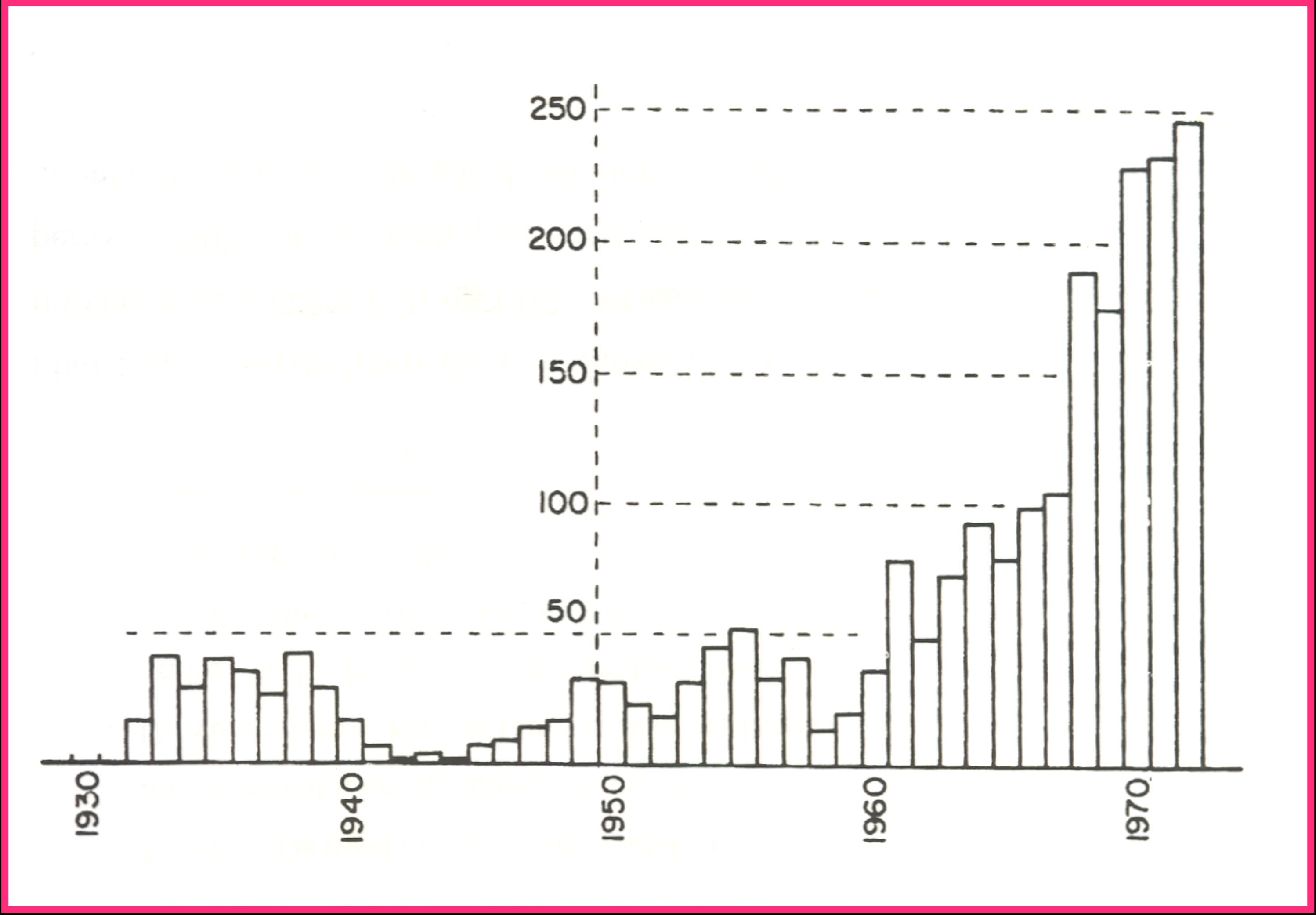
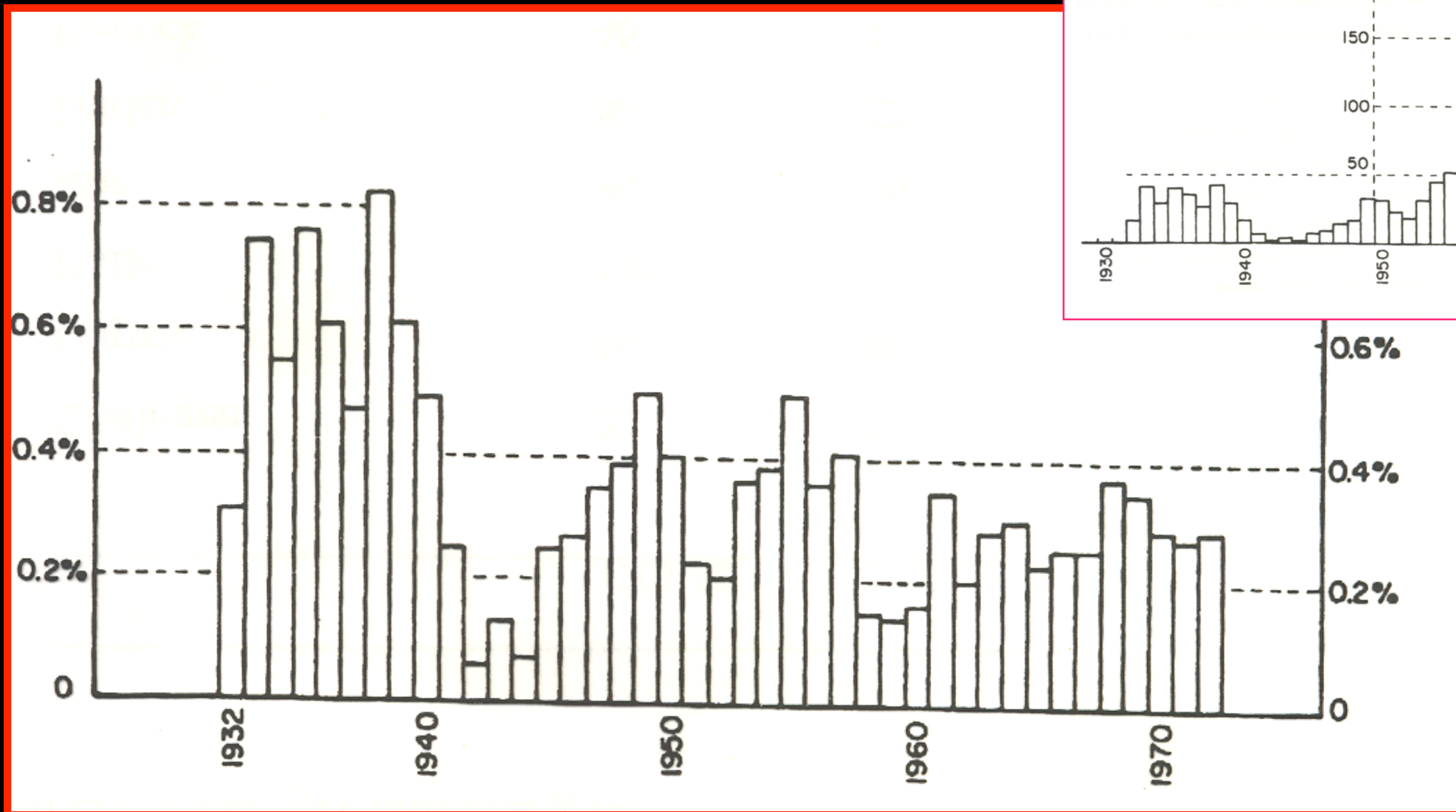
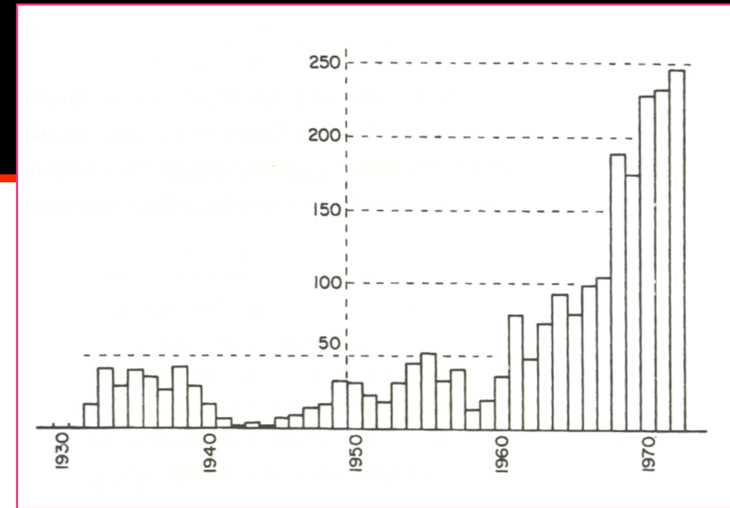
Modern cosmology

A historical sketch



This depiction of the no. of publications on ”cosmology” in *Physics Abstracts* (1930-75) shows a field which only began it ”normal” growth in the 1960s, while in the 1930s it was very small and with no sign of progress.

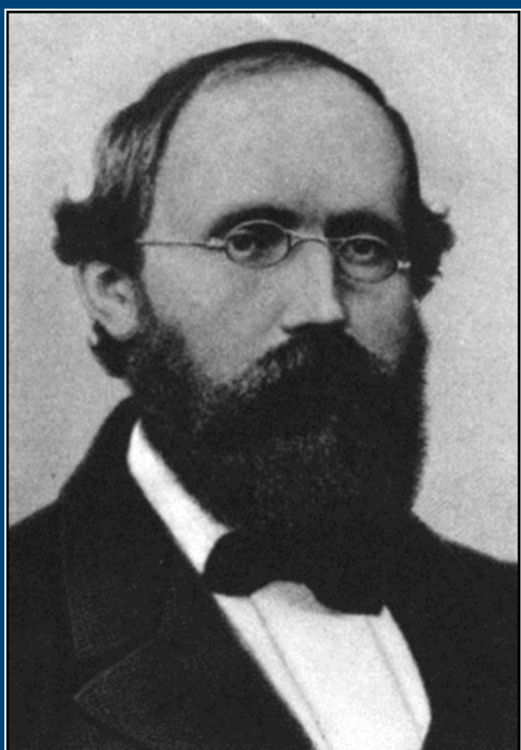




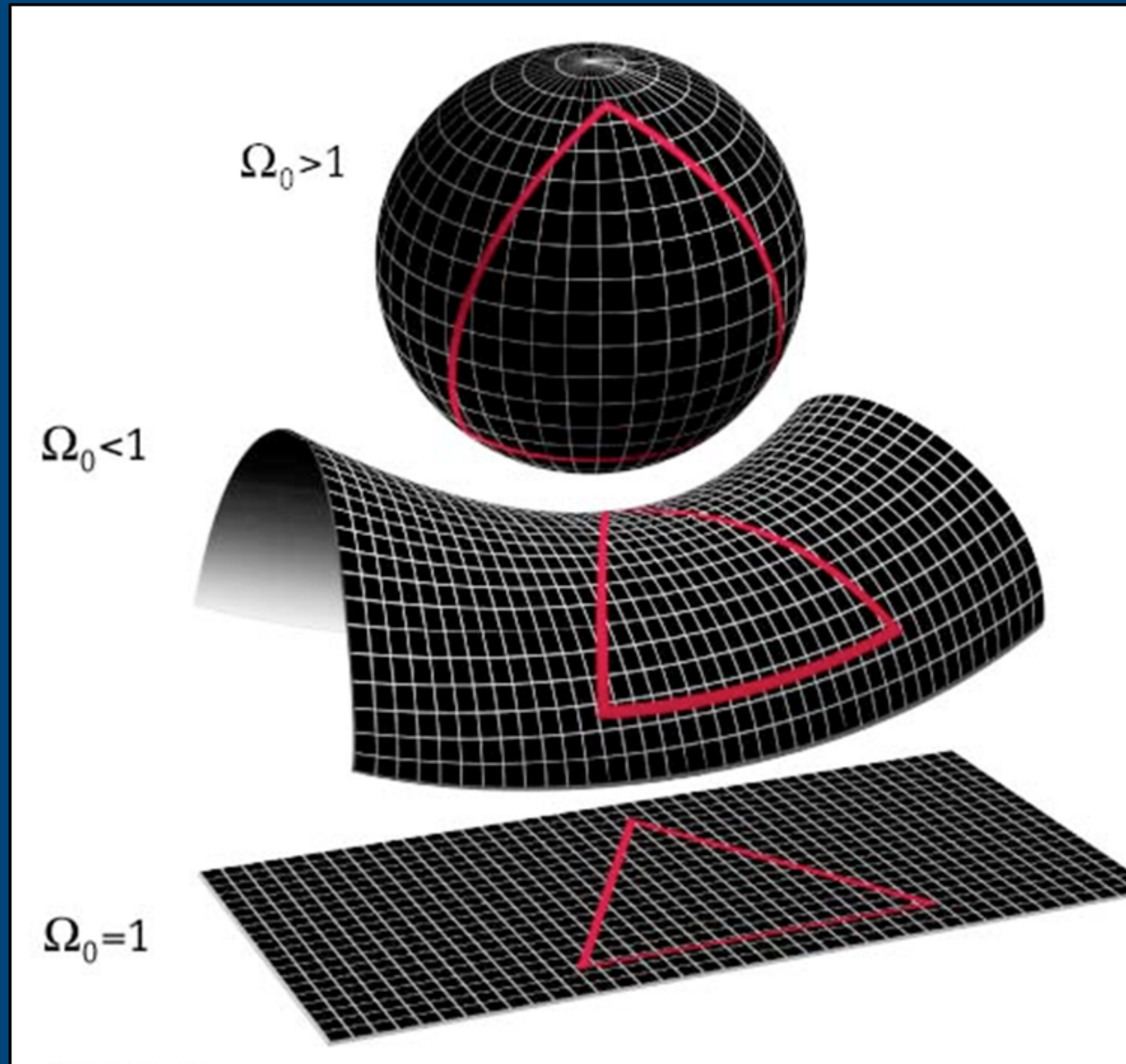
BUT, if the data are taken relative to all articles in *Physics Abstracts*, we get a very different picture: now, the 1930's look like a fine decade, while the progress in the 1960s has entirely vanished!

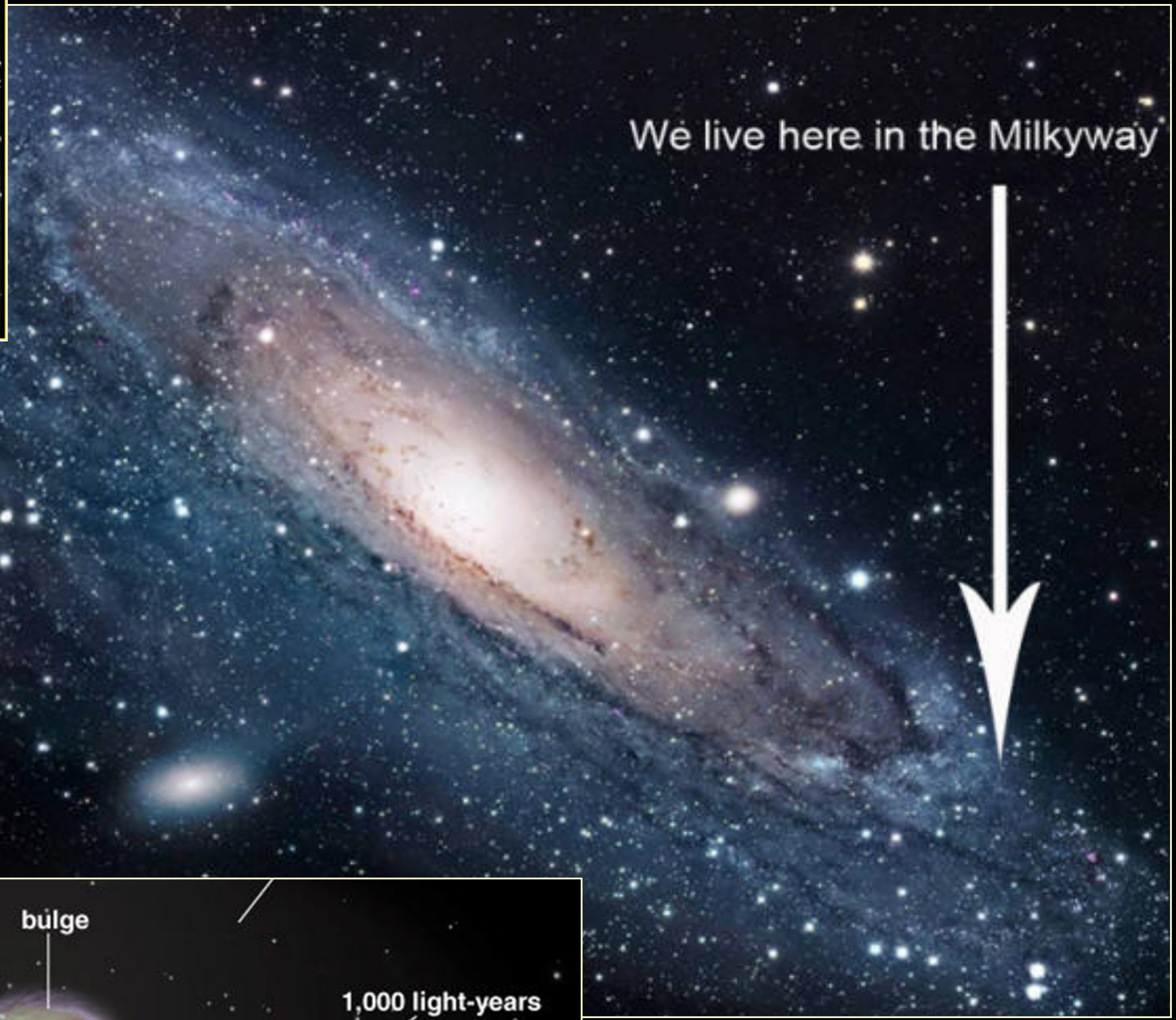
$$\Omega_0 = \rho/\rho_c \quad \text{with} \quad \rho_c = 3H^2/8\pi G$$

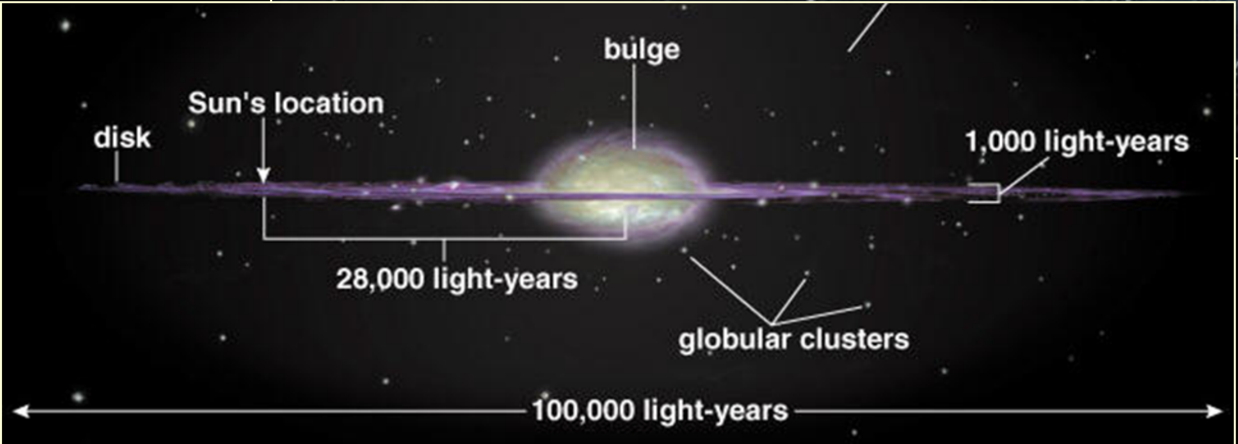
The value of Ω_0 determines the geometry of space.



B. Riemann (1826-1866)



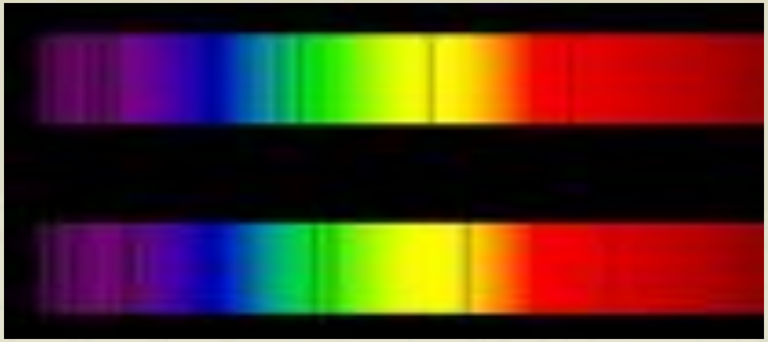

We live here in the Milkyway

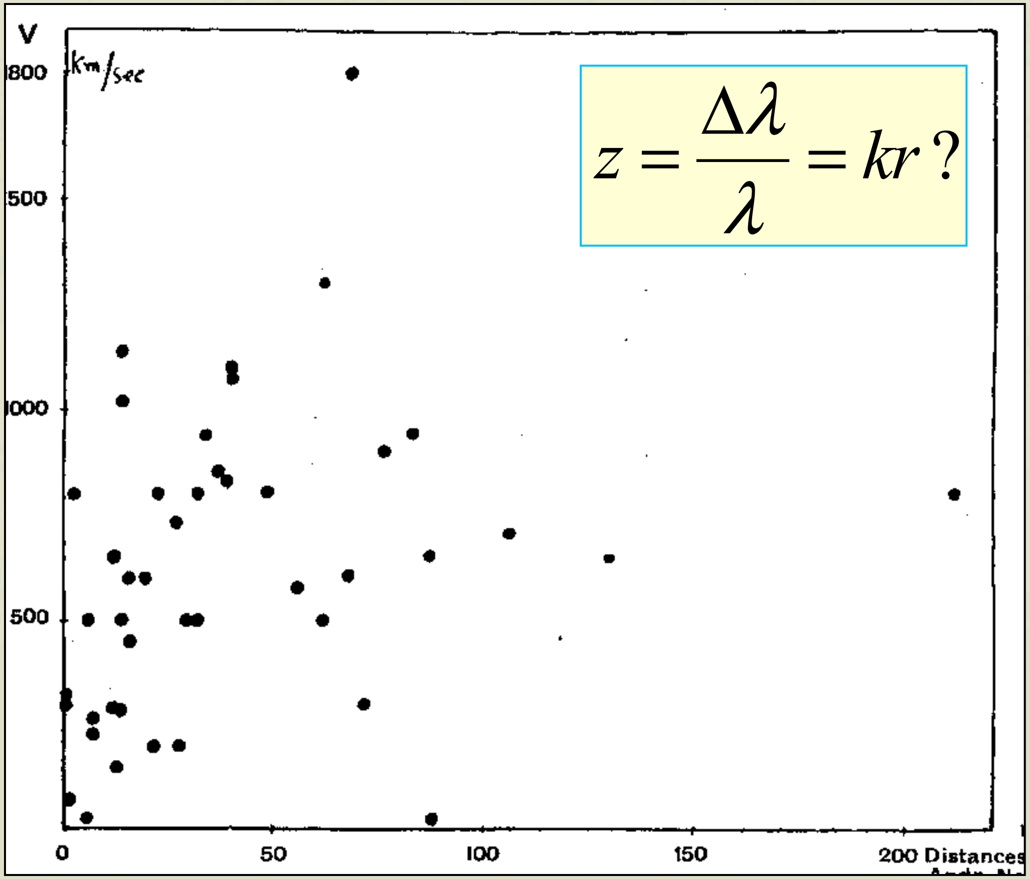

bulge
Sun's location
disk
1,000 light-years
28,000 light-years
globular clusters
100,000 light-years

M. Slipher: galactic redshifts

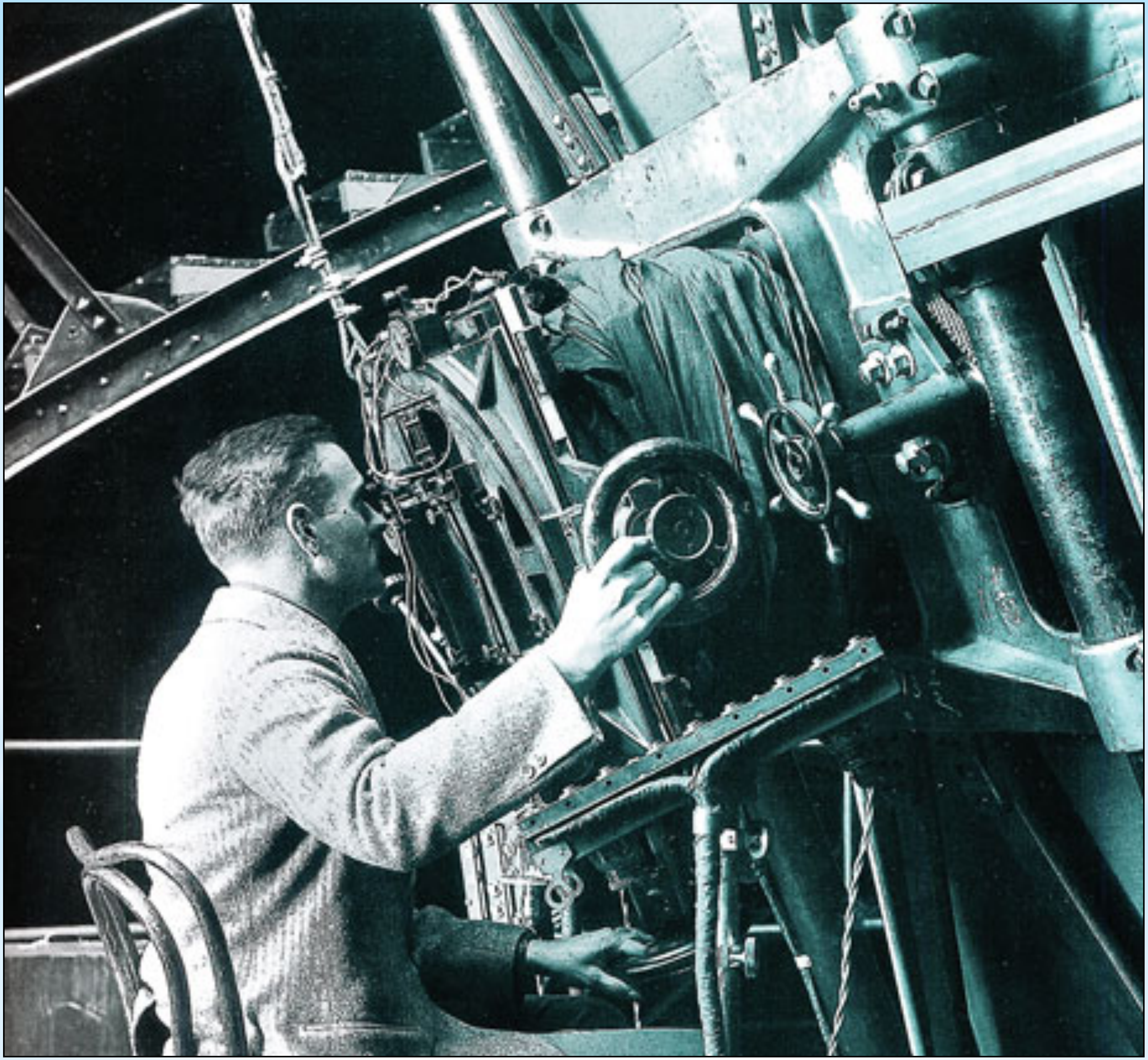
Do the galactic redshifts vary systematically with their distances?

Doppler shift: $z \equiv \Delta\lambda/\lambda = v/c$





$$z = \frac{\Delta\lambda}{\lambda} = kr\,?$$

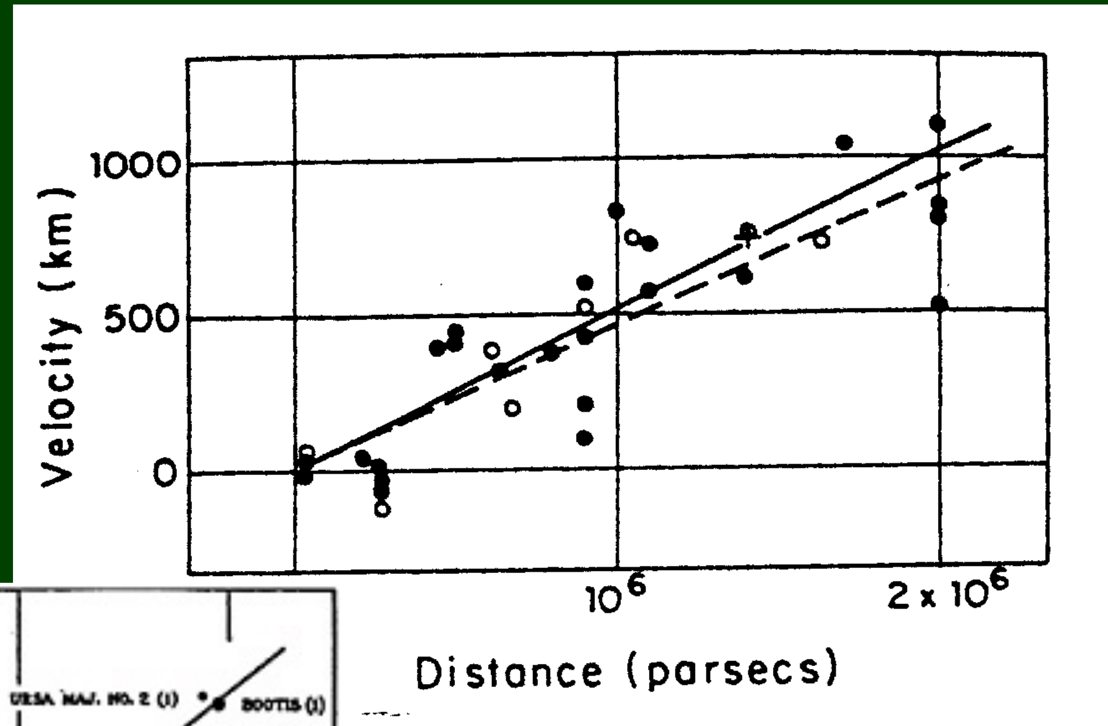


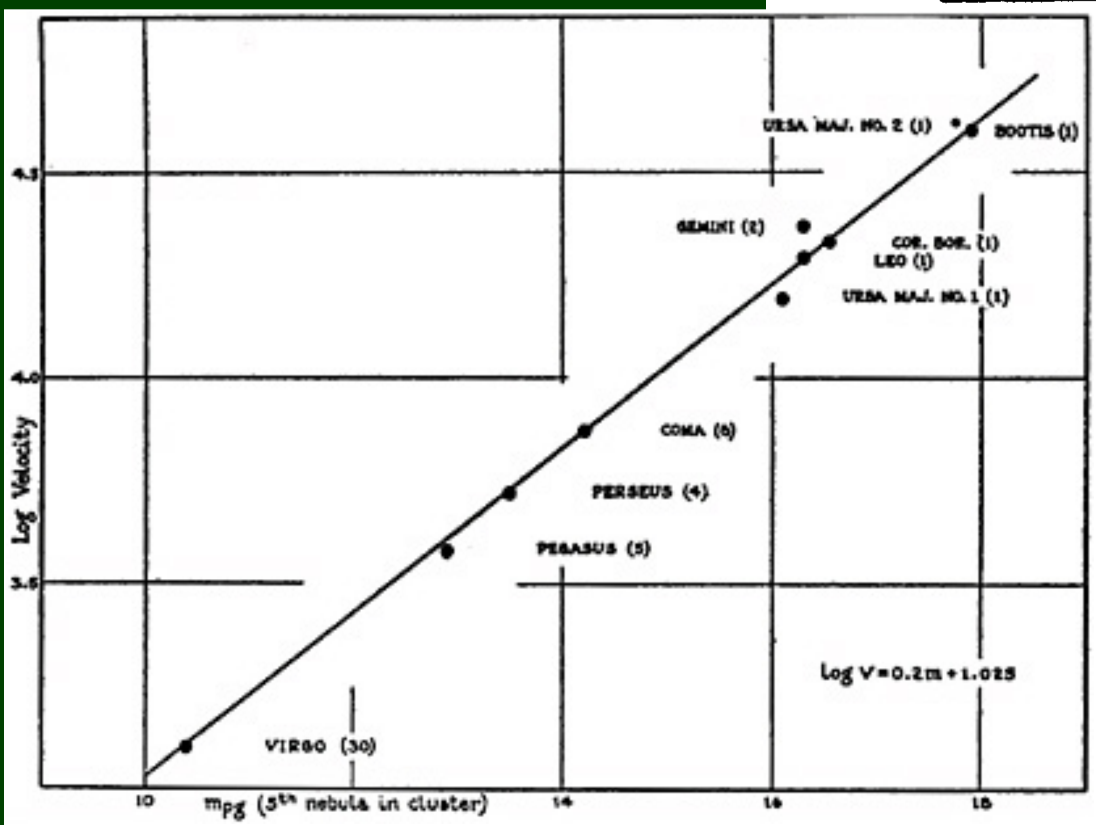
Hubble-diagram

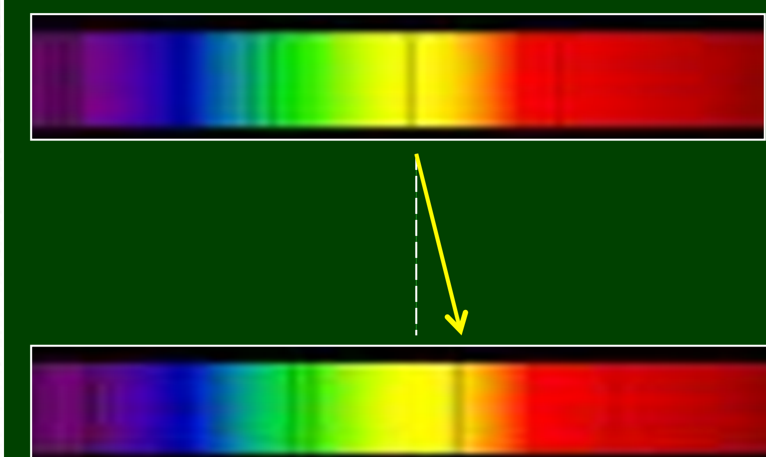
1929, $H \cong 500$ km/s/Mpc

$v = H r$

1931, $H \cong 558$ km/s/Mpc







Cosmological field equations

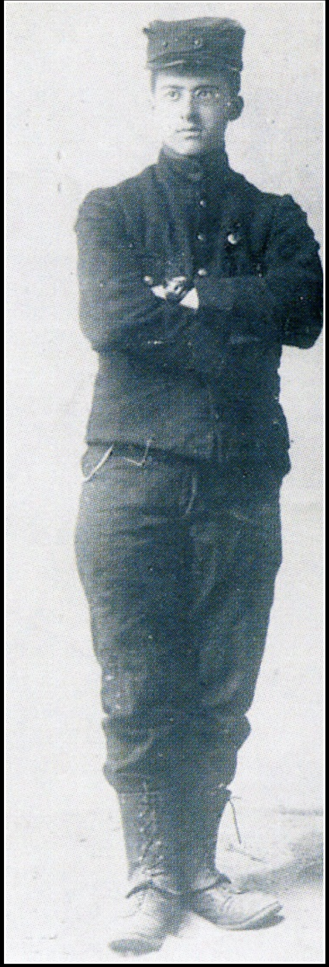
Einsteins model of 1917:

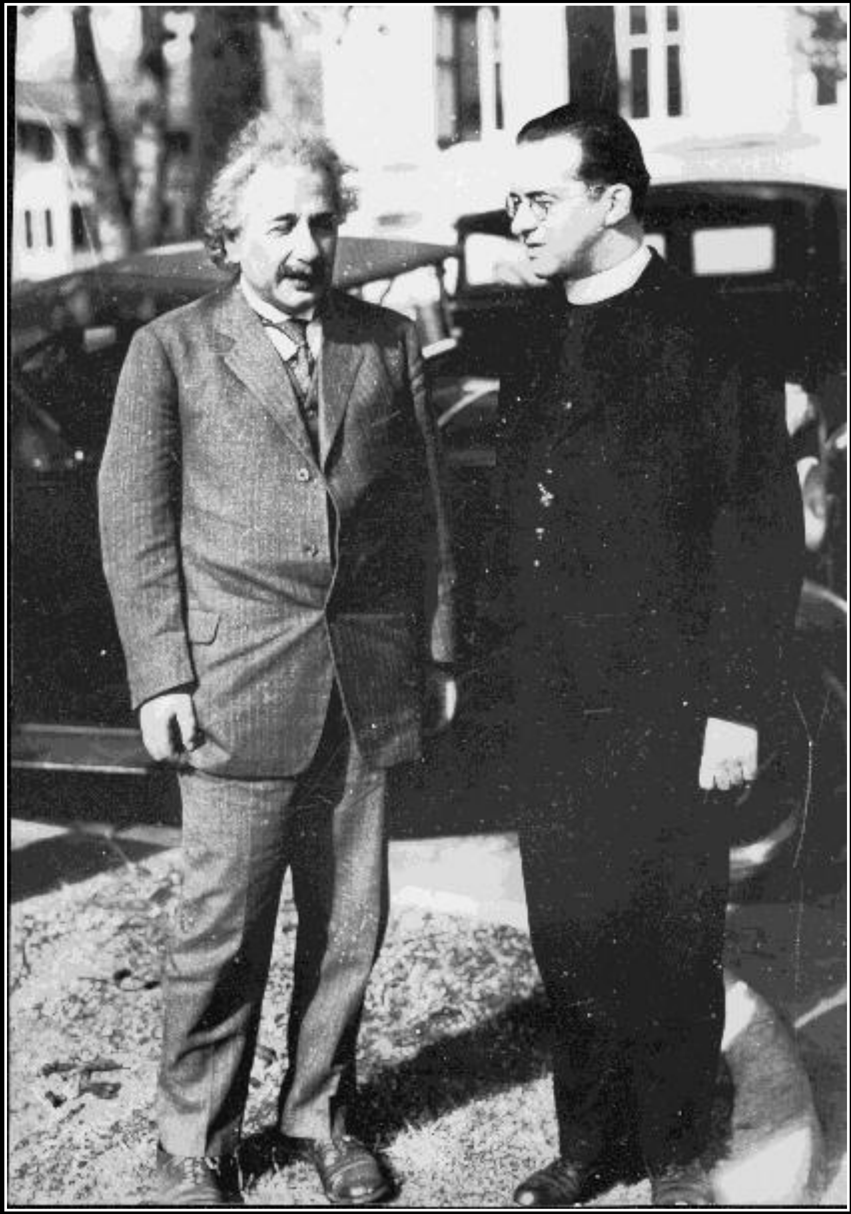
- Static (no beginning, no end)
- Filled with dilute matter
- Spherical space, of finite volume
- Cosmological constant, Λ > 0.

kommen analog ist. Wir können nämlich auf der linken Seite der Feldgleichung (13) den mit einer vorläufig unbekannten universellen Konstante $-\lambda$ multiplizierten Fundamentaltensor $g_{\mu\nu}$ hinzufügen, ohne daß dadurch die allgemeine Kovarianz zerstört wird; wir setzen an die Stelle der Feldgleichung (13)

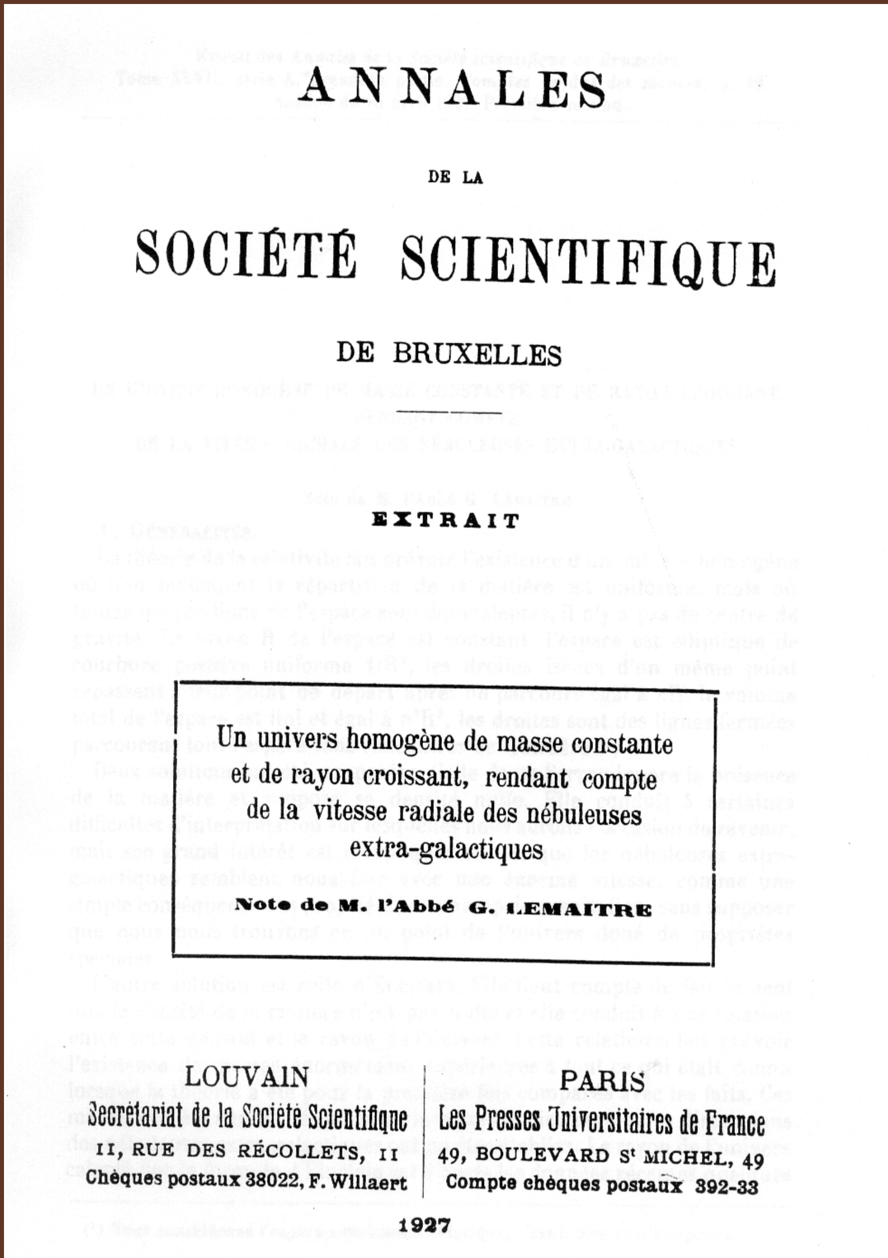
$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \qquad (13a)$$

Auch diese Feldgleichung ist bei genügend kleinem λ mit den am Sonnensystem erlangten Erfahrungstatsachen jedenfalls vereinbar. Sie befriedigt auch Erhaltungssätze des Impulses und der Energie, denn





Georges Lemaître; expanding universe (1927); first big-bang model (1931)



ANNALES

DE LA

SOCIÉTÉ SCIENTIFIQUE

DE BRUXELLES

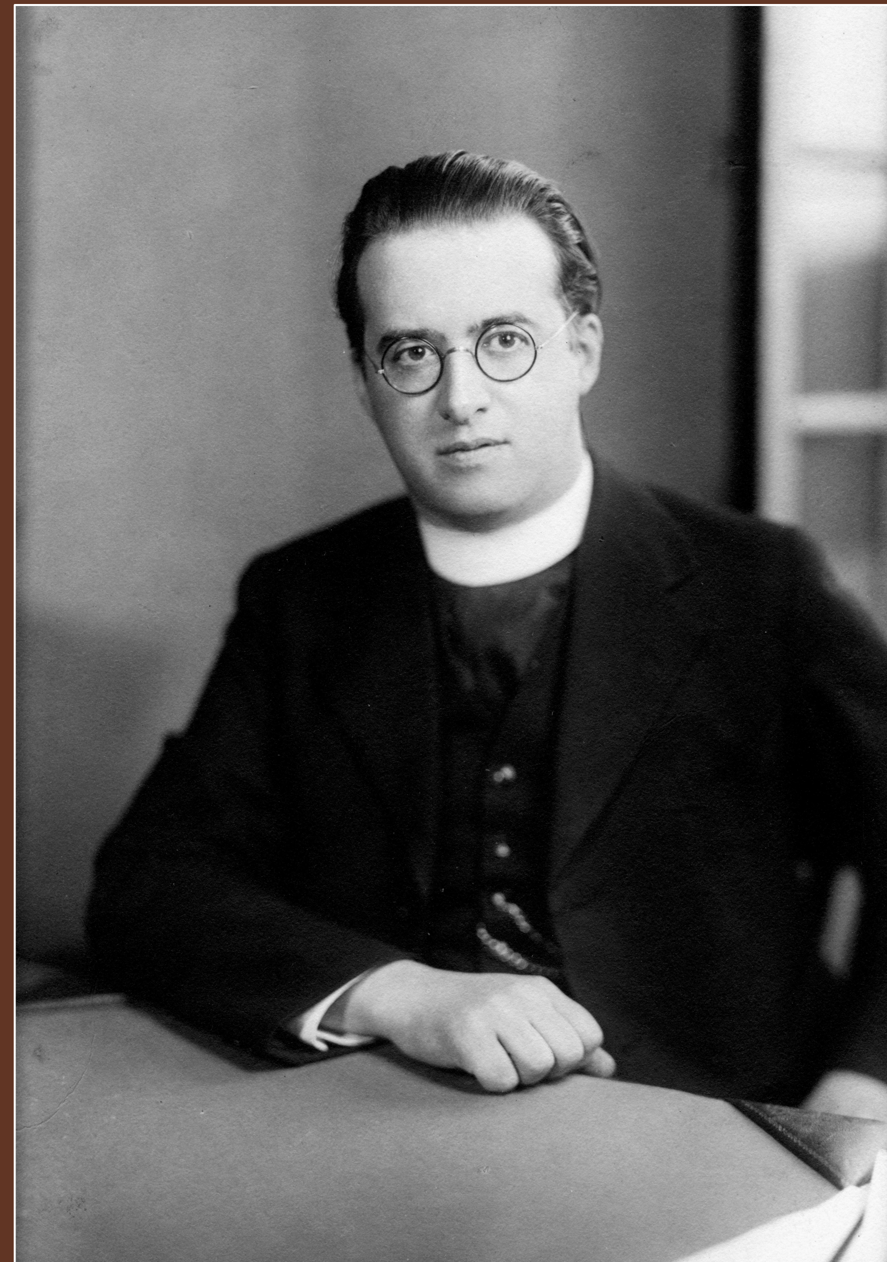
EXTRAIT

Un univers homogène de masse constante et de rayon croissant, rendant compte de la vitesse radiale des nébuleuses extra-galactiques

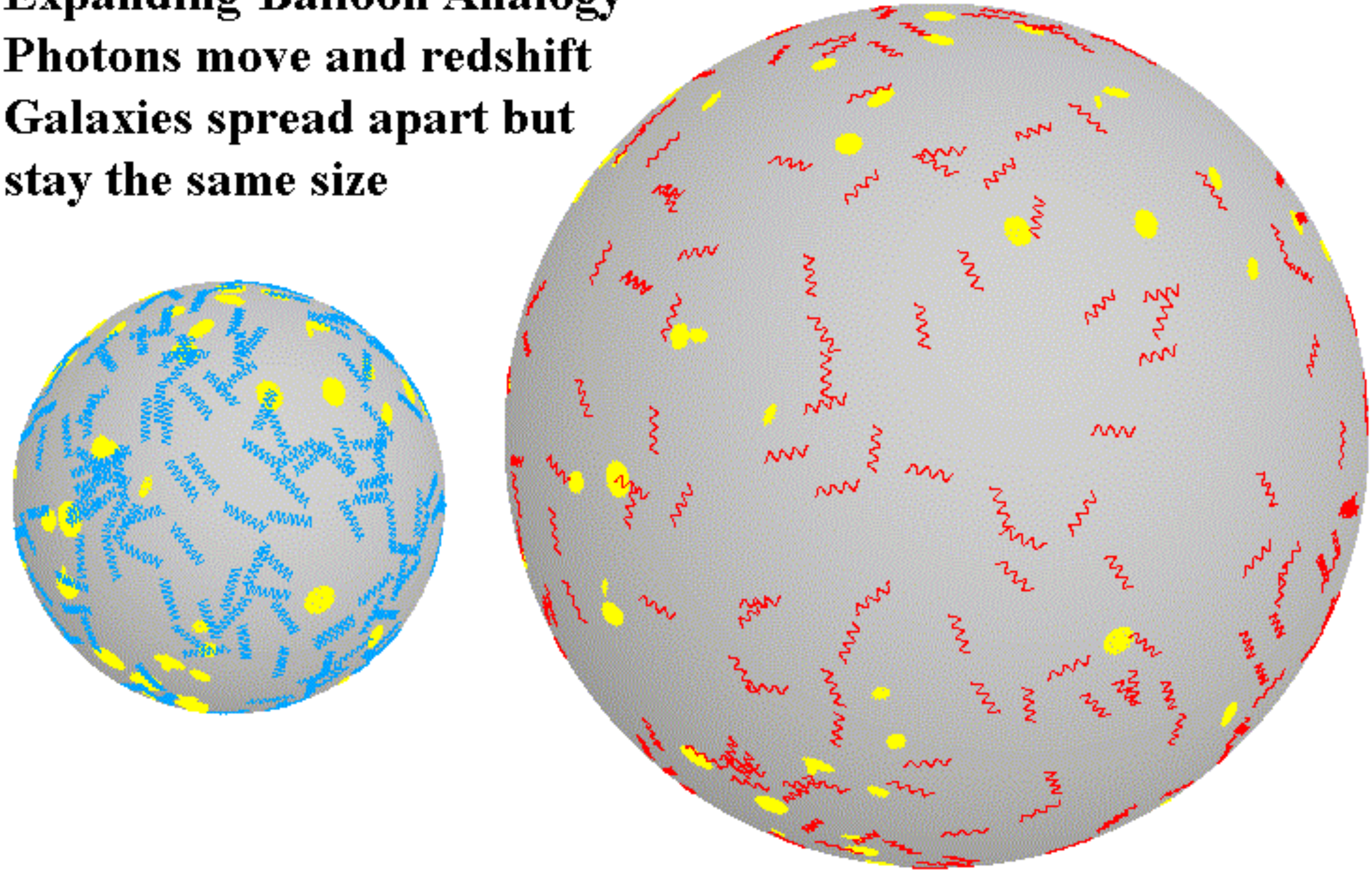
Note de M. l'Abbé G. LEMAITRE

LOUVAIN	PARIS
Secrétariat de la Société Scientifique	Les Presses Universitaires de France
11, RUE DES RÉCOLLETS, 11	49, BOULEVARD S^T MICHEL, 49
Chèques postaux 38022, F. Willaert	Compte chèques postaux 392-33

1927

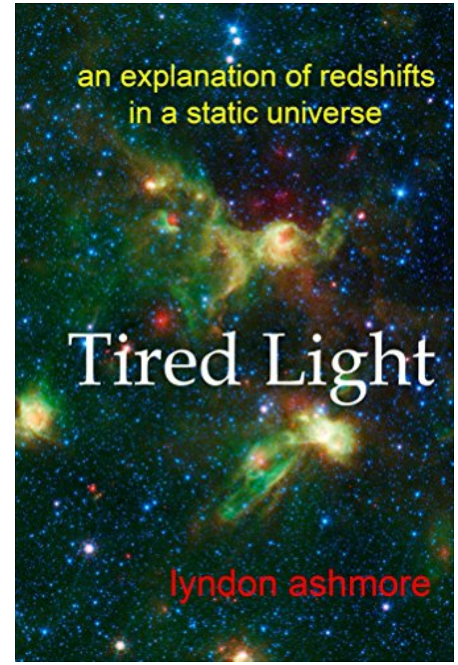


Expanding Balloon Analogy
Photons move and redshift
Galaxies spread apart but
stay the same size



Tired-light hypotheses

Explanation of galactic redshifts on the basis of the static universe, e.g. MacMillan 1932.



$E = h\nu$ $\qquad$ $E = h\nu^*$, $\nu^* < \nu$

galaxy → earth

Assume $dE/dx = -\alpha E$, $E = E_0 \exp(-\alpha x)$,

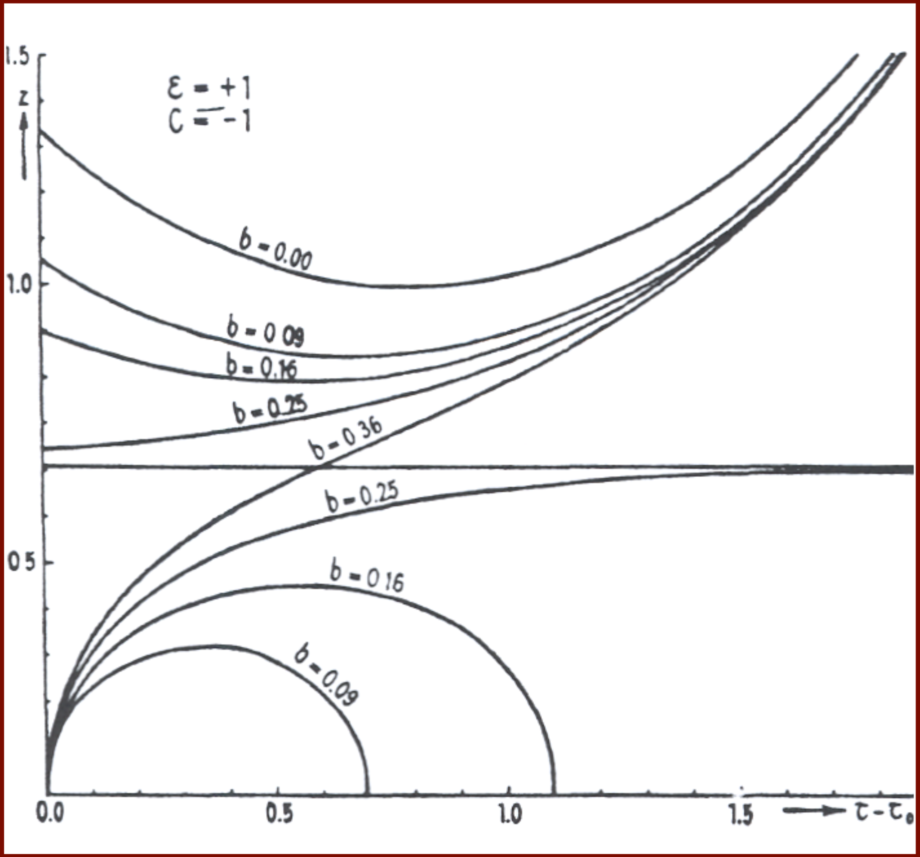
$\lambda = \lambda_0 \exp(\alpha x) \cong \lambda_0 (1 + \alpha x)$, therefore

$\Delta\lambda/\lambda \cong \alpha x$

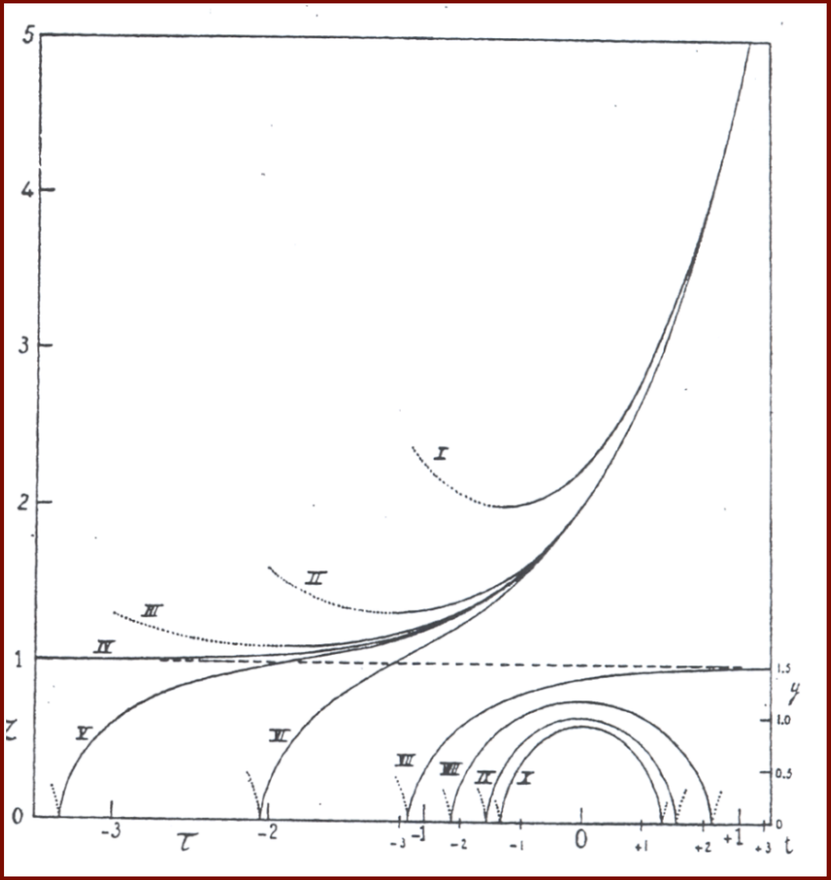
… Hubble law!

Is the simple tired-light hypothesis a better explanation of the galactic redshifts than the complicated hypothesis of the expanding universe based on GR?

Early cosmological models = solutions to Einstein’s field equations satisfying the cosmological principle



O. Heckmann, 1932



W. de Sitter, 1931

GR-cosmological models (assuming CP, $p = 0$, $c = 1$)

Friedmann equations:

$$3(R/R)^2 + 3k/R^2 = \Lambda + \kappa\rho \qquad (R/R)^2 + 2R/R + k/R^2 = \Lambda$$

$R(t)$ = scale factor (relative distance)

k = space curvature parameter ($k = +1, 0, -1$)

Λ = cosmological constant

$\kappa = 8\pi G$ (Einstein gravitation constant)

ρ = average matter density

For $\Lambda = 0$ $\quad k/R^2 = H^2(2q_0 - 1)$ where $H = R/R$ and $q_0 = -R/RH^2$

The Hubble constant H, the deceleration parameter q_0, and the density ρ are measurable quantities

9 May 1931

The birth of the idea of the big-bang universe originating in a "primeval atom."

Clearly the initial quantum could not conceal in itself the whole course of evolution ; but, according to the principle of indeterminacy, that is not necessary. Our world is now understood to be a world where something really happens ; the whole story of the world need not have been written down in the first quantum like a song on the disc of a phonograph. The whole matter of the world must have been present at the beginning, but the story it has to tell may be written step by step. G. LEMAÎTRE.

40 rue de Namur,
Louvain.

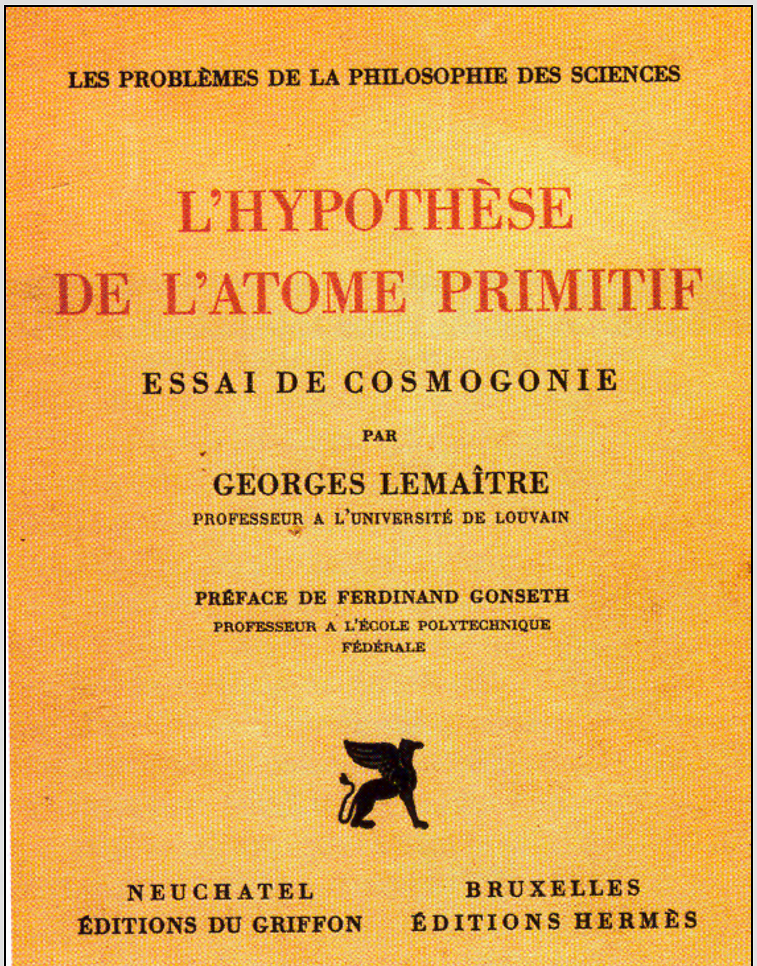
Clearly the in

the whole course of evolution; but, according to the indetermination principle, that is not necessary. Our world is now a world where something happens; the whole story of the world does not need to be written down in the first quantum as a song on the disc of a phonograp. The whole matter of the world must be present at the beginning, but the story it has to tell may be written step by step.

I think that every one who believes in a supreme being supporting every being and every acting, believes also that God is essentially hidden and may be glad to see how present physics provides a veil hiding the creation.

Lemaître's "primeval-atom" universe, 1931

Space and past time are finite. The cosmological constant ($\Lambda > 0$), provides a "stagnation phase" solving the age paradox.


LES PROBLÈMES DE LA PHILOSOPHIE DES SCIENCES

L'HYPOTHÈSE DE L'ATOME PRIMITIF

ESSAI DE COSMOGONIE

PAR

GEORGES LEMAÎTRE

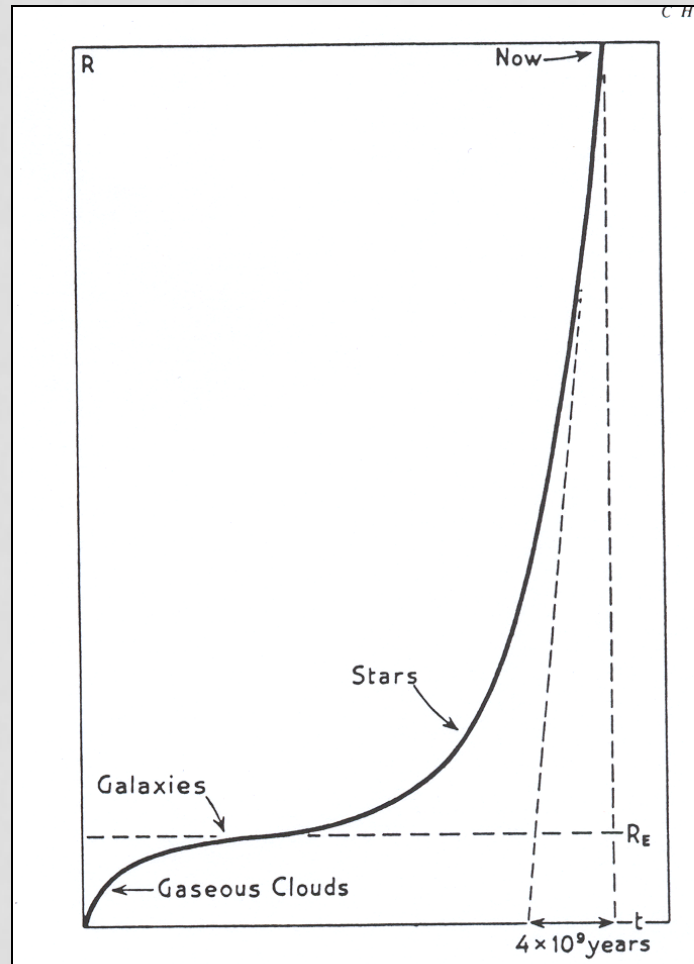
PROFESSEUR A L'UNIVERSITÉ DE LOUVAIN

PRÉFACE DE FERDINAND GONSETH

PROFESSEUR A L'ÉCOLE POLYTECHNIQUE FÉDÉRALE

NEUCHATEL ÉDITIONS DU GRIFFON

BRUXELLES ÉDITIONS HERMÈS



Lemaître's "big bang" described in *Popular Science Monthly* 1932.

Blast of Giant Atom

By
Donald H. Menzel
Harvard Observatory

OUT of a single, bursting atom came all the suns and planets of our universe!

That is the sensational theory advanced by the famous Abbe G. Lemaître, Belgian mathematician. It has aroused the interest of astronomers throughout the world because, startling as the hypothesis is, it explains many observed and puzzling facts.

According to Lemaître's theory, all the matter in the universe was once packed within a single, gigantic atom, which, until ten thousand millions years ago, lay dormant. Then, like a sky-rocket touched off on the Fourth of July after having remained quietly for months on a store shelf, the atom burst, its far-flung fragments forming the stars of which our universe is built.

The manner in which certain kinds of atoms explode can be seen easily in a simple experiment. If you take a radium watch into a dark room and look at the dial through a magnifying glass, you see what appears to be a brilliant display of miscroscopic fireworks. While you are looking at the showering sparks, remember that each flash comes from an exploding atom. In each spark, you see a small-scale reproduction of the new theory of the birth of our universe.

On the average, every radium atom lies dormant for about 1,730 years, after which time it explodes and shoots out particles in much the same way as the parent atom gave birth to the stars.

The new theory provides an explanation for one of the most extraordinary scientific facts ever discovered. Our telescopes show us that there are, out in space, millions of disk-shaped star-clusters known as extra-galactic nebulae. It is generally believed that our Milky Way is such an object and that our sun is but one of billions of stars that go to form it. One of the larger members of the class, the spiral nebula in Canes Venatici, is so far away that light from it takes almost a million years to reach us. Furthermore, observations indicate that every second it moves still farther away from our solar system by some 170 miles.

For every large, bright nebula there are thousands of small, faint, and presumably much more distant ones. Surveys out to one hundred million light years are in progress. The extraordinary feature referred to above is not, however, the magnitude of the figures, but the discovery that the more distant the nebula the more rapid is its motion *in a direction away from us!* The present record-holder is a tiny nebula whose cosmic speedometer registers in excess of twelve thousand miles a second!

Why, astronomers have asked, are the

IF THE EARTH WERE TO EXPAND, YOUR NEIGHBORS HOUSE WOULD MOVE AWAY FROM YOURS BUT THEIR RELATIVE POSITIONS WOULD REMAIN THE SAME

YOU CAN SEE AN ATOM BOMBARDMENT IF YOU LOOK AT THE NUMERALS ON A RADIUM DIAL WATCH UNDER A MAGNIFYING GLASS IN THE DARK

Created Our Universe

WITH THIS GIANT MAGNET UNIVERSITY OF CALIFORNIA SCIENTISTS HOPE TO REVEAL THE SECRETS OF THE TINY ATOMS THAT COMPOSE ALL MATTER IN THE UNIVERSE

THIS DIAGRAM OF THE GROWTH OF A NEBULA IN AN EXPANDING UNIVERSE SHOWS HOW DISTANT STARS (BLACK DOTS) APPARENTLY ARE RUNNING AWAY FROM US DUE TO EXPANSION OF SPACE. NOTE THAT STARS OCCUPY SAME RELATIVE POSITIONS IN EACH STEP

Drawings by B. G. SEIELSTAD

more distant objects moving faster? Why does the motion always seem to be away from us? If the motion is one of simple expansion, why should we find ourselves so nearly at the center, looking outward?

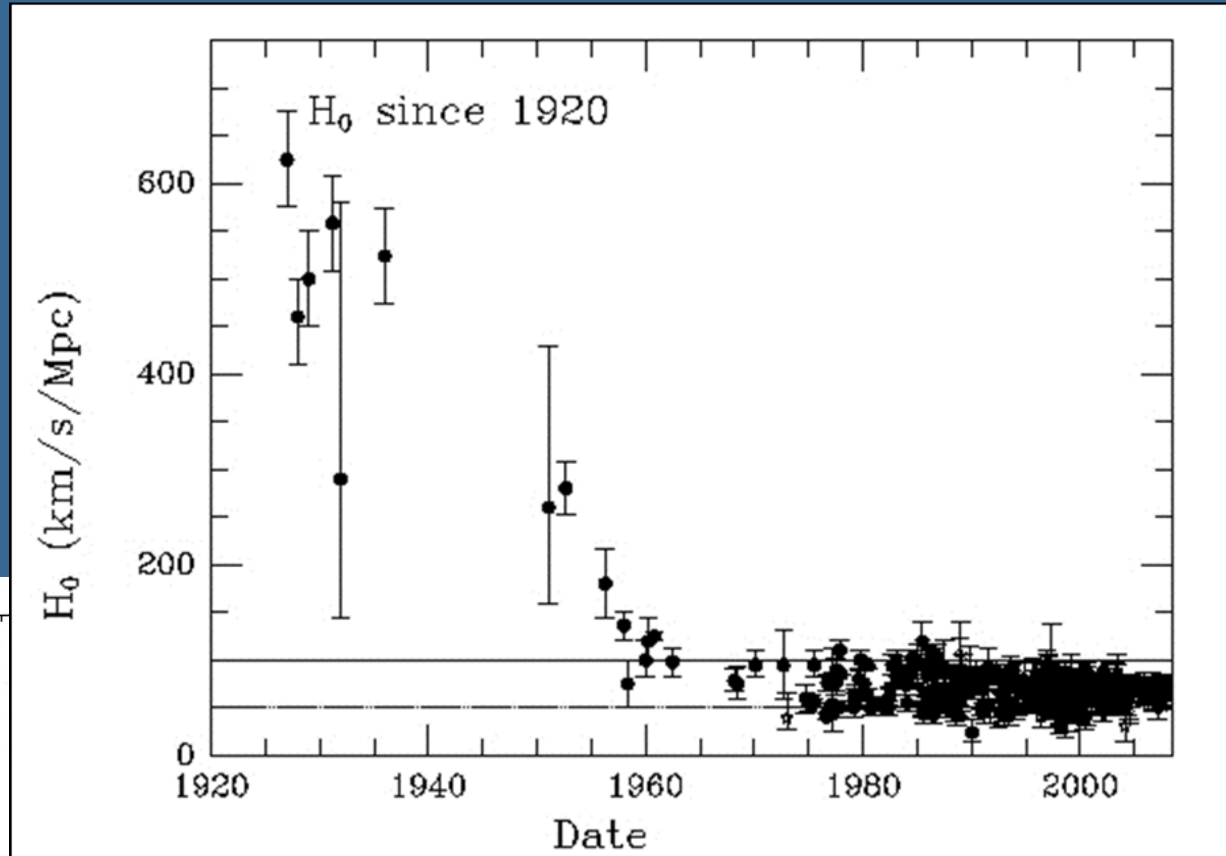
Exponents of the theory of relativity have been inclined to accept the view that the universe is actually expanding. But the apparent central position of our earth, they believe, is an illusion, that may be illustrated by an analogy. Suppose that, during the night, the earth were to double in size, while everything upon its surface were to remain unchanged. In the morning you would awake to find that your neighbor, who previously lived only fifty feet away, was now one hundred feet away. The Smiths, who lived a mile away, would be two miles away. In every direction, there would be an apparent withdrawal, which would be greater for more distant objects. Everybody would be similarly affected and each would believe himself to be the center away from which the other objects had moved.

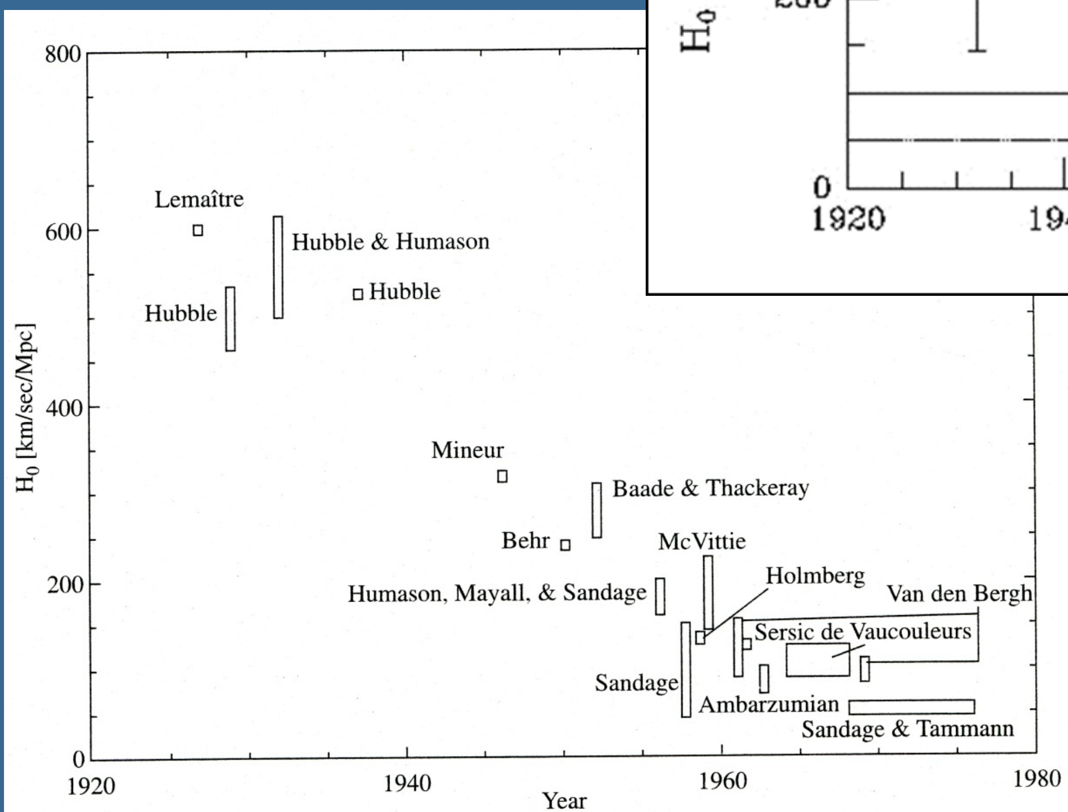
The case of the universe is analogous, except that the expansion, being of a three-dimensional volume, cannot be visualized. The phenomena are, however, comparable. The nebulae are not running away from us. Their recession is due to expansion of space. This may, perhaps, seem to be quibbling over terms, since it amounts to the same thing in the end. Nevertheless, the distinction is worth keeping. According to the relativity theory, there is a difference between the running away of the nebulae and expansion of the medium in which they are imbedded.

The hypothesis, however, is not without difficulties. The expansion is so rapid that, going back only ten thousand million years, we find the stars more closely packed than automobiles are in Times Square in New York City at the theater hour. Ten thousand million years may seem too long to cause us to worry about parking places for prehistoric stars. Nevertheless, geologists tell us that the earth is at least a billion years old and we have come to regard this period as but a minute fraction of the entire lifetime of the universe. Hence the difficulty!

In a sense, this belief is a heritage from the nineteenth century. The great French astronomer, Pierre de Laplace, suggested that the sun and planets might have condensed from a (Continued on page 103)

Hubble's parameter: The incredible shrinking constant





Lemaître 1927 $H_0 \cong 625$ km/s/Mpc

Hubble 1931 $H_0 \cong 558$ km/s/Mpc

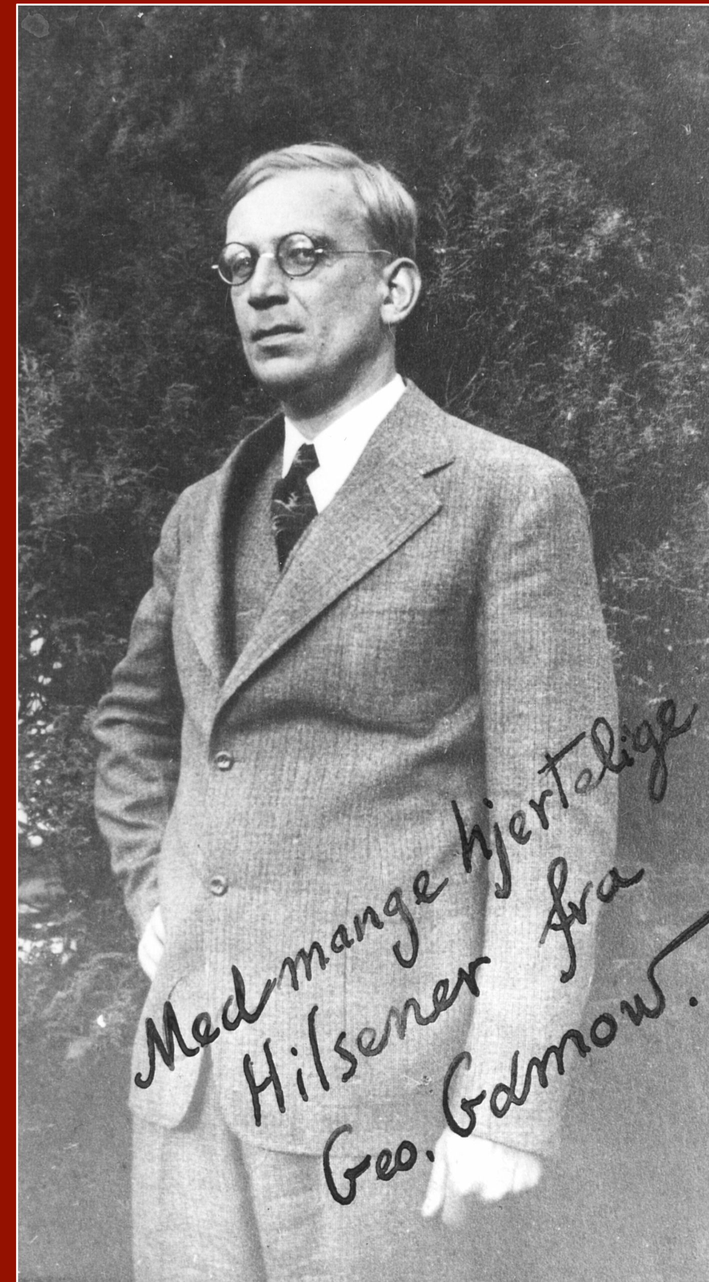
Planck 2015 $H_0 = 67.8$ km/s/Mpc

Oct 24th 1945
19 Thoreau Drive.
Bethesda. Md.

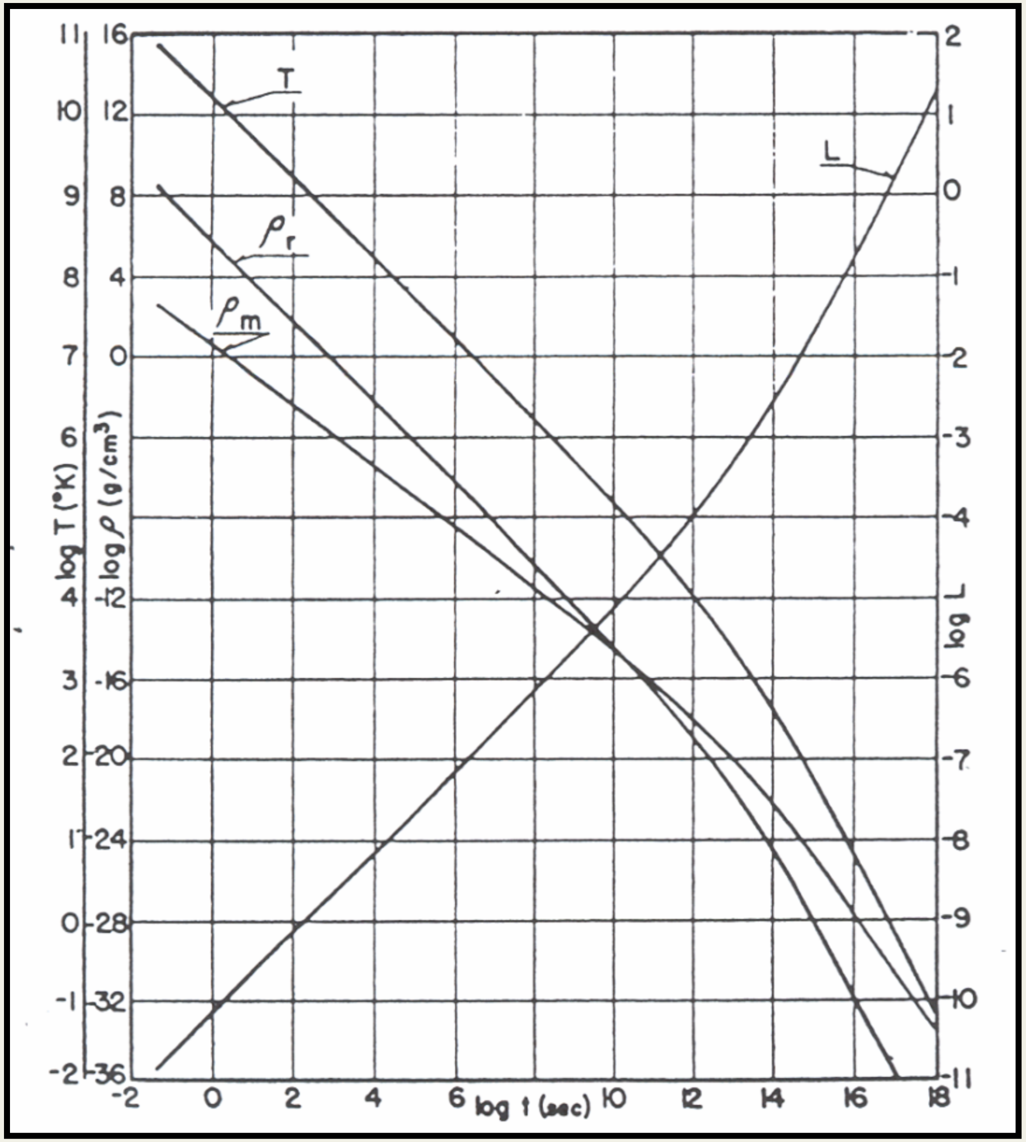
Kære Prof. Bohr, (or should I say Uncle Nick),
Jeg skrive at sende Dem vore bedste Ønskerne for Deres Fødelsedag og ankomst hjeme till København. Det skulde være so morsomt ... no I didn't speak Danish for so long and don't have the dictionary ....

The first suggestion of a nuclear-physical big bang

the expanding univese. It means bringing togeter the relativistic formulæ for expansion and the rates of termonuclear and fission reactions. One interesting point is that the period of time during which the original fission took place* must have been less than one millisecon whereas only about one tenth of the second was avaliable to establish the subsequent termo-dinamical equilibrium (if any) between different lighter nuclei. I am planing to have our next conference here in spring on that problem and the other problems on the borderline between nuclear physics and cosmology. It is such a pitty



The Hot Big Bang



1948-53, G. Gamow, R. Alpher, R. Herman:

A) "hot", radiation-dominated early universe,

B) calculations of primordially produced elements,

C) prediction of a cosmic microwave background.

T. Gold H. Bondi F. Hoyle

Wm. McCrea

J. Narlikar

D. Sciama

The steady-state theory of the universe

The universe expands eternally, with continual creation of matter securing a constant density of mass.

The Perfect Cosmological Principle: On a very large scale, the universe is uniform both in space and time.

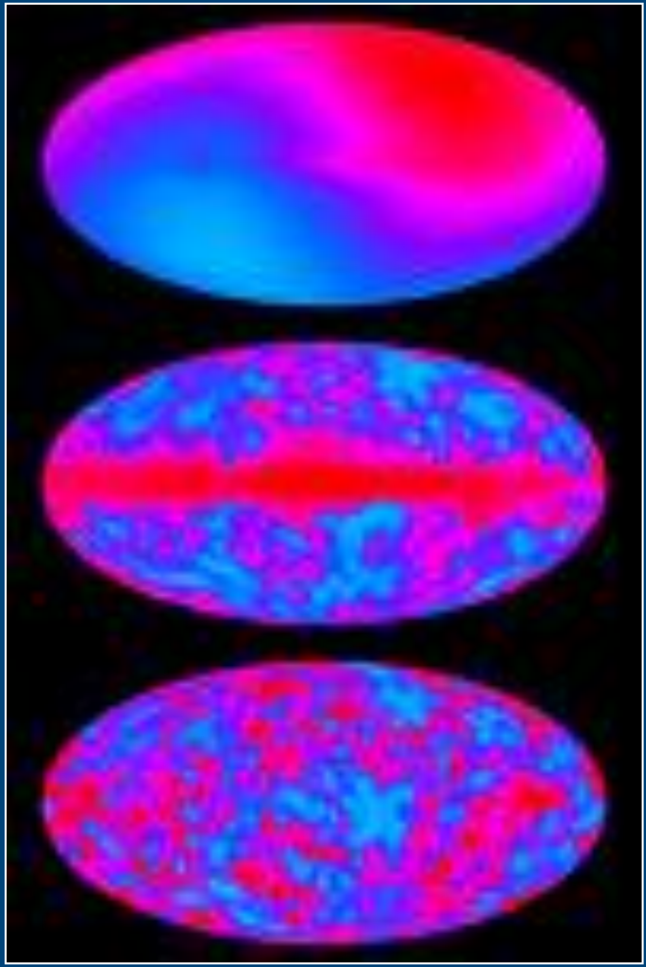
Predictions of classical steady-state theory, ca. 1950

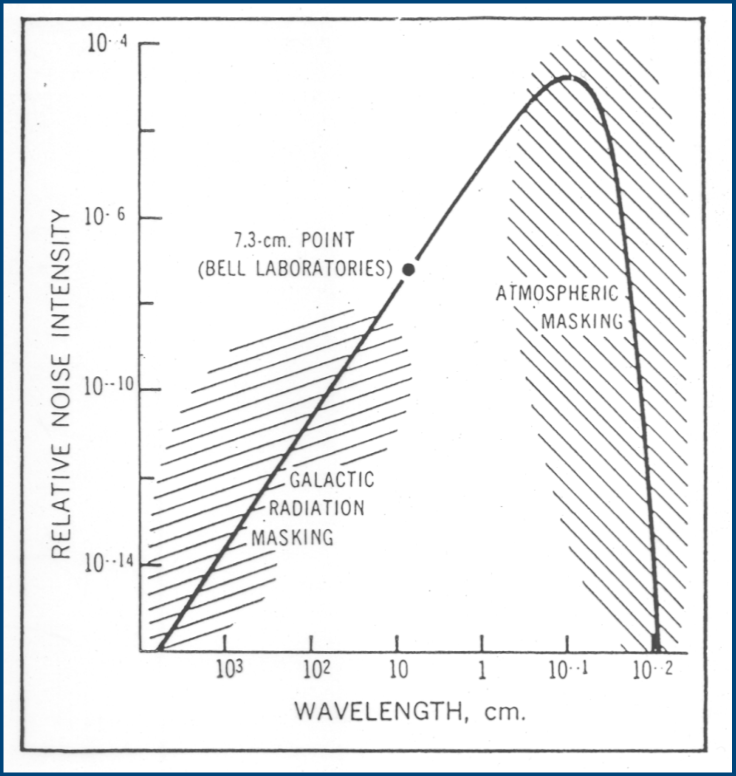
- Space curvature $k = 0$ (flat space)
- Exponential expansion: $R \sim \exp(Ht)$, H constant
- Deceleration parameter $q_0 = -1$
- Matter density $\rho = \rho_{crit} \approx 5 \times 10^{-28}$ g cm^{-3}
- Matter creation rate = $3\rho H \approx 10^{-43}$ g s^{-1} cm^{-3}
- Age of universe: infinite
- All elements synthetized in stars and novae
- Average age of galaxies $\langle t \rangle = T/3 \approx 6 \times 10^{8}$ y ($T \equiv 1/H$)

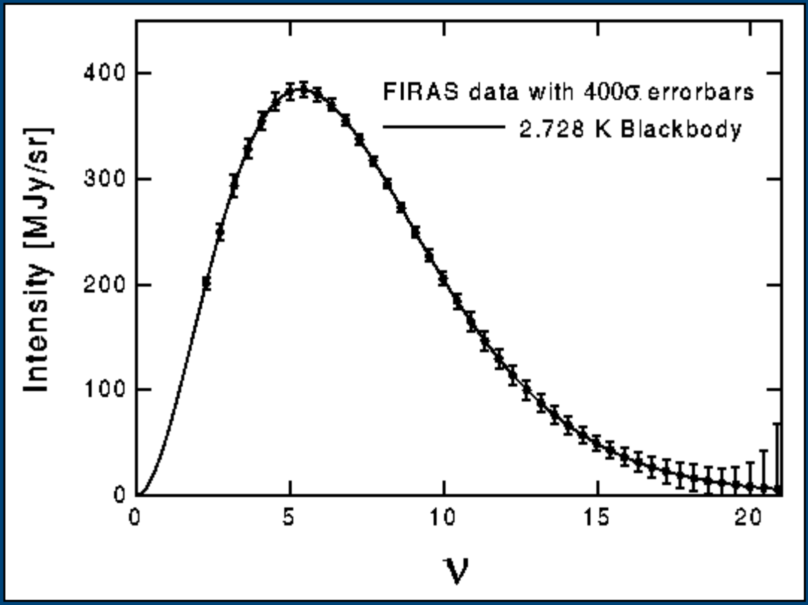
$$q_0 \equiv -\left(\frac{d^2R/dt^2}{RH^2} \right)$$

1965: Discovery of CMB

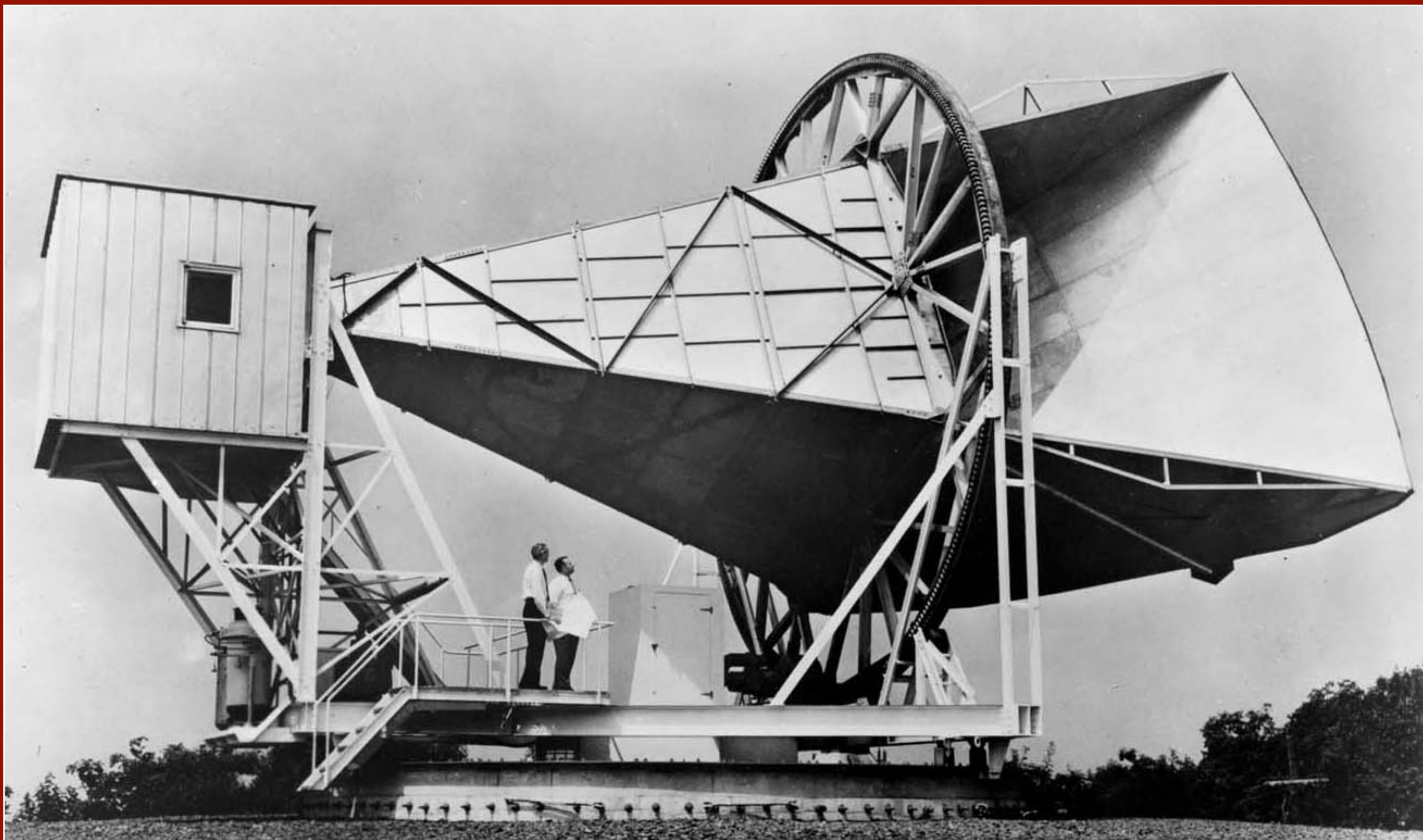
(predicted by R. Alpher og R. Herman in 1948, $T \approx 5$ K)



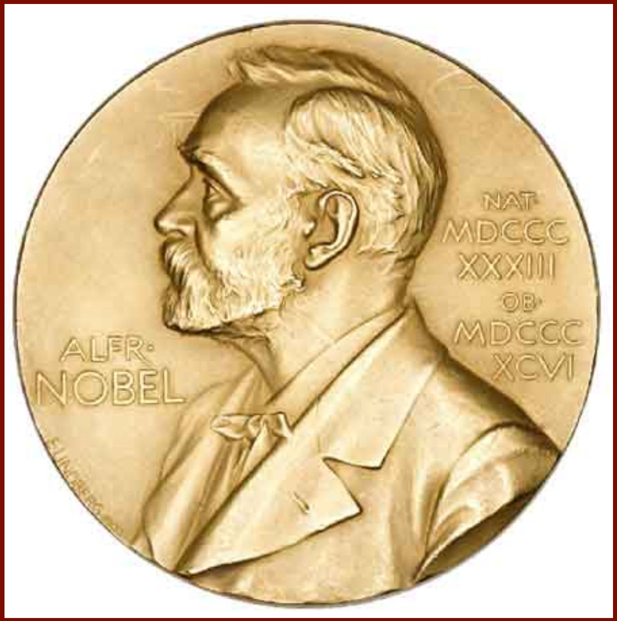




”serendipity”



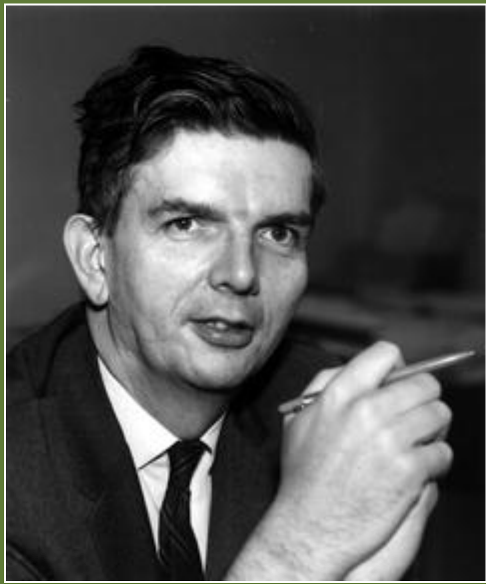
Stockholm, 11 December 1978



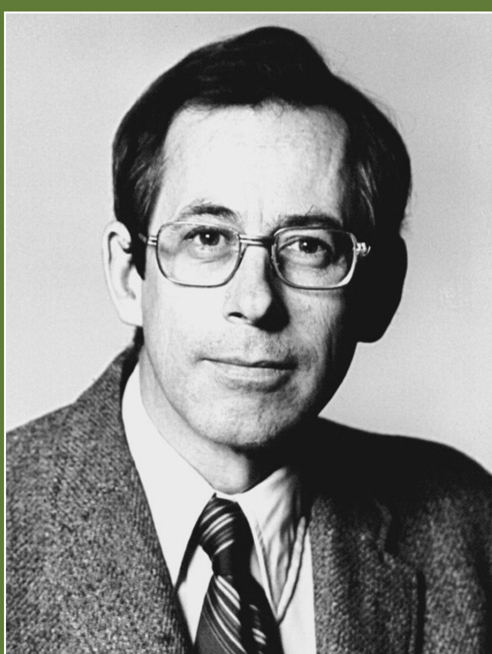
Penzias and Wilson awarded the Nobel Prize "for their discovery of cosmic microwave background radiation," … "after which cosmology is a science, open to verification by experiment and observation."

Did Penzias and Wilson really *discover* the CMB?

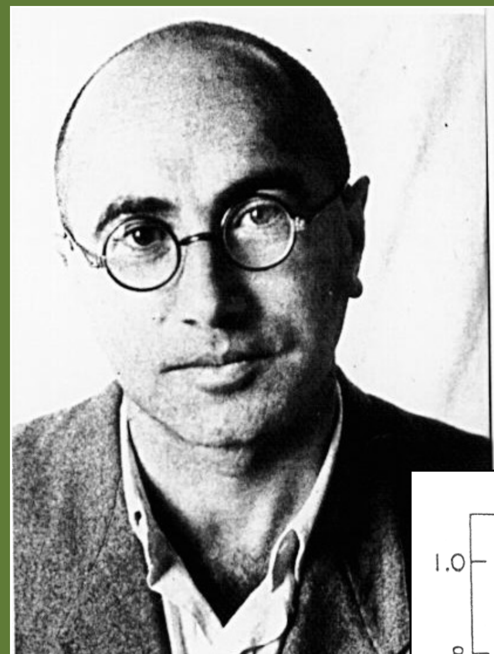
Standard hot-big-bang cosmology (1965+)



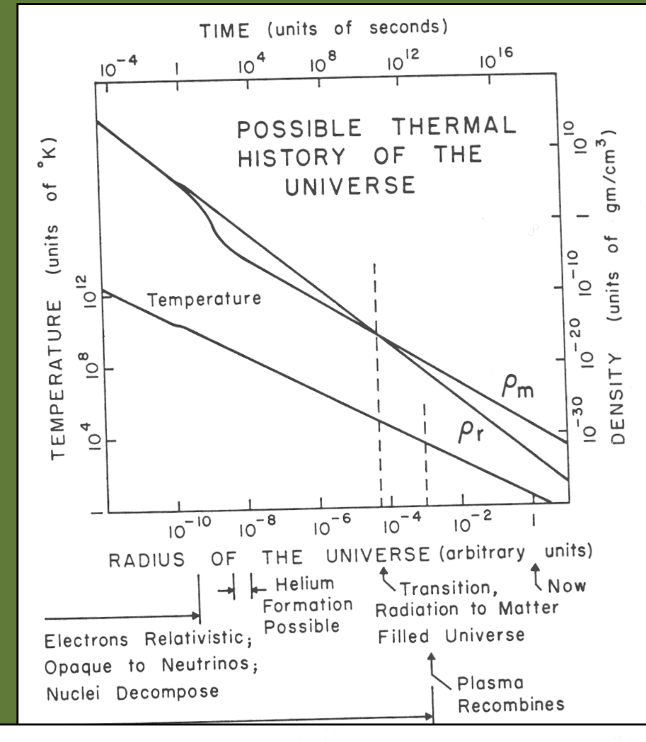
R. Dicke

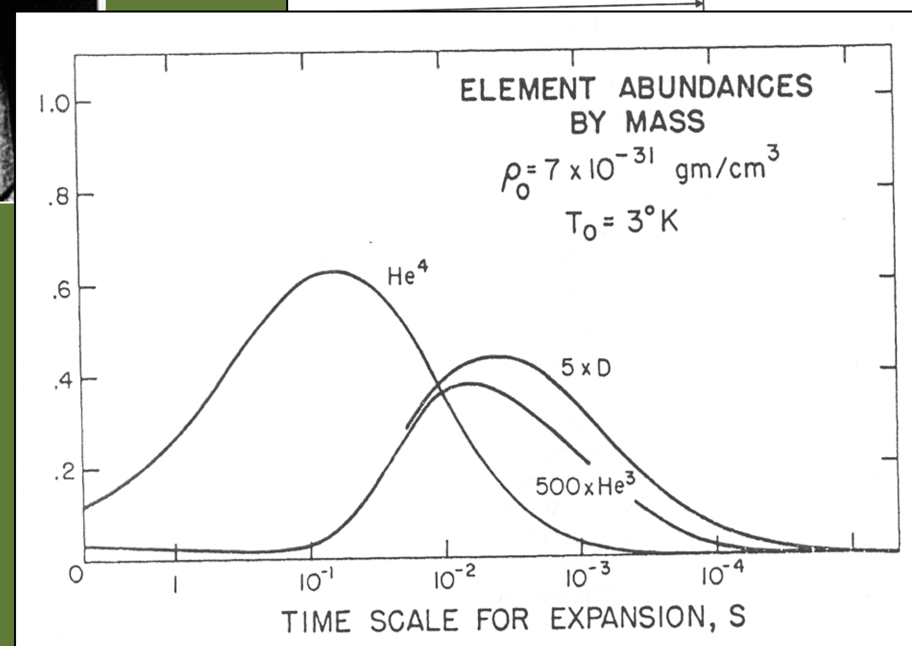


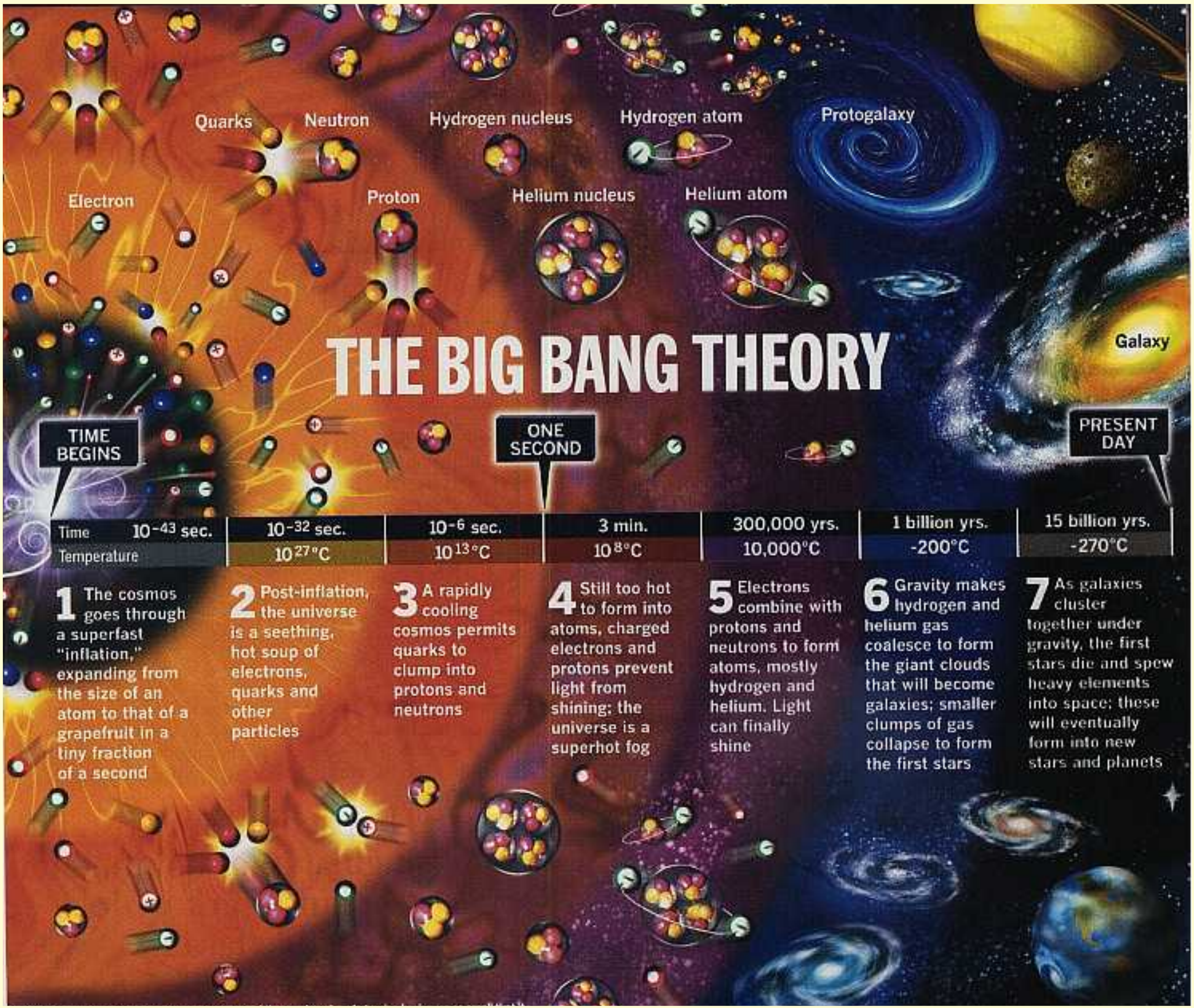
J. Peebles



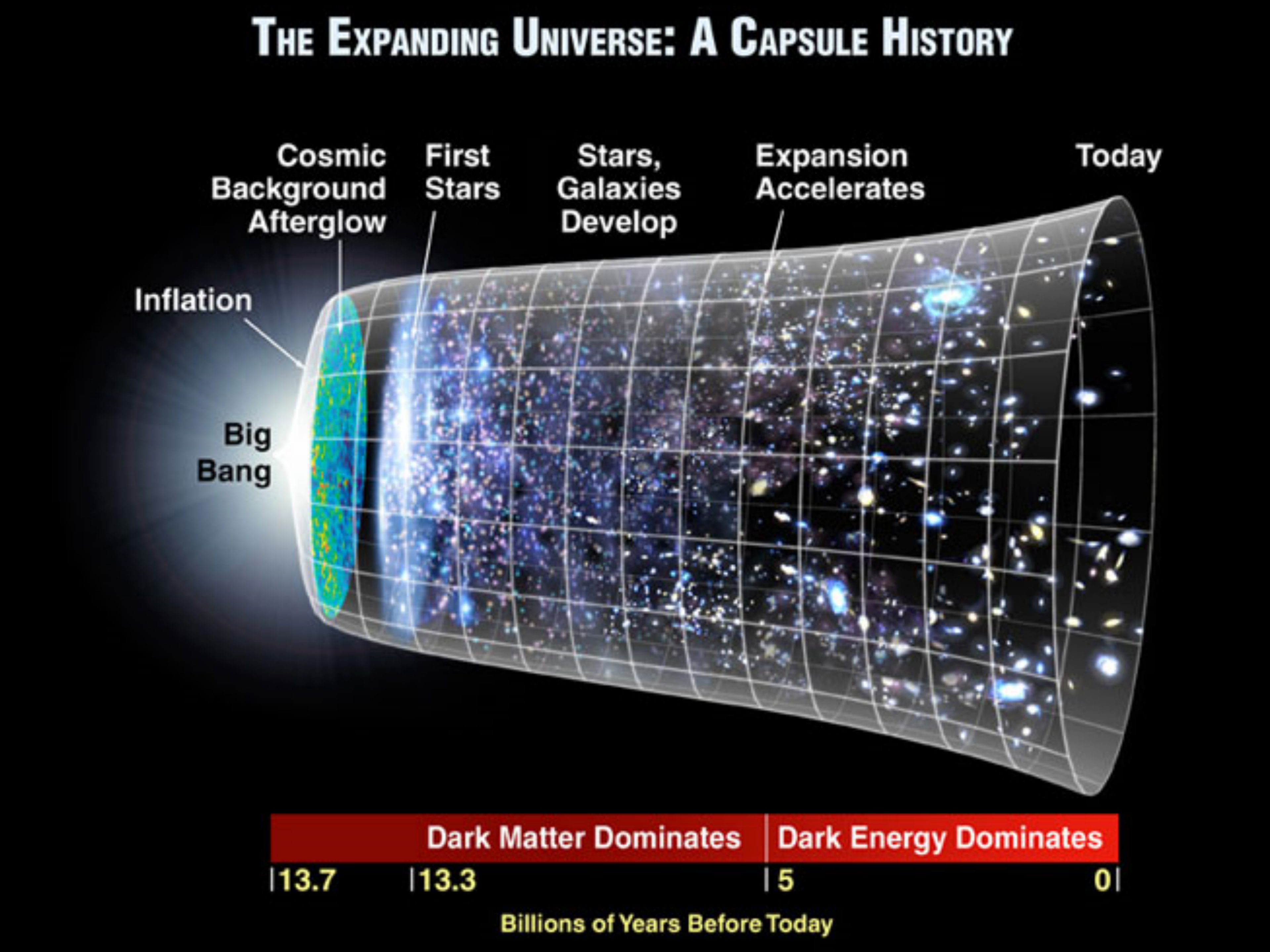
Y. Zel'dovich







Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
THE BIG BANG THEORY
Galaxy
TIME BEGINS
ONE SECOND
PRESENT DAY
Time
Temperature
10^{-43} sec.
10^{-32} sec.
10^{27}°C
10^{-6} sec.
10^{13}°C
3 min.
10^{8}°C
300,000 yrs.
10,000°C
1 billion yrs.
-200°C
15 billion yrs.
-270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets


THE EXPANDING UNIVERSE: A CAPSULE HISTORY
Cosmic Background Afterglow
First Stars
Stars, Galaxies Develop
Expansion Accelerates
Today
Inflation
Big Bang
Dark Matter Dominates
Dark Energy Dominates
13.7
13.3
5
0
Billions of Years Before Today