Einstein, the expanding universe and the big bang

Paradigm shift or slow dawning?

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A drama in three acts?

- **A brief history of observation (1912-1931)**

  The redshifts of the spiral nebulae (Slipher)

  The distances to the nebulae (Hubble)

  The Hubble graph of 1929

- **A brief history of theory (1915-1931)**

  The static universes of Einstein and de Sitter

  The dynamic universes of Friedman and Lemaître

- **An expanding universe? (1930)**

  Explorations of a dynamic universe (1922-35)

  Slow acceptance by physics community (1935-65)

Many other actors

- **A slow dawning?** *Acts IV and V*

Act I, scene I: The starry nebulae

- **Observed by Marius (1614), Halley, Messier**
  Cloudy structures; not planets or stars

- **Island universes? Kant, Laplace (1755-96)**
  Galaxies of stars at immense distance?
  Are stars born in the nebulae?

- **Wilhem Herschel**
  36-inch reflecting telescope
  Catalogue of a thousand (1786)

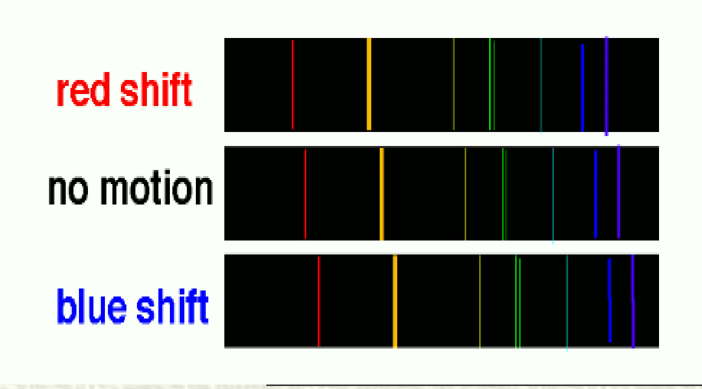
- **Earl of Rosse**
  72-inch reflecting telescope (1845)
  Some nebulae have spiral structure, stars

Problem of resolution, <u>distance</u>

Scene II: The spectra of the nebulae

- **Photography and spectroscopy (19th cent)**
  Emission and absorption lines of celestial objects
- **Composition of the stars and planetary nebulae**
  William Huggins
- **Motion of the stars: Doppler effect**
  William Campbell

$\Delta\lambda/\lambda = v/c$



- **Spectroscopy of spiral nebulae?**
  Composition of nebulae?
  Motion of nebulae?
- **Difficult to resolve**

Scene III: Slipher and the nebulae

V.M. Slipher

- **Analyse light of the spiral nebulae? (1909)**
  Lowell Observatory; evolving solar system?
- **Slipher reluctant**
  24-inch refractor: larger telescopes failed
- **Experiments with spectrograph camera**
  Good results with fast camera lens
- **Clear spectrum for Andromeda nebula (1912)**
  Significantly blue-shifted; approaching at 300 km/s?
- **Many spiral nebulae red-shifted (1915)**
  Standing ovation (AAS, 1914)
  Attended by Hubble

Redshifts of the nebulae

- **Spectra of 25 spirals (1917)**
  Large outward velocities
  Some receding at 1000 km/s

- **Much faster than stars**
  Gravitationally bound by MW?

- **Island universe debate**
  "Island universe hypothesis gains favour"

- **Faintest spectra most redshifted**
  Evidence of expansion? (retrospective)

- **41 redshifts by 1922**
  Published by Eddington, Strömberg
  What did they mean?

$\Delta\lambda/\lambda = v/c$

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

Act II, Scene I: General relativity

- **Space+time = space-time**

  Spacetime dynamic (1905)

- **Spacetime distorted by mass**

  Distortion causes other mass to move *(1915)*

Albert Einstein

<u>Gravity = curvature of space-time</u>

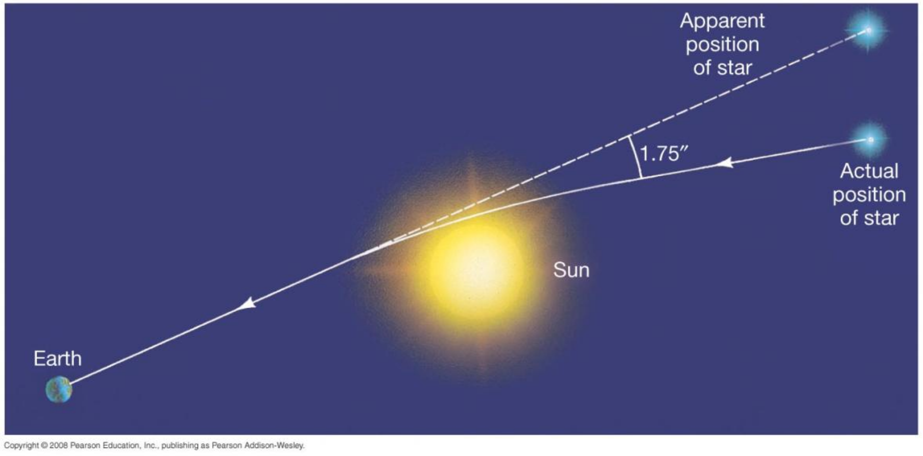
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- **Dyson/Eddington expeditions (1919)**

  Measure bending of light?

  Successful result

  General relativity well-known



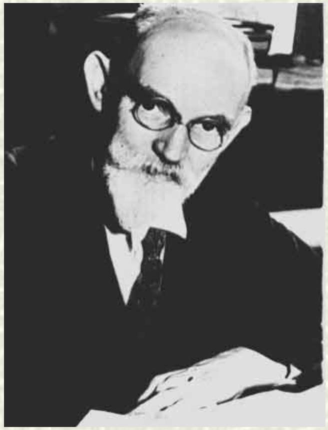
Scene II: Relativity and the cosmos

Einstein model (1917)

- Homogenous fluid of uniform density
- Equations predict dynamic universe
- No evidence for such a universe
- Add cosmic constant – 'static'
- Closed curvature, finite radius

$$\boldsymbol{G}_{\mu\nu} + \lambda g_{\mu\nu} = \frac{8\pi G}{c^4} \boldsymbol{T}_{\mu\nu}$$

De Sitter (1917)



- 'Empty' universe
- Apparently static (co-ordinate system)
- Cosmic constant determined by curvature of space
- Redshifts due to time dilation/matter

Disliked by Einstein: Mach's principle

Scene III: Redshifts and the deS universe

- **Karl Wirtz** (1922,24)

  Redshifts of nebulae increasing with distance

  Dispersal effect? $v = 2200 - 1200 \log (Dm)$

- **Ludwik Silberstein** (1924)

  Relation between redshifts, distance, curvature

  $\Delta\lambda/\lambda = +/- \; r/R$ *(global clusters)*

- **Knut Lundmark** (1924,25)

  Velocity against distance; clusters, nebulae

- **Gustav Strömberg** (1925)

  Vel/dist relation for globular clusters, nebulae?

Scene IV: Friedmann models

Alexander Friedman 1888 -1925

- **Allow time-varying solutions to the field equations**

  Allow cosmic constant

  Expanding, contracting universes

- **Geometry, evolution depends on matter**

  Positive curvature (1922)

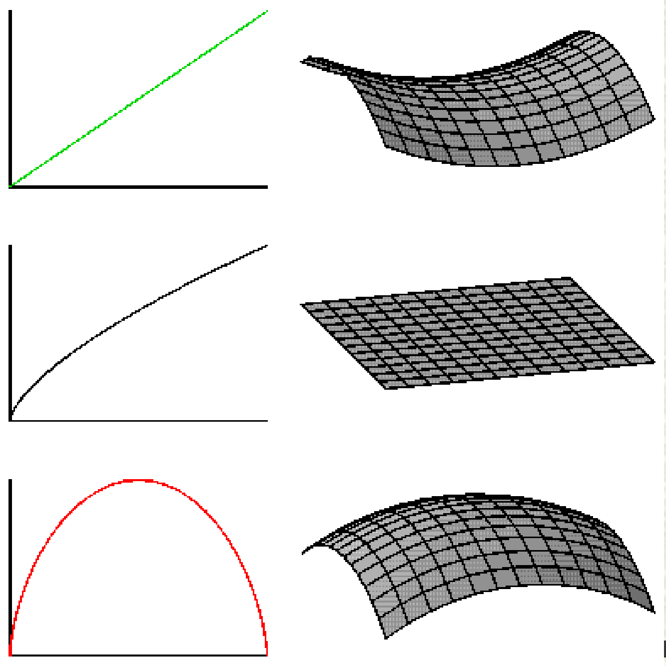
  Hyperbolic curvature (1924)

- **Hypothetical models (Zf. Ph.)**

  To be decided by astronomy

- **Disliked by Einstein**

  Correction and retraction



Ignored by community

Scene V: The distances of the nebulae (1925)

- **Hooker telescope (Mt Wilson)**

  100-inch reflector (1917)

- **Edwin Hubble (1921)**

  Ambitious and dedicated astronomer

- **Resolved Cepheid stars in nebulae (1925)**

  Leavitt's period-luminosity relation

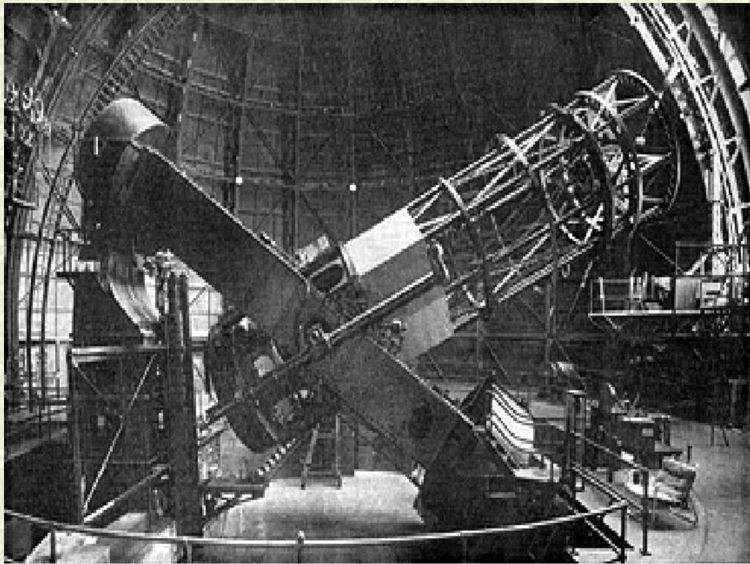
  Standard candle

- **Spirals beyond Milky Way**

  Beginning of end of 'Great Debate'

  Nebulae = galaxies

Edwin Hubble (1889-1953)



Scene VI: A redshift/distance relation (1929)

- **Is there a redshift/distance relation for <u>galaxies</u>?**

  <u>Motivation:</u> establishing distance to the galaxies

- **Combine 24 nebular distances with redshifts**

  Redshifts from Slipher : not acknowleged

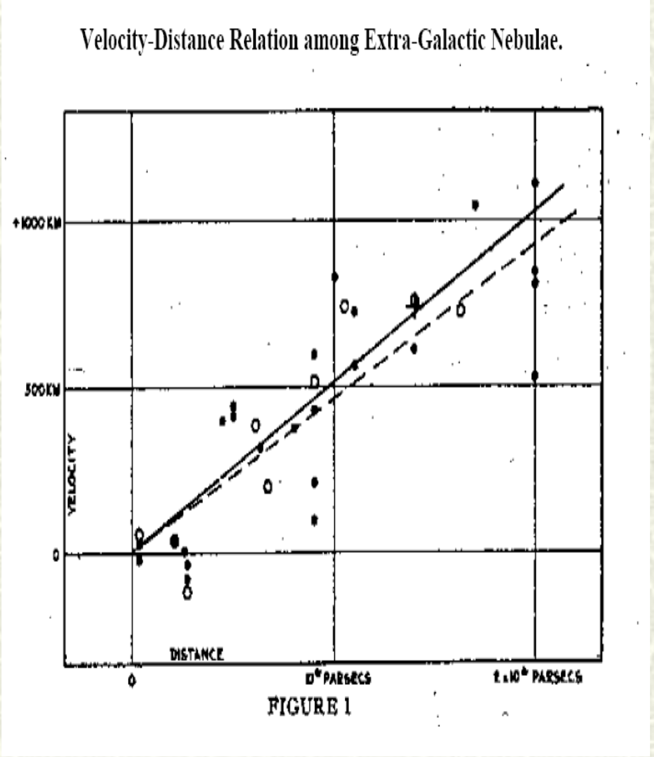
- **Approx linear relation (Hubble, 1929)**

  Some errors (Peacock)

  <u>Most important point not shown</u>

- **What do the redshifts mean?**

  Reference to de Sitter universe



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

Act III   An expanding universe? (1930-)

- **RAS meeting (1930)**

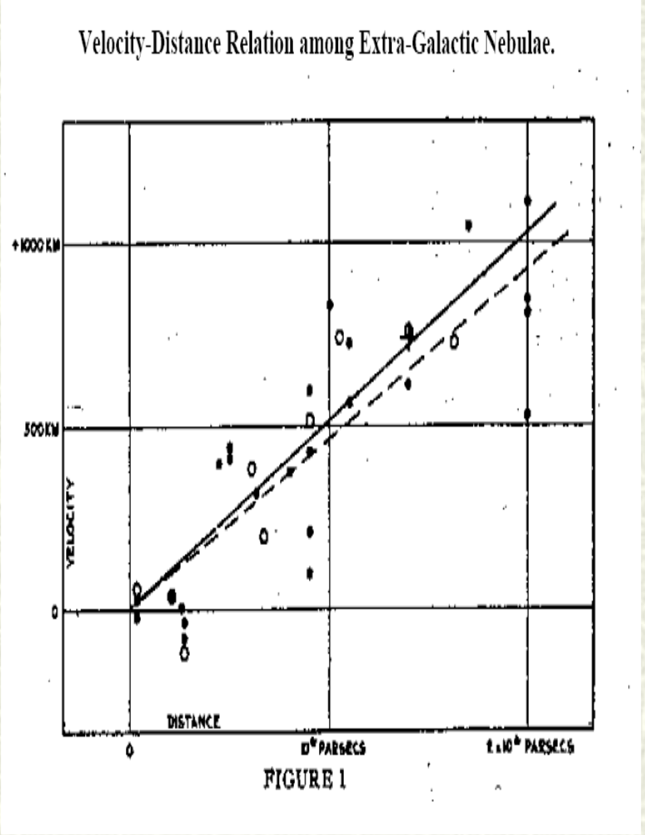
  Eddington, de Sitter
  Redshift/distance relation of the nebulae
  Static models don't fit
  New model required

- **Letter from Lemaître**

  Reminds Eddington of his 1927 model
  Eddington, de Sitter impressed

- **Expansion of space-time metric?**

  Considered by many theoreticians
  If redshifts are velocities (Zwicky)
  If effect is non-local
  Not accepted by astronomers (Hubble)



Cosmic expansion?

Scene 1: Lemaître's universe (1927)

Fr Georges Lemaître

- **Matter-filled *U* of expanding radius**

  de Sitter model not static (1925)

  New evolving solution : Einstein → de Sitter

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

  Rate of expansion from ave. distance and redshift

  H = 585 km/s/Mpc

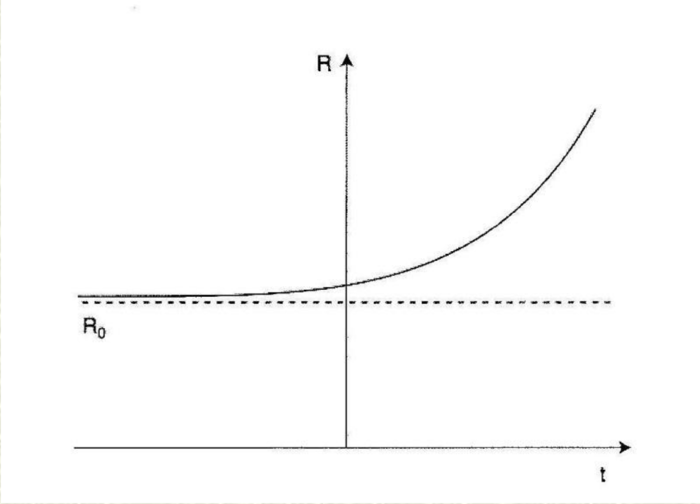
Not an empirical law
Edited in 1931 translation

- **No beginning: indefinite age**

  Starts from Einstein universe at t = - ∞

- **Rejected by Einstein**

  An idea whose time had not yet come



Scene II: Dynamic cosmic models (1931,32)

- **Eddington (1930, 31)**

  On the instability of the Einstein universe
  The Eddington-Lemaître model
  Expansion caused by condensation?

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

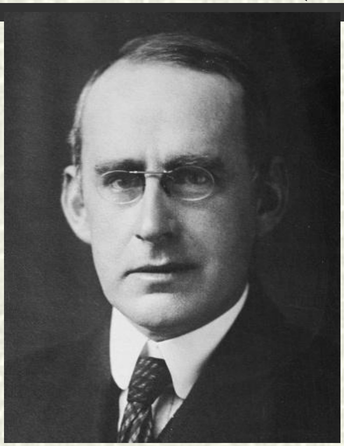
  Further remarks on the expanding universe
  Expanding universes of every flavour

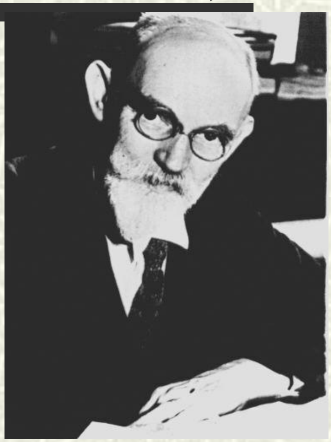
- **Tolman (1930, 31)**

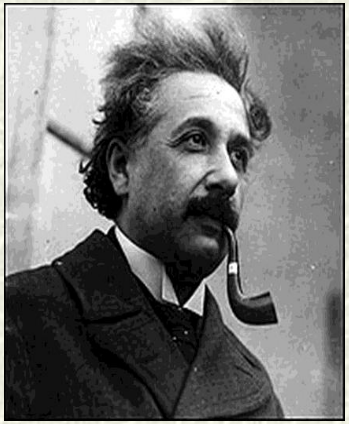
  On the behaviour of non-static models
  Expansion caused by annihilation of matter ?

- **Einstein (1931, 32)**

  Friedmann-Einstein model $\lambda = 0, k = 1$
  Einstein-deSitter model $\lambda = 0, k = 0$

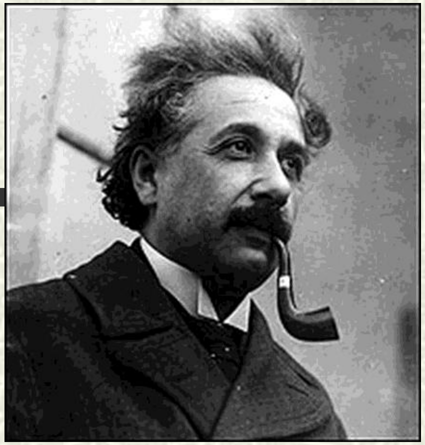






If redshifts represent velocities…
If effect is non-local ….

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



- **Instability of static universe**

  Eddington's paper

- **Hubble's observations**

  Expanding cosmos

  Remove cosmic constant?

- **Adopt Friedmann 1922 analysis**

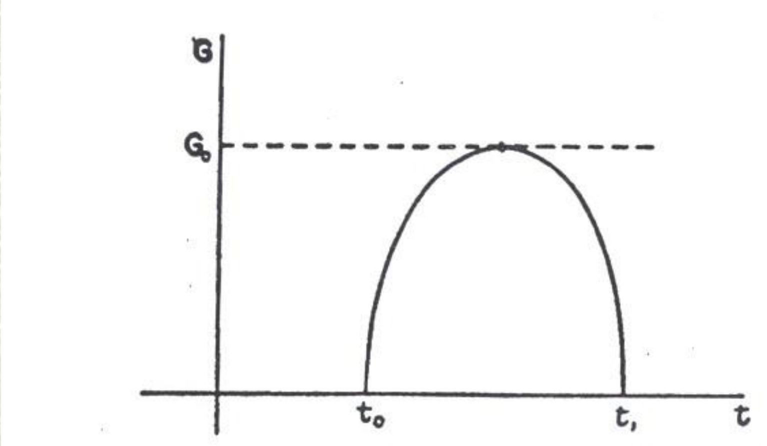
  Time-varying universe, k =1, λ = 0

- **Age and singularity problems**

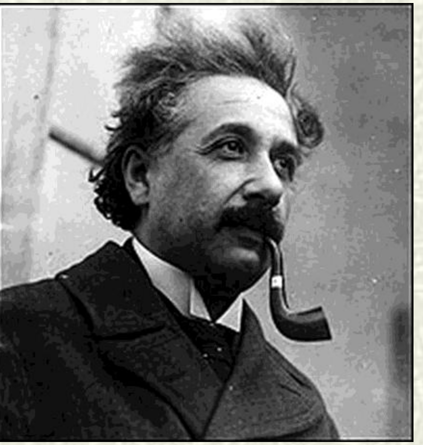
  Attributes to limitations of theory

Friedmann-Einstein universe

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



Einstein's 1931 model (F-E)



- **Numerical estimates of radius and density**

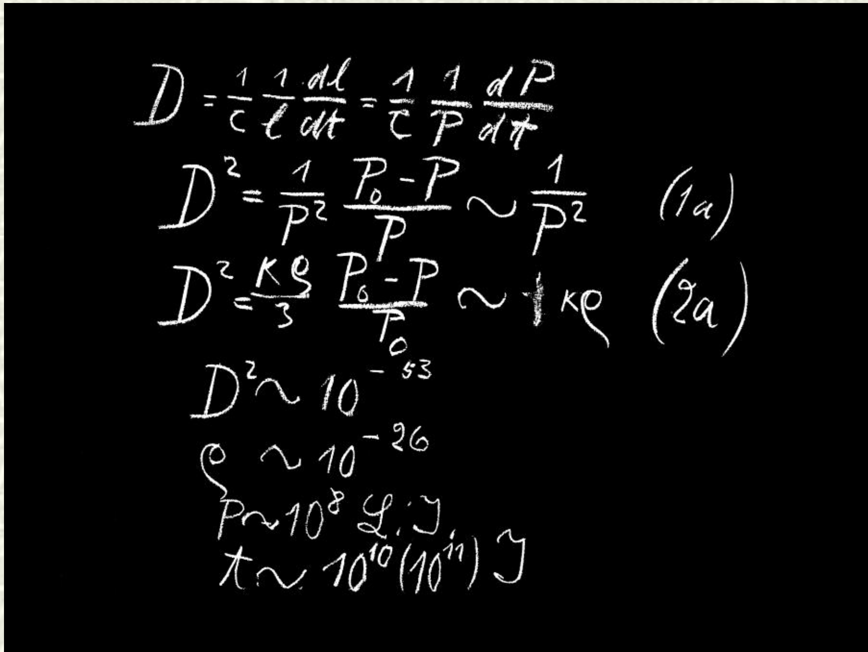
  Use Hubble parameter

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

Oxford lecture (May 1931)

- **Calculations problematic**

  $H_0 \sim 500\ kms^{-1}Mpc^{-1}$: $D^2 \sim 10^{-55}$ cm^{-2}



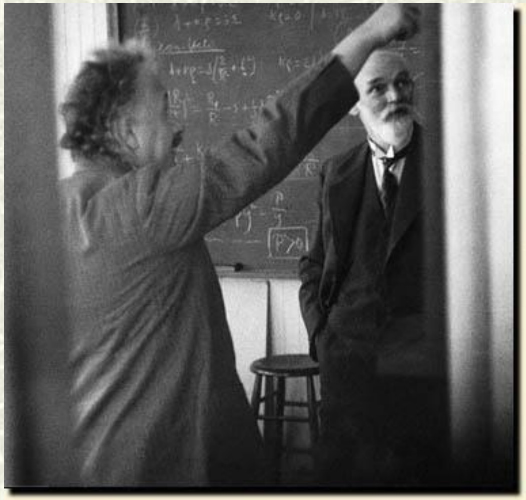
- **Age estimate problematic**

  Age from Friedmann

- **<u>Not a periodic solution</u>**

  "Model fails at P = 0 "

Einstein-deSitter model (1932)



- **Remove curvature**

  Not known (Occam's razor)

- **Adopt Friedmann analysis**

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

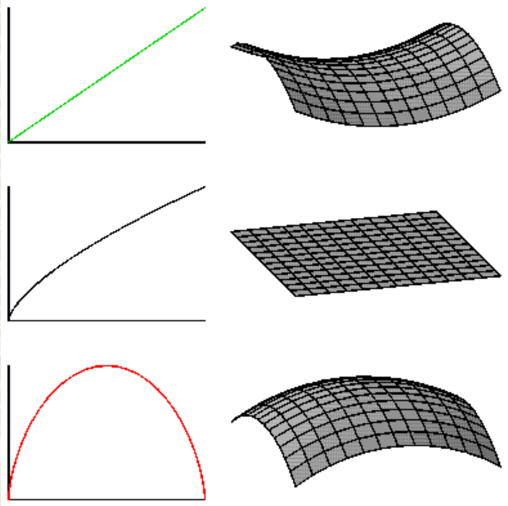
  Critical universe

- **Calculate critical density**

  10^{-28} *g/cm*^{3} : *agrees with astrophysics*

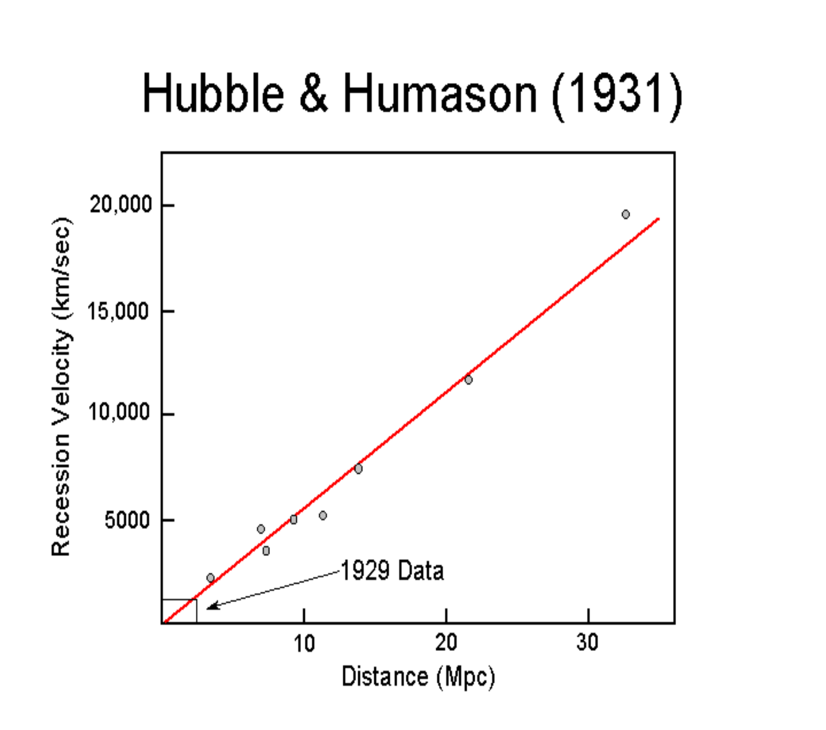
- **<u>Well-known model</u>**

  Despite age problem



Models: observational parameters needed

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



What do redshifts represent?
Is expansion a local effect?

Hubble and Tolman 1935

The formation of galaxies

- **Growth in static medium**

  Natural fluctuations in density

  Exponential growth by gravitational collapse

  $$\lambda_j = c_s/(G\rho_0/\pi)^{1/2}$$

James Jeans

- **Growth in expanding medium**

  Lemaître 1934, Tolman 1935

  Linear growth of density perturbations

  $$\delta\rho/\rho \propto R$$

- **Structure not from density fluctuations?**

  New mechansim needed

  Eddington-Lemaître model?

Scene III: An origin for the universe?

- **Rewind Hubble graph**

  U smaller in the past

- **Extremely dense, extremely hot**

  Primeval atom

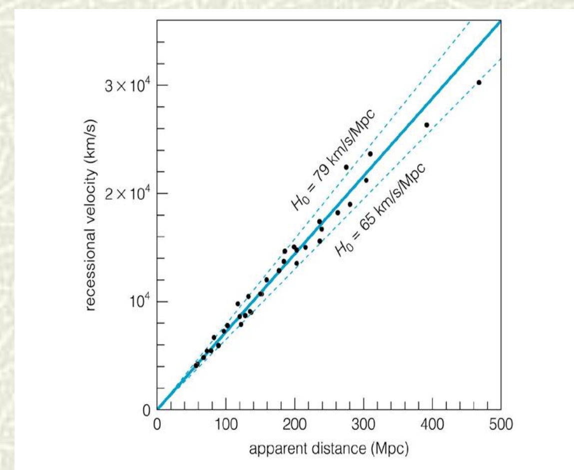
  Expanding and cooling since

The big bang

- **Singularity problem**

  ∞ density, ∞ temp at t = 0 ?

  Quantum theory



- **Age problem**

  U younger than stars?

Lemaître’s hesitating universe (1931-34)

- **Primeval atom**

  Explosive expansion from radioactive decay

- **Expansion slows down**

  Positive cosmic constant

  Energy of vacuum; stagnation

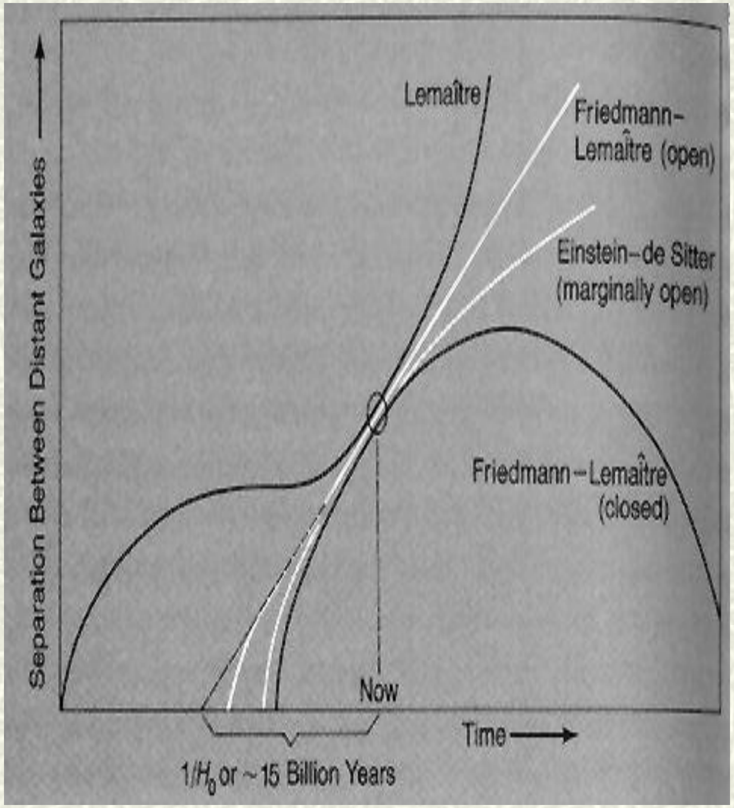
- **Indefinite timespan**

  No age problem

  Formation of structure?

- **Accelerated expansion**

  de Sitter universe at large t



Cosmic rays = radiation from early universe?

Finale: Paradigm shift or slow dawning?

- **Hubble/Slipher** *Empirical law for nebulae*
- **Friedmann** *Time-varying solutions*
- **Lemaître** *Theory and observation*

Obs: Parsons, Huggins, Leavitt, Shapley
Models I: Einstein, de Sitter, Weyl, Lanczos, Robertson
Models II: Einstein, de Sitter, Eddington, Tolman, Robertson

Slow emergence of theory and evidence
<u>Slow acceptance: no upsurge of interest 1935-65</u>

Act IV Slow acceptance: 1935-65

- **Hot big bang** (1940s)

  Nucleosynthesis in the hot infant universe?

  Background radiation from early universe?

- **Little interest from community**

  No search for the cosmic radiation

  General relativity difficult, abstruse

- **Steady-state universe** (1948)

  Continuous creation of matter from vacuum

  No age or singularity problems

- **Later ruled out by experiment** (1960s)

  Radio-galaxy counts, CMB

Gamow, Alpher and Hermann

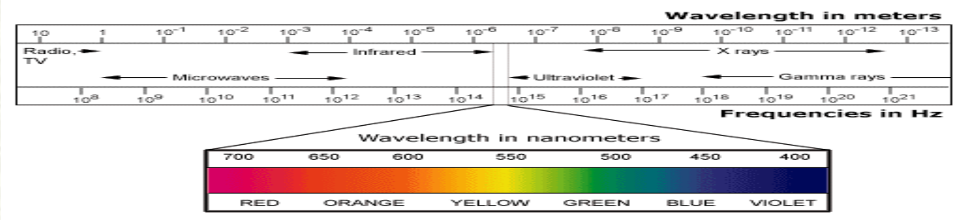
Hoyle, Bondi and Gold

Act V Cosmic background radiation

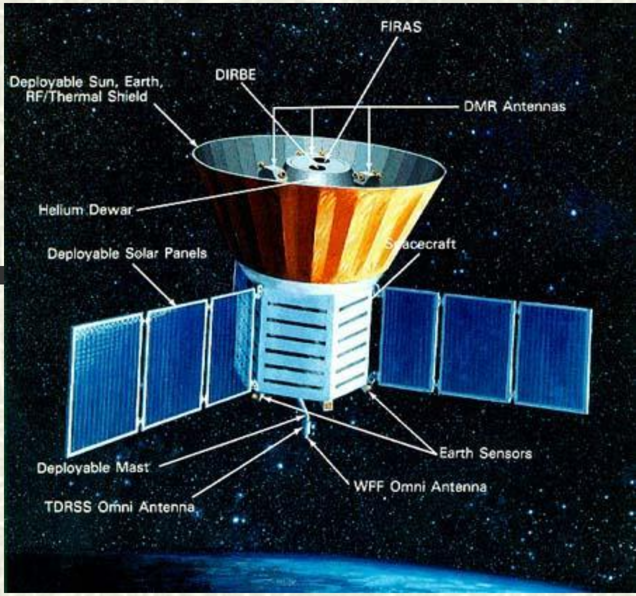
- **Search for radio signals**
  Large, sensitive receiver
- **Universal signal (1965)**
  From every direction
- **Low frequency (microwave)**
  Low temperature (3K)
- **Echo of big bang**
  Radiation from early universe

<u>BB model goes mainstream</u>

Penzias and Wilson



Cosmology today



- **Satellite measurements of CMB**

  No interference from atmosphere

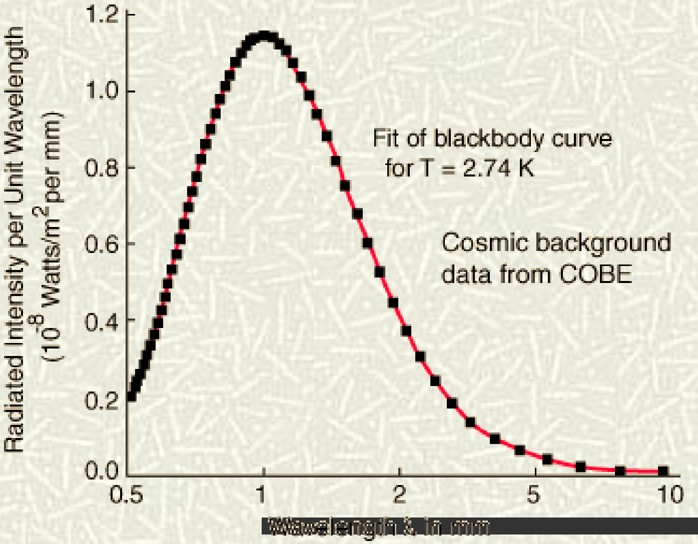
- **Expected temperature**

  Expected frequency

COBE satellite (1992)

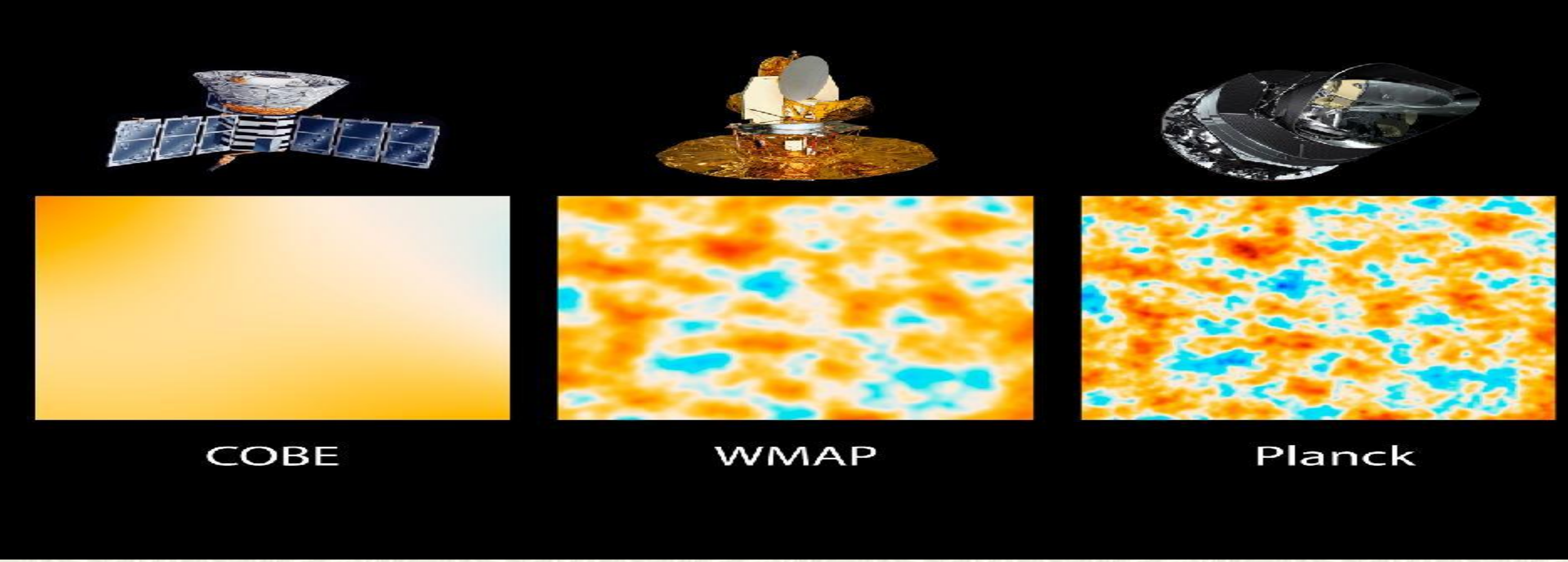
- **Full spectrum**

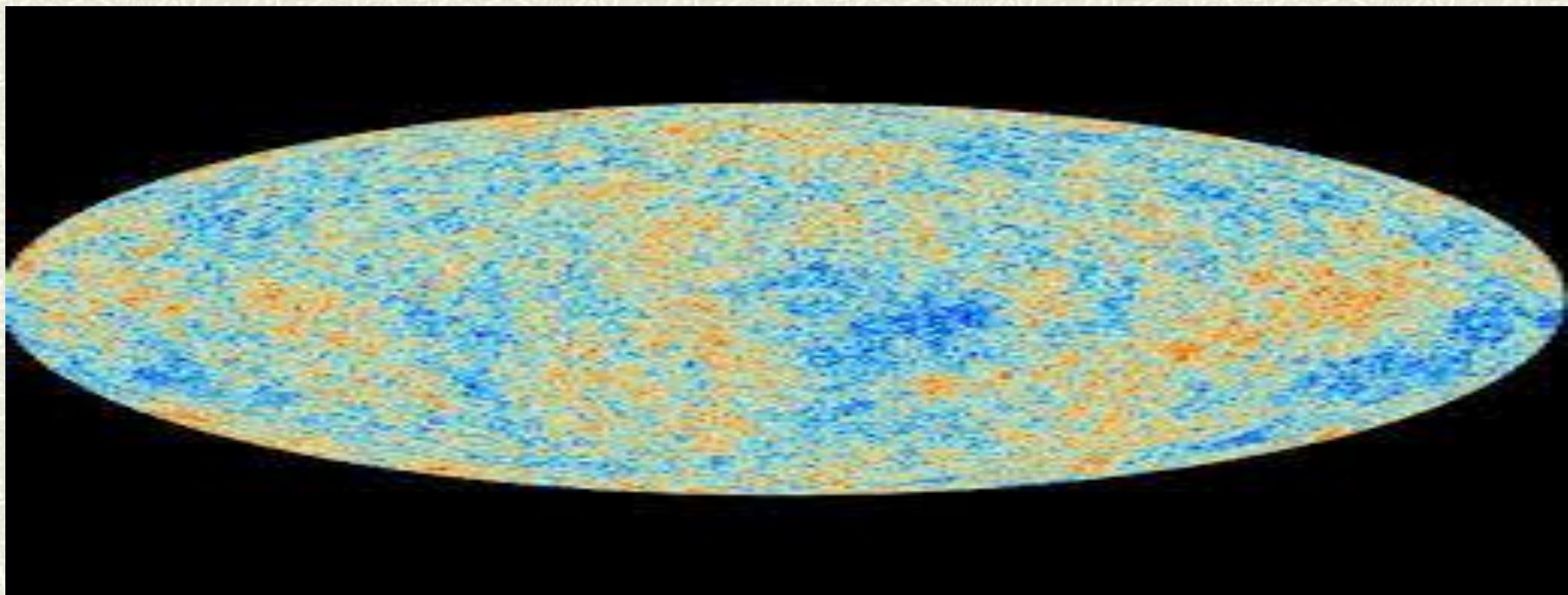
  Perfect blackbody spectrum



- **Perturbations**

  Variation of 1 in 10^5


COBE
WMAP
Planck



Paradigm shift or slow dawning?

- **Revolutionary v normal science**

  Normal science interspersed by revolutions

- **The paradigm shift**

  Change of worldview occurs

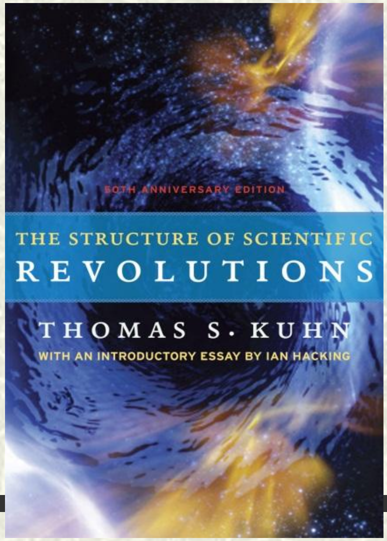
  Social factors important

- **Incommensurability**

  New worldview incommensurate with old

Exp U: ***Slow <u>exploration</u> of theory and observation***
Slow <u>acceptance</u> of new paradigm (1935-65)

Thomas Kuhn



Coda: Einstein's steady-state model

- **Non-static line element (1930)**

$$ds^2 = -e^{2kt}(dx_1^2 + dx_2^2 + dx_3^2) + c^2dt^2$$

- **Age problem**

  Conflict with stellar ages

- **Non-evolving universe**

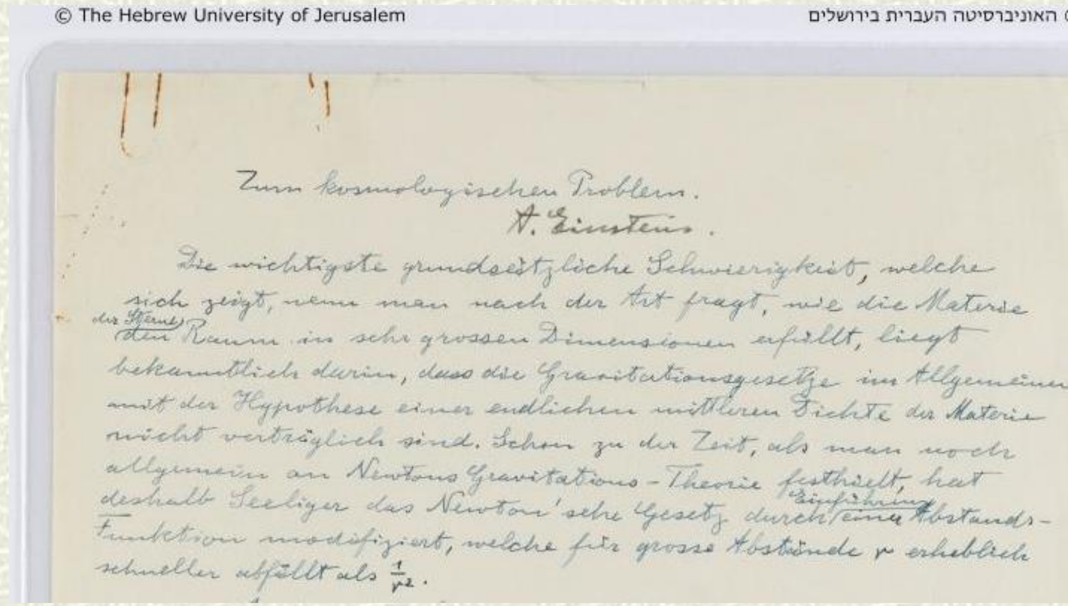
  Continuous creation of matter

  Associated with λ: energy of space

- **Anticipates Hoyle et al.**

  Not published

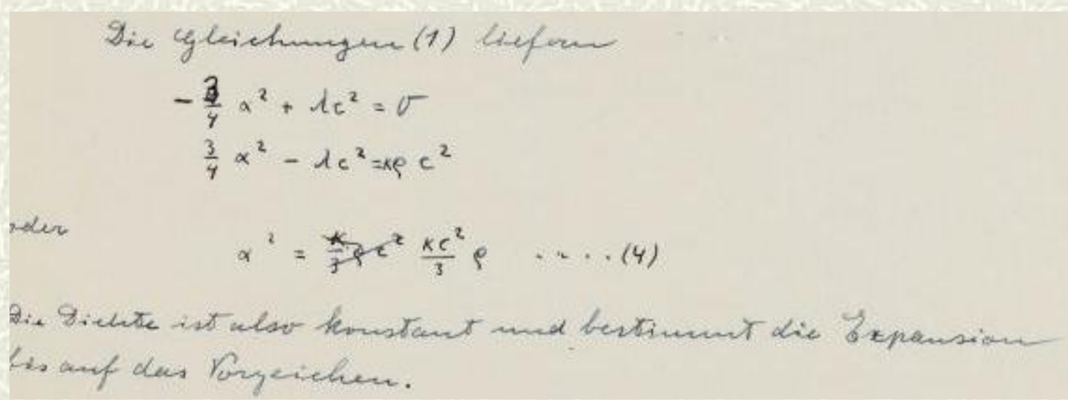
  Declines creation term



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 $\frac{1}{r^2}$.


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

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

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

Tolman's annihilation of matter

- **Non-static line element (1930)**

  Einstein, de Sitter models ruled out

  $$ds^2 = -e^{2kt}(dx_1^2 + dx_2^2 + dx_3^2) + c^2dt^2$$

- **Cause of cosmic expansion?**

  General evolutionary process

  Transformation of matter into radiation

$$\frac{\delta\lambda}{\lambda} = k\Delta l$$

- **Rate of transformation**

  From Hubble's law and from stellar physics

$$\frac{1}{M}\frac{dM}{dt} = -3k$$

$$k = 5 \times 10^{-10}\ yr^{-1}$$

- **Influenced Einstein**

  Steady-state model

New results: Planck Satellite (ESA, 2013)

1. Improved sensitivity

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

2. Full spectrum of *T* anisotropy

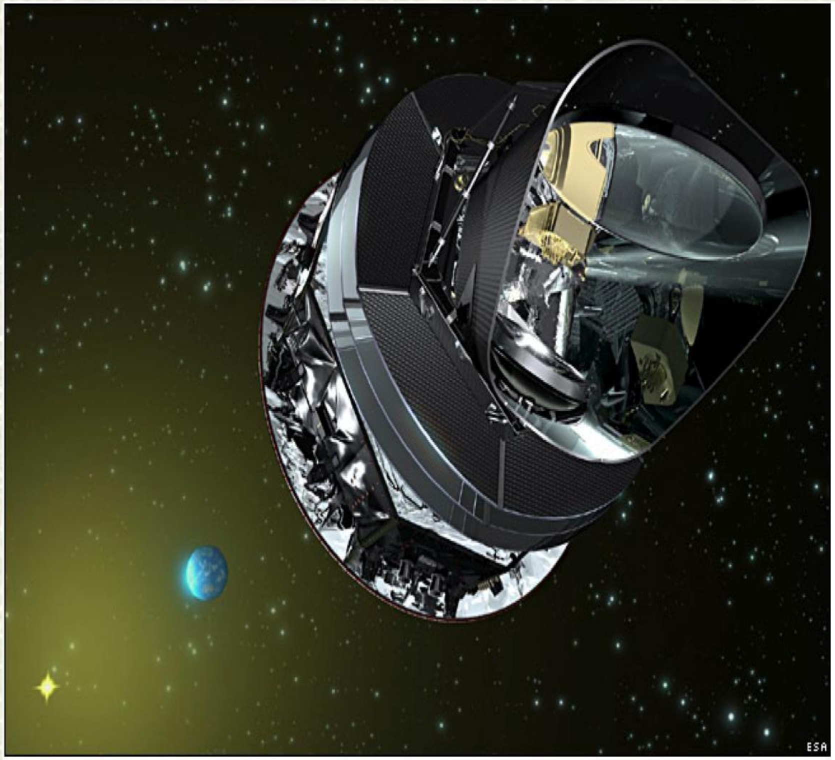
New acoustic peaks :scale invariance?
Accurate values for Ω_Λ , Ω_M

3. Gravitational lensing

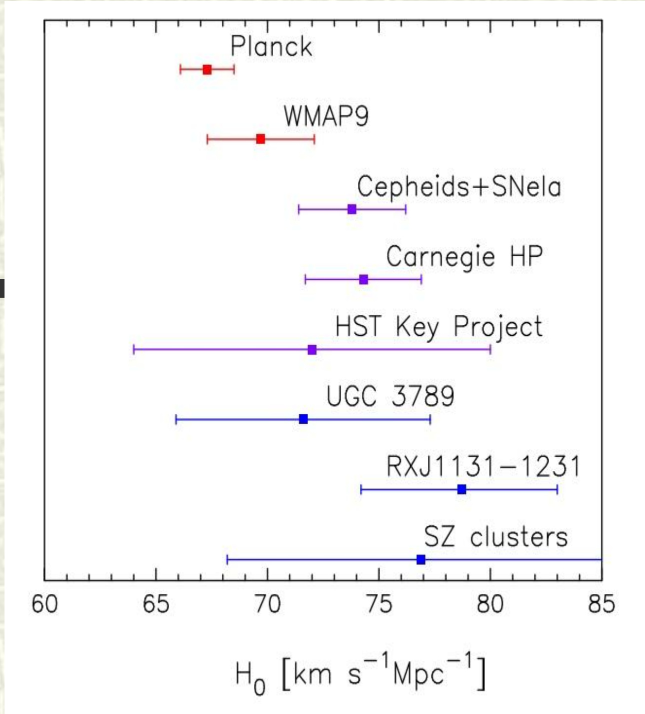
Remove degeneracies

4. Polarization measurements

E-modes: fluctuations
B-modes: gravity waves?



Planck results (2013)



1. New Hubble constant

67.3 +- 1.2 km/s/MPC
Age = 13.8 billion yr
No age conflict with astrophysics

2. Curvature: flat

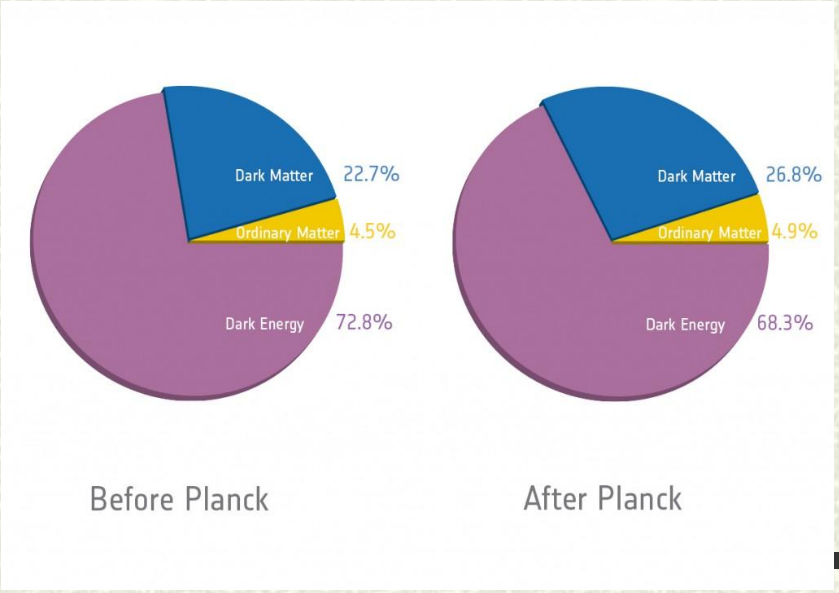
Ω_k = -0.0005 +- .07

3. Positive cosmic constant

Ω_Λ = 68%

4. New mass/energy parameters

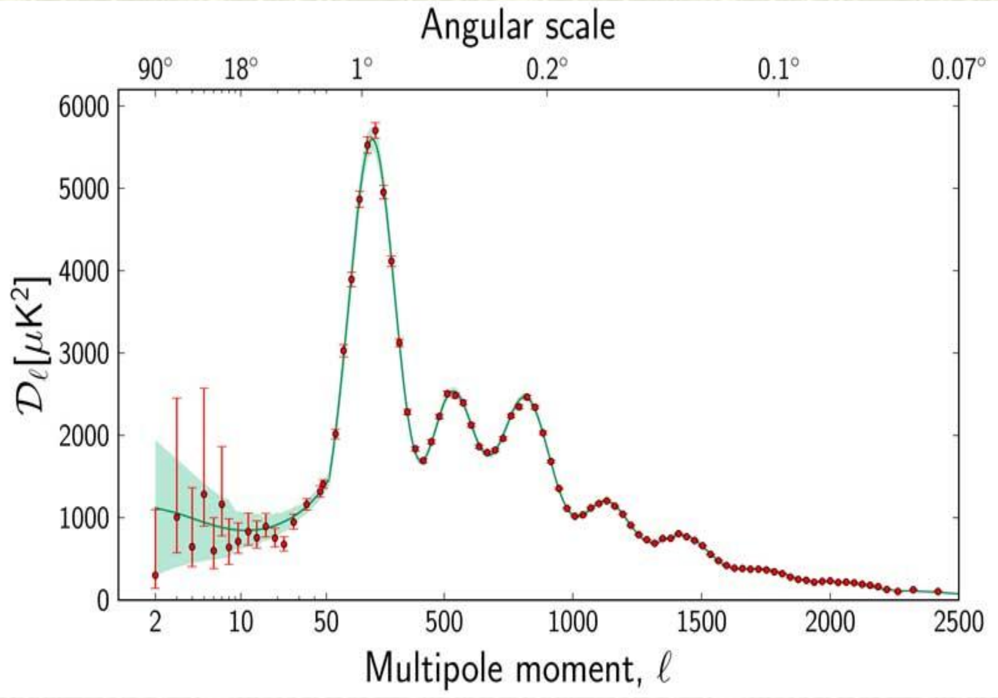
Ω_{DM} = *27%,* Ω_{OM} = *4.9 %*



Planck Results

1. **Power spectrum**

   Not scale invariant $n_s = 0.96$



2. **Compatible with inflation**

   Simple 'slow-roll' models

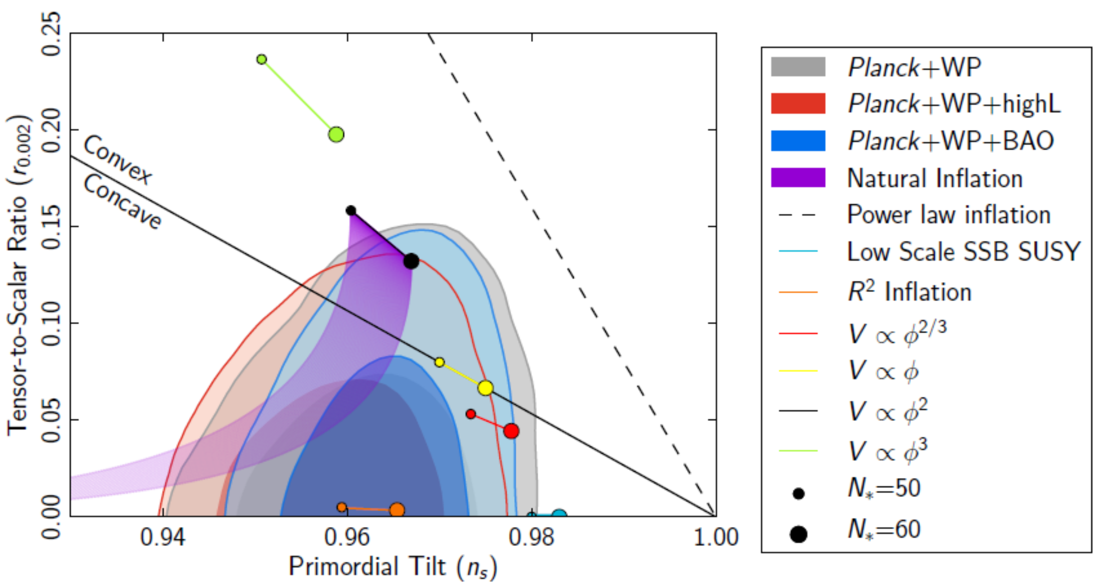
   Higgs-type field?

3. **Complex inflation out**

   Double field out

   Hybrid models out

   Cyclic models out



The big bang model - questions

- **Nature of dark energy?**

  Role in BB?

- **Nature of dark matter?**

  Particle experiments?

- **Which model of inflation?**

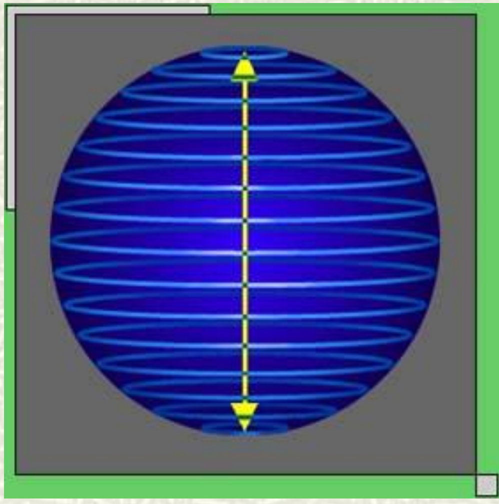
  The multiverse?

- **The singularity problem**

  What banged?

  What does time zero mean?

No-boundary universe



<u>The case is never closed</u>