Gravitational waves

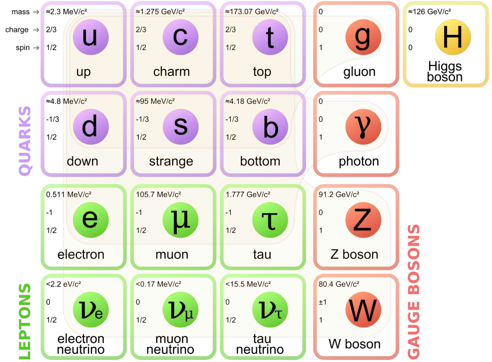
27.10.20

General schedule

- ⋆ History
  - ⋆ Gravity research before modern scientific revolution,
  - ⋆ Gravity and gravitational waves from Newton to Einstein,
  - ⋆ After Einstein - brief overview of the XX century.
- ⋆ Introduction to general relativity
- ⋆ Detection principles
- ⋆ Detectors
- ⋆ Binary black-hole system
- ⋆ Bursts and continuous waves
- ⋆ Rates and populations, stochastic GW background, cosmology
- ⋆ Testing general relativity
- ⋆ Data analysis: waveforms and detection
- ⋆ Data analysis: parameter estimation

Fundamental interactions (known so far)

Standard Model of elementary particles



Organized by their strength (coupling):

- ⋆ Strong interactions (1),
- ⋆ Electromagnetism ($\frac{1}{137}$),
- ⋆ Weak interactions (10^{-9}),

- ⋆ Gravitation (10^{-38})
  - ⋆ not included in the Standard Model,
  - ⋆ the weakest "force",
  - ⋆ does the graviton really exist?

Before modern scientific revolution

Aristotle (384-322 BCE):

- ⋆ There is no effect of motion without a cause,
- ⋆ massive bodies move according to their tendency in natural motion, i.e., towards the centre of the universe, which happens to be the center of Earth,
- ⋆ cause of tendency: inner *gravitas* or heaviness,
- ⋆ 4 elements on Earth, proposed earlier by Empedocles (490-430 BCE), æther in heavens,

Aristotle's elements

Element	Hot/Cold	Wet/Dry	Motion	Modern state of matter
Earth	Cold	Dry	Down	Solid
Water	Cold	Wet	Down	Liquid
Air	Hot	Wet	Up	Gas
Fire	Hot	Dry	Up	Plasma
Aether	(divine substance)	—	Circular (in heavens)	—

- ⋆ natural state of objects is to be at rest.

Before modern scientific revolution

Aristotle (384-322 BCE):

- natural and ”violent” (unnatural) motion ($\rightarrow$ continuous force needed to move bodies)
- speed of falling bodies is
  - proportional to their weight,
  - inversely proportional to the resistance of the medium ($\rightarrow$ infinite speed in vacuum?),

Vitruvius (1st century BCE):

- gravity depends on substance’s ’nature’ (specific gravity) $\leftrightarrow$ Archimedes, buoyancy

India, Islamic world; theory of impetus

- ⋆ Brahmagupta (598-668 CE) describes gravity as an attractive force,
- ⋆ 6th century, John Philoponus of Alexandria: the theory of impetus to explain motion of objects against gravity. Impetus is a causative ‘force‘ which diminishes over time (by dissipation in air, also in vacuum). Initial groundwork for modern concepts of inertia, momentum and acceleration.
- ⋆ 11th century, Ibn Sīnā (Avicenna): object will be in motion until the force/impetus is spent, in vacuum the motion continues forever ($\rightarrow$ Newton’s 1st law)
- ⋆ 12th century, Al-Baghdādī: gravitational acceleration of falling bodies. Constant force/impetus DOES NOT produces a uniform motion, a force applied continuously produces acceleration ($\rightarrow$ Newton’s 2nd law)
- ⋆ 12th-century, Ibn Bajjah: for every force there is a reaction force ($\rightarrow$ Newton’s 3rd law).

Renaissance

14th century:

- ⋆ Jean Buridan, Merton College: impetus = weight$\times$velocity ("momentum")
- ⋆ Albert of Saxony: acceleration of a body in free fall because of increasing impetus

15th century:

- ⋆ Leonardo da Vinci: "origin of gravity" is energy

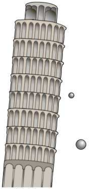
16th century:

- ⋆ Nicolaus Copernicus: heliocentric model of solar system (a re-iteration of Aristarchus and Philolaus ideas, using mathematics of al-Urdi, al-Tusi, Ibn al-Shatir, observations of al-Battani, Thabit ibn Qurra, al-Zarqali, Averroes, al-Bitruji)

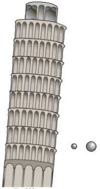
Renaissance

16th/17th century:

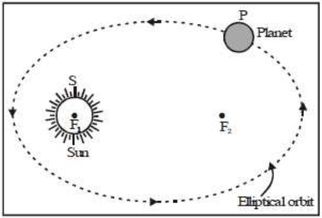
- ⋆ Domingo de Soto (1555): objects in free fall accelerate uniformly,
- ⋆ Galileo (beginning of 17th century): classical mechanics
  - ⋆ correct description of acceleration of falling objects,
  - ⋆ distance proportional to the square of the elapsed time, $d \propto t^2$,
  - ⋆ objects keep their velocity in the absence of any change in their motion (Philoponus, Buridan),
  - ⋆ equivalence principle (objects of different weights fall with the same speed)
- ⋆ Johannes Kepler (1609, 1619): laws of planetary motion (deferents and epicycles $\rightarrow$ ellipses)



Old idea



Galileo



Isaac Newton (1643-1727)

Law of Universal Gravitation (Isaac Newton, Principia Mathematica 1687):

$$F = \frac{Gm_1 m_2}{r^2}$$

(the actual apple tree in Woolsthorpe Manor)

Laws of motion:

In the inertial reference frame:

1. Object remains at rest or moves at constant velocity, if no force acts on it.
2. Force is proportional to acceleration ($\mathbf{F} = m\mathbf{a}$).
3. Force exerted by body m_1 on body m_2 is equal in magnitude (opposite in direction) to force exerted by body m_2 on body m_1.

Isaac Newton (1643-1727)

Newtonian mechanics:

- ⋆ Time is absolute, there is no relation between time and space
- ⋆ Gravitation is a force acting between masses
- ⋆ Force of gravitation acts immediately at any distance

From “Four letters from Sir Isaac Newton to Doctor Bentley, containing some arguments in proof of a deity“ (1692-93):

It is inconceivable that inanimate brute matter should, without the mediation of something else which is not material, operate upon and affect other matter without mutual contact (. . .)

Two problems to explain

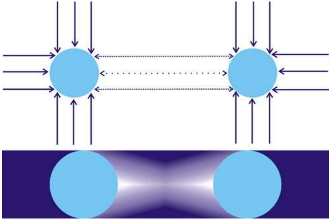
1. Action-at-a-distance, 2. immediacy (no delay in action)

- ⋆ Leucippus, Democritus (5th century BCE): all there is are atoms and void
  - ⋆ How to explain interaction without a medium in-between?
  - ⋆ How to explain sense in structures? (Pre-defined plan → Leibniz meta-physics)
- ⋆ Assuming there is no void:
  - ⋆ Atoms are in constant contact, is movement even possible?
- ⋆ Solution on the basis of materialistic philosophy: æther
  - ⋆ The world consists of two kind of matter: *non-elastic* (atoms, the usual matter) and *elastic* (æther, of not well defined concretness).

Æther gravity theories

Gravity due to particles or waves moving at high speed in all directions, interacting non-uniformly with massive bodies.

- ⋆ René Descartes (1644): no empty space can exist. Vortices in æther model, movement circular $\rightarrow$ inertia due to movement in æther,
- ⋆ Robert Hooke (1671): gravitation is because bodies interact/emit æther waves,
- ⋆ Nicolas Fatio de Duillier (1690), Georges-Louis Le Sage (1748): kinetic theory of gravity, æther in a form of particles.
- ⋆ later Lord Kelvin (1872), Hendrik Lorentz (1900).



Speed of light

- ⋆ Empedocles (490-430 BCE): light has a finite speed ("it is *something* in motion"),
- ⋆ Aristotle: "light is due to the presence of *something*, but it is not a movement",
- ⋆ Ole Rømer (1676): periods of moon of Jupiter ($c \approx 220000$ km/s)
- ⋆ James Bradley (1726): aberration of light (≈ 301000 km/s)
- ⋆ Hippolyte Fizeau (1849), Léon Foucault (1862): rotating gear, rotating mirror and time-of-flight
- ⋆ International System of Units (1983), redefinition of the meter: $c \equiv 299792458$ m/s in vacuum.

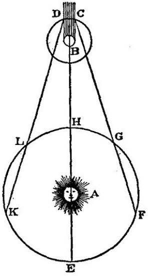
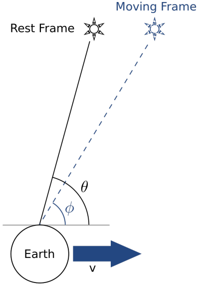
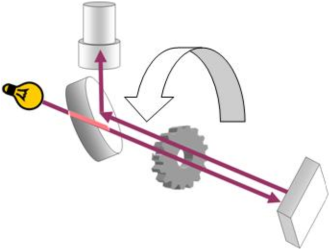


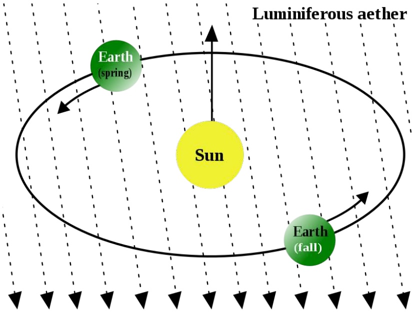
FIG. 70.

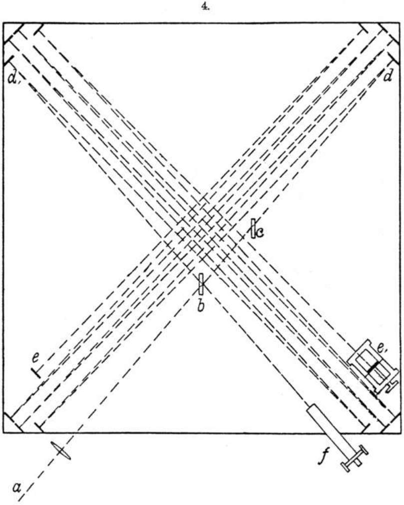




Detecting *luminiferous* æther

Albert A. Michelson (1881), A. Michelson & Edward Morley (1887)





(Delay-line interferometer)

Speed of gravity; Maxwell and electromagnetism

- ⋆ Pierre-Simone Laplace (1776): in order to ‘fix‘ the Newtonian action-at-a-distance, gravity propagates in a kind of fluid, like waves on water. To match the theory with Solar System observations:
  - ⋆ speed of gravity must be very large, $v_g \sim 10^6$ c,
  - ⋆ but... it makes the Solar System highly unstable.
- ⋆ These and similar attempts were useful to create a concept of a field, where objects interact via the potential, e.g. $F = -\nabla\phi$
- ⋆ James Clerk Maxwell (1863): electromagnetism

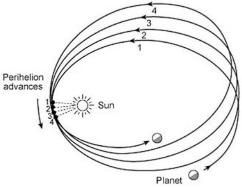
$$\nabla \cdot \mathbf{E} = 4\pi\rho, \quad \nabla \cdot \mathbf{B} = 0, \quad \nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi\mathbf{J} + \frac{\partial \mathbf{E}}{\partial t}\right)$$

- ⋆ Electromagnetic interaction propagates like a wave - theory has solutions of the type $\ddot{u} = c^2\nabla^2 u$
- ⋆ waves first registered by Heinrich Hertz in 1886-1889

The path to gravitational waves

- ⋆ Oliver Heaviside (1893): gravitomagnetism, gravitational analogue of Maxwell equations (still useful for slowly-moving isolated sources) - first ”modern” work on gravitational waves.
- ⋆ Second part of the 19th century: a lot of effort to ‘fix‘ Newton’s dynamics by adding extra terms (no success).

- ⋆ Solid astronomical evidence: Urbain Le Verrier (1859), Mercury perihelion advance
- ⋆ Henri Poincaré (1905): ”Sur la Dynamique de l’Électron”, retardation effect in the field interacting with objects $\rightarrow$ *ondes gravitiques*



”The Secret History of Gravitational Waves”, 2016, Tony Rothman, American Scientist

Why relativity? Maxwell and Newton incompatible

Maxwell's equations describe electromagnetism and optical phenomena within the theory of waves:

- ⋆ A special medium, *"luminiferous æther"*, needed to propagate the waves; Æther weakly interacts with matter, is carried along with astronomical objects,
- ⋆ Light propagates with a finite speed, but this speed is *not invariant* in all frames,
- ⋆ Especially, Maxwell's equations are *not invariant* under Galilean transformations between, say, inertial coordinate frames O and O':

$$x' = x - vt, \quad t' = t$$

- ⋆ To make electromagnetism compatible with classical Newton's mechanics, light has speed $c = 3 \times 10^8$ m/s only in frames where source is at rest.

Why relativity? Maxwell and Newton incompatible

Albert Einstein (1905): Maxwell's unification of electricity and magnetism is complete by showing that the two fields is really one.

Special relativity is based on two postulates:

- ⋆ the laws of physics are invariant (i.e., give the same results) in all inertial systems (non-accelerating frames of reference), $\rightarrow$ no experiment can measure absolute velocity,
- ⋆ the speed of light in vacuum is the same for all observers.

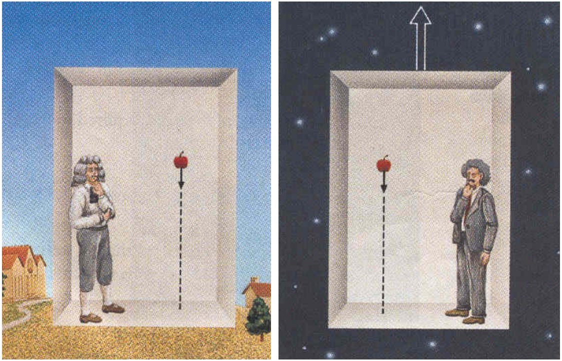
Lorentz transformation instead of Galilean:

$$\begin{aligned} t' &= \gamma\left(t - \frac{vx}{c^2}\right) \\ x' &= \gamma\,(x - vt) \\ \text{with } \gamma &= \frac{1}{\sqrt{1 - v^2/c^2}} \end{aligned}$$

- ⋆ length contraction $\Delta l' = \Delta l/\gamma$,
- ⋆ time dilation $\Delta t' = \Delta t\gamma$,
- ⋆ "relativistic mass" $m\gamma$,
- ⋆ mass–energy equivalence $E = mc^2$,
- ⋆ universal speed limit,
- ⋆ relativity of simultaneity.

Einstein: equivalence principle

Einstein (1907), ”the happiest thought of his life”:



Gravitation is a form of acceleration; locally, the effects of gravitation (motion in a curved space) are the same as those of an accelerated observer (in flat space).

Einstein: equivalence principle

Strong equivalence principle:

- ⋆ The outcome of any local experiment (gravitational or not) in a free-falling laboratory is independent of the velocity of the laboratory and its location in spacetime,
- ⋆ the laws of gravitation are independent of velocity and location,
- ⋆ Locally, the effects of gravitation (motion in a curved space) are the same as that of an accelerated observer in flat space.

Gravitation: Newton vs Einstein

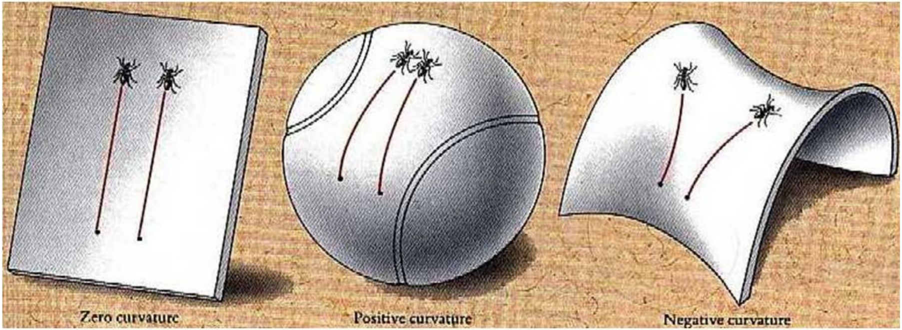
Newton:

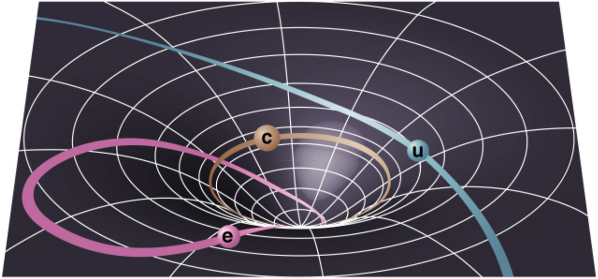
- ⋆ Space is euclidean, time is absolute, there is no relation between them
- ⋆ Gravitation is a force acting between masses
- ⋆ Force of gravitation acts immediately at any distance

Einstein:

- ⋆ Space and time are related
- ⋆ 4-dimensional space-time is curved by masses, and gravitation is an effect of this curvature
- ⋆ Effects of gravitation travel with a finite speed (speed of light)

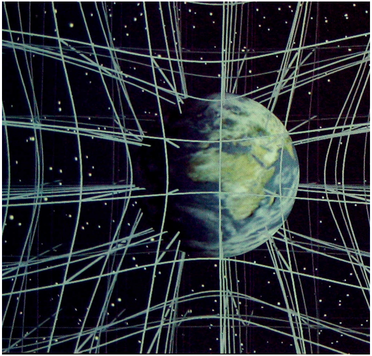
The role of curvature





Einstein (1915): gravitation $\equiv$ spacetime geometry

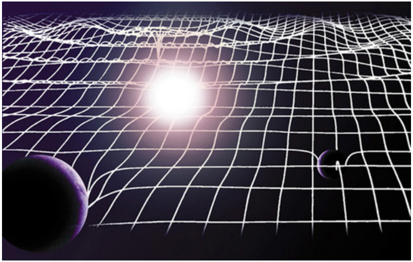
$$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{geometry}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{mass-energy}}$$



"Spacetime grips mass, telling it how to move... Mass grips spacetime, telling it how to curve"

(*John A. Wheeler*)

Einstein (1916, 1918): wave-like solutions in general theory of relativity: time-dependent changes of curvature propagating with the speed of light

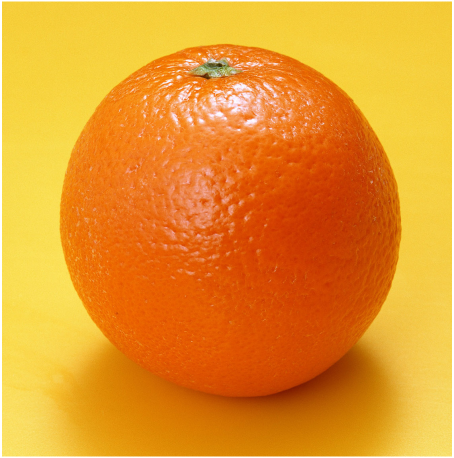


Gravitational waves

Einstein (1916, 1918) - in linear regime there are wave solutions to GR equations *(time-varying distortions of the curvature propagating with the speed of light)*:

- ⋆ In realistic astrophysical situations, length-scale of the wave λ is much smaller than other important curvatures $\mathcal{L}$,
- ⋆ Split of the Riemann curvature tensor

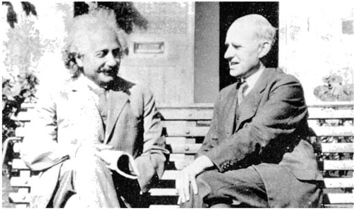
$$R_{\alpha\beta\gamma\delta} = R^{GW}_{\alpha\beta\gamma\delta} + R^{B}_{\alpha\beta\gamma\delta}$$



"Kip Thorne's orange": B - large-scale background ($\mathcal{L} \simeq$ 10 cm), GW - fine-scale distortions/waves ($\lambda \simeq$ few mm).

Do gravitational waves exist?

- ⋆ Many scientists, even (especially?) Einstein are sceptical of their existence (Einstein: ”if they exist, they are undoubtedly undetectable”),
- ⋆ Arthur Stanley Eddington (1922): ”Propagation of Gravitational Waves”, where he shows the waves do not exist (are only a mathematical artifact, famous sentence ”gravitational waves propagate at the speed of thought”)



The Propagation of Gravitational Waves.

By A. S. Eddington, F.R.S.

(Received October 11, 1922.)

1. The problem of the propagation of disturbances of the gravitational field was investigated by Einstein in 1916, and again in 1918.* It has usually been inferred from his discussion that a change in the distribution of matter produces gravitational effects which are propagated with the speed of light; but I think that Einstein really left the question of the speed of propagation rather indefinite. His analysis shows how the co-ordinates must be chosen if it is desired to represent the gravitational potentials as propagated with the speed of light; but there is nothing to indicate that the speed of light appears in the problem, except as the result of this arbitrary choice. So far as I know, the propagation of the absolute physical condition—the altered curvature of space-time—has not hitherto been discussed.

Weyl† has classified plane gravitational waves into three types, viz.: (1) longitudinal-longitudinal; (2) longitudinal-transverse; (3) transverse-transverse. The present investigation leads to the conclusion that transverse-transverse waves are propagated with the speed of light *in all systems of co-ordinates*. Waves of the first and second types have no fixed velocity—a result which

Gravitational waves: Einstein & Rosen (1936)

- ⋆ Einstein to Born (1936): ”Together with a young collaborator [Rosen], I arrived at an interesting result that gravitational waves do not exist,..” (because of unphysical singularities).
- ⋆ Einstein-Rosen (1936) paper „Do Gravitational Waves exist?” (later withdrawn, revised and sent to Journal of the Franklin Institute, with a different answer. Einstein-Rosen waves are exact solutions with cylindrical waves and a singularity at the axis).

Einstein Versus the *Physical Review*

A great scientist can benefit from peer review, even while refusing to have anything to do with it.

Daniel Kennefick

Albert Einstein had two careers as a professional physicist, the first spent through 1933 entirely at German-speaking universities in central Europe, the second at the Institute for Advanced Studies in Princeton, New Jersey, from 1933 until his death in 1955. During the first period he generally published in German physics journals, most famously the *Annalen der Physik*, where all five of his celebrated papers of 1905 appeared.

After relocating to the US, Einstein began to publish frequently in North American journals. Of those, the *Physical Review*, then under the editorship of John Tate (pictured in figure 1), was rapidly assuming the mantle of the world's premier journal of physics.[1] Einstein first published there in 1931 on the first of three winter visits to Caltech. With Nathan Rosen, his first American assistant, Einstein published two more papers in the *Physical Review*: the famous 1935 paper by Einstein, Boris Podolsky, and Rosen (EPR) and a 1936 paper that introduced the concept of the Einstein–Rosen bridge, nowadays better known as a wormhole. But except for a letter to the journal's editor he wrote in 1952—in response to a paper critical of his unified field theory work—that 1936 paper was the last Einstein would ever publish there.

Einstein stopped submitting work to the *Physical Review* after receiving a negative critique from the journal in response to a paper he had written with Rosen on gravitational waves later in 1936.[2] That much has long been known, at least to the editors of Einstein's collected papers. But the story of Einstein's subsequent interaction with the referee in that case is not well known to physicists outside of the gravitational-wave community. Last March, the journal's current editor-in-chief, Martin Blume, and his colleagues uncovered the journal's logbook records from the era, a find that has confirmed the suspicions about that referee's identity.[3] Moreover, the story raises the possibility that Einstein's gravitational-wave paper with Rosen may have been his only genuine encounter with anonymous peer review. Einstein, who reacted angrily to the referee report, would have been well advised to pay more attention to its criticisms, which proved to be valid.

Doubting gravitational waves

Einstein introduced gravitational waves into his theory of general relativity in 1916, within a few months of finding the correct form of the field equations for it. Although the concept of gravitational radiation was then relatively new and no experimental evidence existed to support it, the analogy with the case of the electromagnetic field was so compelling that by the 1930s most scientists thought that gravitational waves must exist in principle. Nevertheless, in 1936 Einstein wrote to his friend Max Born:

> 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 have believed up to now.[4]

Einstein submitted this research to the *Physical Review* under the title "Do Gravitational Waves Exist?" with Rosen as coauthor. Although the original version of the paper no longer exists, Einstein's answer to the title question, to judge from his letter to Born, was "No." It is remarkable that at this stage in his career Einstein was prepared to believe that gravitational waves did not exist, but he also managed to convince his new assistant, Leopold Infeld, who replaced Rosen in 1936, that his argument was valid.[5] Infeld is shown with Einstein in figure 2.

But not everyone was so easily convinced. The *Physical Review* received Einstein's submission on 1 June 1936, according to the journal's logbook. Tate returned the manuscript to Einstein on 23 July with a critical review and the mild request that he "would be glad to have [Einstein's] reaction to the various comments and criticisms the referee has made." Einstein wrote back on 27 July in high dudgeon, withdrawing the paper and dismissing out of hand the referee's comments:

> 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.

On 30 July, Tate replied that he regretted Einstein's decision to withdraw the paper, but stated that he would

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D. Kennefick, Physics Today, 58, 9 (2005)

GWs between the 30s and 60s

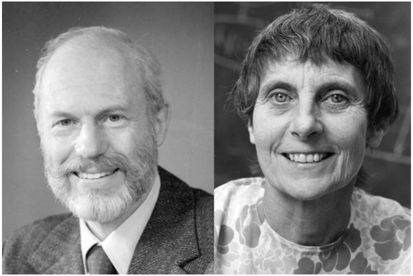
- ⋆ Do gravitational waves exist?
  - ⋆ Are there wave solutions to the full non-linear Einstein equations?
  - ⋆ Do these solutions describe something physically real?
  - ⋆ In particular: are there astrophysical systems emitting gravitational waves?
- ⋆ Do gravitational waves carry energy?
- ⋆ When are gravitational waves just ”coordinate waves”?

The Chapel Hill Conference (1957)

Account by Cécile DeWitt:

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

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



Bryce and Cécile DeWitt, organizers of the conference

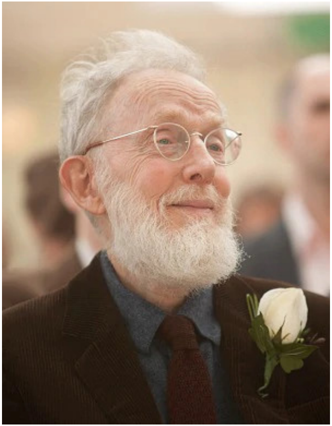
Main difficulties at that time:

- $\star$ General Relativity was difficult to interpret,
- $\rightarrow$ lack of heuristic concepts about the physics of the theory,
- $\rightarrow$ not enough discussion of what is actually observable.

Gravitational waves: indirect evidence

The 50s - breakthrough in theoretical understanding of the nature of the waves: Felix Pirani understands how to detect the wave.

- ⋆ PhD work (advisor Alfred Schild, courses with Leopold Infeld), in 1957 working with Hermann Bondi at King's College, London,
- ⋆ FP: In the presence of a gravitational wave, a set of freely-falling particles would experience measurable relative motions $\rightarrow$ gravitational waves must be real (usually Feynman or Bondi get the credit)



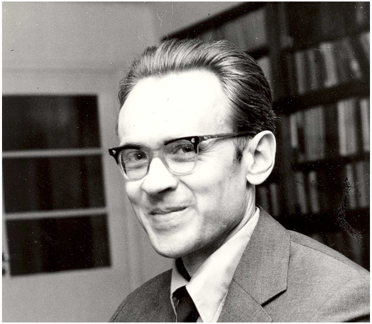
Felix Pirani (1928-2015)

One of key GR papers: "On the Physical significance of the Riemann tensor", Acta Physica Polonica 15 (1956) 389-405

Gravitational waves: indirect evidence

The 50s - breakthrough in theoretical understanding of the nature of the waves: Andrzej Trautman shows that gravitational waves carry energy.

- ⋆ Before Trautman's PhD work (advisor Leopold Infeld, actually Jerzy Plebański) in the 50ties there was no clear understanding of concepts like the gravitational radiation energy,
- ⋆ AT: expansion of the Riemann tensor contains a radiative term equipped with the transversal tensor structure (a transverse wave!)



Famous series of lectures at King's College, London (1958, invited by Felix Pirani, attended by Herman Bondi and Peter Higgs).

More details, list of articles: `www.fuw.edu.pl/∼potor/trautman_waves.html`

Pirani's talk

If now one introduces an orthonormal frame on ζ, v^μ being the timelike vector of the frame, and assumes that the frame is parallelly propagated along ζ (which insures that an observer using this frame will see things in as Newtonian a way as possible) then the equation of geodesic deviation (1) becomes

$$\frac{d^2\eta^a}{d\tau^2} + R^a{}_{obo}\,\eta^b = 0 \qquad (a,b = 1,2,3) \tag{2}$$

Here η^a are the physical components of the infinitesimal displacement and $R^a{}_{obo}$ some of the physical components of the Riemann tensor, referred to the orthonormal frame.

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.

(Peter Saulson talk, APS Meeting, 17 April 2018)

Proof by dialog that gravitational waves are real

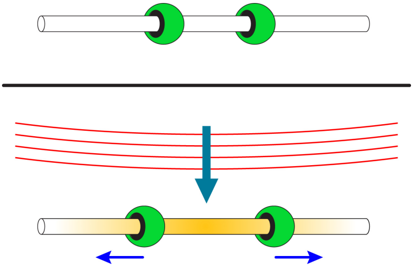
BONDI: Can one construct in this way an absorber for gravitational energy by inserting a $\frac{d\eta}{d\tau}$ term, to learn what part of the Riemann tensor would be the energy-producing one, because it is that part that we want to isolate to study gravitational waves?

PIRANI: I have not put in an absorption term, but I have put in a "spring." You can invent a system with such a term quite easily.

(Peter Saulson talk, APS Meeting, 17 April 2018)

Detecting GW: sticky bead argument

R. Feynman, H. Bondi, J. Weber



Feynman (under the pseudonym ”Mr. Smith”) in 1957 at the Chapel Hill conference:

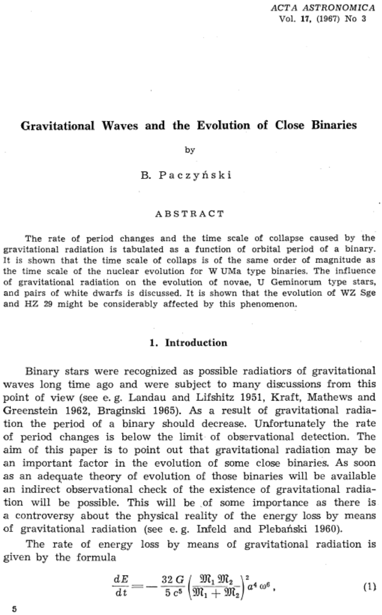
> *Two beads sliding freely (with a small amount of friction) on a rigid rod. As the wave passes over the rod, atomic forces hold the length of the rod fixed, but the proper distance between the two beads oscillates. Thus, the beads rub against the rod, dissipating heat.*

$\rightarrow$ later refined using concepts like tidal interaction, geodesic deviation

Gravitational waves: indirect evidence

The 60s - early insight of Bohdan Paczyński:

- ⋆ *"Gravitational Waves and the Evolution of Close Binaries", AcA 1967* - orbital period evolution of WZ Sge and HZ29 driven by the GW emission.



ACTA ASTRONOMICA
Vol. 17, (1967) No 3

Gravitational Waves and the Evolution of Close Binaries

by

B. Paczyński

ABSTRACT

The rate of period changes and the time scale of collapse caused by the gravitational radiation is tabulated as a function of orbital period of a binary. It is shown that the time scale of collaps is of the same order of magnitude as the time scale of the nuclear evolution for W UMa type binaries. The influence of gravitational radiation on the evolution of novae, U Geminorum type stars, and pairs of white dwarfs is discussed. It is shown that the evolution of WZ Sge and HZ 29 might be considerably affected by this phenomenon.

1. Introduction

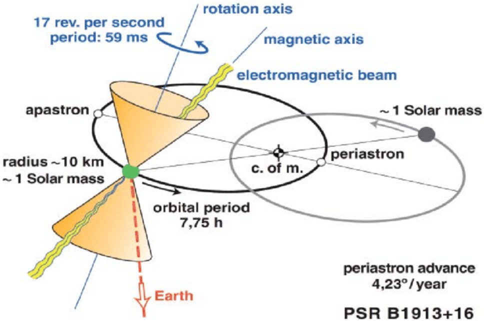
Binary stars were recognized as possible radiatiors of gravitational waves long time ago and were subject to many discussions from this point of view (see e. g. Landau and Lifshitz 1951, Kraft, Mathews and Greenstein 1962, Braginski 1965). As a result of gravitational radiation the period of a binary should decrease. Unfortunately the rate of period changes is below the limit of observational detection. The aim of this paper is to point out that gravitational radiation may be an important factor in the evolution of some close binaries. As soon as an adequate theory of evolution of those binaries will be available an indirect observational check of the existence of gravitational radiation will be possible. This will be of some importance as there is a controversy about the physical reality of the energy loss by means of gravitational radiation (see e. g. Infeld and Plebański 1960).

The rate of energy loss by means of gravitational radiation is given by the formula

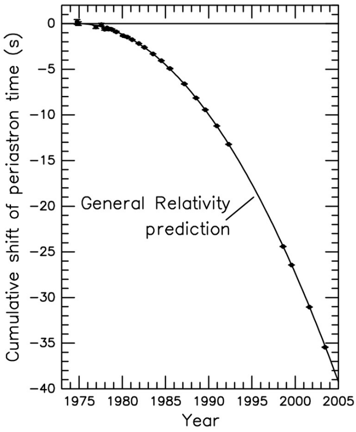
$$\frac{dE}{dt} = -\frac{32\,G}{5\,c^5}\left(\frac{\mathfrak{M}_1\,\mathfrak{M}_2}{\mathfrak{M}_1+\mathfrak{M}_2}\right)^2 a^4\,\omega^6\,, \qquad (1)$$

5

Indirect evidence: relativistic binaries



70s - observations of pulsars in relativistic binary systems e.g. Hulse-Taylor pulsar (1974):



System is losing energy as if by emission of gravitational waves in concordance with GR.

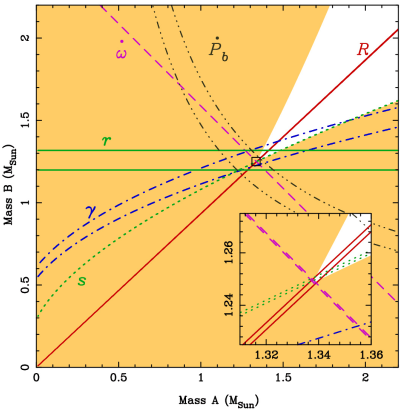
Neutron stars in relativistic binaries: PSR J0737-3039

Post-Keplerian parameters:

- ⋆ Periastron advance:
  $$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}$$
- ⋆ Orbit decay:
  $$\dot{P}_b = -\frac{192\pi m_p m_c}{5M^{1/3}}\left(\frac{P_b}{2\pi}\right)^{-5/3}\times$$
  $$\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2}T_\odot^{5/3}$$
- ⋆ Shapiro effect:
  $$r = T_\odot m_c,$$
  $$s = \frac{a_p \sin i}{c m_c}\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3}$$
- ⋆ Gravitational redshift:
  $$\gamma =$$
  $$e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_c (M+m_c)$$

where $T_\odot = GM_\odot/c^3$, $M = m_p + m_c$.

(A number of effects compatible with GR)



- ⋆ Pulsar A: $P = 22.7\ ms$, pulsar B: $P = 2.77\ s$,
- ⋆ Orbital period $\simeq 2.4$ h,
- ⋆ eccentricity $\simeq 0.08$,
- ⋆ Orbit decay $\simeq 7$ mm/day.

Epistemology of GWs

The direct/indirect detection argument

”We saw some masses, which happened to be mirrors, moving under the influence of gravitational waves. Hulse, Taylor, and Taylor’s later collaborators saw some masses, which happened to be neutron stars, moving under the influence of gravitational waves. What’s the difference?”

”The difference is the Taylor crowd observed a distant GW transmitter and figured out how it worked! We figured out how to build a sufficiently sensitive GW receiver and *since we built it, we know exactly how it works.*

From an interview with unnamed scientist, ”Gravity’s Kiss: The Detection of Gravitational Waves”, Harry Collins MIT Press, 2017

Epistemology of GWs

Difference in the inference from the data to the existence of GWs:

- ⋆ LIGO-Virgo: Direct because the inference relies on the model of interferometer and its response,
- ⋆ Hulse-Taylor: Indirect because the inference relies on the model of the source (Hulse-Taylor pulsar)

Confidence in models of detectors justified through hands-on experience (calibration etc.) Not possible for distant sources.

Joe Weber at Chapel Hill

Joe Weber, co-inventor of the maser, was a U Md professor, on sabbatical in 1956 -57 with John Wheeler at Princeton.

At the Chapel Hill conference in Jan 1957, they heard the key talk by Pirani that clarified that GW's were real, because they could (in principle) be detected.

(Peter Saulson talk, Detection Workshop, IPTA@Banff, 27 June 2014)

Joe Weber starts GW detection

Weber and Wheeler recapped Pirani's argument in a paper written within weeks of the Chapel Hill conference.

Weber developed the experimental ideas in two Gravity Research Foundation essays (3rd prize 1958, 1st prize 1959), leading to his 1960 *Phys. Rev.* paper laying out the bar program.

(Peter Saulson talk, Detection Workshop, IPTA@Banff, 27 June 2014)

Detection principle: resonant bars

Joseph Weber pioneered Pirani's *Gedankenexperiment* in the 1960s (main result 1969) with a cylinder of aluminum with a known characteristic frequency (like two test masses connected with a spring).

- ⋆ Passing gravitational wave carries energy $\rightarrow$ induces mechanical vibrations
- ⋆ A narrow-band detector (sensitive near characteristic frequencies of the bar)
- ⋆ Piezoelectric belt as signal amplifier.

Many key techniques of data analysis invented along the way:

It was an act of genius (and/or madness) to transform a *gendankenexperiment* into a working apparatus and an observing program.

Along the way, Weber developed:

- Sensitivity calculation and noise analysis
- Thermal noise minimization by high Q
- Seismic isolation
- Coincidence for background rejection
- Time slides for background estimation

(Peter Saulson talk, Detection Workshop, IPTA@Banff, 27 June 2014)

Weber started seeing things

In 1969, Weber made his first of many announcements that he was seeing coincident excitations of two detectors.

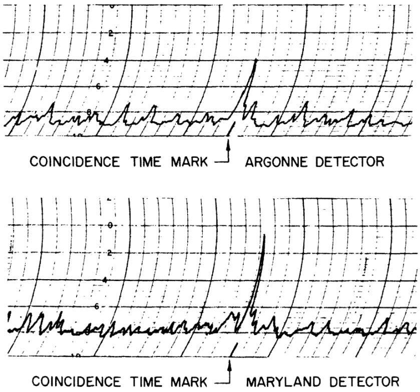


FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

(Peter Saulson talk, Detection Workshop, IPTA@Banff, 27 June 2014)

True, or too good to be true?

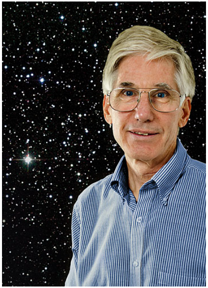
Weber's claims set the world on fire. It seemed that Weber had "opened a new window on the universe."

Of course, if his observations were correct, the signals would have been shockingly large – the Galaxy should be blowing itself up in less than a Hubble time.

Many other groups started building resonant bars, including: Glasgow, Rome, Frascati, Munich, Bell Labs, and IBM (among others).

(Peter Saulson talk, Detection Workshop, IPTA@Banff, 27 June 2014)

Joining the quest ...



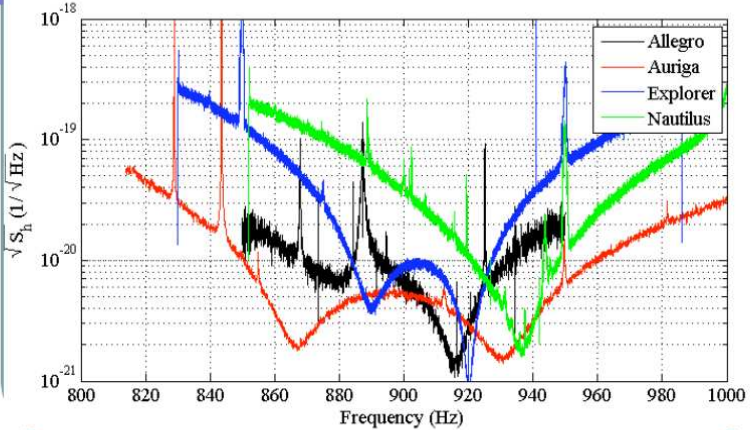
Edoardo Amaldi, Rome   Richard Garwin, IBM   Tony Tyson, Bell Labs

Ron Drever and Jim Hough, Glasgow

(Peter Saulson talk, Detection Workshop, IPTA@Banff, 27 June 2014)

(Odylio Denys Aguiar talk, IV José Plínio Baptista School on Cosmology, October 18, 2018)

Sensitivity of Resonant Detectors



credit: Kostas Kokkotas

(Odylio Denys Aguiar talk, IV José Plínio Baptista School on Cosmology, October 18, 2018)

Weber: what went wrong, what went right?

At the end, no detection claim was confirmed...

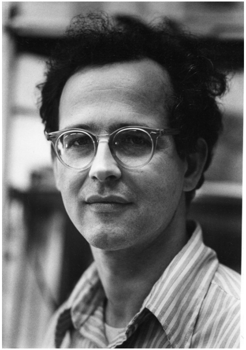
What went wrong:

- ⋆ Blind analysis was never applied (”the main way to judge a search for gravitational waves was whether it produced signals”),
- ⋆ Difficult to learn details of the analysis.

What went right:

- ⋆ Textbook case of replication of an important but controversial experimental claim,
- ⋆ Rapid consensus based on many experiments done in parallel.

Rai Weiss was not at Chapel Hill

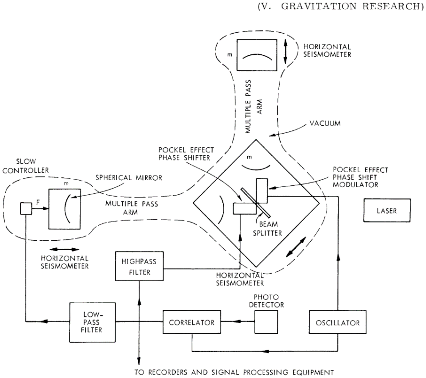


In 1957, Rai Weiss was a grad student at MIT, working with Jerrold Zacharias to make an atomic fountain clock. Their hope was to measure the gravitational redshift.

In the early '60's, he was a postdoc with Bob Dicke at Princeton, working on gravity experiments.

(Peter Saulson slides, APS Meeting, 17 April 2018)

Rai Weiss envisions LIGO in 1972

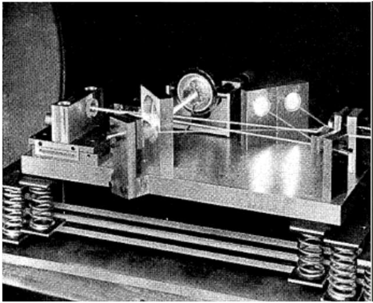


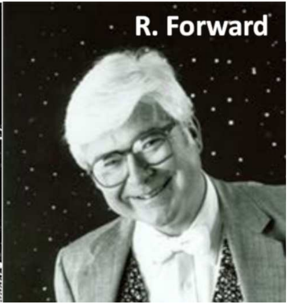
Rai knew of Weber's claimed detections. True or not, Rai saw how to do many orders of magnitude better, by implementing Pirani's free-test-masses-measured-by-lasers as a Michelson interferometer. Arms could be kilometers long. Lasers could measure sub-nuclear distances. One could achieve a sensitivity of $\Delta L/L \sim 10^{-21}$.

(Peter Saulson slides, APS Meeting, 17 April 2018)

Much earlier - Gertsenshtein M.E.; Pustovoit V.I. On the detection of low frequency gravitational waves. Sov. J. Exp. Theor. Phys. 1962, 43, 605–607

The actual interferometers





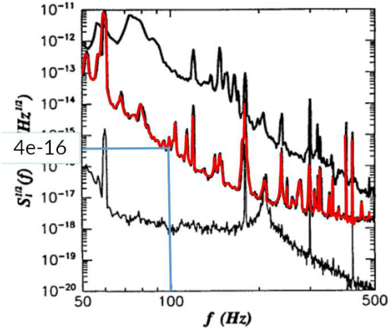
- ⋆ Initiated at the Hughes Research Labs in 1966: ”Generation and Detection of Dynamic Gravitational-Gradient fields”, R.L. Forward, L.R. Miller - Journal of Applied Physics, 1967
- ⋆ ”Photon-noise-limited laser transducer for gravitational antenna”, Moss GE, Miller LR, Forward RL, Appl Opt. 1971 Nov 1;10(11):2495-8
- ⋆ ”Wideband laser-interferometer gravitational-radiation experiment”, R.L. Forward, Phys Rev D, 17, 379 (1978)

$$\Delta L = 3 \times 10^{-16}\ m/Hz^{-1/2}, \quad \text{between 1 and 3 kHz}$$

Actual interferometers: the 80s

Research & development, new ideas and several prototypes of interferometric detector

- ⋆ Glasgow (10 m)
- ⋆ Garching (3m - 30 m)
- ⋆ MIT (1.5m)
- ⋆ Caltech (40 m)



Caltech 40 m prototype

Kilometer-scale detectors

- ⋆ 1979: Rai Weiss proposes the construction of large-scale detectors
- ⋆ 1983: MIT and Caltech join forces
- ⋆ 1985: A. Brillet meets A. Giazotto during the Marcel Grossmann Meeting in Rome
- ⋆ 1985: Plans for a large gravitational wave antenna in Germany (Garching group)
- ⋆ 1989: Proposal of the GEO project in Europe (Garching + Glasgow)
- ⋆ 1989: Proposal for LIGO detectors
- ⋆ 1989: Proposal for the Virgo project

Caltech *GRP-341*

The LIGO/VIRGO Gravitational-Wave Detection System

Kip S. Thorne

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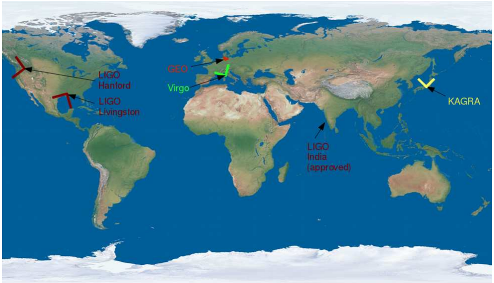
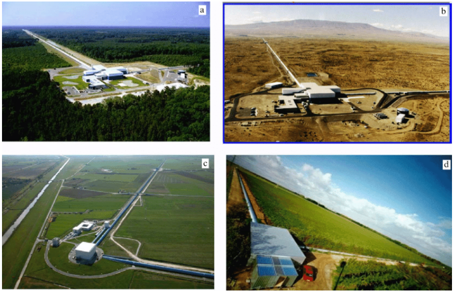
Submitted to *Proceedings of Fourth Rencontres on Particle Astrophysics*, Blois France, July 1992, ed. J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France)

Research supported in part by National Science Foundation Grants PHY-9213508 and PHY-8904035.

- ⋆ 1990: Approval of LIGO by the NSF
- ⋆ 1993: Approval of Virgo by CNRS and INFN
- ⋆ 1994: Approval of the GEO600 project
- ⋆ 1994: Start of the LIGO construction
- ⋆ 1996: Start of the Virgo construction

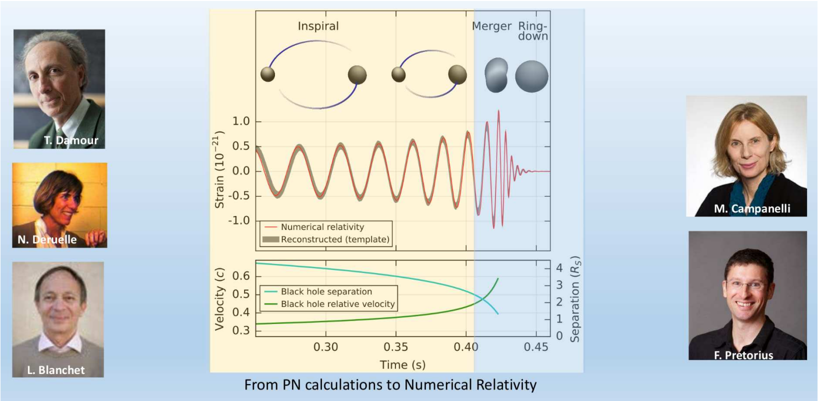
Kilometer-scale detectors





a. LIGO Livingston, b. LIGO Hanford, c. Virgo (Cascina, near Pisa), d. GEO600 (near Hannover)

On the theory side...



- ⋆ 1938 - Einstein, Infeld and Hoffman develop ”post-Newtonian theory” (EIH method) to study the problem of motion in a binary system,
- ⋆ 1990s - Thibault Damour, Natalie Deruelle, Luc Blanchet (Effective One Body & post-Newtonian approach),
- ⋆ 2000s - Manuela Campanelli, Frans Pretorius (numerical solution for the merger).

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