



A short history of gravitational waves

Edoardo Milotti

Dipartimento di Fisica - UniTS

A couple of Einstein quotes:

I always think of Michelson as the artist in science. His greatest joy seemed to come from the beauty of the experiment itself and the elegance of the method employed.

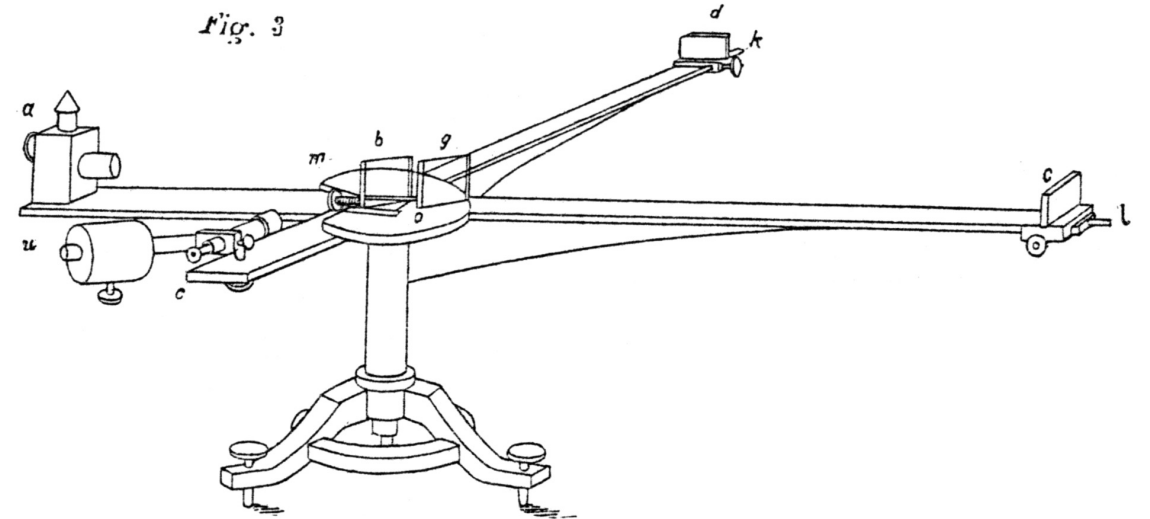
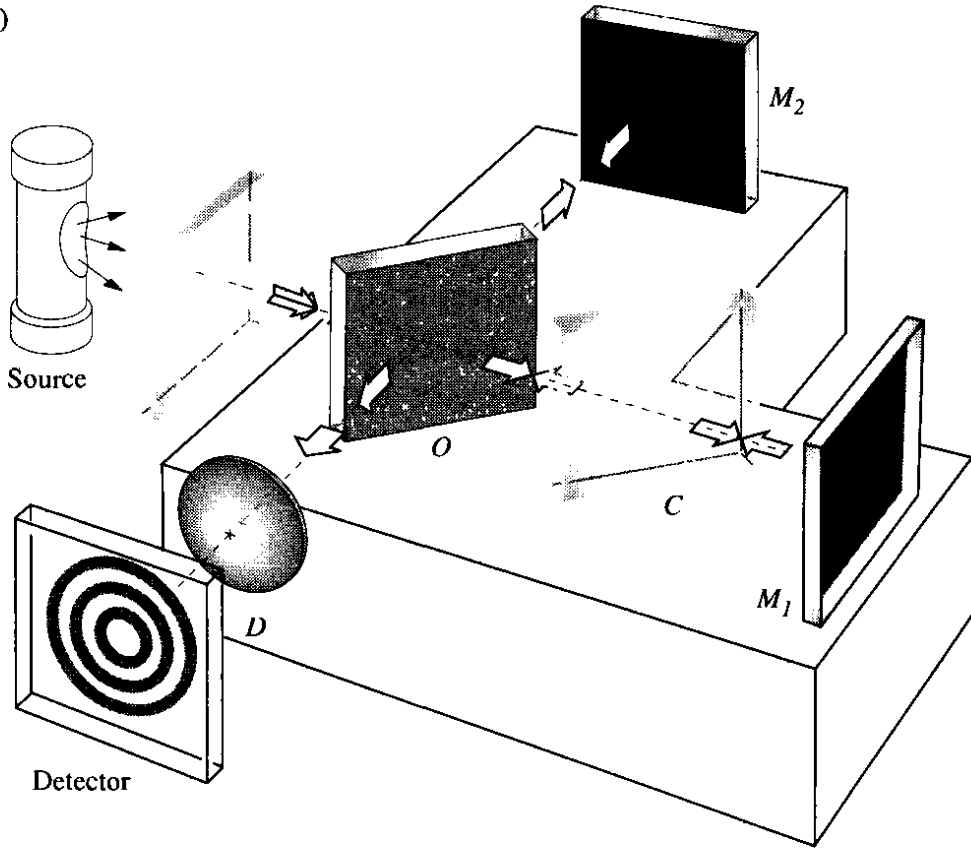
To Robert Shankland, September 17, 1953, on Albert A. Michelson, who with Edward Morley in 1881, had already experimentally validated Einstein's postulation that the speed of light is independent of the frame of reference in which it is measured. Einstein said that he was unaware of the experiment when he wrote his 1905 paper on the special theory of relativity. (from Alice Calaprice, *The Extended Quotable Einstein*, University Presses of California, 2000)

The theory is beautiful beyond comparison. However, only one colleague has really been able to understand it and [use it].

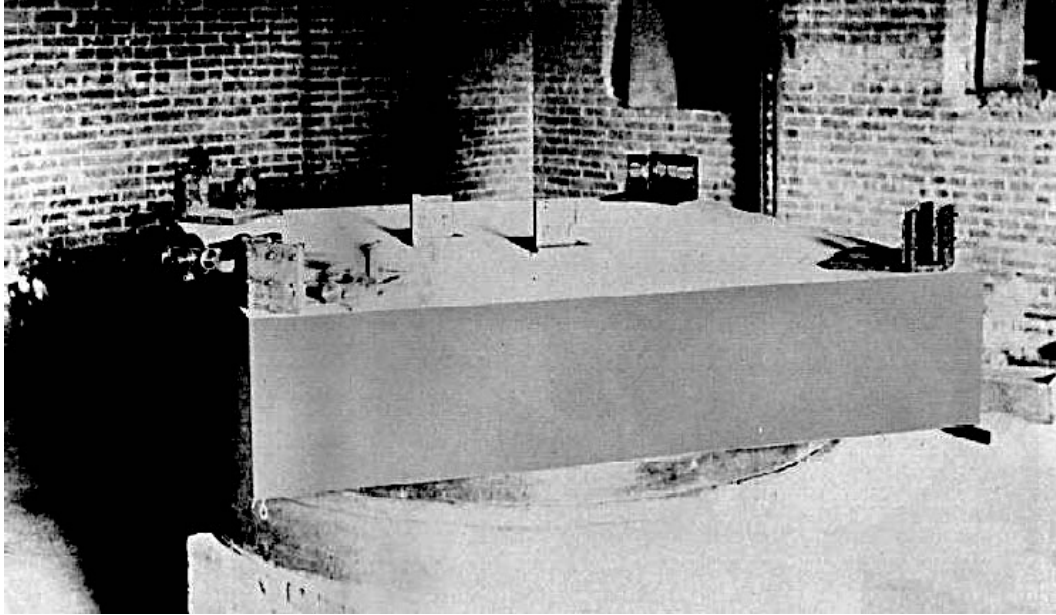
To Heinrich Zangger, November 26, 1915, regarding the reception of the general theory of relativity. *CPAE*, Vol. 8, Doc. 152. The colleague was David Hilbert. (from Alice Calaprice, *The Extended Quotable Einstein*, University Presses of California, 2000)

The Michelson interferometer

(a)



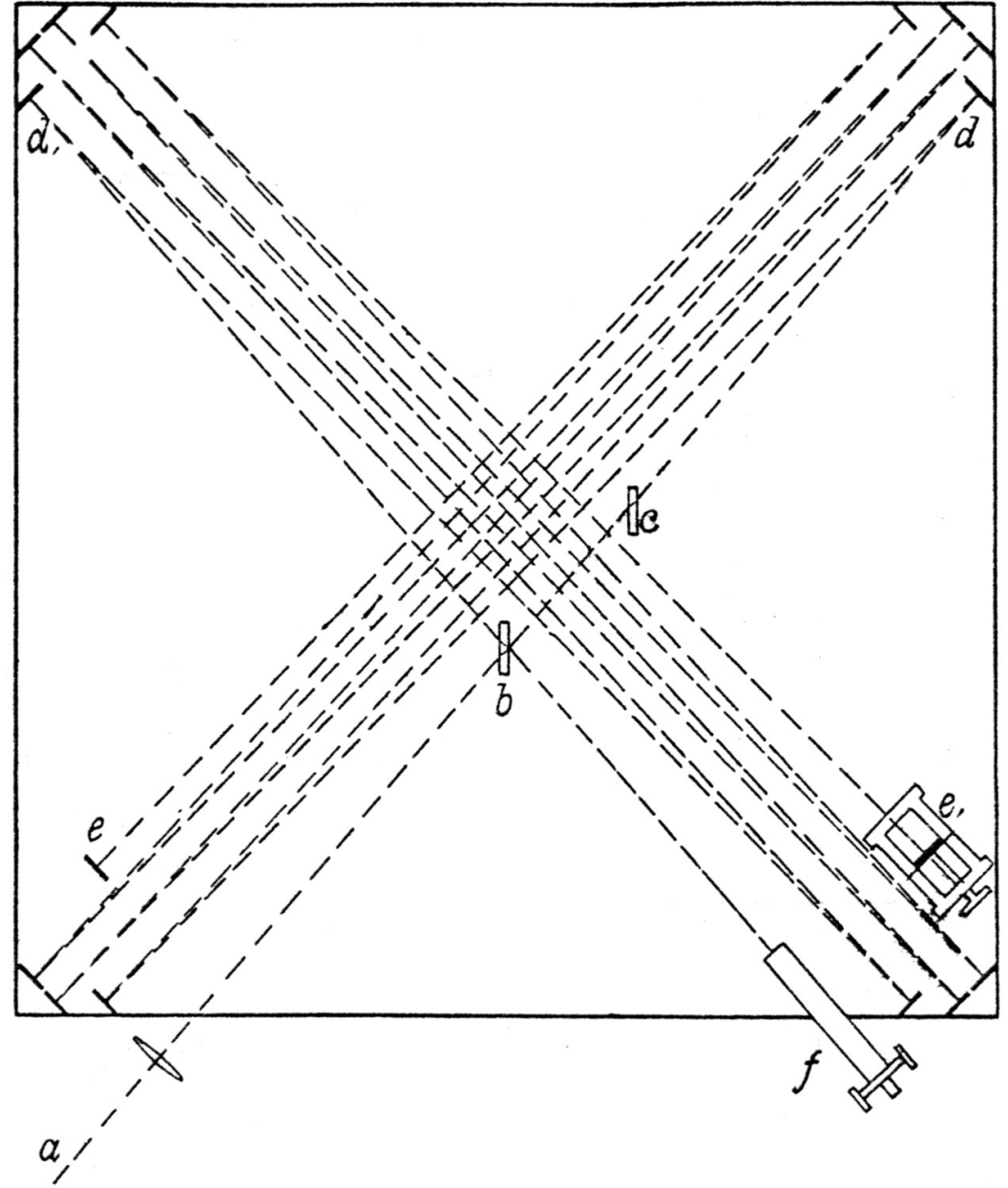
Michelson's 1881 interferometer. Although ultimately it proved incapable of distinguishing between differing theories of aether-dragging, its construction provided important lessons for the design of Michelson and Morley's 1887 instrument (from Wikipedia).



Michelson and Morley's interferometric setup, mounted on a stone slab that floats in an annular trough of mercury (from Wikipedia)

This figure illustrates the folded light path used in the Michelson–Morley interferometer that enabled a path length of 11 m.

a is the light source, an oil lamp. *b* is a beam splitter. *c* is a compensating plate so that both the reflected and transmitted beams travel through the same amount of glass (important since experiments were run with white light which has an extremely short coherence length requiring precise matching of optical path lengths for fringes to be visible; monochromatic sodium light was used only for initial alignment). *d*, *d'* and *e* are mirrors. *e'* is a fine adjustment mirror. *f* is a telescope (from Wikipedia).



Einstein and the mixing of space and time

(from Thorne, "Black holes and time warps, Einstein's outrageous legacy", Norton, 1994)

How did Einstein arrive at such a radical description of space and time?

Not by examining the results of experiments. Clocks of his era were too inaccurate to exhibit, at the low speeds available, any time dilation or disagreements about simultaneity, and measuring rods were too inaccurate to exhibit length contraction. The only relevant experiments were those few, such as Michelson and Morley's, which suggested that the speed of light on the Earth's surface might be the same in all directions. These were very skimpy data indeed on which to base such a radical revision of one's notions of space and time! ...

... Einstein relied on his own innate intuition as to how things ought to behave. After much reflection, it became intuitively obvious to him that the speed of light must be a universal constant, independent of direction and independent of one's motion. Only then, he reasoned, could Maxwell's electromagnetic laws be made uniformly simple and beautiful (for example, "magnetic field lines never ever have any ends"), and he was firmly convinced that the Universe in some deep sense insists on having simple and beautiful laws. He therefore introduced, as a new principle on which to base all of physics, his principle of the absoluteness of the speed of light.

This principle by itself, without anything else, already guaranteed that the edifice of physical laws built on Einstein's foundation would differ profoundly from that of Newton. *A Newtonian physicist, by presuming space and time to be absolute, is forced to conclude that the speed of light is relative—it depends on one's state of motion. Einstein, by presuming the speed of light to be absolute, was forced to conclude that space and time are relative—they depend on one's state of motion. Having deduced that space and time are relative, Einstein was then led onward by his quest for simplicity and beauty to his principle of relativity: No one state of motion is to be preferred over any other; all states of motion must be equal, in the eyes of physical law.*

Not only was experiment unimportant in Einstein's construction of a new foundation for physics, the ideas of other physicists were also unimportant. He paid little attention to others' work. He seems not even to have read any of the important technical articles on space, time, and the aether that Hendrik Lorentz, Henri Poincaré, Joseph Larmor, and others wrote between 1896 and 1905.

In their articles, Lorentz, Poincaré, and Larmor were groping toward the same revision of our notions of space and time as Einstein, but they were groping through a fog of misconceptions foisted on them by Newtonian physics. Einstein, by contrast, was able to cast off the Newtonian misconceptions. His conviction that the Universe loves simplicity and beauty, and his willingness to be guided by this conviction, even if it meant destroying the foundations of Newtonian physics, led him, with a clarity of thought that others could not match, to his new description of space and time.

A short history of gravitational waves

(mostly based and adapted on Tony Rothman's paper <https://www.americanscientist.org/article/the-secret-history-of-gravitational-waves>)

- In 1687 Newton introduces gravitational attraction with *action-at-a-distance*

"that one body may act on another at a distance through a vacuum, without the mediation of anything else ... is to me so great an absurdity, that I believe no man, who has in philosophical matters a competent faculty for thinking, can ever fall into it." (excerpt of a letter from Newton to theologian Richard Bentley, see <https://www.newtonproject.ox.ac.uk/view/texts/normalized/THEM00258>)

- The problem with Newton's theory of gravitation is that propagation of the effects is *instantaneous*, and this forbids waves of any kind (**why?**)

The Long Path to Gravitational Waves

The image shows a horizontal timeline of scientists and their contributions to the theory of gravity. It starts with Isaac Newton in 1687, followed by James Clerk Maxwell in 1865, Oliver Heaviside in 1893, Henri Poincaré in 1905, Max Abraham in 1912, Gustav Mie in 1912, Gunnar Nordström in 1912-13, Karl Schwarzschild in 1916, Johannes Droste in 1916, and Albert Einstein in 1918. The timeline is set against a dark blue background with a bright light source at the bottom center. On the far left and right, there are images of the covers of Newton's 'Philosophiæ Naturalis Principia Mathematica' and Einstein's 'Die Gravitationsfelder'.

Year	Scientist
1687	ISAAC NEWTON
1865	JAMES CLERK MAXWELL
1893	OLIVER HEAVISIDE
1905	HENRI POINCARÉ
1912	MAX ABRAHAM
1912	GUSTAV MIE
1912-13	GUNNAR NORDSTRÖM
1916	KARL SCHWARZSCHILD
1916	JOHANNES DROSTE
1918	ALBERT EINSTEIN

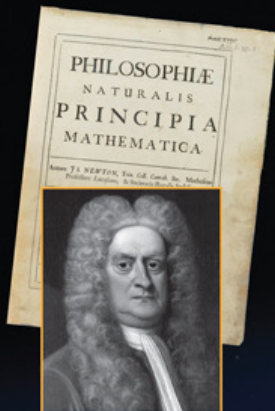
- Any further progress on waves had to wait for the theory of hydrodynamics and the developments in electrodynamics (Maxwell)

"After tracing to the action of the surrounding medium both the magnetic and the electric attractions and repulsions [oscillations]...we are naturally led to inquire whether the attraction of gravitation, which follows the same law of the distance, is not also traceable to the action of a surrounding medium [i.e., can gravity be associated with a field?]."

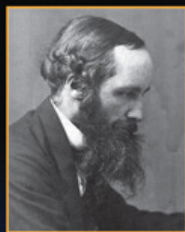
Gravitation differs from magnetism and electricity in this; that the bodies concerned are all of the same kind, instead of being of opposite signs, like magnetic poles and electrified bodies, and that the force between these bodies is an attraction and not a repulsion, as is the case between like electric and magnetic bodies."

(J.C.Maxwell, "VIII. A dynamical theory of the electromagnetic field", Phil. Trans. Royal Soc., <https://royalsocietypublishing.org/doi/10.1098/rstl.1865.0008>)

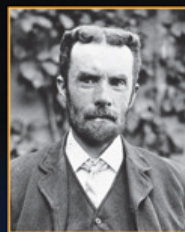
The Long Path to Gravitational Waves



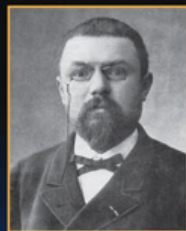
1687
ISAAC NEWTON



1865
JAMES CLERK
MAXWELL



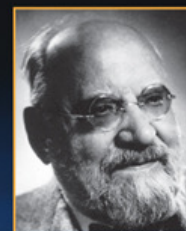
1893
OLIVER HEAVISIDE



1905
HENRI POINCARÉ



1912
MAX ABRAHAM



1912
GUSTAV MIE



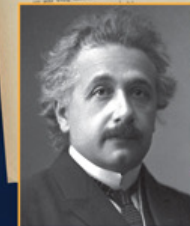
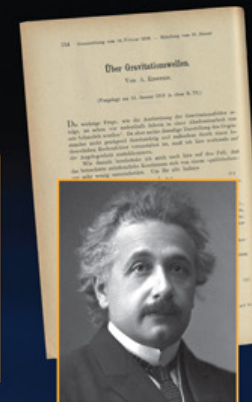
1912–13
GUNNAR
NORDSTRÖM



1916
KARL
SCHWARZSCHILD



1916
JOHANNES DROSTE



1918
ALBERT EINSTEIN

- Vector gravitational theory by Oliver Heaviside (1893). Heaviside's paper may be the first to have seriously treated the topic of gravitational waves. (see, e.g., <https://arxiv.org/abs/1709.06876>)
- Subsequently, Heaviside found that the field propagates at finite speed. The nondetection of gravitational perturbations set an upper limit to this speed, likely the same as the speed of light.
- The concept of a finite speed of gravity was hardly new, Laplace had already suggested it as early as the 1770s (although not in a wave context)

Field Equations of Heaviside Gravity (HG)

$$\nabla \cdot \mathbf{g} = -4\pi G\rho_0 = -\rho_0/\epsilon_{0g},$$

$$\nabla \times \mathbf{b} = \frac{4\pi G}{c_g^2} \mathbf{j} - \frac{1}{c_g^2} \frac{\partial \mathbf{g}}{\partial t} = \mu_{0g} \mathbf{j} - \frac{1}{c_g^2} \frac{\partial \mathbf{g}}{\partial t},$$

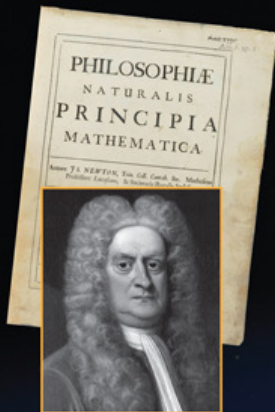
$$\nabla \cdot \mathbf{b} = 0,$$

$$\nabla \times \mathbf{g} = \frac{\partial \mathbf{b}}{\partial t}.$$

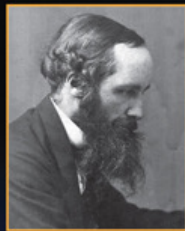
where

$$\epsilon_{0g} = \frac{1}{4\pi G}, \quad \mu_{0g} = \frac{4\pi G}{c_g^2} \quad \Rightarrow \quad c_g = \frac{1}{\sqrt{\epsilon_{0g}\mu_{0g}}}$$

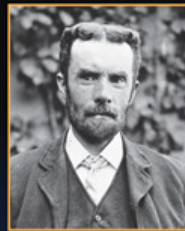
The Long Path to Gravitational Waves



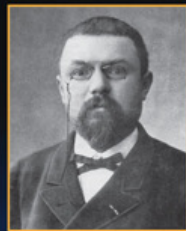
1687
ISAAC NEWTON



1865
JAMES CLERK
MAXWELL



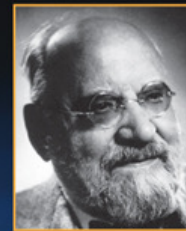
1893
OLIVER HEAVISIDE



1905
HENRI POINCARÉ



1912
MAX ABRAHAM



1912
GUSTAV MIE



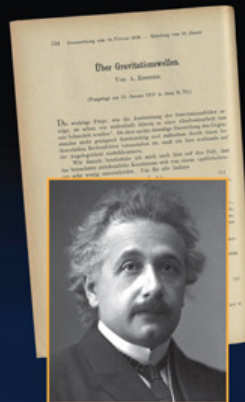
1912–13
GUNNAR
NORDSTRÖM



1916
KARL
SCHWARZSCHILD



1916
JOHANNES DROSTE



1918
ALBERT EINSTEIN

- In 1901, Jonathan Zenneck wrote an article on gravitation for a German encyclopedia. He surveyed multiple proposals to modify Newtonian gravity to make it more closely resemble Maxwellian electromagnetism, which by then many natural philosophers believed was the basis of all physics.

Zenneck described the work of several contemporaries who assumed that gravitational effects propagated at the speed of light. Some proposals were designed to explain the notorious riddle of Mercury's perihelion shift: The longitude of the planet's closest approach to the Sun kept advancing by the small but mysterious angle of 43 seconds of arc per century, and no known Newtonian forces could account for it.

One modified theory of gravity, devised by the German physicist Paul Gerber (1854–1909), astoundingly gave the correct answer for Mercury's movements. However, none of the schemes mentioned in the encyclopedia article resembled a modern relativistic theory of gravity.

Zenneck lamented, *"All attempts to connect gravitation with other phenomena in a satisfying way are to be regarded as unsuccessful or as yet not adequately established."*

The Long Path to Gravitational Waves

1687
ISAAC NEWTON

1865
JAMES CLERK
MAXWELL

1893
OLIVER HEAVISIDE

1905
HENRI POINCARÉ

1912
MAX ABRAHAM

1912
GUSTAV MIE

1912–13
GUNNAR
NORDSTRÖM

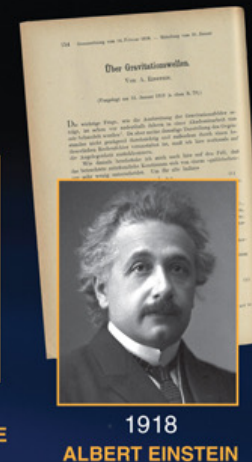
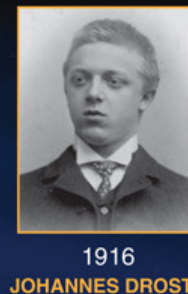
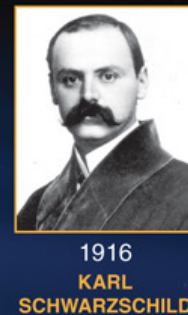
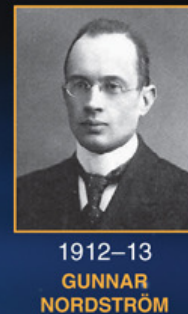
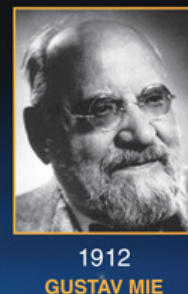
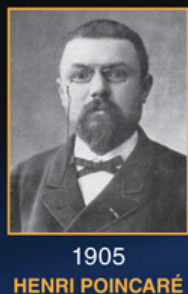
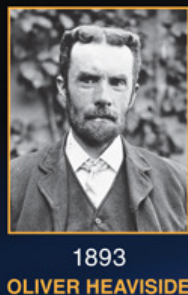
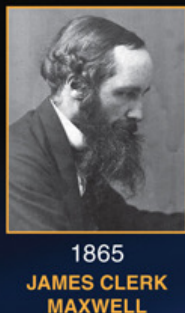
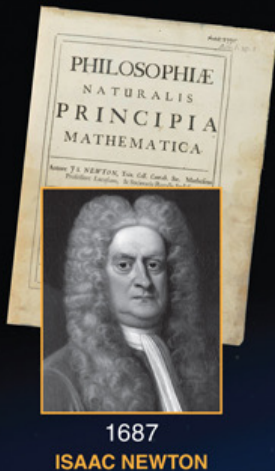
1916
KARL
SCHWARZSCHILD

1916
JOHANNES DROSTE

1918
ALBERT EINSTEIN

- The special relativity paper is one of the papers published by Einstein in his *annus mirabilis* (1905), "*Zur Elektrodynamik bewegeter Körper*" ("*On the electrodynamics of moving bodies*")
(German original, <https://onlinelibrary.wiley.com/doi/10.1002/andp.19053221004>)
- In his 1905 paper, Einstein unified electric and magnetic field. The basic physical postulates are 1) the invariance of physical laws in inertial frames; 2) the invariance of the speed of light.
- Einstein's paper is not isolated in the physics literature of the late 19th – early 20th century. E.g., it was preceded by Lorentz's papers and it was paralleled by Poincaré's studies (although Einstein retains the priority on SR, especially because of his deep physical insights) (see also Damour's paper on Poincaré, <https://www.sciencedirect.com/science/article/pii/S1631070517300762>)

The Long Path to Gravitational Waves



- In 1907, Einstein had what he called "the luckiest thought" of his life, "there is no way to discriminate between acceleration due to motion and acceleration due to a gravitational field" (principle of equivalence).

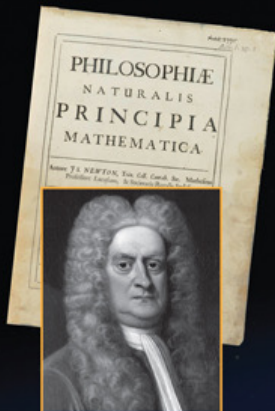
This means that SR cannot be extended to explain gravity (as some of his competitors were attempting to do). Conversely, this also means that a theory that includes accelerated frames would also provide a theory of gravity.

- In a 1911 paper, Einstein took the first step, using equivalence to demonstrate that photons must gain energy as they fall toward a gravitating body and lose energy as they climb away from it.

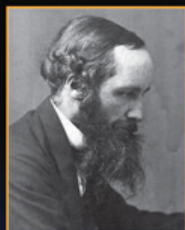
Light emitted by a massive body is stretched, resulting in a gravitational redshift, a phenomenon inconsistent with gravity-free SR. Clocks at different heights above a gravitating body likewise tick at different rates.

As a result – or so Einstein initially believed – the speed of light must change in a gravitational field.

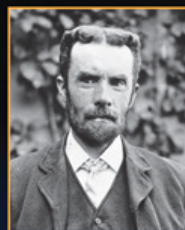
The Long Path to Gravitational Waves



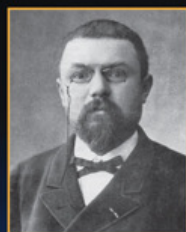
1687
ISAAC NEWTON



1865
JAMES CLERK
MAXWELL



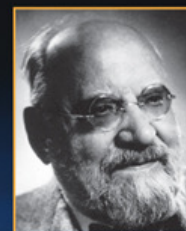
1893
OLIVER HEAVISIDE



1905
HENRI POINCARÉ



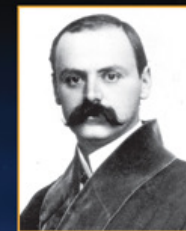
1912
MAX ABRAHAM



1912
GUSTAV MIE



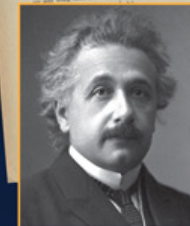
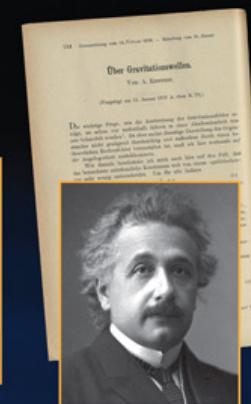
1912–13
GUNNAR
NORDSTRÖM



1916
KARL
SCHWARZSCHILD



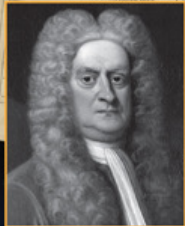
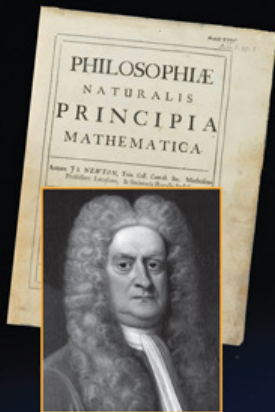
1916
JOHANNES DROSTE



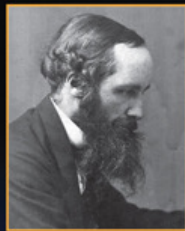
1918
ALBERT EINSTEIN

- A variable speed of light did not survive in GR, but Einstein’s thinking had an immediate impact on Max Abraham. Abraham (1875–1922) is remembered largely as having fallen on the wrong side of history by bitterly opposing both Einstein’s SR and GR. During his lifetime, though, he was widely acknowledged as a leading physicist, especially in matters of electromagnetism, which he believed was the foundation of all reality.
- In 1912, Abraham published a theory of gravity in which he modified SR (somewhat inconsistently) to include a variable speed of light along the lines Einstein had proposed. Abraham’s scheme was what we call a scalar theory.
- Abraham’s scalar was the gravitational potential energy of the field itself. In Abraham’s theory, an accelerating mass emits gravitational radiation, which he discussed extensively early in 1912 at a conference in Italy – a lecture which later that year was published in the journal *Nuovo Cimento*. It may well have been the world’s second paper devoted to gravitational waves.

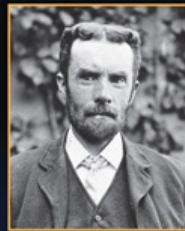
The Long Path to Gravitational Waves



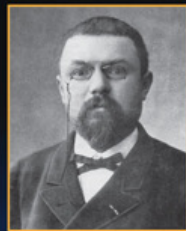
1687
ISAAC NEWTON



1865
JAMES CLERK
MAXWELL



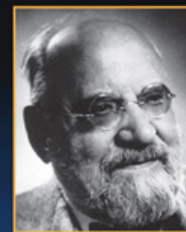
1893
OLIVER HEAVISIDE



1905
HENRI POINCARÉ



1912
MAX ABRAHAM



1912
GUSTAV MIE



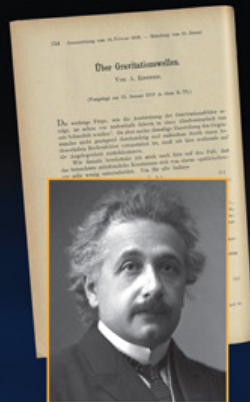
1912–13
GUNNAR
NORDSTRÖM



1916
KARL
SCHWARZSCHILD



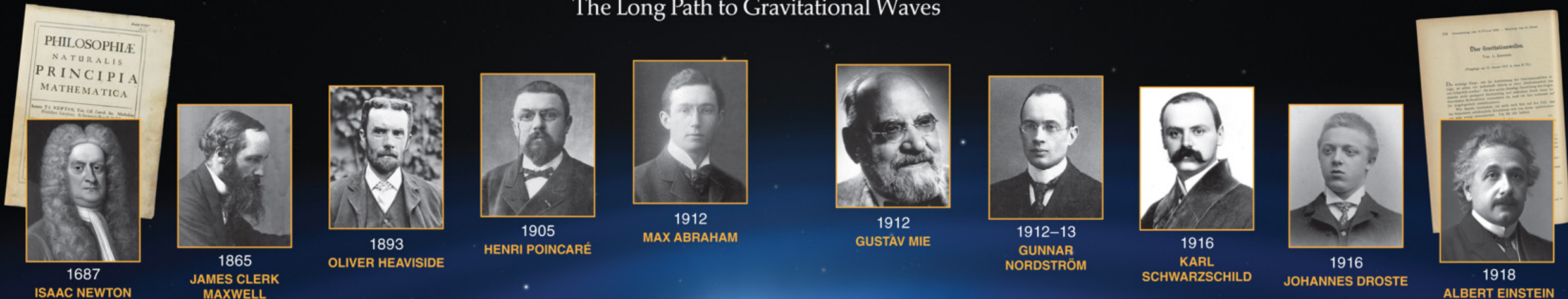
1916
JOHANNES DROSTE



1918
ALBERT EINSTEIN

- Abraham realized that the waves produced by his theory were longitudinal. By contrast, EM waves are transverse, meaning that the waves vibrate in a direction perpendicular to the direction of propagation. It turns out that gravitational waves are transverse as well, so Abraham didn't get it right.
- Even as Abraham discussed gravitational waves in relation to EM waves, he understood that the comparison was not entirely legitimate. By far the dominant type of electromagnetic radiation is dipole radiation, and one might think that if a single mass were accelerated it should analogously emit gravitational dipole radiation. However, Abraham noted that the law of conservation of momentum would forbid a single mass from accelerating without a second mass accelerating in the opposite direction. That correct conclusion forbade the existence of any gravitational dipole radiation, leading him to declare that the hope to observe gravitational waves "is futile."
- Along the way, Abraham had another gravitational insight: he anticipated the German physicist Karl Schwarzschild by predicting what we now call the "Schwarzschild radius" — the size of the event horizon of a black hole.

The Long Path to Gravitational Waves



NO GRAVITATIONAL DIPOLE RADIATION!

$$\mathbf{d} = \sum_i m_i \mathbf{r}_i$$

Mass dipole



$$\frac{d\mathbf{d}}{dt} = \sum_i m_i \mathbf{v}_i = \sum_i \mathbf{p}_i = \text{constant}$$

Conservation of total momentum



$$\frac{d^2\mathbf{d}}{dt^2} = \sum_i m_i \mathbf{a}_i = \mathbf{0}$$

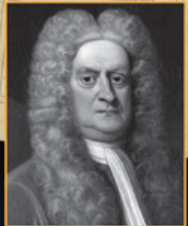
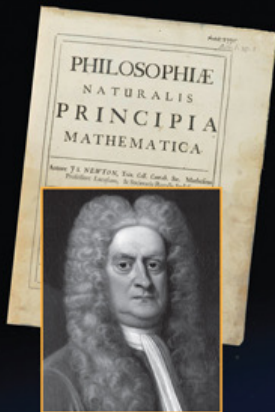
Therefore, there is no gravitational dipole radiation equivalent to the EM dipole radiation!

- Einstein and Abraham were not alone. The German physicist Gustav Mie (1868 – 1957) also contributed to the scientific ferment. Today, Mie is remembered primarily for his theory of light scattering off spherical particles. A century ago, his overarching goal was to create a unified field theory that explained electromagnetism, gravitation, and matter by means of a single “world function” from which all else followed.
- Mie’s work was so vast that apparently few people noticed that chapter 5 of his opus on unified field theory contains a theory of gravity. His proposal retains a constant speed of light, and with it the principles of SR, but in many respects it is quite similar to Abraham’s. It is a scalar theory, and, like Abraham’s, it predicts longitudinal gravitational waves propagating at the speed of light.

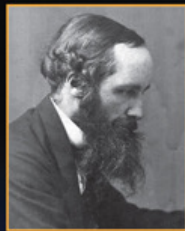
Mie does not appear to realize that gravitational dipole radiation is forbidden, but he does conclude that *“The gravitational radiation emitted by oscillating electrons (or by any oscillating mass particle) is so extraordinarily weak that it is unthinkable ever to detect it by any means whatsoever [Mie’s italics].”*

In his view, *“if one could ever prove the existence of gravitational waves, the processes responsible for their generation would probably be much more curious and interesting than even the waves themselves.”*

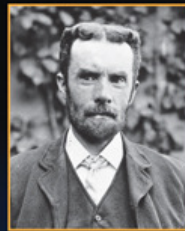
The Long Path to Gravitational Waves



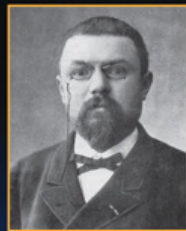
1687
ISAAC NEWTON



1865
JAMES CLERK
MAXWELL



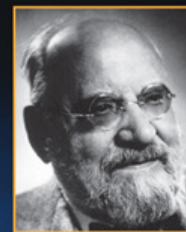
1893
OLIVER HEAVISIDE



1905
HENRI POINCARÉ



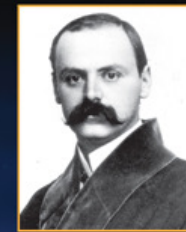
1912
MAX ABRAHAM



1912
GUSTAV MIE



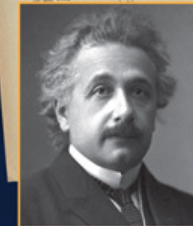
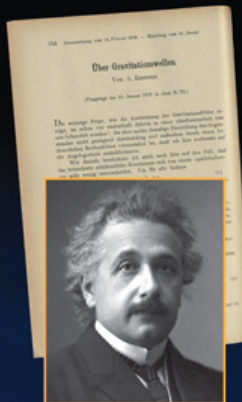
1912–13
GUNNAR
NORDSTRÖM



1916
KARL
SCHWARZSCHILD



1916
JOHANNES DROSTE



1918
ALBERT EINSTEIN

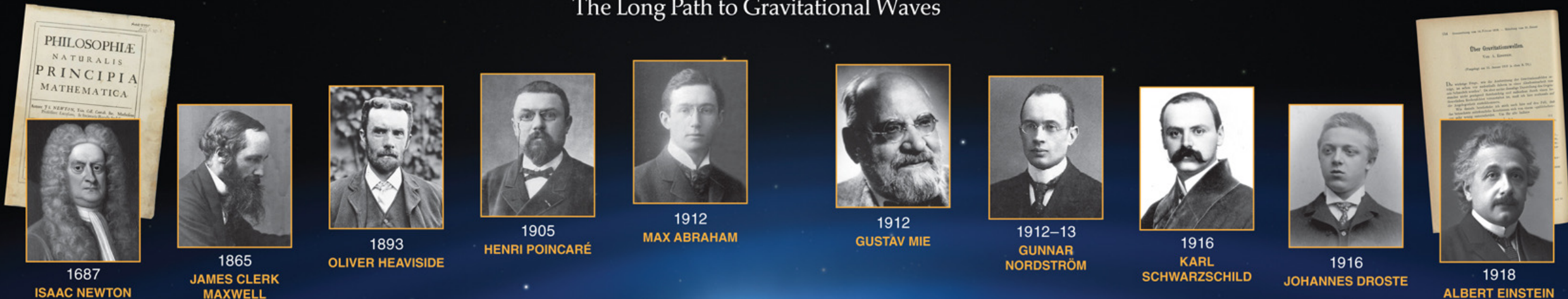
- Einstein – not yet world-famous, but already a towering figure in physics – gave short shrift to Abraham and failed to mention Mie at all in a 1913 lecture, “On the Present State of the Problem of Gravitation,” presented at the 85th Naturforscherversammlung (Congress of Natural Philosophers) in Vienna.

That omission led to a lively exchange during the discussion afterward. Mie complained about being overlooked, while admitting that *“my theory is tucked away in a comprehensive work on the theory of matter in general, and for that reason my investigation probably escaped Mr. Einstein’s notice.”*

“No, no,” Einstein interjected, showing that he was at least aware of Mie’s work. In his full response, Einstein admitted that he had not read Mie *“as attentively as perhaps would have been good, but I had not the slightest intention of disparaging Mie’s theory by not mentioning it.”*

But Einstein does not retreat: He didn’t mention Mie’s work, he explains, because in it all masses do not fall at the same rate in a gravitational field; Mie violated the principle of equivalence. Consequently, *“it would have been illogical of me to start from certain postulates and then not adhere to them.”* As for Abraham, Einstein stated that his theory violated the basic premises of relativity.

The Long Path to Gravitational Waves



- Einstein displayed far more appreciation for the work of the young Finnish physicist Gunnar Nordström (1881–1923) and spent a large portion of his lecture explaining his theory.

Nordström is remembered among relativists as the independent codiscoverer, along with the German engineer Hans Reissner, of the “Reissner- Nordström metric.” That metric was an early solution to the equations of general relativity that, like the more famous solution discovered by Karl Schwarzschild, describes spacetime around a black hole – except that in the Reissner-Nordström case, the black hole is electrically charged.

- A friendly competitor and sometime collaborator of Einstein’s, Nordström – observing the ongoing clash between Einstein and Abraham— created two different gravitational theories in 1912–1913, the second of which Einstein showcased in Vienna.

Textbooks and popular accounts universally claim that Einstein was the first to equate the geometry of spacetime with the matter affecting that geometry, demonstrating the revolutionary idea that mass and geometry are intimately connected. In truth, that honor belongs to Nordström, who had created the first consistent field theory of gravity.

The Long Path to Gravitational Waves

Year	Scientist
1687	ISAAC NEWTON
1865	JAMES CLERK MAXWELL
1893	OLIVER HEAVISIDE
1905	HENRI POINCARÉ
1912	MAX ABRAHAM
1912	GUSTAV MIE
1912–13	GUNNAR NORDSTRÖM
1916	KARL SCHWARZSCHILD
1916	JOHANNES DROSTE
1918	ALBERT EINSTEIN

- Like the theory of GR that was to come, Nordström's theory allowed matter to curve spacetime, albeit in a mathematically more restrictive sense. It was still a scalar theory, like Abraham's had been, but in it the speed of light remained strictly constant and the principle of equivalence was respected. All in all, Nordström's formulation resembles Einstein's general relativity closely enough that it is still occasionally enlisted for illustrative purposes because it is much simpler.

(see, e.g., <https://arxiv.org/abs/gr-qc/0405030>)

- In available documents, Nordström did not explicitly discuss gravitational waves. His theory did predict them, however; his field equation is precisely an equation for transverse gravitational waves.

The main problem with Nordström's theory was that it turned out to be wrong. It incorrectly predicted that light would go undeflected by the Sun's gravity, and it gave the wrong direction for the Mercury's perihelion shift. Whether Nordström remained mute on the subject of gravitational waves because of Abraham's conclusions is unclear. What is clear is that the time was ripe for GR.

The Long Path to Gravitational Waves

Year	Figure
1687	ISAAC NEWTON
1865	JAMES CLERK MAXWELL
1893	OLIVER HEAVISIDE
1905	HENRI POINCARÉ
1912	MAX ABRAHAM
1912	GUSTAV MIE
1912-13	GUNNAR NORDSTRÖM
1916	KARL SCHWARZSCHILD
1916	JOHANNES DROSTE
1918	ALBERT EINSTEIN

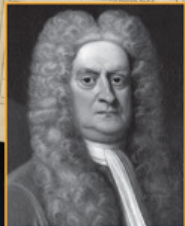
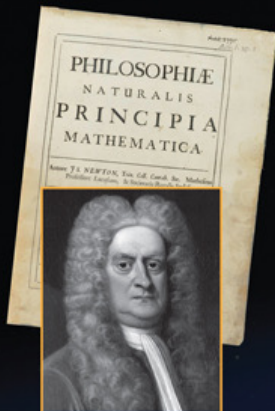
- In Einstein’s monumental 1916 paper announcing the completion of GR, one of the first things he did was to return to the problem of Mercury’s perihelion – and he got the orbital shift exactly right.

There was no mention of gravitational waves in the paper, however. Strangely, it appears that Einstein did not believe in them at the time. On February 19, 1916, he replied to a letter from Schwarzschild, which has not survived, but Einstein’s response makes fairly clear his feelings about the subject: *“There are no gravitational waves analogous to light waves.”*

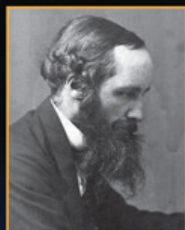
- Regardless, within a few months Einstein produced his own paper on the topic, “Approximate Integration of the Field Equations of Gravitation.” In it, he gave no more evidence than his predecessors that he believed gravitational waves would ever be detected.

He also arrived at the erroneous conclusion that an oscillating spherical mass would produce gravitational radiation in a form known as monopole radiation, something that is forbidden even in EM.

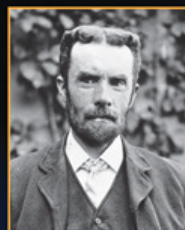
The Long Path to Gravitational Waves



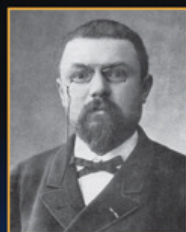
1687
ISAAC NEWTON



1865
JAMES CLERK
MAXWELL



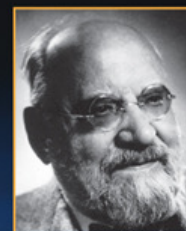
1893
OLIVER HEAVISIDE



1905
HENRI POINCARÉ



1912
MAX ABRAHAM



1912
GUSTAV MIE



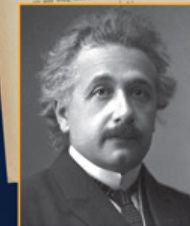
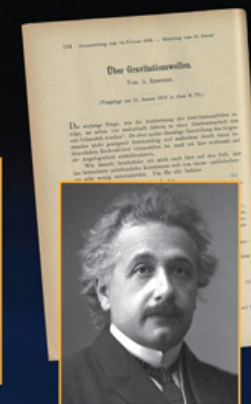
1912–13
GUNNAR
NORDSTRÖM



1916
KARL
SCHWARZSCHILD

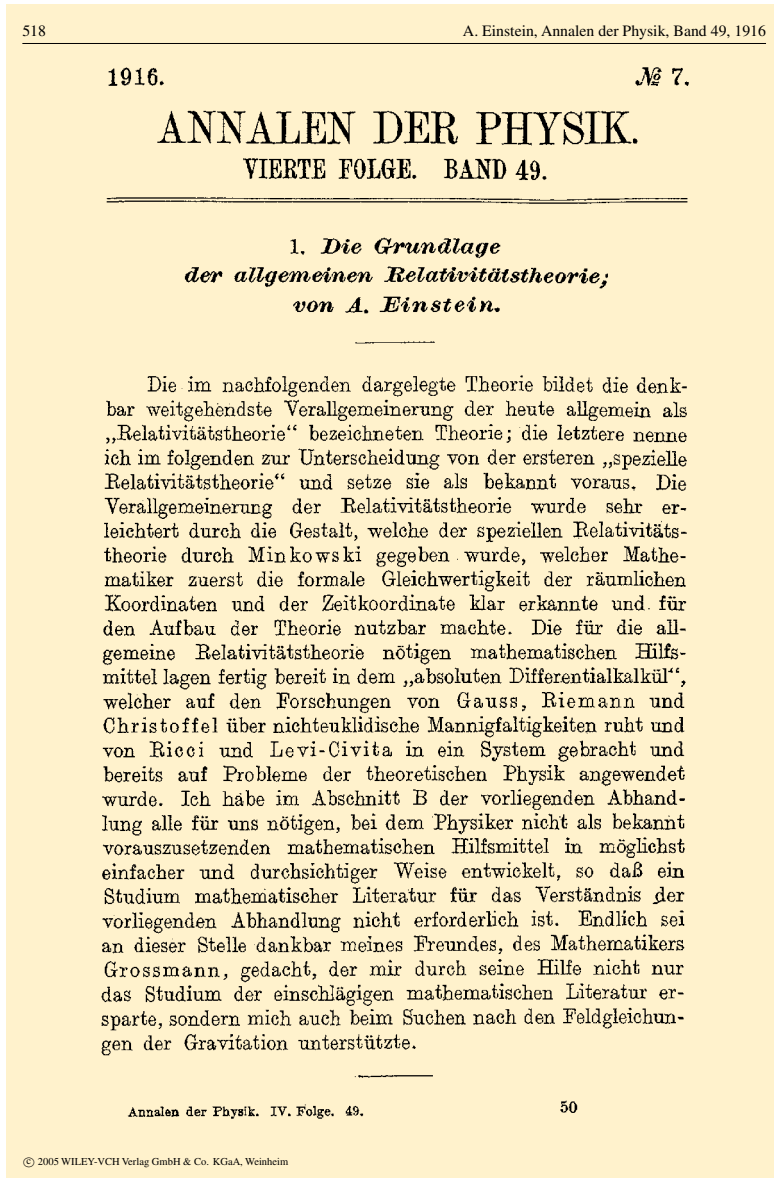


1916
JOHANNES DROSTE



1918
ALBERT EINSTEIN

March 1916, first successful description of General Relativity by Albert Einstein



Näherungsweise Integration der Feldgleichungen der Gravitation.

VON A. EINSTEIN.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist. Ich wurde hierauf aufmerksam durch eine briefliche Mitteilung des Astronomen DE SITTER, der fand, daß man durch eine andere Wahl des Bezugssystems zu einem einfacheren Ausdruck des Gravitationsfeldes eines ruhenden Massenpunktes gelangen kann, als ich ihn früher gegeben hatte¹. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

¹ Sitzungsber. XLVII, 1915, S. 833.

In his June 1916 paper, Einstein predicts important static phenomena, like the deflection of light, but he also introduces the analogy with electromagnetism.

Soon after the first paper, another Einstein paper is published, where he pushes the analogy further.

Just like the Maxwell theory predicted gravitational waves, General Relativity predicts the existence of gravitational waves.

... We shall show that these quantities $\gamma_{\mu\nu}$ can be computed just like the retarded potentials in electrodynamics. We shall use the general solution to study gravitational waves and their manifestations

Einstein's January 1918 paper corrects the mistakes in the June 1916 GW paper.

Über Gravitationswellen.

VON A. EINSTEIN.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden¹. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber LORENTZ-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen² Feldgleichungen

$$\begin{aligned} -\sum_{\alpha} \frac{\partial}{\partial x_{\alpha}} \left\{ \begin{matrix} \mu\nu \\ \alpha \end{matrix} \right\} + \sum_{\alpha} \frac{\partial}{\partial x_{\nu}} \left\{ \begin{matrix} \mu\alpha \\ \alpha \end{matrix} \right\} + \sum_{\alpha\beta} \left\{ \begin{matrix} \mu\alpha \\ \beta \end{matrix} \right\} \left\{ \begin{matrix} \nu\beta \\ \alpha \end{matrix} \right\} - \sum_{\alpha\beta} \left\{ \begin{matrix} \mu\nu \\ \alpha \end{matrix} \right\} \left\{ \begin{matrix} \alpha\beta \\ \beta \end{matrix} \right\} \\ = -\kappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \end{aligned} \quad (2)$$

¹ Diese Sitzungsber. 1916, S. 688 ff.

² Von der Einführung des » γ -Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

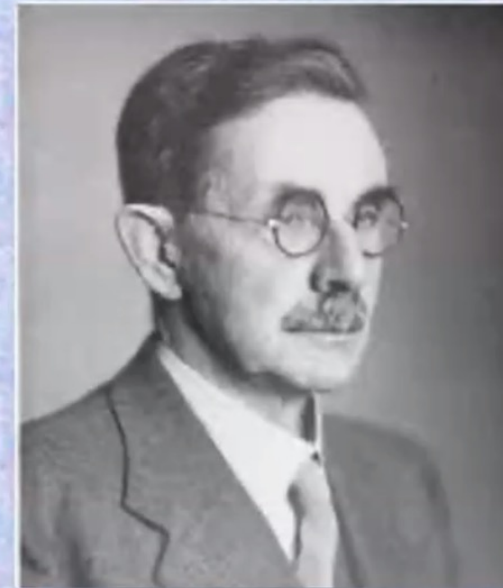
The 1919 Eclipse Expedition



Sir Frank Dyson



Arthur S. Eddington



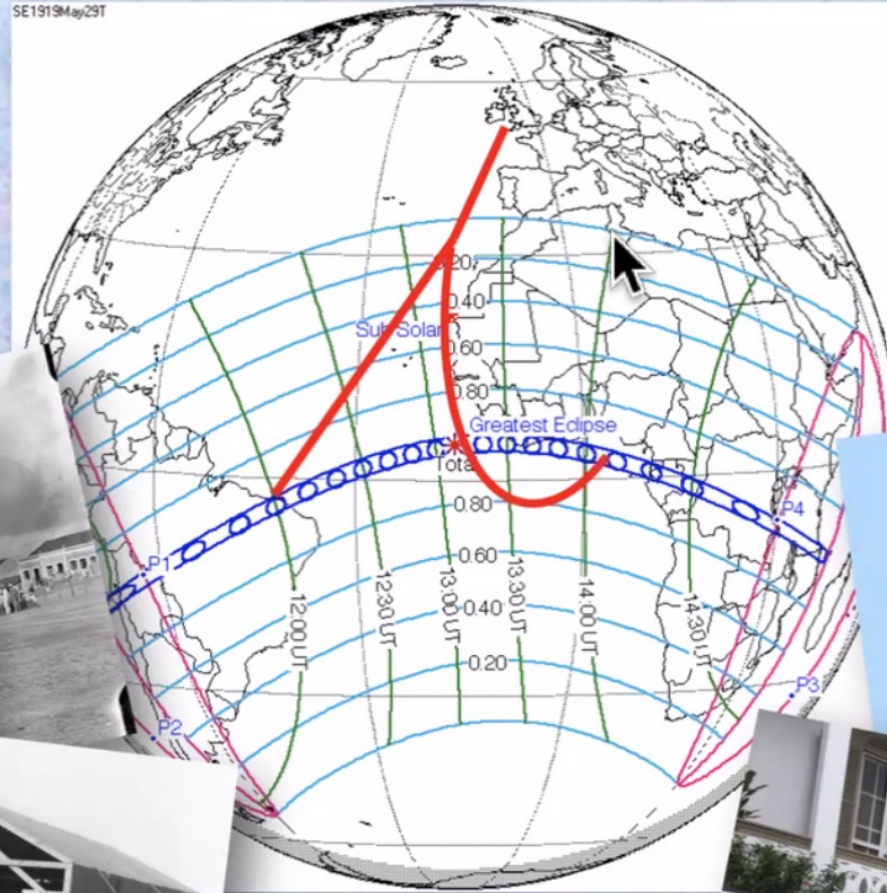
Charles R. Davidson

- 1916 - De Sitter sends Einstein's papers to Eddington
- 1917 - Eddington prepares report on GR for London Physical Society
- 1917 - Dyson & Eddington start planning, get £1,000 grant
- 1918 - Eddington almost drafted for WW I
- 1918 - Nov. 11 - war ends
- 1919 - April departure for Sobral and Principe

The 1919 Eclipse Expedition

Davidson &
Crommelin
@ Sobral

Eddington &
Cottingham
@ Principe



The 1919 Eclipse Expedition

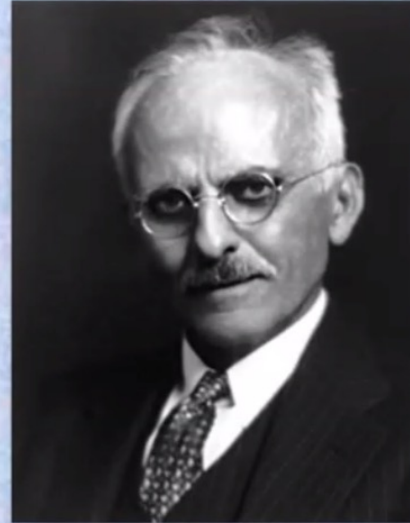
The Sobral Measurements

- 4" and 13" telescopes
- Cloudy weather during eclipse
- 13" changed focal length during eclipse - data not used
- 4" gave 7 plates with 7 stars each
- Comparison plates made on July 11
- Departed on July 22

The Principe Measurements

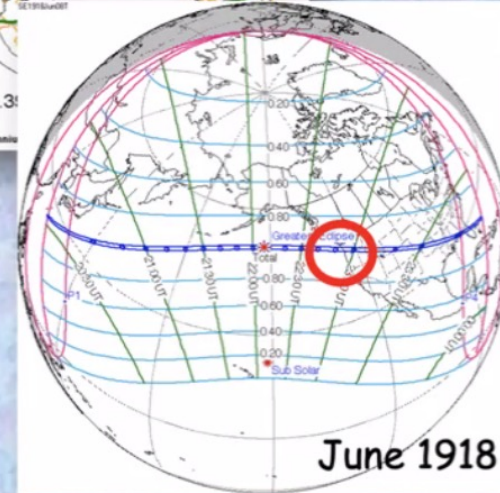
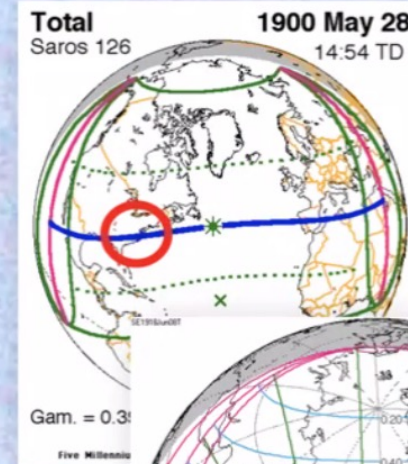
- One telescope
- Morning rain, mostly cloudy
- 2 usable plates with 5 stars each
- No comparison plates made (plates from Oxford made in Jan 1919 used instead)
- "check" plates used
- Departed on June 12, arrived Liverpool July 14

The Lick Eclipse Measurements



William W. Campbell Heber Curtis

- Anxious to beat the Brits to a GR test
- Analyzed plates from 1900 eclipse near Augusta Georgia, and a 1918 eclipse at Goldendale Washington
- Images poor; no unambiguous evidence of deflection
- Reported results at July 11 1919 meeting of the Royal Astronomical Society
- Dyson reported that Eddington might have a positive result



The 1919 Eclipse Expedition

The Sobral Measurements

- 4" and 13" telescopes
- Cloudy weather during eclipse
- 13" changed focal length during eclipse - data not used
- 4" gave 7 plates with 7 stars each
- Comparison plates made on July 11
- Departed on July 22

Sobral Result

$$\begin{aligned}\Delta\theta &= 1''.98 \pm 0''.12 \\ &= (1.13 \pm 0.07)\Delta\theta_{GR}\end{aligned}$$

1979 re-analysis

$$\begin{aligned}\Delta\theta_{4''} &= 1''.90 \pm 0''.11 \\ \Delta\theta_{13''} &= 1''.55 \pm 0''.34\end{aligned}$$

The Principe Measurements

- One telescope
- Morning rain, mostly cloudy
- 2 usable plates with 5 stars each
- No comparison plates made (plates from Oxford made in Jan 1919 used instead)
- "check" plates used
- Departed on June 12, arrived Liverpool July 14

Principe Result

$$\begin{aligned}\Delta\theta &= 1''.61 \pm 0''.30 \\ &= (0.92 \pm 0.17)\Delta\theta_{GR}\end{aligned}$$

The 1919 Eclipse Expedition

November 6, 1919:

Alfred North Whitehead:

The whole atmosphere ... was exactly that of a Greek drama... 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.

The 1919 Eclipse Expedition

NY Times, Nov 10 1919

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less
Agog Over Results of Eclipse
Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed
or Were Calculated to be,
but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could
Comprehend It, Said Einstein When
His Daring Publishers Accepted It.

Nov 6, 1919:
Alfr
rth
heh
here

London Times, Nov 7 1919

REVOLUTION IN SCIENCE

NEW THEORY OF THE UNIVERSE

NEWTONIAN IDEAS
OVERTHROWN



From Adulation to Denouncement

The public Einstein



Initial US skepticism

Campbell & Trumpler 1922

$$\Delta\theta = 1''.72 \pm 0''.11$$

German anti-relativity campaigns

- Philipp Lenard
- Nobel prize 1905
- Supported Nazi ideology
- Denounced "jewish" science such as relativity



HUNDERT AUTOREN GEGEN EINSTEIN

Herausgegeben

von

Dr. HANS ISRAEL, Dr. ERICH RUCKHABER,
Dr. RUDOLF WEINMANN

Mit Beiträgen von

Prof. Dr. DEL-NEGRO, Prof. Dr. DRIESCH, Prof. Dr. DE HARTOG,
Prof. Dr. KRAUS, Prof. Dr. LEROUX, Prof. Dr. LINKE, Prof. Dr.
LOTHIGIUS, Prof. Dr. MELLIN, Dr. PETRASCHEK, Dr. RAUSCHEN-
BERGER, Dr. REUTERDAHL, Dr. VOGTHERR u. v. a.

1931

R. VOIGTLÄNDER'S VERLAG · LEIPZIG

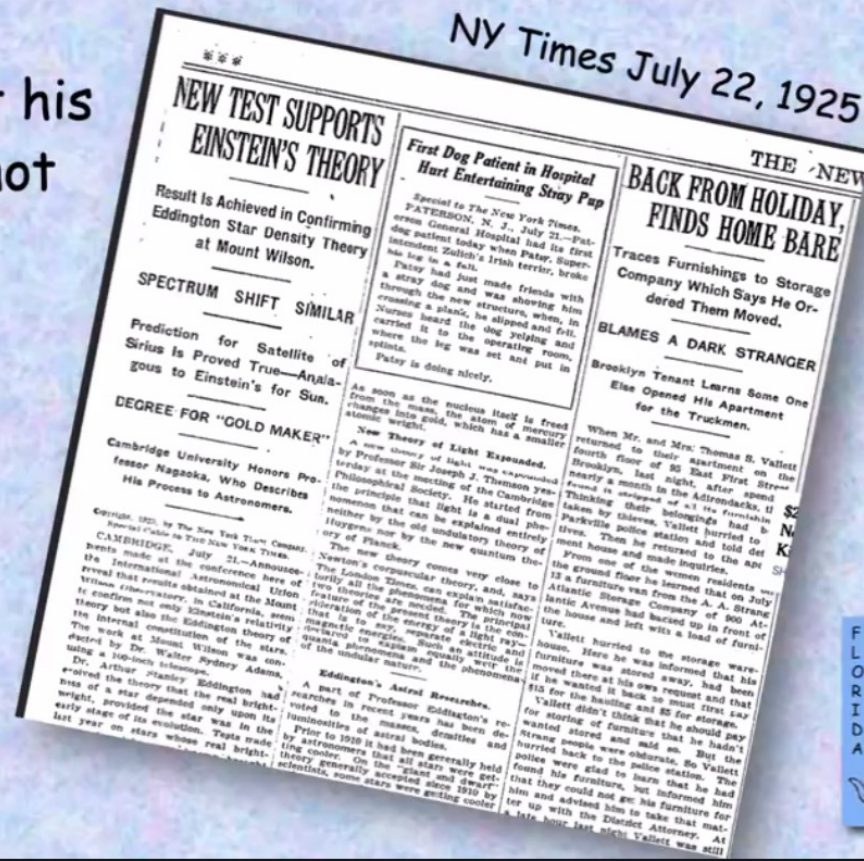
...

I worked for two hours every morning, and at the first sitting the Professor was so surrounded, with tobacco smoke from his pipe that I saw nothing. At the second sitting I asked him to smoke in the interval, Einstein's manner was full of charm and bonhomie. He enjoyed a joke and had many a jibe at the Nazi professors, one hundred of whom in a book had condemned his theory. "Were I wrong," he said, "one professor would have been quite enough."

From J. Epstein, "Let There Be Sculpture", G. Putnam and Sons (1940). Epstein spoke with Einstein while carving his bust.

Einstein's crucial test: the redshift

- 1907: Einstein's "happiest thought"
- 1917: C. E. St. John and others: no Solar redshift effect probably hurt Einstein's chances for the 1918 Nobel
- 1925: Walter Adams, Eddington & Sirius B spectra of the white dwarf Sirius B - Adams model of the white dwarf to predict R - Eddington
- 1926: it began to fall apart
- 1950: Einstein admitted that his redshift effect was "not yet confirmed"



NY Times July 22, 1925

Jean Eisenstaedt: The "low water mark"

- ❑ 1920s to the late 1950s: the backwaters of physics
- ❑ 1962: "do not study general relativity"
- ❑ 1962: Feynman at GR-3 in Jablonna: "Because there are no experiments, this field is not an active one, so few of the best men are doing work in it. The result is that there are a host of dopes here and it is not good for my blood pressure."
- ❑ Common saying of the day: GR is a theorist's Paradise and an experimentalist's Hell



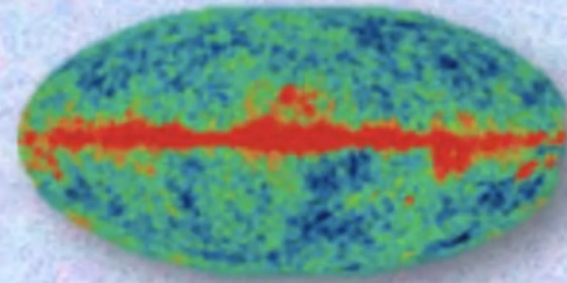
Jean Eisenstaedt
1940-2024

The 60's: a Revolution in Astronomy

1961
Discovery
of quasars



1964
Discovery
of 3°
cosmic
background
radiation



1967
Discovery
of pulsars



1971
Discovery
of a black
hole
candidate

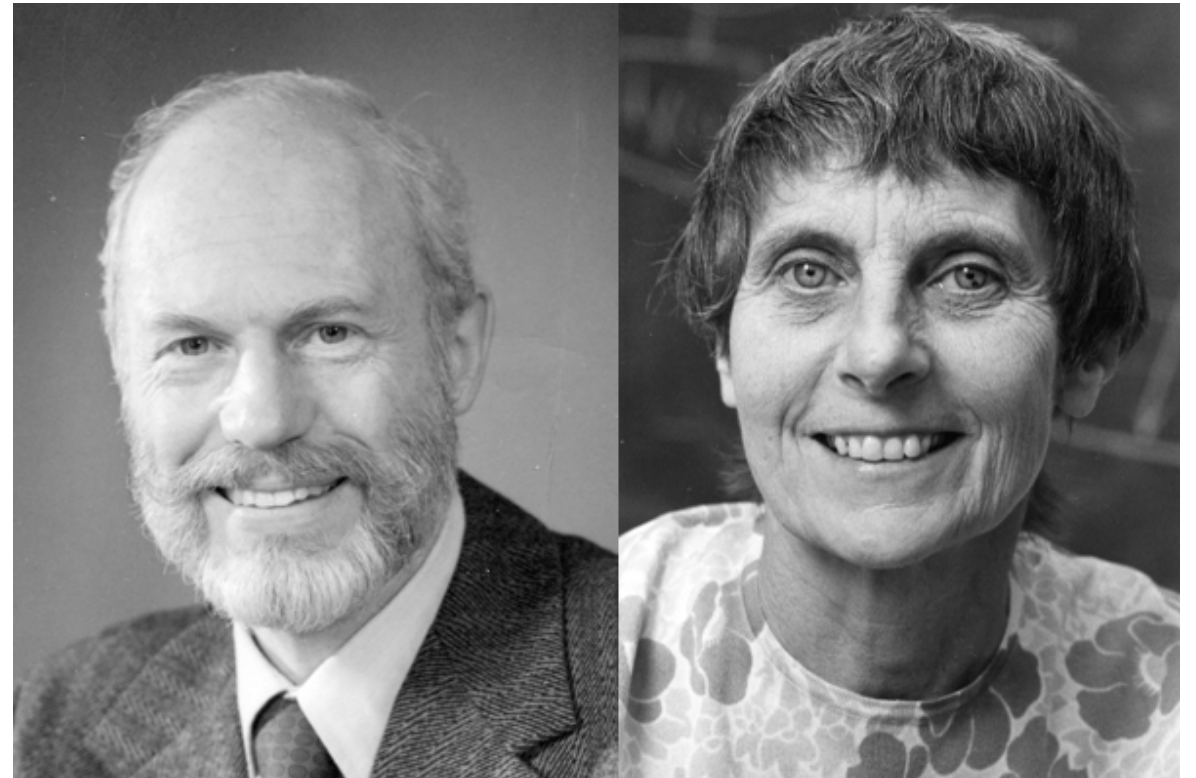


The Role of Gravitation in Physics

*Report from the 1957 Chapel Hill
Conference*

Cécile M. DeWitt and Dean Rickles (eds.)

Communicated by
Jürgen Renn, Alexander Blum and Peter Damerow



Bryce and Cécile DeWitt, organizers of the conference

Cécile DeWitt on the need for the Chapel Hill Conference from her Foreword to the proceedings:

Research in gravitational theory has been relatively neglected in the past two or three decades for several good reasons:

- the lack of experimental guideposts,
- the mathematical difficulties encountered in the study of non-linear fields,
- the experience of repeated early failures to extend general relativity theory in a permanently interesting fashion.

The “lack of experimental guideposts” in gravitational physics was due to two main difficulties:

- Many gravitational effects are very weak, in most circumstances.
- General relativity can be very hard to interpret.

There’s not much that can be done about the first difficulty.

At the Chapel Hill Conference, there was tremendous progress on the second difficulty.

Felix Pirani solved the problem of the reality of gravitational waves

Felix Pirani was a student of Alfred Schild's and then of Hermann Bondi's. In 1957 he was a junior colleague of Bondi at King's College, London.

At Chapel Hill, he gave the solution of the gravity wave problem, although Bondi (or Feynman) usually get the credit.

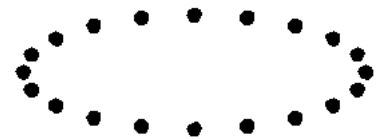


*Pirani's insight was to analyze the **detection** of gravitational waves, not their generation.*

He showed that, in the presence of a gravitational wave, a set of freely-falling particles would experience genuine (i.e., measurable) motions with respect to one another. Thus, gravitational waves must be real.

He made this case in two papers presented at the Chapel Hill conference (that he had submitted for publication beforehand.)

“By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.”



see Saulson's presentation

1963: The Texas Symposium

Astronomers and Relativists feel the love!

- ❑ Dallas, TX, 16 - 18 December 1963
- ❑ Gov John Connally greeted attendees (arm still in a sling from Pres. Kennedy assassination)
- ❑ 240 astronomers/astrophysicists
60 relativists
- ❑ Quasars:
 - supermassive stars? (Fowler, Hoyle, ...)
 - star clusters? (Gold, ...)
 - collapse of compact objects (Wheeler,...)
- ❑ "It's the collapse, stupid"
Almost no discussion of black holes as the central engine
- ❑ "Gravitational Collapse and Rotation" by R. P. Kerr
- ❑ Phil Morrison - "interested but unpersuaded ..."
Peter Bergmann - "not very optimistic..."



Tommy Gold on "the relativists"

It was, I believe, chiefly Hoyle's genius which produced the extremely attractive idea that ... the relativists, with their sophisticated work, were not only magnificent cultural ornaments, but might actually be useful to science!



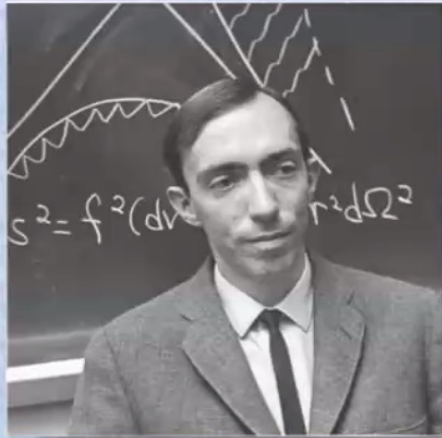
Everyone is pleased: the relativists, who feel they are being appreciated, who are suddenly experts in a field they hardly knew existed; the astrophysicists, for having enlarged their domain, their empire, by the annexation of another subject, general relativity.

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!

Banquet speech, 1st Texas Symposium



Research in relativistic astrophysics



Kip

Kip's group in 1969:
Bill Burke
Richard Price
Jim Ipser
John Dykla
Bernie Schutz
Wei-Tou (Victor) Ni



Cliff

Could Einstein be wrong?

- June 1969 PRL: Joe Weber announces detection of gravitational waves



Weber

Kip: "Cliff, find out how right GR is"



How right was Einstein in 1969?

- ❑ Eötvös experiment by Dicke to 10^{-11} (1964)
- ❑ Gravitational redshift by Pound & Rebka to 1% (1960,65)
- ❑ Solar redshift by Brault to 5% (1962)
- ❑ Mercury's perihelion advance good to $\sim 20\%$
- ❑ Deflection of light from solar eclipses good to 10% (1952)
- ❑ Brans-Dicke theory (1961) satisfied all tests with $\omega \sim 7$



Dicke

Is help on the way?

- ❑ Radar ranging promises to improve accuracy of planetary orbits (1960)
- ❑ Shapiro discovers "fourth test" (1964)
- ❑ Shapiro proposes radio interferometry for bending (1967)
- ❑ NASA considers putting a laser retroreflector on the Moon



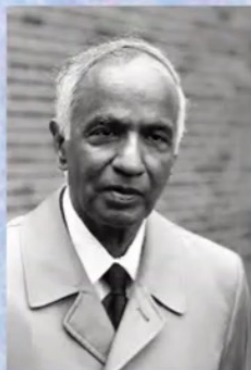
Shapiro



Up to JPL



- ❑ Shapiro measured time delay in 1968
- ❑ Mariner 6 & 7 launched in June 1969
- ❑ JPL's plans for delay measurement



Chandra

Chandrasekhar's post-Newtonian hydrodynamics
With Kip, the PPN formalism

The big "discovery"

3 remarkable papers in 1968 by Ken Nordtved Jr.

- ◆ Parametrized PN metric
- ◆ Discovered the Nordtvedt effect
- ◆ Propose a test using LLR



Ken



The golden age of GR testing

Shapiro Delay (γ):
1975 - Mariner 6 & 7
1978 - Mariner 9
1979 - Viking (0.1%)



Viking lander

Gravitational redshift
1972 - clocks on aircraft
1979 - GP-A (H maser on rocket) (0.02%)



Levine, Vessot & clock

Mercury's perihelion (γ, β)
1976 - 10 yrs of range data (0.5%)

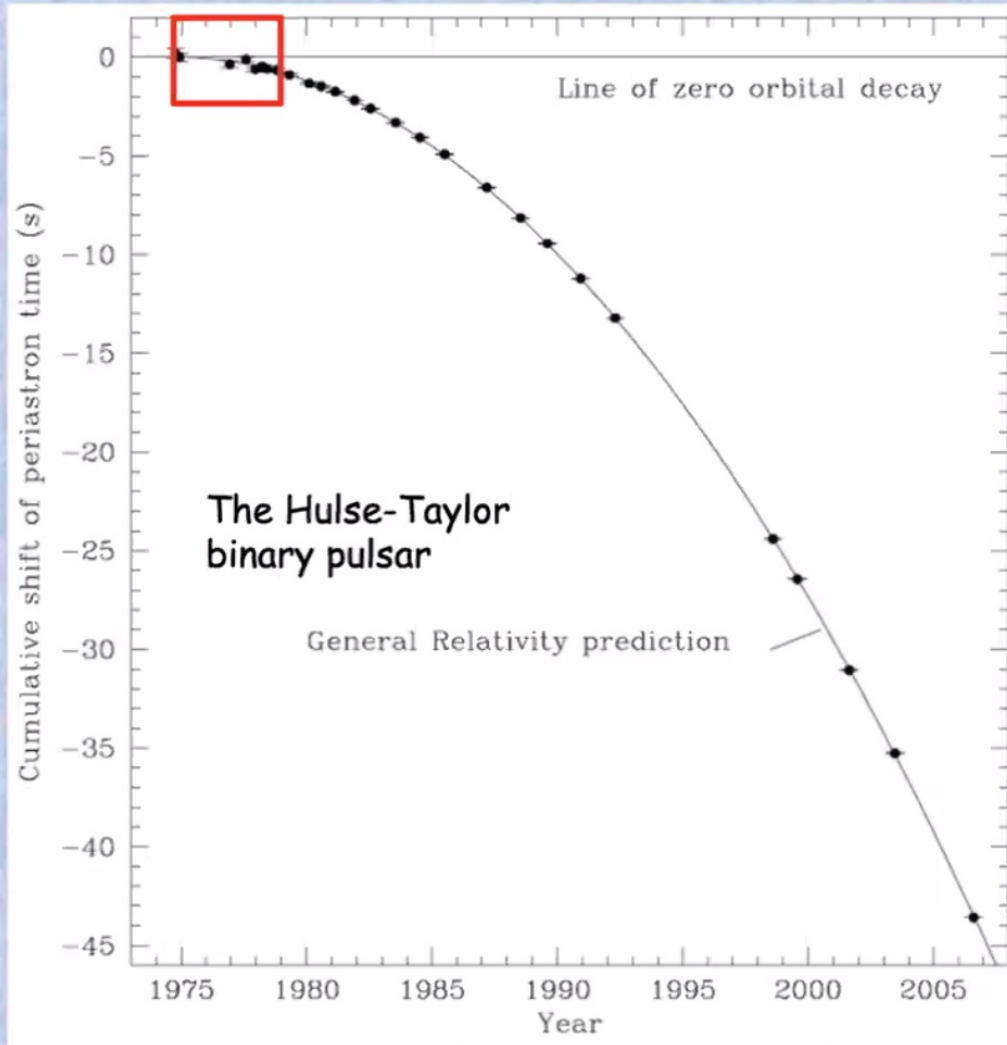


Laser ranging

Nordtvedt effect (γ, β)
1976 - LLR data (< 0.01)

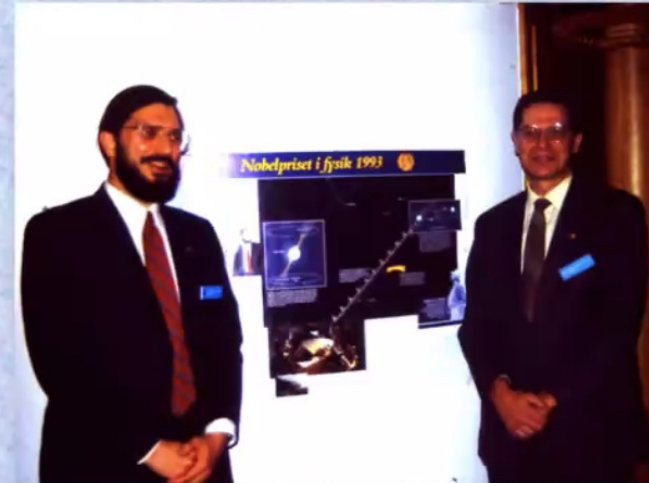


The golden age of GR testing



From Weisberg
Nice & Taylor (2010)

Dec. 1978:
9th Texas Symposium, Munich
Taylor announces measurement
of dP/dt



Hulse & Taylor



Cliff



