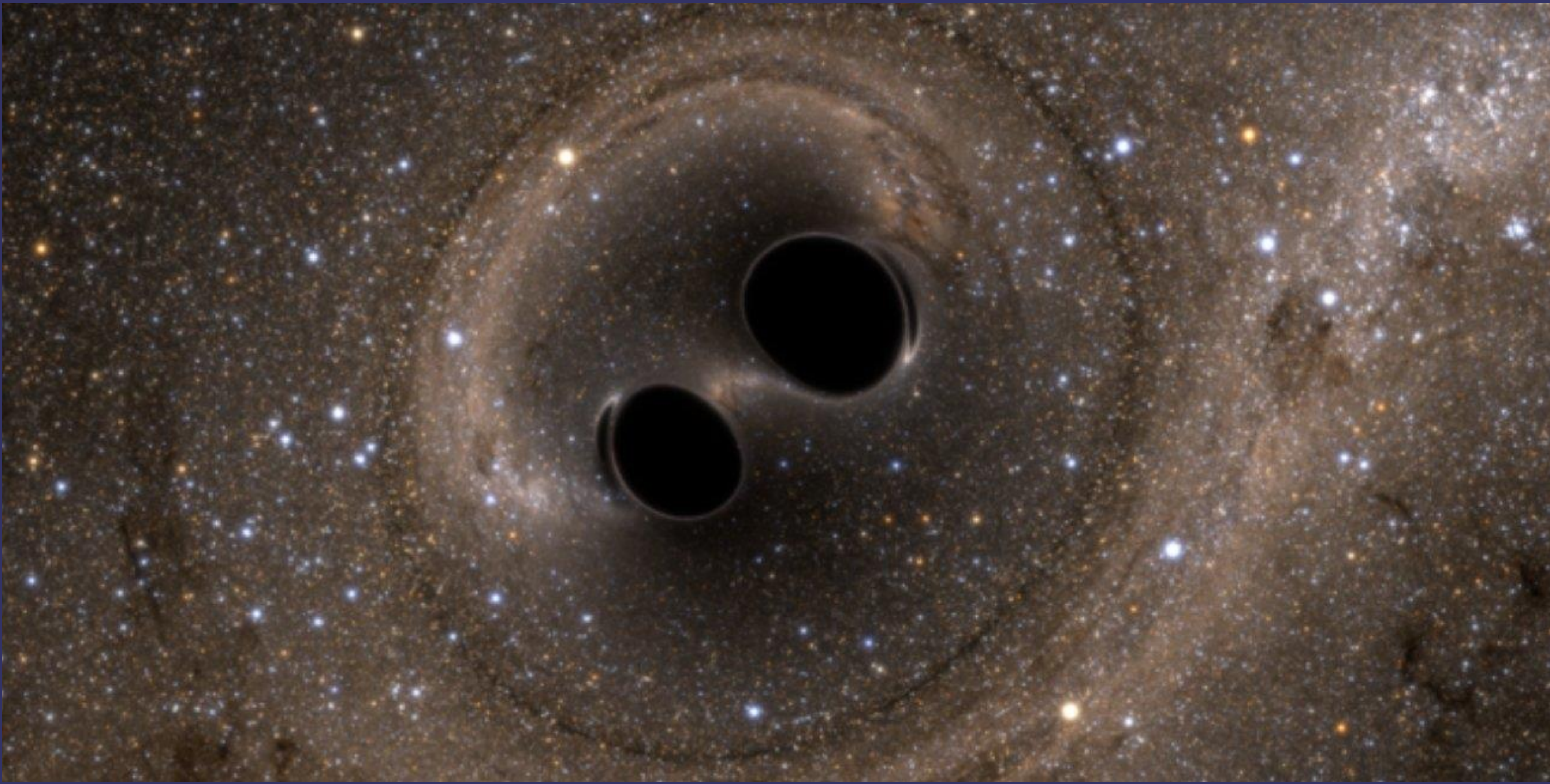
Gravity Waves and Black Holes



Mike Whybray
Orwell Astronomical Society (Ipswich)
14th March 2016

Overview

- Introduction to Special and General Relativity
- The nature of Black Holes
- What to expect when Black Holes collide
- Laser Interferometer Gravitational-Wave Observatory (LIGO)
- LIGO results announced on 11^{th} Feb 2016
- What next?

Special Relativity

- Published in 1905 by Einstein
- Built on the following ideas:
  - Relativity of motion ideas dating from Galileo and Newton
  - Maxwell's equations of electrodynamics (1861)
  - Michelson & Morley experiment (1887) $\sqrt{1-v^2/c^2}$
  - Lorentz transformation (1892 to 1904)
  - Poincaré (1902) suggests perhaps all physical laws should be invariant under Lorentz transformation

Special Relativity

- Assumes light travels at a constant velocity, whatever the velocity of the observer
- Treats Time as a 4th dimension → Spacetime
- Time is no longer a fixed/universal thing and simultaneity has no obvious meaning
- Mass increases with velocity:

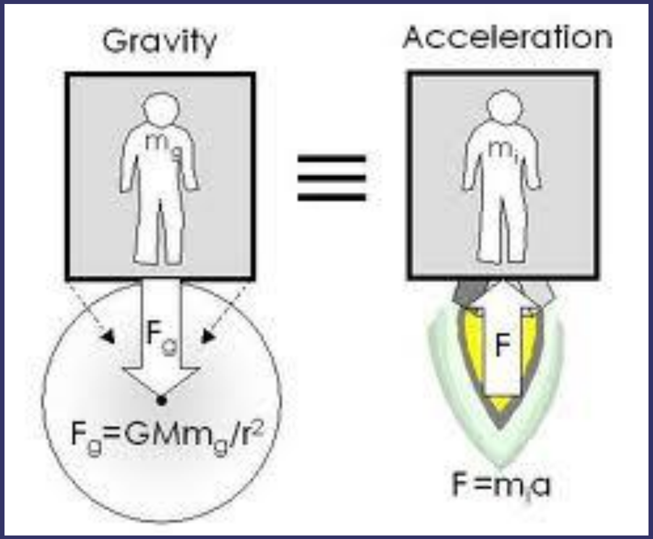
$$M = M_0 / \sqrt{(1 - v^2/c^2)}$$

- Energy/Mass equivalence:

$$E \approx M_0 c^2 + 1/2\, M_0 v^2$$

General Relativity

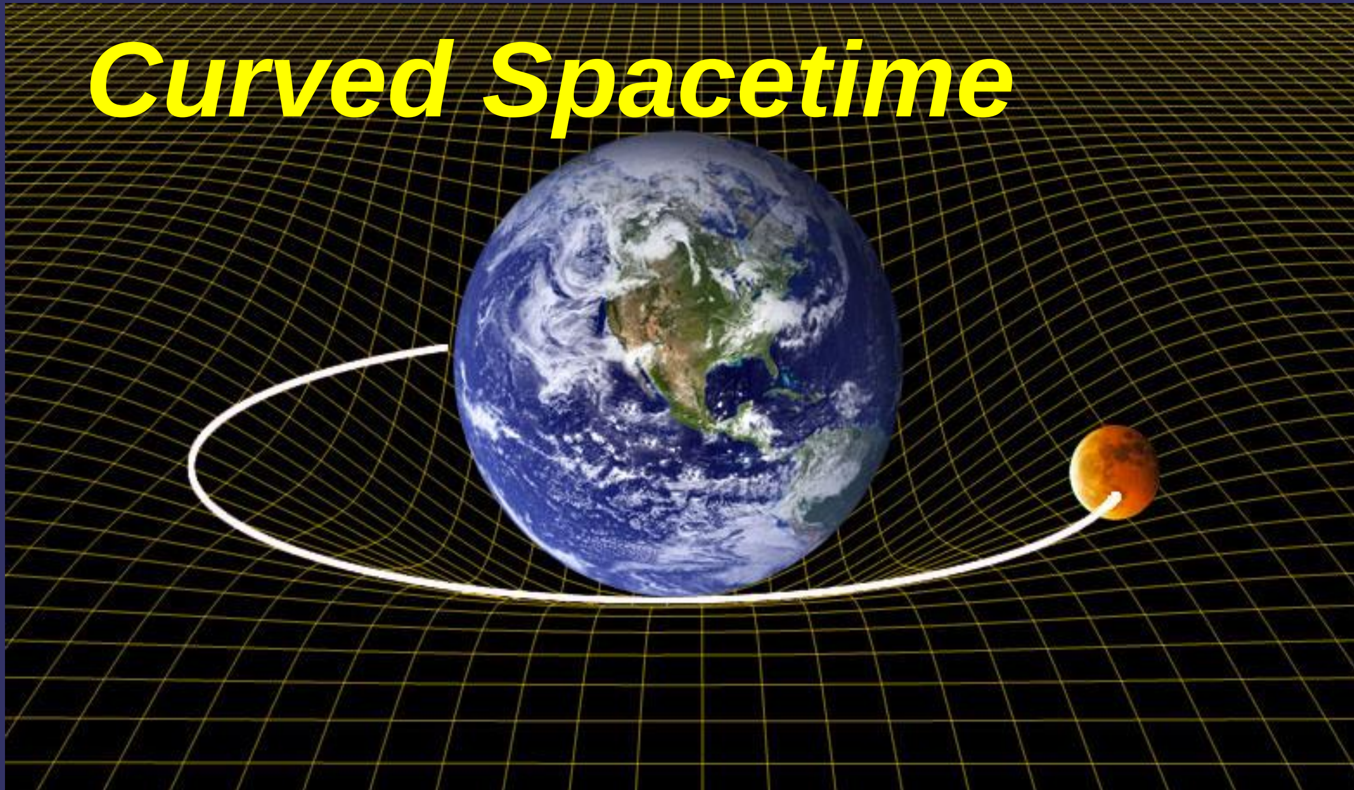
- Published in 1915 by Einstein
- Generalised his Special theory to include the effects of Gravity



- Asserts that Gravity and Acceleration are the same thing (Principle of Equivalence)

Implications of General Relativity

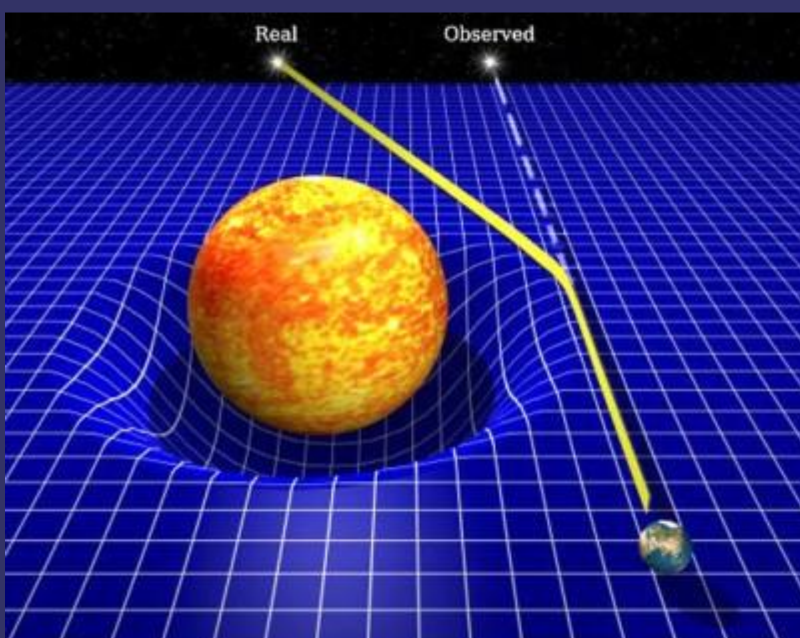
- Space [and hence spacetime] is no longer geometrically flat
  - E.g. the Earth causes a local distortion:
  - Radius of Earth calculated from its Area is given by $r = \sqrt{A/4\pi}$
  - But measure the radius directly and it would be 1.5mm longer than this!



Spacetime tells matter how to move;

Matter tells spacetime how to curve.

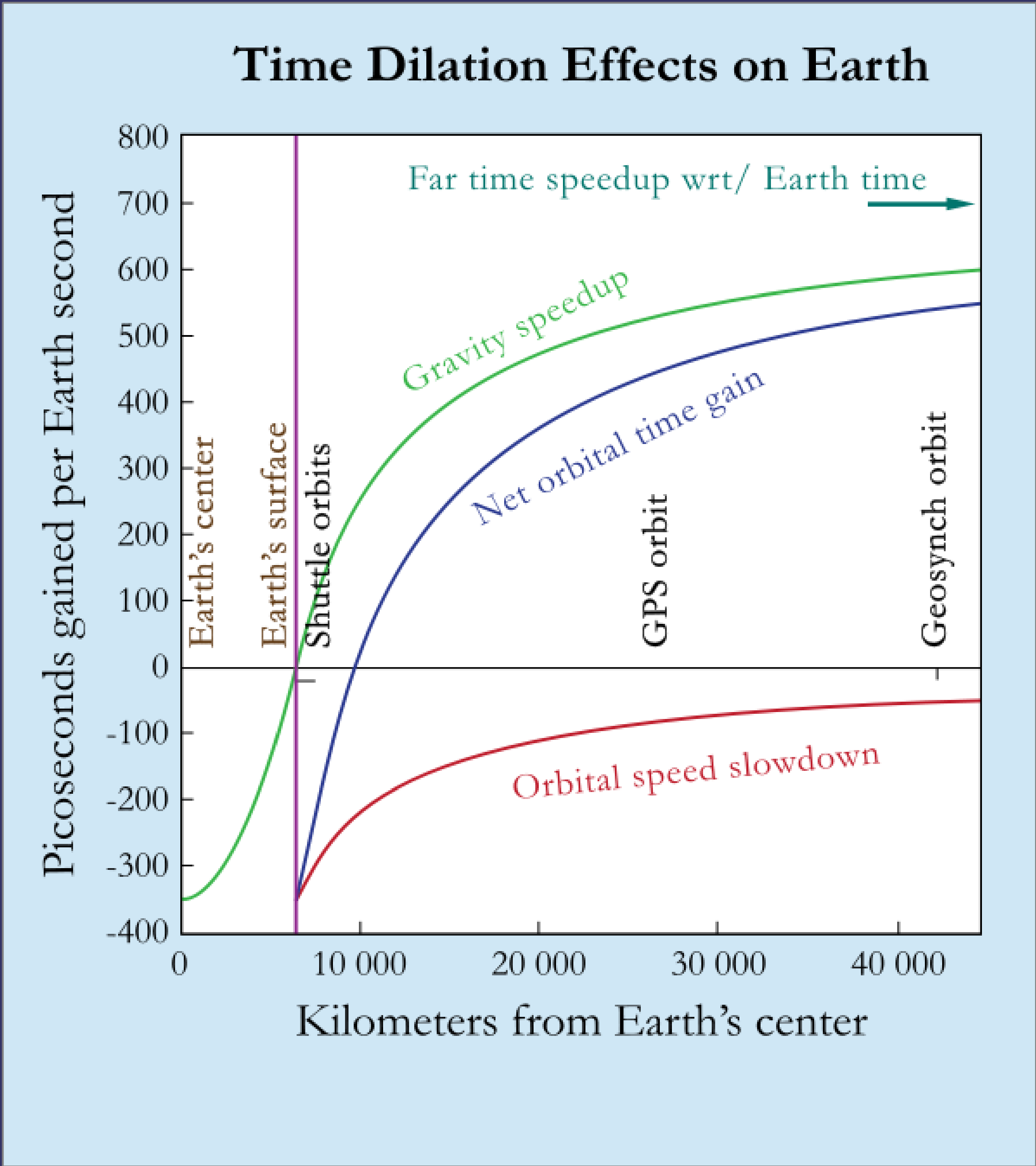
(John Wheeler)



Further Implications

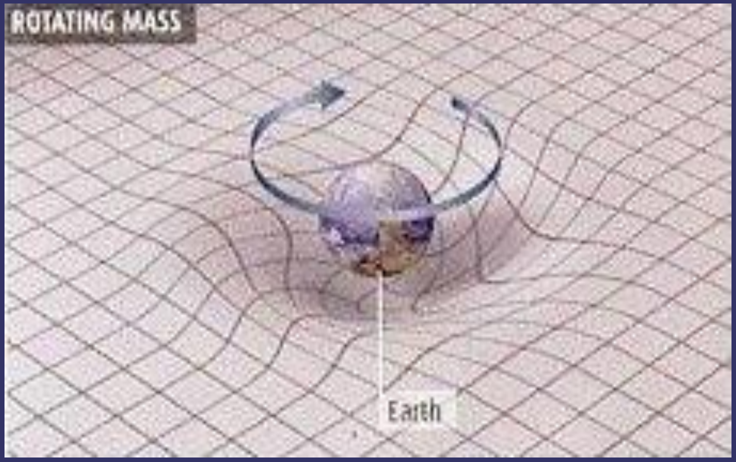
Time slows down in a gravitational field

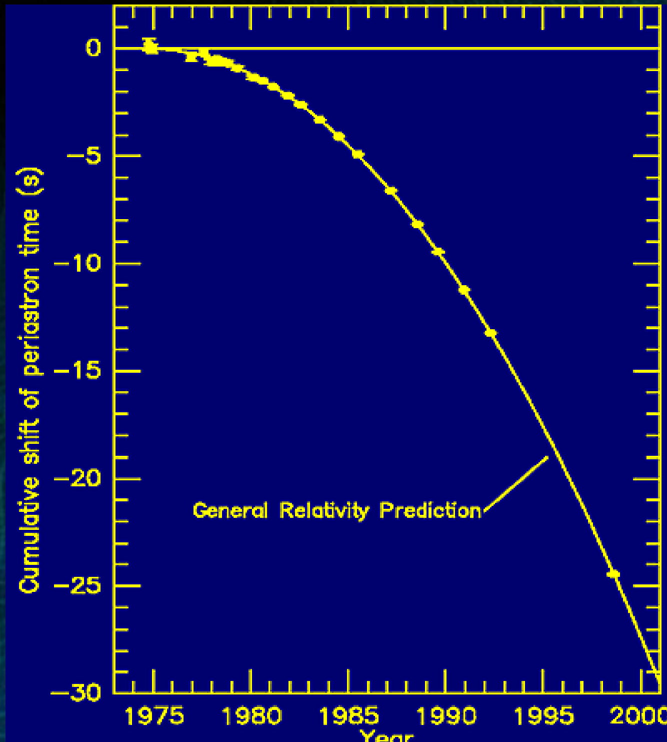
(and also as you move faster, as in Special Relativity)



Confirmations of General Relativity

- Advance of the perihelion of Mercury (1916)
- Deflection of starlight by the sun (1919)
- Redshift due to gravity (1925)
- Gravitational lensing (1979)
- Slowing of orbits of binary pulsars (1982)
- Frame dragging (2011)





Gravitational Waves

- Disturbances to spacetime travel at the speed of light
- PSR 1913+16 Hulse–Taylor binary of two neutron stars (pulsars)
- Accurate timing studies show orbital decay matching predicted energy loss to gravitational waves

Black Hole

- 'Something so massive that even light cannot escape its gravity'

- Conjectured using Newtonian gravity by John Mitchell (1784) and Laplace (1796)

- Schwarzschild (1915) solved Einstein's GR equations for a non-rotating non-charged spherical mass:

$$R_s = 2GM/c^2$$

- The Schwarzschild Radius is the size of the Event Horizon of a Black Hole

Black Hole sizes

Mass compressed to become a Black Hole	Mass (kg)	Rs (m)	Diameter	'Density' g/cm3
Moon	7.3E+22	1.1E-04	0.22 mm	1.4E+31
Earth	6.0E+24	8.9E-03	1.8 cm	2.0E+27
Jupiter	1.9E+27	2.8E+00	5.6 m	2.0E+22
Sun 1M⊙	2.0E+30	3.0E+03	6.0 km	1.8E+16
Neutron Star	2.8E+30	4.2E+03	8.4 km	9.3E+15
Black Hole 10M⊙ (Stellar BH)	2.0E+31	3.0E+04	60 km	1.8E+14
Black Hole 30M⊙ (Stellar BH)	6.0E+31	8.9E+04	180 km	2.0E+13
Black Hole 100M⊙ (Intermediate BH)	2.0E+32	3.0E+05	600 km	1.8E+12
Black Hole 1E4M⊙ (Intermediate BH)	2.0E+34	3.0E+07	0.4 AU	1.8E+08
Black Hole 1E6M⊙ (Intermediate BH)	2.0E+36	3.0E+09	40 AU	1.8E+04
Black Hole 4.1E6M⊙ Sagittarius A*	8.2E+36	1.2E+10	160 AU	1.1E+03
Black Hole 1E8M⊙ (Supermassive BH)	2.0E+38	3.0E+11	4000 AU	1.8
Black Hole 1E10M⊙ (Supermassive BH)	2.0E+40	3.0E+13	6.4 LY	0.00018
Black Hole 4E10M⊙ Blazar S5 0014+81	8.0E+40	1.2E+14	260 LY	0.00001

Black Hole properties

- Black Holes are completely characterised by the parameters:

  Mass

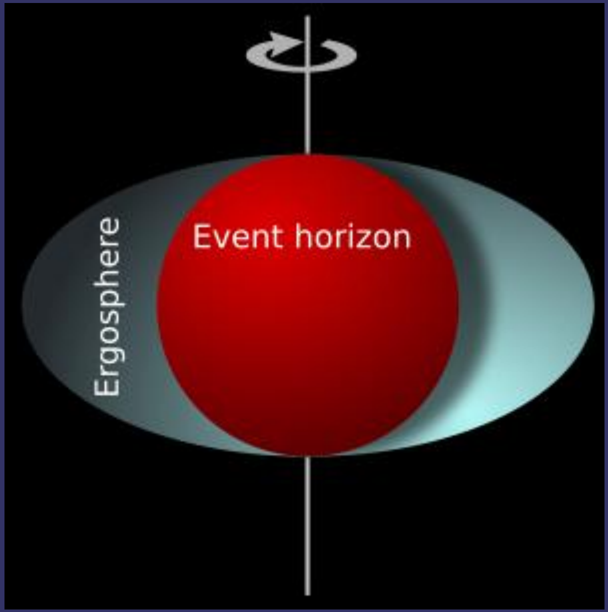
  Charge

  Angular Momentum (spin)

- All astrophysical Black Holes are expected to have very little intrinsic charge

- Most Black Holes will have significant angular momentum – a Kerr Black Hole

Kerr Black Holes



- A Black Hole with angular momentum
- Frame dragging creates a region called the Ergosphere in which space rotates so fast that it is impossible to remain stationary
- The Singularity becomes a Ring Singularity
- There is a maximum spin (Kerr parameter = 1)

Formation of Black Holes

- Big Bang – could have formed Black Holes of any size including microscopic ones
- End of life of a star of original mass over about 20 solar masses → Black Hole with mass in the range 1 to ~1000⊙
- Growth of Intermediate and Supermassive Black Holes through accreting nearby gas, dust, stars, etc., and by mergers

Evaporation of Black Holes

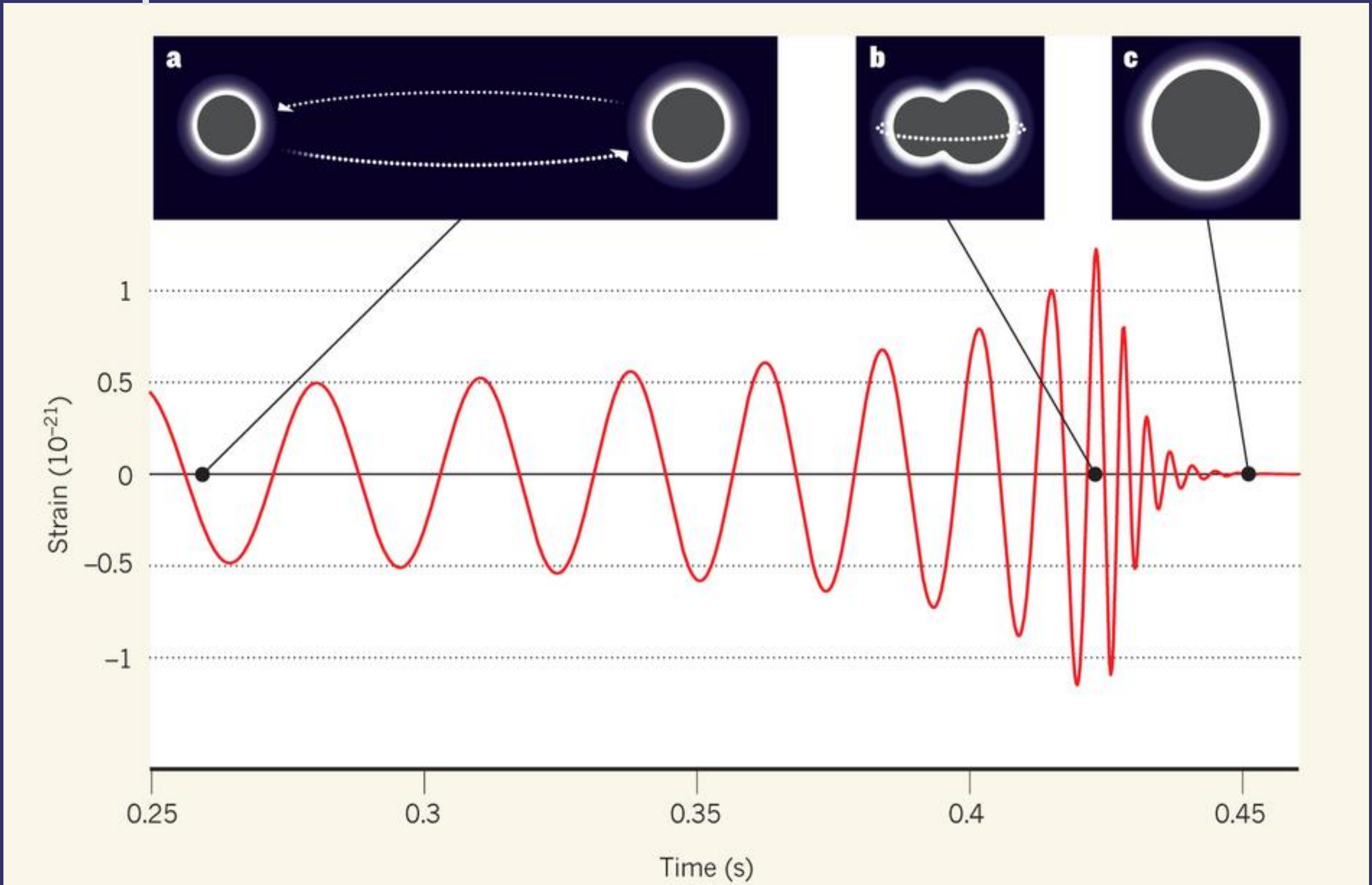
- Hawking radiation

Equivalent Mass	Schwarzschild Radius	Temperature
Sun	3 km	1E-9 K
Earth	9 mm	0.02 K
Moon	0.1mm	1.7 K
1/10 Moon	0.01mm	17 K
1/100 Moon	1 µm	170 K
1/1000 Moon	0.1 µm	1700 K
1/2000 Moon	0.05 µm	3300 K
1/5000 Moon	0.02 µm	8400 K

- The Information Paradox - ongoing debate about destruction of 'physical' information

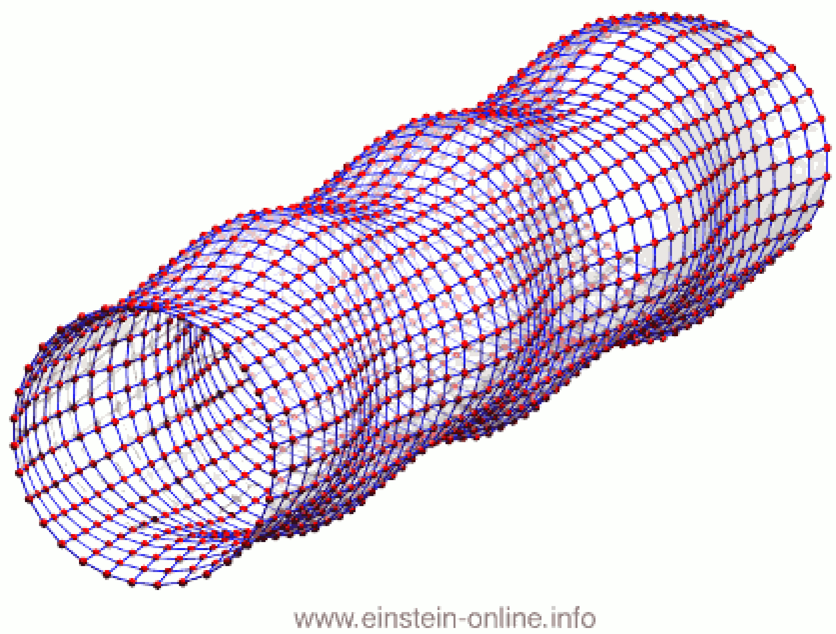
Mergers of Black Holes

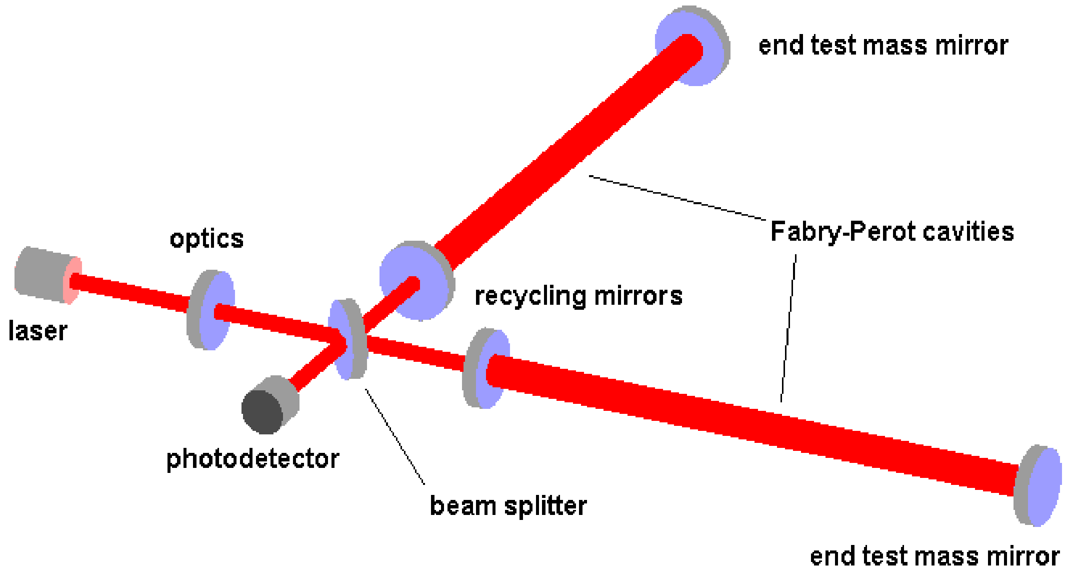
- Simulations indicate the expected form of gravitational waves from Black Hole mergers: a 'chirp'



Detection of Gravitational Waves

- 1960: First attempts by Weber using resonant mass detectors
- 2000: Interferometer based detectors
  TAMA300, GEO600, LIGO
- 2015: Advanced LIGO, and Virgo

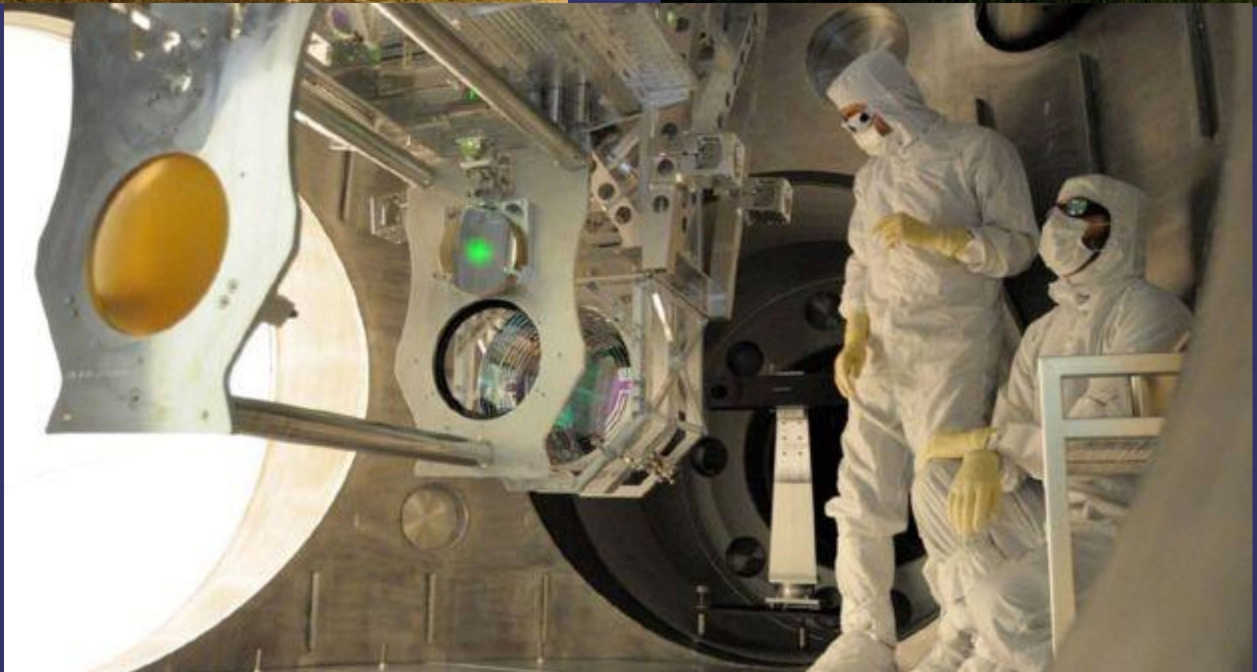


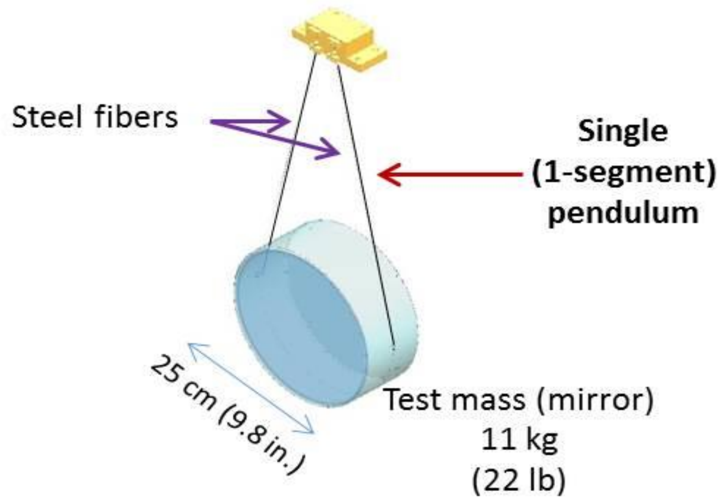


Hanford

Advanced LIGO

Livingston





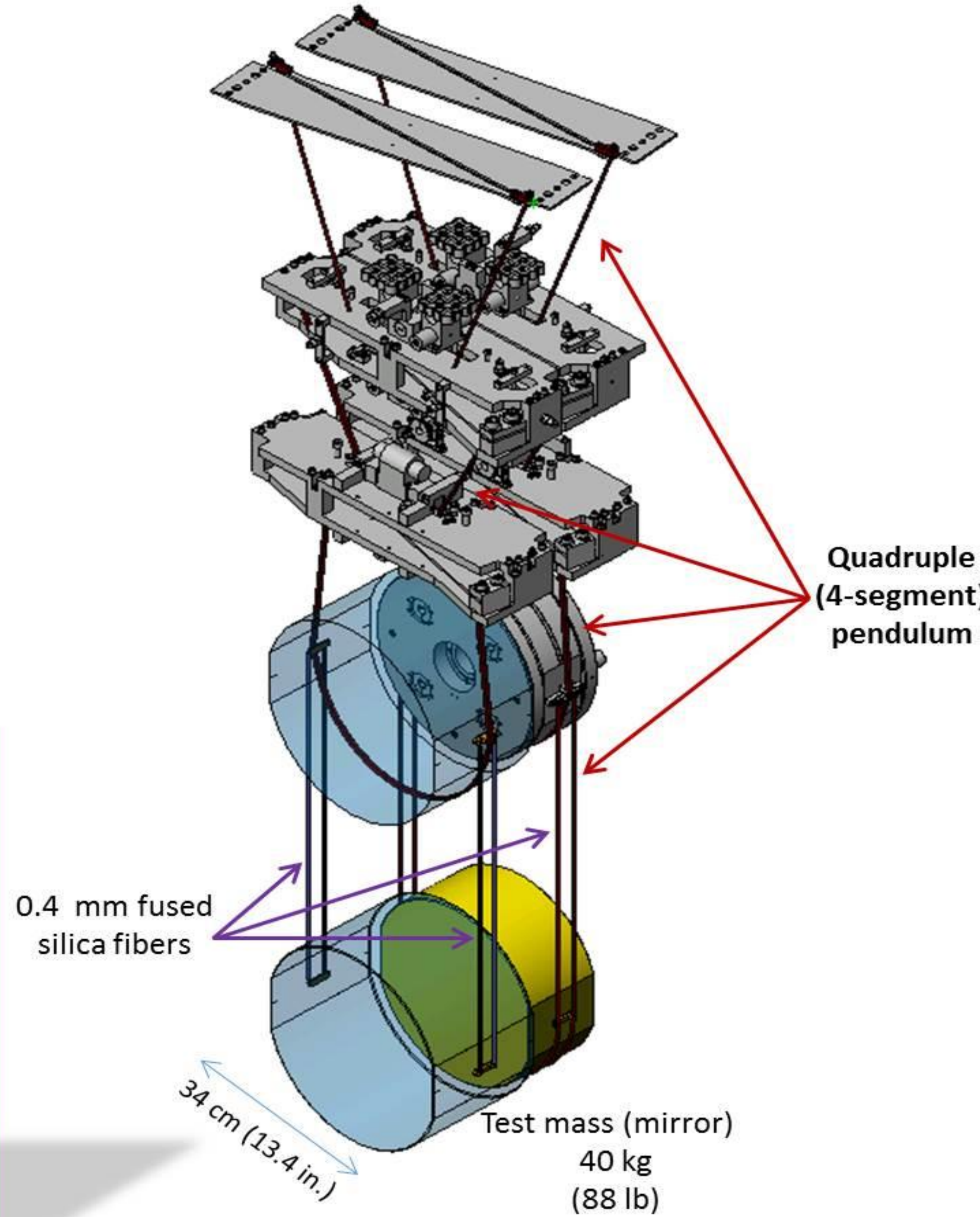
Initial LIGO Suspension

iLIGO vs aLIGO suspension systems

These engineering drawings illustrate the striking differences between Initial- and Advanced LIGO's suspensions. The suspensions are shown to scale.

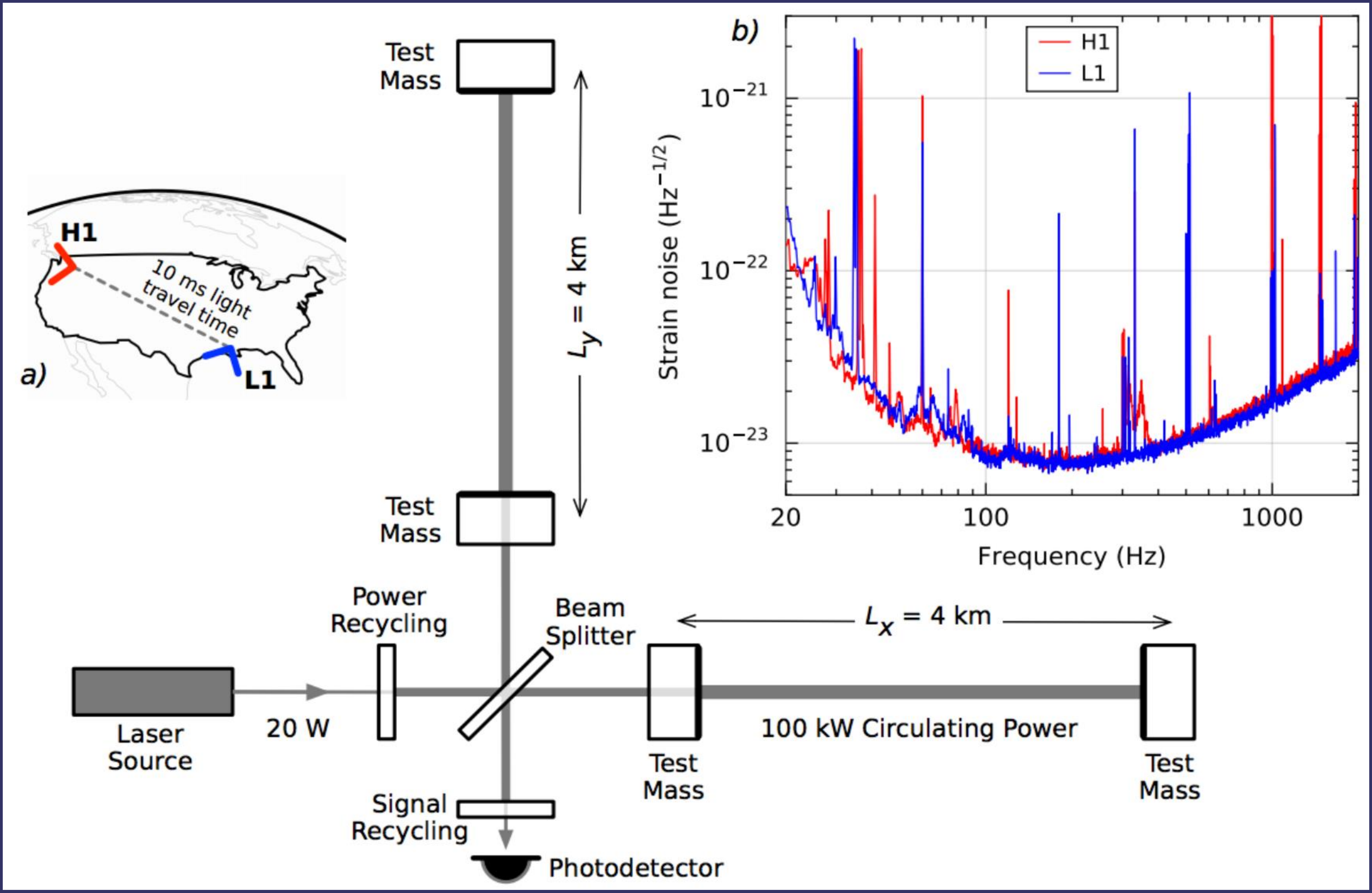
Initial LIGO's suspension was a single pendulum design with an 11 kg (22 lb) 'test mass' (mirror) hung by steel fibers.

Advanced LIGO's suspension system is a **much** heftier quadruple ("quad") pendulum with a 40 kg (88 lb) 'test mass' (mirror) hung by fused silica fibers.

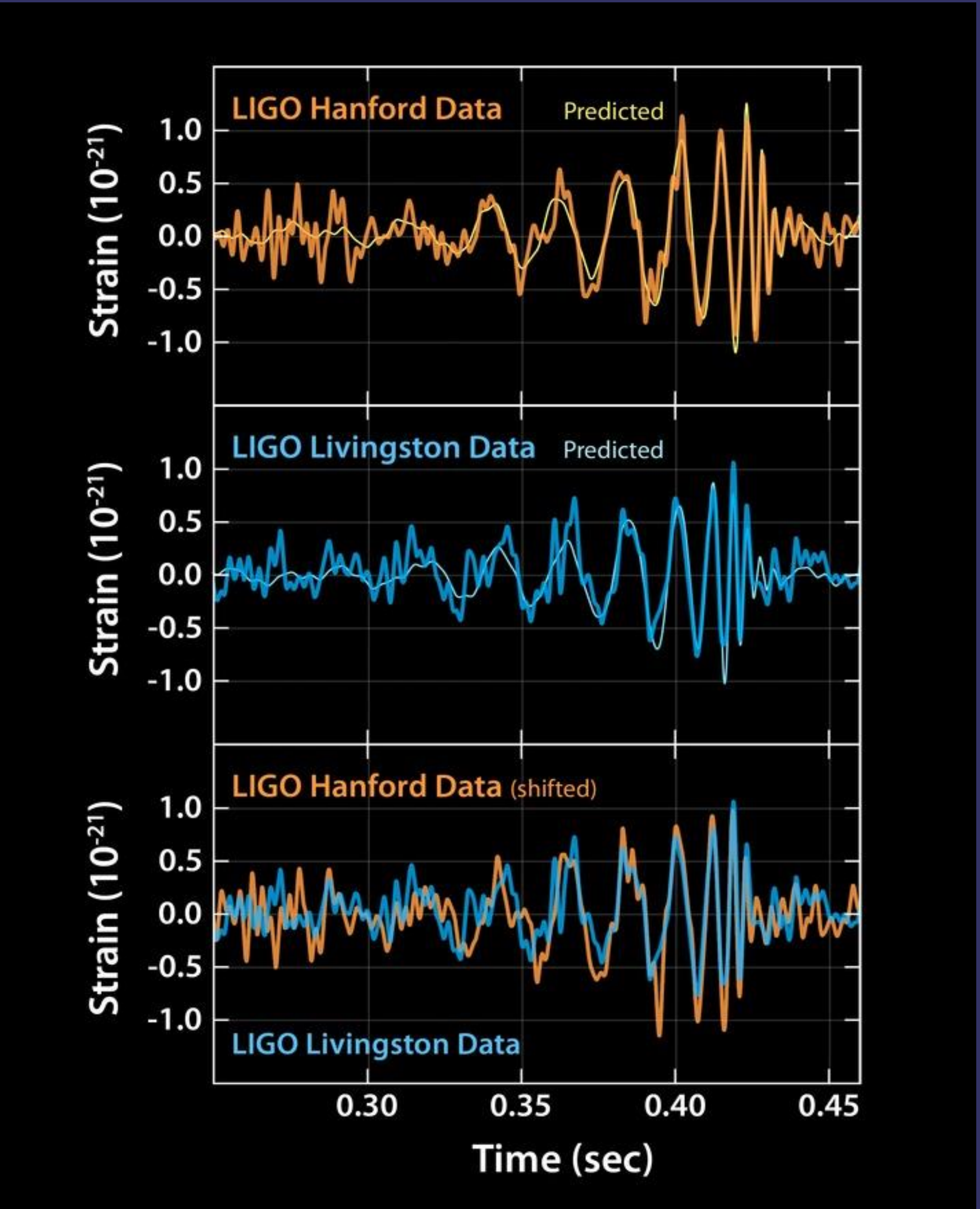


Advanced LIGO Suspension

Advanced LIGO



First Gravitational Wave Detected!



- Date: 14^{th} Sept 2015
- Time: 09:50:45 UTC
- Name: GW150914
- Arrival at Hanford 6.9ms later than at Livingston
- Peak strain of 10^{-21} equal to about 1/10,000 width of a proton.

Interpretation of GW150914 data

TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Simulation of GW150914 type merger

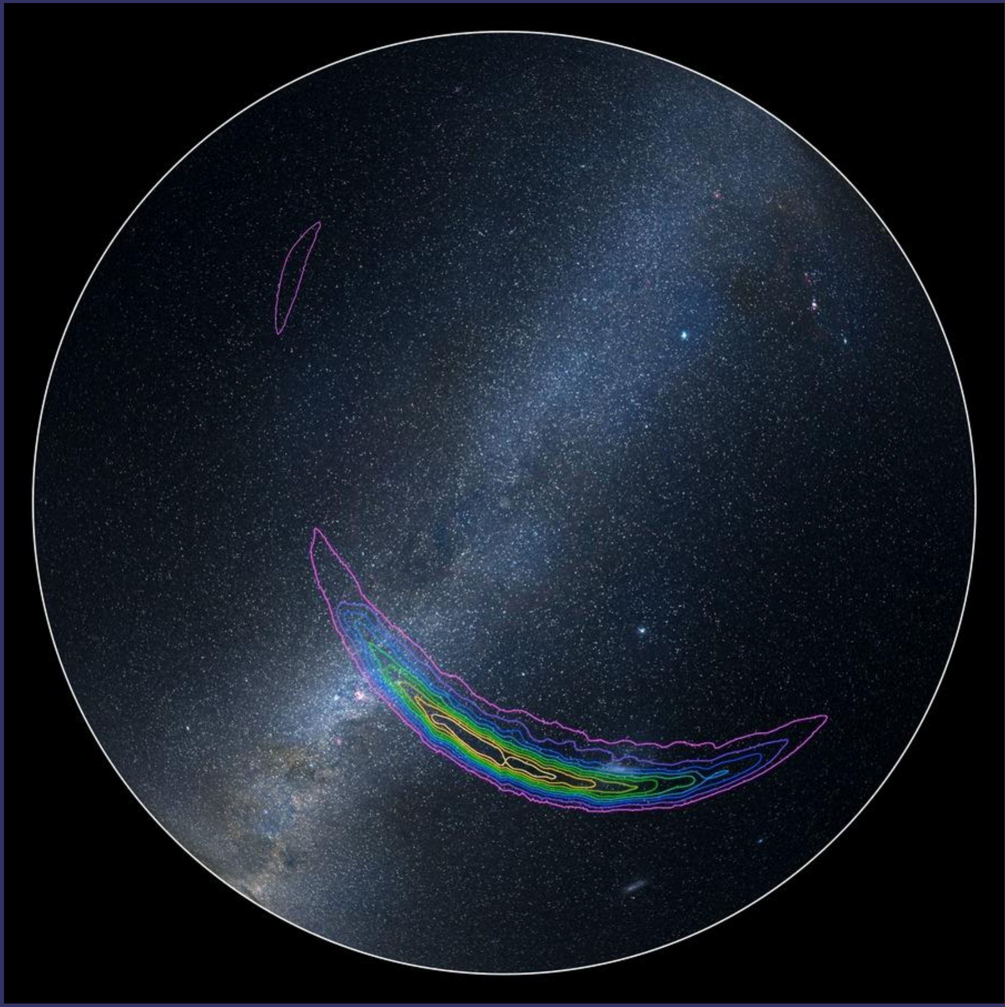
- Video link here:

https://www.ligo.caltech.edu/video/ligo20160211v10

Location of GW150914

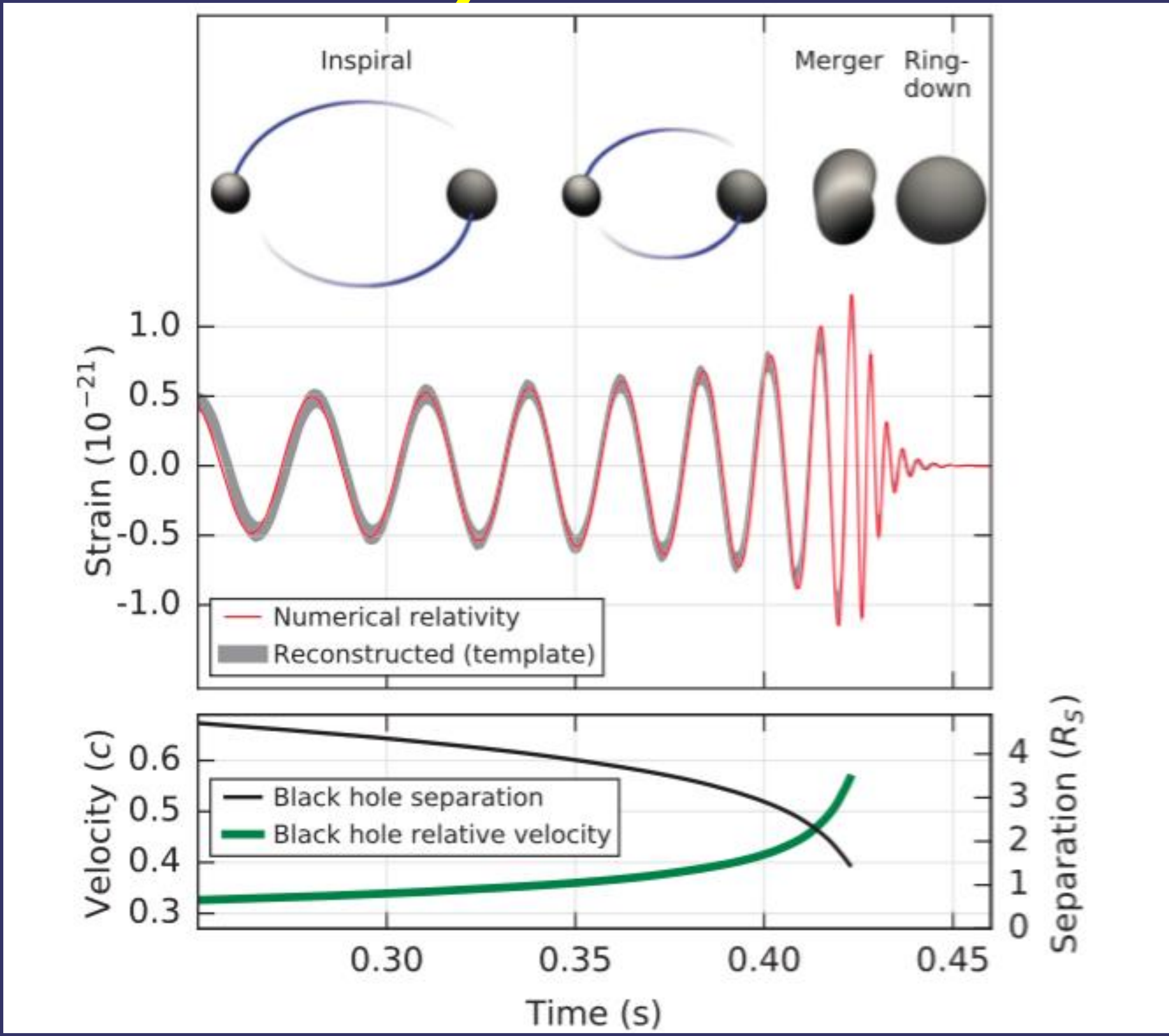
- 'Circle' defined by arrival time difference (6.9ms)
- Location on circle set by weaker constraints (amplitude, phase etc.)
- Masses determined by chirp 'frequency' then distance derived from luminosity/amplitude

~410Mpc
(~1.3 Billion Light Years)



Consistency with General Relativity

- Inspiral models based on relativity match GW150914 data
- Parameters for BH spin etc. inferred from early inspiral stage match those derived independently from late stage



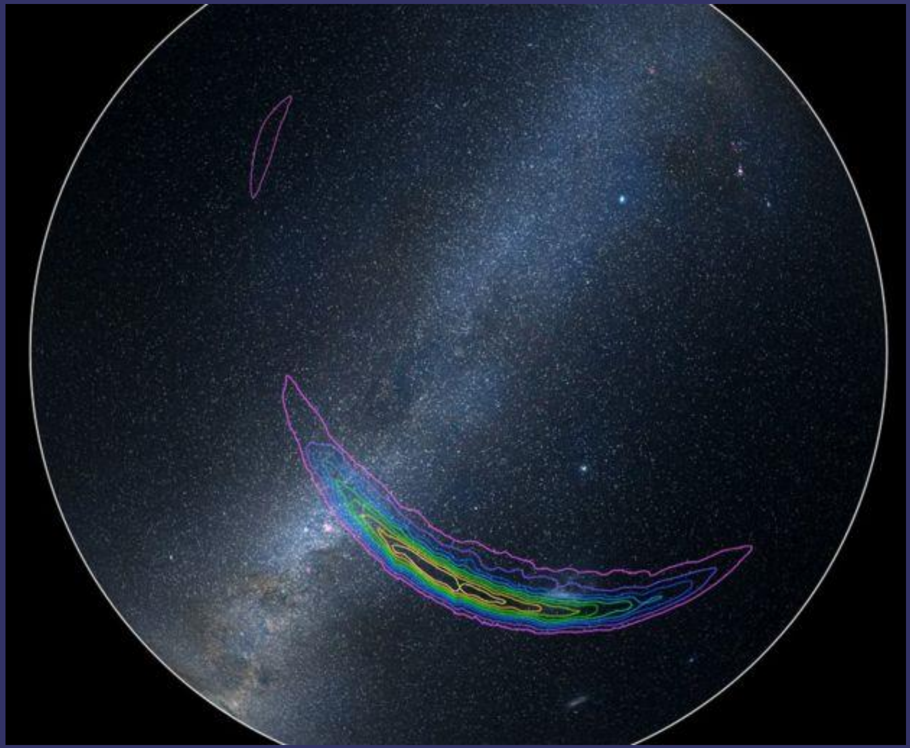
A second detection?

- LVT151012
- Much weaker event – false alarm probability about 0.4 per year
- If of astrophysical origin corresponds to another binary Black Hole merger
- Properties:

M1 23⊙ (+18 / -5)
M2 13⊙ (+4 / -5)
Distance 1100 Mpc (+/- 500)

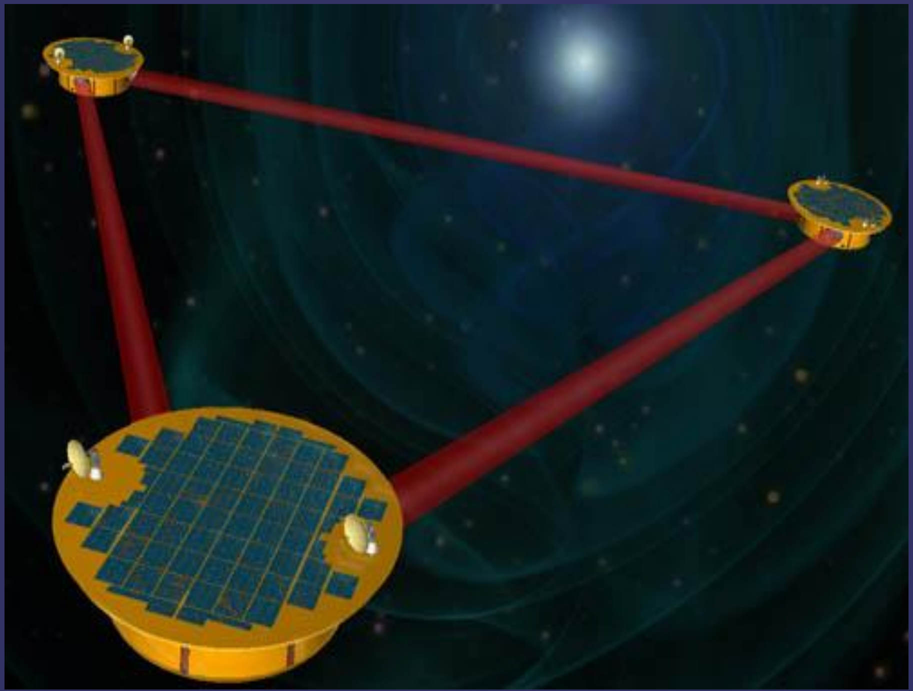
Expectations

- More similar detectors (Virgo, Kagra, maybe LIGO in India)
- Improvements to Signal/Noise Ratio



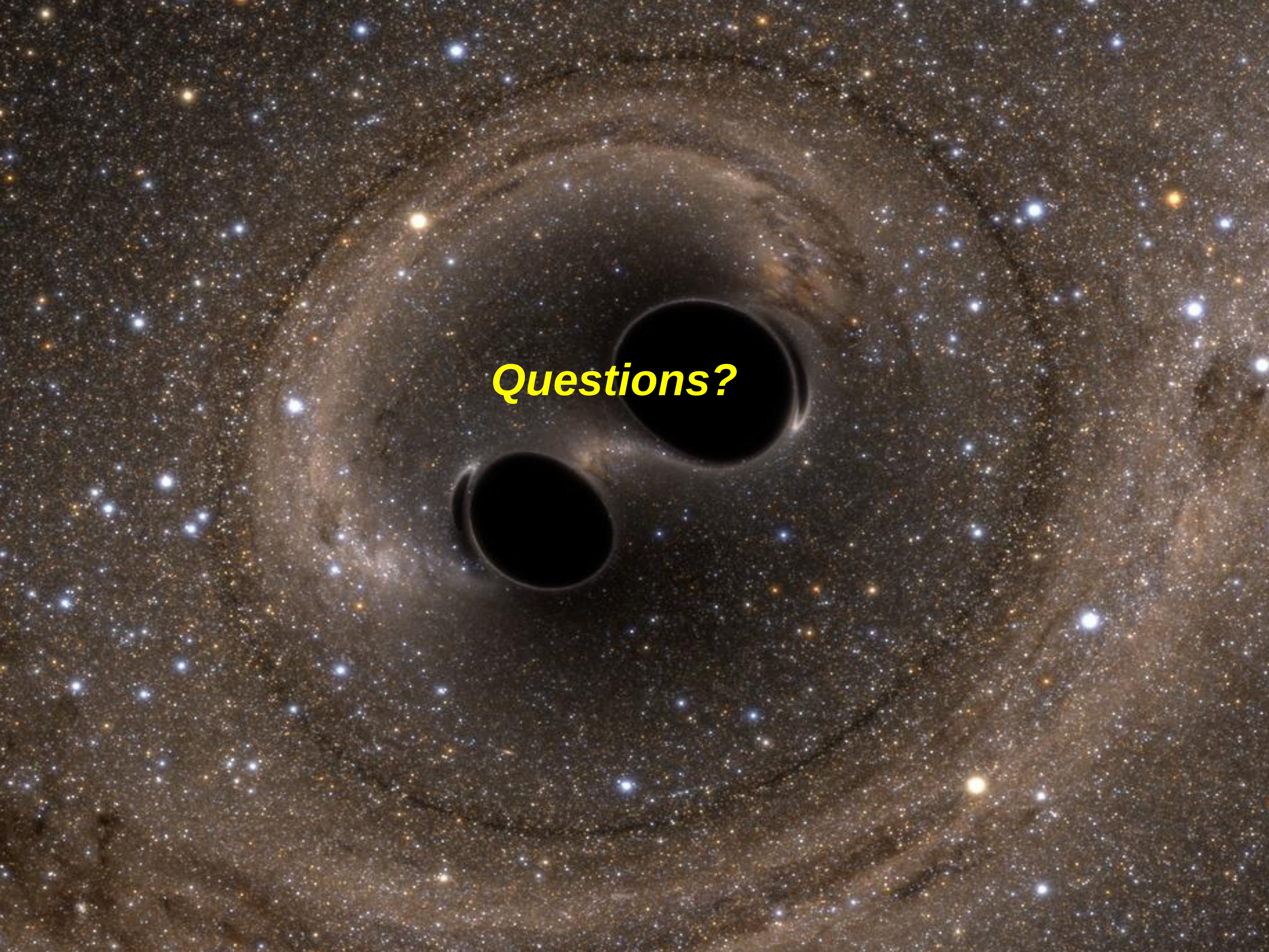
- Space based detectors e.g. LISA (Laser Interferometer Space Antenna) in ~2025
- Sensitive over range 0.00003Hz to 0.1Hz

->High redshift sources, and supermassive BHs



Credits and references

- Relativity – Richard Feynman's lectures:
Six not-so-easy pieces.
Allen Lane The Penguin Press 1998.
- LIGO – Various papers, images, video etc:
https://www.ligo.caltech.edu/ including:
- Observation of Gravitational Waves from a Binary Black Hole Merger. B P Abbott et al. Physical Review Letters. 11 Jan 2016
- Gravity Wave moving GIF:
http://www.einstein-online.info/
- Orbit_times.png: P. Fraundorf


Questions?