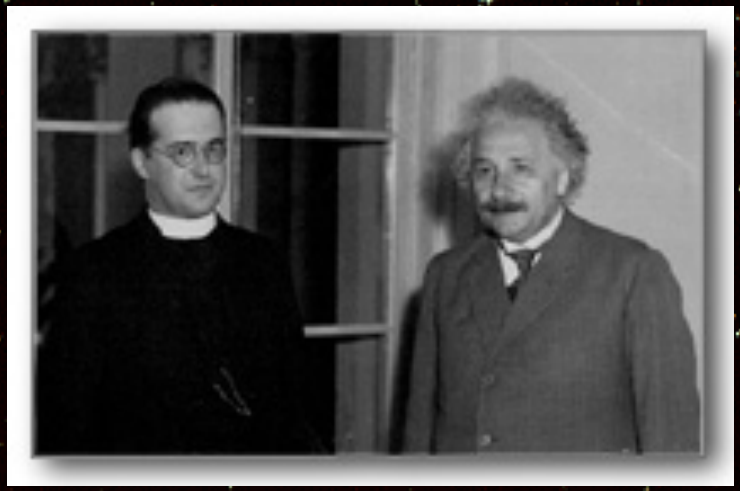
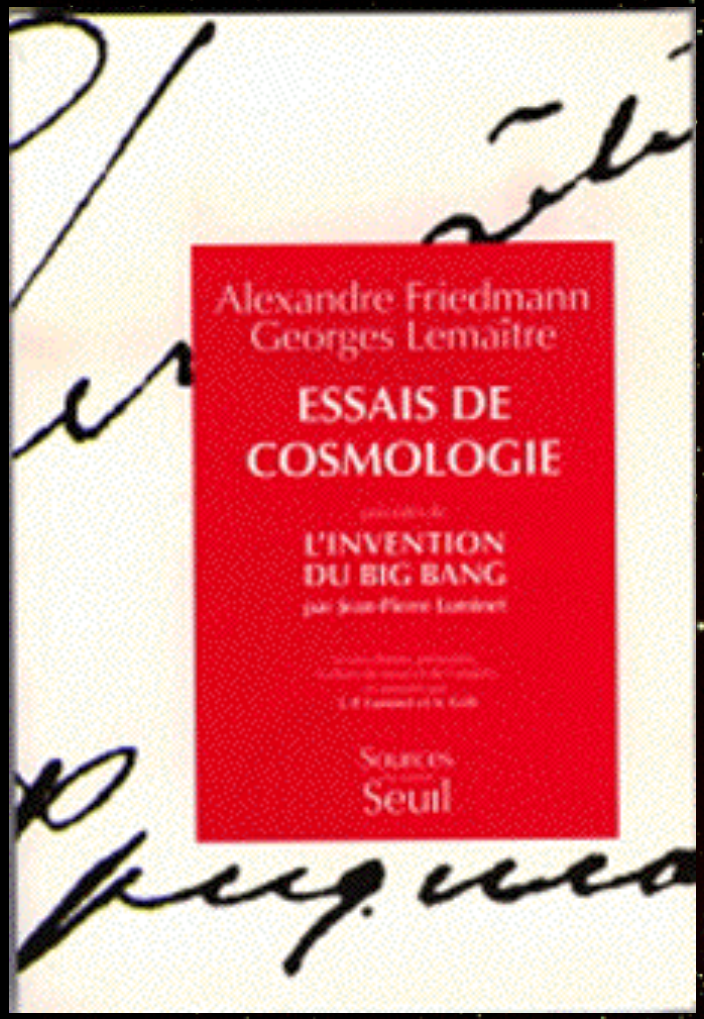
Lemaître's contributions to modern cosmology



J.-P. Luminet – Laboratoire d'Astrophysique de Marseille / Observatoire de Paris)

Symposium 125th Anniversary of Georges Lemaître, Bern 2019



1998

Gen Relativ Gravit (2013) 45:1619–1633
DOI 10.1007/s10714-013-1547-4

GOLDEN OLDIE EDITORIAL

Editorial note to: Georges Lemaître, A homogeneous universe of constant mass and increasing radius accounting for the radial velocity of extra-galactic nebulae

Jean-Pierre Luminet

Published online: 13 June 2013
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Keywords Expanding Universe · Generalised Friedmann models · Georges Lemaître · Golden Oldie

1 Introduction

As already pointed out in a previous Golden Oldie devoted to the Lemaître's short note of 1931 which can be considered as the true "Charter" of the modern big bang theory [1], although the Belgian scientist was primarily a remarkable mathematician and a theoretical physicist, he stayed closely related to astronomy all his life and always felt the absolute need for confronting the observational data and the general relativity theory. This basic fact explains why as soon as 1927, while still a beginner in cosmology, he was the first one to be able to understand the recent observations on the recession velocities of galaxies as a natural consequence of *dynamical* cosmological solutions of Einstein's field equations.[1] Before examining in detail the contents of his outstanding article, let us summarize the road which, in the few preceding years, led the young Lemaître to the expanding universe (see e.g. [6]).

In 1923, the same year as he was ordained as a priest, Georges Lemaître obtained a 3-year fellowship from the Belgian government, enabling him to study abroad.

[1] A number of other authors such as Hermann Weyl [2], Carl Wirtz [3], Ludwig Silberstein [4], Knut Lundmark [5] had looked for a relation that fit into the context of De Sitter's static model which presented *spurious* radial velocities.

The republication of the original paper can be found in this issue following the editorial note and online via doi:10.1007/s10714-013-1548-3.

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Gen Relativ Gravit (2011) 43:2911–2928
DOI 10.1007/s10714-011-1213-7

GOLDEN OLDIE EDITORIAL

Editorial note to: Georges Lemaître, The beginning of the world from the point of view of quantum theory

Jean-Pierre Luminet

Published online: 16 July 2011
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Keywords Beginning of the universe · Evolution of the universe · Georges Lemaître · Quantum birth of the universe · Primeval-atom model · Golden Oldie

The year 1931 can undoubtedly be called Georges Lemaître's *annus mirabilis*. Indeed, major contributions to relativistic cosmology by the Belgian physicist and priest appeared within a few months:

(a) *A homogeneous universe of constant mass and increasing radius accounting for the radial velocity of extra-galactic nebulae* [1] in the March 7 issue of the *Monthly Notices of the Royal Astronomical Society*, as an English translation of the article published four years earlier in French [2], in which Lemaître was the first to interpret the astronomical data about the galaxy redshifts by a positively curved space model in which the universe slowly expanded from an equilibrium Einstein state at $t = -\infty$,

(b) *The expanding universe* [3],[1] just following the previous one in the same *M.N.R.A.S.* issue, in which Lemaître calculated that the expansion of space could be induced by a preceding phase of "stagnation" taking place about 10^{10} years in the past,

[1] Not to be confused with *L'Univers en expansion*, reproduced as a Golden Oldie as *The expanding Universe* [4].

This Golden Oldie Editorial forms a unit with the Golden Oldie republication of a paper by G. Lemaître that can be found in this issue following the editorial note and online via doi:10.1007/s10714-011-1214-6.

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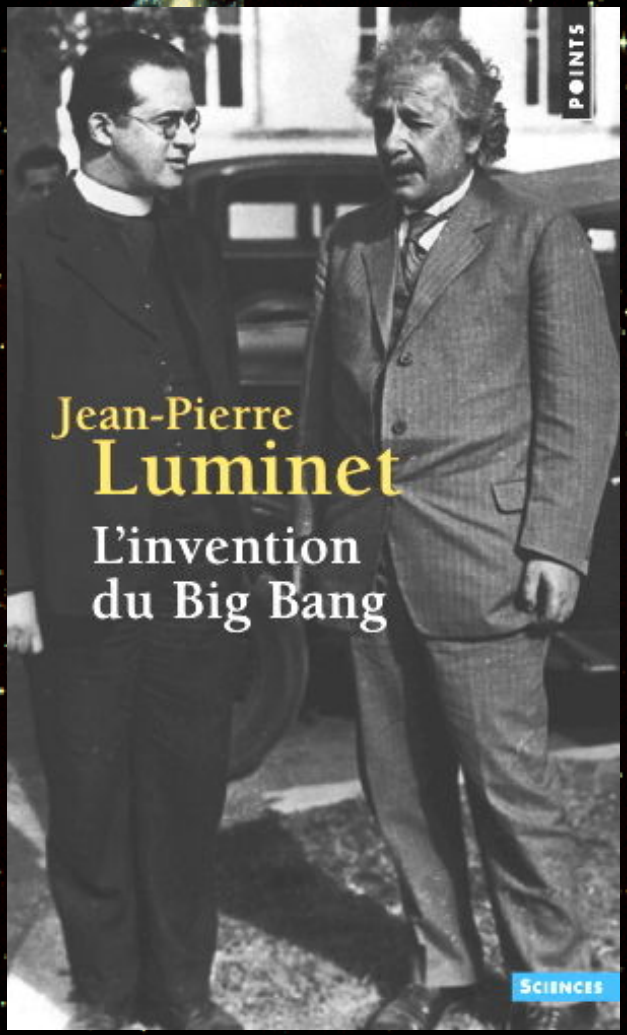


2004

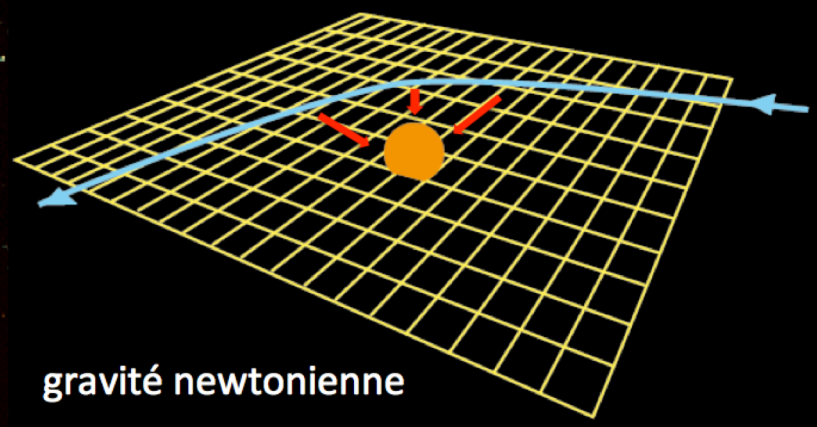
A new gravitational theory

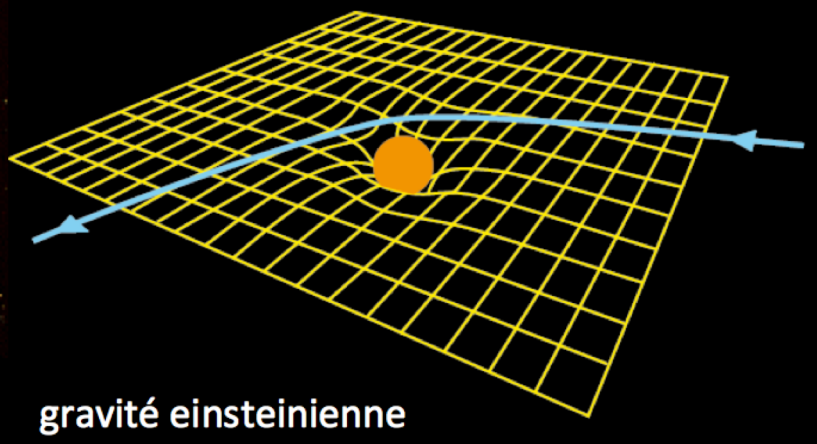
November 1915 :

Einstein and Hilbert give correct field equations for General Relativty (without c.c.)

$$G_{ij} = k\, T_{ij}$$

geometry ⇔ matter-energy





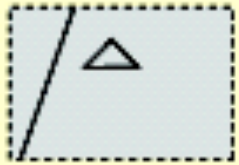
Cosmological Solutions:

Homogeneity

& Isotropy

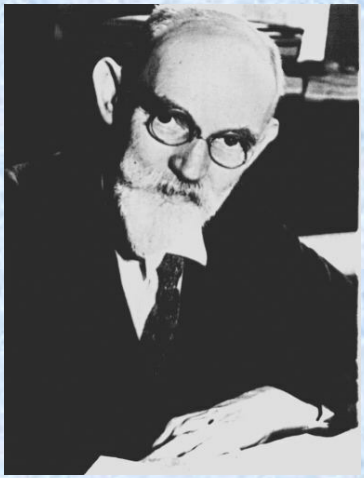
➔

Uniform Space Curvature

Curvature	Topology
k=+1  Spherical Space	finite (no edge)
k=0  Euclidian Space	finite or infinite (multi-connected)
k=-1  Hyperbolic Space	finite or infinite (multi-connected)

1917 : Einstein derives the first relativistic cosmological model

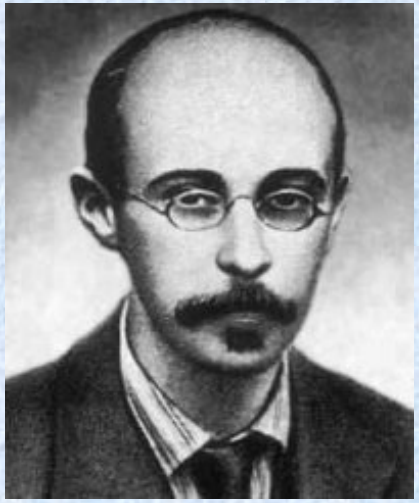
- Curvature : +1
- Matter : ρ = constant
- **Static model =>** $G_{ij} + \square\square g_{ij} = k\, T_{ij}$
- Cosmological constant : $\lambda_E = 1 / R^2$



1917 : De Sitter derives another relativistic cosmological model

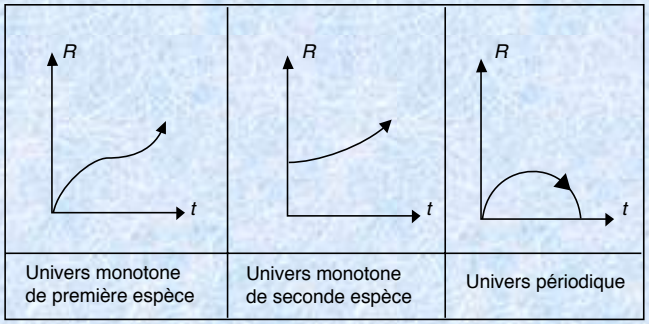
- Curvature : +1
- Matter : $\rho = 0$ (empty space)
- Cosmological constant : $\lambda = 3/R^2$
- **Static model**

But the cosmological constant induces accelerated separation of worldlines : $d \propto \exp(\lambda/3)^{1/2}\, t$



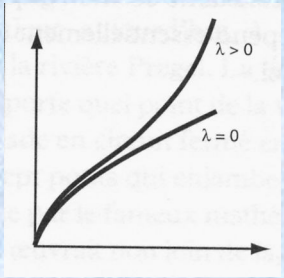
1922 : Friedmann derives the first dynamical solutions of cosmological equations

Curvature : +1
Matter : ρ(t) variable, p = 0
Cosmological constant :
0 or λ



1924 : On the possibility of a world with constant negative curvature

Curvature : –1
Matter : ρ(t) variable, p = 0
Cosmological constant : 0 or λ
Perpetual expansion (open model)
First discussion on cosmic topology



1925 : accidental death of Friedmann

EINSTEIN RESISTS…

- **1922 : Einstein,** ***Note on A. Friedmann's work:***

The results concerning the non-stationary world, contained in [Friedmann's] work, appear to me suspicious. In reality it turns out that the solution given in it does not satisfy the field equations

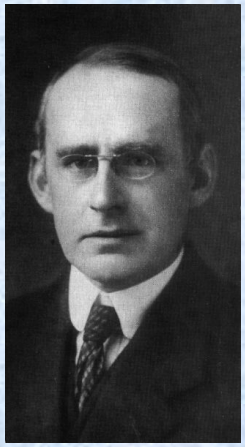
- **1923 : Einstein,** ***Note on A. Friedmann's work:***

In my previous note I criticised [Friedmann's work On the curvature of Space]. However, my criticism, as I became convinced by Friedmann's letter communicated to me by Mr Krutkov, was based on an error in my calculations. I consider that Mr Friedmann's results are correct and shed new light. They show that the field equations admit, for the structure of spherically symmetric space, in addition to static solutions, dynamical solutions.»

Manuscript's last sentence suppressed : « *…**to which it is hardly possible to give a physical meaning*** ».

WHAT ABOUT ASTRONOMICAL OBSERVATIONS ?

- 1923 : Slipher has measured 41 spectral shifts with 36 redshifs. HE DOES NOT PUBLISH HIS RESULTS !
- 1924 : Eddington reproduces Slipher's results in his book *Mathematical theory of Relativity*



additional nebula N.G.C. 1[illegible] has been observed by Pease, who found a large receding velocity but gave no numerical estimate.

RADIAL VELOCITIES OF SPIRAL NEBULAE

+ indicates receding, − approaching

N.G.C.	R.A. h m	Dec. ° ′	Rad. Vel. km. per sec.	N.G.C.	R.A. h m	Dec. ° ′	Rad. Vel. km. per sec
221	0 38	+40 26	− 300	4151*	12 6	+39 51	+ 980
224*	0 38	+40 50	− 300	4214	12 12	+36 46	+ 300
278†	0 47	+47 7	+ 650	4258	12 15	+47 45	+ 500
404	1 5	+35 17	− 25	4382†	12 21	+18 38	+ 500
584†	1 27	− 7 17	+1800	4449	12 24	+44 32	+ 200
598*	1 29	+30 15	− 260	4472	12 25	+ 8 27	+ 850
936	2 24	− 1 31	+1300	4486†	12 27	+12 50	+ 800
1023	2 35	+38 43	+ 300	4526	12 30	+ 8 9	+ 580
1068*	2 39	− 0 21	+1120	4565†	12 32	+26 26	+1100
2683	8 48	+33 43	+ 400	4594*	12 36	−11 11	+1100
2841†	9 16	+51 19	+ 600	4649	12 40	+12 0	+1090
3031	9 49	+69 27	− 30	4736	12 47	+41 33	+ 290
3034	9 49	+70 5	+ 290	4826	12 53	+22 7	+ 150
3115†	10 1	− 7 29	+ 600	5005	13 7	+37 29	+ 900
3368	10 42	+12 14	+ 940	5055	13 12	+42 37	+ 450
3379*	10 43	+13 9	+ 780	5194	13 26	+47 36	+ 270
3489†	10 56	+14 20	+ 600	5195†	13 27	+47 41	+ 240
3521	11 2	+ 0 24	+ 730	5236†	13 32	−29 27	+ 500
3623	11 15	+13 32	+ 800	5866	15 4	+56 4	+ 650
3627	11 16	+13 26	+ 650	7331	22 33	+33 23	+ 500
4111†	12 3	+43 31	+ 800				

The great preponderance of positive (receding) velocities is very striking; but the lack of observations of southern nebulae is unfortunate, and forbids a final conclusion. [illegible]

« One of the most perplexing problems in cosmogony is the great speed of spiral nebulae. Their radial velocities average about 600 km. per sec. and there is a great preponderance of velocities of recession from the solar system »

➔ He advocates for the De Sitter solution

G. Lemaître : « Un univers homogène de masse constante et de rayon croissant, rendant compte de la vitesse radiale des nébuleuses extragalactiques » *(Ann. Soc. Sci. Bruxelles, 1927)*

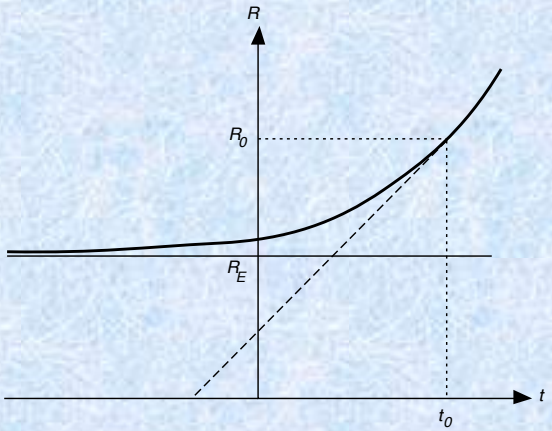
Curvature : +1

Matter : ρ(t), p (t) variable

Cosmological Constant : λ_E

Dynamics : accelerated perpetual expansion

The cosmological constant is adjusted such as *R(t)* grows from the radius of the Einstein's static hypersphere at $t = -\infty$. There is no past singularity and no « age problem ».

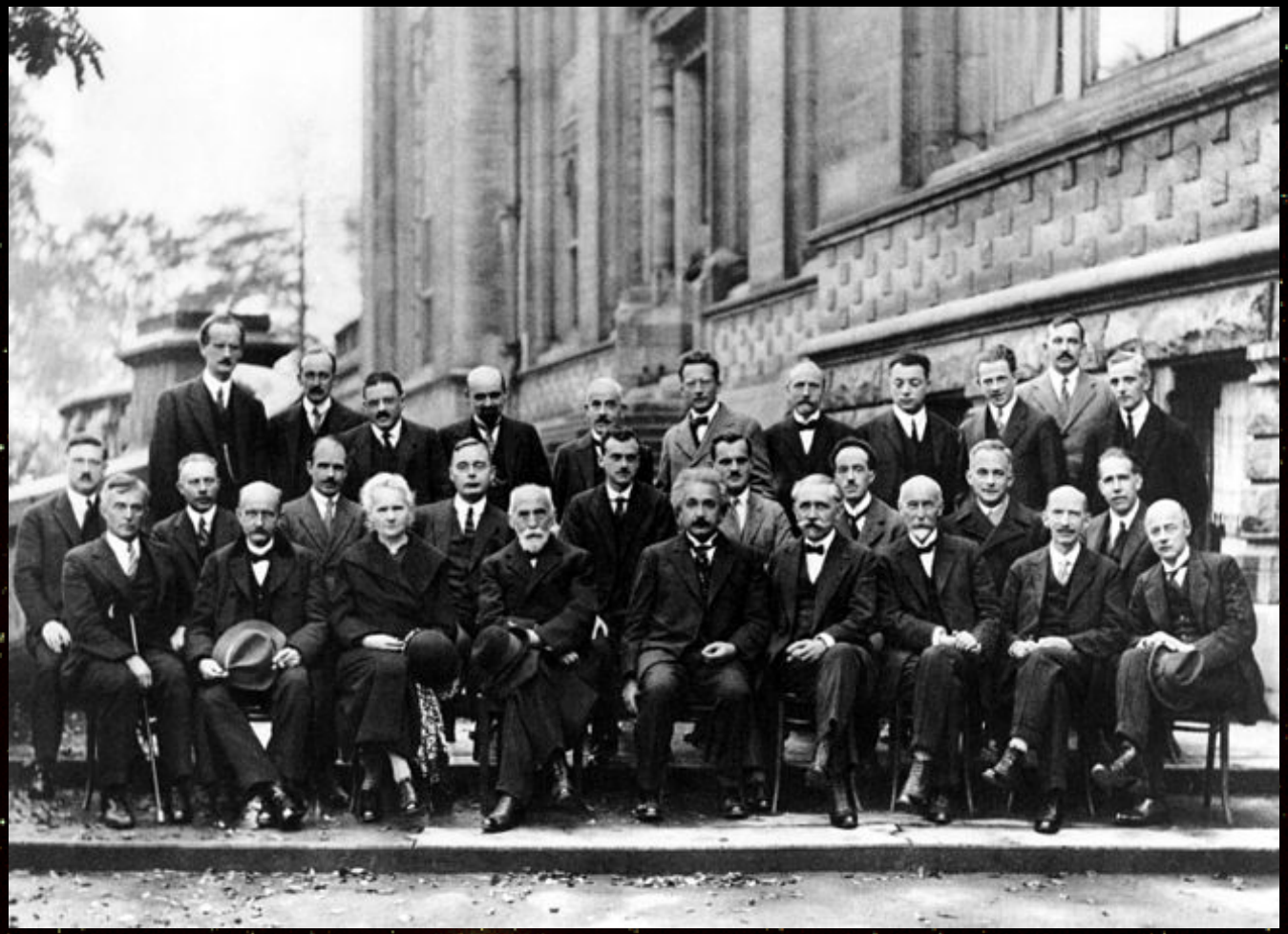


- First interpretation of redshifts in terms of space expansion.

« Hubble » law!

« Utilisant les 42 nébuleuses extra-galactiques figurant dans les listes de Hubble et de Strömberg, et tenant compte de la vitesse propre du Soleil, on trouve une distance moyenne de 0,95 millions de parsecs et une vitesse radiale de 600 km/s, soit 625 km/s à 10^6 parsecs. Nous adopterons donc $R'/R = v/rc = 0{,}68\times10^{-27}$ cm^{-1} (Eq. 24) »

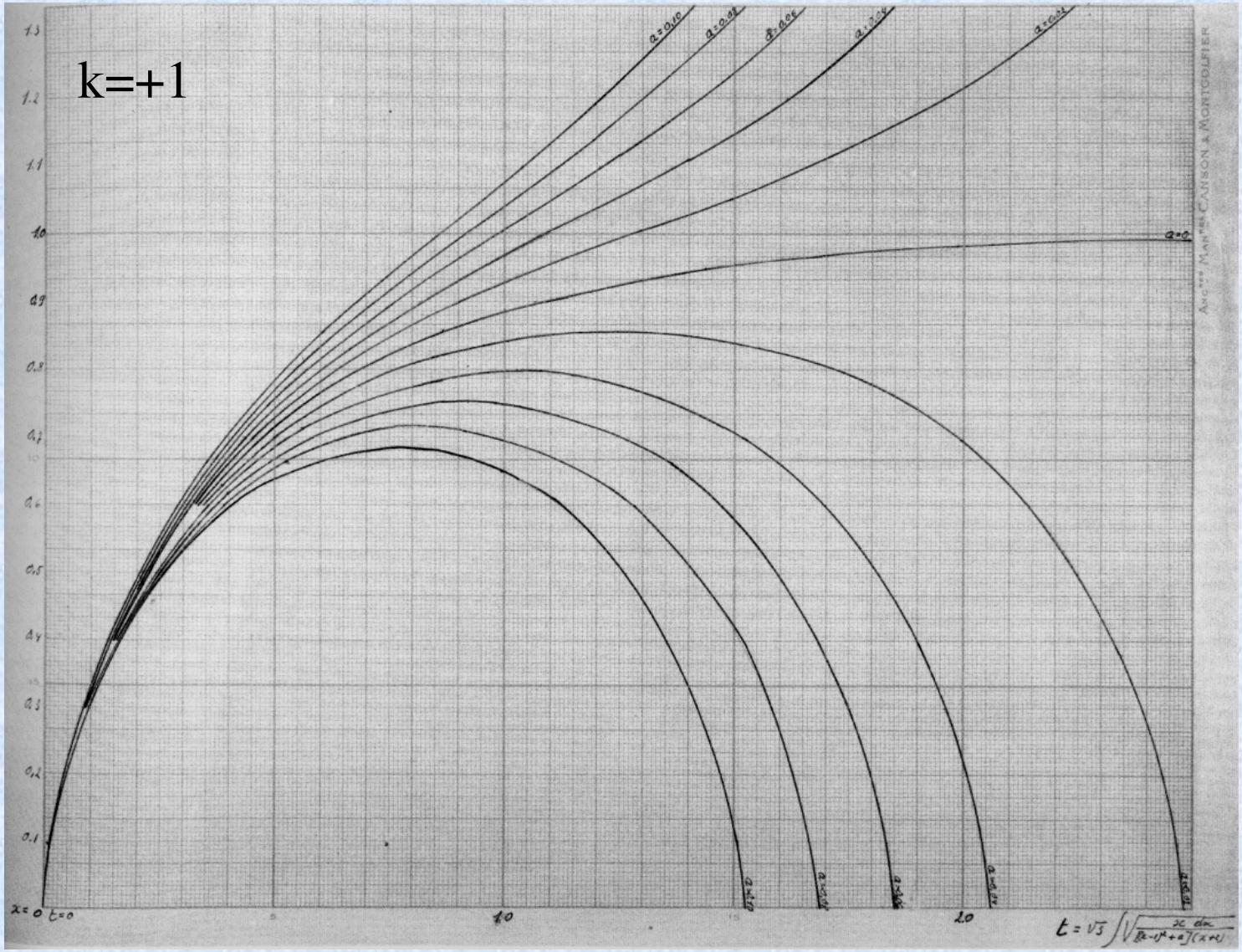
Detailed analysis : J.-P. L., « Golden Oldie »CQG (2013) [arXiv :1305.6470]



- 1927 : First meeting Einstein - Lemaître (Solvay conference) :

« Your calculations are correct, but your physical insight is quite ugly »

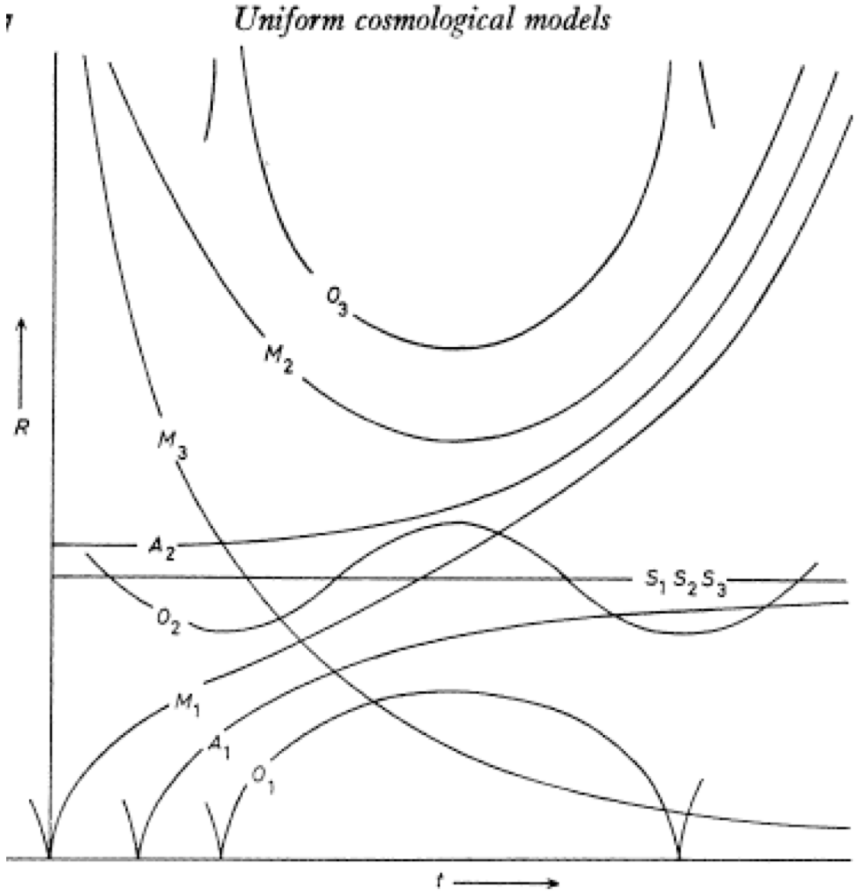
The Lemaître's graphics (between 1927 and 1931)



Archives G. Lemaître, Louvain

H.P. Robertson : On the Foundations of Relativistic Cosmology *Proc. Nat. Acad. Sci., vol. 15, n° 11, 1929*

Full classification of Homogeneous and Isotropic Models



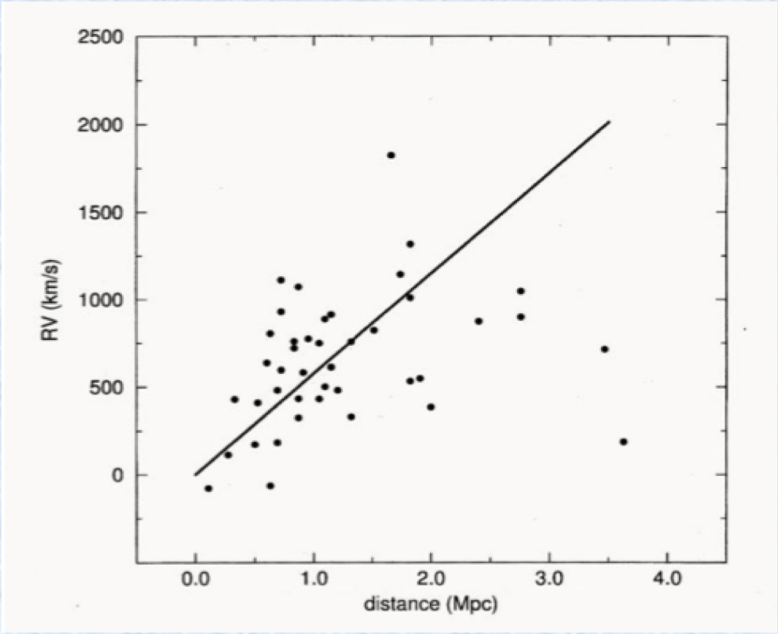
$$ds^2 = -c^2dt^2 + R^2(t)\left[d\chi^2 + f^2(\chi)(d\theta^2 + \sin^2\theta d\varphi^2)\right],$$

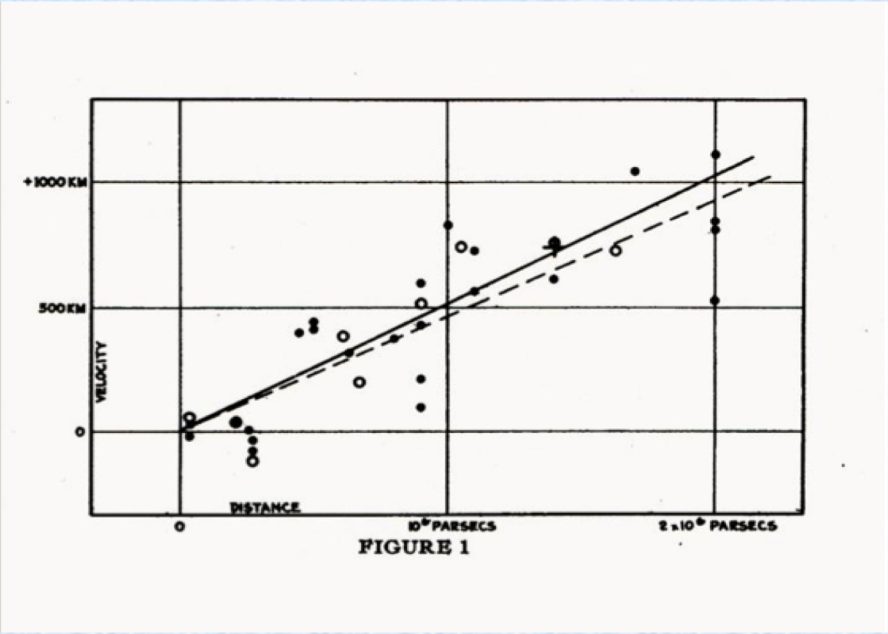
où $r \equiv f(\chi) = \begin{cases} \sin\chi & (\text{si } k = +1), \\ \chi & (\text{si } k = 0), \\ sh\chi & (\text{si } k = -1). \end{cases}$

+ Walker 1936 ⇨ **RW models, FRW models, FLRW models !**

- 1929 : Hubble publishes experimental data showing a linear velocity-distance relation $v = Hr$ from a sample of 24 redshifts (20 measured by Slipher and 4 by Humason).

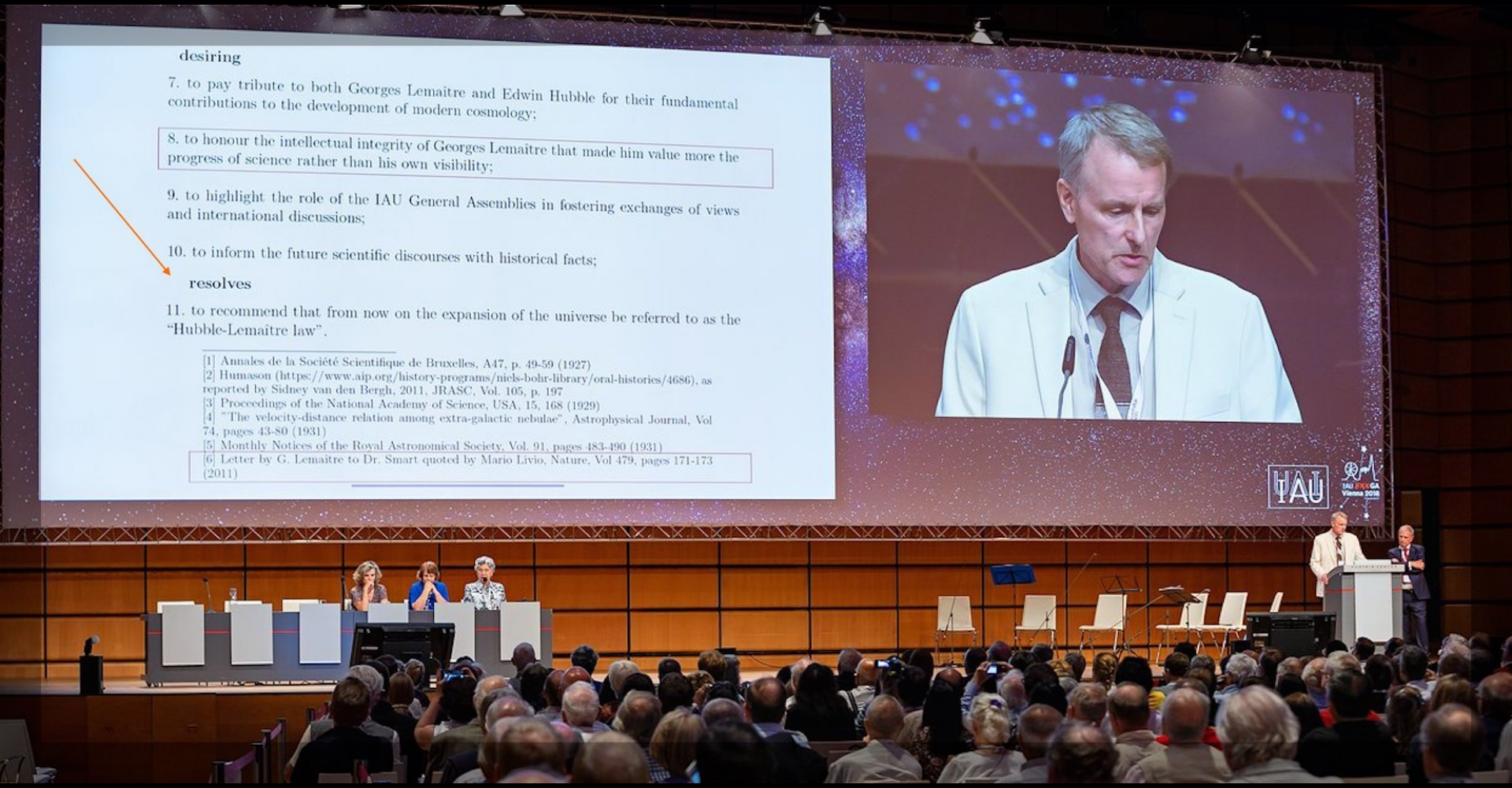
He does not mention any link with expanding universe models.





Lemaître 1927, H=575 km/s/Mpc

Hubble 1929, H=530 km/s/Mpc



IAU Resolution (2018) : Hubble-Lemaître's Law !

• 1930 : Eddington proves the instability of Einstein's static universe and calls for new searches to explain the recession velocities in terms on dynamical space model

• 1930 : Lemaître writes to Eddington : « Dear Prof. Eddington, I made these investigations two years ago […] »

• 1930 : Eddington adopts the 1927 Lemaître's model of expanding space.

• 1931 : Eddington recommends the English translation of the 1927 Lemaître's article for M.N.R.A.S.

BUT :

période de la lumière reçue et δt_1 peut encore être considéré comme la période d'une lumière émise dans les mêmes conditions dans le voisinage de l'observateur. En effet, la période de la lumière émise dans des conditions physiques semblables doit être partout la même lorsqu'elle est exprimée en temps propre.

$$\frac{v}{c} = \frac{\delta t_2}{\delta t_1} - 1 = \frac{R_2}{R_1} - 1 \qquad (22)$$

mesure donc l'effet Doppler apparent dû à la variation du rayon de l'univers. *Il est égal à l'excès sur l'unité du rapport des rayons de l'univers à l'instant où la lumière est reçue et à l'instant où elle est émise.* v est la vitesse de l'observateur qui produirait le même effet. Lorsque la source est suffisamment proche nous pouvons écrire approximativement

$$\frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R}\,dt = \frac{R'}{R}\,r$$

où r est la distance de la source. Nous avons donc

$$\frac{R'}{R} = \frac{v}{cr} \qquad (23)$$

Les vitesses radiales de 43 nébuleuses extra-galactiques sont données par Strömberg (1).

La grandeur apparente m de ces nébuleuses se trouve dans le travail de Hubble. Il est possible d'en déduire leur distance, car Hubble a montré que les nébuleuses extra-galactiques sont de grandeurs absolues sensiblement égales (grandeur — 15,2 à 10 parsecs, les écarts individuels pouvant atteindre deux grandeurs en plus ou en moins), la distance r exprimée en parsecs est alors donnée par la formule $\log r = 0{,}2m + 4{,}04$.

On trouve une distance de l'ordre de 10^6 parsecs, variant de quelques dixièmes à 3,3 millions de parsecs. L'erreur probable résultant de la dispersion en grandeur absolue est d'ailleurs considérable. Pour une différence de grandeur absolue de deux grandeurs en plus ou en moins, la distance passe de 0,4 à 2,5 fois la distance calculée. De plus, l'erreur à craindre est proportionnelle à la distance. On peut admettre que pour une distance d'un million de parsecs, l'erreur résultant de la dispersion en grandeur est du même ordre que celle résultant de la dispersion en vitesse. En effet, une différence d'éclat d'une grandeur correspond à une vitesse propre de 300 Km. égale à la vitesse propre du soleil par rapport aux nébuleuses. On peut espérer éviter une erreur systématique en donnant aux observations un poids proportionnel à $\frac{1}{\sqrt{1+r^2}}$, où r est la distance en millions de parsecs.

(1) Analysis of radial velocities of globular clusters and non galactic nebulae. *Ap. J.* Vol. 61, p. 353, 1925. *Mt Wilson Contr.* N° 292.

Utilisant les 42 nébuleuses figurant dans les listes de Hubble et de Strömberg (1), et tenant compte de la vitesse propre du soleil (300 Km. dans la direction $\alpha = 315°$, $\delta = 62°$), on trouve une distance moyenne de 0,95 millions de parsecs et une vitesse radiale de 600 Km./sec, soit 625 Km./sec à 10^6 parsecs (2).

Nous adopterons donc

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3{,}08 \times 10^{18} \times 3 \times 10^{10}} = 0{,}68 \times 10^{-27}\ \mathrm{cm}^{-1} \qquad (24)$$

Cette relation nous permet de calculer R_o. Nous avons en effet par (16)

$$\frac{R'}{R} = \frac{1}{R_o\sqrt{3}}\sqrt{1 - 3y^2 + 2y^3} \qquad (25)$$

où nous avons posé

$$y = \frac{R_o}{R} \qquad (26)$$

D'autre part, d'après (18) et (26),

$$R_o^2 = R_E^2\, y^3 \qquad (27)$$

et donc

$$3\left(\frac{R'}{R}\right)^2 R_K^2 = \frac{1 - 3y^2 + 2y^3}{y^3} \qquad (28)$$

Introduisant les valeurs numériques de $\frac{R'}{R}$ (24) et de R_E (19), il vient :

$$y = 0{,}0465.$$

On a alors :

$$R = R_E\sqrt{y} = 0{,}215\ R_E = 1{,}83 \times 10^{28}\ \mathrm{cm.} = 6 \times 10^9\ \mathrm{parsecs}$$

$$R_o = Ry = R_E\, y^{\frac{3}{2}} = 8{,}5 \times 10^{26}\ \mathrm{cm.} = 2{,}7 \times 10^8\ \mathrm{parsecs}$$

$$= 9 \times 10^8\ \text{années de lumière.}$$

(1) Il n'est pas tenu compte de N. G. C. 5194 qui est associé à N. G. C. 5195. L'introduction des nuées de Magellan serait sans influence sur le résultat.

(2) En ne donnant pas de poids aux observations, on trouverait 670 Km./sec à $1{,}16 \times 10^6$ parsecs, 575 Km./sec à 10^6 parsecs. Certains auteurs ont cherché à mettre en évidence la relation entre v et r et n'ont obtenu qu'une très faible corrélation entre ces deux grandeurs. L'erreur dans la détermination des distances individuelles est du même ordre de grandeur que l'intervalle que couvrent les observations et la vitesse propre des nébuleuses (en toute direction) est grande (300 Km./sec. d'après Strömberg), il semble donc que ces résultats négatifs ne sont ni pour ni contre l'interprétation relativistique de l'effet Doppler. Tout ce que l'imprécision des observations permet de faire est de supposer v proportionnel à r et d'essayer d'éviter une erreur systématique dans la détermination du rapport v/r. Cf. LUNDMARK. The determination of the curvature of space time in de Sitter's world M. N., vol. 84, p. 747, 1924, et STRÖMBERG, *l. c.*

REPLACED BY :

« From a discussion of available data, we adopt
$R'/R = 0{,}68 \times 10^{-27}\ cm^{-1}$ *(Eq. 24) »*


1931 TRANSLATED ARTICLE OF G. LEMAÎTRE
WHY THEY OMITTED CRUCIAL PARTS OF ARTICLE FROM TRANSLATION?

W. Smart (M.N.R.A.S. editor) to Lemaître

Observatory,
Cambridge

TELEGRAMS: "URANOMETRY, LONDON."
TELEPHONE: GERRARD 2982.

ROYAL ASTRONOMICAL SOCIETY,
BURLINGTON HOUSE,
LONDON, W.1.

17 February 1931

Dear Dr. Lemaître,

At the R.A.S. Council meeting last Friday it was resolved to ask you if you would allow your paper "Un Univers homogène ...." in the Annales de la Soc. Sci. de Bruxelles to be reprinted in the Monthly Notices. It has been felt that it has not circulated as widely — or isn't as well known — as its importance warrants — especially in English speaking countries. This request of the Council is almost unique in the Society's annals and it shows you how much the Society would appreciate the honour of giving your paper a greater publicity amongst English speaking Scientists.

Briefly — if the Soc. Scientifique de Bruxelles is also willing to give its permission — we should prefer the paper translated into English. Also, if you have any further additions etc on the subject, we would glad print these too. I suppose that if there were additions a note could be inserted to the effect that §§1—n are substantially from the Brussels paper & the remainder is new (or something more elegant). Personally and also on behalf of the Society I hope that you will be able to do this.

By the way, you are not a fellow of the Society: if you would like to become a Fellow, would you let me know and Eddington & I will sign your nomination paper. In case you are ignorant of the fees etc, the annual subscription is £2-2-0 with an entrance ~~fee~~ fee of the same amount.

With kind Regards,

Sincerely yours

W. M. Smart.

Mario Livio : *Mystery of the missing text solved*, Nature, 10 November 2011

« I send you a translation of the paper. I did not find advisable to reprint the provisional discussion of radial velocities which is clearly of no actual interest, and also the geometrical one, which could be replaced by a small bibliography of ancient and new papers on the subject. »

(Letter of Lemaître to W. Smart, 9 march 1931)

Detailes list of Discrepancies and commentaries:
J.-P. L., CQG (2013) [arXiv :1305.6470]

W. Smart (M.N.R.A.S. editor) to Lemaître

Observatory,
Cambridge

TELEGRAMS: "URANOMETRY, LONDON."
TELEPHONE: GERRARD 2982.

ROYAL ASTRONOMICAL SOCIETY,
BURLINGTON HOUSE,
LONDON, W.1.

17 February 1931

Dear Dr. Lemaître,

At the R.A.S. Council meeting last Friday it was resolved to ask you if you would allow your paper "Un Univers homogène ...." in the Annales de la Soc. Sci. de Bruxelles to be reprinted in the Monthly Notices. It has been felt that it has not circulated as widely — or isn't as well known — as its importance warrants — especially in English speaking countries. This request of the Council is almost unique in the Society's annals and it shows you how much the Society would appreciate the honour of giving your paper a greater publicity amongst English speaking Scientists.

Briefly — if the Soc. Scientifique de Bruxelles is also willing to give its permission — we should prefer the paper translated into English. Also, if you have any further additions etc on the subject, we would gladly print these too. I suppose that if there were additions a note could be inserted to the effect that §§1–7 are substantially from the Brussels paper & the remainder is new (or something more elegant). Personally and also on behalf of the Society I hope that you will be able to do this.

By the way, you are not a Fellow of the Society: if you would like to become a Fellow, would you let me know and Eddington & I will sign your nomination paper. In case you are ignorant of the fees etc, the annual subscription is £2-2-0 with an entrance ~~fee~~ fee of the same amount.

With kind Regards,

Sincerely yours

W. M. Smart.

G. Lemaître : « The Expanding Universe »

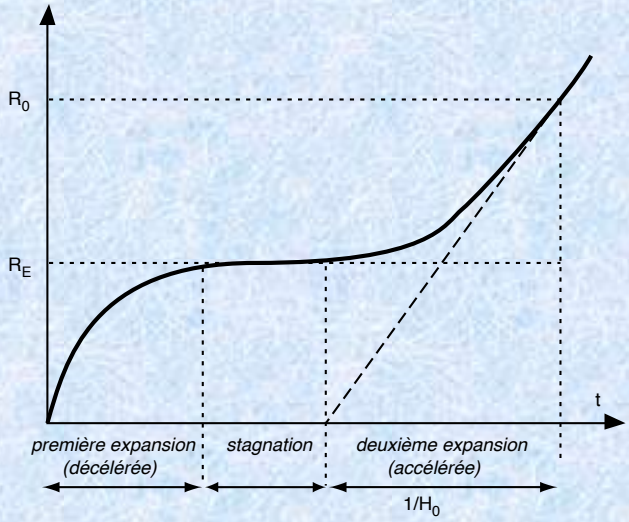
(M.N.R.A.S., march 1931)

Curvature : +1

Matter : ρ(t), p (t) variable

Cosmological constant : $\lambda > \lambda_E$

Dynamics : **perpetual expansion, initially decelerated, then accelerated**



Starting from a singularity, the Universe first expands, then passes through a phase of « stagnation » during which its radius coasts that of the Einstein's static solution, then starts again in accelerated expansion. This « hesitating model » **solves the age problem** and provides enough time to **form galaxies**.

« *The evolution of the world can be compared to a display of fireworks that has just ended : some few red wisps, ashes and smoke. Standing on a well-chilled cinder, we see the slow fading of suns, and we try to recall the vanishing brtilliance of the origin of the worlds.*

- Introduces the **Primeval Atom**

Some negative reactions …

Einstein : « *This recalls too much the dogma of Creation* »

Eddington : « *The notion of a beginning of the world is repugnant to me* »

However abbé Lemaître :

- *beginning (physical) ≠ creation (metaphysical)*
- *« The cosmological theory remains completely out of any metaphysical or religious question. »*
- *science and religion correspond to separate levels of understanding*

G. Lemaître : The quantum birth of the Universe

(« The beginning of the world from the point of view of quantum theory », Nature, 1931)

Eddington : « *The notion of a beginning of the world is repugnant to me* »

« In atomic processes, the notions of space and time are no more than statistical notions : they fade out when applied to individual phenomena involving but a small number of quanta. If the world has begun with a single quantum, the notions of space and time would altogether fail to have any sense at the beginning and would only begin to get some sensible meaning when the original quantum would have been divided in a sufficient number of quanta. If this suggestion is correct, the beginning of the world happened a little before the beginning of space and time. Such a beginning of the world is far enough from the present order of nature to be not at all repugnant. »

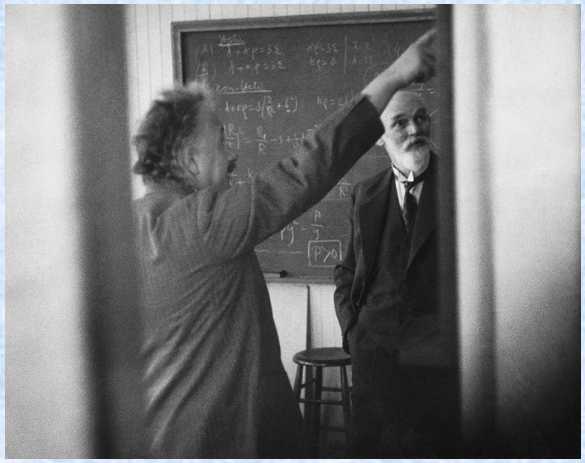
Detailed analysis : J.-P. L., « Golden Oldie » CQG (2011) [arXiv :1105.6271]

The « Hidden God » of Lemaître

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

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

Einstein - de Sitter : « On the Relation between the Expansion and the Mean Density of the Universe » *(1932)*



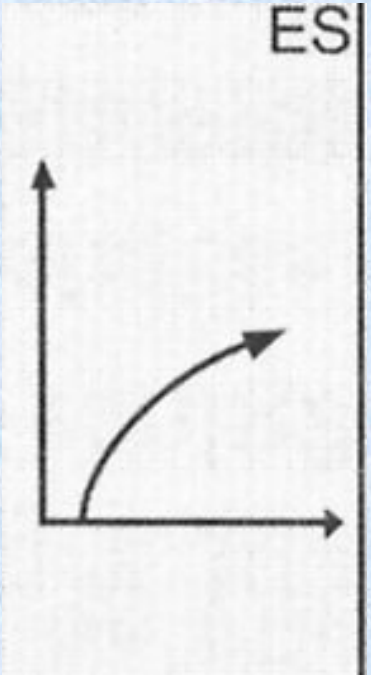
Curvature : 0

Matter : $\rho(t)$ variable, $p = 0$

Cosmological constant : 0

Dynamics : decelerated perpetual expansion

Over-simplified solution ==> « standard model » for the next 60 years. Reinforced in the 1980's by inflationary models (which predict flat universe). Now rejected (predicted age of the Universe too short, preponderance of dark energy).



☺ Needs (implicitly) dark matter

☹ No reference to Friedmann and Lemaître!

Einstein - Lemaître Discussions (1932-1934)

- Einstein considers the primeval atom hypothesis *« inspired by the Christian dogma of creation, and totally unjustified from the physical point of view »* (Pasadena, 1932)

- Einstein rejects the cosmological constant (Einstein : « *my greatest blunder* »; Lemaître : « *your greatest discovery!* »)
- Einstein gives up research in cosmology (1934)
- Einstein however supports Lemaître for the Franqui prize (1934)

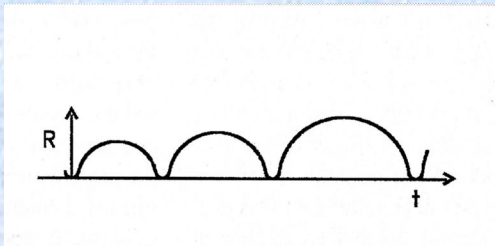
G. Lemaître : « L'univers en expansion »

Annales de la Société Scientifique de Bruxelles (1932)

- Proves that the Schwarzschild surface $r = 2GM/c^2$ is a fictitious singularity (by introducing the later called « Eddington-Finkelstein » coordinates!)

- Proves the unavoidable occurrence of singularities in general relativity if no quantum corrections (« later called Hawking-Penrose theorems »)

- Proves the non-viability of « phenix universes »



- Settles down the first models of galaxy formation

The Lemaître-Tolman-Bondi Metric :

Spherically symmetric dust solution with radial inhomogeneities

Lemaître, Ann. Soc. Sci. Bruxelles (1933).
Tolman, Proc. Nat. Acad. Sci. USA (1934)
Bondi, M.N.R.A.S. (1947)

- Schwarzschild and Friedmann-Lemaître solutions are special cases

- Could dark energy be a misidentification of gradients in local gravitational energy in LTB universe?
Buchert et al. (2016)

G. Lemaître : « Evolution of the expanding universe »

Proc. Nat. Acad. Sci. USA (1934)

- Suggestion of a cosmic radiation relics

« If all the atoms of the stars were equally distributed through space there would be about one atom per cubic yard, or the total energy would be that of an equilibrium radiation at the temperature of liquid hydrogen. »

- The cosmological constant as vacuum energy

« The theory of relativity suggests that, when we identify gravitational mass and energy, we have to introduce a constant. Everything happens as though the energy in vacuo would be different from zero. In order that motion relative to vacuum may not be detected, ***we must associate a pressure*** $p = -\rho c^2$ ***to the density of energy*** ρc^2 ***of vacuum***. *This is essentially the meaning of the cosmological constant* λ *which corresponds to a negative density of vacuum* ρ_0 *according to* $\rho_0 = \lambda c^2 / 4\pi G \cong 10^{-27}\, gr./cm.^3$

(later: Zeldovich, 1967)


Merci