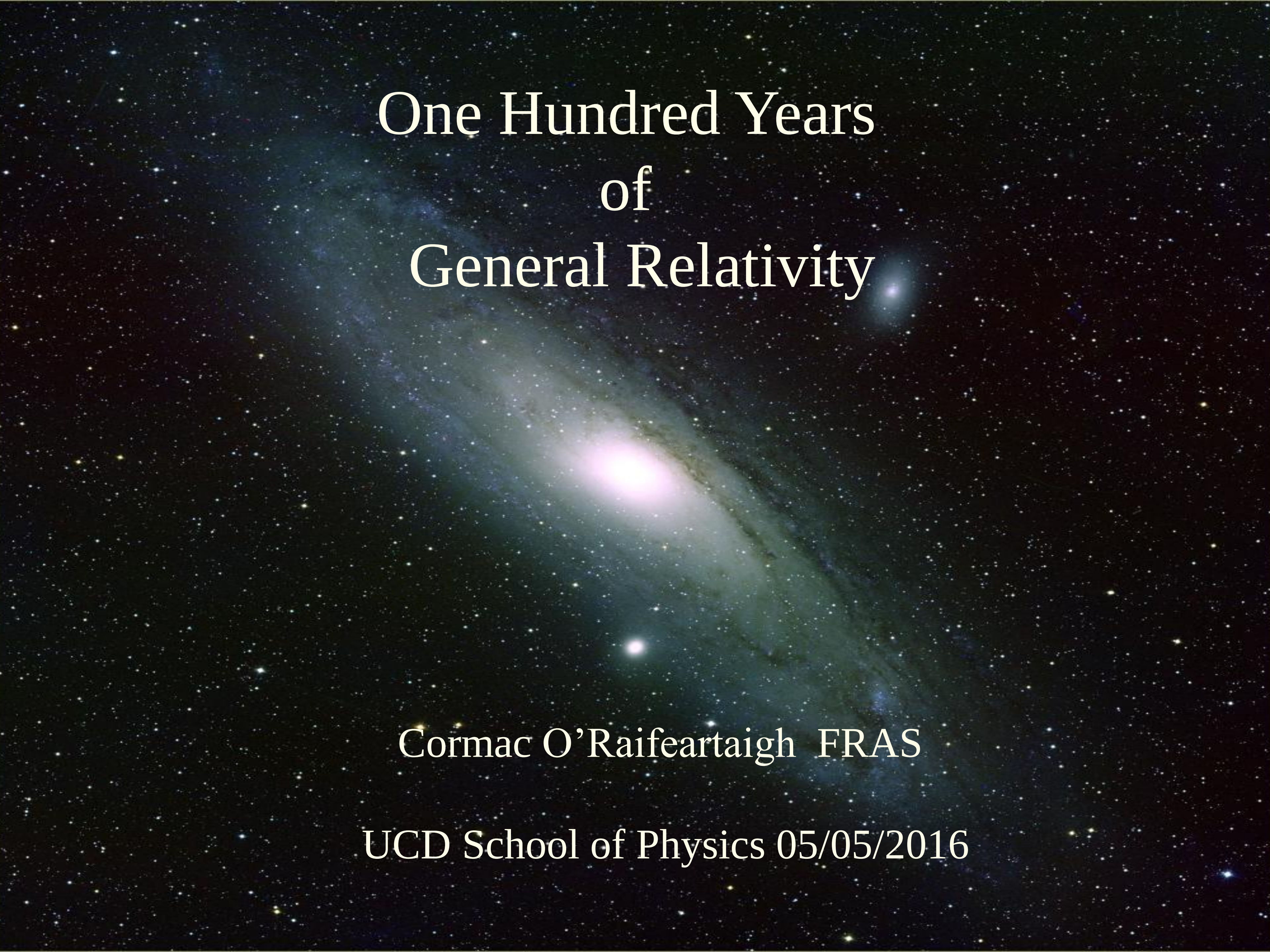


One Hundred Years of General Relativity

Cormac O’Raifeartaigh FRAS

UCD School of Physics 05/05/2016

100 years of general relativity

First covariant formulation of the field equations (PAS Nov 1915)

844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

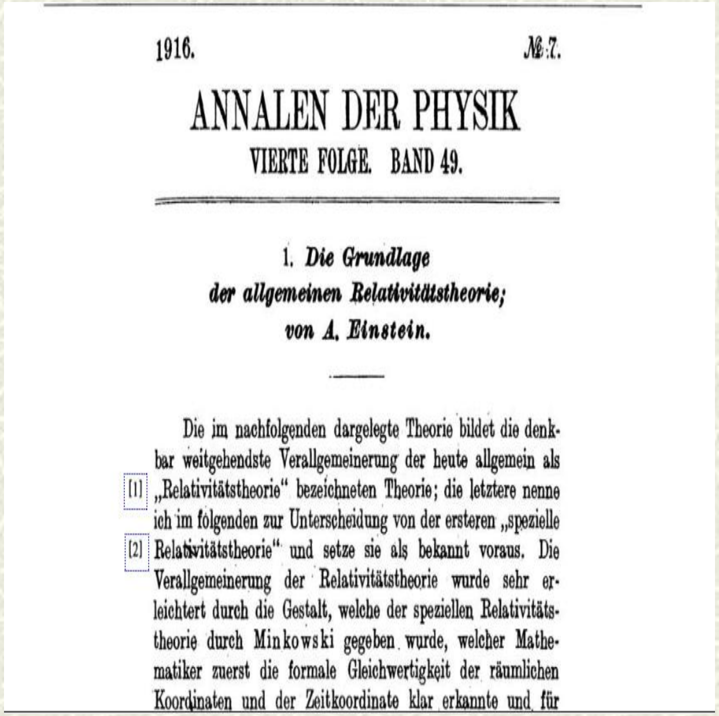
Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden,

First formulation of the full theory (Ann. Phys. May 1916)



1916. №7.

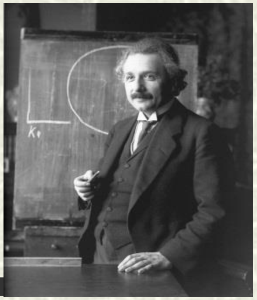
ANNALEN DER PHYSIK

VIERTE FOLGE. BAND 49.

1. ***Die Grundlage der allgemeinen Relativitätstheorie;***
von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als [1] „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle [2] Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für

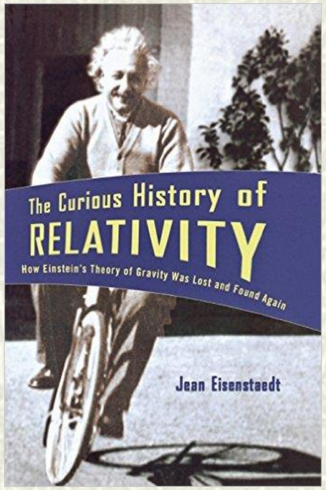
Overview

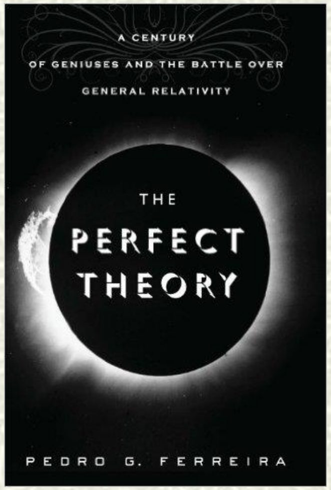


- **The road to general relativity**
  - *The special theory of relativity (1905)*
  - *The general theory of relativity (1907-16)*

- **Three classic tests (1916)**
  - *The perihelion of Mercury; the bending of starlight*
  - *The gravitational redshift*

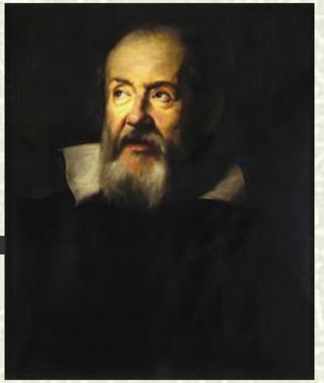
- **Cosmological predictions (1916-18)**
  - *Black holes; gravitational waves*
  - *The dynamic universe; the big bang model*





- **A curious history**
  - *Initial success followed by low watermark (1930-60)*
  - *The renaissance 1960- astronomy catches up*

Relativity



Galileo (1564-1642)

- **The principle of relativity**

  Equivalence of a system at rest or moving at constant speed?

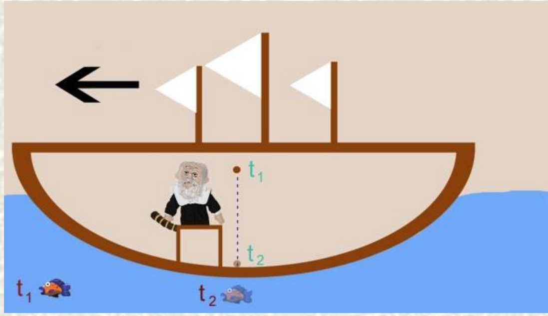
  Impossible to distinguish by experiments within the system

  Buridan, Oresme, Bruno, Copernicus

- **Galileo's galleon (1632)**

  Motion of objects in closed cabin of ship

  Independent of motion of ship

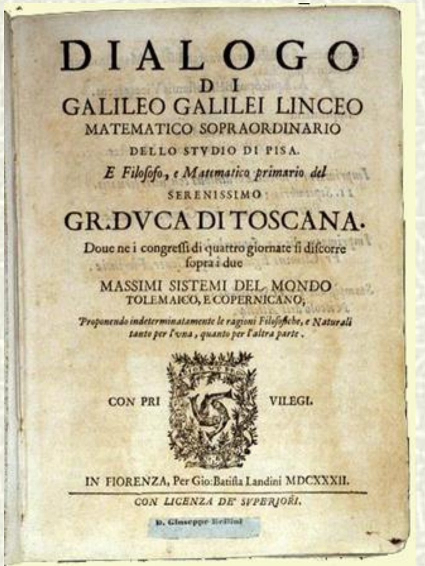


- **Implication for cosmology**

  Motion of vessel (<u>earth)</u> undetectable to passengers

- **Implication for mechanics**

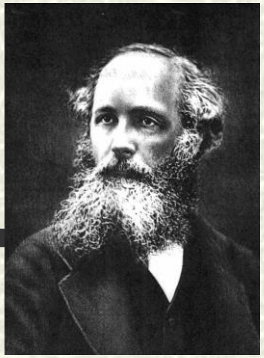
  Anticipates Newton's law of inertia



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'una, quanto per l'altra parte.
CON PRI VILEGI.
IN FIORENZA, Per Gio: Batista Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

Relativity in the 19th century

Michael Faraday

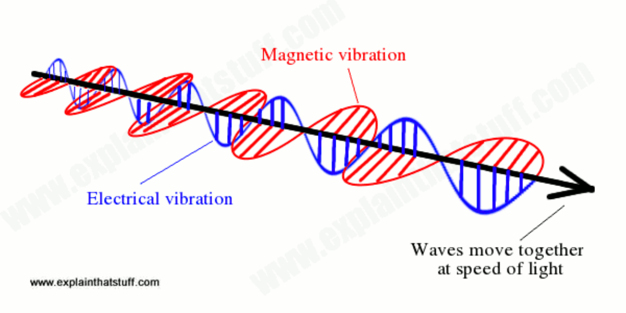


JC Maxwell

- **Electromagnetism**

  Electricity and magnetism = electromagnetism

  Speed of electromagnetic wave = speed of light in vac



- **Light = an electromagnetic wave**

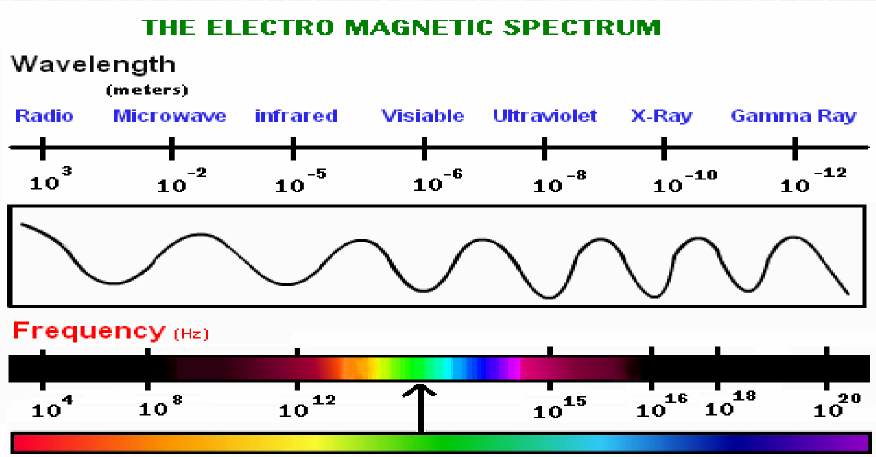
  Changing electric and magnetic fields

  The electromagnetic spectrum

- **Speed relative to what?**

  The concept of the ether

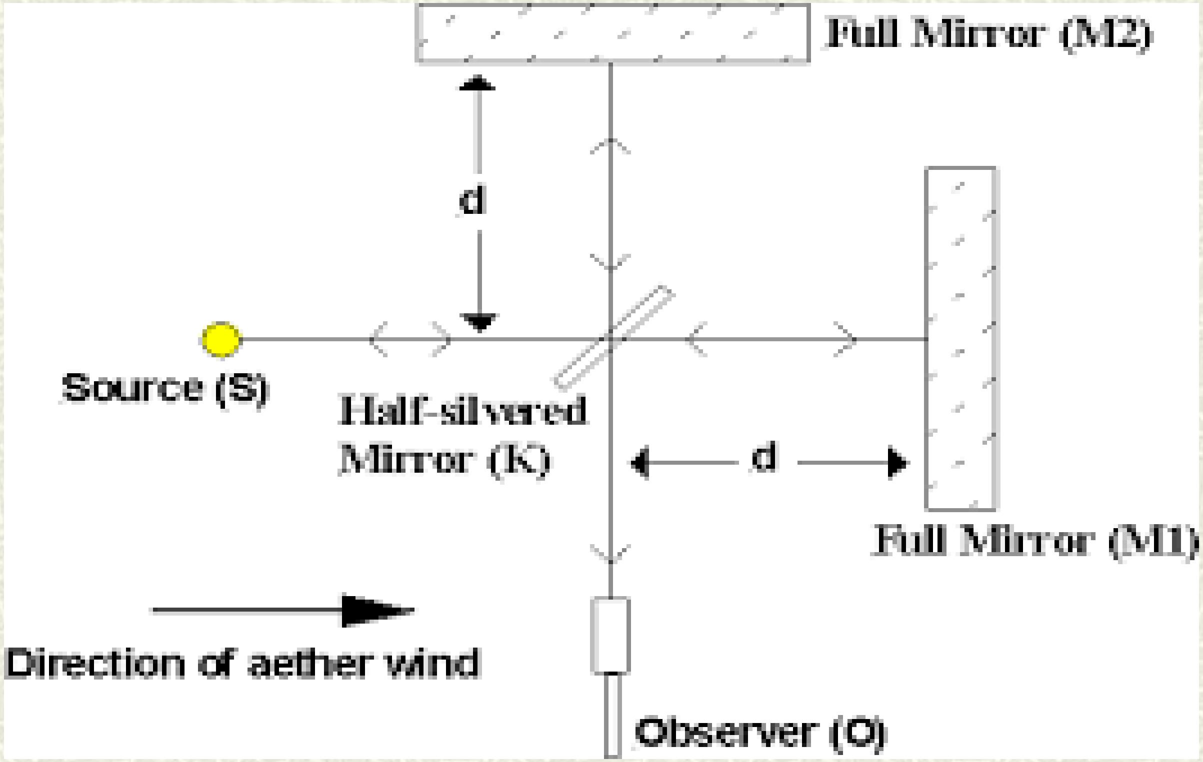
  Motion of observer relative to source?



- **Michelson-Morley experiment**

  Motion of earth relative to ether?

Michelson-Morley experiment



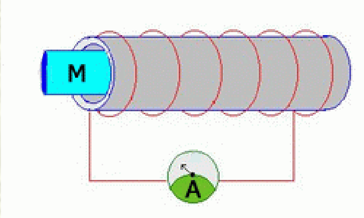
Expect: rays should arrive at O out of phase
Result: no effect detected

Einstein's special theory of relativity

- **Two new principles (1905)**

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

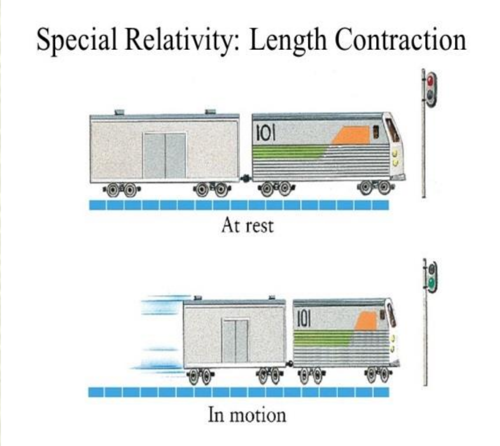
  Speed of light in vacuum identical for observers in relative uniform motion



- **Strange implications**

  Distance and time not universal $v = ds/dt$

  Experienced differently by bodies in relative uniform motion



- **Predictions for high-speed bodies**

  Length contraction : time dilation

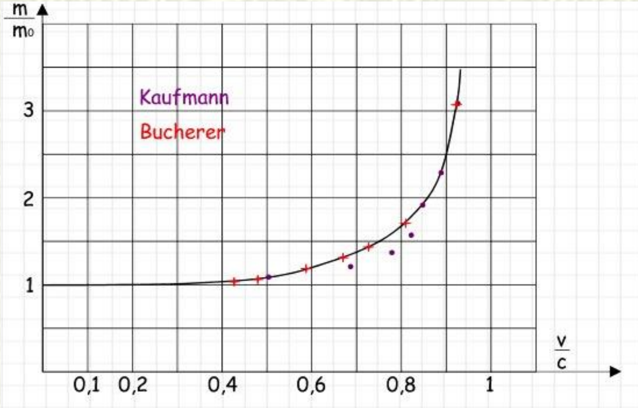
  Mass increase; mass-energy equivalence $E = mc^2$

- **Minkowski formulation (1908)**

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

  Space-time invariant for observers in inertial frames

Evidence for special relativity

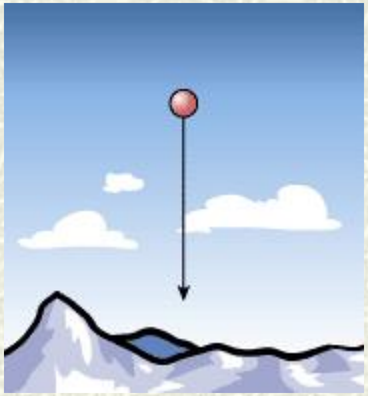


- **Mass increase (1901-1912)**

  The experiments of Kaufmann and Bucherer

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

- **Time dilation**

  The long-lived muon 2 μs → 22 μs

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

- **Particle physics experiments**

  Maximum velocity = c

  Mass increase x 1000

  Length contraction

  Particle creation

  $$E = mc^2$$

- **Special relativity and the media**

  'Relativity disproven' (Dingle)

  Asymmetric controversies

The general theory of relativity (1915,16)

- **General relativity**

  Relativity and accelerated motion? (1907)

  Relativity and gravity?

- **The principle of equivalence**

  Equivalence of gravity and acceleration

- **Mach's principle**

  Inertial mass defined relative to matter

  "No such thing as empty space"

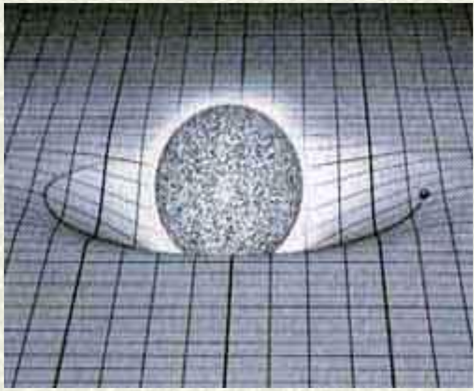
- **A long road (1907-1915)**

  Space-time defined by mass

  Gravity = curvature of space-time

  Curvilinear geometry, tensor algebra

Falling man doesn't feel his weight



The field equations of GR (1915)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = - \frac{8\pi G}{c^4} T_{\mu\nu}$$

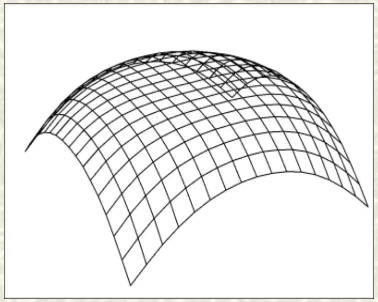
$$G_{\mu\nu} = - \frac{8\pi G}{c^4} T_{\mu\nu}$$

10 non-linear differential equations that relate the spacetime metric to the density and flow of energy and momentum in a region

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

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

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



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

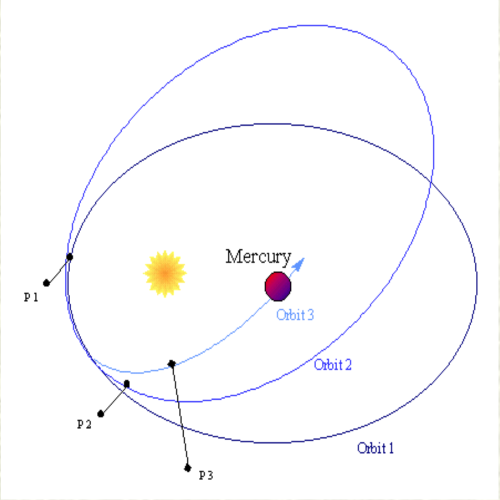
$$ds^2 = \sum_{\mu,\nu=1}^{4} g_{\mu\nu} dx^\mu dx^\nu$$

$g_{\mu\nu}$ are functions of the co-ordinates x

Three classic tests for GR (1916)

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

  But small deviations in predictions (weak scale)



- **The perihelion of Mercury**

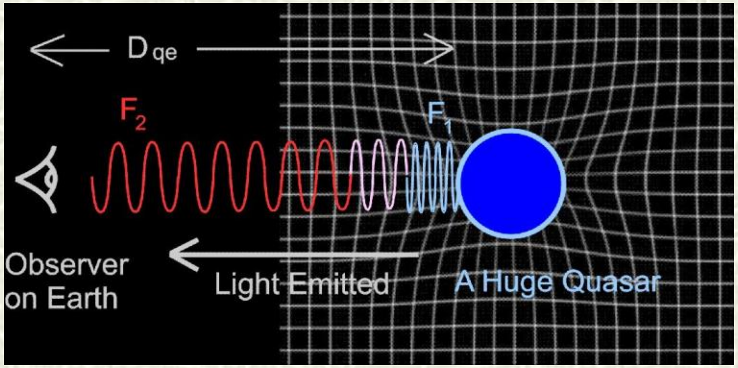
  Well-known anomaly in Mercury's orbit (43" per century)

  Correctly predicted by GR (1916)

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

  Eclipse expeditions of Eddington and Dyson (1919)

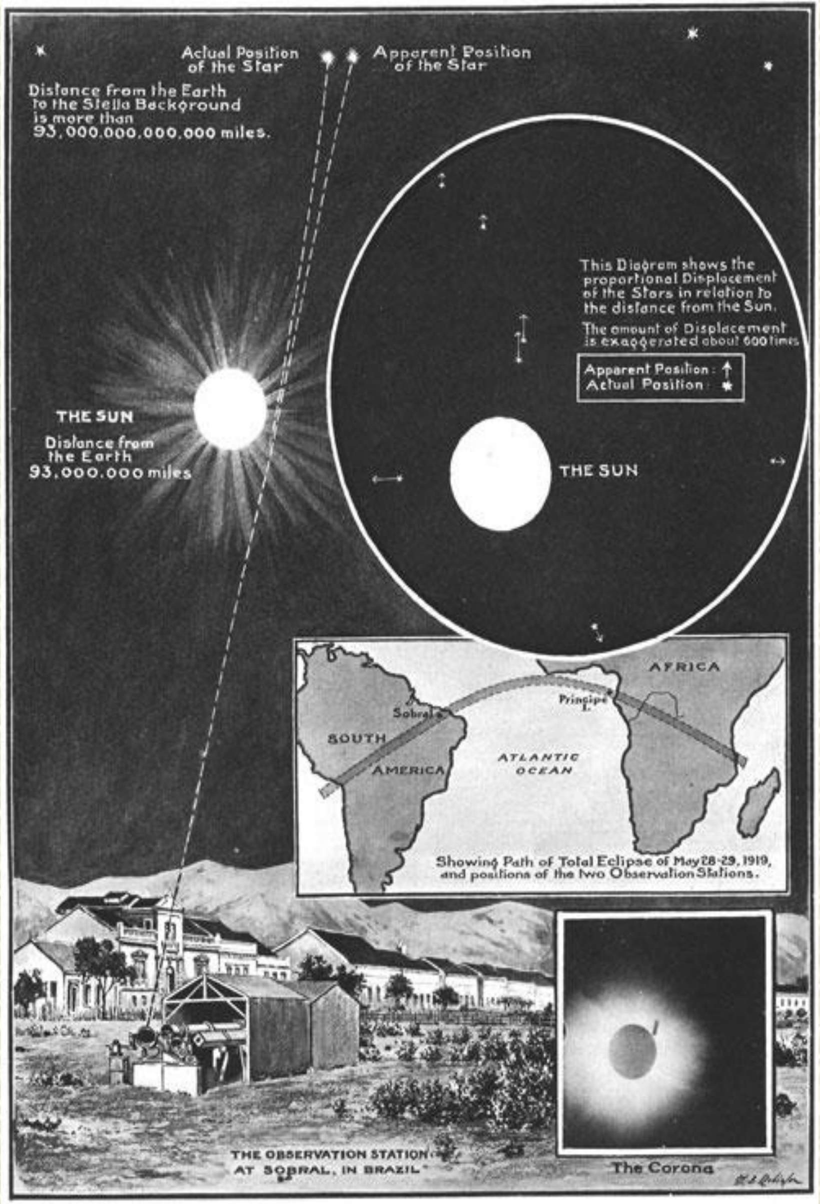
  Successful measurement (within error margin)



- **Gravitational redshift**

  Time dilation in strong gravitational field

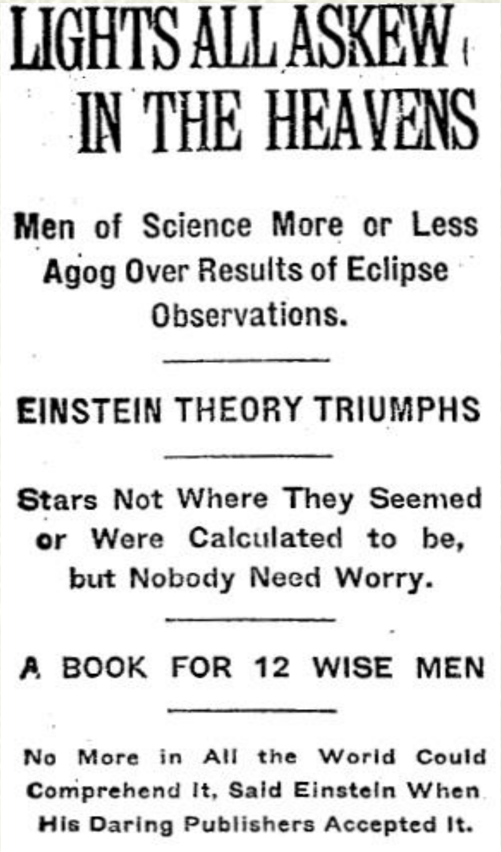
  Light from a massive star redshifted?



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.

Controversy (Collins and Pinch 1970s)

Claim of bias; rebutted by astronomers (RAS)

Three classic tests (1916)

Albert Einstein, The Times (Nov 28th 1919)

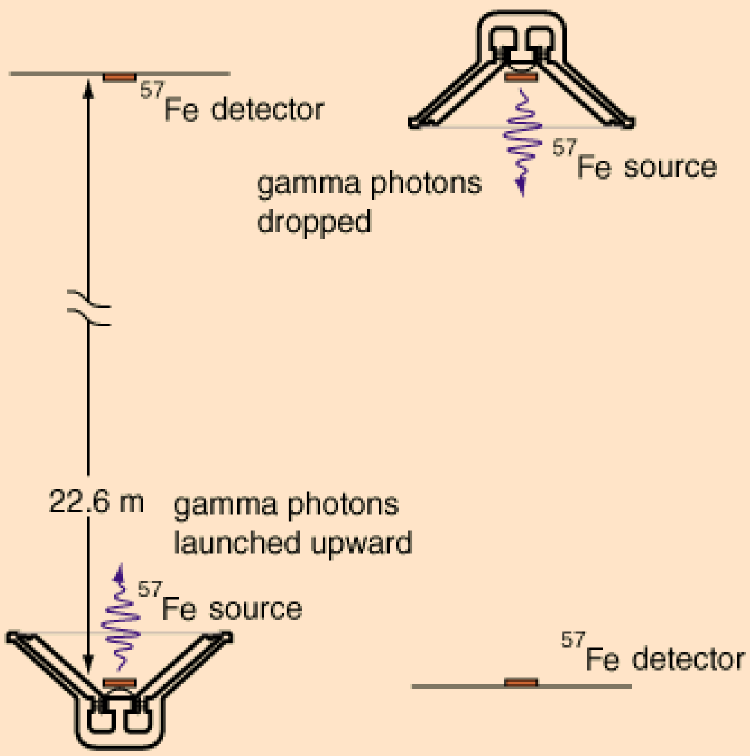
The new theory of gravitation diverges considerably, as regards principles, from Newton's theory. But its practical results agree so nearly with those of Newton's theory that it is difficult to find criteria for distinguishing them which are accessible to experience. Such have been discovered so far:

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 (1959)

Harvard Tower Experiment



In just 22.6 meters, the fractional gravitational red shift given by

$$\nu = \nu_0 \left[1 + \frac{gh}{c^2}\right]$$

is just 4.92 x 10^-15 , but the Mossbauer effect with the 14.4 keV gamma ray from iron-57 has a high enough resolution to detect that difference. In the early 60's physicists Pound, Rebka,and Snyder at the Jefferson Physical Laboratory at Harvard measured the shift to within 1% of the predicted shift.

- Sirius B (Adams, 1925)
- Gravity Probe A (1970s)
- Redshifted light from quasars (1990s)

Cosmic prediction I: Black Holes

- **Schwarzschild (1916)**

  Exact solution for the field equations

  Body of spherical symmetry

- **Enigma**

  Solution becomes singular at $r = 0$, $r = 2GM/c^2$

  Space closed up around mass?

- **Rejected**

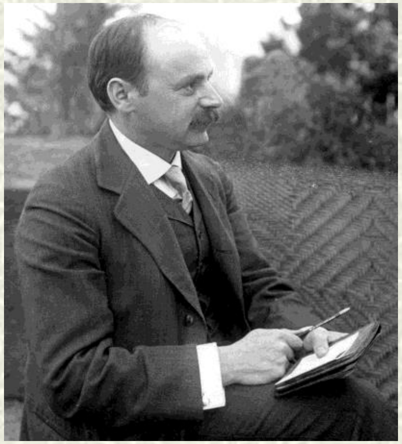
  Co-ordinate problem (Eddington)

  Prevented by internal pressure (Einstein 1922)

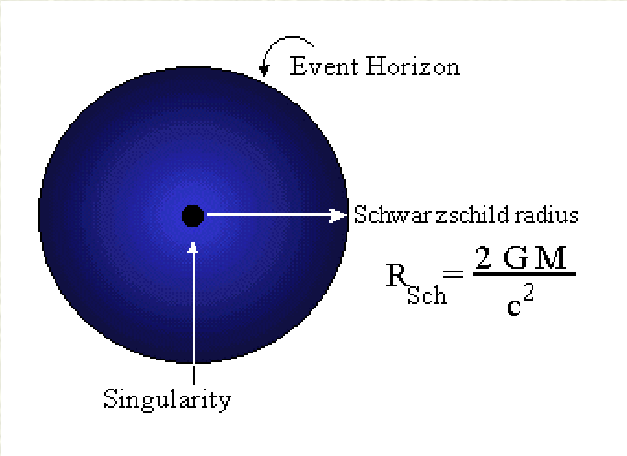
- **Physical reality?**

  Collapse of sun? Anderson (UCG)

  Collapse of large stellar ensemble : Lodge (Oxford)



Karl Schwarzschild (1873–1916)



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

- **<u>Compact</u> 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

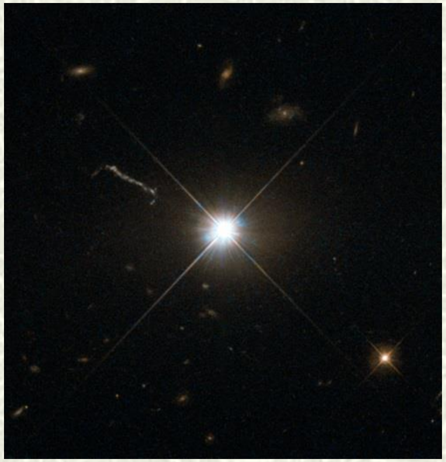
- **Orbit studies**

  Supermassive BH at centre of MW? (1990s)

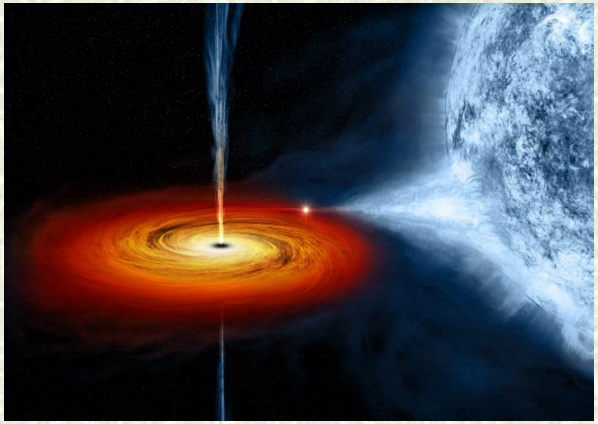
  Supermassive BH at centre of many galaxies (2000-)

- **2015-16**

  Gravitational waves from binary BH system!

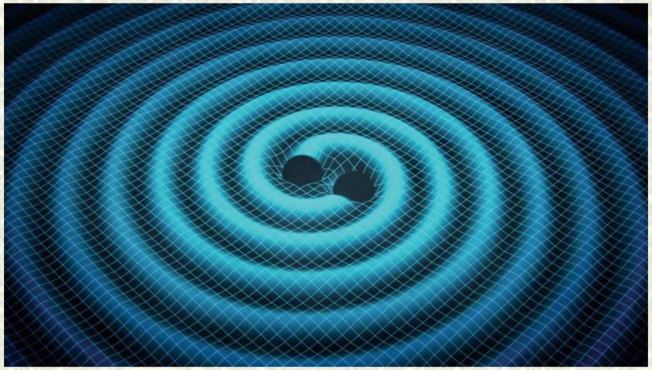


Quasar 3C273



Cygnus X-1 (1964)

Cosmic prediction II: gravitational waves



- **Einstein (1916, 18)**

  Linearized wave-like solutions of GFE

  Cosmic events cause tiny ripples in spacetime?

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

  Cylindrical wave solutions - no gravitational waves (1936)

  Corrected with assistance from HP Robertson (1937)

- **Wheeler (1960s)**

  Numerical wave solutions

- **Weber bars (1960s)**

  Reports signal of gravitational waves

  Not reproduced, not accepted by community

Joseph Weber

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)**

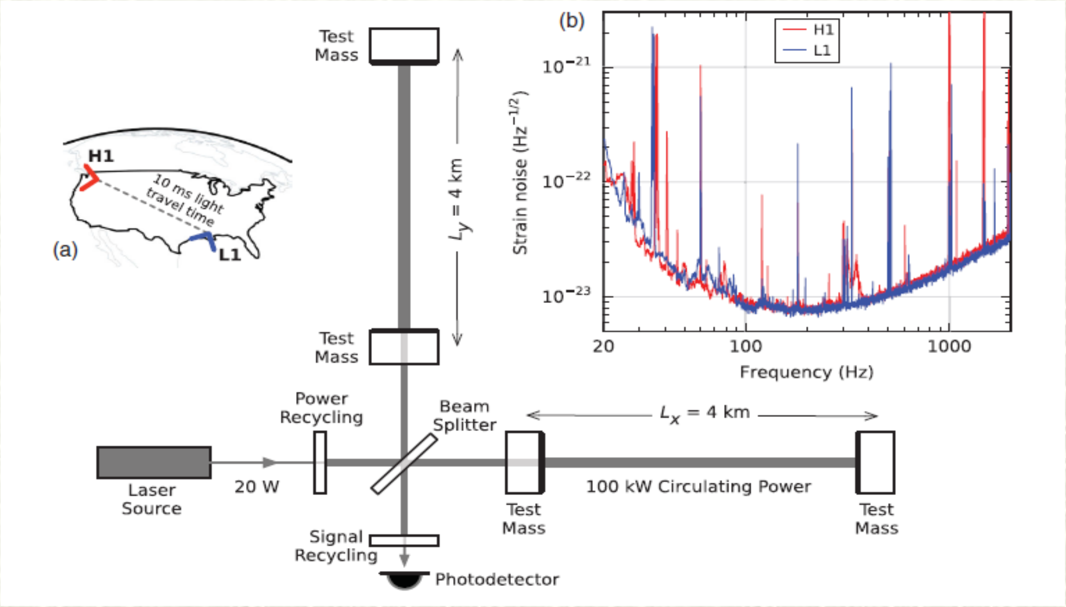
  Clear signal (September 2015)

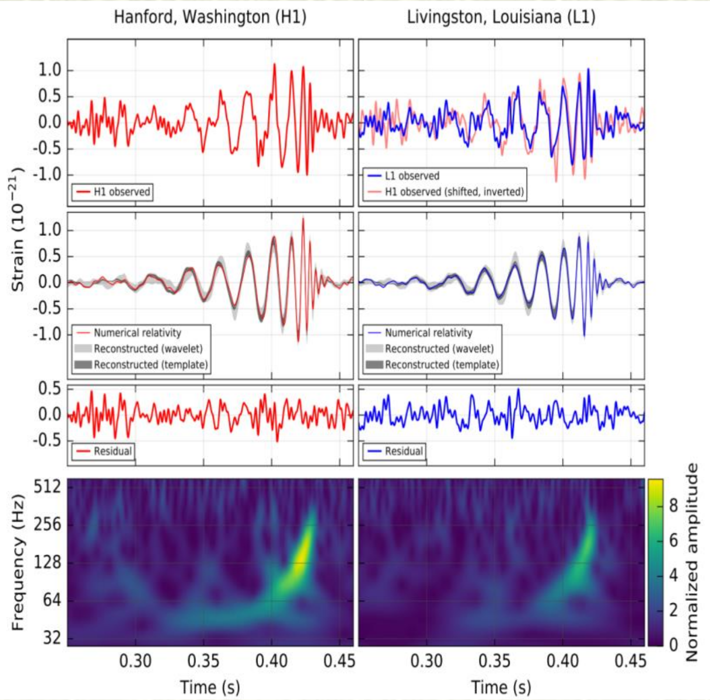
- **BH merger**

  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*
PHYSICAL REVIEW LETTERS
, 061102 (2016)
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 !

Cosmic prediction III: The expanding universe

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

  Ultimate test for new theory of gravitation

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

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

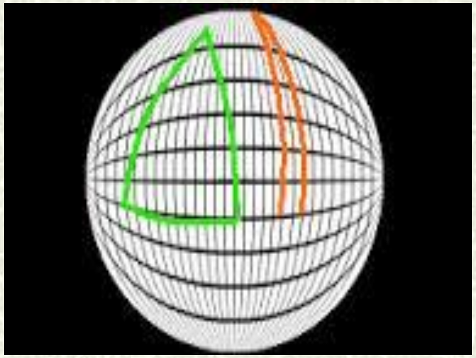
in combination with the equations of motion of a material point is not as yet a perfect substitute for Newton's theory of action at a distance. There is still to be taken into account the condition that at spatial infinity the potential ϕ tends

- **Assumptions**

  Static universe (small velocities of the stars)

  Mach's principle (metric tensor to vanish at infinity)

  Isotropy and homogeneity (simplicity)



- **Boundary problem**

  Assume cosmos of closed curvature

  But…no consistent solution

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

- **New term in field equations!**

  Cosmic constant - anti-gravity term

  Radius and density defined by λ

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

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

Friedman's universe

- **Allow time-varying solutions (1922)**

  Assume homogeneity, isotropy, positive curvature

  Two independent differential equations from GFE

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

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

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

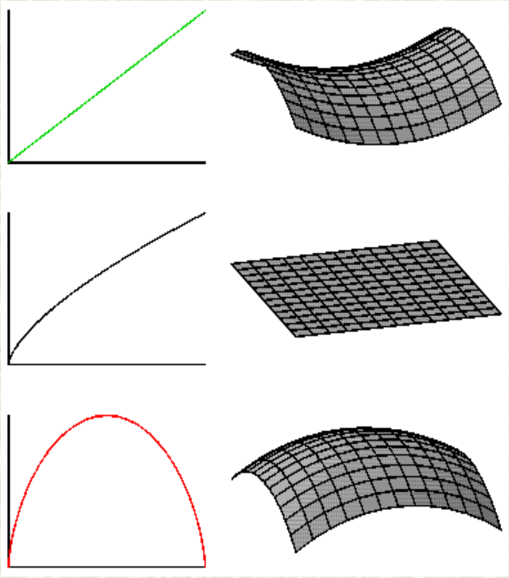
Alexander Friedman (1888 -1925)

- **Evolving universes**

  Density of matter varies over time

- **Negative spatial curvature (1924)**

  Cosmic evolution, geometry depends on matter



- **Overlooked by community**

  Considered 'suspicious' by Einstein

  Mathematical correction, later retracted

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

Lemaître’s universe (1927)

Fr Georges Lemaître

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

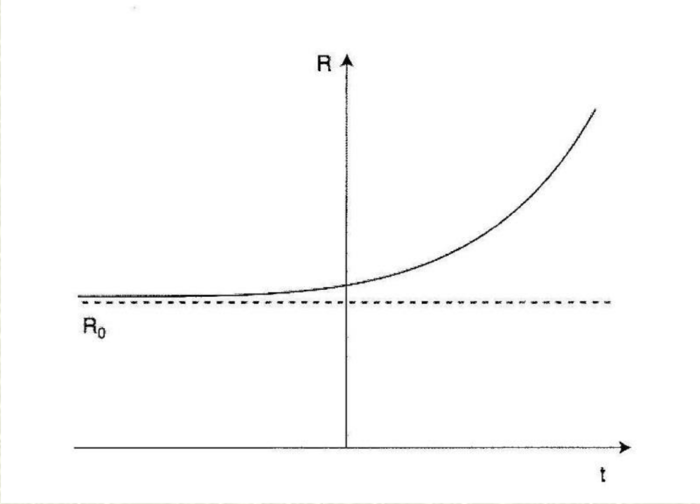
$$2\frac{R''}{R}+\frac{R'^2}{R^2}+\frac{1}{R^2}=\lambda-\kappa p$$

- **Expanding model of the cosmos from GR**
  Similar but not identical to Friedman 1922

- **Redshifts of galaxies = expansion of space***?*
  Redshifts from Slipher, distances from Hubble

- **Ignored by community**
  Belgian journal (in French)
  Rejected by Einstein: “Vôtre physique est abominable”

- **Lemaître’s recollection (1958)**
  “Einstein not up-to-date with astronomy”



The watershed: Hubble's law (1929)

- **The redshifts of the spiral nebulae**

  Doppler shifts? (Slipher 1915, 1917)

- **The distances to the nebulae**

  Far beyond Milky Way (Hubble 1925)

- **A redshift/distance relation?**

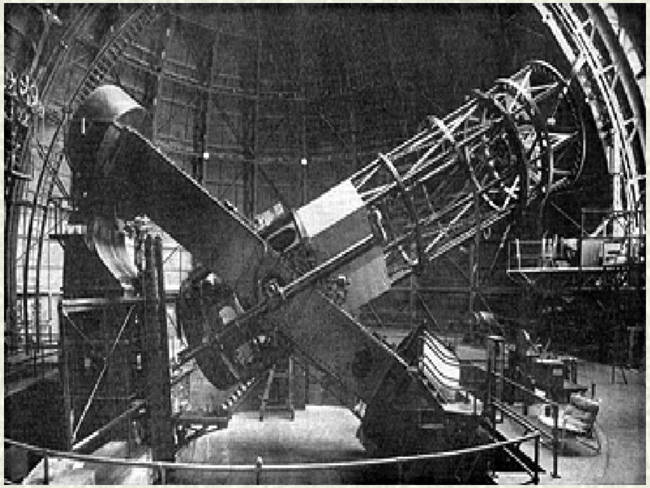
  Linear relation (Hubble, 1929)

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

- **Landmark result in astronomy**

  Furthest galaxies receding the fastest

What is causing the effect?



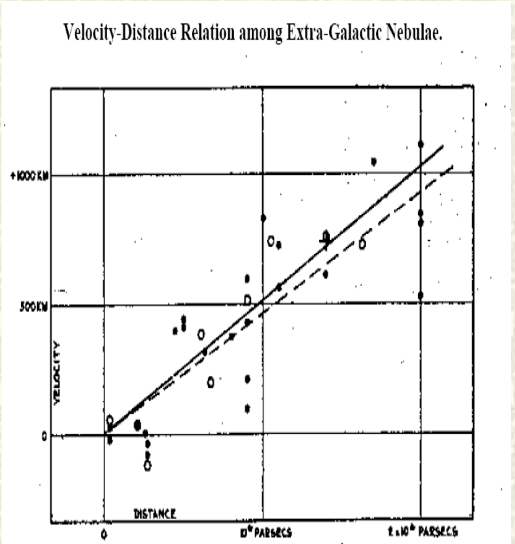
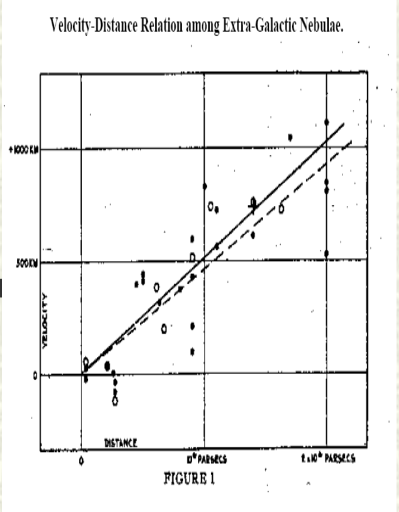
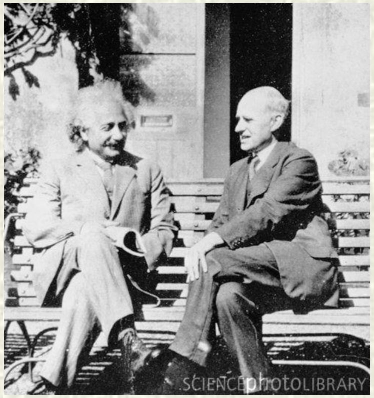


FIGURE 1

The expanding universe (1930)



- **RAS meeting (May 1930)**
  If redshifts are velocities, and if effect is non-local
  Hubble's law = expansion of space? (Edd., de Sitter)



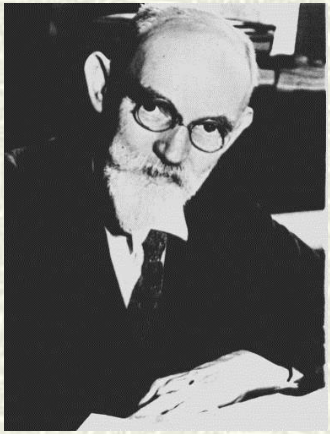
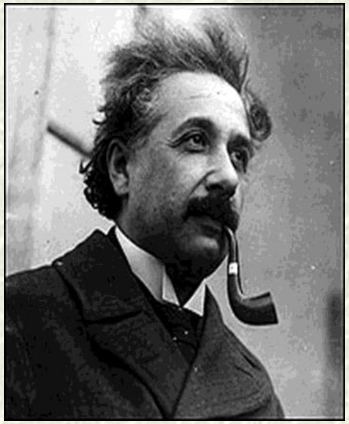
- **Dynamic model required**
  Static model unstable

- **Lemaître model adopted**
  1927 expanding model republished in English (1931)
  Observational section omitted (rightly)

- **Lemaître-Friedman cosmology accepted**
  Time-varying radius, decreasing density of matter

Models of the expanding universe (1930 -)



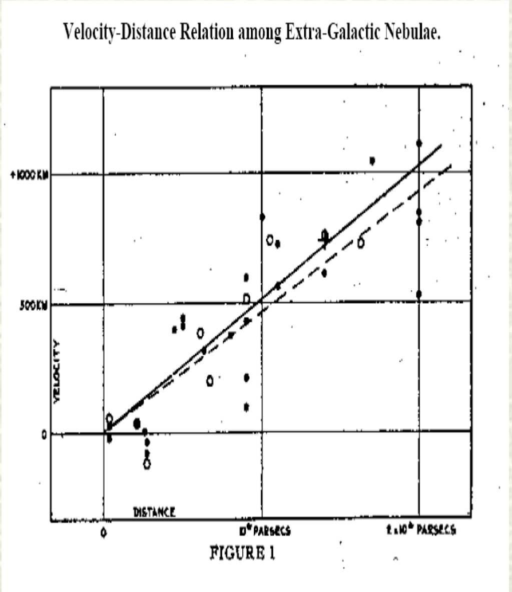
- **Tolman (1930, 31)**
  Expansion caused by annihilation of matter ?
- **Eddington (1930, 31)**
  On the instability of the Einstein universe
  Expansion caused by condensation?
- **de Sitter (1930, 31)**
  Variety of expanding models
- **Heckmann (1931,32)**
  Spatial curvature (not translated)
- **Einstein (1931, 32)**
  Friedman-Einstein model $\lambda = 0, \; k = 1$
  Einstein-de Sitter model $\lambda = 0, k = 0$

***If** redshifts represent expansion…*
***If** effect is global…*

Cosmic prediction IV: the big bang

Fr Georges Lemaître

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



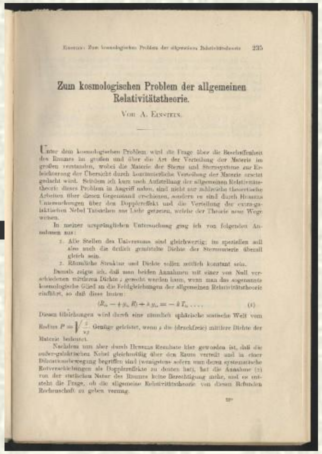
Rejected by community (1930-60)

Simplified models

Timescale problem

Later called ***<u>‘The big bang’</u>***

Einstein’s 1931 model



Zum kosmologischen Problem der allgemeinen Relativitätstheorie.

Von A. Einstein.

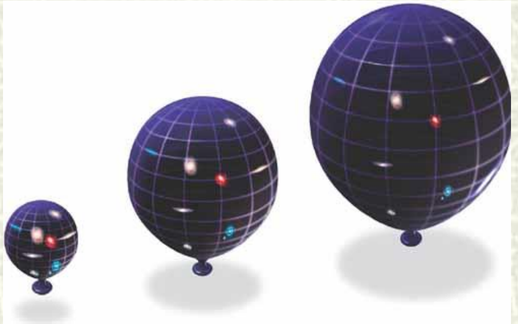
- **Einstein’s first dynamic model of the cosmos**

  Often cited, rarely read (not translated)

- **Adopts Friedman 1922 model**

  Time-varying, closed universe: k =1

  Cosmic constant redundant: set $\lambda = 0$



- **Use Hubble to extract parameters**

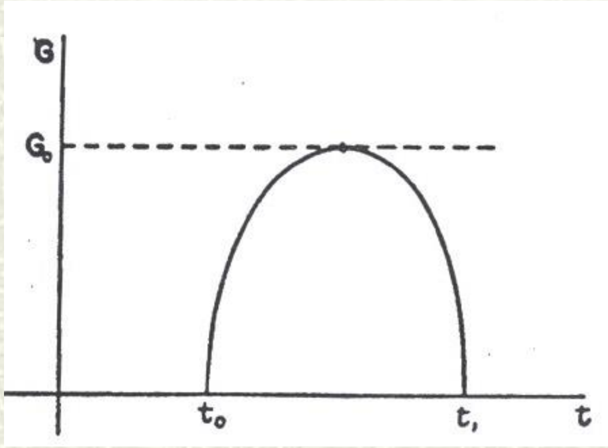
  Radius R ~ 10^8 lyr

  Density of matter $\rho \sim 10^{-26}$ g/cm^3

- **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

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

  $R \sim 10^8$ lyr : *should be 10^9 lyr*

  $\rho \sim 10^{-26}$ g/cm^3 : *should be 10^{-28} g/cm^3*

  $t \sim 10^{10}$ yr : *should be 10^9 yr*

- **Source of error?**

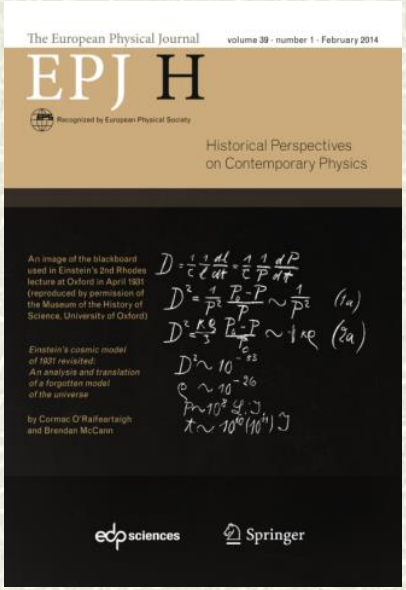
  Error in Hubble constant (Oxford blackboard)

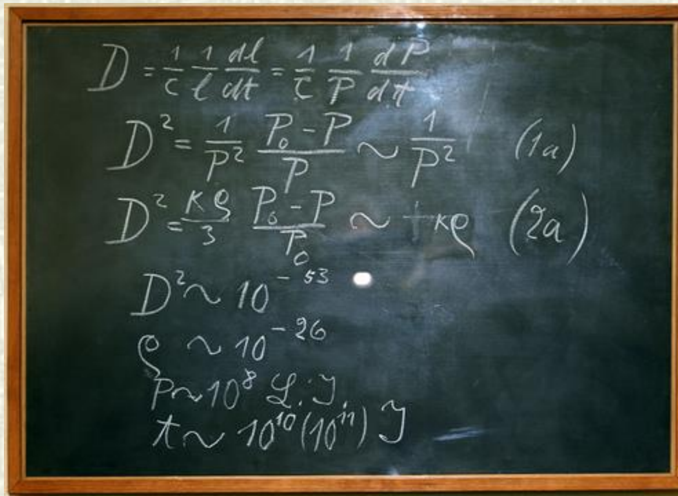
  $D^2 \sim 10^{-53}$ *instead of* 10^{-55} cm^{-2}

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

  “Model fails at P = 0 ”

  Contrary to what is often stated





Bonus: Einstein's steady-state model

- **Unpublished manuscript**

  Archived as draft of Friedman-Einstein model

  Similar title, opening

- **Something different**

  Cosmological constant λ

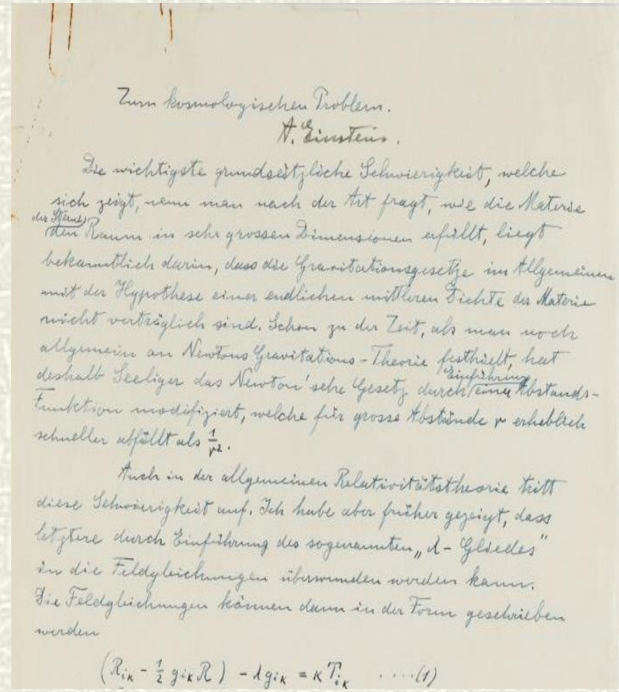
  "The density is constant and determines the expansion"

- **Steady-state model**

  Continuous formation of matter from vacuum

  Anticipates Hoyle's model

  Fatal flaw: abandoned

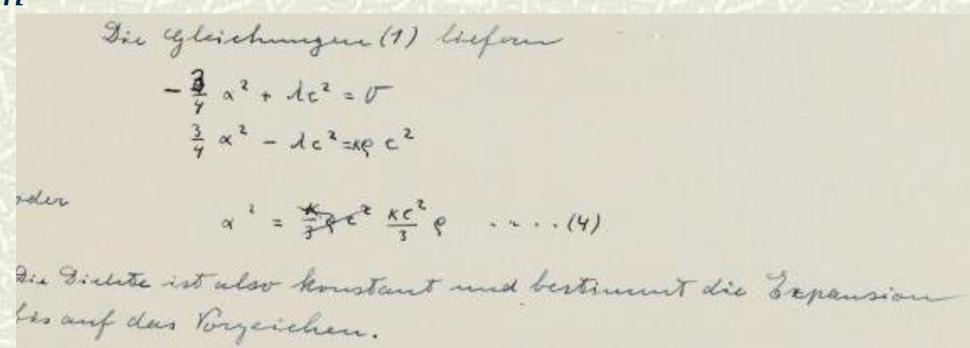


Zum kosmologischen Problem.
A. Einstein.

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.

The steady-state universe (1948)

- **Expanding but unchanging universe**
  Hoyle, Bondi and Gold (1948)
  Disliked extrapolation to early epochs
  Perfect cosmological principle?

Bondi, Gold and Hoyle

- **Requires continuous creation of matter**
  Very little matter required
  No beginning, no age paradox

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

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

Hoyle and Narlikar (1962)

- **Improved version (1962)**

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

Steady-state vs big bang (1950-70)

- **Optical astronomy (1950s)**

  Revised distances to the nebulae (Baade, Sandage)

  New timescale of expansion

Allen Sandage

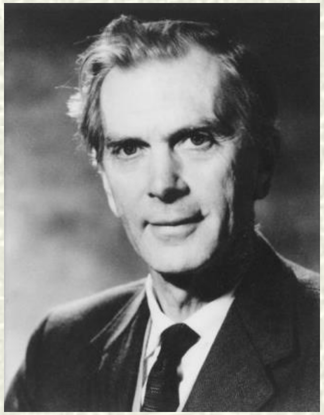
- **Radio-astronomy (1960s)**

  Galaxy distributions at different epochs

  Cambridge 3C Survey (Ryle)

- **Nucleosynthesis of light elements**

  Gamow et al. 1948



- **Cosmic microwave background (1965)**

  Low temperature, low frequency

  Remnant of young, hot universe

Martin Ryle

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

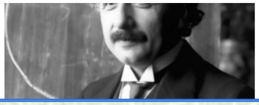
2 comments, 2 called-out + Comment Now + Follow Comments

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,

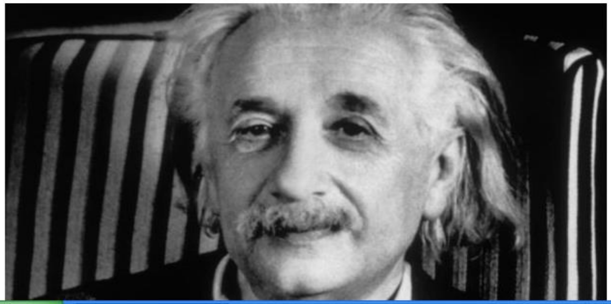
model of the universe very different to today's Big Bang Theory.

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



WIT researchers discover 'lost' Einstein model of universe

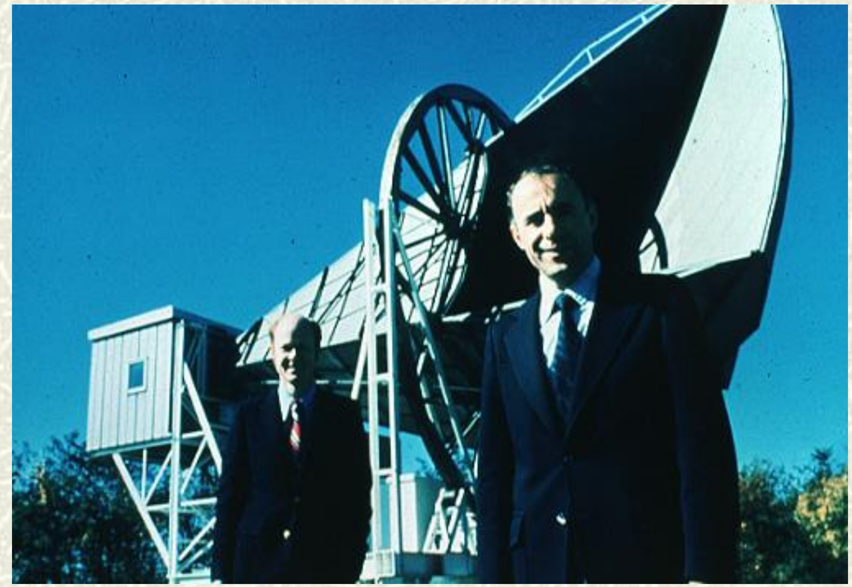
Scientists uncovered misfiled papers while searching Jerusalem university's online archive



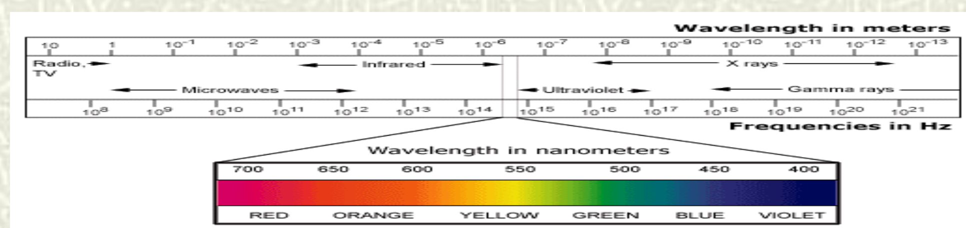
Cosmic background radiation (exp)

CMB discovered accidentally

- Universal signal (1965)
- Low frequency (microwave)
- Low temperature (3K)



Penzias and Wilson (1965)

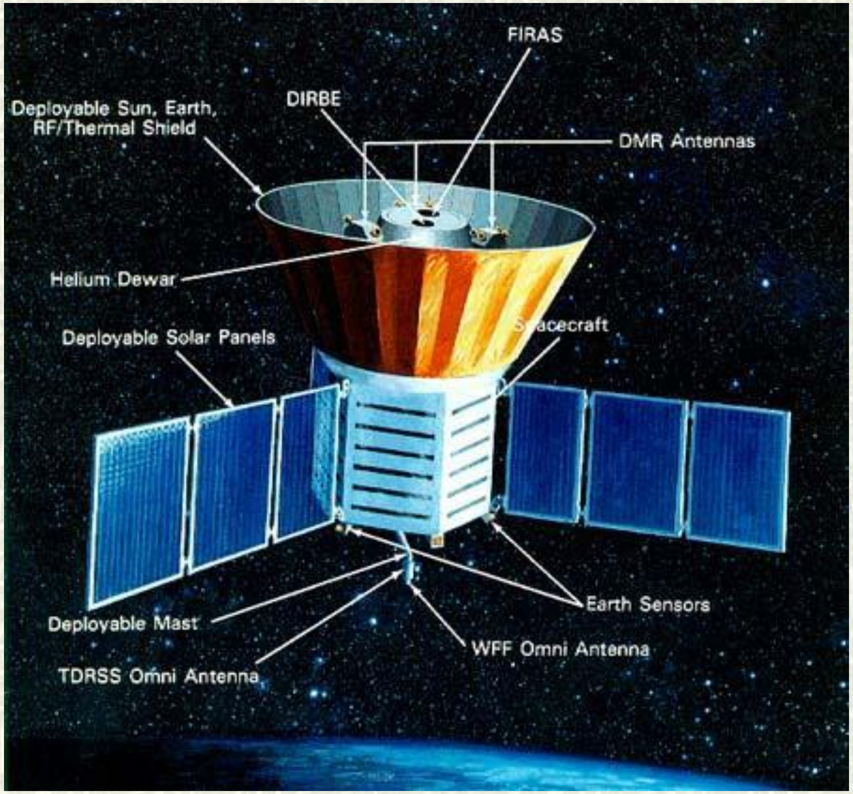


Echo of Big Bang!

Modern measurements of the CMB

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

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

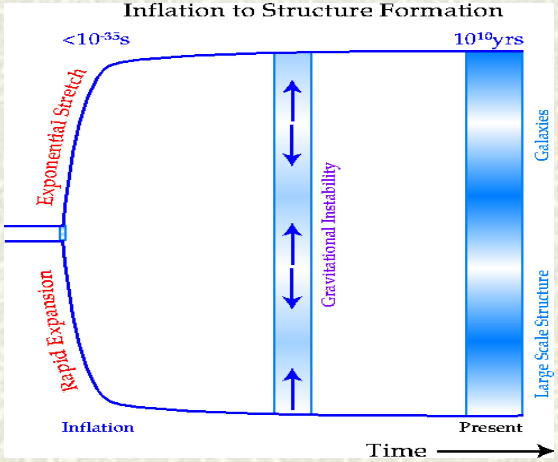


COBE satellite (1992)

Today’s cosmological puzzles

- **Characteristics of background radiation**

  Isotropy, homogeneity, flatness (1970-80)



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

  Exponential expansion within first second?

  Explanation for homogeneity, flatness, galaxy formation

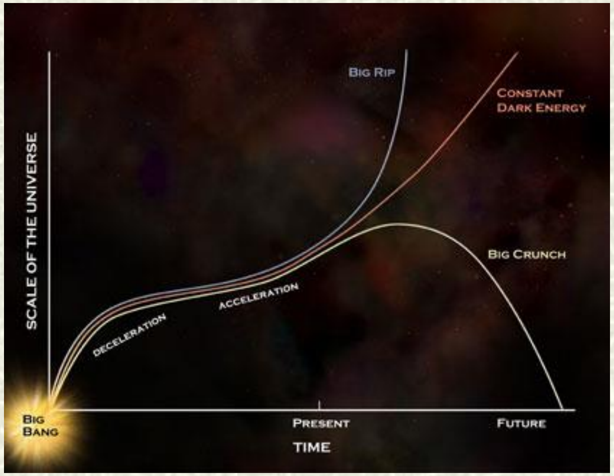
  Which model of inflation? Bubble inflation?

- **Dark energy (1998)**

  Observation of accelerated expansion

  The return of the cosmological constant

  U mainly composed of dark energy



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

Nature of DE unknown

100 years of general relativity

- **Published 1915, 1916**

  From Swiss patent office to Berlin

- **A new theory of gravity**

  Gravity = curvature of spacetime

- **Classic predictions supported by experiment**

  Perihelion of Mercury: bending of light by a star

  Gravitational redshift ; GPS

- **Cosmological predictions supported by experiment**

  Black holes: gravitational waves

  The expanding universe: the big bang

Skeptical of extrapolations

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**

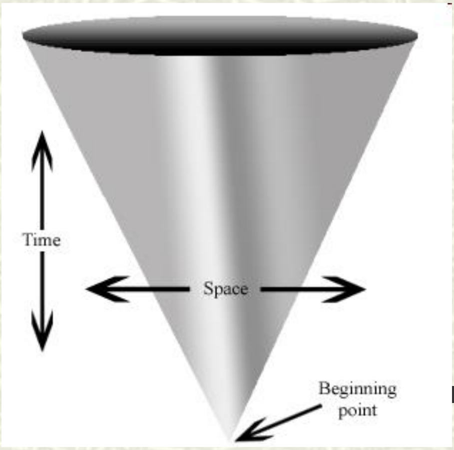
  Black hole thermodynamics

  Hawking-Bekenstein radiation

- **Quantum cosmology**

  The quantum big bang

Stephen Hawking



A universe from nothing?

Einstein-de Sitter model (1932)

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

  Not observed empirically

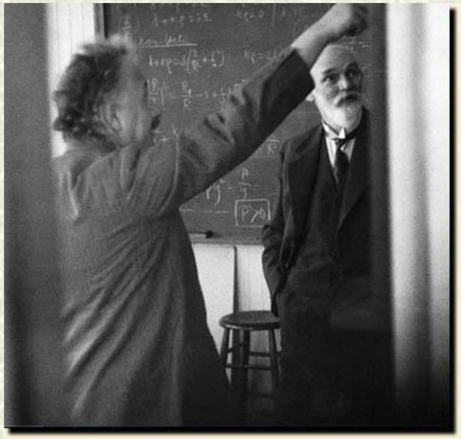
  Remove spatial curvature (Occam's razor)

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

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

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

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



- **Simplest Friedman model**

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

  Important hypothetical case: critical universe

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

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

  Despite high density of matter

  Despite age problem

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

PROCEEDINGS

OF THE

NATIONAL ACADEMY OF SCIENCES

Volume 18 March 15, 1932 Number 3

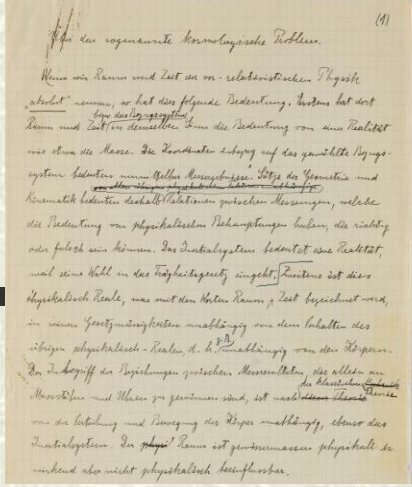
ON THE RELATION BETWEEN THE EXPANSION AND THE MEAN DENSITY OF THE UNIVERSE

BY A. EINSTEIN AND W. DE SITTER

Communicated by the Mount Wilson Observatory, January 25, 1932

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

Einstein-de Sitter model revisited



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

  Review of dynamic models from first principles

  Culminates in Einstein-de Sitter model

  Cosmic constant banished

  Possibility of flat geometry

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

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

- **Parameters extracted**

  Critical density of 10^{-28} g/cm^3 : reasonable

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

  Attributed to simplifications (incorrect estimate)

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

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

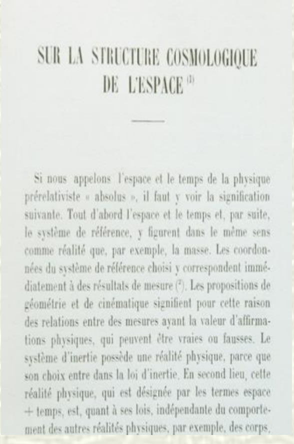
$$t-t_0=\frac{2}{3h}.$$

- **Published in 1933!**

  French book; small print run

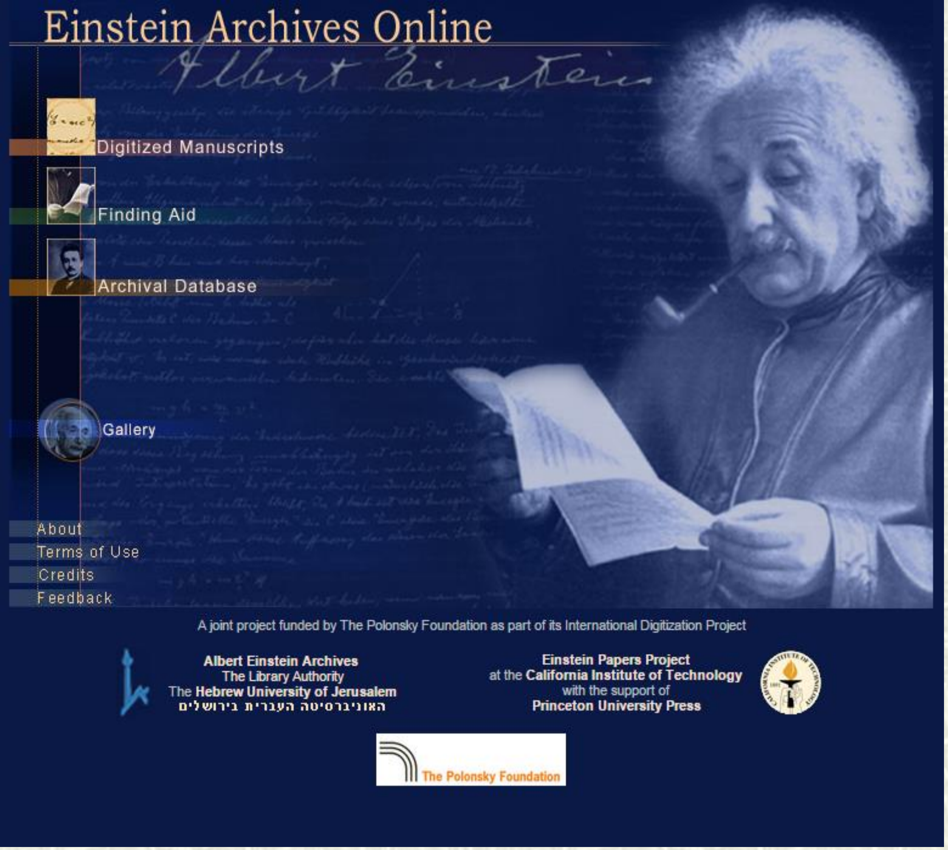
  Intended for scientific journal; not submitted

  Significant paper



SUR LA STRUCTURE COSMOLOGIQUE DE L'ESPACE (1)

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



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

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

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)

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

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Über das sogenannte kosmologische Problem.

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Other Persons:	Mayer, Walther (Author)
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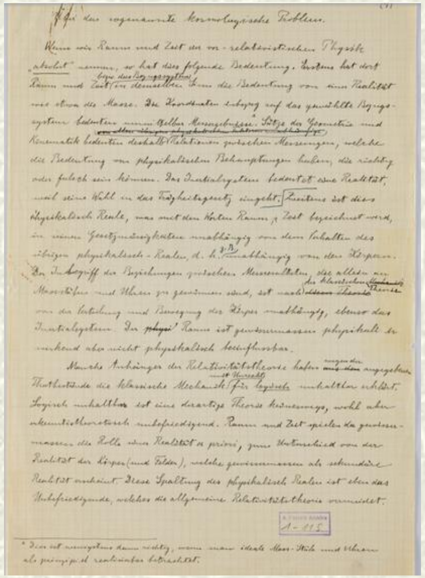


Abandoned model

- **de Sitter line element**

  Correct geometry

- **Simultaneous equations**

  Error in derivation

  Null solution

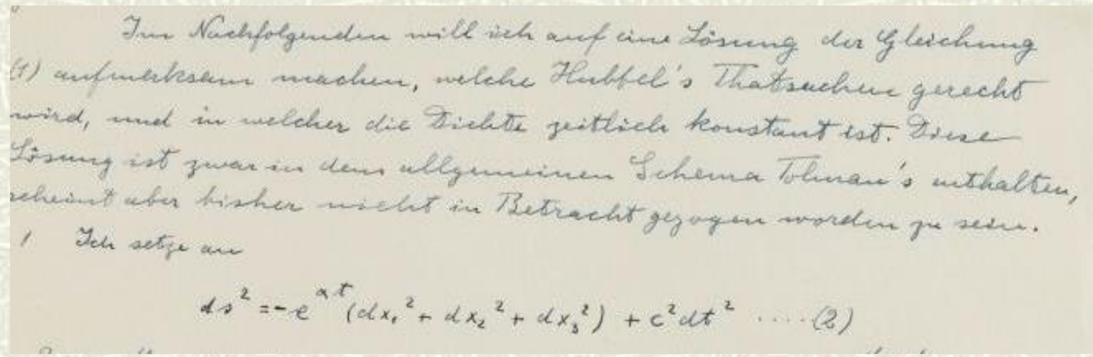
- **Einstein's crossroads**

  Realised problem on revision

  Declined to amend model

- **Evolving models**

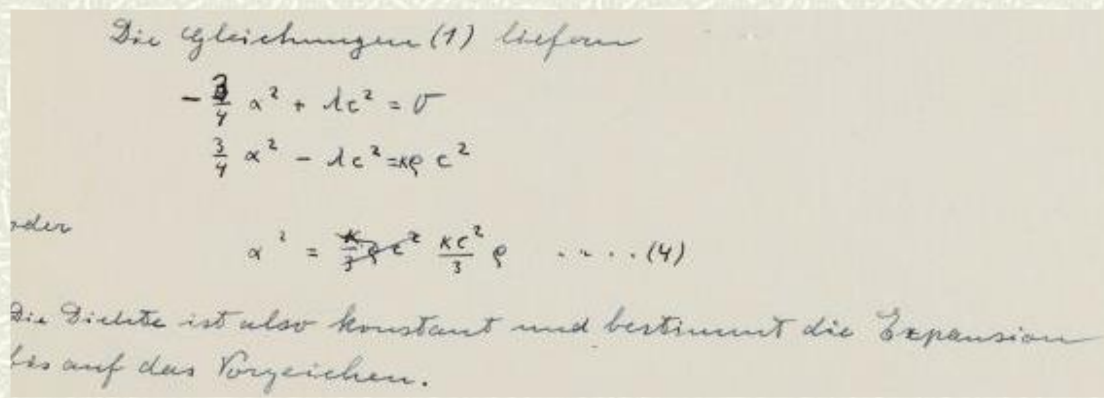
  Less contrived and set $\lambda = 0$



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

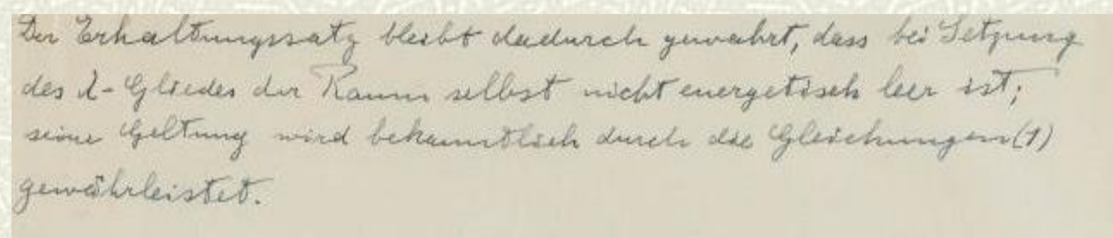
$$-\frac{3}{4}\alpha^2 + \lambda c^2 = 0$$

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

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.

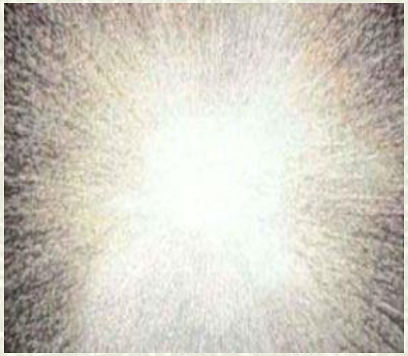


Der Erhaltungssatz bleibt dadurch gewahrt, dass bei Setzung des λ-Gliedes der Raum selbst nicht energetisch leer ist; seine Geltung wird bekanntlich durch die Gleichungen (1) gewährleistet.

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**
  Victory for big bang model

Georges Gamow



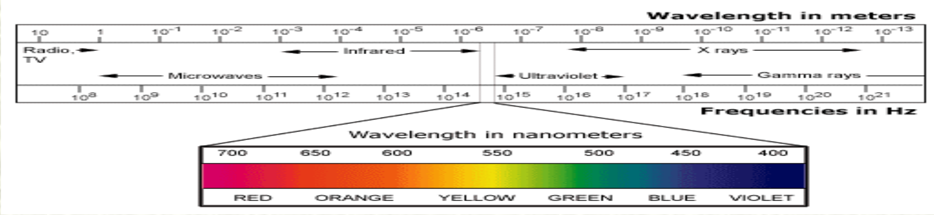
Heavier atoms formed in stars

Bonus: cosmic background radiation

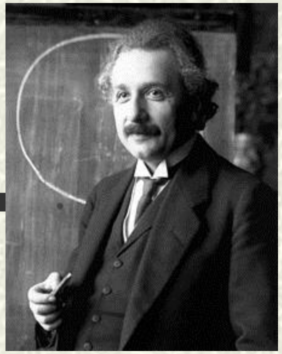
- **Infant universe very hot**
- **Dominated by radiation**
- **Radiation still observable today?**
  Low temp, microwave frequency
- **A fossil from the early universe!**
  Released when atoms formed (300,000 yr)

Alpher, Gamow and Herman

<u>No-one looked</u>



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

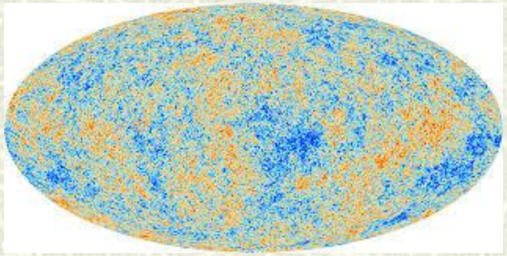
- **Evolving models (less contrived)**

  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

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**

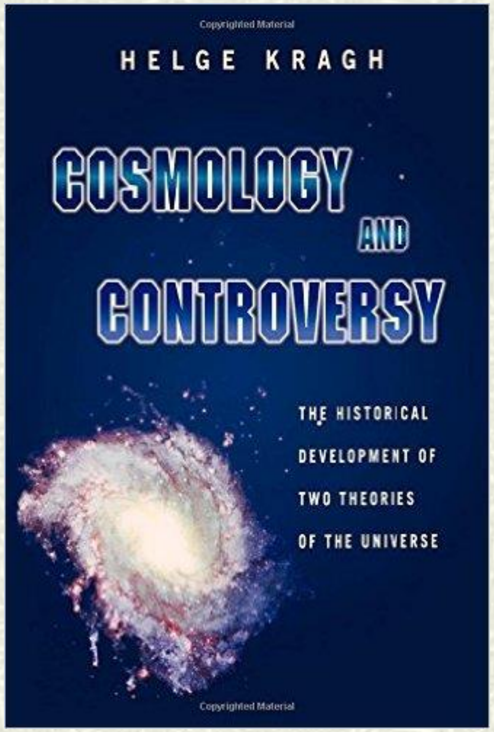
  Creation energy and λ: dark energy

  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)**

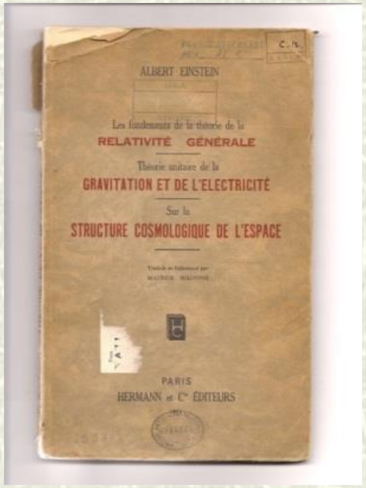
  Use of Hubble constant to extract observational parameters

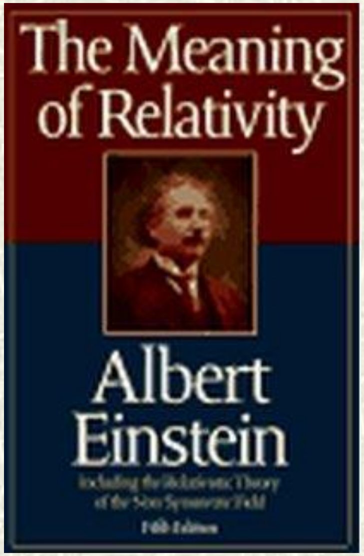
- **Einstein-de Sitter model of the Universe (1932)**

- **1933 review: 1945 review (Appendix)**

  Conversations with Gamow, Godel, Straus

No mention of origins

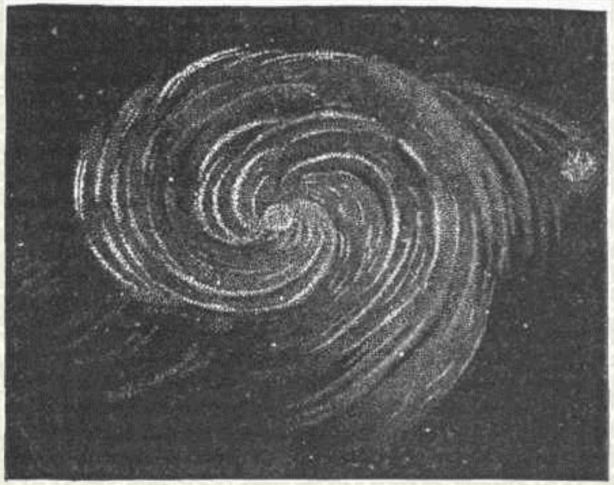




III   Astronomy and the Universe

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

  Spiral nebulae = galaxies beyond Milky Way?



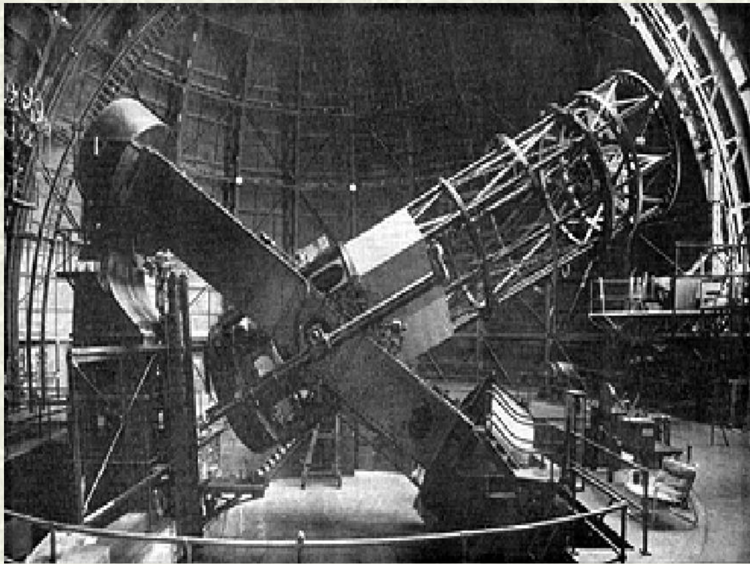
- **The Hooker telescope (1917)**

  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)

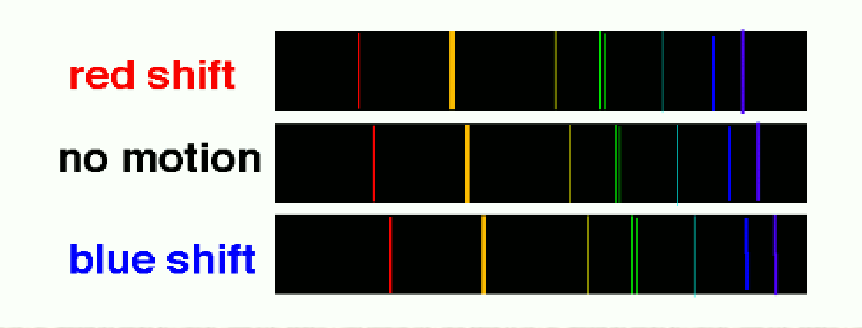
- **Doppler effect**

  Frequency of light depends on

  motion of source relative to observer

- **Nebulae moving outward?**

  Galaxies moving outward?



Vesto Slipher

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

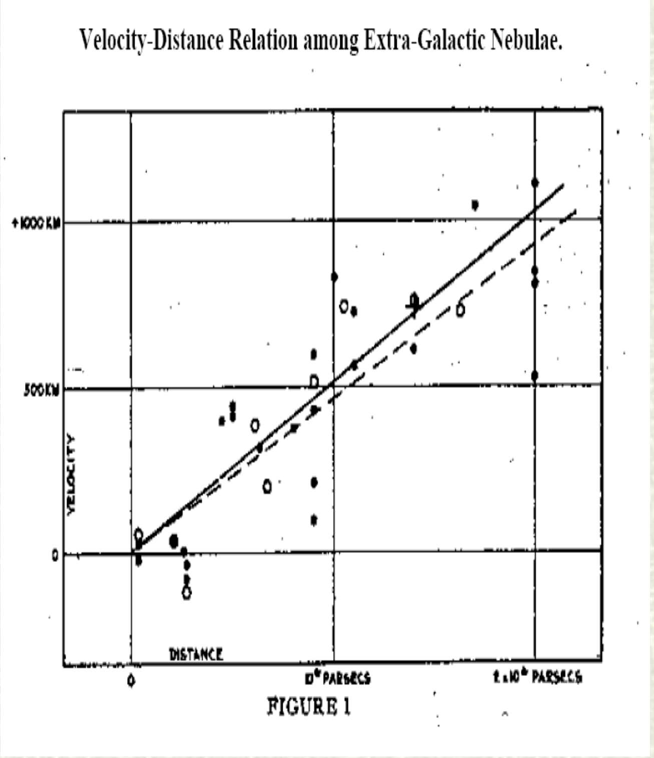


FIGURE 1

Why ?

Lemaître's universe (1927)

Fr Georges Lemaître

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

  Similar to Friedman 1922 model

  Starts from static Einstein universe

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

  Redshifts from Slipher, distances from Hubble

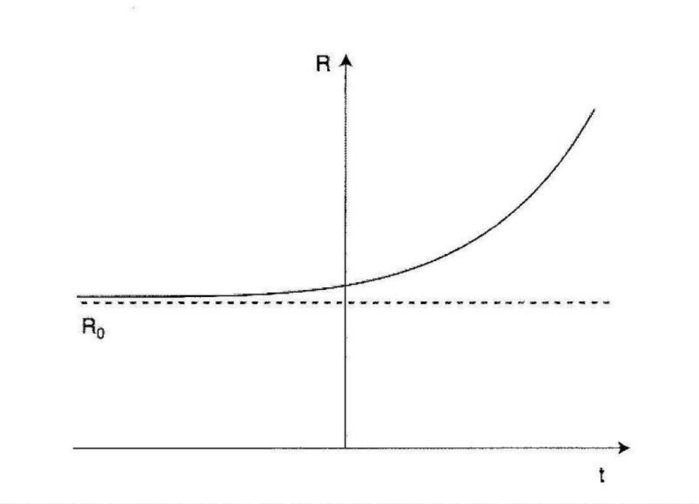
  $H = 585\ kms^{-1}Mpc^{-1}$

- **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)**

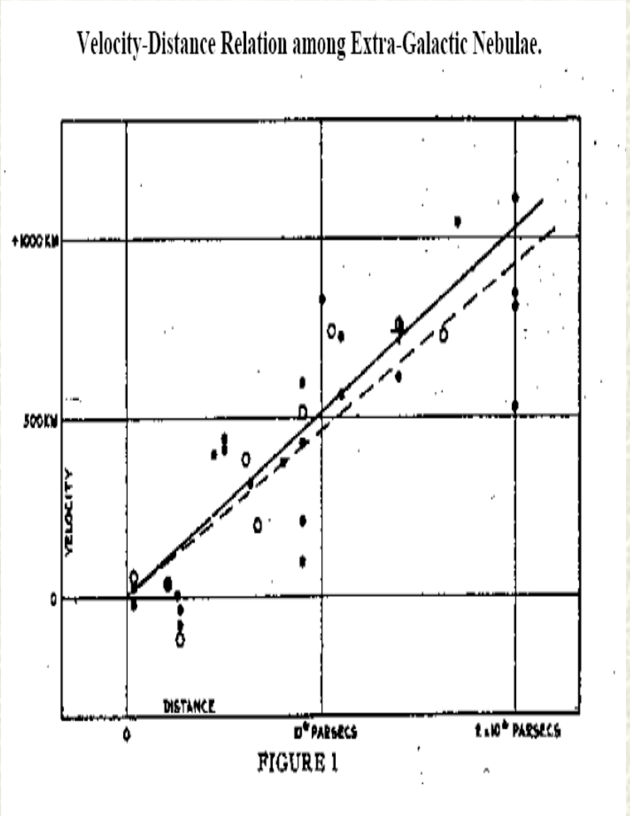
  Eddington, de Sitter
  If redshifts are velocities, and if effect is non-local
  Static cosmic models don't match observations

- **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



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

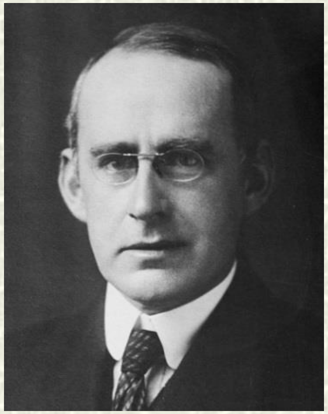
  Expanding universes of every flavour

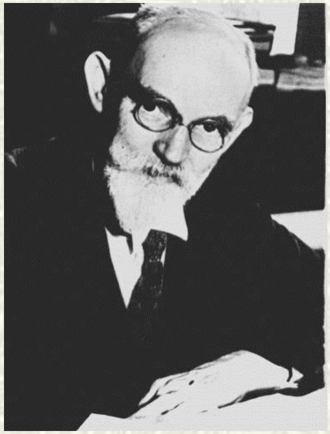
- **Einstein (1931, 32)**

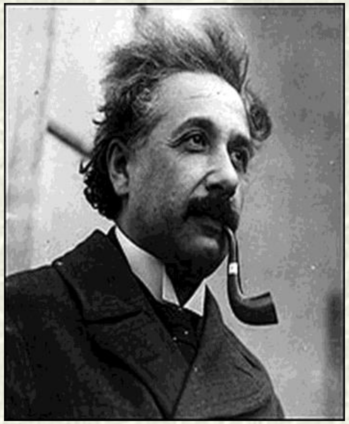
  Friedman-Einstein model $\lambda = 0$, $k = 1$

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

Occam's razor?



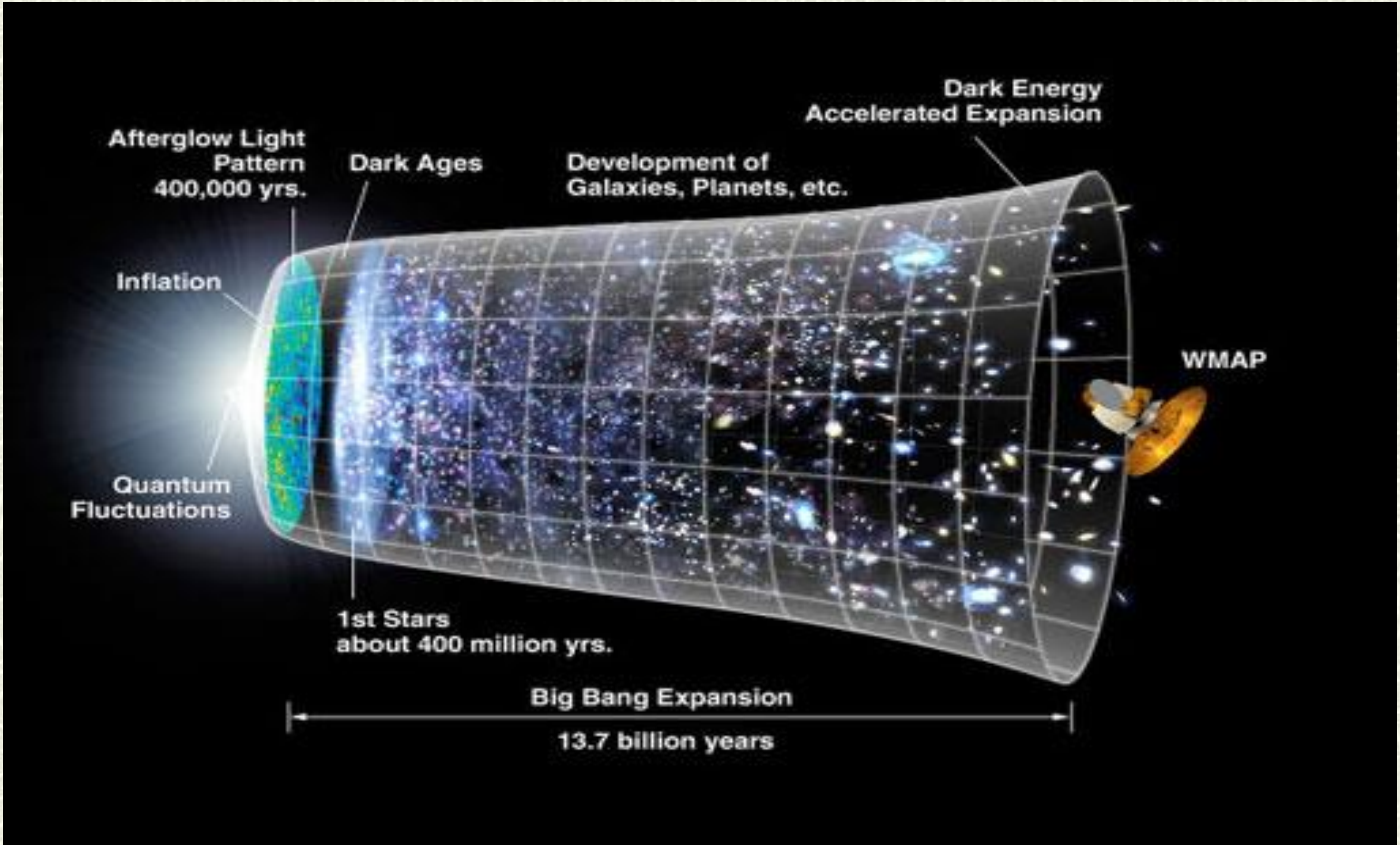




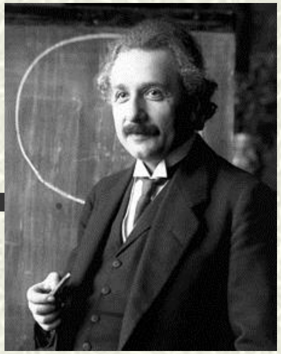
Evolving models

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

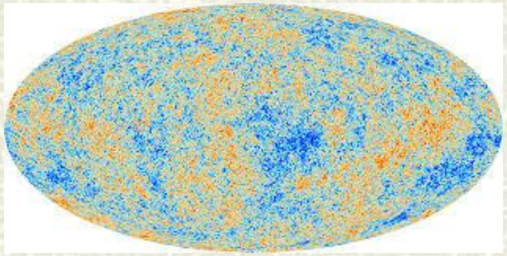
  Evolving models simpler: remove λ*-term*

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**

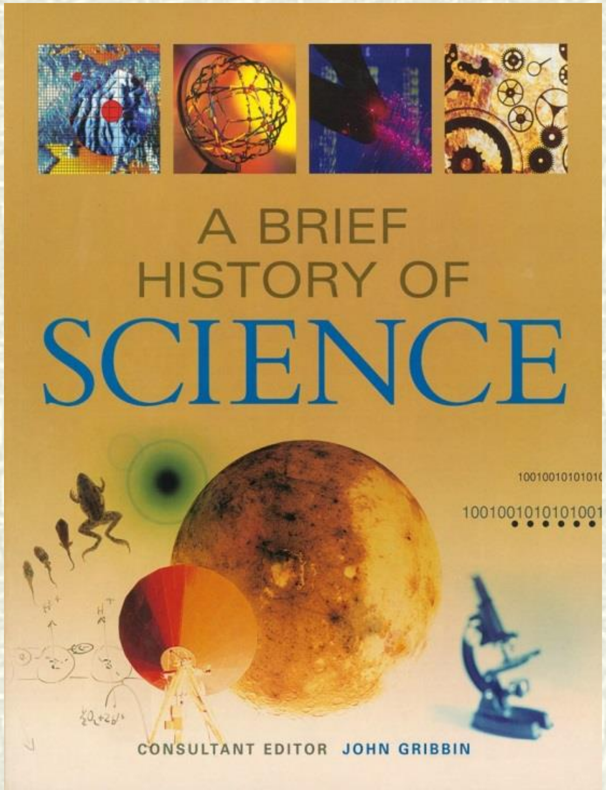
  Simple solution?

  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 ?

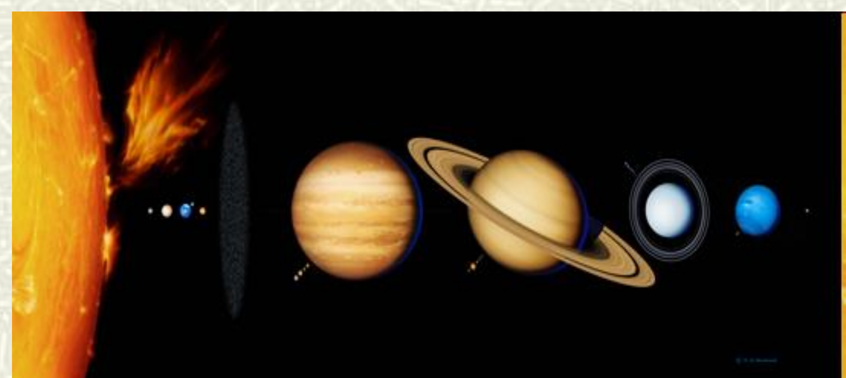
Explanation for runaway galaxies?

Isaac Newton

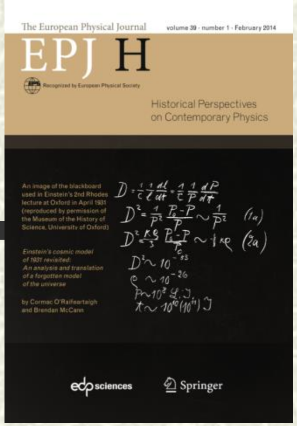
Newton

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

How can galaxies be receding?
What is pushing out?

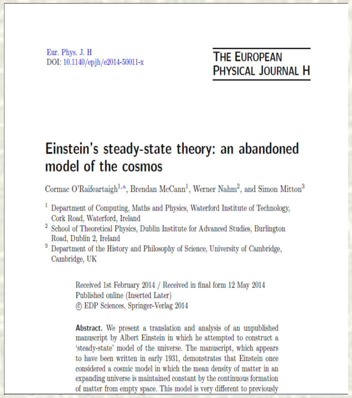


Results: publications



- **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

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

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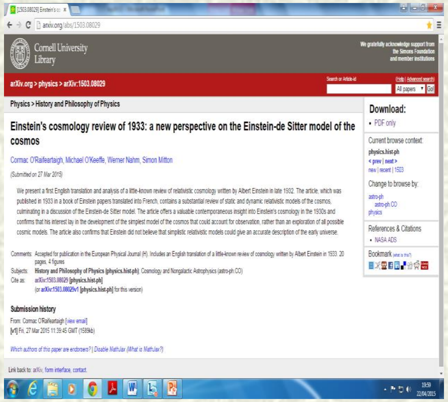
Abstract. We present a translation and analysis of an unpublished manuscript by Albert Einstein in which he attempted to construct a 'steady-state' model of the universe. The manuscript, which appears to have been written in early 1931, demonstrates that Einstein once considered a cosmic model in which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



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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)

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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]
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- **Review paper: conclusions**

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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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Department of Computing, Maths and Physics, Waterford Institute of Technology, Cork Road, Waterford, Ireland

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

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

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

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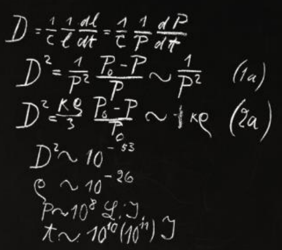
Historical Perspectives on Contemporary Physics

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



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THE EUROPEAN PHYSICAL JOURNAL H

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

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

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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)
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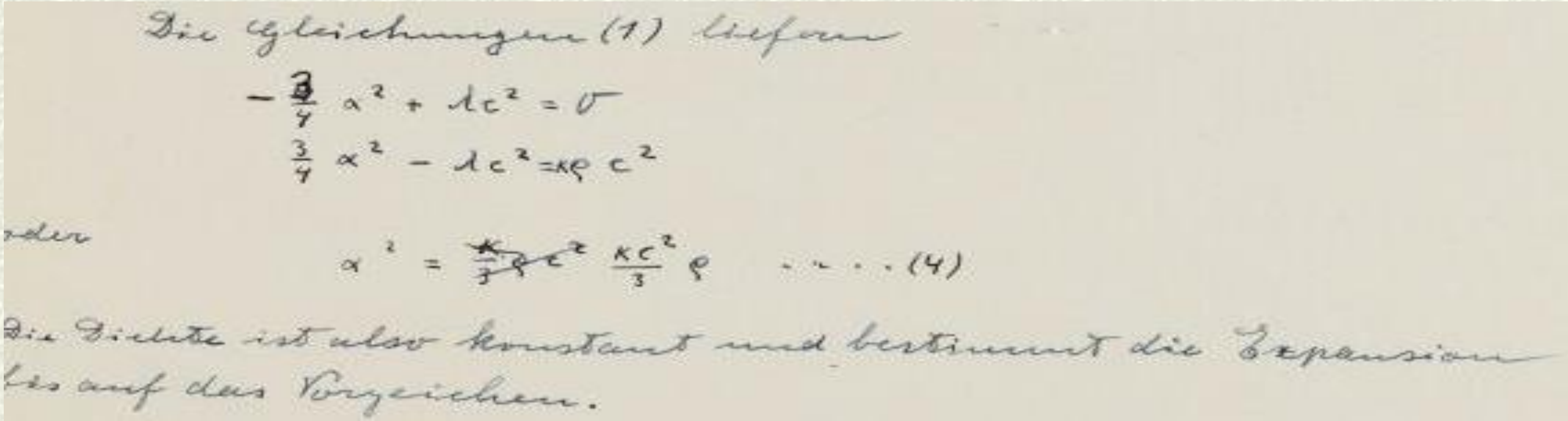

Die Gleichungen (1) liefern

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

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

oder

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

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**

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

  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”

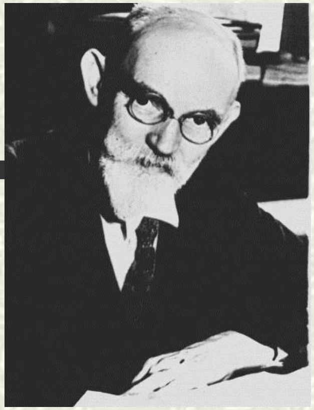
“I have not succeeding in formulating boundary conditions for spatial infinity. Nevertheless, there is still a way out…for if it were possible to regard the universe as a continuum which is finite (closed) with respect to is spatial dimensions, we should have no need at all of any such boundary conditions”

“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)

de Sitter's universe



- **Alternative solution of the GFE**

  A universe empty of matter (1917)

- **Solution B**

  Cosmic constant proportional to curvature of space

  $$\lambda = 3/R$$

- **Disliked by Einstein**

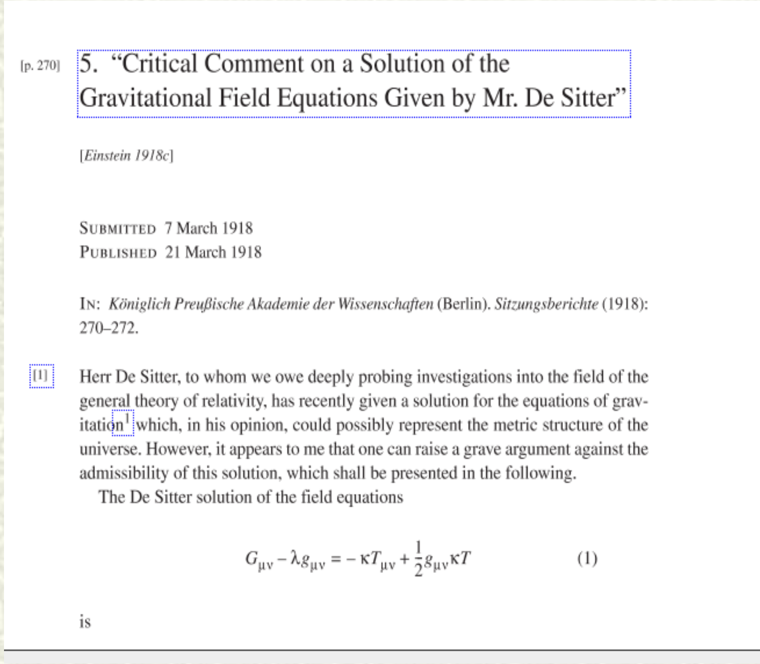
  Conflict with Mach's principle

  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

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

is

Prediction of redshifts – Slipher effect?

An abandoned model

- **Correct geometry**

  de Sitter metric

- **Simultaneous equations**

  Eliminate λ

  Relation between α^2 *and* ρ

- **Einstein's crossroads**

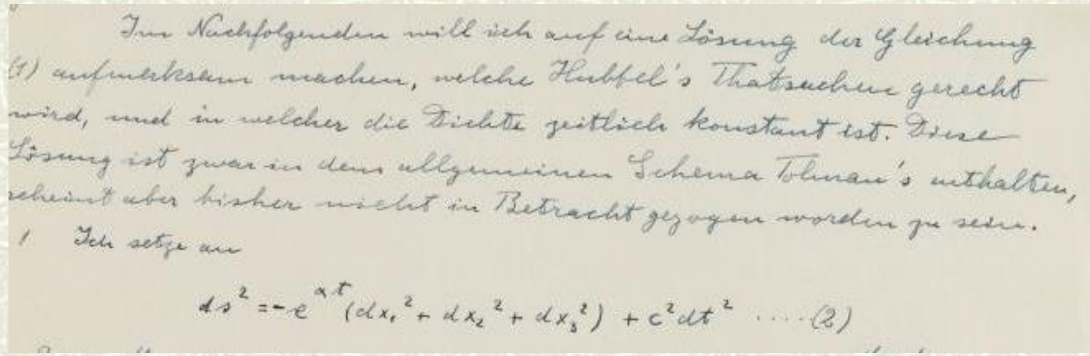
  Null solution on revision

  Tolman? (Nussbaumer 2014)

  Declined to amend GFE

- **Evolving models**

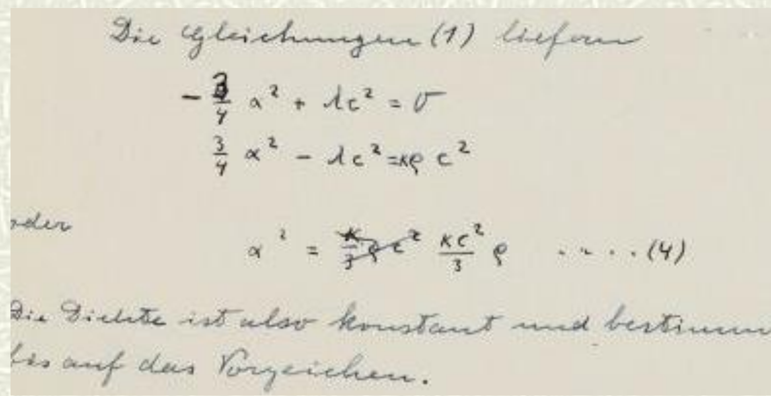
  Less contrived: set $\lambda = 0$



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

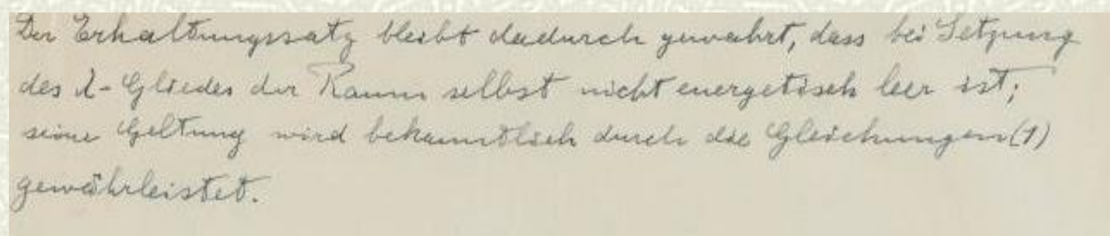
$$\alpha^2 = \frac{\kappa c^2}{3}\rho \quad \ldots (4)$$

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

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

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

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



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.

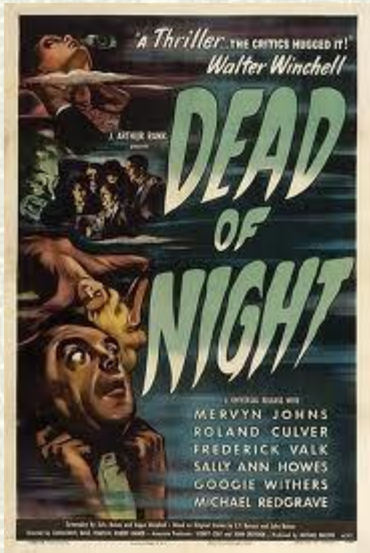
Steady-state universe (1948)

- 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>



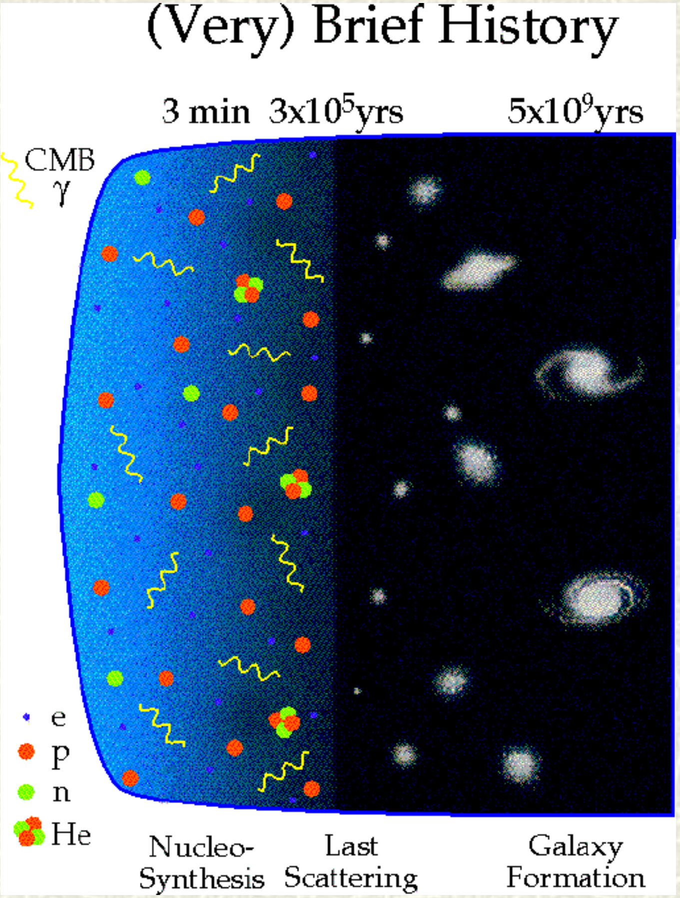
The big bang – evidence

1. The expansion of the *U*

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

3. The distribution of the galaxies

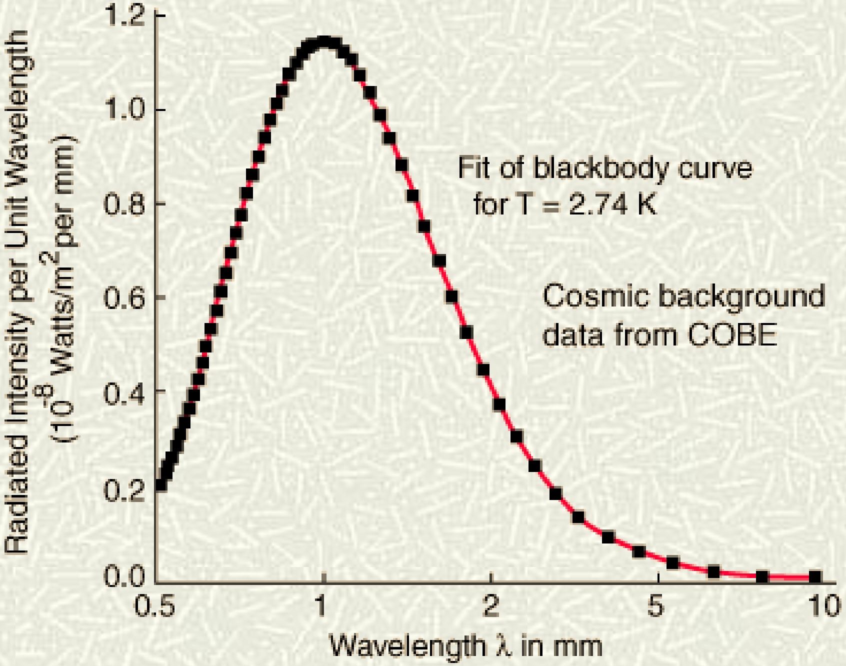
4. The cosmic microwave background



How did it start?

COBE measurements of CMB

- Expected temperature
- Expected frequency
- Perfect blackbody spectrum



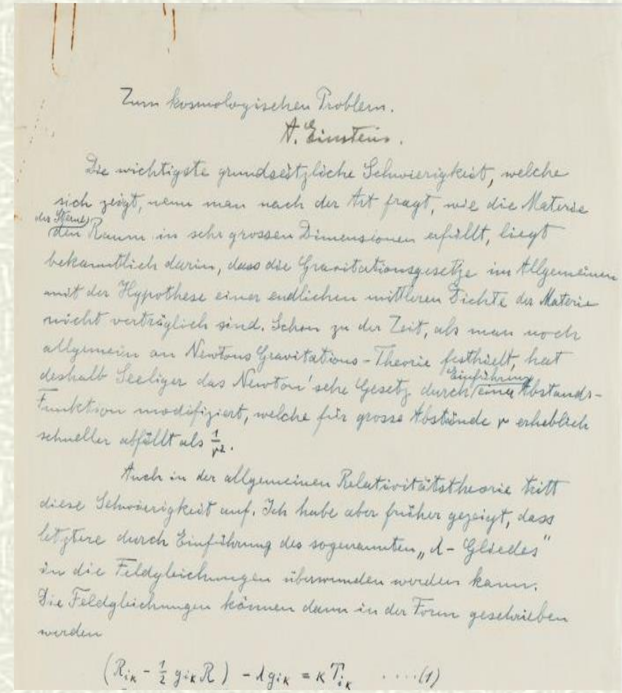
- *Radiation very uniform*
- *Variation of 1 in* 10^5
- *Seeds of galaxies ?*

COBE (1992)

Nobel Prize

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*

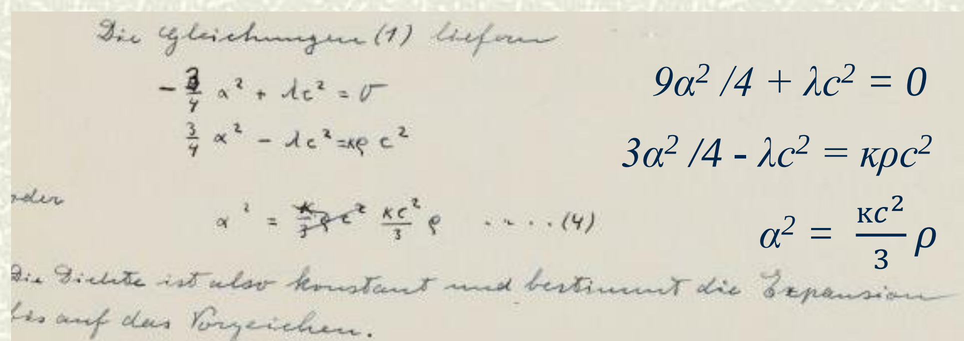


Zum kosmologischen Problem.
A. Einstein.

Die wichtigste grundsätzliche Schwierigkeit, welche sich zeigt, wenn man nach der Art fragt, wie die Materie der Sterne 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

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

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NATURE | NEWS

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

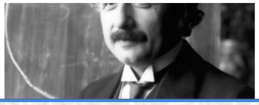
2 comments, 2 called-out + Comment Now + Follow Comments

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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www.irishtimes.com/news/science/wit-researchers-discover-lost-einstein-model-of-universe-1.1713487

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THE IRISH TIMES

Science

Monday, March 10, 2014

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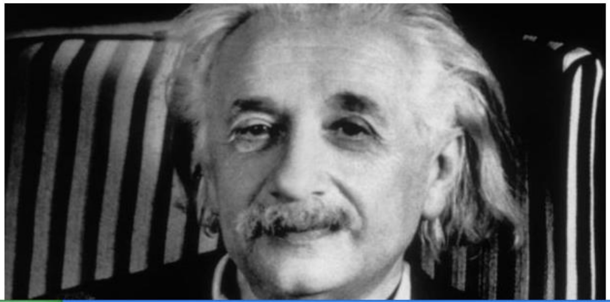
News / Science

WIT researchers discover 'lost' Einstein model of universe

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



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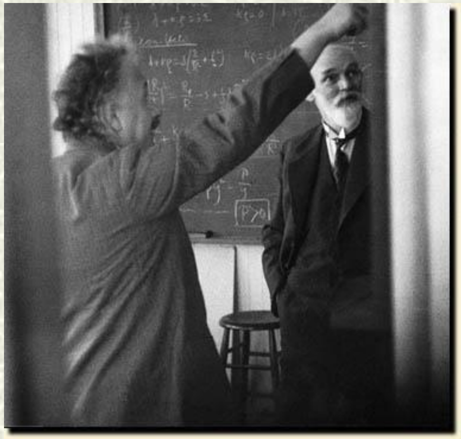
09:07 Man in his twenties stabbed in north Dublin

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

2. Einstein-de Sitter model (1932)



- **Remove spatial curvature**

  Curvature not a given in dynamic models (Heckmann)

  Not observed empirically (Occam's razor)

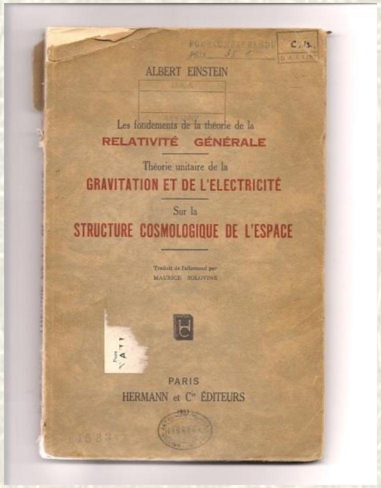
$$ds^2 = -R^2(dx^2 + dy^2 + dz^2) + c^2dt^2$$

- **Simplest Friedman model**

  Time-varying universe with λ = 0, k = 0, p =0

  Estimate of density : ρ =10^{-28} g/cm^{3}

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



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

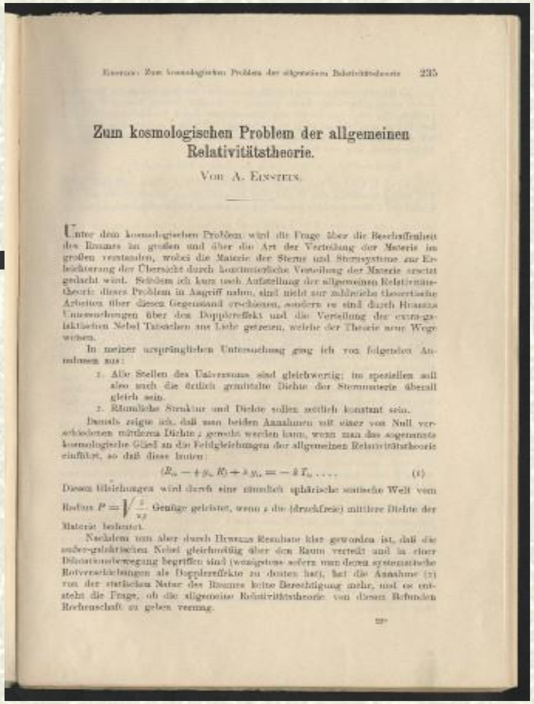
- **<u>Becomes standard model</u>**

  Despite high density of matter, age problem

  Time evolution not considered

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

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:

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

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.

29*

- **Einstein's first expanding model**

  Rarely cited (not translated)

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

- **Adopts Friedman 1922 model**

  Instability of static solution

  Hubble's observations

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

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

- **Sets cosmic constant to zero**

  Redundant

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

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

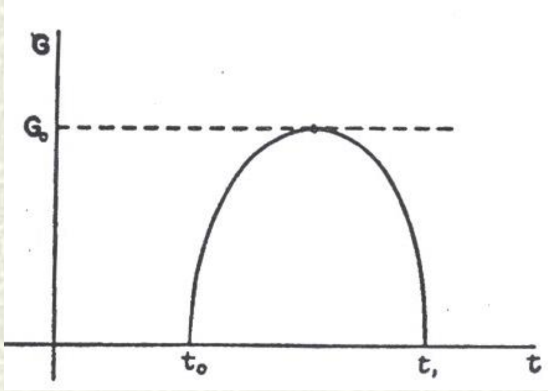
- **Extraction of cosmic parameters**

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

  $t \sim$ 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

$$D = \frac{1}{P}\frac{dP}{dt}.\frac{1}{c} \qquad D^2 = \frac{1}{P^2}\frac{P_0 - P}{P} \qquad P \sim \frac{1}{D}$$

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

  "Model fails at P = 0 "

  Contrary to what is usually stated

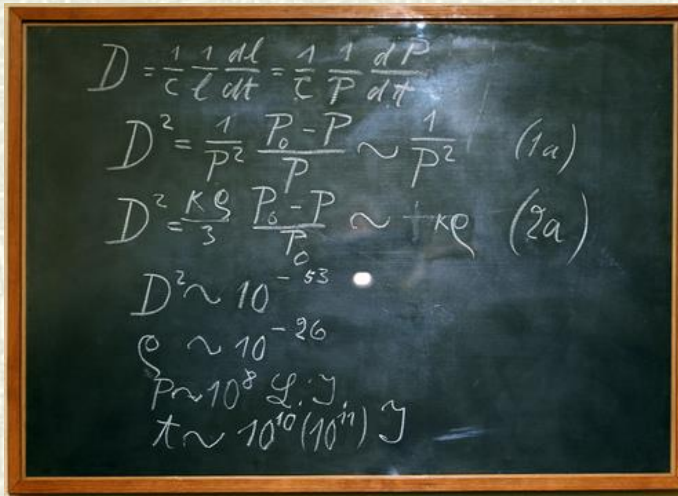
$$D^2 \sim \kappa\rho$$

Oxford lecture (May 1931)

- **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?**

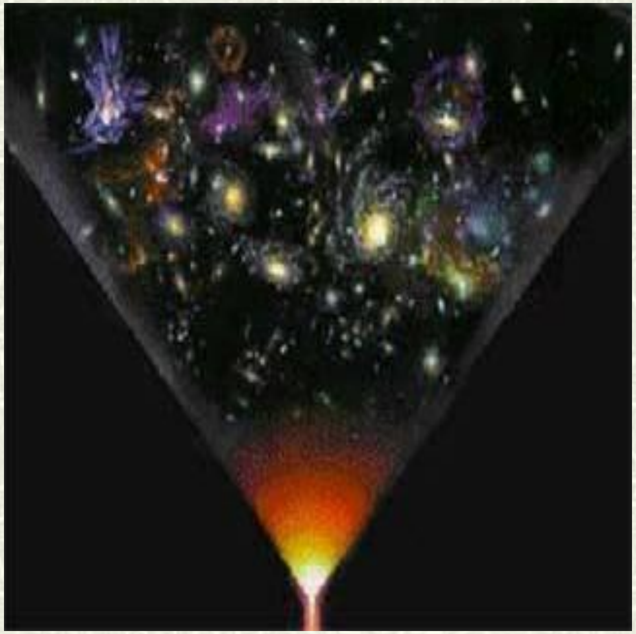
  Oxford blackboard: $D^2 \sim 10^{-53}$ cm^{-2} *should be* 10^{-55} cm^{-2}

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

  Non-trivial error: misses conflict with radioactivity

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 $t = 0$?