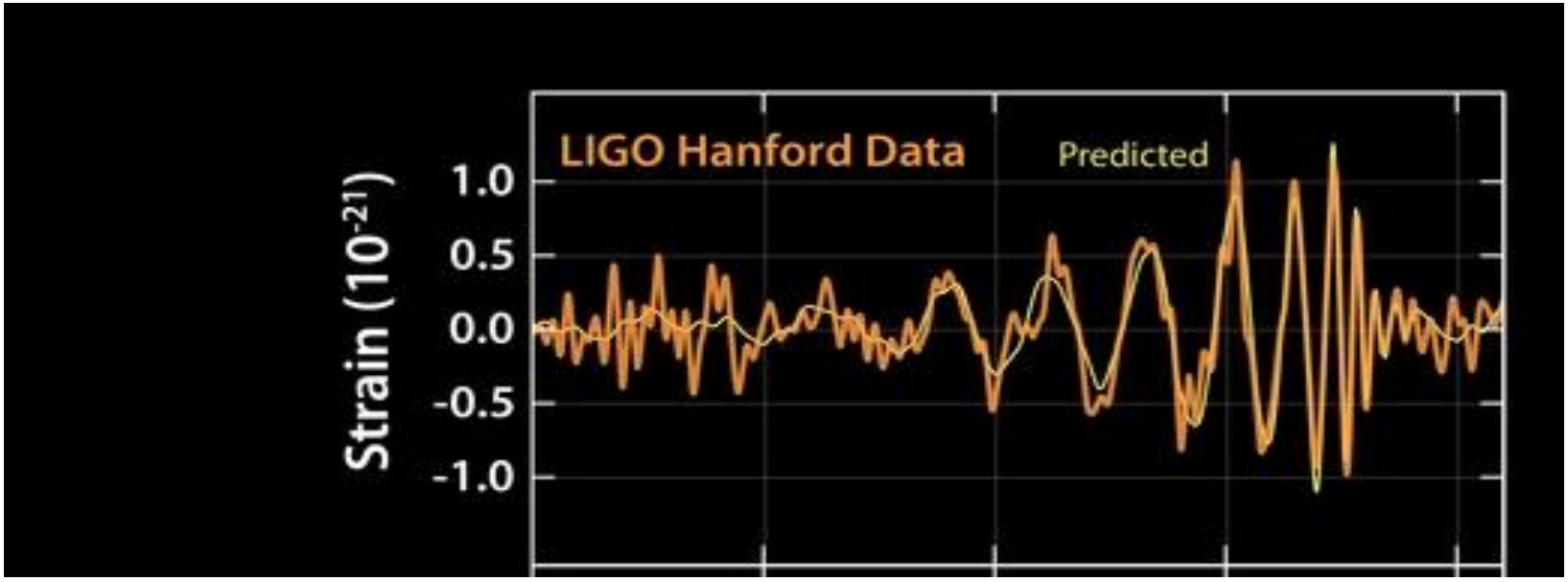
History of Gravitational Wave Emission

Daniel Kennefick
Univ. of Arkansas
and
Einstein Papers Project

6th Francis Bacon Conference, 2016

It has suddenly become a long history

1.3 billion years ago (very roughly) a binary system consisting of two roughly thirty solar mass black holes coalesced, sending out three solar masses of gravitational radiation.



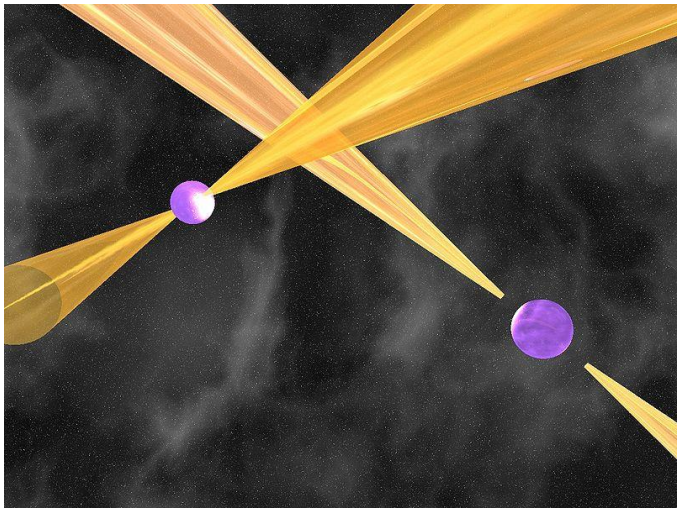
then

now

It has suddenly become a long history

1.3 billion years ago (very roughly) a binary system consisting of two roughly thirty solar mass black holes coalesced, sending out three solar masses of gravitational radiation.

21,040 years ago a binary neutron star system in our galaxy emitted gravitational waves which damped its own orbit enough for radio astronomers to detect the change using the Arecibo dish in Puerto Rico.



then

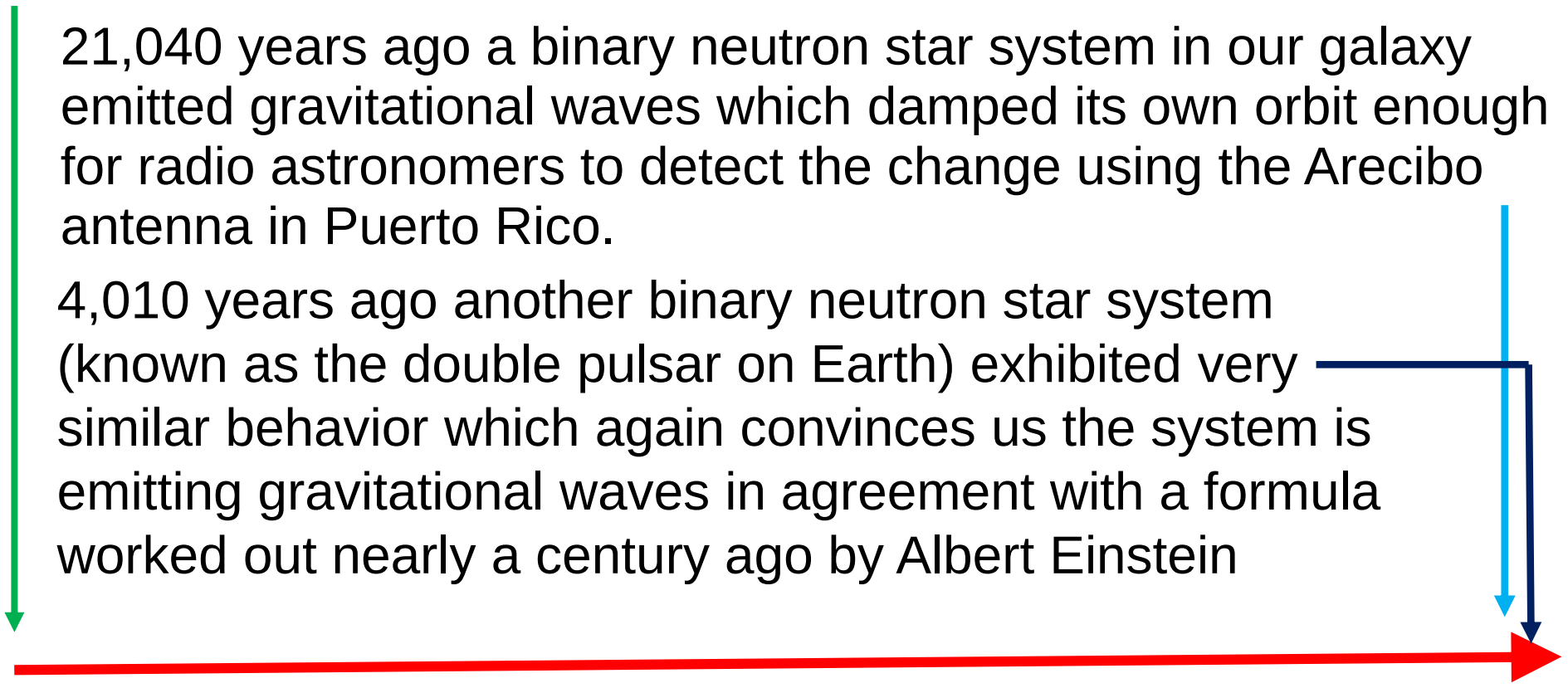
now

It has suddenly become a long history

1.3 billion years ago (very roughly) a binary system consisting of two roughly thirty solar mass black holes coalesced, sending out three solar masses of gravitational radiation.

21,040 years ago a binary neutron star system in our galaxy emitted gravitational waves which damped its own orbit enough for radio astronomers to detect the change using the Arecibo antenna in Puerto Rico.

4,010 years ago another binary neutron star system (known as the double pulsar on Earth) exhibited very similar behavior which again convinces us the system is emitting gravitational waves in agreement with a formula worked out nearly a century ago by Albert Einstein



then

now

A History of How we pieced this history together

That history began 100 years and 22 days ago:

“Since then, I have handled Newton's case differently, of course, according to the final theory. - Thus there are no gravitational waves analogous to light waves. This probably is also related to the one-sidedness of the sign of scalar T, incidentally (Nonexistence of the 'dipole.')”

- A. Einstein to K. Schwarzschild 19 Feb, 1916

Karl Schwarzschild
1873 - 1916

Some Prehistory

Three physicists had discussed the emission of gravitational waves before Einstein:

Pierre-Simon Laplace

Henri Poincare

Max Abraham

All three considered what happens when a system emits gravitational waves.

As Jurgen Renn has pointed out Abraham was the first to point out that conservation laws forbid the emission of dipole gravitational waves.

Max Abraham 1875-1922

Some Prehistory

Three physicists had discussed the emission of gravitational waves before Einstein:

Pierre-Simon Laplace

Henri Poincare

Max Abraham

Laplace did not actually consider the concept of the gravitational waves, only the damping of the Moon's orbit around the Earth due to a finite propagation time of gravity. This is what we now call Radiation reaction or Radiation Damping.

P. S. Laplace 1749-1827

Some Prehistory

Three physicists had discussed the emission of gravitational waves before Einstein:

Pierre-Simon Laplace

Henri Poincare

Max Abraham

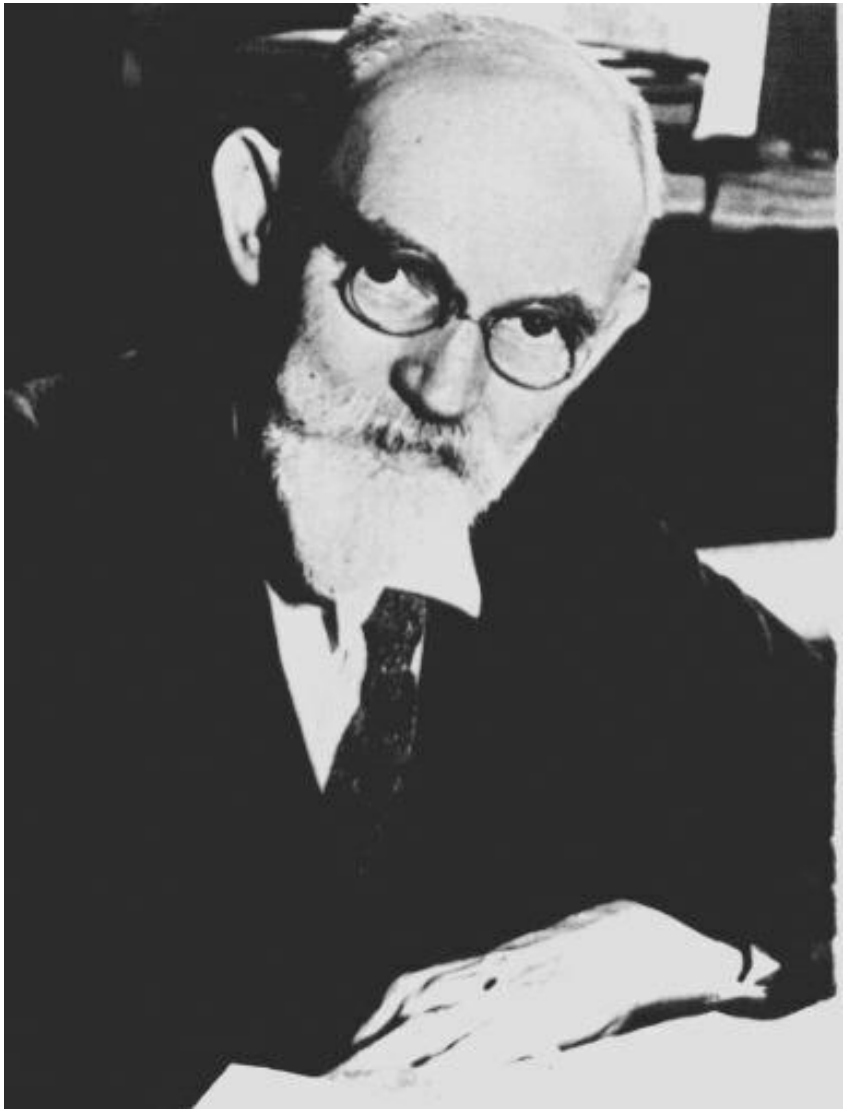
They all concluded that there was no evidence that radiation damping (and by extension gravitational waves) existed at all, though Poincare did not rule out the possibility that it could be observed in the perihelion advance of Mercury's orbit.

Henri Poincare 1854-1912

Einstein changes his mind

In mid 1916, at the suggestion of the Dutch Astronomer Willem de Sitter, Einstein used harmonic coordinates to study the linearized approximation of General Relativity.

In these coordinates the linearized equations look very similar to Maxwell's equations of the electromagnetic field. It is easy to derive a wave equation and Einstein discussed them at length in his 1916 paper.



Willem de Sitter
1872-1934

Let me rephrase that

However Einstein had made a critical error in constructing the energy pseudo-tensor in his 1916 paper.

He only realized this when the Finnish theorist Gunnar Nordstrom wrote to him puzzled by his own attempt to use this pseudo-tensor in his own calculations.

Einstein had to rewrite the paper in 1918.

Gunnar Nordstrom 1881-1923

The Quadrupole Formula

In his 1918 paper Einstein first presented the quadrupole formula for the flux of energy in a gravitational wave from a generic source.

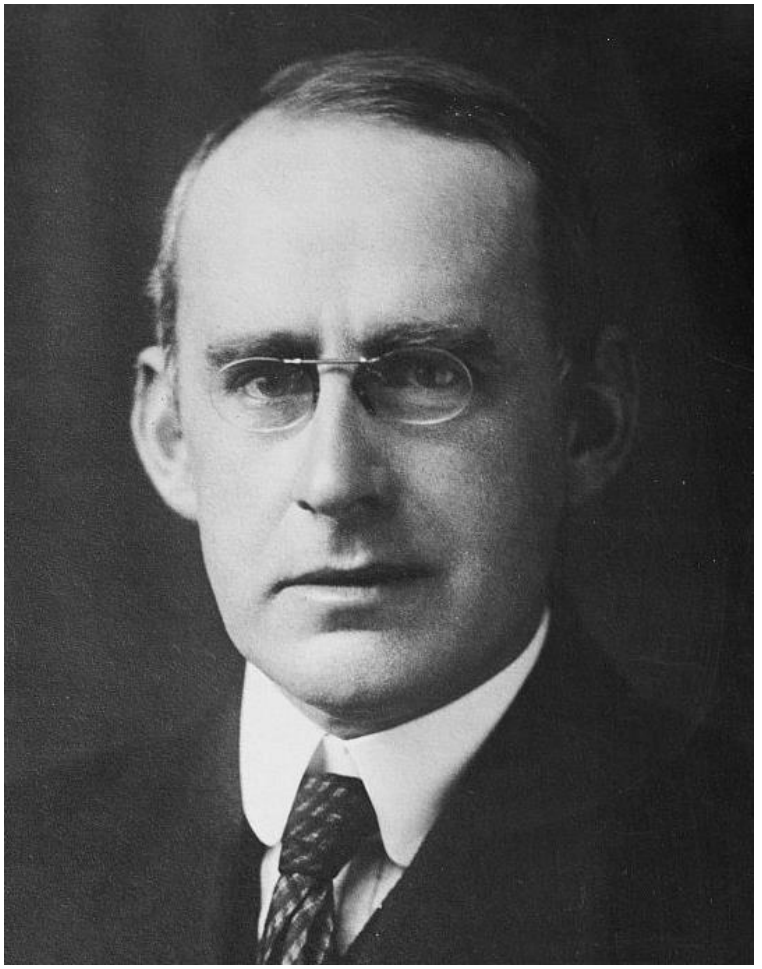
But his calculation was valid only for systems with weak gravity.

The Bridge Annex gravitational wave generator.

The Speed of Thought

Even in his 1918 paper Einstein made some errors. He at first thought he had discovered three different types of gravitational waves. Two of these types are spurious.

Einstein quickly realized this and Eddington later showed these spurious waves travel at arbitrary speeds depending on the choice of coordinates. As he put it, they travel not at the speed of light, but at “the speed of thought.”

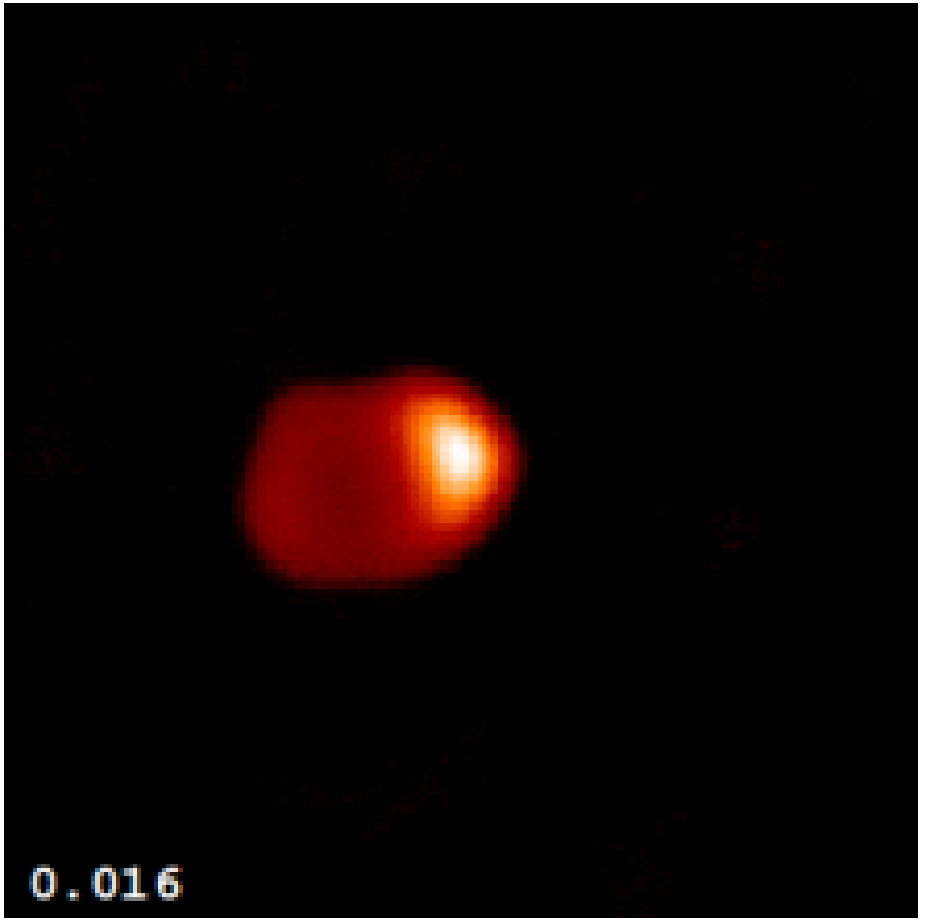


Arthur Stanley Eddington 1882-1944

A binary in straight lines

Why can't Einstein's 1918 calculation be applied to a binary star system?

Because if we solve the linearized Einstein's equations for the star's motion, they don't even orbit each other. The "gravity" has been taken out of these linearized "gravitational" equations.



Algol, a very famous close stellar binary. It is not emitting detectable gravitational waves. Images taken at Mt. Wilson Observatory.

A promotion

Unlike many relativists, I live with an astronomer.

Cost of each Keck 10m telescope = $70 million.

You can get 5 Kecks for the cost of initial LIGO.

A promotion

He’s not really an astronomer, but he does play one on TV.

- my wife

(in response to a History channel documentary which described me as an astronomer)

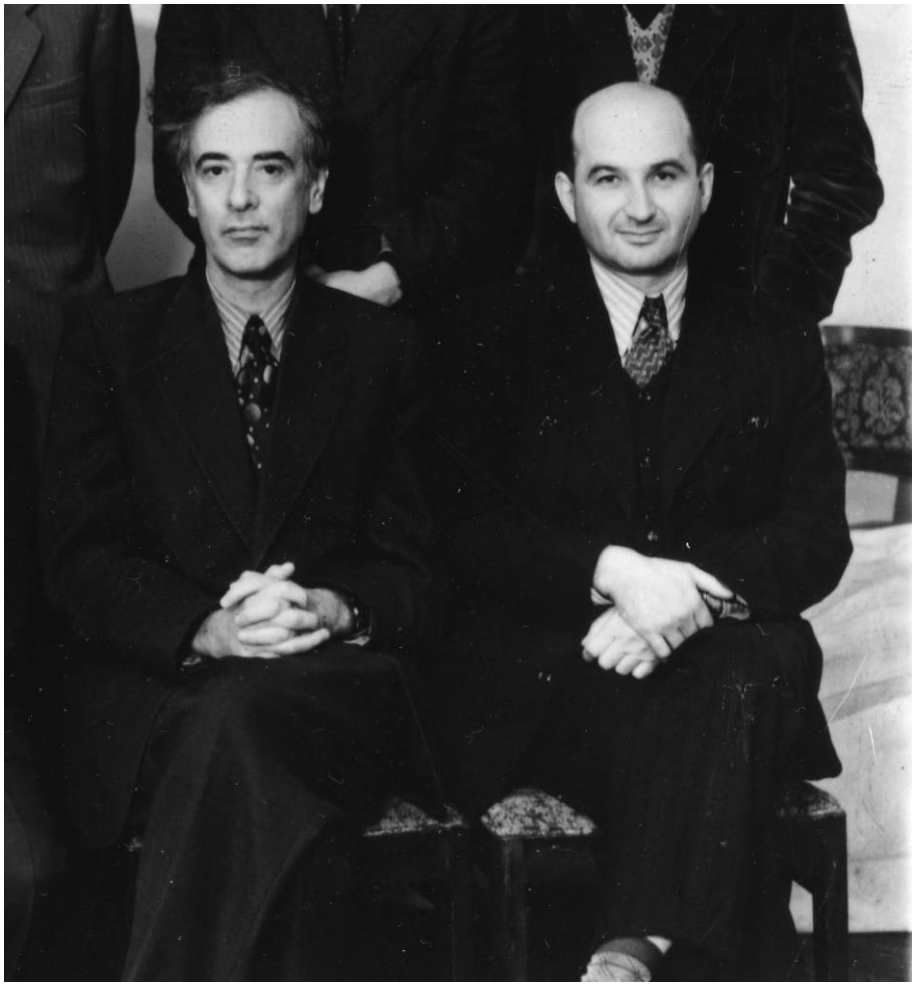
Cost of each Keck 10m telescope = $70 million.

You could get 5 Kecks for the cost of initial LIGO.

Landau and Lifshitz

In their famous textbook on Field theory (1941) the Russian physicists Lev Landau and Evgeny Lifshitz argue that an essentially linearized calculation like Einstein's from 1918 can be generalized to the case of a binary star system by simply importing into the calculation the known solutions for the stars' motion from the exact theory in the absence of gravitational waves.

This argument, though physically appealing (why not use more physically correct information even if it is mathematically inconsistent?) left many relativists skeptical, even though, or perhaps because, it obtained the same result Einstein had in in 1918 (the quadrupole formula).



Lev Landau 1908-1968
and
Evgeny Lifshitz 1915-1985

Very interesting … but irrelevant

If you believe Landau and Lifshitz, one lesson stands out. Gravitational waves from binary star systems will never be detectable. They are too weak, given what was known about stars in the 1940s.

Ironically skepticism of “glib” results like this one, which you could only credit “if you believe Landau was connected to God” helped convince some people to work on gravitational waves, purely to answer the question of principle: Did they exist?

Second Thoughts Again

“Next term we are going to have your temporary collaborator Infeld here in Princeton, and I am looking forward to discussions with him. Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we had believed up to now.”

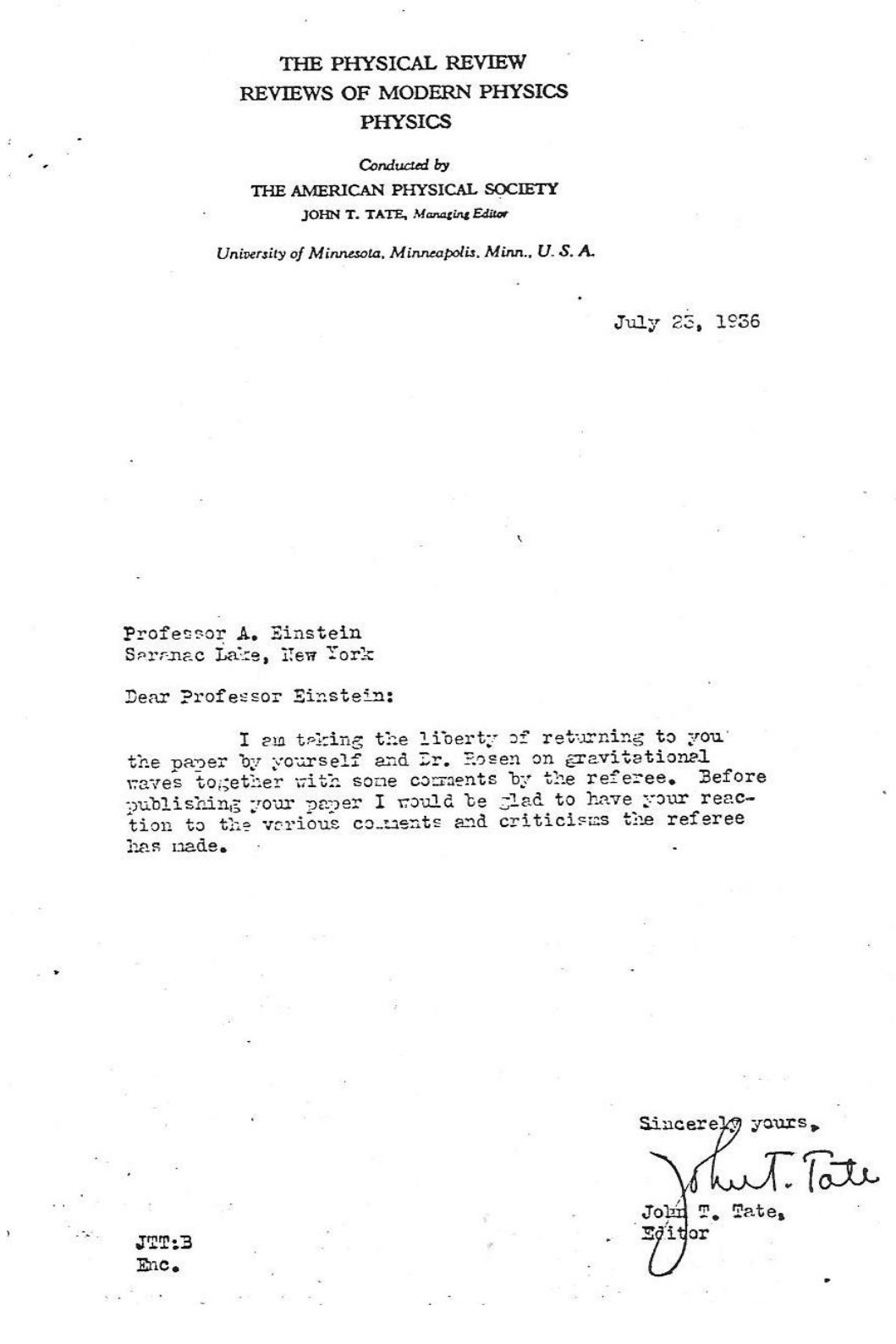
-Albert Einstein to Max Born, written in mid-1936.

Born and Infeld after the war

Title: “Do Gravitational Waves Exist?” Answer: No!

In June 1936 Einstein and his “young collaborator,” Nathan Rosen had sent a paper on gravitational waves to *The Physical Review*. This was their third joint paper submitted to that journal. The first two are very famous, the EPR paper and the Einstein-Rosen bridge (aka Wormhole) paper.

The gravitational wave paper met with a different response from the journal than the previous two, which had been published promptly.



THE PHYSICAL REVIEW
REVIEWS OF MODERN PHYSICS
PHYSICS

Conducted by
THE AMERICAN PHYSICAL SOCIETY
JOHN T. TATE, *Managing Editor*

University of Minnesota, Minneapolis, Minn., U. S. A.

July 23, 1936

Professor A. Einstein
Saranac Lake, New York

Dear Professor Einstein:

I am taking the liberty of returning to you the paper by yourself and Dr. Rosen on gravitational waves together with some comments by the referee. Before publishing your paper I would be glad to have your reaction to the various comments and criticisms the referee has made.

Sincerely yours,

John T. Tate

John T. Tate,
Editor

JTT:B
Enc.

Einstein's Reply

Herrn John T. Tate
Editor The Physical Review
University of Minnesota
Minneapolis, Minn.

Sehr geehrter Herr:

Wir (Herr Rosen und ich) hatten Ihnen unser Manuskript zur Publikation gesandt und Sie nicht autorisiert, dasselbe Fachleuten zu zeigen, bevor es gedruckt ist. Auf die - übrigens irrtümlichen - Ausführungen Ihres anonymen Gewährsmannes einzugehen sehe ich keine Veranlassung. Auf Grund des Vorkommnisses ziehe ich es vor, die Arbeit anderweitig zu publizieren.

Mit vorzüglicher Hochachtung

P.S. Herr Rosen, der nach Sowjet-Russland abgereist ist, hat mich autorisiert, ihn in dieser Sache zu vertreten.

Einstein's Reply

Dear Sir,

We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the - in any case erroneous - comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere.

respectfully,

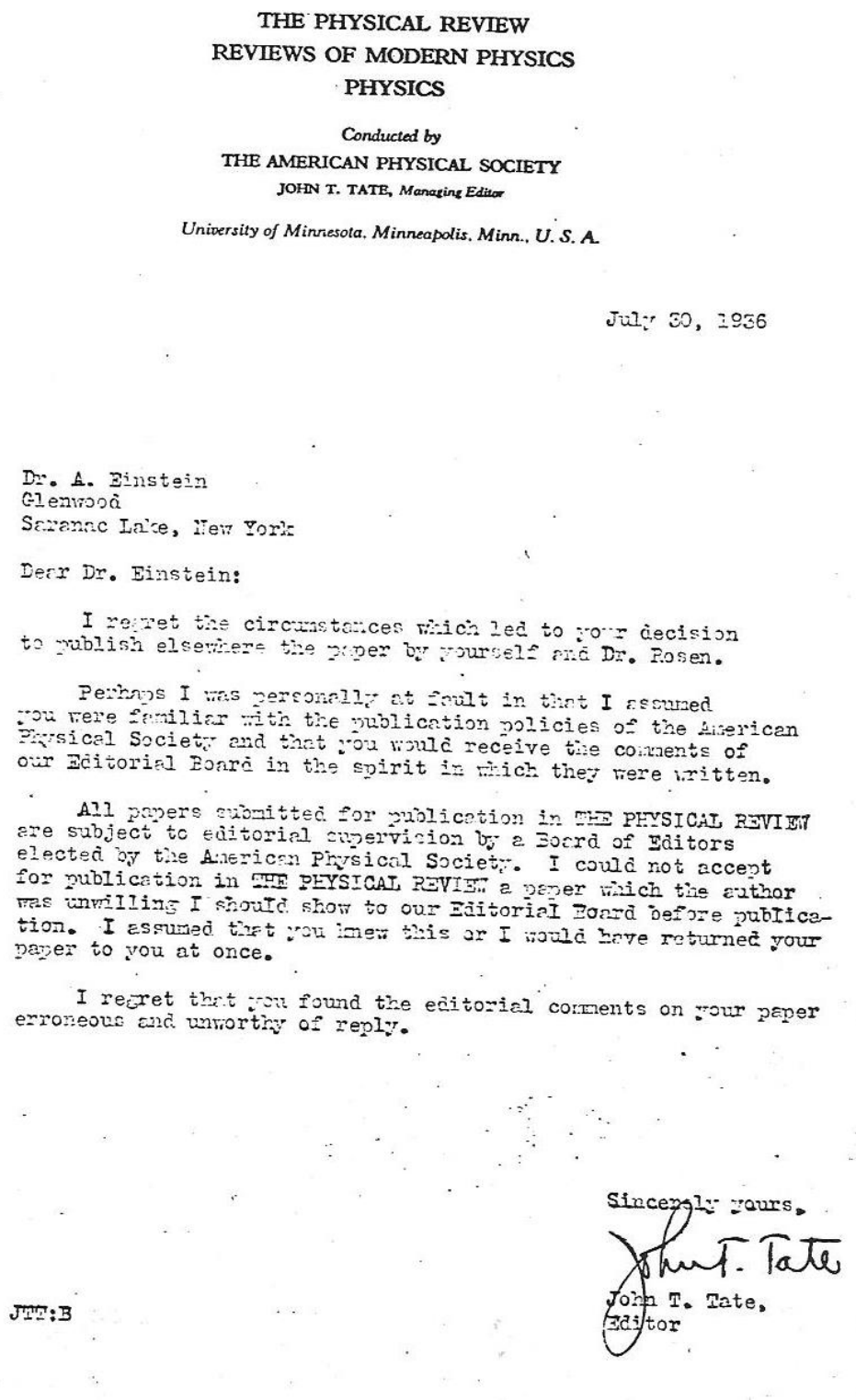
P.S. Mr. Rosen, who has left for the Soviet Union, has authorized me to represent him in this matter.

Peer Review

In fairness to Einstein, this was likely his first experience of anonymous peer review. It was not the normal practice in the German journals where he was used to publishing.

As we now know, his two previous submissions with Rosen to *The Physical Review* were not refereed.

Other European émigré physicists at this time made reference to the “rigorous criticism common for American journals.” In Germany it was considered an insult to reject a paper by an established physicist.



THE PHYSICAL REVIEW
REVIEWS OF MODERN PHYSICS
PHYSICS

Conducted by
THE AMERICAN PHYSICAL SOCIETY
JOHN T. TATE, *Managing Editor*

University of Minnesota, Minneapolis, Minn., U. S. A.

July 30, 1936

Dr. A. Einstein
Glenwood
Saranac Lake, New York

Dear Dr. Einstein:

I regret the circumstances which led to your decision to publish elsewhere the paper by yourself and Dr. Rosen.

Perhaps I was personally at fault in that I assumed you were familiar with the publication policies of the American Physical Society and that you would receive the comments of our Editorial Board in the spirit in which they were written.

All papers submitted for publication in THE PHYSICAL REVIEW are subject to editorial supervision by a Board of Editors elected by the American Physical Society. I could not accept for publication in THE PHYSICAL REVIEW a paper which the author was unwilling I should show to our Editorial Board before publication. I assumed that you knew this or I would have returned your paper to you at once.

I regret that you found the editorial comments on your paper erroneous and unworthy of reply.

Sincerely yours,

John T. Tate

John T. Tate,
Editor

JTT:B

Who Was The Referee?

The 10 page referee's report survives. The spelling used follows the American fashion, and at this time there were very few American physicists capable of writing this review, which shows a thorough familiarity with the General Theory of Relativity and its literature.

The chief three candidates would be Robert Oppenheimer, Richard Tolman, and H. P. Robertson.

Robertson actually had a known connection to this paper. He is acknowledged in the published version in the *Bulletin of the Franklin Institute.*

What about Robertson himself? Interestingly he was not in Princeton for the first half of 1936, when Einstein and Rosen were writing the paper. He was on sabbatical at Caltech, his alma mater. He only returned to Princeton in August.

The First Evidence

February 18,1937.

Dear Tate:

Thanks for your felicitations on my becoming a member of your revered staff. I celebrate my canonization by holding this first refereeing job more than the allowed ten days - at which, considering what it is, I expect no kicks from you. I am glad to recommend an unequivocal rejection - he might be advised to try to get the Oxford or Cambridge University Presses to allow him to expand it into a book, concerning the sort of stuff they have been flooding the market with lately.

You neglected to keep me informed on the paper submitted last summer by your most distinguished contributor. But I shall nevertheless let you in on the subsequent history. It was sent (without even the correction of one or two numerical slips pointed out by your referee) to another journal, and when it came back in galley proofs was completely revised because I had been able to convince him in the meantime that it proved the opposite of what he thought.

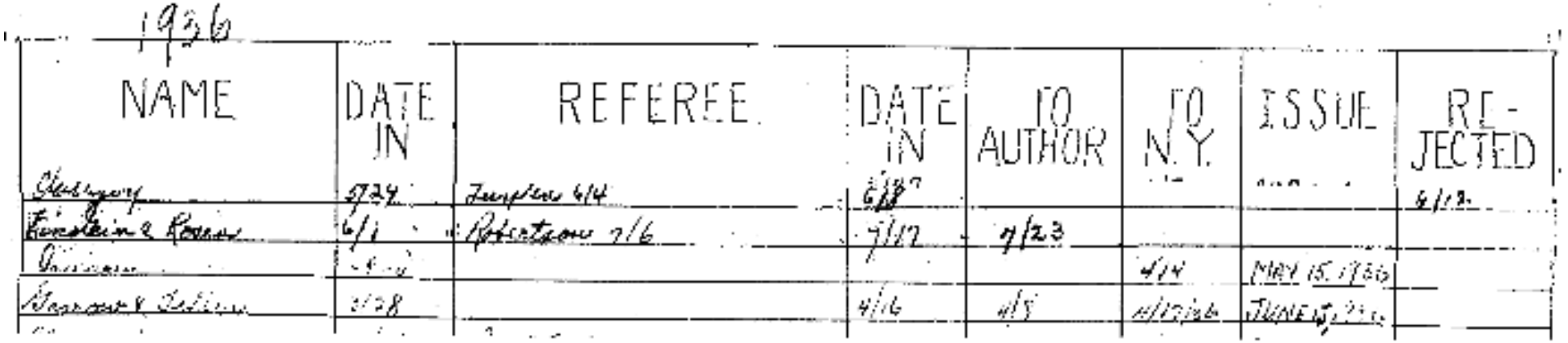
You might be interested in looking up an article in the Journal of the Franklin Institute, January 1937, p. 43, and comparing the conclusions reached with your referee's criticisms.

I have to confess a great scandal in connection with that paper of Swicky's, which I maintained I never saw. But imagine my chagrin last July in discovering it, unopened, in the attic of our house on our return from a fifteen months leave. The only solution I can give is that (1) it was rather inappropriately delivered at my home address, (2) it was lost in the pile of junk destined for the attic or the incinerator (I wish it had gone to the latter so I could go to my grave protesting my innonence), and, (3) discovered in the attic after a leave of 18 months, during which I waxed indigent at the postal authorities. I can only say I am sorry it occurred, and make what amends I can by returning this in your stamped self-addressed envelope, instead of soaking off the stamps and using them for air mail letters as I was at first inclined to do.

Sincerely yours,

H. P. Robertson.

The Smoking Gun



1926

NAME	DATE IN	REFEREE	DATE IN	TO AUTHOR	TO N.Y.	ISSUE	RE-JECTED
Einstein & Rosen	6/1	Robertson 7/6	7/17	7/23			
Oppenheimer & Serber	3/28		4/16	4/5	4/14	MAY 15, 1926	

The Physical Review Logbook from the 1930s, a scan from which has been kindly provided by the current editor of the *Review*, Martin Blume.

It shows that the Einstein and Rosen paper was received on June 1, sent to the referee Robertson on July 6, arrived back from Robertson on July 17 and was returned to Einstein on July 23.

By contrast, the same logbook shows that neither of the previous two Einstein and Rosen submissions were refereed at all, and the EPR paper was sent “TO N.Y.” the day after its submission.

Infeld's arrival on the scene

In the Fall of 1936 Infeld arrived in Princeton and discovered the importance of Football on American College Campuses.

At his first meeting with Einstein he learned of Einstein's disproof of the existence of gravitational waves as he listened to Einstein and Levi-Civita discuss the proof "in a language which they took to be English."

Infeld quickly became convinced that Einstein was right.

Tullio Levi-Civita 1873-1941

A Timely Intervention

In his memoir, Infeld tells how he came to accept Einstein's claim, and even came up with his own version of the proof, but his new friend "Bob" Robertson did not believe him and insisted on checking his calculation.

"He began quickly and efficiently to check all the steps of my argument, even the most simple ones, comparing the results on the blackboard with those in my notes …

I marveled at the quickness and sureness with which Robertson performed all the computations."

from *Quest*, p. 267

Howard Percy Robertson 1903-1961

Boss, we have a problem

Infeld continues:

“The next day I went to Einstein and announced:

`My result was wrong. I made a mistake in calculating. I believe that the waves do exist.’

Einstein said simply:

`I found a mistake in my paper last night. My proof is wrong too.’ ”

From *Quest*, p. 268.

Robertson then convinced Einstein that his calculation with Rosen could be modified so as to yield an exact solution for gravitational waves with cylindrical symmetry. The paper with Rosen was completely rewritten in proofs.

.

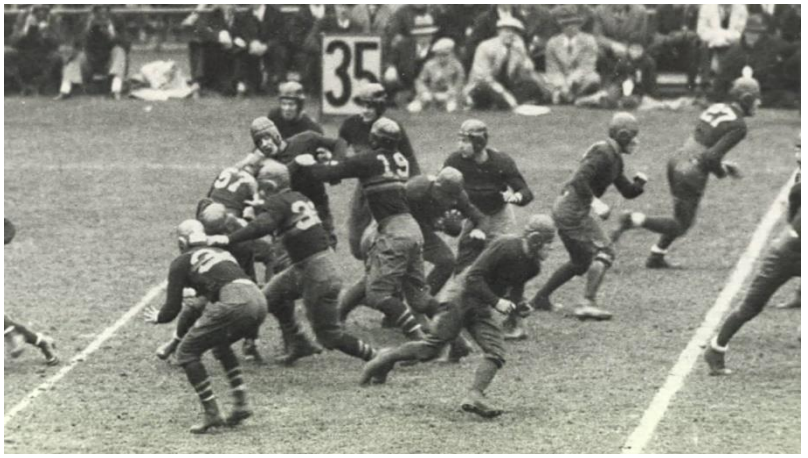
Einstein and Infeld

What a coincidence

Can it really be true, as Infeld alleges, that Einstein discovered the error in his proof the same day that Robertson (the referee) managed to convince Infeld?

We do know that Einstein was still thinking about the proof. He was working on a draft of a new paper exploring further implications of the argument which he abandoned in mid draft. Perhaps this was the moment at which he saw the light.

On the other hand, Infeld is not always the most reliable of informants



Notre Dame's football team. They haven't played Princeton since the 1920s.

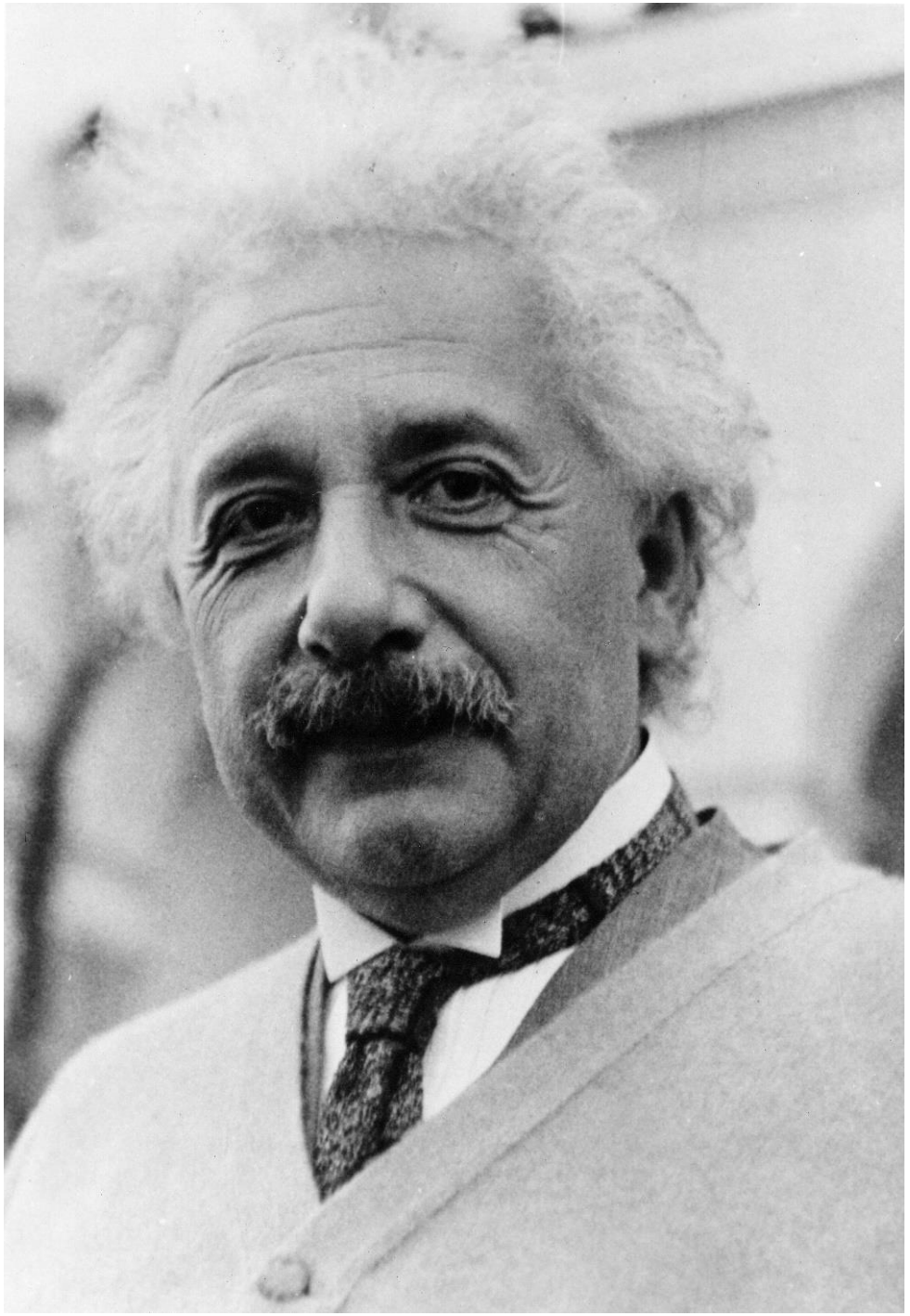
Would Einstein have cared?

It is certainly clear that Tate and Robertson saved Einstein from a very public controversy.

Given that even the innocuous paper that was eventually published in a relatively obscure journal attracted newspaper coverage, one can only imagine what the press would have made of the retraction of an Einstein paper.

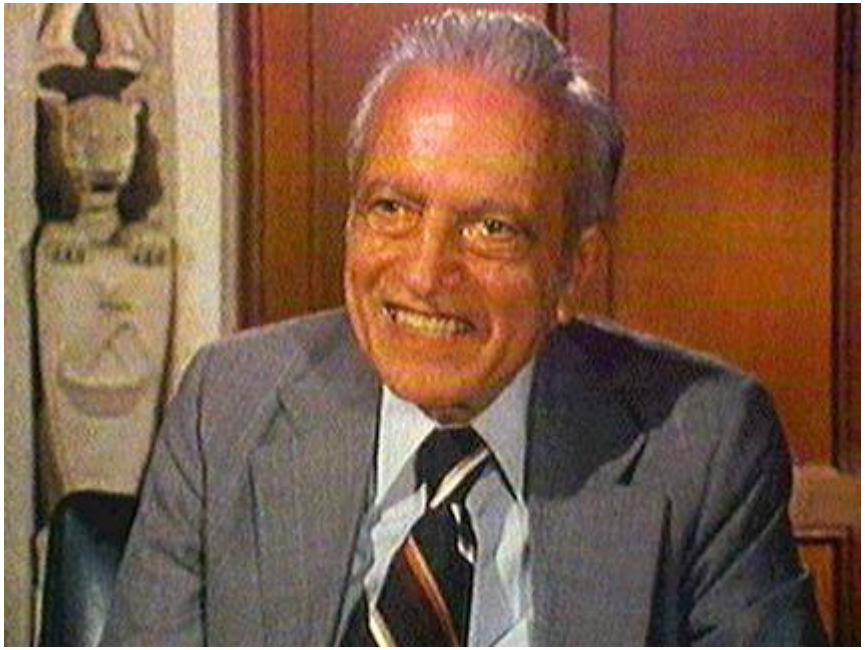
On the other hand, Einstein constantly joked at how he changed his mind every other year about his unified field theory. He would not have been greatly perturbed by a newspaper ruckus.

All the same, he never published in *The Physical Review* again.



EIH - Einstein Infeld Hoffmann

Einstein then decided to tackle the problem of motion of two binary stars, with Infeld and another assistant, Banesh Hoffmann. They did not go beyond the second order in this “post-Newtonian” expansion, but it was clear that in principle one could continue the calculation to the fifth order to try to answer the question as to whether binary stars would radiate gravitational waves.



Banesh Hoffmann 1906-1986

The Sceptics

After the war Rosen and Infeld were two influential figures in the postwar renaissance of GR. They each founded a school of relativity (in Israel and Poland) and they each continued to be skeptical of the existence of gravitational waves.

Rosen had learnt of the drastic revision of his paper with Einstein in the newspapers. After the war he used the cylindrical wave solution to argue that gravitational waves cannot carry energy.

Nathan Rosen 1909 - 1995

Felix Pirani

Pirani began his career in relativity at the University of Toronto in the school founded there by Infeld and John Synge. He played a central role in the rebuttal of the early arguments of the sceptics, especially Rosen's argument that gravitational wave cannot carry energy.

Inspired by Synge, Pirani showed how the equation of geodesic deviation could show how real particles move in response to gravitational waves.

Felix Pirani 1928-2015

Bondi and Feynmann

Both Hermann Bondi and Richard Feynman seized upon Pirani's work, presented at the seminal Chapel Hill conference of 1957 to propose a thought experiment which convinced many that gravitational waves must carry energy. And if they can transmit energy to an absorber, as Feynman pointed out, then surely they can also carry energy off from a source.

Feynman at a gravity conference with Dirac, 1962.

Infeld and Bondi's objection

But if Bondi had helped answer Rosen's skepticism, he initially agreed with Infeld that binary star systems would not be a source of gravitational waves.

His (and Infeld's) argument was based on the belief that it is accelerating masses that generate gravitational waves. This belief is based on the analogy with electromagnetism.

Hermann Bondi 1919 - 2005

Newman's Anecdote

General Relativity is a theory which relativizes the concept of acceleration. This makes it problematic to identify the sources of gravitational waves.

Suppose Galileo were to hold onto one ball and drop the other. Which one emits gravitational waves?

Infeld and Bondi argued that the dropped ball, like a binary star, does not radiate.

An evenly split vote

Problem of Motion

One way to answer this question is to carry out the EIH program to sufficiently high order to see the radiation damping effects in the binary system (a more advanced version of Laplace's calculation).

Unfortunately efforts to do this produced, up until the mid 1960s, conflicting results. Some theorists even derived the counter-intuitive result that the system would not be damped but would instead paradoxically gain energy and outspiral instead of inspiral!

The Theoreticians' Regress

Just as there is an Experimenters' Regress, there is a Theoreticians' Regress.

Theories don't make predictions, Theorists make predictions.

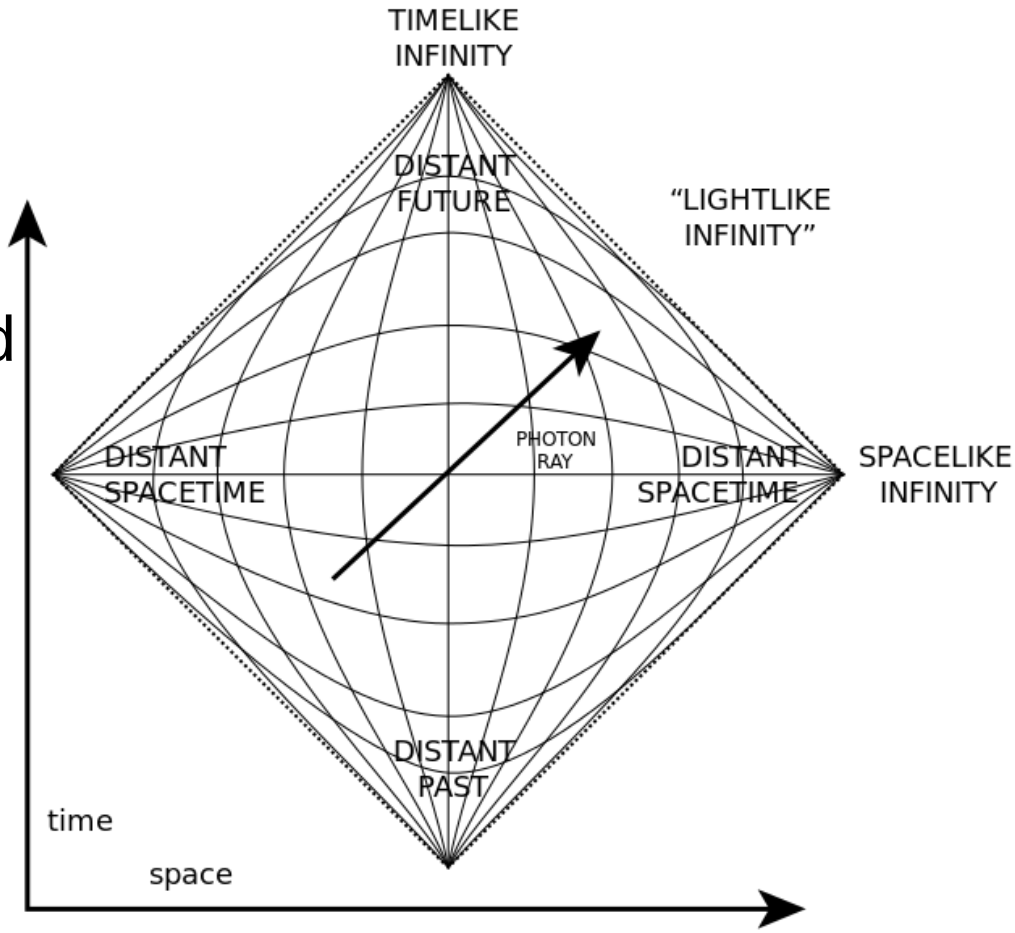
But to make a prediction, theorists need to perform the right calculation.

The right calculation must be the one that makes the right prediction!

Infinity

One of the reasons for the incorrect calculations was the failure to properly impose boundary conditions on the binary system. These boundary conditions needed to be imposed far from the source, in asymptotically flat spacetime.

The study of asymptotic spacetime led to an understanding that there is more than one infinity in spacetime, as demonstrated in the compactified spacetime diagrams of Roger Penrose.



Matched Asymptotic Expansions

Even with a better understanding of infinity, imposing boundary conditions far from the source onto the equations of motion of the source itself was not easy to do in an unambiguous way.

In 1969 a Caltech graduate student of Kip Thorne's, Bill Burke, introduced a technique from applied math, that of matched asymptotic expansions, to facilitate this.

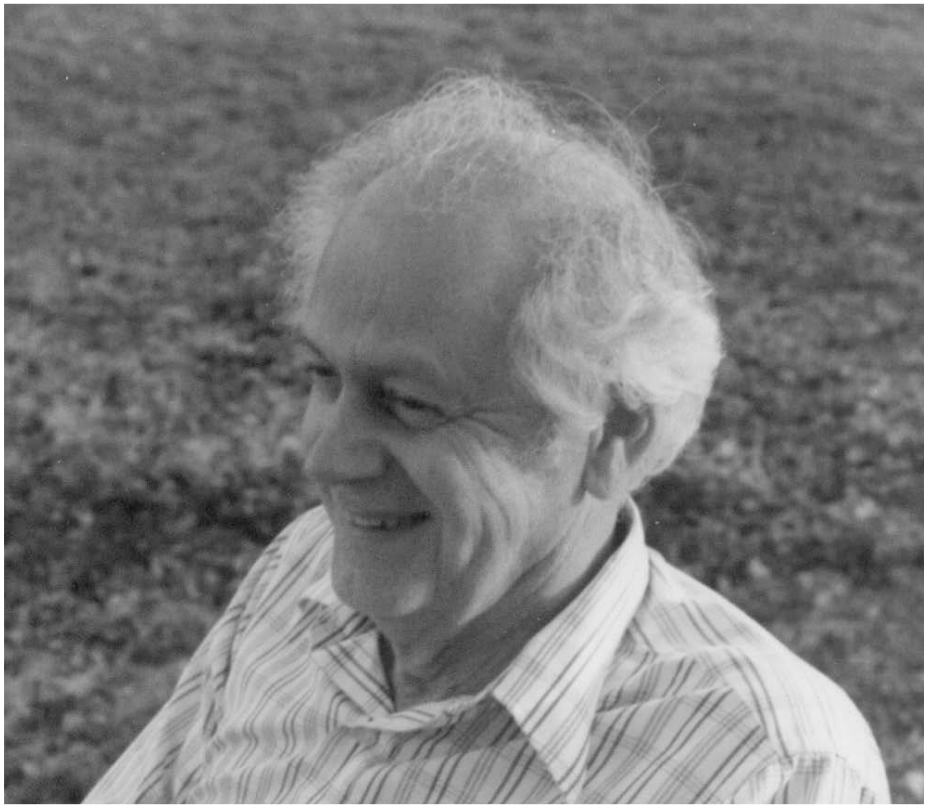
A decade later another of Kip's students, Cliff Will, showed another way you could identify the correct calculation (Walker and Will.

Bill Burke 1941 - 1996

Quadrupole Formula Controversy

By the early 1970s many relativists agreed with Kip Thorne that the emission of gravitational waves by binary stars was well understood.

But some champions of mathematical rigor, such as Peter Havas and Jurgen Ehlers, complained that it was not yet proven that Einstein's quadrupole formula applied to such systems.



Peter Havas 1921 - 2004

The Binary Pulsar

Joseph Taylor
Nobel Laureate, 1993

1963 Freeman Dyson proposes that binary neutron stars might be constructed by alien civilizations, and thus SETI should focus on gravitational wave sources

1967 Discovery of first pulsar

1974 Discover of first binary pulsar PSR1913+16 by Hulse and Taylor

1978 Measurement of Orbital Decay agrees with Einstein's quadrupole formula prediction of 1918

1980s Resolution of the Quadrupole Formula Controversy. Interestingly Taylor's results arguably revitalized the controversy rather than initially settling it.

Sources and Templates

In the 1990s the recognition that optimal filtering of LIGO signals would require theoretical templates provided renewed impetus for work in this area.

In 1991, at one of my first group meetings Kip came in with a sheaf of papers laying out the work that needed to be done by theorists to assist the LIGO effort.

Kip

Different theoretical tools

Most of the GW 150914 signal cannot be described with the kind of post-Newtonian calculations which dominated the history of the subject in the 20th century.

One must solve the exact equations of GR to describe the late inspiral and merger phase, which requires Numerical Relativity programs run on super computers.

Numerical Relativity

Numerical Relativity began tentatively in the 1960s and took some important steps in the 1970s, for instance with the work of Bryce DeWitt's student Larry Smarr, together with Kenneth Eppley.

In the 1990s the NSF funded a Grand Challenge Alliance to kick start the effort to model a binary coalescence.

Larry Smarr

Kip's wager

Around 2000 I was present at a numerical relativity meeting when Kip proposed a wager with the leaders of the Numerical Relativity Grand Challenge Alliance.

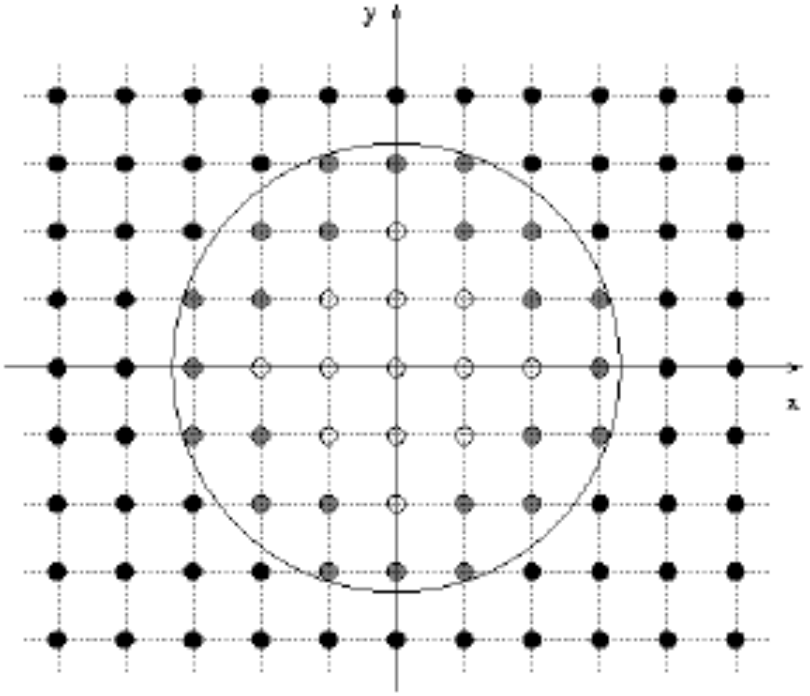
He bet that LIGO would see the signal from a merging pair of black holes before they could correctly predict the waveform.

In my recollection, though they took the bet, the numerical relativists did not look very confident of their chances. At that time, no simulation of a 3D binary had run for even one complete orbit.

The Challenges

An example of the kind of issue they faced is Black Hole excision. The computer cannot handle singularities so, taking advantage of the fact that nothing can escape from inside a black hole, the computational grid is not extended far inside the horizon.

Nothing can escape from inside the horizon unless it can travel faster than the speed of light. But it turns out that numerical error travels at the speed of thought. The speed of thought of a super computer is blazingly fast. Errors can propagate across the grid and crash the code.

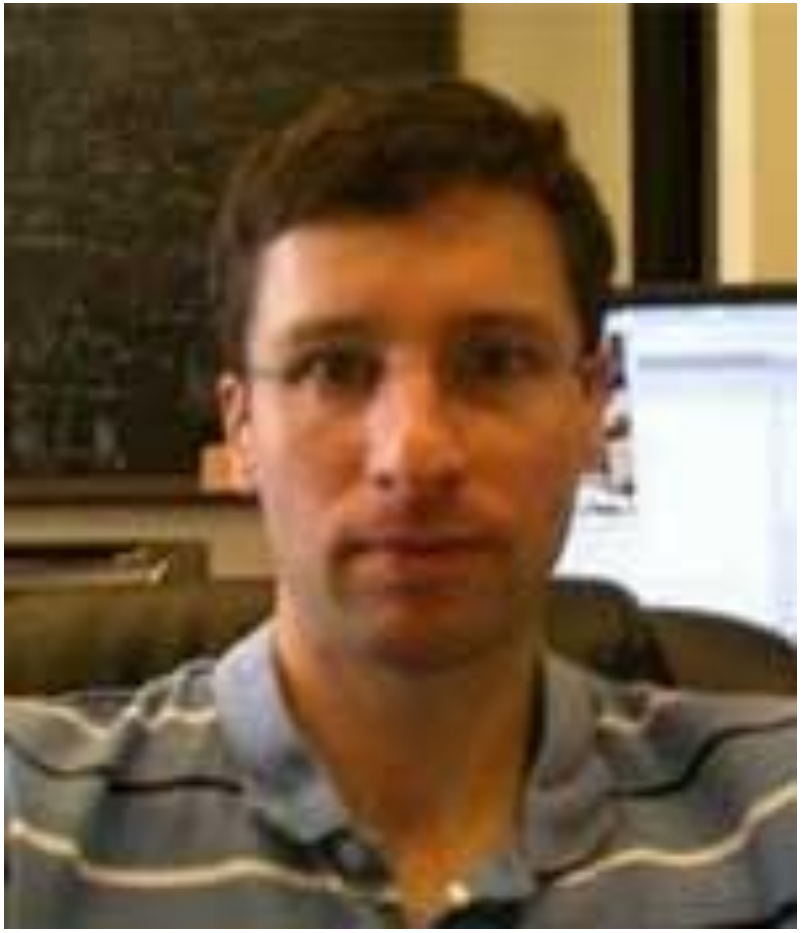


Inside the event horizon (the circle) most points on the grid (marked by open circles) are not evolved in time as the rest of the computational grid is.

The Breakthrough

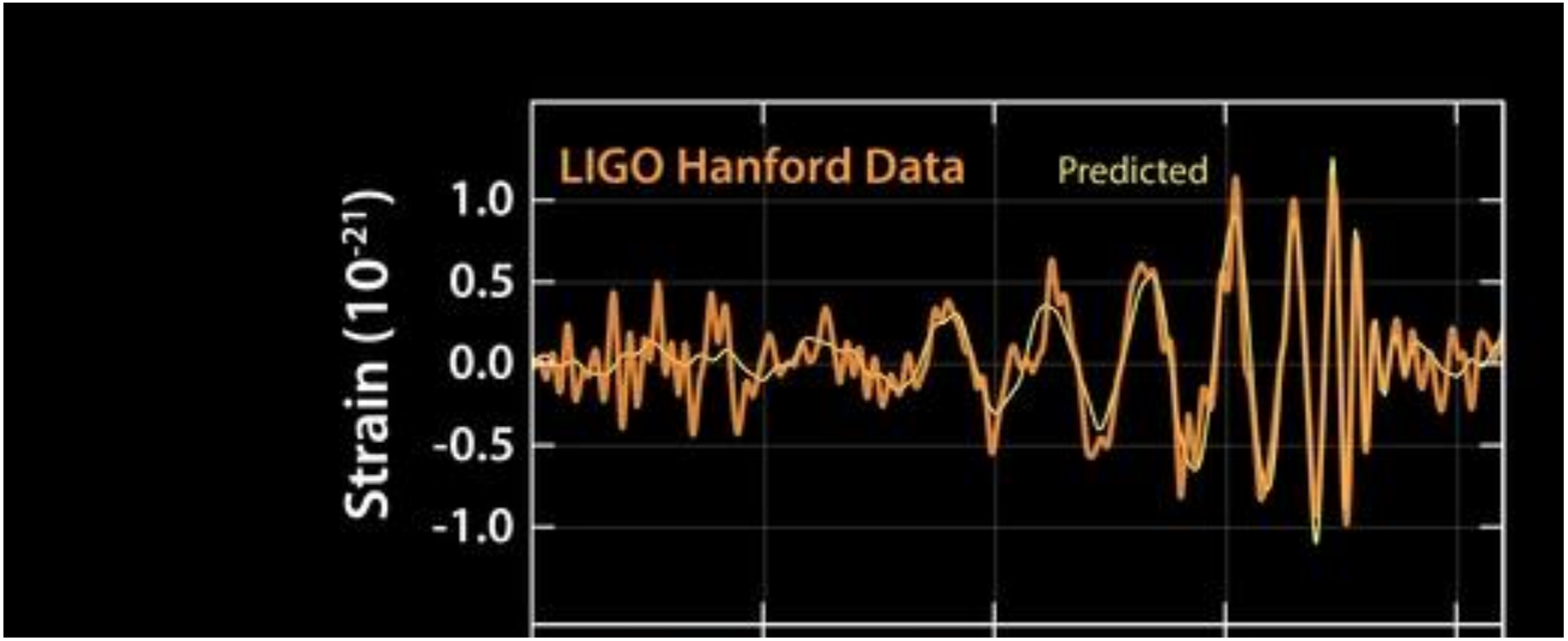
In 2005 Frans Pretorius, a Caltech postdoc, was able to evolve a black hole binary through a last orbit merger and ringdown, followed shortly after by other groups.

Since then Numerical Relativists have made a number of remarkable discoveries about black hole mergers.



Frans Pretorius

The Triumph of Theory



With a 50 year head start, theorists were fortunate that it took experimenters 50 years to detect gravitational waves.

Einstein’s response

Einstein would have been thrilled by this dramatic vindication of his theory.

Though the detection of gravitational waves proves just how impressively right he was, this was one case where he was right, but by no means certain of his rightness.

Einstein’s response to gravitational waves