One Hundred Years of Cosmology

Einstein, Hawking and the Big Bang

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Midlands Astronomy Club April 2018

Overview

I The theory of relativity

The special theory of relativity

The general theory of relativity

II Relativity and the universe

The static models of Einstein and deSitter

The dynamic models of Friedman and Lemaitre

Hubble's law and the expanding universe

III The big bang model

The question of origins

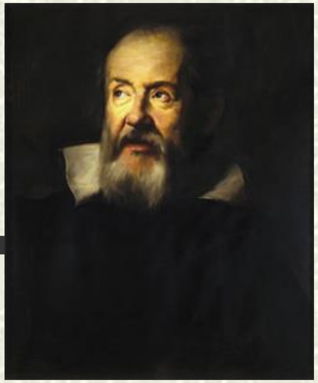
Hawking-Penrose singularity theorems

Hawking's no-boundary universe

Einstein in 1918

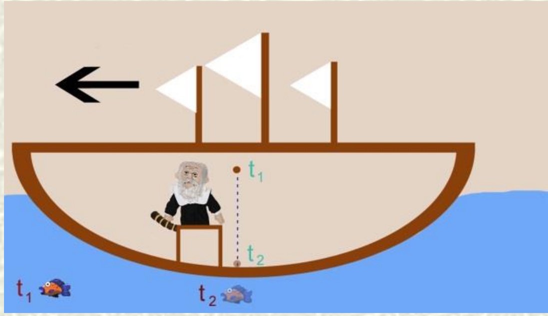
Hawking in 2014

Relativity

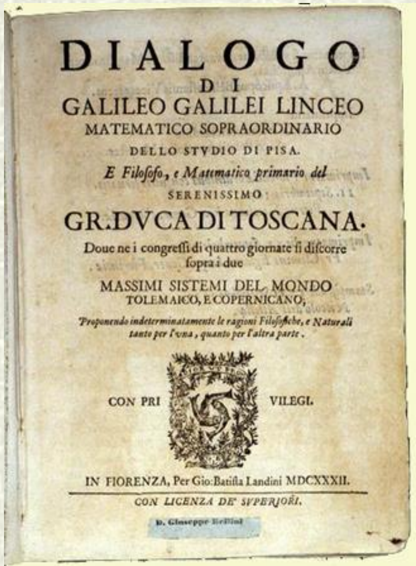


Galileo (1564-1642)

- **The principle of relativity**
  Relativity of motion
  Buridan, Oresme, Bruno, Copernicus



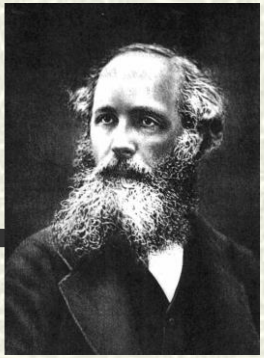
- **Galileo's galleon (1632)**
  Motion of objects in closed cabin of ship
  Impossible to detect motion of ship by experiments in cabin


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'una, 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

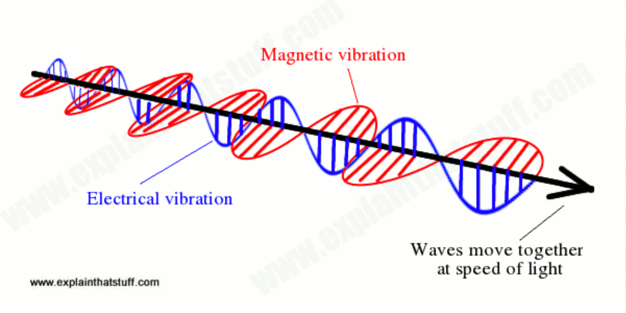
- **Implications for mechanics**
  Anticipates Newton's law of inertia

Relativity in the 19th century

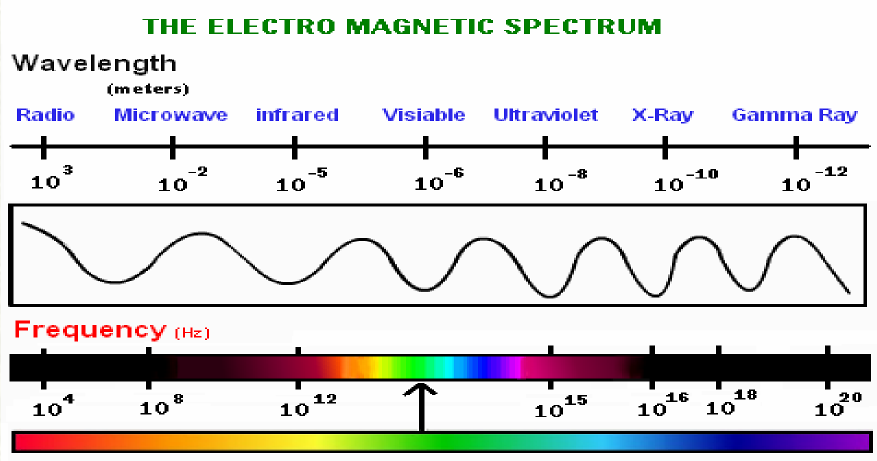



Michael Faraday   JC Maxwell

- **Electromagnetism**
  - *Electricity and magnetism = electromagnetism*
  - *Speed of electromagnetic wave = speed of light in vac*

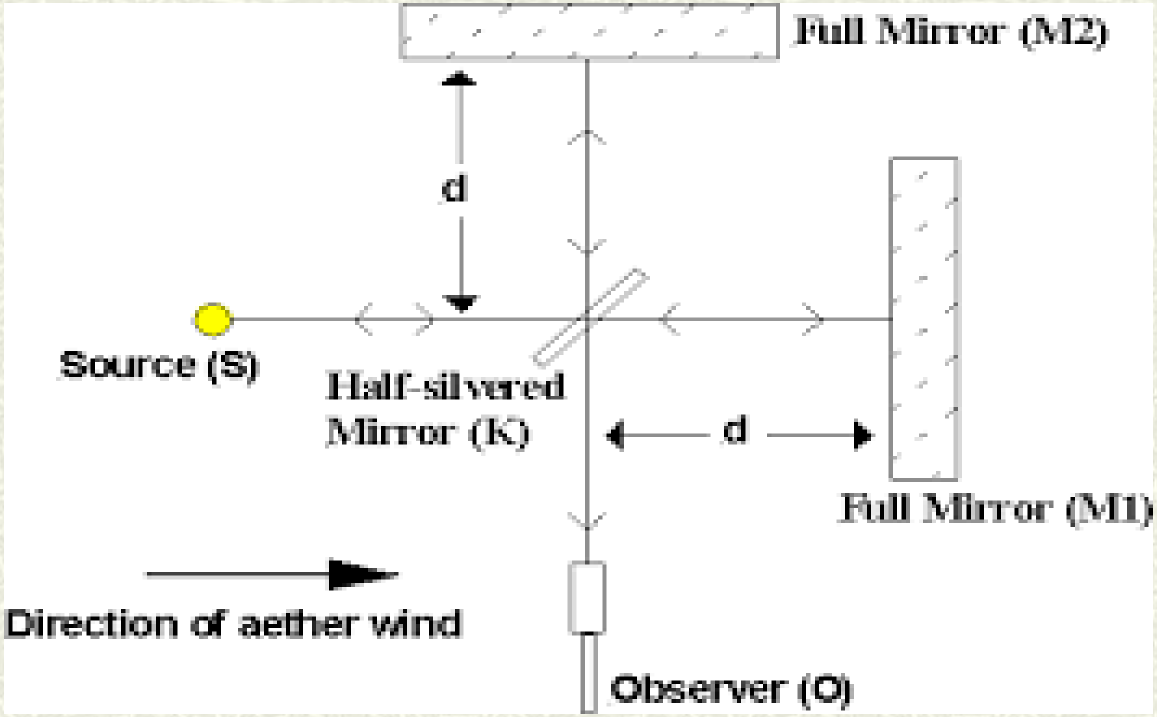


- **Light = an electromagnetic wave**
  - *Changing electric and magnetic fields*
  - *The electromagnetic spectrum*



- **Speed relative to what?**
  - *The concept of the ether*
- **The search for the ether**
  - *Michelson-Morley experiment*

Michelson-Morley experiment



Expect: rays should arrive at O out of phase

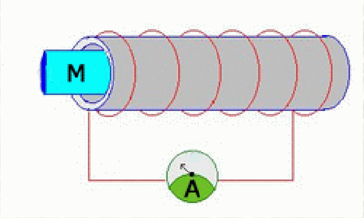
Result: no effect detected

The special theory of relativity (1905)

- **Two principles**

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

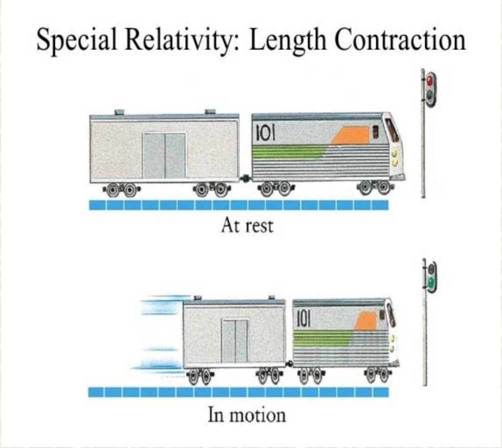
  Speed of light in vacuum a universal constant



- **Implications**

  Intervals in distance and time not universal

  Experienced differently by bodies in relative uniform motion



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

  Length contraction : time dilation

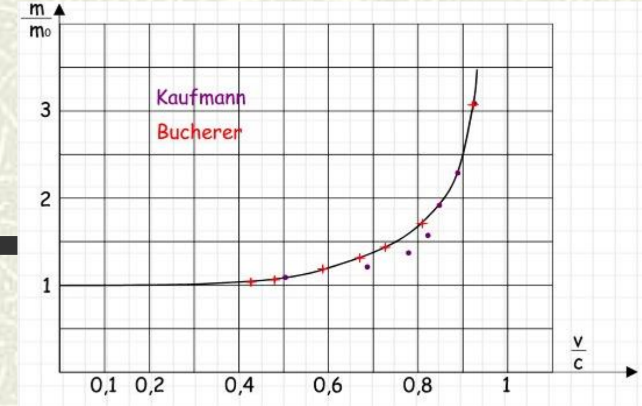
  Mass increase; mass-energy equivalence

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

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

  <u>Space-time</u> invariant for observers in relative uniform motion

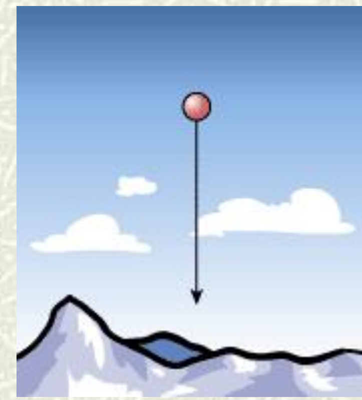
Evidence for SR



- **Mass increase**

  The experiments of Kaufmann and Bucherer

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



- **Time dilation**

  The long-lived muon

  2 μs $\rightarrow$ 22 μs

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

- **Invariance of the speed of light**

  Always measured as c

- **Particle experiments at the LHC**

  Maximum velocity = c

  Mass increase

  Particle creation

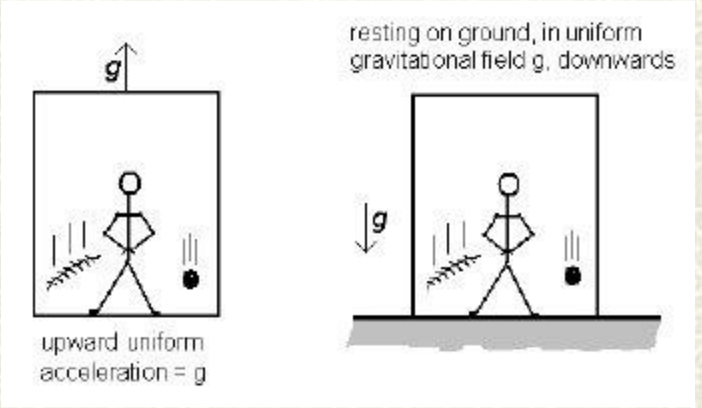
$$E = mc^2$$

The general theory of relativity (1916)

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

  Relativity and accelerated motion?

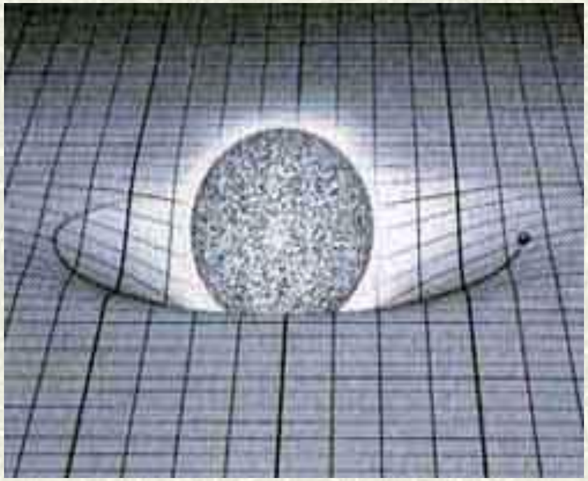
  Relativity and gravity?



- **<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)

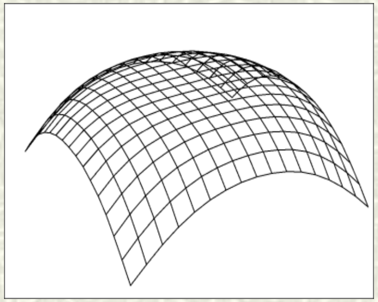
$$\boldsymbol{G}_{\mu\nu} \quad = \quad - \; \frac{8\pi G}{c^4} \, \boldsymbol{T}_{\mu\nu}$$

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

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

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

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



GR $\quad \mathrm{d}s^2 = g_{\mu\nu} \mathrm{d}x^\mu \mathrm{d}x^\nu$

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

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

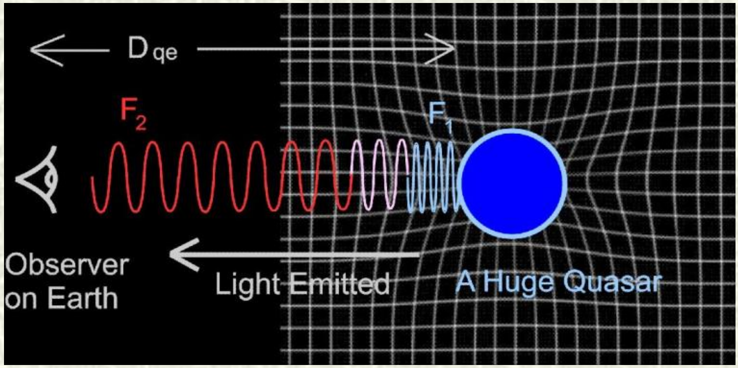
Evidence for GR

- **Bending of distant light by stars**

  Gravitational lensing

- **Gravitational redshift**

  Shift in wavelength of light due to gravity



- **Gravitational time dilation**

  GPS corrections

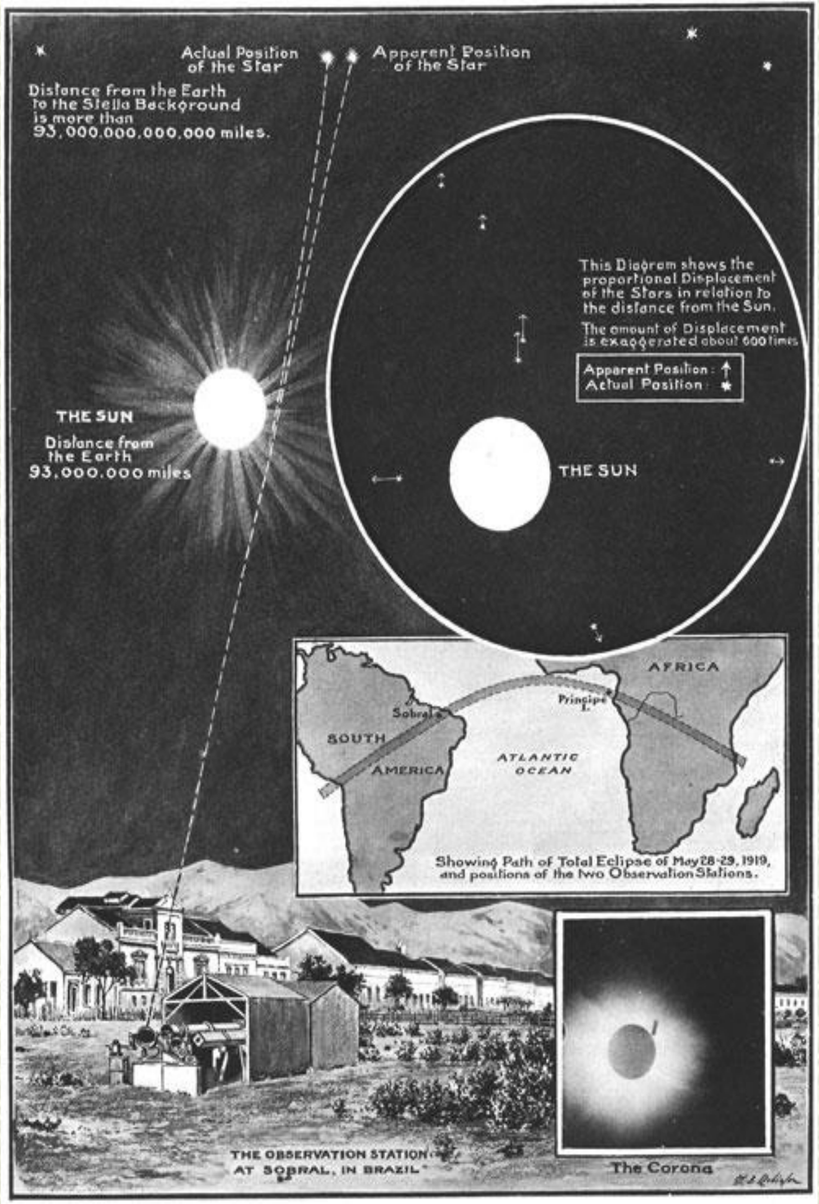
- **Black holes** $G_{\mu\nu} = -\kappa T_{\mu\nu}$

  Centre of galaxies

- **Gravitational waves**

  Hulse –Taylor binary system

  BH, neutron-star mergers



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

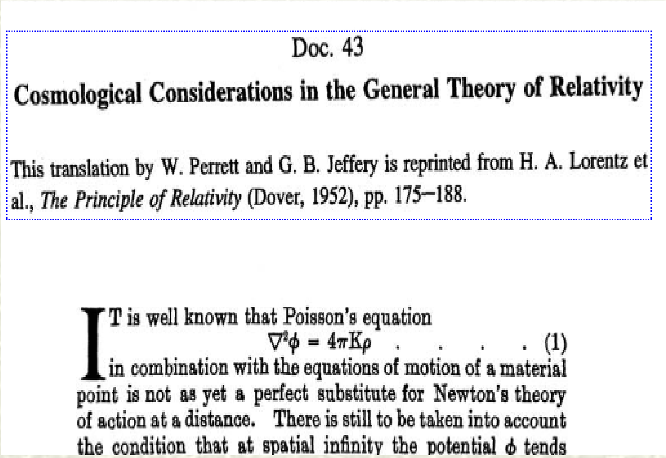
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Asymmetric controversy (Collins and Pinch 1970s)

Claim of bias; rebutted by astronomers (RAS)

Relativity and the universe

- **Einstein: apply GR to the Universe (1917)**
  Ultimate test for new theory of gravitation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Cosmological Considerations in the General Theory of Relativity

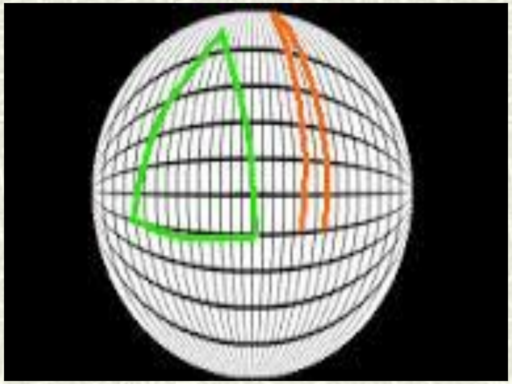
This translation by W. Perrett and G. B. Jeffery is reprinted from H. A. Lorentz et al., *The Principle of Relativity* (Dover, 1952), pp. 175–188.

It is well known that Poisson's equation

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

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**
  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

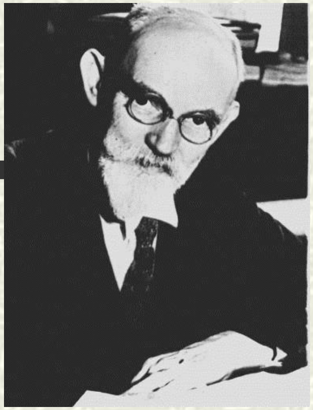
$$G_{\mu\nu} = -\kappa T_{\mu\nu}$$

- **New term needed in field equations!**
  Cosmic constant – allowed by theory
  Anti-gravity effect?
  Radius and density defined by λ

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

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

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**

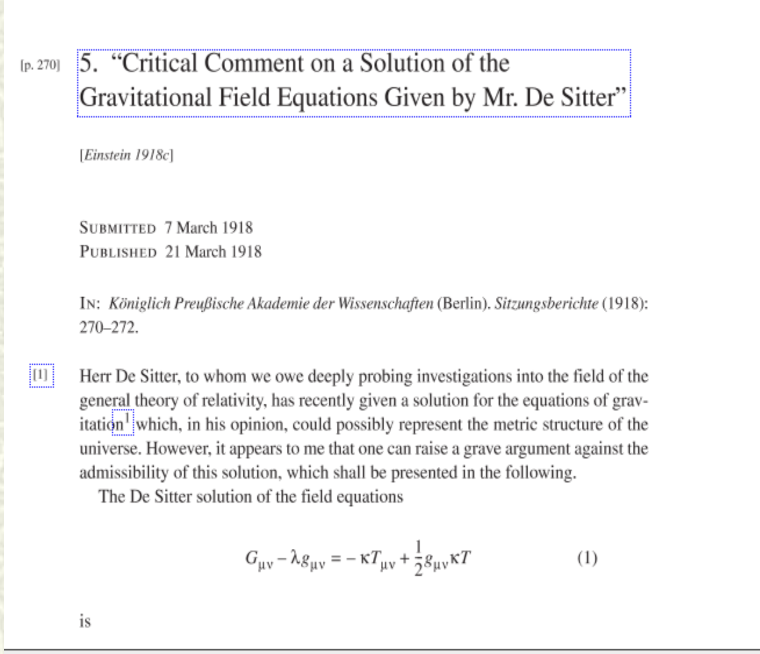
  Conflict with Mach's principle

  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 motion of the nebulae

Vesto Slipher

- **The redshift of the nebulae**

  V.M Slipher (Lowell Observatory)

  Light from most nebulae redshifted (1915, 1917)

- **Doppler effect**

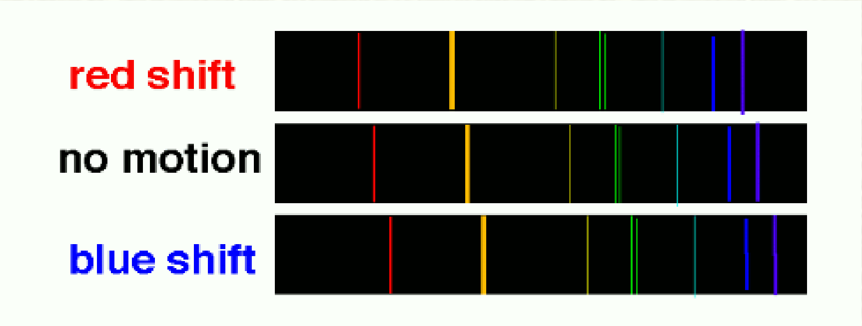
  Frequency of light depends on

  motion of source relative to observer

- **Nebulae moving outward?**

  Galaxies moving outward?

Lowell Observatory

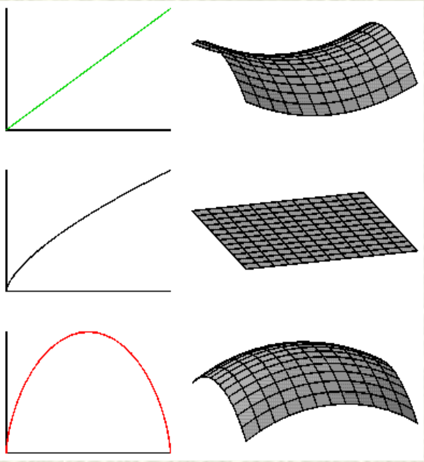


The dynamic universe (theory)

- **Alexander Friedman (1922)**

  Allow time-varying solutions for the cosmos

  Two differential equations for R



- **Evolving universe**

  Time-varying radius and density of matter

  Considered 'suspicious' by Einstein

- **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)

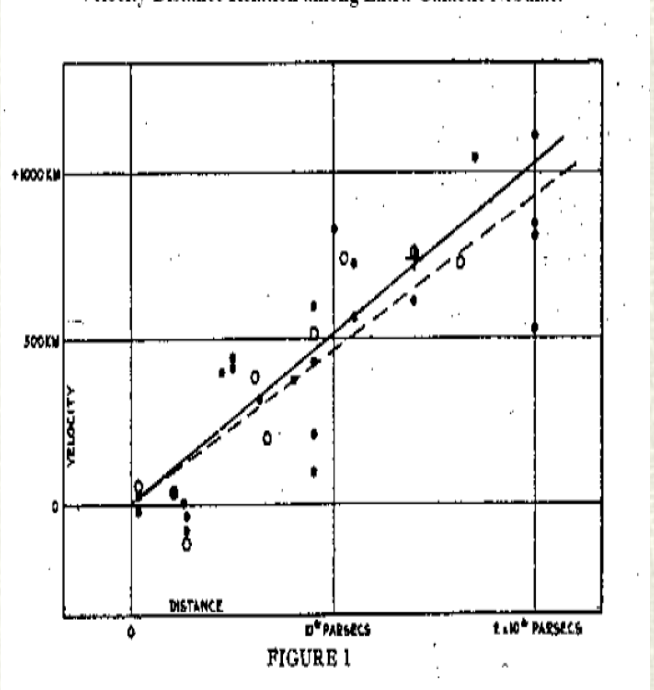


FIGURE 1

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)**

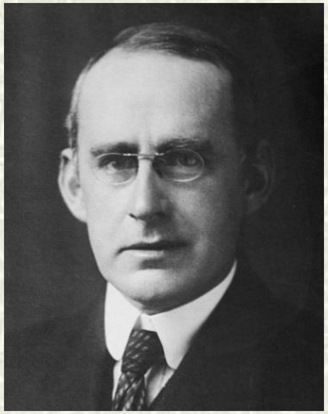
  Further remarks on the expanding universe

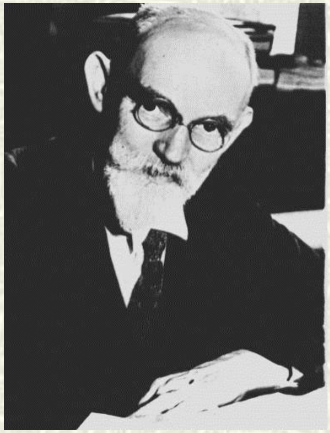
  Expanding universes of every flavour

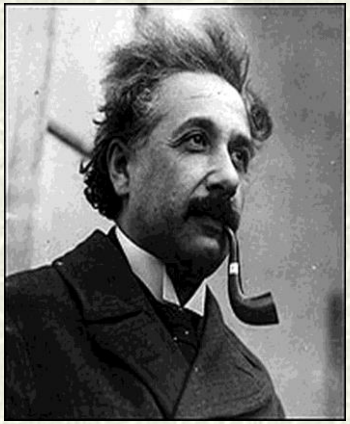
- **Einstein (1931, 32)**

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

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







Expanding models

No mention of origins

Cosmic prediction: 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>

Not endorsed by community (1930-60)

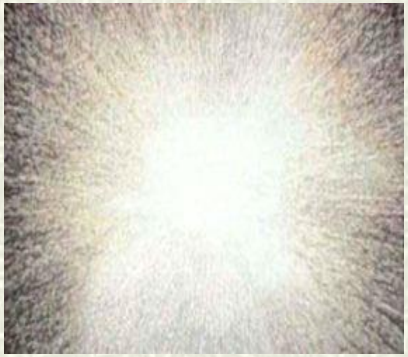
Singularity problem: timescale problem

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

A second 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



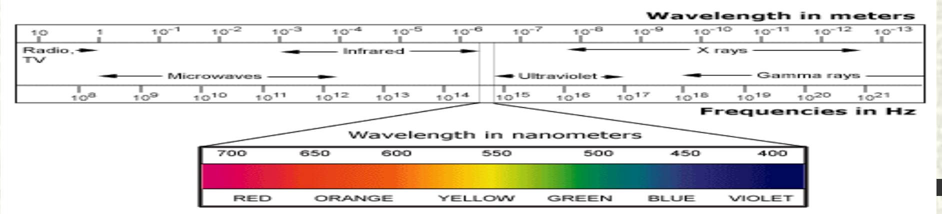
Heavier atoms formed in stars

Bonus: a third 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**

  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)

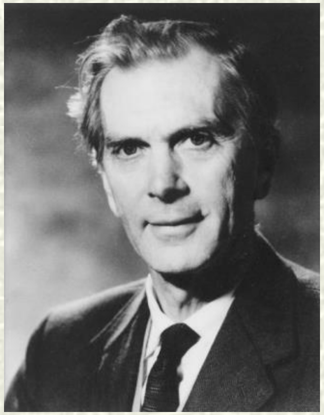
  New timescale of expansion

Allen Sandage

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

  Galaxy distributions at different epochs

  Cambridge 3C Survey (Ryle)



Martin Ryle

- **Nucleosynthesis of light elements**

  Gamow et al. 1948

- **Cosmic microwave background (1965)**

  Low temperature, low frequency

  Remnant of young, hot universe

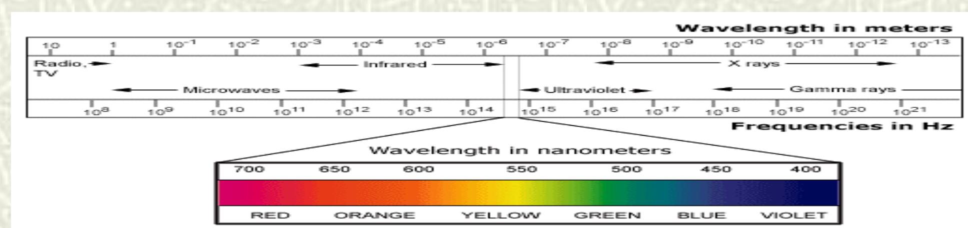
Cosmic background radiation (1965)

CMB discovered accidentally

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

Penzias and Wilson (1965)

Echo of Big Bang!



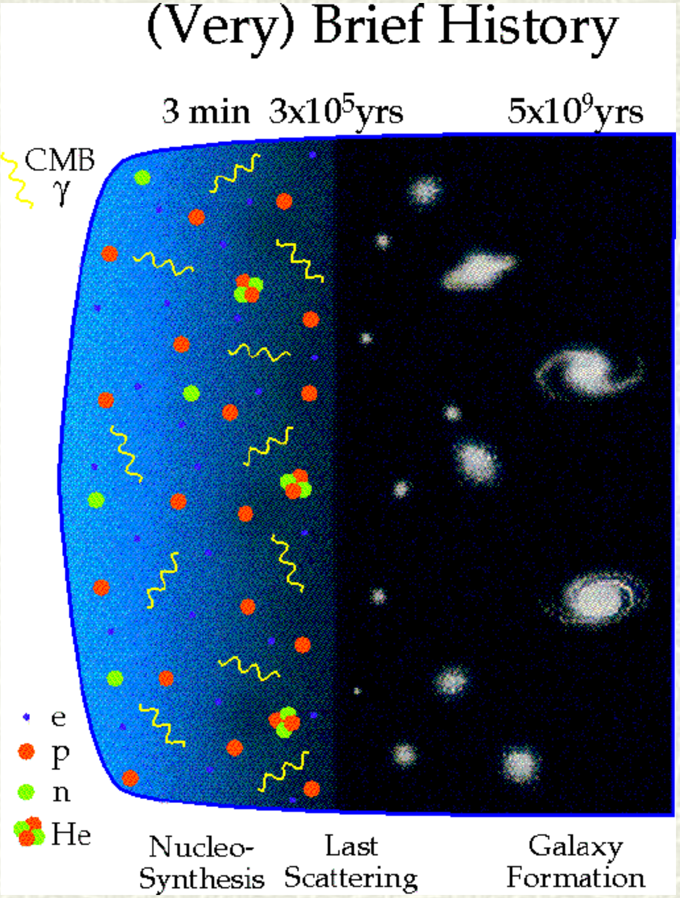
The big bang – evidence

1. The expansion of the *U*

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

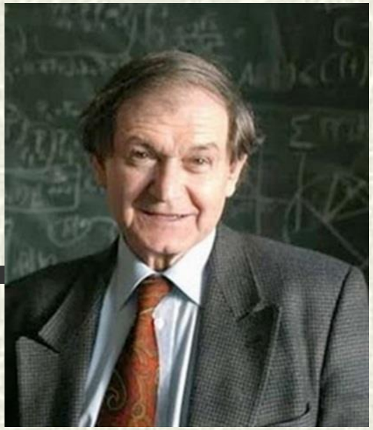
3. The distribution of the galaxies

4. The cosmic microwave background



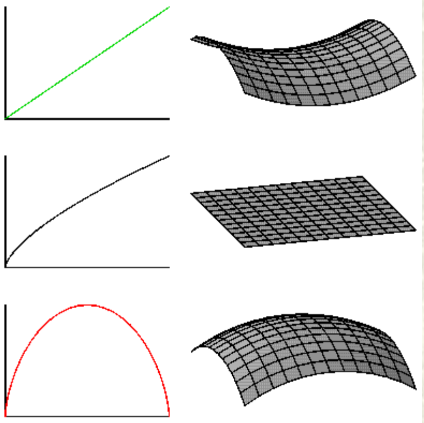
How did it start?

Problems : theory



- The singularity problem revisited

  A facet of simplified assumptions?



- Roger Penrose: black holes

  GR → BH must contain spacetime singularity

- Stephen Hawking: cosmology

  GR → U must begin in a spacetime singularity

- Grand cosmological theorem (Hawking/Penrose)

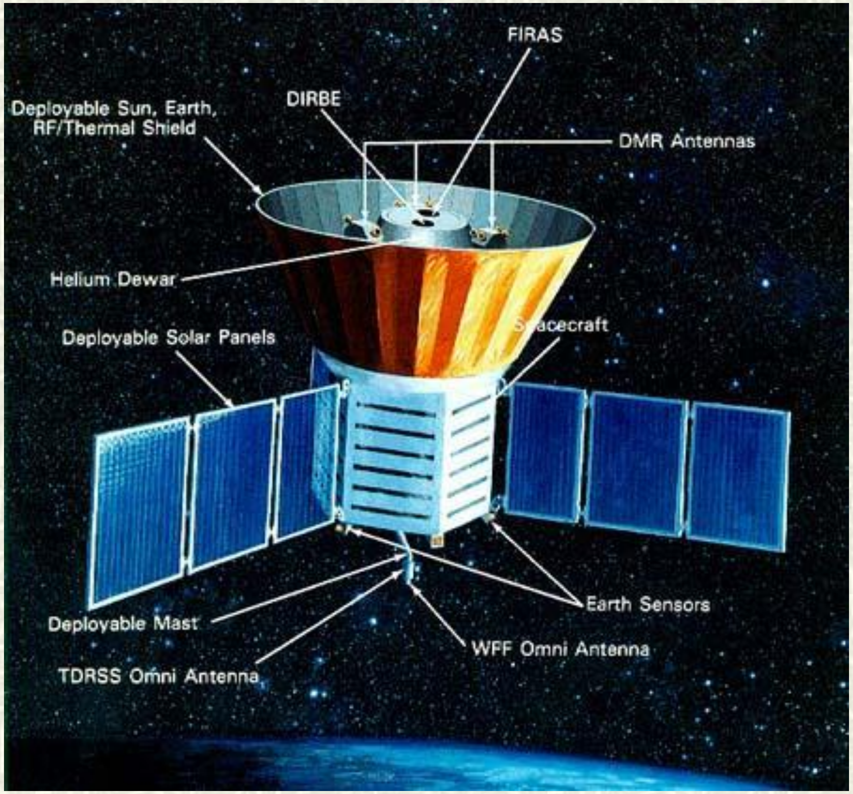
  "There is a singularity in our past" (PhD, 1966)

Big bang not a full theory?

Modern measurements of the CMB

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

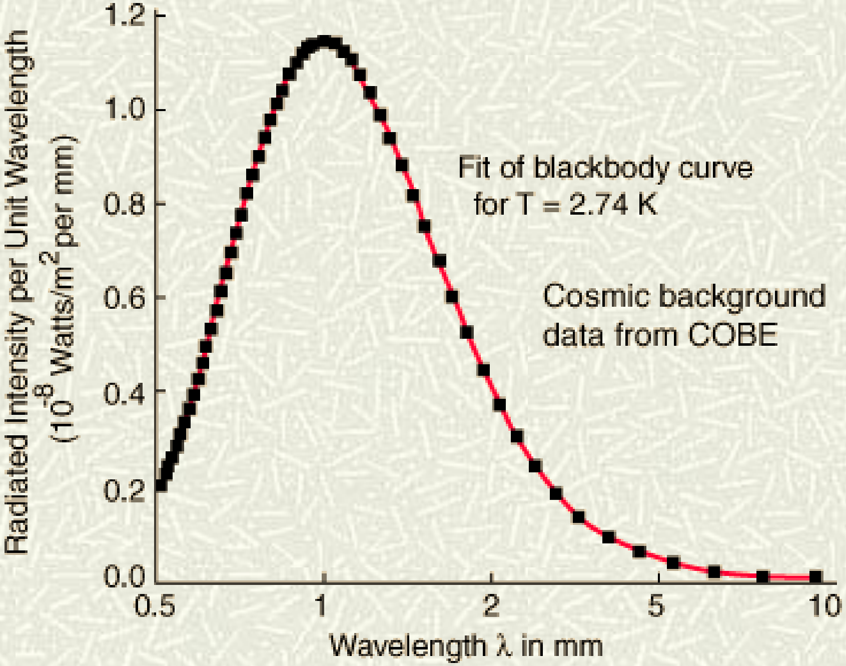
  - ***Ground telescopes***
  - ***Balloon experiments***
  - ***Satellite experiments***



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)

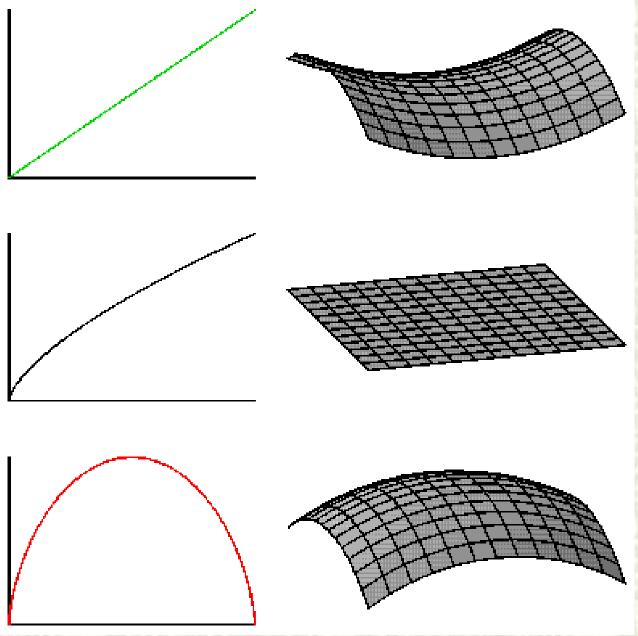
<u>Nobel Prize</u>

Problems: observation

Robert Dicke

Background radiation raised new questions

- Horizon problem *why so uniform?*
- Galaxy problem *how did galaxies form?*
- Flatness problem *fine balance?*



Conflict between theory and experiment

Astrophysics: $\Omega = 0.3$ (incl. DM)

Dark Matter

- First suggested in 1930s
- Stellar motion

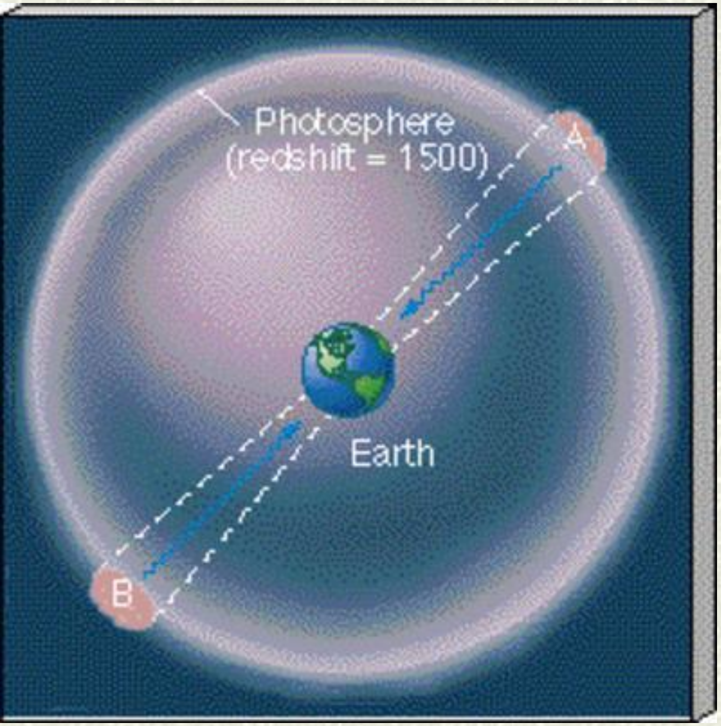
<u>normal gravitational effect but cannot be seen directly</u>

- Explains motion of stars
- Explains motion of galaxies
- Explains gravitational lensing

Matter = OM (20%) + DM (80%)

Ω = 0.3 ?

The horizon problem



•Two distant regions of microwave background have similar temps

Why?

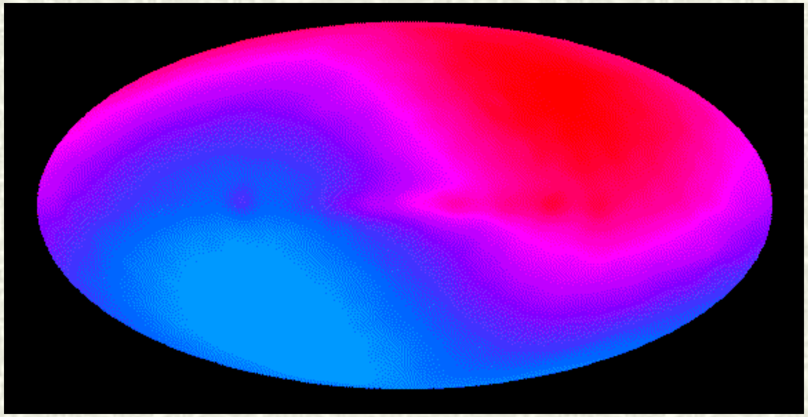
Too far apart to be causally connected

• Finite speed of light

• Finite age of cosmos

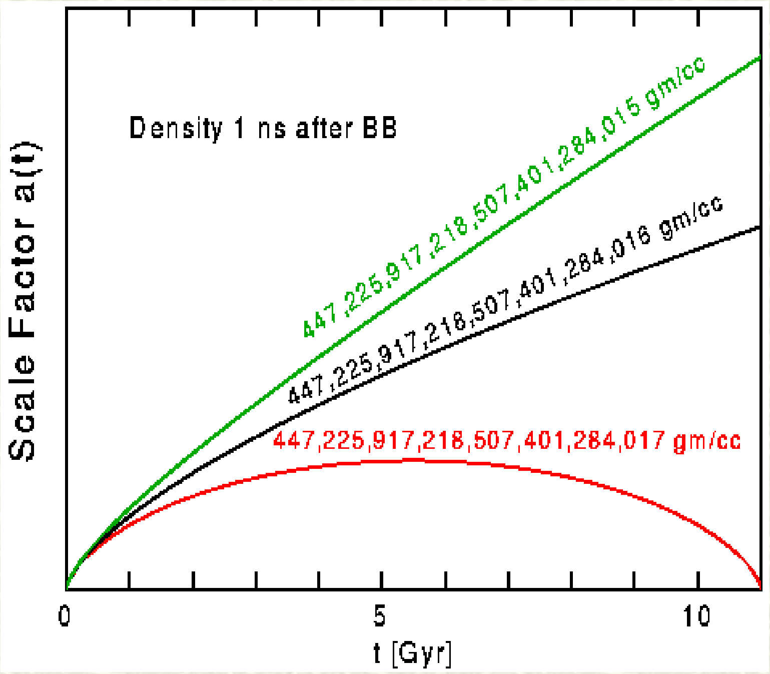
Something wrong with lookback

Galaxy formation problem



- Microwave background smooth on large scale
- No deviations from homogeneity obvious
  (1 in 10,000)
- How did slight perturbations become galaxies?

The flatness problem



At t = 1 s, Ω = 1 to within 1:10^{15})

Slightest deviation from flatness

→

runaway expansion or crunch

Not observed

Why so finely balanced initially?

Ω = 1?

Astrophysics: **Ω= *0.3* ?**

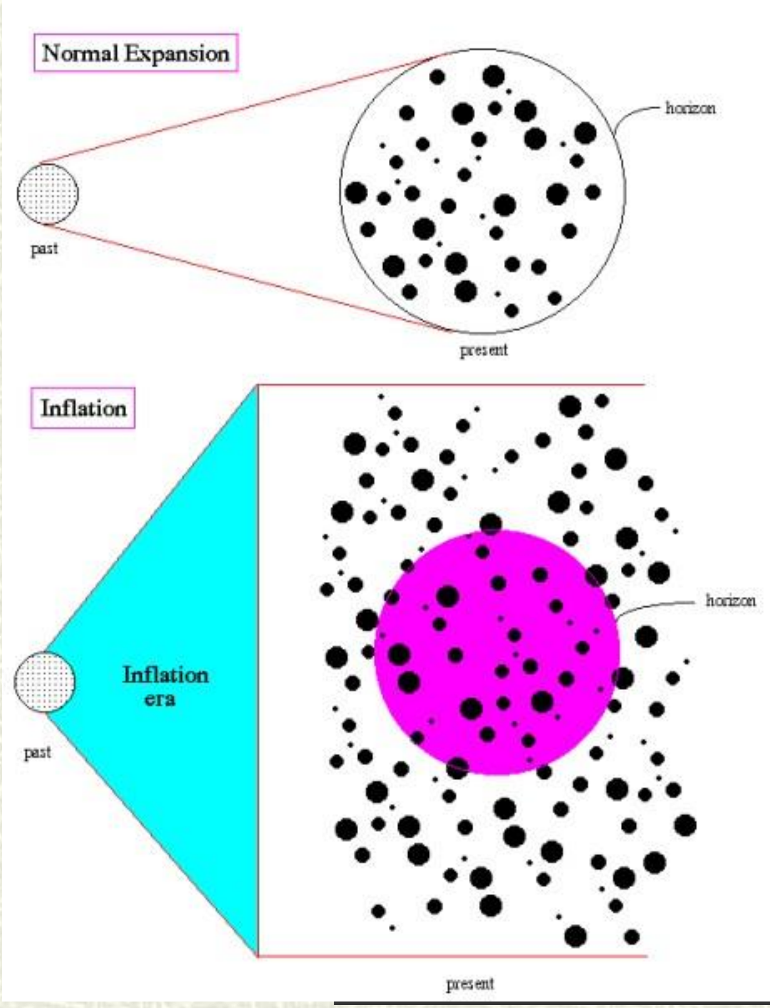
The Theory of Inflation (1981)

- Initial **exponential expansion**
- Driven by *phase transition*

Repulsive force

- Expansion of 10^{35} in 10^{-32} s
- Smooths out inhomogeneities
- Smooths out curvature

<u>'No hair' universe</u>



The inflationary universe (1981)

- Solves horizon problem

  Early U incredibly small

- Solves flatness problem

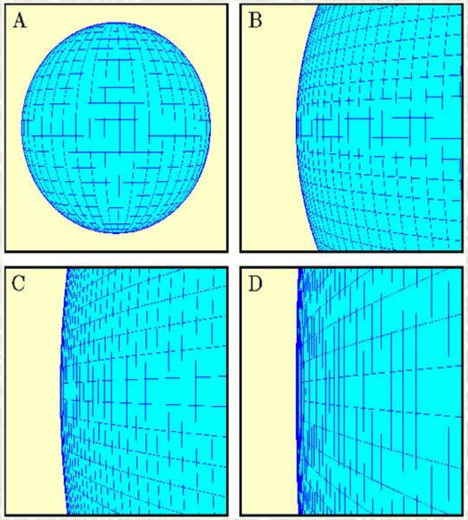
  Geometry driven towards flatness

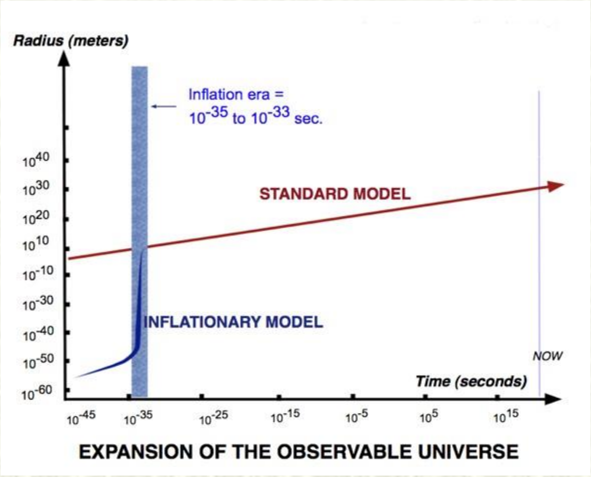
- <u>Mechanism for galaxy formation</u>

  1982 Nuffield workshop (Hawking)

  Quantum fluctuations inflated

  Correct spectrum





$$\Omega = 1\ ?$$

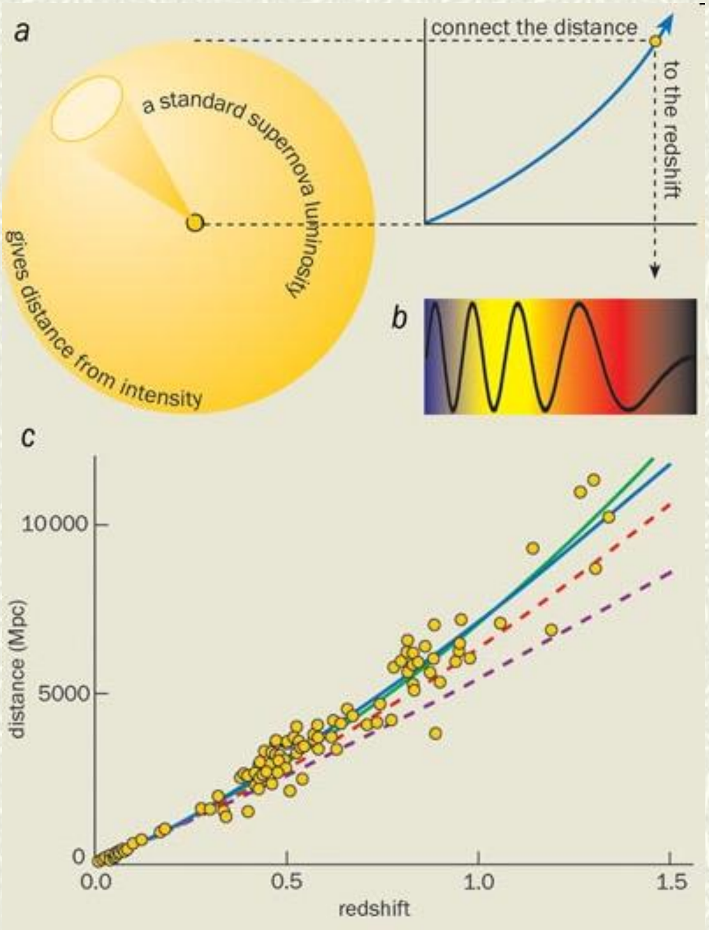
Conflict between theorists and experimentalists

The accelerating universe (1998)

- Supernovae as standard candles (1998)
- Furthest galaxies too far away
- Expansion accelerating
- Implies repulsive energy

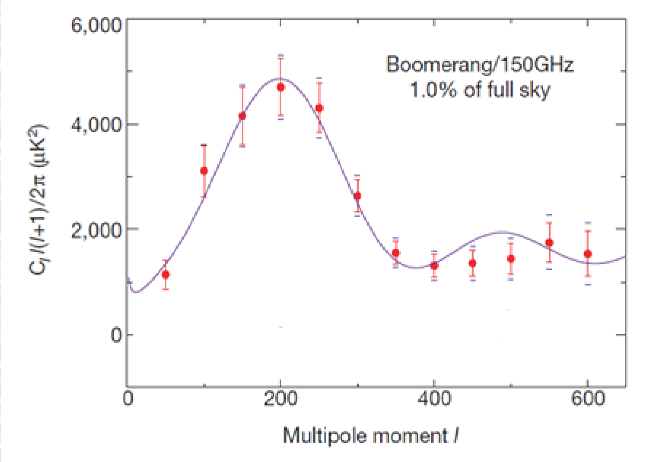
  ***Dark Energy** ($\lambda \neq 0$)*

- Possible support for inflation (Ω = 1?)



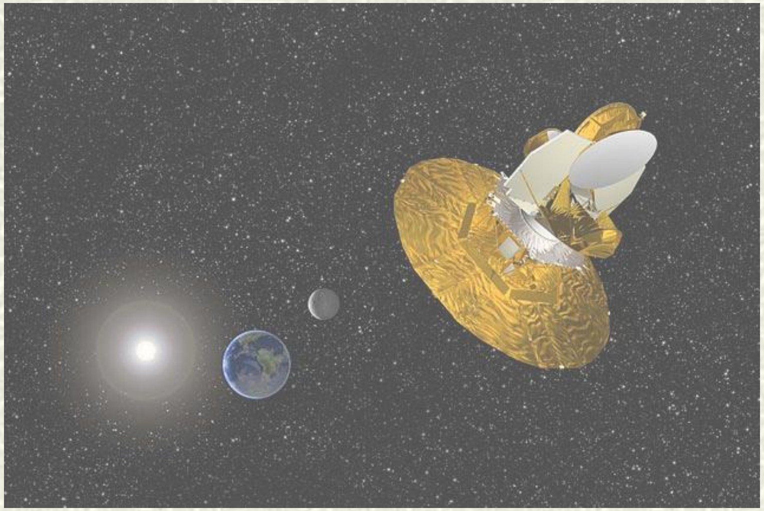
The flat universe (2000)

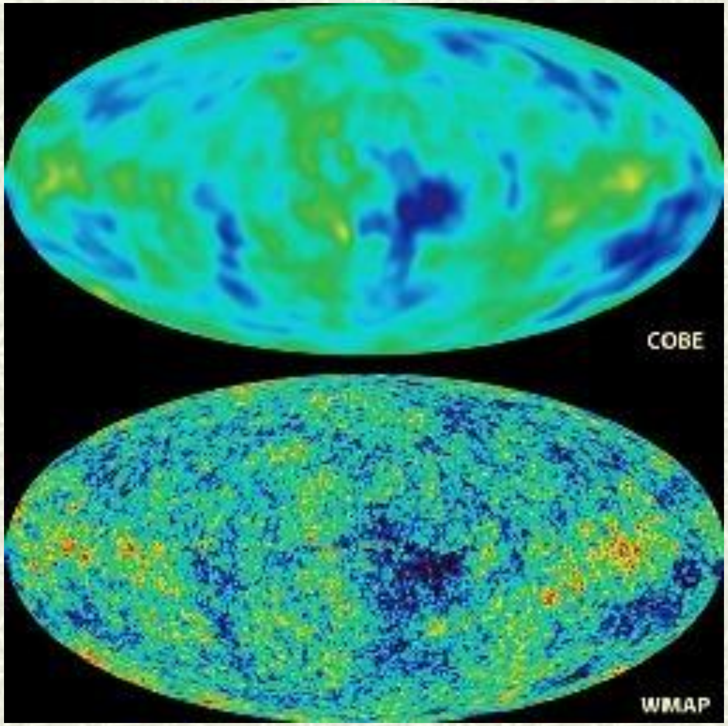
- Balloon measurements of CMB
- The BOOMERANG experiment
- The MAXIMA experiment
- Geometry is flat (Ω = 1)
  Implies dark energy component
  $$\Omega_M + \Omega_\lambda = 1 \quad (\Omega_\lambda = 0.7)$$
- Support for inflation



WMAP Satellite (2002)

- Details of *CMB* spectrum
- Details of galaxy formation
- Details of flatness of *U*
- Details of dark energy





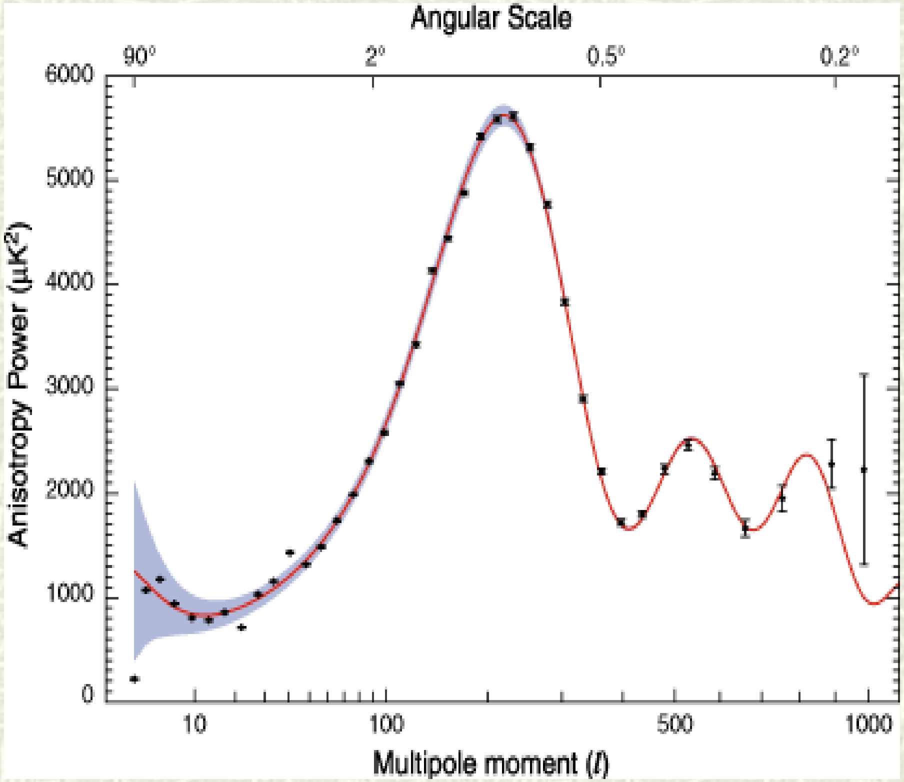
Cosmic microwave background

WMAP measurements of CMB (2005)

- Spectrum of *T* variations
- Geometry is flat (to 1%)
- Dark energy 74%

Strong support for dark energy

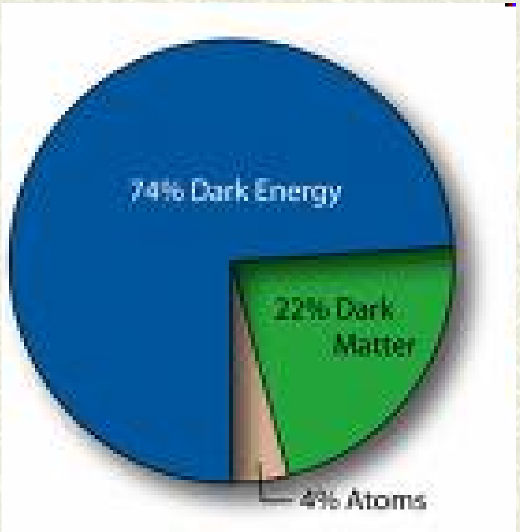
Strong support for inflation



Fit to theory

Modern big bang model: *Λ-CDM*

A flat, accelerating universe containing matter, dark matter and dark energy



1. Ordinary matter: 4% (astrophysics)
2. Dark matter: 22% (astrophysics)
3. Dark energy : 74% (supernova, CMB)

ΛCDM

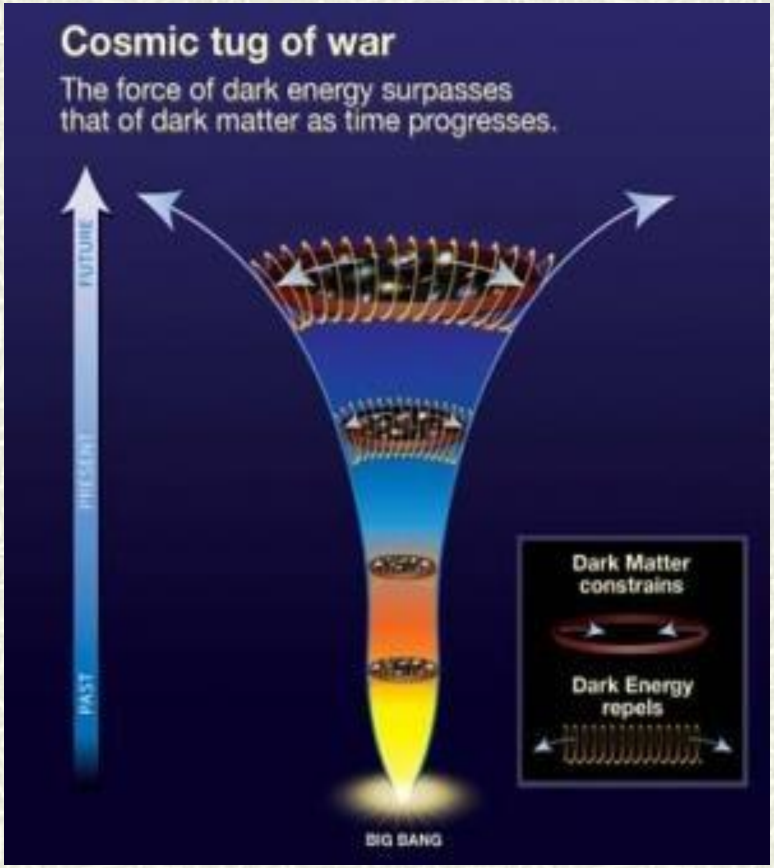
$\Omega = 1$

Cause of acceleration: dark energy

- Predicted by relativity
- Cosmological constant
- Natural tendency of space to expand

- Energy of vacuum?
- Why so small?
- Why of similar density to matter?

- Not well understood
- Fate of universe?



New results: Planck Satellite (ESA, 2013)

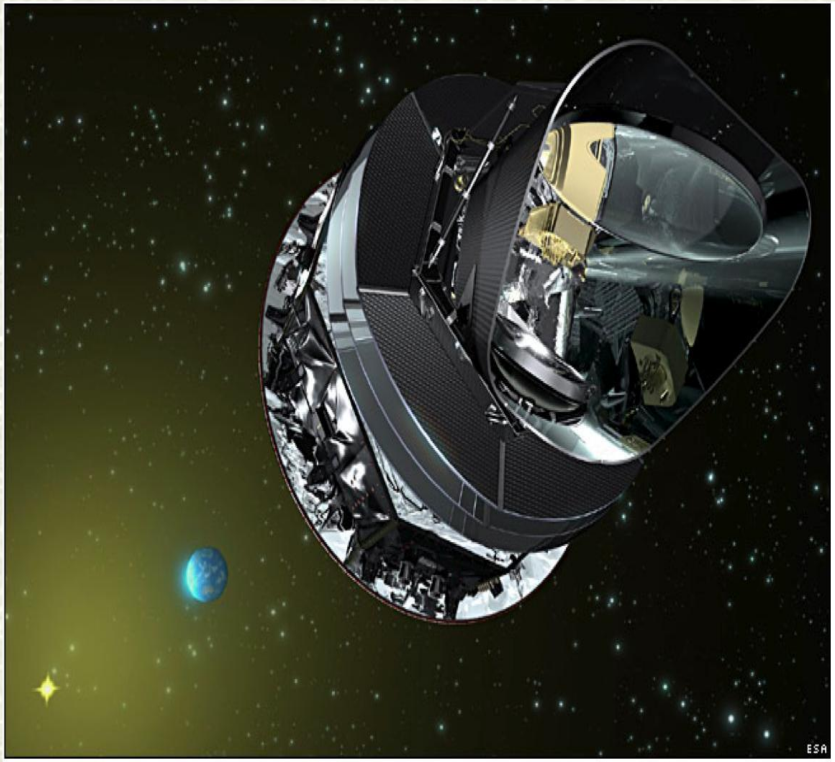
1. Improved sensitivity

$$\Delta T / T \approx 1x10^{-6}$$

2. Full spectrum of *T* anisotropy

New acoustic peaks :scale invariance?

Accurate values for Ω_{Λ} , Ω_{M}



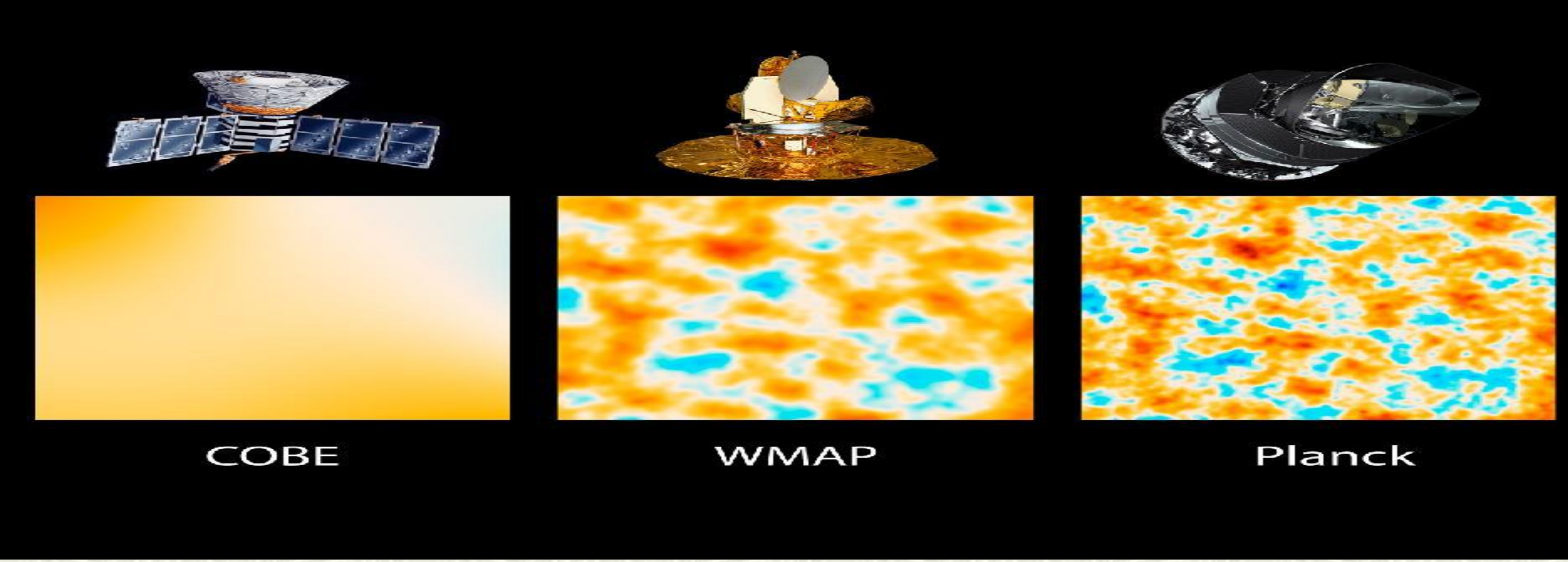
3. Gravitational lensing

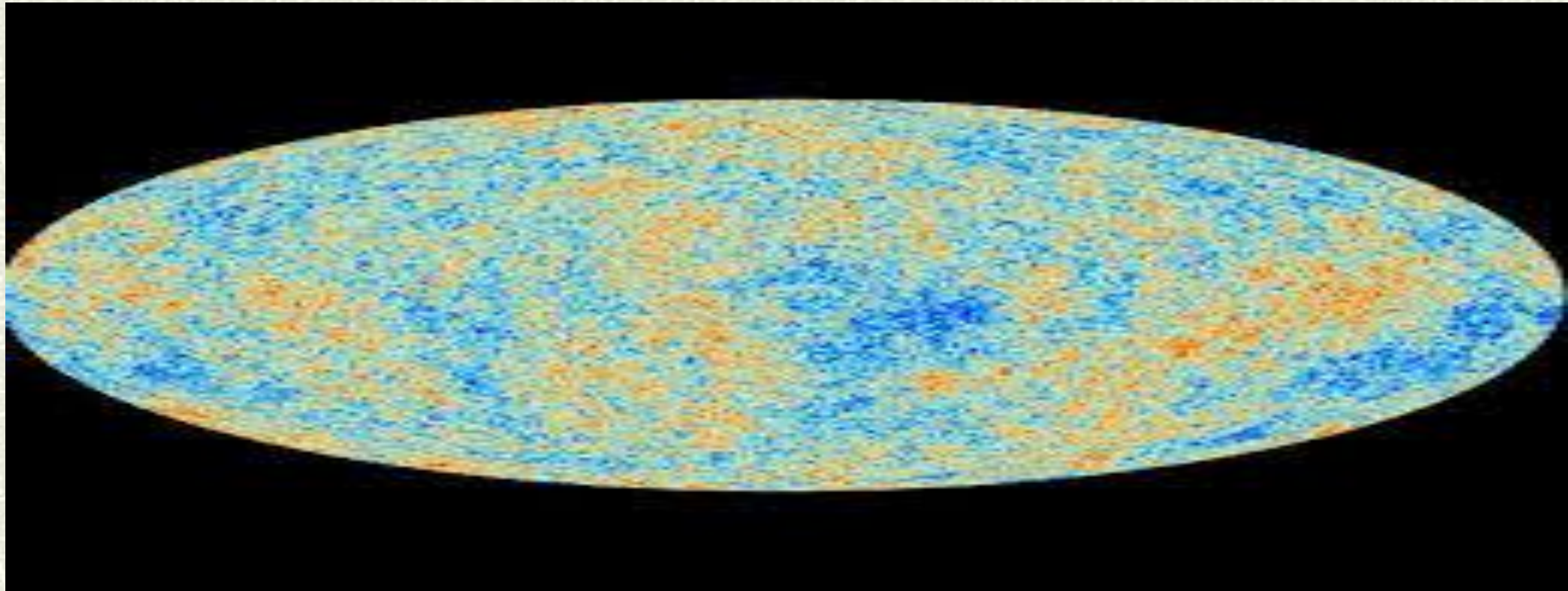
Remove degeneracies

4. Polarization measurements

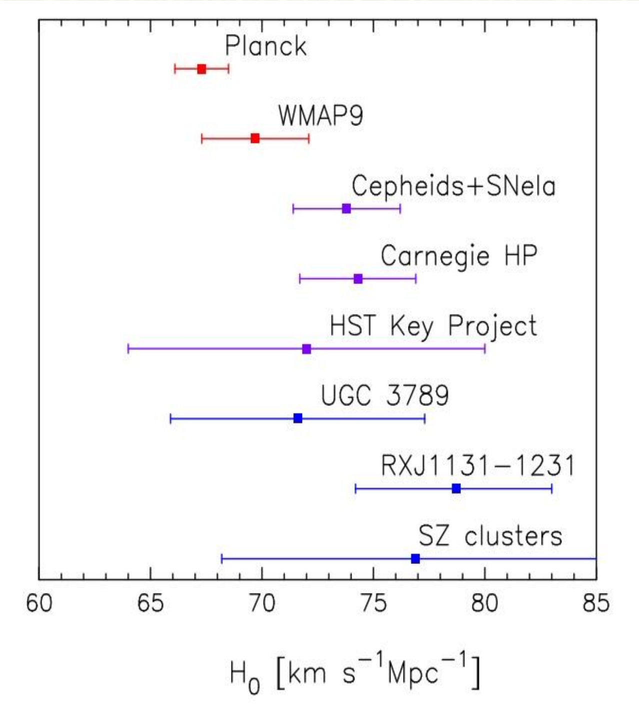
E-modes: fluctuations

B-modes: gravity waves?


COBE
WMAP
Planck



Planck results (2013)



1. New Hubble constant

67.3 +- 1.2 km/s/MPC

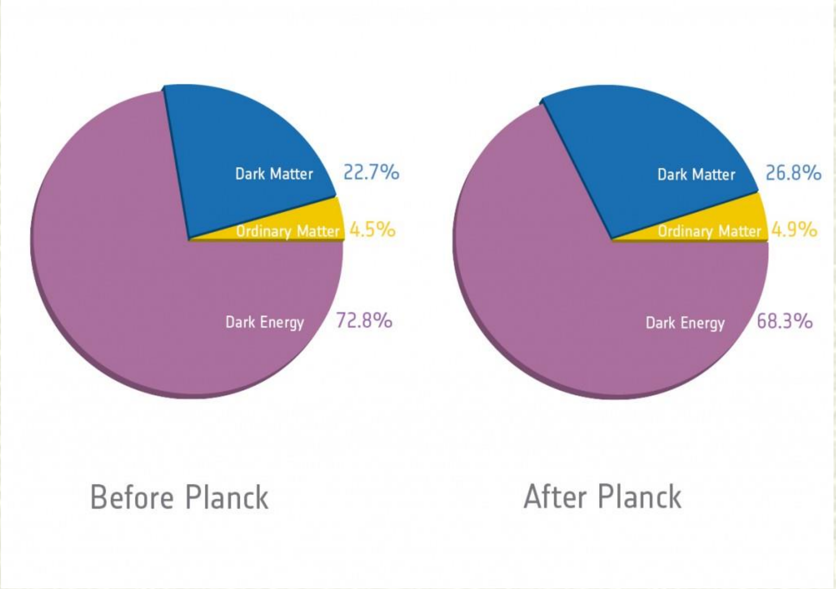
Age = 13.8 billion yr

2. Curvature ; flat

Ω_k = -0.0005 +- .07

3. New mass/energy parameters

Ω_Λ = 68, Ω_{DM} = *27*, Ω_{OM} = *4.9 %*



The big bang - problems

- Nature of dark energy?

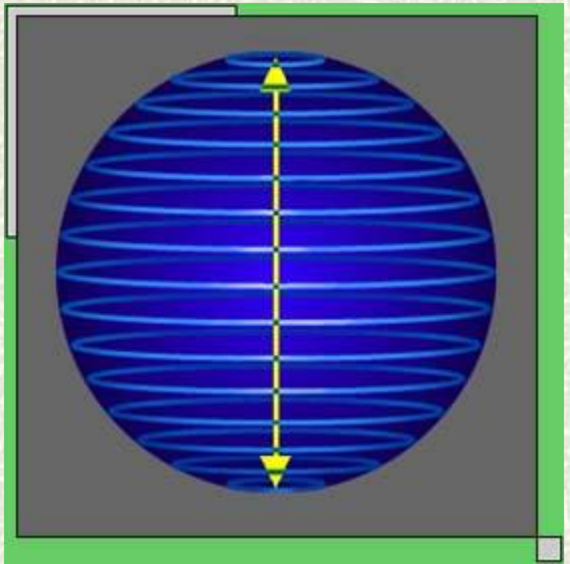
  Role in BB?

- Which model of inflation?

  The multiverse?

- The singularity problem

  What banged?
  What does time zero mean?
  No-boundary universe



The no-boundary universe

- Apply quantum physics to spacetime

  Quantum gravity

- Hawking/Hartle state (1983)

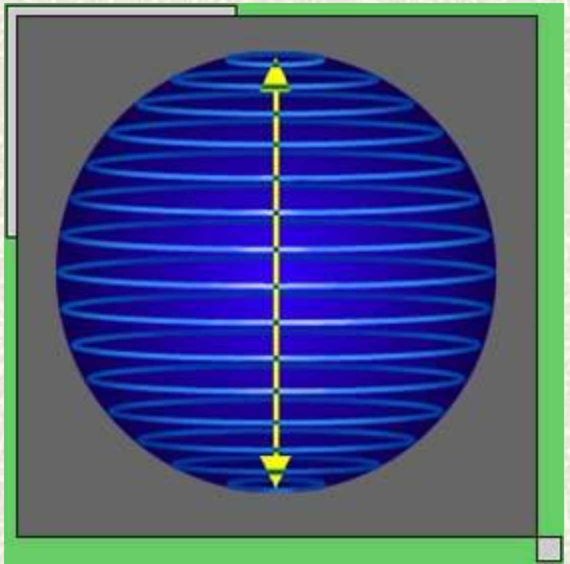
  No spacetime singularity

- No boundary in time

  Time does not exist before Planck era

  Spacetime smeared out

"What is north of the North Pole?"



The singularity: a cyclic universe?

- Breakdown at time zero
- No model of bang itself

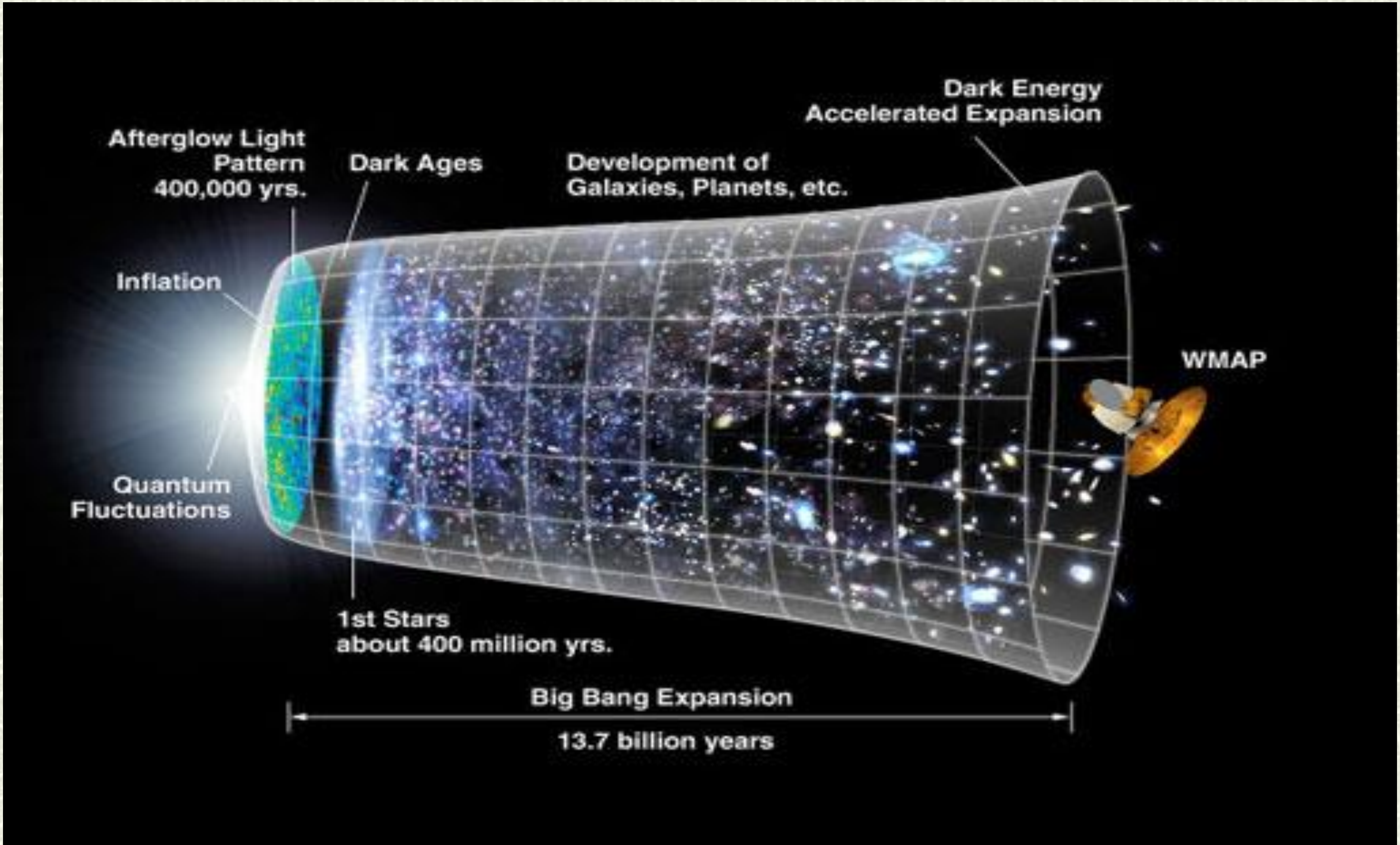
- Multiple bangs?
- Colliding branes
- Prediction of string theory

- Cyclic universe
- Eternal universe

Cyclic universe

Tests? Non-Gaussianities in CMB

The big bang model



Where next for general relativity?

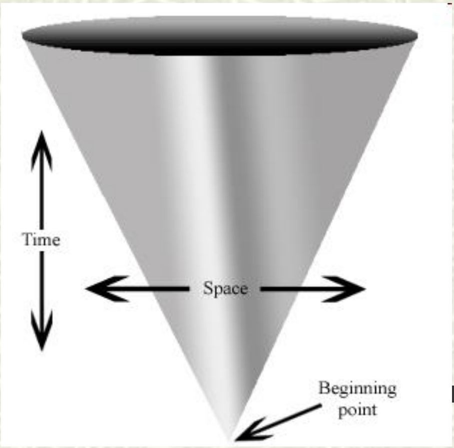
- **More general theory**
  Unified field theory; the forces of nature (Einstein)

- **Reconcile GR with quantum theory**
  Quantum gravity

- **Some progress**
  Black hole thermodynamics
  Hawking-Bekenstein radiation

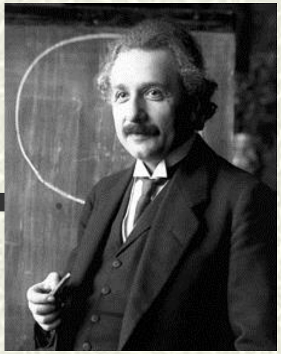
- **Quantum cosmology**
  The quantum big bang

Stephen Hawking



A universe from nothing?

Einstein's cosmology: conclusions



- **Major test for general relativity**

  Conscious of assumptions of homogeneity, isotropy

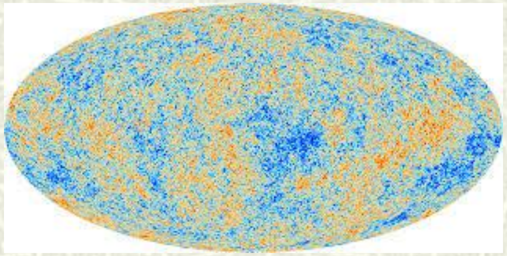
Hubble constant revised

- **Embraces dynamic cosmology**

  New evidence – new models (JMK)

  Timespan of expanding models puzzling

  Steady-state universe?



Cosmic microwave background
Homogeneous, flat universe

- **Evolving models (less contrived)**

  Cosmic constant not necessary

  Extraction of parameters compatible with observation

  Closed and open models

  Timespan problem attributed to simplifying assumptions

Verdict (1933, 1945): more observational data needed

<u>No mention of origins</u>

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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

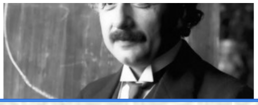
2 comments, 2 called-out + Comment Now + Follow Comments

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

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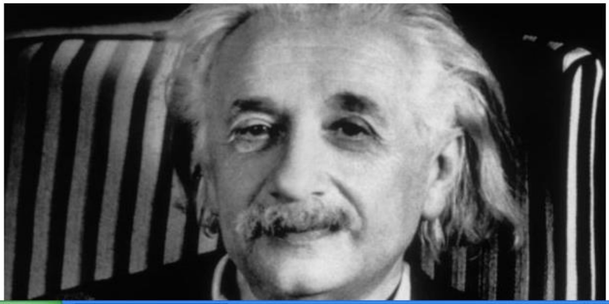
News / Science

WIT researchers discover 'lost' Einstein model of universe

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



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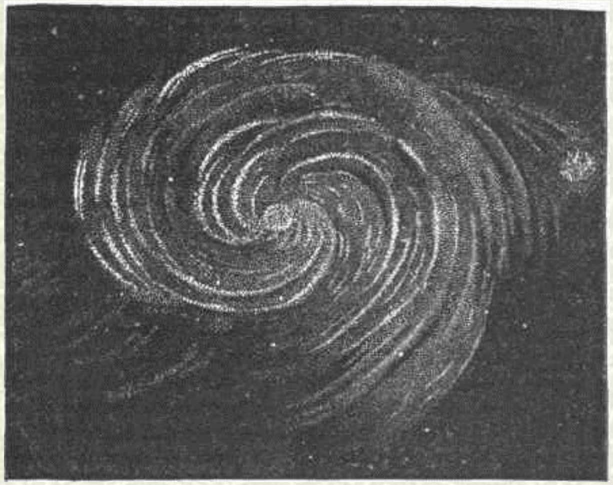
08:25 Flannery faces call from all parties to attend PAC

III Astronomy and the Universe



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

  Spiral nebulae = galaxies beyond Milky Way?

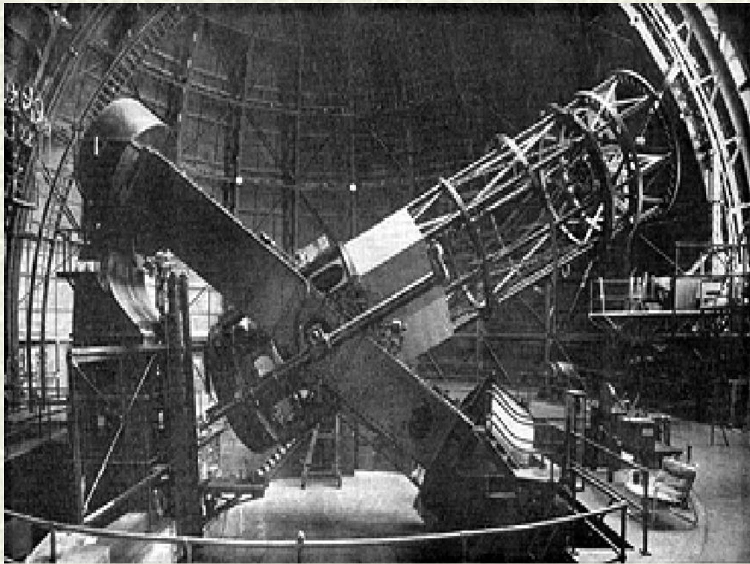
- **The Hooker telescope (1917)**

  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 runaway galaxies (1929)

Edwin Hubble (1889-1953)

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

- **Combine 24 distances with redshifts**

  Redshifts from Slipher: not acknowledged

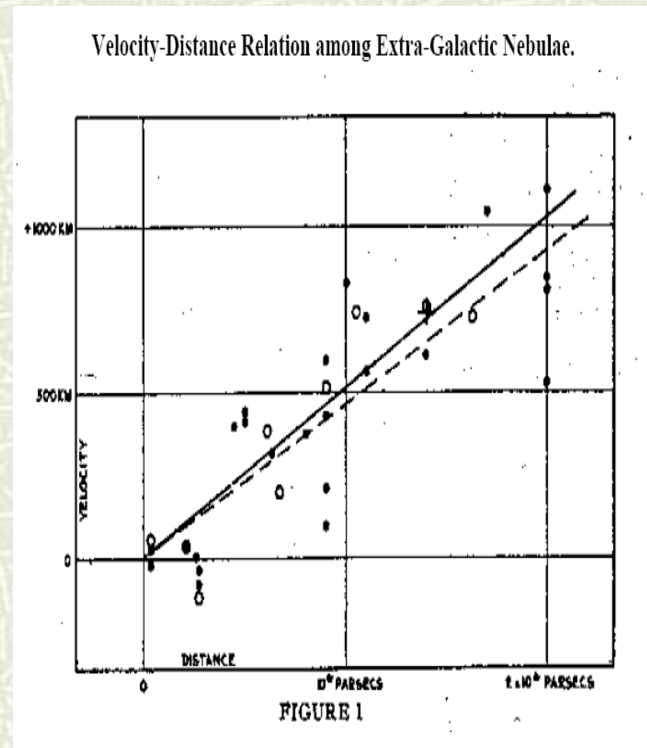
- **Linear relation: Hubble's law (1929)**

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

- **Landmark result in astronomy**

  Far-away galaxies rushing away

  at a speed proportional to distance



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

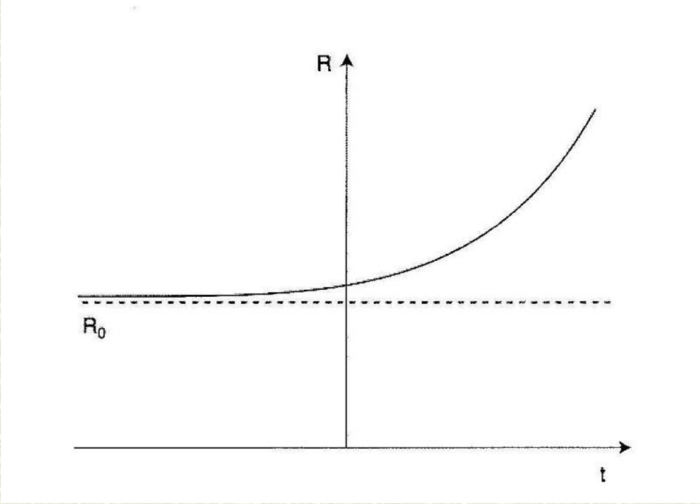
  $H = 585\ kms^{-1}Mpc^{-1}$

- **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)**

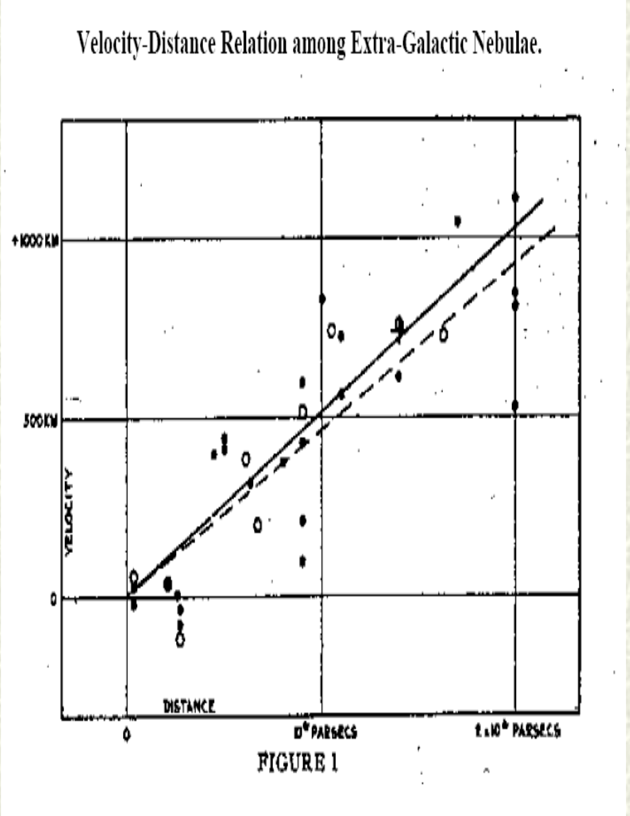
  Eddington, de Sitter
  If redshifts are velocities, and if effect is non-local
  Static cosmic models don't match observations

- **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



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

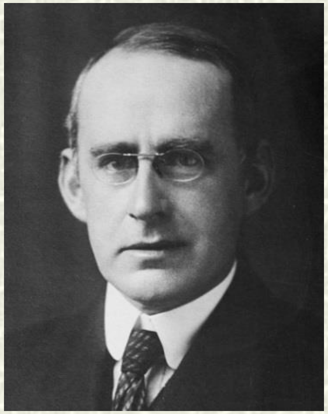
  Expanding universes of every flavour

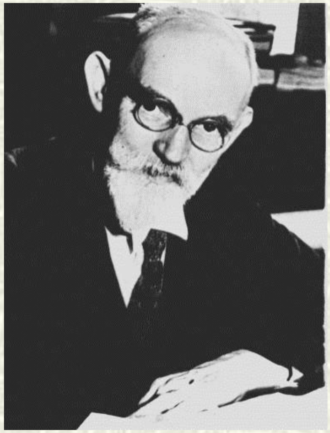
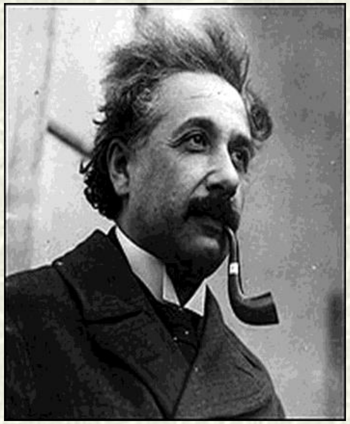
- **Einstein (1931, 32)**

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

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

Occam's razor?

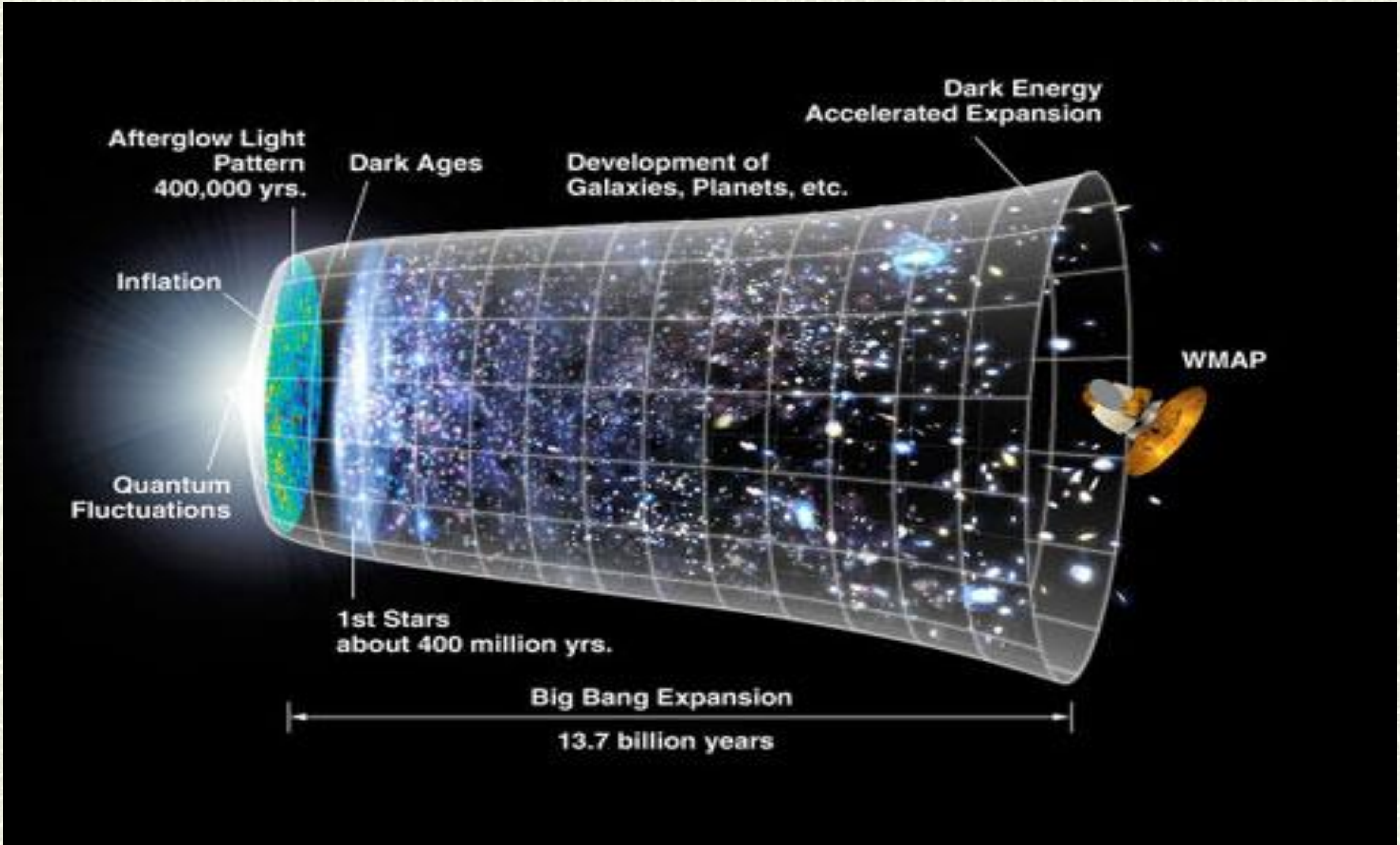


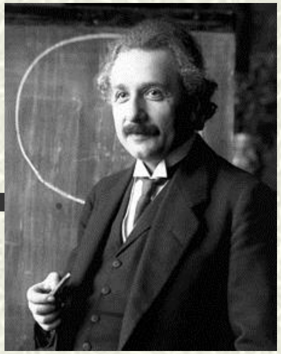
Evolving models

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

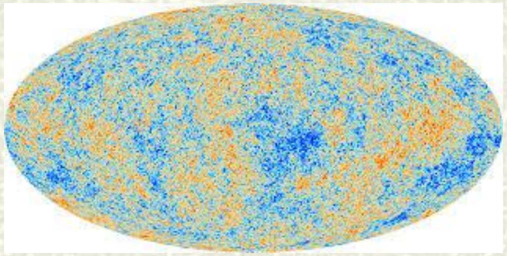
  Evolving models simpler: remove λ-term

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**

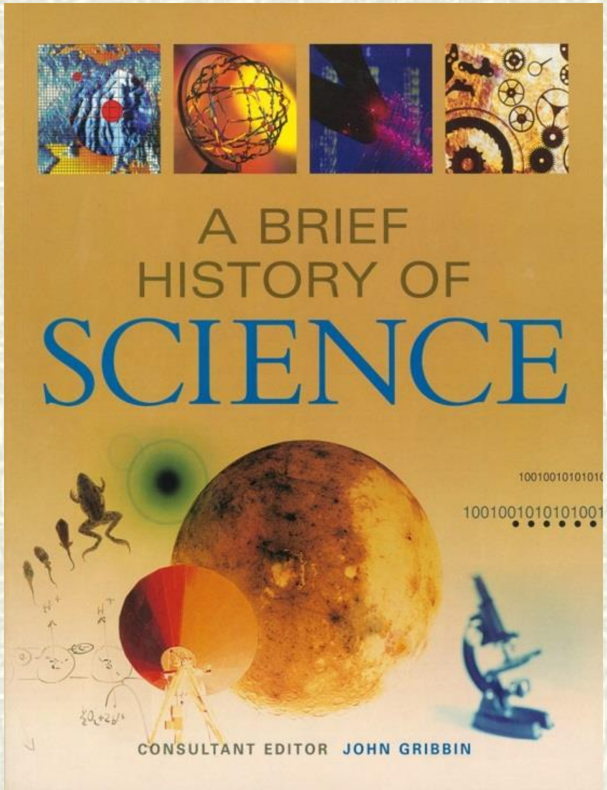
  Simple solution?

  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 ?

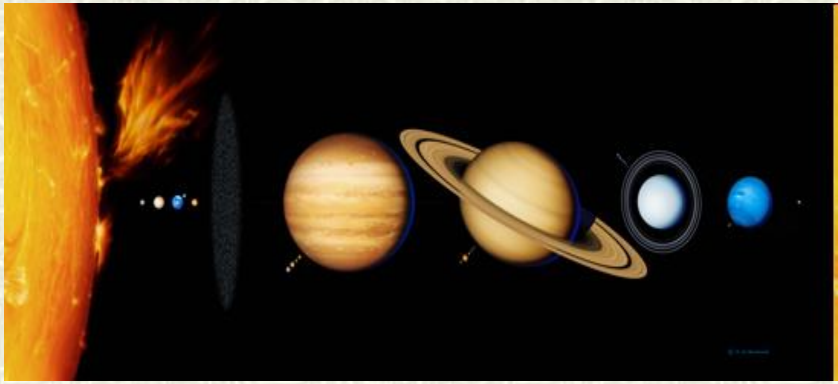
Explanation for runaway galaxies?

Isaac Newton

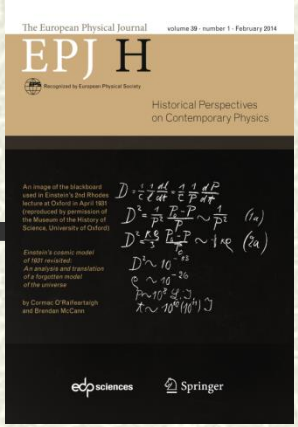
Newton

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

How can galaxies be receding?
What is pushing out?

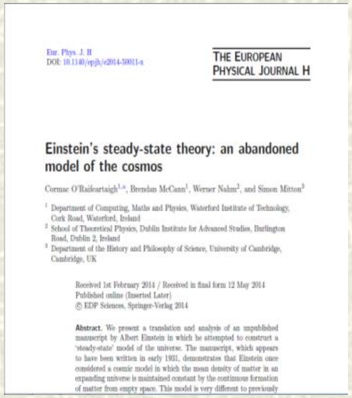


Results: publications



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**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THE EUROPEAN PHYSICAL JOURNAL H

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

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[1] Department of Computing, Maths and Physics, Waterford Institute of Technology, Cork Road, Waterford, Ireland
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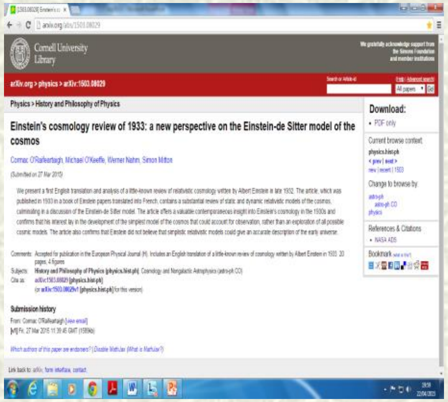
Abstract. We present a translation and analysis of an unpublished manuscript by Albert Einstein in which he attempted to construct a 'steady-state' model of the universe. The manuscript, which appears to have been written in early 1931, demonstrates that Einstein once considered a cosmic model in which 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

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

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DOI: 10.1140/epjh/e2013-40038-x

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

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EPJ H

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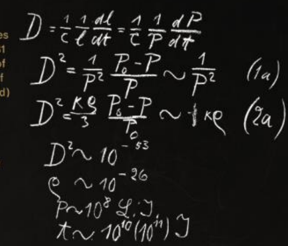
Historical Perspectives on Contemporary Physics

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



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

by Cormac O'Raifeartaigh and Brendan McCann

edp sciences Springer

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

THE EUROPEAN PHYSICAL JOURNAL H

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

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[3] Department of the History and Philosophy of Science, University of Cambridge, Cambridge, UK

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Published online (Inserted Later)

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

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arXiv.org > physics > arXiv:1503.08029

Physics > History and Philosophy of Physics

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

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

(Submitted on 27 Mar 2015)

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

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

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[v1] Fri, 27 Mar 2015 11:39:45 GMT (1589kb)

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arXiv.org > physics > arXiv:1504.02873

Physics > History and Philosophy of Physics

A new perspective on Einstein's philosophy of cosmology

Cormac O'Raifeartaigh

(Submitted on 11 Apr 2015)

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

Comments: 20 pages, 2 figures. To be published in the book 'The Philosophy of Cosmology: Foundations and Perspectives' (Cambridge University Press)
Subjects: **History and Philosophy of Physics (physics.hist-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO)
Cite as: arXiv:1504.02873 **[physics.hist-ph]**
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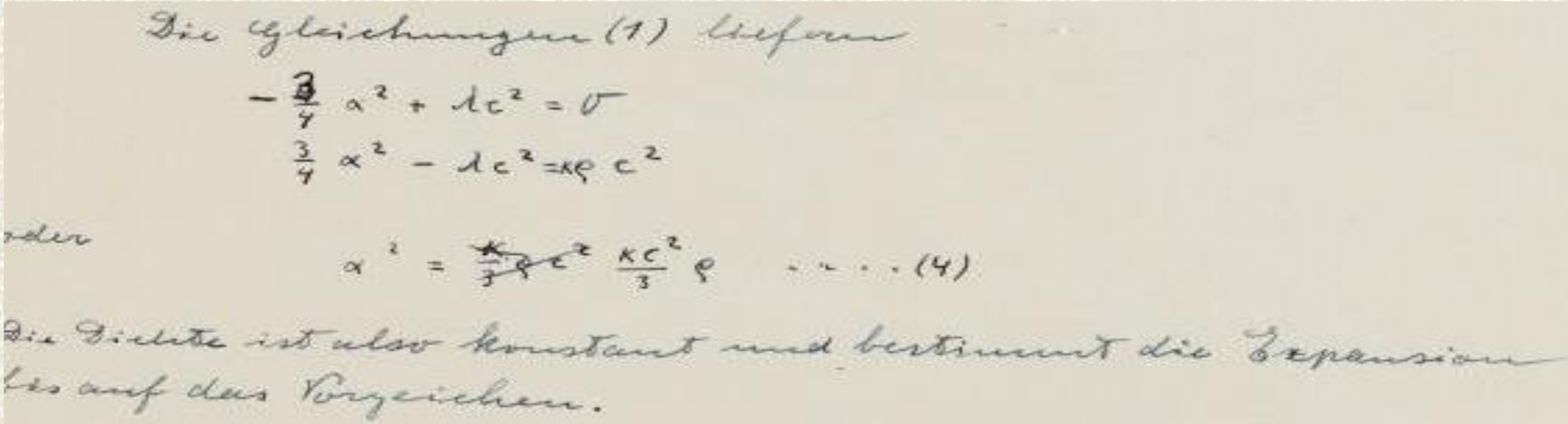
Submission history
From: Cormac O'Raifeartaigh [view email]
[v1] Sat, 11 Apr 2015 13:38:49 GMT (663kb)


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**

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

  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**

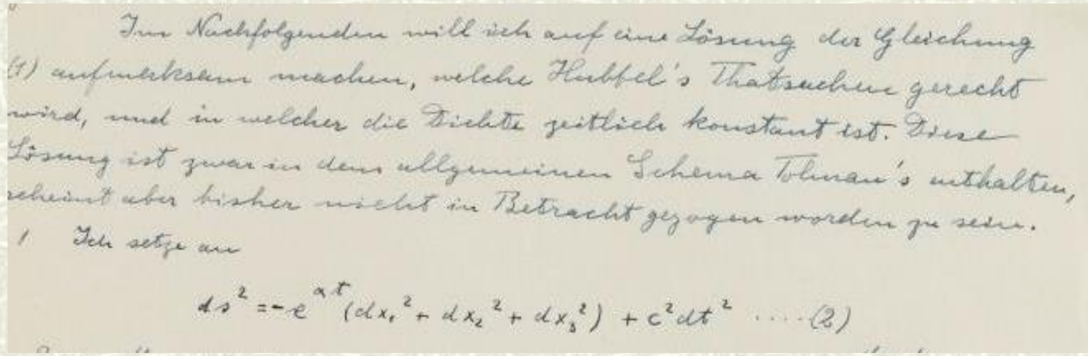
  Null solution on revision

  Tolman? (Nussbaumer 2014)

  Declined to amend GFE

- **Evolving models**

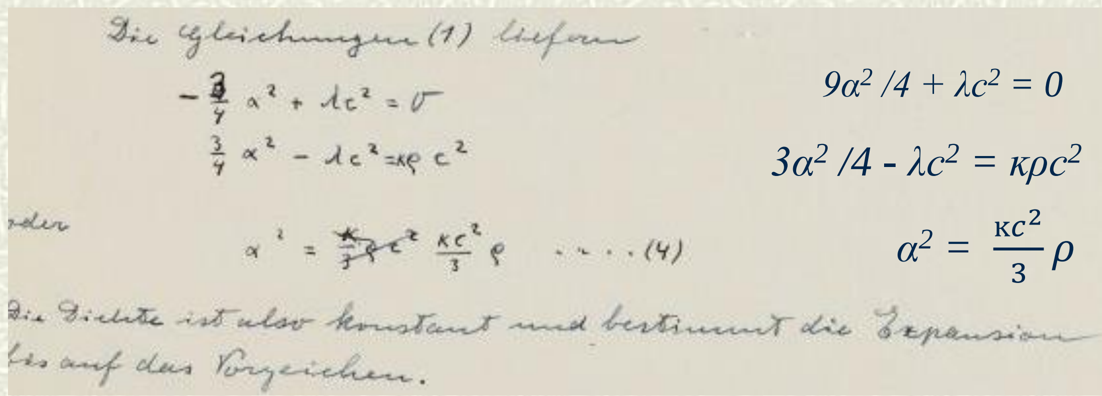
  Less contrived: set $\lambda = 0$



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

Ich setze an

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



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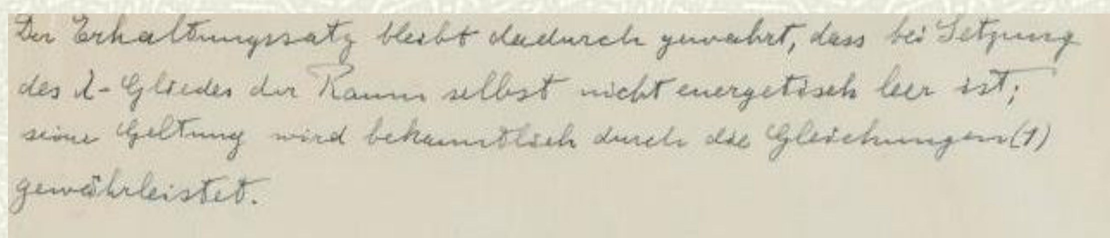
Die Dichte ist also konstant und bestimmt die Expansion bis auf das Vorzeichen.

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

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

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



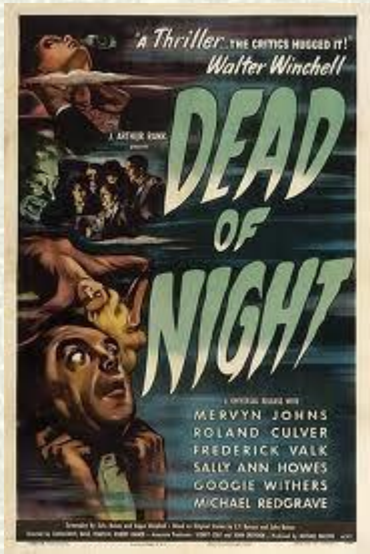
Der Erhaltungssatz bleibt dadurch gewahrt, dass bei Setzung des λ-Gliedes der Raum selbst nicht energetisch leer ist; seine Geltung wird bekanntlich durch die Gleichungen (1) gewährleistet.

Steady-state universe (1948)

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

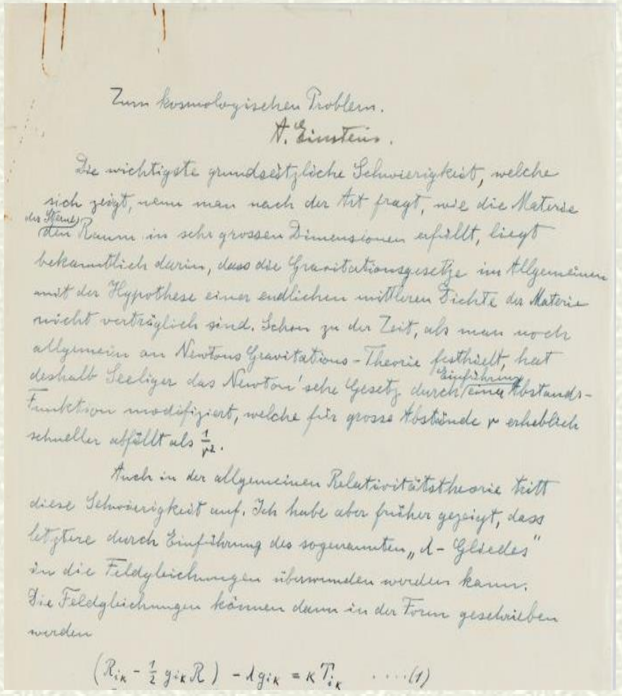
BUT

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



<u>Very little matter needed</u>

3. Einstein's steady-state model



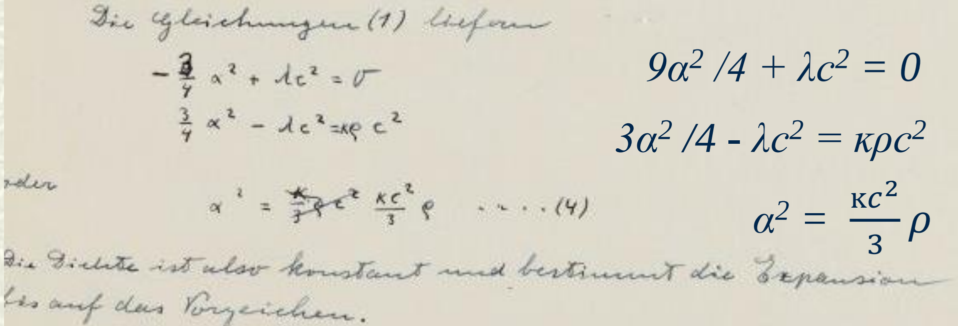
Zum kosmologischen Problem.
A. Einstein.

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

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

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

- **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*



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

NATURE | NEWS

Top

Einstein's lost theory uncovered

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

Davide Castelvecchi

24 February 2014

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.

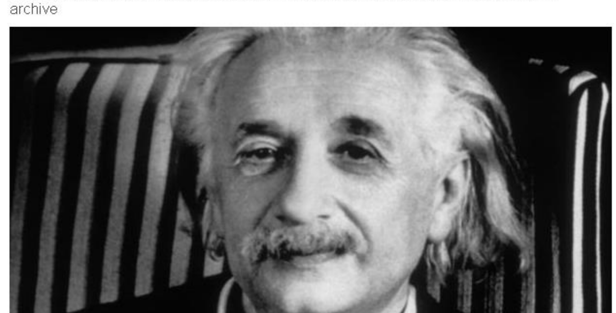
An Irish physicist came across the paper last year and could hardly believe. According to this week's article in Nature,

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



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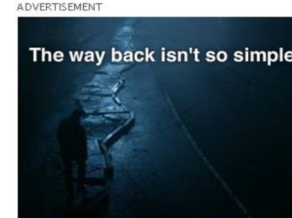
- 08:42 Gardaí investigate death of woman in Dublin
- 08:25 Flannery faces call from all parties to attend PAC

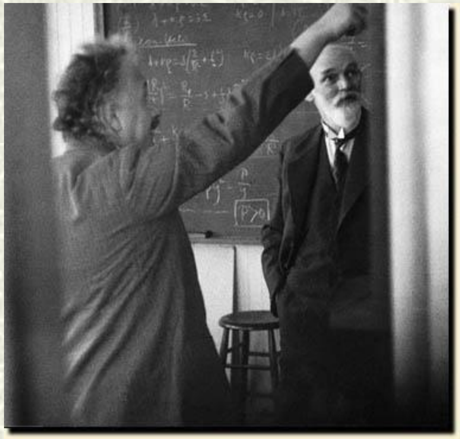


2. Einstein-de Sitter model (1932)

- **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 $\lambda = 0$, $k = 0$, $p = 0$

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

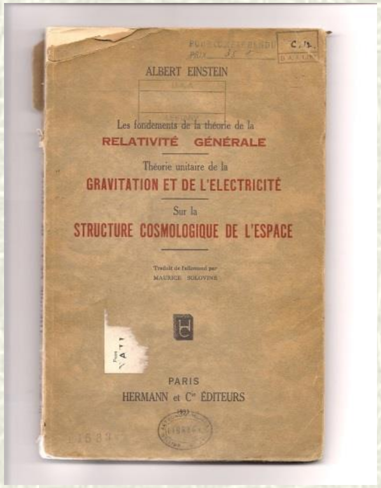
$$\frac{1}{R^2}\left(\frac{dR}{cdt}\right)^2 = \frac{1}{3}\kappa\rho.$$

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

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

  Despite high density of matter, age problem

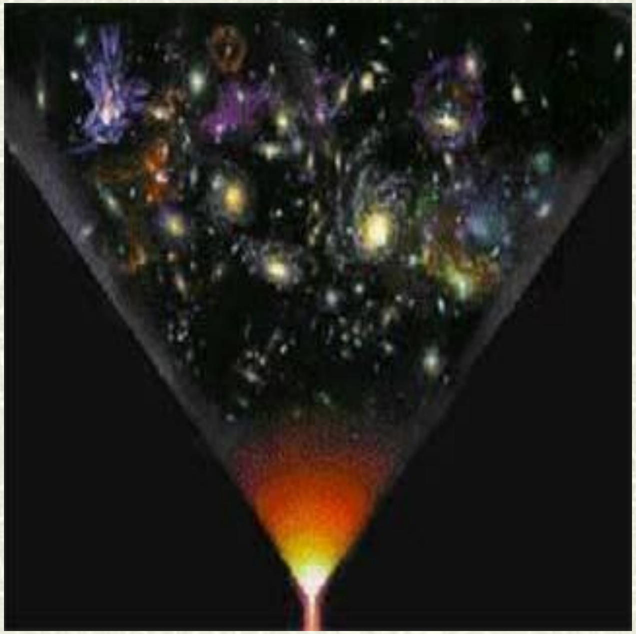
  Time evolution not considered



- **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

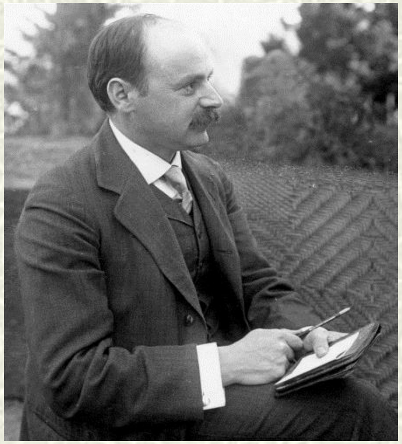
∞ density, ∞ temp at $t = 0$?

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**

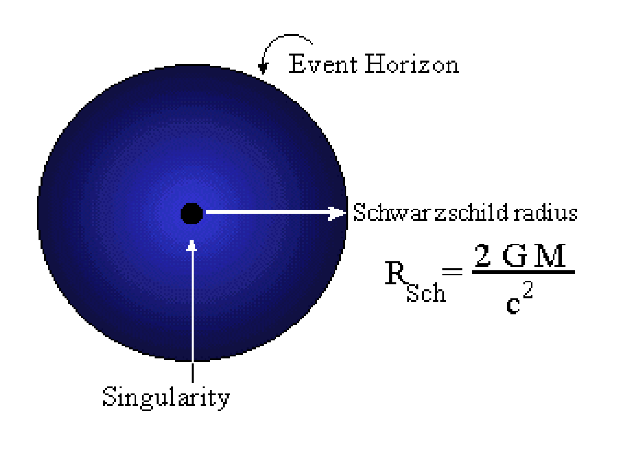
  Co-ordinate problem (Eddington)

  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

- **<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

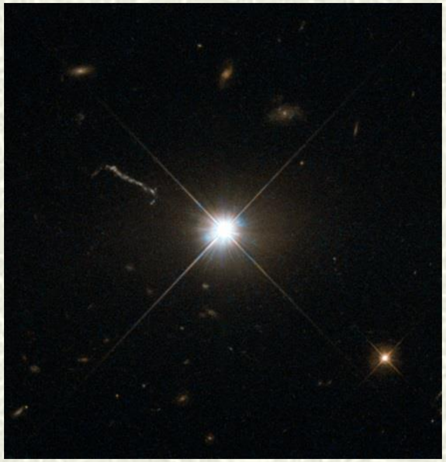
- **Orbit studies**

  Supermassive BH at centre of MW? (1990s)

  Supermassive BH at centre of many galaxies (2000-)

- **2015-16**

  Gravitational waves from binary BH system!



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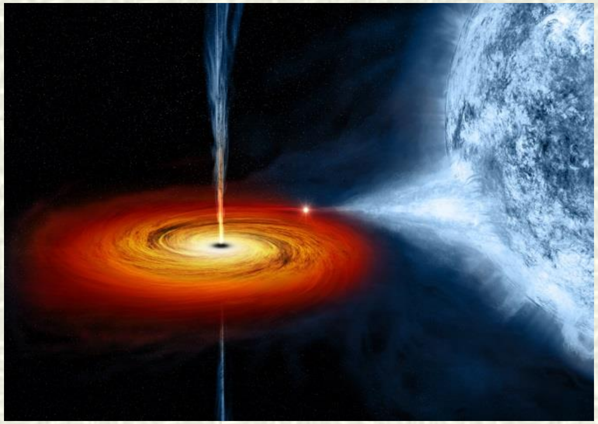


Cygnus X-1 (1964)

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**

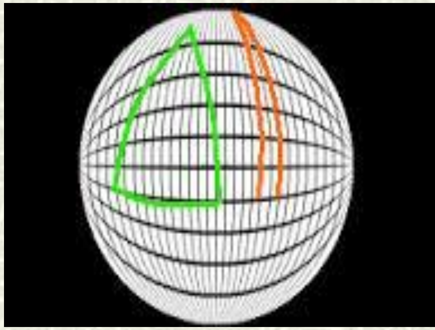
  Uniform, static distribution of matter

  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

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

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)**

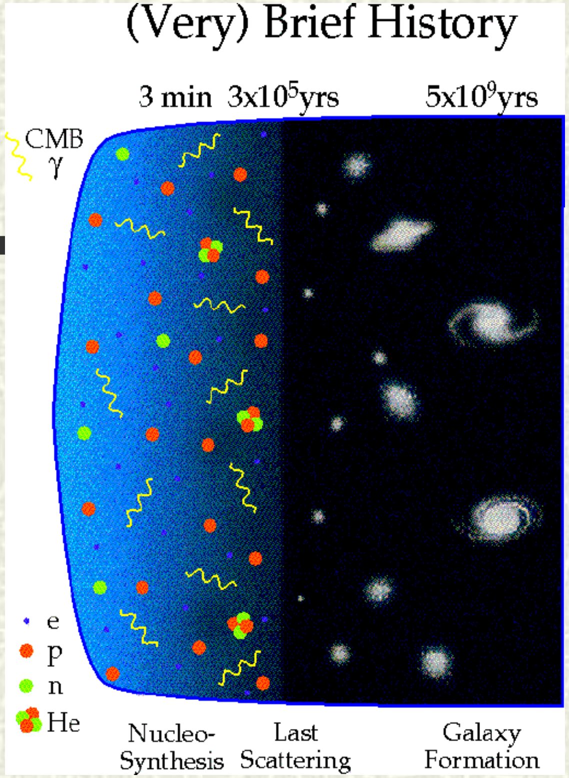
  Observation of accelerated expansion

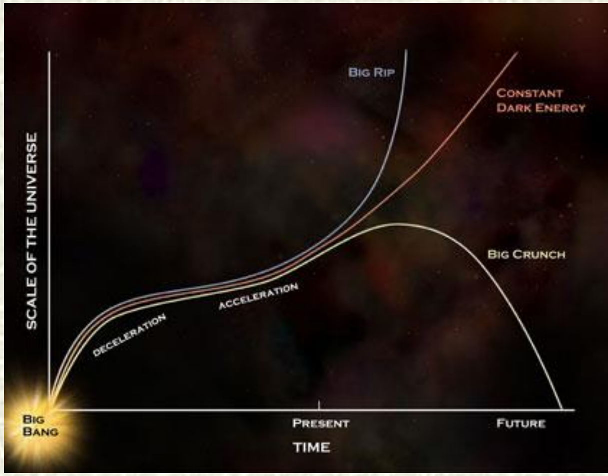
  The return of the cosmological constant

  Problems of interpretation

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

Nature of DE unknown





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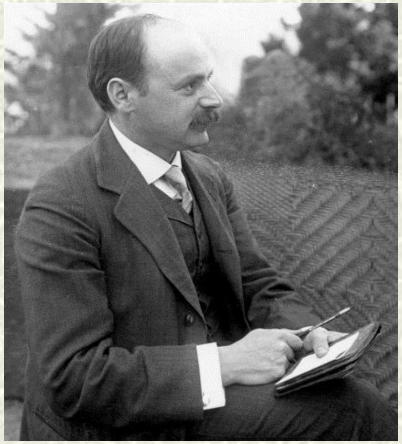

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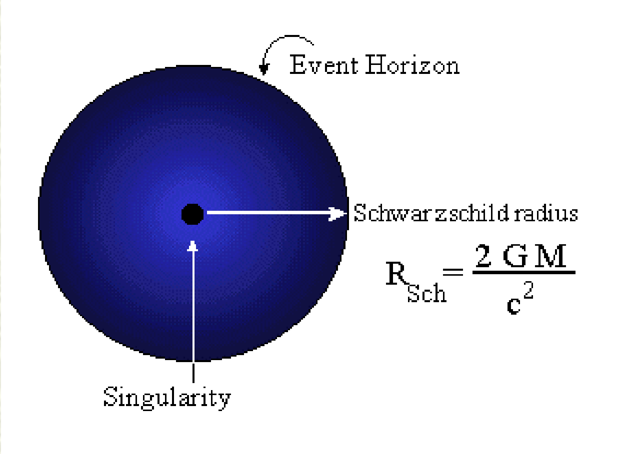

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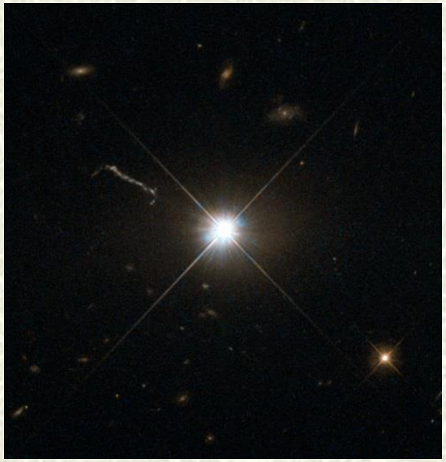

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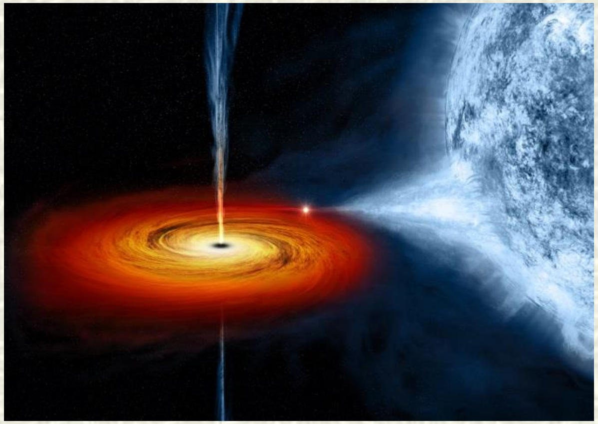


Cygnus X-1 (1964)

Three astronomical tests (Einstein, 1916)

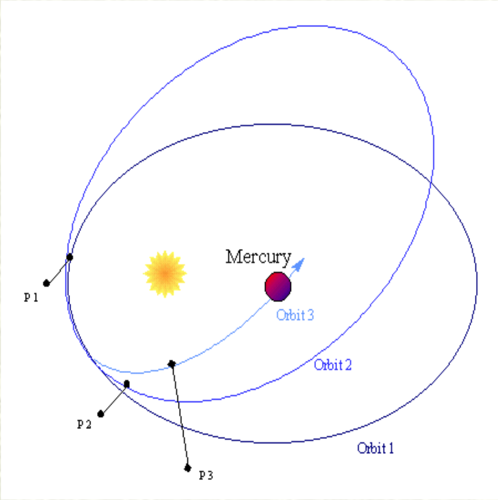
- **Different in principle from Newton's gravity**

  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")

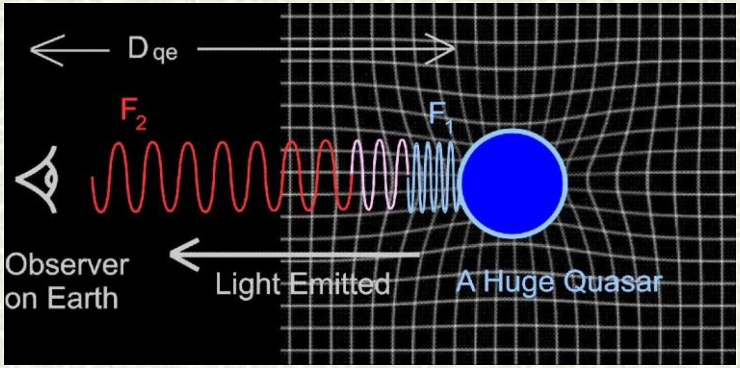
  Eclipse expeditions of Eddington and Dyson (1919)

  Successful measurement (large error margin)

- **Gravitational redshift**

  Time dilation in strong gravitational field

  Light from a star redshifted by stellar mass?



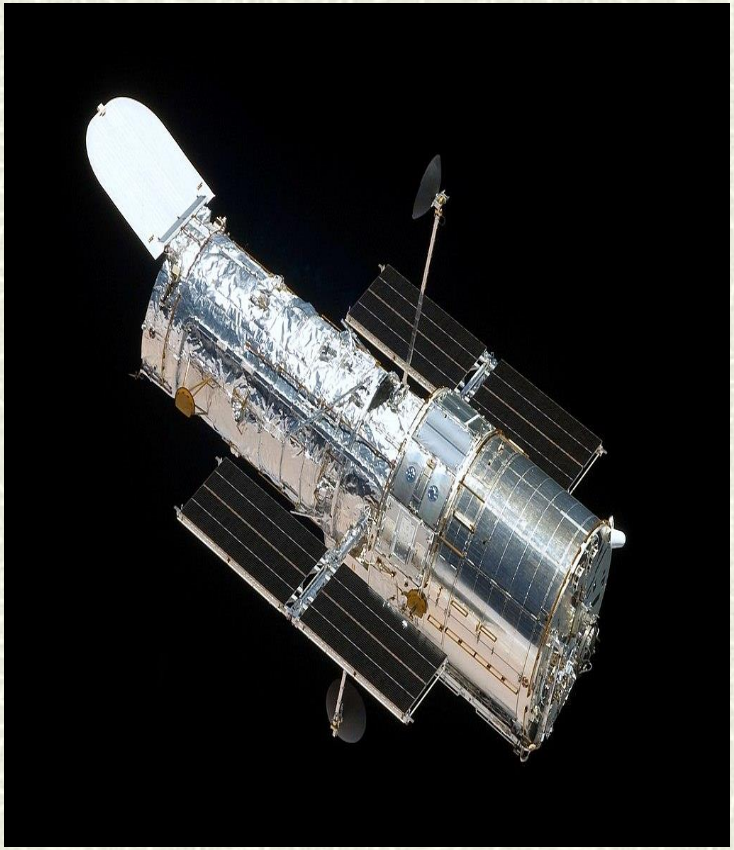
Problems with standard model (1980-1998)

- Einstein-de Sitter: $\lambda = 0, k = 0$
- Flatness prediction (Dicke, inflation)

  $k = 0$
- But: $\Omega_M = 0.3$
- But: new timescale problem from HST

  $H = 87\ kms^{-1}\ Mpc^{-1} : t = 11.2 \times 10^9\ yr$

  too young



Hubble Space Telescope
1990

Is model wrong? Is $\lambda \neq 0$?