Seven Pines Symposium XIX
"General Relativity; a hundred years after its birth"
13–17 May 2015

The Low Watermark of General Relativity, a Theory Ahead of its Time.

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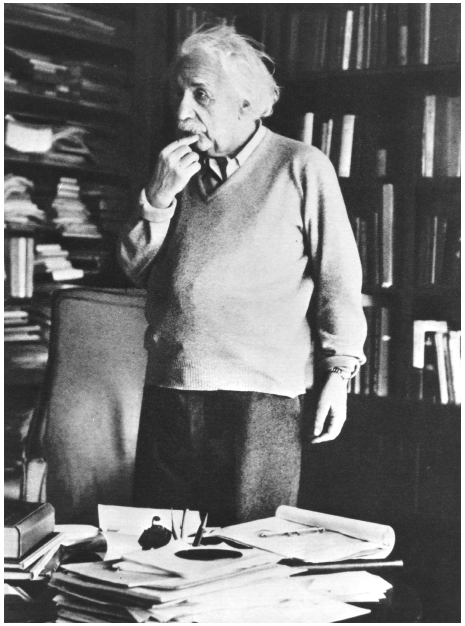
Jean Eisenstaedt (Observatoire de Paris)

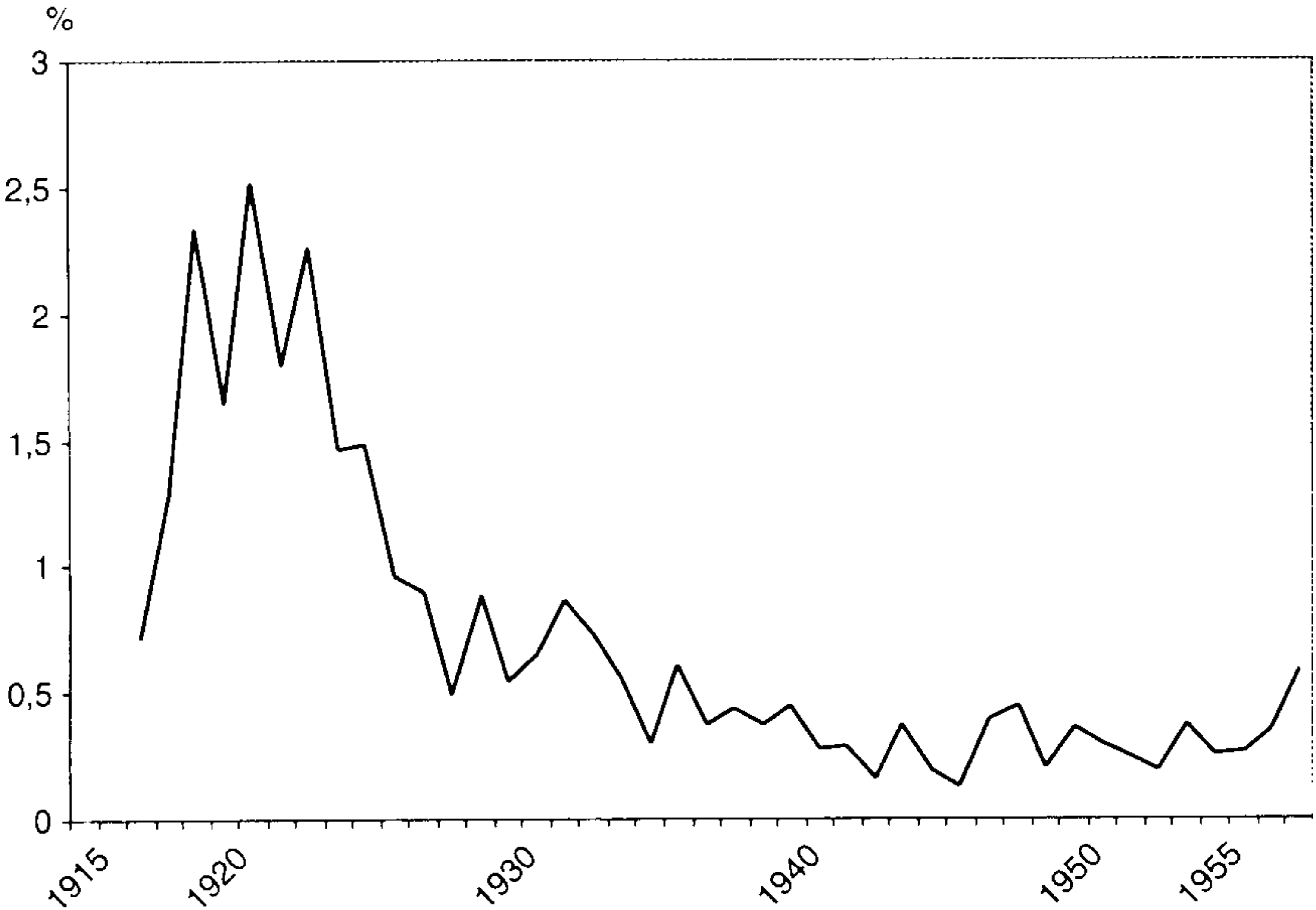


Albert Einstein 1954

- 1955, Bern. A congress organized for the fifty years of special relativity. Actually general relativity is at stake. Einstein died some monthes ago. Max Born, Einstein's close friend, recalls...

- "I remember that on my honeymoon in 1913 I had in my luggage some reprints of Einstein's papers which absorbed my attention for hours, much to the annoyance of my bride. These papers seemed to me fascinating, but difficult and almost frightening. When I met Einstein in Berlin in 1915 the theory was much improved and crowned by the explanation of the anomaly of the perihelion of Mertisy, discovered by Leverrier. I learned it not only from the publications but from numerous discussions with Einstein, - which had the effect that I decided never to attempt any work in this field. The foundation of general relativity appeared to me then, and it still does, the greatest feat of human thinking about Nature, the most amazing combination of philosophical penetration, physical intuition and mathematical skill. But its connections with experience were slender. It appealed to me like a great work of art, to be enjoyed and admired from a distance. "

Max Born, Bern's Colloquium, 1955.



Number of publications in general relativity
as a percentage of the total number of publication in physics (from Science Abstract:1915–1955).
N.B. The absolute number of pubications goes from 10 in 1916 to 42 (greatest) in 1920; 4 in 1945 (lowest).

From Special to General Relativity.

Lorentz, Einstein, Poincaré.

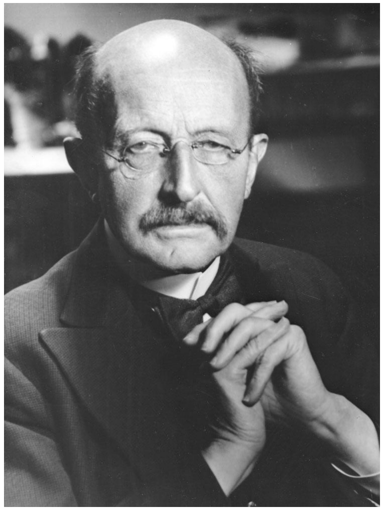
Einstein's special relativity was quite easily acccepted.
Was it so soon well understood?

"slowly but steadily a new world opened before me. I had to spend a great deal of effort on it.... And particularly epistemological difficulties gave me much trouble. I believe that only since about 1950 have I mastered them."

Max Laue to Margot Einstein, October 23 1959

Einstein is faced with two kinematics: the Galilean one for Newton's theory, the relativistic one for Maxwell's equations: it's incoherent! He will construct a relativistic theory of gravitation.

1907: towards a relativistic theory of gravitation



Planck to Einstein: "Everything is now so nearly settled, why do you bother about these other problems?"

1907: towards a relativistic theory of gravitation

In 1907, Einstein already think of what are often called the three "classical" tests: the Mercury's perihelion, the deviation of light, the line shift.

1907: towards a relativistic theory of gravitation

Hermann Minkowski

Albert Einstein, 1897

Minkowski described Einstein, then his student, as "a lazy dog who never bothered about mathematics at all ». Year later Einstein has to come to Minkowsk'is views of general relativity. Spacetime and proper time!

Minkowski and Einstein...

4. *Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes;*
von A. Einstein.

Die Frage, ob die Ausbreitung des Lichtes durch die Schwere beinflußt wird, habe ich schon an einer vor 3 Jahren erschienenen Abhandlung zu beantworten gesucht.[1]) Ich komme auf dies Thema wieder zurück, weil mich meine damalige Darstellung des Gegenstandes nicht befriedigt, noch mehr aber, weil ich nun nachträglich einsehe, daß eine der wichtigsten Konsequenzen jener Betrachtung der experimentellen Prüfung zugänglich ist. Es ergibt sich nämlich, daß Lichtstrahlen, die in der Nähe der Sonne vorbeigehen, durch das Gravitationsfeld derselben nach der vorzubringenden Theorie eine Ablenkung erfahren, so daß eine scheinbare Vergrößerung des Winkelabstandes eines nahe an der Sonne erscheinenden Fixsternes von dieser im Betrage von fast einer Bogensekunde eintritt.

Es haben sich bei der Durchführung der Überlegungen auch noch weitere Resultate ergeben, die sich auf die Gravitation beziehen. Da aber die Darlegung der ganzen Betrachtung ziemlich unübersichtlich würde, sollen im folgenden nur einige ganz elementare Überlegungen gegeben werden, aus denen man sich bequem über die Voraussetzungen und den Gedankengang der Theorie orientieren kann. Die hier abgeleiteten Beziehungen sind, auch wenn die theoretische Grundlage zutrifft, nur in erster Näherung gültig.

§ 1. Hypothese über die physikalische Natur des Gravitationsfeldes.

In einem homogenen Schwerefeld (Schwerebeschleunigung γ) befinde sich ein ruhendes Koordinatensystem K, das so orientiert sei, daß die Kraftlinien des Schwerefeldes in Richtung

1) A. Einstein, Jahrb. f. Radioakt. u. Elektronik IV. 4.

1911: on the light deviation

Would you be so kind to support my investigation and send to me good copies on glass of such eclipse-plates you have, which contain at least ~~one~~ a few stars and at the same time send to me also the dates wanted for measuring the plates: the time of the beginning and end of the exposure, the length and latitude of the place of observation, the focal-length of the instrument (if possible even, to deduce the scale, another plate of the same instrument containing a known group of stars taken as soon as possible after or before the eclipse) if possible the identification of the stars on the plates and the parallel of every plate.

I hope, it will not be too much pain for you to have these dates sent with the plates, if you send the latter, and I assure you my most sincere thankfullnes for every help.

Naturally the Royal Observatory, Berlin will overtake all guarantee for the objects send to us, as Professor Struve the director of the Royal Observatory Berlin, assured me today, bevor I wrote this letter, and I beg you to adress everything to the Royal Observatory, Berlin.

Yours truly

Erw. Finlay Freundlich
Dr. phil

Assistant of the Royal Observatory
B e r l i n.

Freundlich on the bending of light, circular letter, 1911

Marcel Grossmann

With the help of Marcel Grossmann, expert on Riemannian geometry, Einstein works hard at a theory based on a Riemanian space-time.

1912-1914: the Zürich years

Erklärung der Perihelbewegung des Merkur aus der allgemeinen Relativitätstheorie.

Von A. Einstein.

In einer jüngst in diesen Berichten erschienenen Arbeit, habe ich Feldgleichungen der Gravitation aufgestellt, welche bezüglich beliebiger Transformationen von der Determinante 1 kovariant sind. In einem Nachtrage habe ich gezeigt, daß jenen Feldgleichungen allgemein kovariante entsprechen, wenn der Skalar des Energietensors der »Materie« verschwindet, und ich habe dargetan, daß der Einführung dieser Hypothese, durch welche Zeit und Raum der letzten Spur objektiver Realität beraubt werden, keine prinzipiellen Bedenken entgegenstehen[1].

In der vorliegenden Arbeit finde ich eine wichtige Bestätigung dieser radikalsten Relativitätstheorie; es zeigt sich nämlich, daß sie die von Leverrier entdeckte säkulare Drehung der Merkurbahn im Sinne der Bahnbewegung, welche etwa 45″ im Jahrhundert beträgt qualitativ und quantitativ erklärt, ohne daß irgendwelche besondere Hypothese zugrunde gelegt werden müßte[2].

Es ergibt sich ferner, daß die Theorie eine stärkere (doppelt so starke) Lichtstrahlenkrümmung durch Gravitationsfelder zur Konsequenz hat als gemäß meinen früheren Untersuchungen.

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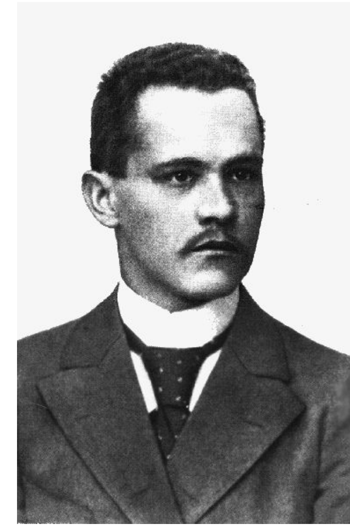
[1] In einer bald folgenden Mitteilung wird gezeigt werden, daß jene Hypothese entbehrlich ist. Wesentlich ist nur, daß eine solche Wahl des Bezugssystems möglich ist, daß die Determinante $|g_{\mu\nu}|$ den Wert -1 annimmt. Die nachfolgende Untersuchung ist hiervon unabhängig.

[2] Über die Unmöglichkeit, die Anomalien der Merkurbewegung auf der Basis der Newtonschen Theorie befriedigend zu erklären, schrieb E. Freundlich jüngst einen beachtenswerten Aufsatz (Astr. Nachr. 4803, Bd. 201. Juni 1915).

Einstein, November 25,1915

Mercury's perihelion, for years, the cornerstone of general relativity.



Arnold Sommerfeld

"The result of the perihelion motion of Mercury gives me great satisfaction. How helpful to us here is astronomy's pedantic accuracy, which I often used to ridicule secretly!"

Einstein to Sommerfeld, 9 december 1915

1916. № 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;*

von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie“ bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie“ und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitäts-

The general theory of relativity published

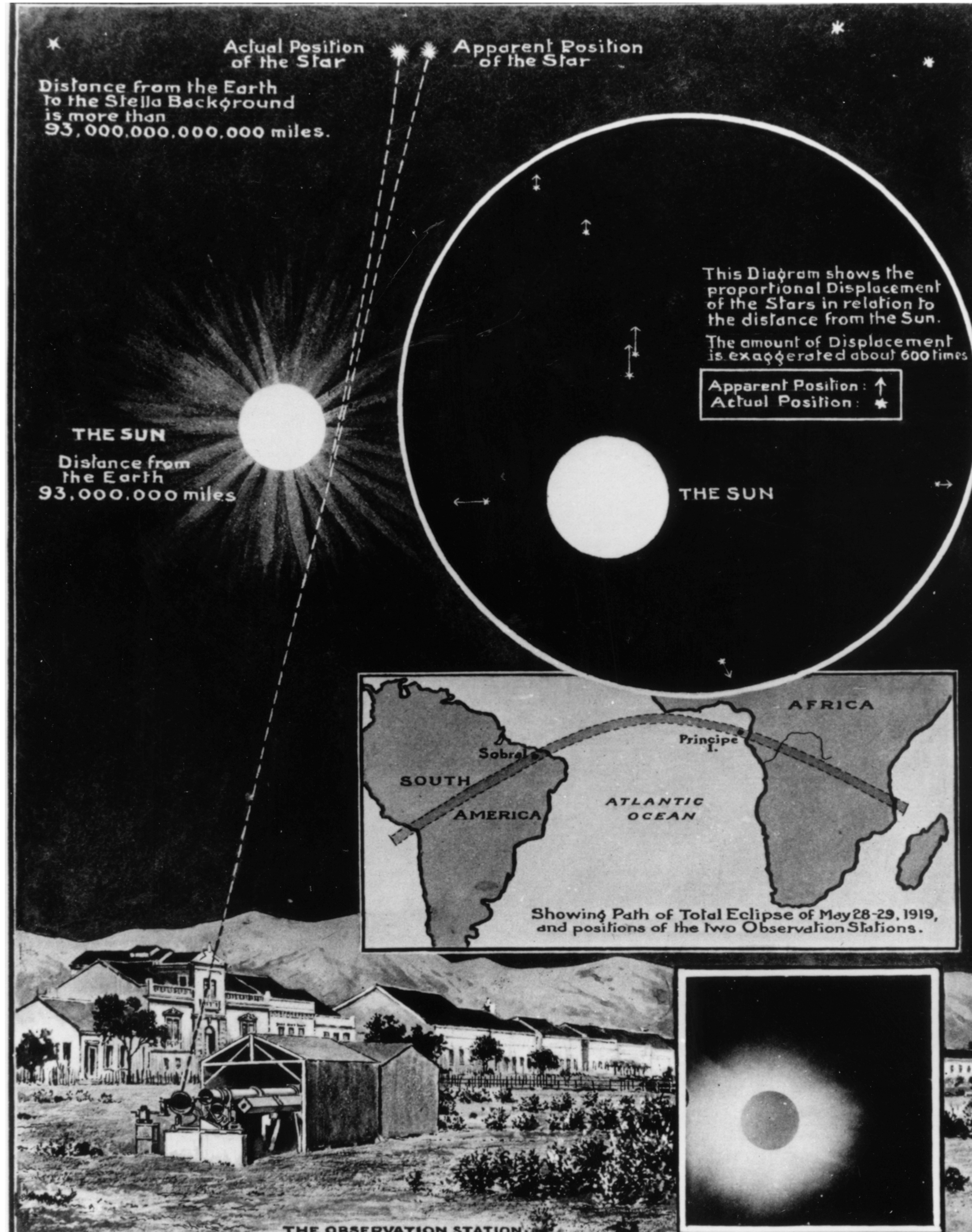
Karl Schwarzschild (1873–1916)

$$ds^2 = \left(1 - \frac{2MG}{\mathrm{r}\,c^2}\right)c^2\,\mathrm{d}t^2 - \frac{\mathrm{dr}^2}{1 - \frac{2MG}{\mathrm{r}\,c^2}} - \mathrm{r}^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

January 1916: Schwarzschild’s solution, paradigm of GR

Sobral: instruments

Sobral 1919



The Illustrated London News

"The whole atmosphere of tense interest was exactly that of the Greek drama: we were the chorus commenting on the decree of destiny as disclosed in the development of a supreme incident. There was dramatic quality in the very staging: –the traditional ceremonial, and in the background the picture of Newton to remind us that the greatest of scientific generalizations was now, after more than two centuries, to receive its first modification. Nor was the personal interest wanting: a great adventure in thought had at length come safe to shore." (Whitehead, 1926).

The 1919 eclipse at the Royal Society

REVOLUTION IN SCIENCE.

NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying of the prediction of the famous physicist, Einstein, stated by the President of the Royal Society as being the most remarkable scientific event since the discovery of the predicted existence of the planet Neptune. But there was difference of opinion as to whether science had to face merely a new and unexplained fact, or to reckon with a theory that would completely revolutionize the accepted fundamentals of physics.

SIR FRANK DYSON, the Astronomer Royal, described the work of the expeditions sent respectively to Sobral in North Brazil and the island of Principe, off the West Coast of Africa. At each of these places, if the weather were propitious on the day of the eclipse, it would be possible to take during totality a set of photographs of the obscured sun and of a number of bright stars which happened to be in its immediate vicinity. The desired object was to ascertain whether the light from these stars, as it passed the sun, came as directly towards us as if the sun were not there, or if there was a deflection due to its presence, and if the latter proved to be the case, what the amount of the deflection was. If deflection did occur, the stars would appear on the photographic plates at a measurable distance from their theoretical positions. He explained in detail the apparatus that had been employed, the corrections that had to be made for various disturbing factors, and the methods by which comparison between the theoretical and the observed positions had been made. He convinced the meeting that the results were definite and conclusive. Deflection did take place, and the measurements showed that the extent of the deflection was in close accord with the theoretical degree predicted by Einstein, as opposed to half that degree, the amount that would follow from the principles of Newton. It is interesting to recall that Sir Oliver Lodge, speaking at the Royal Institution last February, had also ventured on a prediction. He doubted if deflection would be observed, but was confident that if it did take place, it would follow the law of Newton and not that of Einstein.

DR. CROMMELIN and PROFESSOR EDDINGTON, two of the actual observers, followed the Astronomer-Royal, and gave interesting accounts of their work, in every way confirming the general conclusions that had been enunciated.

"MOMENTOUS PRONOUNCEMENT."

So far the matter was clear, but when the discussion began, it was plain that the scientific interest centred more in the theoretical bearings of the results than in the results themselves. Even the President of the Royal Society, in stating that they had just listened to "one of the most momentous, if not the most momentous, pronouncements of human thought," had to confess that no one had yet succeeded in stating in clear language what the theory of Einstein really was. It was accepted, however, that Einstein, on the basis of his theory, had made three predictions. The first, as to the motion of the planet Mercury, had been verified. The second, as to the existence and the degree of deflection of light as it passed the sphere of influence of the sun, had now been verified. As to the third, which depended on spectroscopic observations there was still uncertainty. But he was confident that the Einstein theory must now be reckoned with, and that our conceptions of the fabric of the universe must be fundamentally altered.

At this stage Sir Oliver Lodge, whose contribution to the discussion had been eagerly expected, left the meeting.

Subsequent speakers joined in congratulating the observers, and agreed in accepting their results. More than one, however, including Professor Newall, of Cambridge, hesitated as to the full extent of the inferences that had been drawn and suggested that the phenomena might be due to an unknown solar atmosphere further in its extent than had been supposed and with unknown properties. No speaker succeeded in giving a clear non-mathematical statement of the theoretical question.

SPACE "WARPED."

Put in the most general way it may be described as follows: the Newtonian principles assume that space is invariable, that, for instance, the three angles of a triangle always equal, and must equal, two right angles. But these principles really rest on the observation that the angles of a triangle do equal two right angles, and that a circle is really circular. But there are certain physical facts that seem to throw doubt on the universality of these observations, and suggest that space may acquire a twist or warp in certain circumstances, as, for instance, under the influence of gravitation, a dislocation in itself slight and applying to the instruments of measurement as well as to the things measured. The Einstein doctrine is that the qualities of space, hitherto believed absolute, are relative to their circumstances. He drew the inference from his theory that in certain cases actual measurement of light would show the effects of the warping in a degree that could be predicted and calculated. His predictions in two of these cases have now been verified, but the question remains open as to whether the verifications prove the theory from which the predictions were deduced.

London Times, Nov 7 1919

— Quel concert de louanges ! Ces dames parlent encore de leurs couturiers.

— Mais non, il s'agit d'Einstein. (*Dessin de* P. PORTELETTE.)

Einstein in Paris: Fashionable!

The Low Watermark of General Relativity.

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Heber Curtis

"It is not going too far to say, that the announcement that physicists would have in the future to study the theory of tensors created a veritable panic among them when the verification of Einstein's prediction was first announced." (Whitehead 1920).

"While it would be possible, in a four-dimensioned universe, to turn an egg inside out without breaking its shell, still he realized that there were many practical difficulties in the way of the accomplishment of this feat." (Curtis 1917).

"Perhaps I am wrong, but it does not seem to me at present hat I shall ever be willing to accept Einstein's theory, beautiful but bizarre, -clever but not a true representation of the physical universe." (Curtis to Vogtherr, 1923) .

"There may be a deflection, but I do not feel that I shall be ready to swallow the Einstein theory for a long time to come, if ever. I'm a heretic." (Curtis to Chant, 1923).

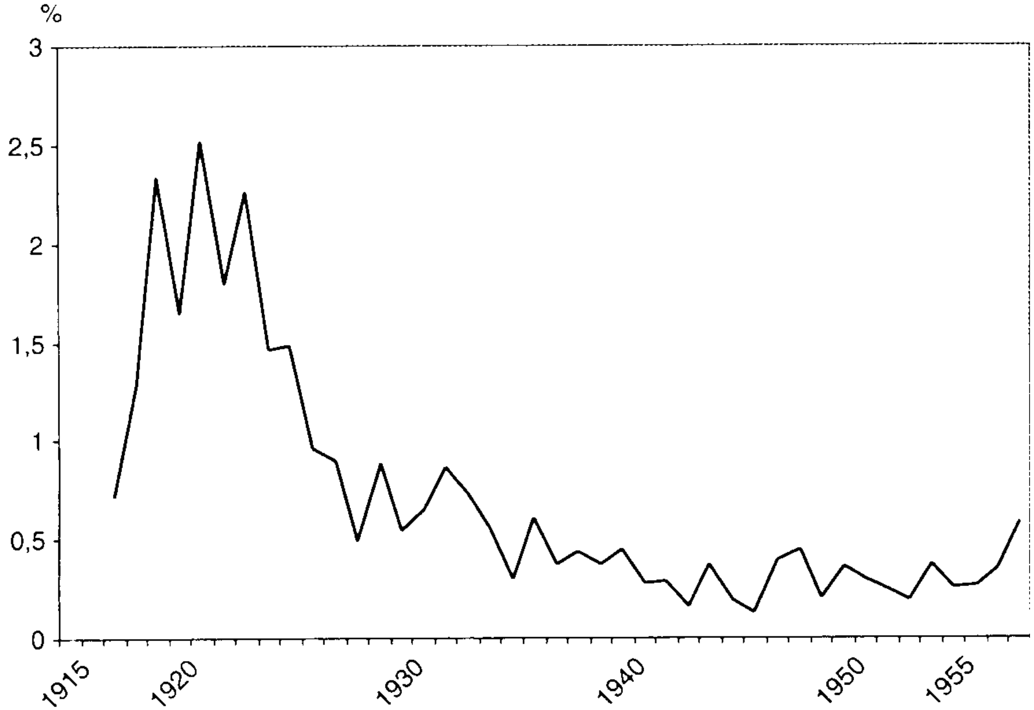
A panic among astronomers and physicists!

James Jean

- James Jeans feared that "Einstein's Theory may meet with an unfavourable reception on account of the somewhat metaphysical --one might almost say mystical-- form in which his results have been expressed." (Jeans, 1917).

- "While I personally have not much doubt about the accuracy of Einstein's conclusions and consider it a great piece of work, I am a little afraid it will have the tendency to ruin many scientific men in drawing them away from the field of experiment to the broad road of metaphysical conceptions. We already have plenty of that type in this country and we do not want to have many more if Science is to go ahead." (Rutherford to Hale 1920).

A metaphysical theory



Number of publications in general relativity as a percentage of the total number of publication in physics (from Science Abstract:1915–1955).
N.B. The absolute number of pubications goes from 10 in 1916 to 42 (greatest) in 1920; 4 in 1945 (lowest).

- We can see the spectacular growth of the theory after its birth followed by its peak in 1920 (the verification of the second test takes place in 1919). The fact that the theory becomes fashionable at the beginning of the 1920s is reflected in the increased number of publications. And then a sharp decline starting in 1922-23, a situation that would last until the end of the 1950s.

The Low Watermark

- "In any case, the greatest interest in this discipline was evinced by scientists in the 1920's. Then, already in 1936 when I was in contact with Einstein in Princeton, I observed that this interest had almost completely lapsed. The number of physicists working in this field in Princeton could be counted on the fingers of one hand. I remember that very few of us met in the late Professor H. Robertson's room and then even those meetings ceased. We, who worked in this field, were looked upon rather askance by other physicists. Einstein himself often remarked to me “In Princeton they regard me as an old fool: Sie glauben ich bin ein alter Trottel.” This situation remained almost unchanged up to Einstein's death. Relativity Theory was not very highly estimated in the "West" and frowned upon in the “East”" ((Infeld 1964).

- "You only had to know what your six best friends were doing and you would know what was happening in general relativity." (Bergmann to Pais).

Relativists isolated...

- "I sent the paper to the “Annalen der Physik” and I got it immediately back, together with a card of the editor stating that general relativity was no physics and that his periodical was too good to deal with such stuff. The editor, however, was not just anybody, he was, at that time, one of German most brilliant physicists, Willy Wien." (Beck 1974).
- "Chandra particularly mentions that Niels Bohr discouraged him from making a move into relativity. [...] Kip Thorne reports that he received similarly negative advice when he was contemplating doing graduate work in relativity in the early 1960s. [...] when I moved into gravitational wave detection, many astronomers told me I was throwing away my career." (Schutz 2012, 260).
- "John Archibald Wheeler has told me that in 1952 he gave the first course on general relativity ever to be given at Princeton University." (Crelinsten 1980).

Relativists discouraged...

"I find it difficult to believe that 1".75 can be wrong. Light is a strange thing, and we must recognise that we do not know as much about it as we thought we did in 1919; but I should be very surprised if it is as strange as all that." (Eddington 1932).

Eddington and the Sumatra eclipse expedition


MEASURING THE STARS
San Francisco Examiner--Wed. Jan. 30, 1924

Prof. Trumpler of Lick Observatory at work with instrument which corroborates the Einstein theory of relativity.

"...the confirmation of the theory by the solar observations is not very convincing." (Trumpler 1955).
Nor more than that of the “third test“! Then, only the perihelium was to resist.

Robert Trumpler in Bern

John L. Synge

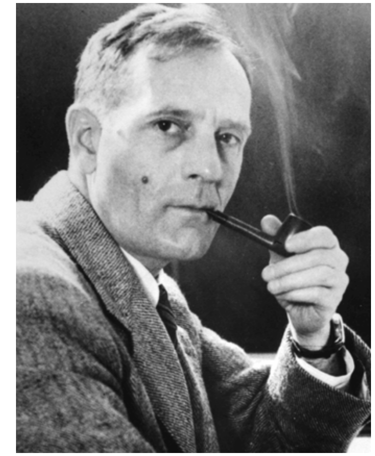
"Astronomers still think in terms of these pre-relativistic concepts" (Synge 1960).

"Mechanical laws, according to Einstein's theory, are much more complicated in conception than under the assumption of Newton. However, the motion of celestial bodies under ordinary circumstances differs so little from their Newtonian representation that, for astronomical purposes, relativistic effects may be conveniently treated as first-order perturbations. (Levi-Civita 1937)."

"One unfortunate part of the Einstein myth was that what he did was so new, so recondite, so hard to understand, that it was not part of the cultural heritage. Newton was digested and redigested by the century that followed him [...] with Einstein it took the other form." (Oppenheimer 1965).

A neo-Newtonian interpretation

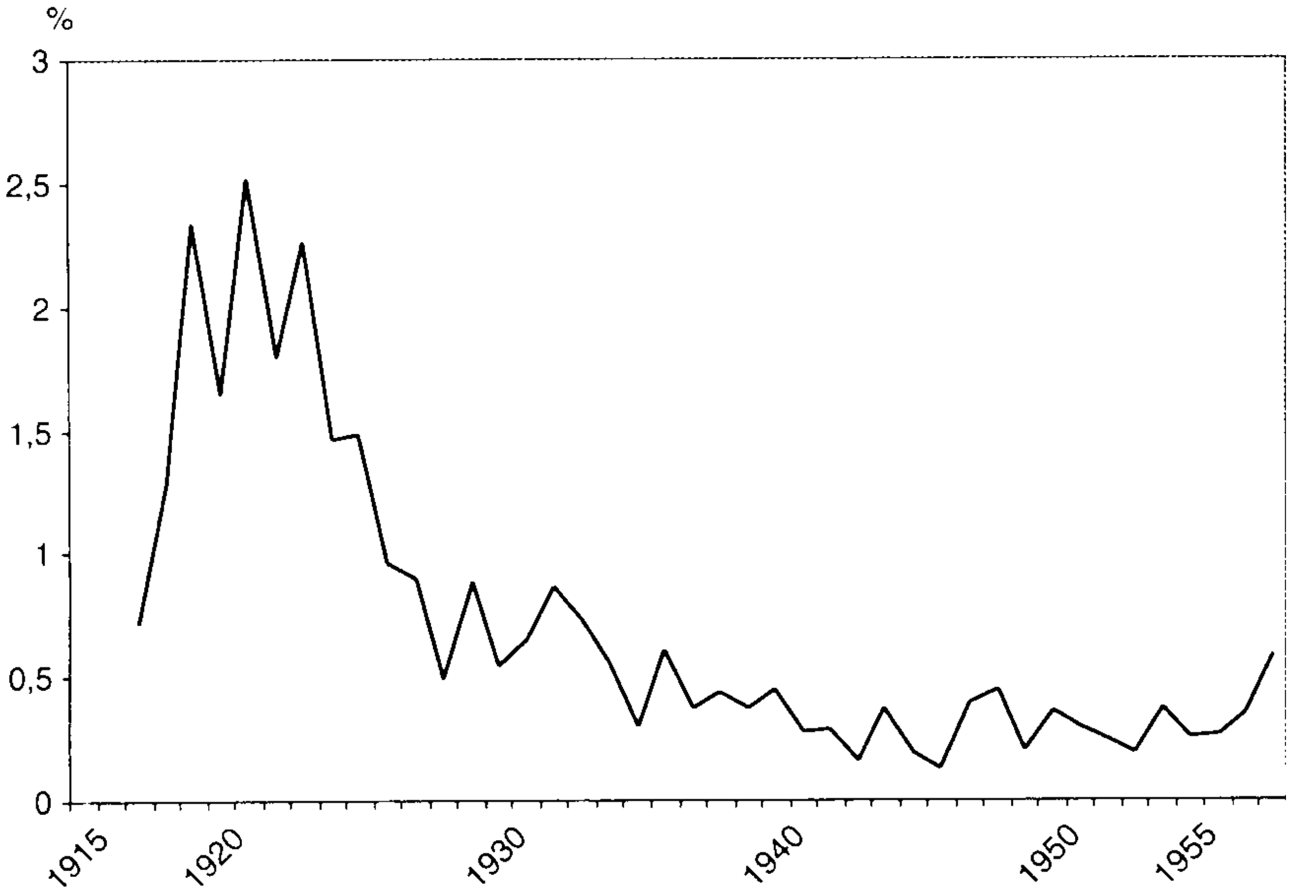
Vesto M. Slipher



Edwin Hubbble

"Although general relativity was recognized as a major conceptual revolution, it was generally felt to be of little practical significance because it was thought that gravitational fields could never be so strong that there would be much difference between its predictions and those of the much simpler Newtonian theory. The first evidence that this view was mistaken came in the early 1920's with the discovery, by Slipher and Hubble" (Hawking and Israel, 1979).

Twenties-Thirties, the time for cosmology



- There is a small hill that indicates a slight improvement around the 1930s corresponding to the works prompted by the interest in cosmology.

1920th–1930th, the time for cosmology

Richard Tolman

"Indeed we shall feel justified in studying some models, which are known to differ from the real universe in important ways, provided the results can illuminate our thinking by indicating the kind of phenomena that might occur without controverting established theory. With the help of such studies, however, we shall certainly make progress in understanding the behaviour of nature on the largest possible scale." (Tolman 1934).

"In the forty years that have elapsed these have remained the principal and, with one exception, the only connections between the general theory and experience. The exception lies in the field of cosmology, where Einstein himself was the first to see wholly new approaches opened by the theory of relativity." (Oppenheimer 1956).

"For many reasons, the history of general relativity (from 1920 to 1960) has been much less spectacular. The one field on which it had a decisive and most stimulating influence is cosmology." (Bargmann 1960).

Cosmology, a space for thought

- "It is true that the theory of relativity, particularly the general theory, has played a rather modest role in the correlation of empirical facts so far." (Einstein 1942).
- "its connections with experience were slender." (Born 1955).
- "It seems to me that a great deal of the interest of general relativity lies in asking what the theory would say in conditions which admittedly do not occur in those parts of the universe about which we know much. [...] I was looking at Newtonian theory as a particular and well-worked-through approximation to the relativistic equations, and I felt that this particular method of approximation -admittedly invented 250 years before the theory- nevertheless, is highly successful in practically all cases appertaining to reality." (Bondi to Synge 1962).
- "as an experimentalist I attempted to counteract in some small measure the decided tendency in times past for General Relativity to develop into a formal science divorced from both observations and the rest of physics." (Dicke 1964).

A lack of experiments

- "A difficulty in general relativity theory is the lack of what might be called a theory of measurement." (Pirani 1956).
- "At the logical beginning of the theory of relativity we find instead only two elementary concepts : the idea of space-time coincidences ("events") and the proper time: this is all there is in our equipment for the long journey to a complete understanding of gravitation. Every other physical quantity-distance, angle, energy, etc.- has only a secondary meaning and must be constructed, if possible, from the two fundamental concepts." (Bertotti 1962).
- "it is not obvious that a well-defined notion of mass or energy-momentum exists." (Wald 1984).
- "In the 1930s relativity had few such heuristic concepts to offer, and it did not look like it was moving toward constructing many more of them. I suggest that this is what led to the big gulf between relativists and mainstream theoretical physicists between 1930 and 1950. If this picture is right, then general relativity emerged mathematically complete in 1916, but as a theory of physics it was not completed until the 1980s." (Schutz 2013).

A lack of concepts

- "The theory of General Relativity, after its invention by Albert Einstein, remained for many years a monument of mathematical speculation, striking in its ambition and its formal beauty, but quite separated from the main stream of modern Physics, which had centered, after the early twenties, on quantum mechanics and its applications " (Levy and Deser 1978).

- "As an experimentalist I attempted to counteract in some small measure the decided tendency in times past for General Relativity to develop into a formal science divorced from both observations and the rest of physics. [...] An examination of the scientific literature of the past 50 years will testify to the truth of this statement, the number of experimental papers being entirely negligible in comparison with the flood of theoretical publications, mostly formal." (Dicke 1964)

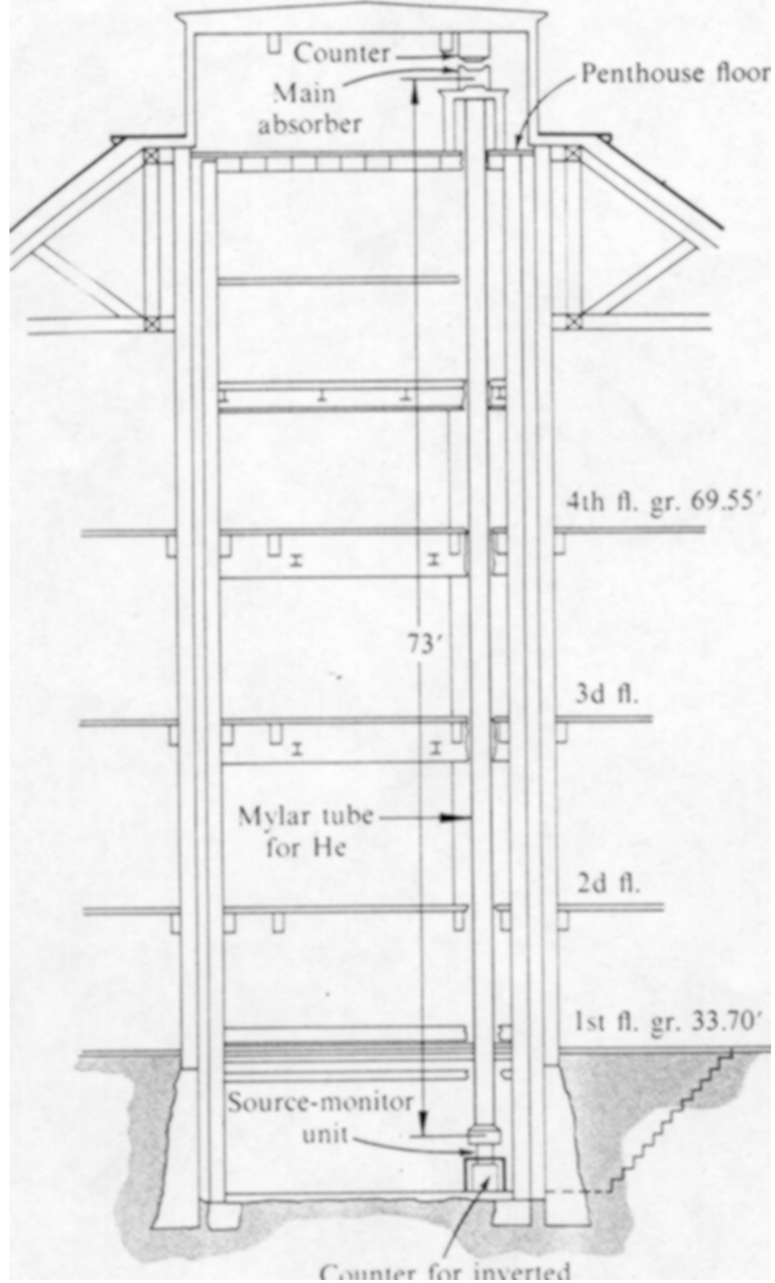
Too formal a science?

- "Many physicists are very emotional about the Einstein theory. Most of them admit that the general theory of relativity is a beautiful theory, but then they add that because of the weakness of gravitational forces the theory of gravitation is on the sidelines relative to the rest of physics. Some physicists go so far as to say that GR should not be regarded as a physical theory. A less extreme position consists in the assertion that those who are at present developing the Einstein theory are mathematicians rather than physicists. In certain circles relativists are regarded as "socially undesirable elements." (Trautman 1966).

- "Though most physicists refused to say anything in public the great majority of them thought of general relativity as an obscure backwater which took an awful lot of learning to get into." (Bondi 1990).

Relativists reply to critics...

The Renewal!



Pound and Rebka, 1959

"These are exciting days: Einstein's theory of gravitation, his general theory of relativity of 1915, is moving from the realm of mathematics to that of physics. After 40 years of sparse meager astronomical checks, new terrestrial experiments are possible and are being planned." (Schild 1960, 778)

Alfred Schild on the Pound and Rebka experiment

- "Everyone is pleased : the relativists who feel they are being appreciated, who are suddenly experts in a field they hardly knew existed ; the astrophysicists for having enlarged their domain, their empire, by the annexation of another subject - general relativity. It is all very pleasing, so let us all hope that it is right. What a shame it would be if we had to go and dismiss all the relativists again." (Gold 1964, After-dinner speech at the 1st Texas Meeting).

- "The story of the phenomenal transformation of general relativity within little more than a decade, from a quiet backwater of research, harboring a handful of theorists, to a blooming outpost attracting increasing numbers of highly talented young people as well as heavy investment in experiments, is by now familiar." (De Witt 1973).

- "Elie Cartan in his fundamental paper, "Sur les variétés à connexion affine et la théorie de la relativité généralisée", published in 1923-24 [...] did not receive the attention it deserved for the simple reason it was ahead of its time." (Chern 1980).

- "My thesis is that general relativity, despite its essential mathematical completeness in 1916, did not become a complete theory of physics until the 1970s." (Schutz 2012).

A theory ahead of its time: the renewal!

Bibliography

In English:

- Brian, Denis (1996). *Einstein: a Life*. New York: John Wiley & Sons.
- Chandrasekhar, Subrahmanyan (1976). "Verifying the Theory of Relativity." *Bulletin of Atomic Scientists* 31: 17–22; *Royal Society of London. Notes and Records* 30: 249–260.
- Earman, John, and Glymour, Clark (1980). "Relativity and Eclipses: The British Eclipse Expeditions of 1919 and their Predecessors." *Historical Studies in the Physical Sciences* 11: 49–85.
- Earman, John, and Glymour, Clark (1980). "The Gravitational Red Shift as a Test of General Relativity: History and Analysis." *Studies in History and Philosophy of Science* 11: 175–214.
- Eisenstaedt, Jean (2006). *The Curious History of Relativity. How Einstein's Theory of Gravity Was Lost and Found Again. Translated by Arturo Sangalli.* Princeton and Oxford: University Press.
- Eisenstaedt, Jean (1989). "Cosmology: a Space for Thought on General Relativity." In *Foundation of Big Bang Cosmology. Proceedings of the Seminar on the Foundations of Big Bang Cosmology*. F. Walter Meyerstein, ed. Singapore: World Scientific, 271–295.
- Eisenstaedt, Jean (1989). "The Low Water-Mark of General Relativity, 1925–1955." In *Einstein and the History of General Relativity. Proceedings of the 1986 Osgood Hill Conference. Einstein Studies*, Vol. 1, J. Stachel and Don Howard, eds. Boston: Birkhäuser, 277–292.
- Kennefick, Daniel (2007). *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves*. Princeton University Press.
- Roseveare, N.T. (1982). *Mercury's Perihelion from Le Verrier to Einstein*. Oxford: Clarendon Press.
- Schutz, Bernard F. (2012). "Thoughts About a Conceptual Framework for Relativistic Gravity." In: Lehner et al. (eds.), *Einstein and the Changing Worldviews of Physics*, Einstein Studies 12, The Center for Einstein Studies, 259–269.

En Français:

- Eisenstaedt, Jean (1986). "La relativité générale à l'étiage: 1925–1955." *Archive for History of Exact Sciences* 35: 115–185.
- Eisenstaedt, Jean (1987). "Trajectoires et impasses de la solution de Schwarzschild." *Archive for History of Exact Sciences* 37: 275–357.