A short history of gravitational waves

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A couple of Einstein quotes:

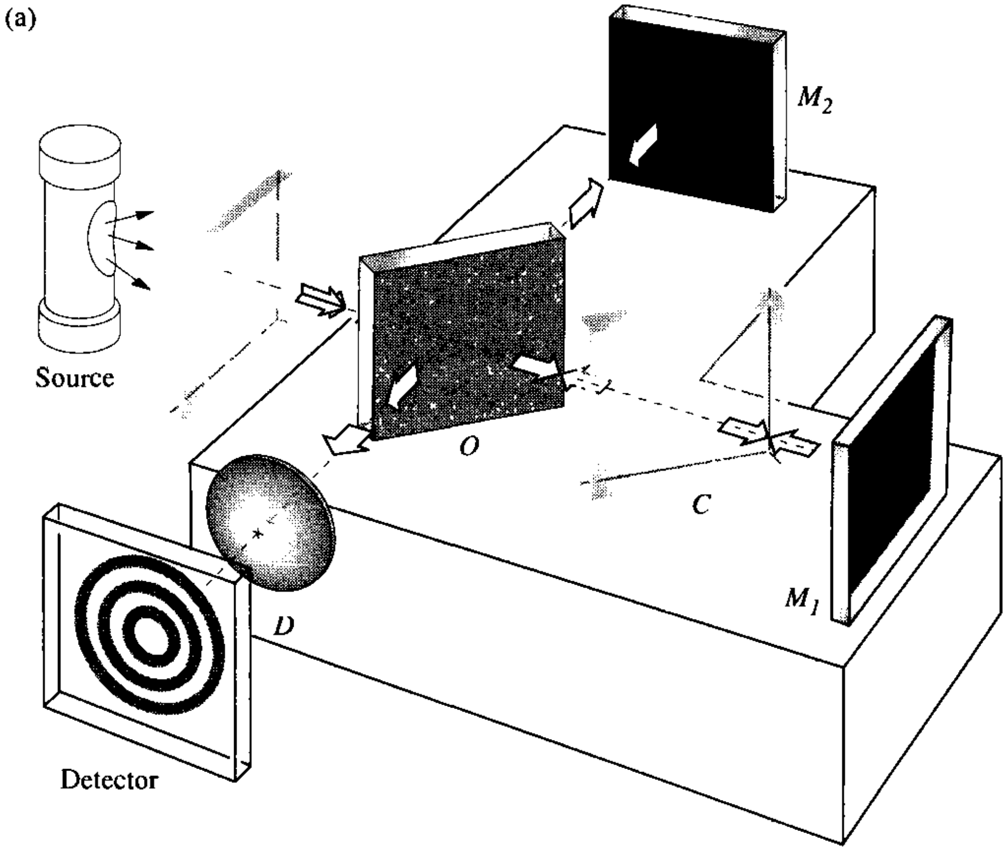
I always think of Michelson as the artist in science. His greatest joy seemed to come from the beauty of the experiment itself and the elegance of the method employed.

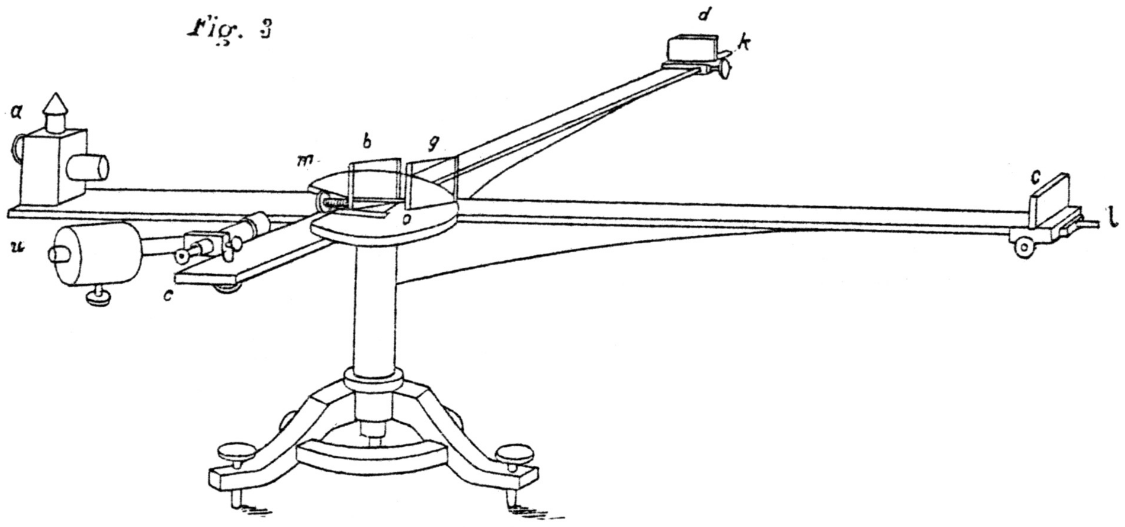
To Robert Shankland, September 17, 1953, on Albert A. Michelson, who with Edward Morley in 1881, had already experimentally validated Einstein's postulation that the speed of light is independent of the frame of reference in which it is measured. Einstein said that he was unaware of the experiment when 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].

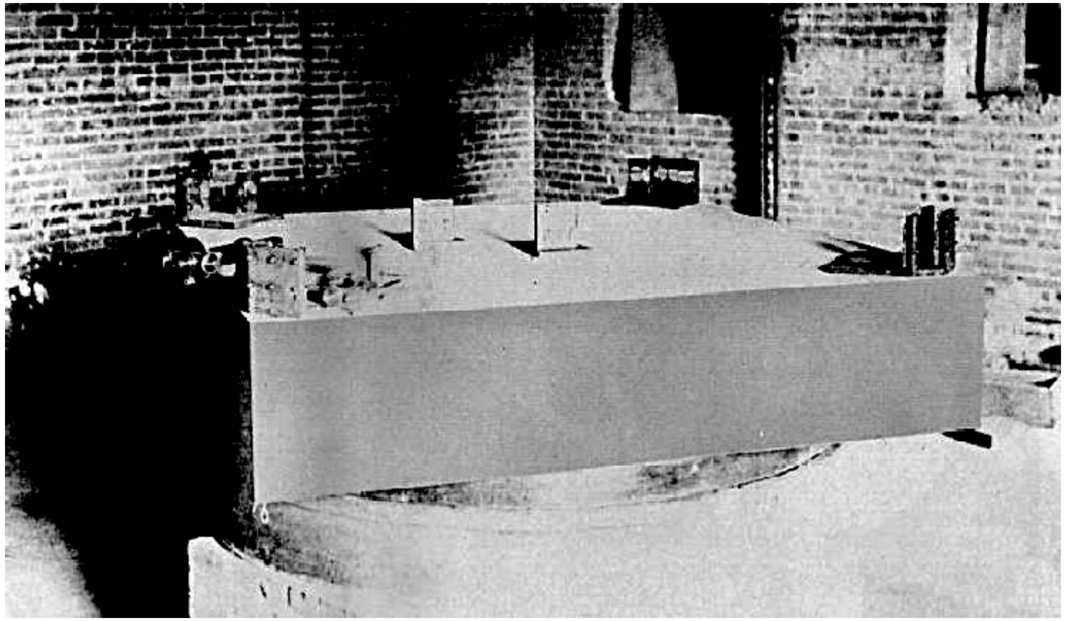
To Heinrich Zangger, November 26, 1915, regarding the reception of the general theory of relativity. *CPAE,* Vol. 8, Doc. 152. The colleague was David Hilbert. (from Alice Calaprice, *The Extended Quotable Einstein*, University Presses of California, 2000)

The Michelson interferometer

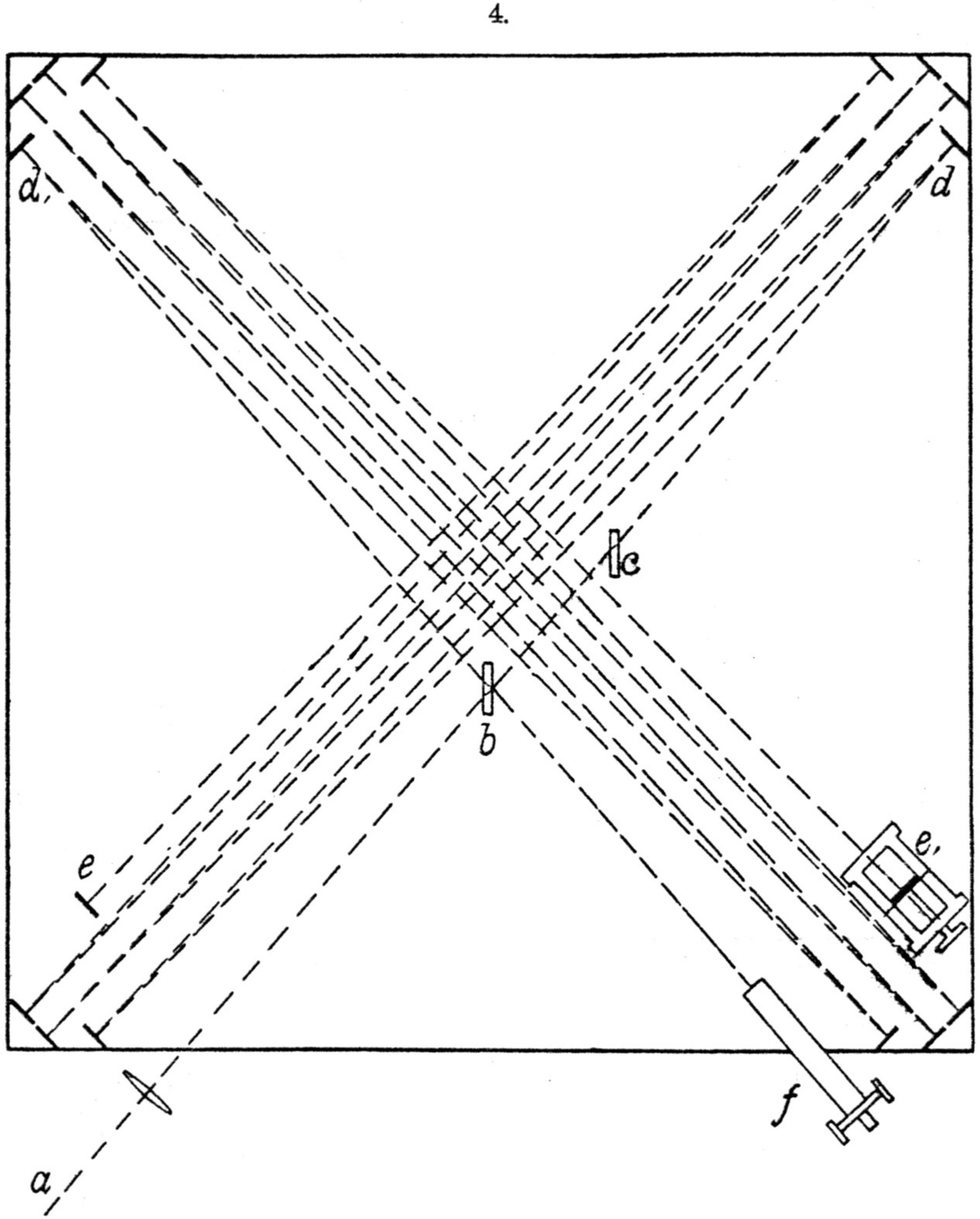




Michelson's 1881 interferometer. Although ultimately it proved incapable of distinguishing between differing theories of aether-dragging, its construction provided important lessons for the design of Michelson and Morley's 1887 instrument (from Wikipedia).



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! Moreover, Einstein paid little attention to these experiments.

Instead, 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.

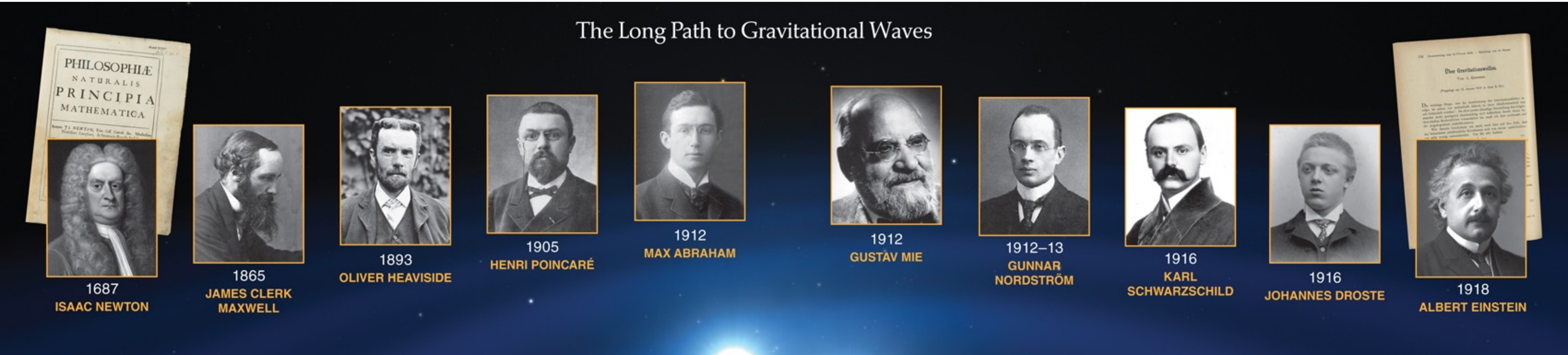
A short history of gravitational waves

(partly adapted from 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)*

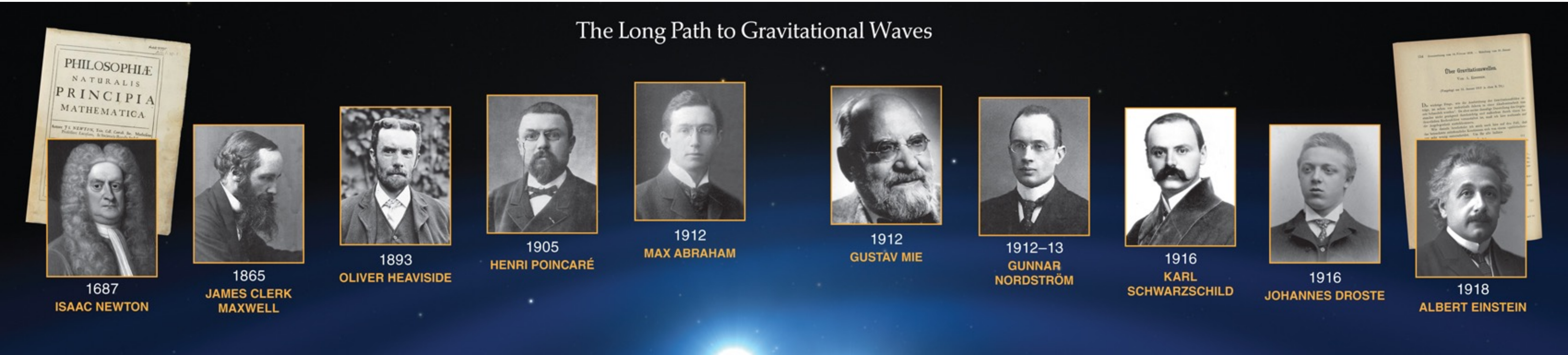
- The problem with Newton's theory of gravitation is that propagation of the effects is *instantaneous*, and this forbids waves of any kind



- 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)



- 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)

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

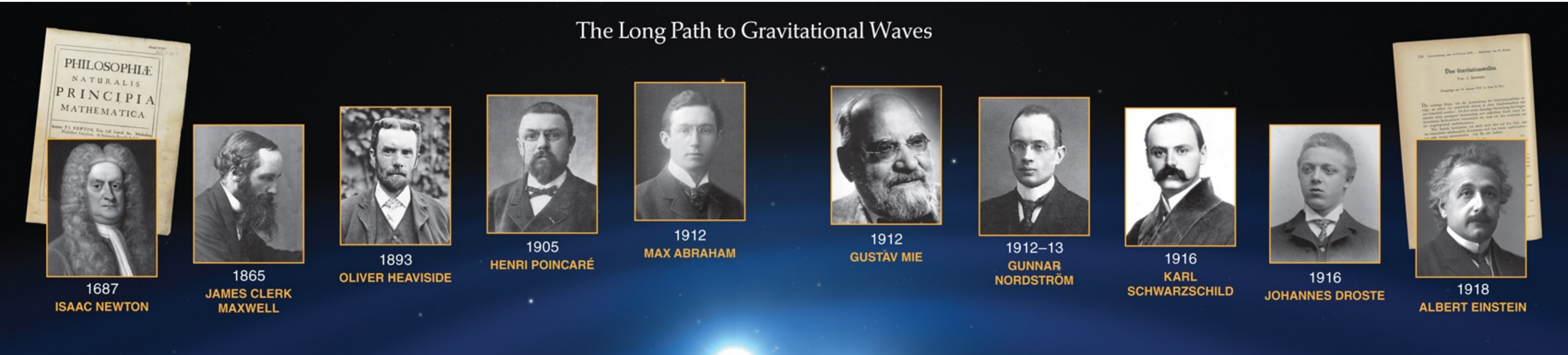
$$\nabla \times \mathbf{b} = \frac{4\pi G}{c_g^2}\mathbf{j} - \frac{1}{c_g^2}\frac{\partial \mathbf{g}}{\partial t} = \mu_{0g}\mathbf{j} - \frac{1}{c_g^2}\frac{\partial \mathbf{g}}{\partial t},$$

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

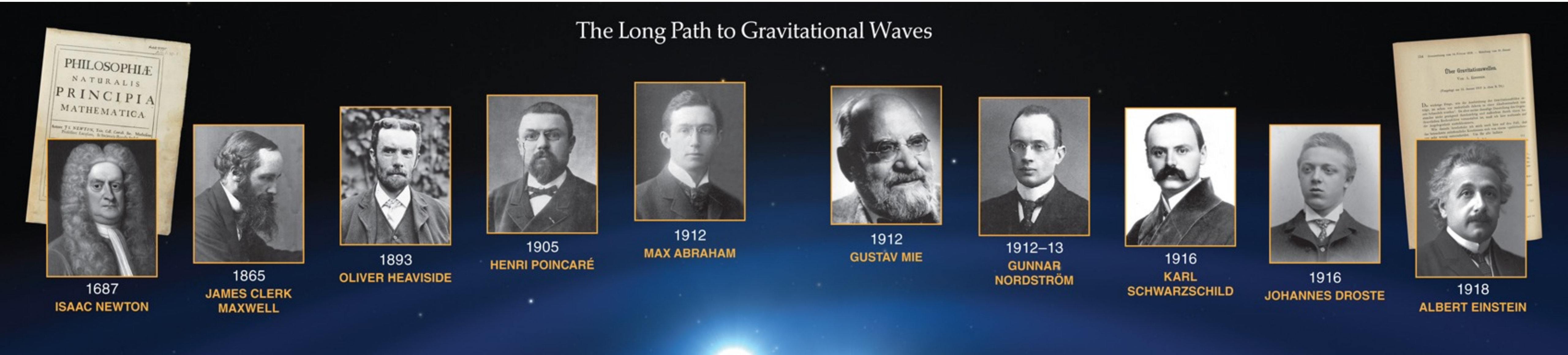
$$\nabla \times \mathbf{g} = \frac{\partial \mathbf{b}}{\partial t}.$$

where

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



- 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.*"

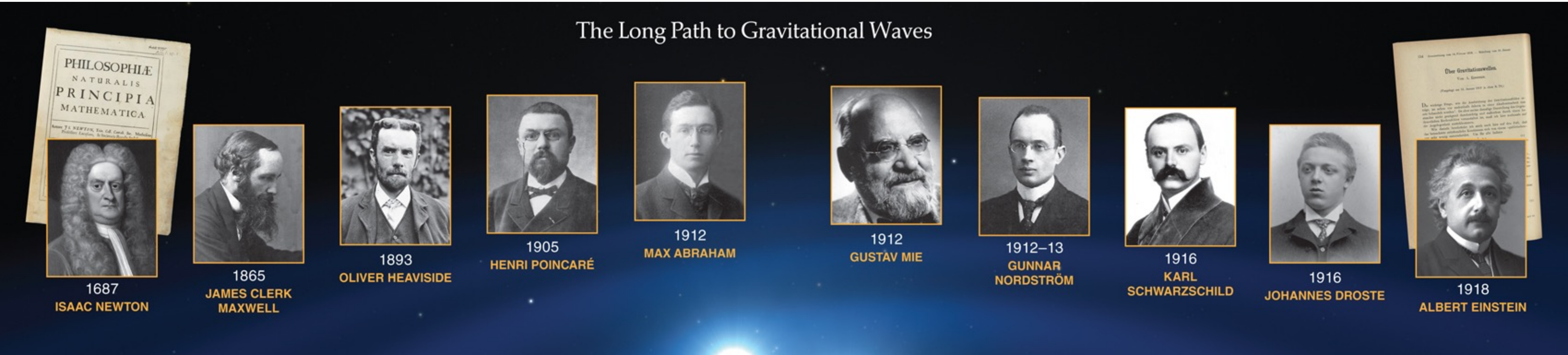


- The special relativity paper is one of the papers published by Einstein in his *annus mirabilis* (1905), "*Zur Elektrodynamik bewegeter Körper*" ("*On the electrodynamics of moving bodies*")
(German original, https://onlinelibrary.wiley.com/doi/10.1002/andp.19053221004)

- 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.

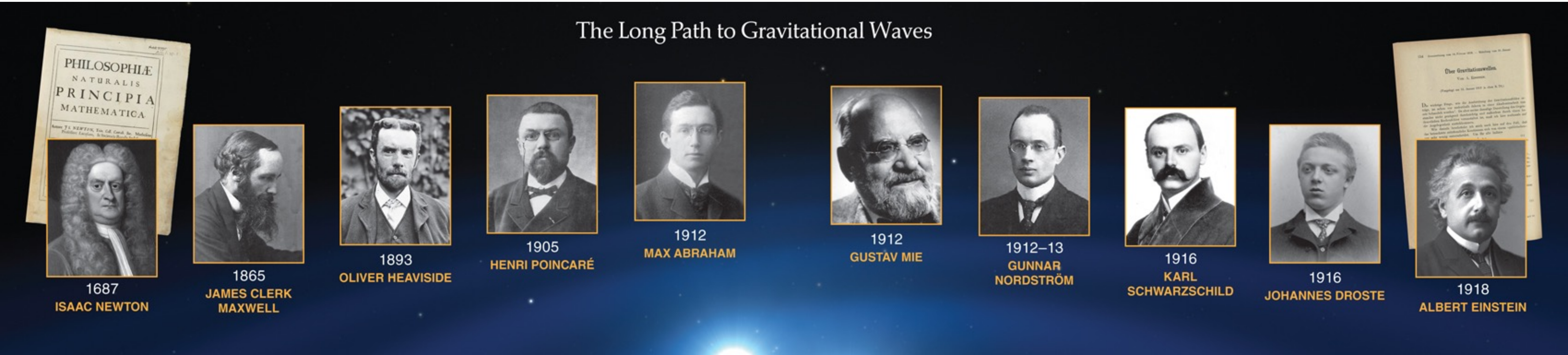
- Einstein's paper is not isolated in the physics literature of the late 19th – early 20th century. E.g., it was preceded by Lorentz's papers and it was paralleled by Poincaré's studies (although Einstein retains the priority on SR, especially because of his deep physical insights) (see also Damour's paper on Poincaré, https://www.sciencedirect.com/science/article/pii/S1631070517300762)

- In 1907, Einstein has 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.



- In 1907, Einstein has 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.

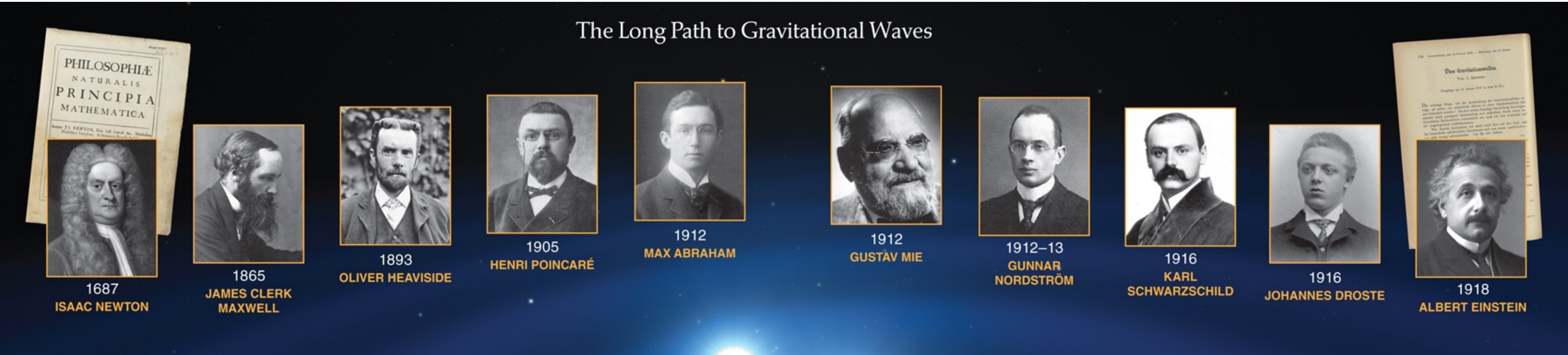
- In a 1911 paper, Einstein took the first, using equivalence to demonstrate that photons must gain energy as they fall toward a gravitating body and lose energy as they climb away from it.
  Light emitted by a massive body is stretched, resulting in a gravitational redshift, a phenomenon inconsistent 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.



- 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.

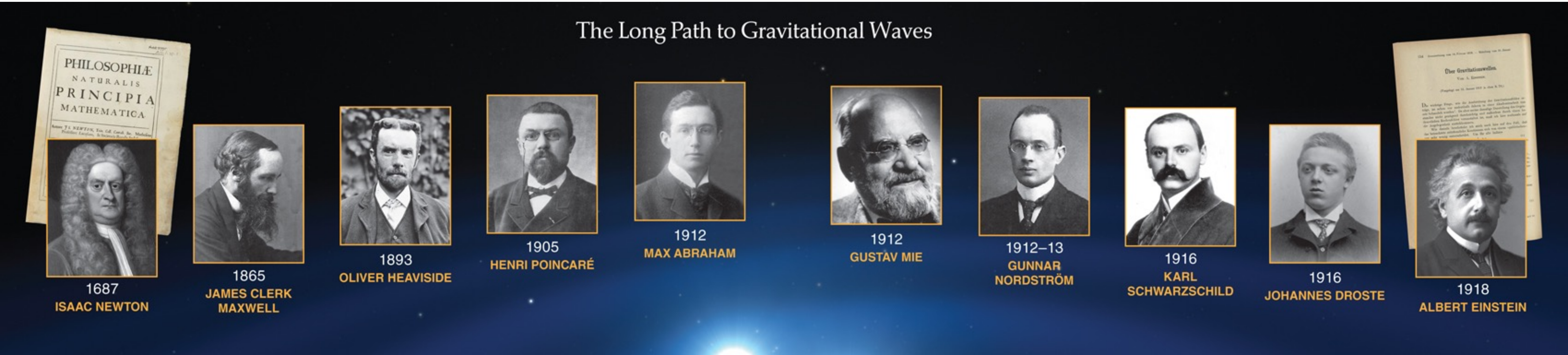
- Abraham's scalar was the gravitational potential energy of the field itself. In Abraham's theory, an accelerating mass emits gravitational radiation, which he discussed extensively early in 1912 at a conference in Italy – a lecture which later that year was published in the journal Nuovo Cimento. It may well have been the world's second paper devoted to gravitational waves.



- 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.

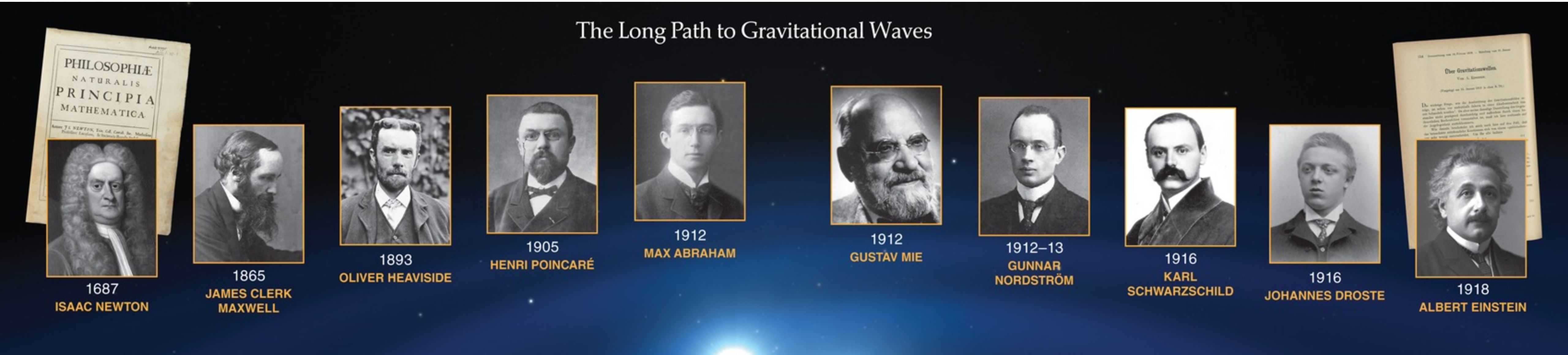
- Even as Abraham discussed gravitational waves in relation to EM waves, he understood that the comparison was not entirely legitimate. By far the dominant type of electromagnetic radiation is dipole radiation, and one might think that if a single mass were accelerated it should analogously emit gravitational 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.



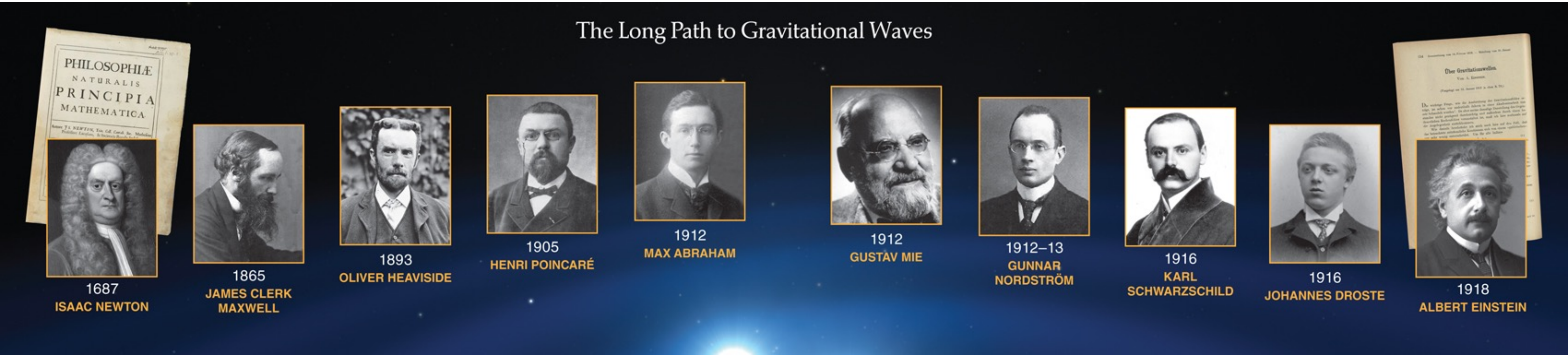
- Einstein and Abraham were not alone. The German physicist Gustav Mie (1868 – 1957) also contributed to the scientific ferment. Today, Mie is remembered primarily for his theory of light scattering off spherical particles. A century ago, his overarching goal was to create a unified field theory that 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*."



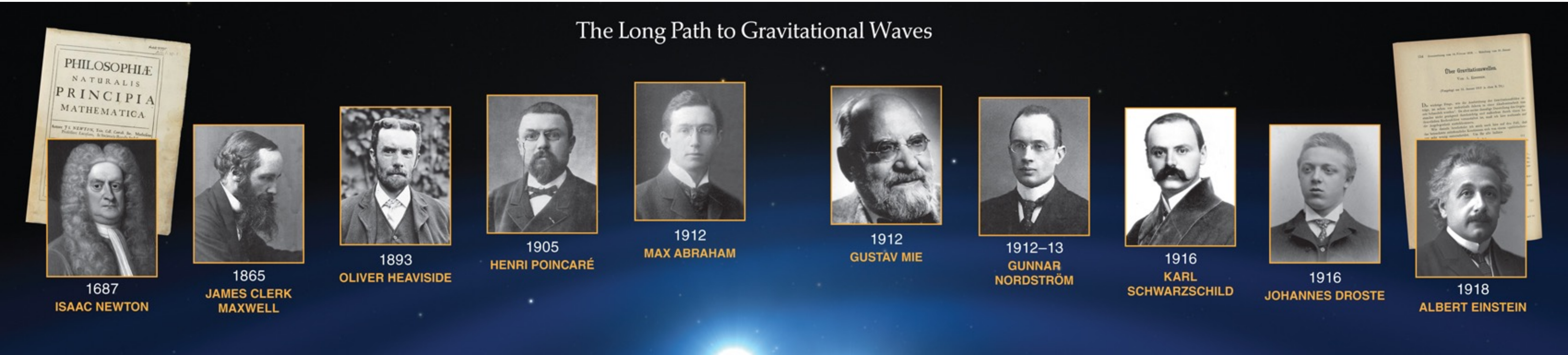
- Einstein – not yet world-famous, but already a towering figure in physics – gave short shrift to Abraham and failed to mention Mie at all in a 1913 lecture, "On the Present State of the Problem of Gravitation," presented at the 85th Naturforscherversammlung (Congress of Natural Philosophers) in Vienna.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



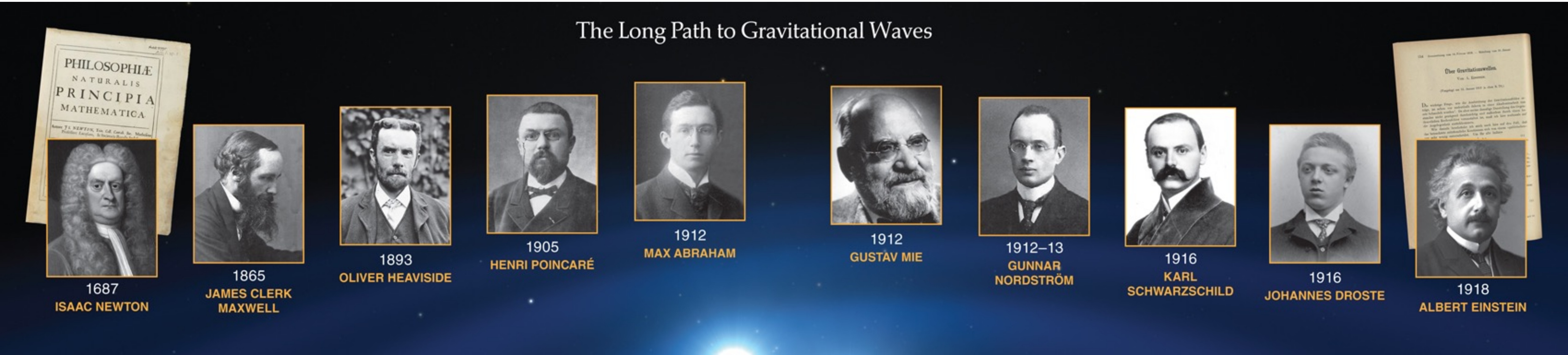
- Einstein displayed far more appreciation for the work of the young Finnish physicist Gunnar Nordström (1881–1923), and spent a large portion of his lecture explaining his theory. Nordström is remembered among relativists as the independent codiscoverer, along with the German engineer Hans Reissner, 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.



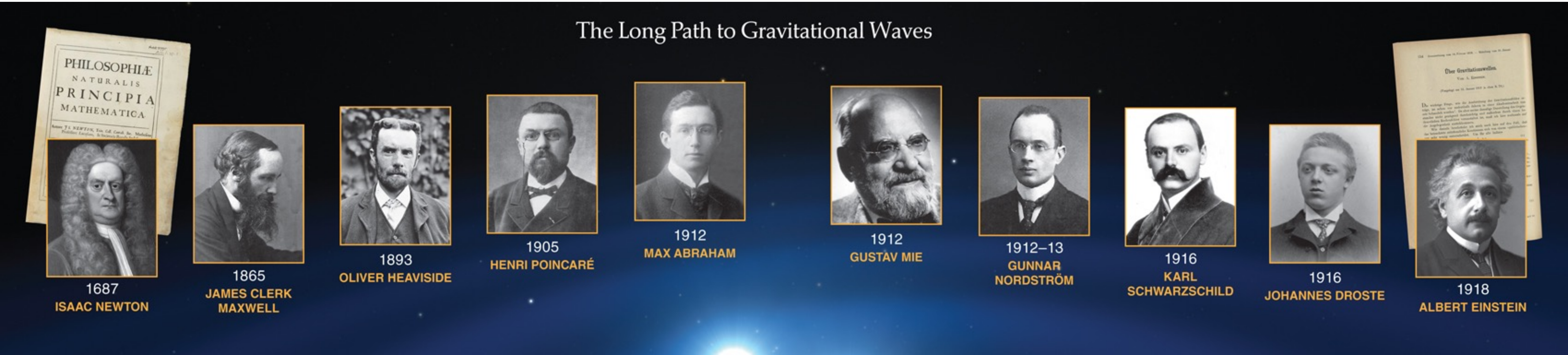
- Like the theory of GR that was to come, Nordström's theory allowed matter to curve spacetime, albeit in a mathematically more restrictive sense. It was still a scalar theory, like Abraham's had been, but in it the speed of light remained strictly constant and the principle of equivalence was respected. 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.

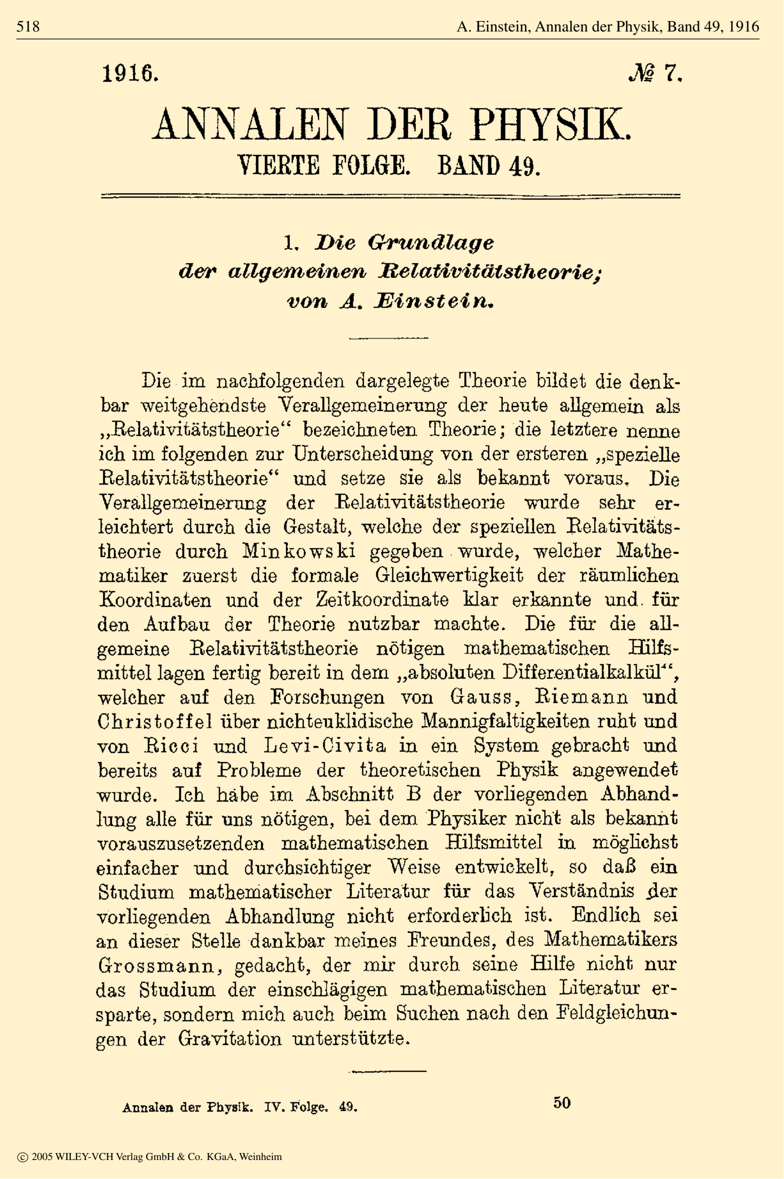


- In Einstein's monumental 1916 paper announcing the completion of GR, one of the first things he did was to return to the problem of Mercury's perihelion – and he got the orbital shift exactly right.
  There was no mention of gravitational waves in the paper, however. Strangely, it appears that Einstein 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.



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



518 A. Einstein, Annalen der Physik, Band 49, 1916

1916. № 7.

ANNALEN DER PHYSIK.

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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 Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

Annalen der Physik. IV. Folge. 49. 50

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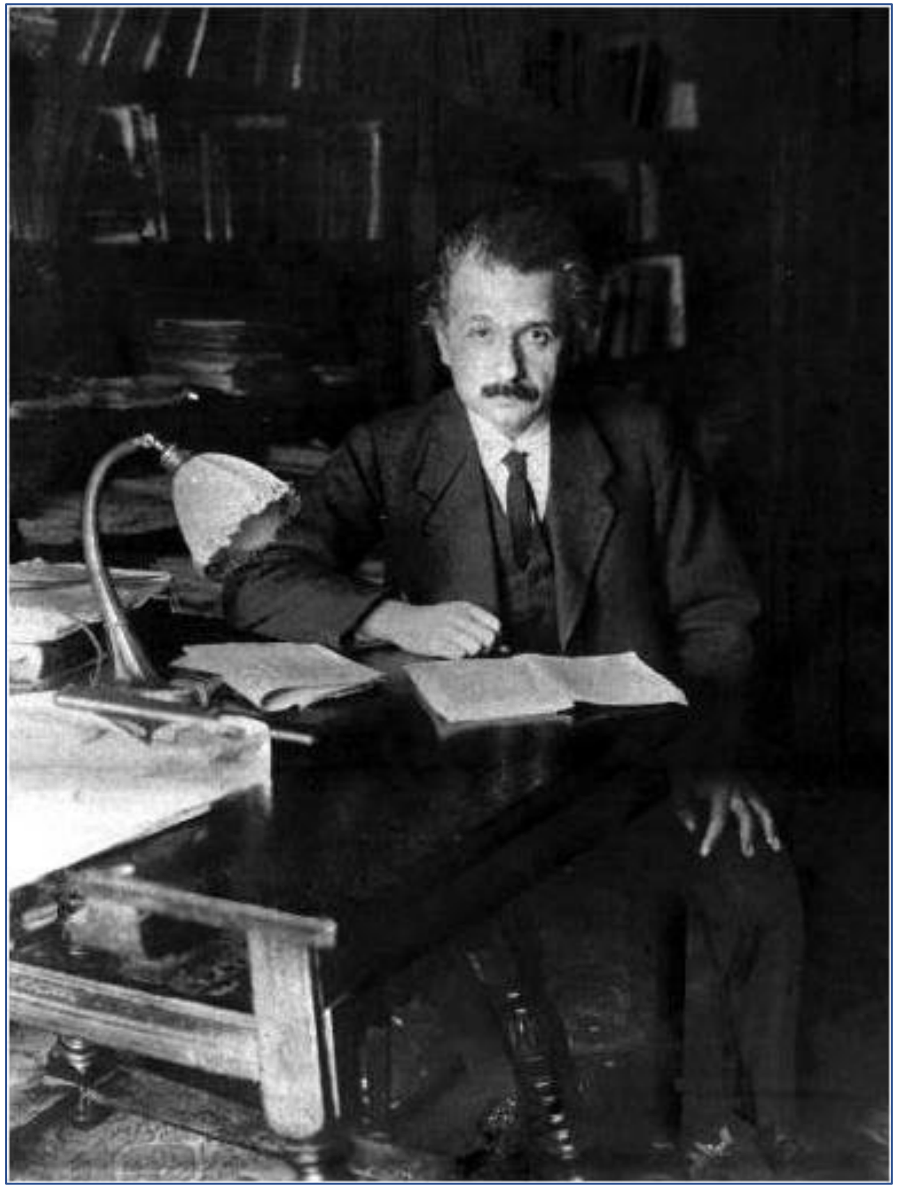


In his 1916 paper, Einstein predicts important static phenomena, like the deflection of light, but he also introduces the analogy with electromagnetism.

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.

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

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

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 hatte[1]. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

[1] Sitzungsber. XLVII, 1915, S. 833.

... We shall shaw 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 1918 paper corrects the mistakes in the 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 worden[1]. 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

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

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 gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha \end{Bmatrix} - \sum_{\alpha\beta} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} \begin{Bmatrix} \alpha\beta \\ \beta \end{Bmatrix} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \tag{2}$$

[1] Diese Sitzungsber. 1916, S. 688 ff.

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

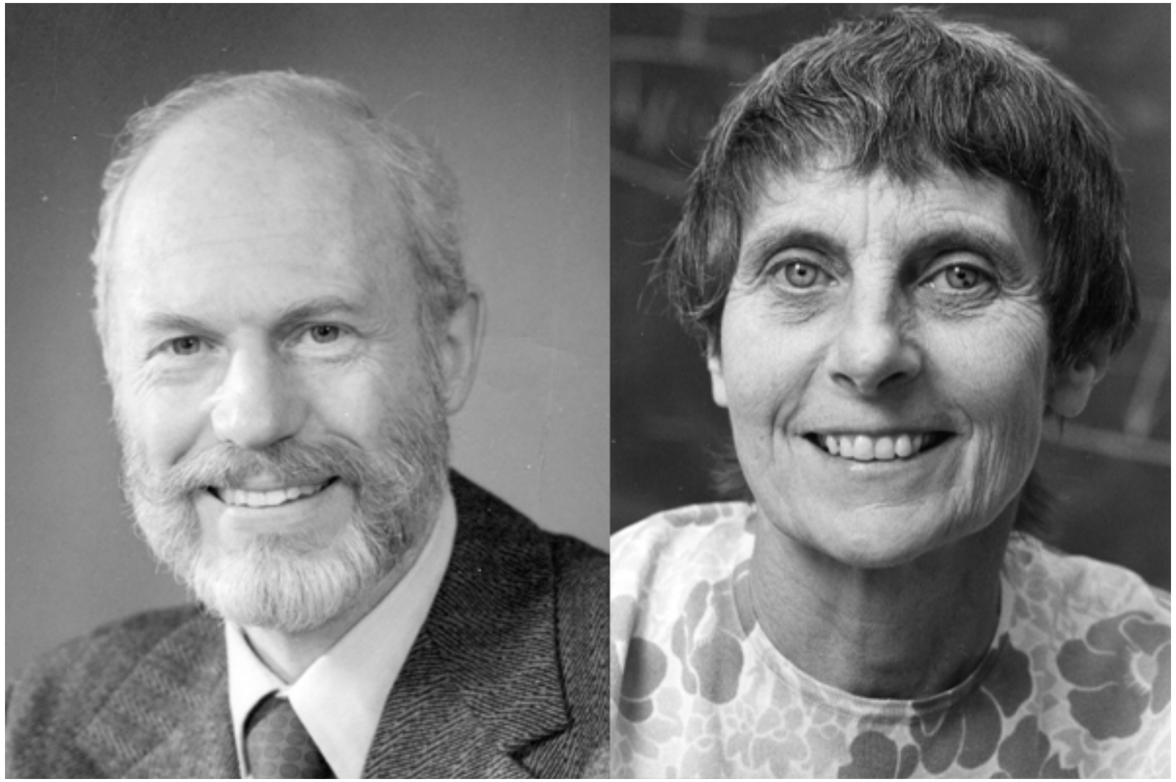
The Role of Gravitation in Physics

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

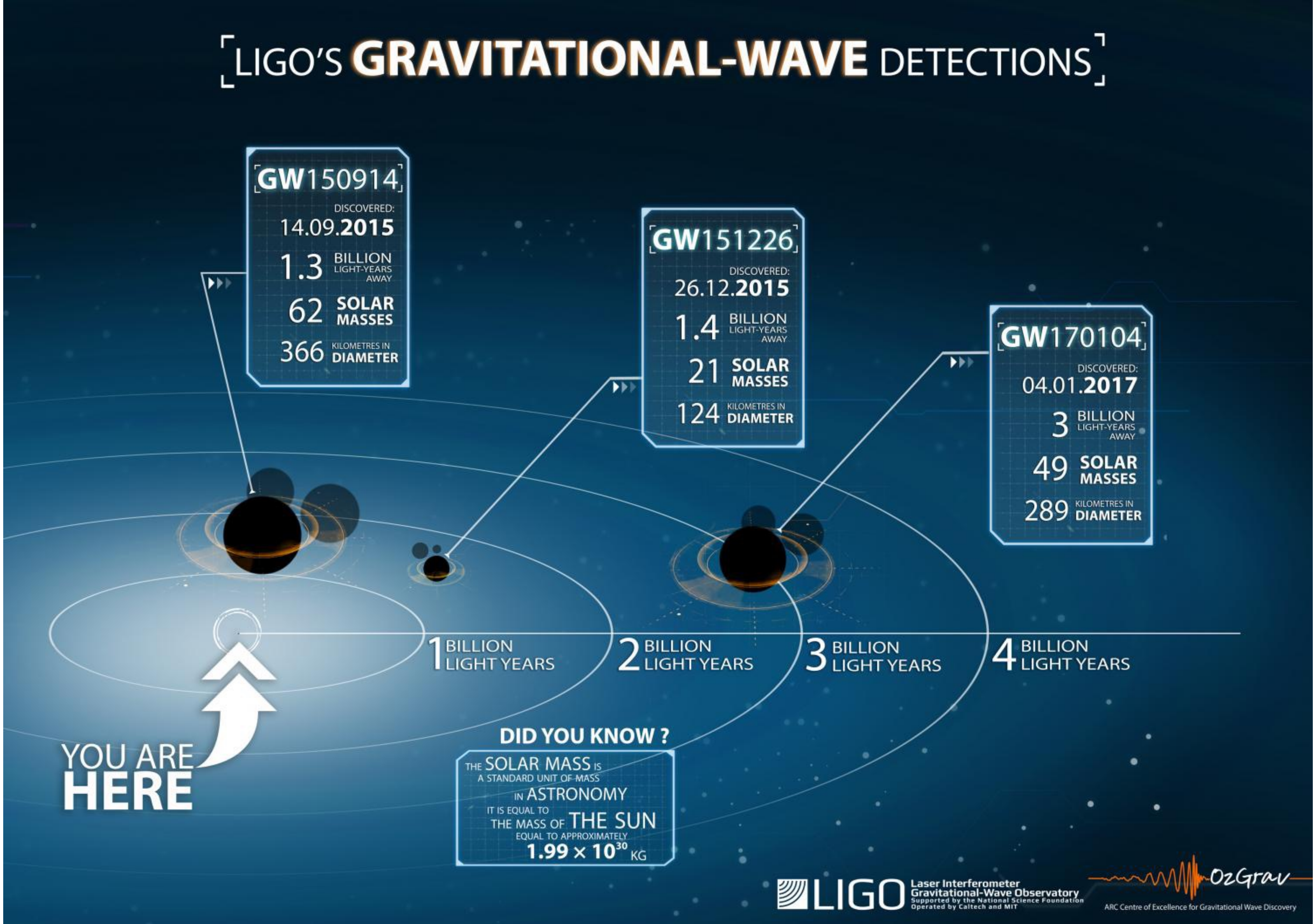
Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

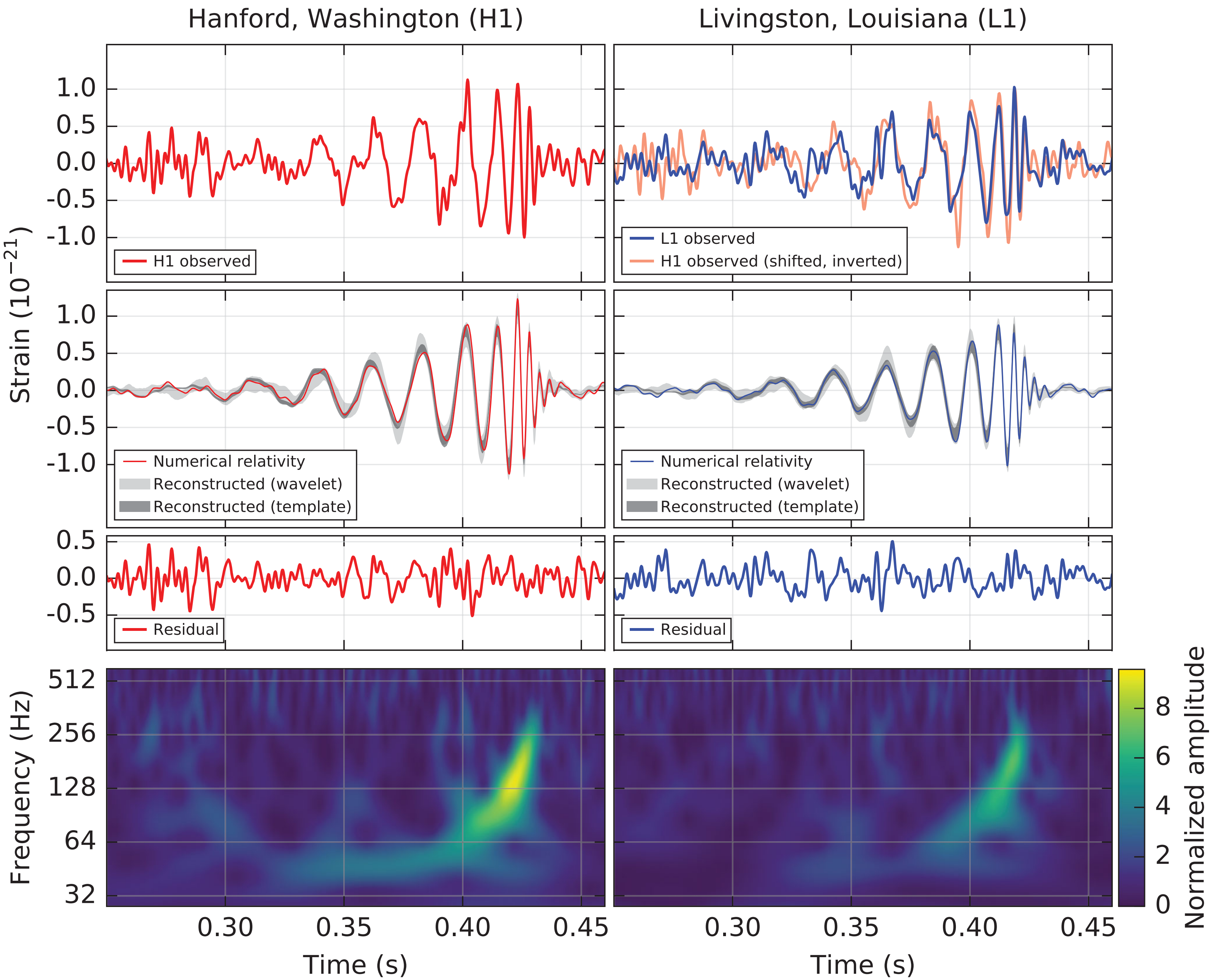
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102


LIGO'S GRAVITATIONAL-WAVE DETECTIONS
GW150914
DISCOVERED: 14.09.2015
1.3 BILLION LIGHT-YEARS AWAY
62 SOLAR MASSES
366 KILOMETRES IN DIAMETER
GW151226
DISCOVERED: 26.12.2015
1.4 BILLION LIGHT-YEARS AWAY
21 SOLAR MASSES
124 KILOMETRES IN DIAMETER
GW170104
DISCOVERED: 04.01.2017
3 BILLION LIGHT-YEARS AWAY
49 SOLAR MASSES
289 KILOMETRES IN DIAMETER
1 BILLION LIGHT YEARS
2 BILLION LIGHT YEARS
3 BILLION LIGHT YEARS
4 BILLION LIGHT YEARS
YOU ARE HERE
DID YOU KNOW ?
THE SOLAR MASS IS A STANDARD UNIT OF MASS IN ASTRONOMY
IT IS EQUAL TO THE MASS OF THE SUN
EQUAL TO APPROXIMATELY 1.99 × 10^30 KG
LIGO Laser Interferometer Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

GW150914


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

The Nobel Prize in Physics 2017

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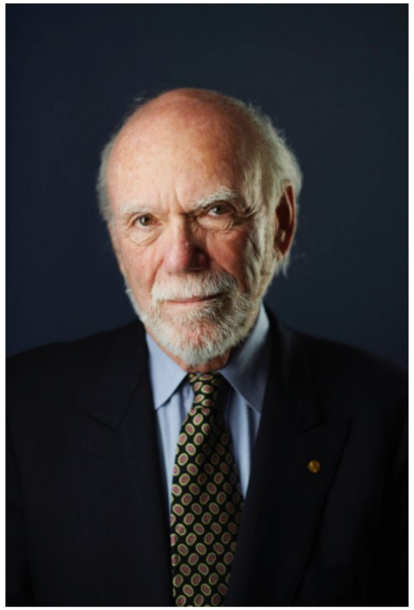
Rainer Weiss

Prize share: 1/2



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Barry C. Barish

Prize share: 1/4

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Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves"