Gravitational waves

What they are, how to detect them, and what they're good for

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Einstein's general theory of relativity

Short version by John Wheeler: "Matter tells spacetime how to curve/distort, spacetime tells matter how to move"

Alternative short version: Fluorescent actors moving on a dark, invisible stage — form of the stage restricts actors' movement.

Predictions: Light deflection (gravitational lensing), compact objects such as black holes

Gravitational waves

Space and time become flexible — by Summer 1916, Einstein shows that this means small disturbances of space and time can travel through space (and do so at the speed of light).

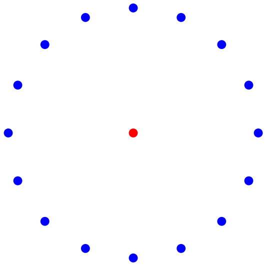
Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

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

…analogous to electromagnetic radiation! (Complications: Long time unclear whether coordinate effect or physical / real!)

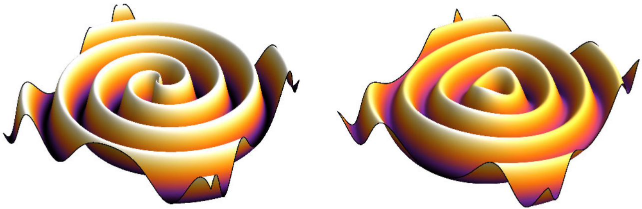
Effect of gravitational waves

Effect on freely floating particles in space (extremely exaggerated — realistic relative changes in distance $h \sim 10^{-21}$):



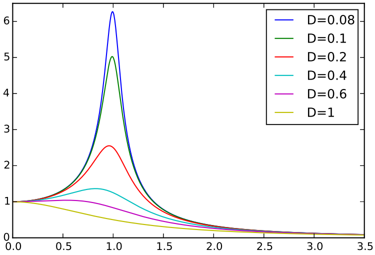
Production of gravitational waves

In general: accelerated masses (except strict dipole). Simplest situation: orbiting masses (Animation: Sascha Husa, Universitat de les Illes Balears):



In this way, the system loses energy, and rotates faster!

First attempts: Joseph Weber



with $D = \gamma/\omega_0$ (x axis: $\omega/\sqrt{\omega_0^2 - 2\gamma^2}$, y axis / A.

Image: LIGO

Weber bar
(Joseph Weber, 1960s).

Indirect detection: Binary pulsar

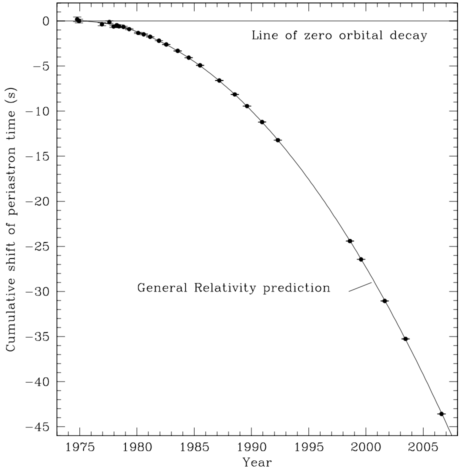
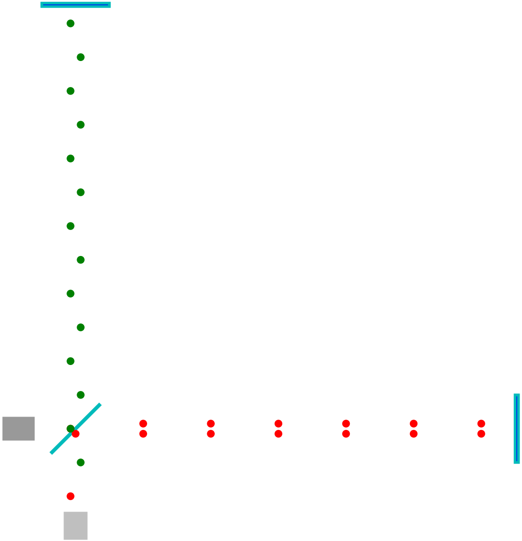


Image: Weisberg et al. 2010

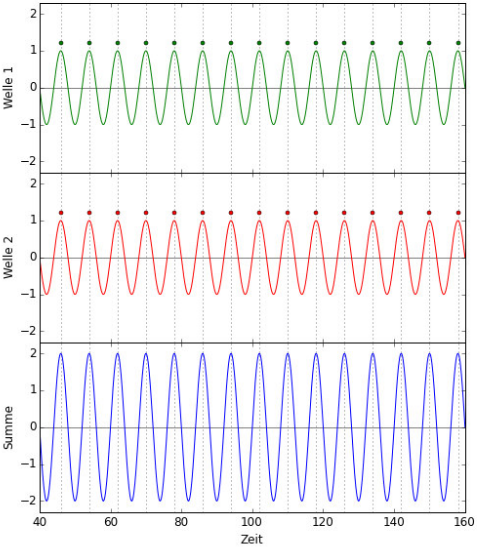
Indirect detection starting 1974 by Taylor, Weisberg
⇒ Orbital period is getting shorter exactly as predicted by the gravitational wave (quadrupole) formula

Nobel Prize Physics 1993 for Taylor and Hulse!

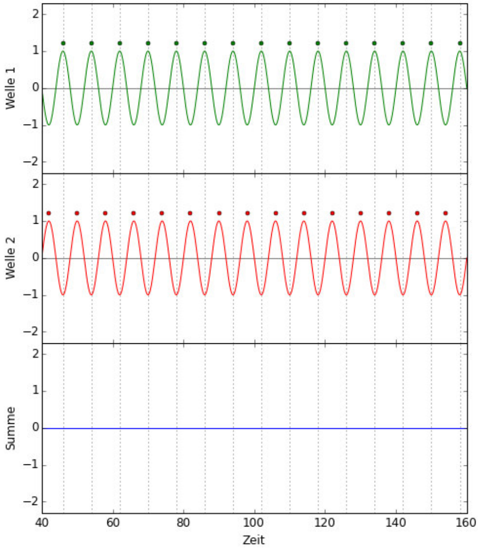
Interferometric detector



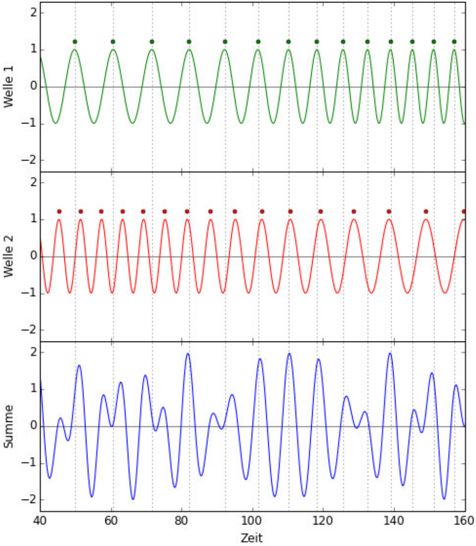
Interferometric detector



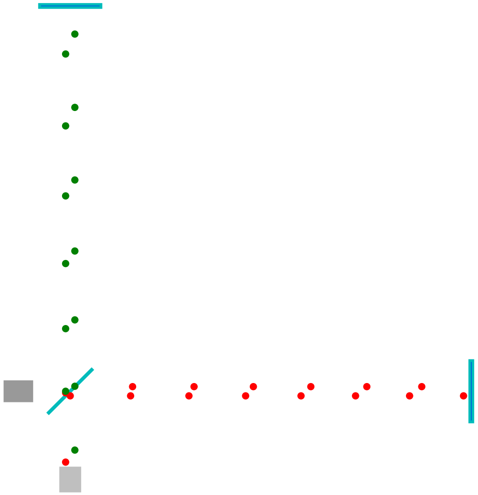
Interferometric detector



Interferometric detector



Interferometric detector



Gravitational wave detectors

LIGO Livingston (near-twin of LIGO Hanford):

Image: LIGO

Gravitational wave detectors

LIGO Livingston (near-twin of LIGO Hanford):

Image: M. Pössel 2004

Gravitational wave detectors

Sep 18, 2015 to Jan 12, 2016: First Advanced LIGO „observing run“ (O1), following a last „engineering run“ for the improved technology, partially from our friends at MPI for Gravitational Physics

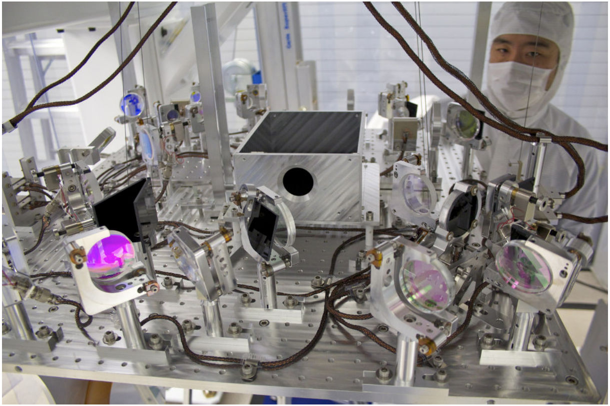


Image: Caltech/MIT/LIGO Lab

Various kinds of noise

Bild: Caltech/MIT/LIGO Lab

Seismic noice, thermal noise, photon shot noise, . . .

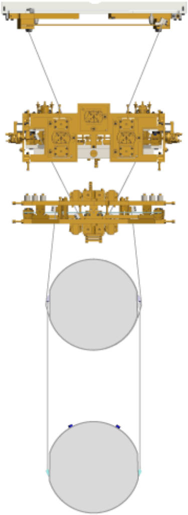


Bild: Abb. 6 in Pitkin et al. 2011

Detector Layout for Advanced LIGO

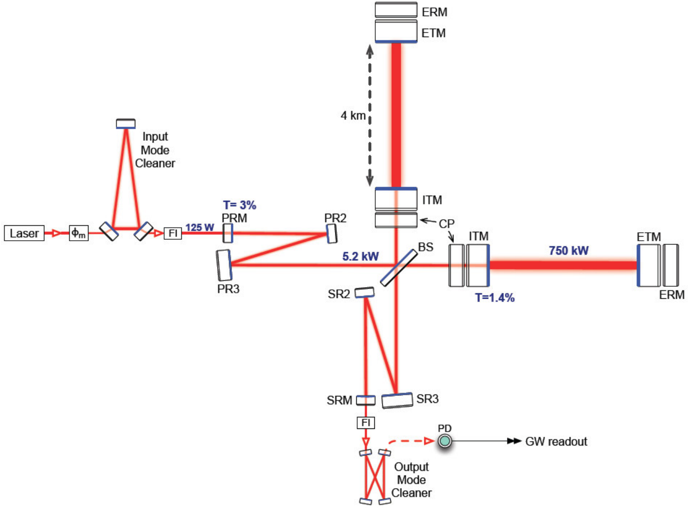


Fig. 1 in LIGO Scientific Collaboration 2014

Noise-limited measurements!

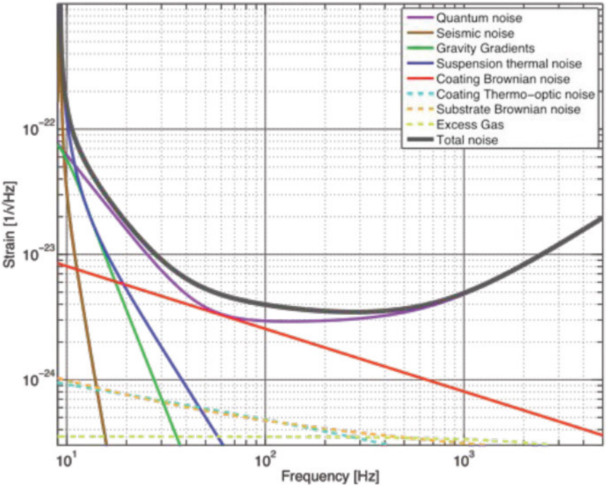


Fig. 2 in LIGO Scientific Collaboration 2014

Search for known signals

Search for known signals: merging neutron stars and/or black holes. Problem: Complete understanding needs simulations of gravitational wave spacetimes — numerical relativity!

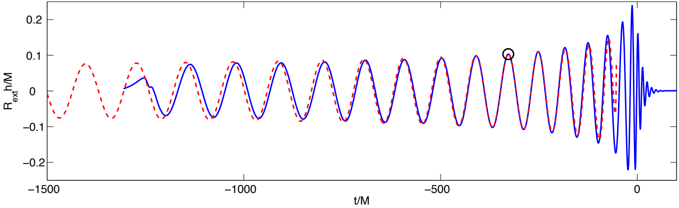


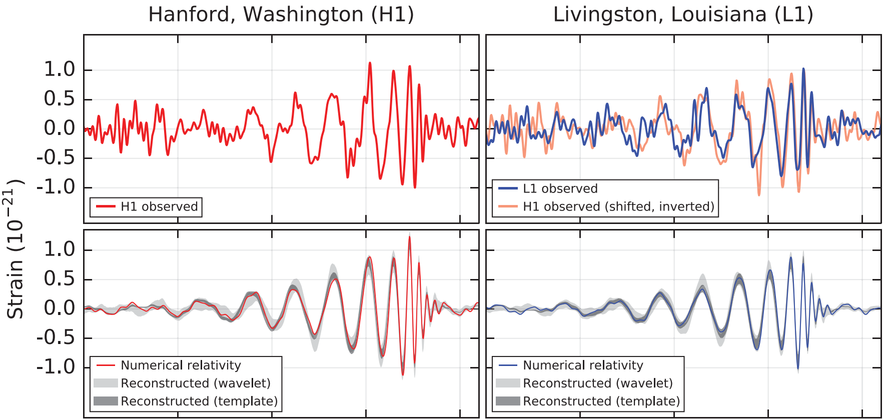
Image: Baker et al.

2006

Only from 2005 onwards stable, long-term simulations (Frans Pretorius)

Gravitational waves detected

Signal from 14 September 2015, published 11 February 2016



Gravitational waves detected

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr

Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

Source: LIGO fact sheet for GW150914

Gravitational waves detected

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 $M_\odot$
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV

coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Source: LIGO fact sheet for GW150914

Why is this important?

- First direct detection of gravitational waves
- First test of (numerical) predictions for strongest gravitational fields
- Direct detection of black holes
- Detection of comparatively massive black holes — interesting for star formation/evolution

Current and future detectors

More detectors ⇒ better localization ⇒ optical etc. counterparts

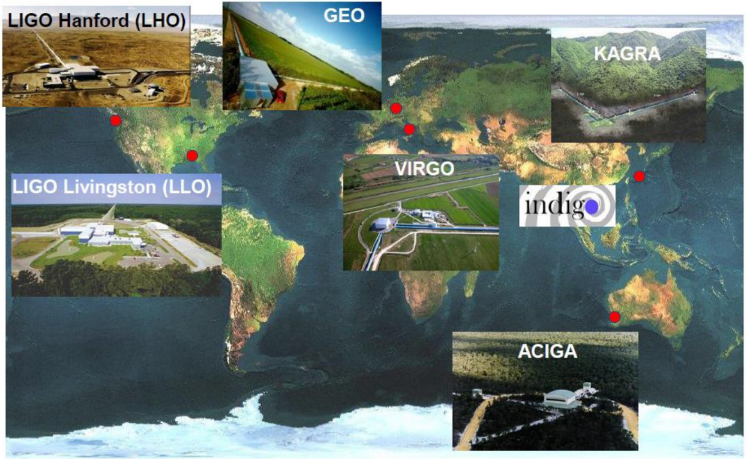


Image: Giles Hammond

Interesting objects by frequency

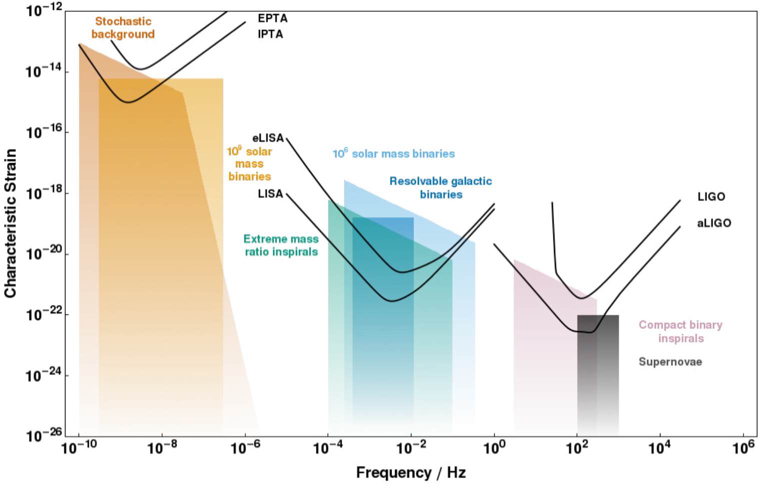


Image: Christopher Moore, Robert Cole and Christopher Berry via Wikimedia Commons under licence CC-BY-SA 1.0

ESA mission: LISA Pathfinder (LPF)

Image: ESA–P. Sebirot, 2015

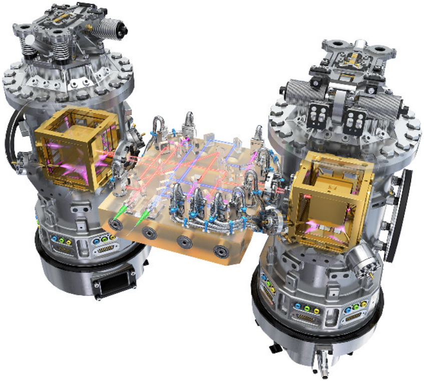


Bild: ESA/ATG medialab

Launch Dec 3, 2015, free-fall 22 Feb, 2016, science mission start 1 Mar, 2016

eLISA

eLISA - ESA version of the Laser Interferometer Space Antenna. Launch by 2034?

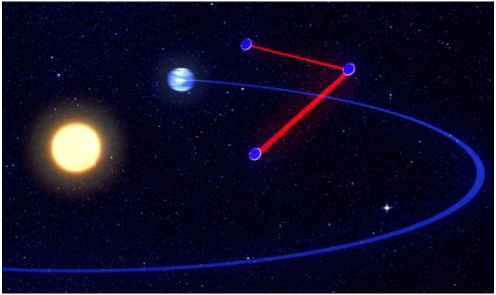


Image: AEI / Milde Marketing / Exozet

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What do we hope to find?

Ground-based:

1. Statistics of stellar end states (how many black holes of what mass?)
2. With counterparts: Independent tests of distance ladder ("Chirps" have distance information built in!)
3. With counterparts: Independent tests of Hubble relation
4. Understanding supernova explosions

Space-based:

1. Statistics of white dwarf binaries
2. Statistics for binary supermassive black holes
3. Extreme mass ratio inspirals: testing black hole geometry
4. Primordial gravitational waves from cosmic times before recombination