Outline: Gravitational waves

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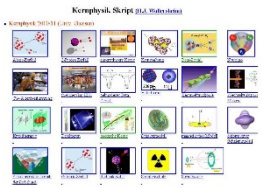


1. Albert Einstein: ripple of space-time
2. Isaac Newton vs Albert Einstein
3. gravitational waves
4. LIGO observatories
5. gravitational waves vs EM waves

Gravitational waves – ripples of space-time

154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

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.

First publication on gravitational waves in June 1916

Almost 100 years later

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.

first direct evidence of gravitational waves

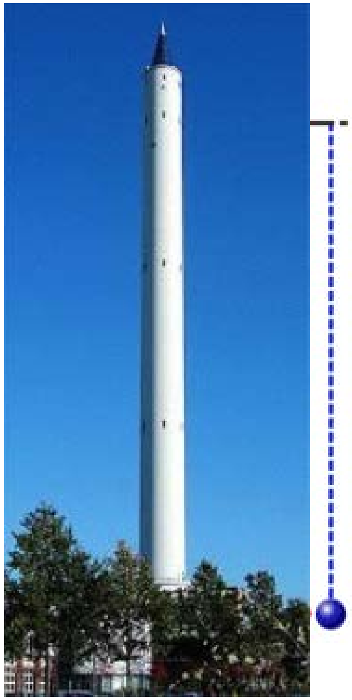
signal indicates the merging of two black holes

LIGO: Laser Interferometer Gravitational-Wave Observatory

Equivalence principle

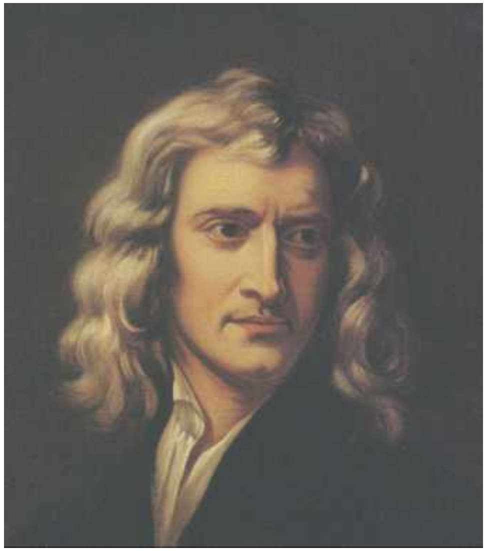
- ❖ Heavy mass: How strongly is a body attracted by the Earth?
- ❖ Inertial mass: How much power is needed to accelerate a body?
- ❖ Galileo Galilei (1590): All bodies fall equally fast (in vacuum)

$$\rightarrow heavy\ mass = inertial\ mass$$



The Bremen drop tower

Gravity: the old school

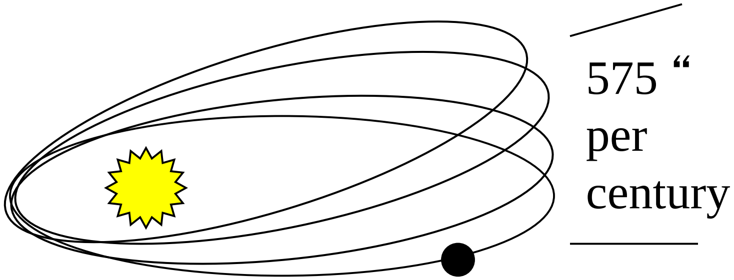


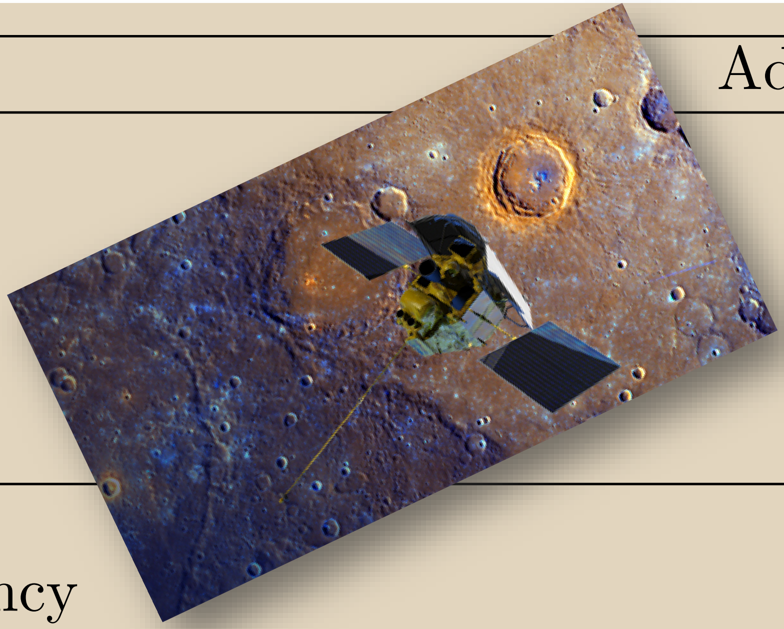
Sir Isaac Newton (1684)

universal law of gravitation

- Unified the gravity on Earth, the motion of the Moon, planets and comets
- Final confirmation of Newton´s theory: Halley´s Comet returns as predicted in 1758
- Newton´s theory good, but not perfect!

- **1687 Newtonian triumph**
- **1859 Le Verrier´s puzzle** (Mercury orbit anomaly)
- **1900 A turn-of-the century crisis**





Planet	Advance
Venus	277.8
Earth	90.0
Mars	2.5
Jupiter	153.6
Saturn	7.3
Total	531.2
Discrepancy	42.9

Electromagnetism

REMINDER

❖ James Clerk Maxwell (1864):
Unification of electricity and magnetism

$\boxed{\rightarrow electromagnetism}$

❖ Heinrich Hertz (1888):
Light, radio waves, X-rays
are electromagnetic waves

velocity: 299792 km/s
duration Sun – Earth ~ 8 min

$\boxed{\begin{array}{l}\rightarrow interaction\ delayed, \\ e.g.\ between\ electrical\ charges\end{array}}$

REMINDER

The special relativity

❖ Newton´s gravitation:
Foundation for classical mechanics.

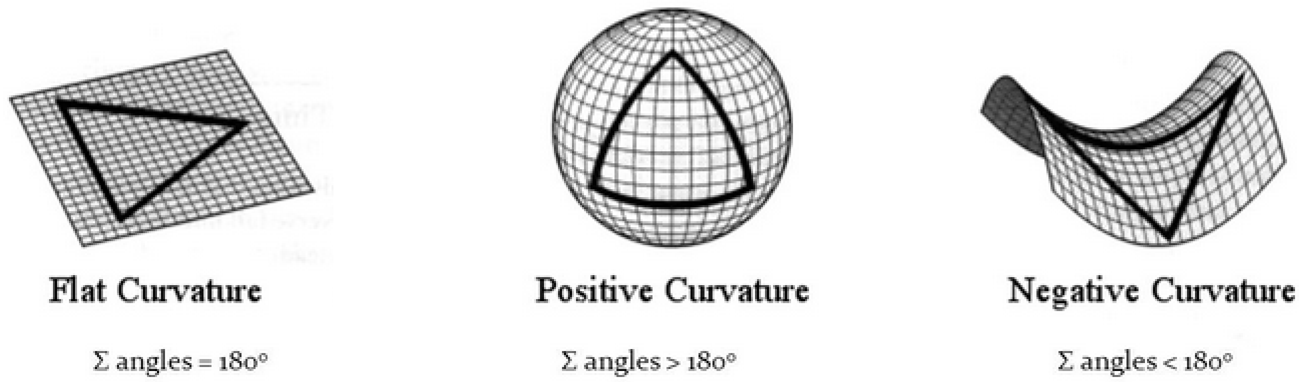
- no maximum velocity
  instantaneous interaction

❖ Albert Einstein (1905):
Theory of special relativity:

- velocity of light is the limit
- instantaneous interaction
  is not allowed! contradiction with Newton!

- Space and time (space-time) are curved
- Matter causes this curvature
- Space tells matter how to move
- Gravity is geometry

Curved space



❖ In 2 dimensions

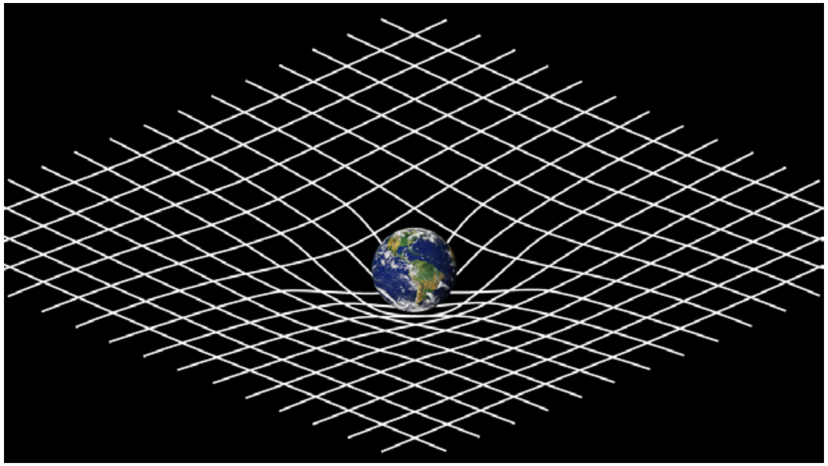
- flat space: plane
  $triangle: \ \alpha + \beta + \gamma = 180^0$

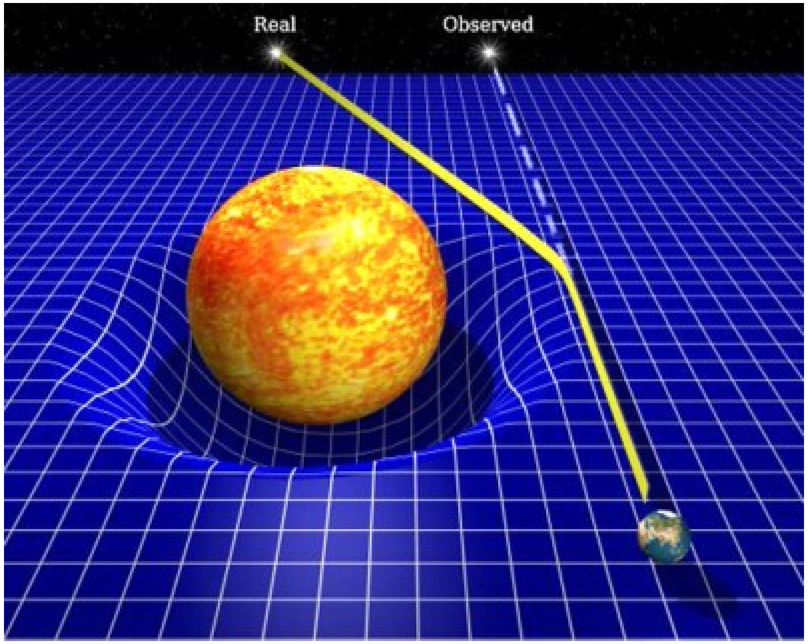
- positive curvature: sphere
  $triangle: \ \alpha + \beta + \gamma > 180^0$

- negative curvature: saddle
  $triangle: \ \alpha + \beta + \gamma < 180^0$

Curved space-time

❖ Space-time curved by the Earth mass





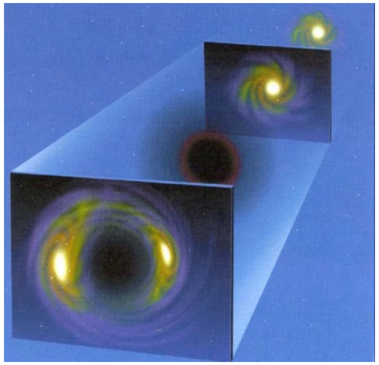
❖ Arthur Eddington (1919):
Deflection of light by sun´s gravitational field

First successful test of Einstein´s theory
Geometry bends light

Other phenomena

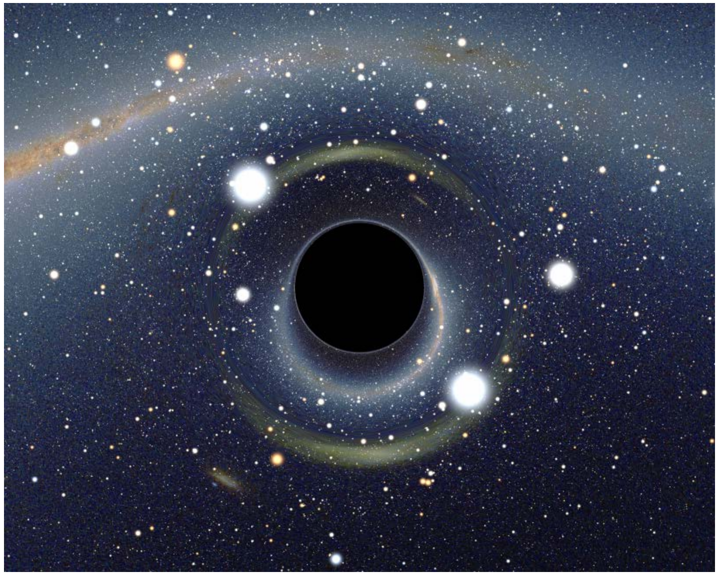
- Gravitational lenses

→ *Einstein rings*

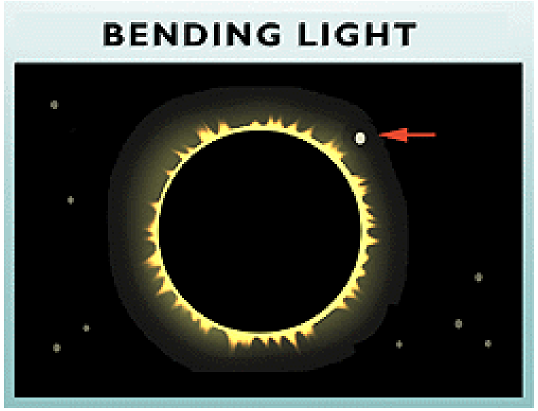


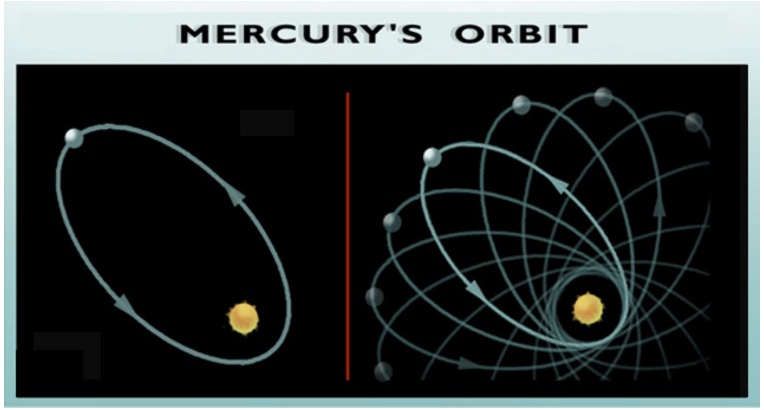
- Karl Schwarzschild (1916): curvature can be as strong, that light can not escape.

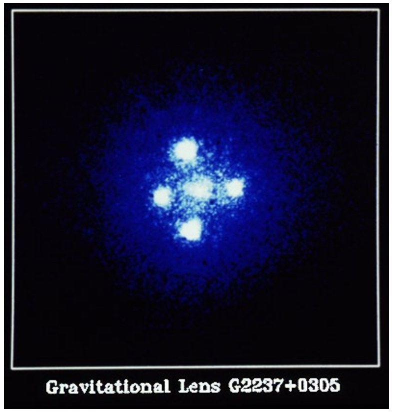
→ *black hole*



Einstein´s theory of gravitation experimental tests







bending of light
as it passes in the vicinity of massive objects

First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

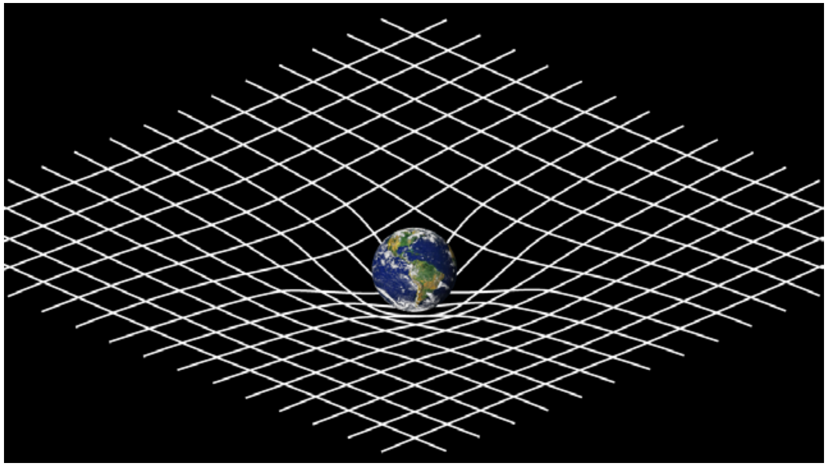
Mercury’s orbit
perihelion shifts forward twice Post-Newton theory

Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or perihelion) shifts forward with each pass.

“Einstein Cross” the bending of light rays
gravitational lensing

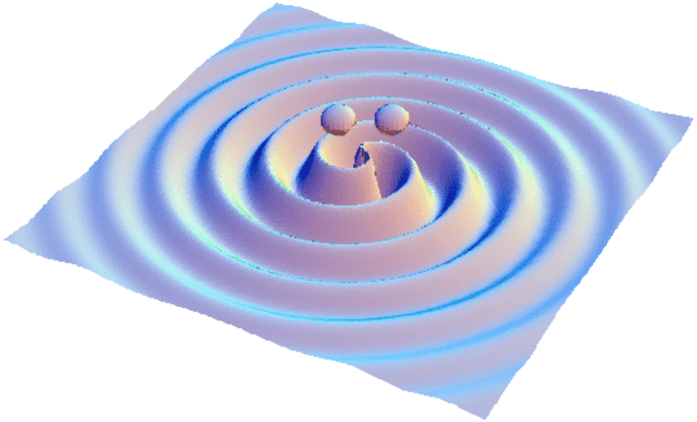
Quasar image appears around the central glow formed by nearby galaxy. Such gravitational lensing images are used to detect a ‘dark matter’ body as the central object

What are gravitational waves?



- Einstein's General theory of relativity:

  Gravity → Curvature of 4-dimensional
  space-time produced by matter

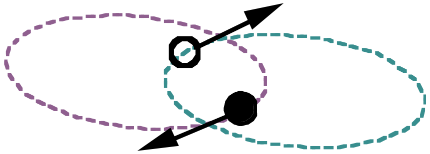


- Gravitational waves:
  Ripples on space-time
  produced by accelerated matter

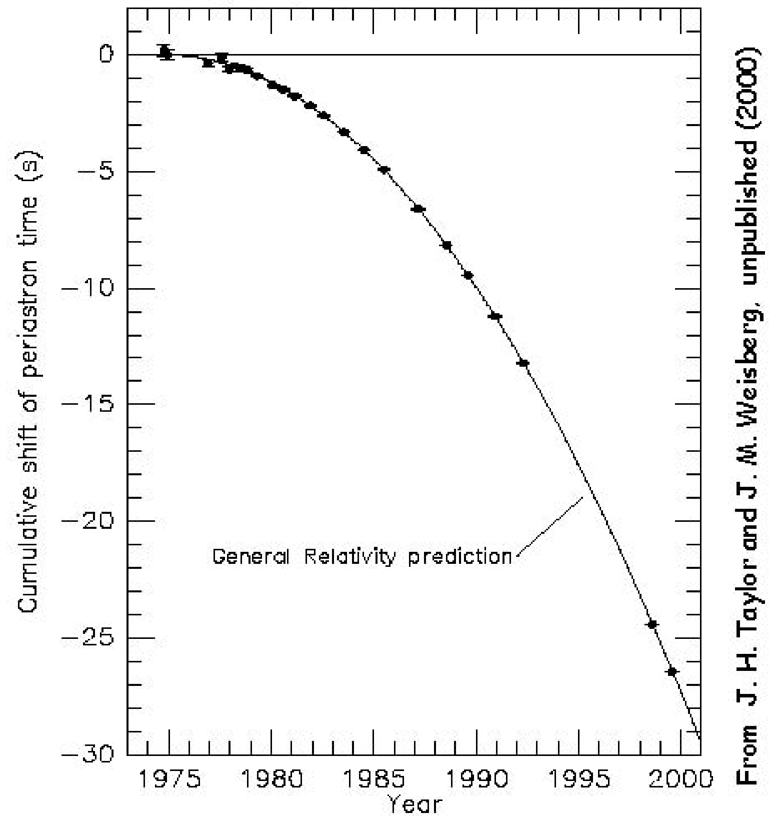
  not EM or particles

Decay of the orbit strong indirect evidence

Emission of gravitational waves



Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

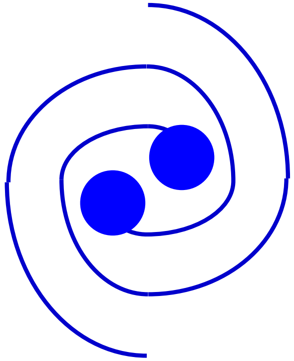


- Binary systems (neutron stars) emit gravitational waves
- Gravitational waves carry energy
- System looses energy, spiral inwards
- Orbit period decreases at a predicted rate
  $0.0000758 \; sec/year$

- Observed rate:
  $0.0000759 \pm 2 \; sec/year$

Joseph Taylor & Russell Hulse
Nobel Price 1993

Binary orbit evolution



- **A binary system in a close orbit**

has a time-varying quadrupole moment

➔ emits gravitational waves

$$f_{GW} = 2\, f_{orbit}$$

Gravitational waves carry away energy and angular momentum

$$dE/dt \propto -f^{10/3}$$

➔ Frequency increases, orbit shrinks

$$df/dt \propto f^{11/3} \qquad dr/dt \propto -f^{2}$$

Objects spiral in until they finally coalesce

Additional relativistic effects kick in as (Gm/rc^2) grows away from zero

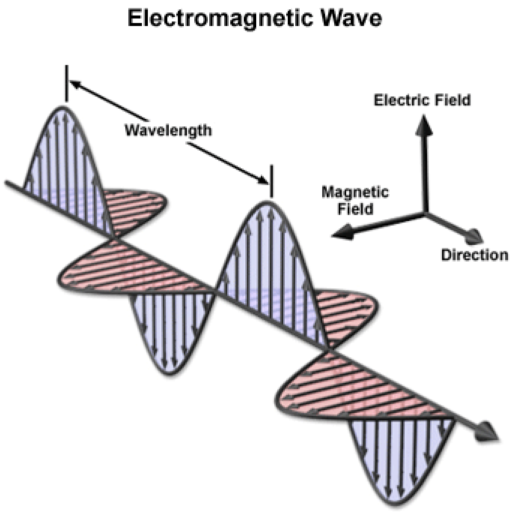
REMINDER

Electromagnetic waves

- So far, nearly all our knowledge of the Universe comes from electromagnetic radiation

- Time-varying disturbance in electromagnetic field (vector field)
- Arise as a direct consequence of relativity (causality)
  - field of a stationary charge
  - field of a moving charge
  - field of an accelerated charge

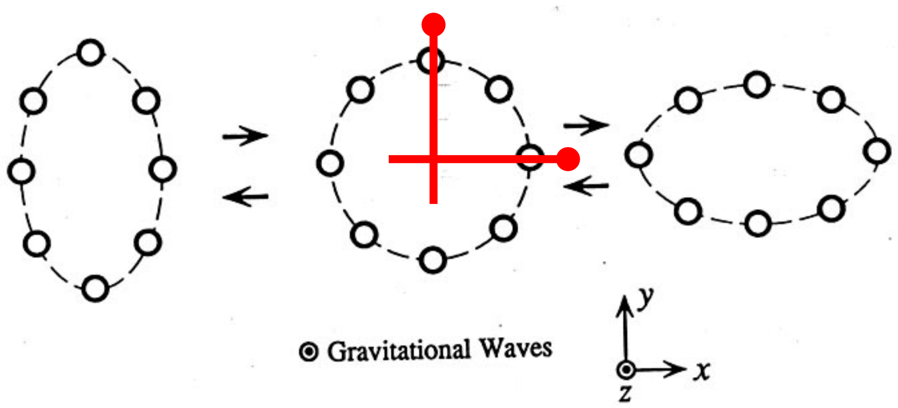
- Oscillating charges → waves with characteristic lengths

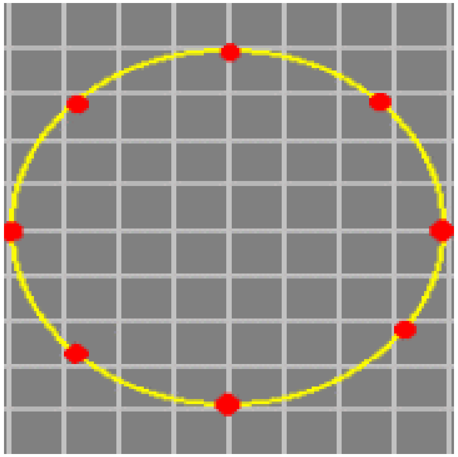


Gravitational waves

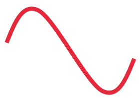
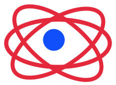
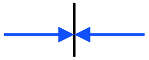
- The key property of gravity is that it affects all bodies equivalently, with a force that is proportional to the body´s mass.
- This means that it is impossible to measure directly an overall gravitational field (tensor field). The best one can do is to measure the change in the gravitational field.
- The effect of gravity from a remote object, such as the Sun or Moon, can be felt by the manner in which it changes from location to location, gravity tidal field.

strain amplitude $h = \Delta L/L \leq 10^{-21}$





How small is 10^{-18} meter?

		One meter
$\div$10,000		*Human hair, about 100 microns*
$\div$100		*Wavelength of light, about 1 micron*
$\div$10,000		*Atomic diameter, 10^{-10} meter*
$\div$100,000		*Nuclear diameter, 10^{-15} meter*
$\div$1,000		*LIGO sensitivity, 10^{-18} meter*

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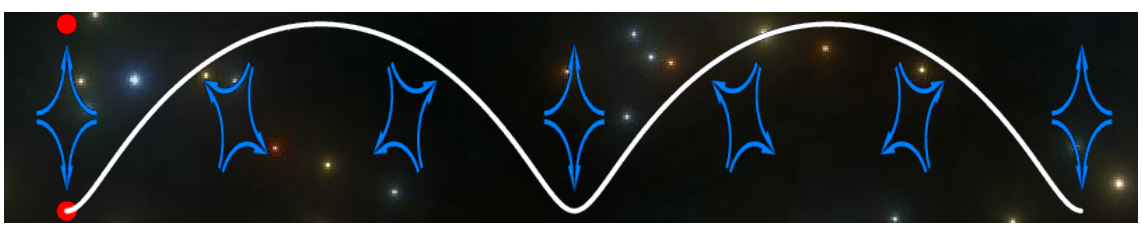
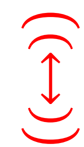
two polarizations: plus (⊕) and cross (⊗)

spin of graviton = 2

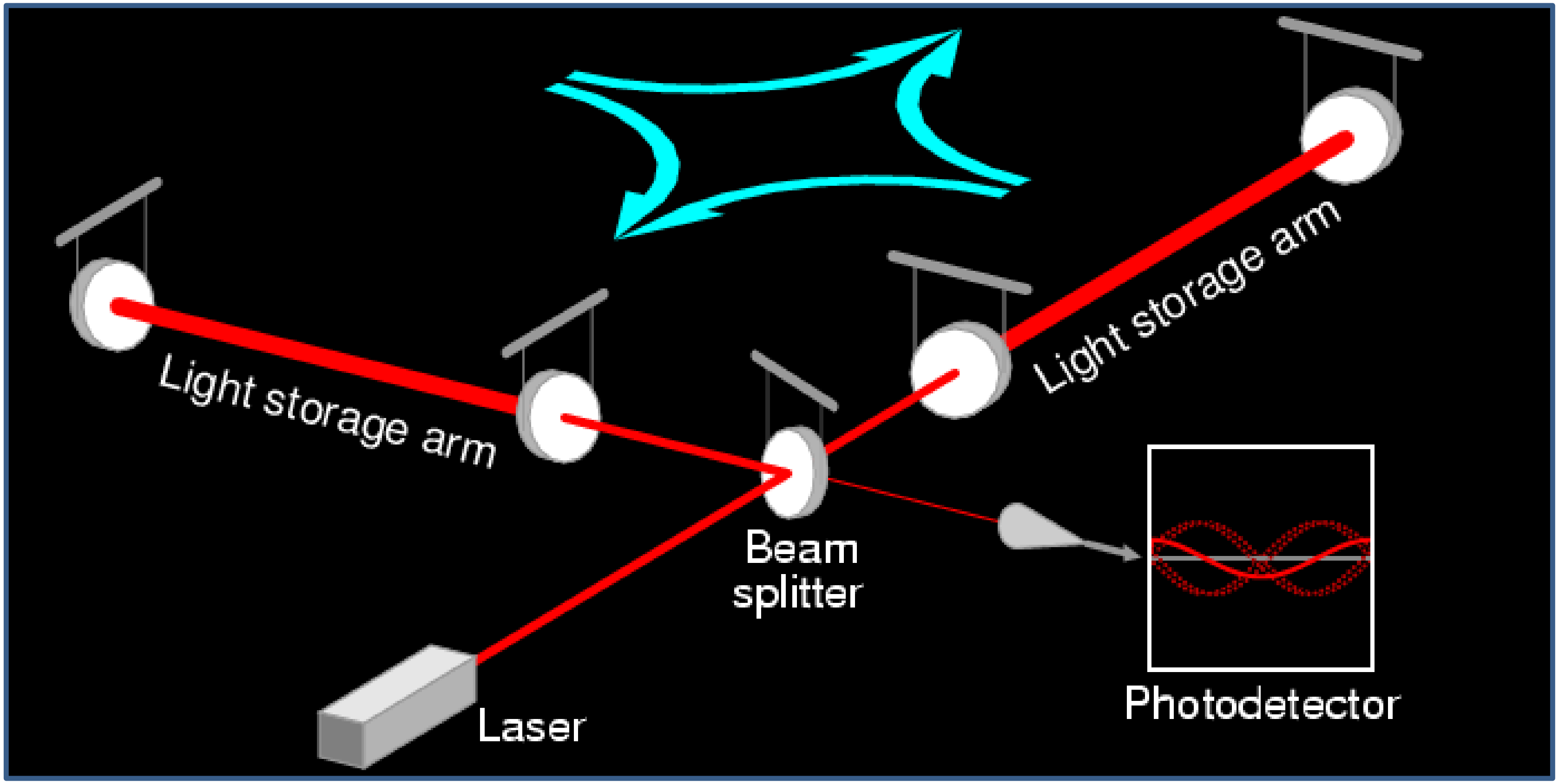


contrast with EM dipole radiation:

$\hat{x}$ $((\leftrightarrow))$ $\hat{y}$ 

Detecting gravitational waves

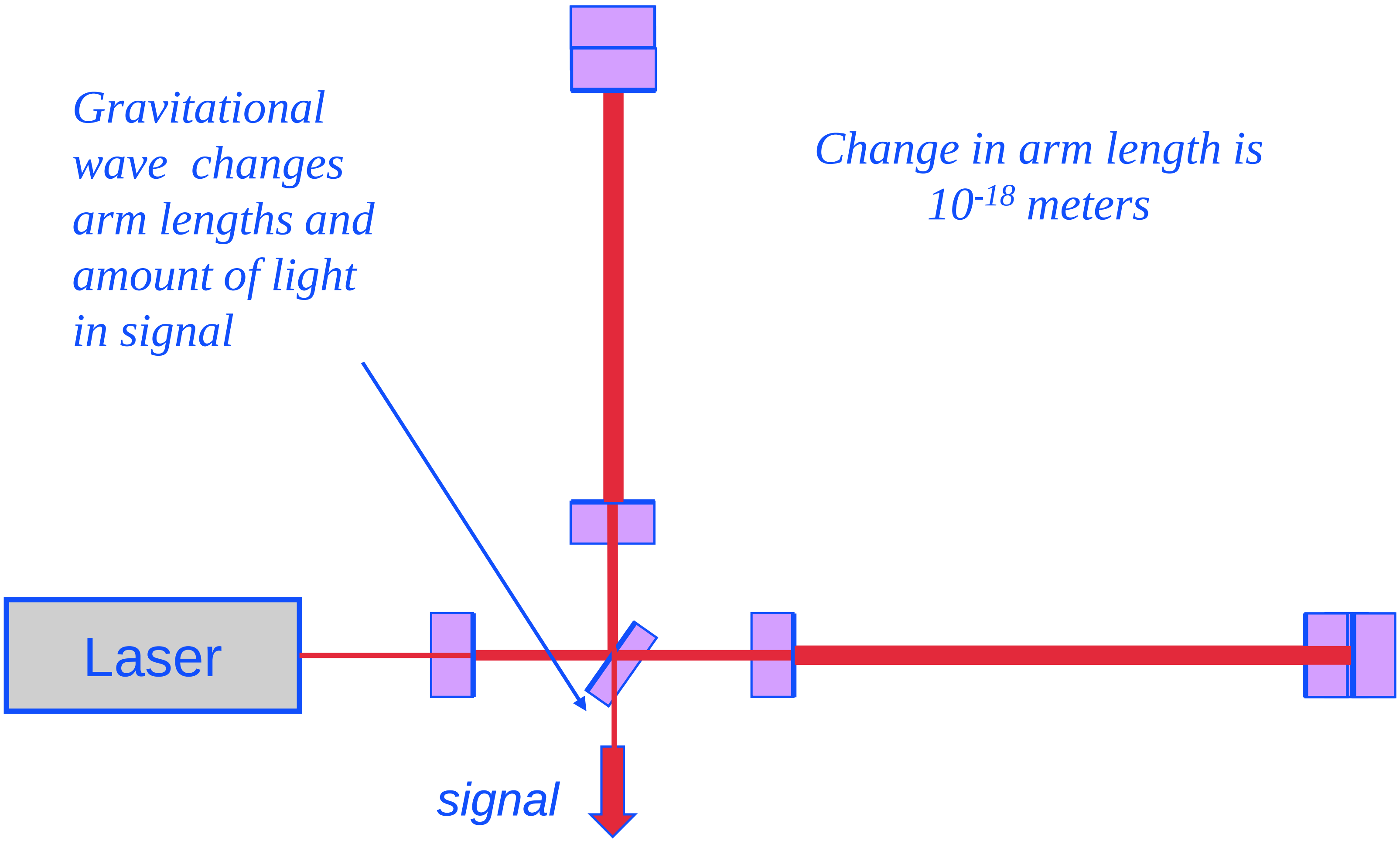
- **Laser interferometers**: measure relative motions of separate, freely-hanging masses



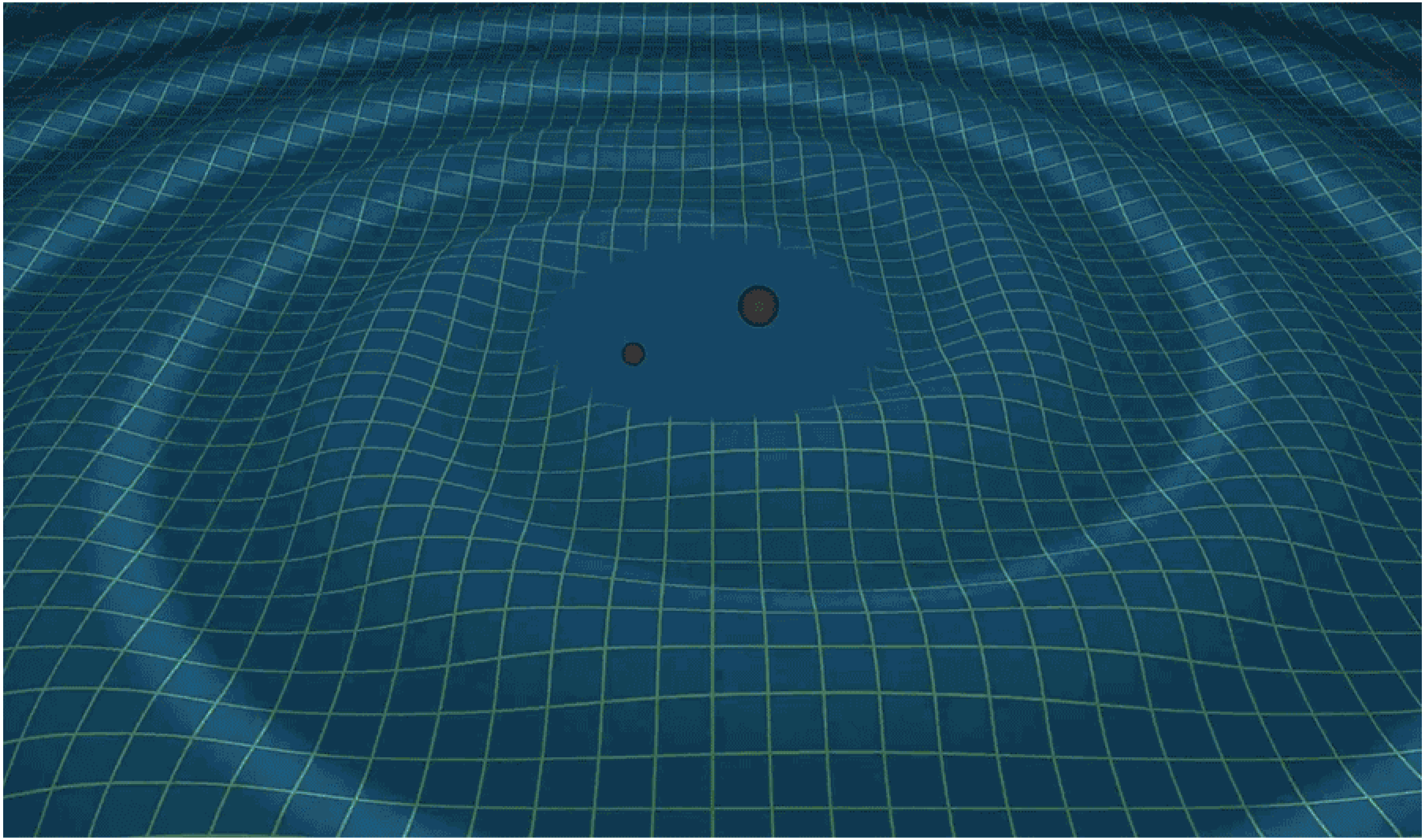
Sensing the effect of a gravitational wave

Gravitational wave changes arm lengths and amount of light in signal

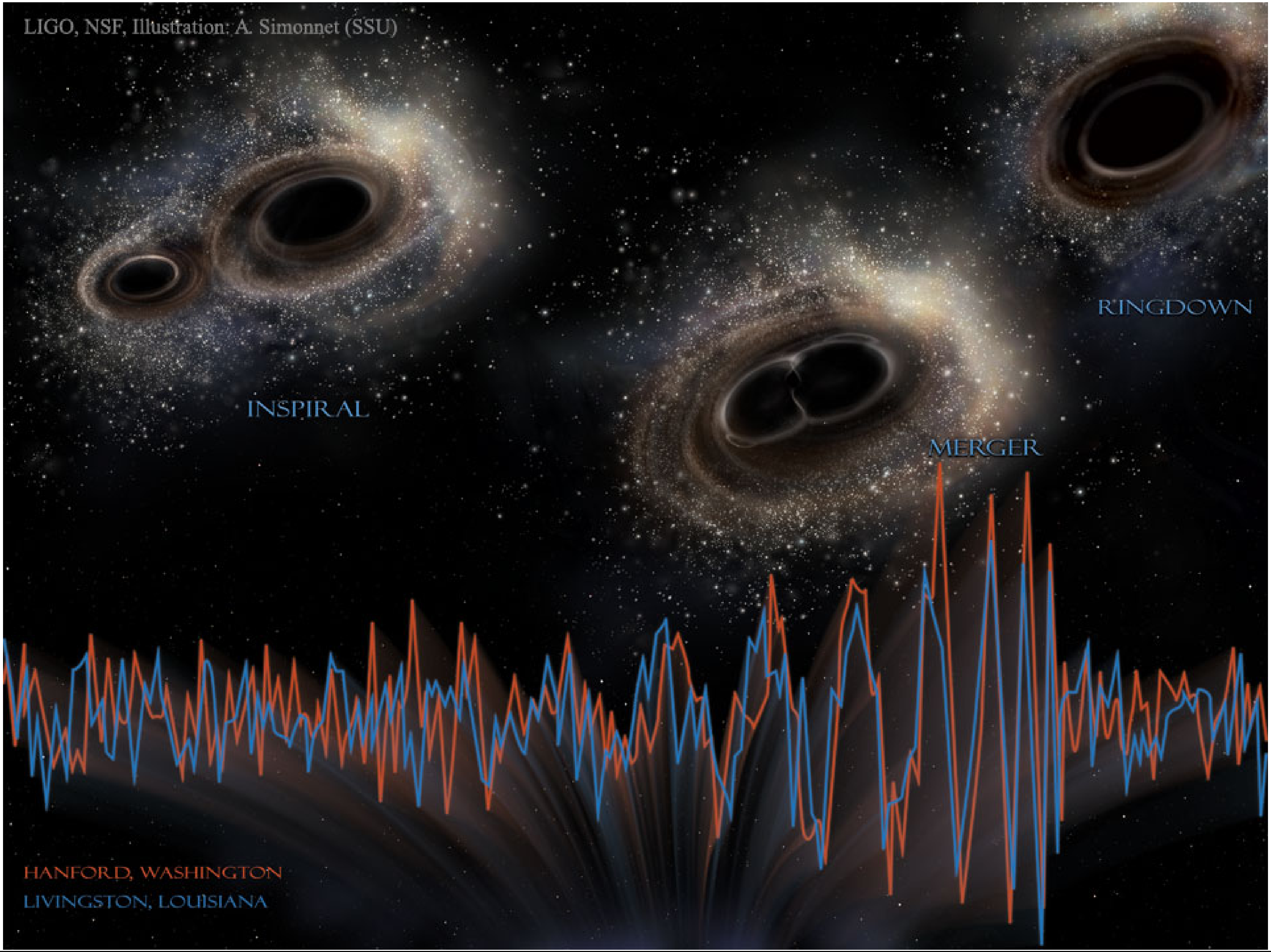
Change in arm length is 10^{-18} meters



Gravitational waves



Gravitational waves



Inspiralling Compact Binaries

Ground-Based (hectohertz)

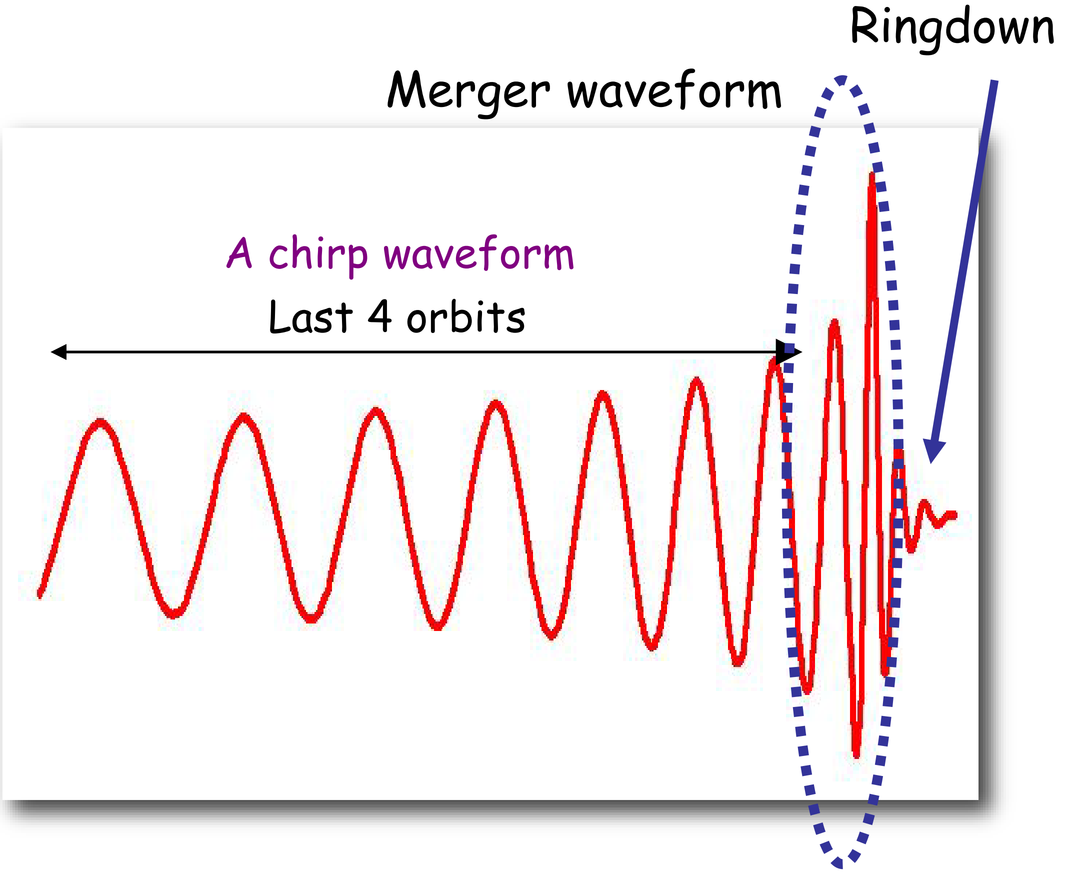
- Last few minutes (10K cycles) for NS-NS
- 0.4 - 400 per year by 2018
- BH-BH could be 0.4 - 1000

Space-Based (millihertz)

- MBH pairs (10^5 - 10^7 M_s) in galaxies to large Z
- EMRIs
- Close WD binaries

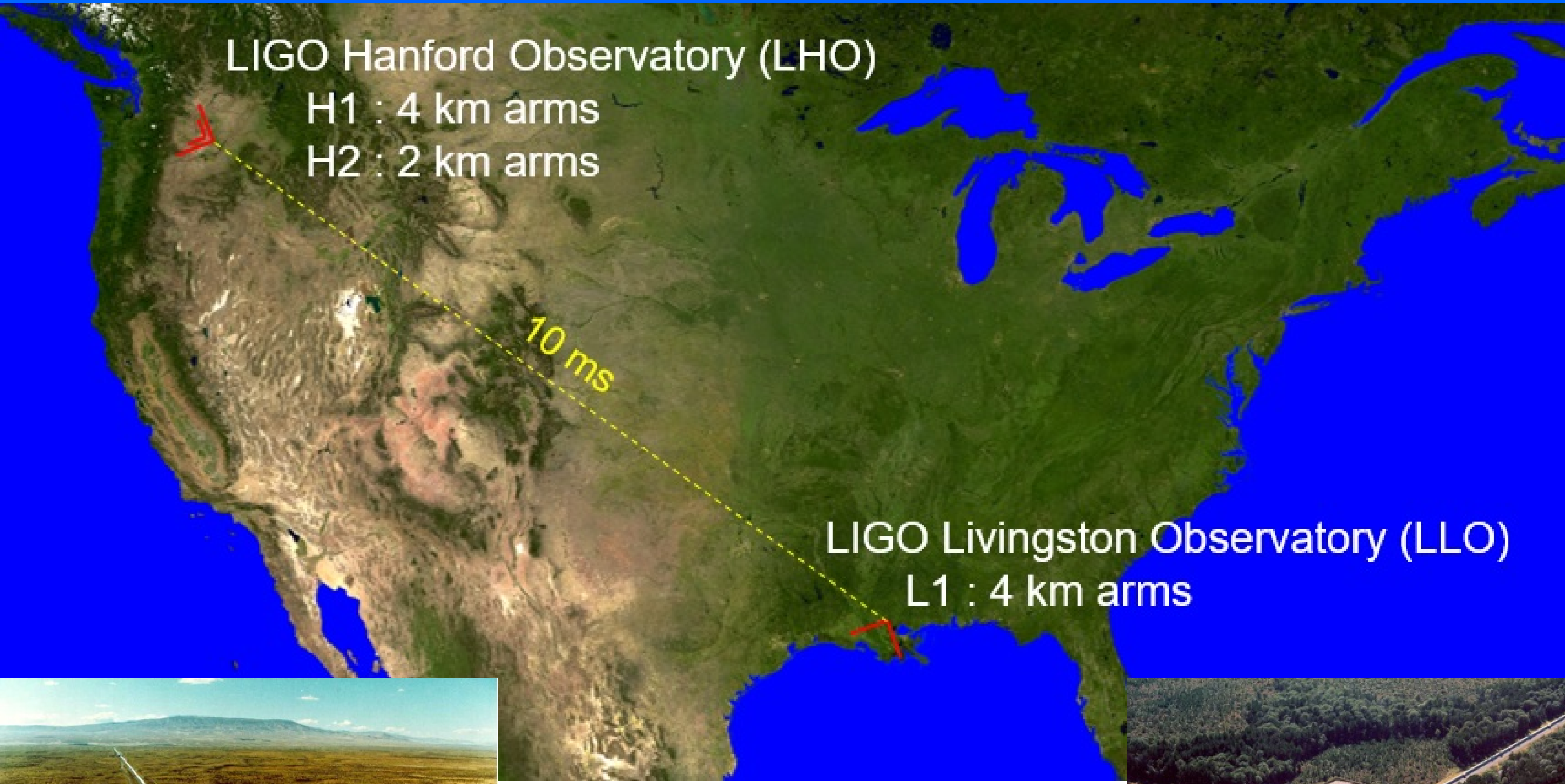
Pulsar Timing Arrays (nanohertz)

- MBH pairs



NS ≡ neutron star BH ≡ black hole MBH ≡ massive black holes EMRI ≡ extreme mass ratio inspiral WD ≡ white dwarf

The LIGO observatories

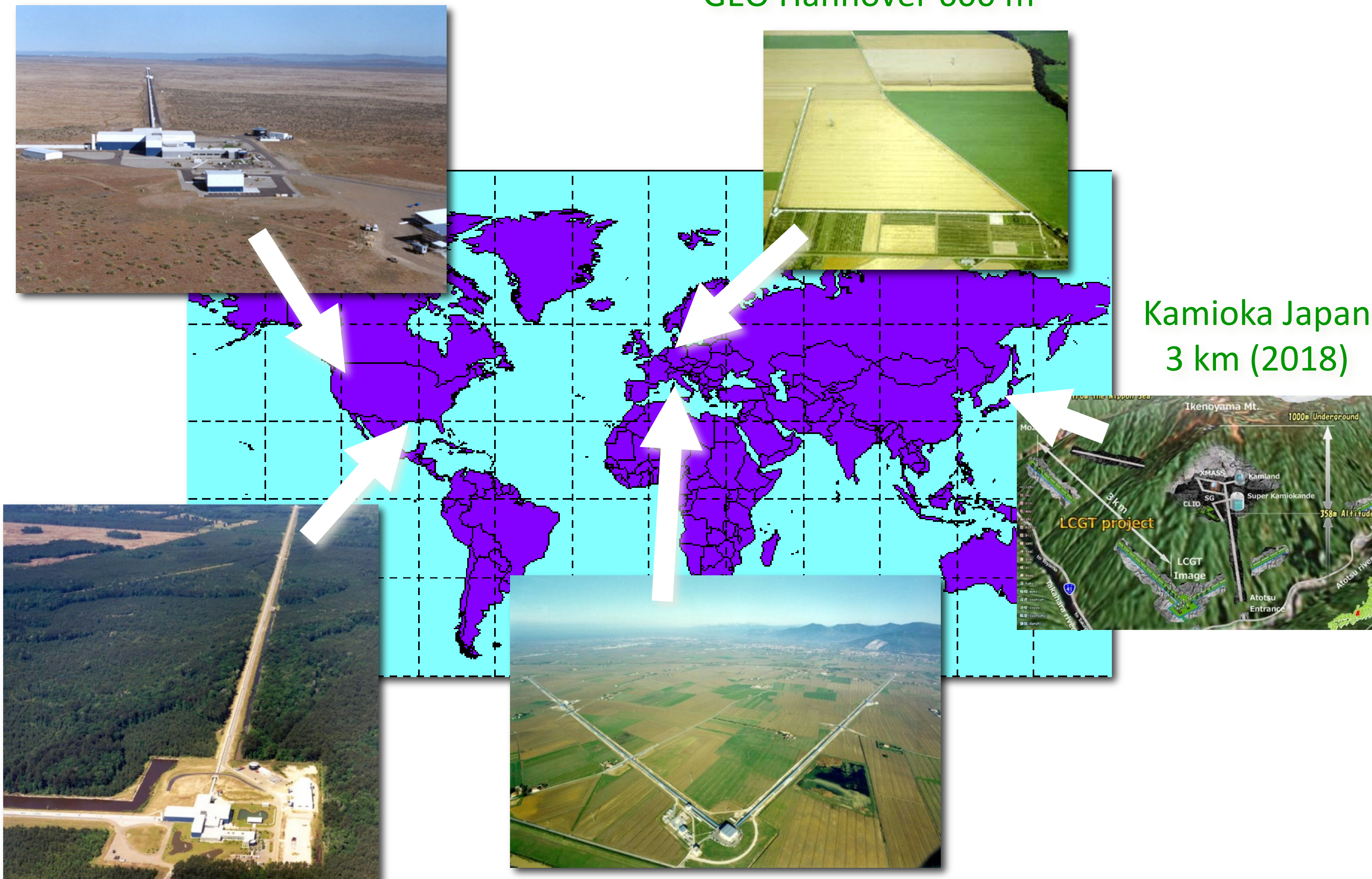


Global Network of Interferometers

LIGO Hanford 4 km (2015)

GEO Hannover 600 m

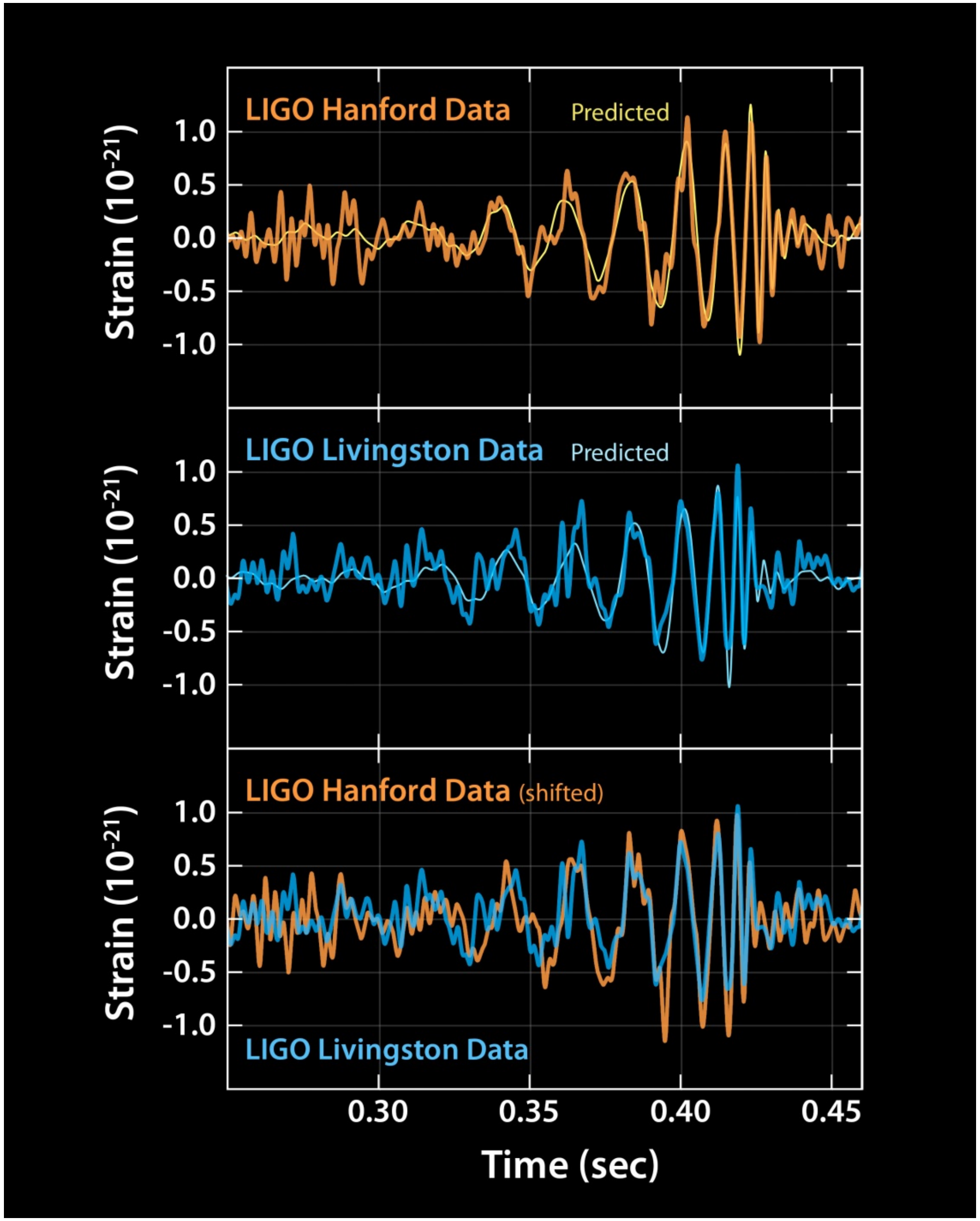
Kamioka Japan 3 km (2018)



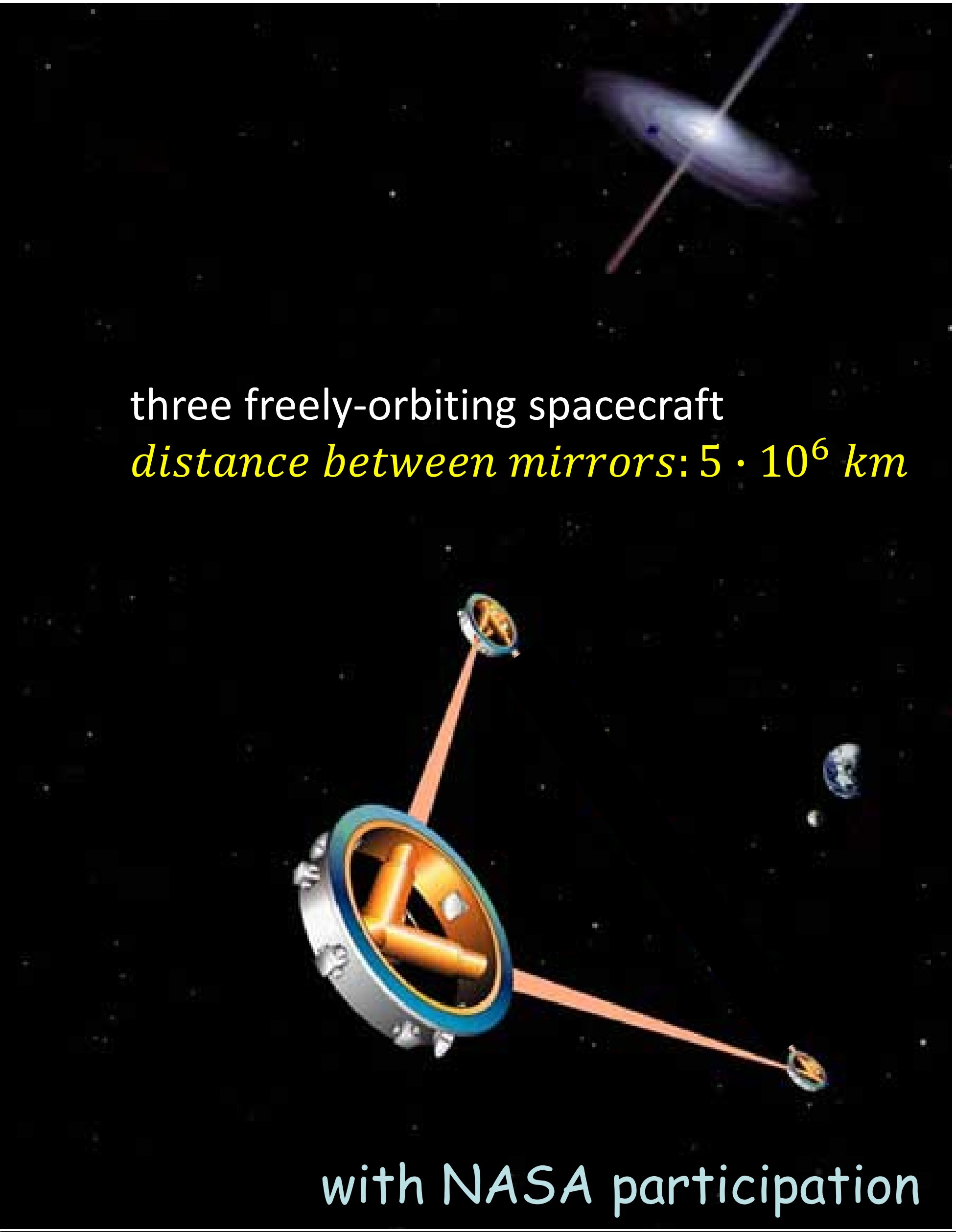
LIGO Livingston 4 km (2015)

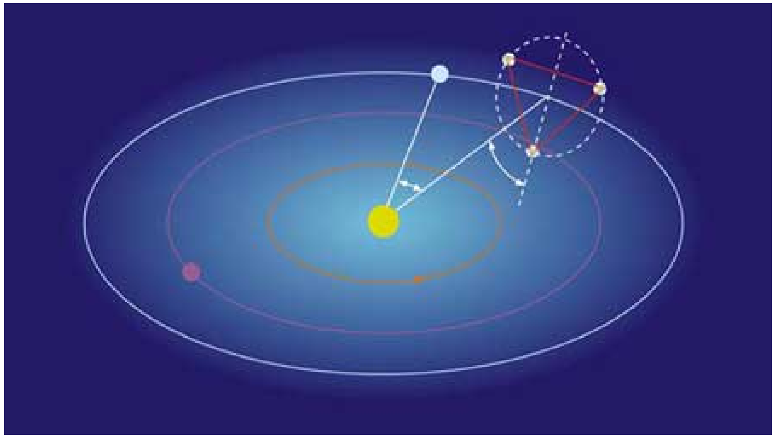
Virgo 3 km (2016)

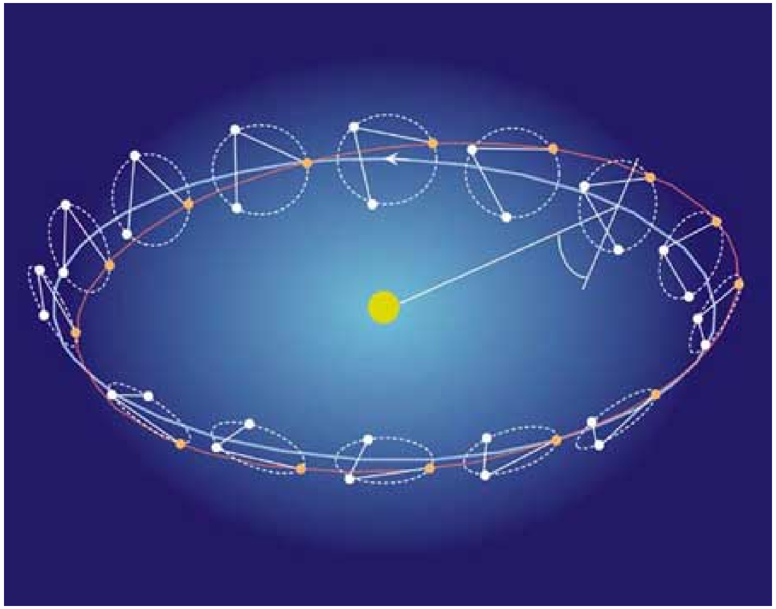
Experimental results



LISA: Laser Interferometer Space Antenna (ESA 2034)







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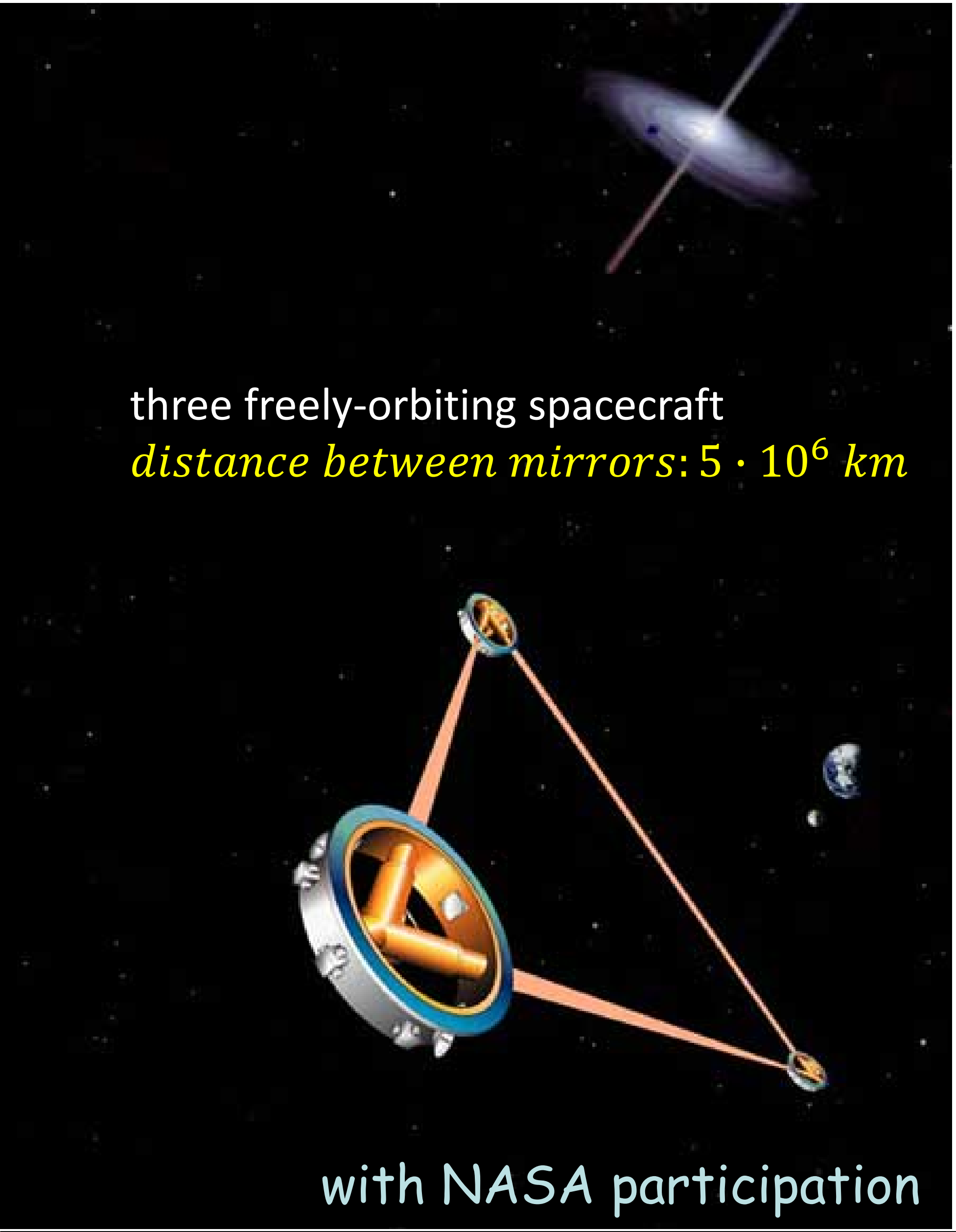
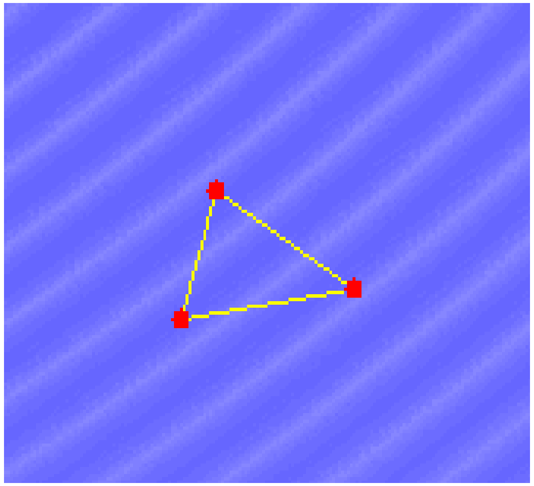
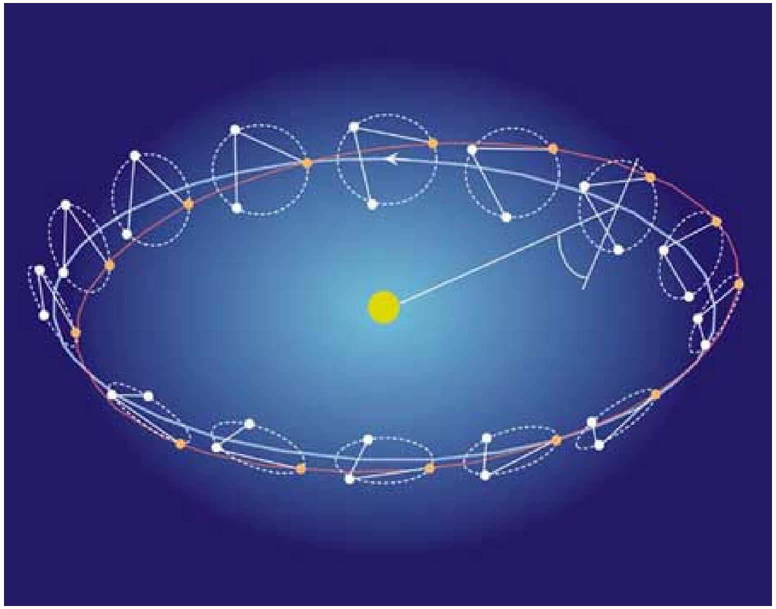


three freely-orbiting spacecraft

distance between mirrors: $5 \cdot 10^6\ km$

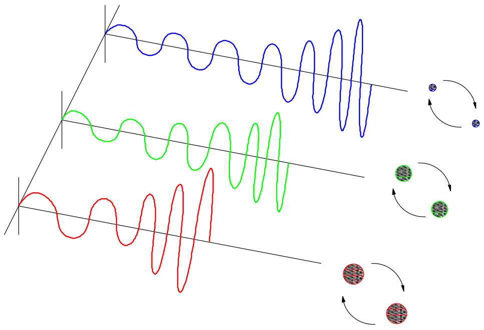
with NASA participation

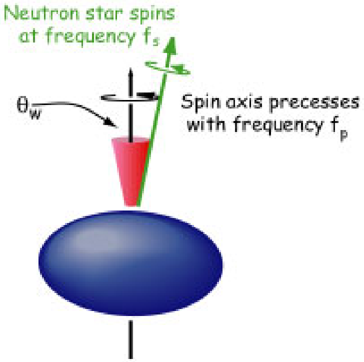


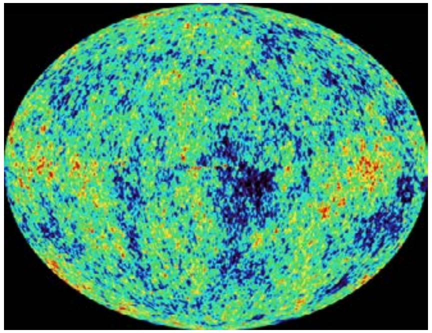


Astrophysical sources of gravitational waves

- **Compact binary systems**
  - Black holes and neutron stars
  - Inspiral → merger → ring-down
  - Probe internal structure, nuclear equation of state of NS crust, populations, and space-time geometry
- **Spinning neutron stars**
  - known & unknown pulsars
  - low mass X-ray binaries LMXBs
  - Probe internal structure and populations
- **Neutron star birth**
  - Supernova core collapse
  - Instabilities: tumbling, convection
  - Correlations with EM observations
- **Stochastic background**
  - Big bang & other early universe
  - Background of GW bursts







Analog from cosmic microwave background -- WMAP 2003

Gravitational waves: differences from EM waves

Electromagnetism:

- A strong force, but with opposing charges (+ and -)
- Fields built up incoherently from microscopic charge separations

» Wavelengths smaller than the source

- Waves are easy to detect, but easily blocked

» Show the surfaces of energetic bodies

- Used to construct *images* of celestial objects
- photon massless, J = 1

Gravity:

- A weak force, but with only one charge (mass)
- Fields built up coherently from bulk accumulation of matter

» Wavelengths larger than the source

- Waves are hard to detect, but pass undisturbed through anything

» Reveal the bulk motion of dense matter

- Can be though of as *sounds* emitted by those objects
- graviton massless, J = 2

→ A fundamentally different way of observing the Cosmos!

EM-waves: $10^{7} – 10^{20}$ Hz

GW: $10^{-9} – 10^{4}$ Hz