COSMOLOGY THEN AND NOW*

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In this talk a brief survey has been carried out on the development of cosmology from the days Leopold Infeld was active in the field up to the present. Attention in particular is paid to the history of our knowledge of Hubble's expansion, of the cosmological constant, of the average density of matter and its distribution, and of the related issue of possible types of matter in the Universe.

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First of all I would like to thank the organizers of this Meeting for inviting me. It is a honor to give this talk. It is a special honor for me, because Polish cosmologists are very well known. Coming back to the subject of this conference, I would like to say that the name of Leopold Infeld and especially his book "The Evolution of Physics", [1], written with Albert Einstein played a crucial role in my life. Before reading this book, which I read in the Russian version, I had thought that the real mystery is only in astronomy. After having read this book I understood that real mysterious puzzles are also in physics, and I started to learn physics as well as astronomy, and after that I started doing physics also. I am going to talk about cosmology many, many years ago in the epoch of Leopold Infeld and cosmology today. What was cosmology 30 or 40 years ago? I want to call witnesses to describe the situation then. First quotation is from Malcolm Longair's paper [7], a very well known cosmologist who wrote about those early days "When I began

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research in radio astronomy as a student in 1963, my supervisor Dr. Peter Scheuer gave me a copy of Sir Hermann Bondi's classic text *Cosmology* to absorb and he warned me that "there are only two and a half facts in cosmology". The second quotation is from the paper [3] of Steven Hawking. He wrote: "There has been a great change in the status of general relativity and cosmology in the last thirty years. When I began research in the Department of Applied Mathematics and Theoretical Physics (DAMPT) at Cambridge in 1962, general relativity was regarded as a beautiful but impossibly complicated theory that had practically no contact with the real world. Cosmology was thought of as a pseudo-science where wild speculation was unconstrained by any possible observations". So it was the situation in the period when Leopold Infeld actively worked and did his research in cosmology. Indeed at this period cosmology was only a science about the mechanics of motion of huge mass of matter in the Universe. So, we can call it celestial mechanics of the Universe. There was not any physics in cosmology at this period. We can compare this period with the period in astronomy at the beginning of the last century, when there was not any astrophysics at all. Astronomy itself was only the science about the motion of celestial bodies, the motion of planets and their satellites and so on, but there was nothing about the physical processes. Analogous situation was at the beginning of the second half of our century in cosmology. Mainly it was the science about only two values, the speed of the expansion of the Universe – the Hubble parameter, and the deceleration parameter which characterizes the total average density of the matter and the gravity of this matter which leads to deceleration of its motion. It was the situation in the epoch when Infeld wrote his cosmological papers. Leopold Infeld published a few papers on cosmology, one of them, [4], had the title "A new approach to kinematic cosmology" and was published in Nature in 1945. Two other papers, [5], with the same title were published in the Physical Review in the same year. In these papers Infeld proposed a new approach to kinematics of the cosmological models. He wrote: "We shall see that an approach to cosmology is possible in which the structure of three-dimensional space does not enter the picture. We believe that this new approach puts into the foreground the more essential concepts of kinematical cosmology, *i.e.*, the type of motion of fundamental particles rather than the space structure". This is a quotation from one of these papers. He proposed the following approach. Before Infeld in cosmology mostly was discussed the problem of 3 dimensional space — a 3 dimensional slice of 4 dimensional spacetime, so the structure of 3 dimensional space of cosmological models. Cosmologists discussed the open Universe, closed Universe, and flat Universe. It was the characteristics of geometry of the 3 dimensional slices. Infeld proposed to consider not the 3 dimensional slices, but the world lines of the galaxies themselves, so the configuration of these world lines in 4 dimensional spacetime. This configuration is really related with the physics of the motion, with the kinematics of this motion. So these world lines specify the motion of reference frame and all physics is related with this motion. The 3 dimensional slices are related with the synchronization of clocks along different world lines of the cosmological model, but this synchronization has nothing to do with the physics. This is a mathematical choice of a time coordinate, nothing more. Thus the Infeld's approach was really the beginning of physical approach to the description of the properties of the motion of fundamental particles in cosmological models. Soon after that these ideas were developed by many other physicists and cosmologists, and first of all by Abram Zelmanov in the former Soviet Union. He developed these ideas absolutely independently from Infeld and now this approach, the description of the motion of the reference frame is a very powerful tool not only in cosmology but in general relativity as well. This was the first very important contribution of L. Infeld to cosmology, and an absolutely new approach to the description of cosmological models. Another idea which existed in these papers is the following: L. Infeld emphasized that any cosmological space can be looked upon as a Minkowski space with a non-Minkowski gauging. It means that if we know a solution of the Maxwell equation in the Minkowski space, then we can immediately obtain analogous solution in the case of cosmological models. This remark and this approach was the approach from the point of view of the future of cosmology, from the point of view of the physical cosmology, and especially was related with the solution of the physical problems, not only with the kinematics and the description of the speed of expansion of the Universe. One more paper on cosmology by Infeld, "On the structure of our Universe", [6], was published in 1949, and it was devoted to some critical review of the situation in cosmology at that time. Let us come back to the situation with the cosmology at the period of Leopold Infeld, so approximately 40 years ago. We can summarize the situation as follows, see Table I. How far have we came in 40 years? What can we say about the

TABLE I

Cosmology 40 years ago

* Mainly search for 2 numbers (H_0 and q_0).
* No physics
* Universe assumed to be baryonic
* No knowledge about Large Scale Structure
* No knowledge about the beginning of the expansion

modern Universe, and about the development of cosmology after this period? Today the situation in cosmology has changed dramatically and the cosmology was transformed from the celestial mechanics of the Universe into the physics of the Universe. Cosmology today can be characterized from two points of view: from the point of view of the observational cosmology and the theoretical cosmology, see Table II. Let us start our discussion from the

TABLE II

Cosmology today

	Observational pillars
*	Hubble's expansion, q_0.
*	Microwave Background Radiation
*	Cosmic abundance of light chemical elements
*	Average matter density
*	Large Scale Structure
	Theory
*	Hot Universe
*	Very Early Universe; Inflation
*	Origin of the Large Scale Structure

description of the evolution of our knowledge about the rate of expansion of the Universe, so about the Hubble constant, H_0 (see Fig. 1). At the beginning of the thirties, the Hubble constant was estimated as $H_0 \approx 500\mathrm{km}s^{-1}\mathrm{Mpc}^{-1}$. Starting from the Infeld period our knowledge about the value of the Hubble constant practically did not change. Of course our determination become more precise, that is true, but there is still a scattering of points around the average value and this scattering is only a little bit less than it was in the Infeld period.

It was the beginning of a serious disagreement between different groups of astronomers, who were specialists in this field, and one group supported the idea of a big value of the Hubble constant, and the other supported the idea that the Hubble constant should be rather small. The values preferred by the first group where about 100 km/sMpc, and by the second about 50 km/sMpc. It was a very serious disagreement. Unfortunately today the situation is not much better. Allow me to show a few results. In Table III you see the results from the paper [12] of Gustav Tammann (1997), one of the authoritative specialists in this field, and you see the different methods of determination of the Hubble parameter lead to the values between 45 and 55 km/sMpc with errors which are not large. According to him the

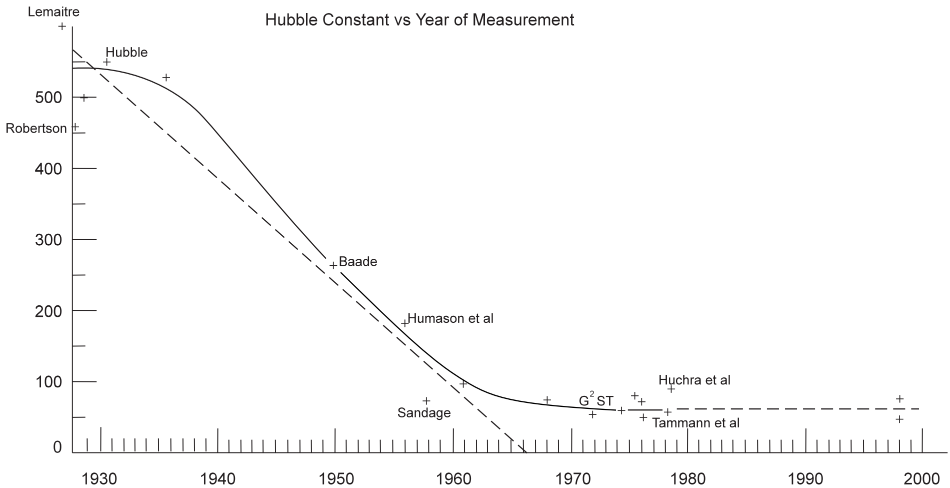

Fig. 1. Schematic from Schramm [11] of the approach to the current range of H between 50 and 100 km s^{-1} Mpc^{-1} in the 60 years since Hubble's 1929 estimate.

TABLE III

H_0 determinations from field galaxies (G.A. Tammann [12])

Method	H_0
Tully-Fisher, distance-limited (local)	48 ± 5
Tully-Fisher, flux-limited (distance)	< 60
M 101 look-alike diameters	43 ± 11
M 31 look-alike diameters	45 ± 12
Luminosity classes of spirals	56 ± 5
M 101, M 31 look-alike luminosities	55 ± 5
Tully-Fisher	57 ± 5
Tully-Fisher (using magn. + diameters)	55 ± 5
weighted mean	53 ± 3

best present value of the Hubble constant is 55 ± 8 km/sMpc, if we take into account all types of errors including the systematic error. He wrote: "values larger than 65 still present in the literature can be attributed to a few quite obvious error sources". On the other hand, the result of another very good specialist in this field, Wendy Freedman, published in a paper approximately at the same time (1996), but by using different methods, is $H_0 = 73 \pm 6$ (statistical) ± 8 (systematical), which lies far beyond the upper limit given by Tammann, see Table IV. So discrepancy still exists and it is in

TABLE IV

Summary of key project results on H_0 (W. Freedman (1996))

Method	H_0			
Virgo			80 ± 17	
Coma via Virgo			77 ± 16	
Fornax			72 ± 18	
Local			75 ± 8	
JT clusters			72 ± 8	
SNIa			67 ± 8	
TF			73 ± 7	
SNII			73 ± 7	
$D_{N-\sigma}$			73 ± 6	
Mean			73 ± 4	
Systematic errors	± 4 (LMC)	± 4 ([Fe/H])	± 5 (global)	± 2 (photometric)

spite of the fact that today we have new technological possibilities of making observations. Let me mention, for example, the Hubble Space Telescope. We now know much more reliable so-called standard candles for determination of distances of far galaxies and so on. But in spite of this fact, there is still a large discrepancy between the two groups which give different values of the Hubble constant. Probably the best value today is 65 ± 7 km/sMpc, it is just the value which I personally favor. This value was given by Kirschner in May 1998 (see [2]). Observations are still going on and we will see what the future will bring. This is the situation with the Hubble constant today. Another important cosmological parameter is the average matter density in the Universe. Usually astronomers and cosmologists use the dimensionless parameter

$$\Omega \equiv \frac{\langle\rho\rangle}{\rho_{\rm crit}},$$

where

$$\rho_{\rm crit} = \frac{3H_0^2}{8\pi G},$$

which gives the average matter density in units of the critical density. The critical density is a density of a flat Euclidean Universe which separates closed Universes from the open ones. We will use this dimensionless parameter to describe the average matter density. The standard approach to determination of this parameter is the following (it was proposed by Edwin Hubble). If we observe very far galaxies, with large visible magnitudes, then the dependence between the redshift and the magnitude is not linear any more, and the deviation from the linear relation depends on the amount of matter in the Universe, so it depends on Ω. If we compare observations with the theoretical predictions, we can estimate the possible value of Ω. According to results of Riess *et.al.* [10], see Fig. 2, the most probable value of Ω for so called standard matter (including invisible matter) is $\Omega_M = 0.24$. Observations indicate that in addition there is a so-called vacuum type of matter in the Universe with $\Omega_\Lambda = 0.76$. This $\Omega_\Lambda = 0.76$ corresponds to the cosmological Λ-term in the Einstein equations. This matter is not usual matter, it is very exotic one and it creates anti-gravity: gravitational repulsion instead of gravitational attraction. Probably the model with rather big Λ term gives the best fit with the observational data and it means that we can expect that in the Universe there is a huge amount of very exotic matter of the vacuum type which creates anti-gravity and creates acceleration of expansion of the Universe. We have different other methods of determination of the Λ parameter in the Universe from observations; see Fig. 3. For all possible values of the Hubble constant, the value of Λ is of the order of $\Omega_\Lambda \approx 0.55$ to 0.8, so we come to the conclusion that the Λ term in the Einstein equations probably is not zero and observations give a definite value of this parameter. How many redshifts of galaxies we know? At the period of L. Infeld the total number of known redshifts was about 10^3. Today the total number jumped to 10^5, so it is two orders of magnitude greater. In the period of L. Infeld the redshifts were mainly used for determination of the Hubble parameter. Today they are used for determination of distances of very far galaxies and for the investigation of the 3 dimensional distribution of galaxies in the Universe. The depth of the largest modern Las Campanas redshift survey is about 500 Mpc, so 1.5 billions of light years. The space distribution of galaxies in this survey is very far from being uniform. The total number of galaxies is about 26 000. The analysis of the survey shows that there are great voids practically empty from galaxies and also the borders of these voids which can be described as some kind of 2 dimensional walls, super clusters of galaxies, and there is also some filamentary structure around these voids with the characteristic separation between filaments of the order of 10–15 Mpc. The characteristic size of these voids is about 50 Mpc. Now we know much about the large scale structure in the Universe, and there are special theories which describe the process of formation of this large scale structure. But the problem number one in modern cosmology is the problem of dark matter. We know for sure that the main part of matter in the Universe is not visible, so the main part of matter is dark. Why can this be stated with confidence? This is because of the following. Surveys of visible matter give the average matter density $\Omega_{\rm vis} = 0.004$. This is matter in the form of stars, galaxies, hot gas, dust and so on. On the other hand we have very strong evidence

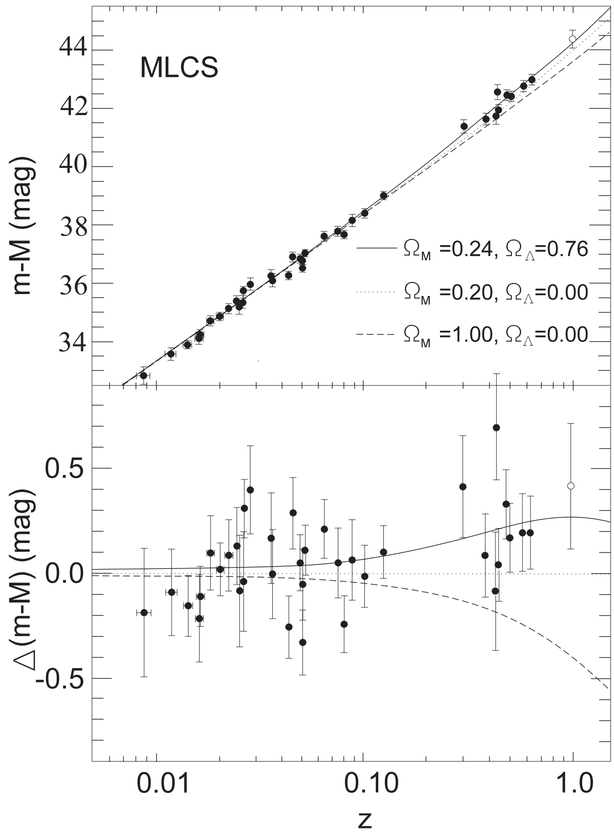

Fig. 2. Taken from Riess *et al.* [10].

for invisible matter on the scales starting from the size of clusters of galaxies and larger. We know that the main part of mass in clusters of galaxies is invisible. We know this because we can measure the dispersion of velocities of galaxies in the total gravitational fields of clusters of galaxies, and the gravitational field there is created by the total amount of matter present there, including invisible matter. Using dispersion of velocities, we can calculate the gravitational potential of the cluster and from this we can calculate the total mass of the cluster and hence the average matter density on these scales. In such a way we obtain that $\Omega_{\rm clusters} = 0.2$ - 0.4. This means that the Universe contains about at least 50 to 100 times more matter than the visible matter. So the main part of matter is invisible. There are different methods of determination of the amount of invisible dark matter. Another method is based on observations of the temperature of hot gas in clusters of galaxies which radiate X-rays. If we know the temperature, we can calculate the gravitational field of total matter in the clusters of galaxies, and hence determine their total mass. The new and very powerful method of detection of invisible matter is the method of gravitational lenses. When a light ray propagates through the cluster, it will be deflected from a straight line by gravity. Because of the gravitational lensing effect, we observe distortions of images of the background galaxies, and we can reconstruct the distribution of the gravitational potential using distortions of different images. After that one can reconstruct the distribution of all types of matter inside the cluster. One can go to even larger scales, using the motion of clusters of galaxies to probe the mater distribution in the Universe. It turns out that on the largest scales the total mass density could be even larger than on smaller scales. Once again we can conclude that the main part of matter in the Universe should be invisible, should be dark. But the main question remains, what is the nature of this dark matter. Is it the standard matter of baryonic type, so it consists of protons and other elementary particles, or is it some kind of exotic matter? We are absolutely sure that some part of the invisible matter must be baryonic, but not all of the invisible matter, only rather a small part of it. Indeed, our knowledge about the amount of the baryonic matter in the Universe is implied by the following types of observations and theoretical conclusions. One can calculate the amount of baryonic matter using the observed abundance of light elements. These elements were created during the first five minutes of expansion of the hot Universe and the results of the process of creation of chemical elements depend on the baryonic matter density. So if we compare theoretical estimates with real observations, we can estimate the baryonic matter density. However even if we take into account all possible uncertainty in the determination of main parameters of the Universe, we are still sure that the baryonic mass density must lie between the two values $0.01 < \Omega_b < 0.1$. This is bigger than the visible baryonic matter density. The estimates of amount of visible matter give $\Omega_{\text{vis}} = 0.004$, so less than the lower limit of the amount of baryonic matter. This means that the main part of baryonic matter is invisible. But still this value is essentially less than the total amount of invisible matter which is at least a few times greater than this one. This means that the main part, probably 90% of the total invisible matter is exotic one, not the standard one, see Table V. What can we say about the nature of this invisible

TABLE V

Various types of matter in the Universe

Visible	0.4%
Baryonic dark	$\leq 10\%$
Exotic	90%

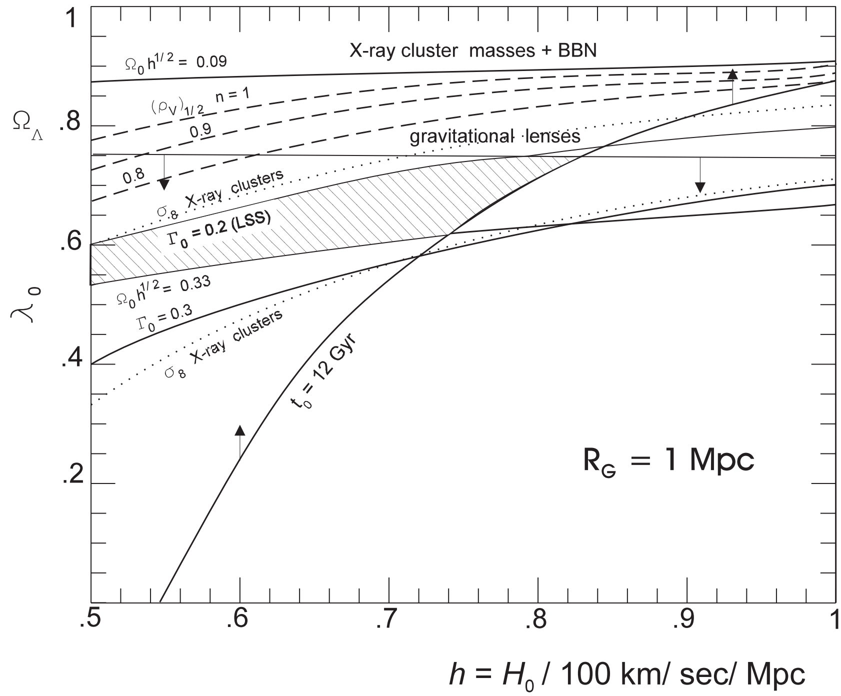

Fig. 3. Observational constraints on $\lambda_0 \equiv \rho_V^*/(\rho_V^* + \rho_0)$ and $h \equiv H_0/(100\text{km/sec/Mpc})$. Curves labelled "LSS" and "$\Gamma_0 = 0.2$"or "$\Gamma_0 = 0.3$" bound the region allowed by the constraint $\Gamma_0 = \Omega_0 h = 0.25 \pm 0.05$ derived by matching the spatial and angular correlation statistics from galaxy surveys with the theoretical predictions of the large-scale clustering of galaxies in a COBE-normalized, flat CDM model with primordial power spectrum index $n = 1$. The curves labelled "σ_8 X-ray clusters" bound the values of λ_0 and h which make this CDM model satisfy the constraint on the present space density of X-ray clusters. The curve labelled "$t_0 = 12$ Gyr" indicates the lower limit which makes the age of the universe at least as large as current estimates of the minimum age of globular clusters. The curves labelled "$\Omega_0 h^{1/2}$" indicate the boundaries defined by the X-ray-measured total and barionic masses of clusters of galaxies, together with the big bang nucleosynthesis limits on the baryon mean density and the assumption that the ratio of baryon to total mass inside each cluster equals the ratio of universal mean values. The curve labelled "gravitational lenses" indicates the upper limit imposed by counts of quasars lensed by intervening galaxies. The dashed curves labelled "$(\rho_V)_{1/2}$" are the values for which our own subuniverse has the median value of ρ_V for all subuniverses, if $R_G = 1$ Mpc, and $n = 1$ (top dashed curves), 0.9 (midle dashed curve), or 0.8 (bottom dashed curve). (Taken from Martel *et al.* [8].)

matter? There are different candidates for this invisible matter. Cosmologists divide it into two categories: the so-called cold dark matter and the hot dark matter. The cold dark matter consists of hypothetical particles with the velocities of motion essentially less than the velocity of light, so non relativistic exotic particles or partly baryonic particles as well. The hot dark matter is the opposite case, it consists of ultra relativistic particles. Once again I am not going into details. There are many exotic candidates for the invisible matter: axions, neutrinos, photinos, and many, many others. At the beginning majority of specialists believed that the model which describes the dark matter could be constructed very easily, and this model could describe all peculiarities of the observational data. Only one question was: what type of dark matter does correspond to reality? Specialists tried to compare different types of theories which described different models of dark matter: the cold dark matter, the hot dark matter, and some other exotic matter. The conclusion is that this comparison produces no clear winner, and there are great contradictions between different conclusions. It means that practically we know nothing about the nature of this exotic matter and probably we should come to the conclusion reached by Edward Kolb about our hypothesis: "Our motto is: often in error, never in doubt". The reason of this situation is clear: too many dark matter candidates, too many theories, and no definite results, because there are not enough observational data. Allow me to quote once again from the review paper of L. Infeld: "Yet many possibilities remain. Such a situation is not encouraging. We expect a good theory to lead us to definite conclusion, to a model that can be accepted or rejected by experiment. This is not true in this case. There are too many possibilities!" He talked about too many models of the kinematical motions of the matter in the Universe, but we can repeat the same conclusion today about new hypotheses. Situation is clear, we need more precise observations in cosmology. The new methods came into cosmology. The most important method is related with the observations of the cosmic microwave background radiation (CMB). This radiation was discovered by Penzias and Wilson in 1965, [9]. It is the radiation which comes from a very big distance and was born when the Universe was hot and opaque. After its discovery the radiation was investigated by many methods. The most precise methods were performed from space, from satellites. The pioneer observations were performed by the Russian satellite Relict and after that by the American satellite COBE. This was the first very precise measurement of the properties of the CMB. Observations of very small fluctuations of the intensity of the CMB polarization can give unique information about the main parameters of the Universe, about its physics and about the physics of the very early Universe. New space projects: American project MAP and

TABLE VI

Main goals of MAP and PLANCK projects

1.	Determination of H_0, Ω_b, Ω to a precision of $\sim 3\%$
2.	Determination of the spectrum of primordial fluctuations and amount of gravitational waves (tests of inflation)
3.	Tests of topological defects.
4.	Tests of exotic matter.
5.	Some problems of extragalactic astrophysics (peculiar motions, unknown sources, ...)
6.	Strong impact on particle physics (testing physics at energies $\geq 10^{15}$Gev).

European project PLANK will revolutionize our understanding of Cosmology. In Table VI we summarize the main goals of the new projects. For conclusion allow me to give two quotations from L. Infeld which demonstrate that he foresaw in the tremendous future of cosmology. In 1949 he wrote: "We ask: are the laws governing our Universe independent of the quantum mechanical laws governing the atom?" and else: "At the present time our observations can penetrate only a small corner of our Universe. It is possible that future observations may force us to retreat from these simple assumptions".

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REFERENCES

[1] A. Einstein, L. Infeld, *The Evolution of Physics*, Cambridge University Press, Cambridge 1938.

[2] P. M. Garnavich, R. P. Kirshner, *et al.*, Constraints on Cosmological Models from Hubble Space Telescope Observations of High-z Supernovae, *Astrophys. J.* **509**, 74 (1998).

[3] S. W. Hawking, *Hawking on the Big Bang and Black Holes*, World Scientific Publishers, 1993.

[4] L. Infeld, A. Schild, A New Approach to Kinematic Cosmology, *Nature* **156**, 114 (1945).

[5] L. Infeld, A. Schild, A New Approach to Kinematic Cosmology, *Phys. Rev.* **68**, 250 (1945); *Phys. Rev.* **70**, 410 (1945).

[6] L. Infeld, *On the Structure of our Universe* in *Albert Einstein Philosopher — Scientist* Vol. II, ed. P. A. Schlipp, Harper & Brothers Publishers, New York 1949.

[7] M.S. Longair, Modern Cosmology — a Critical Assessment, *Q. J. R. Astr. Soc.* **34**, 157 (1993).

[8] H. Martel, P.R. Shapiro, S. Weinberg, Like values of the cosmological constant, preprint UTTG-01-97 (1997), available as astro-ph9701099.

[9] A.A. Penzias, R.W. Wilson, *Astrophys. J.* **142**, 419 (1965).

[10] A.G. Riess *et al.*, *Astronom. J.* **116**, 1009 (1998).

[11] D.N. Schramm, in *Essays in Nuclear Astrophysics*, eds. C.A. Barnes, D.D. Clayton, D.N. Schramm, Cambridge University Press 1982.

[12] G. A. Tammann, *The Size and the Age of the Universe* in *Relativistic Astrophysics*, eds. B.J.T. Jones, and D. Marković, Cambridge University Press, Cambridge 1997.