Renaissance of General Relativity
2–5 December 2015

General Relativity, a Theory Ahead of its Time.

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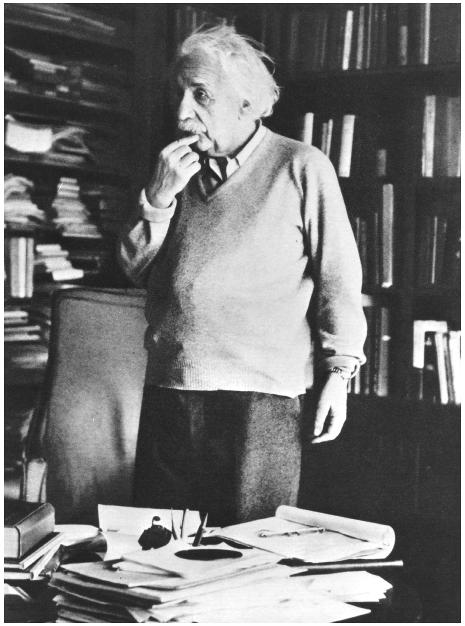
Observatoire de Paris



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...

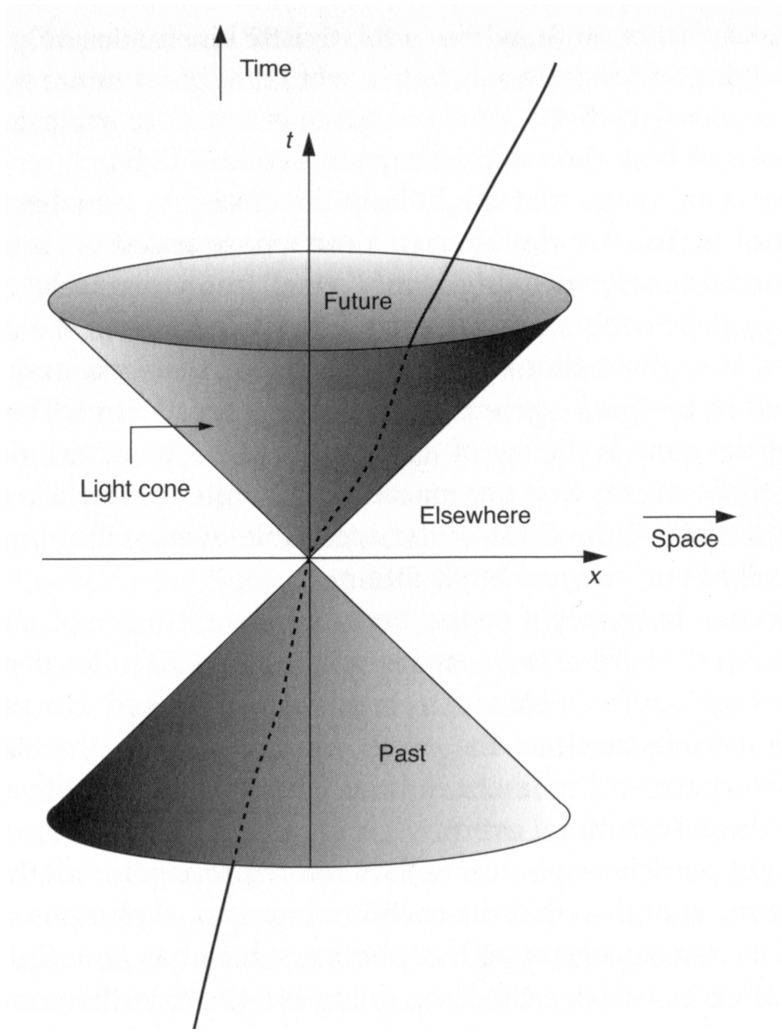
- "I remember that on my honeymoon in 1913 I had in my luggage some reprints of Einstein's papers which absorbed my attention for hours, much to the annoyance of my bride. These papers seemed to me fascinating, but difficult and almost frightening. When I met Einstein in Berlin in 1915 the theory was 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.

From Special to General Relativity.

Lorentz, Einstein, Poincaré.

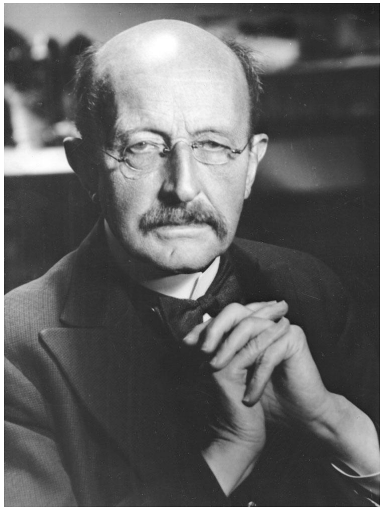
Einstein's special relativity was quite easily acccepted.
Was it so soon well understood?



Light-cone

"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



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

Marcel Grossmann

With the essential 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

The Low Watermark of General Relativity.

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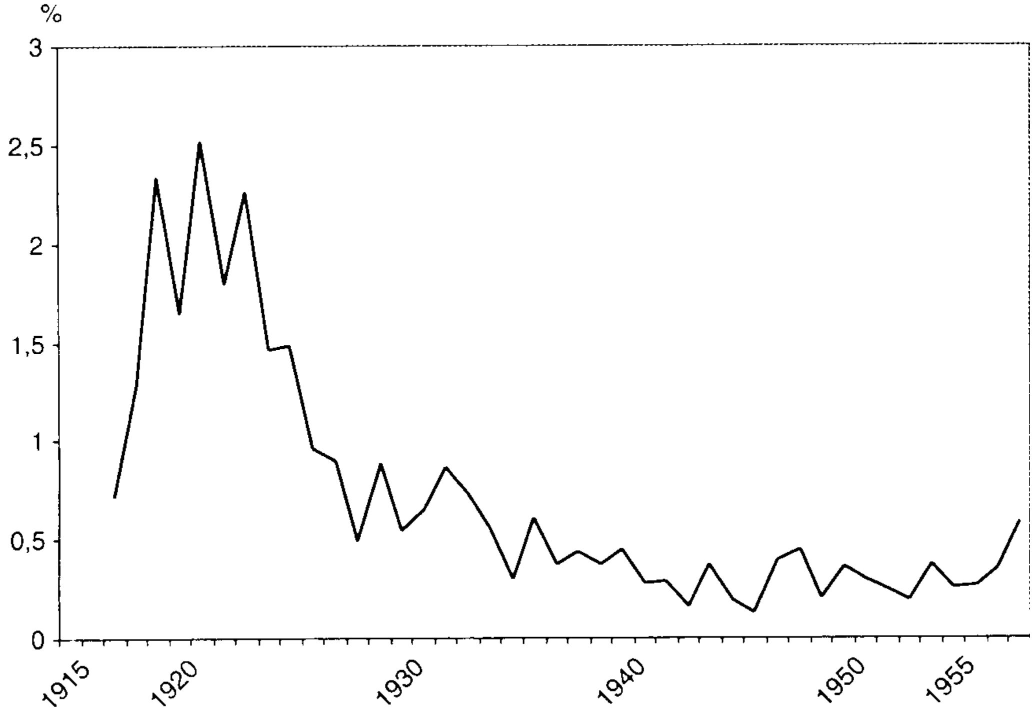


Number of publications in general relativity as a percentage of the total number of publication in physics (from Science Abstract:1915-1955).
N.B. The absolute number of pubications goes from 10 in 1916 to 42 (greatest) in 1920; 4 in 1945 (lowest).

- 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

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 Jeans

- 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

- "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

"...the confirmation of the theory by the solar observations is not very convincing." (Trumpler 1955).
Then, only the perihelium of Mercury was to resist.

1955: 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**." (Oppenheimer 1965).

A neo-Newtonian interpretation

- "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 [...] **highly successful in practically all cases appertaining to reality**." (Bondi to Synge 1962).

- "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).

A lack of experiments

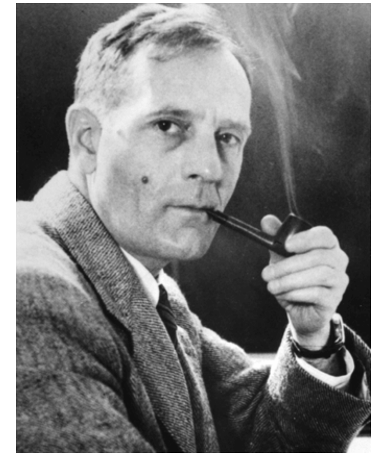
- "As an experimentalist I attempted to counteract in some small measure the decided tendency in times past for General Relativity to develop into a formal science divorced from both observations and the rest of physics. [...] An examination of the scientific literature of the past 50 years will testify 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)

- "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).

Too formal a science?

The time for cosmology.

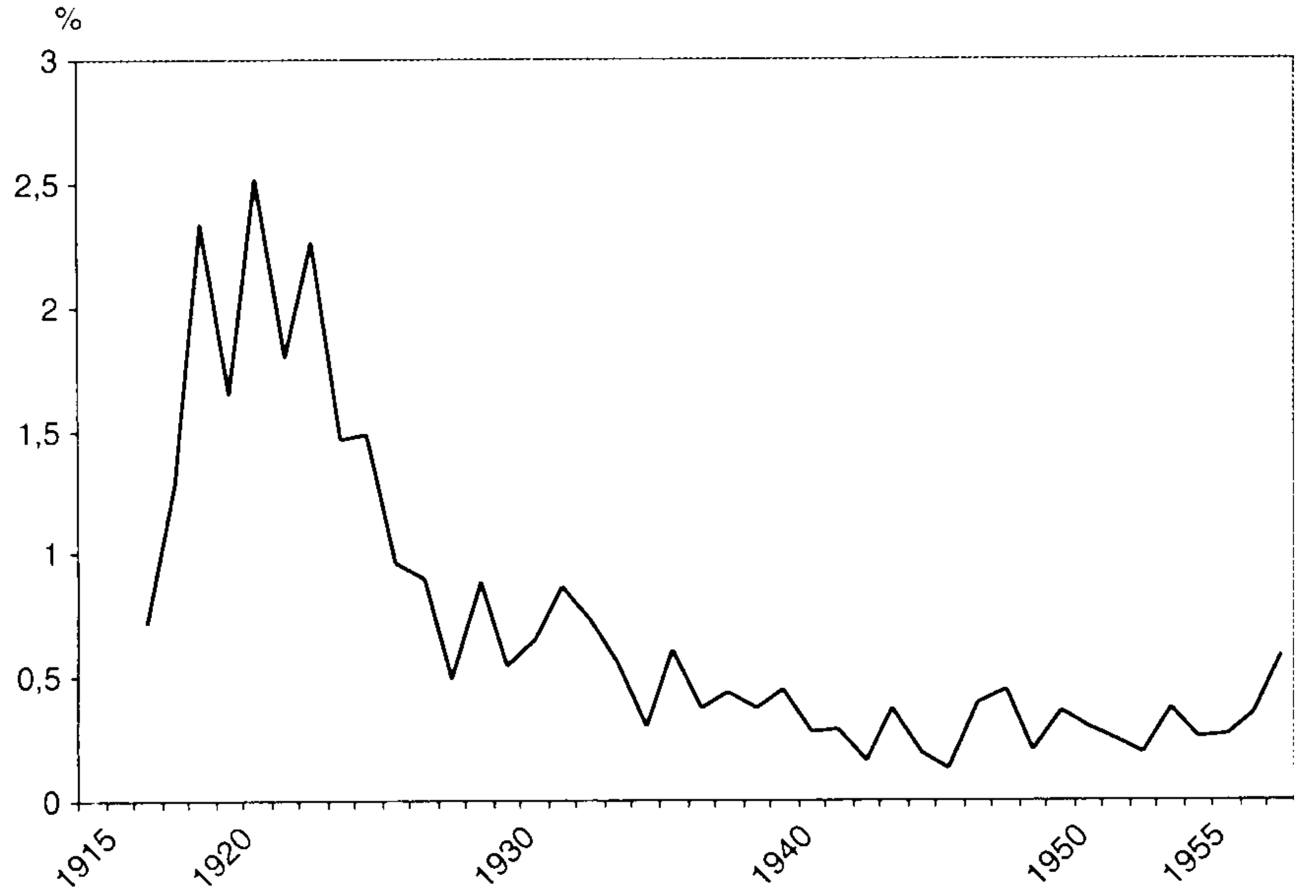
Vesto M. Slipher



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

Questions and criticisms

- A lack of experiments (Dicke)

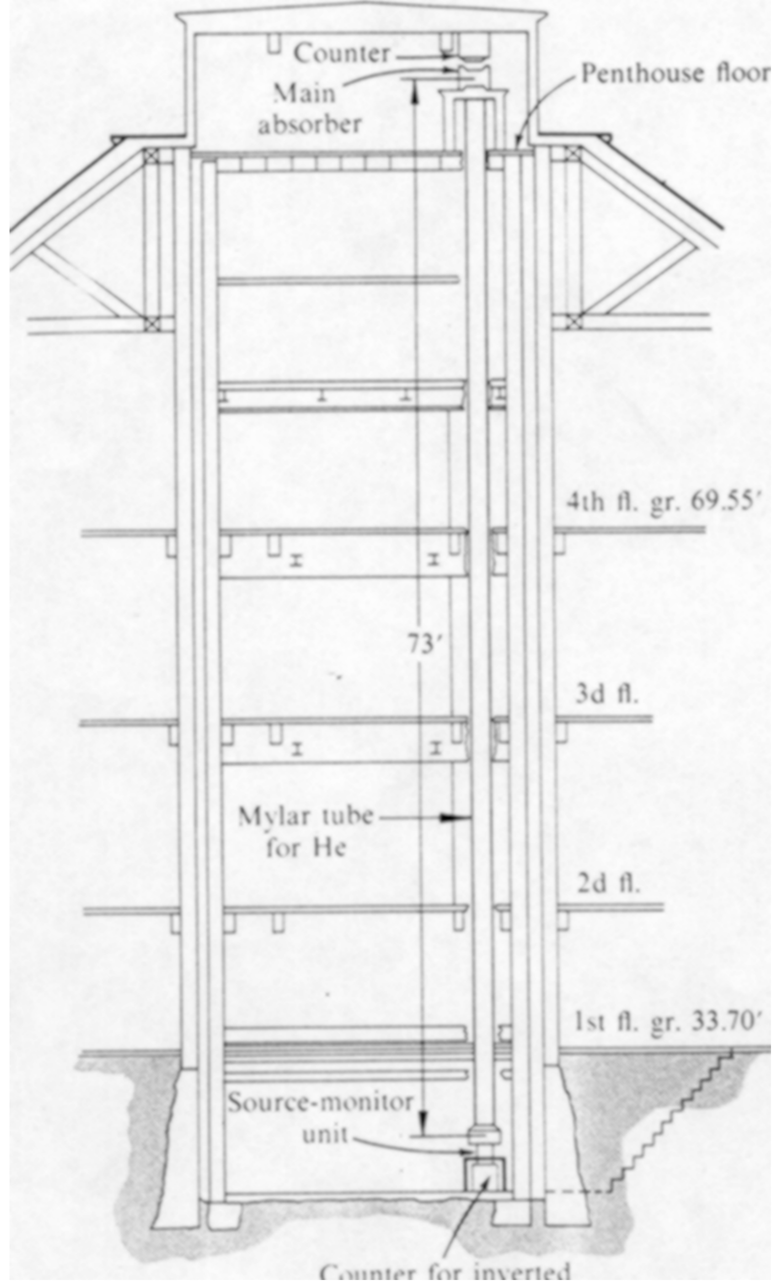
- A lack of a theory of measurements... (Bertotti)

- The question of the physical field of GR: a weak gravitational field up to the sixties! (Dallas, astrophysical technics)

- Why the black hole concept was not accepted, invented before? (the definition of a singularity...)

- "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



The Pound and Rebka Experiment

"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

- "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).

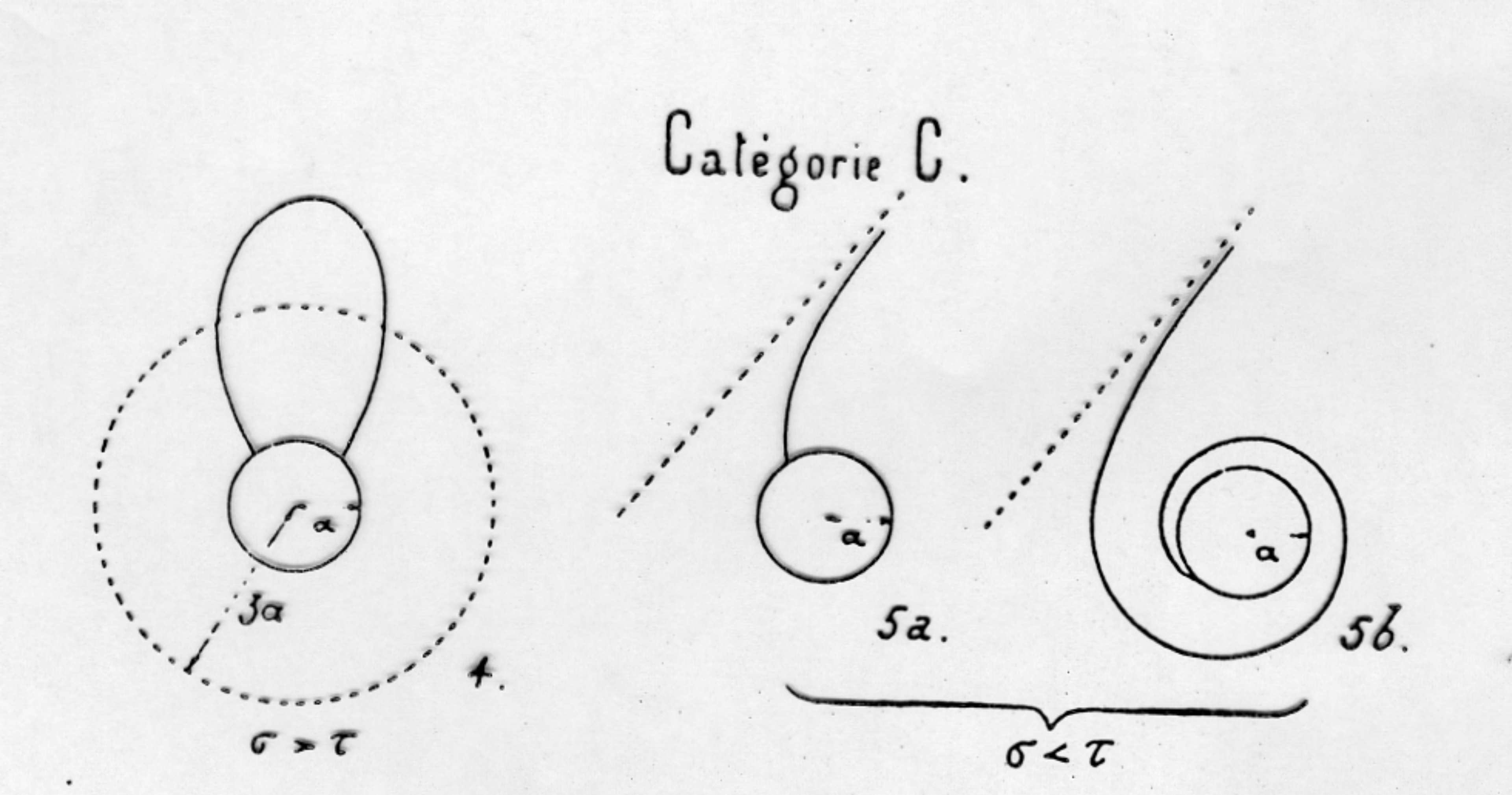
A lack of concepts, of a theory of measurement

Around Schwarzschild's singularity

- Why the black hole concept was not accepted, invented before the sixties?
- The impenetrability of Schwarzschild's singularity: a dogma, a blocade of the community....

Eddington: Schwarzschild’s singularity, a magic circle.

"We can go on shifting the measuring-rod through its own length time after time, but *dr* is zero; that is to say, we do not reduce *r*. There is a magic circle which no measurement can bring us inside. It is not unnatural that we should picture something **obstructing our closer approach**, and say that a particle of matter is filling up the interior." (Eddington 1920).



De Jans, 1923, point-masses trajectories

1931: Hagihara on Schwarzschild's trajectories

"In fact, it is **quite improbable** that in any star the distance r = α or 2m from the center lies outside its radius. In order that the radius of a star with its mass comparable with our Sun be equal to the distance r = α, its density ought to be about 10^{17} times that of water, while in the densest star, the companion of Sirius, a white dwarf, the density is about $6x10^4$ times that of water. There is no such diversity in the masses of the stars as to overcome this tremendous high magnitude of the critical density. **Therefore the orbit inside is physically inadmissible**" (Hagihara 1931, 106–107).

Eddington « to save the star »

"I felt driven to the conclusion that this was almost a *reductio ad absurdum* of the relativistic degeneracy formula. Various accidents may intervene to save the star, but I want more protection than that. I think there should be a law of Nature to prevent a star to behave in this absurd way." (Meeting of the Royal Astronomical Society, 11 Janvier 1935, in : *The Observatory* 58 : 38)

Ratio of gravitational radius to radius

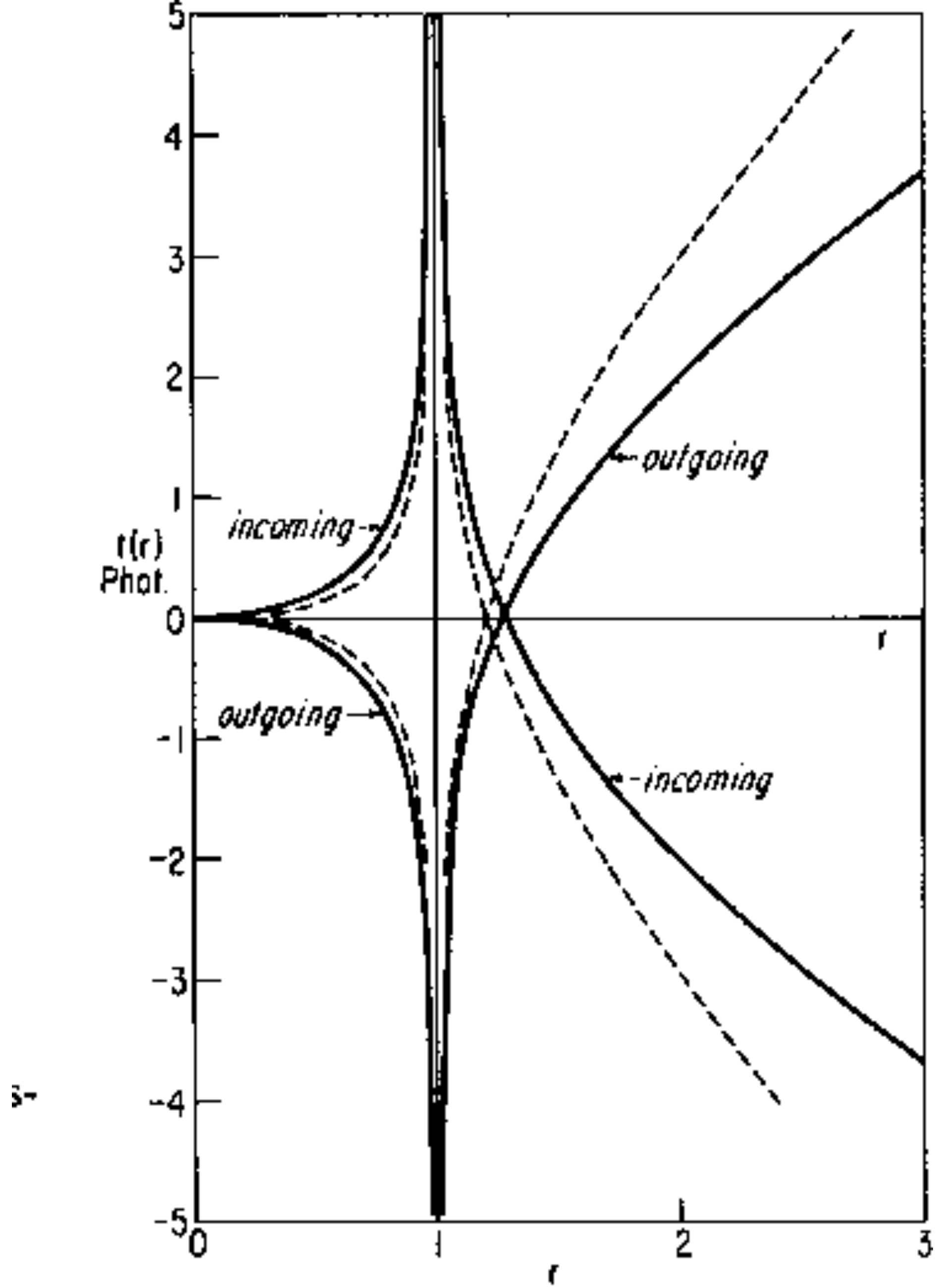
Objet	mG/ac^2
Proton	$1.0\ 10^{-39}$
Metal sphere with radius 1 meter $3\ 10^{-23}$	
Earth	$6.95\ 10^{-10}$
Sun	$2.12\ 10^{-6}$
Certain white dwarfs stars	$2.5\ 10^{-4}$
Galactic nucleus	$3\ 10^{-7}$

- "There are no known objects with so small a size"

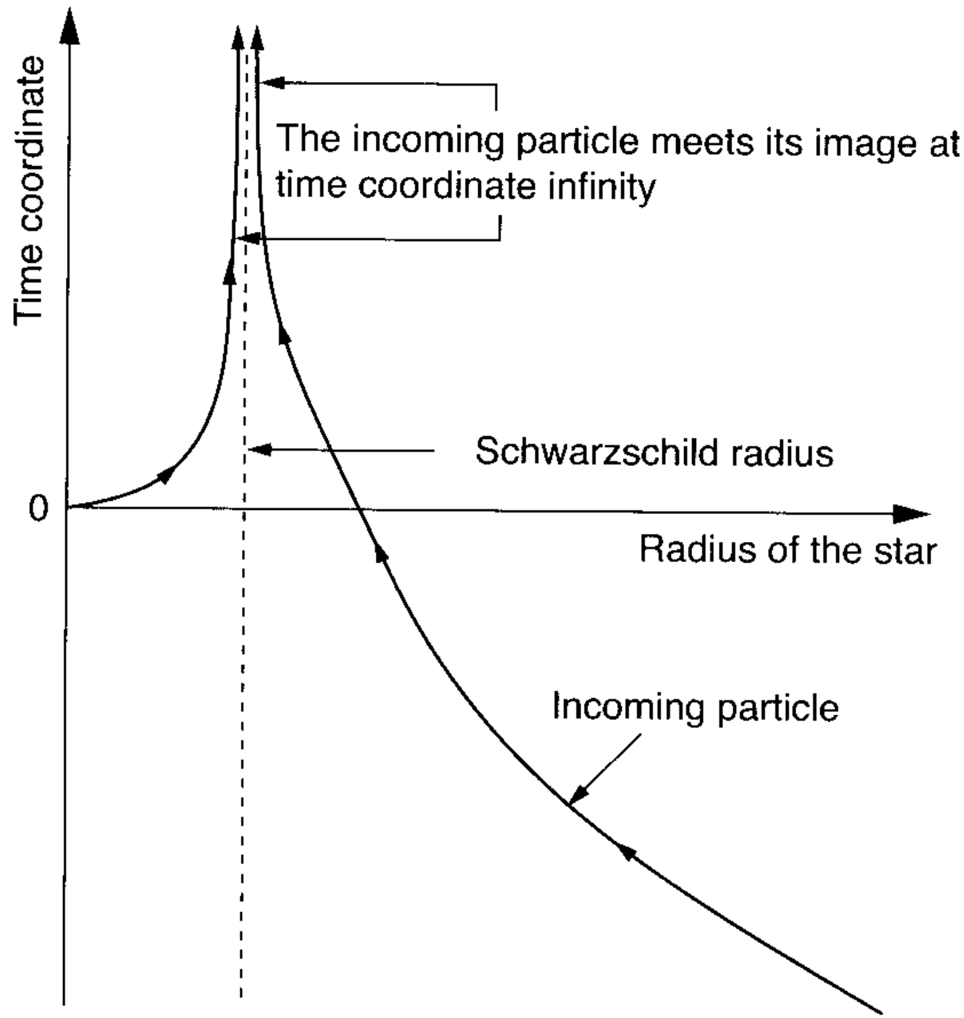
Robertson & Noonan,
1930th, 1968

Collapse, the missing link: Lemaître, Robertson, Tolman, Oppenheimer, Synge, Kruskal…

Lemaître 1933 on Schwarzschild’s singularity



Robertson's trajectories of a Schwarzschild's field



A trajectory in Schwarzschild's space.
(from H. P. Robertson and T. W. Noonan, 1968).

Robertson approach to « r = 2m »

"The observer never sees the particle reach r = 2m, although the **particle passes r = 2m and reaches r = 0 in a finite proper time** ! [. . .] the light from the particle is redshited more and more; as the particle approaches r = 2m, z approaches ∞." (Robertson & Noonan 1968, 252).

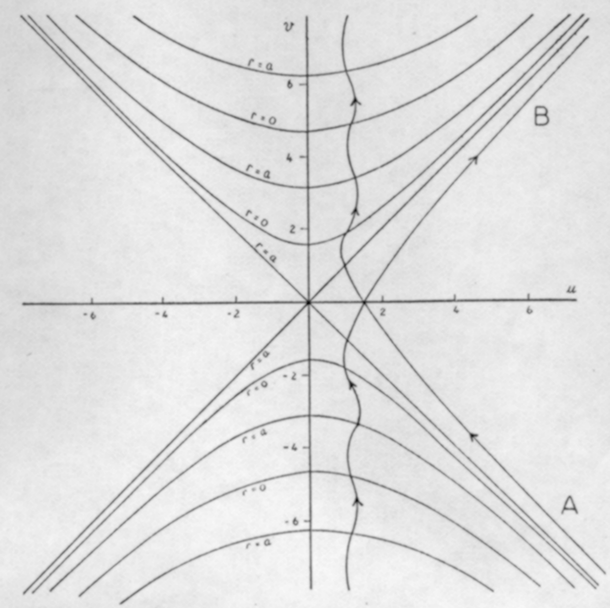


Fig. 14.—Histories of particles projected radially in from $r = \infty$ (A), and projected radially out to $r = \infty$ (B), with zero velocity at $r = \infty$ in each case.

Drawn for $a = 1$.

Synge 1950

Oppenheimer and Snyder on collapse

- "When all thermonuclear sources of energy are exhausted a sufficiently heavy star will collapse...the radius of the star approaches asymptotically its gravitational radius; light from the surface of the star is progressively reddened, and can escape over a progressively narrower range of angles...The total time of collapse for an observer comoving with the stellar matter is finite [...] an external observer sees the star asymptotically shrinking to its gravitational radius." (Oppenheimer and Snyder 1939, 455)

TABLE II. Relation of new coordinates to Schwarzschild coordinates.

New coordinates in terms of Schwarzschild coordinates	Schwarzschild coordinates in terms of new coordinates
$u=\left[\left(\frac{r}{2m^*}\right)-1\right]^{\frac{1}{2}}\exp\left(\frac{r}{4m^*}\right)\cosh\left(\frac{T}{4m^*}\right)$	$\left[\left(\frac{r}{2m^*}\right)-1\right]\exp\left(\frac{r}{2m^*}\right)=u^2-v^2$
$v=\left[\left(\frac{r}{2m^*}\right)-1\right]^{\frac{1}{2}}\exp\left(\frac{r}{4m^*}\right)\sinh\left(\frac{T}{4m^*}\right)$	$T/4m^*=\operatorname{arctanh}(v/u)$ $=\frac{1}{2}\operatorname{arctanh}[2uv/(u^2+v^2)]$
$f^2=(32m^{*3}/r)\exp(-r/2m^*)=$ a transcendental function of (u^2-v^2)	

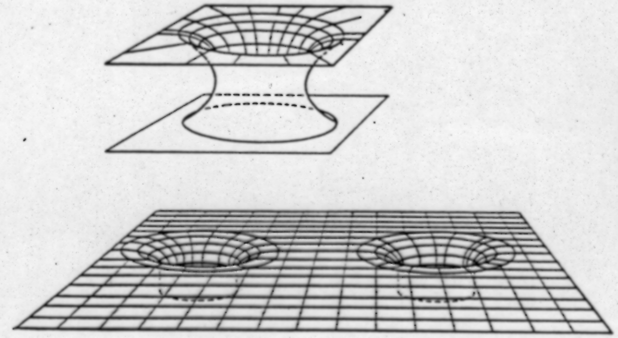


FIG. 1. Two interpretations of the 3-dimensional "maximally extended Schwarzschild metric" at the time $T=0$. Above: A connection or bridge in the sense of Einstein and Rosen between *two* otherwise Euclidean spaces. Below: A wormhole in the sense of Wheeler connecting two regions in *one* Euclidean space, in the limiting case where these regions are extremely far apart compared to the dimensions of the throat of the wormhole.

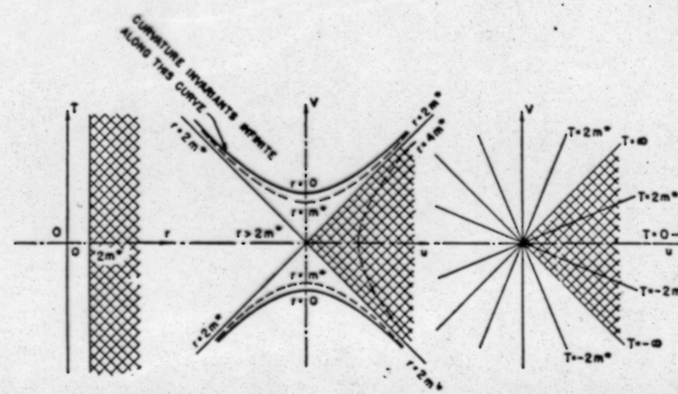


FIG. 2. Corresponding regions of the (r,T) and (u,v) planes. In the latter, curves of constant r are hyperbolas asymptotic to the lines $r=2m^*$ while T is constant on straight lines through the origin. The exterior of the singular sphere, $r>2m^*$, corresponds to the region $|v|<u$ (the hatched areas). The whole line $r=2m^*$ in the (r,T) plane corresponds to the origin $u=v=0$, while two one-dimensional families of ideal limit points with $r\to 2m^*$ and $T\to\pm\infty$ correspond to the remaining boundary points $u=|v|>0$.
In the (u,v) plane the metric is entirely regular not only in the hatched area but in the entire area between the two branches of the hyperbola $r=0$. This comprises two images of the exterior of the spherical singularity and two of its interior. (The expressions in Table II are valid in the right-hand quadrant $u>|v|$. To obtain formulas valid in the left-hand quadrant replace u and v by their negatives everywhere. To obtain formulas valid in the upper or lower quadrant replace u by $\pm v$, v by $\pm u$, and $r/2m^*-1$ by its negative everywhere. Note that the formula for r and the final formula for T remain invariant under these substitutions.) The purely radial ($d\theta=d\varphi=0$) null geodesics are lines inclined at 45°. The points with $r=2m^*$ have no local topological distinction, but still a global one: if a test particle crosses $r=2m^*$ into the interior (where r is time-like and T space-like), it can never get back out but must inevitably hit the irremovable singularity $r=0$ (curvature invariants infinite). This circumstance guarantees that one cannot violate ordinary causality in the "main universe" by sending signals via the wormhole effectively faster than light.

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Maximal Extension of Schwarzschild Metric*

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(Received December 21, 1959)

1960: Kruskal’s Extension

The physical field of GR

In the sixties the field of GR exploded

- The physical field of GR: a weak gravitational field up to the sixties.

- The field of general relativity was not different from Newton's **except with cosmology**.

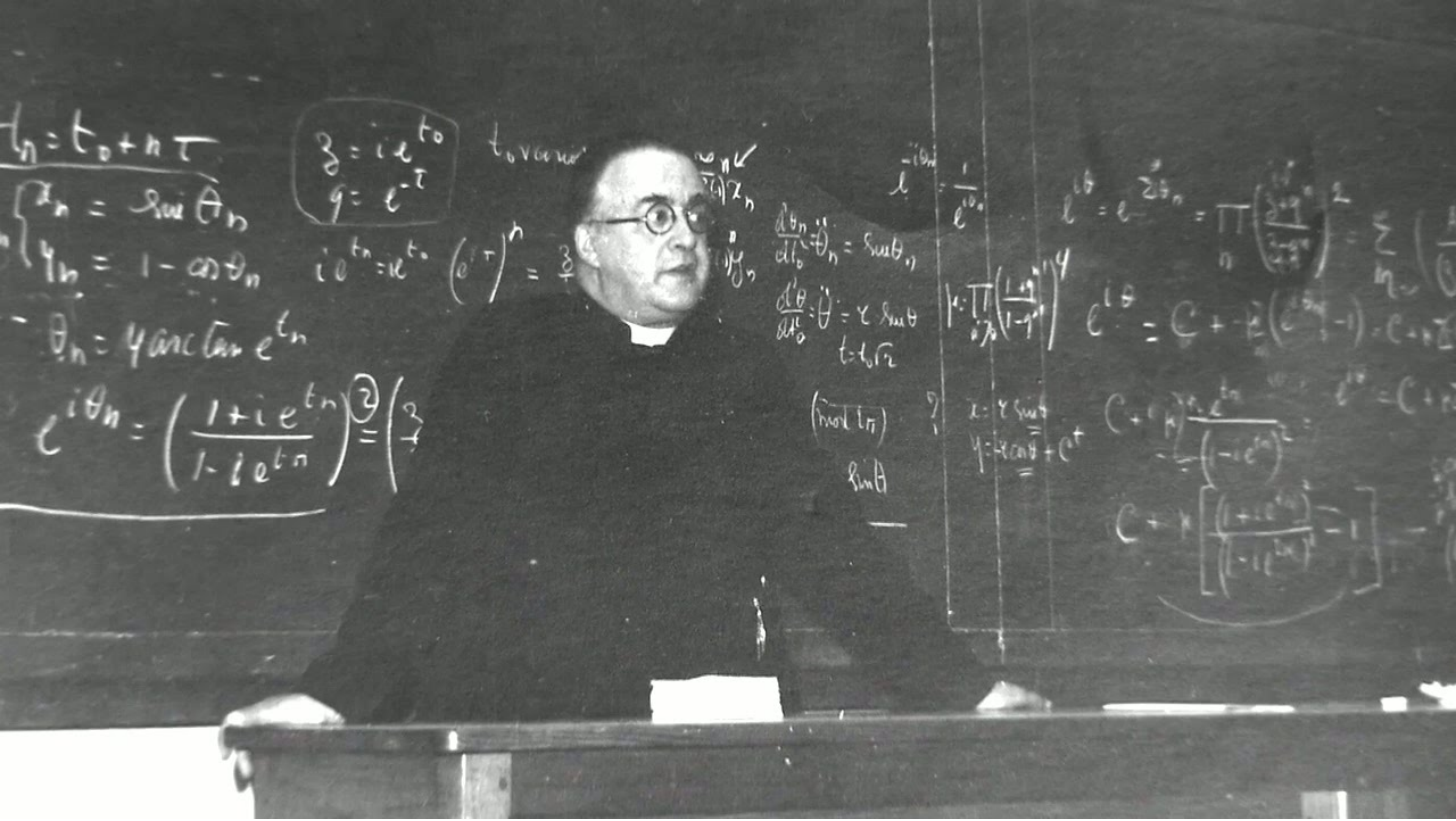
- All of the effects were of a neo-Newtonian tone.

- From 1963 general relativity was to be implicated in astrophysics.

- Its field enlarged enormously, it exploded.

1960th, the time for astrophysics and general relativity.

1929, Edwin Hubble: the universe is expanding



1931, Lemaître: the primeval atom

Ralph Alpher, Robert Herman and George Gamow predicted the cosmic microwave background

1963, Maarten Schmidt discovers the first quasar

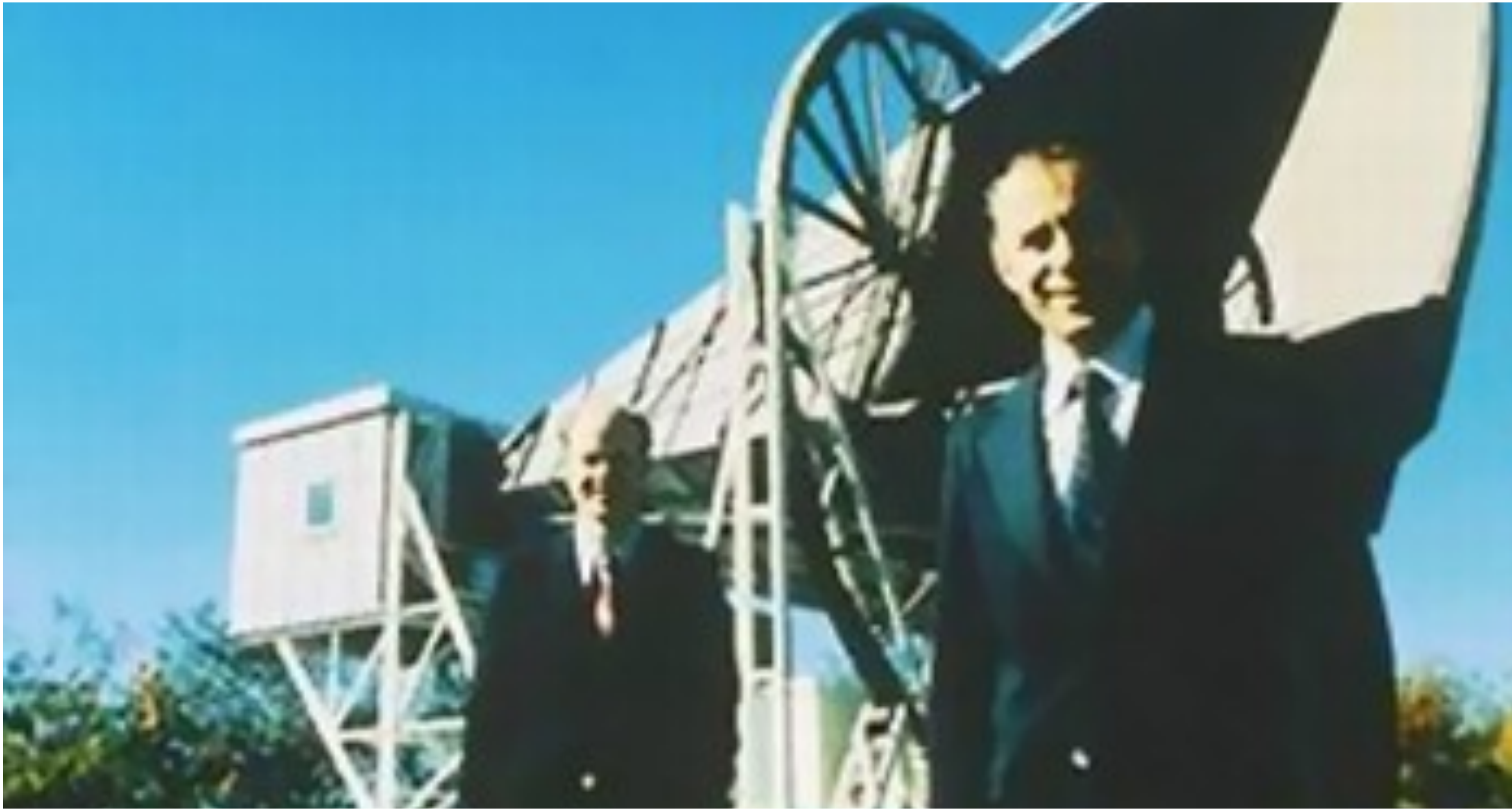
1963, The Dallas conference.

- A the Dallas Conference, quasars were at stake. Radio astronomy played a great role in their discovery.
- A mechanism to explain the energy was proposed: the gravitational collapse.
- Astrophysical technics were fondamental in the renewal of GR.

"This, of course, is a historic meeting. [...]

The relativists with their sophisticated work were not only magnificent cultural ornaments but might actually be useful to science! 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."

The Dallas conference, 1963, Thomas Gold After-Dinner Speech



1964, Arno Penzias and Robert Wilson observed the cosmic microwave background.

1967, Jocelyn Bell discovers pulsars

1974 Hulse and Taylor discovered the first binary pulsar

- "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).

- "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!

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