Histories of dark matter

historical perspective

Book, chapter 17

Evolution of the Universe
Ralph A. Alpher
Robert Herman
Applied Physics Laboratory,
Johns Hopkins University,
Silver Spring, Maryland.
Oct. 25.

THE EVOLUTION OF THE UNIVERSE
By Dr. G. Gamow

NUMERICAL EXPERIMENTS WITH A DISK OF STARS
Frank Hohl
…search Center, …ton, Virginia

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY
S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

PRIMEVAL HELIUM ABUNDANCE AND THE PRIMEVAL FIREBALL*
P. J. E. Peebles

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*
Vera C. Rubin† and W. Kent Ford, Jr.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡
Received 1969 July 7; revised 1969 August 21

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*
J. P. Ostriker
Princeton University Observatory
and
P. J. E. Peebles
…eph Henry Laboratories, Princeton University
Received 1973 May 29

Die Rotverschiebung von extragala…
von F. Zwicky.
(16. II. 33.)

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Radio Waves from Outside the Solar System
Karl G. Jansky.

…olume 59
1954 September ~ No. 1220

MASS DISTRIBUTION AND MASS-LUMINOSITY RATIO IN GALAXIES
By M. Schwarzschild

COSMIC BLACK-BODY RADIATION*
R. H. Dicke
P. J. E. Peeb…
P. G. Roll
D. T. Wilki…

THE ROTATION OF THE ANDROMEDA NEBULA*
by
Horace W. Babcock

…ommunication from the Observatory at Leiden.
The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

The Origin of Chemical Elements
R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
and
H. Bethe
Cornell University, Ithaca, New York
and
G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

The Origin of Elements and the Separation of Galaxies
G. Gamow

ROTATION AND DENSITY DISTRIBUTION OF THE ANDROMEDA NEBULA DERIVED FROM OBSERVATIONS OF THE 21-cm LINE
by H. C. van de Hulst, E. Raimond and H. van Woerden

université PARIS-SACLAY

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Yann Mambrini

General Perspective

Observing the present sky

Clusters of Galaxies (1933)

Rotations curves (1939)

Simulating the Universe (1971)

The dark halo hypothesis (1973)

Observing the primordial sky

The genesis of nucleosynthesis and the CMB (1948)

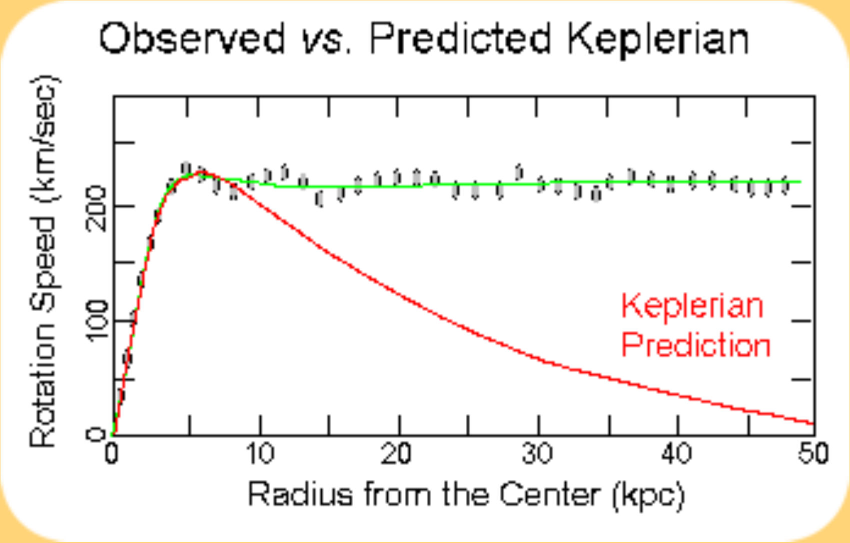
The observation (1965)

Filling the Universe with particles (1967)

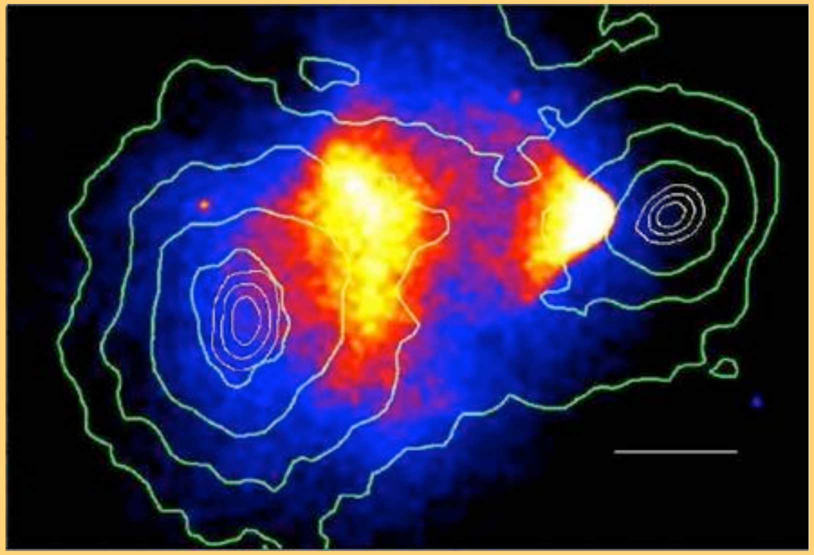
Measuring its composition (Novembre 1984)

3 scales of study

Astrophysics scale

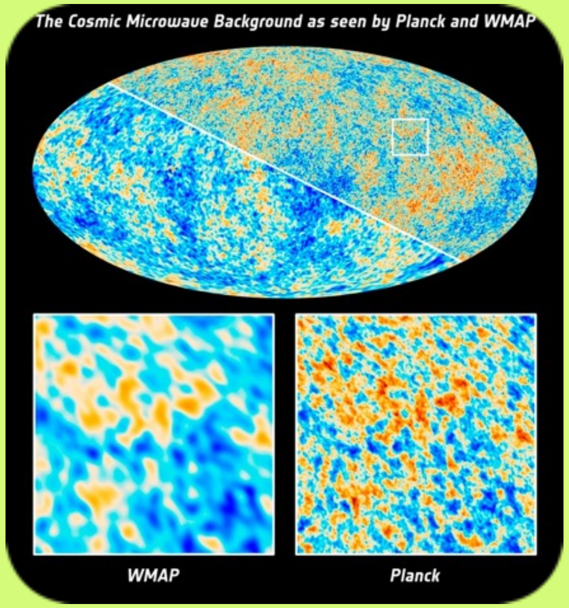


The rotation curve

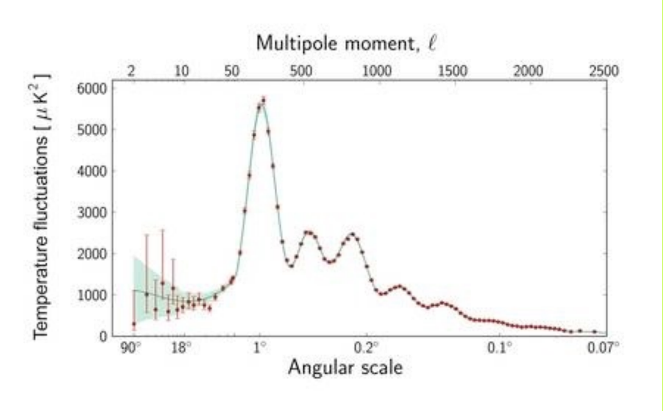


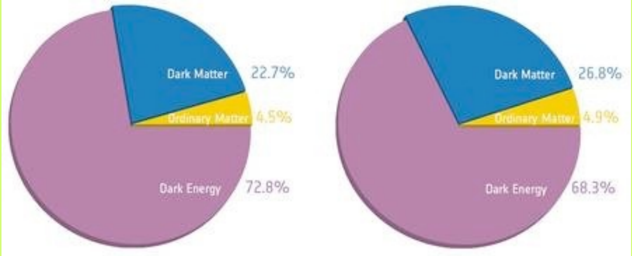
The bullet cluster

Cosmological scale



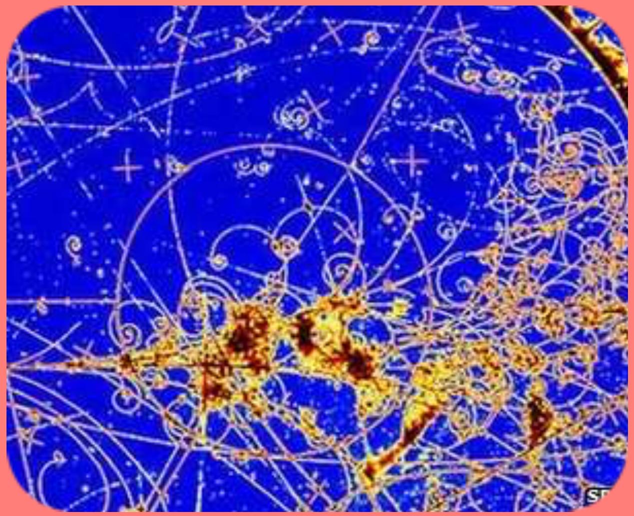
Measurement of the CMB





Particle physics

Cosmic rays

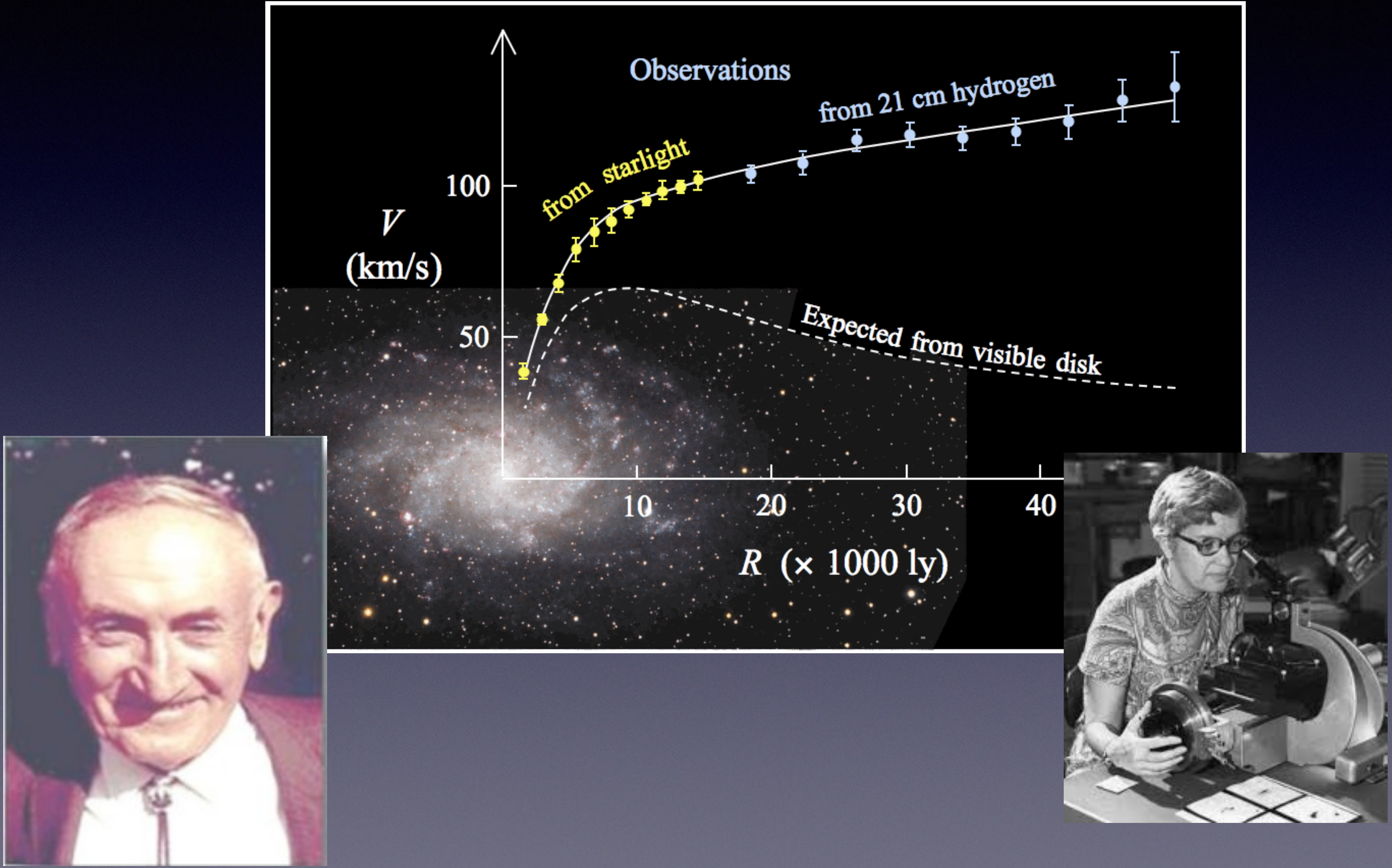


Neutrino sector

Classical introduction on DM

In atrophysics

Rotation curve, Zwicky, Vera Rubin..



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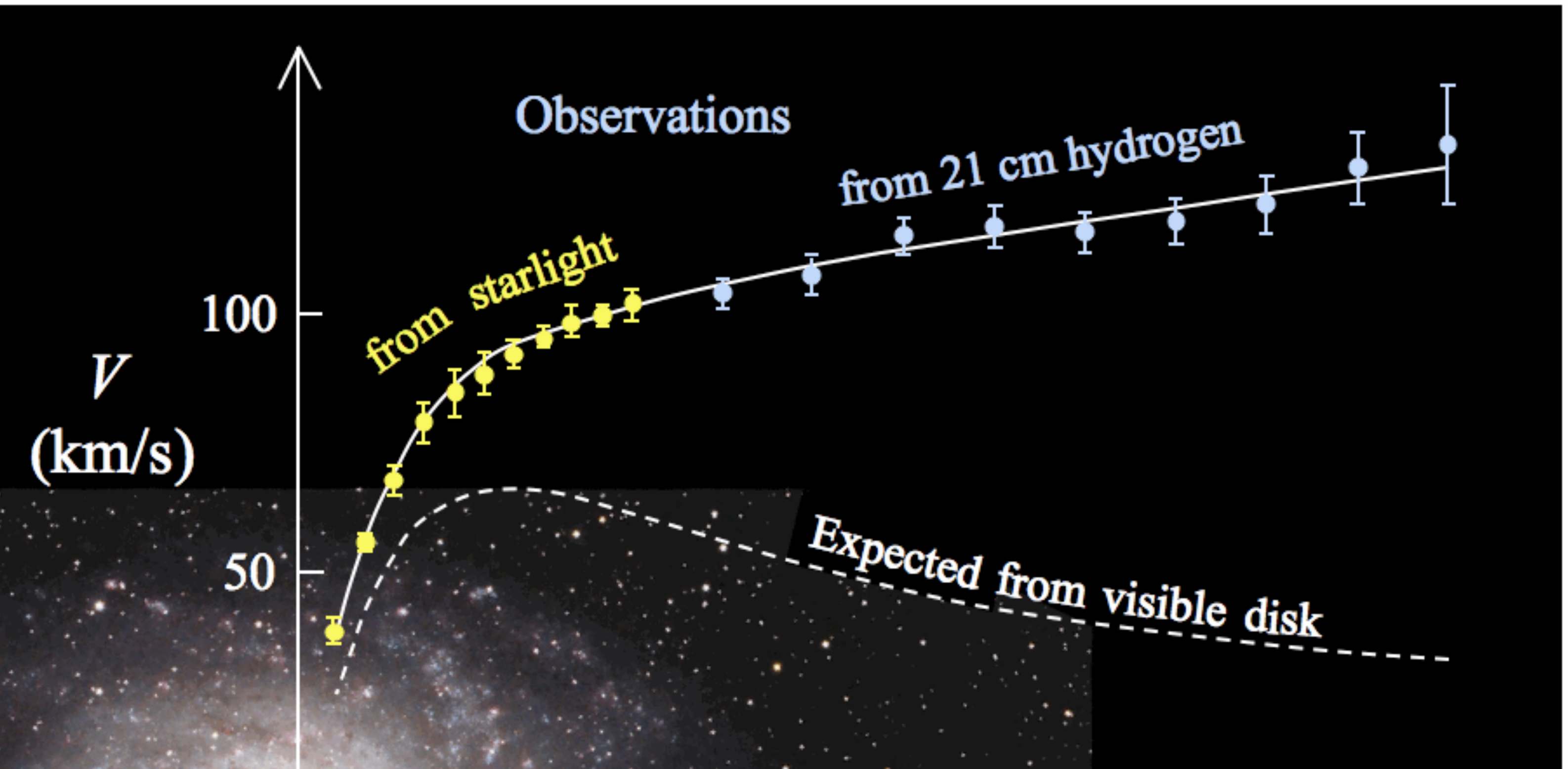

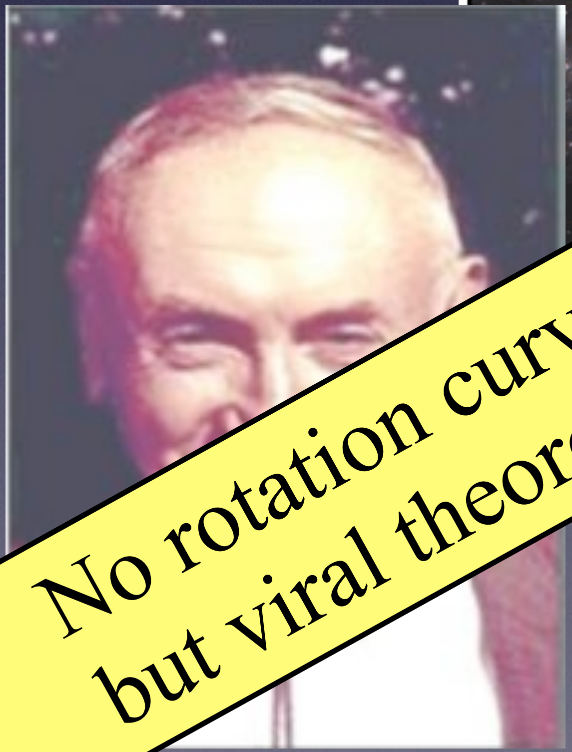

No rotation curve
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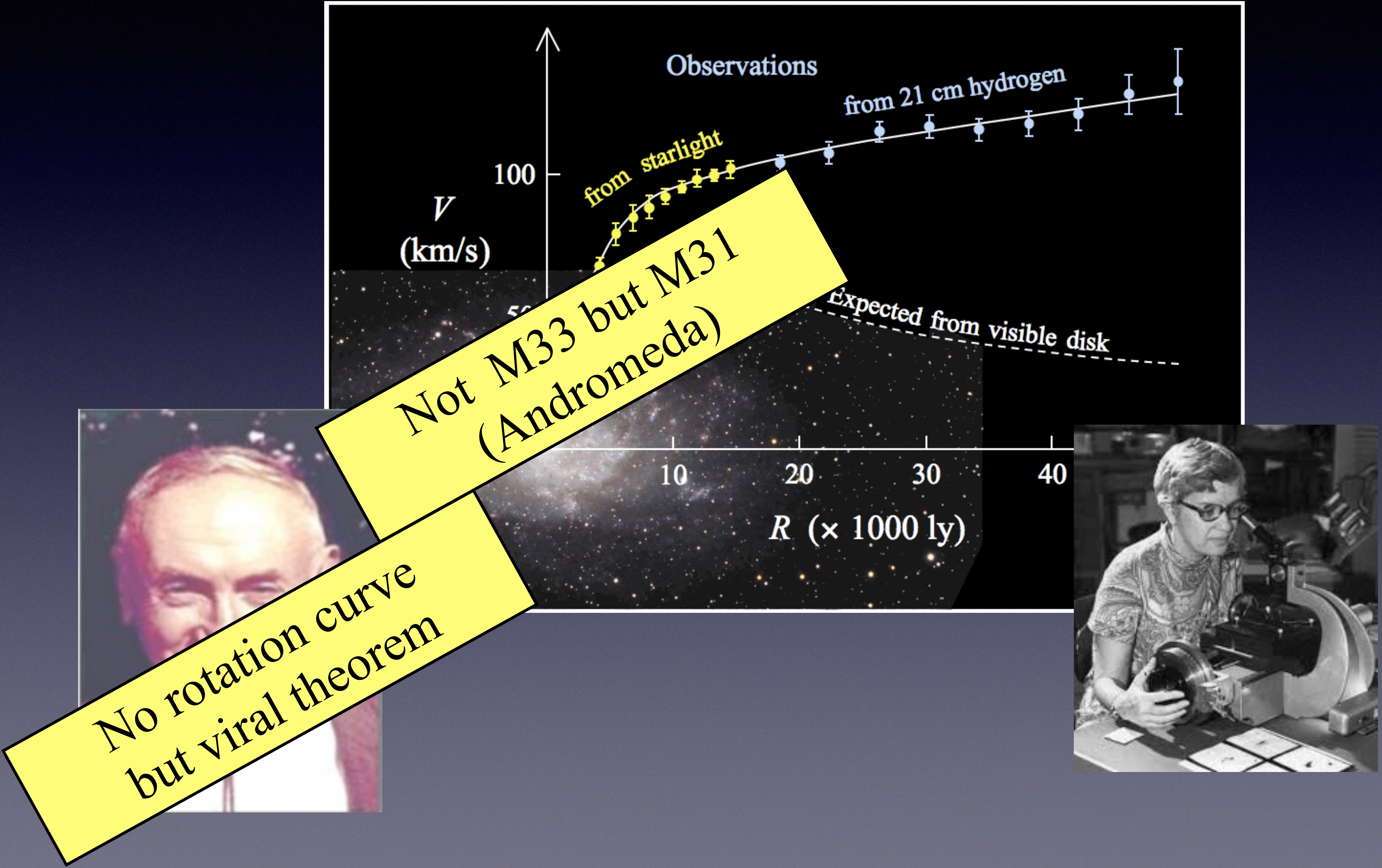

Not M33 but M31 (Andromeda)

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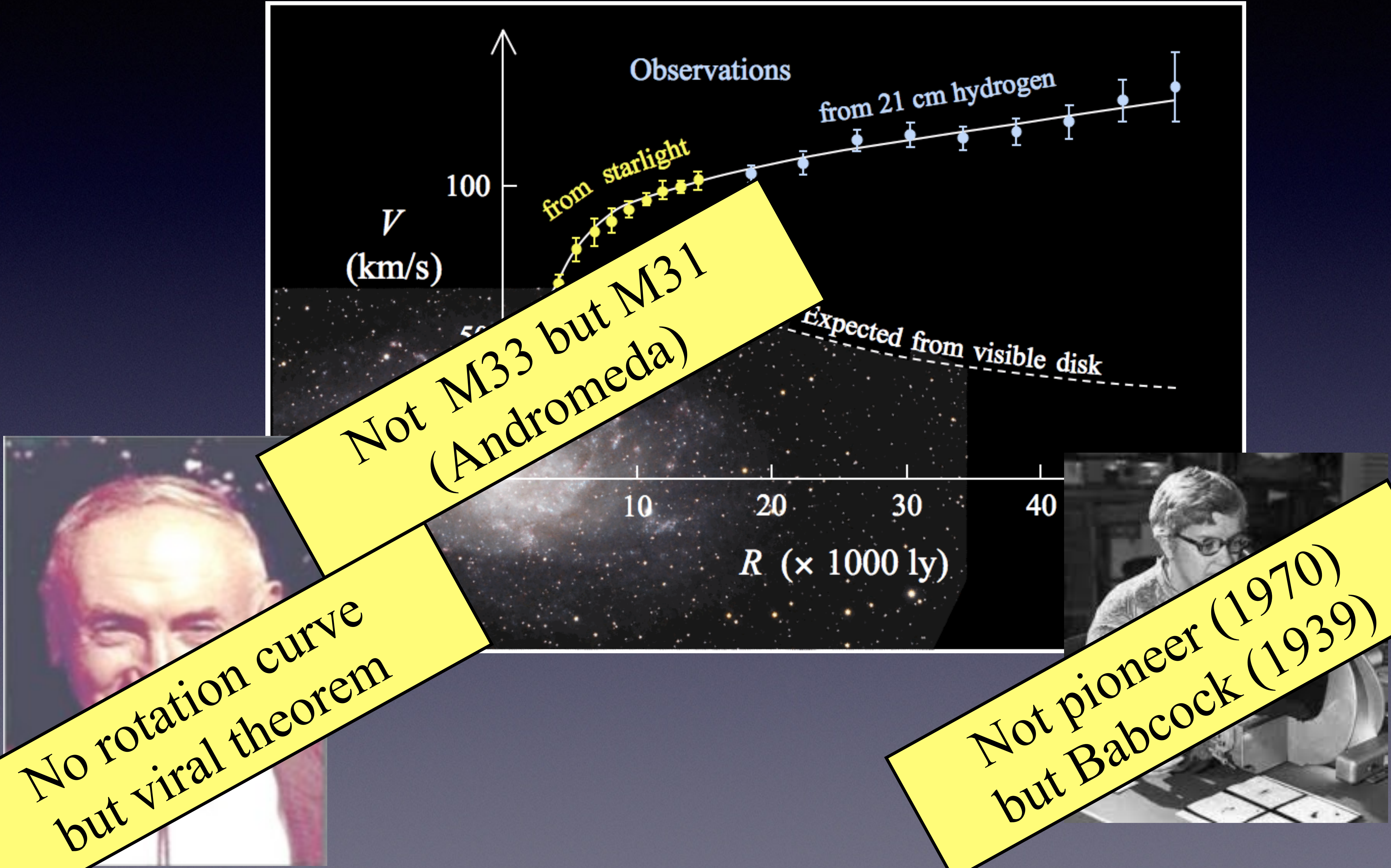


Not M33 but M31 (Andromeda)

No rotation curve but viral theorem

Not pioneer (1970) but Babcock (1939)

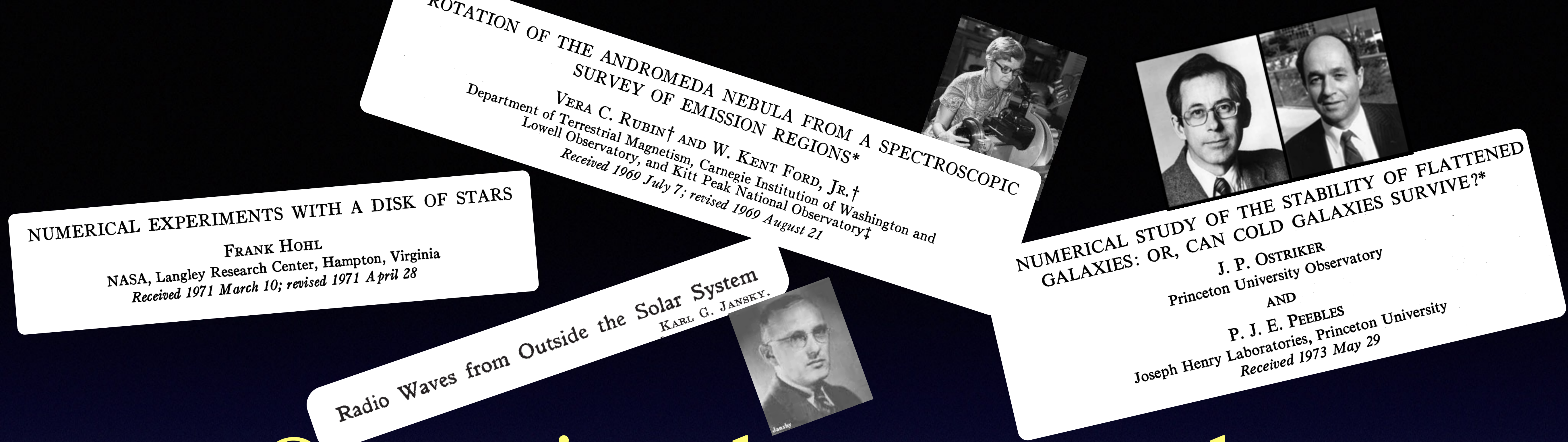
Global Warning

In this historical section, I will retrace the scientific dark matter history. In other words, I will reconstruct step by step how the hypothesis of the existence of a dark structure in the clusters of galaxies, then in the galaxies and finally in the imprints of the Cosmological Microwave Background. It means that several numbers, observations, conclusions will be falsified during the lecture. The distances for instance are twice smaller in the early time due do the Hubble parameter which has been divided by two between its first evaluation in 1930 and now. Same for the age of the Universe, or temperature of the CMB. The aim of the lecture is indeed to make you understand the process of model building from hypothesis that can change with time due to new observations.

All reasonings will be based on the original articles, the complete list of references being given at the end of the lecture.

All the original historical articles discussed in this section can be found on the page:

http://www.ymambrini.com/My_World/History.html



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FRANK HOHL

NASA, Langley Research Center, Hampton, Virginia

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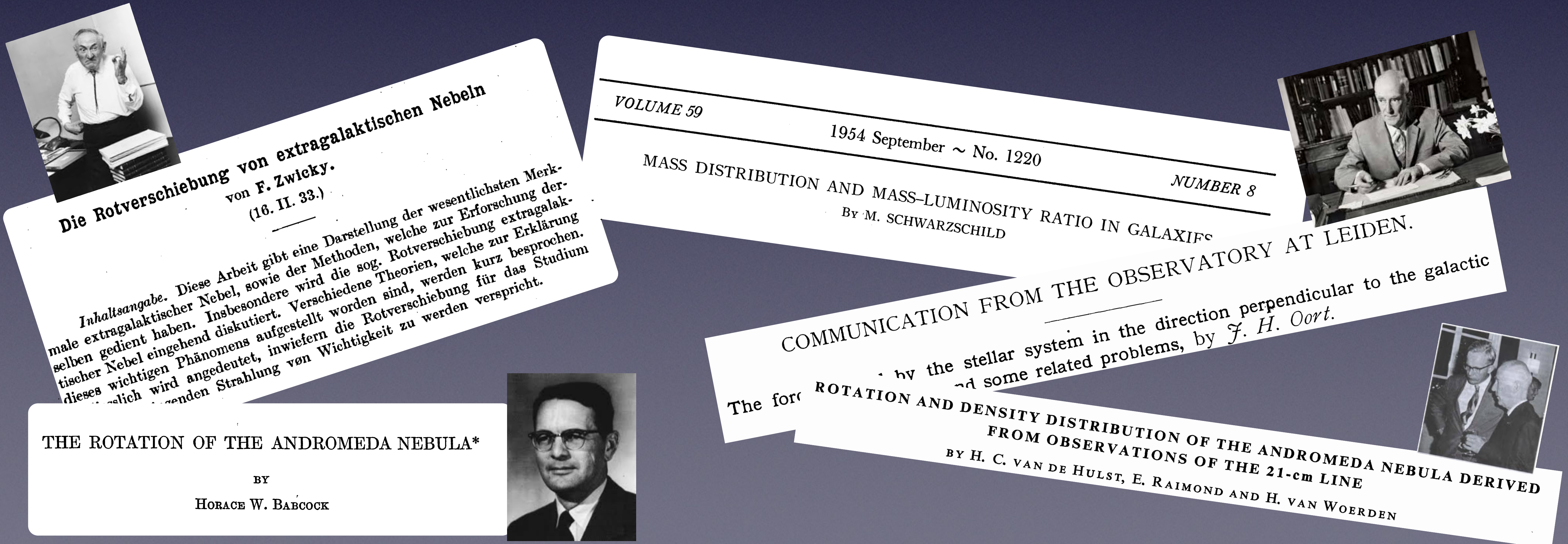
Observing the present sky

From the clusters to the galaxies



Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

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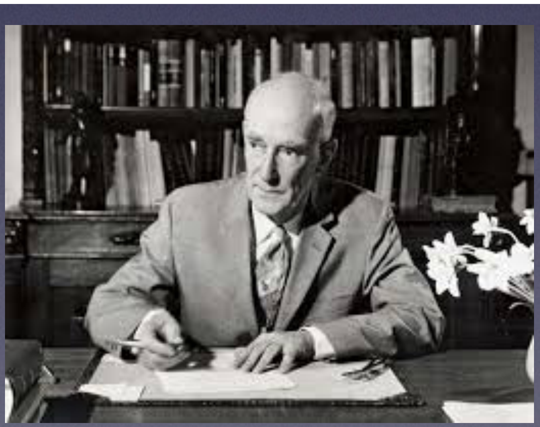
THE ROTATION OF THE ANDROMEDA NEBULA*

BY

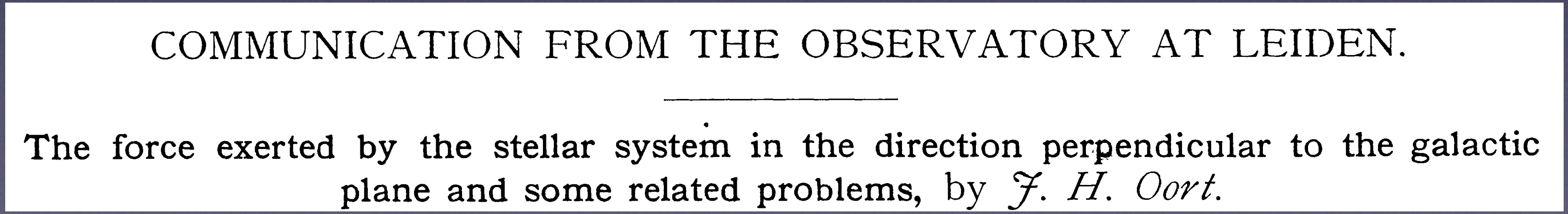
HORACE W. BABCOCK

The early times (1930-1960)

The first appearance of the word « dark matter » in the literature is in a paper of the physicist Jan Oort from Netherland in 1932. While he was analyzing the radial velocities, he notice a discrepancy with Newton law. He computed that only one third of the dynamically inferred mass was present in bright visible stars. It is clear from the context that, as characterizing the remainder as « dark » («Dunkle Materie »), Oort was describing all matter not in the form of visible stars with luminosity comparable or larger than that of the Sun. Gas and dusts between the stars was his « invisible mass » that should be found (for him) soon. The main reason evoked at this time was the presence of low luminosity objects (dead stars) or large absorbing gas. Imagining a new dark component took a very long time to physicists, who even preferred to modified the law of gravity at large scale before invoking a new particle.



Jan Oort



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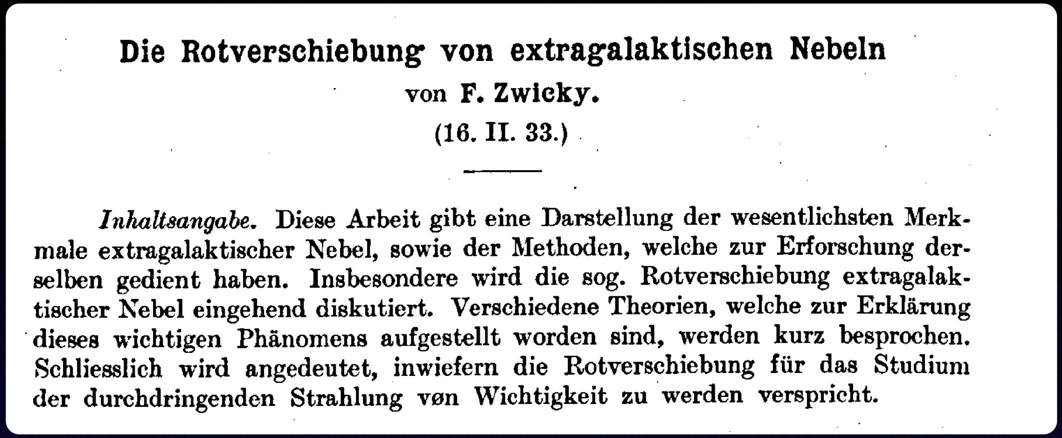
Jan Oort, Bulletin of the Astronomical Institutes of the Netherlands, Vol. 6, p.249

(the original articles can be found there: http://www.ymambrini.com/My_World/History.html)

In this sense, the first real work underlining that the missing mass could be problematic is Fritz Zwicky in 1933

« The Redshift of Extragalactic Nebulae »

Fritz Zwicky, Helv. Phys. Acta 6, 110-127 (1933)



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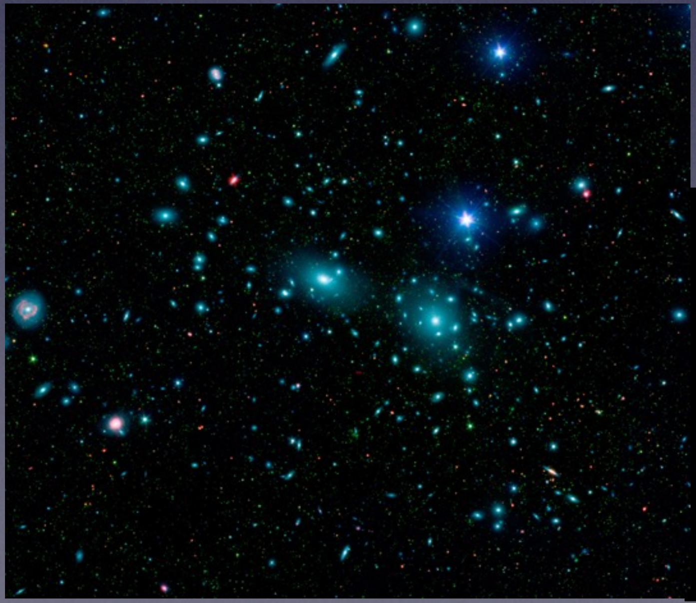
The Redshift of Extragalactic Nebulae

by F. Zwicky.

(16.II.33.)

Contents. This paper gives a representation of the main characteristics of extragalactic nebulae and of the methods which served their exploration. In particular, the so called redshift of extragalactic nebulae is discussed in detail. Different theories which have been worked out in order to explain this important phenomenon will be discussed briefly. Finally it will be indicated to what degree the redshift promises to be important for the study of penetrating radiation.



The Coma Cluster of Galaxies. This is a highly regular gravitationally bound system of thousands of galaxies at a distance of about **100 Mpc** (NASA, SDSS)

§5. Remarks concerning the dispersion of velociti nebular cluster.

As the data in §3 show, there are in the Coma clust velocity of at least 1500 to 2000 km/sec. In the context variation of velocities the following considerations can be m

1. Under the supposition that the Coma system has re cally, a stationary state, the Virial Theorem implies

$$\bar{\epsilon}_k = -\tfrac{1}{2}\bar{\epsilon}_p, \qquad (4)$$

where $\bar{\epsilon}_k$ and $\bar{\epsilon}_p$ denote average kinetic and potential energies, e.g. of the unit of mass in the system. For the purpose of estimation we assume that the matter in the cluster is distributed uniformly in space. The cluster has a radius R of about one million light-years (equal to 10^{24} cm) and contains 800 individual nebulae with a mass of each corresponding to 10^9 solar masses. The mass M of the whole system is therefore

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45} \text{ g}. \qquad (5)$$

This implies for the total potential energy Ω:

$$\boxed{\Omega = -\frac{3}{5}\Gamma\frac{M^2}{R}} \qquad (6)$$

Γ = Gravitational constant

or

$$\bar{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12} \text{ cm}^2\text{s}^{-2} \qquad (7)$$

and then

$$\bar{\varepsilon}_k = \overline{v^2}/2 \sim -\bar{\varepsilon}_p/2 = 32 \times 10^{12} \text{ cm}^2\text{s}^{-2}$$

$$\boxed{\left(\overline{v^2}\right)^{1/2} = 80 \text{ km/s}.} \qquad (8)$$

In order to obtain the observed value of an average Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter.[8] If this would be confirmed we would get the surprising result that dark matter is present in much greater amount than luminous matter.

The calculation

Book, chapter 17

Statement of the virial theorem:

For the n point particles, bound together into a system, the *time average* of the kinetic energy of the particles, $\sum \frac{1}{2} m_i v_i^2$, plus one half of the *time average* of $\sum \vec{F}_i.\vec{r}_i$ is equal to zero.

$$H = \sum \vec{p}_i.\vec{r}_i$$

The average of the derivative of a finite function cancels for large time or periodic H

$$\frac{dH}{dt} = \sum \vec{F}_i.\vec{r}_i + 2K$$

$$\overline{\left(\frac{dH}{dt}\right)} = \sum \overline{\vec{F}_i}.\overline{\vec{r}_i} + 2\overline{K}.$$

$$\overline{K} + \frac{1}{2} \sum \overline{\vec{F}_i}.\overline{\vec{r}_i} = 0$$

$$\vec{F}_i = -\partial V/\partial r_i$$

$$V = -\alpha \frac{GM^2}{R}$$

$$\boxed{\frac{M}{2}\overline{v^2} = \frac{1}{2}\alpha\frac{GM^2}{R}}$$

α depends on the shape of the halo
(3/5 for an homogenous sphere)

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Zwicky took 7500 km/s as a mean velocity to obtain D=50 Mpc (v=H x D)

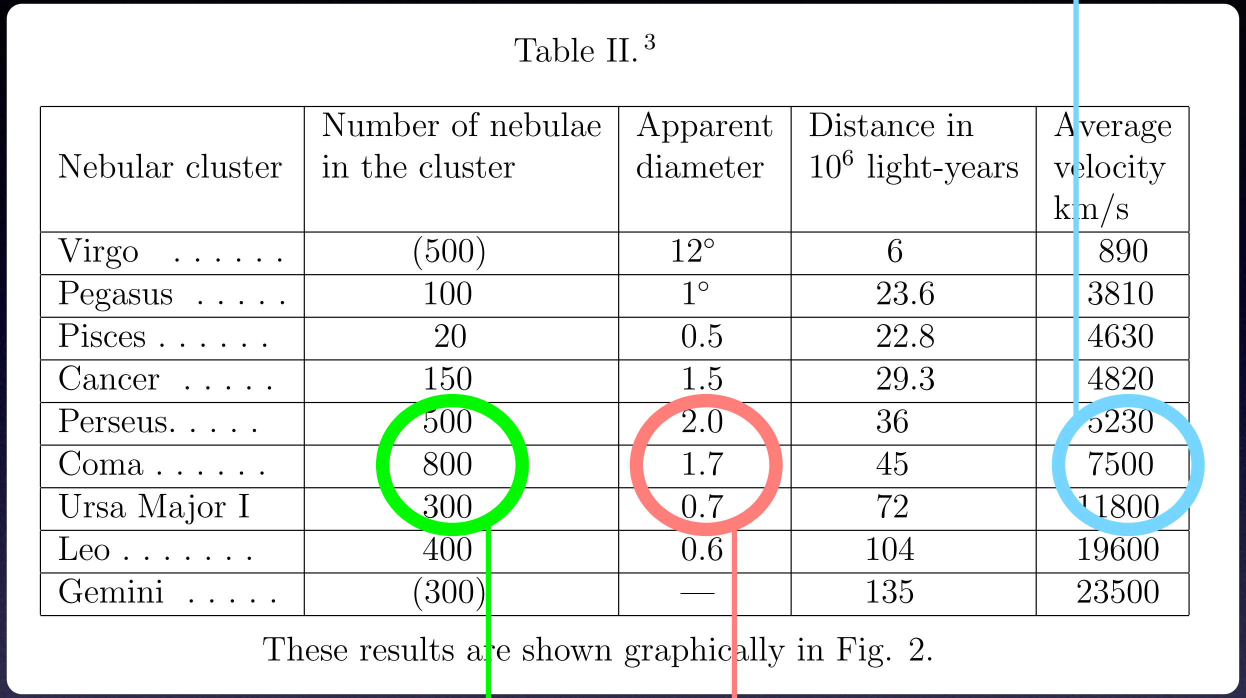


Table II.[3]

Nebular cluster	Number of nebulae in the cluster	Apparent diameter	Distance in 10^6 light-years	Average velocity km/s
Virgo	(500)	12°	6	890
Pegasus	100	1°	23.6	3810
Pisces	20	0.5	22.8	4630
Cancer	150	1.5	29.3	4820
Perseus.	500	2.0	36	5230
Coma	800	1.7	45	7500
Ursa Major I	300	0.7	72	11800
Leo	400	0.6	104	19600
Gemini	(300)	—	135	23500

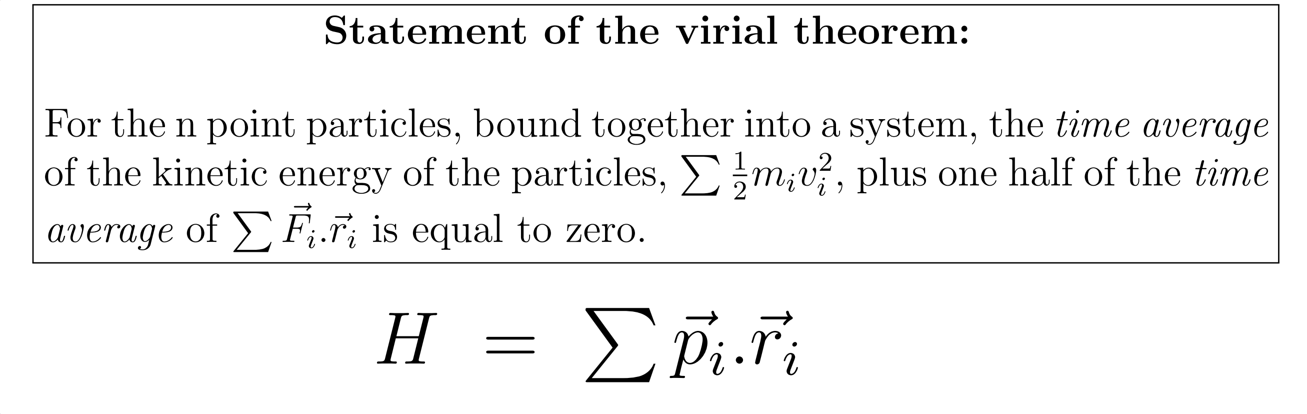
These results are shown graphically in Fig. 2.

From the apparent diameter d, Zwicky deduced the radius of the cluster, R= d x D = 1Mpc

And 800 galaxies of 10^9 solar mass in the cluster

The calculation

Book, chapter 17



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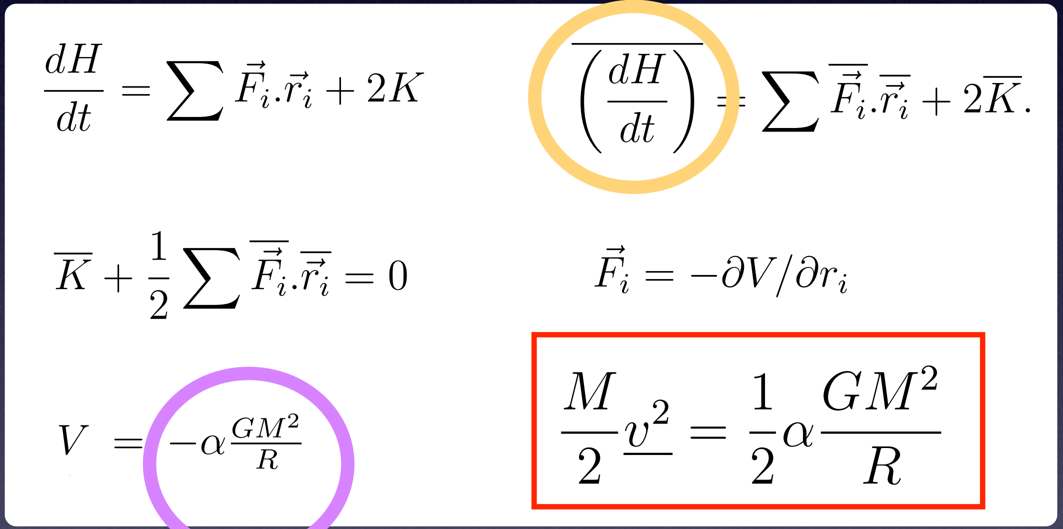

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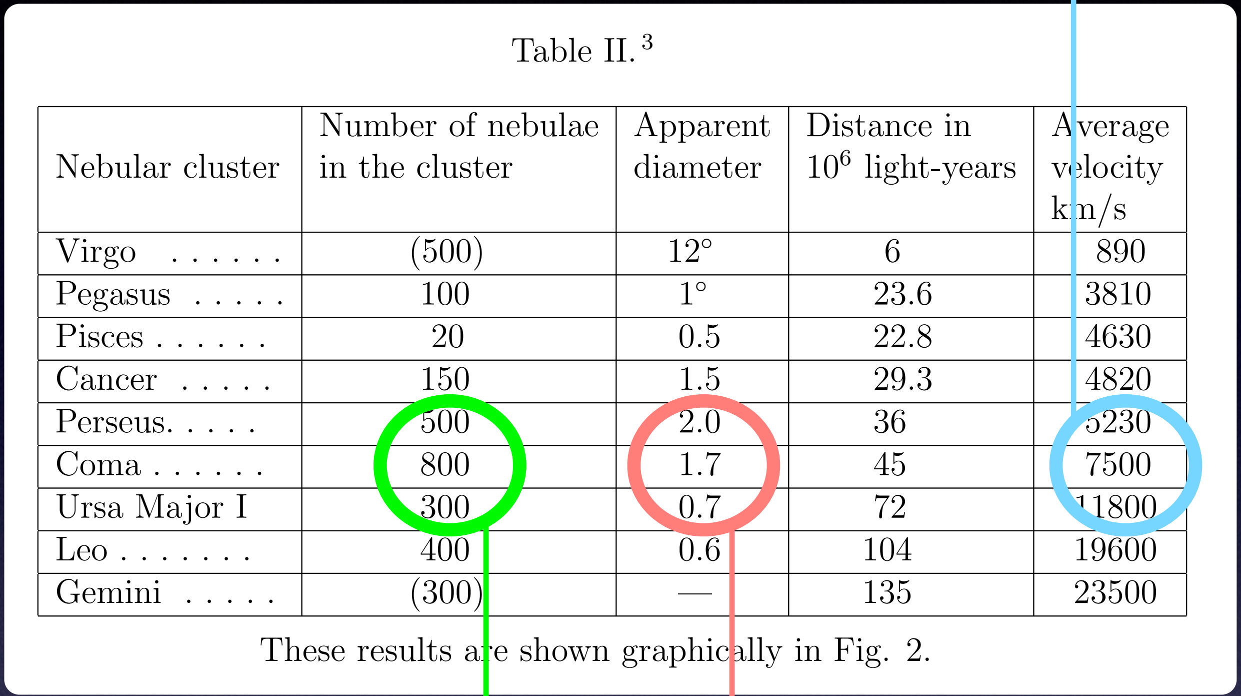

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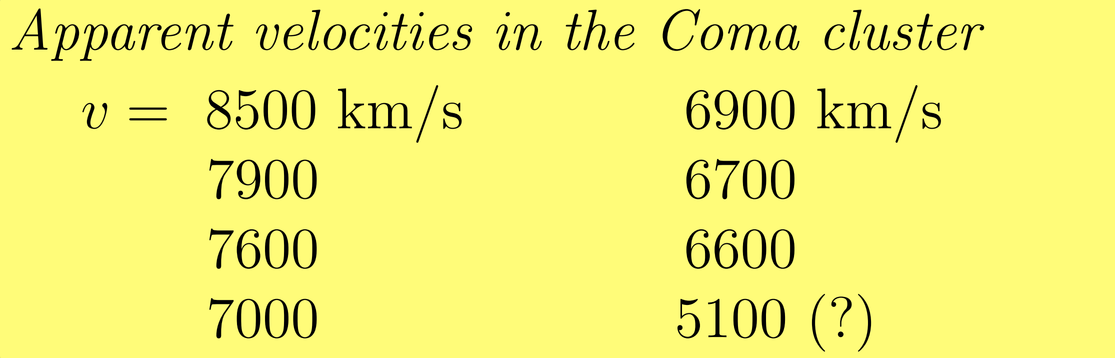
He considered that the spread in velocities (~1000km/s) correspond to a mean velocity of the galaxies inside the cluster

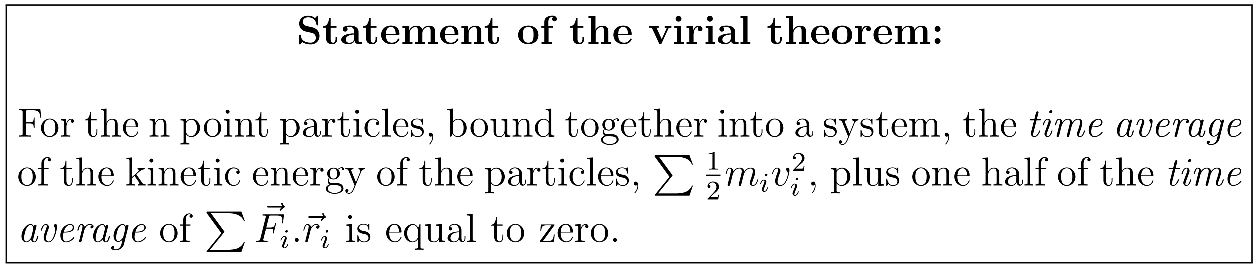


Apparent velocities in the Coma cluster

$v =$	8500 km/s	6900 km/s
	7900	6700
	7600	6600
	7000	5100 (?)

The calculation

Book, chapter 17



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$$\underline{v^2} = \frac{3}{5} \frac{GM}{R} = \frac{3}{5} \times \frac{6.67 \times 10^{-11} \times 1.6 \times 10^{42}}{10^{22}} \Rightarrow \sqrt{\underline{v^2}} \simeq 80 \text{ km/s}.$$

One observed velocity spread of 1000 km/s whereas one should oversee 80 km/s. Mass of the Coma should then be larger by a factor **few thousands**.

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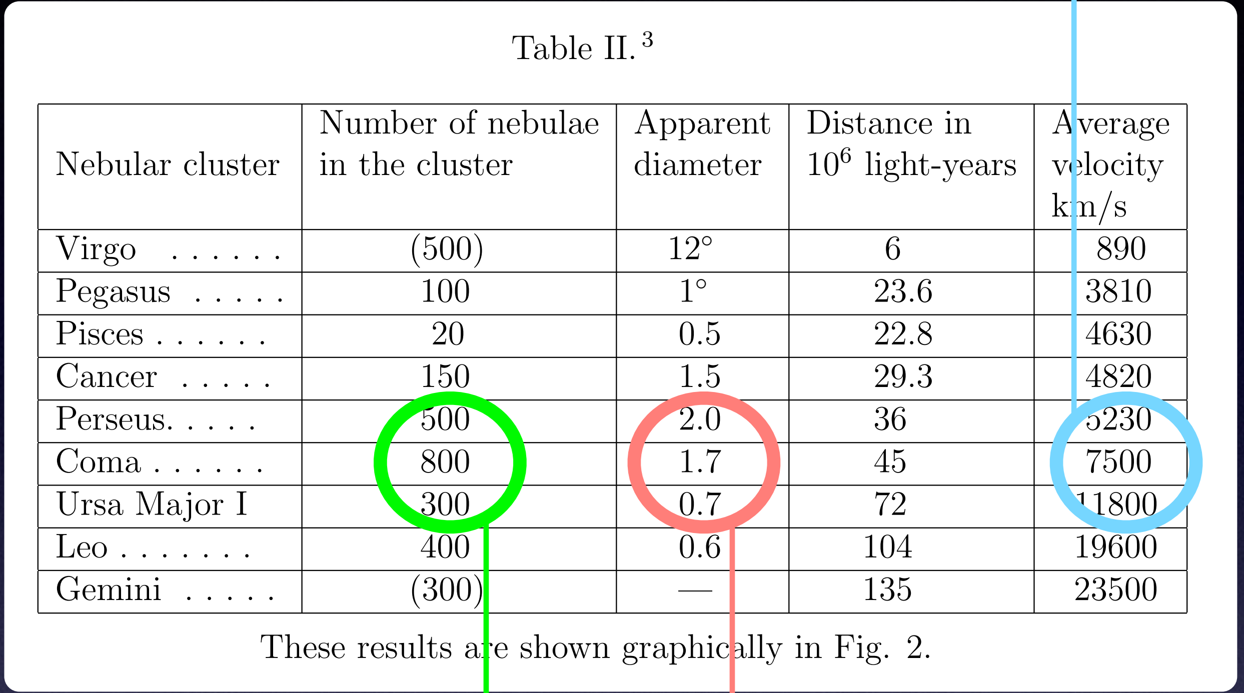

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Pisces	20	0.5	22.8	4630
Cancer	150	1.5	29.3	4820
Perseus.	500	2.0	36	5230
Coma	800	1.7	45	7500
Ursa Major I	300	0.7	72	11800
Leo	400	0.6	104	19600
Gemini	(300)	—	135	23500

These results are shown graphically in Fig. 2.

From the apparent diameter d, Zwicky deduced the radius of the cluster, R= d x D = 1Mpc

And 800 galaxies of 10^9 solar mass in the cluster

He considered that the spread in velocities (~1000km/s) correspond to a mean velocity of the galaxies inside the cluster

Apparent velocities in the Coma cluster

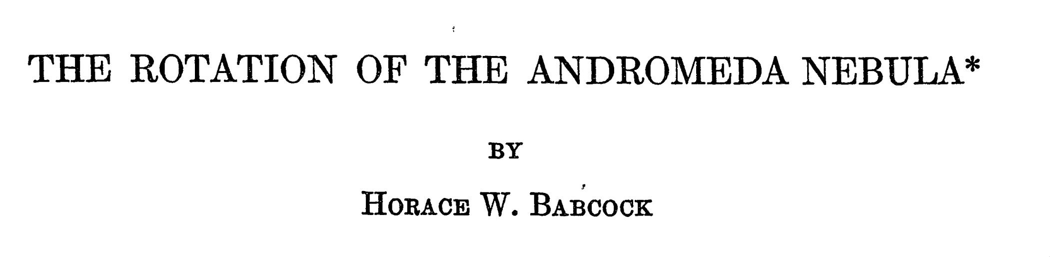
$v =$	8500 km/s	6900 km/s
	7900	6700
	7600	6600
	7000	5100 (?)

Conclusion of the Zwicky article

« In order to obtain the observed value of an average Doppler effect of 1000 km/s or more, the average density in the Coma system **would have to be at least 400 times larger** than that derived on the grounds of observations of luminous matter. If this would be confirmed we would get the surprising result that **dark matter is present in much greater amount than luminous matter** »

This result was completely forgotten and nobody took really seriously this comment of Zwicky. Indeed, the large scale astrophysics was at its beginning after the Hubble discovery and a lot of physicists believed that the « missing mass » problem will be solved once we will understand better the mechanism of absorption of light in the interstellar/internebulae medium. In fact, the « missing mass » problem was a this time considered as a « missing luminosity » problem: why we do not see the astrophysics bodies that should be responsible of the Newtonian dynamics. On the other hand, several scientists tried to modify (already in the 30's) the $1/r^2$ attraction law. Then began the galaxies analysis.

At the Galactic scale


THE ROTATION OF THE ANDROMEDA NEBULA*

BY

HORACE W. BABCOCK

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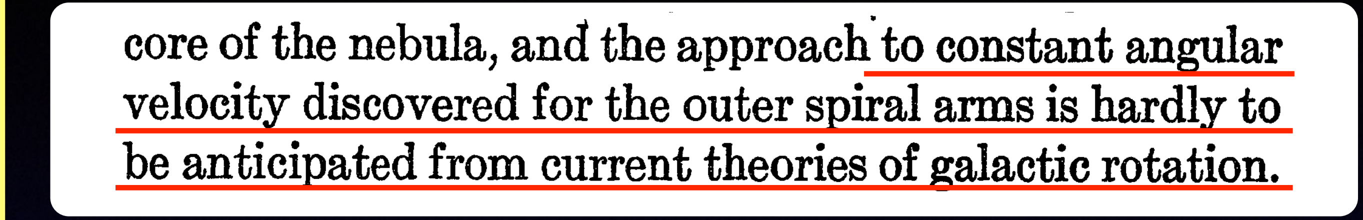
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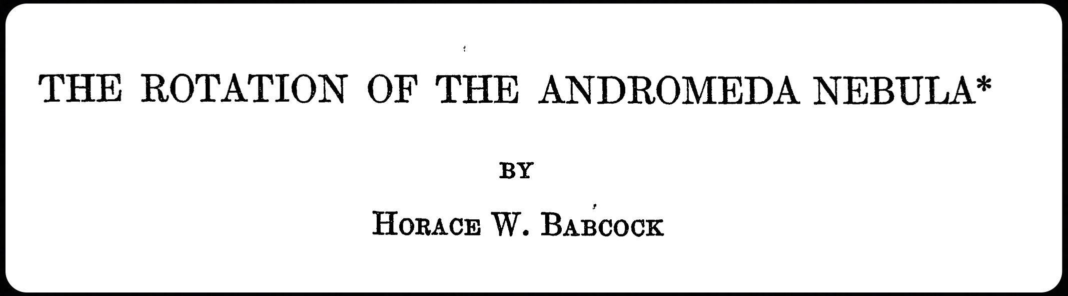
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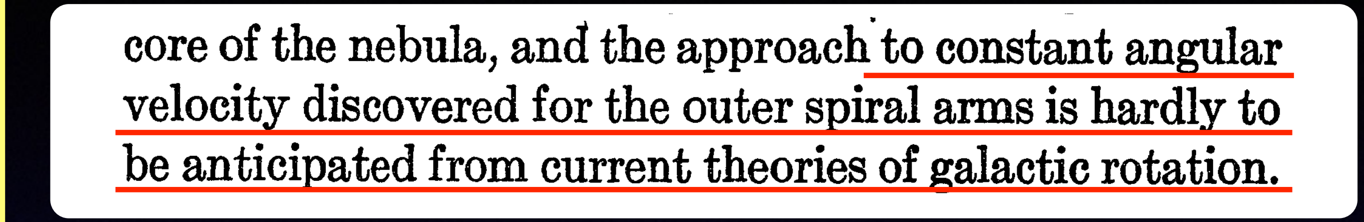
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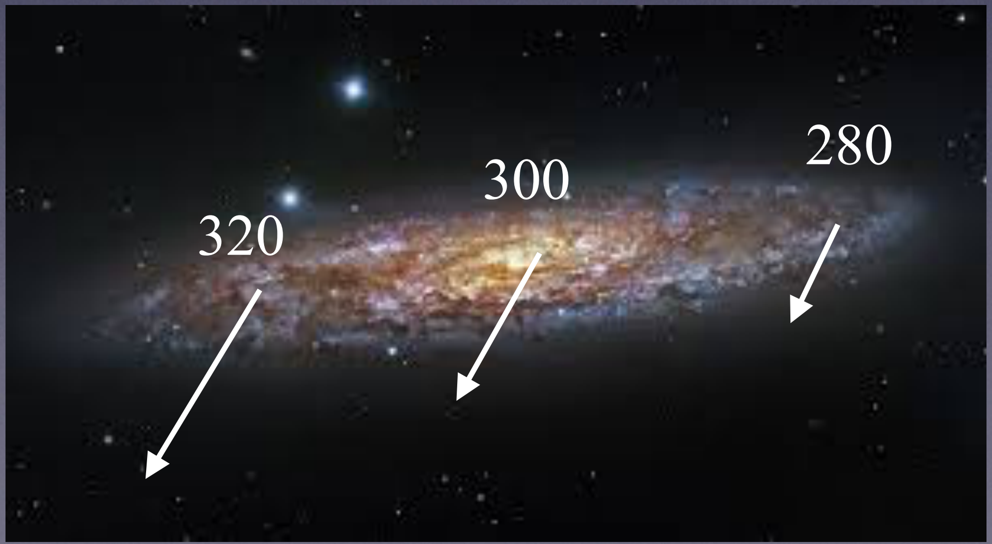

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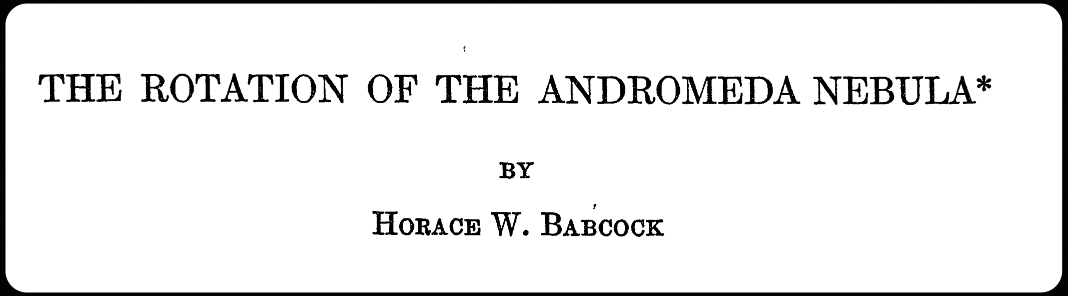

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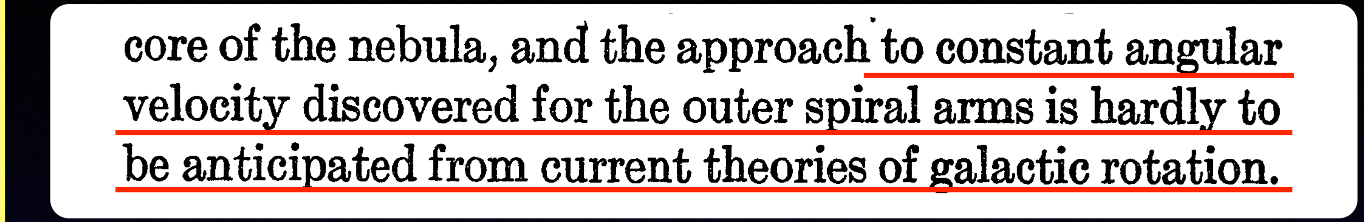

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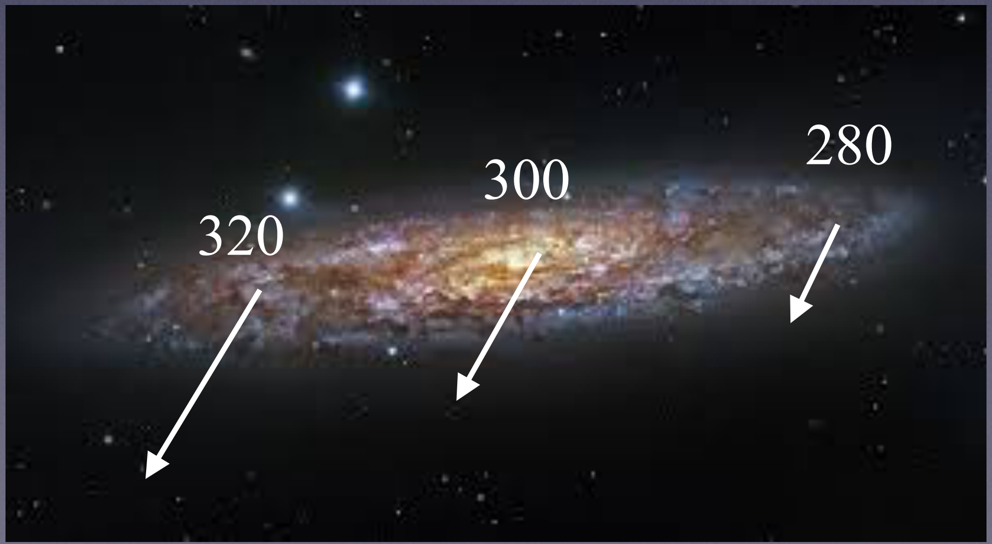

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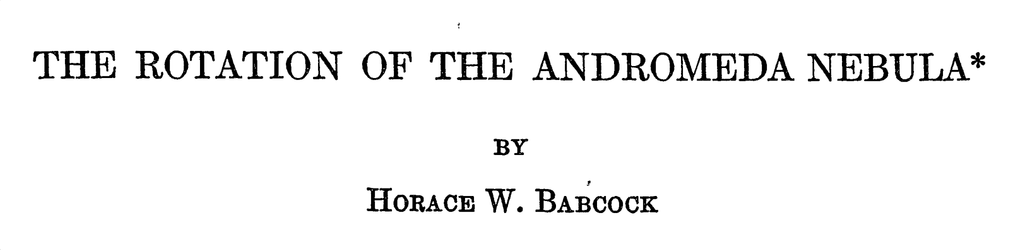

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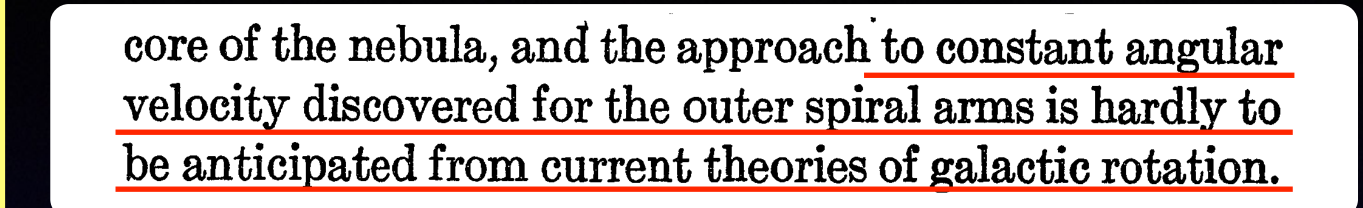

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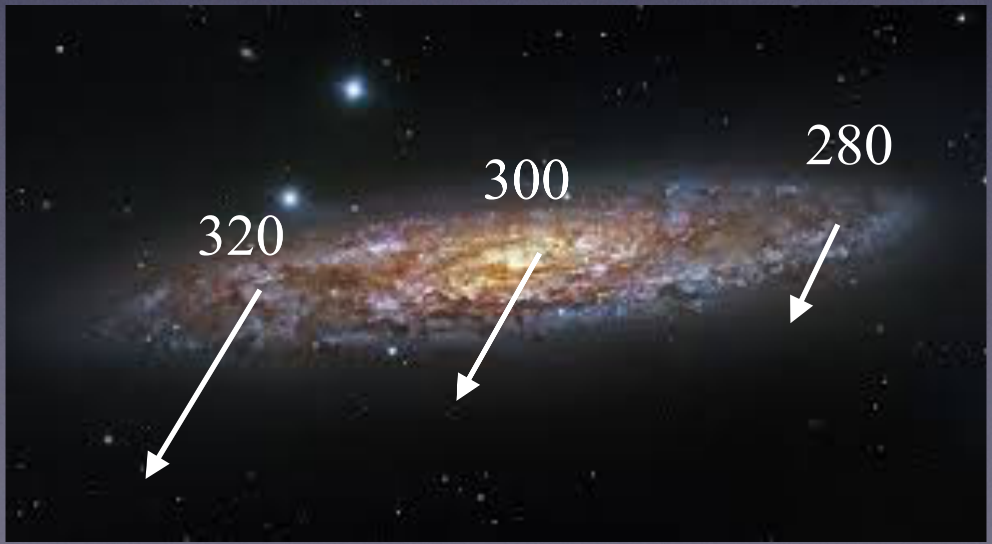

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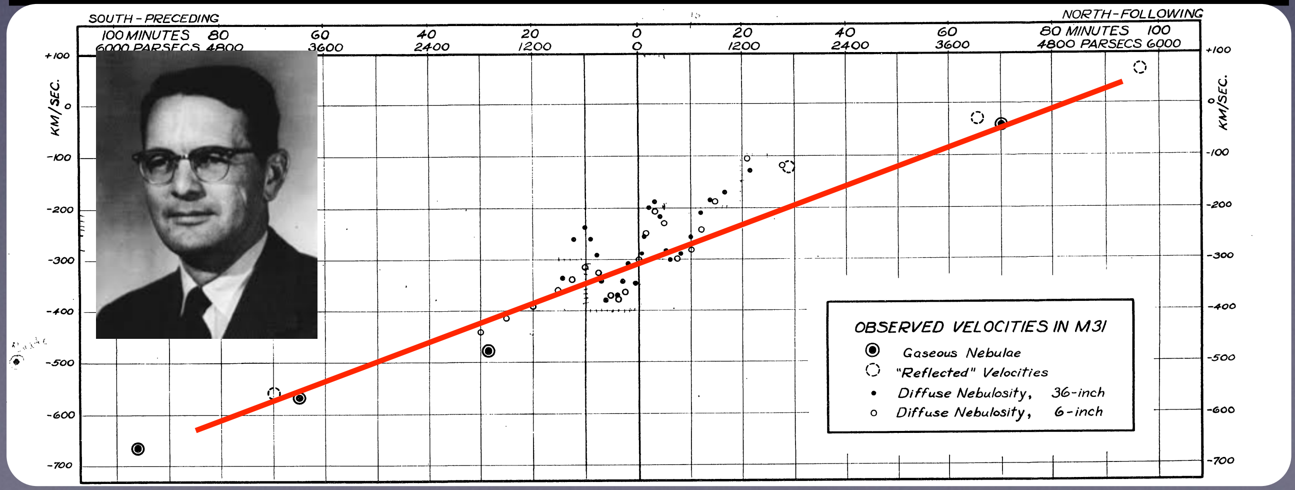
Babcock in **1939** extend the study to larger scale, up to **24 kpc** from the center.



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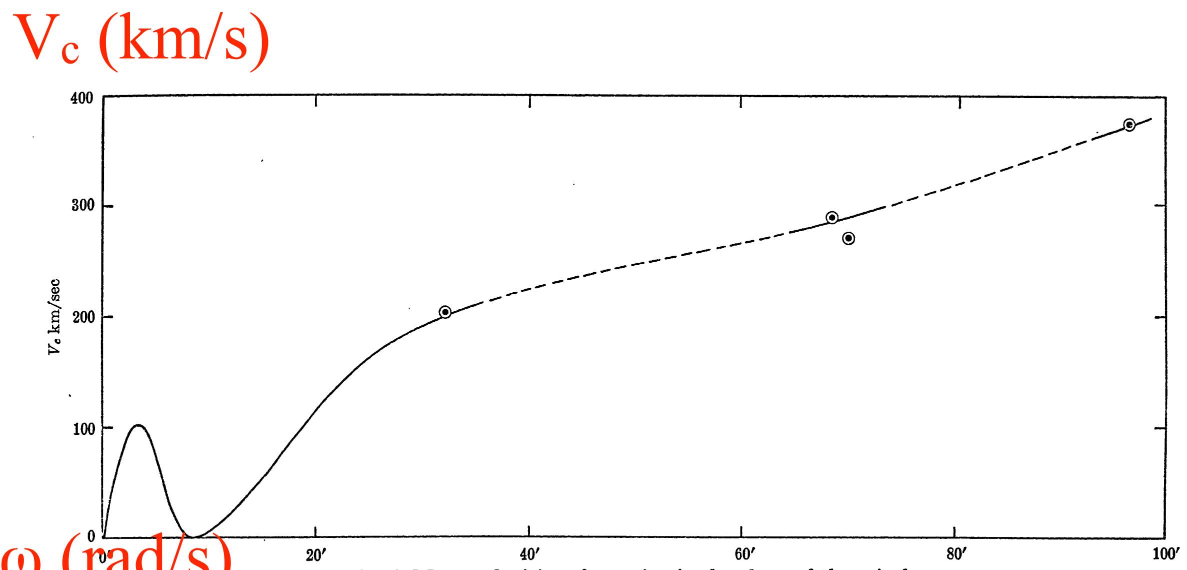
Babcock measured the rotation curve much more far away from the central bulge of Andromeda, and **plotted** the circular velocity and the angular velocity as **function of the distance r** from the center of Andromeda.



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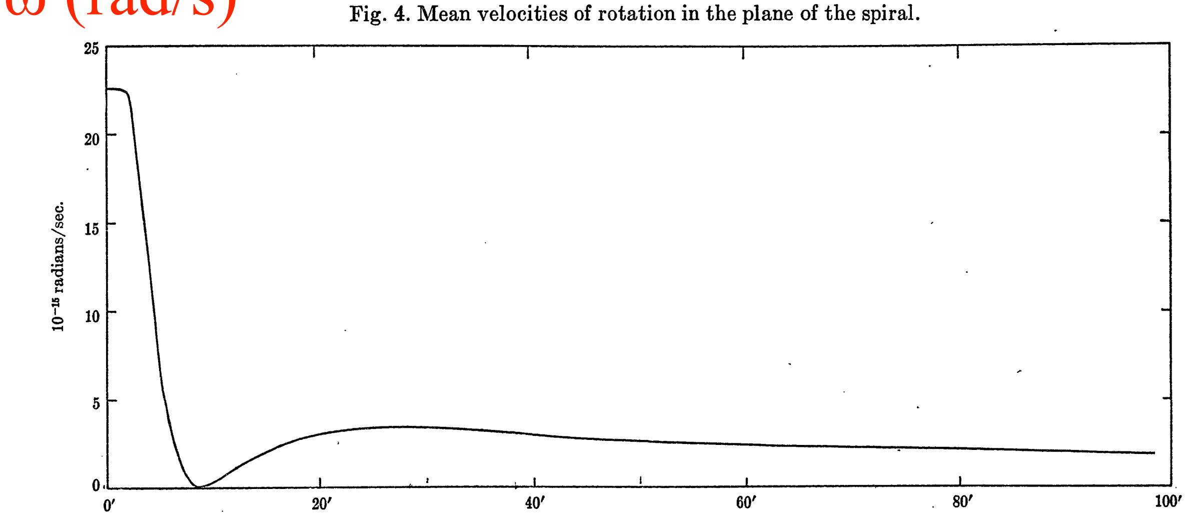

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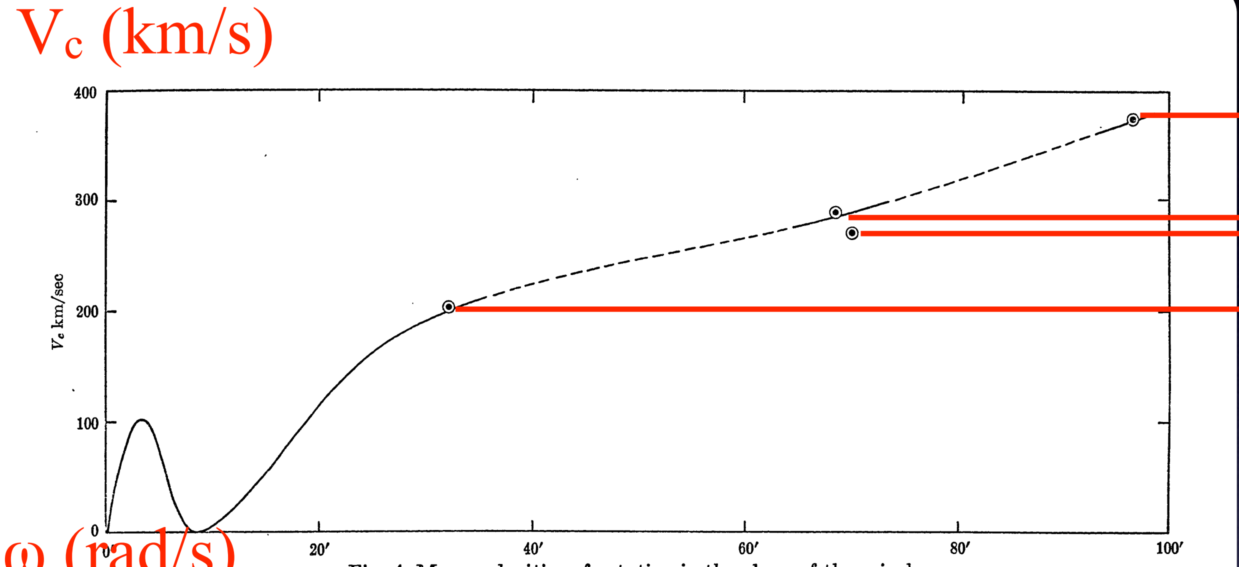

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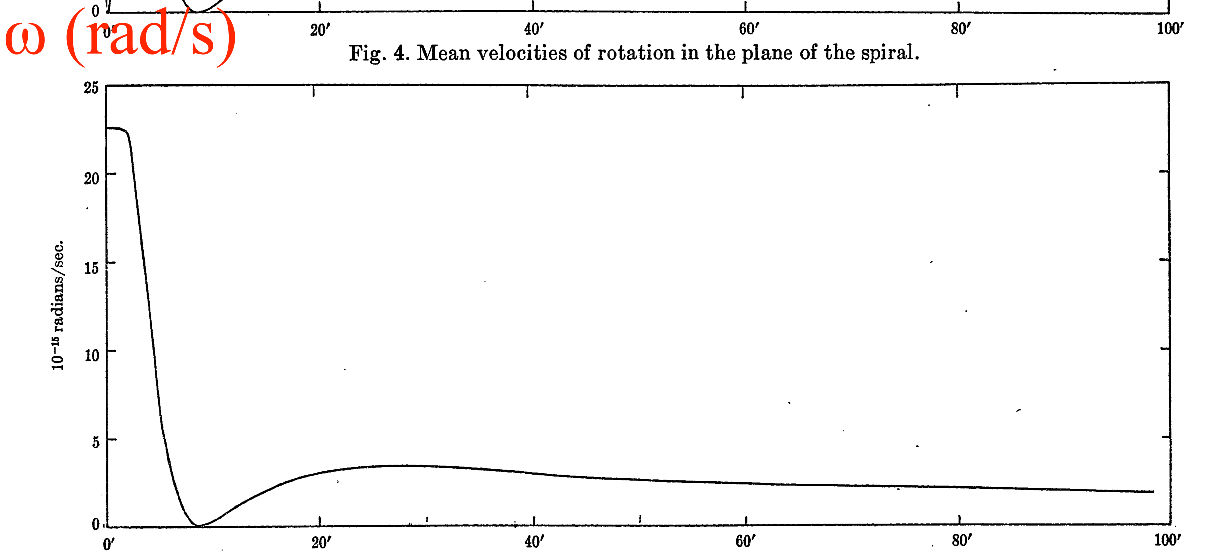

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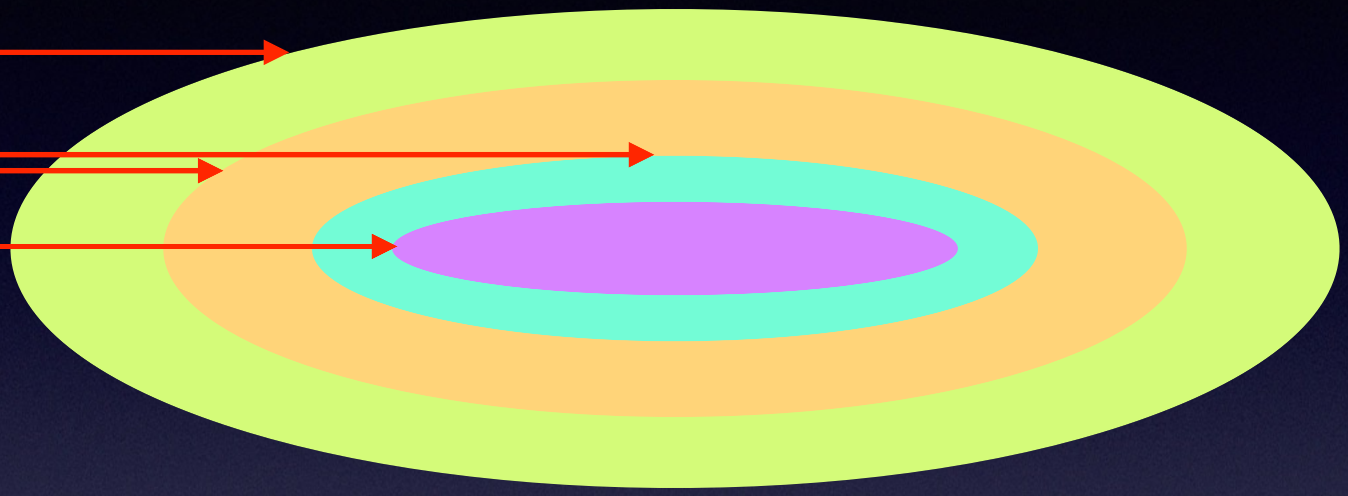
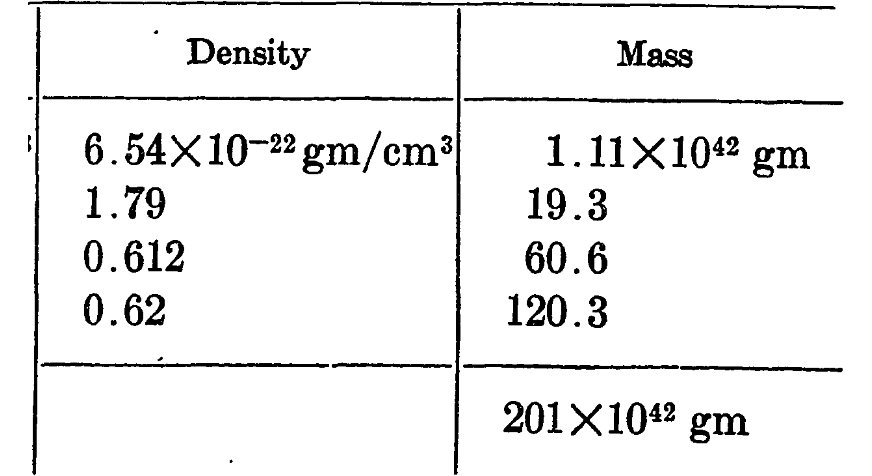


Babcock supposed a concentration of spheroids of densities σ_1, σ_2, σ_3, and σ_4. He then computed the 4 densities to respect the velocities measured on the left. He obtained



Density	Mass
6.54×10^{-22} gm/cm^3	1.11×10^{42} gm
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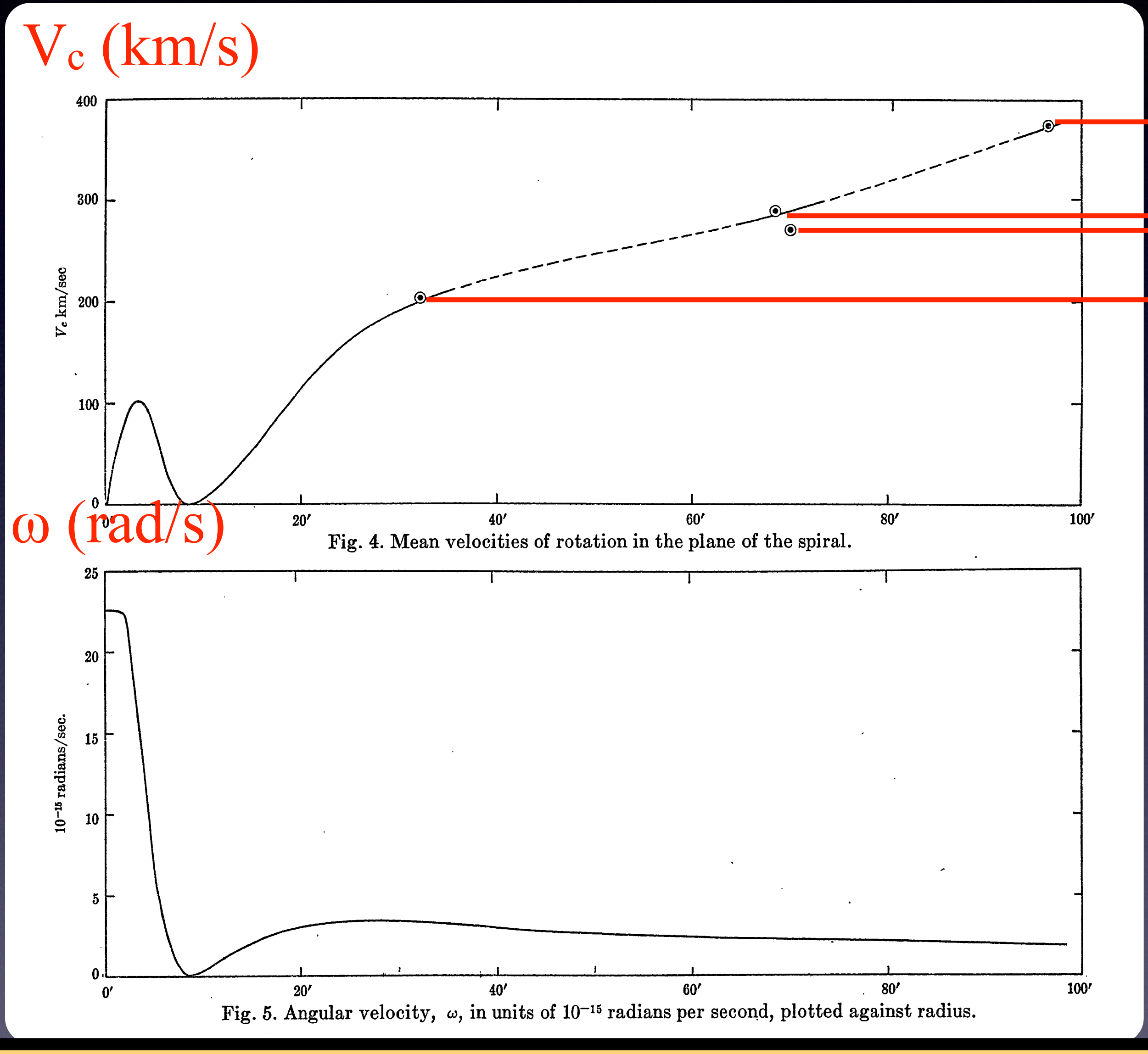

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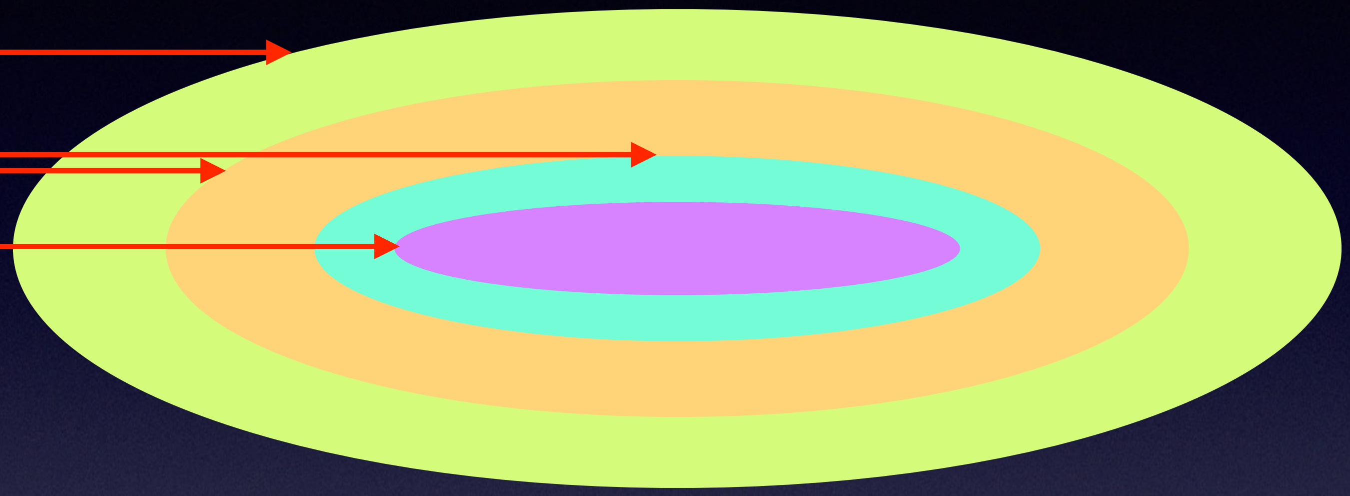

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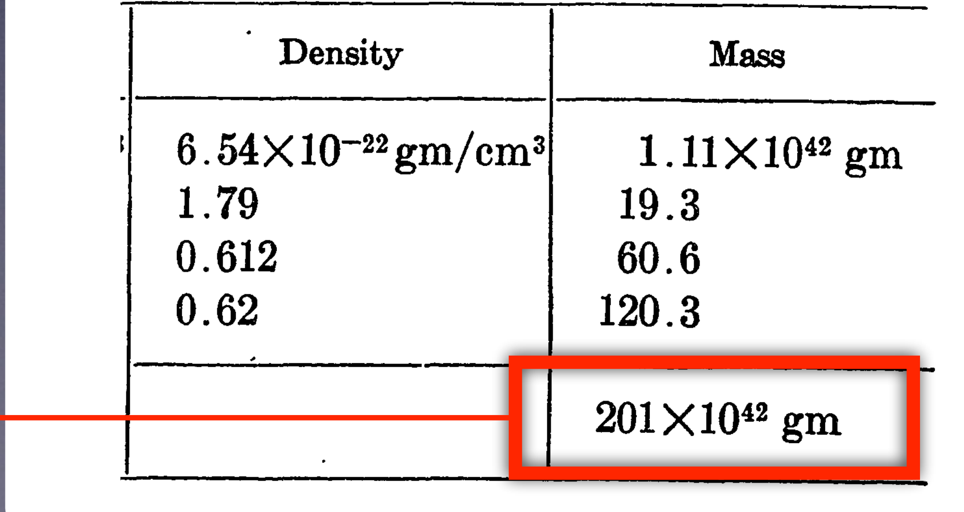

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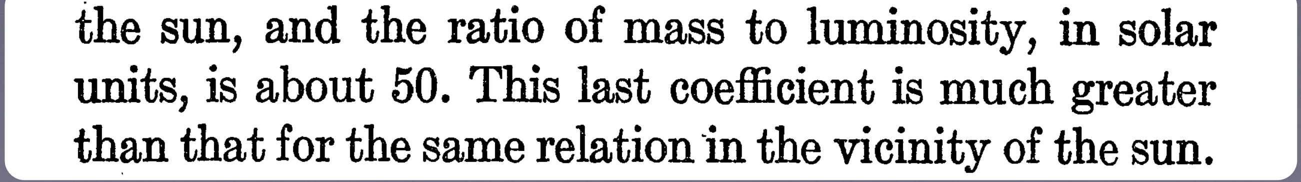
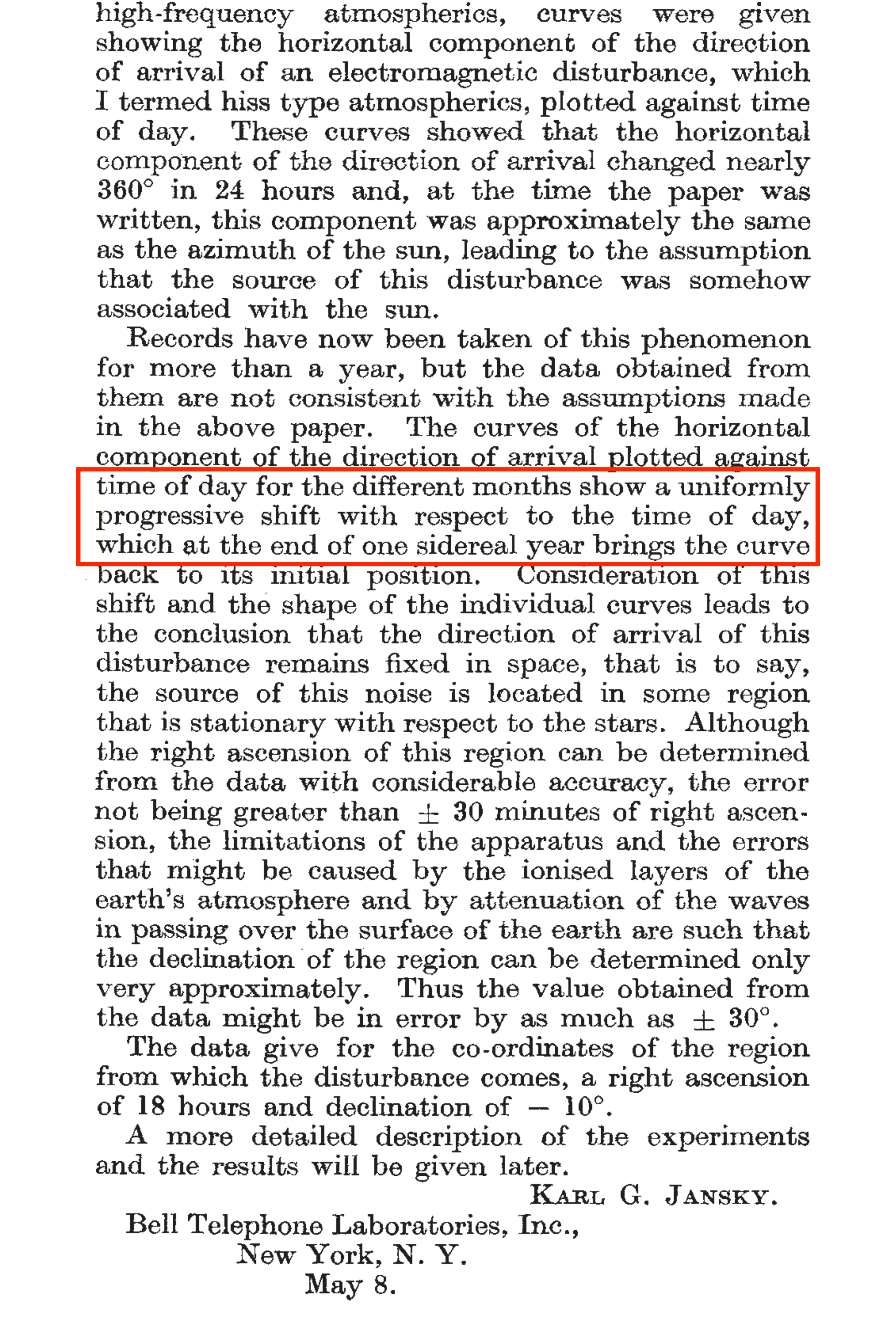
From the computation of the density, he deduced the total mass of Andromeda of **10^{11} solar mass**, equivalent to a mass to light ratio **M/L=50.** He then concludes:



the sun, and the ratio of mass to luminosity, in solar units, is about 50. This last coefficient is much greater than that for the same relation in the vicinity of the sun.

Jansky sees the invisible (1932)



Radio Waves from Outside the Solar System

In a recent paper[1] on the direction of arrival of high-frequency atmospherics, curves were given showing the horizontal component of the direction of arrival of an electromagnetic disturbance, which I termed hiss type atmospherics, plotted against time of day. These curves showed that the horizontal component of the direction of arrival changed nearly 360° in 24 hours and, at the time the paper was written, this component was approximately the same as the azimuth of the sun, leading to the assumption that the source of this disturbance was somehow associated with the sun.

Records have now been taken of this phenomenon for more than a year, but the data obtained from them are not consistent with the assumptions made in the above paper. The curves of the horizontal component of the direction of arrival plotted against time of day for the different months show a uniformly progressive shift with respect to the time of day, which at the end of one sidereal year brings the curve back to its initial position. Consideration of this shift and the shape of the individual curves leads to the conclusion that the direction of arrival of this disturbance remains fixed in space, that is to say, the source of this noise is located in some region that is stationary with respect to the stars. Although the right ascension of this region can be determined from the data with considerable accuracy, the error not being greater than ± 30 minutes of right ascension, the limitations of the apparatus and the errors that might be caused by the ionised layers of the earth's atmosphere and by attenuation of the waves in passing over the surface of the earth are such that the declination of the region can be determined only very approximately. Thus the value obtained from the data might be in error by as much as ± 30°.

The data give for the co-ordinates of the region from which the disturbance comes, a right ascension of 18 hours and declination of − 10°.

A more detailed description of the experiments and the results will be given later.

KARL G. JANSKY.

Bell Telephone Laboratories, Inc.,
New York, N. Y.
May 8.

Karl Jansky

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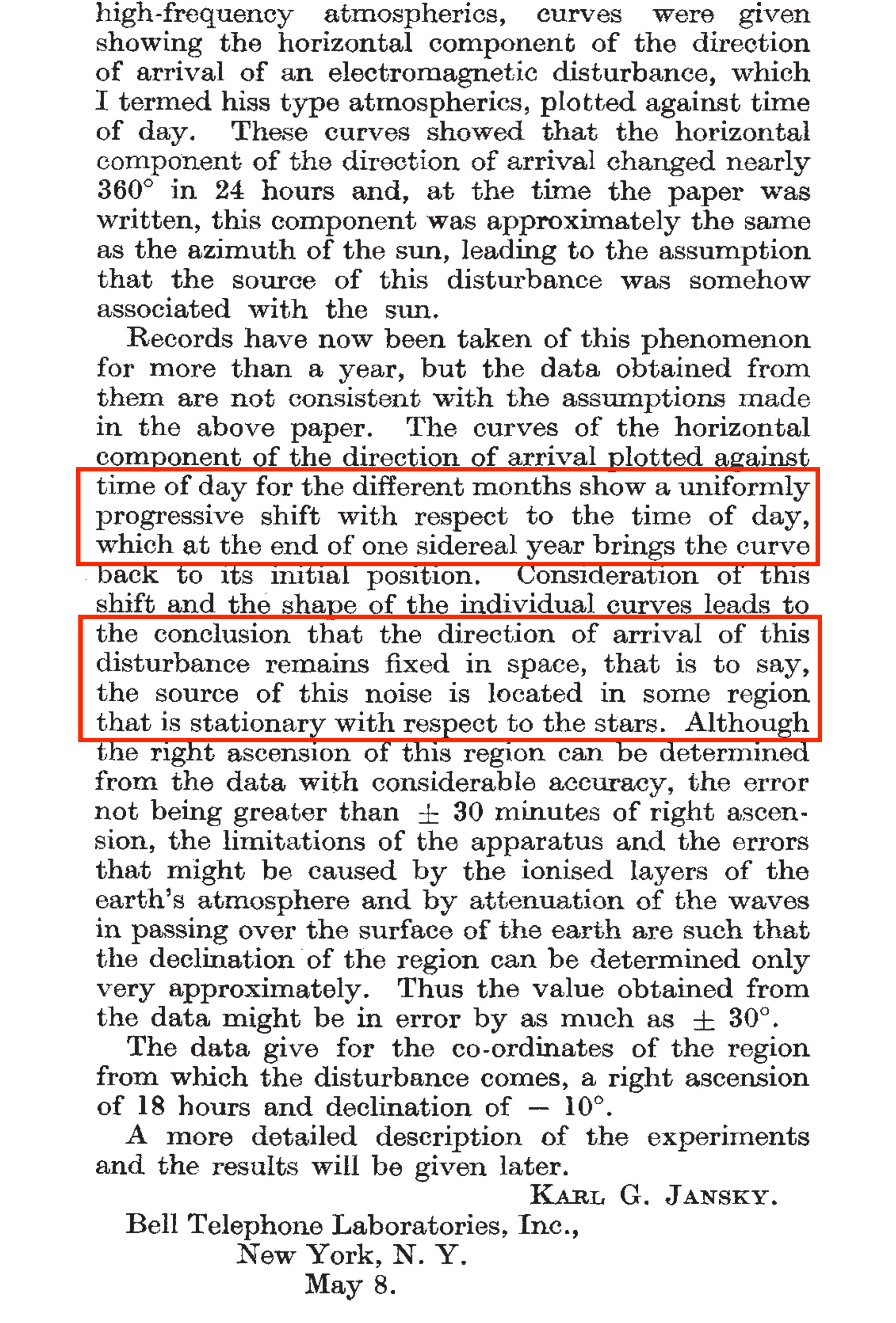

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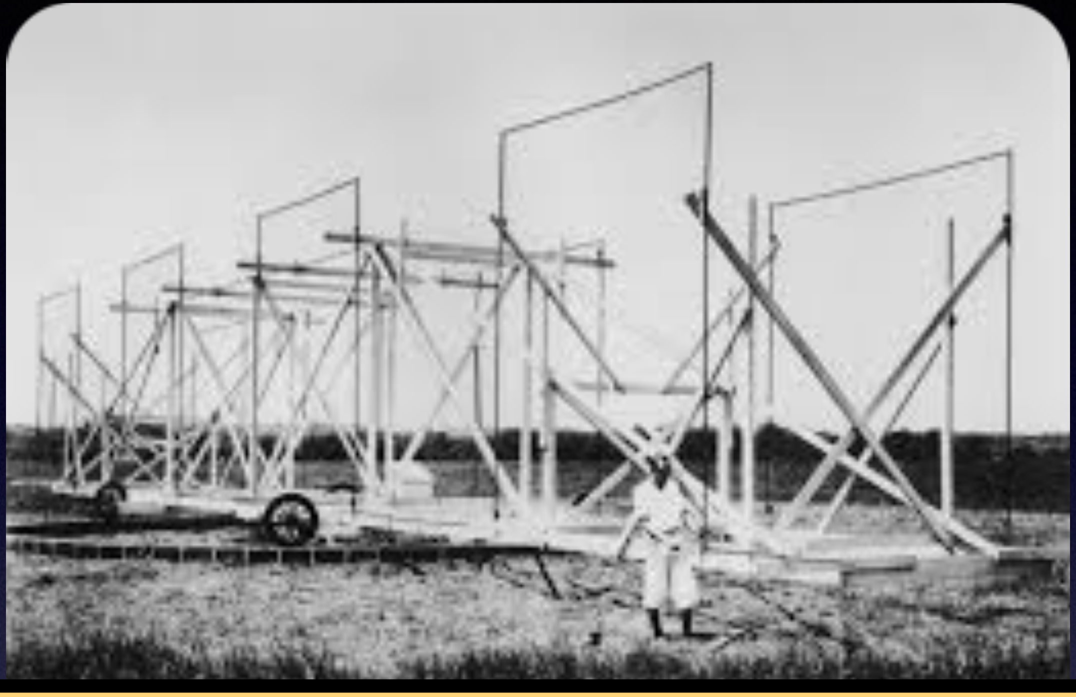

« An airplane wing rotating on automobile (Ford Model T) wheels in potato field »
Was built to investigate and eliminate the **crackling thunderstorm** noise (« **static** ») which interfered with **radio-telephone conversations** over trans-Atlantic short-wave links of the **Bell system**.

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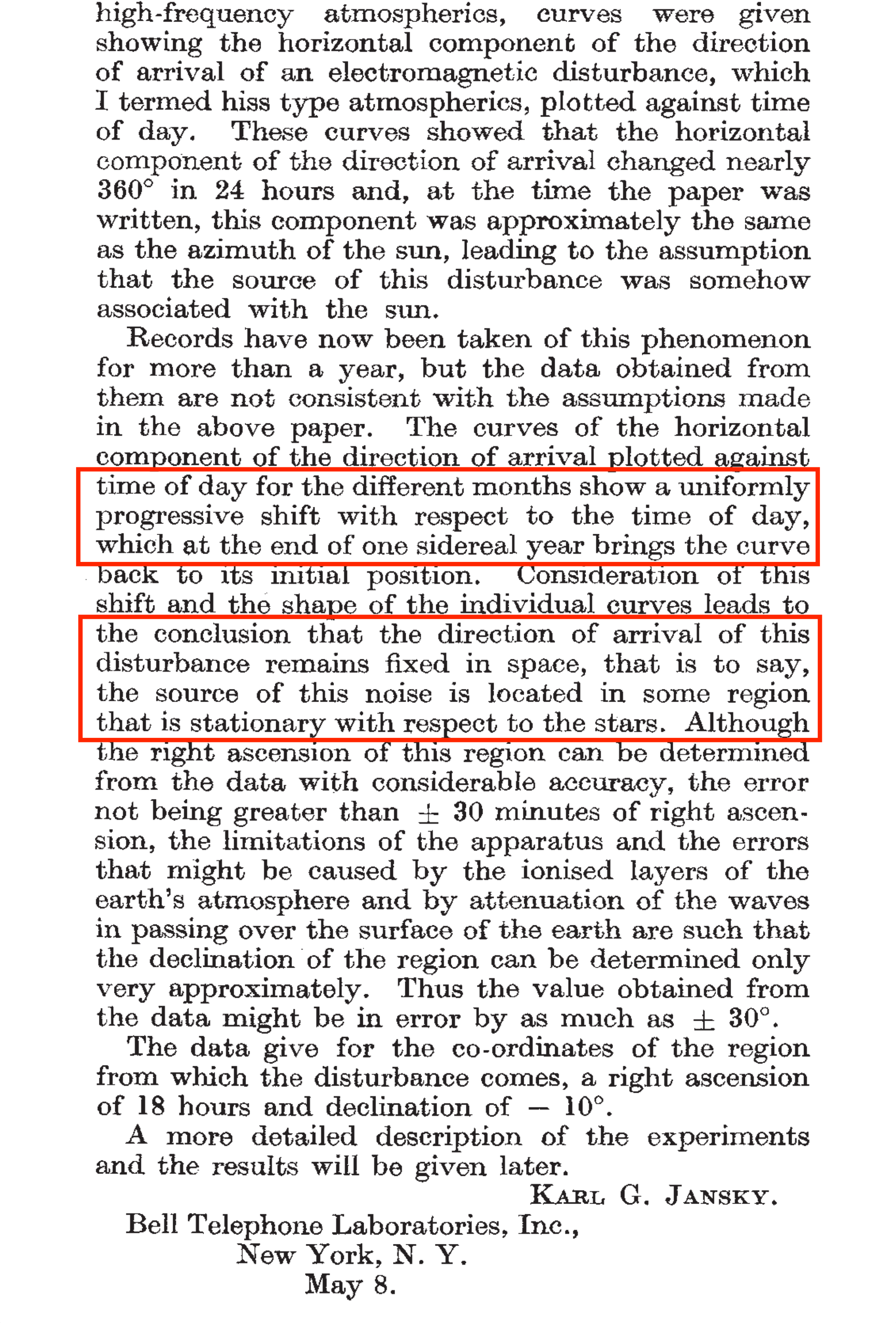

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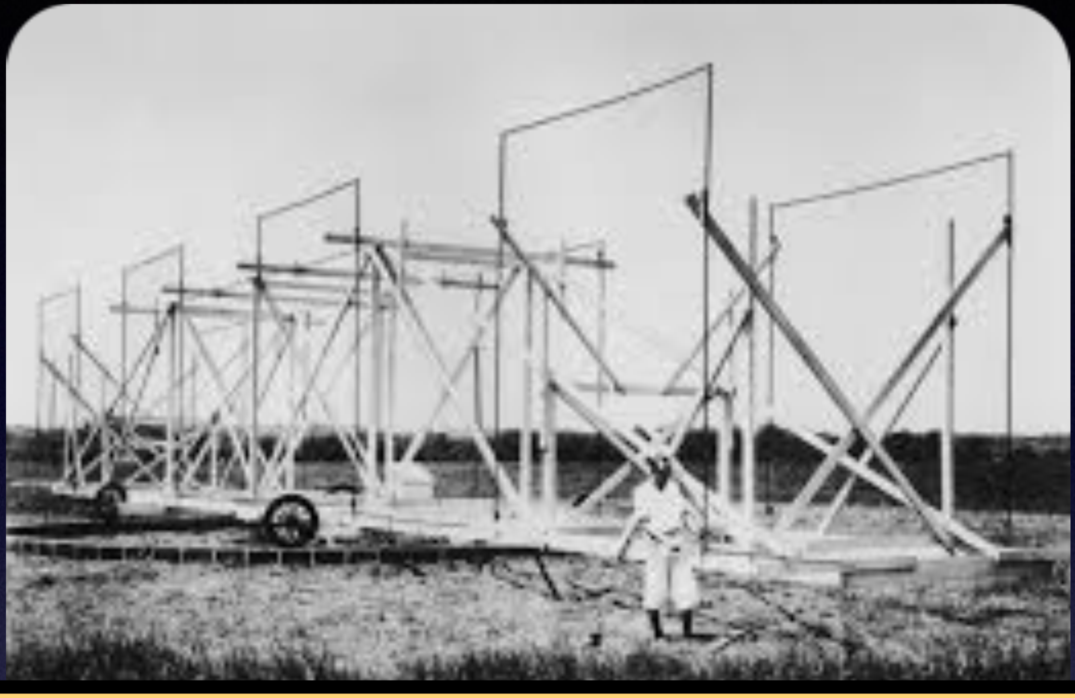

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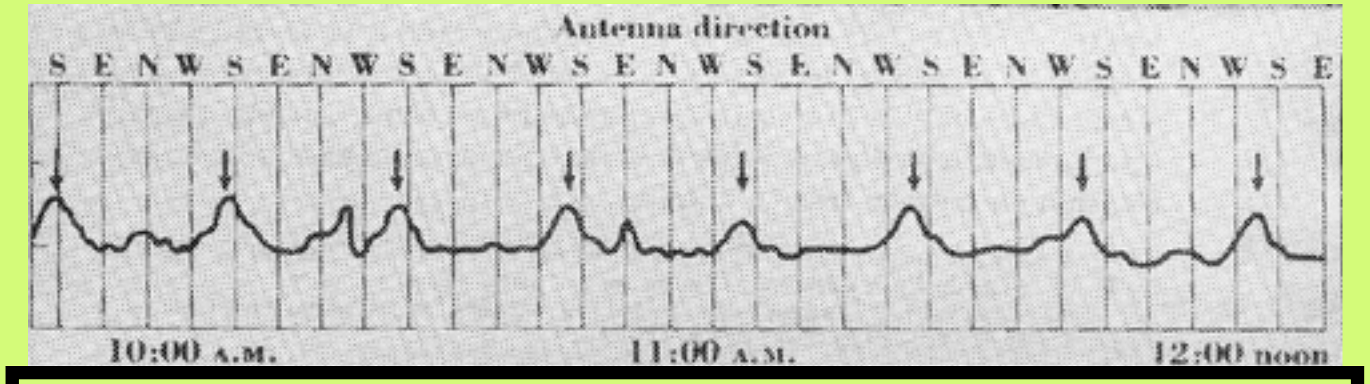

Small « bumps » observed by **Karl Jansky**, one for each revolution of the antenna every **20 minutes** (rotation time)

Jansky sees the invisible (1932)

However, after making an analysis on a complete year, **Jansky** noticed that the periodicity of the larger signal was **not 24 hours, but 23h56**, which corresponds to a **sidereal day and not a solar day**: the signal was coming from the center of the galaxy and not from the sun (« stationary with respect to the stars »).

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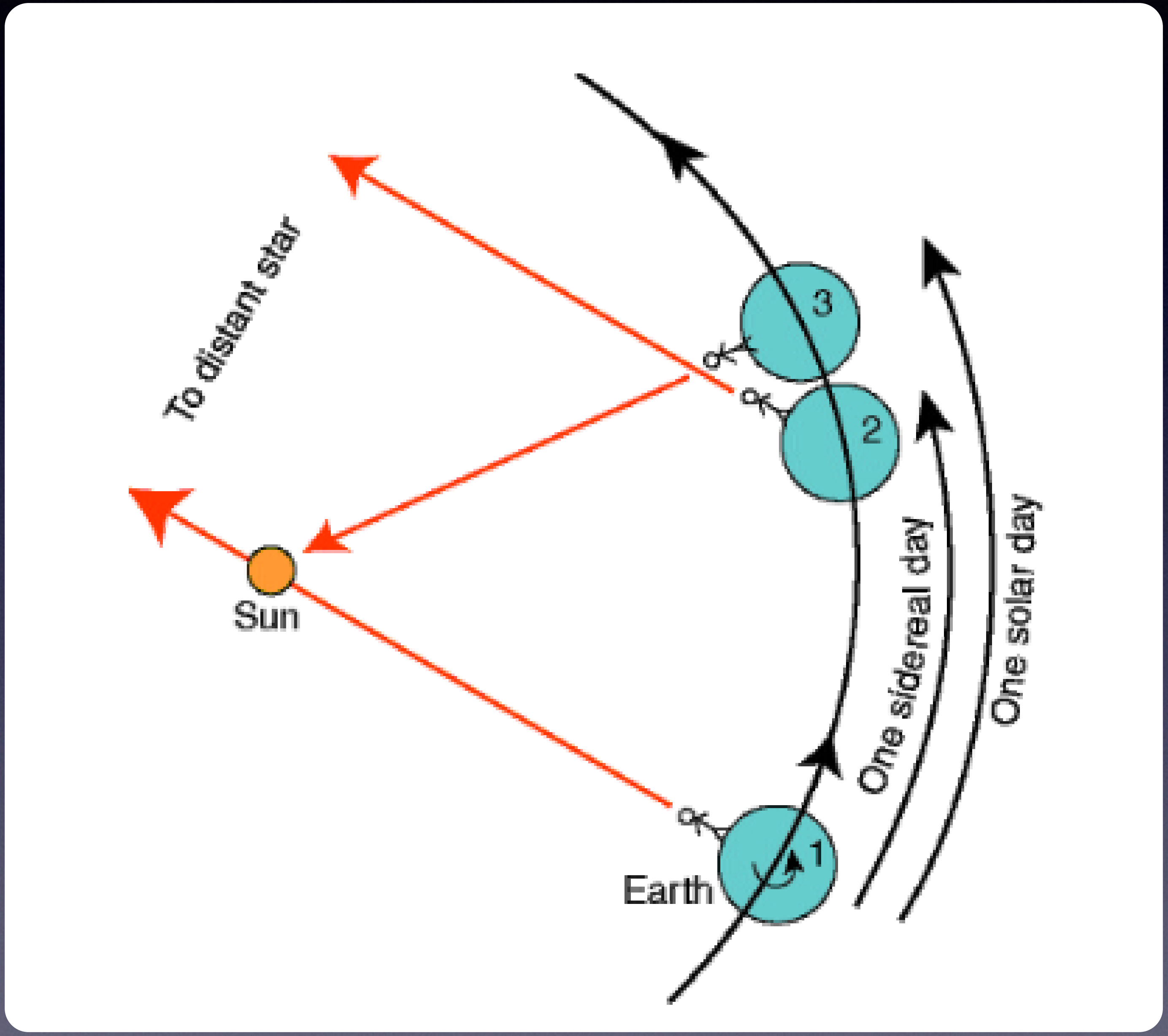

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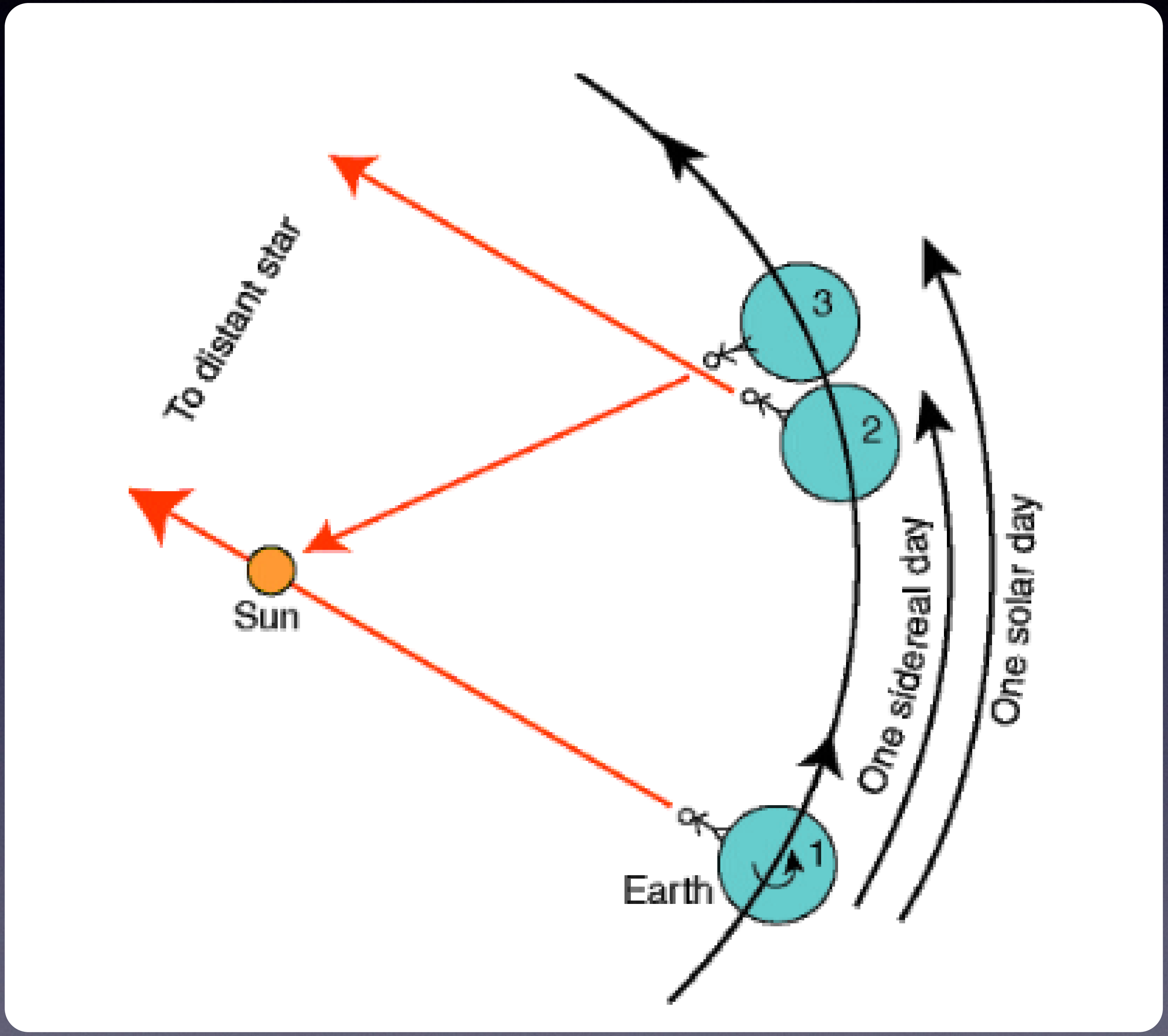

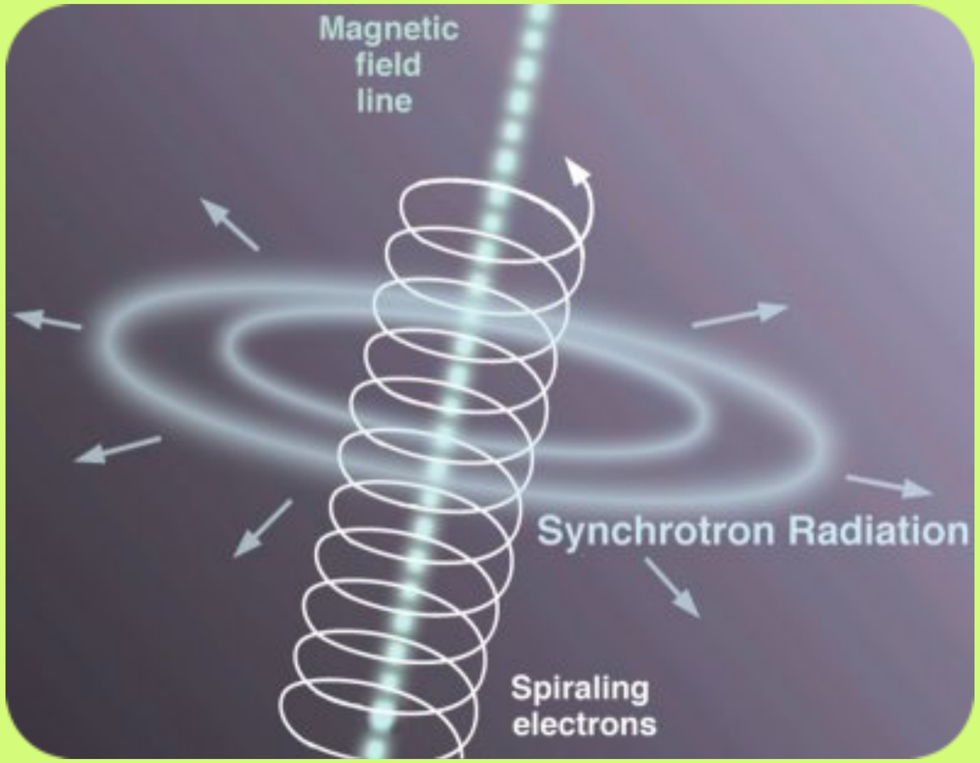

What observed **Jansky** was in fact the **synchrotron radiation** of ultra high energy electrons produced in the Galactic Center. A GeV electron emit synchrotron photons at radio-wave (**1 MHz=300m, 1GHz=30cm**, frequencies measured by **WMAP** and **PLANCK**)

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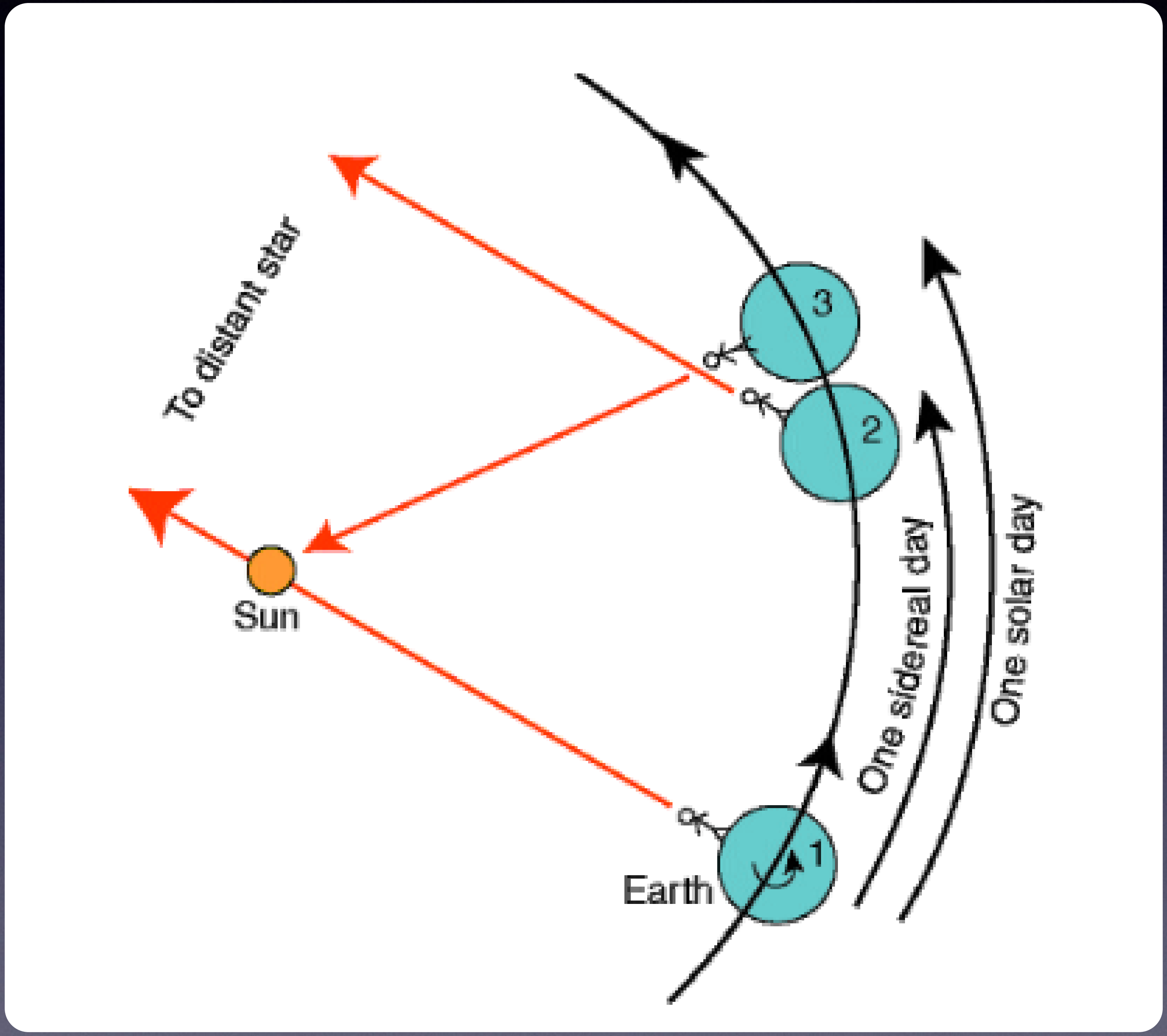

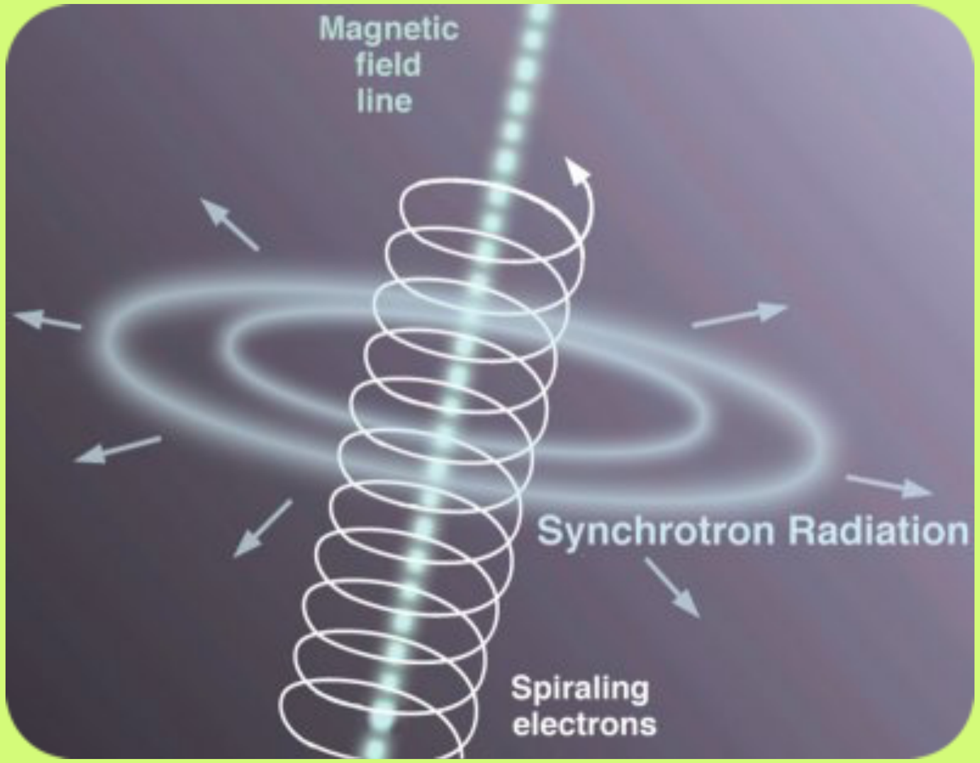

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Jansky died in **1950** (at 44) without knowing the revolution he initiated.
p.s.: he was lucky to look at a wavelength of 14 meters, which was the range **not absorbed by the ionosphere** while still emitted by galactic center.

The 21cm tracer (1944-1951)

Hendrick van de Hulst

Jan Oort

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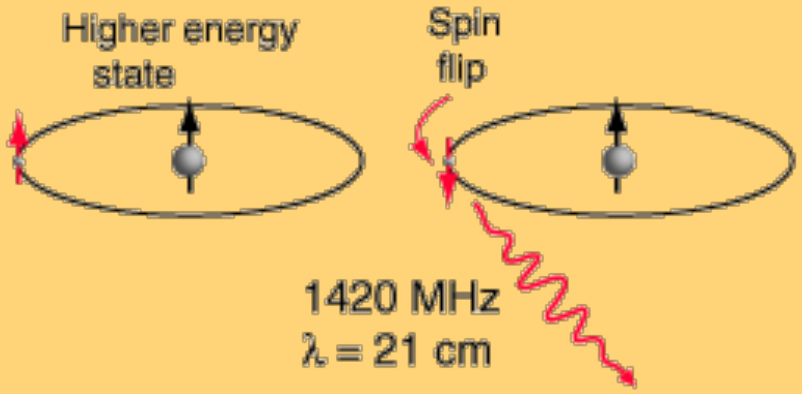

In a **magnetic field**, there is a slight difference in energy of the ground state depending wether the spin of the proton and electron are in the same or opposite sense (**Casimir**, friend of **Oort**). This transition between them gives rise to a **line close to 1420 MHz-21 cm in wavelength**

The 21cm tracer (1944-1951)

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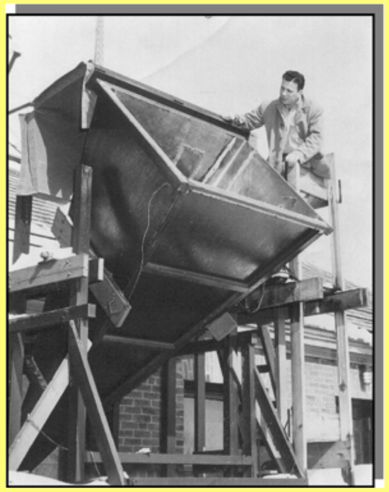

Ewen on his horn telescope

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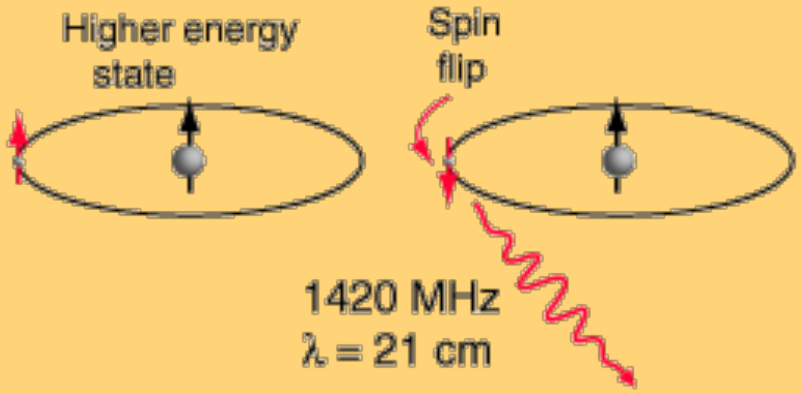

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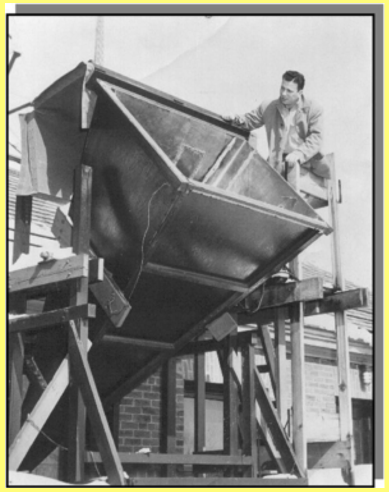

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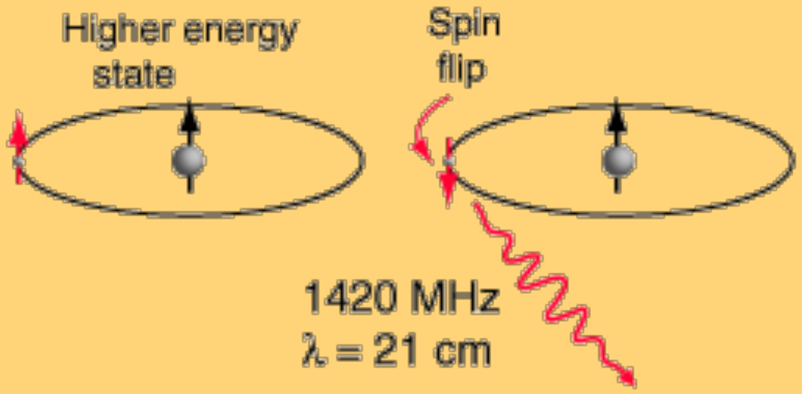

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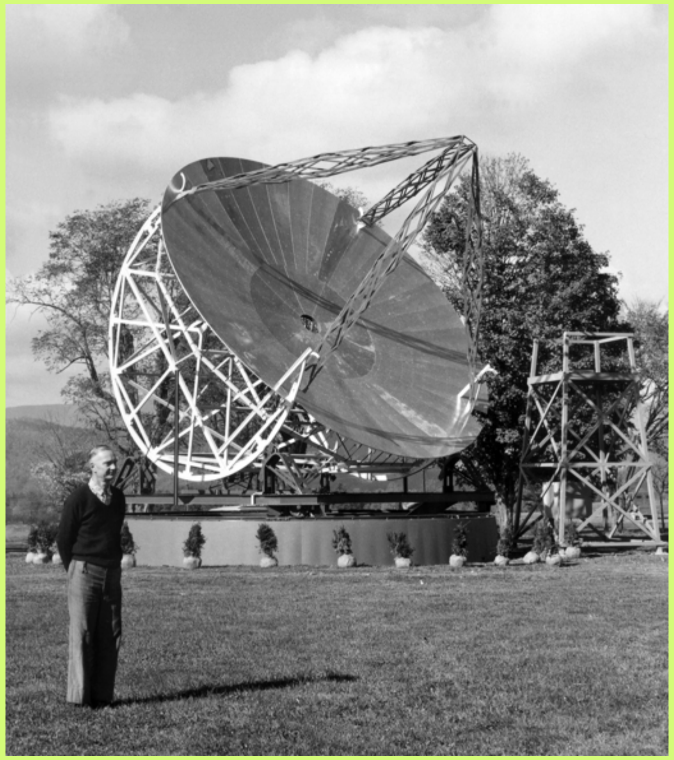
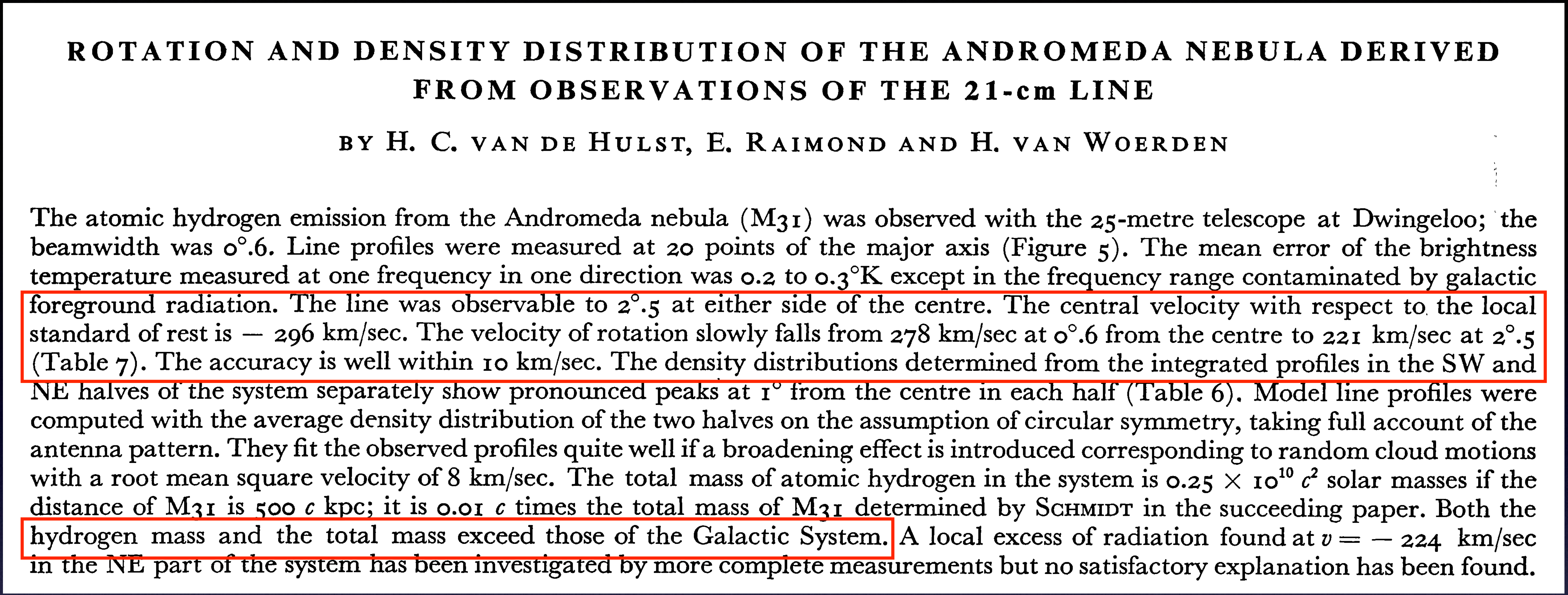


***Van de Hulst** at Dwingeloo*

However, **van de Hulst** never stopped and gave the first 21cm map of Andromeda in 1957, showing that the velocities stays constant **much far away from the visible region** with the **Dwingeloo telescope**

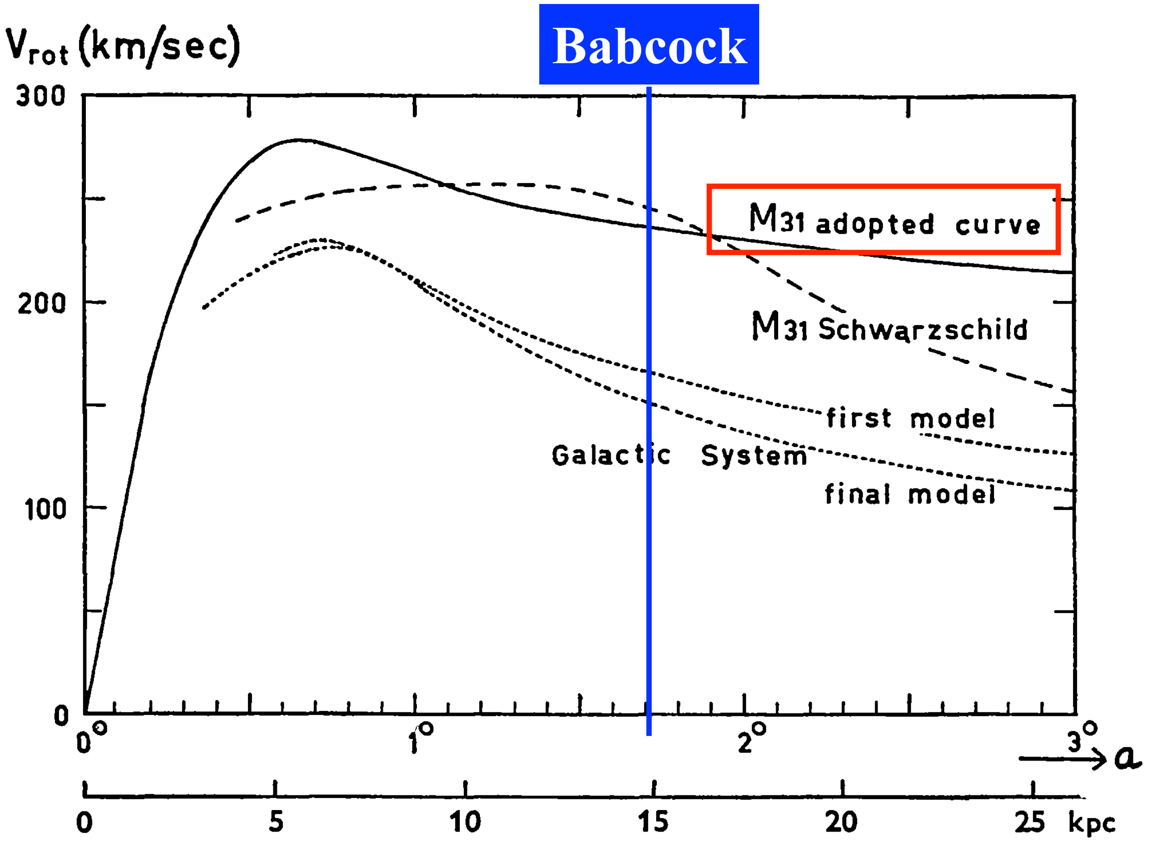


ROTATION AND DENSITY DISTRIBUTION OF THE ANDROMEDA NEBULA DERIVED FROM OBSERVATIONS OF THE 21-cm LINE

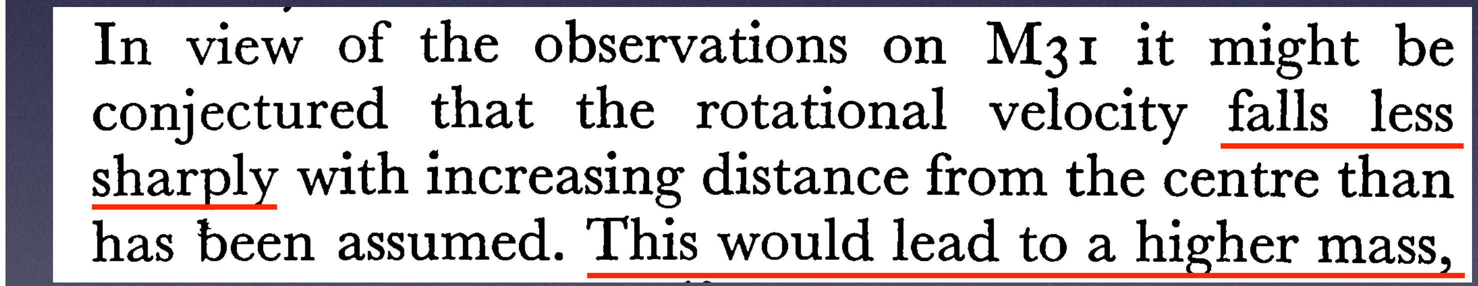
BY H. C. VAN DE HULST, E. RAIMOND AND H. VAN WOERDEN

The atomic hydrogen emission from the Andromeda nebula (M31) was observed with the 25-metre telescope at Dwingeloo; the beamwidth was 0°.6. Line profiles were measured at 20 points of the major axis (Figure 5). The mean error of the brightness temperature measured at one frequency in one direction was 0.2 to 0.3°K except in the frequency range contaminated by galactic foreground radiation. The line was observable to 2°.5 at either side of the centre. The central velocity with respect to the local standard of rest is — 296 km/sec. The velocity of rotation slowly falls from 278 km/sec at 0°.6 from the centre to 221 km/sec at 2°.5 (Table 7). The accuracy is well within 10 km/sec. The density distributions determined from the integrated profiles in the SW and NE halves of the system separately show pronounced peaks at 1° from the centre in each half (Table 6). Model line profiles were computed with the average density distribution of the two halves on the assumption of circular symmetry, taking full account of the antenna pattern. They fit the observed profiles quite well if a broadening effect is introduced corresponding to random cloud motions with a root mean square velocity of 8 km/sec. The total mass of atomic hydrogen in the system is $0.25 \times 10^{10} c^2$ solar masses if the distance of M31 is 500 c kpc; it is 0.01 c times the total mass of M31 determined by SCHMIDT in the succeeding paper. Both the hydrogen mass and the total mass exceed those of the Galactic System. A local excess of radiation found at $v = -224$ km/sec in the NE part of the system has been investigated by more complete measurements but no satisfactory explanation has been found.

FIGURE 11



Rotation laws of M31 and the Galactic System.



In view of the observations on M31 it might be conjectured that the rotational velocity falls less sharply with increasing distance from the centre than has been assumed. This would lead to a higher mass,

Van de Hulst do not insist so much in his paper about the flatness of the rotation curve. But, computing the mass of M31 he conclude that is is much larger than the Milky way. The « dark matter » hypothesis does not (yet) strikes the Galactic scale.

The problem of instability at a galactic scale

In the 70’s, **the Moore law** of **exponential** development describing the time evolution of computing power reached astrophysics studies: **the computing power doubling every two years**, it was possible in the late 60’s to apply electronic computing machines in the numerical solution of complex problems (technically, it was the replacement of **vacuum tubes** by **transistors** which gives a large leap in the field).

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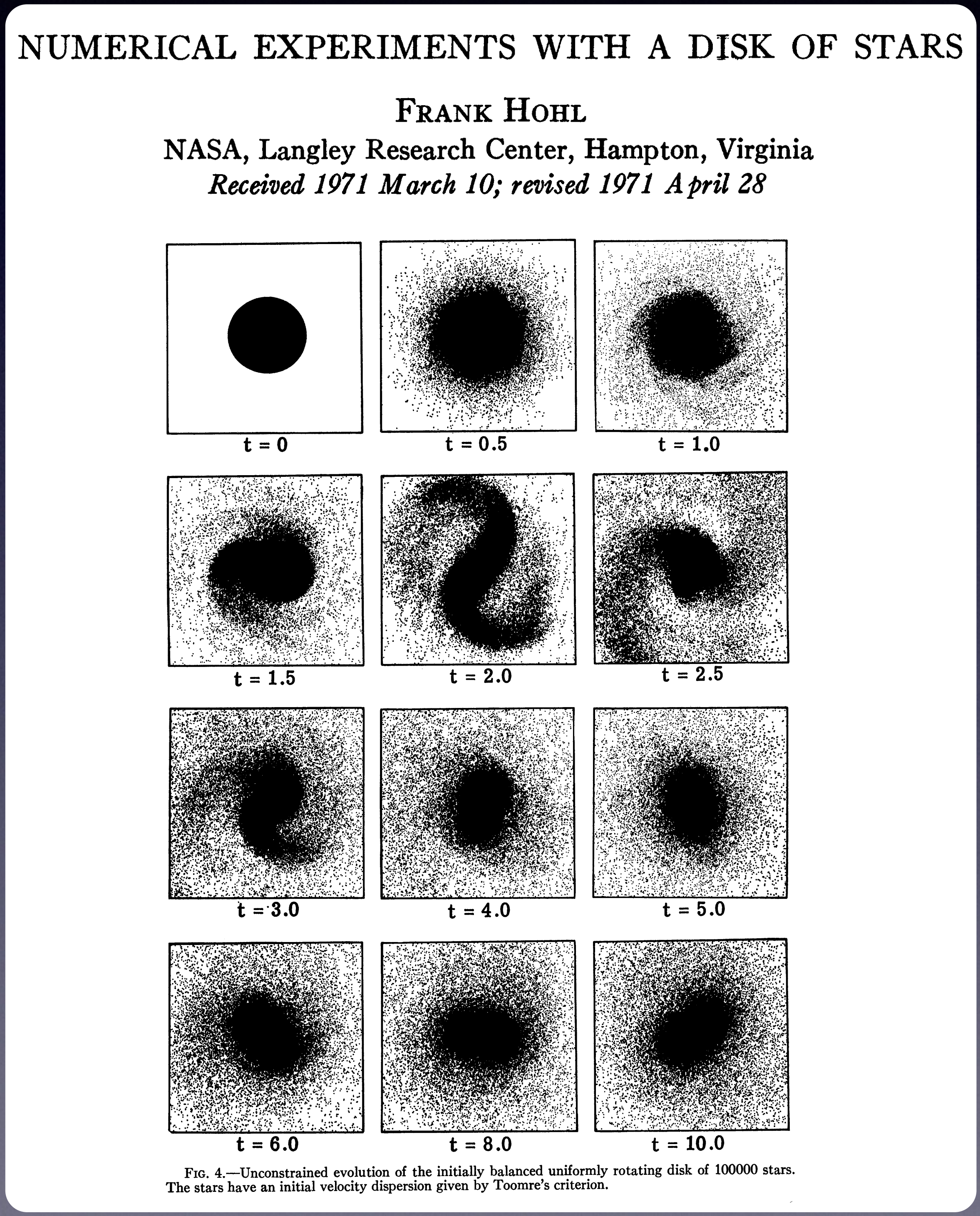

NUMERICAL EXPERIMENTS WITH A DISK OF STARS

Frank Hohl
NASA, Langley Research Center, Hampton, Virginia
Received 1971 March 10; revised 1971 April 28

Fig. 4.—Unconstrained evolution of the initially balanced uniformly rotating disk of 100000 stars. The stars have an initial velocity dispersion given by Toomre’s criterion.

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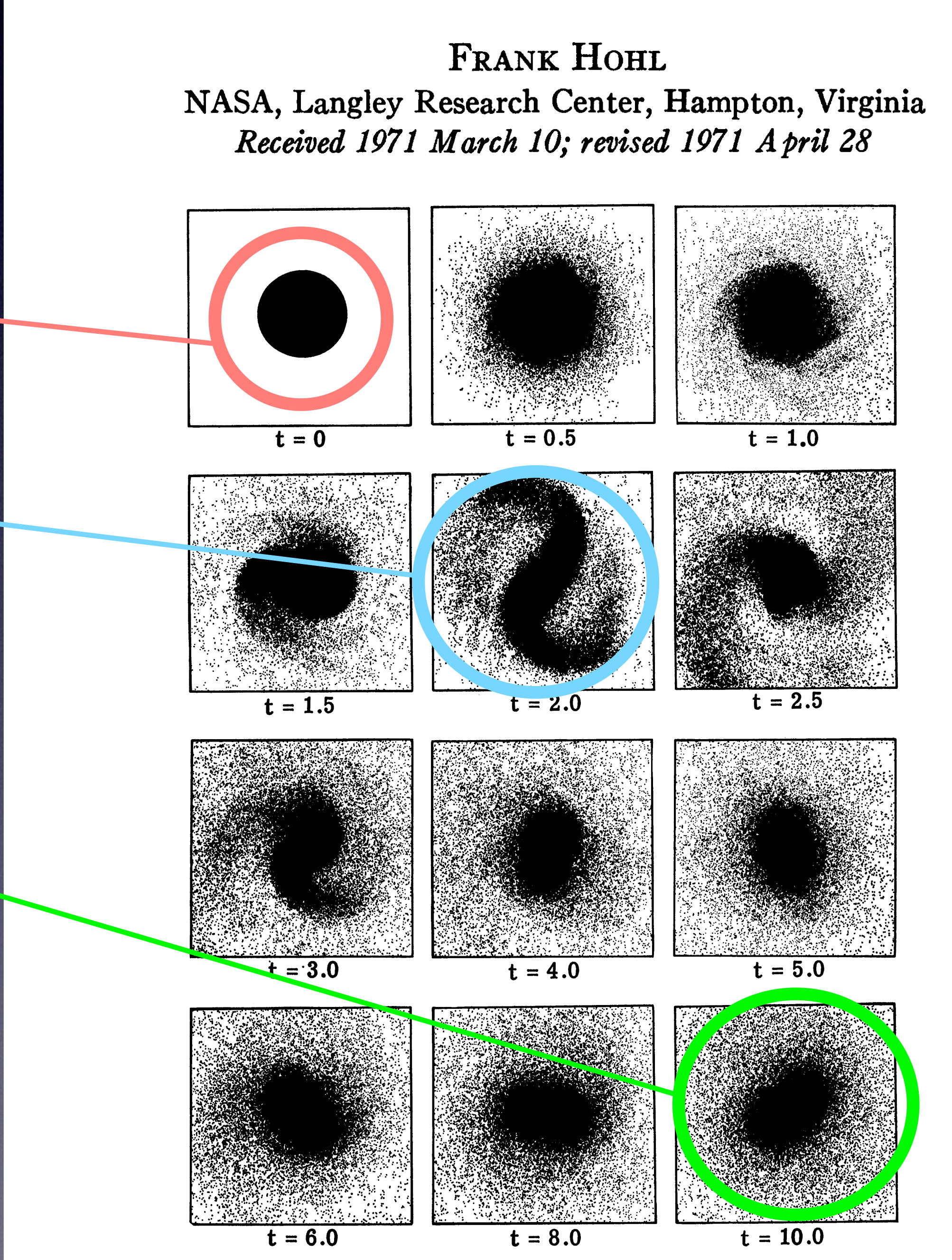

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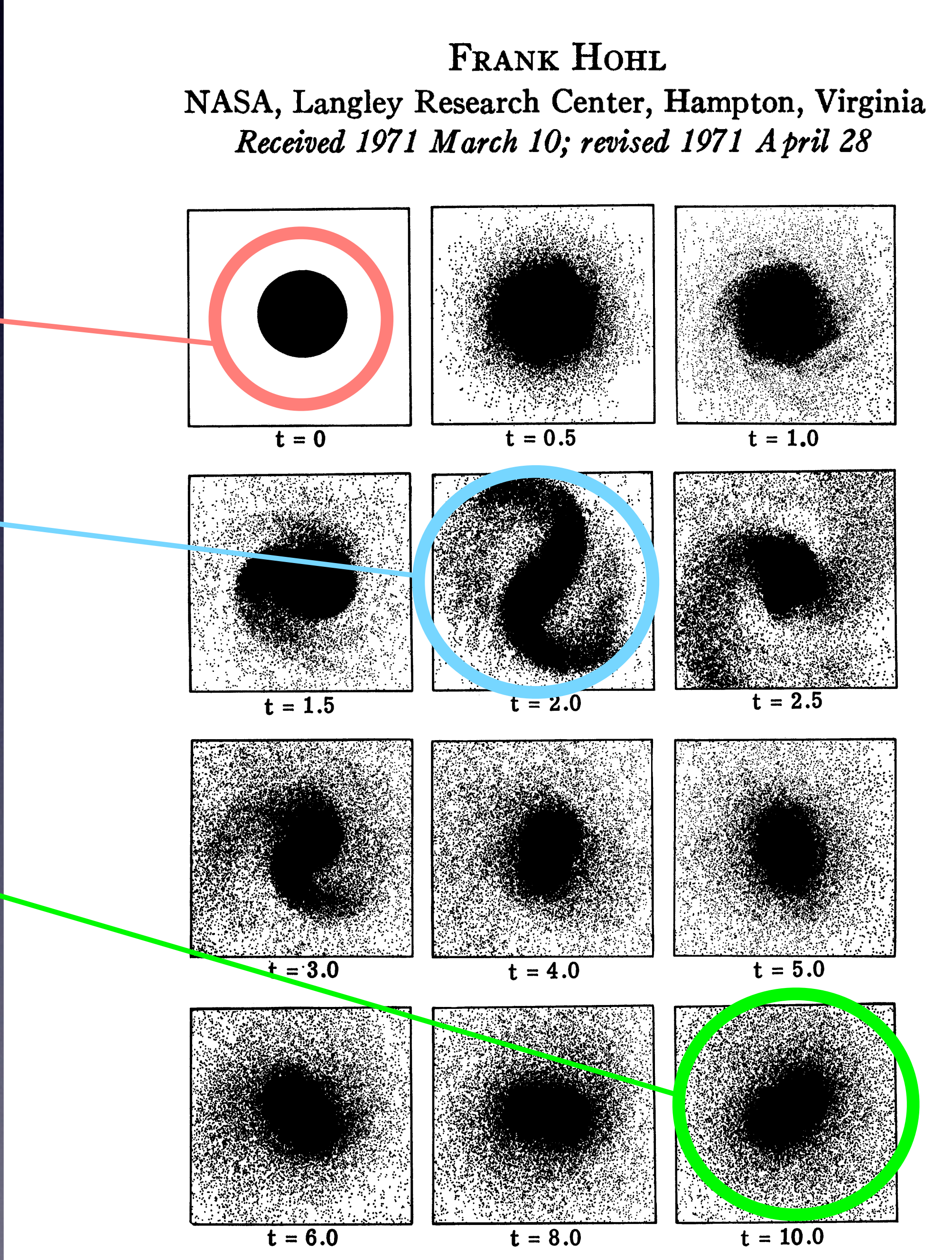
Miller, **Pendergast** and **Quirk** tried to stabilized the model by adding energy lost, but still, reheating of the gas destroys the structures some revolutions after. This is when a **dark halo** came to the rescue and is first mentioned in a paper.



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First hypothesis of dark halo

The idea

Peebles and **Ostriker** noticed that the **random velocities** in our galaxies (around **30-40 km/s**) are much smaller than the **systematic circular motion** (around **200 km/s**). Thus, not only the system is unstable as remarked by **Hohl et al.**, but it shows that galaxies seems to be dominated by a **cold gravitational** system and **not a kinetic** pressure dominated one.

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$$\mathbf{2\,T + U} = 0\text{, or } \mathbf{2\,T_{rot} + 2\,T_{ran} = U}\text{, which can be written } \mathbf{t + r = 1/2}$$

with $t=T_{rot}/(-U)$ and $r = T_{ran}/(-U)$. So, if **t=1/2** (r=0) the system is completely supported against gravity by **rotation**, but if **r=1/2** (t=0) the system is completely supported by **random motion**.

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Peebles and **Ostriker** noticed that **if $t > 0.14$** (28% of the kinetic energy is rotational), **the system is unstable** and becomes elongated very quickly. However, we just saw that in our Milky Way, the rotation velocity is around **200 km/s** whereas the random one approaches **40 km/s**, which gives **$t \sim$ 0.49**, **far in excess of the stability limit!!**

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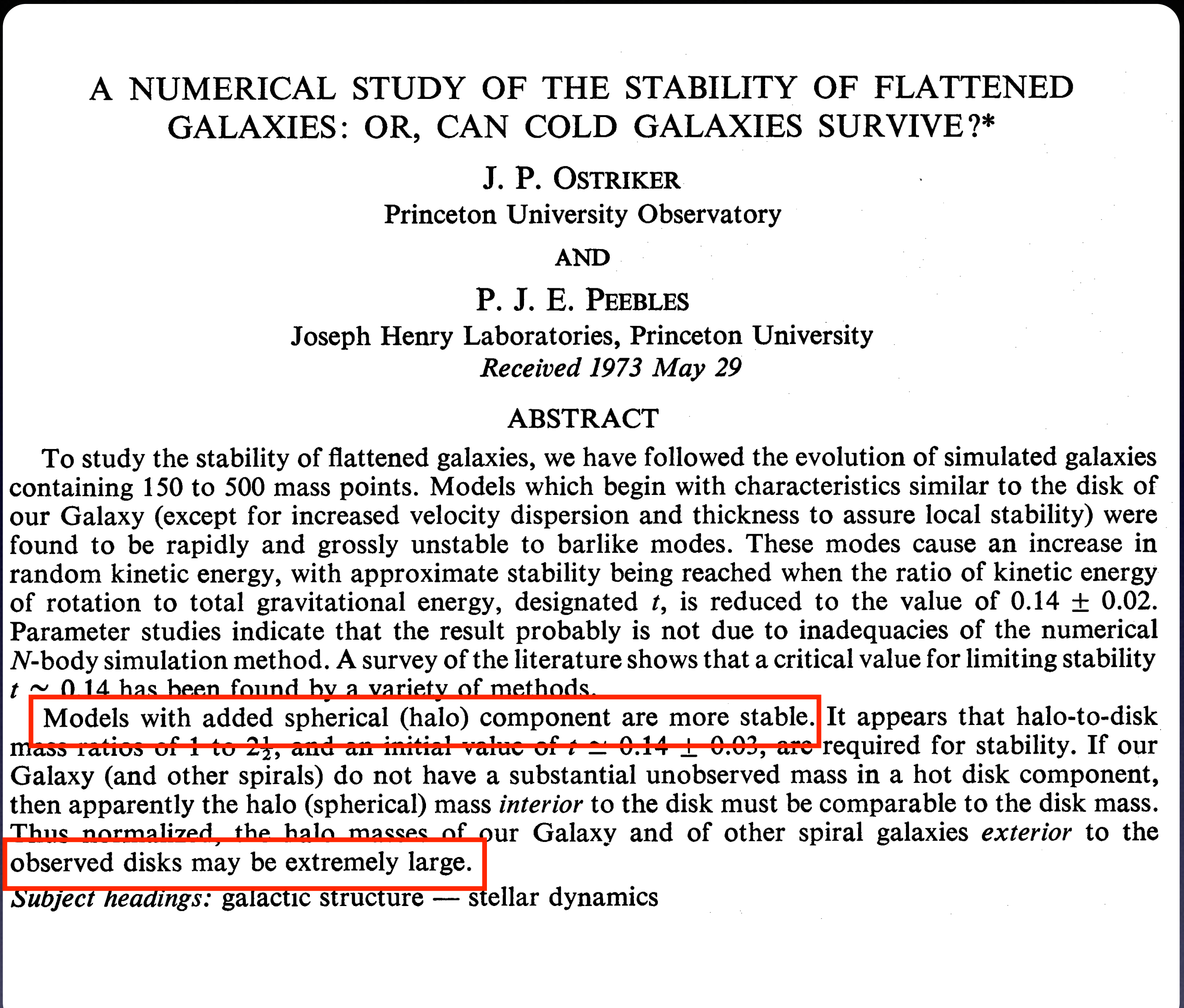
The clever idea of **Peebles** and **Ostriker** is then to add an **additional component** to the galaxy, a **dark halo** which contributes at least **50% of the mass** inside the position of the Sun

$U \rightarrow U + U_{dark}$

Then this spheroidal system would **add to the gravitational potential** energy, but add **nothing to the rotational energy**; **t would be decreased** and perhaps stability restored.

The article



A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

J. P. OSTRIKER
Princeton University Observatory

AND

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University

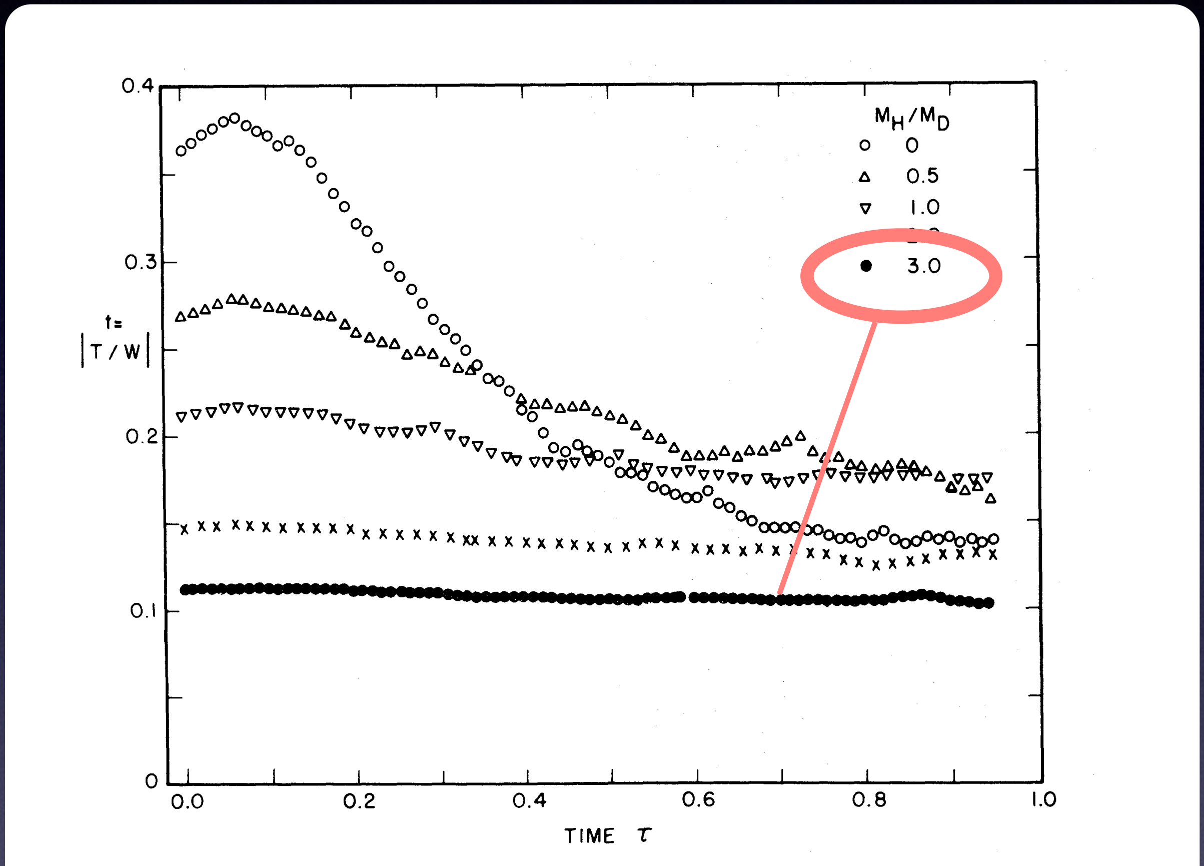
Received 1973 May 29

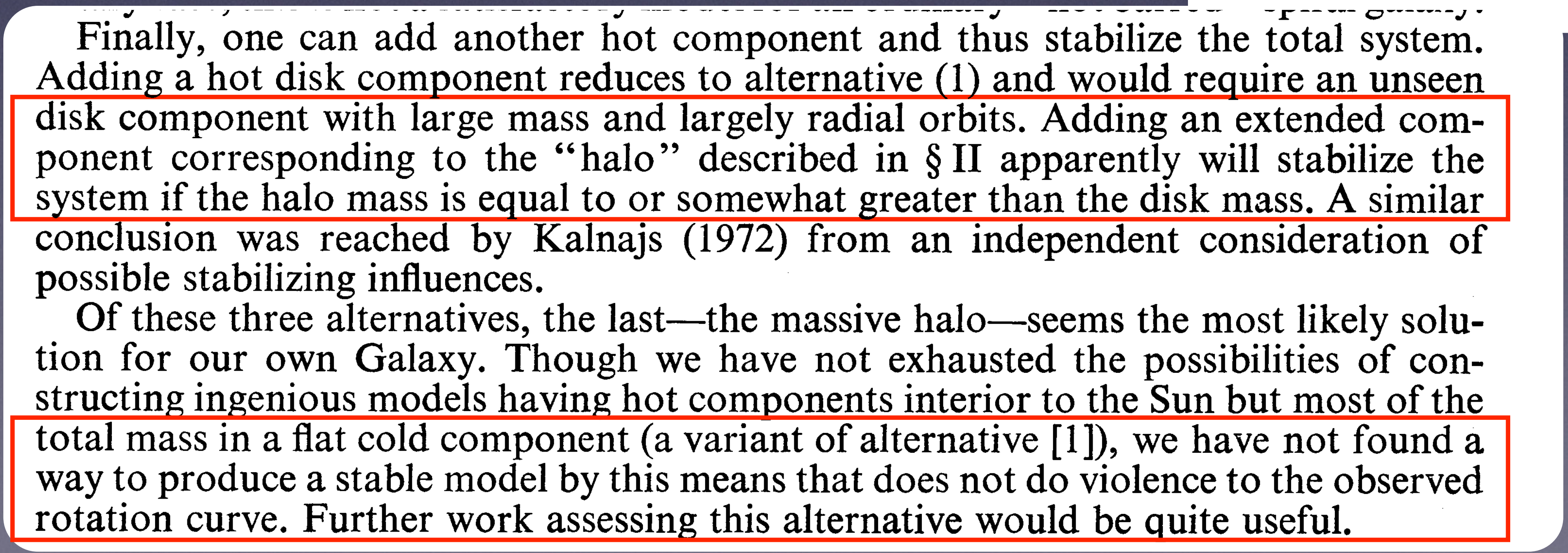
ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \sim 0.14$ has been found by a variety of methods. Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

Subject headings: galactic structure — stellar dynamics

P.J. Peebles J.P. Ostriker





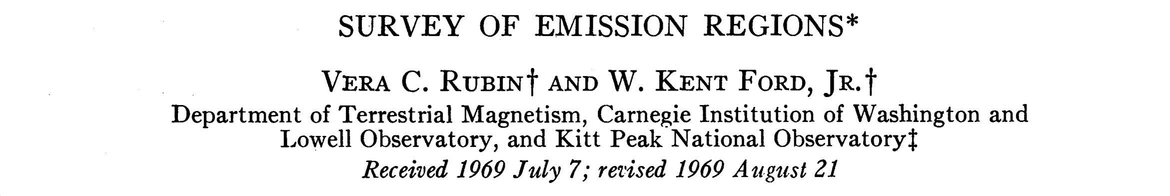
Finally, one can add another hot component and thus stabilize the total system. Adding a hot disk component reduces to alternative (1) and would require an unseen disk component with large mass and largely radial orbits. Adding an extended component corresponding to the "halo" described in § II apparently will stabilize the system if the halo mass is equal to or somewhat greater than the disk mass. A similar conclusion was reached by Kalnajs (1972) from an independent consideration of possible stabilizing influences.

Of these three alternatives, the last—the massive halo—seems the most likely solution for our own Galaxy. Though we have not exhausted the possibilities of constructing ingenious models having hot components interior to the Sun but most of the total mass in a flat cold component (a variant of alternative [1]), we have not found a way to produce a stable model by this means that does not do violence to the observed rotation curve. Further work assessing this alternative would be quite useful.

Combining 21cm observations with Peebles idea

Vera Rubin

After the work of **Van de Hulst**, a lot of instrumental developments allowed to have a better understanding of the rotation curves of galaxies much above the optical limit.

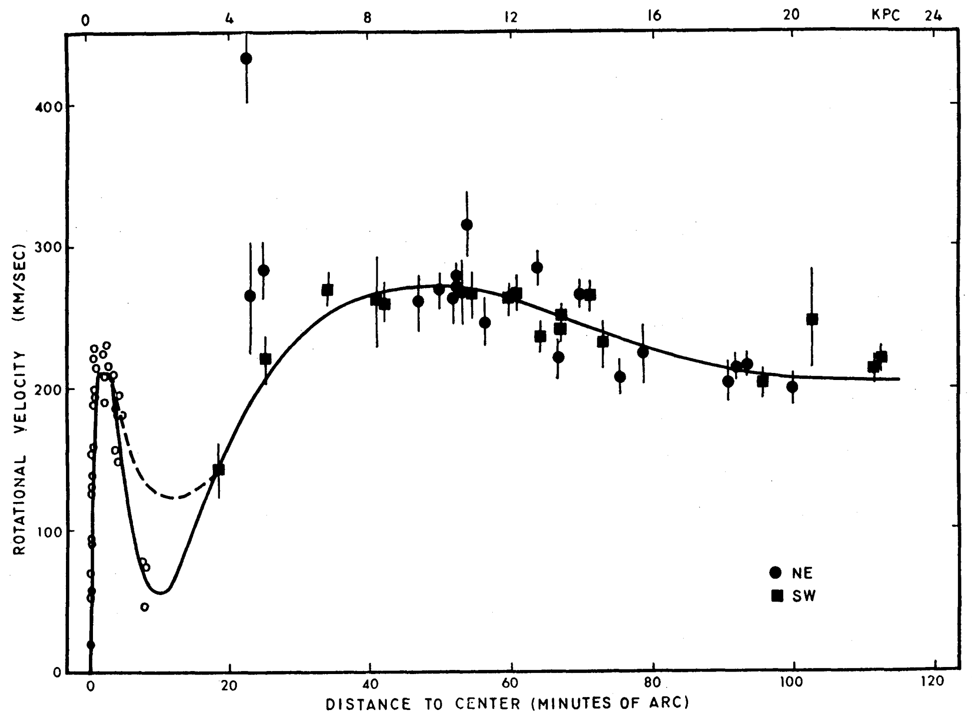


ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

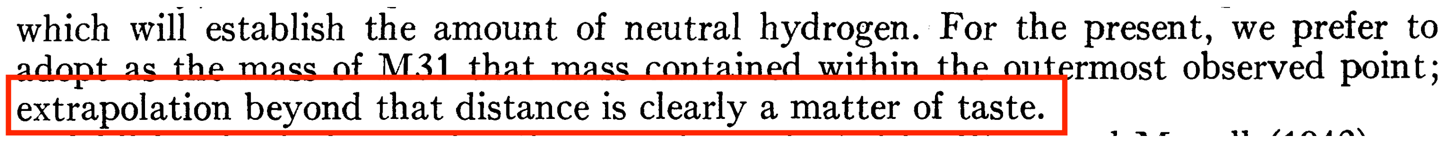
Vera C. Rubin† and W. Kent Ford, Jr.†

Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21



Andromeda, M31



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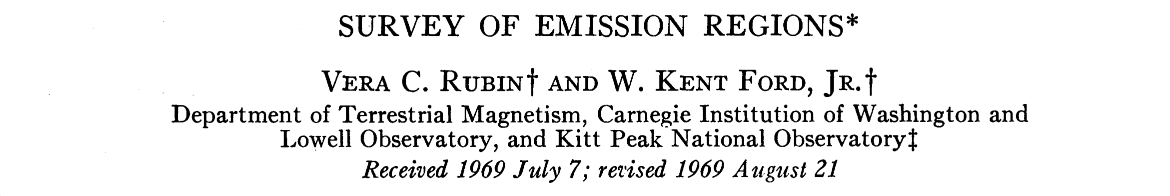

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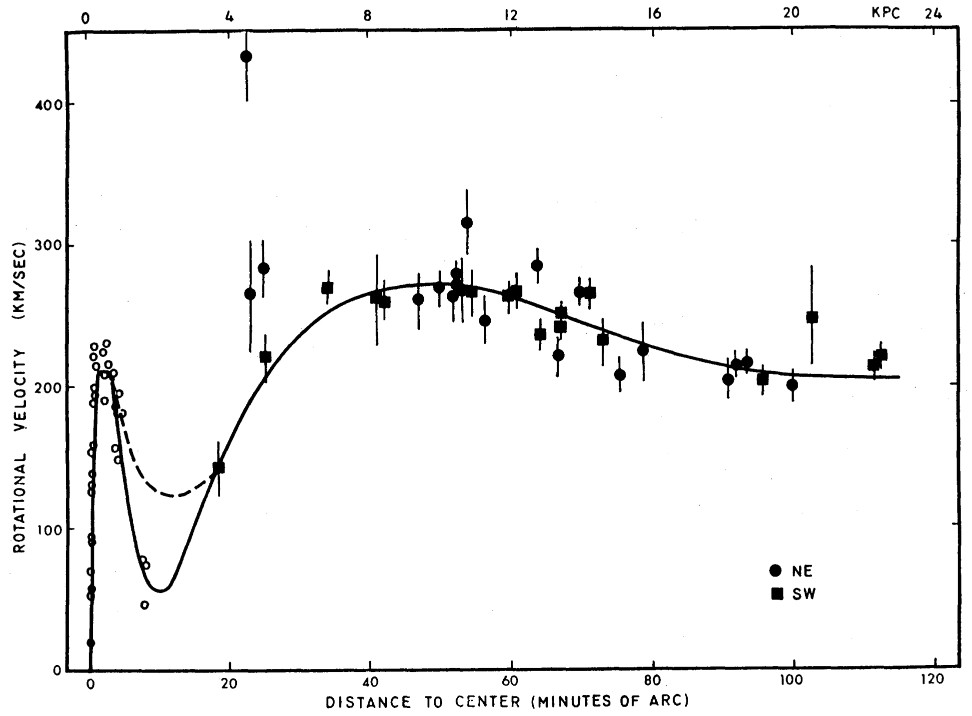

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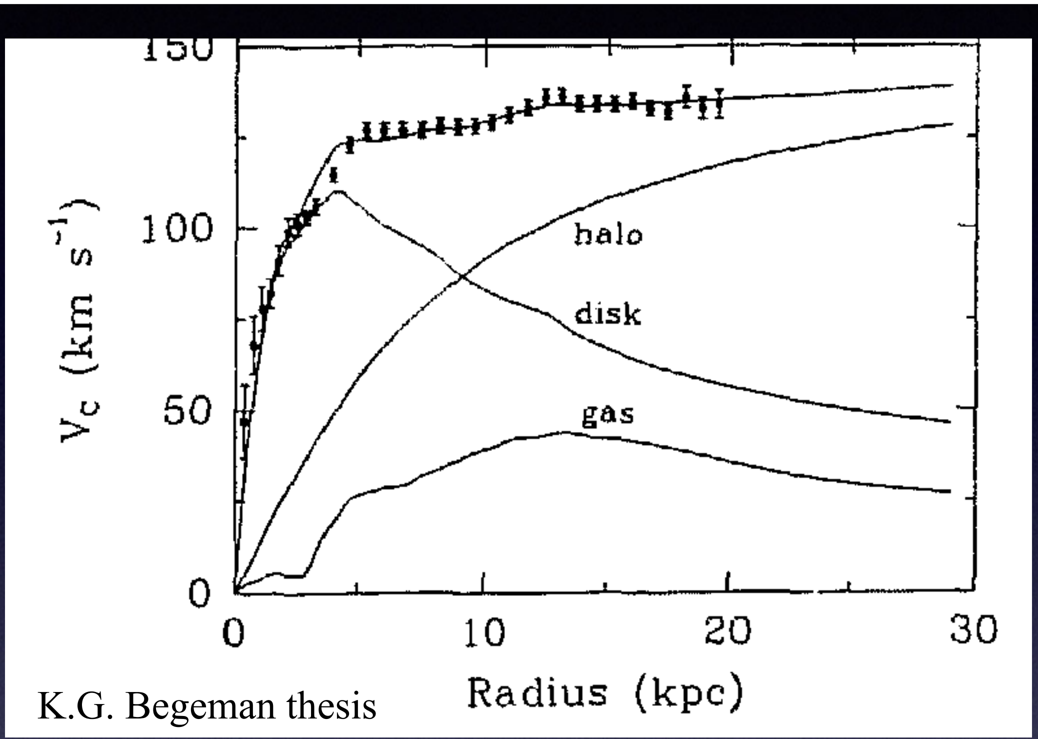


K.G. Begeman thesis

NGC2403

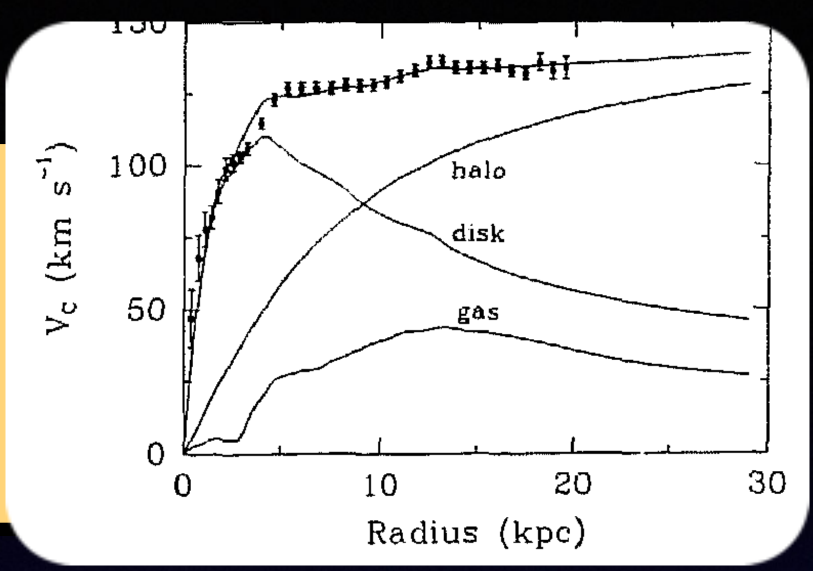
Which profiles?

The rotation curve is given by

$v^2(r) = GM(r)/r$

A constant velocity at large radius means

$$M(r) = \int 4\pi r^2 \rho(r) dr \ \propto r \Rightarrow \rho(r) = \frac{\rho_0}{r^2}$$



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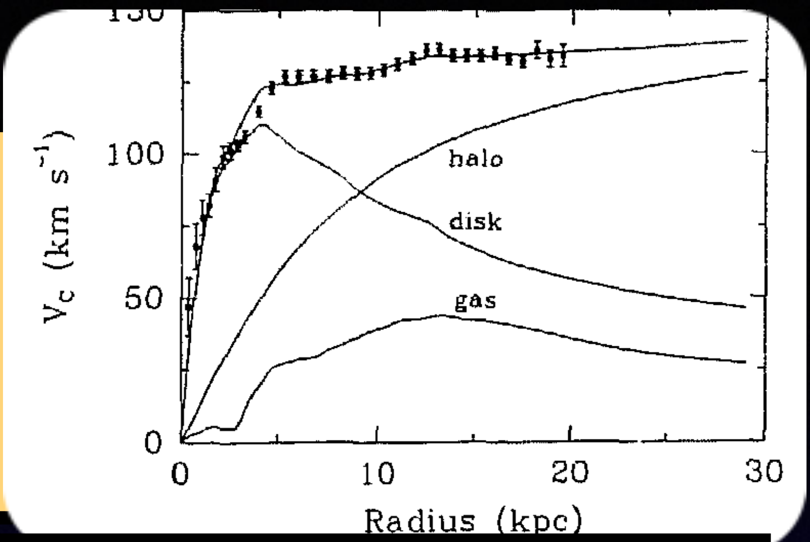

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$$\rho^{iso}(r) = \frac{\rho_0}{1 + \left(\frac{r}{r_c}\right)^2}$$

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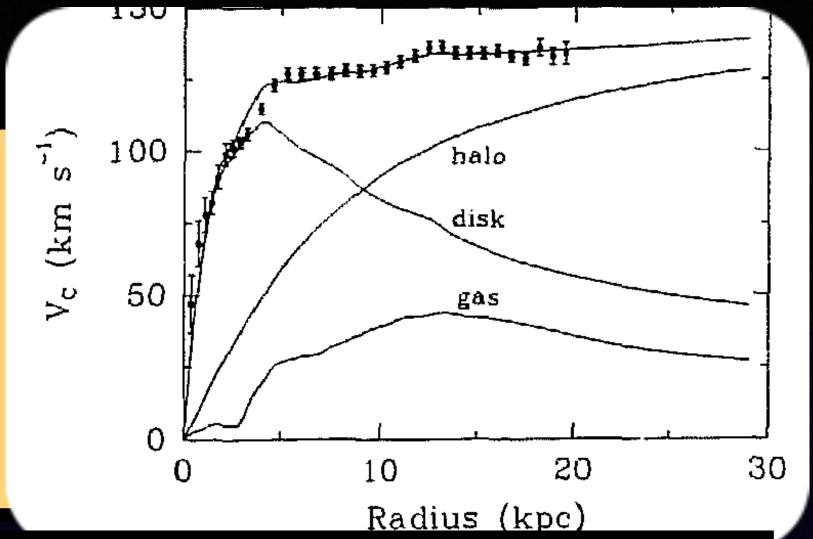

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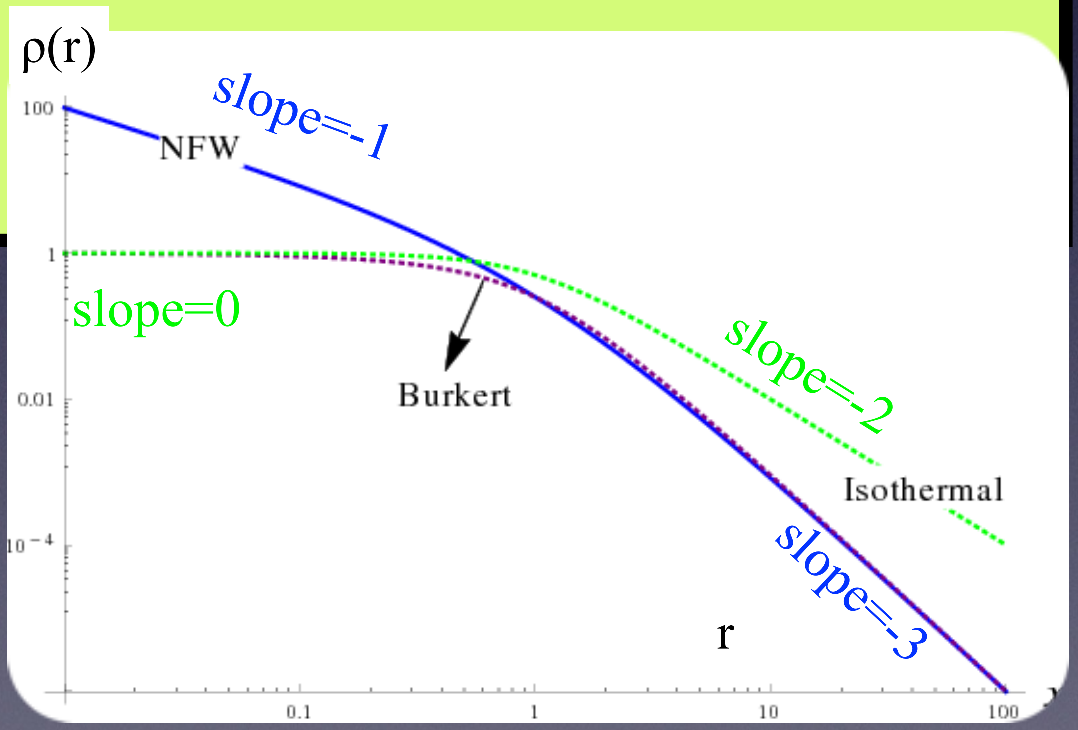

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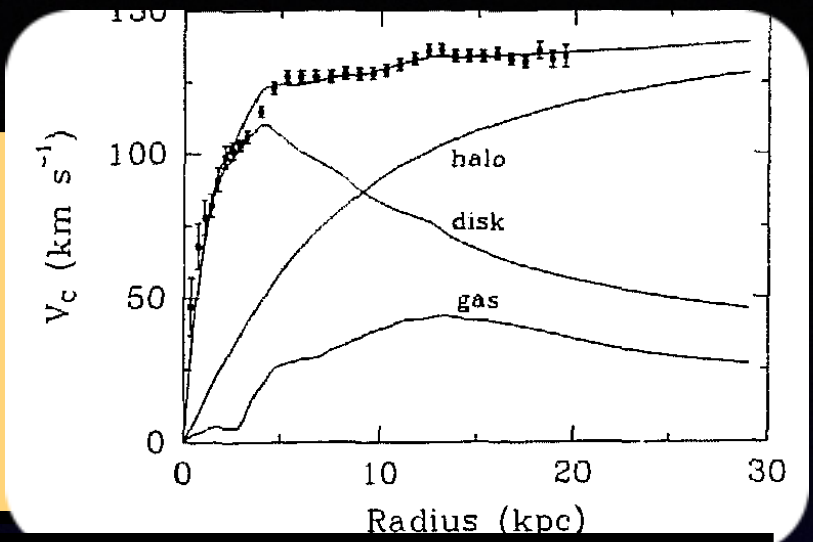

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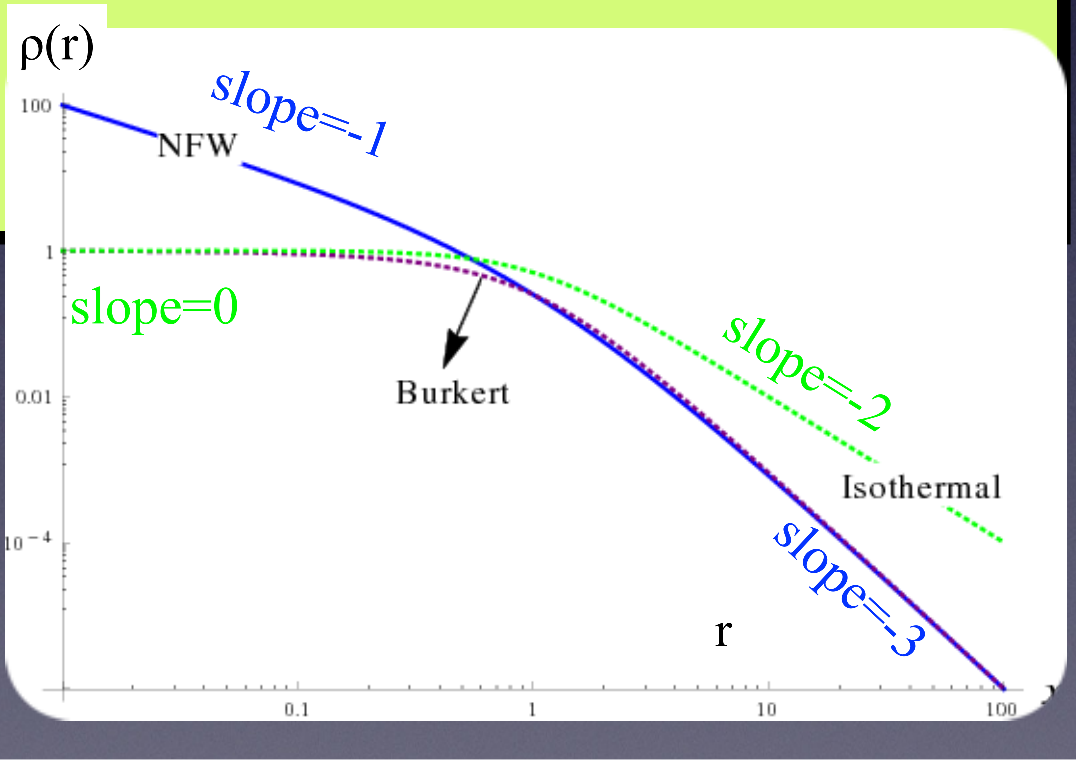


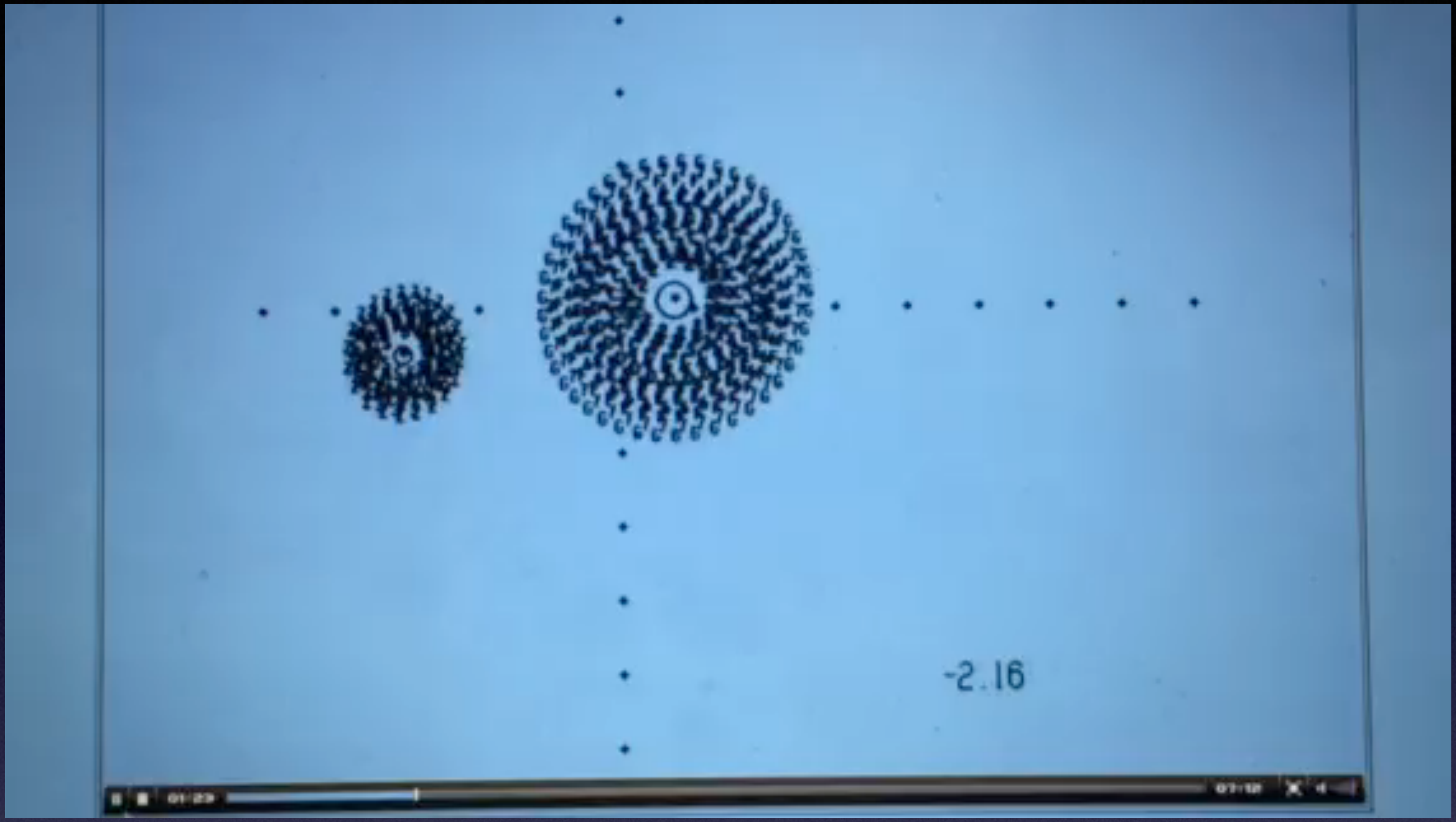
Navarro (Arizona), **Frenk** (Durham) and **White** (Munchen), in a series of papers between **1995** and **1997** extracted from precise N-body simulation that the dark matter profile observes a cusp feature near the center proportional to **1/r** and then evolves toward a **$1/r^3$** shape in the outskirt regions. This profile is called **NFW**

$$\rho^{NFW}(r) = \frac{\rho_0}{\frac{r}{r_c}\left(1 + \frac{r}{r_c}\right)^2}$$

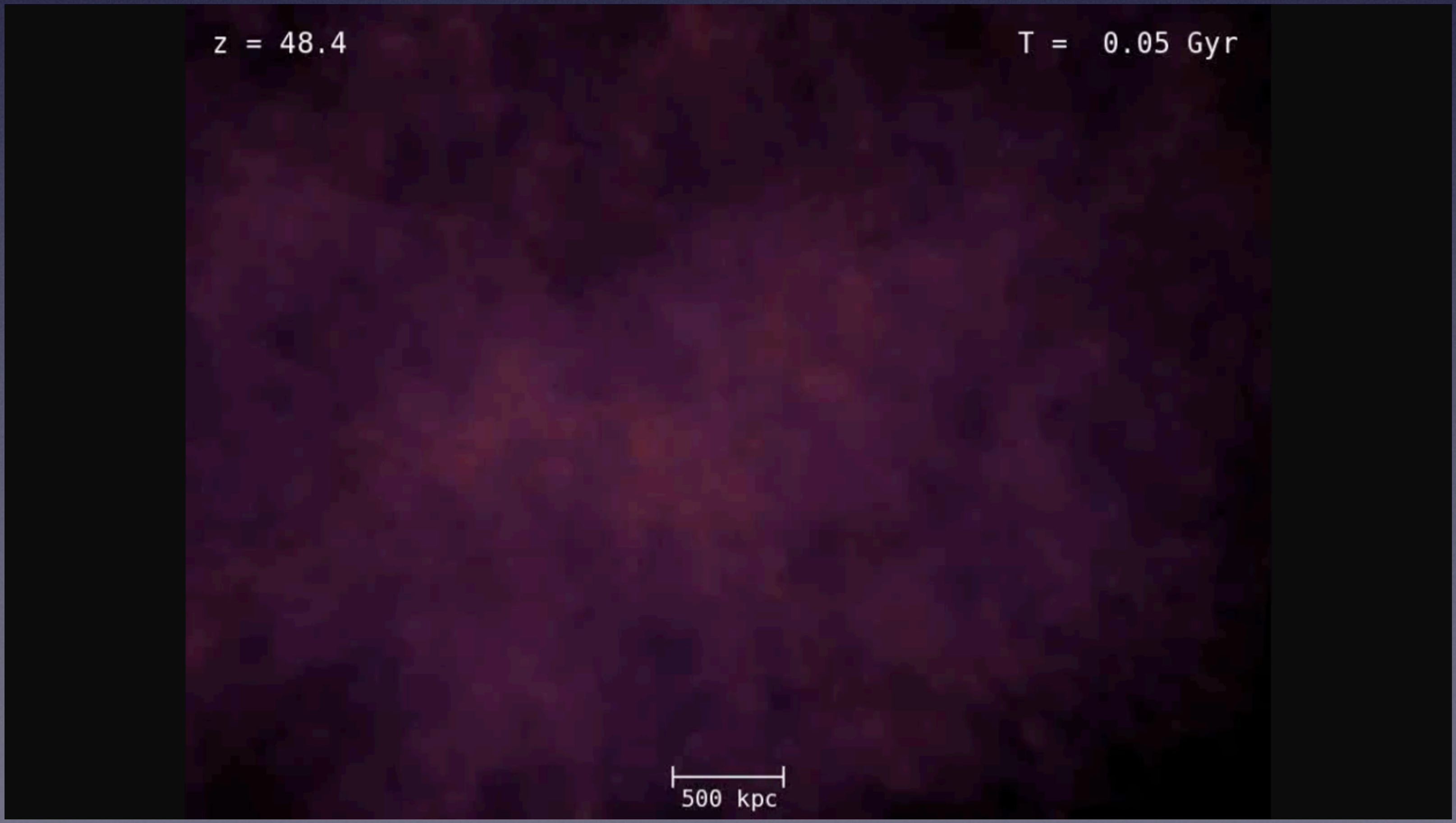
A Universal Density Profile from Hierarchical Clustering

Navaro, Frenk and White 1995

Two examples

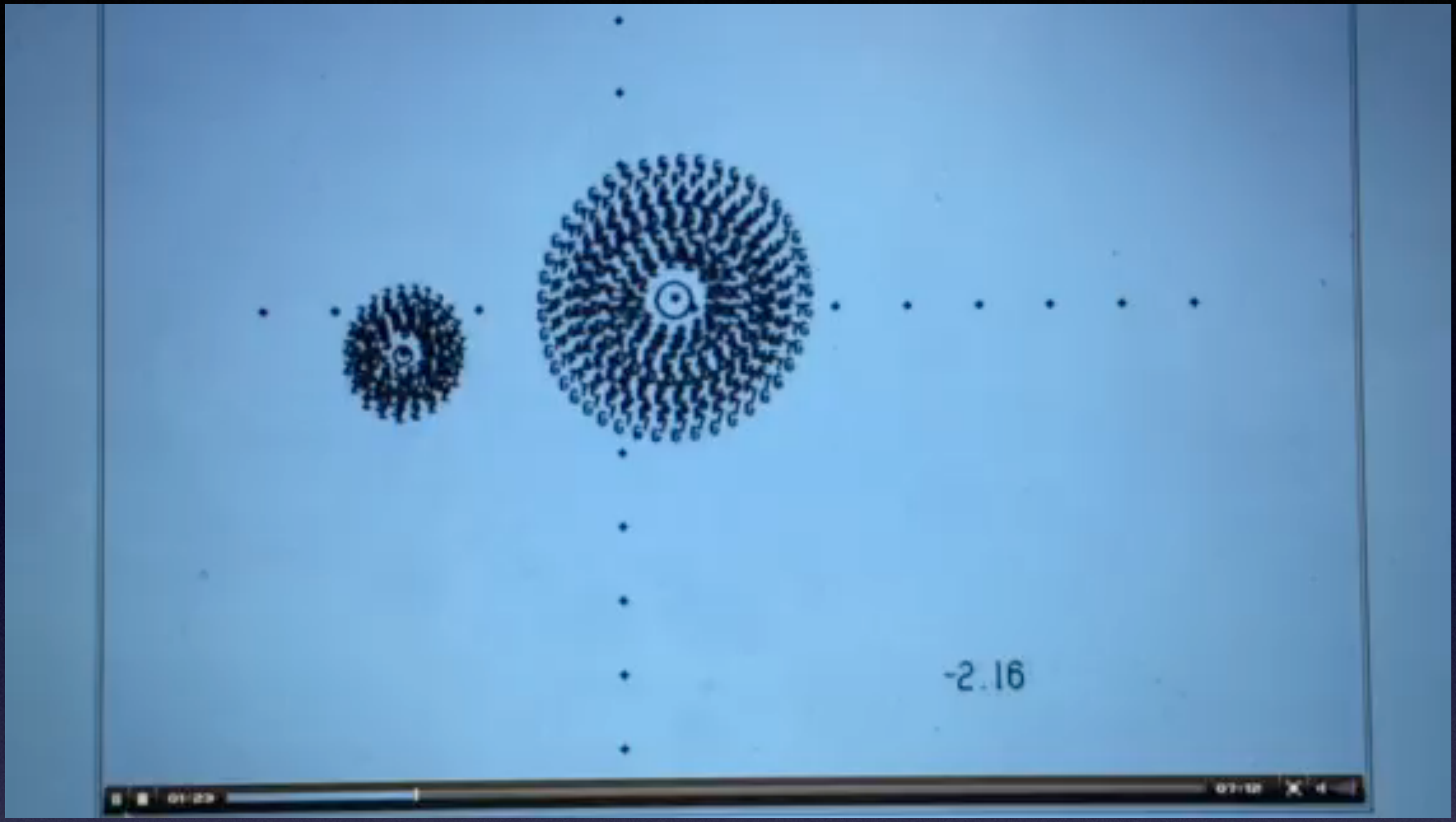


The first N-body simulation was made by the **Toomre brothers (Alar and Juri)** in 1972 (!!!) with 200 points.



Aquarius simulation (2009) with 10^9 points

Two examples



The first N-body simulation was made by the **Toomre brothers (Alar and Juri)** in 1972 (!!!) with 200 points.

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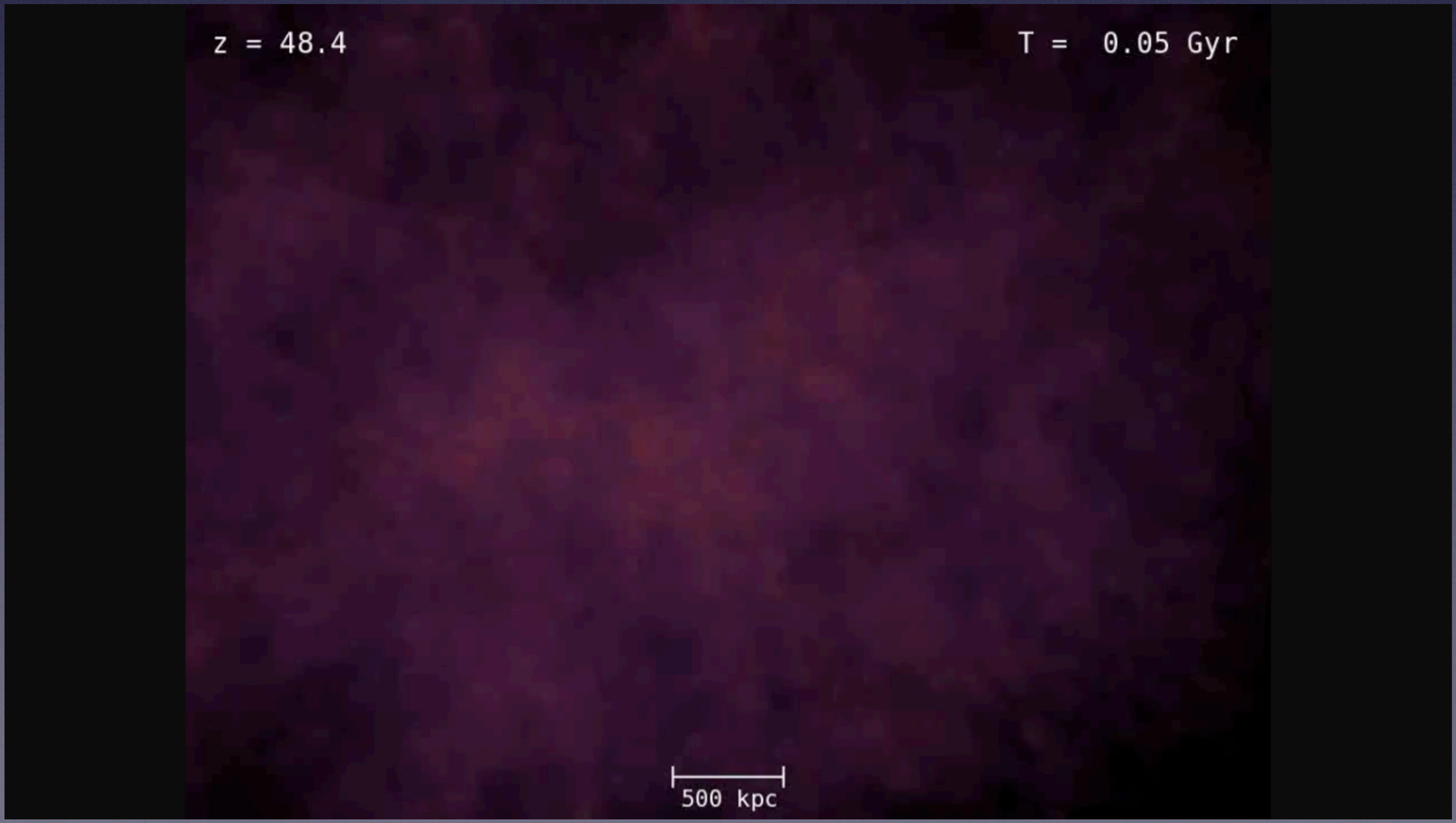

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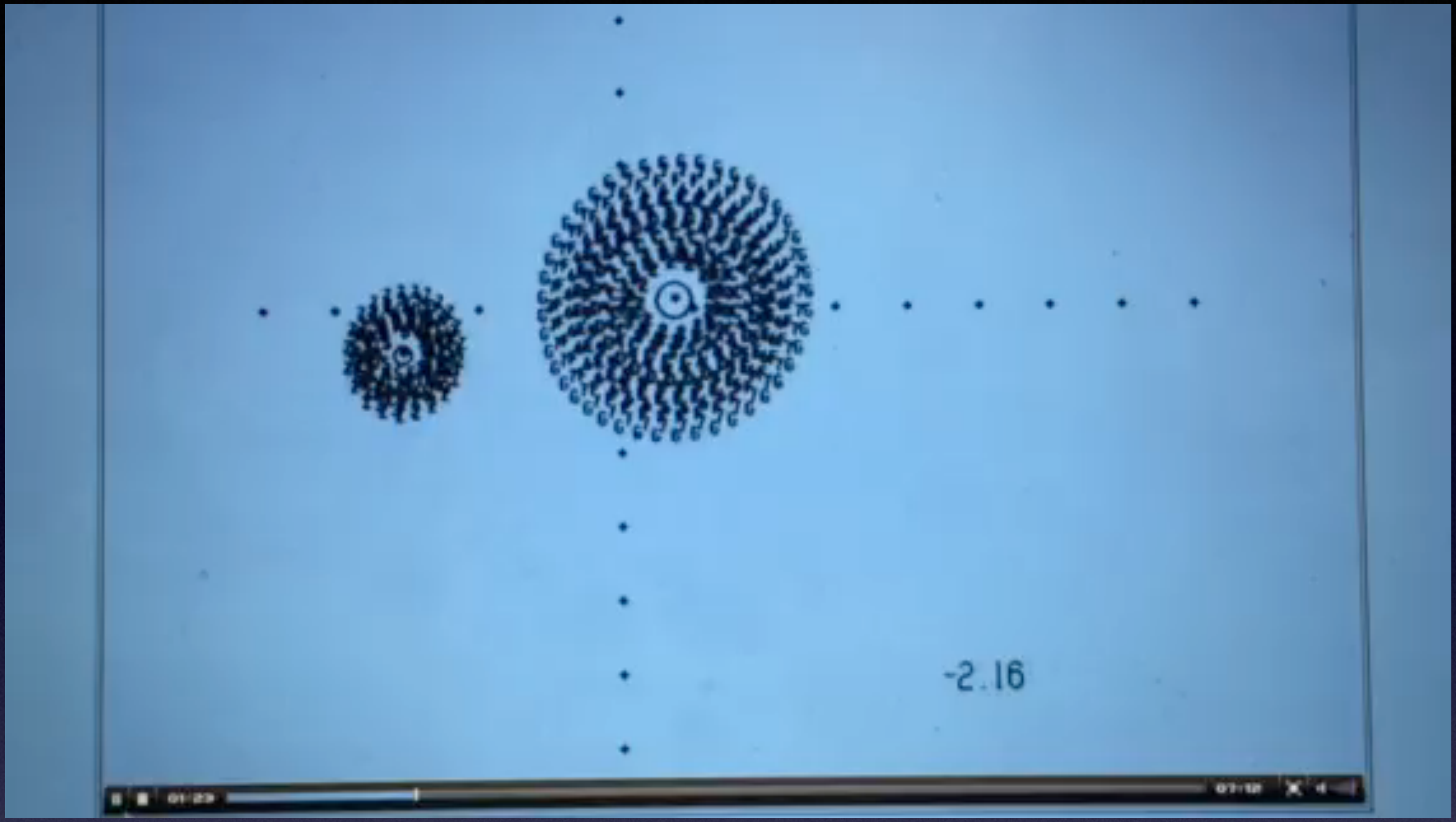

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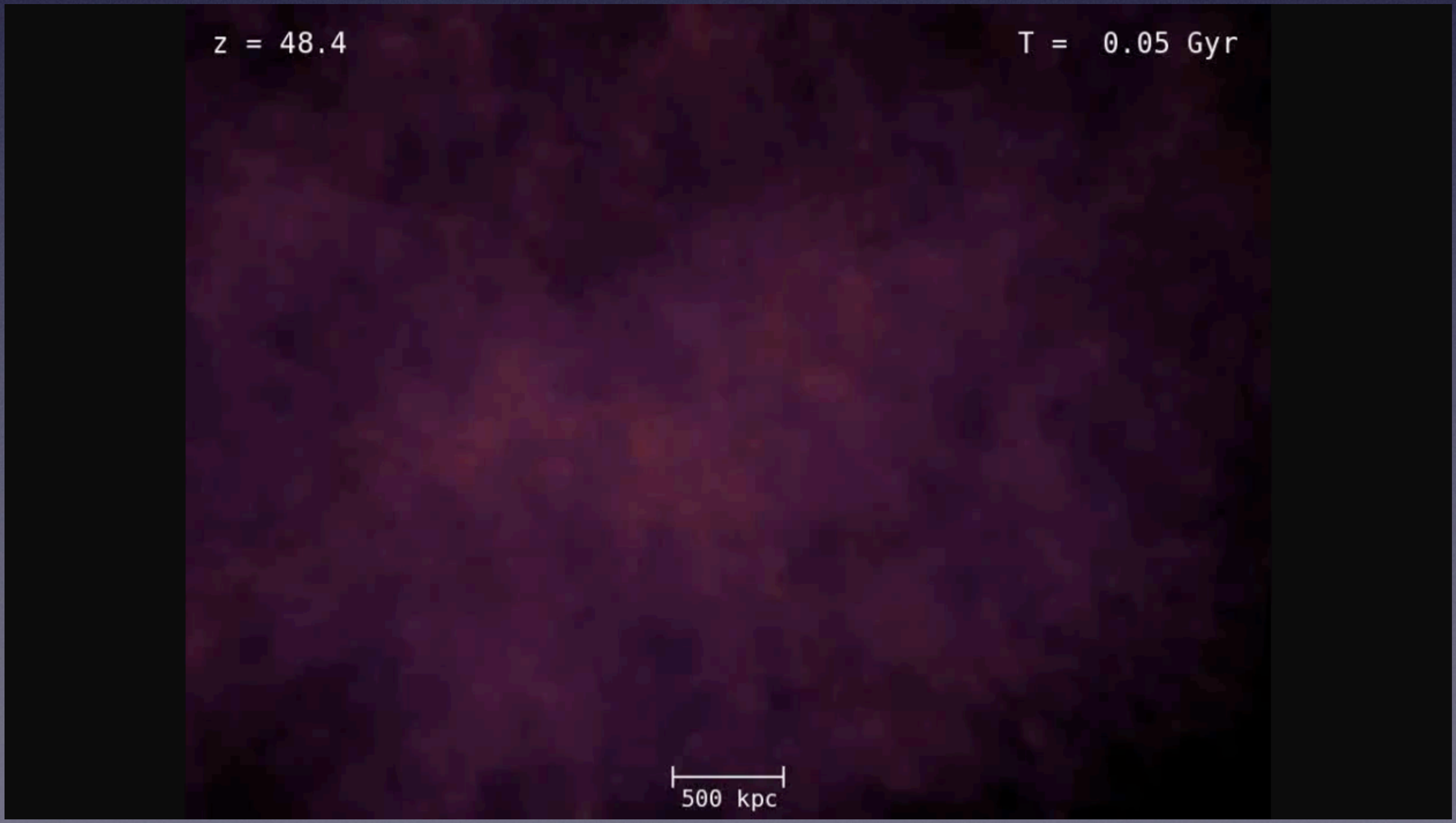
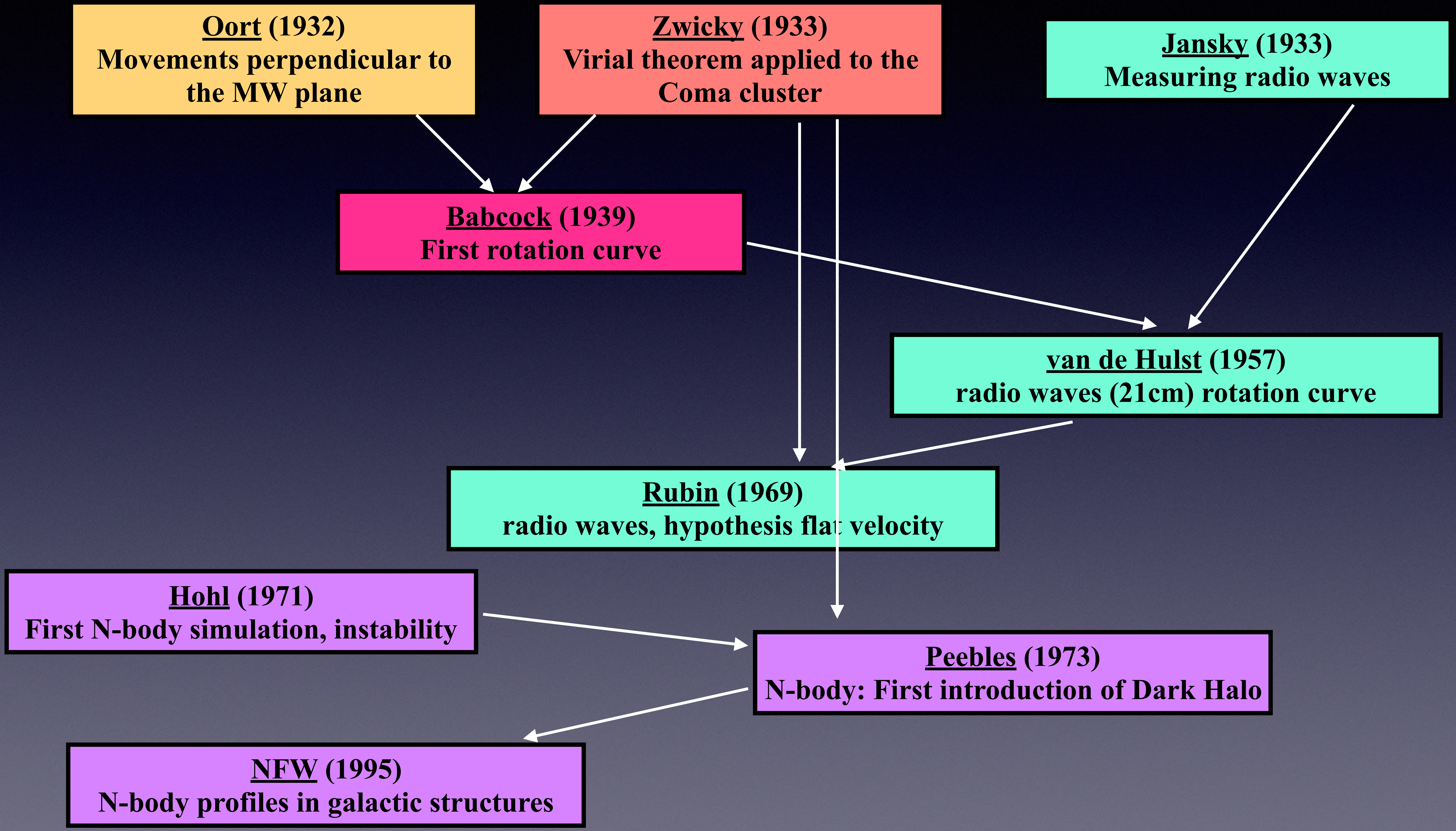


Aquarius simulation (2009) with 10^9 points

Summary (present sky)



Oort (1932)
Movements perpendicular to the MW plane

Zwicky (1933)
Virial theorem applied to the Coma cluster

Jansky (1933)
Measuring radio waves

Babcock (1939)
First rotation curve

van de Hulst (1957)
radio waves (21cm) rotation curve

Rubin (1969)
radio waves, hypothesis flat velocity

Hohl (1971)
First N-body simulation, instability

Peebles (1973)
N-body: First introduction of Dark Halo

NFW (1995)
N-body profiles in galactic structures

pre-conclusion

We have seen in this first part that it was a long way from the first papers of Oort and Zwicky in the 30's to the latest N-Body simulation in the 90's to picture a coherent framework in the analysis of dark matter in the structures and substructures of the Universe. However, in the 60's the discovery of the CMB will shed a completely new light on the content of the Universe and will reinforce the notion of dark matter. This is the subject of the next lecture.

Historical references

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F. Zwicky, « Der Rotverschiebung von extragalaktischen Neblen», *Act. Helm. Phys.,* **6**, 110-127 (1933).

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H. van de Hulst, E. Raimond and H. van Woerden, « Rotation and density distribution of the Andromeda Nebula derived from observations of the 21-cm line», *Bull. Astro. Inst. Neth.,* **14**, 1-16 (1957).

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J. Navarro, C. Frenk and S. White, « The structure of cold dark matter halos», *Astrophys. J.,* **463**, 563-575 (1996).

Book, chapter 18

THE EVOLUTION OF THE UNIVERSE
By Dr. G. Gamow

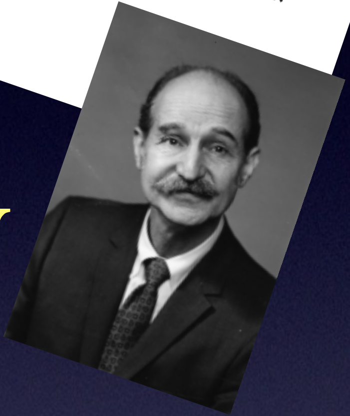
PRIMEVAL HELIUM ABUNDANCE AND THE PRIMEVAL FIREBALL*
P. J. E. Peebles

Evolution of the Universe

Ralph A. Alpher
Robert Herman

Applied Physics Laboratory,
Johns Hopkins University,
Silver Spring, Maryland.
Oct. 25.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s



Observing the primordial sky

Dissecting the CMB

The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University,
Silver Spring, Maryland
and
H. Bethe
Cornell University, Ithaca, New York
and
G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

COSMIC BLACK-BODY RADIATION*

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

Palmer

The Origin of Elements and the Separation of Galaxies
G. Gamow

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

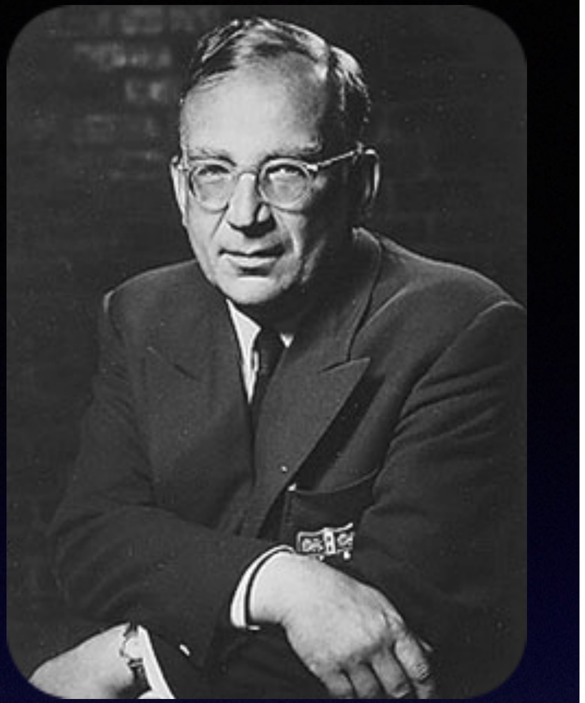
SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A
HEAVY STABLE NEUTRAL LEPTON
J. E. Gunn*
California Institute of Technology; and Institute of Astronomy, Cambridge, England

By 1980, the perceived problems of the stability of rotationally supported disk galaxies and the observation of non-declining rotation curves of spiral galaxies had led most astronomers **to accept the idea that galaxies are embedded in a dark halo** that become dynamically **more important in the outer region**.

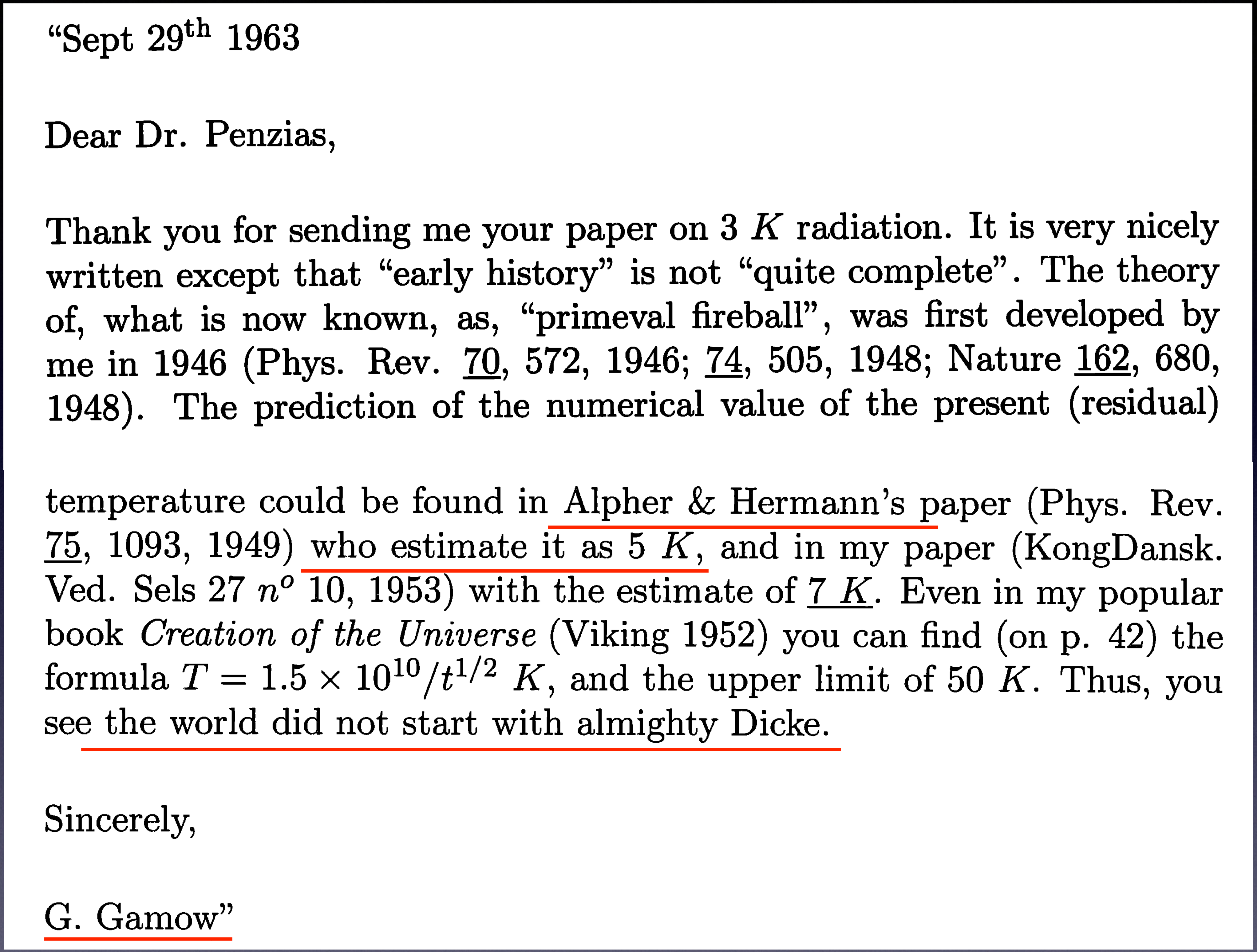
Astronomers in general thought in terms of **rather conventional dark matter** - cold gas, very low mass stars, failed stars (or super planets), stellar remnants such as cold white dwarfs, neutron stars, or low-mass black holes -
i.e. **baryonic dark matter**

At about the same time **a rather different idea** was gaining credence among cosmologists and particle physicists: that the **dark matter consists of subatomic particles; non-baryonic dark matter** that interacts only weakly with baryons and photons.

That is the story we propose to tell now..



G. Gamow



“Sept 29th 1963

Dear Dr. Penzias,

Thank you for sending me your paper on $3\ K$ radiation. It is very nicely written except that “early history” is not “quite complete”. The theory of, what is now known, as, “primeval fireball”, was first developed by me in 1946 (Phys. Rev. 70, 572, 1946; 74, 505, 1948; Nature 162, 680, 1948). The prediction of the numerical value of the present (residual) temperature could be found in Alpher & Hermann’s paper (Phys. Rev. 75, 1093, 1949) who estimate it as $5\ K$, and in my paper (KongDansk. Ved. Sels 27 n^o 10, 1953) with the estimate of $7\ K$. Even in my popular book *Creation of the Universe* (Viking 1952) you can find (on p. 42) the formula $T = 1.5 \times 10^{10}/t^{1/2}\ K$, and the upper limit of $50\ K$. Thus, you see the world did not start with almighty Dicke.

Sincerely,

G. Gamow”

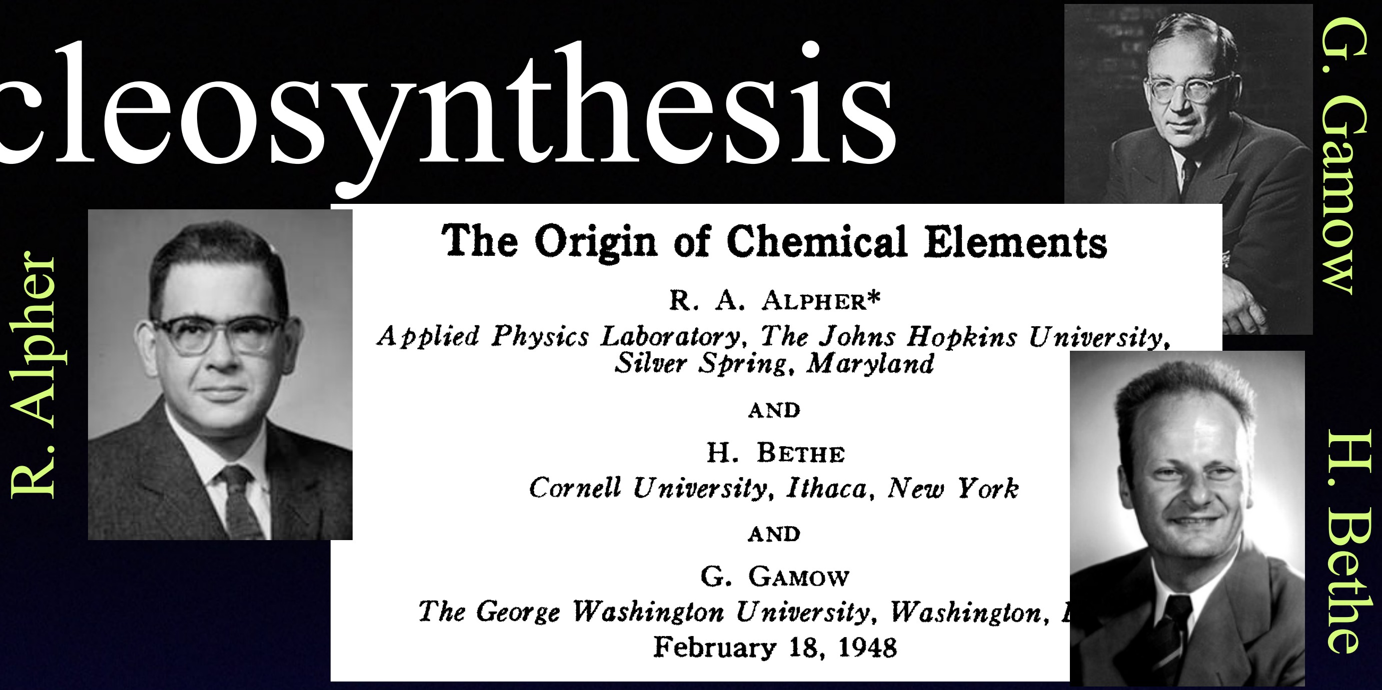
A. Penzias

« Gamow? A man whose idea is wrong in almost every detail», Penzias in his Nobel lecture, 1978.

The concept of nucleosynthesis

Alpher, Bethe Gamow (April 1st, 1948)
+ thesis of Alpher

The approach of a **building-up** universe was **not obvious in 1948**, when the common thought was that the elements were **generated from decay processes**, from the heavier element to the lighter one. The concept was proposed by **Alpher in his thesis** supervised by **Gamow** (from which the famous **Alpher, Bethe Gamow** paper know as the **αβγ paper** is extracted).



The Origin of Chemical Elements

R. A. Alpher*
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AND

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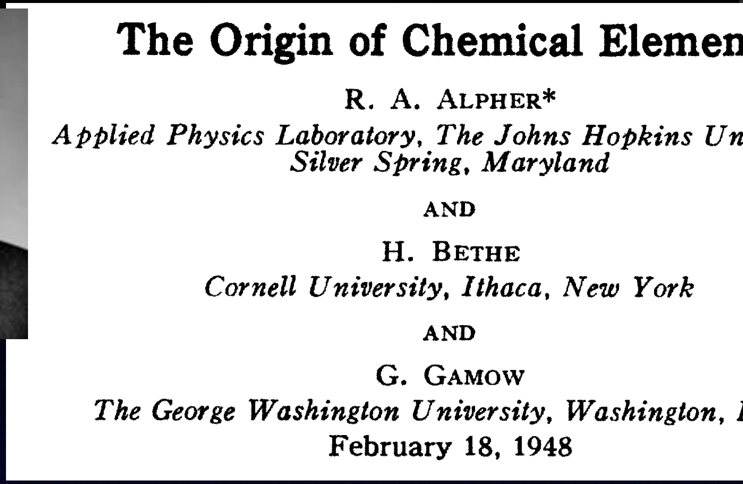

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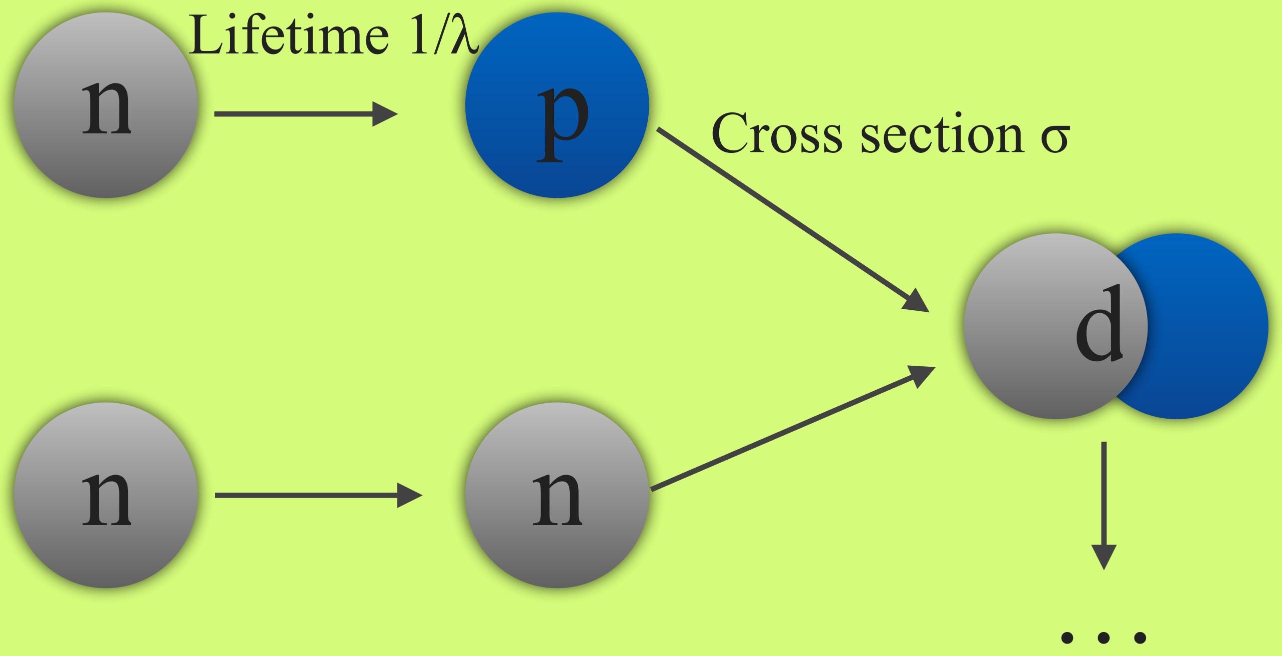
The fundamental idea is that the primordial Universe is made of **neutron** only, which decay into **proton**. Then, their combination form the nucleus of **deuterium** which subsequently will form the heavier elements like Helium, Lithium.. This is the « **deuterium bottleneck** » process.



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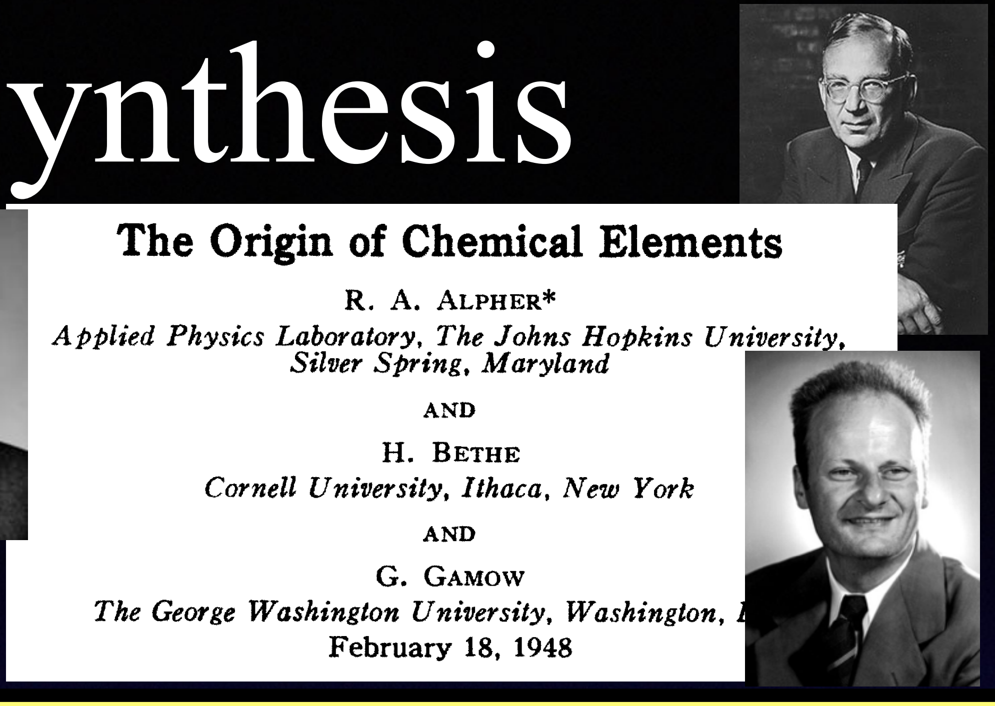

The Origin of Chemical Elements

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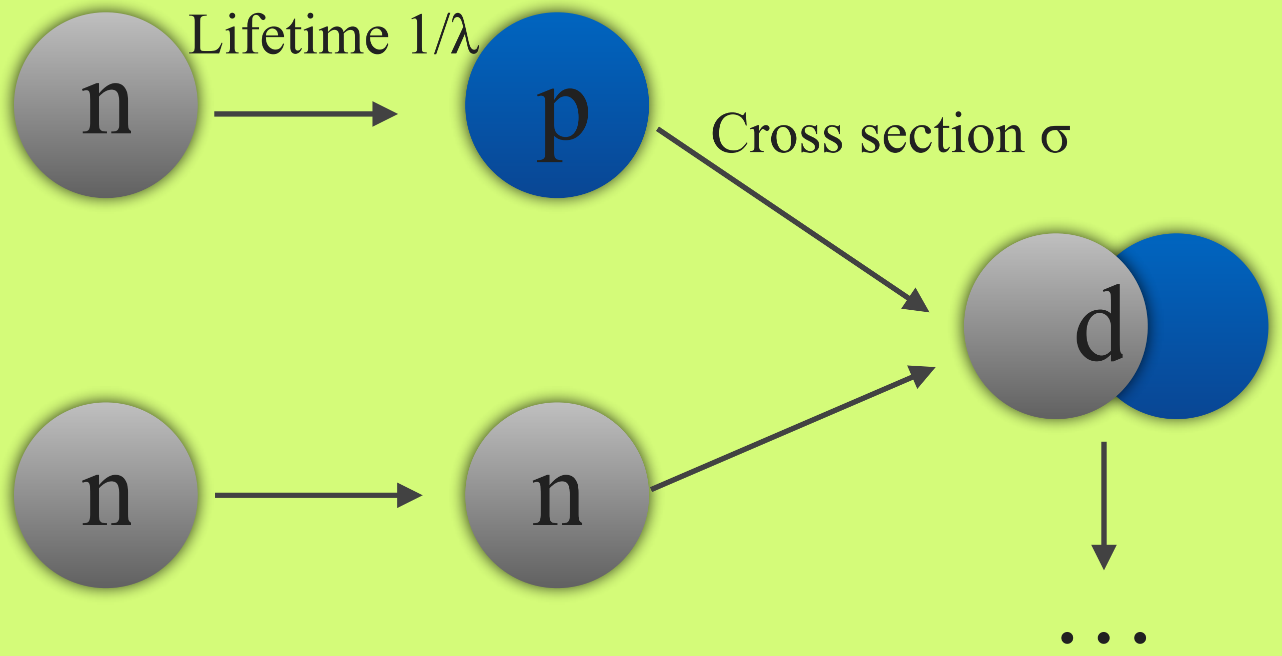


To compute the time **t** needed for the process with a **density of neutron n**, Alpher and Gamow supposed

$$nt\,\sigma v \sim 1.$$

It means that the exposure **nt** was sufficiently long to initiate one reaction. Using a tabulation by **Hughes (1946)** for **σ*$(E/1\ \mathrm{eV})^{1/2}$ = 10^{-25} cm²** and the approximation $E \sim 1/2\ mv^2$ to deduce

$$\sigma v \sim\ 1.5 \times 10^{-19}\ \mathrm{cm}^3\ \mathrm{s}^{-1}.$$

nt should then be equal to 7×10^{18} s cm^{-3} to initiate the process. However, **Alpher and Gamow** mistakenly considered a **matter dominated Universe** to compute t:

$$G\ M\ /a = 1/2\ v^2 \Rightarrow \sim\rho = nm = (3/8\pi G)\ /\ t^2.$$

giving

$$nt \sim 5 \times 10^{29}\ (s/t)\ \mathrm{s\ cm}^{-3}.$$

The lifetime of the neutron being ~**1000 seconds**, **ntσv is equal to 10^8 (very large exposure!)** which means that all the protons has been absorbed to form the deuterium, leaving a Universe empty of Hydrogen. **The mistake** was of course coming from the **matter domination hypothesis** of the Universe as Gamow will notice 2 months later.

Universe is radiation

G. Gamow (June 1948)

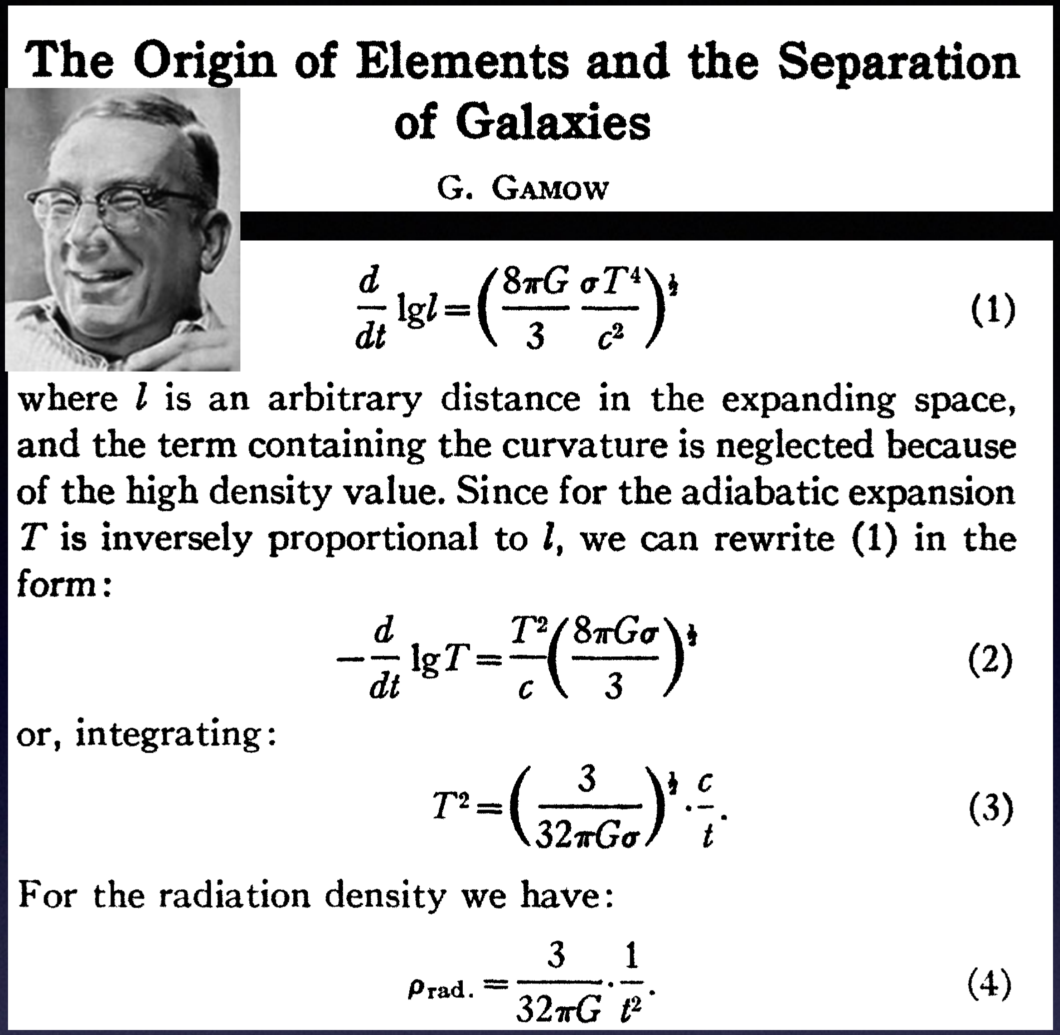
The novelty in this paper is the **new approach** that **Gamow** took in the computation of the temperature at which the deuterium formation begins. Indeed, he understood that for large temperature, the reverse **dissociation process**

$$\gamma + d \to n + p$$

forbid the formation of the deuterium. In other words, the nucleosynthesis process **can only be initiated** once T drops to

$$T_D = 10^9 \text{ K} = 0.085 \text{ MeV}.$$

Notice that **Gamow** took a temperature well below the **binding energy** of the deuterium (**B_D=2.1 MeV**) as he should have been aware of the Saha equation.



The Origin of Elements and the Separation of Galaxies

G. Gamow

$$\frac{d}{dt}\lg l=\left(\frac{8\pi G}{3}\frac{\sigma T^4}{c^2}\right)^{\frac{1}{2}} \quad (1)$$

where l is an arbitrary distance in the expanding space, and the term containing the curvature is neglected because of the high density value. Since for the adiabatic expansion T is inversely proportional to l, we can rewrite (1) in the form:

$$-\frac{d}{dt}\lg T=\frac{T^2}{c}\left(\frac{8\pi G\sigma}{3}\right)^{\frac{1}{2}} \quad (2)$$

or, integrating:

$$T^2=\left(\frac{3}{32\pi G\sigma}\right)^{\frac{1}{2}}\cdot\frac{c}{t}. \quad (3)$$

For the radiation density we have:

$$\rho_{\text{rad.}}=\frac{3}{32\pi G}\cdot\frac{1}{t^2}. \quad (4)$$

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From **Friedmann equation**, one can write

$$d\mathrm{Log}(a)/dt = (8\pi\, G/3\ \rho_{rad})^{1/2}$$

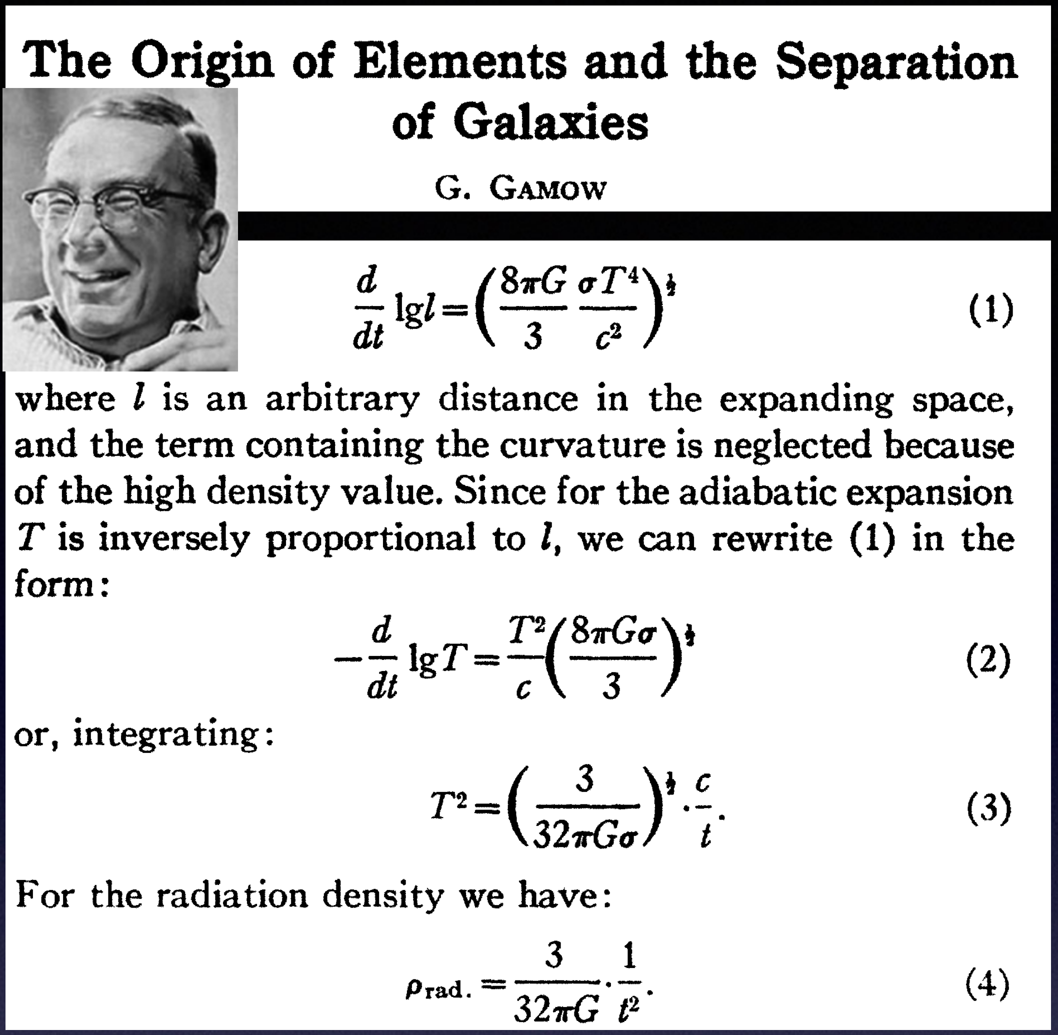
and a*T = cste implies **dLog(a)/dt = -dLog(T)/dt**, and then after integration

$$\rho_{rad} = (3/32\ \pi\ G)*(1/t^2) = \pi/15\ T^4 \sim 8.40\ (T/10^9K)^4 \text{ g cm}^{-3}$$

which leads to

$$t=231\ (10^9K/T)^2 \text{ seconds}$$

confirming that the nucleosynthesis is initiated at about 200 seconds



The Origin of Elements and the Separation of Galaxies

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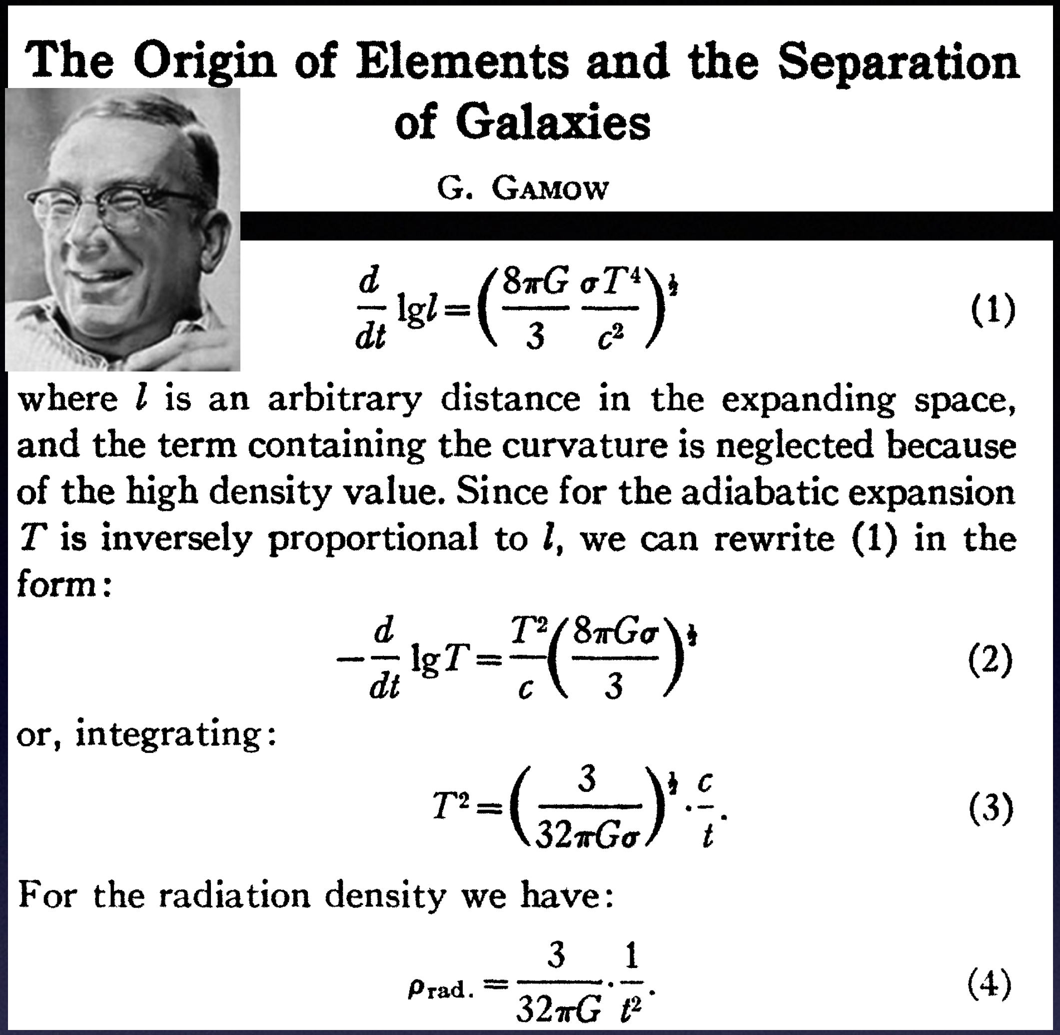

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confirming that the nucleosynthesis is initiated at about 200 seconds

Gamow then computed the density of matter at this time (**200 seconds**) to check that it is effectively **radiated dominated**.

From T=10^9 K, **Gamow** deduces

$$v = 4.8 \times 10^8 \text{ cm s}^{-1}$$

and then using **nt σv = 1**, with t~200, one can compute n~10^{18} cm^{-3}, and then

$$\rho_m = n\ m \sim 3.6 \times 10^{-6} \text{ g cm}^{-3}$$

which is much less than the radiation density **ρ_{rad} ~10 g cm^{-3}** (order of the water density). However, **Gamow** 4 months later will develop a more detailed analysis of the **nucleosynthesis**.

Computing ρ_{matter}

G. Gamow (October 1948)

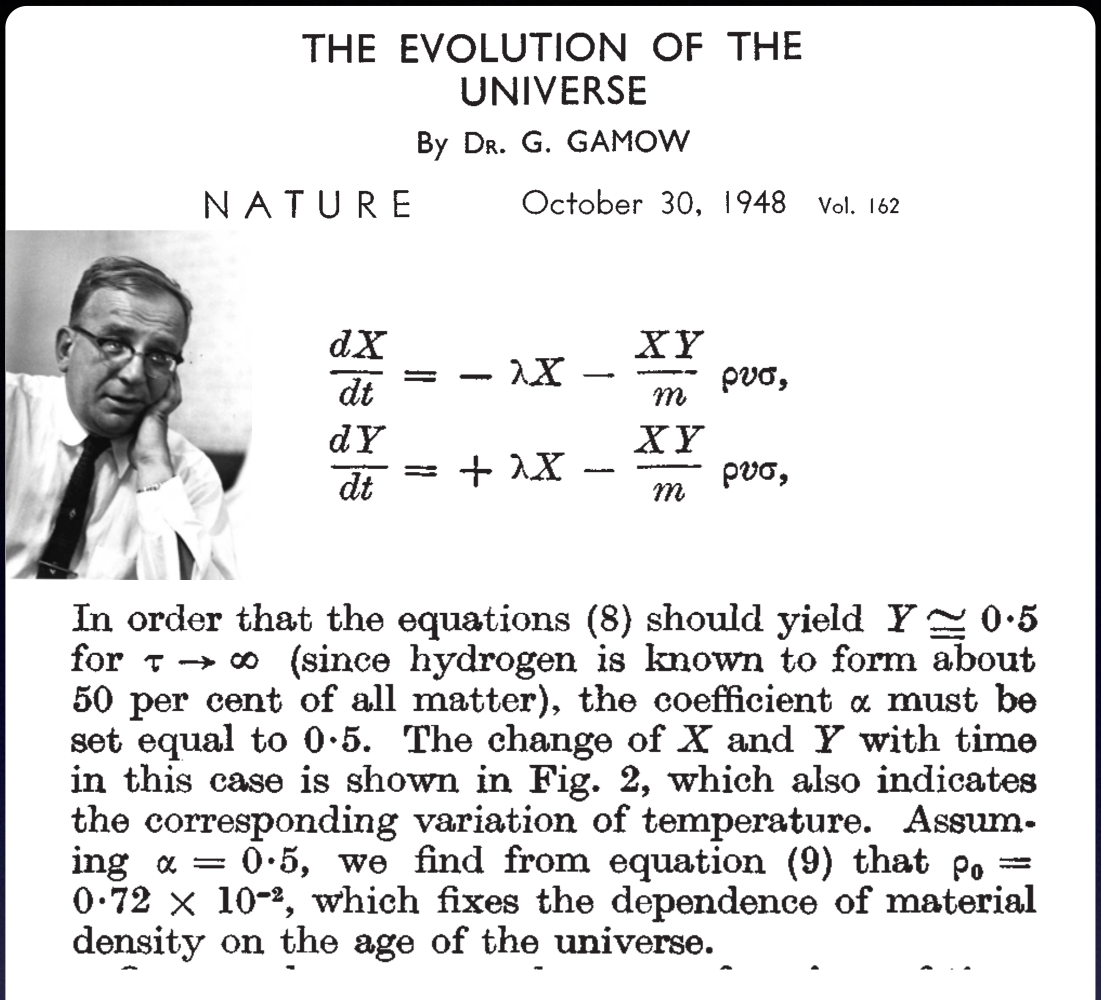
After having understood that the Universe is not dominated by the dust (mass) but by the radiation at the time of deuterium formation, **Gamow** decided to compute the **density of matter ρ_m** at that time.

$$N_n = X\rho a^3; \quad N_p = Y\rho a^3$$

$$\frac{dN_n}{dt} = -\lambda N_n - N_n(\frac{Y\rho}{m})\sigma v$$
$$\Rightarrow \rho a^3\frac{dX}{dt} = -\lambda\rho a^3 X - \rho a^3 XY\frac{\rho}{m}\sigma v$$

Which gives when combining with the equation for the proton

$$\frac{dX}{dt} = -\lambda X - XY\frac{\rho}{m}v\sigma$$
$$\frac{dY}{dt} = +\lambda X - XY\frac{\rho}{m}v\sigma$$



THE EVOLUTION OF THE UNIVERSE

By Dr. G. GAMOW

NATURE October 30, 1948 Vol. 162

$$\frac{dX}{dt} = -\lambda X - \frac{XY}{m}\rho v\sigma,$$
$$\frac{dY}{dt} = +\lambda X - \frac{XY}{m}\rho v\sigma,$$

In order that the equations (8) should yield $Y \cong 0{\cdot}5$ for $\tau \rightarrow \infty$ (since hydrogen is known to form about 50 per cent of all matter), the coefficient α must be set equal to $0{\cdot}5$. The change of X and Y with time in this case is shown in Fig. 2, which also indicates the corresponding variation of temperature. Assuming $\alpha = 0{\cdot}5$, we find from equation (9) that $\rho_0 = 0{\cdot}72 \times 10^{-2}$, which fixes the dependence of material density on the age of the universe.

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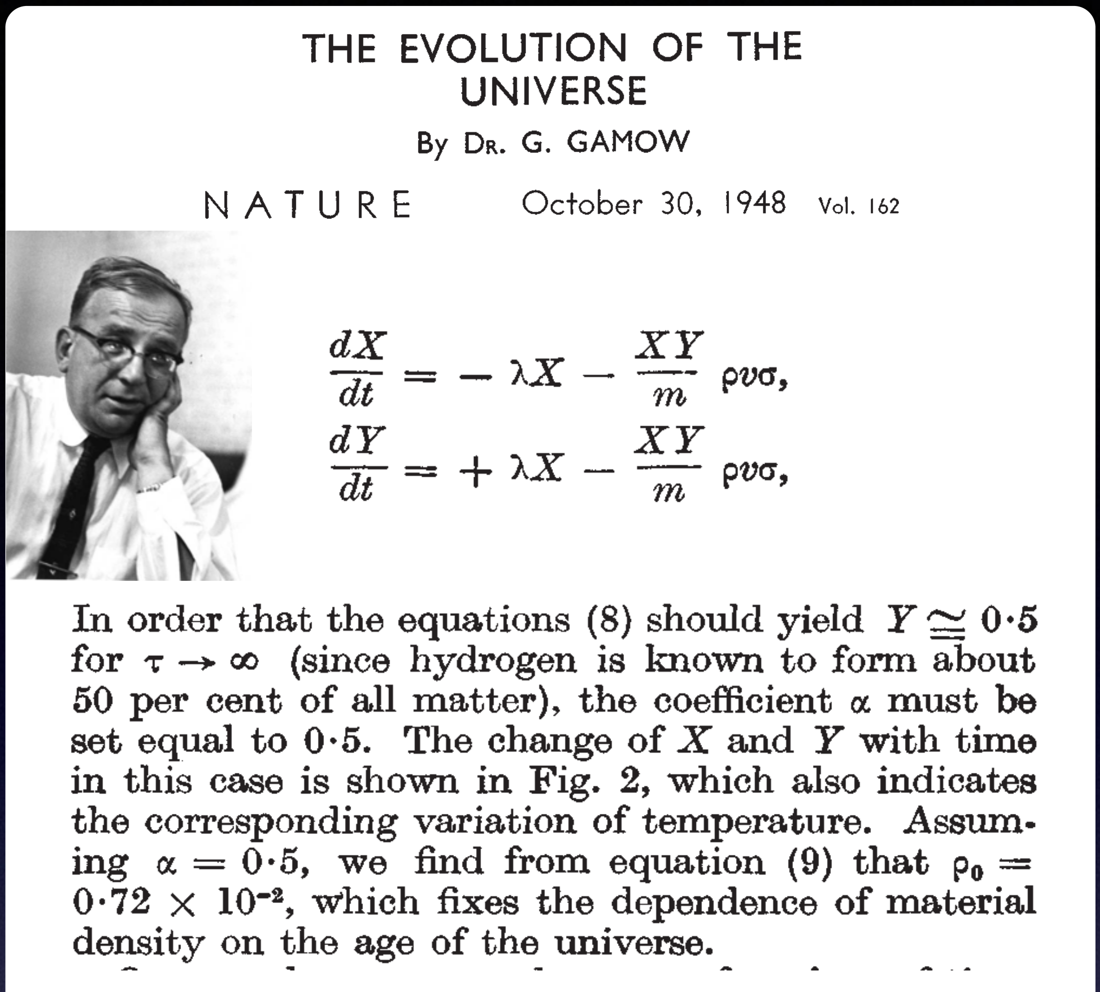

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Gamow supposed the limit condition **Y = 0.5** when **t goes to infinity** : he supposed that half of the mass component of the Universe is made of hydrogen. As a result he obtained

$$\rho_m(10^9K) = 7.2 \text{ x } 10^{-3} \ (1s/t)^{3/2} \text{ g cm}^{-3}.$$

However, **Gamow** was not interested to the present temperature of the radiation, but to the formation of galaxies. It is **Alpher and Herman** who will, **2 weeks later**, compute it.

The prediction

Alpher, Herman (October 1948)

The article of **Alpher and Herman** began by 4 corrections to the preceding article of Gamow. The relation between **Gamow**, **Alpher** (his PhD student) and **Herman** (his postdoc) was not so clear, but some tensions seemed to have appeared after the **αβγ event**. In any case, correcting the ρ_m of **Gamow**, they computed the relic temperature nowadays. They obtained

$$\rho_m = 1.7 \times 10^{-2} (1s/t)^{3/2} \text{ g cm}^{-3} \sim 2 \text{x} 10^{-6} \text{ g cm}^{-3} \text{ at } 10^9 \text{ K.}$$

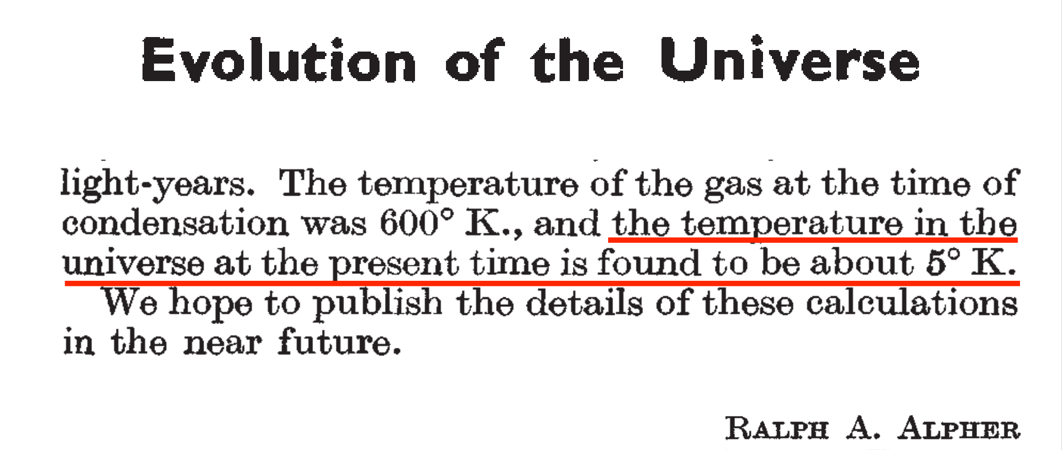
Noting that $\boldsymbol{\rho(T)/T^3 = \text{constant}}$, we can deduce

$$T_{now} = 10^9 K \, [\rho_{now} / \rho(10^9 K)]^{1/3}.$$

Taking from galaxies observations $\boldsymbol{\rho_{now} = 10^{-30} \text{ g cm}^{-3}}$ ($\rho_c = 2 \times 10^{-29} h^2 \text{ g cm}^{-3}$), one obtains

$$T_{now} \sim 5 \text{ K.}$$

This is the first prediction of the Cosmic Microwave Background



Evolution of the Universe

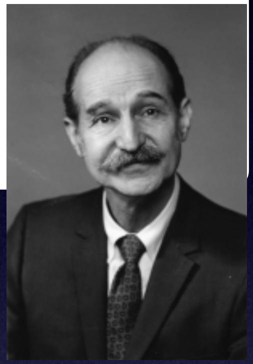
light-years. The temperature of the gas at the time of condensation was 600° K., and the temperature in the universe at the present time is found to be about 5° K.

We hope to publish the details of these calculations in the near future.

RALPH A. ALPHER
ROBERT HERMAN

Applied Physics Laboratory,
Johns Hopkins University,
Silver Spring, Maryland.
Oct. 25.

R. Alpher



R. Herman

The prediction

Alpher, Herman (October 1948)

The article of **Alpher and Herman** began by 4 corrections to the preceding article of Gamow. The relation between **Gamow**, **Alpher** (his PhD student) and **Herman** (his postdoc) was not so clear, but some tensions seemed to have appeared after the **αβγ event**. In any case, correcting the ρ_m of **Gamow**, they computed the relic temperature nowadays. They obtained

$$\rho_m = 1.7 \times 10^{-2} (1s/t)^{3/2} \text{ g cm}^{-3} \sim 2\times10^{-6} \text{ g cm}^{-3} \text{ at } 10^9 \text{ K.}$$

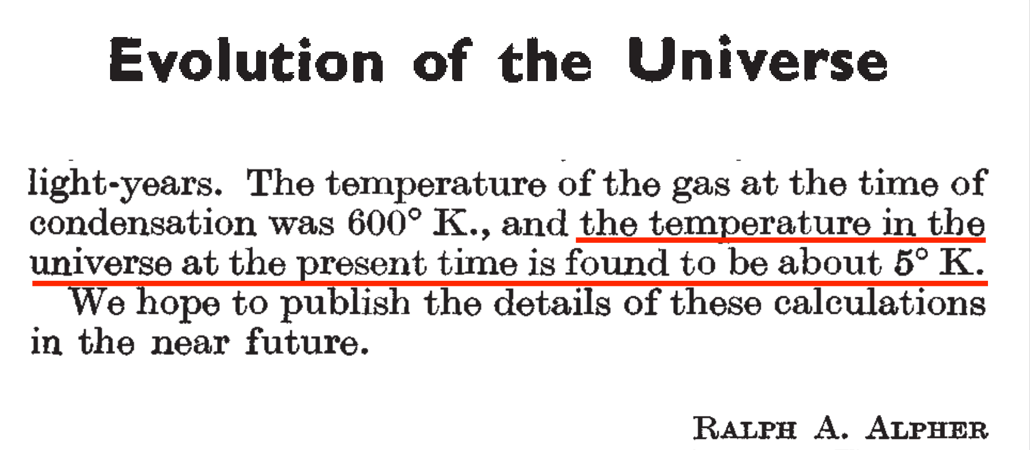
Noting that $\boldsymbol{\rho(T)/T^3 = \text{constant}}$, we can deduce

$$T_{now} = 10^9\text{K} \left[\rho_{now} / \rho(10^9\text{K})\right]^{1/3}.$$

Taking from galaxies observations $\boldsymbol{\rho_{now} = 10^{-30} \text{ g cm}^{-3}}$ ($\rho_c = 2 \times 10^{-29} h^2 \text{ g cm}^{-3}$), one obtains

$$T_{now} \sim 5 \text{ K.}$$

This is the first prediction of the Cosmic Microwave Background



Evolution of the Universe

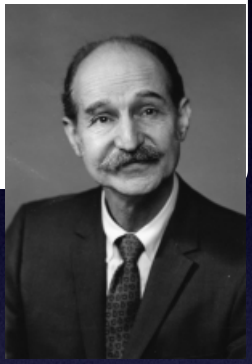
light-years. The temperature of the gas at the time of condensation was 600° K., and the temperature in the universe at the present time is found to be about 5° K.

We hope to publish the details of these calculations in the near future.

RALPH A. ALPHER
ROBERT HERMAN

Applied Physics Laboratory,
Johns Hopkins University,
Silver Spring, Maryland.
Oct. 25.

R. Alpher

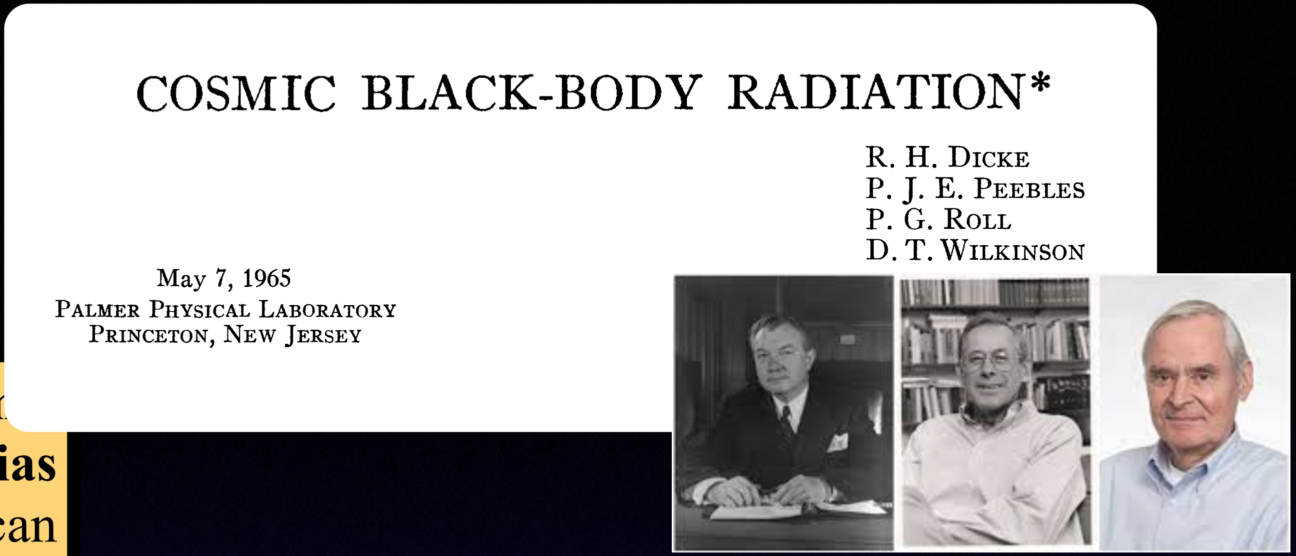


R. Herman

And then…… the field came to sleep for a long 20 years period….

The rediscovery

« Well, boys, we've been scooped »,
Dicke after a phone call by Penzias , december 1964



COSMIC BLACK-BODY RADIATION*

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

The story of the « accidental » discovery of the **Cosm** **Microwave Background** (**CMB**) in 1965, which led **Penzias and Wilson** to the **1978 Nobel prize** (shared with **Kapitsa**) can be found in many textbook/websites/forums.. To make it short, **Dicke** and its team (**Peebles** then student, **Roll** and **Wilkinson**, the « **W** » of **WMAP**) recomputed, independently in 1963, the prediction of **Gamow**, and **Alpher/Herman**. They were in their offices in Princeton discussing about how to build an antennae able to measure such a **5 K radiation** (**3 K** in their calculation), when **Dicke** answer to a phone-call by **Penzias**. As **Dicke** put the phone down, he turned to his colleagues and said « **Well, boys, we've been scooped** ».

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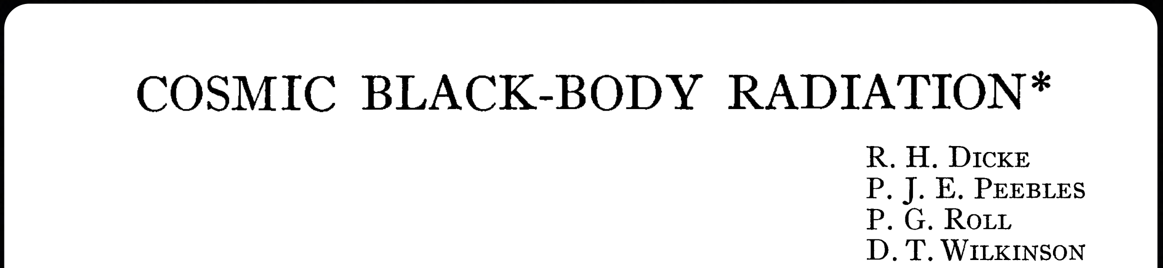

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Dicke et al. noticed that an **upper bound** on the **Helium density** in the protogalaxies lead to an upper limit of mass density at deuterium composition time $\boldsymbol{\rho_d^{max}}$. Leading at the end by a **lower value to the present radiation** :

$$T_0 = T_d (\rho_0 / \rho_d)^{1/3} > T_d (\rho_0 / \rho_d^{max})$$

A **3.5 K** radiation however leads to a too small mass density nowadays, inviting **Dicke** et al. to propose a **new scalar field** inspired by General Relativity.

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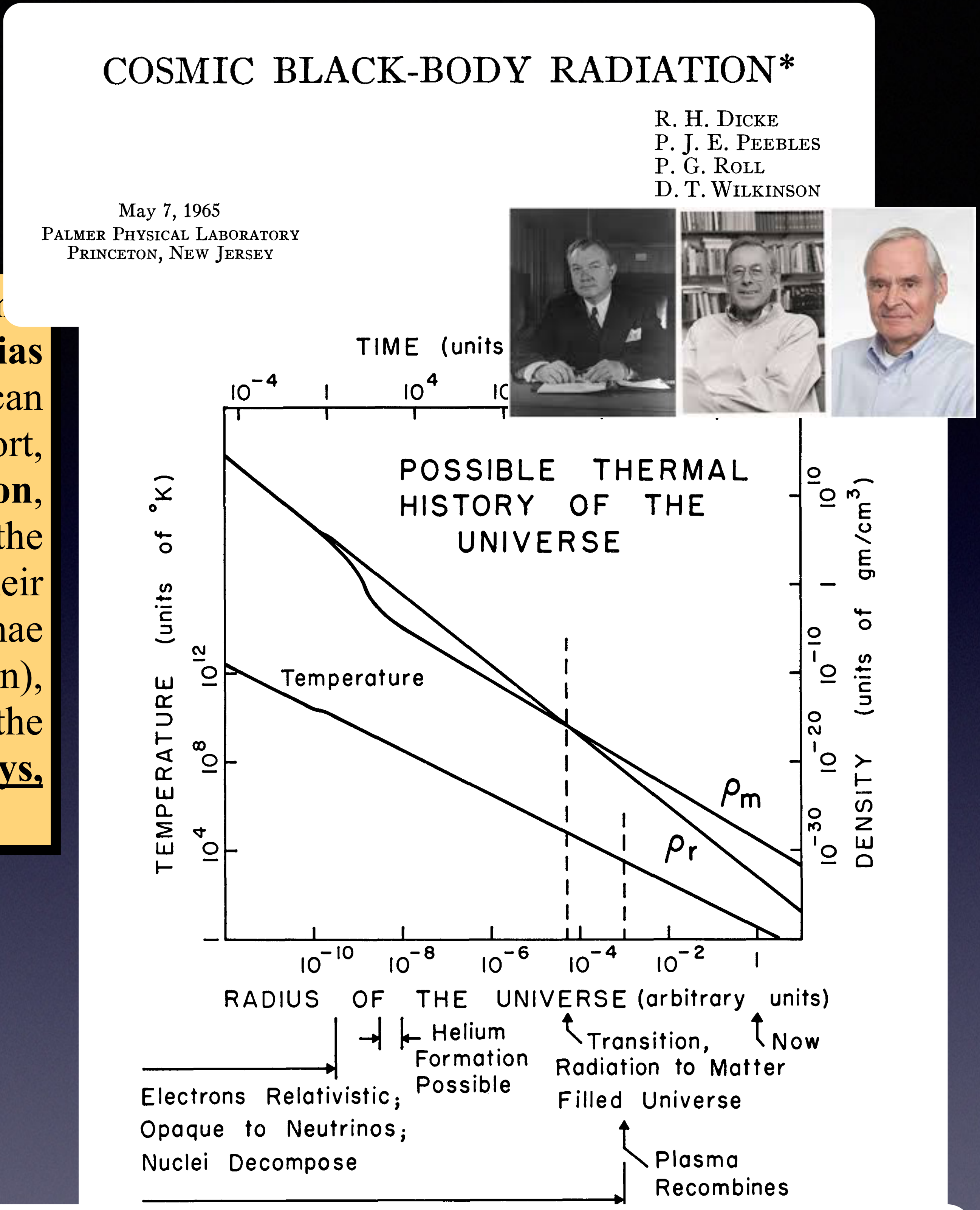

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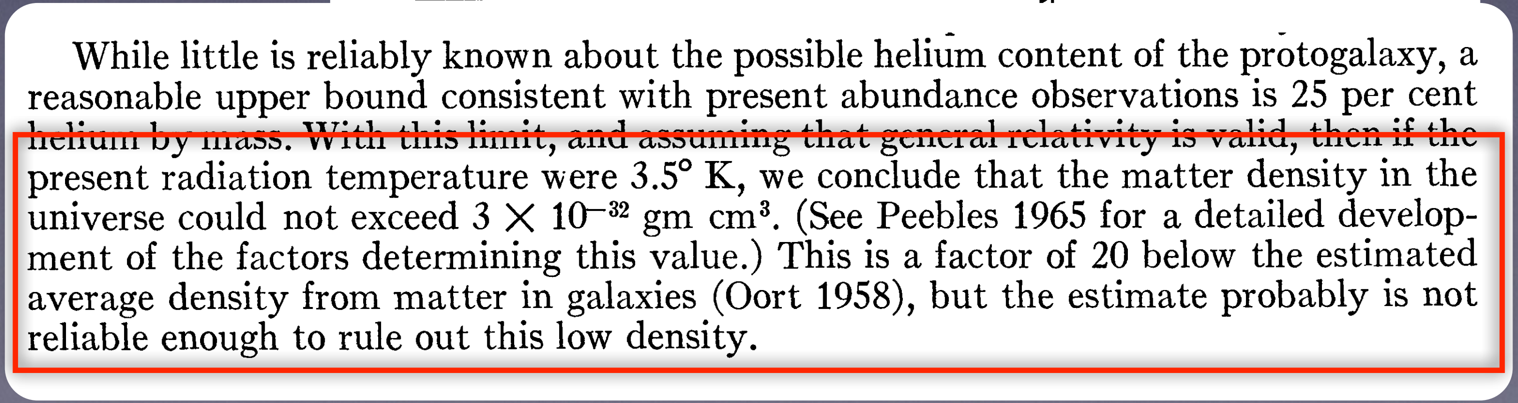
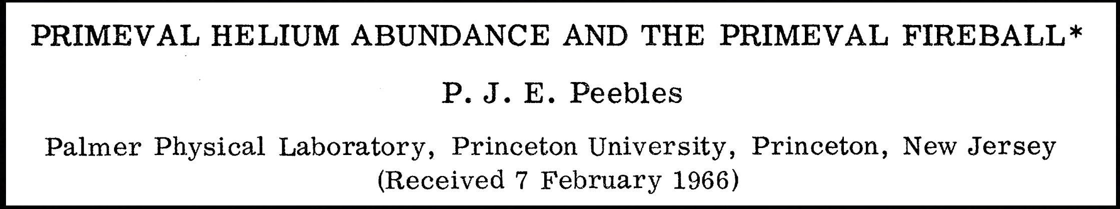


While little is reliably known about the possible helium content of the protogalaxy, a reasonable upper bound consistent with present abundance observations is 25 per cent helium by mass. With this limit, and assuming that general relativity is valid, then if the present radiation temperature were 3.5° K, we conclude that the matter density in the universe could not exceed 3×10^{-32} gm cm^3. (See Peebles 1965 for a detailed development of the factors determining this value.) This is a factor of 20 below the estimated average density from matter in galaxies (Oort 1958), but the estimate probably is not reliable enough to rule out this low density.

The Helium abundance



PRIMEVAL HELIUM ABUNDANCE AND THE PRIMEVAL FIREBALL*

P. J. E. Peebles

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 7 February 1966)

The novelty in the **Dicke** et al. article, compared to the **Gamow** one is the introduction of a more complete fundamental setup (**positron**, **electron**, and the newly discovered **neutrino** in **1956**) and the computation of the **Helium abundance**. Indeed, **Gamow** stopped the process to the proton abundance, computing the constraints from the hydrogen limits measured in our Universe. **Peebles** went much further away, solving **numerically** the complete set of equation governing the formation of the **Helium and its isotopes** in an article published just 5 months after the **Dicke** et al. one.

P.J. Peebles

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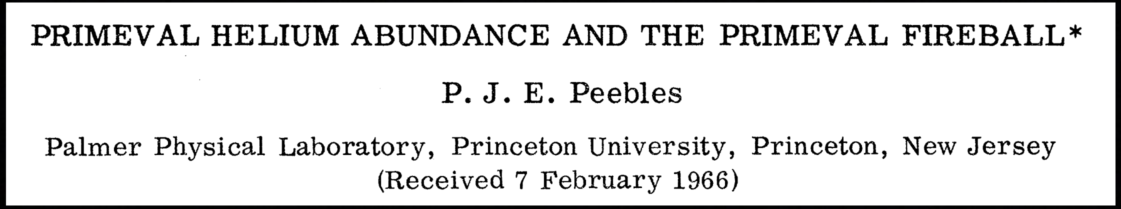
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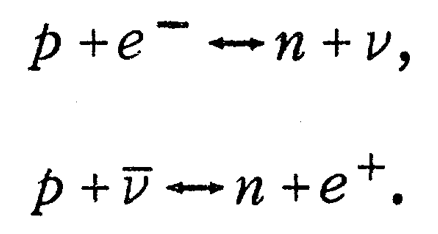
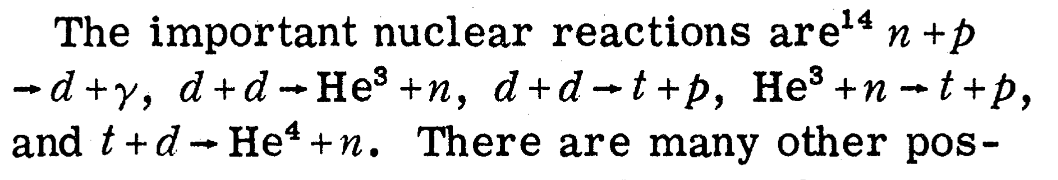
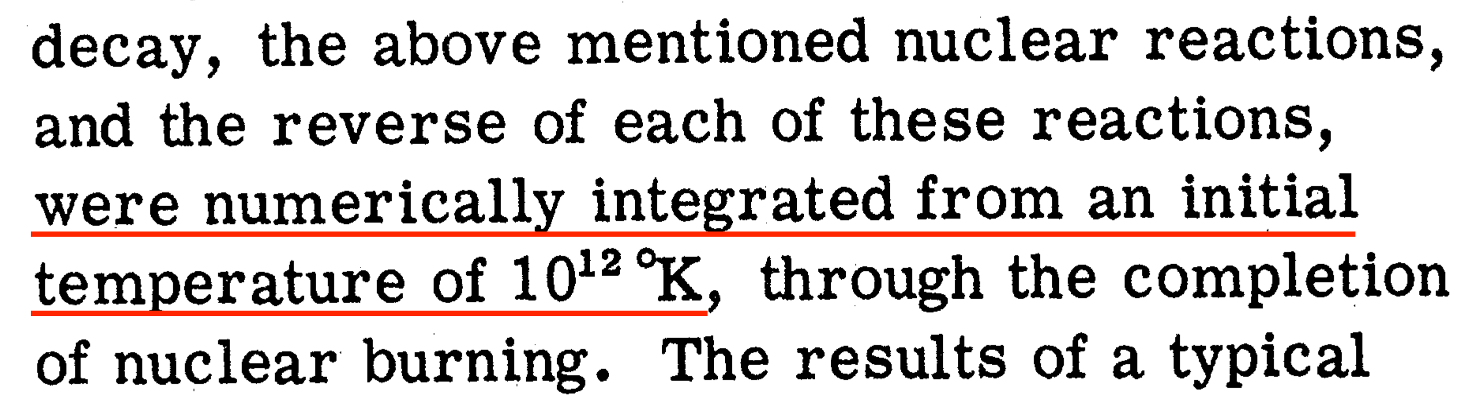
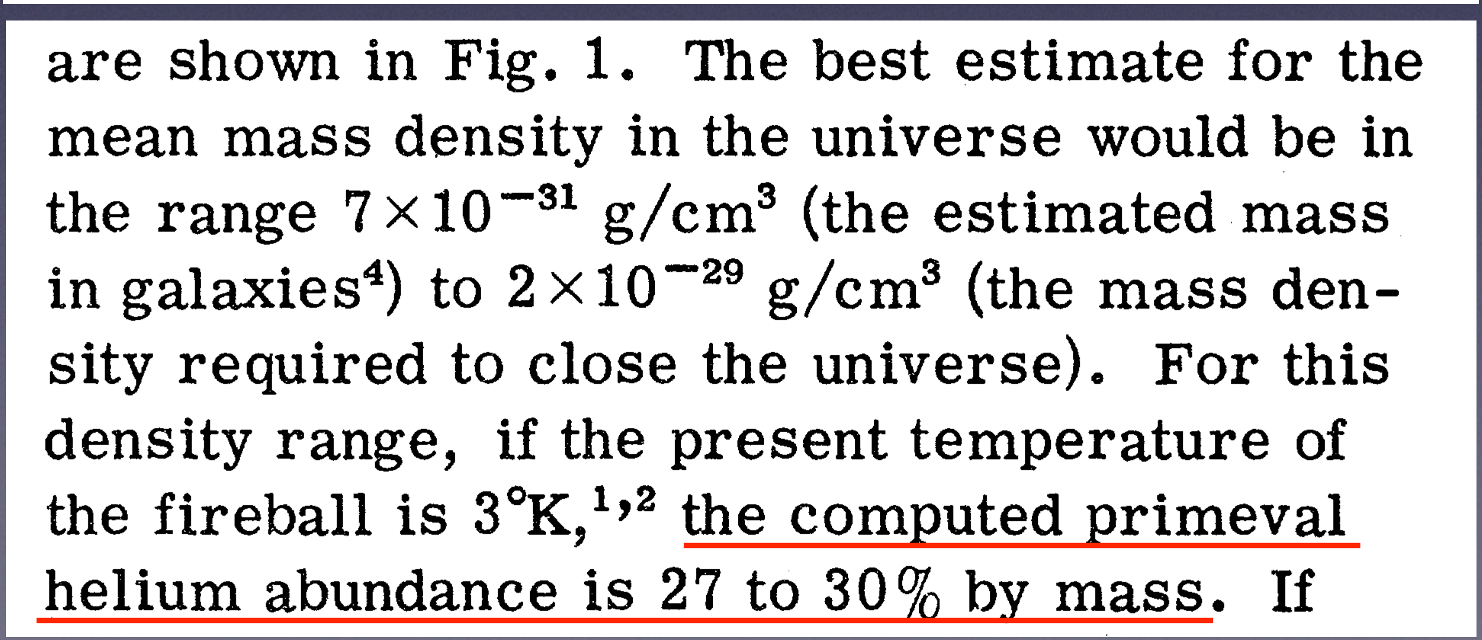

$p+e^- \longleftrightarrow n+\nu,$

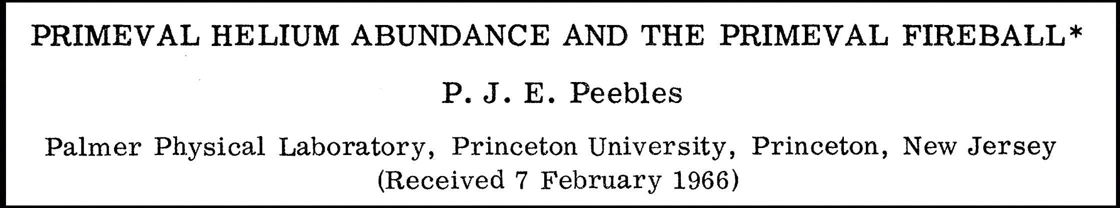
$p+\bar{\nu} \longleftrightarrow n+e^+.$


The important nuclear reactions are[14] $n+p \rightarrow d+\gamma$, $d+d \rightarrow \mathrm{He}^3+n$, $d+d \rightarrow t+p$, $\mathrm{He}^3+n \rightarrow t+p$, and $t+d \rightarrow \mathrm{He}^4+n$. There are many other pos-


decay, the above mentioned nuclear reactions, and the reverse of each of these reactions, were numerically integrated from an initial temperature of 10^{12} °K, through the completion of nuclear burning. The results of a typical


are shown in Fig. 1. The best estimate for the mean mass density in the universe would be in the range 7×10^{-31} g/cm^3 (the estimated mass in galaxies[4]) to 2×10^{-29} g/cm^3 (the mass density required to close the universe). For this density range, if the present temperature of the fireball is 3°K,[1,2] the computed primeval helium abundance is 27 to 30% by mass. If

The Helium abundance



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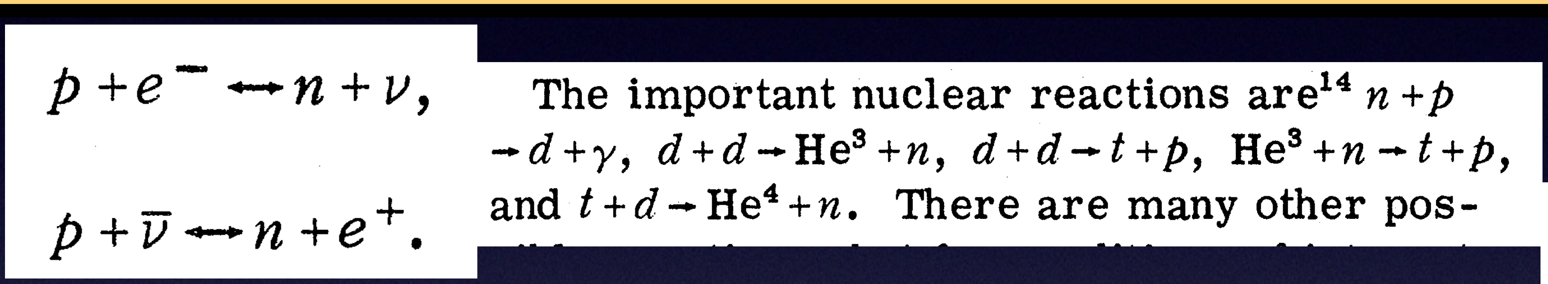

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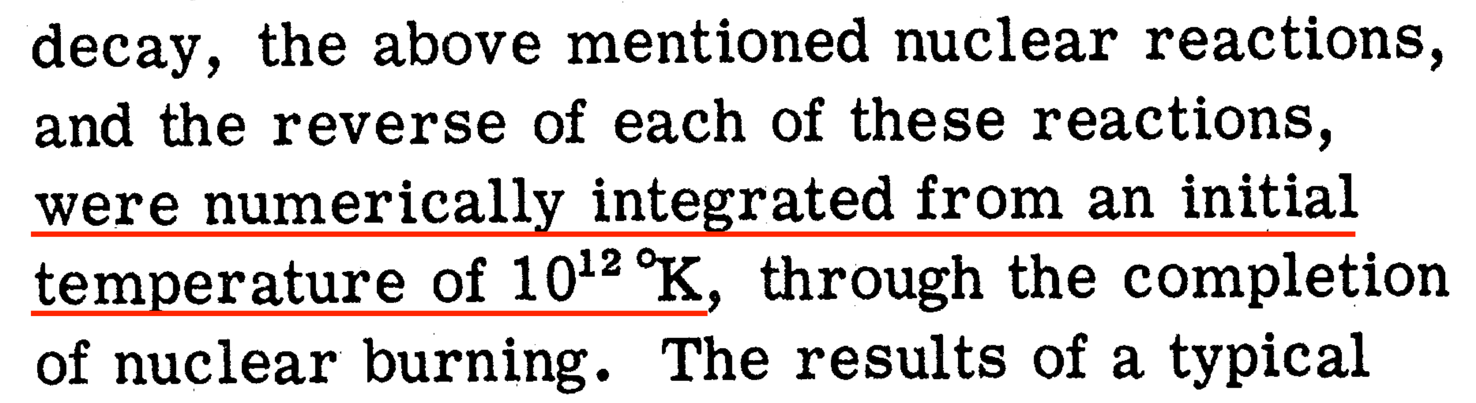

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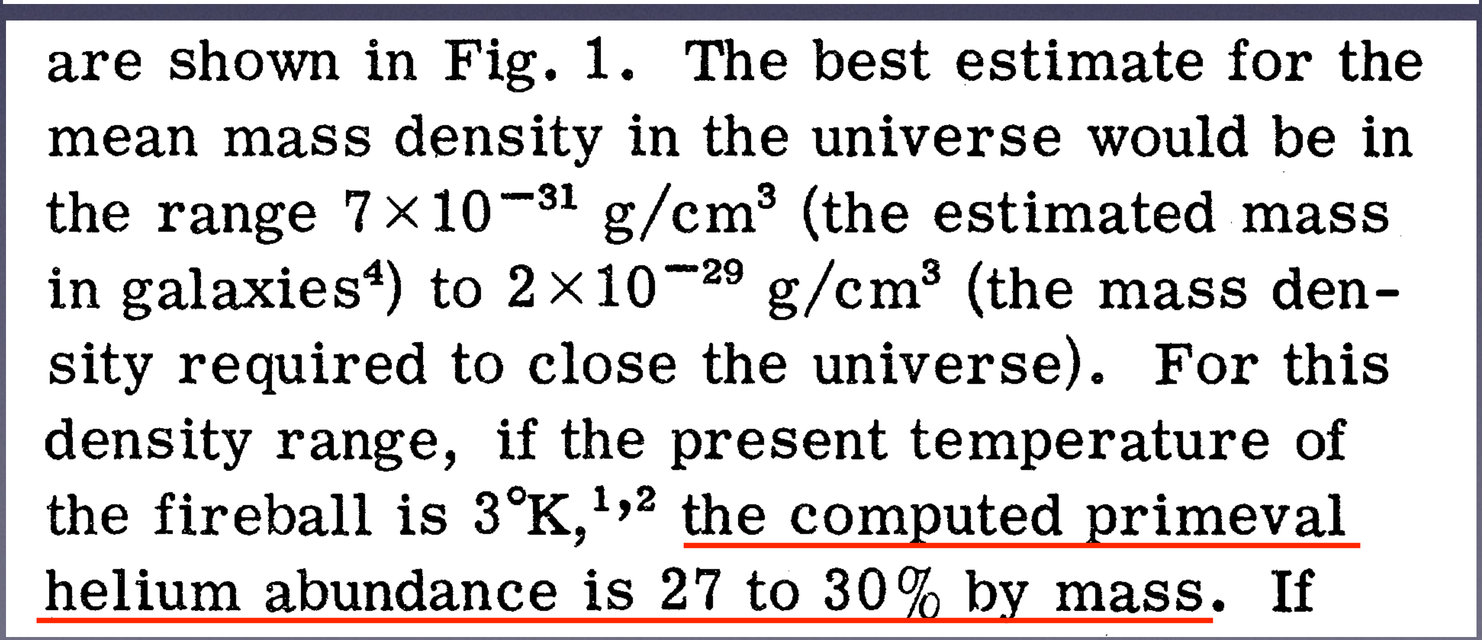

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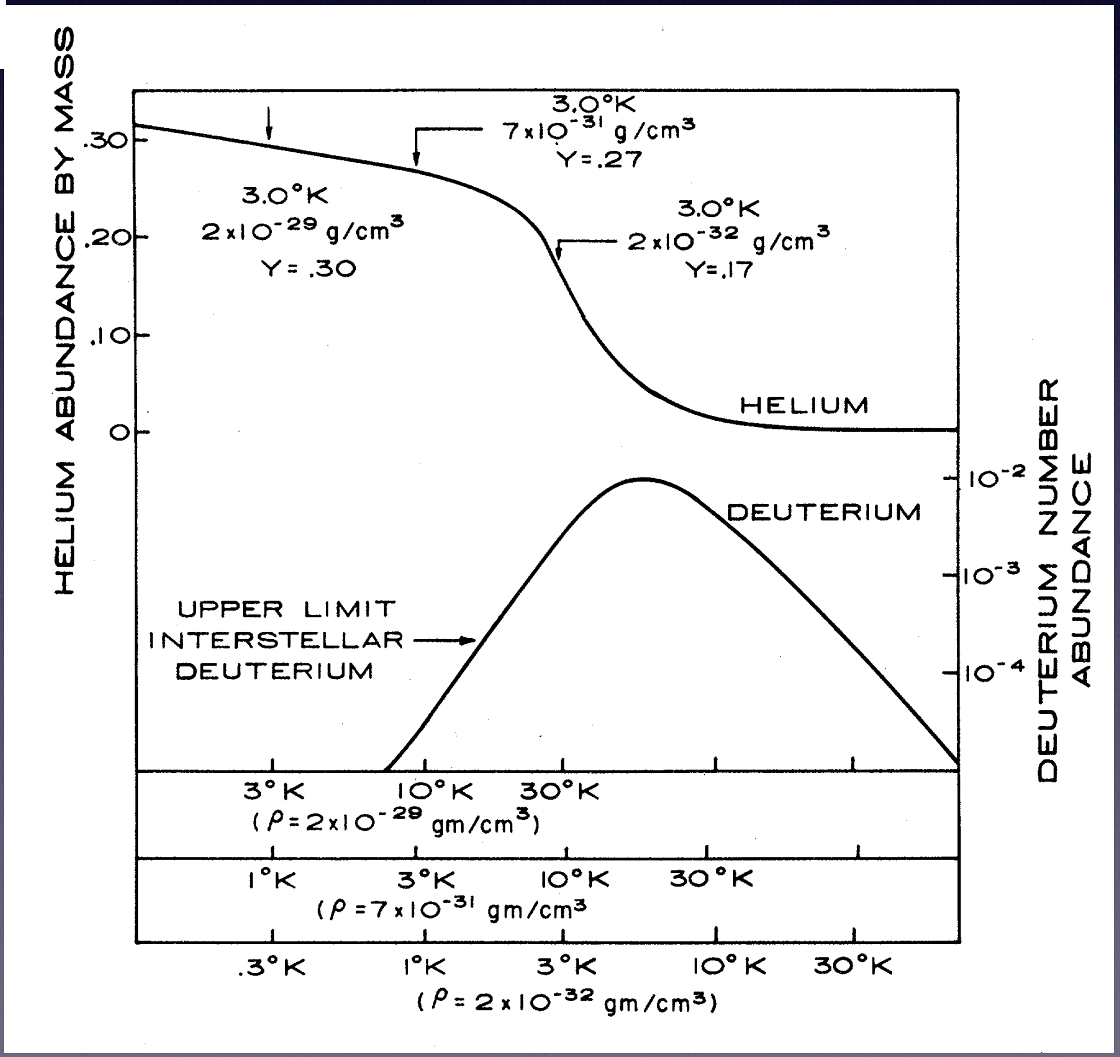
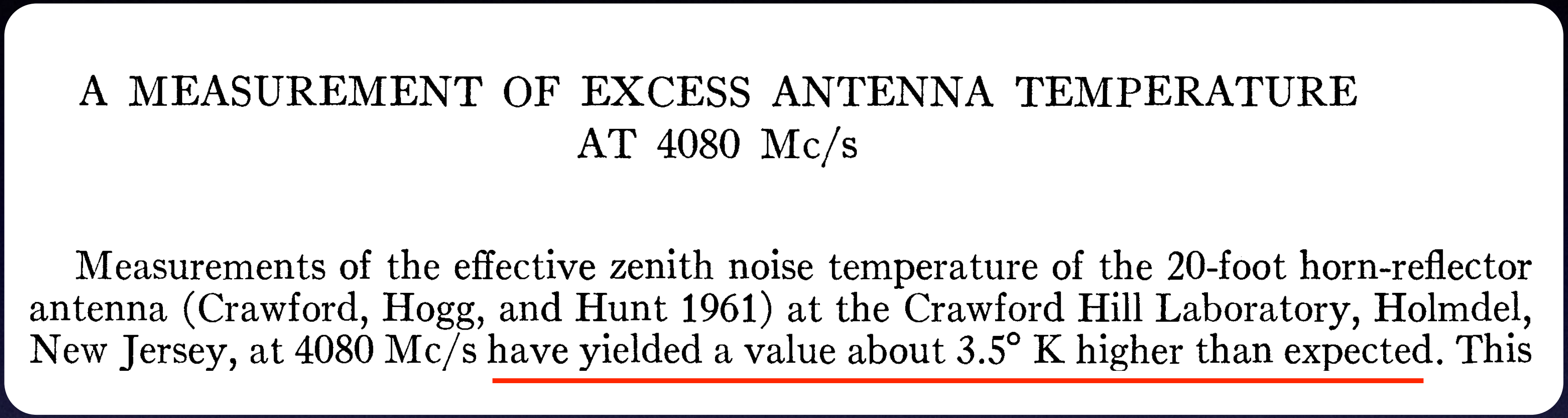
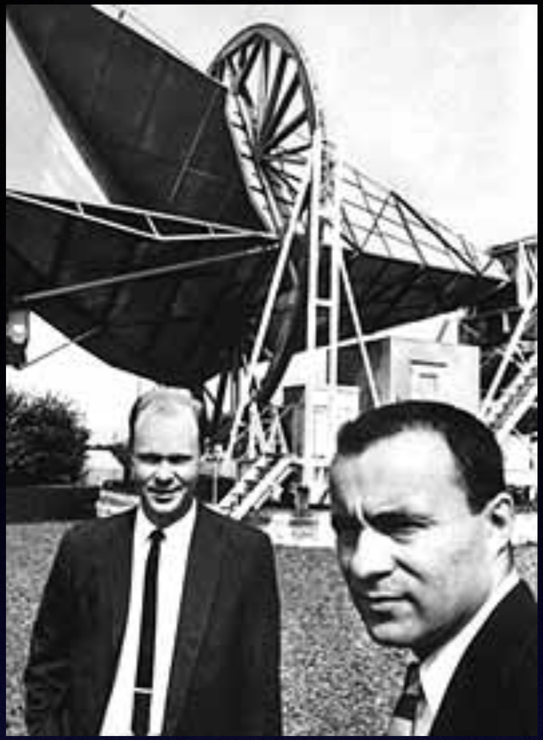


The discovery



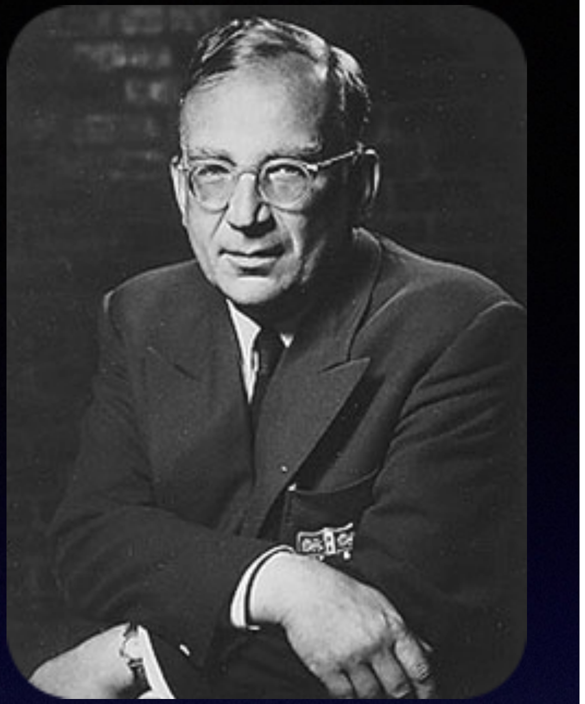
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This

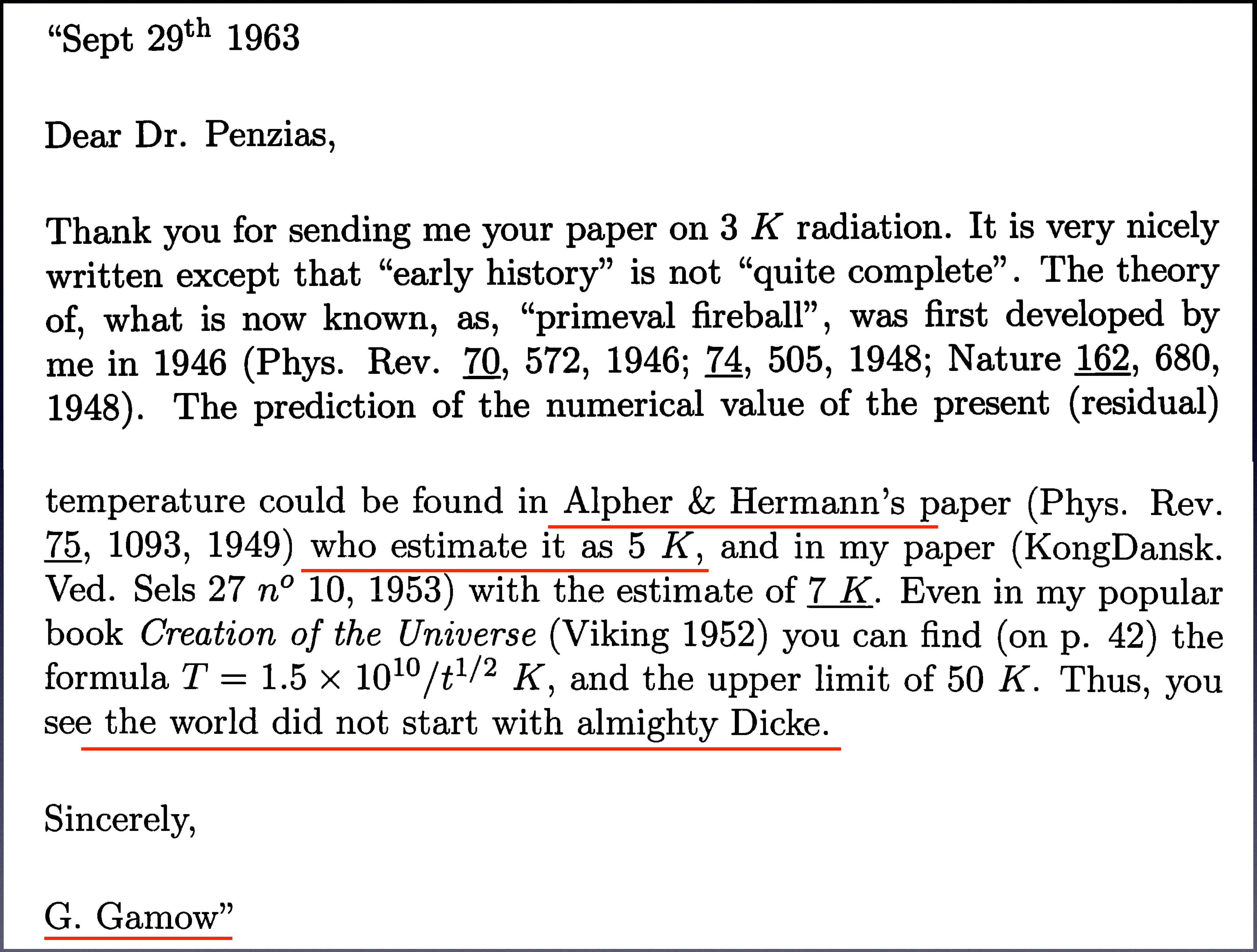


R. Wilson A. Penzias

Penzias and **Wilson**, ingeener at Bell telecom discovered in **1965** the CMB at **3.5 K** (**2.7 K** now) and received the Nobel prize of physics for that ion 1978. Neither **Gamow**, **Alpher**, **Herman**, **Dicke** or **Peebles** received Nobel prize for their work.



G. Gamow



“Sept 29th 1963

Dear Dr. Penzias,

Thank you for sending me your paper on 3 K radiation. It is very nicely written except that “early history” is not “quite complete”. The theory of, what is now known, as, “primeval fireball”, was first developed by me in 1946 (Phys. Rev. 70, 572, 1946; 74, 505, 1948; Nature 162, 680, 1948). The prediction of the numerical value of the present (residual) temperature could be found in Alpher & Hermann’s paper (Phys. Rev. 75, 1093, 1949) who estimate it as 5 K, and in my paper (KongDansk. Ved. Sels 27 n^o 10, 1953) with the estimate of 7 K. Even in my popular book *Creation of the Universe* (Viking 1952) you can find (on p. 42) the formula $T = 1.5 \times 10^{10}/t^{1/2}$ K, and the upper limit of 50 K. Thus, you see the world did not start with almighty Dicke.

Sincerely,

G. Gamow”

A. Penzias

« Gamow? A man whose idea is wrong in almost every detail», Penzias in his Nobel lecture, 1978.

Summary : how to predict a CMB temperature?

1) You suppose, as **Gamow** in **1948** that the Universe has been **building up** from the lightest elements and is **not originated from the decay** of a « primeval atom » of the Uranium type as Lemaitre imagined in the 20's (you should for that have a strong sense of intuition)

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2) You then feel as **Gamow** that there was a time **t_D** in the Universe, where its temperature **T_D** was below the **binding energy** of the deuterium **B_D=2.2 MeV = 2.2 x 10^{10} K** to forbid the **dissociation** process $\gamma + d \rightarrow p + n$. But as you heard about the **Saha equation**, you know that the real temperature of dissociation is **0.1 MeV (10^9 K)** due to the photon statistic distribution.

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$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_{rad}(T) = \frac{8\pi G}{3}\frac{\pi^2}{15}T^4$$

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And using the principle of entropy conservation $aT = \text{cste} \quad \Rightarrow \quad \frac{da}{a} = -\frac{dT}{T}$ you deduce

$$\frac{dT}{T^3} = -\sqrt{\frac{8\pi^3 G}{45}}dt \quad \Rightarrow \quad t = \frac{M_{PL}}{T^2}\sqrt{\frac{45}{32\pi^3}} \simeq 0.2\frac{M_{PL}}{T^2}$$

Which gives for $\mathbf{T=T_D=10^9}$ **K**

$$t \simeq 3 \times 10^{27}\ \text{GeV}^{-1} \sim 200 \text{ seconds}$$

4) Remarking that the universe was radiation dominated, you then compute the density of mass a the time of dissociation $\rho_m(10^9\ K) = n(10^9\ K)\ m_p$, noticing that at the time t_D, **at least one reaction should have happened**

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You deduce **$n(t_D) \sim 10^{18}$ cm^{-3}**, implying **$\rho_m(10^9 \text{ K}) \sim 10^{18}$ GeV/cm^3 = 1.78×10^{-6} g/cm^3**

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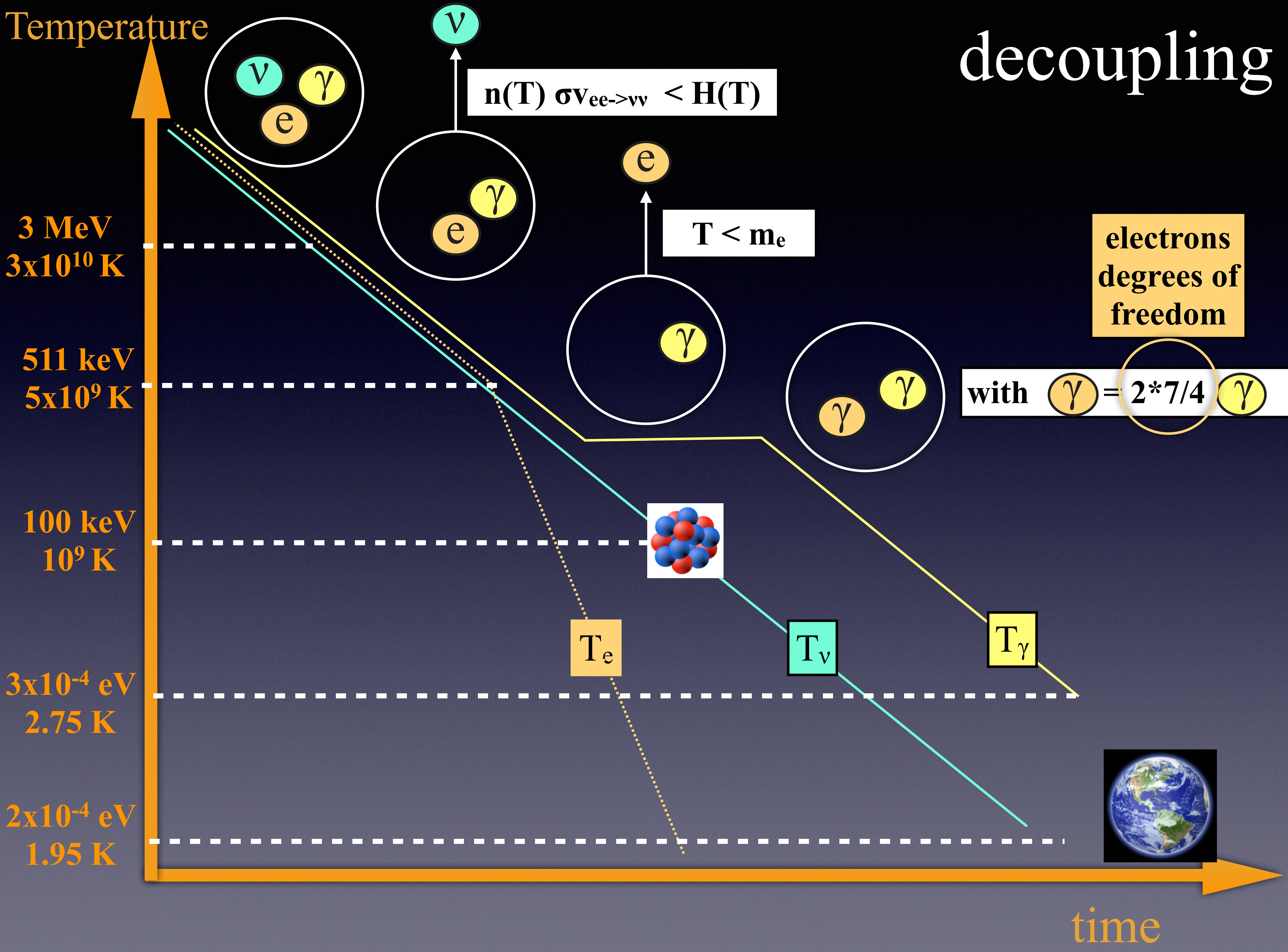
5) Then, noticing that mass should be conserved in an expanding universe, $\rho_m\, a^3 = \boldsymbol{\rho_m/T^3}$**= constant** implies

$$T^{now} = \left(\frac{\rho_m^{now}}{\rho_m(10^9\ \mathrm{K})}\right)^{1/3} 10^9\ \mathrm{K} = \left(\frac{10^{-30}}{1.78 \times 10^{-6}\ \mathrm{g/cm^3}}\right)^{1/3} 10^9\ \mathrm{K} \boxed{\simeq 8\ \mathrm{K}}$$

Where you have supposed that the **density of mass today**, measured by experimentalists like **Oort** is around **10^{-30} g/cm^3** (the critical density **ρ_c** is **$2\mathrm{x}10^{-29}$ h^2 g/cm^3**)
The last argument, correcting the mistakes of **Gamow**, was proposed by **Alpher and Hermann** in their paper which appeared 2 weeks after the **Gamow** one **in 1948**

decoupling



$n(T)\ \sigma v_{ee\to\nu\nu} < H(T)$

$T < m_e$

electrons degrees of freedom

with γ = **2*7/4** γ

Filling the Universe with neutrino

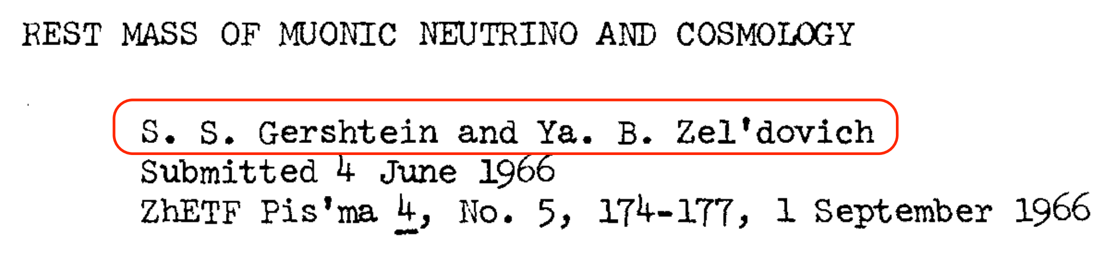
The Zeldovich-Cowsik-McClelland bound, or the birth of cosmological astroparticle

Once the **CMB** has been discovered, and measured, a lot of particle physicists jumped on it to test their predictions through interactions on it (**GZK cutoff** and cosmic ray) to astrophysical consequences.

Zeldovich and **Ghershtein in June 1966** (!!) were the first to obtain limits on a heavy neutrino (the muonic neutrino $\boldsymbol{\nu_\mu}$ has been discovered by **Lederman** in **1962**) from cosmological consideration, asking for a Universe respecting the deceleration parameter, obtaining $m_{\nu\mu} < 400$ eV.

Cowsik and **Mac Clelland in 1972** (!!) recomputed it (without citing Zeldovich) with more accurate values of the Hubble parameter and obtained $m_{\nu\mu} < 8$ eV (the now called « Cowsik Mac Clelland » bound).

The idea of Zeldovich



REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Y. Zeldovich

Suppose a gas of electrons, neutrinos and photons in equilibrium.

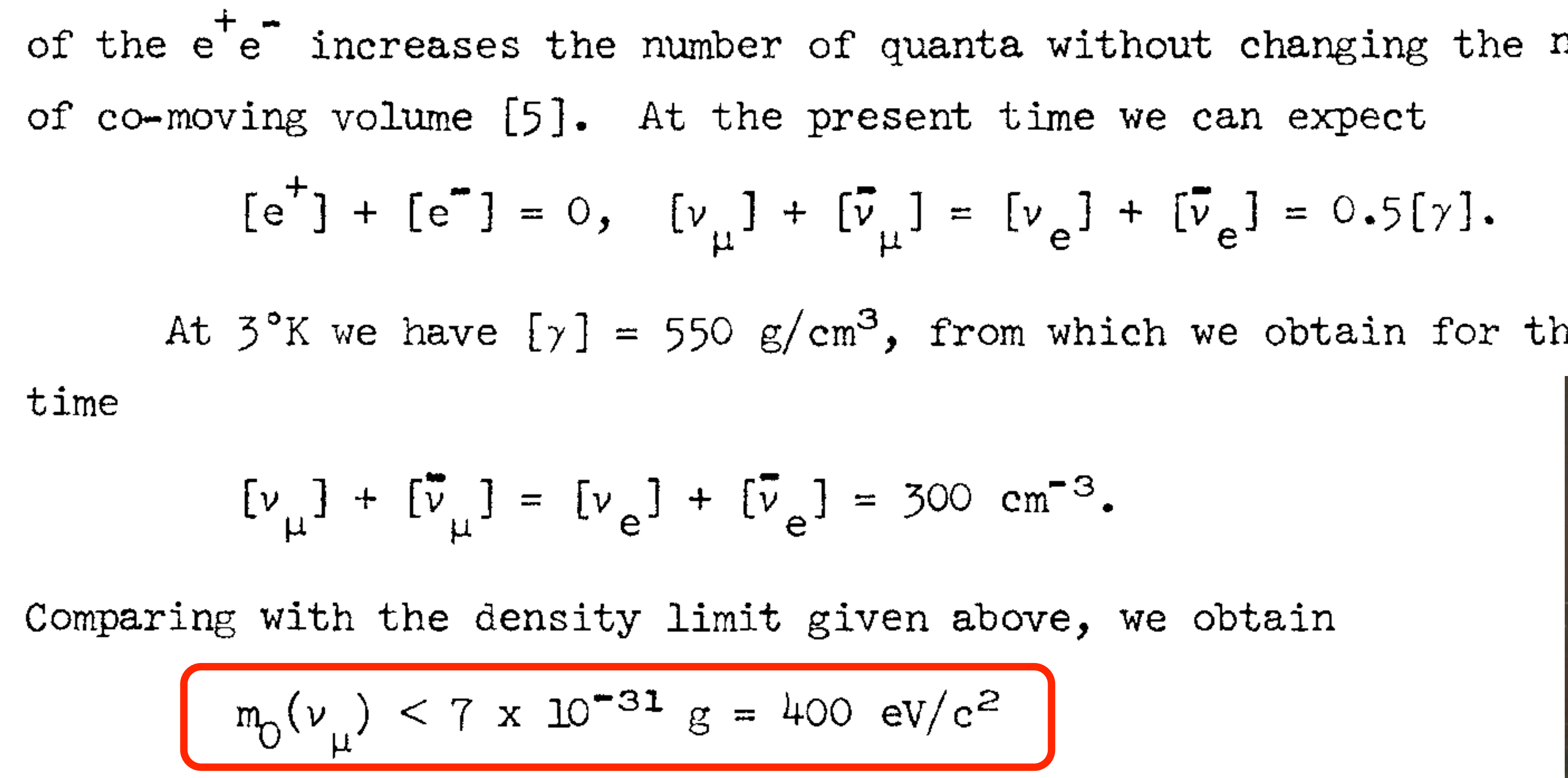
$$\boxed{n_{e^-} + n_{e^+} = n_\nu + n_{\bar{\nu}} = \frac{3}{2} n_\gamma}$$

where 3/2 = 3/4 (fermi gas versus boson gas)
*2 (2+2 degrees of freedom for fermions vs 2 degrees of freedom for photons)
whereas after decoupling of the e^+ e^- :

$$\boxed{n_{e^-} + n_{e^+} = 0 \; ; \quad n_\nu + n_{\bar{\nu}} = \frac{1}{2} n_\gamma}$$

where 1/2 = 3/2 * 4/11 [(2 + 7/8*4)/2 = 11/4] corresponds to the degrees of freedom of the e^+ e^- absorbed by the photons (and not the neutrino that already decoupled)

Then, from the measurements of the CMB, **Zeldovich** inferred **n_γ = 550 cm^{-3}** implying **n_ν = 300 cm^{-3}**. Having a limit on the mass density of the Universe
ρ_m < 1.25 x10^{-28} g cm^{-3}, they inferred
n_ν x m_ν < ρ_m => **m_ν < 7 x10^{-31} g =400 eV**



of the e^+e^- increases the number of quanta without changing the number of neutrinos per unit of co-moving volume [5]. At the present time we can expect

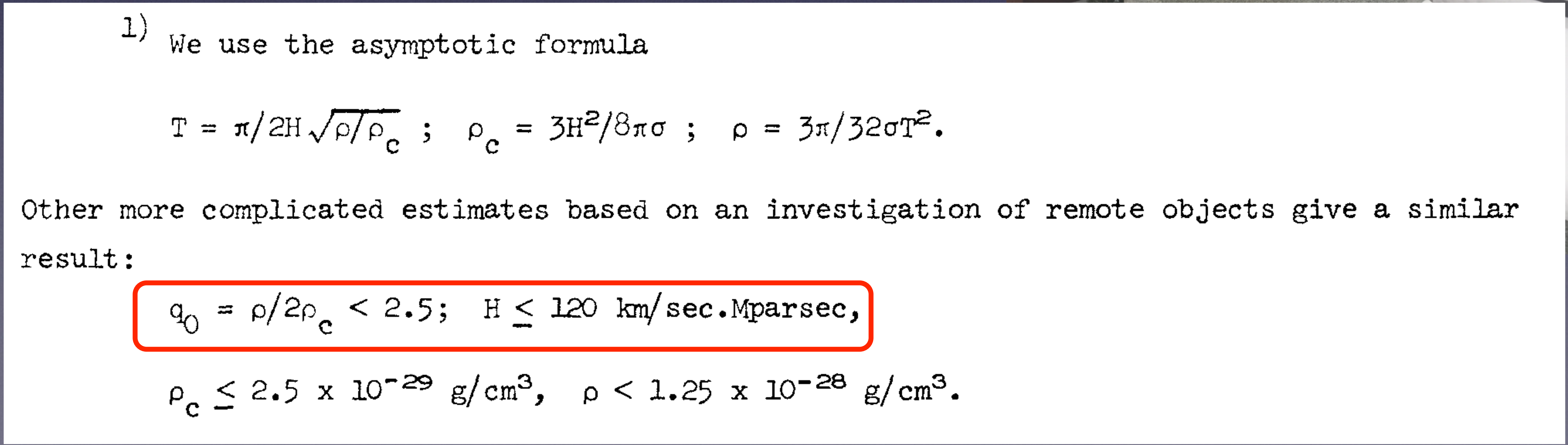
$$[e^+] + [e^-] = 0, \quad [\nu_\mu] + [\bar{\nu}_\mu] = [\nu_e] + [\bar{\nu}_e] = 0.5[\gamma].$$

At 3°K we have $[\gamma] = 550\ \mathrm{g/cm^3}$, from which we obtain for the neutrino at the present time

$$[\nu_\mu] + [\bar{\nu}_\mu] = [\nu_e] + [\bar{\nu}_e] = 300\ \mathrm{cm}^{-3}.$$

Comparing with the density limit given above, we obtain

$$\boxed{m_0(\nu_\mu) < 7 \times 10^{-31}\ \mathrm{g} = 400\ \mathrm{eV}/c^2}$$



1) We use the asymptotic formula

$$T = \pi/2H\sqrt{\rho/\rho_c}\ ; \quad \rho_c = 3H^2/8\pi\sigma\ ; \quad \rho = 3\pi/32\sigma T^2.$$

Other more complicated estimates based on an investigation of remote objects give a similar result:

$$\boxed{q_0 = \rho/2\rho_c < 2.5; \quad H \leq 120\ \mathrm{km/sec.Mparsec},}$$

$$\rho_c \leq 2.5 \times 10^{-29}\ \mathrm{g/cm^3}, \quad \rho < 1.25 \times 10^{-28}\ \mathrm{g/cm^3}.$$

The limit used by Zeldovich

The deceleration parameter

Before the observation of the **anisotropies of the CMB** (and thus the determination of the cosmological parameters through the measurements of the **acoustic peaks**) the only way to determine the matter content of the Universe, without the knowledge of the curvature was to **use the second Friedmann equation:**

$$\boxed{\begin{aligned}\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho \;\Rightarrow\; q(t) &= -\frac{1}{H^2}\frac{\ddot{a}}{a} = \frac{4\pi G}{3H^2}\rho \\ &= \frac{1}{2}\frac{\rho}{\rho_c} = \frac{1}{2}\Omega, \qquad \text{with } H^2 = \frac{8\pi G}{3}\rho_c\end{aligned}}$$

The limit on **$q < 2.5$** from 1966 gives $\Omega < 5$,
and **$\rho_c = 1.8 \times 10^{-29}\, h^2$ g cm^{-3}** gives for $h < 1.20$, $\rho_c < 2.5 \times 10^{-29}$ g cm^{-3}
implying **$\rho < 1.25 \times 10^{-28}$ g cm^{-3}**.

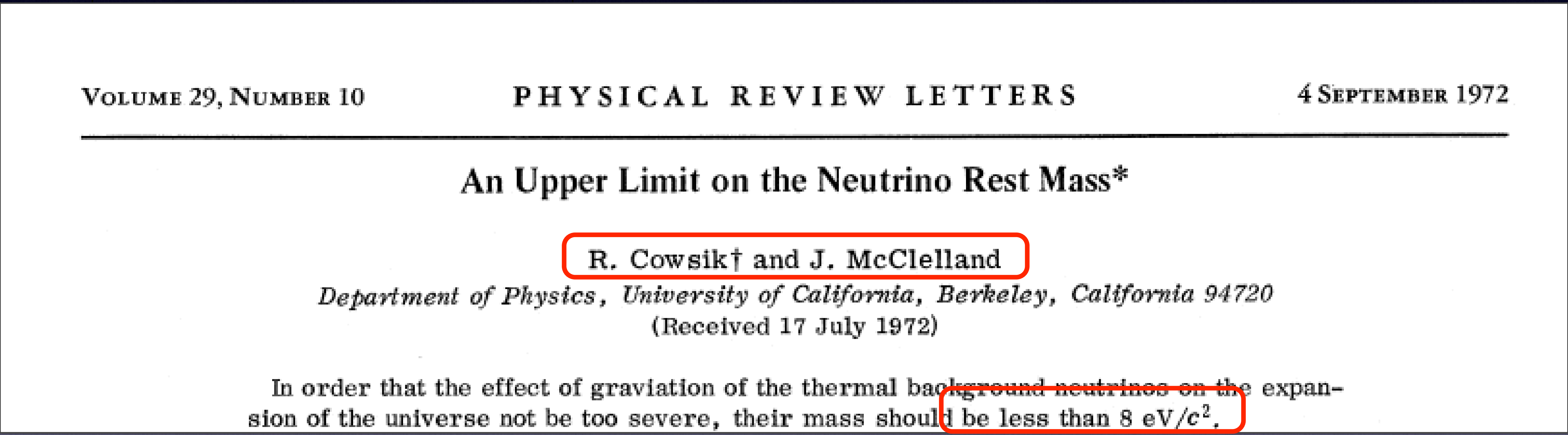
n.b. : Nowadays, $\rho < 1.8 \times 10^{-30}$ g cm^{-3}, explaining the limit $m_\nu < 8$ eV

The Cowsik-Mac Clelland bound (1972)

The rediscovering of Zeldovich bound

Enrico Fermi

"Tentativo di una teoria dei raggi β".



VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

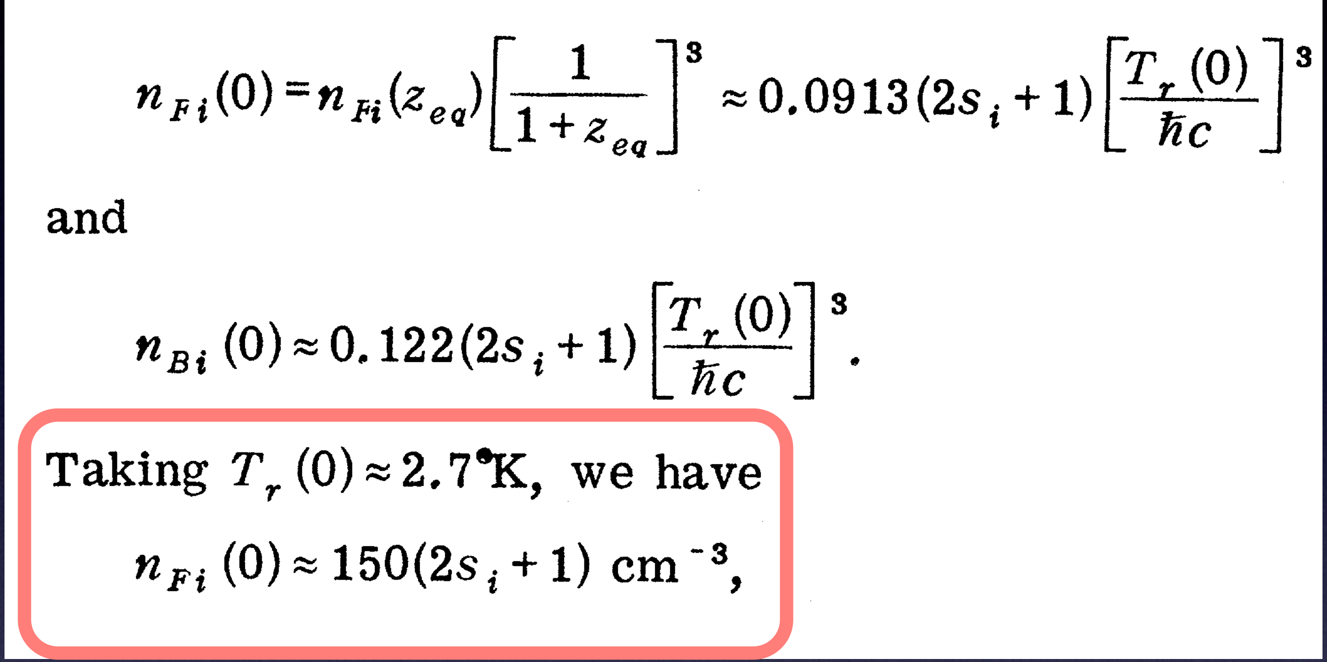
R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720

(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

A little remark

Treatment of Zeldovich is ok but two little mistakes has been made by Cowsik:
(the original article can be found there: http://www.ymambrini.com/My_World/History.html)



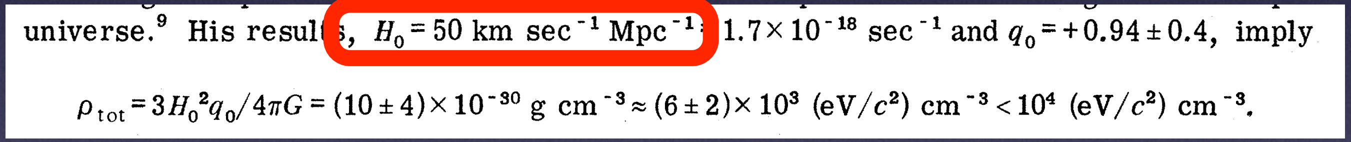
$$n_{Fi}(0)=n_{Fi}(z_{eq})\left[\frac{1}{1+z_{eq}}\right]^3\approx 0.0913(2s_i+1)\left[\frac{T_r(0)}{\hbar c}\right]^3$$

and

$$n_{Bi}(0)\approx 0.122(2s_i+1)\left[\frac{T_r(0)}{\hbar c}\right]^3.$$

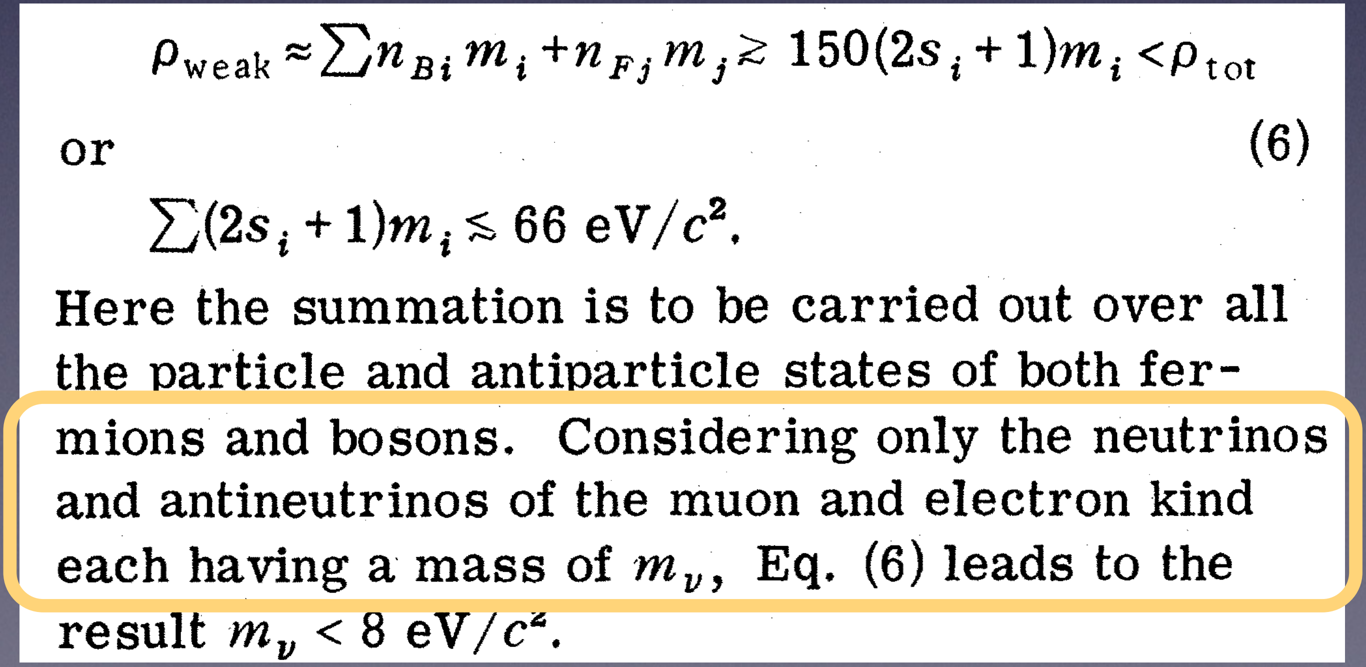
Taking $T_r(0)\approx 2.7°\text{K}$, we have

$$n_{Fi}(0)\approx 150(2s_i+1)\ \text{cm}^{-3},$$



universe.[9] His resul s, $H_0 = 50$ km sec^{-1} Mpc^{-1} 1.7×10^{-18} sec^{-1} and $q_0 = +0.94\pm0.4$, imply

$$\rho_{\text{tot}} = 3H_0^2q_0/4\pi G = (10\pm4)\times10^{-30}\ \text{g cm}^{-3}\approx(6\pm2)\times10^3\ (\text{eV}/c^2)\ \text{cm}^{-3} < 10^4\ (\text{eV}/c^2)\ \text{cm}^{-3}.$$



$$\rho_{\text{weak}}\approx\sum n_{Bi}m_i+n_{Fj}m_j\gtrsim 150(2s_i+1)m_i<\rho_{\text{tot}}$$

or (6)

$$\sum(2s_i+1)m_i\lesssim 66\ \text{eV}/c^2.$$

Here the summation is to be carried out over all the particle and antiparticle states of both fermions and bosons. Considering only the neutrinos and antineutrinos of the muon and electron kind each having a mass of m_ν, Eq. (6) leads to the result $m_\nu < 8$ eV$/c^2$.

Not true. Cowsik forgot to take into account the reheating of the thermal bath (photons) due to the entropy conservation once the electrons/positrons decoupled. Factor $(4/11)^{1/3}$ (see book section 2.2.7 + Entropy slide)

Cowsik considered left + right handed neutrino whereas right handed neutrino does not feel weak interaction, i.e. cannot be considered as in thermal equilibrium with the left handed ones: only 2 degrees of freedom for neutrinos should be considered ($\nu_L+\underline{\nu}_L$), not 4

But.. luckily..

A miraculous cancelation of mistakes makes this limit still valid today.
Cowsik took h=0.5, Ω=2 giving $\mathbf{\Omega h^2 = 0.5}$, a factor 5 larger compensated by the fact the **(11/4)** [e^+e^- degrees of freedom] ***(2)** [neutrino helicity] gives also an overabundance of ~5-6 for the neutrinos.

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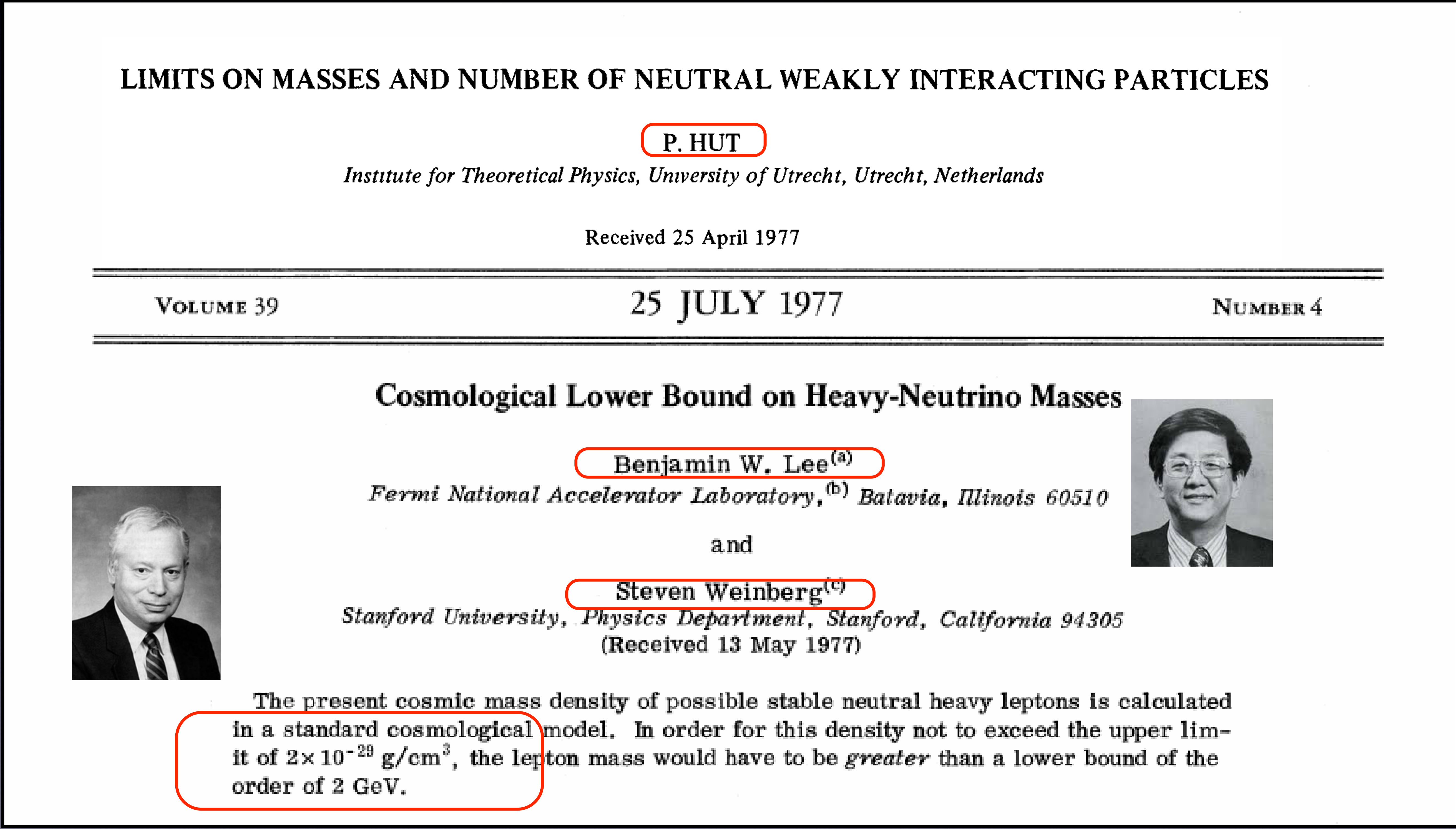
In any case, the **Zeldovich/Cowsik** work can be considered as **the first suggestion** that dark matter in gravitationally bound astronomical systems might consist of **non-baryonic subatomic particles**. However, it is in **1977** and **1978** in papers by **Lee &Weinberg** and by **Gunn et al.** that for the first time, physicists proposed the existence of a **stable, massive neutral non-baryonic particle** that can dominate the present mass density in the Universe.

The Zeldovich-Hut-Lee-Weinberg bound (1977)



LIMITS ON MASSES AND NUMBER OF NEUTRAL WEAKLY INTERACTING PARTICLES

P. HUT
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Received 25 April 1977

VOLUME 39 25 JULY 1977 NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
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and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

The Lee-Weinberg way (1977)

The recipe

1) Compute the temperature of freeze out T_f of χ (mass m) from the thermal bath :

$$\boxed{n(T_f)\langle\sigma v\rangle = H(T_f) \quad \Rightarrow \quad (T_f m)^{3/2}\, e^{-m/T_f}\,\langle\sigma v\rangle < \frac{T_f^2}{M_{Pl}} \quad \Rightarrow \quad T_f = \frac{m}{\ln M_{Pl}} = \frac{m}{26}}$$

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2) Solve the Boltzmann equation for the Yields Y=(n$_\chi$ / n$_\gamma$) from the thermal equilibrium χ χ <—> γ γ

$$\boxed{\frac{dY}{dT} = \frac{T^2}{H(T)}\langle\sigma v\rangle Y^2 \quad \Rightarrow \quad Y(T_{now}) = \frac{1}{M_{Pl}T_f\langle\sigma v\rangle} = \frac{26}{M_{Pl}m\langle\sigma v\rangle}}$$

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3) Compute the relic abundance and compare with the experimental limits

$$\boxed{\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26 \times 400\ \mathrm{cm}^{-3}}{\rho_c M_{Pl}\langle\sigma v\rangle} < 1 \qquad \Rightarrow \langle\sigma v\rangle > 10^{-9} h^{-2}\ \mathrm{GeV}^{-2}}$$

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4) Conclude

$$\boxed{\langle\sigma v\rangle \simeq G_F^2 m^2 > 10^{-9}\ \mathrm{GeV}^{-2} \quad\Rightarrow\quad m > 2\ \mathrm{GeV}}$$

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5) Wait for applauses for that **first lower bound** on a massive non-baryonic matter filling the Universe.

SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

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AND
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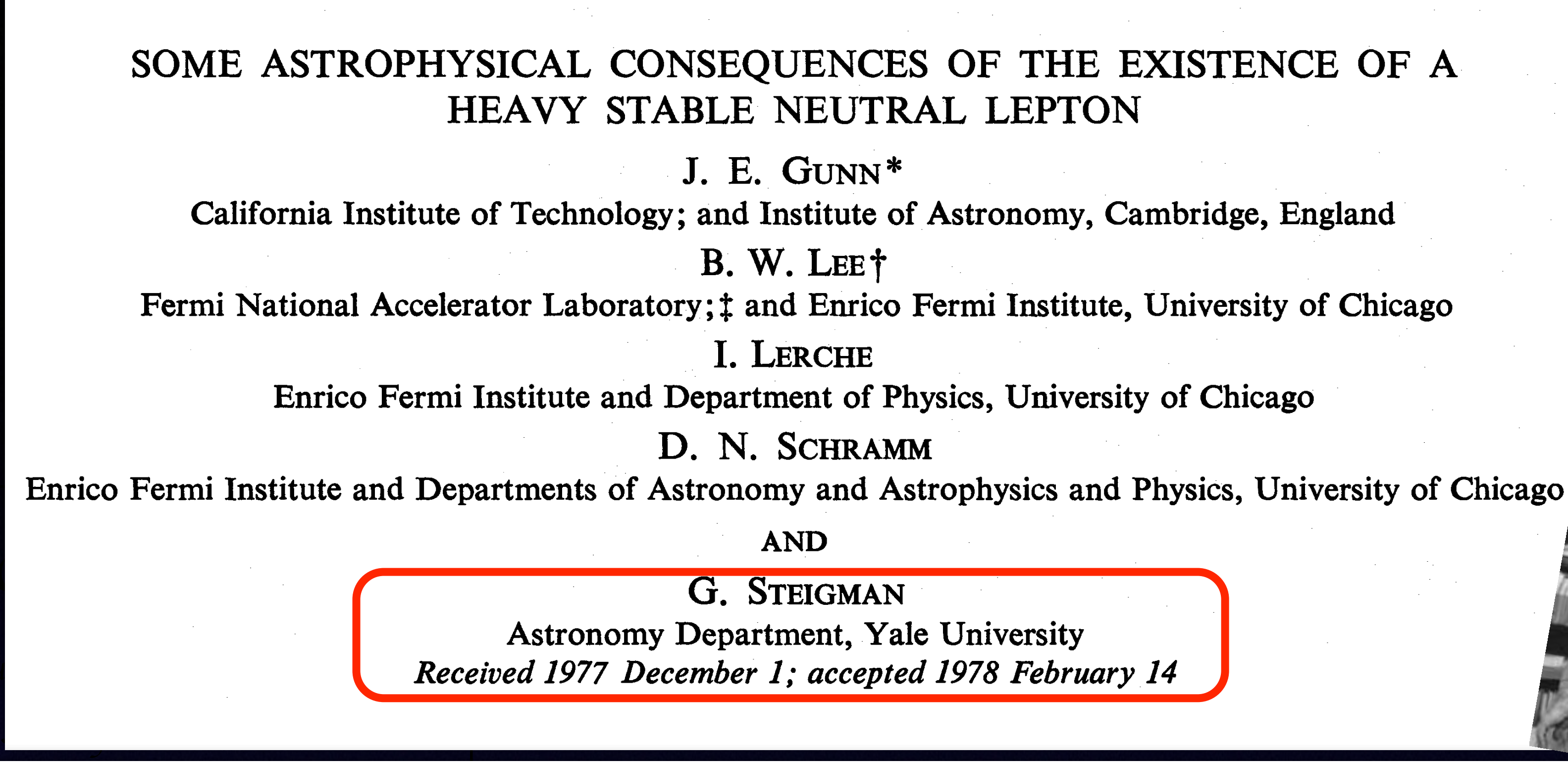
Astronomy Department, Yale University

Received 1977 December 1; accepted 1978 February 14

ABSTRACT

Recently, high-energy particle theorists have constructed new extended gauge theories which may fit experiment somewhat better than previous already very successful theories. One of the predictions which is often discussed is the possible existence of a stable neutral lepton, probably with a mass of a few GeV/c^2. Following this motivation we here investigate some cosmological consequences of the existence of *any* stable, massive, neutral lepton, and show that it could well dominate the present mass density in the universe. The contribution to the mass density depends on the mass of the lepton, which should eventually be determined with high-energy accelerators. It is interesting that the more massive the lepton, the smaller its contribution to the present mass density. It is unlikely that these leptons affect big bang nucleosynthesis or condense into stellar size objects. However, such a lepton is an excellent candidate for the material in galactic halos and for the mass required to bind the great clusters of galaxies. Annihilation radiation from these structures should be detectable. At the end of the paper a brief mention is made of the astrophysical constraints on the mass-lifetime relationship if the neutral lepton is unstable.

Subject headings: cosmology — elementary particles



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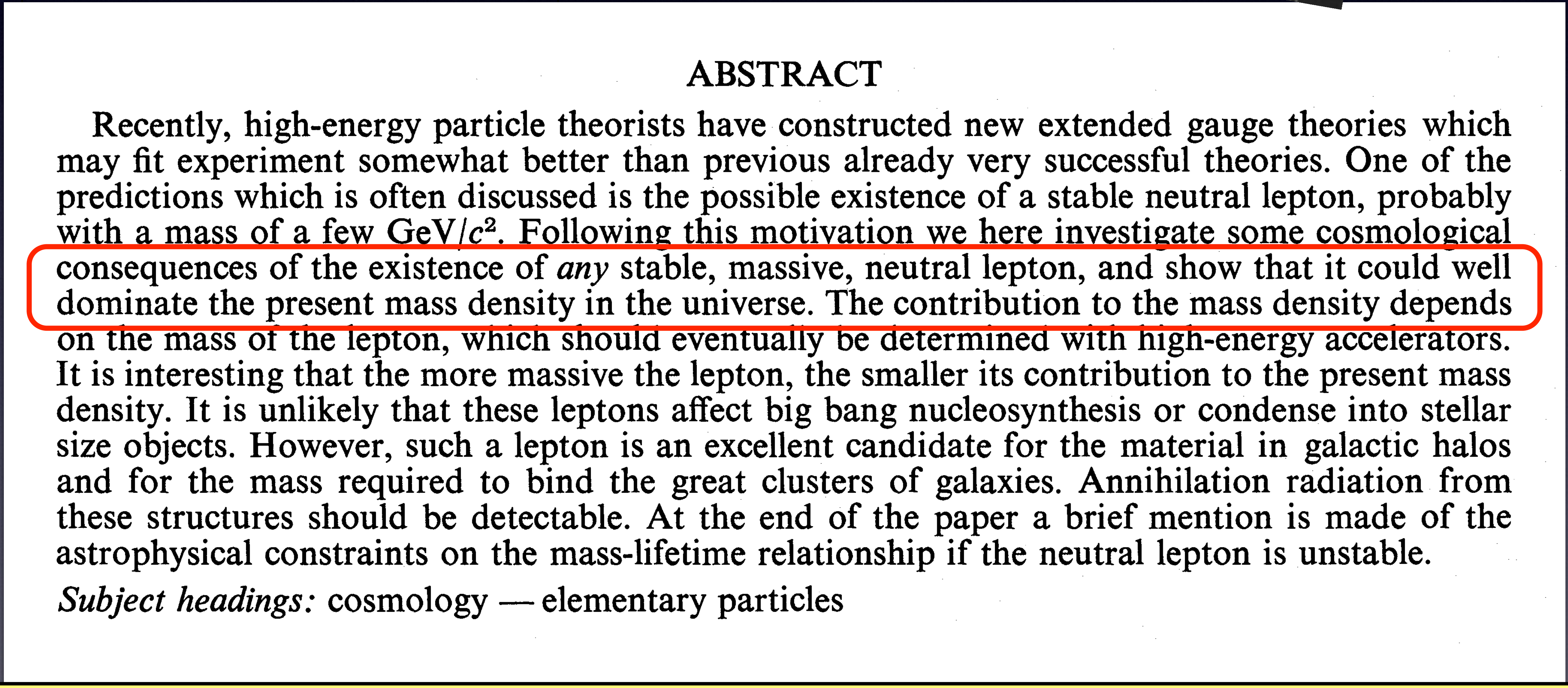

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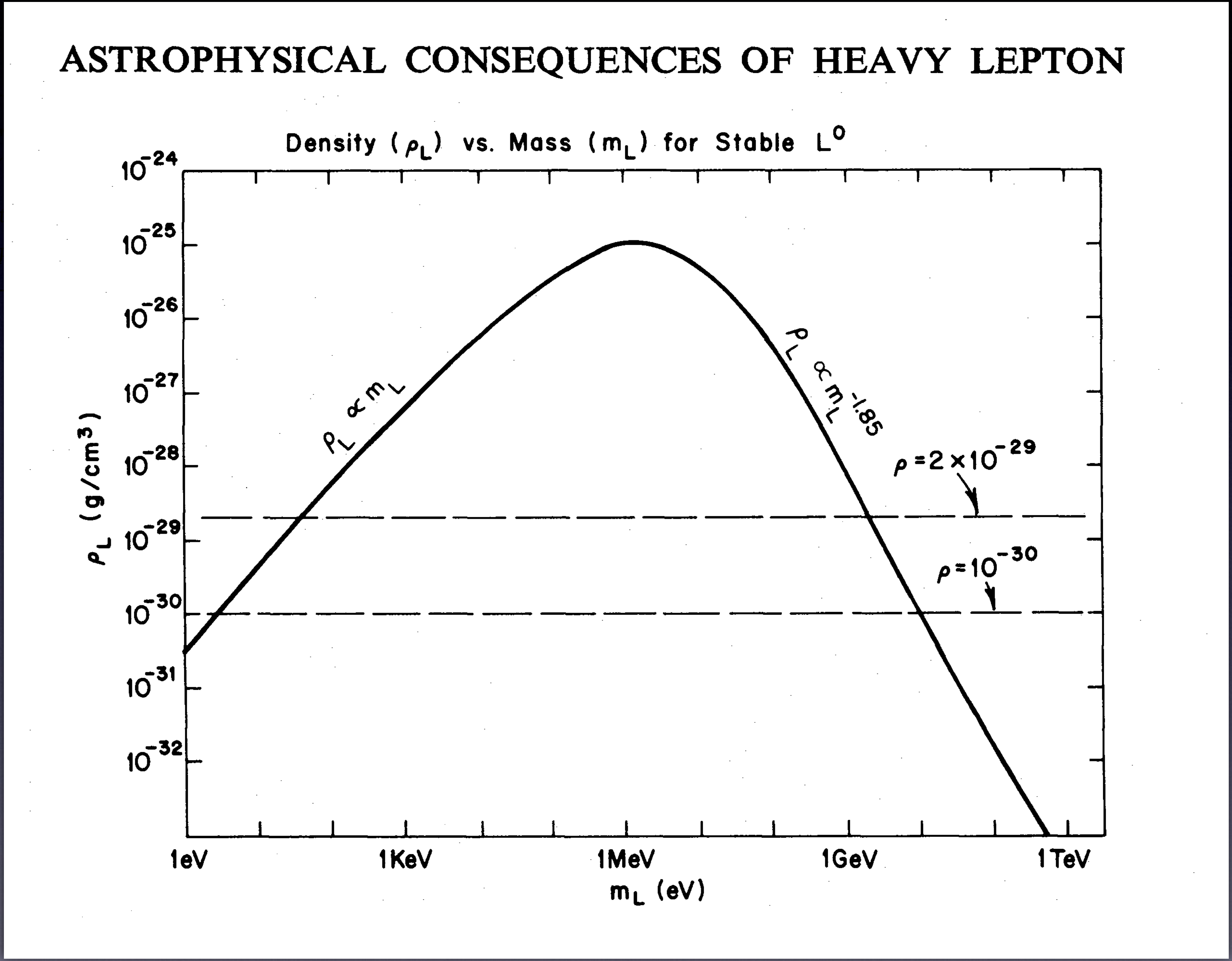
Subject headings: cosmology — elementary particles

The difference with the « neutrino » dark matter paradigm of **Zeldovich** is that they were not limited in the ranges of masses, **could be above the GeV scale**.

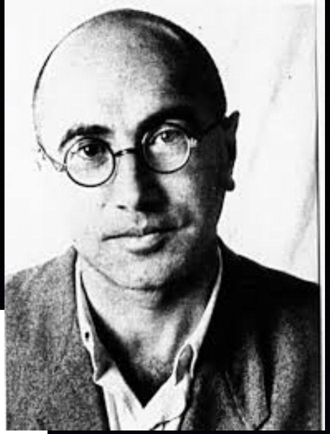
SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

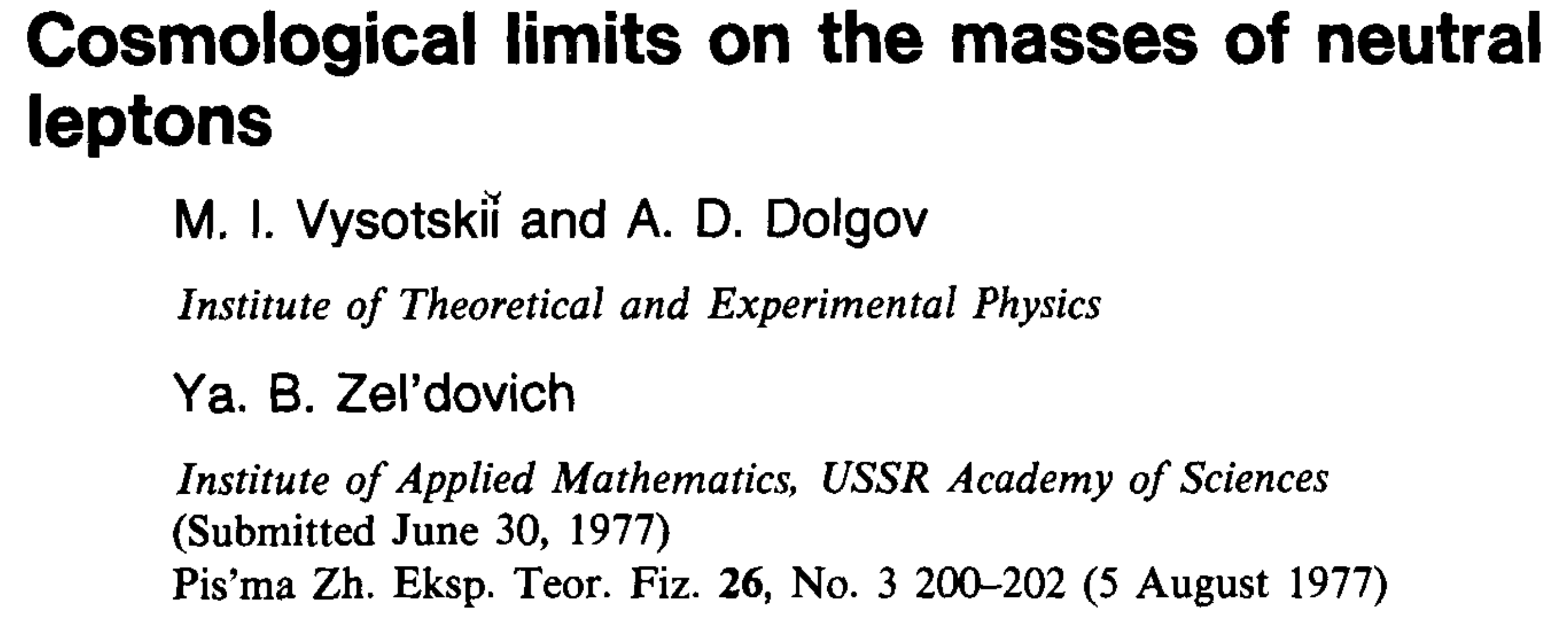
J. E. GUNN*



ASTROPHYSICAL CONSEQUENCES OF HEAVY LEPTON

Zeldovich paper





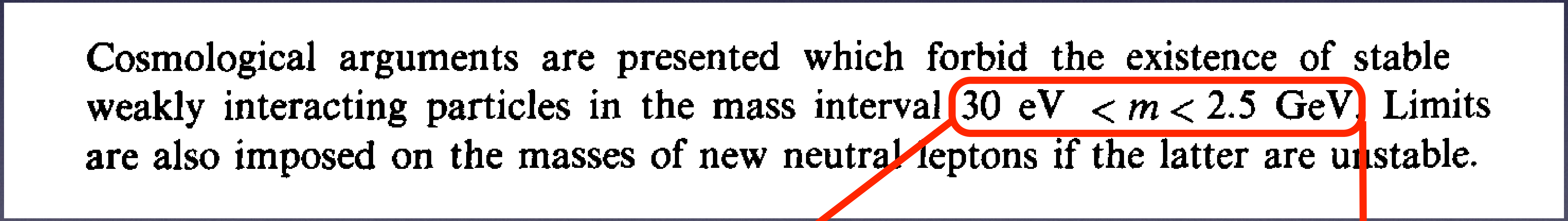
Cosmological limits on the masses of neutral leptons

M. I. Vysotskiĭ and A. D. Dolgov

Institute of Theoretical and Experimental Physics

Ya. B. Zel'dovich

Institute of Applied Mathematics, USSR Academy of Sciences
(Submitted June 30, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 3 200–202 (5 August 1977)



Cosmological arguments are presented which forbid the existence of stable weakly interacting particles in the mass interval $\boxed{30\ \text{eV} < m < 2.5\ \text{GeV}}$. Limits are also imposed on the masses of new neutral leptons if the latter are unstable.

Cowsik-McClelland bound

Lee-Weinberg bound

Summary (primordial sky)

Gamow (1948)
Combining nuclear reactions in a Freidmann's universe

Alpher, Herman (1948)
Prediction of the CMB

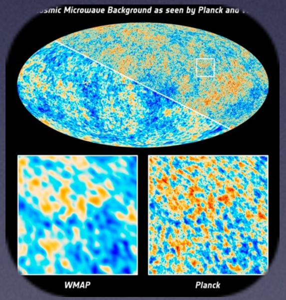
Dicke, Peebles, Roll Wilkinson (1965)
Peebles (1966)
Link between Helium abundance and the Helium abundance with a 3K CMB

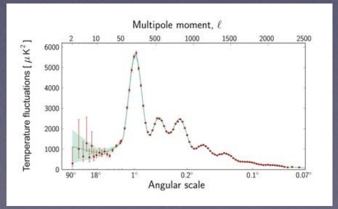
Penzias, Wilson (1965)
Discovery of the CMB

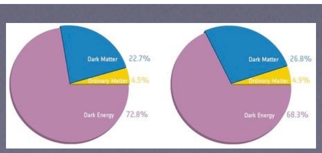
Zeldovich (1967)
Anisotropies in CMB

Peebles (1970)
First N-body simulation, instability

Bond, Neftassiou (1986)
Dark matter and anisotropies







Zeldovich (1966)
Filling the Universe with a massive neutrino

Cowsik McCleland (1972)
Filling the Universe with a massive neutrino

Steigman (1978)
Filling the Universe with a massive neutral non-baryonic candidate

Historical references

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Conclusion

We have then seen that 4 main periods have seen a fast developments of new ideas and concepts around the dark matter hypothesis :

1) In the 40's during the development of the observations of the sky at the radio-waves, following the developments of the radar especially during the WWII

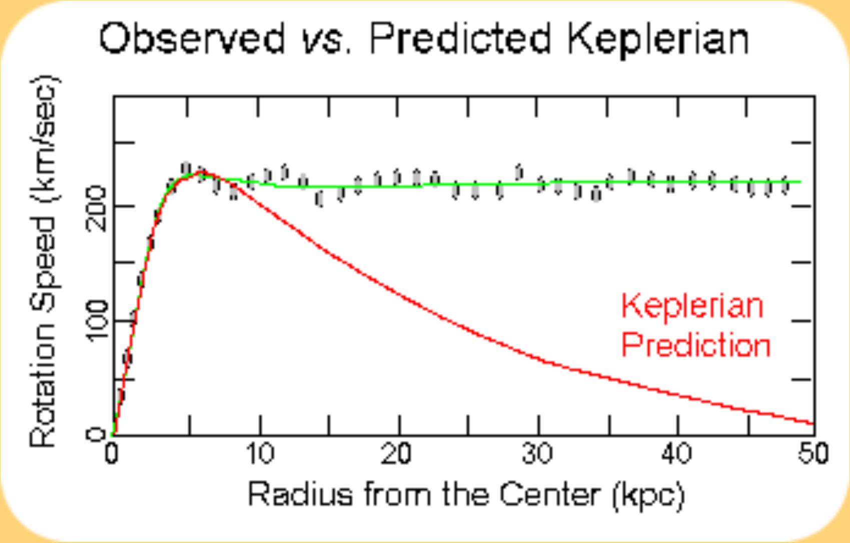
2) In the 50's once the nuclear physics fused with the model of expansion of Universe

3) In the 60's following the outbreaking discovery of the cosmic microwave background

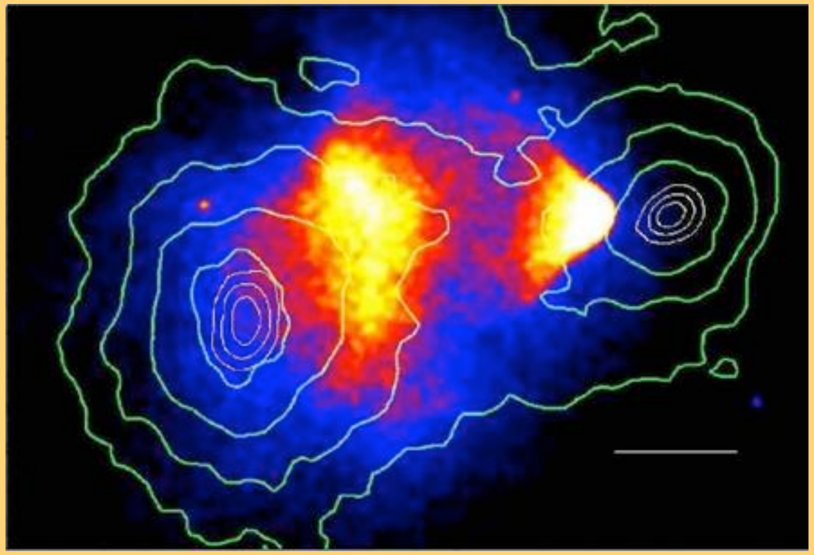
4) And finally in the 70's once computing progress made possible the first simulations of our Universe by solving Einstein's equation from the CMB till present day.

Did it make the introductory slide clearer?

Astrophysics scale

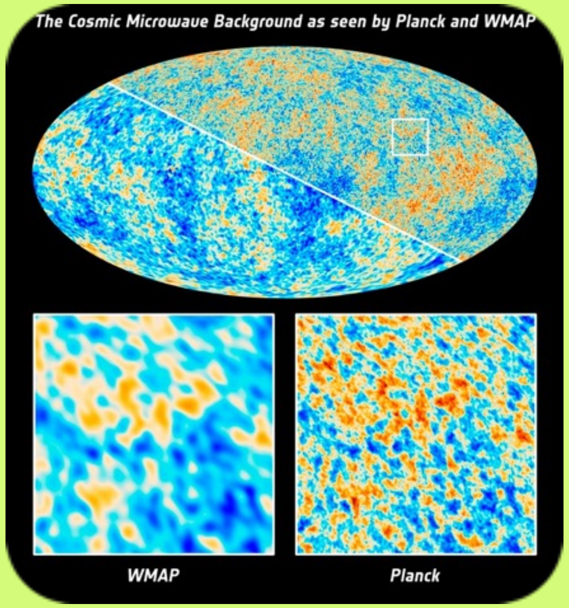


The rotation curve

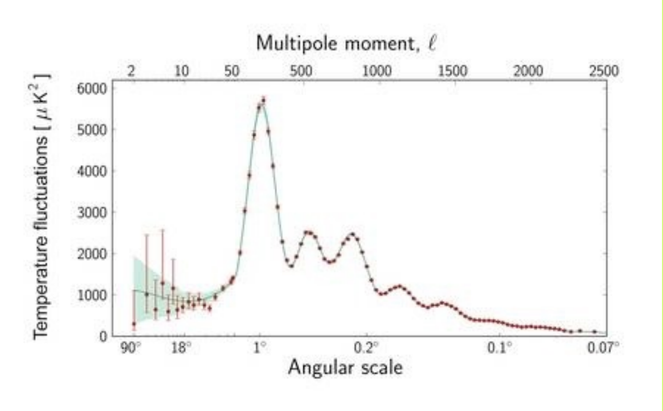


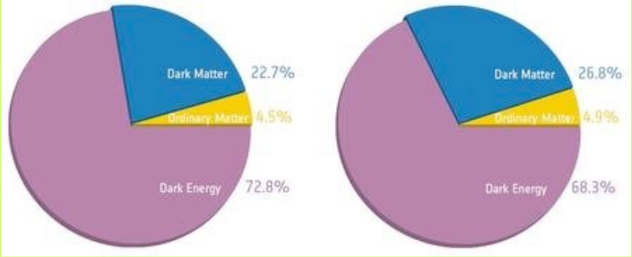
The bullet cluster

Cosmological scale



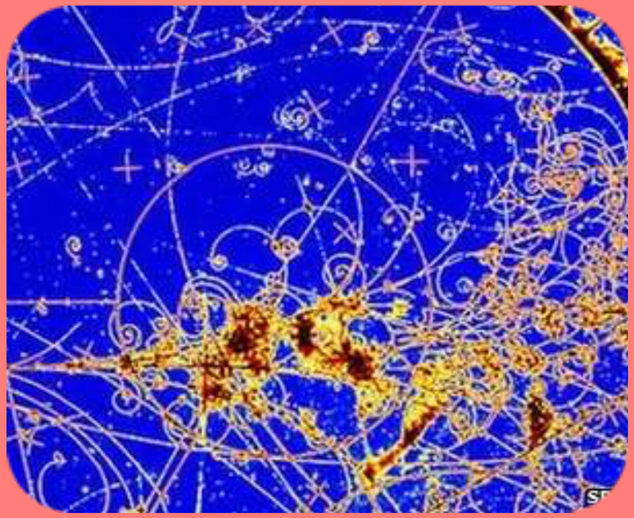
Measurement of the CMB





Particle physics

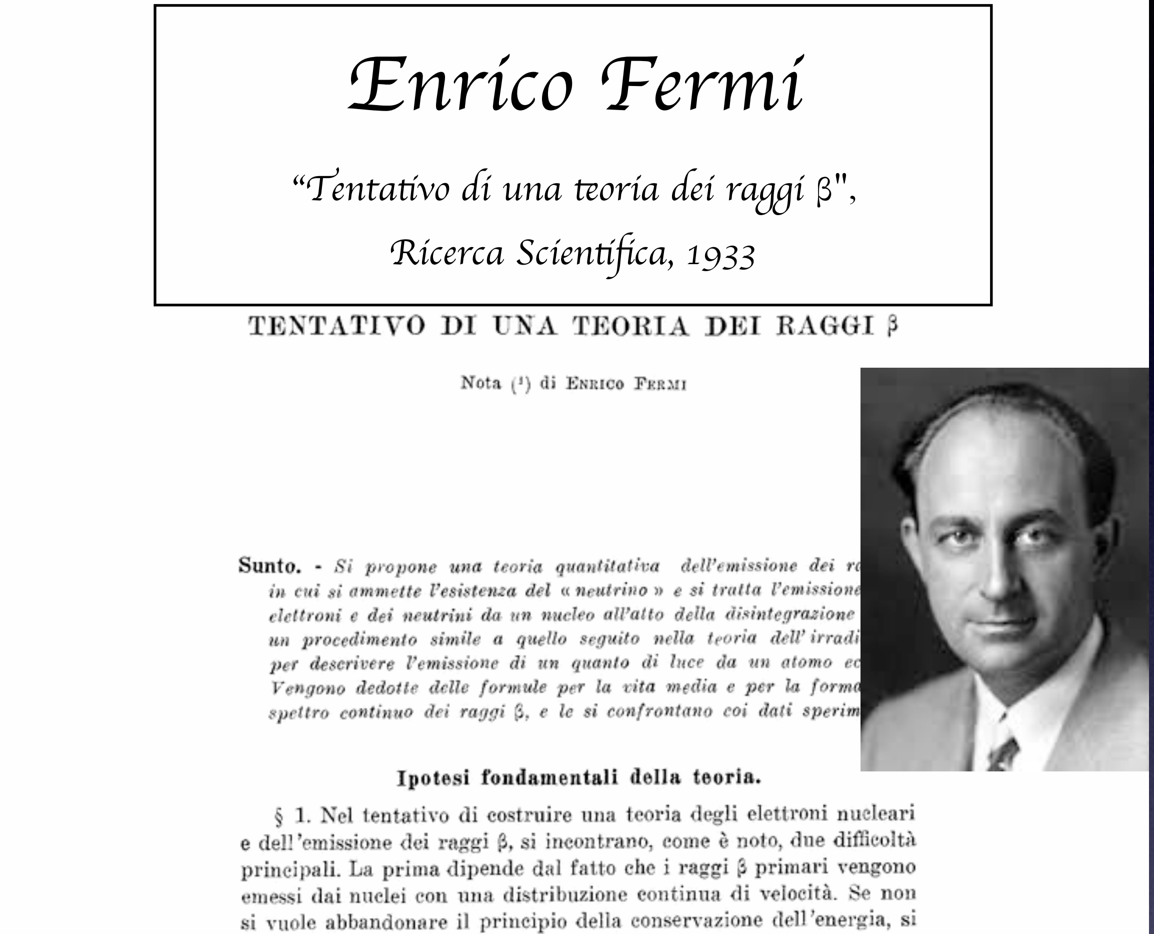
Cosmic rays



Neutrino sector

The pure effective approach « a la Fermi »

Application: the Zeldovich-Hut-Lee-Weinberg bound



Enrico Fermi

"Tentativo di una teoria dei raggi β",

Ricerca Scientifica, 1933

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (1) di Enrico Fermi

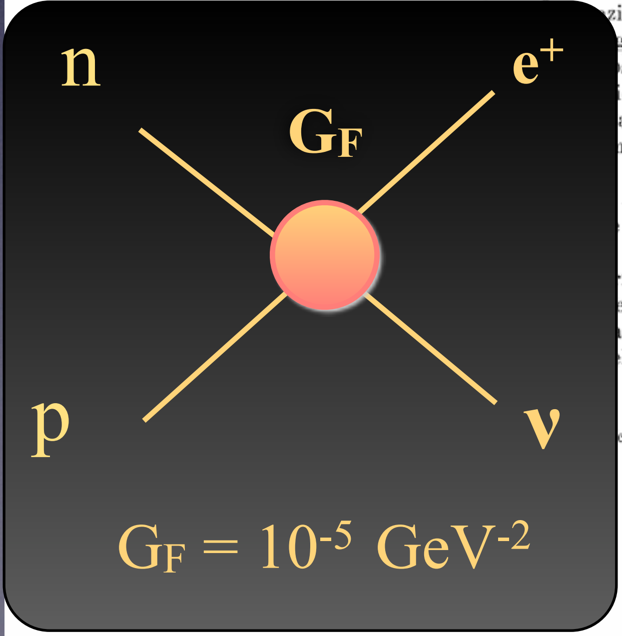
Sunto. - *Si propone una teoria quantitativa dell'emissione dei ra in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione elettroni e dei neutrini da un nucleo all'atto della disintegrazione un procedimento simile a quello seguito nella teoria dell' irradi per descrivere l'emissione di un quanto di luce da un atomo ec Vengono dedotte delle formule per la vita media e per la forma spettro continuo dei raggi β, e le si confrontano coi dati sperim*

Ipotesi fondamentali della teoria.

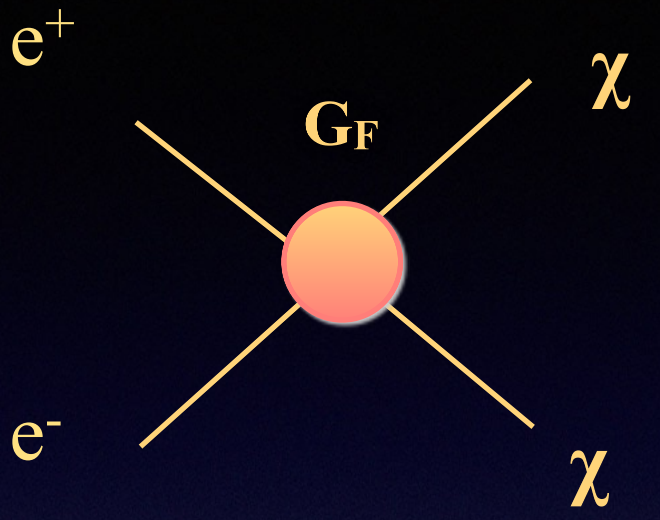
§ 1. Nel tentativo di costruire una teoria degli elettroni nucleari e dell'emissione dei raggi β, si incontrano, come è noto, due difficoltà principali. La prima dipende dal fatto che i raggi β primari vengono emessi dai nuclei con una distribuzione continua di velocità. Se non si vuole abbandonare il principio della conservazione dell'energia, si zione dell'energia che si libera ga alle nostre attuali possibi- sta di Pauli si può p. es. am- cella, il così detto « neutrino », a dell'ordine di grandezza di ette poi che in ogni processo β elettrone, che si osserva come all'osservazione portando seco teoria ci baseremo sopra l'ipo-

ia degli elettroni nucleari, di- e relativistiche delle particelle nno una soddisfacente spiega- lle vengano legate in orbite di

cerca Scientifica », 2, fasc. 12, 1933.

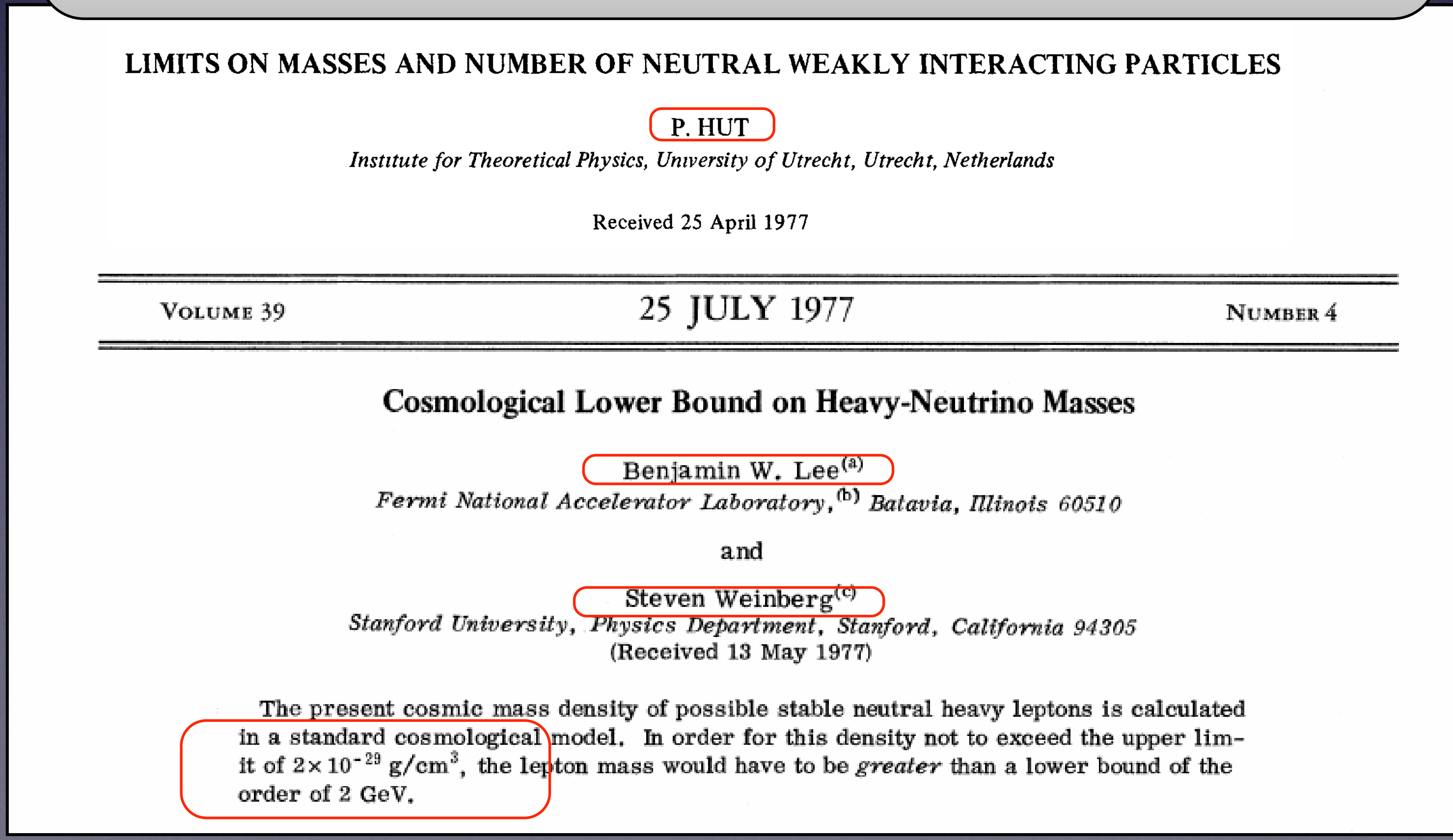


$G_F = 10^{-5}$ GeV^{-2}



The (Hut-)Lee-Weinberg bound (1977)

$$\langle\sigma v\rangle = G_F^2 m_\chi^2 > 10^{-9}\ \text{GeV}^{-2} \quad \Rightarrow \quad m_\chi > 2\ \text{GeV}$$



LIMITS ON MASSES AND NUMBER OF NEUTRAL WEAKLY INTERACTING PARTICLES

P. HUT

Institute for Theoretical Physics, University of Utrecht, Utrecht, Netherlands

Received 25 April 1977

Volume 39 — 25 JULY 1977 — Number 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]

Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

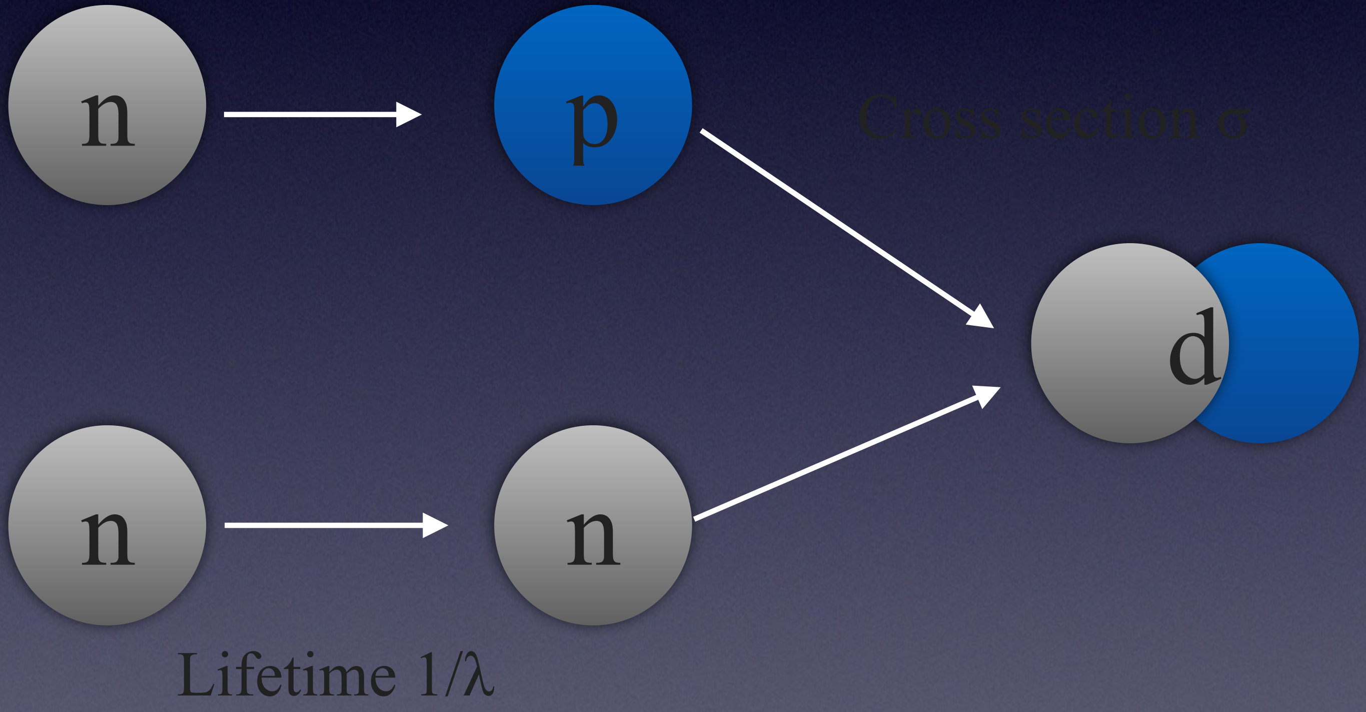
Steven Weinberg[c]

Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

End of the primordial Universe part.



General Plan

Historical perspective

Primordial Universe

Properties of Dark Matter

Detection of Dark Matter

Modelization of Dark Matter

Historical plan/menu

Breakfast

Observing the structure in the sky

(1930-1970)

Lunch

Observing the Cosmological Microwave Background [CMB]

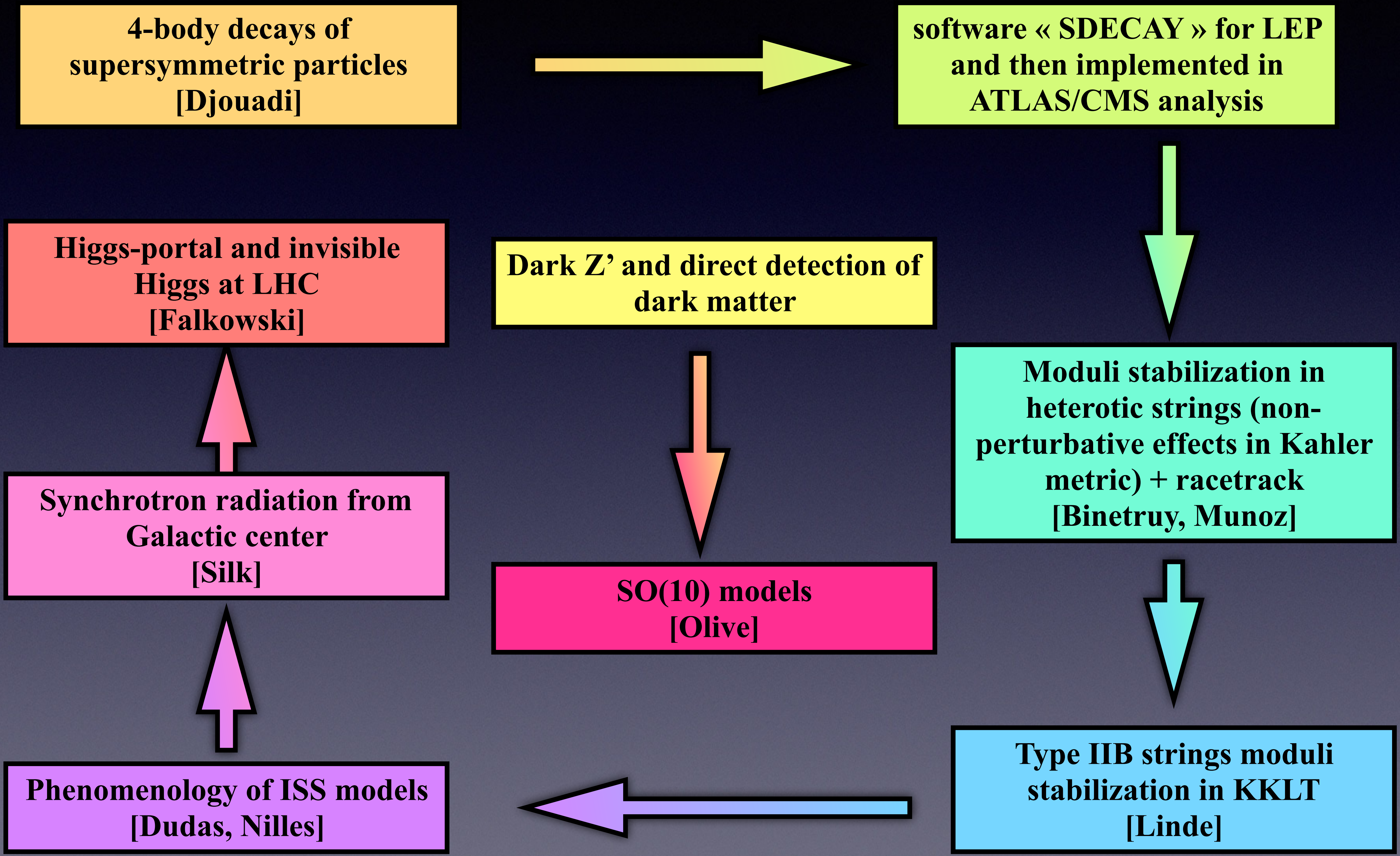
(1948-1967)

Dessert

Introducing new particles

(1965-1980)

Who am I?



4-body decays of supersymmetric particles
[Djouadi]

software « SDECAY » for LEP and then implemented in ATLAS/CMS analysis

Moduli stabilization in heterotic strings (non-perturbative effects in Kahler metric) + racetrack
[Binetruy, Munoz]

Type IIB strings moduli stabilization in KKLT
[Linde]

Phenomenology of ISS models
[Dudas, Nilles]

Synchrotron radiation from Galactic center
[Silk]

Higgs-portal and invisible Higgs at LHC
[Falkowski]

Dark Z’ and direct detection of dark matter

SO(10) models
[Olive]

```
H^2 = \left( \frac{\dot a}{a} \right)^2 = \frac{8 \pi G}{3} \rho_{rad}(T) = \frac{8 \pi G}{3} \frac{\pi^2}{15} T^4
\\
aT = \mathrm{cste} ~~~~ \Rightarrow ~~~~ \frac{da}{a} = - \frac{dT}{T}
\\
\frac{dT}{T^3}= -\sqrt{\frac{8 \pi^3 G}{45}} dt ~~~~\Rightarrow ~~~~ t = \frac{M_{PL}}{T^2}\sqrt{\frac{45}{32
\pi^3}} \simeq 0.2 \frac{M_{PL}}{T^2}
\\
t \simeq 3 \times 10^{27}~\mathrm{GeV^{-1}} \sim 200 ~\mathrm{seconds}
\\
n(t_D) \sigma v ~ t_D \simeq 1 ~~~~\Rightarrow n(t_D) \simeq \frac{1}{\sigma v t_D}
\\
v = \sqrt{\frac{3 T_D}{m_p}}\times c \simeq 5 \times 10^8 ~\mathrm{cm ~s^{-1}}
\\
T^{now} = \left(\frac{\rho_m^{now}}{\rho_m(10^9~\mathrm{K})}\right)^{1/3} 10^9~\mathrm{K} = \left( \frac{10^{-30}}
{1.78 \times 10^{-6}~\mathrm{g/cm^3}} \right)^{1/3}10^9~\mathrm{K} \simeq 8 ~\mathrm{K}
```

```
n_{e^-} + n_{e^+} = 0 ~ ; ~~ n_{\nu} + n_{\bar \nu} = \frac{1}{2} n_{\gamma}


\frac{\ddot a}{a} = - \frac{4 \pi G}{3}  \rho ~\Rightarrow ~ q(t) = - \frac{1}{H^2} \frac{\ddot a}{a} = \frac{4 \pi
G}{3 H^2} \rho
\\
= \frac{1}{2} \frac{\rho}{\rho_c}= \frac{1}{2} \Omega,
 ~~~~~~ \mathrm{with} ~ H^2 = \frac{8 \pi G}{3} \rho_c


n(T_f) \langle \sigma v \rangle = H(T_f) ~~ \Rightarrow ~~\left(T_f m \right)^{3/2} e^{-m/T_f} \langle \sigma v
\rangle < \frac{T_f^2}{M_{Pl}} ~~\Rightarrow ~~ T_f=\frac{m}{\ln{M_{Pl}}} = \frac{m}{26}


\frac{dY}{dT} = \frac{T^2}{H(T)} \langle \sigma v \rangle Y^2 ~~\Rightarrow ~~ Y(T_{now}) = \frac{1}{M_{Pl} T_f
\langle \sigma v \rangle } = \frac{26}{M_{Pl} m \langle \sigma v \rangle }



\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26
\times 400~\mathrm{cm^{-3}}}{\rho_c M_{Pl} \langle \sigma v \rangle} < 1



\langle \sigma v \rangle \simeq G_F^2 m^2 > 10^{-9} ~\mathrm{GeV^{-2}} ~~\Rightarrow ~~ m > 2 ~\mathrm{GeV}
```

```
n_{e^-} + n_{e^+} = 0 ~ ; ~~ n_{\nu} + n_{\bar \nu} = \frac{1}{2} n_{\gamma}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G}{3 H^2} \rho
\\
= \frac{1}{2} \frac{\rho}{\rho_c}= \frac{1}{2} \Omega,
 ~~~~~~ \mathrm{with} ~ H^2 = \frac{8 \pi G}{3} \rho_c


n(T_f) \langle \sigma v \rangle = H(T_f) ~~ \Rightarrow ~~\left(T_f m \right)^{3/2} e^{-m/T_f} \langle \sigma v
\rangle < \frac{T_f^2}{M_{Pl}} ~~\Rightarrow ~~ T_f=\frac{m}{\ln{M_{Pl}}} = \frac{m}{26}


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\langle \sigma v \rangle } = \frac{26}{M_{Pl} m \langle \sigma v \rangle }



\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26
\times 400~\mathrm{cm^{-3}}}{\rho_c M_{Pl} \langle \sigma v \rangle} < 1



\langle \sigma v \rangle \simeq G_F^2 m^2 > 10^{-9} ~\mathrm{GeV^{-2}} ~~\Rightarrow ~~ m > 2 ~\mathrm{GeV}
```
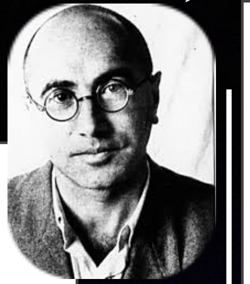
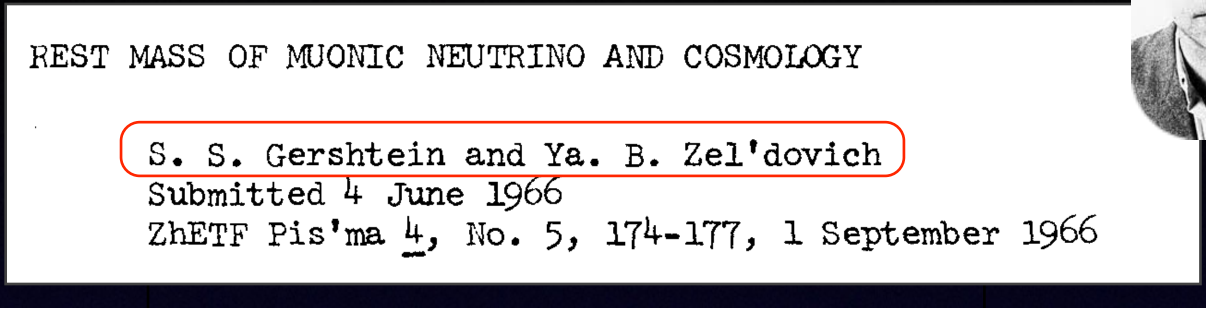

This **LIA** is a unique opportunity to strengthens our links and develop new directions of research in this future very (!!) exciting and bright future for our discipline..

Filling the Universe with massive dark neutrino

The Zeldovich-Cowsik-McClelland bound, or the birth of cosmological astroparticle

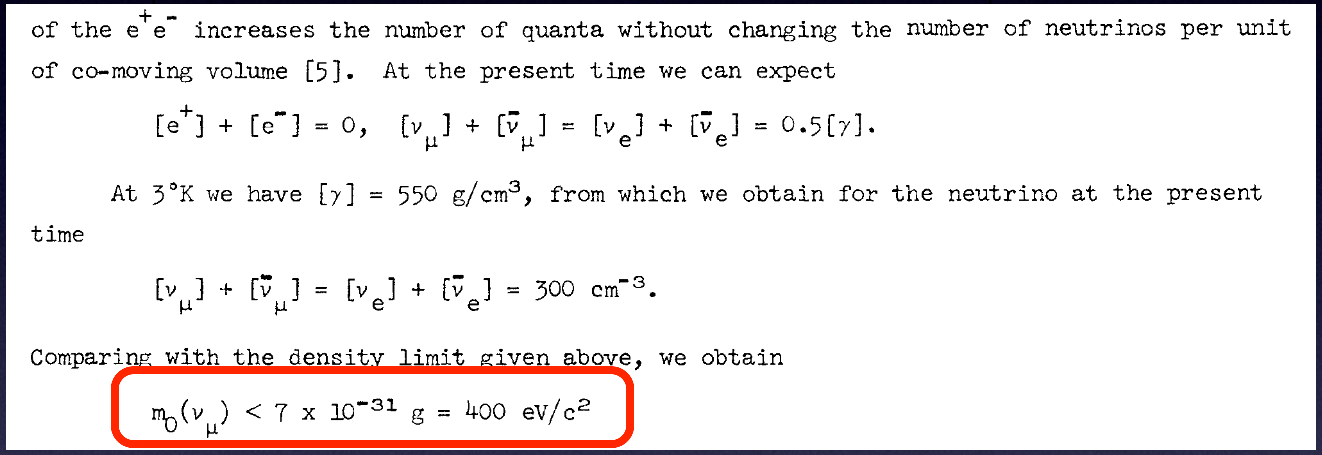
Y. Zeldovich





REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966



of the e^+e^- increases the number of quanta without changing the number of neutrinos per unit of co-moving volume [5]. At the present time we can expect

$$[e^+] + [e^-] = 0, \quad [\nu_\mu] + [\bar{\nu}_\mu] = [\nu_e] + [\bar{\nu}_e] = 0.5[\gamma].$$

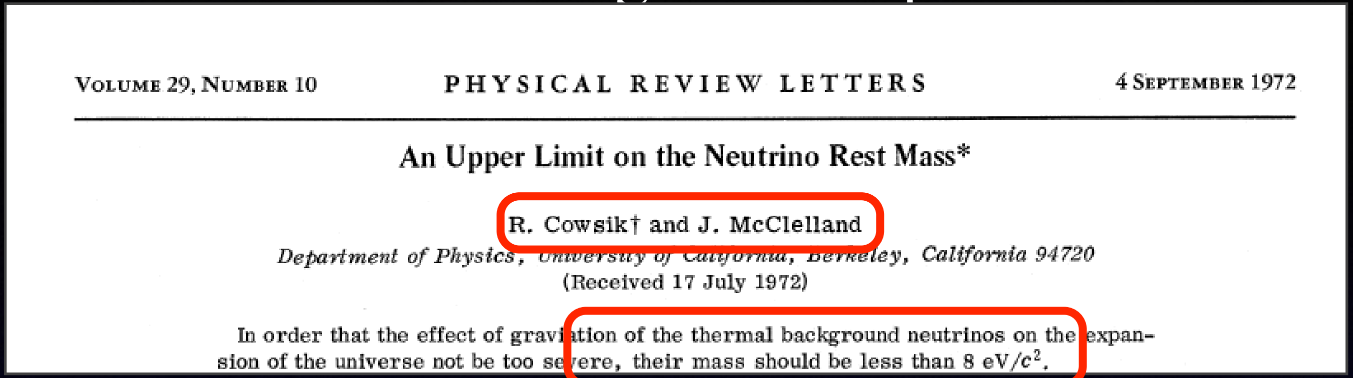
At 3°K we have $[\gamma] = 550$ g/cm^3, from which we obtain for the neutrino at the present time

$$[\nu_\mu] + [\bar{\nu}_\mu] = [\nu_e] + [\bar{\nu}_e] = 300 \text{ cm}^{-3}.$$

Comparing with the density limit given above, we obtain

$$m_0(\nu_\mu) < 7 \text{ x } 10^{-31} \text{ g} = 400 \text{ eV}/c^2$$

[CMB, Penzias 1965 + discovery ν_μ, Lederman 1962]



VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720
(Received 17 July 1972)

In order that the effect of gravitation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

at $T < m_e$, e^- and e^+ decouple from the thermal bath: they give their degrees of freedom (2+2=4) to the photons and not the neutrinos because the latter are already out of equilibrium since T ~ 3 MeV
$2\ n_\gamma \to (2+ 7/8\ 4\ )n_\gamma = 11/2\ n_\gamma$.

The photons are then almost 3 times more « dense » than the neutrino in the bath after the decoupling of the electrons,
resulting at T_0=2.7 K, $n_\gamma = 300$ cm^{-3} [CMB] => $n_\nu + n_{\underline{\nu}} = 100$ cm^{-3}

To avoid overclosing the Universe, one needs
$\rho_\nu = m_\nu\ (n_\nu + n_{\underline{\nu}}) < \rho_{crit} = 3\ H^2/8\ \pi\ G = 2 \times 10^{-29}\ h^2$ g / cm^3
=> $m_\nu < 2\ 10^{-31}\ h^2$ g = 94 h^2 eV = 45 eV **[H_0=67 km/s/Mpc]**
[corrections 1/3 from Ω_m versus 1 (or 5, Zeldovich)
+ number of families]

[Zeldovich considered $\rho < 2 \times 10^{-28}$ g/cm^3]