Testing General Relativity

Using Observations of Gravitational Waves from Binary Black Hole Coalescences

Abhirup Ghosh

International Centre for Theoretical Sciences, Bangalore

ICTS Postdoc/Graduate Student Seminar Series

October 13, 2017

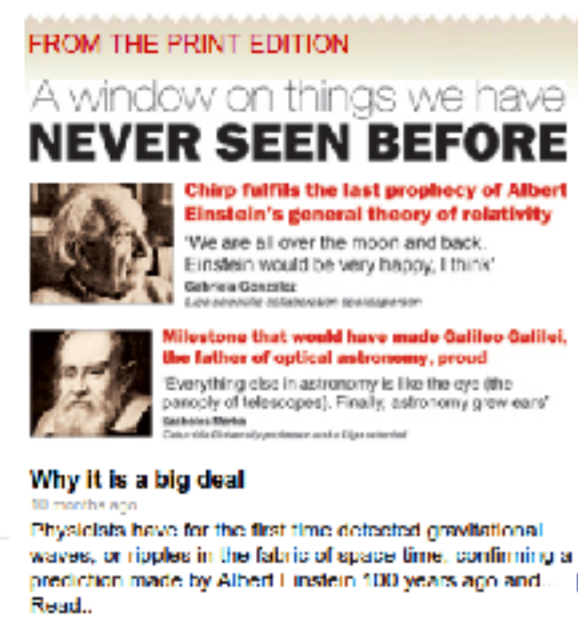
February 12, 2016: The day after

Boilermakers help prove Einstein theory

Scientists make history by detecting gravitational waves

BOILERMAKER-BUILT STAINLESS steel vacuum tubes at advanced scientific test facilities in Washington and Louisiana have contributed to a major breakthrough in physics and astronomy. On Feb. 11, scientists announced that for the first time ever mankind has detected gravitational waves that were postulated by Albert Einstein 100 years ago as part of his general theory of relativity.

Tags *Headline News*



October 4, 2017: The day after

Einstein's waves win Nobel Prize in physics

By Paul Rincon and Jonathan Amos
BBC Science News

3 October 2017 | Science & Environment Share

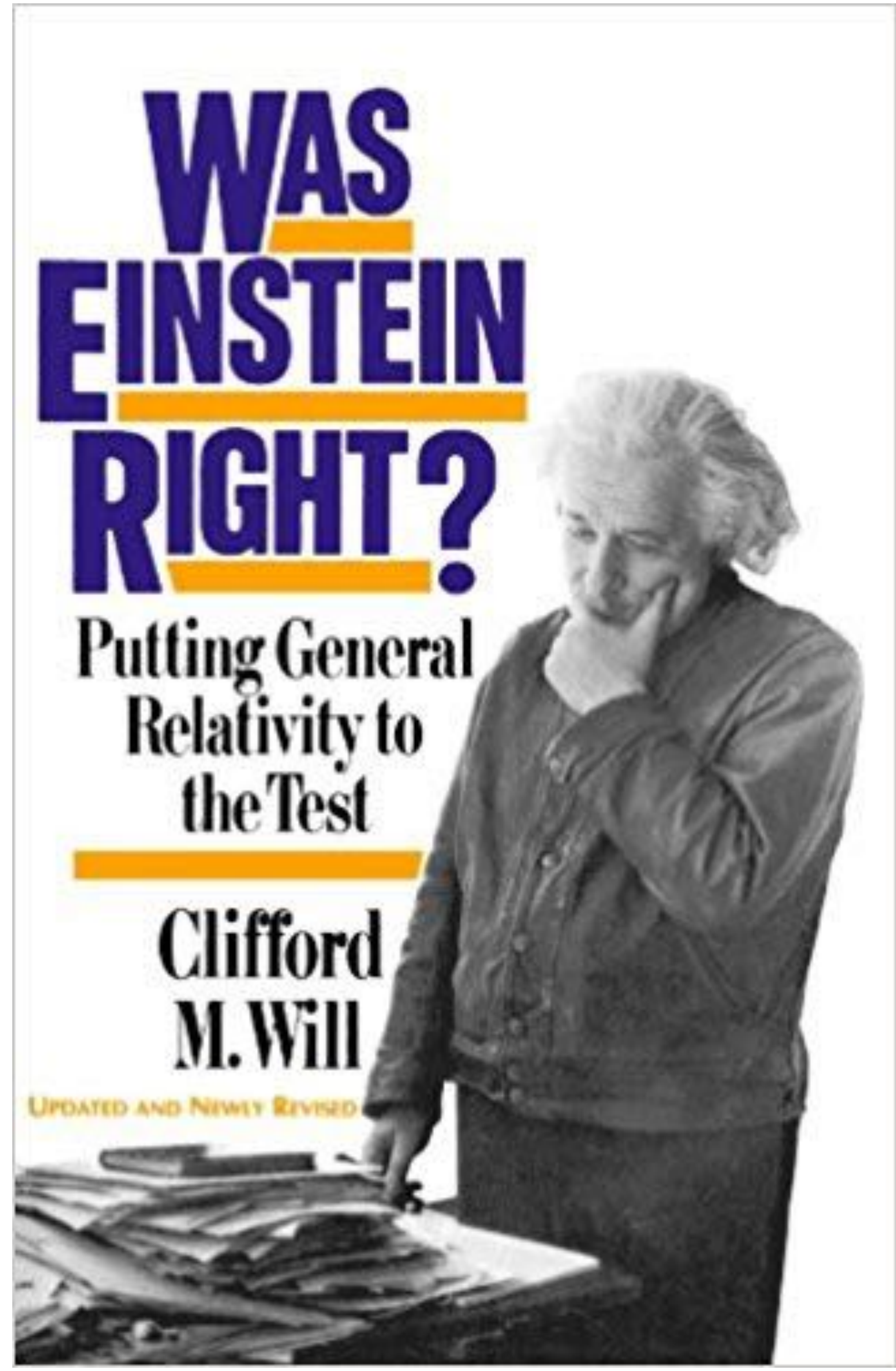
Weiss (L) takes half the prize; Thorne (C) and Barish (R) share the other half

Einstein Was Right -- Again: Nobel Winners Find Ripples in Universe

By Jim Heintz and David Keyton

Trio win **Nobel** for finding **Einstein's gravitational waves**
Reuters TV - 03-Oct-2017
... >> Albert **Einstein** didn't think it could be done. The scientist was convinced that we'd never be able to measure **gravitational waves**, ripples ...

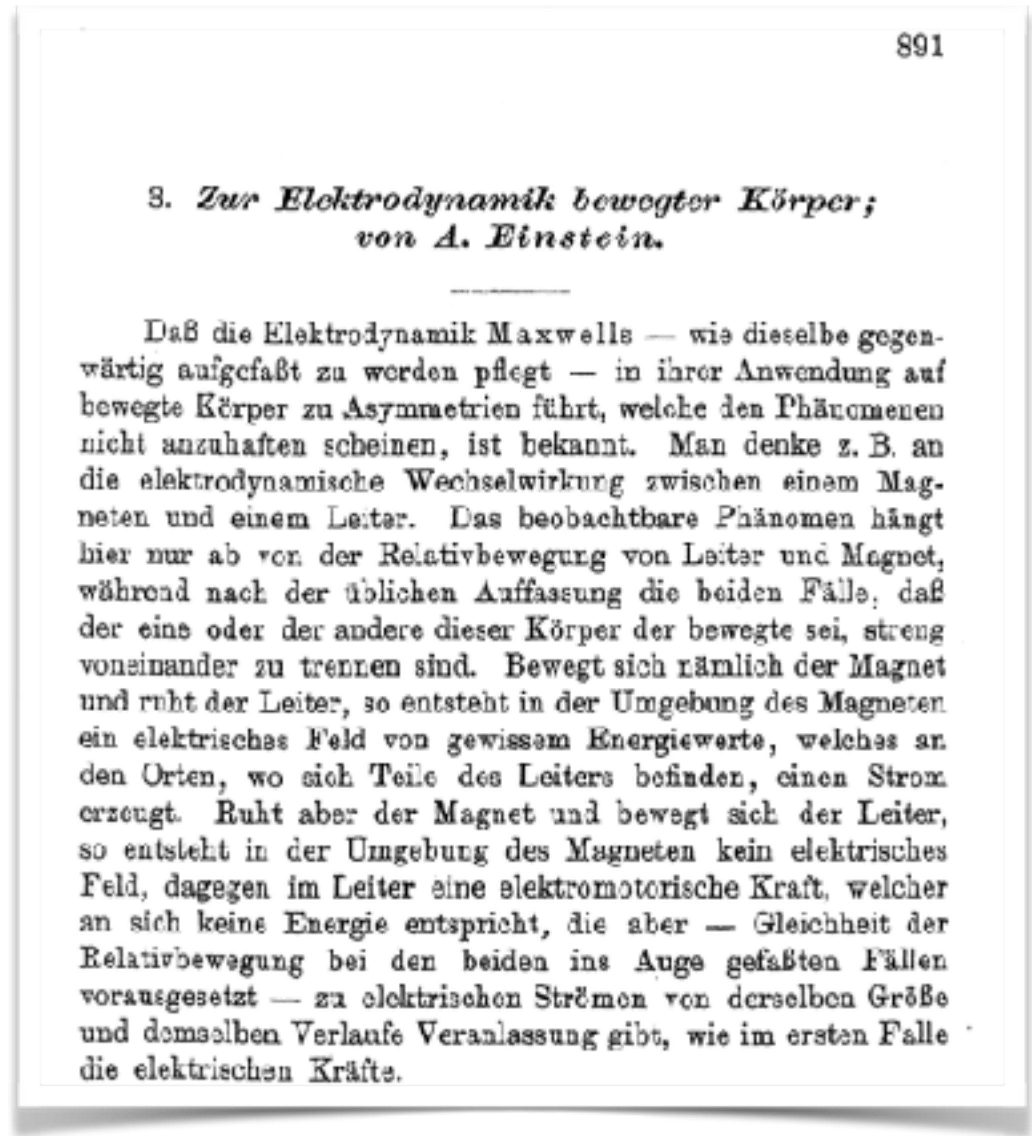
#EinsteinRight


WAS
EINSTEIN
RIGHT?
Putting General Relativity to the Test
Clifford M. Will
UPDATED AND NEWLY REVISED

Einstein’s Gravity

Special Theory of Relativity (1905)

- The laws of physics are invariant in all inertial systems.
- The speed of light in vacuum is the same for all observers.



891

3. *Zur Elektrodynamik bewegter Körper;*
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

“On the electrodynamics of moving bodies”, Einstein
Annalen der Physik. 17, 1905

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Nothing can travel faster than the speed of light...

.... including gravitational interactions.

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Einstein's Gravity

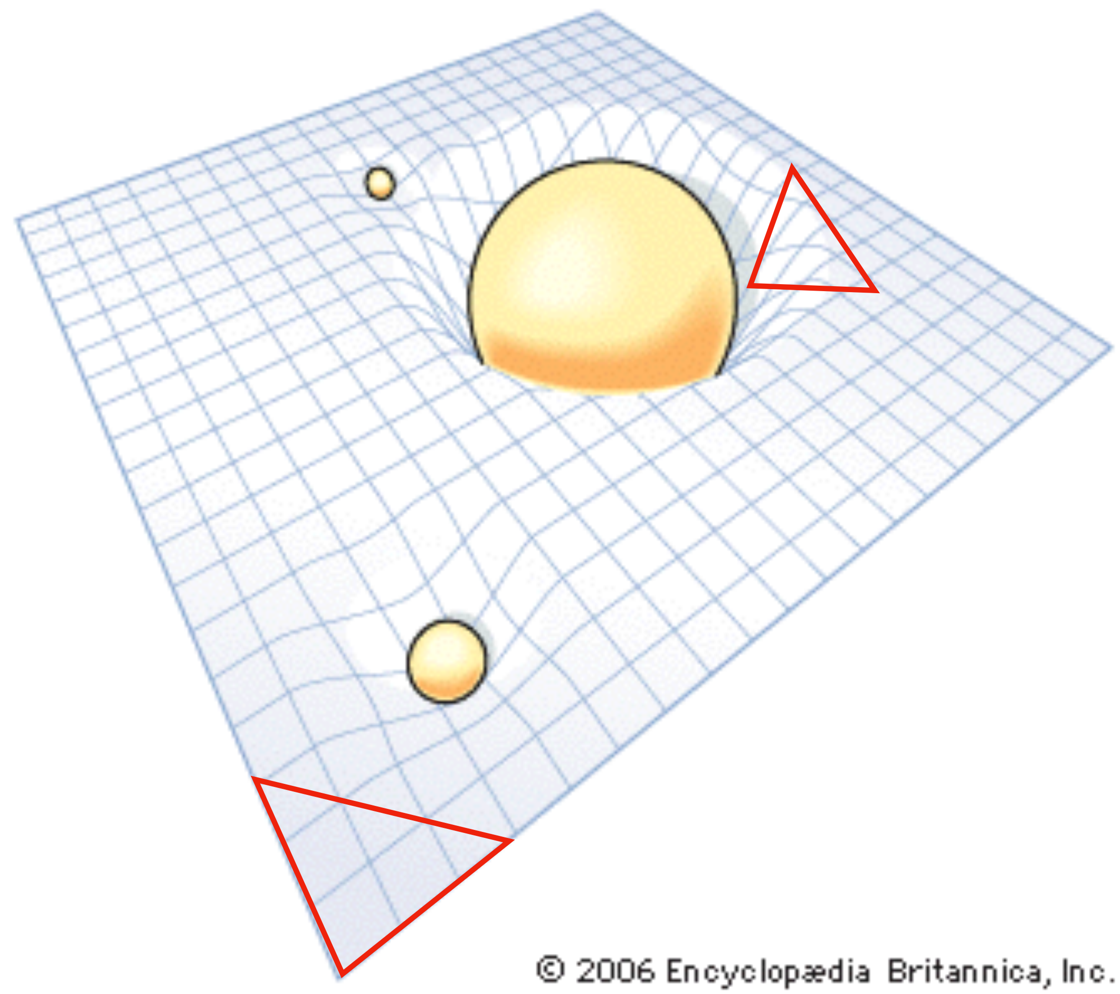
General Theory of Relativity (1915)

Gravity:

Curvature of spacetime, produced by the matter-energy content in the spacetime.

Curvature Matter/Energy

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



Classical Tests

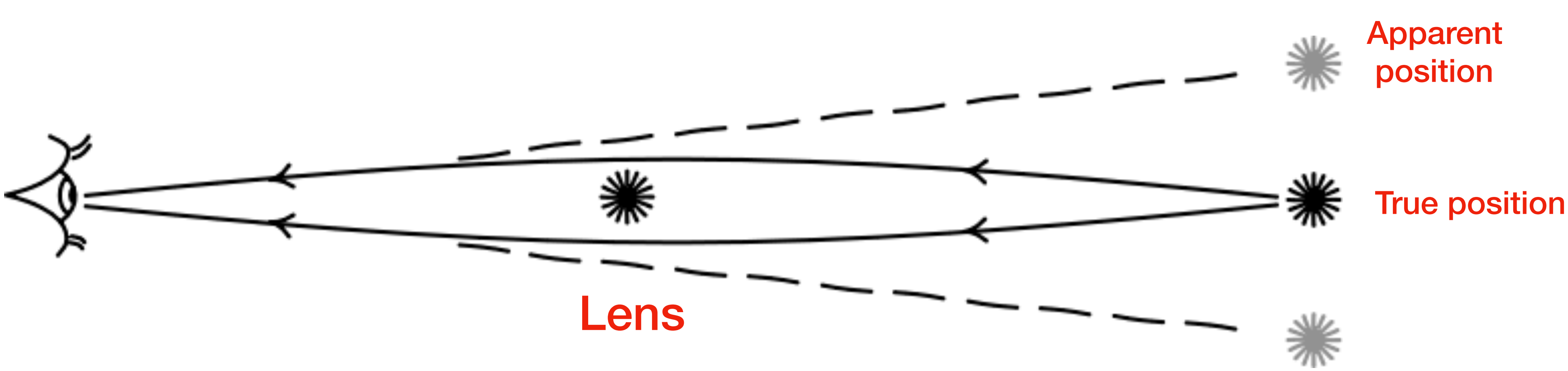
General Theory of Relativity (1915)

Gravity:

Curvature of spacetime, produced by the matter-energy content in the spacetime.

Classical Tests (1916):

- Deflection of light by the sun



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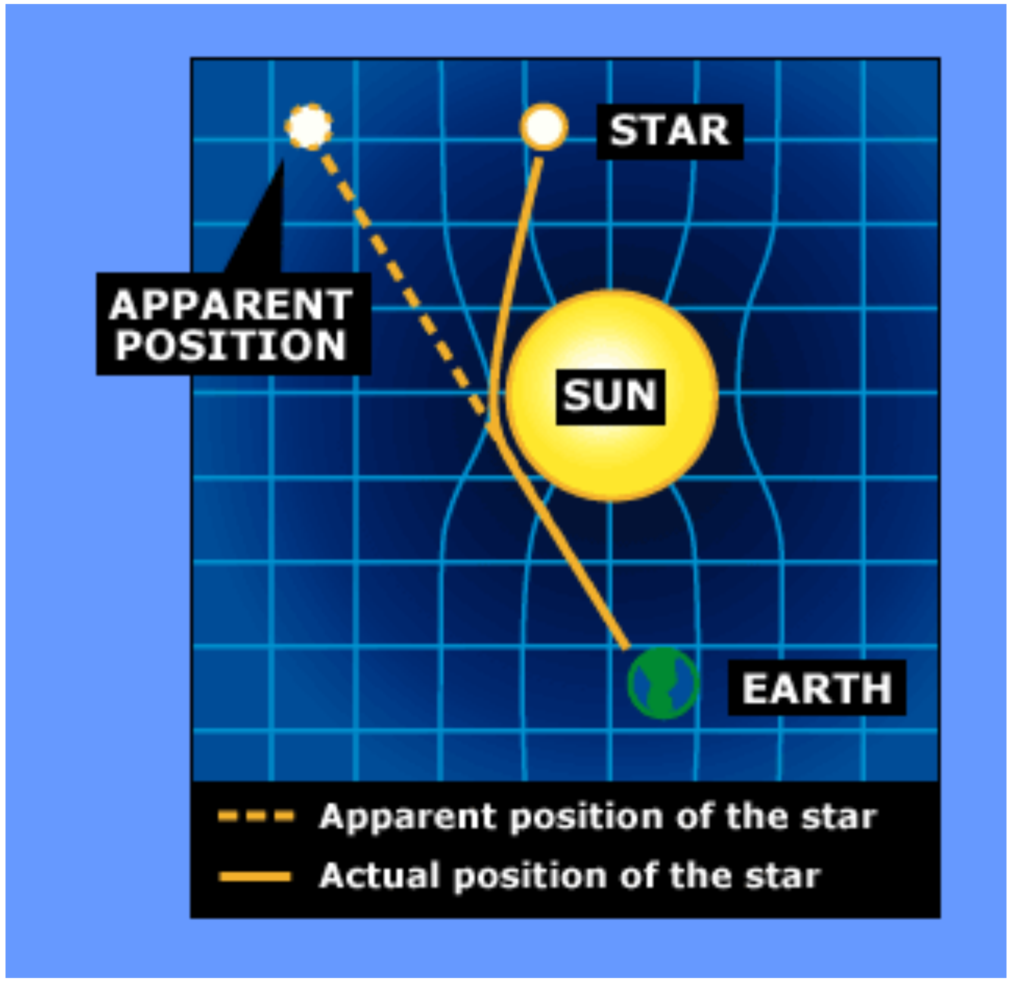

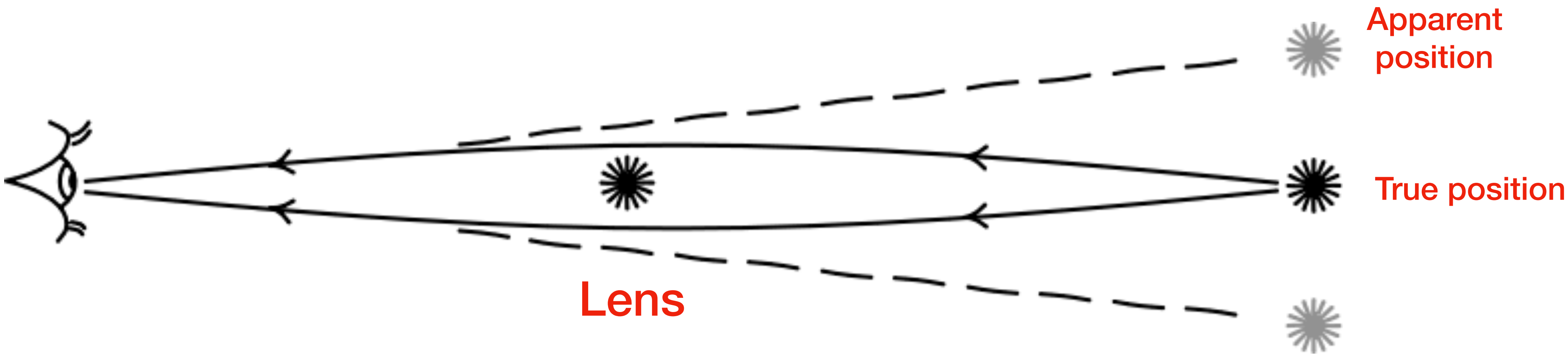

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http://undsci.berkeley.edu/article/0_0_0/fair_tests_04

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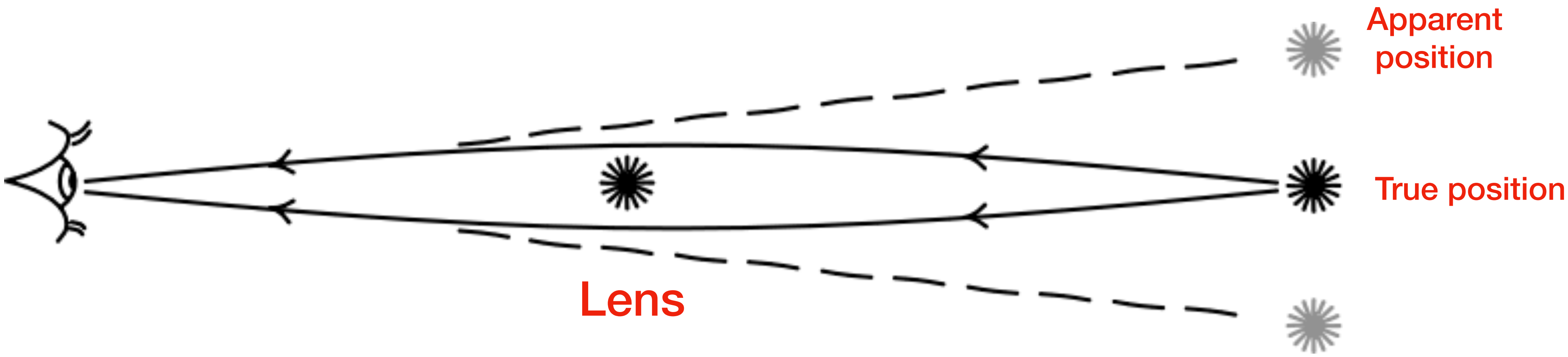
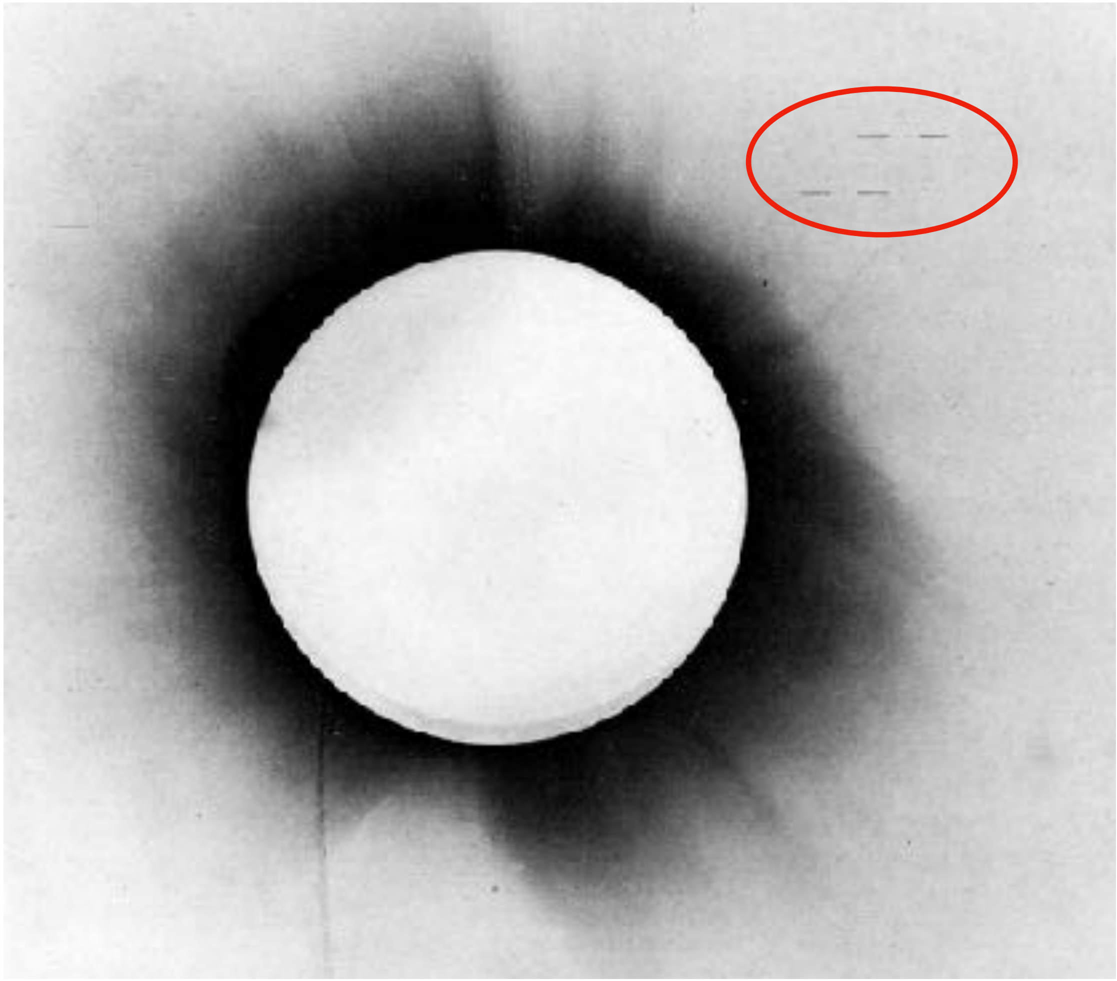


Classical Tests

Negative of one of Eddington's photographic plates from his expedition to the island of Principe, during the total solar eclipse on May 29, 1919



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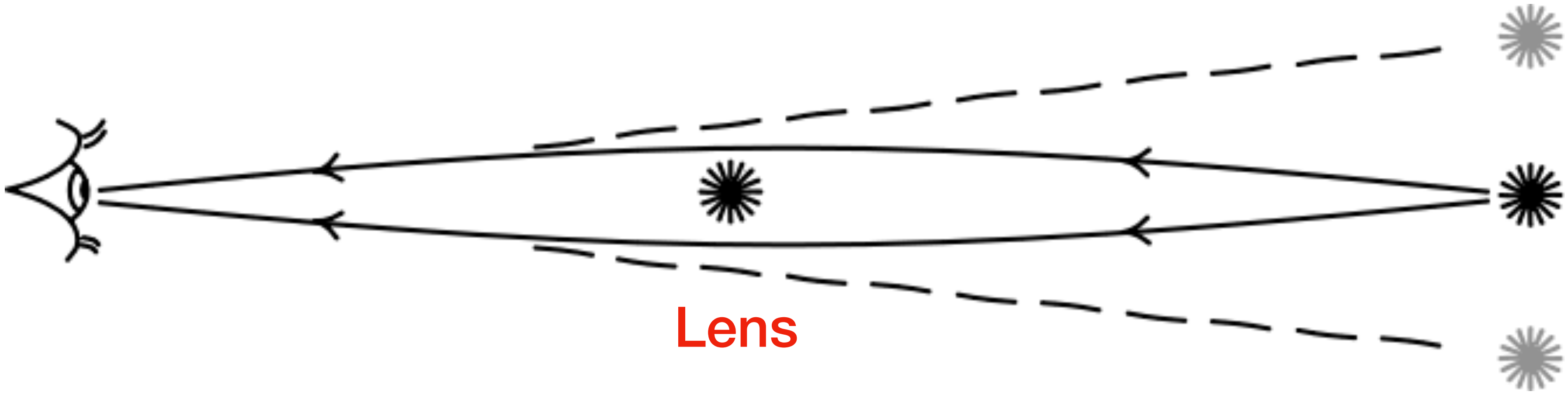

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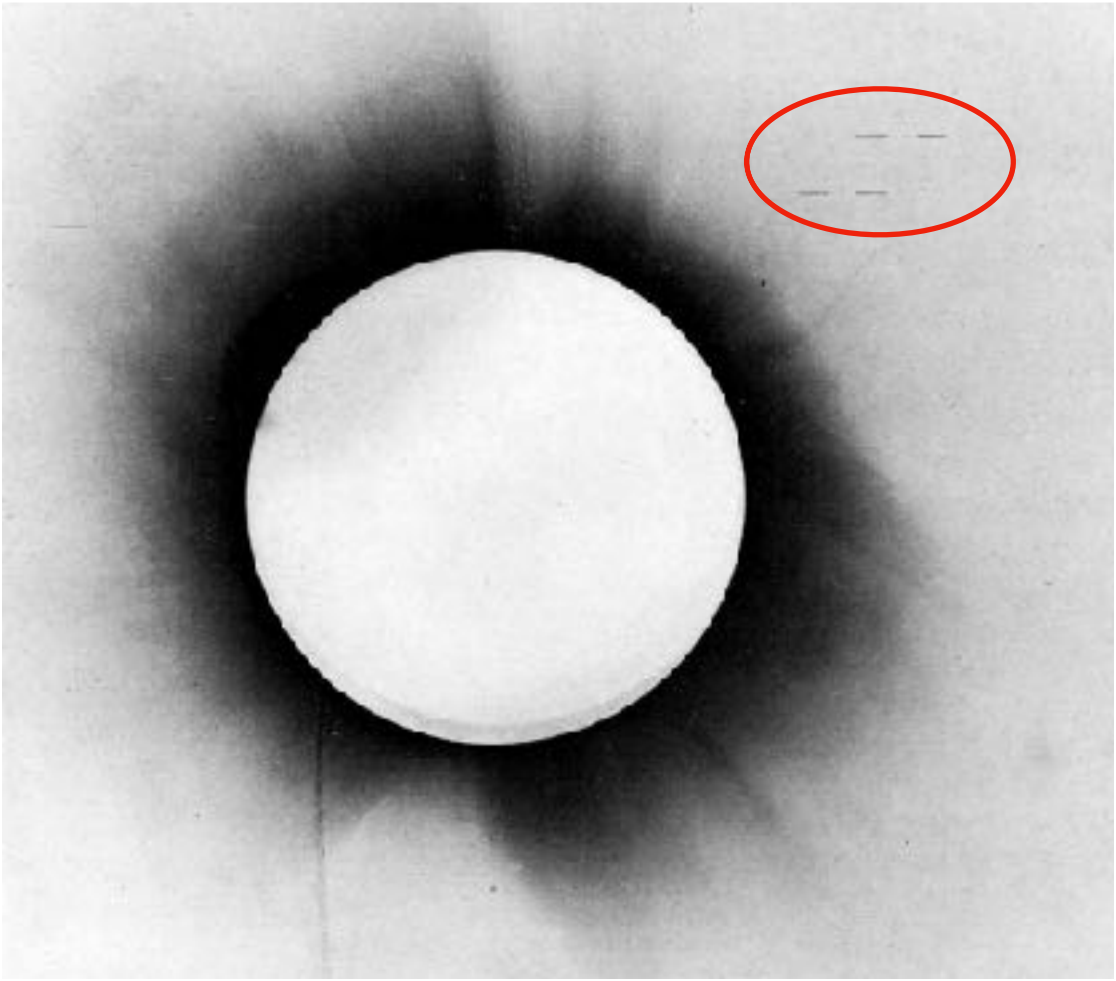

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prediction: 1.75"

observation: 1.61" $\pm$ 0.40

Classical Tests

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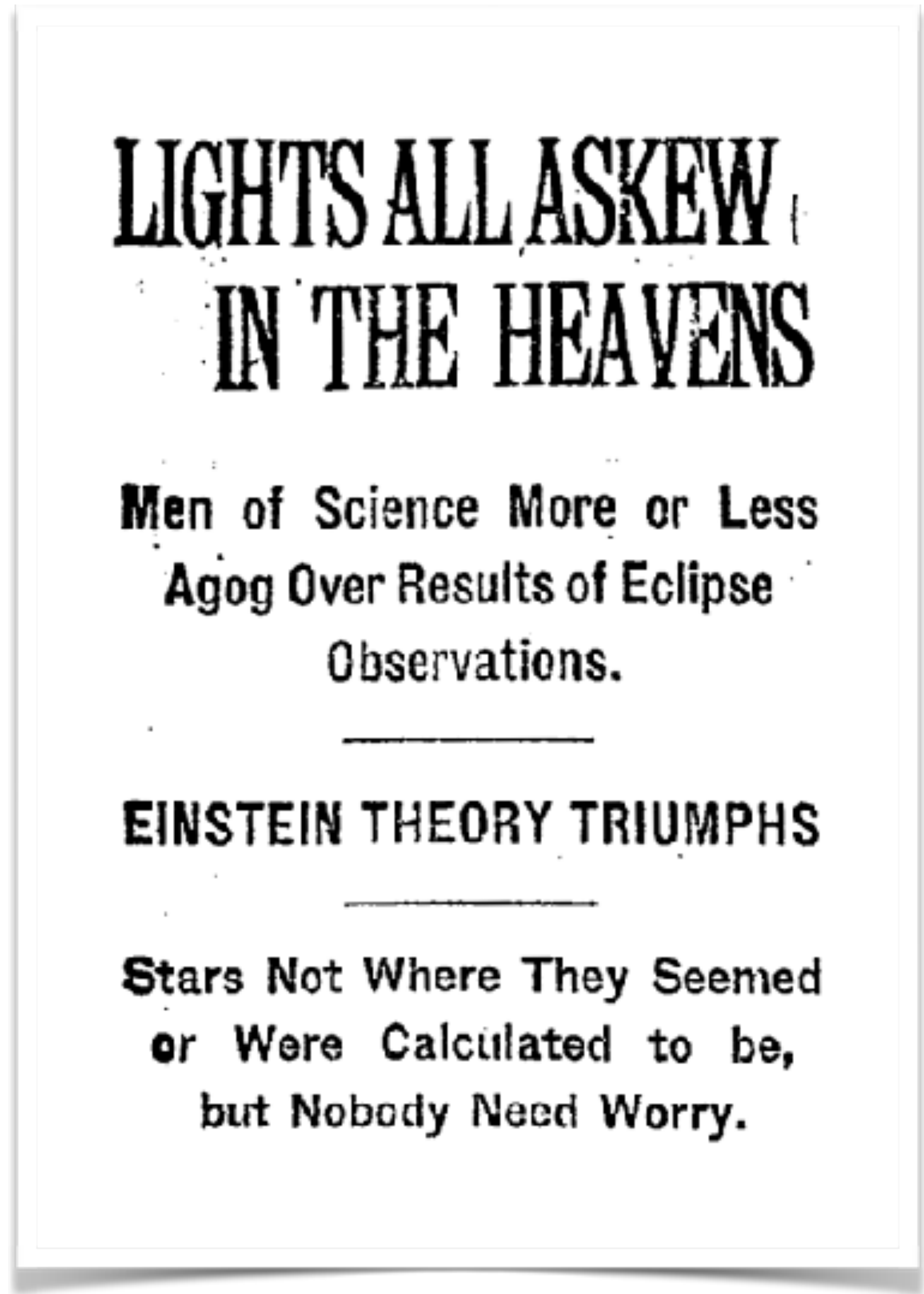
A journalist asked Einstein what he would do if Eddington's observations failed to match his theory.

Einstein famously replied: "Then I would feel sorry for the good Lord. The theory is correct."



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

Classical Tests

General Theory of Relativity (1915)

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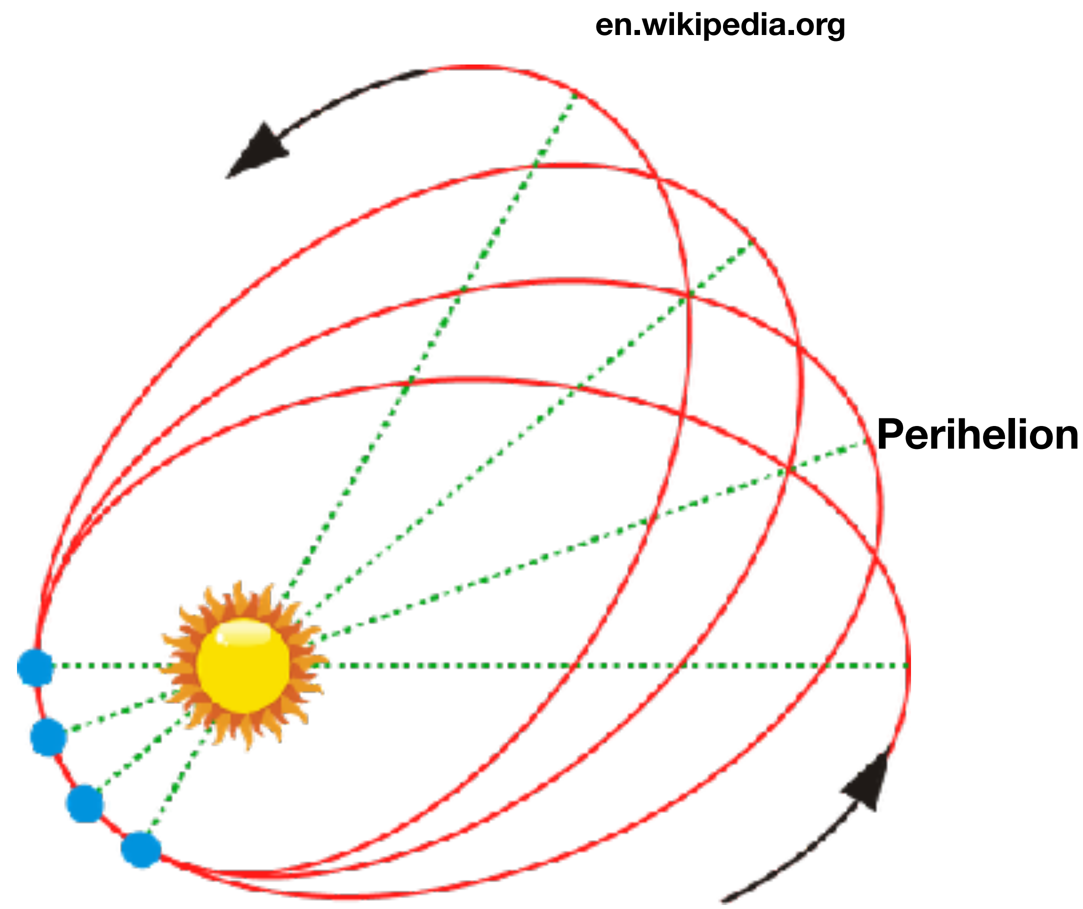
- Deflection of light by the sun
- Perihelion precession of Mercury's orbit



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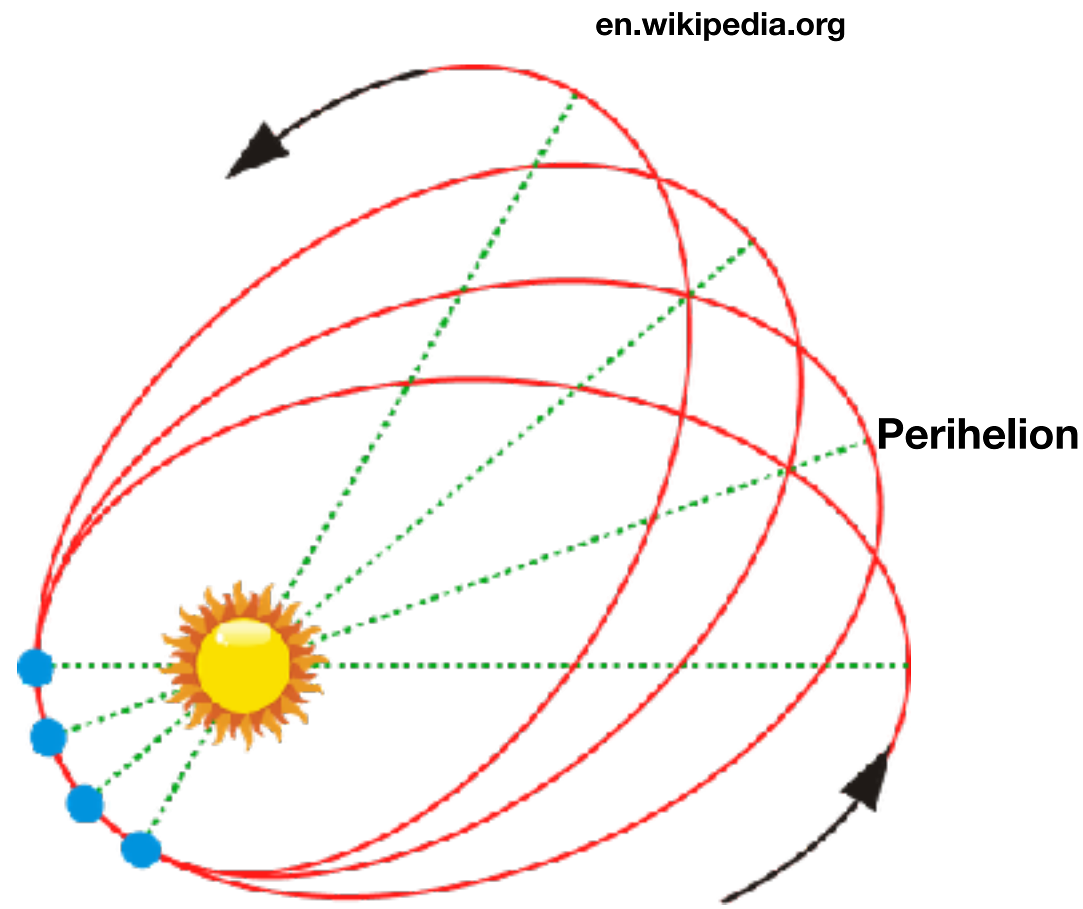

prediction: 43.03” per century
observation: 43.11±0.45 per century

Classical Tests

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Classical Tests (1916):

- Deflection of light by the sun
- Perihelion precession of Mercury's orbit
- Gravitational redshift of light

$$\frac{\Delta\nu}{\nu} = \phi(x_2) - \phi(x_1)$$

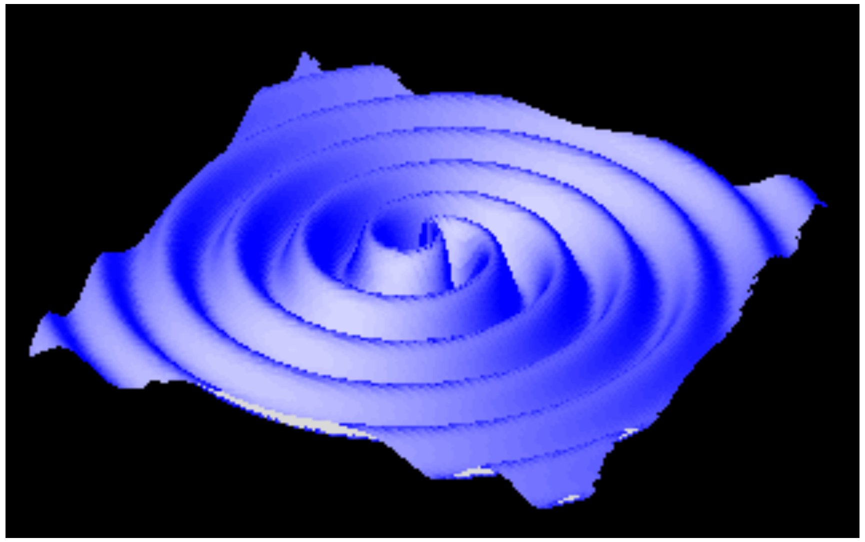
Doppler shift in the spectral lines of white dwarf Sirius B and Eridani B, observed by J. Adams, 1925

Principle of Equivalence (1907):

At every spacetime point in an arbitrary gravitational field it is possible to choose a "locally inertial coordinate system" such that, within a sufficiently small region of the point in question the laws of nature take the same form as in unaccelerated Cartesian coordinate systems in the absence of gravitation.

Gravitational Waves

- One of the most interesting predictions of GR, is the existence of gravitational waves (GWs).
- According to GR, a change in the matter distribution in spacetime, causes a change in the curvature of spacetime.
- GWs are the propagating changes in the geometry of spacetime – ripples in the fabric of spacetime, that carry energy and angular momentum away from the source.



wikipedia.org

[C] 'Do gravitational waves exist?
A Einstein, N Rosen - Physical Review, 1936
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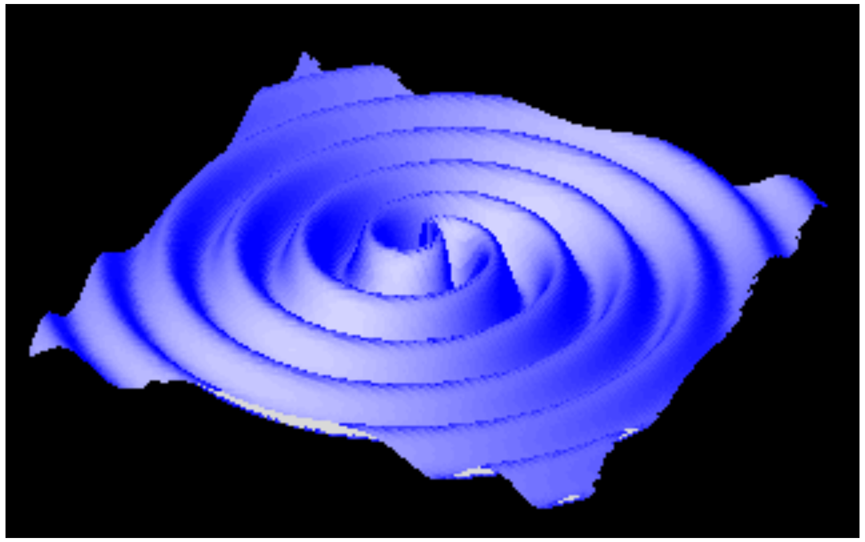
- GWs are produced by a time-varying quadrupole moment of a system (analogous to a time-varying dipole moment producing EM waves)



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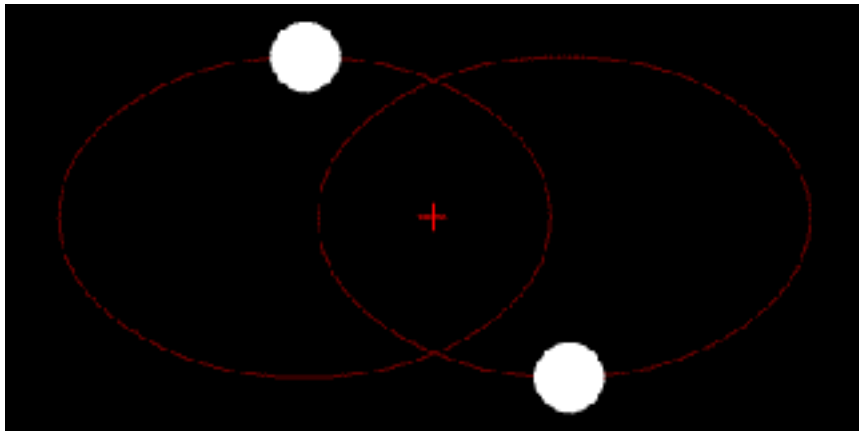
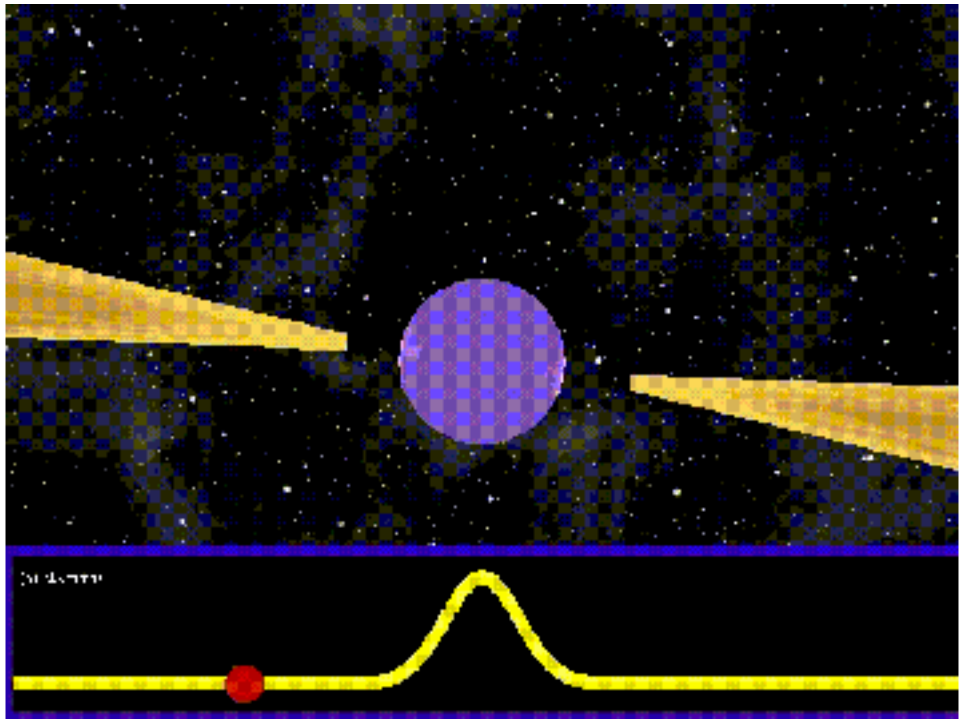


wikipedia.org

Observational Evidence of gravitational waves

- Binary Pulsars: Binaries of neutrons stars/white dwarfs, where atleast one of them emit a beam of electromagnetic radiation.



(C.Berry, LIGO)

Observational Evidence of gravitational waves

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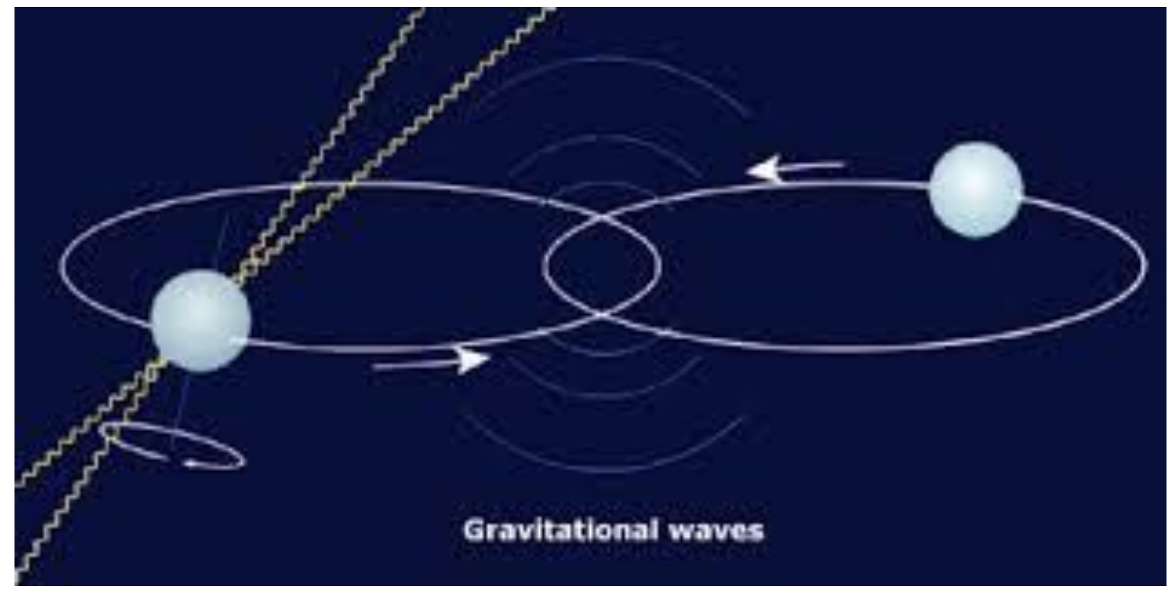
- In 1974, Russell Hulse and Joseph Taylor, discovered the binary pulsar system PSR B1913+16.



nobelprize.org

wikipedia.org

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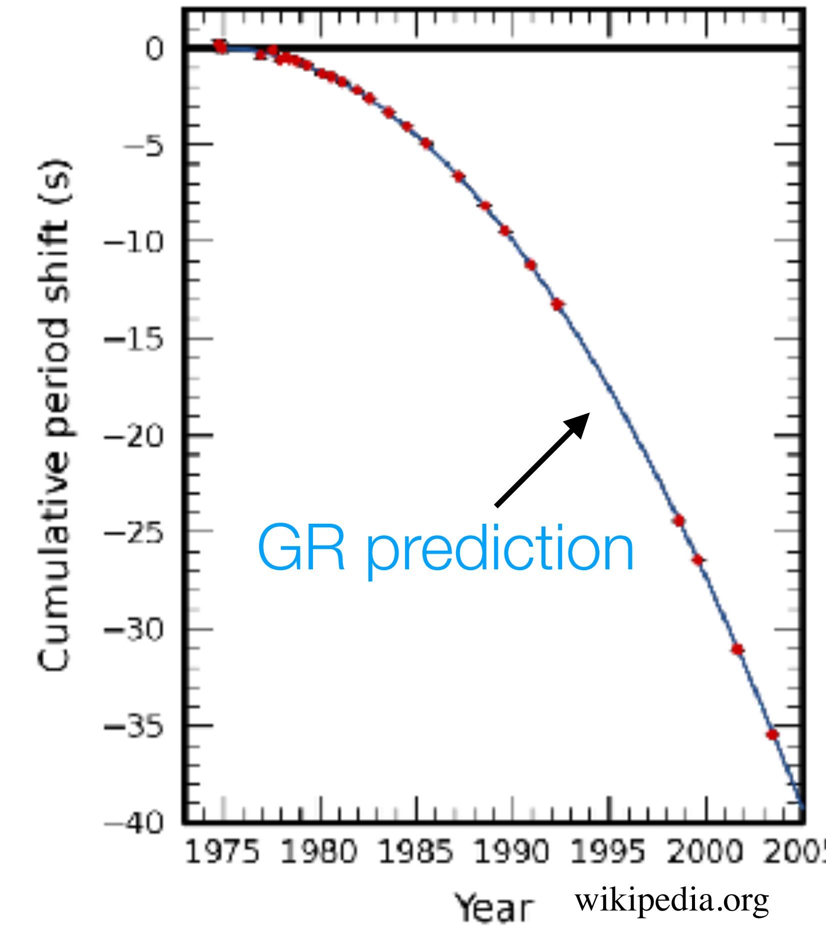
- The decay in the orbital period of the PSR B1913+16 system was studied over a period of > 30 years.



wikipedia.org

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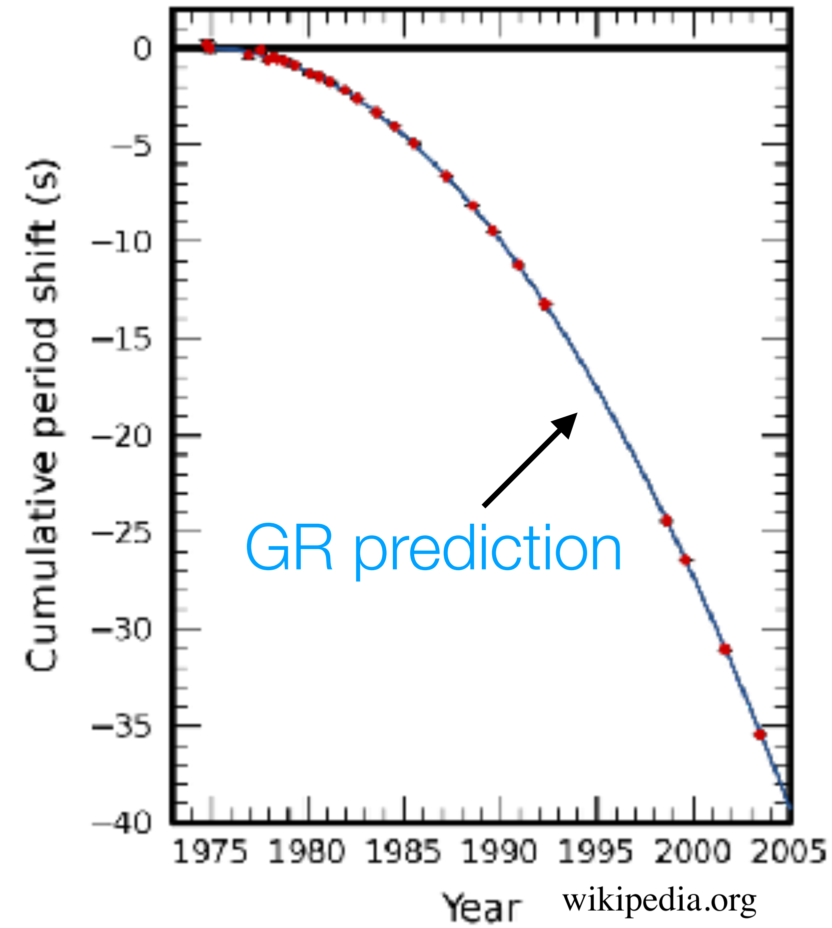
- First indirect evidence for the existence of gravitational waves.



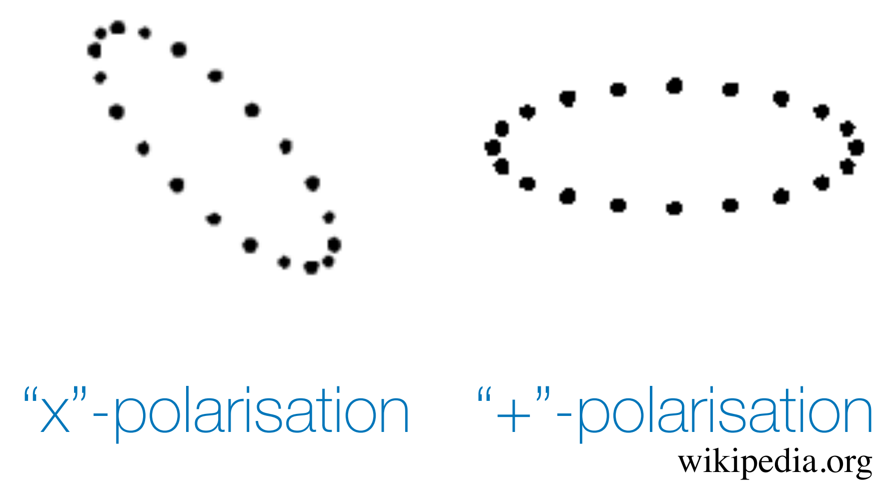
wikipedia.org

Nobel Prize in Physics, 1993

Direct detection of gravitational waves

- When GWs pass through an object, they create a time-varying tidal forces. Direct detection involves measuring these spacetime strains.

$$h = \frac{\Delta L}{L}$$



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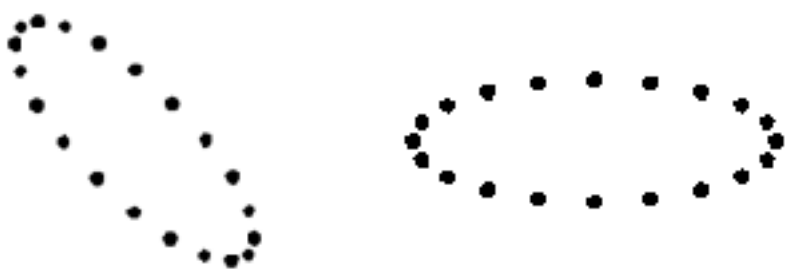
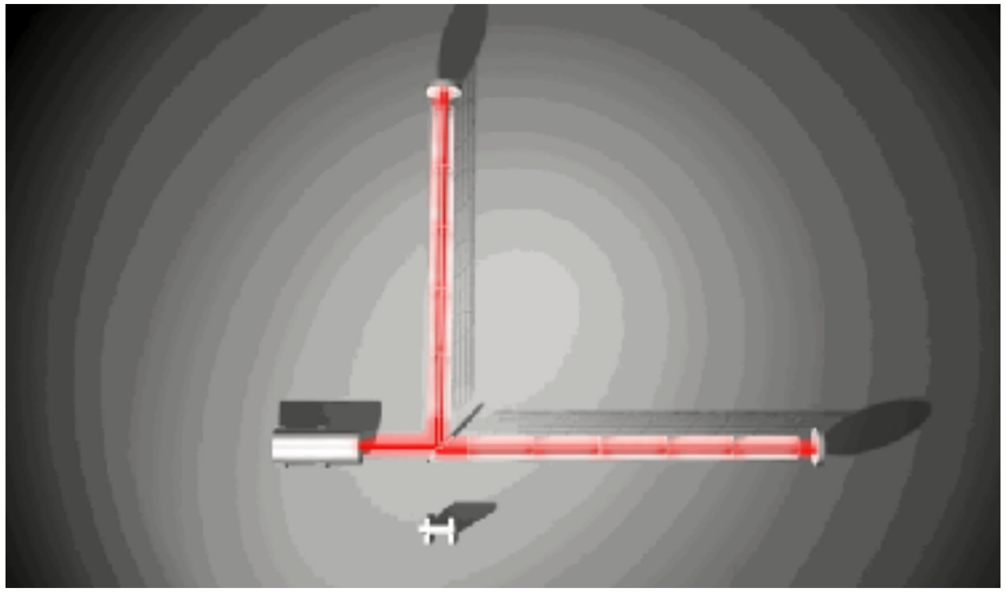


"x"-polarisation "+"-polarisation

wikipedia.org

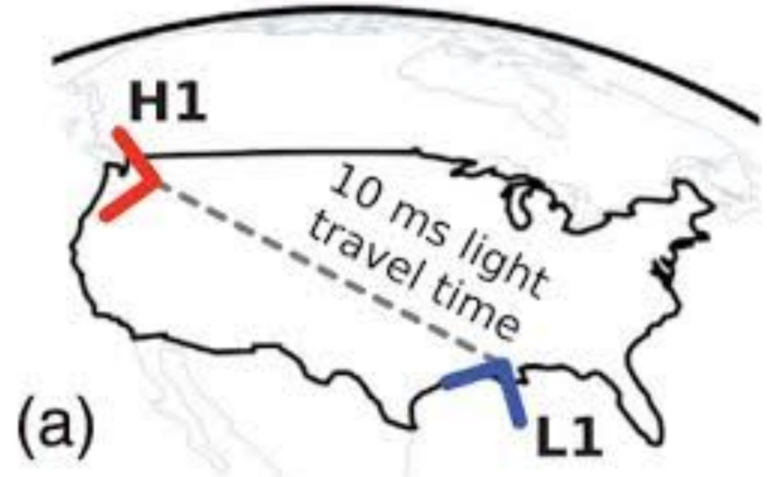
- These spacetimes strains can be measured by Michelson interferometers.



https://media.giphy.com/media/3o6UB2IcnqwluDIXv2/giphy-downsized-large.gif

LIGO

Laser Interferometer Gravitational-wave Observatory

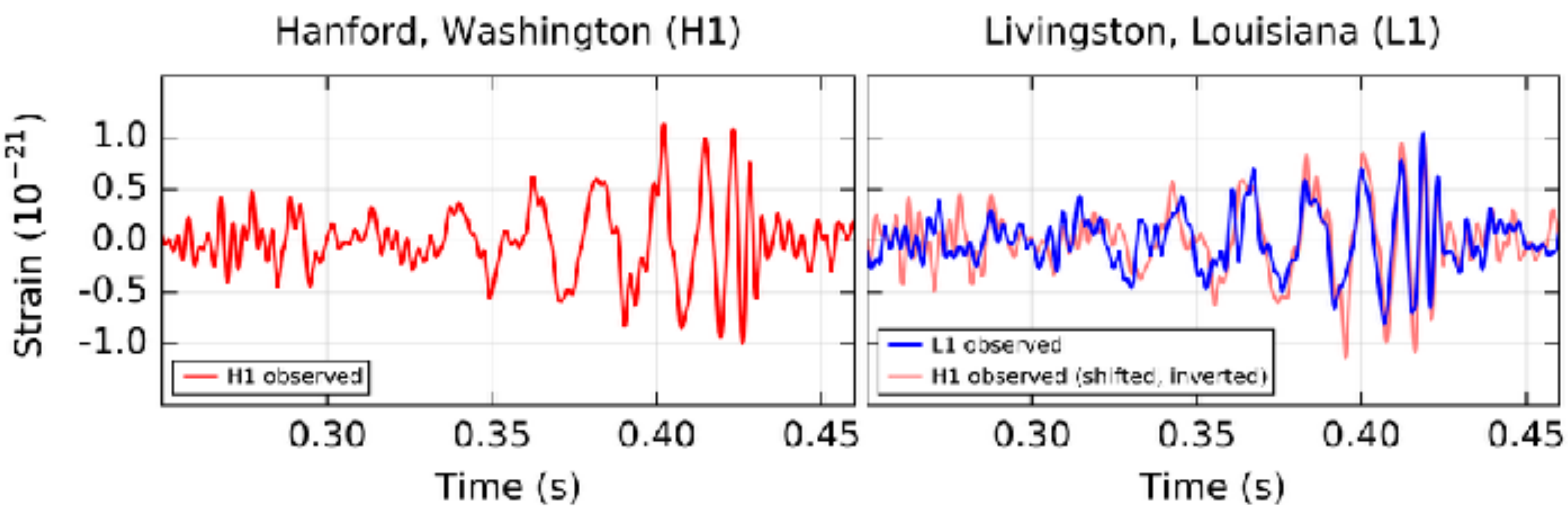


LSC & Virgo: Phys. Rev. Lett. 116, 061102

ligo.caltech.edu

4 km long Michelson interferometers

September 14, 2015



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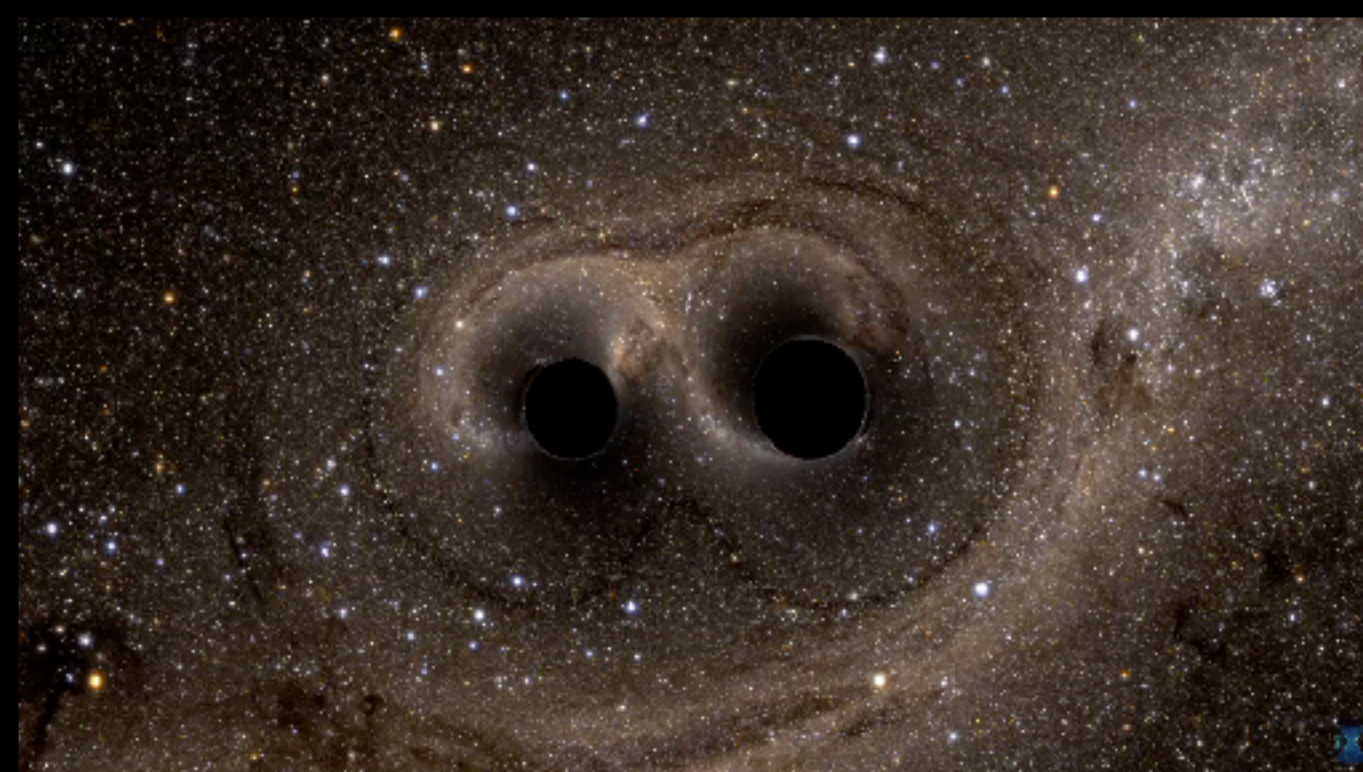
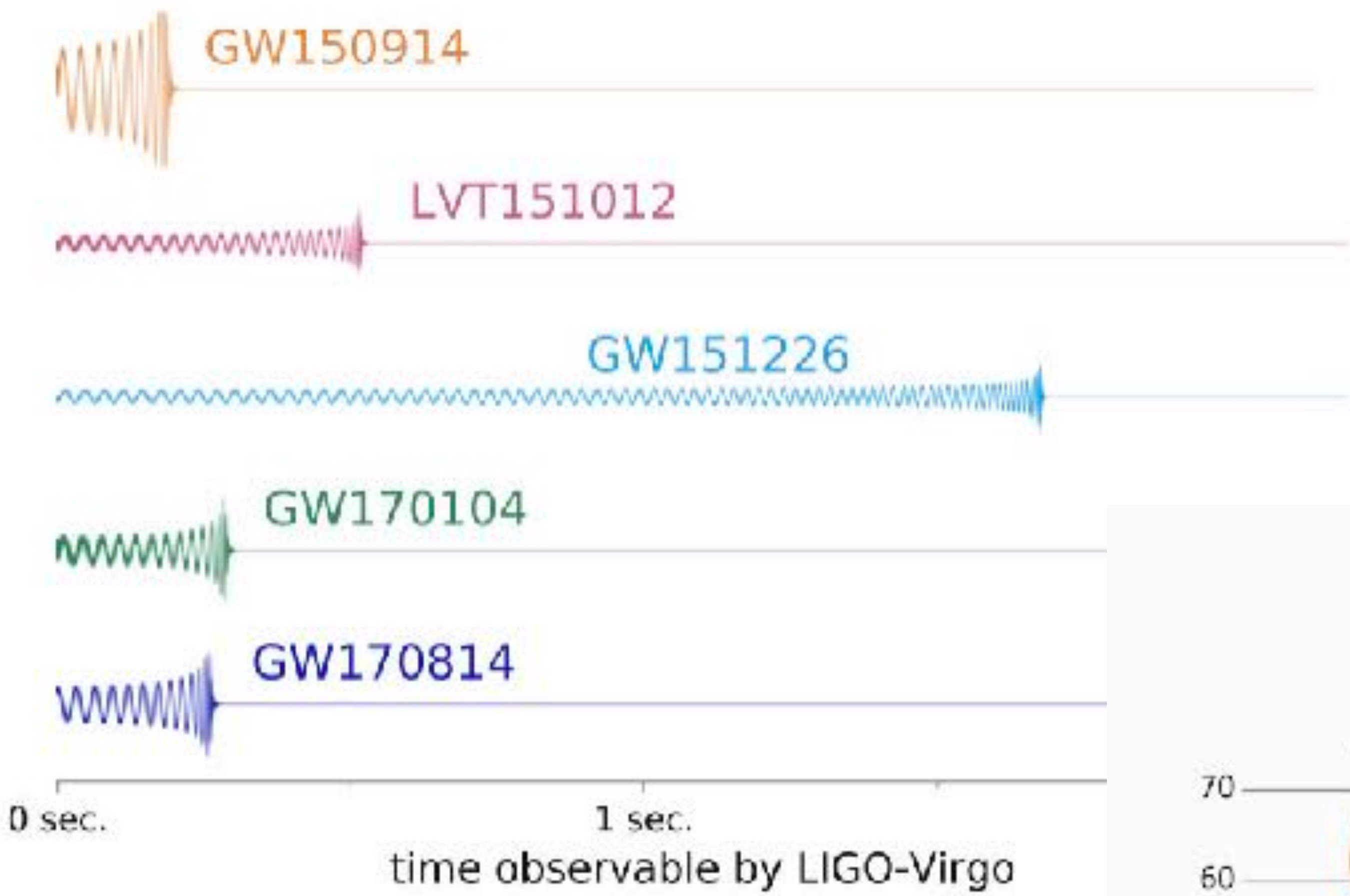
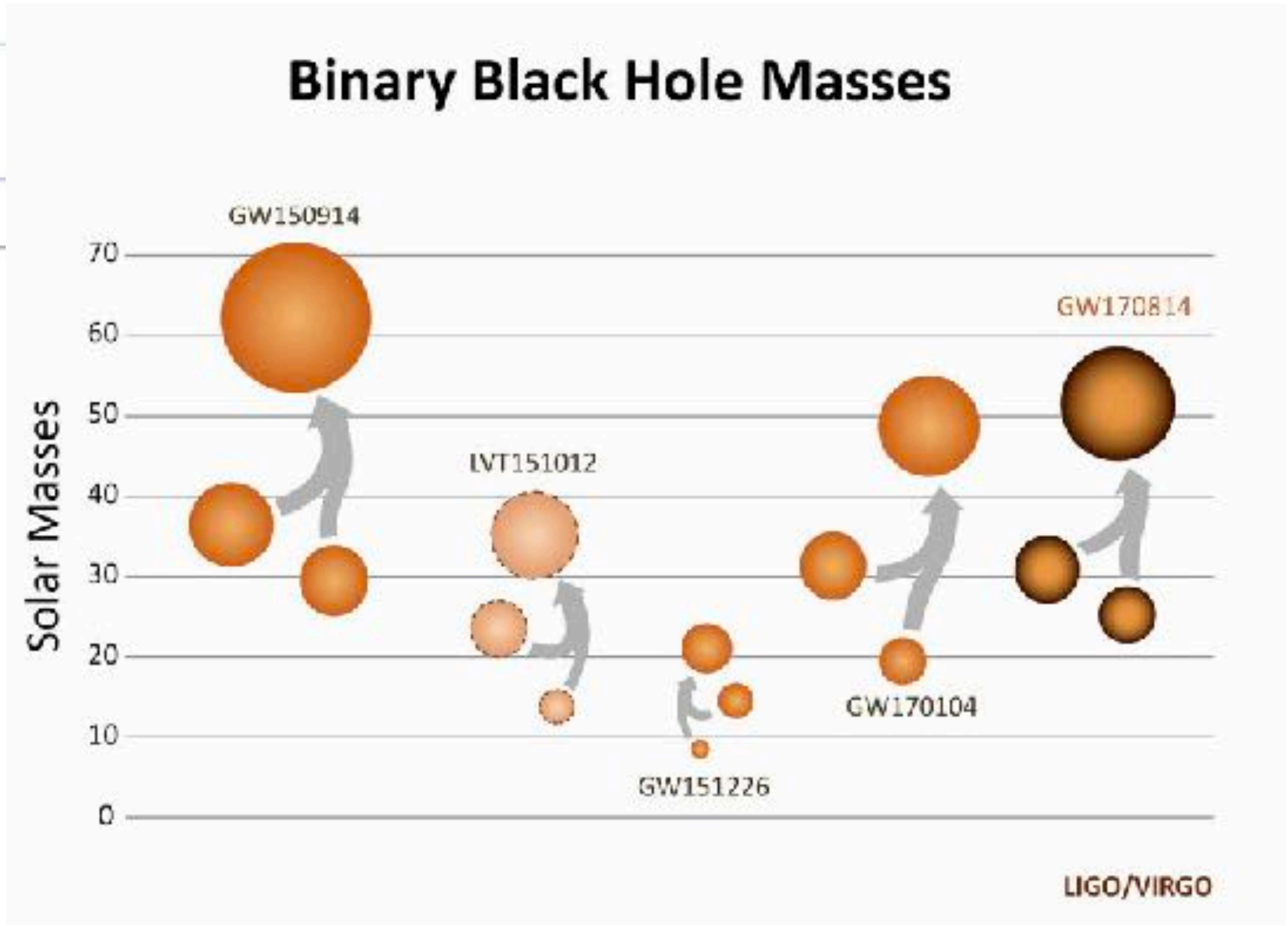


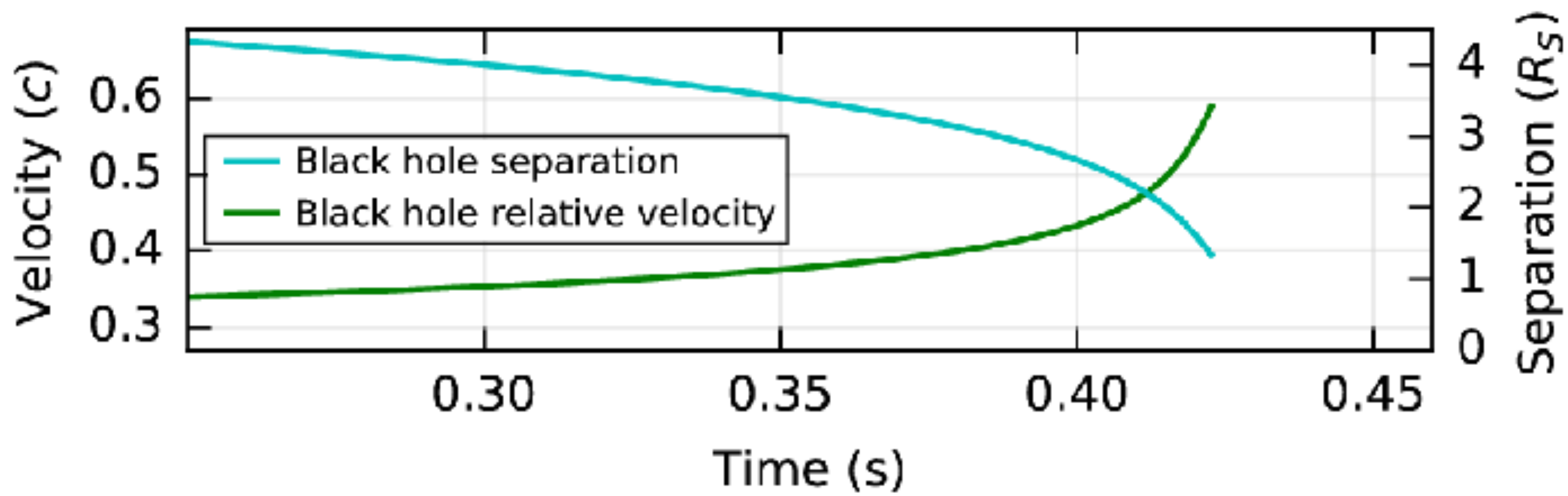
LIGO detections of BBH mergers





Tests of GR using gravitational waves

- Coalescences of binary black holes (BBHs) provides an opportunity to test GR in highly relativistic strong-field regimes of gravity.

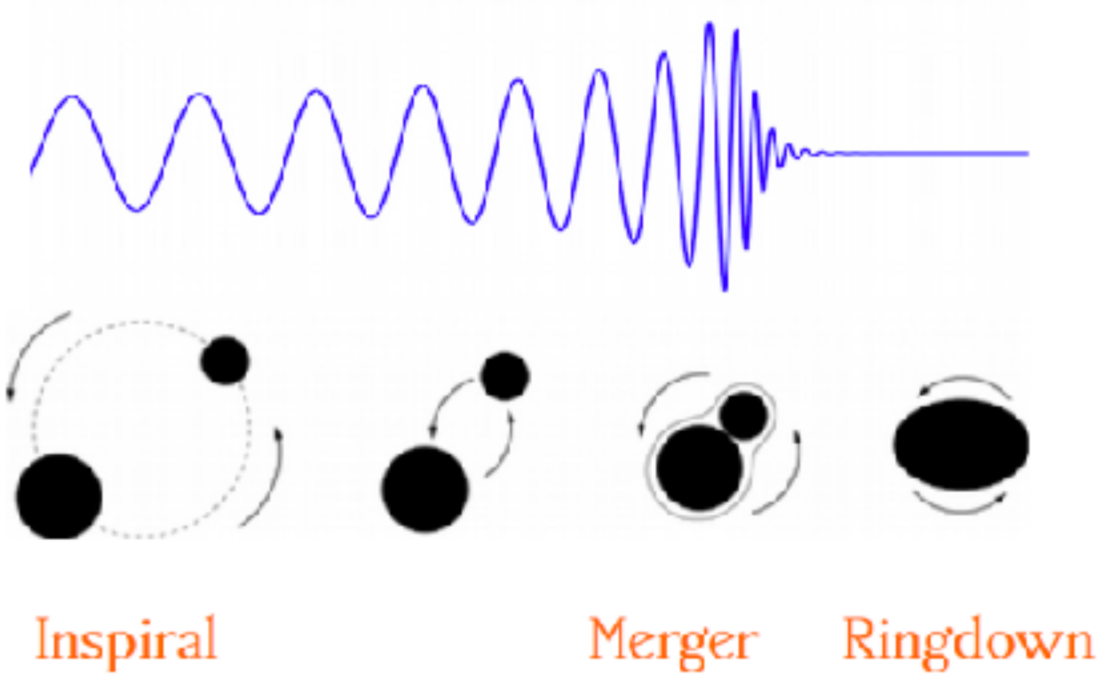


LSC & Virgo: Phys. Rev. Lett. 116, 061102

Inspiral-merger-ringdown consistency test

AG et al. (PRD 94, 021101)
AG et al. (arXiv:1704.06784)

- The IMR consistency test is based on estimating the final mass and spin from the initial (low frequency) and final (high frequency) stages of a BBH coalescence and checking their consistency.



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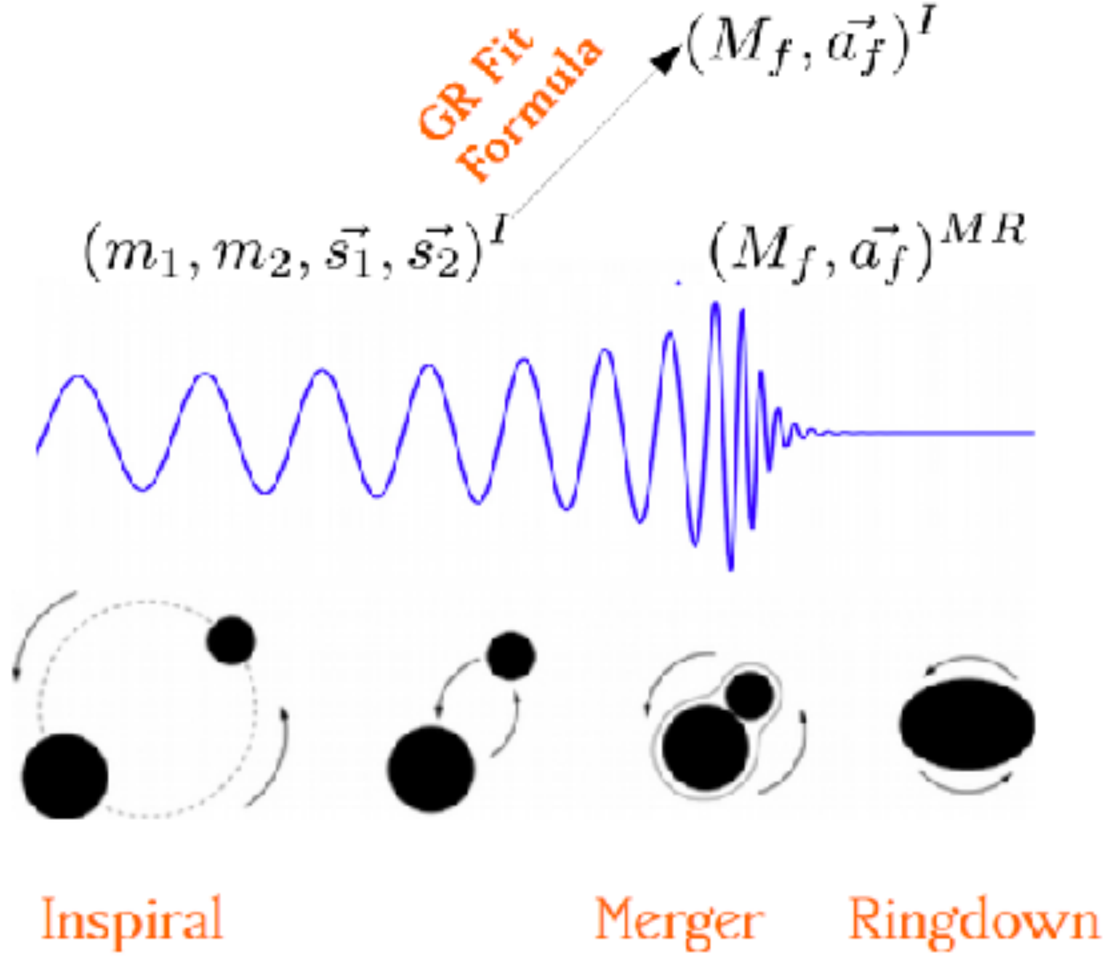

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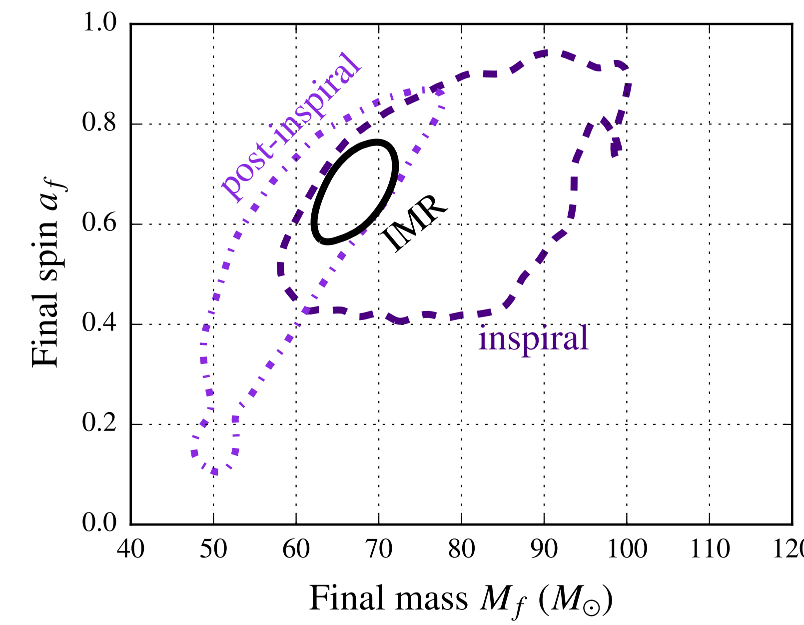
- If GR is right, then the independent estimates of the mass and spin of the final BH should be consistent with one another.
- Alternatively, one can define fractional parameters in the final mass and spin, that should be consistent with the GR prediction (0,0).

GW150914



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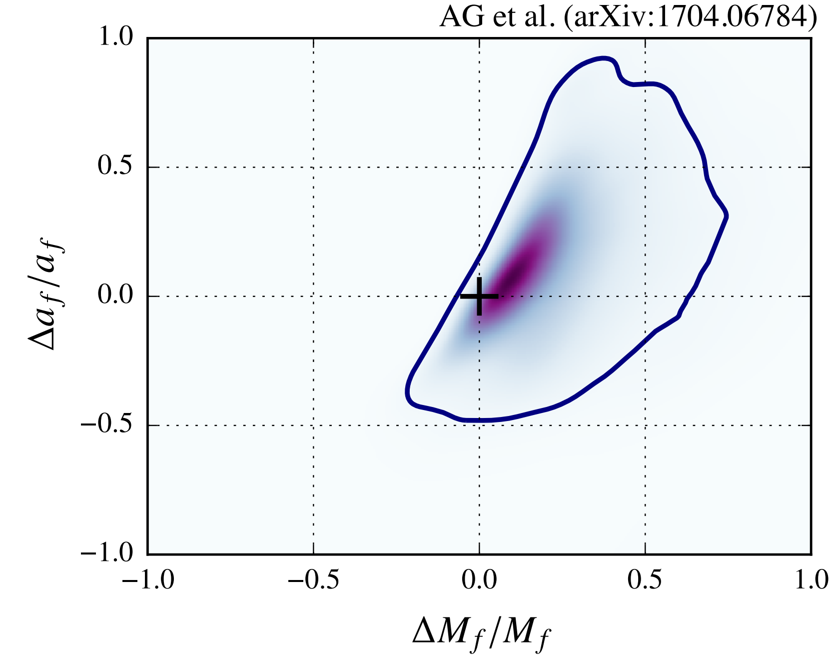

LSC & Virgo, PRL 116 (22), 221101

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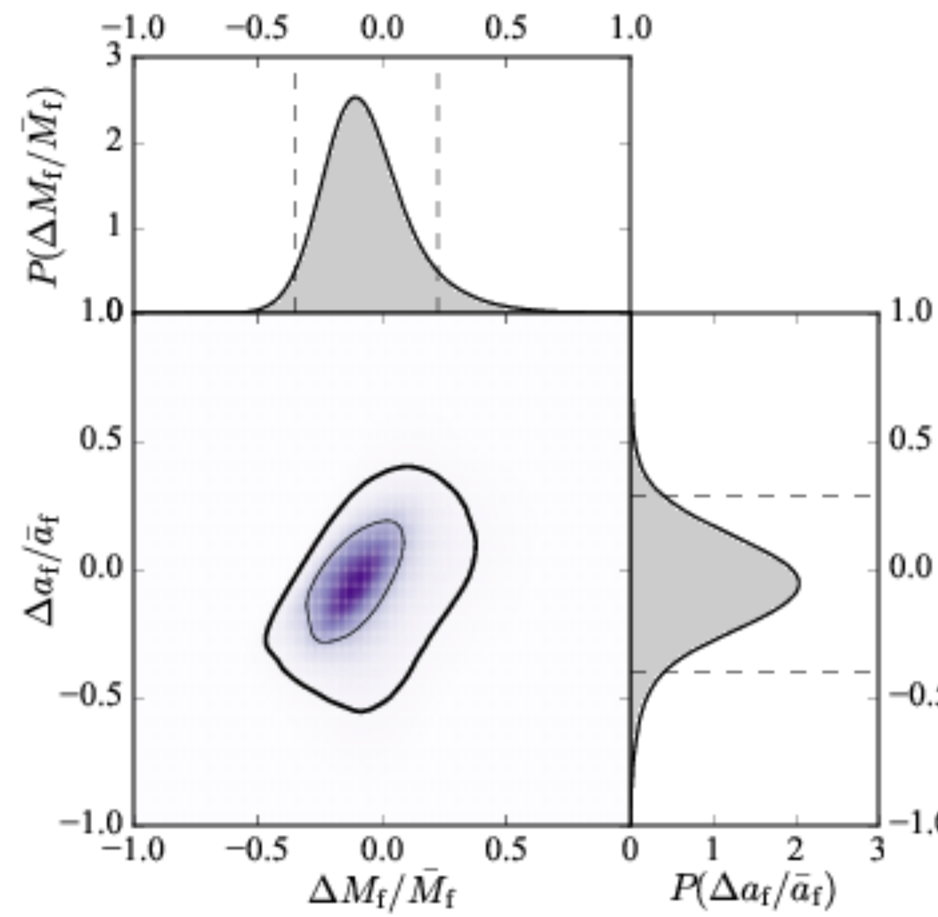
GW170104



LSC & VIRGO: PRL 118.221101

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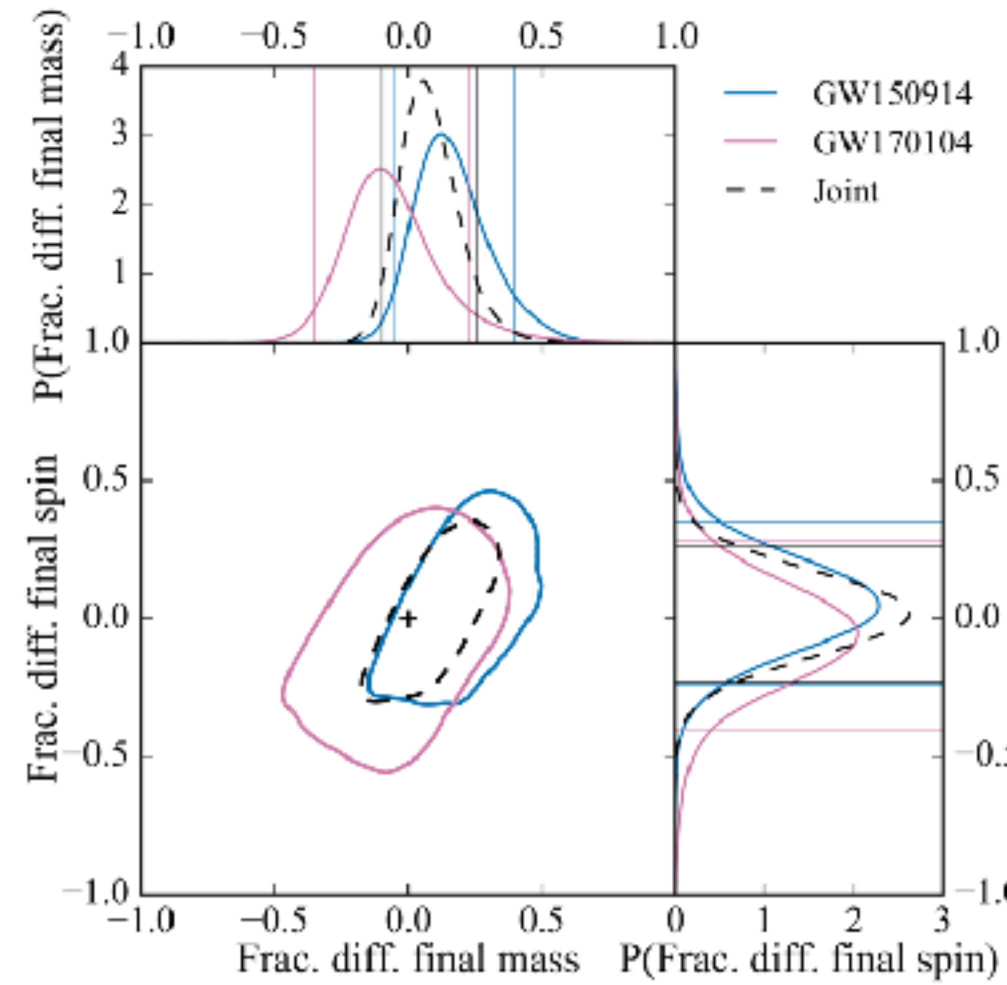
- If GR is right, then the independent estimates of the mass and spin of the final BH should be consistent with one another.
- Alternatively, one can define fractional parameters in the final mass and spin, that should be consistent with the GR prediction (0,0).
- Finally, we combine information from multiple events to obtain tighter bounds on possible deviations from GR.



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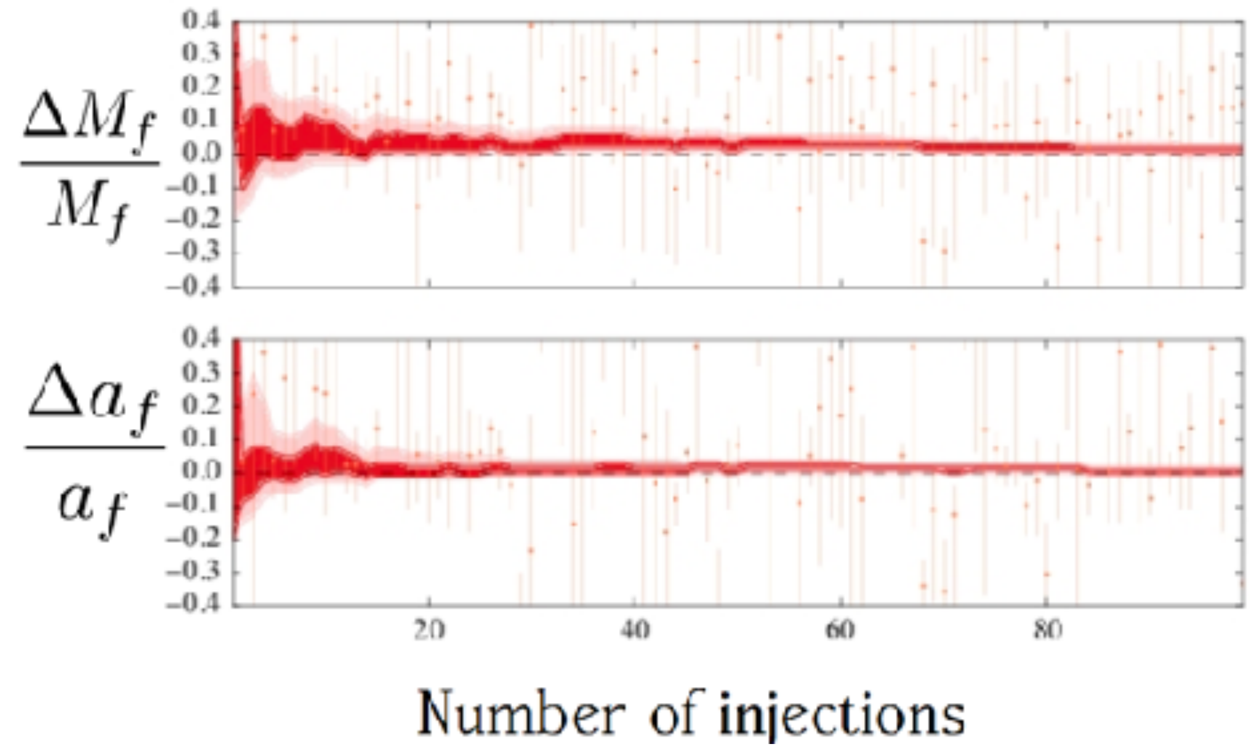
Inspiral-merger-ringdown consistency test

- Observation of GWs from a population of BBH systems would allow us to obtain much tighter constraints on possible deviations from GR.



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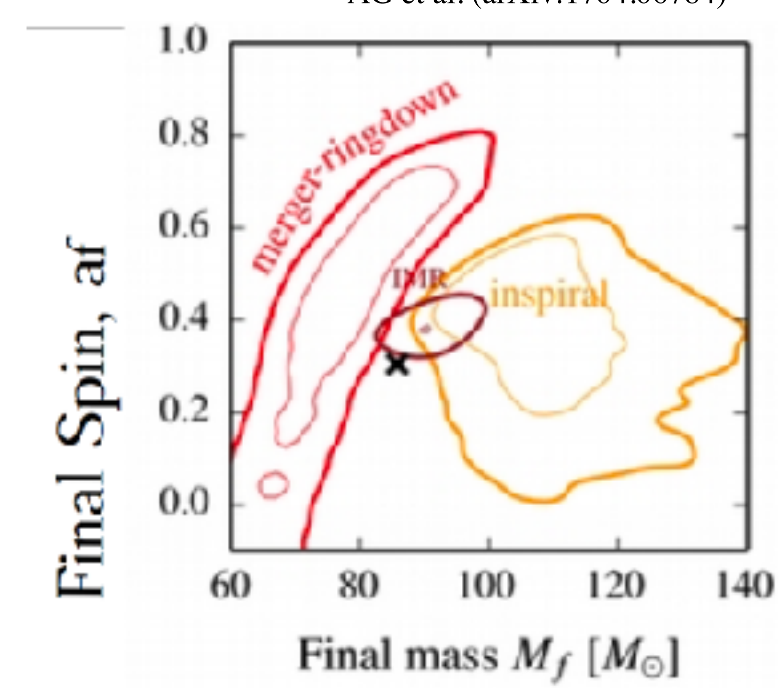
- The test can be used to detect certain deviations from GR, for example, where the energy and angular momentum loss differs from the predictions of GR.



- In all the tests of GR performed so far using the LIGO and Virgo detections of gravitational waves, including the IMR consistency test, there have been no deviations from GR observed yet.

- All the detections are consistent with a quasi-circular binary black hole coalescence as described in GR.

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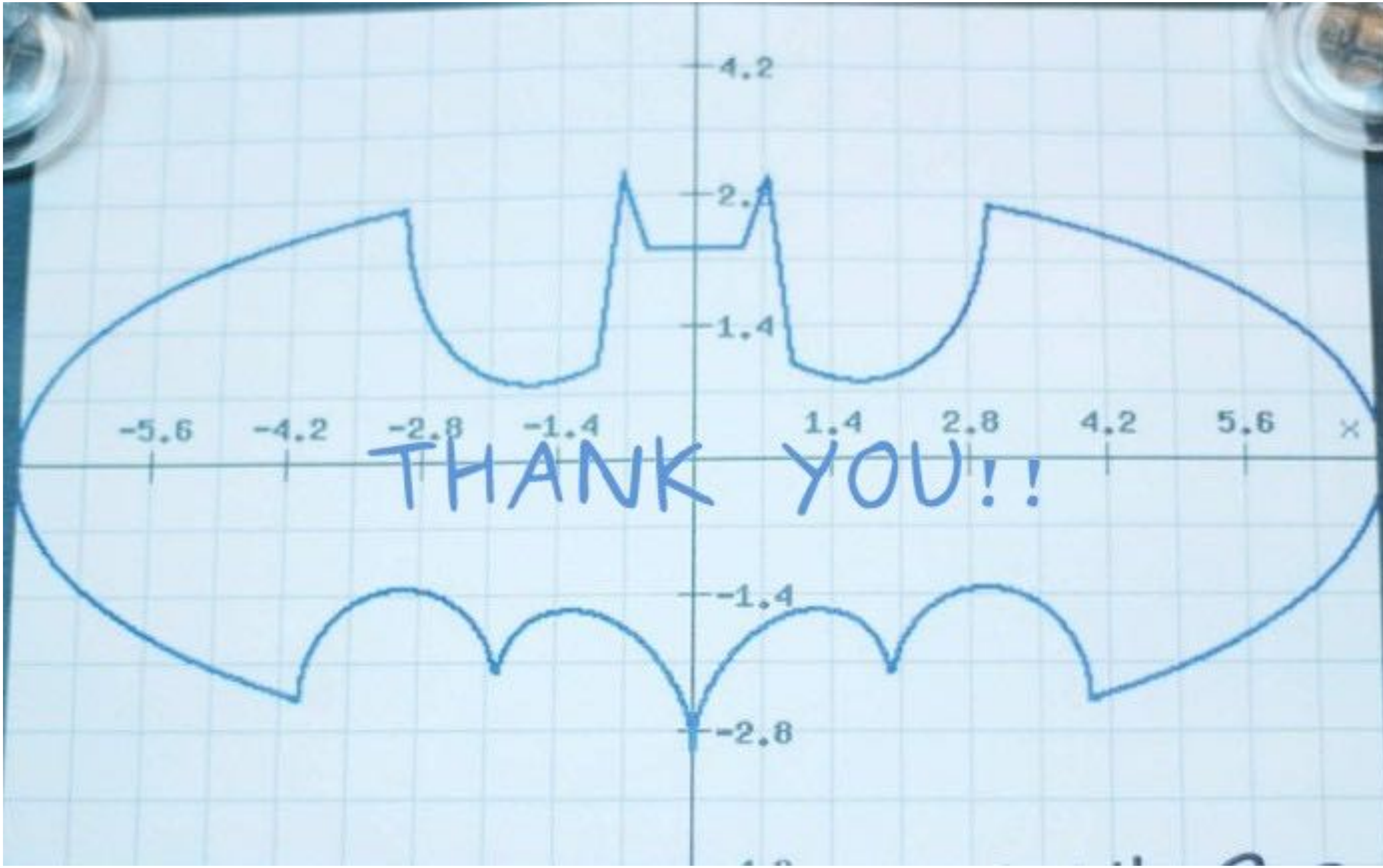
“Don’t Panic.”

Hitchhikers’ Guide to the Galaxy
Douglas Adams


4.2
2.8
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THANK YOU!!
-1.4
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