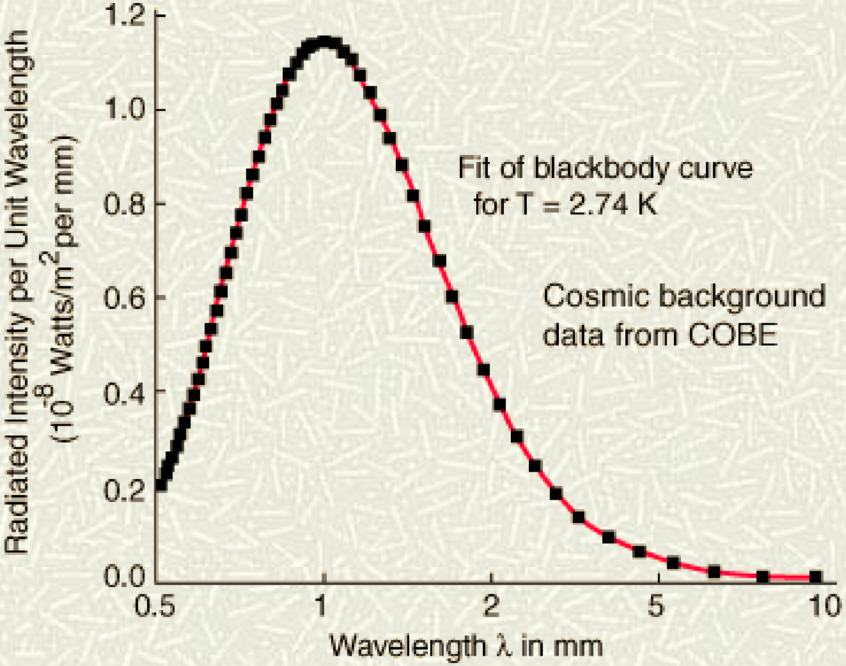
  - ***Ground telescopes***
  - ***Balloon experiments***
  - ***Satellite experiments***



COBE satellite (1992)

COBE measurements of CMB

- Expected temperature
- Expected frequency
- Perfect blackbody spectrum

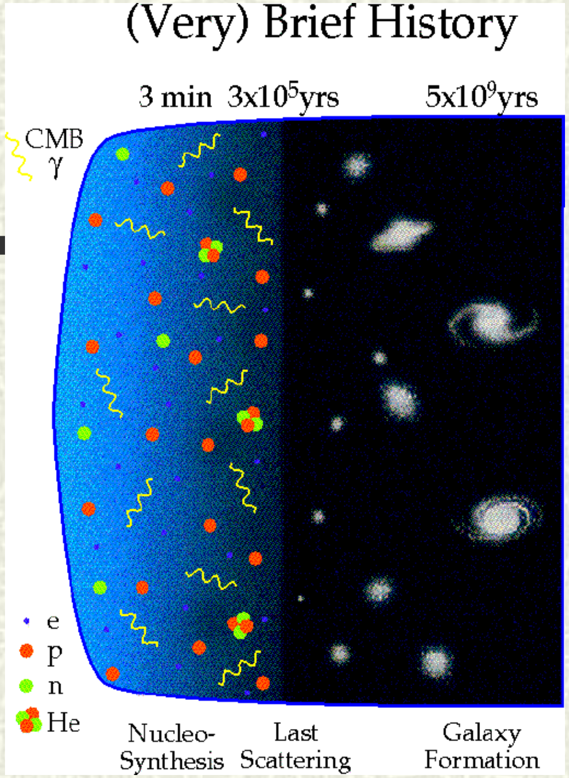


- *Radiation very uniform*
- *Variation of 1 in* 10^5
- *Seeds of galaxies ?*

COBE (1992)

<u>Nobel Prize</u>

Big bang puzzles



- **Characteristics of background radiation**

  Homogeneity, flatness, galaxy formation?(1970-80)

- **The theory of inflation (1981)**

  Exponential expansion within first second?

  Initial conditions?

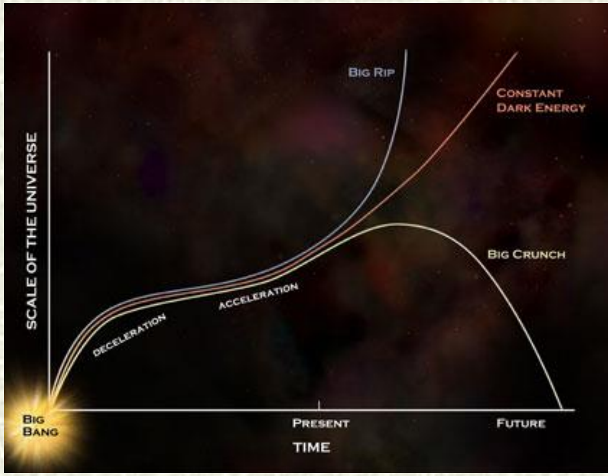
  Which model of inflation?

- **Dark energy (1998)**

  Observation of accelerated expansion

  The return of the cosmological constant

  Problems of interpretation



$$G_{\mu\nu} + \lambda g_{\mu\nu} = - \kappa T_{\mu\nu}$$

Nature of DE unknown

Relativity, astronomy and the universe: the first 100 years

- **Published May, 1916**

  A new theory of gravity

- **Classic predictions supported by observation**

  Perihelion of Mercury: bending of light by a star

  Gravitational redshift

- **Cosmological predictions supported by observation**

  The expanding universe: the big bang

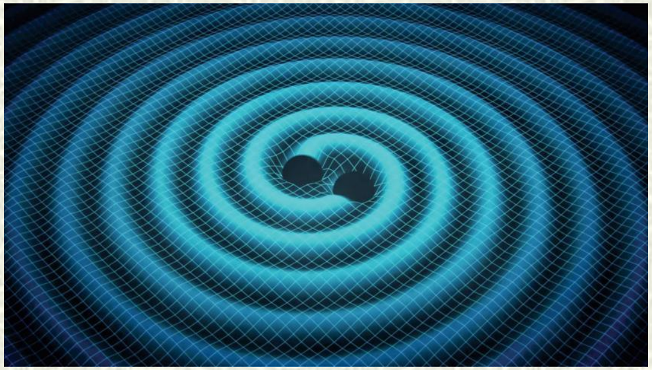
  Black holes: gravitational waves

- **Relevant today**

  GPS

Skeptical of extrapolations

Coda: gravitational waves



- **Einstein (1916, 18)**

  Linearized wave-like solutions of GFE

  Cosmic events cause tiny ripples in space-time?

- **Einstein and Rosen (1936, 37)**

  Cylindrical wave solutions – carry no energy? (1936)

  Corrected with assistance from HP Robertson (1937)

Joseph Weber

- **John Archibald Wheeler (1960s)**

  Numerical wave solutions

- **Weber bars (1960s)**

  Reports signal of gravitational waves

  Not reproduced, not accepted by community

Gravitational Waves: Observation

- **Binary pulsar PSR1913+16**

  Hulse-Taylor (1974)

  Decrease in orbital period exactly as predicted

- **Direct measurement?**

  Interferometers: 1980-

  Interferometers with 4 km arms (LIGO, VIRGO)

- **Advanced LIGO (2015)**

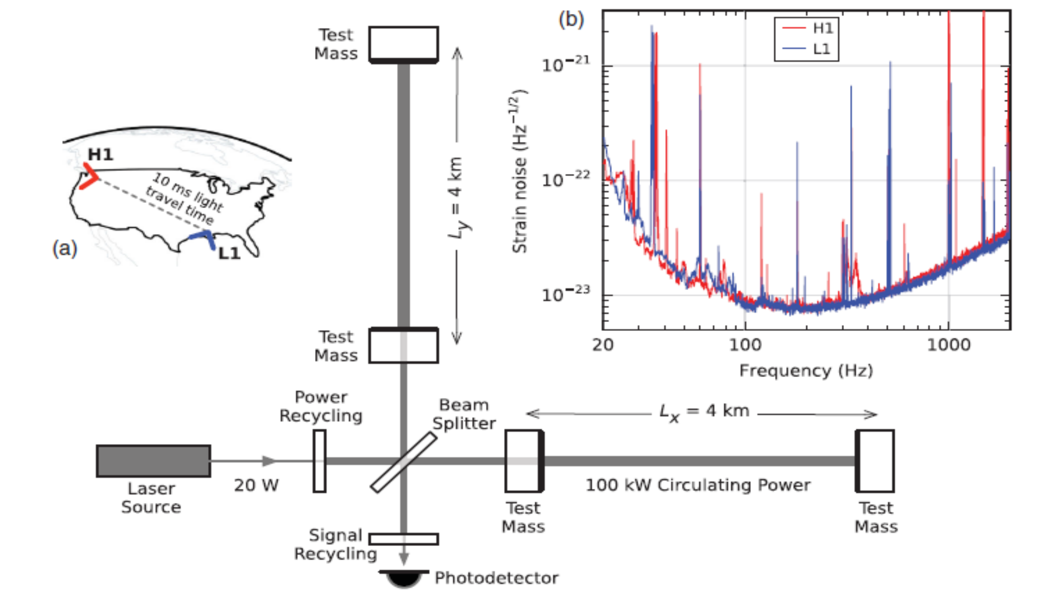
  Clear signal (September 2015)

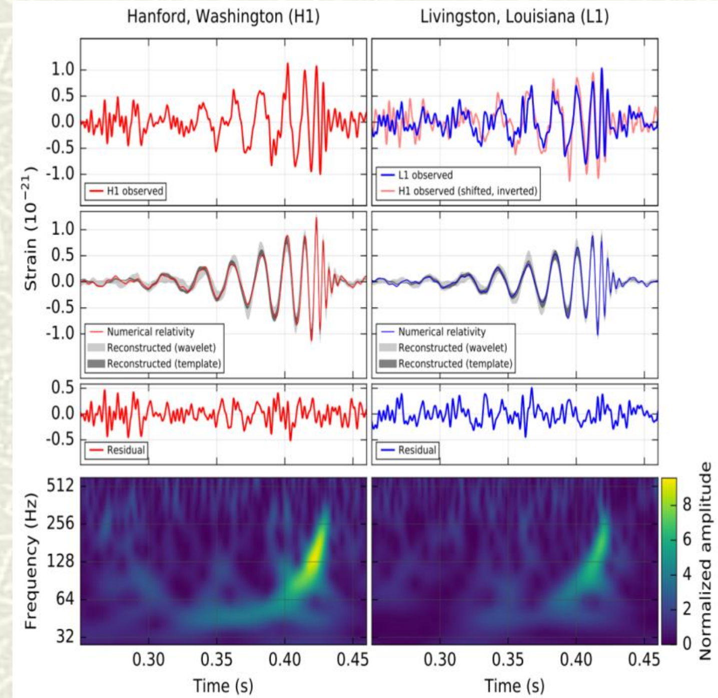
- **Double whammy!**

  Exact match with merging BHs

  29 $M_\odot$, 36 $M_\odot$; *1.3 billion LY away*

Hulse-Taylor pulsar





Selected for a Viewpoint in *Physics*

, 061102 (2016) PHYSICAL REVIEW LETTERS week 12 FEBRU

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

1. ***Shape of waveform***
2. ***Frequency of orbit***

BBH !

Nobel prize 1916?

Relativity and GPS

- Signal from satellite

  compare time received to transmitted

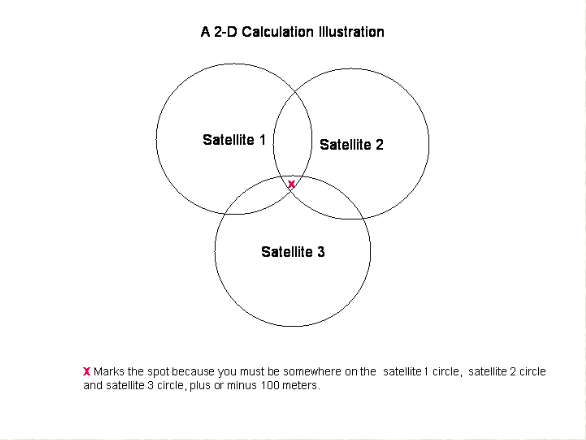
  synchronized clocks

- Convert time to distance

  x speed of radiowaves

- Triangulation using 4 sources

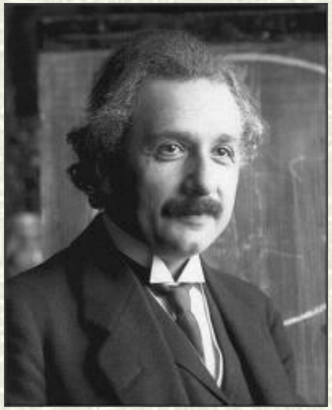
  accurate to within 5 metres



Assumes constancy of speed of light

GPS: a relativistic correction

Synchronization of satellite/earth clocks



- Motion of satellite (SR)

  Clocks slow by 7 μs/day

- Reduced gravity field (GR)

  Clocks fast by 45 μs/day

Satellite clocks fast by 38 μs/ day

Successful correction to GPS

Where next for general relativity?

- **More general theory**

  Unified field theory; the forces of nature (Einstein)

- **Reconcile GR with quantum theory**

  Quantum gravity

- **Some progress**

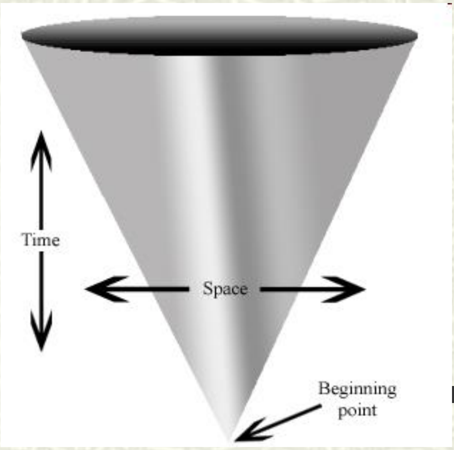
  Black hole thermodynamics

  Hawking-Bekenstein radiation

- **Quantum cosmology**

  The quantum big bang

Stephen Hawking



A universe from nothing?

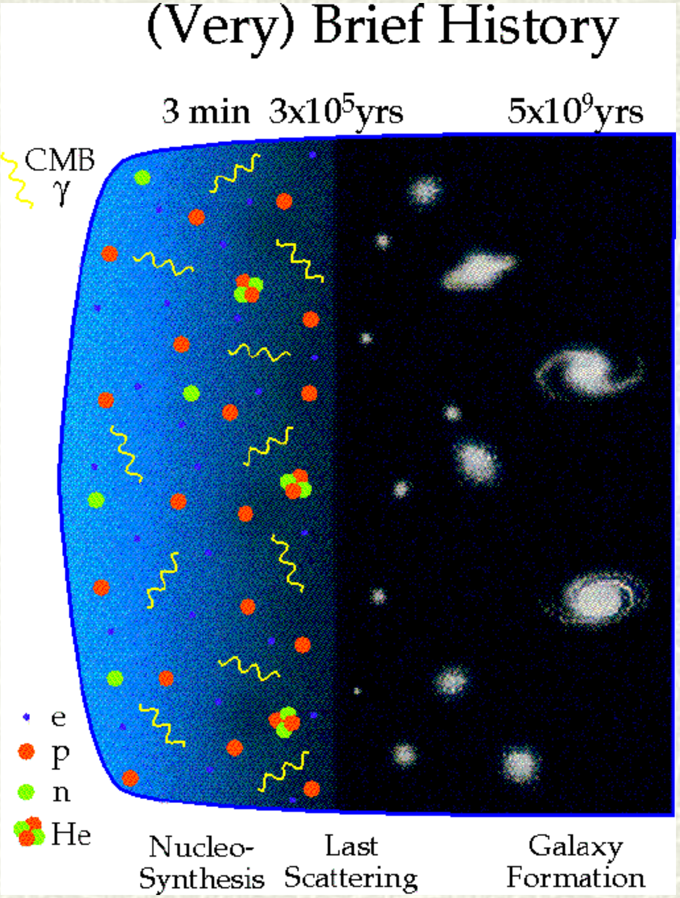
The big bang – evidence

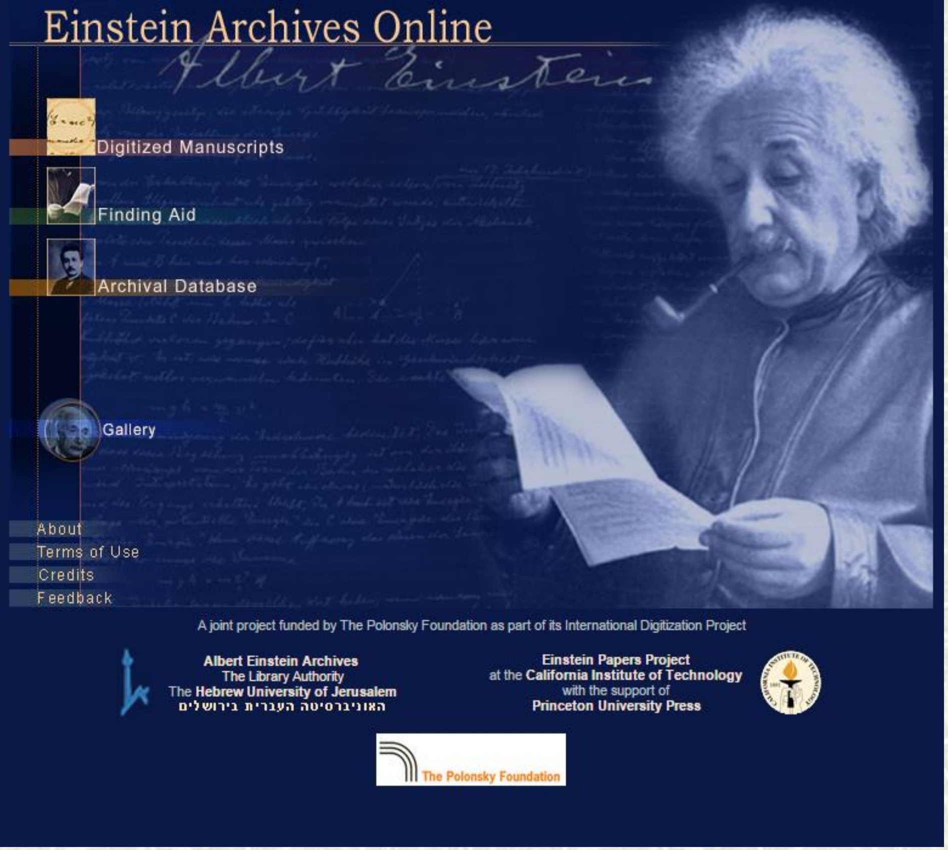
1. The expansion of the *U*

2. The abundance of ***H*** and ***He***

3. The distribution of the galaxies

4. The cosmic microwave background





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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.

Archival Call Number:	1-115
Begin Date:	1932-09-01
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Main Author:	Einstein, Albert (Author)
Other Persons:	Mayer, Walther (Author)
Language:	German
Archival Location:	Albert Einstein Archives, The Hebrew University of Jerusalem, Israel
Number of Pages:	11.

Document Type | Related Items | Associated Documents | Copyright

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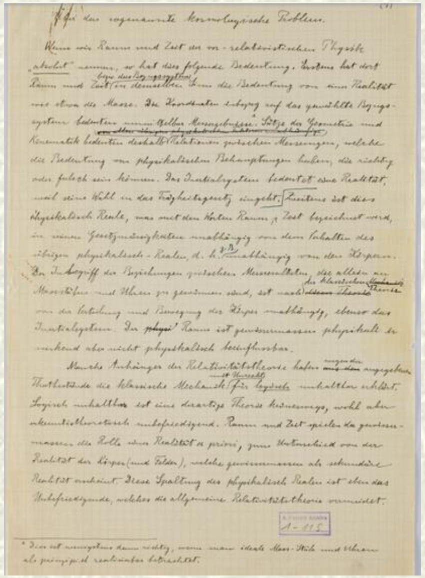
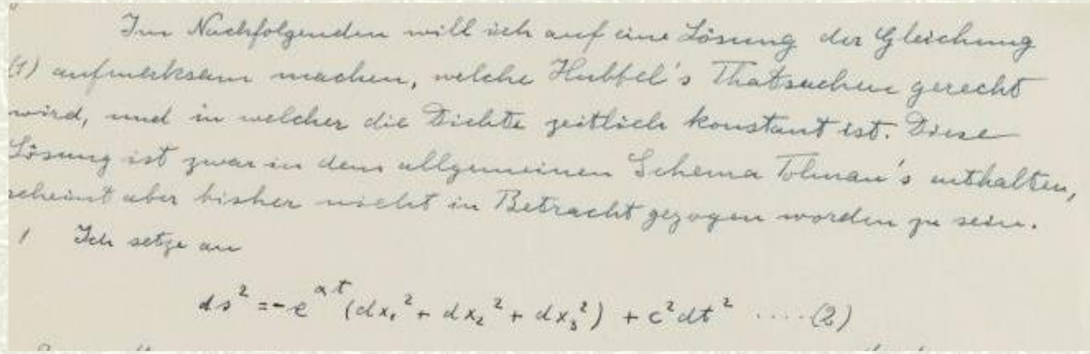

Über das sogenannte kosmologische Problem.

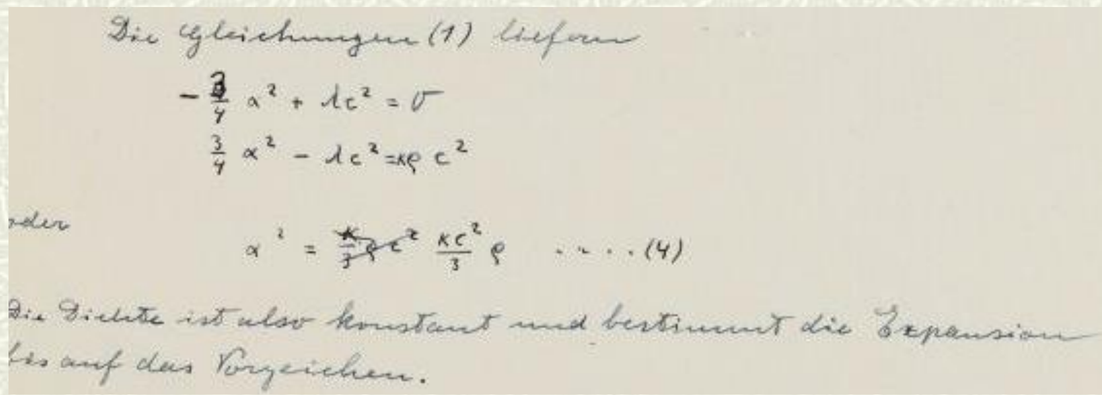
1-115

Abandoned model

- **de Sitter line element**
  Correct geometry
- **Simultaneous equations**
  Error in derivation
  Null solution
- **Einstein’s crossroads**
  Realised problem on revision
  Declined to amend model
- **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

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


Die Gleichungen (1) liefern

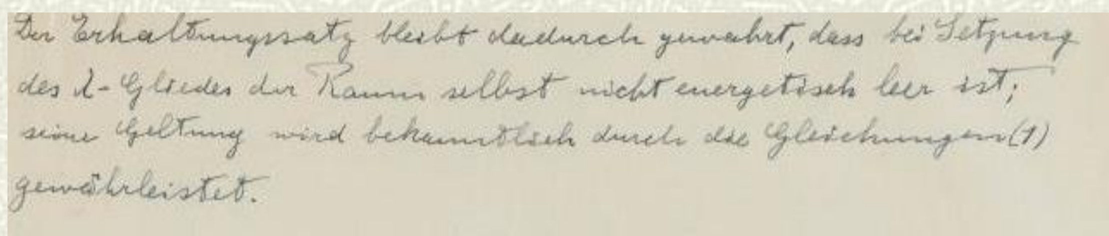
$$-\frac{3}{4}\alpha^2 + \lambda c^2 = 0$$

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

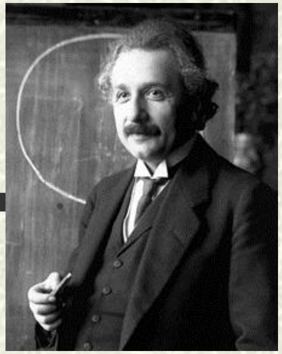
oder

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

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


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.

Einstein's cosmology: conclusions



- **Major test for general relativity**

  Conscious of assumptions of homogeneity, isotropy

- **Embraces dynamic cosmology**

  New evidence – new models (JMK)

  Timespan of expanding models puzzling

  Steady-state universe?

Hubble constant revised

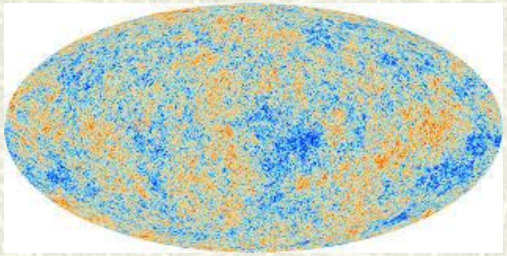
- **Evolving models (less contrived)**

  Cosmic constant not necessary

  Extraction of parameters compatible with observation

  Closed and open models

  Timespan problem attributed to simplifying assumptions



Cosmic microwave background
Homogeneous, flat universe

Verdict (1933, 1945): more observational data needed

No mention of origins

nature International weekly journal of science

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,

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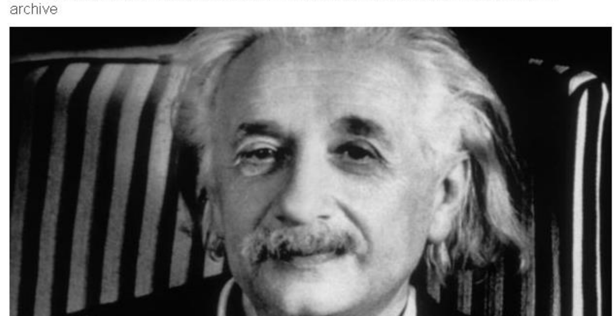
WIT researchers discover 'lost' Einstein model of universe

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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Einstein’s steady-state model (Jan 31)

Problem with evolving models

“De Sitter and Tolman have already shown that there are solutions to equations (1) that can account for these [Hubbel’s] observations. However the difficulty arose that the theory unvaryingly led to a beginning in time about 10^{10} – 10^{11} years ago, which for various reasons seemed unacceptable.”

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..

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 “

Mechanism

“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).”

Some key quotes (Einstein 1931)

"The cosmological problem is understood to concern the question of the nature of space and the manner of the distribution of matter on a large scale, where the material of the stars and stellar systems is assumed for simplicity to be replaced by a continuous distribution of matter."

"Now that it has become clear from Hubbel's results that the extra-galactic nebulae are uniformly distributed throughout space and are in dilatory motion (at least if their systematic redshifts are to be interpreted as Doppler effects), assumption (2) concerning the static nature of space has no longer any justification…."

"Several investigators have attempted to account for the new facts by means of a spherical space whose radius *P* is variable over time. The first to try this approach, uninfluenced by observations, was A. Friedman,[1] on whose calculations I base the following remarks. "

"However, the greatest difficulty with the whole approach… is that according to (2 a), the elapsed time since P = 0 comes out at only about 10^{10} years. One can seek to escape this difficulty by noting that the inhomogeneity of the distribution of stellar material makes our approximate treatment illusory."

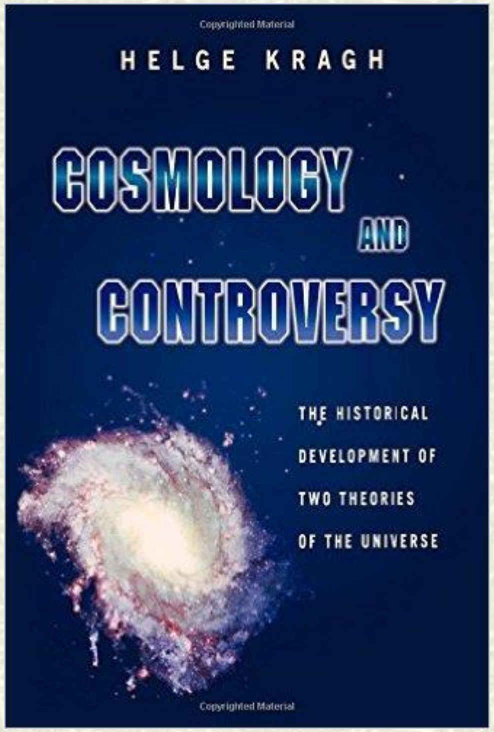
A useful find

- **New perspective on steady-state theory (1950s)**
  Logical idea: not a crank theory
  Tolman, Schroedinger, Mimura : considered steady-state universe

- **Insight into scientific progress**
  Unuccessful theories important in the development of science

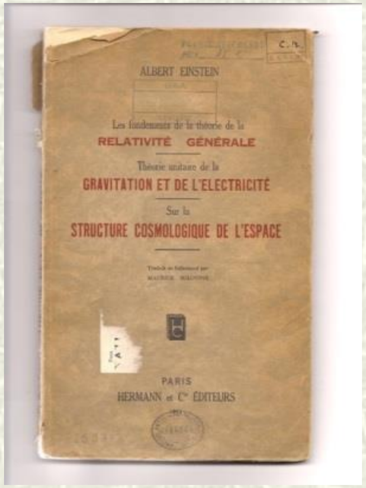
- **Links with modern cosmology**
  Creation energy and λ: dark energy
  de Sitter metric: cosmic inflation

- **Insight into Einstein's cosmology**
  Turns to evolving models rather than introduce new term to GFE
  Pragmatic approach: F-E model



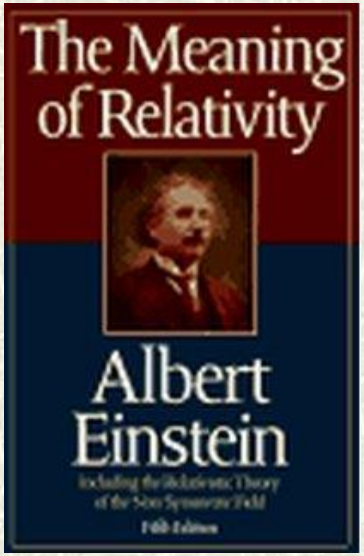
Einstein's greatest hits (cosmology)

- **Einstein's model of the Static Universe (1917)**
  First relativistic model of the cosmos



- **Einstein's steady-state model (Jan 31)**
  Natural successor to static model: abandoned

- **Friedman-Einstein model of the Universe (1931)**
  Use of Hubble constant to extract observational parameters



- **Einstein-de Sitter model of the Universe (1932)**

- **1933 review: 1945 review (Appendix)**
  Conversations with Gamow, Godel, Straus

No mention of origins

III Astronomy and the Universe

- **The Great Debate (1900-1925)**

  Spiral nebulae = galaxies beyond Milky Way?

- **The Hooker telescope (1917)**

  Edwin Hubble (1921)

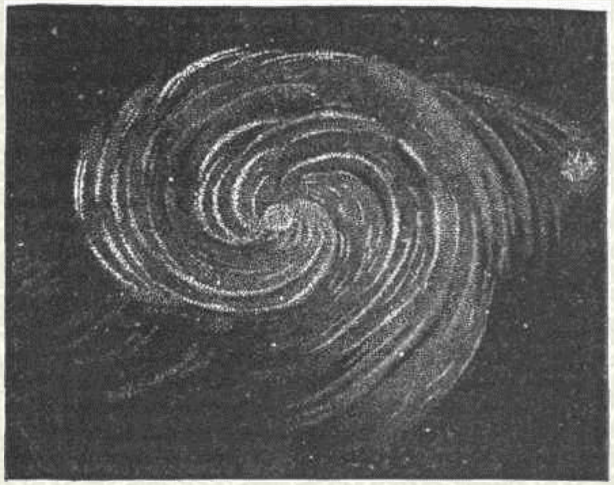
- **The distances of the nebulae (1925)**

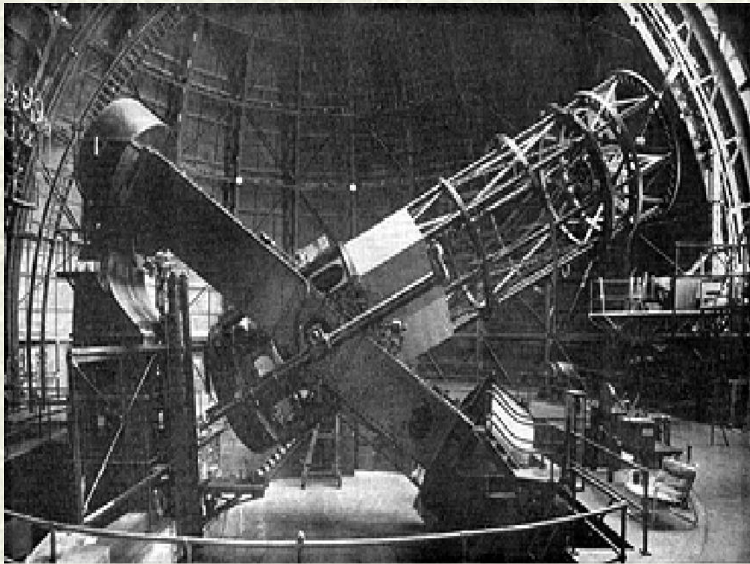
  Cepheid variables resolved in two nebulae

  Leavitt's period-luminosity relation

- **Spirals far beyond Milky Way**

  A universe of galaxies





The motion of the nebulae

- **The redshift of the nebulae**

  V.M Slipher (Lowell Observatory)

  Light from most nebulae redshifted (1915, 1917)

Vesto Slipher

- **Doppler effect**

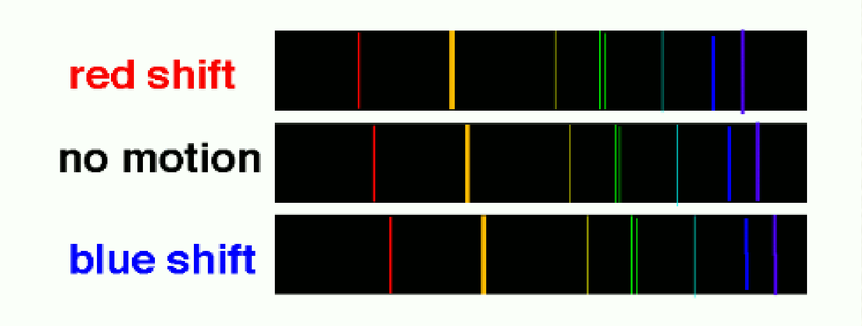
  Frequency of light depends on

  motion of source relative to observer

- **Nebulae moving outward?**

  Galaxies moving outward?

Lowell Observatory



The runaway galaxies (1929)

- **A relation between redshift and distance for the galaxies?**

Edwin Hubble (1889-1953)

- **Combine 24 distances with redshifts**

  Redshifts from Slipher: not acknowledged

- **Linear relation: Hubble's law (1929)**

  $\boldsymbol{v} = H_o \boldsymbol{d}$ *with* $H = 500\ kms^{-1}Mpc^{-1}$

- **Landmark result in astronomy**

  Far-away galaxies rushing away

  at a speed proportional to distance

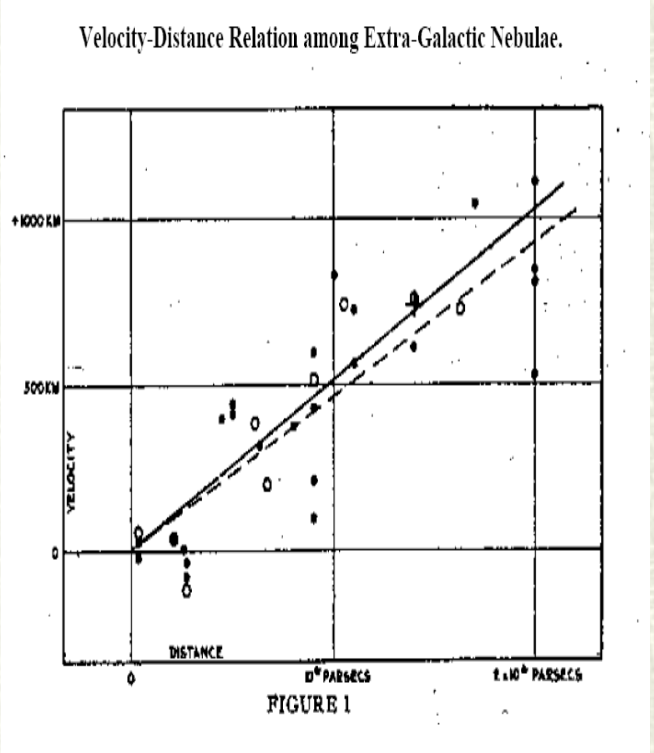


FIGURE 1

Why ?

Lemaître's universe (1927)

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

  Similar to Friedman 1922 model

  Starts from static Einstein universe

Fr Georges Lemaître

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

  Redshifts from Slipher, distances from Hubble

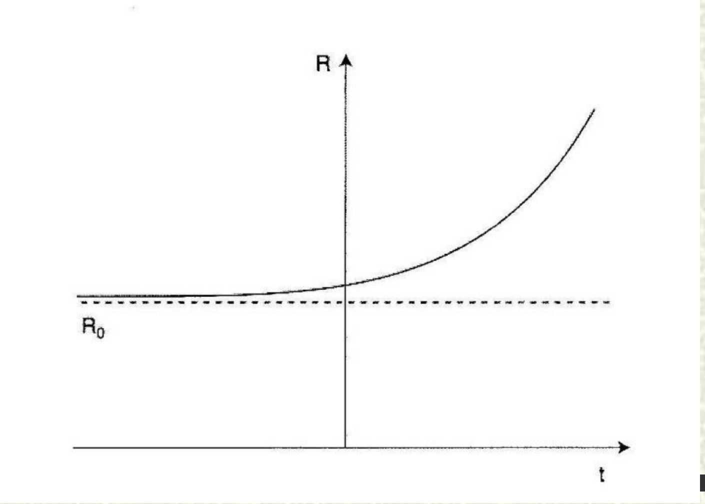
  $H = 585\ kms^{-1}Mpc^{-1}$

- **Ignored by community**

  Belgian journal (in French)

  Rejected by Einstein: "Votre physique est abominable"

  Einstein not up-to-date with astronomy?



The expanding universe (1930)

- **RAS meeting (1930)**

  Eddington, de Sitter

  If redshifts are velocities, and if effect is non-local

  Static cosmic models don't match observations

- **Expanding universe?**

  Hubble's law = expansion of space?

  $H = 500\ kms^{-1}Mpc^{-1}$

- **Friedman-Lemaître model circulated**

  Time-varying radius

  Time-varying density of matter

  Evolving universe

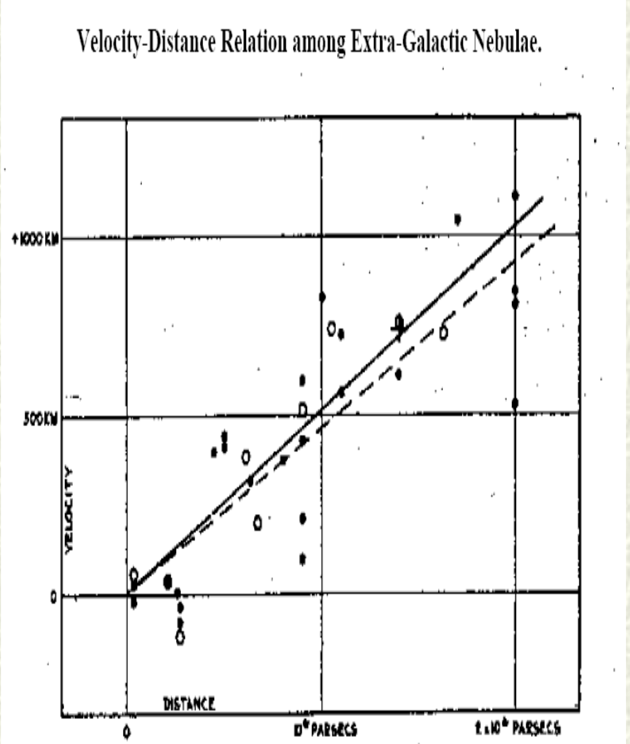


FIGURE 1

Models of the expanding 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

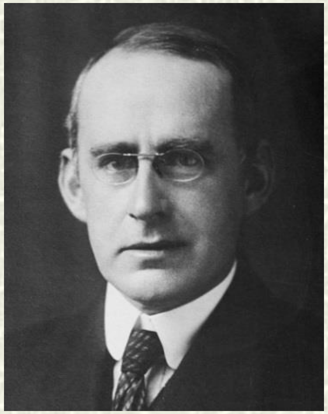
  Expanding universes of every flavour

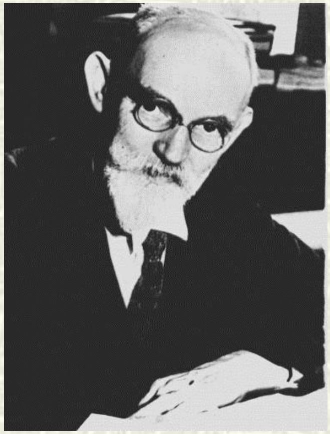
- **Einstein (1931, 32)**

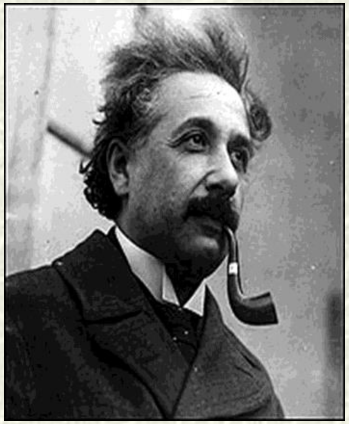
  Friedman-Einstein model $\lambda = 0$, $k = 1$

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

Occam's razor?



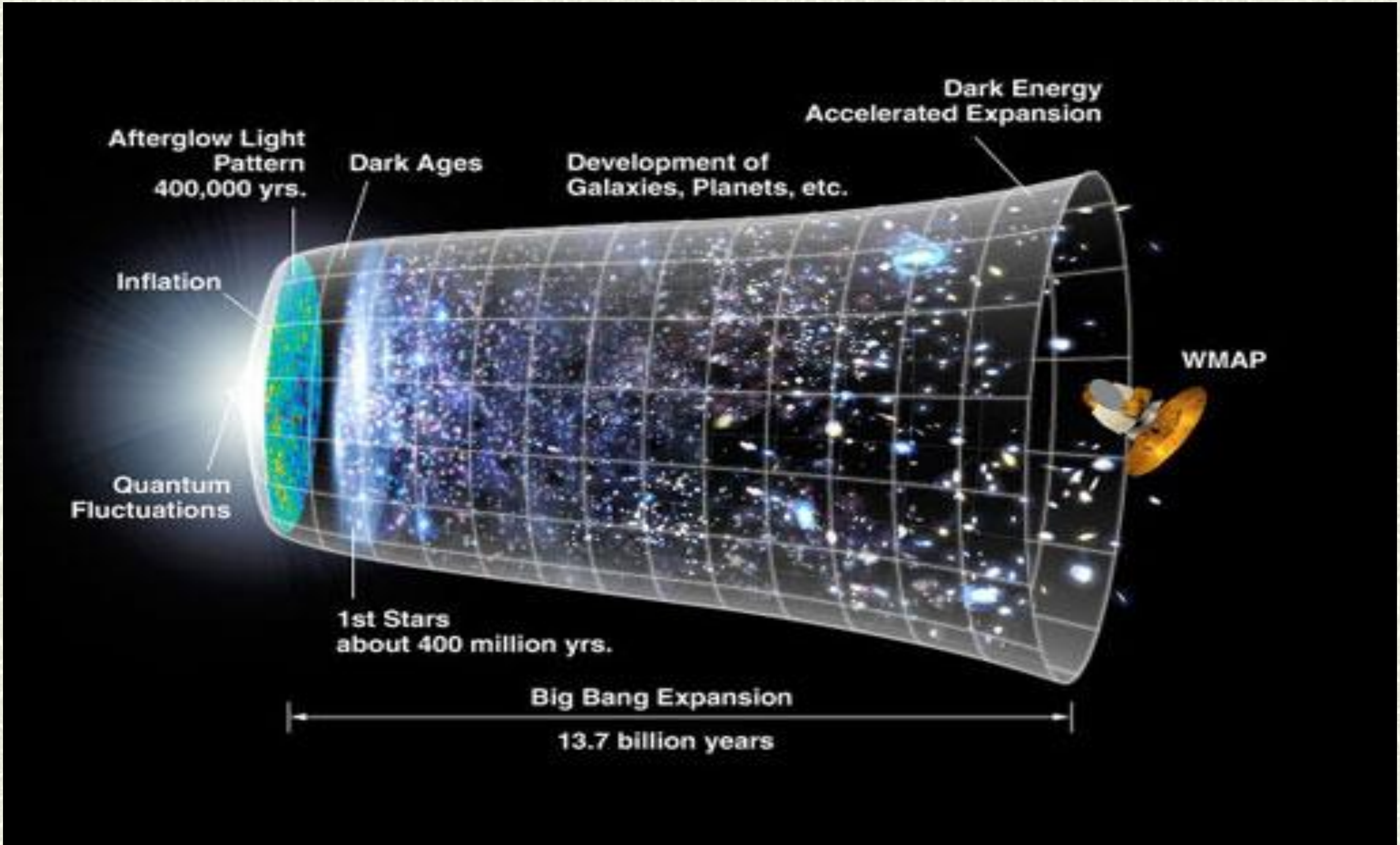




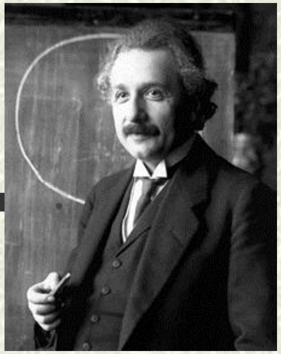
Evolving models

No mention of origins

The big bang model



Einstein's universe: conclusions



- **Cosmology = test for general relativity**

  Introduces λ-term to the field equations

- **Embraces dynamic cosmology**

  New evidence – new models

  Steady-state vs evolving universe

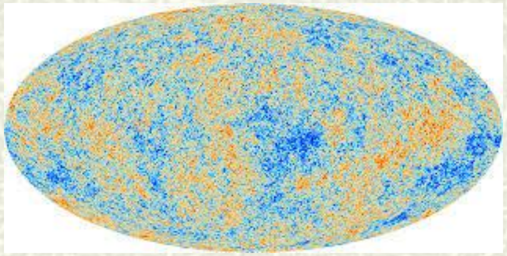
  Evolving models simpler: remove λ-term

Hubble constant revised

- **The evolving universe**

  Extract observational parameters

  Timespan problem attributed to simplifying assumptions



- **No discussion of origins**

  Wary of extrapolations

Cosmic microwave background
Homogeneous, flat universe

Einstein’s steady-state model: key quotes

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).”

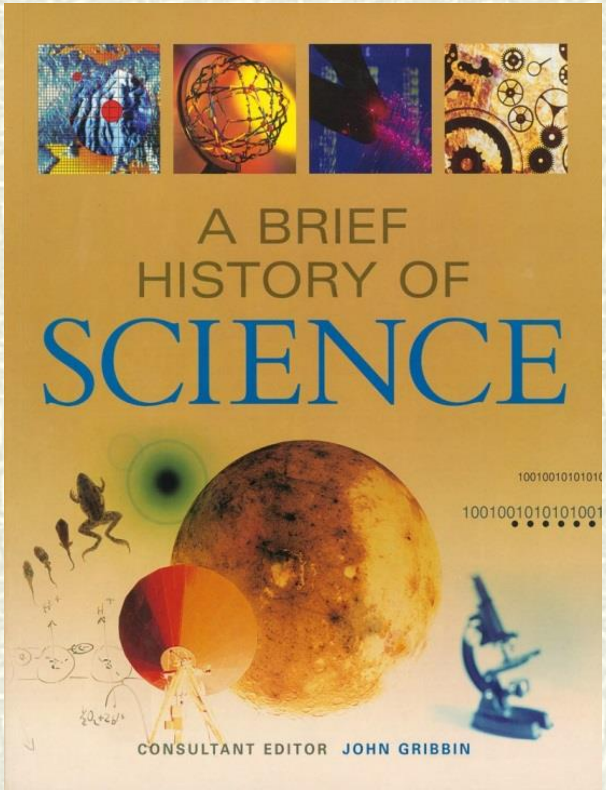
Einstein’s steady-state theory: a significant find?

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

- **Insight into scientific progress**
  Evolution of successful theories
  No Kuhnian paradigm shift to ‘big bang’ model
  Slow dawning

- **Insight into Einstein’s philosophy**
  Simple solution?
  Discards model rather than introduce new term to GFE
  Occam’s razor approach

- **Links with modern cosmology**
  Dark energy, cosmic inflation



Paradigm shift or slow dawning ?

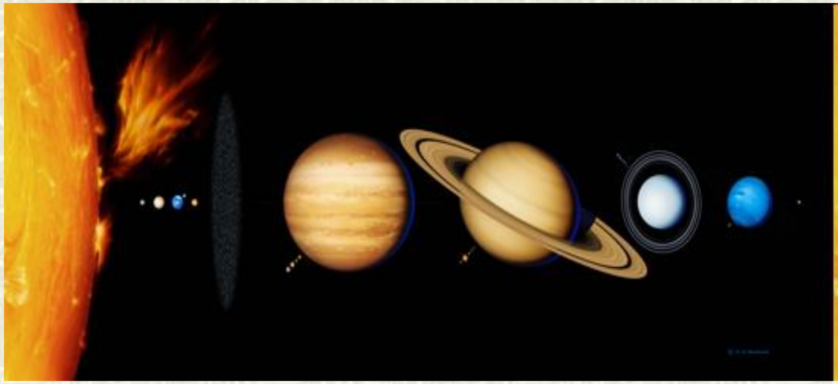
Explanation for runaway galaxies?

Newton

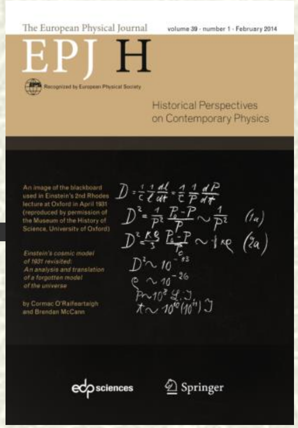
- Gravity pulls in not out
- Space is fixed
- Time has no beginning

Isaac Newton

How can galaxies be receding?
What is pushing out?

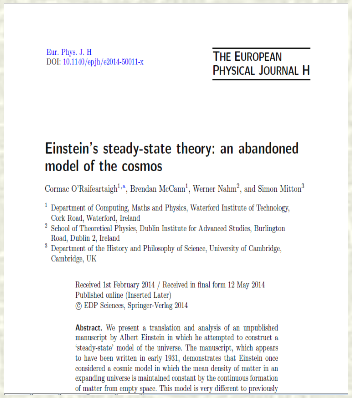


Results: publications



- ## 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

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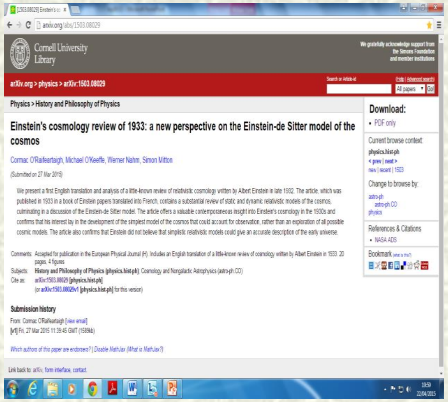
Abstract. We present a translation and analysis of an unpublished manuscript by Albert Einstein in which he attempted to construct a 'steady-state' model of the universe. The manuscript, which appears to have been written in early 1931, demonstrates that Einstein once considered a cosmic model in which 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

Astronomical Society of the Pacific
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VOLUME 471

ORIGINS OF THE EXPANDING UNIVERSE: 1912–1932

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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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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

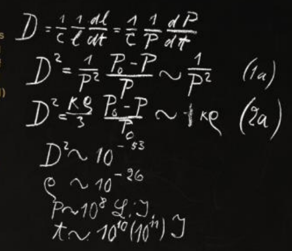
The European Physical Journal volume 39 · number 1 · February 2014

EPJ H

Recognized by European Physical Society

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)



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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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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

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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)

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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)

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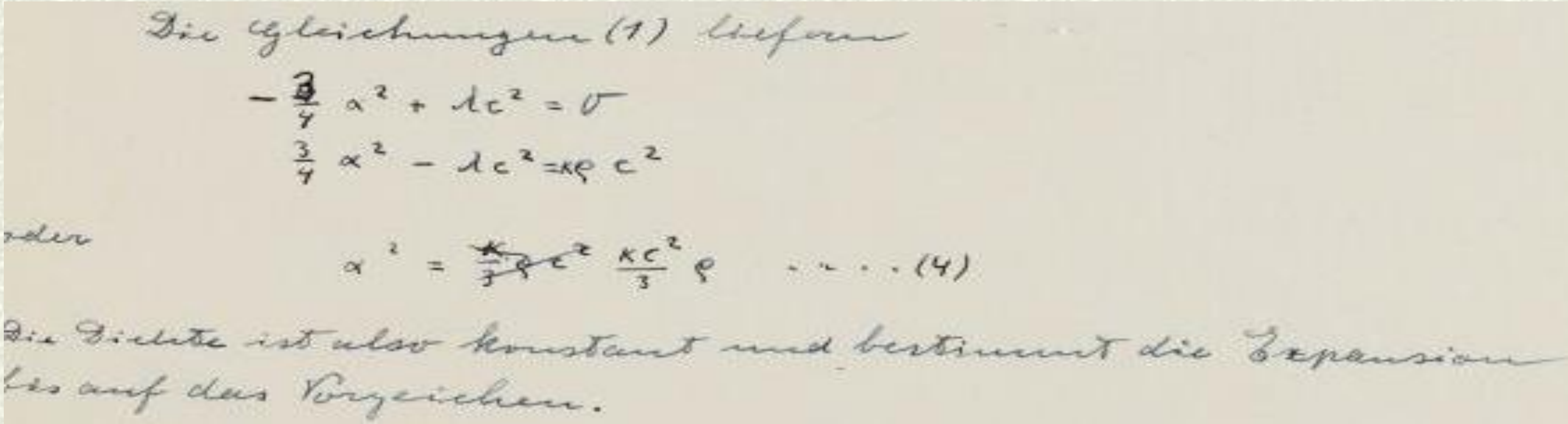


Die Gleichungen (1) liefern

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

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

oder

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

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)

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)

Some key quotes (Einstein 1917)

"In a consistent theory of relativity, there can be no inertia relative to "space", but only an inertia of masses relative to one another"

"I have not succeeding in formulating boundary conditions for spatial infinity. Nevertheless, there is still a way out…for if it were possible to regard the universe as a continuum which is finite (closed) with respect to is spatial dimensions, we should have no need at all of any such boundary conditions"

"The most important fact that we draw from experience as to the distribution of matter is that the relative velocities of the stars are very small compared with the velocity of light….. There is a system of reference relative to which matter may be looked upon as being permanently at rest "

"**However, the system of equations ..allows a readily suggested extension which is compatible with the relativity postulate**... For on the left hand side of the field equation…we may add the fundamental tensor $g_{\mu\nu}$, multiplied by a universal constant , $-\lambda$, at present unknown, without destroying the general covariance "

Schroedinger's comment (1918): Einstein's response (1918)

An abandoned model

- **Correct geometry**

  de Sitter metric

- **Simultaneous equations**

  Eliminate λ

  Relation between α^2 and ρ

- **Einstein's crossroads**

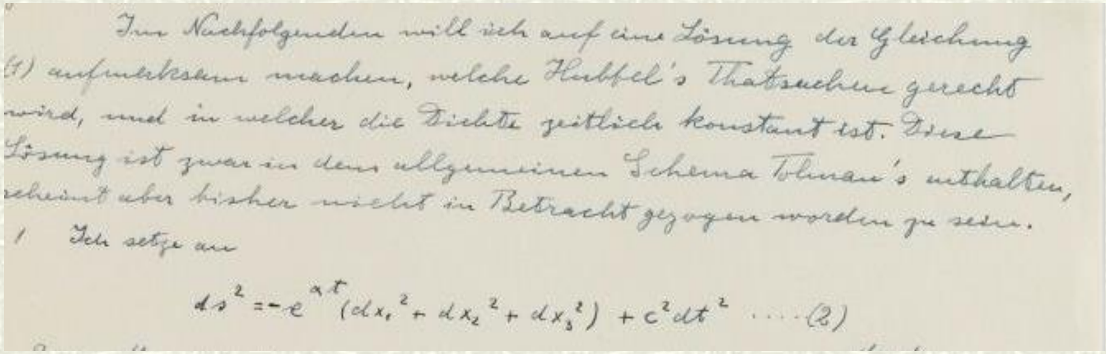
  Null solution on revision

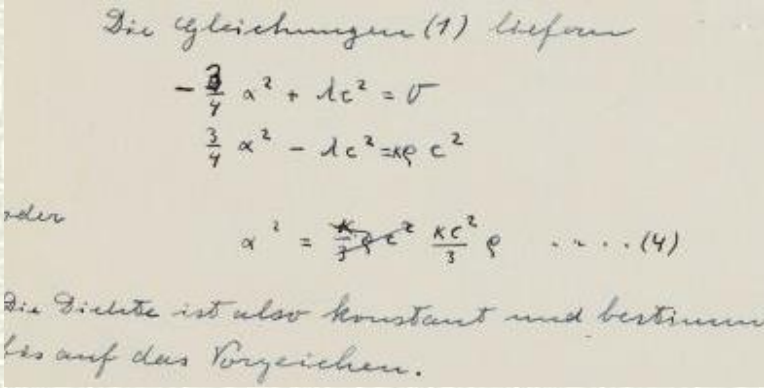
  Tolman? (Nussbaumer 2014)

  Declined to amend GFE

- **Evolving models**

  Less contrived: set $\lambda = 0$

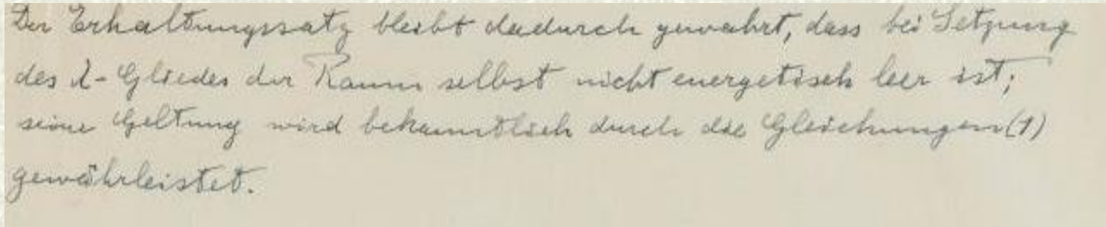




$$9\alpha^2/4 + \lambda c^2 = 0$$

$$3\alpha^2/4 - \lambda c^2 = \kappa\rho c^2$$

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

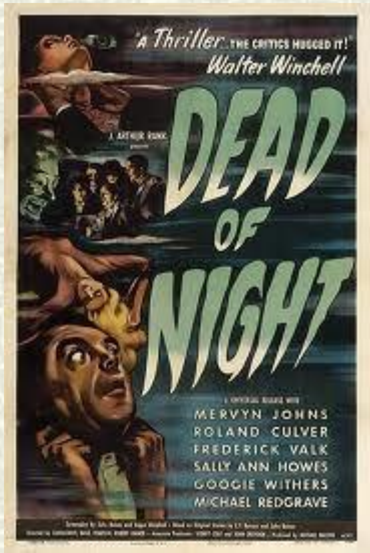


Steady-state universe (1948)

- Alternative to big bang *(Fred Hoyle)*
- Expanding universe

BUT

- Continuous creation of matter?
- Unchanging universe
- No beginning, no age problem
- No assumptions about early epochs



<u>Very little matter needed</u>

3. 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

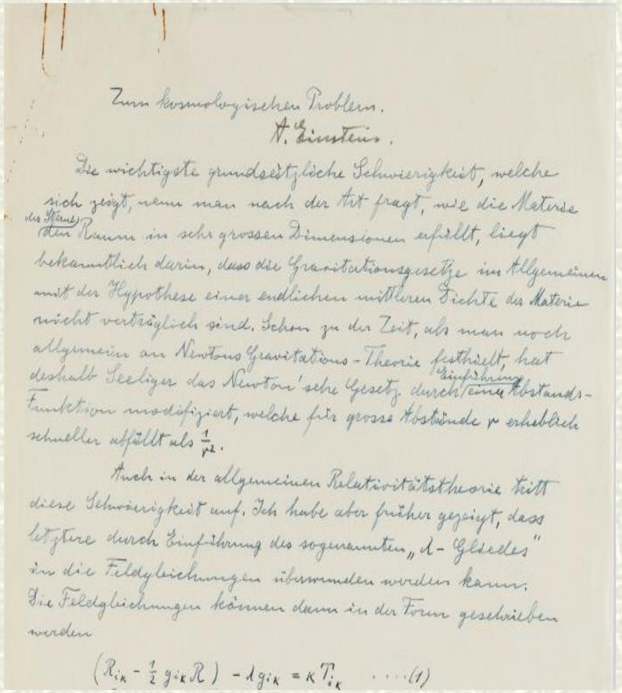
  "The density is thus constant and determines the expansion"

- **Steady-state model of the Expanding Universe**

  Anticipates Hoyle solution

  Written in early 1931

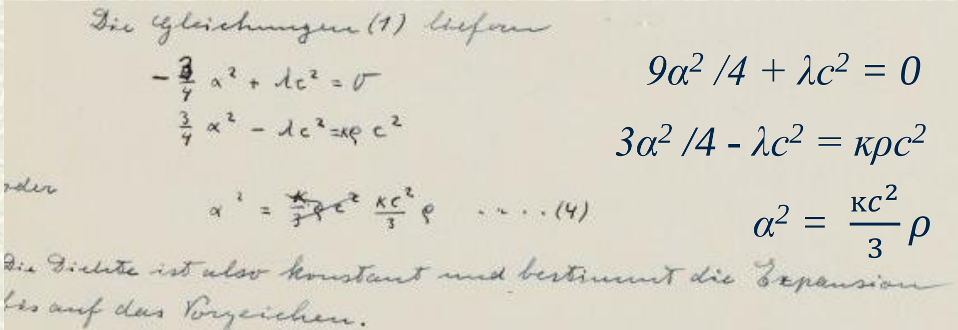
  Fatal flaw: abandoned


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

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


Die Gleichungen (1) liefern

$$-\frac{9}{4}\alpha^2 + \lambda c^2 = 0$$

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

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.

$$9\alpha^2/4 + \lambda c^2 = 0$$

$$3\alpha^2/4 - \lambda c^2 = \kappa\rho c^2$$

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

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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

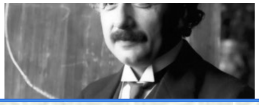
2 comments, 2 called-out + Comment Now + Follow Comments

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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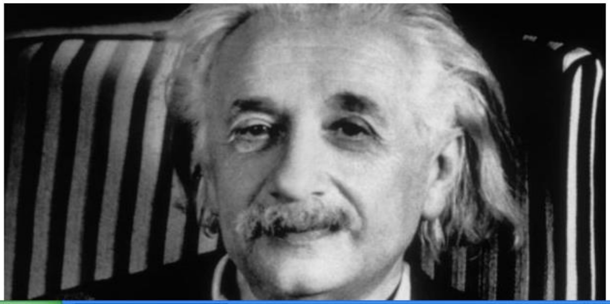
News / Science

WIT researchers discover 'lost' Einstein model of universe

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



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09:07 Man in his twenties stabbed in north Dublin

09:05 Family hope public appeal will help daughter beat cancer

08:42 Gardaí investigate death of woman in Dublin

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

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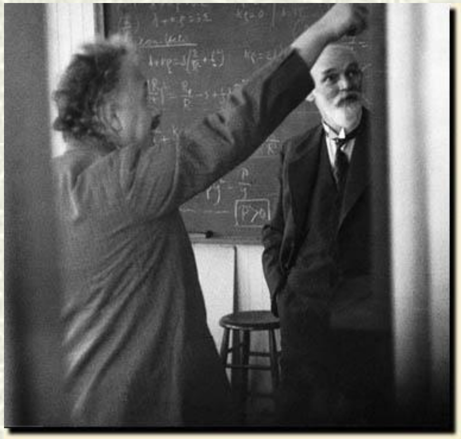
2. Einstein-de Sitter model (1932)



- **Remove spatial curvature**

  Curvature not a given in dynamic models (Heckmann)

  Not observed empirically (Occam's razor)

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

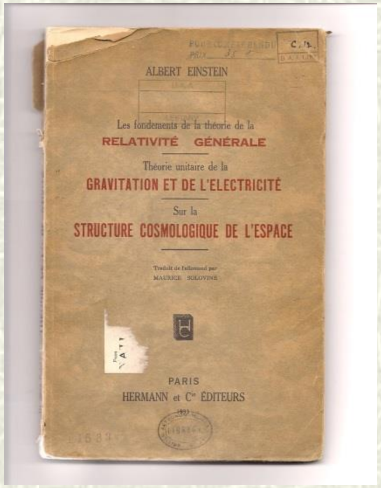
- **Simplest Friedman model**

  Time-varying universe with $\lambda = 0$, $k = 0$, $p = 0$

  Estimate of density : $\rho = 10^{-28}$ g/cm^3

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

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



- **<u>Becomes standard model</u>**

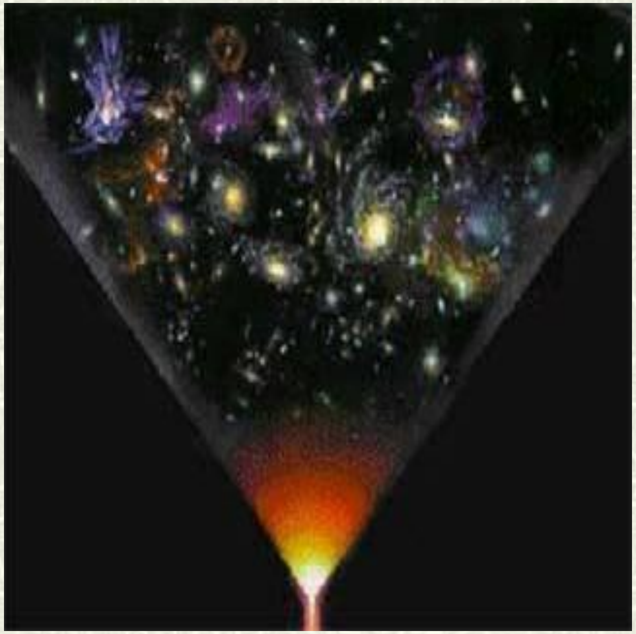
  Despite high density of matter, age problem

  Time evolution not considered

- **Longer version with time evolution (Einstein 1933)**

IV The 'big bang' model (1931)

- Infant *U* concentrated in tiny volume
- Extremely dense, hot
- Expanding and cooling ever since



Where do the laws of physics come from?

Wrong age (Hubble constant)

Singularity problem

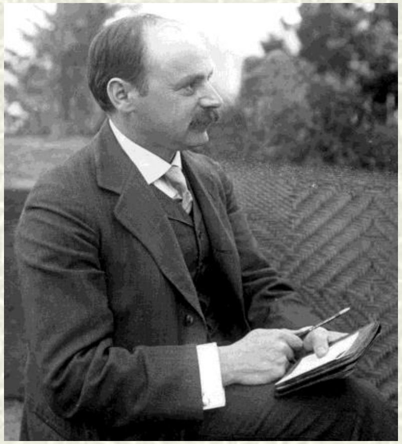
∞ density, ∞ temp at $t = 0$?

Cosmic prediction I: Black Holes

- **Schwarzschild (1916)**

  Exact solution for the field equations

  Body of spherical symmetry



Karl Schwarzschild (1873–1916)

- **Enigma**

  Solution becomes singular at $r = 2GM/c^2$

  Space closed up around mass?

- **Rejected**

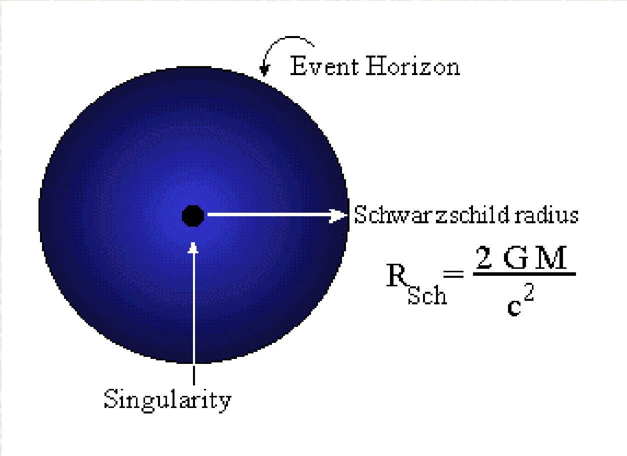
  Co-ordinate problem (Eddington)

  Prevented by internal pressure (Einstein 1922)

- **Physical reality?**

  Collapse of sun? Anderson (UCG)

  Collapse of large stellar ensemble : Lodge (Oxford)



The physics of black holes

- **Chandrasekhar (1931)**

  The physics of white dwarf stars (quantum degeneracy)

  SR: collapse to infinite density for $M > 1.4\ M_\odot$

  Rejected by Eddington, community

- **Oppenheimer (1939,40)**

  GR: Continued stellar collapse for $M > 3\ M_\odot$

  Rejected by Einstein (1939)

- **Wheeler, Thorne, Zeldovitch (1960s)**

  Numerical solutions of the field equations

  Simulation of stellar collapse

- **Penrose (1965)**

  No avoiding BH singularity

Black Holes: Observation

- **Compact astronomical objects (1960s)**

  Quasars: small, distant sources of incredible energy (1963)

  Pulsars: rapidly rotating neutron stars (1967)

- **X-ray binaries**

  Cygnus X-1 (1964)

  Matter pulled from star into massive companion emits X-rays

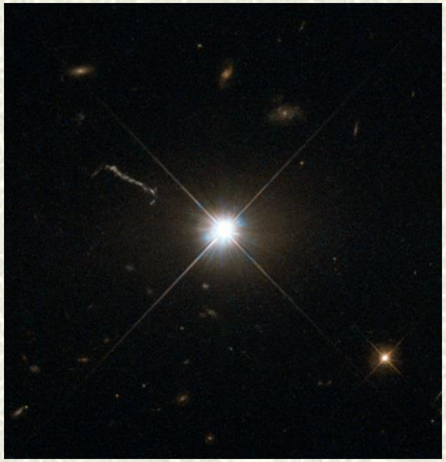
- **Orbit studies**

  Supermassive BH at centre of MW? (1990s)

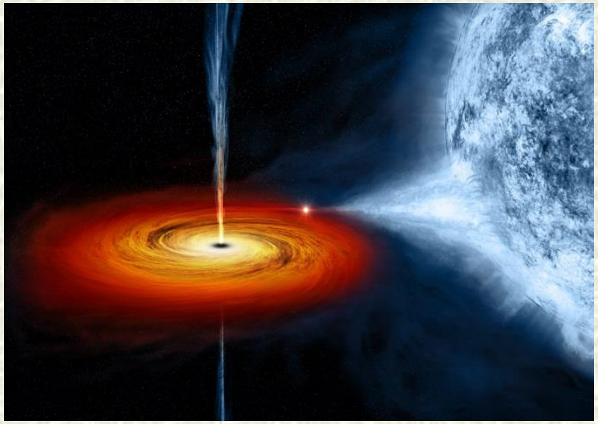
  Supermassive BH at centre of many galaxies (2000-)

- **2015-16**

  Gravitational waves from binary BH system!



Quasar 3C273



Cygnus X-1 (1964)

Relativity and the universe

- **The field equations of general relativity (1916)**

$$G_{\mu\nu} = -\kappa T_{\mu\nu}$$

- **Solution for the case of the universe?**

  Ultimate test for new theory of gravitation

- **Assumptions**

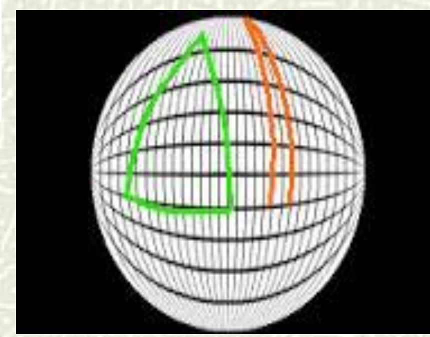
  Uniform, static distribution of matter

  Closed spatial curvature

  Introduce the cosmic constant λ

$$G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu}$$

The Einstein World



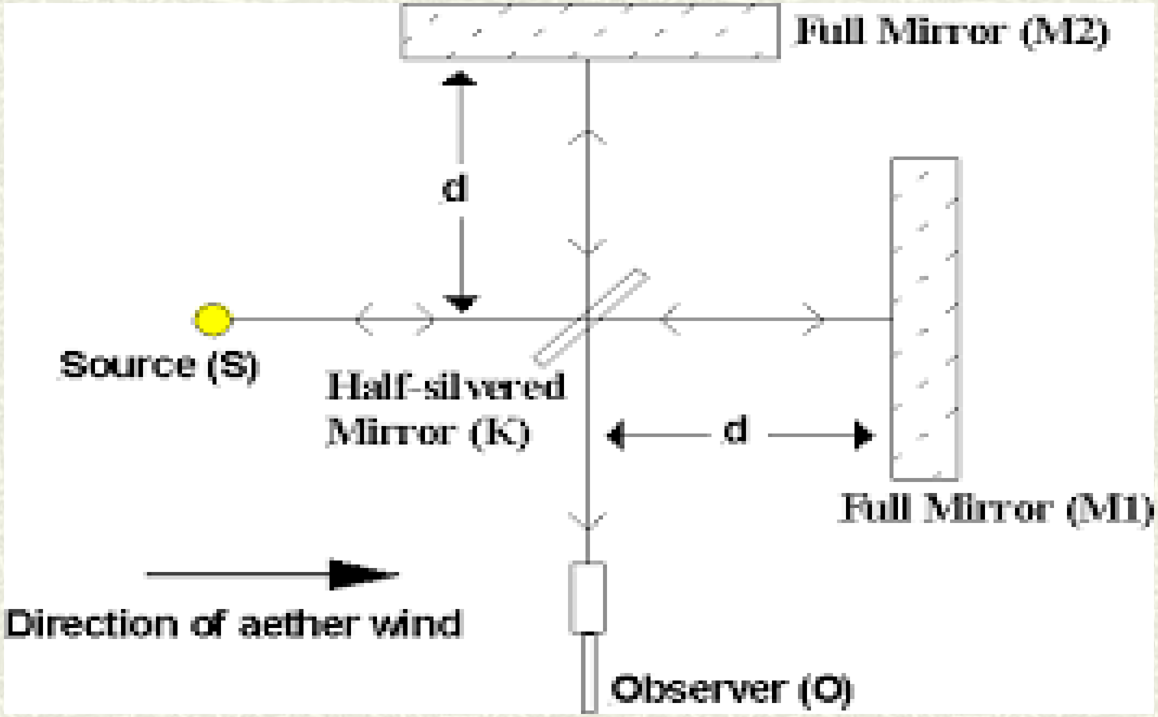
- **The Einstein World (1917)**

  Static universe of spherical geometry

  Cosmic radius and matter density defined by λ

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

Michelson-Morley experiment



Expect: rays should arrive at O out of phase
Result: no effect detected