Gravitational waves

The dawn of gravitational wave astronomy

DCC: G1602181-v2

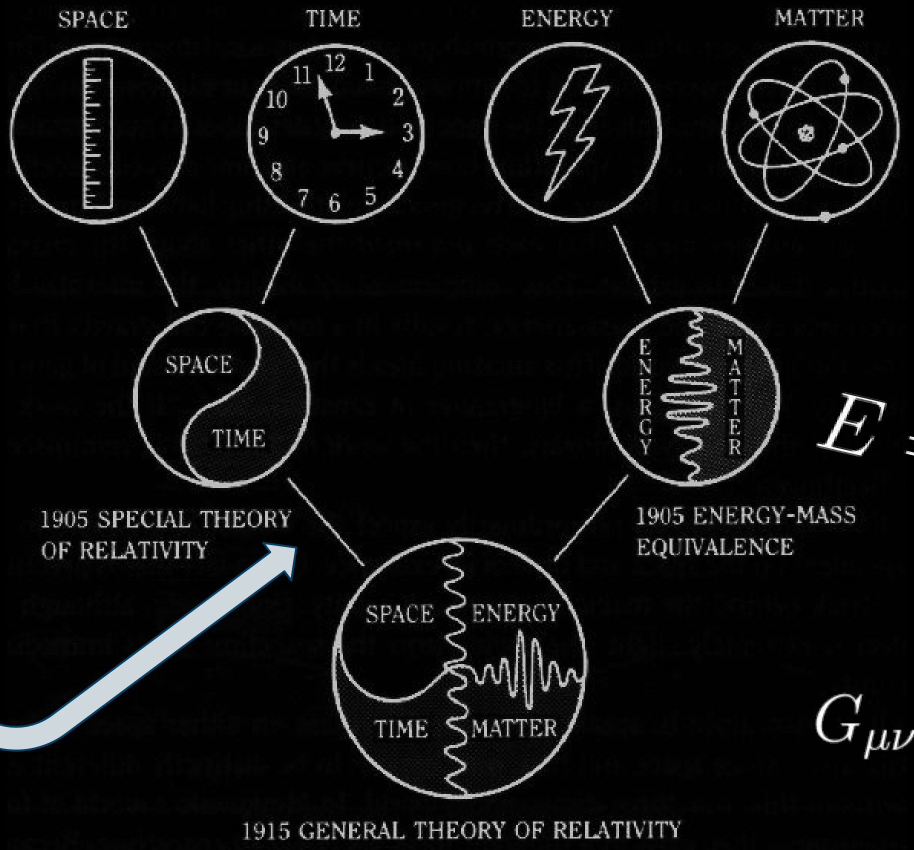
Einstein's ideas:
Unifying space-time and energy and matter

Before 1905

SR Postulates

1) Laws of physics invariant in inertial systems
2) Speed of light the same for all observers

Einstein realises SR indicates Newton's gravity is incomplete

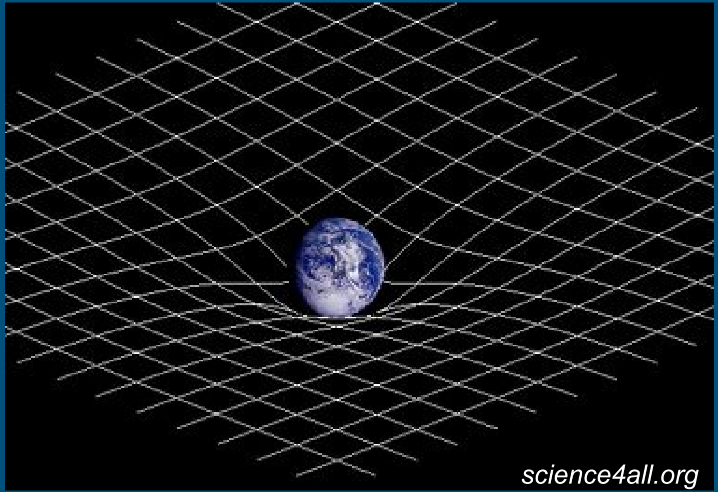


$$E = mc^2$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Understanding General Relativity

"Spacetime tells matter how to move; matter tells spacetime how to curve."
– J. A. Wheeler

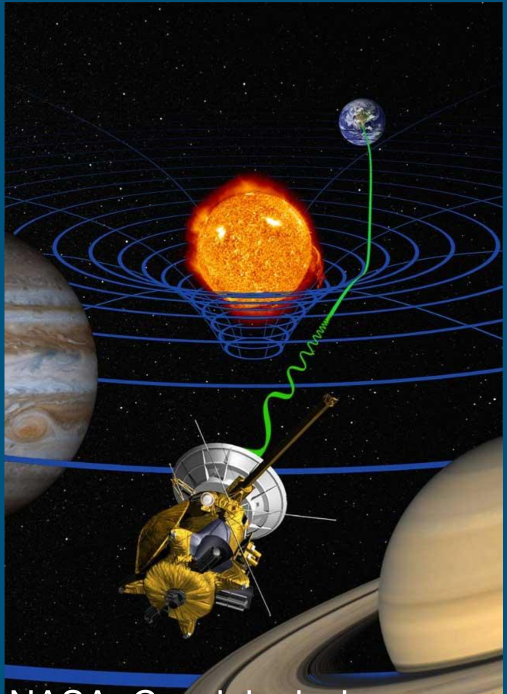


$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Testing General Relativity

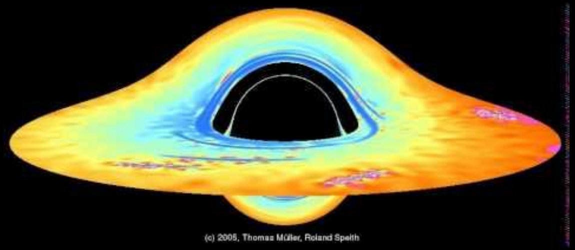
Predictions of GR: gravity bends light

$$E = mc^2$$

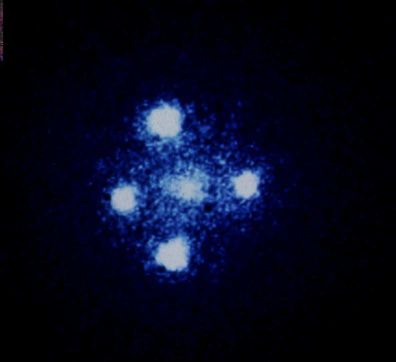


NASA: Cassini mission

Predictions of GR: gravity bends light

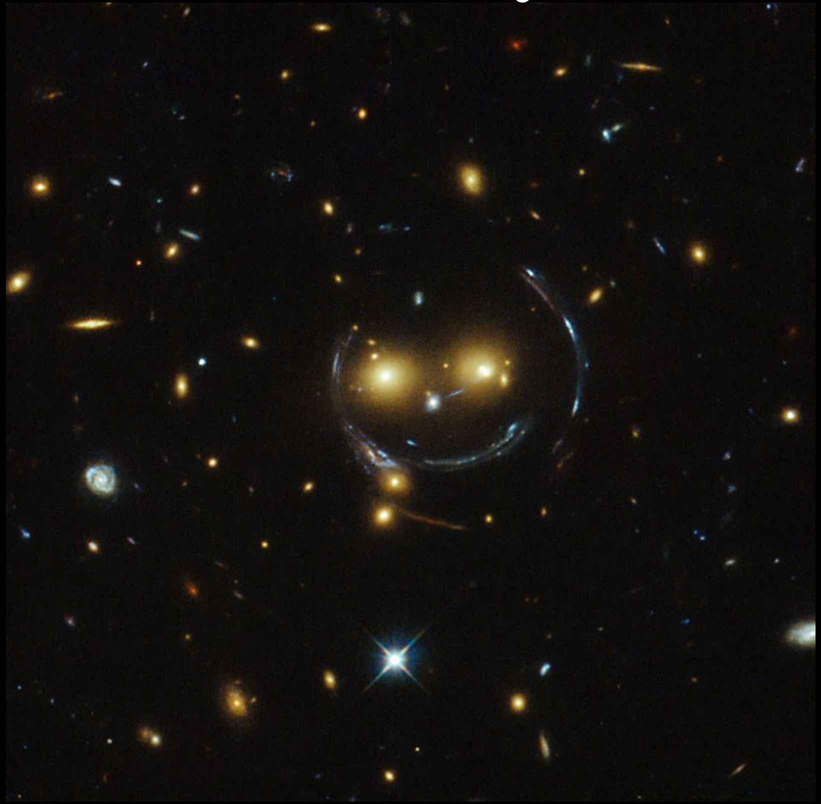


Simulation of an accretion disk around a black-hole

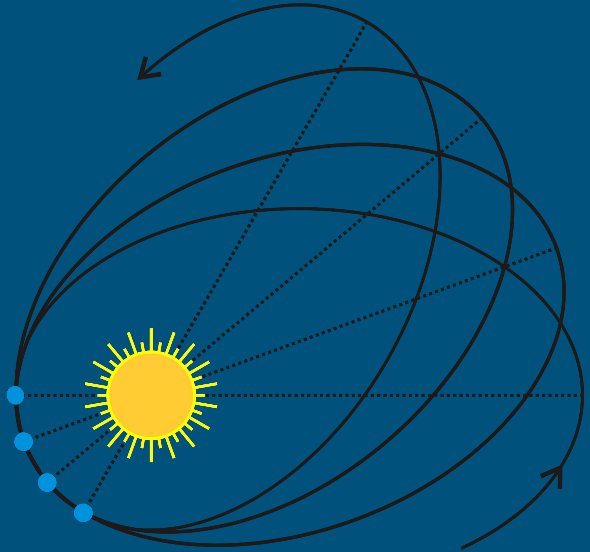


Einstein's cross

The cosmic grin



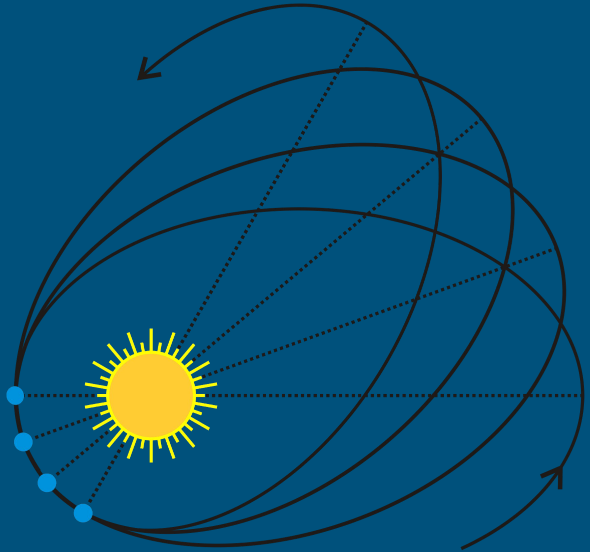
Predictions of GR: Perihelion advance of Mercury



Amount arcsec/century	Cause
531.63 +/- 0.69	Gravitational tugs of the other planets
531.63 +/- 0.69	Total
574.10 +/- 0.65	Observed

source: wikipedia.org/wiki/Tests_of_general_relativity

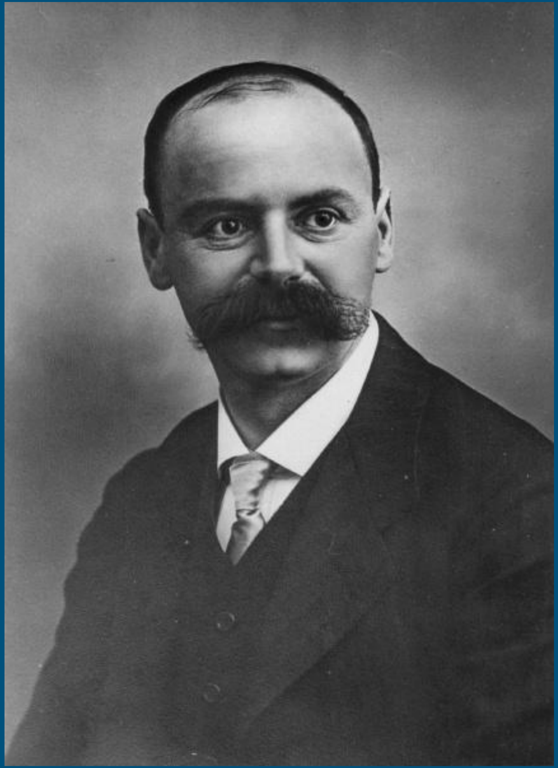
Predictions of GR: Perihelion advance of Mercury

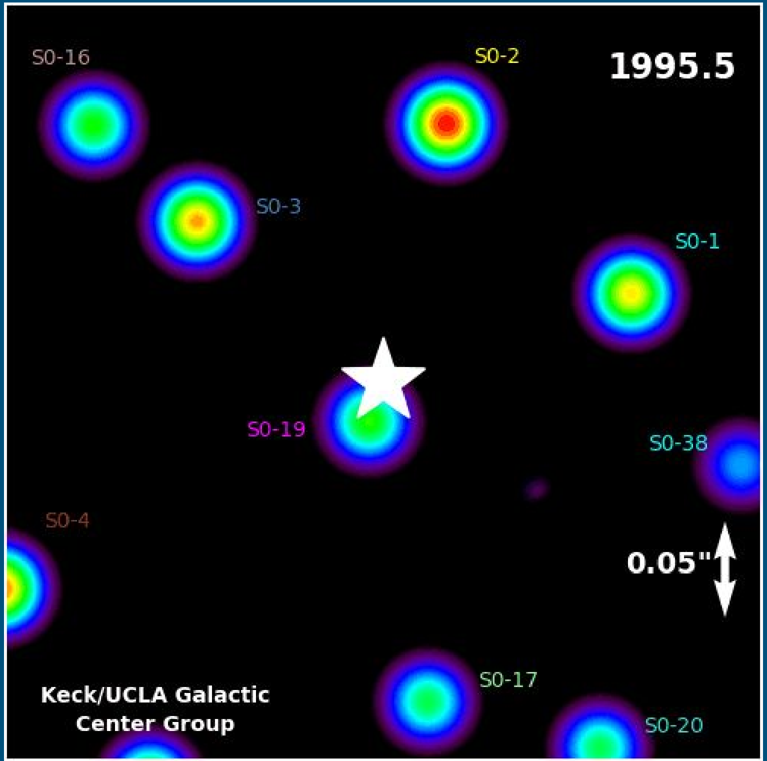


Amount arcsec/Julian century	Cause
531.63 +/- 0.69	Gravitational tugs of the other planets
42.98 +/- 0.04	General Relativity
574.64 +/- 0.69	Total
574.10 +/- 0.65	Observed

source: wikipedia.org/wiki/Tests_of_general_relativity

Predictions of GR: Black holes

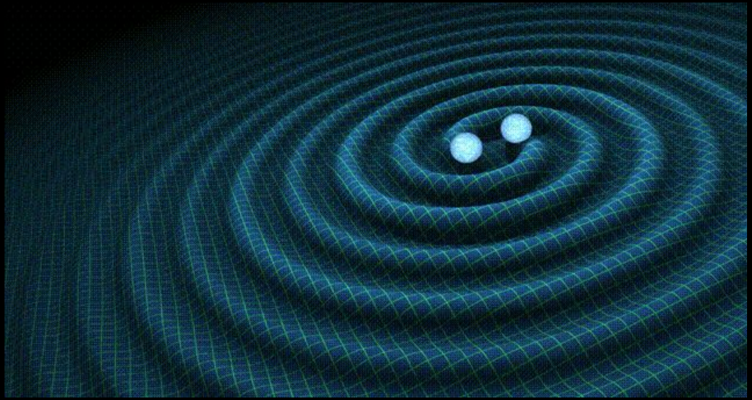




Predictions of GR: Gravitational waves

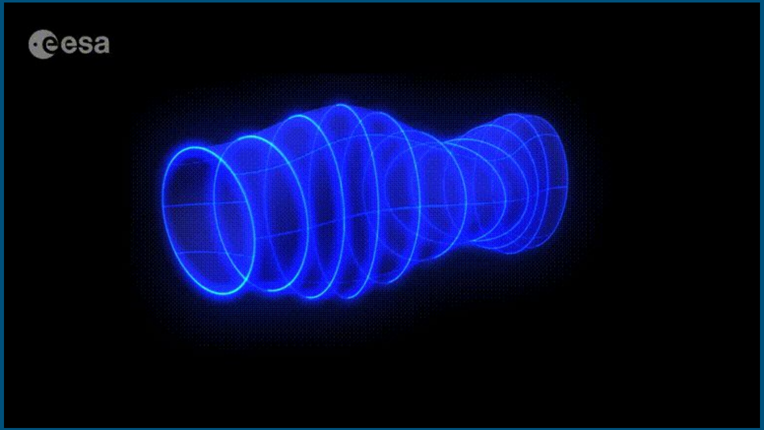
Predictions of GR: Gravitational waves

- In 1916 Einstein took the full GR equations and linearised them looking at a special case, this resulted in a so-called wave equation
- Gravitational waves will be produced in systems with a time-varying quadrupole moment
- They are understood to be ripples in the fabric of spacetime

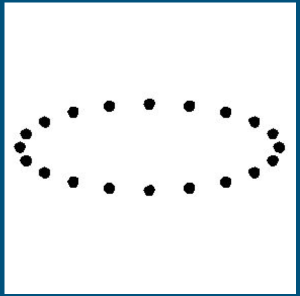


The effect of gravitational waves

- The wave stretches and squeezes spacetime as it passes through

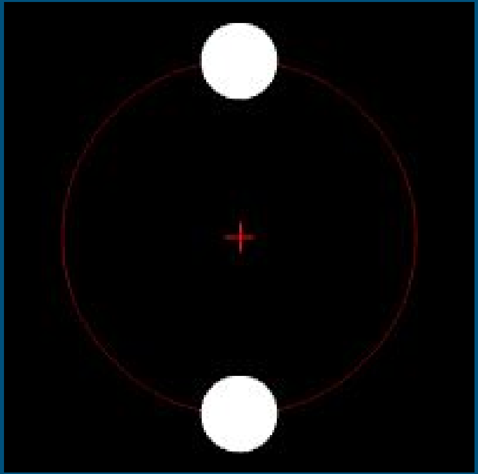


- Definition of strain: $h = \frac{\Delta L}{L}$



- *h*~1e-21 corresponds to changing the radius of the Earth's orbit around the Sun by the diameter of single atom

Sources of gravitational waves



- Terrestrial sources are small:
  - Shaking your hand: *h*~1e-52
  - Battleships colliding *h*~1e-46

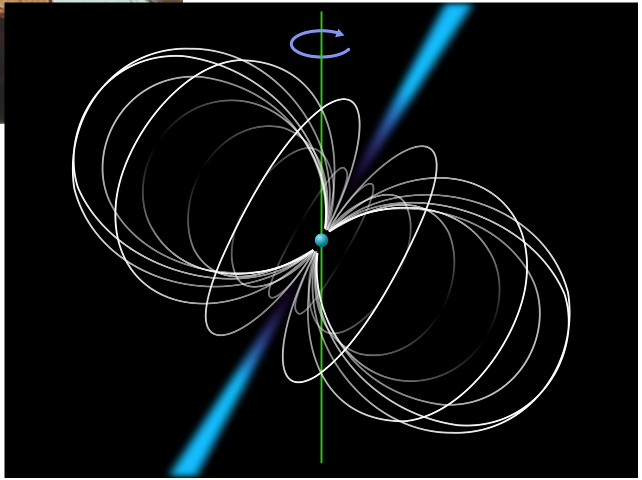
- So we look to space and Binary systems
  - Binary strain:

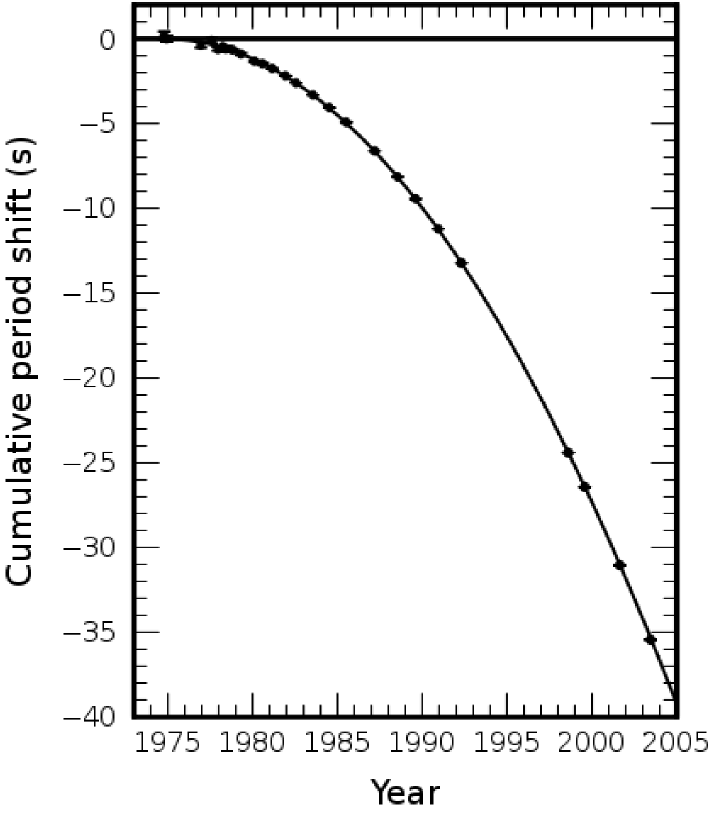
$$h \sim \left(\frac{1}{R}\right) \times \left(\frac{G^2}{c^4}\right) \times \left(\frac{m_1 m_2}{r}\right)$$

  - Io orbiting Jupiter: *h*~1e-25
  - Typical compact object binary *coalescence* system: *h*~1e-19 or smaller

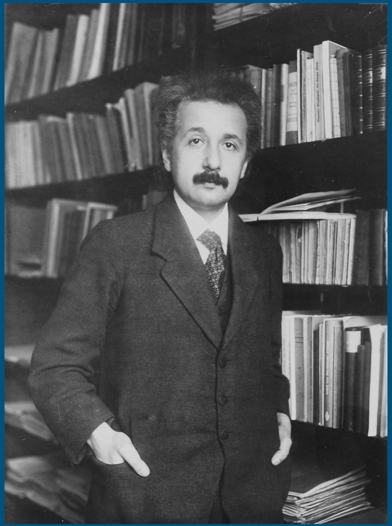
Predictions of GR: Orbital decay due to gravitational wave emission

Hulse & Taylor
1993 Nobel prize





Detecting gravitational waves



1916: Einstein predicts GWs

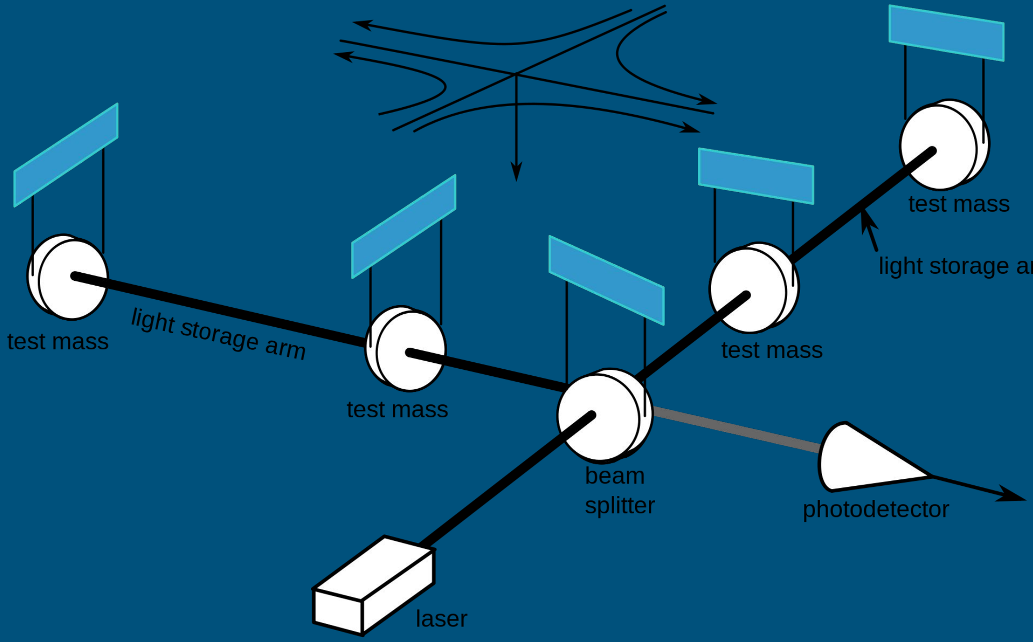
1960's: Joseph Weber's resonant bar detectors

1980's: LIGO (Laser interferometer gravitational wave observatory)

Directly detecting gravitational waves

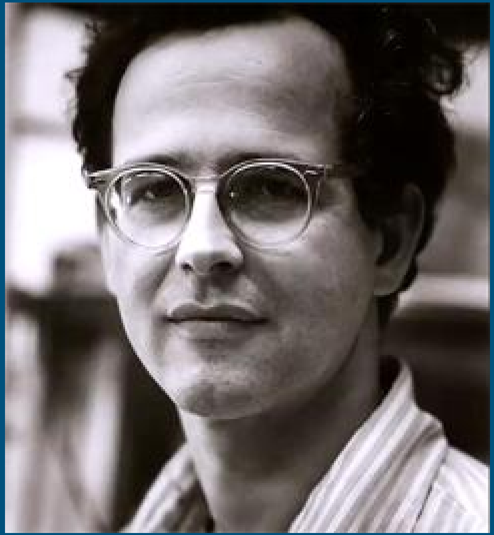
In 1962 Michael Gertsenshtein and Vladislav Pustovoit in Moscow Russia outlined the idea for a laser interferometer to:

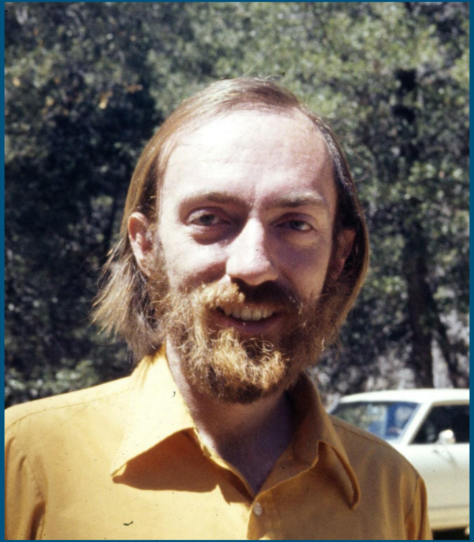
"monitor the relative motion of freely hanging mirrors in response to a gravitational wave"



LIGO: Laser Interferometer Gravitational-Wave Observatory

- Founded in the 70's by Rainer Weiss, Kip Thorne and Ron Drever

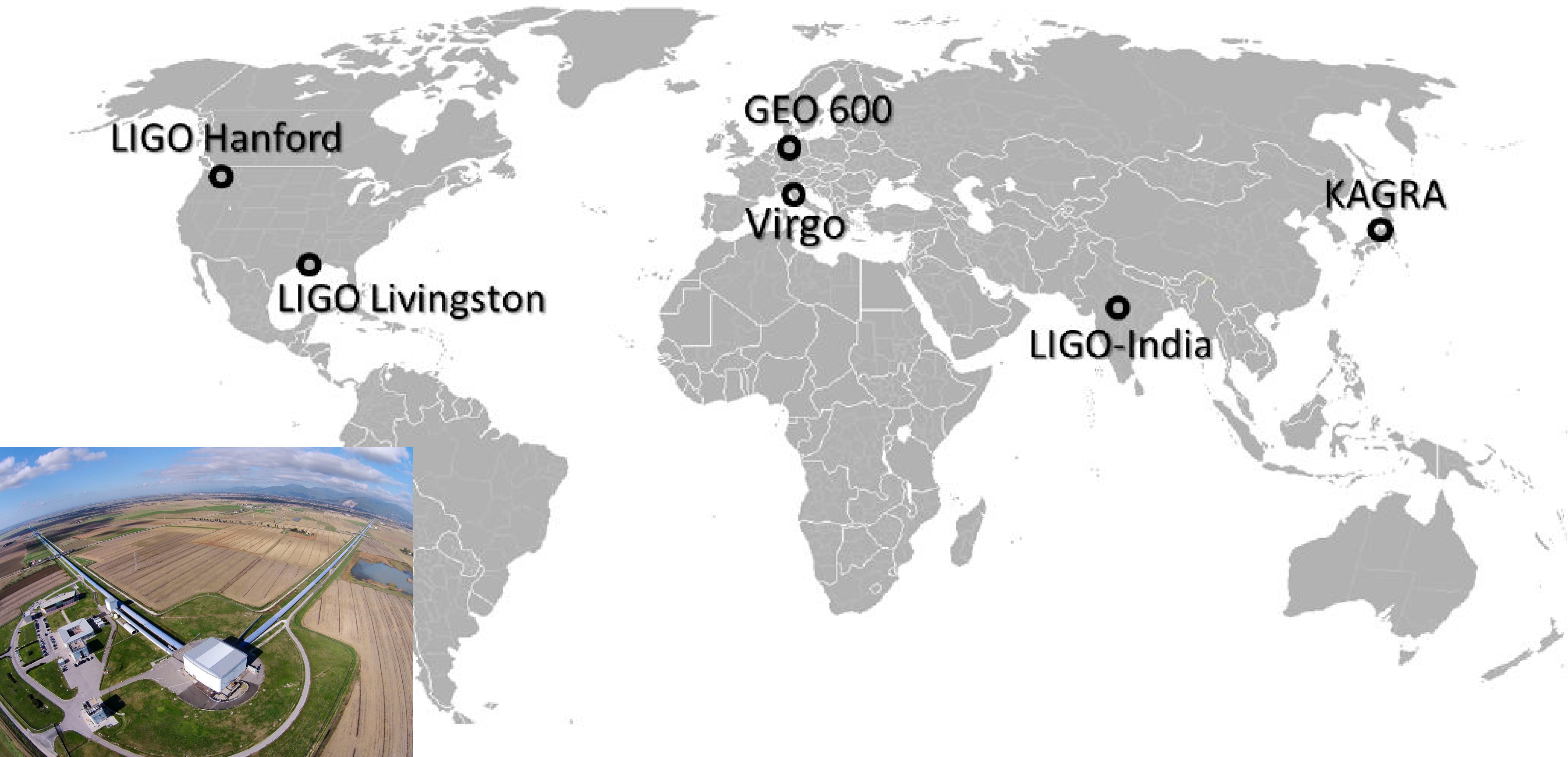




History of LIGO

- 1972 Rai Weiss completes the invention of the detector by identifying all the fundamental noise sources and detailing how to reduce them
- 1980s NSF funded a 40m and 1.5m prototype to demonstrate feasibility
- 1989 LIGO envisioned with a two-stage proposal for 4km detectors:
  - Initial LIGO: low probability of detection, but allows technology to be developed
  - Advanced LIGO: high probability of detection
- 1989 GEO collaboration (British and German) established with plan to build 3km detector
- 1993 Virgo detector approved by French and Italian collaboration
- 1992-2005 Building detector sites and commissioning, first runs
- 2007 Unification of LIGO, Virgo and GEO into Ligo-Virgo collaboration (LVC)
- 2006-2011 Initial detector era science runs
- 2011 - 2015 Advanced detector upgrades
- 2015 Start of Advanced detector observation runs

The interferometer network

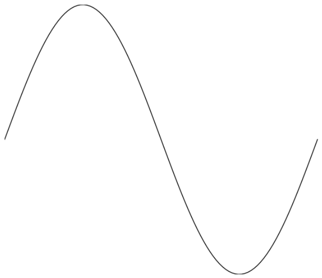
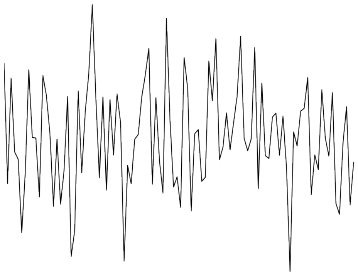
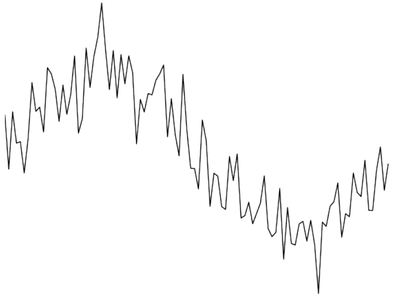


LIGO-Virgo collaboration

- Over 1000 people in the collaboration consisting of experts in
  - Theoretical physics
  - Data analysis
  - Data engineering
  - Detector characterisation + calibration
  - Detector design
- On the detection side, we are split into four groups by the source type
  - Compact binary coalescence
  - Bursts and transience (generic search)
  - Continuous wave emission
  - Stochastic

Detecting gravitational waves

signal + noise = data

 +  = 

1. Guess what the signal looks like to make a *template*
2. Used *matched filtering* to search the data for the template

The detection

September 14th 2015

From: Marco Drago <marco.drago@aei.mpg.de>
Subject: [lsc-all] Very interesting event on ER8
Date: Mon, 14 Sep 2015 12:55:46 +0200

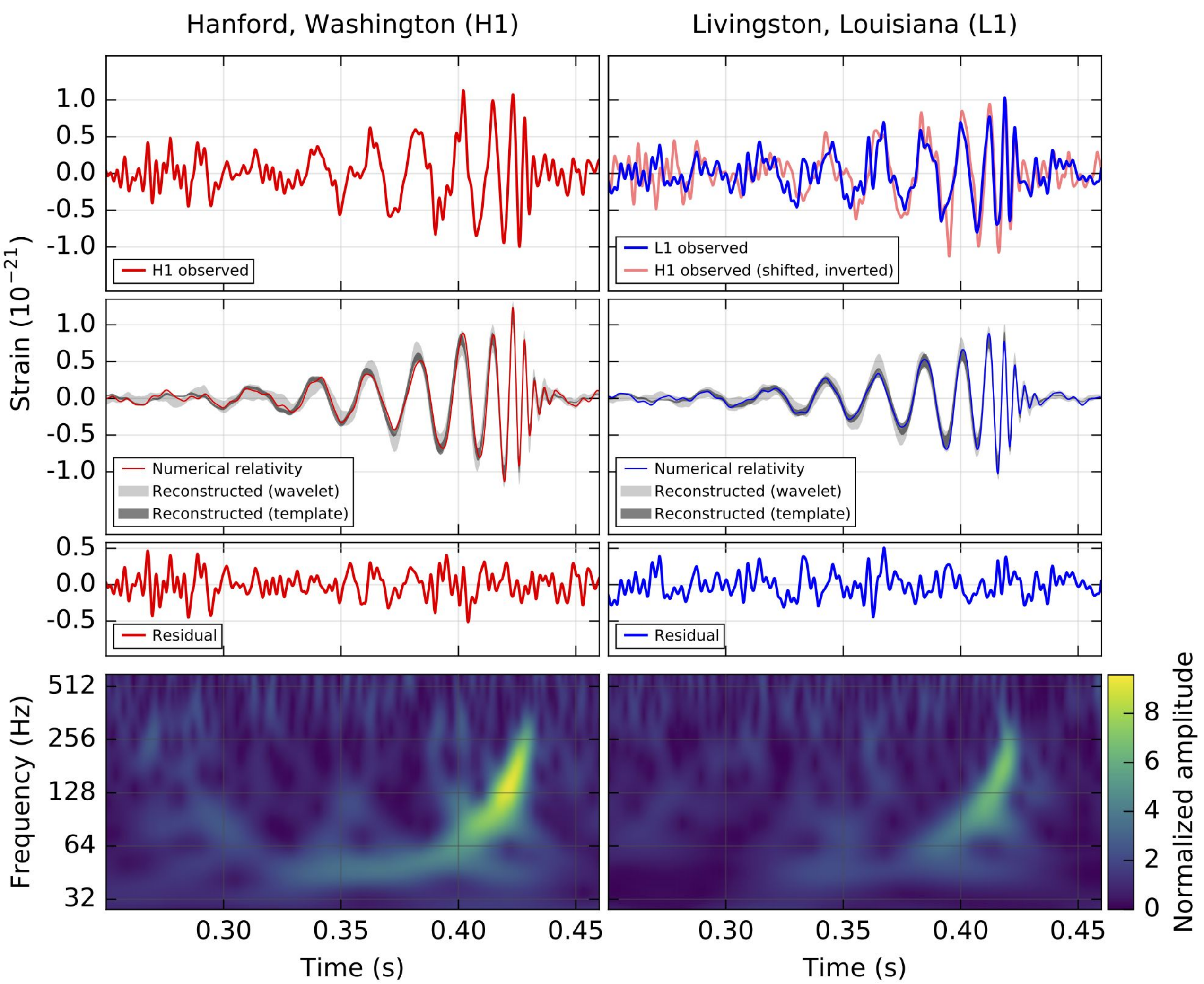
Hi all,
cWB has put on gracedb a very interesting event in the last hour.
[...]
It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

Marco

Detection process: GW140915

- Signal detected at both Hanford and Livingston - no other detectors online at the time
- Detectors frozen in configuration and checked for
  - Any terrestrial cause (via on-site instruments)
  - Any malicious or accidental injection
- Signal detected by two independent pipelines (more about this later..)
- Detection committee established to ‘play devil's advocate’

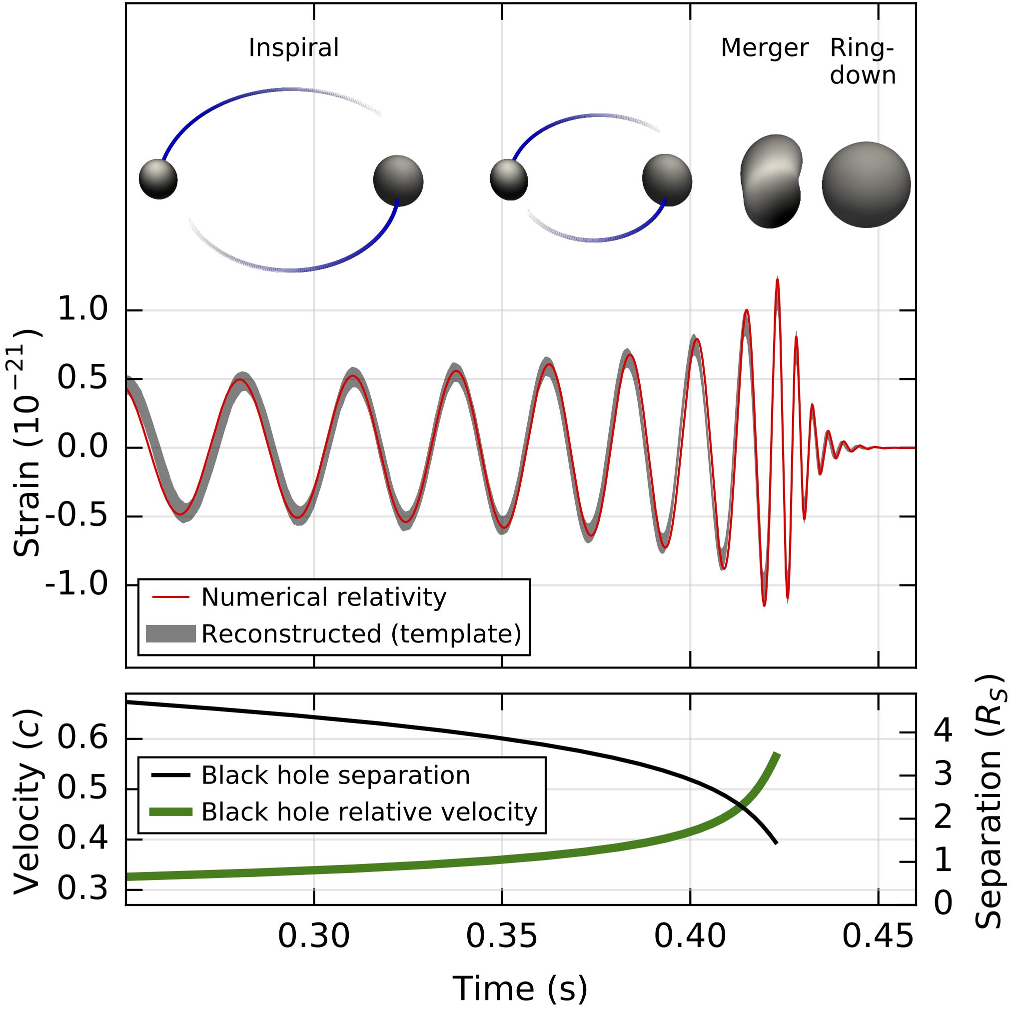
Observed signal strain h(t)



Plots taken from:
[B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) (2016) Phys. Rev. Lett. 116, 061102]

The source:

- Peak strain: *h*~1e-21
- R = 410 Mpc or 1.3 billion ly
- Initial blackholes had mass 36 M☉ and 29 M☉
- Final blackhole has mass 62 M☉
- 3 M☉ radiated in GWs
- Occurred 1.3 Billion years ago prior to multicellular life on earth



How certain are we that this isn't noise?

- Signal to noise ratio: 24
- False alarm rate: 1 event per 202 600 years
- Next loudest event was 1 event per 10 years
- Equivalent to a significance greater than 5.1 σ
- Possible electromagnetic confirmation from Fermi gamma ray telescope (although BBH mergers not expected to be visible)

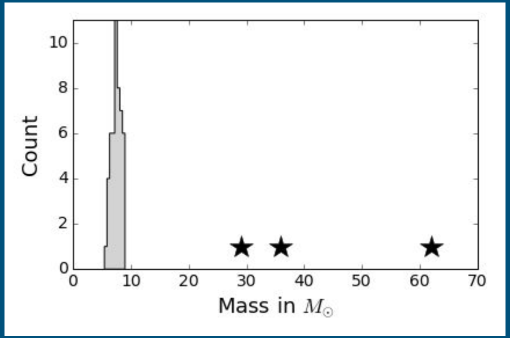
The announcement

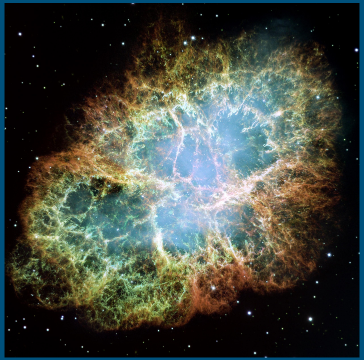
- February 11th 2016 LIGO held a press conference
- *“We have detected gravitational waves, we did it”* - David Reitze
- Simultaneously released the detection paper “Observation of Gravitational Waves from a Binary Black Hole Merger” and the data
- 10 other papers were also released covering astrophysics and detector

So, what did we learn from GW140915?

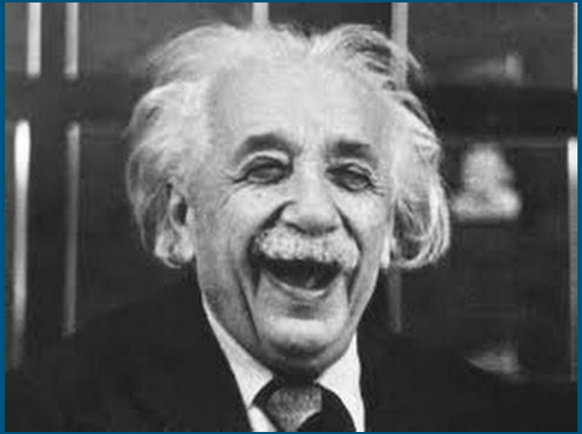
The dawn of gravitational wave astronomy

- GW140915 tells us:
  - GWs exist and can be measured
  - Tests General Relativity
  - Blackholes with masses around 30 - 60 $M_{\odot}$ exist
  - Blackholes coalesce within the age of the universe
  - We can detect other events!
- In the future we might:
  - Detect more BBH systems
  - Detect BNS and BH+NS systems
  - Multimessenger astronomy
  - Detect isolated NS
  - Have a headstart when detecting a supernova event - last one was in 1604
  - Detect the stochastic background





Conclusions



- First detection of gravitational waves
- Further confirms Einstein's theory of GR
- Result of 30+ years of hard-work and commitment
- We can look forward to an exciting era of gravitational wave astronomy

Current detector status