Gravitational wave astronomy of black holes by LIGO

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Introduction: What the astronomers knew

Pulsars are exquisite clocks

A pulsar is a clock- and Hulse and Taylor discovered a pulsar in orbit around another compact companion: PSR 1913+16.

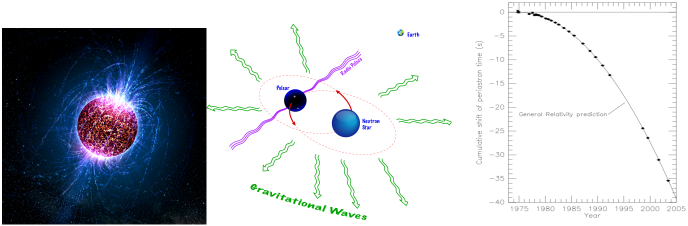


Figure 1: Weisberg & Taylor 2004

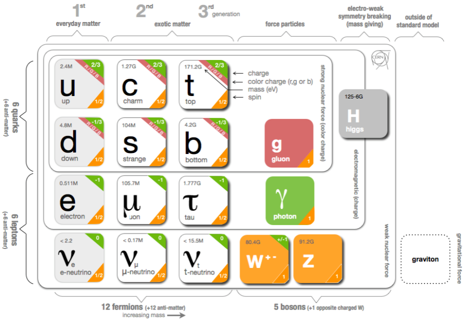
They used the clock to measure the orbit, and in particular the time of closest approach to the barycenter. The timing showed the orbit time decreasing exactly as predicted by GR's prediction of gravitational wave emission.

Introduction: Why is LIGO important?

The importance of the LIGO observations lies in that it allowed us to see (hear, really) two black holes colliding 400 Mpc away via gravity waves: it was the beginning of gravitational wave astronomy.

Gravity: The standard model of matter

The great success of the last century of particle physics is the standard model of matter- including the four forces and the Higgs boson. Gravity is entirely outside of this- all fields are particles says quantum field theory, but there is no known theory of quantitized gravity. Gravity is currently geometry.



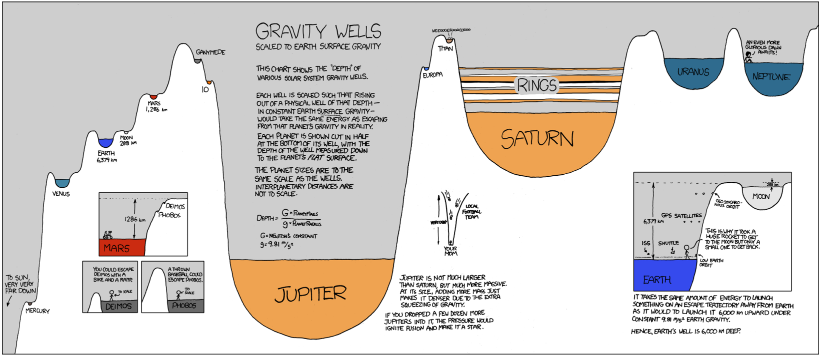


Figure 2: Randall Munroe's xkcd comic on gravity wells.

http://xkcd.com/681/

Gravity is the shape of spacetime near matter: the spacetime tells the matter how to free fall, and matter tells spacetime what shape to have. Black holes are the steepest gravity wells.

Gravity: Black holes

Black holes are very simple, says the no hair conjecture. If one considers a BH at rest (eliminating position and velocity), then they are described only by:

- mass
- charge
- spin (angular momentum)

If BH have identical mass, charge, spin, then they are indistinguishable, just as electrons.

- electron at rest: mass, charge, spin (quantized angular momentum)
- electron in an atom: m, q, n, l, m, s

The single most important feature of a BH is the event horizon, the radius from the center at which even a radially propagating photon does not have escape velocity

What is a black hole: mental models

What is a black hole? A curved empty spacetime…a knot of slow time…the memory of matter…in any event, BH aren't made of matter.

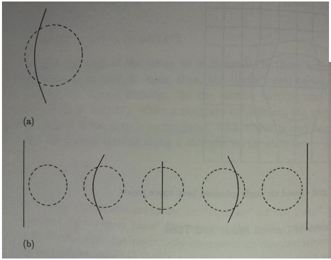
We use various mental models:

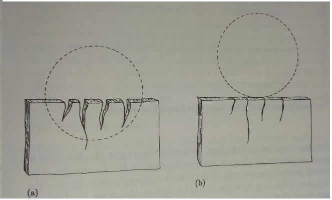
- optical astronomers: a 1 $M_\odot$ point source surrounded by a sphere of radius 3km, inside of which nothing can get out
- frozen star: seen from far away, things approach the event horizon but never reach it as gravitational redshift retards the light. The collapsing star is frozen into place
- membrane paradigm: the stuff near the event horizon acts as a 2-d viscous fluid which is charged and can conduct current but not heat, and has finite entropy and temperature.

What is a black hole: curved space

We will need to gain some physical intuition of what curved space is. Imagine we have a beachball sized volume of curved space and you:

- Push a wire through it: the wire bends
- Push a board into it: the board splits
- Put it into a full bath tub: the water level goes down





What is a black hole: Metrics in curved space

How does on deal with curved space? Choose a coordinate system, get the unit vectors, decide how to combine them into a distance; that is, choose a metric.

Euclidean space:

- cartesian coordinates: $ds^2 = dx^2 + dy^2 + dz^2$
- spherical coordinates:
  $ds^2 = dr^2 + r^2(d\theta^2 + \sin^2\theta d\theta^2) \equiv dr^2 + r^2 d\Omega$

Space in cosmology: $ds^2 = a(t)dr^2 + a(t)S_k^2\, r^2 d\Omega$

where

$$S_k^2 = \begin{cases} \frac{R_o^2}{r^2}\sin^2(r/R_o) & k=1 \\ 1 & k=0 \\ \frac{R_o^2}{r^2}\sinh^2(r/R_o) & k=-1 \end{cases} \tag{1}$$

and $a(t) = 1/(1+z)$ is the universe's size relative to today.

Space near a BH: $ds^2 = \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 d\Omega$

What is a black hole: 3+1 formalism

Spacetime includes time. The real Schwarzschild metric is:

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 d\Omega$$

Most numerical relativity, and the membrane paradigm in particular, use the 3+1 decompostion of spacetime into space and time. For an isolated BH, and far from it, there is a universal time t, whereas near the BH observers experience a redshifted time τ: $\frac{d\tau}{dt} \equiv \alpha = \left(1 - \frac{2M}{r}\right)^{1/2}$. The term α, bounded at $(0, 1]$, tells you how slowly τ ticks with universal time t. The mental model is that one works with the spatial metric and the redshifted time separately. Thus

$$d\tau = \alpha dt\,,\ ds^2 = dr^2/\alpha^2 + r^2 d\Omega$$

Of the two, most of the exotic physical effects of a BH are caused by the redshifted time τ, not the spatial curvature.

What is a black hole: the membrane

The membrane is a representation of the effect of the matter and fields deep in the redshifted time of the BH, but outside the event horizon. Examining Maxwell's equations at the membrane, one finds that effectively, the BH membrane has:

- surface charge
- electrically conductive
- has a surface resistivity of 377 Ohms
- charge is conserved on the surface

What is a black hole: an engine

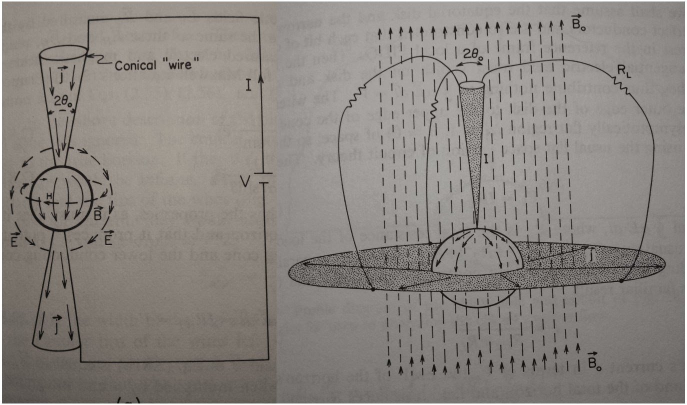


Figure 3: The black hole acts as a resistor in a circuit, and when surrounded by magnetized material forms a motor.

Black holes out in the universe: M87

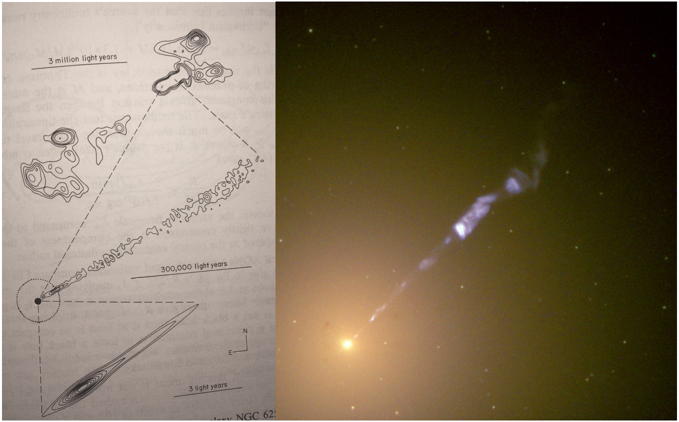


Figure 4: The motor powers a jet- a tornado-like twistor of magnetic fields along which matter flows and is accelerated, and the BH becomes a engine of a quasar. M87 has a jet visible in the optical- it is $10^9 M_\odot$ BH starved of gas.

Black holes out in the universe: quasar engines

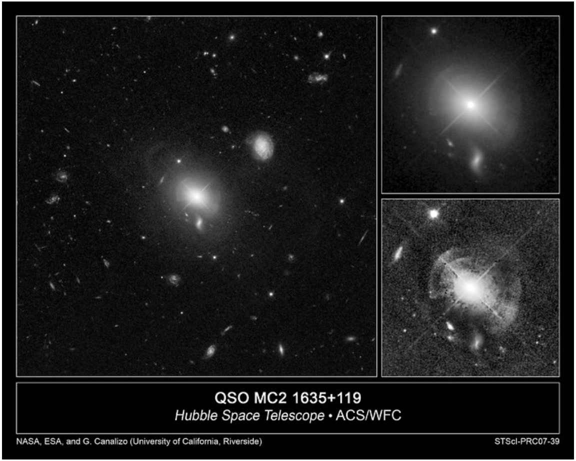


Figure 5: If enough gas is flowing down to the black hole to form an accretion disk, the BH becomes a quasar. The BH at the centers of galaxies have masses of $\sim 10^9 M_\odot$

Black holes and information: temperature

The membrane also has a temperature:

$$T = \frac{\hbar c}{4\pi r_{BH}\, k_B}$$

where R_{BH} is the "radius" of the BH, $r_{BH} = 2M$. The derivation includes the redshift effect of α: this is T seen at distance.

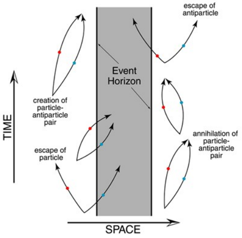


Figure 6: The mechanism for the thermal atmosphere is a quantum field theory effect: virtual particles are created near the horizen, and some half pairs cross the horizon. This is called Hawking radiation.

Black holes and information: entropy and the holographic principle

Because the membrane has a temperature, it has an entropy:

$$S = \frac{k_B}{4\hbar} 4\pi r_{BH}$$

Notice that this depends on the area of the BH, $4\pi r_{BH}$. For a $1 M_\odot$ BH, $S = 10^{77}$, whereas for the $1 M_\odot$ Sun, $S = 10^{58}$. BH are both simple (having no hair) and complicated (but having enormous entropy).

That for BH $S \propto$ area and not $S \propto$ volume led directly to the holographic principle: perhaps the information content of the universe is encoded on an 2 dimensional boundary and not in the 3 dimensional volume.

Fermilab's Holometer made a test of this idea.

Black holes and information: information loss?

Hawking started this line of thought in 1976, in a paper titled: “Breakdown of Predictability in Gravitational Collapse”.

Information flows down into a BH with the matter; Hawking thermal radiation comes out; in time the BH evaporates. What happened to the information? The thermal bath can’t carry it. Technically what breaks is unitarity: the sum of the probabilities of outcomes is 1.

Recently it has become the question of “Is there a firewall at the horizon?”.

The arguments intersect physics, quantum computing, and quantum information theory and are fascinating: my favorite worker is currently John Preskill- google “quantum information and spacetime”.

What is a black hole: spin

One last insight into black holes:

If your mental model for spin of a BH is a black ball that is spinning, that is insufficient.

- drop a bucket on a strong rope down to a neutron star surface- it will run into a neutron star mountain
- drop the same bucket down to the membrane of a non-rotating BH: time slows down but nothing happens.
- drop the same bucket down to the membrane of a BH with spin: the bucket starts orbiting the BH.

This is called frame dragging: space is carried around the BH.

BH aren't a "thing", they are a feature in spacetime geometry.

LIGO: what is a gravity wave?

A gravity wave is a propagating curvature perturbation.

LIGO: how do you measure a GW

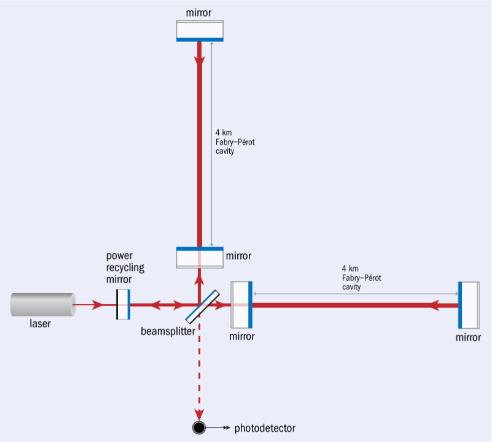
Get two rulers of the same length, use one to measure the other while it is in the curvature perturbation.

This is hard: the GW of interest have wavelengths of 100-1000 km.

The LIGO solution was to use a pair at right angles over 4 km.

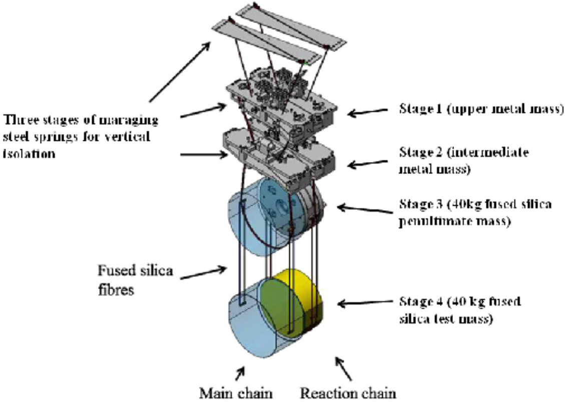
The measurement is of strain: strain $= \Delta L/L$ and the signal of interest is strain$\approx 10^{-22}$. At LIGO's 4km length the change is still $\ll 1$ nm.

LIGO: the experimental layout



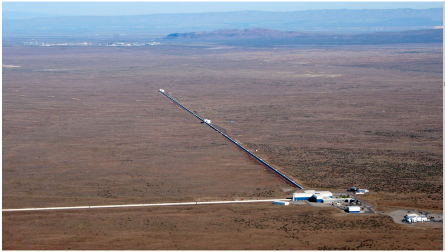
LIGO is an interferometer: they arrange the arms to null at the sensor when the lengths are the same. They see signal when an arm length changes. (curvature perturbation?)

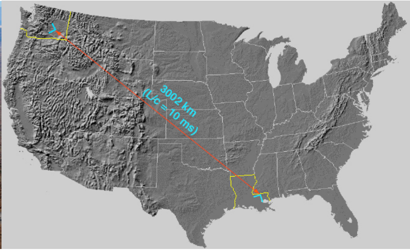
LIGO: the mirrors



The arms are bounded by mirrors on quadruple pendulum suspensions to isolate them from vibrations. Earthquakes, wind, and trucks are still a problem.

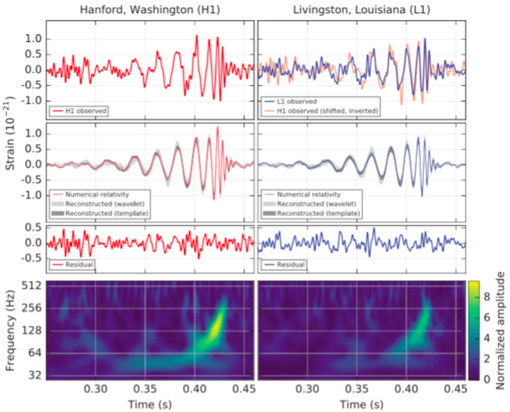
LIGO: the observatory is two sites





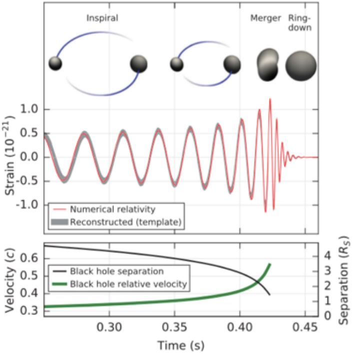
They partly solve the noise problem by having two sites and demanding the signals make sense by a time of flight argument.

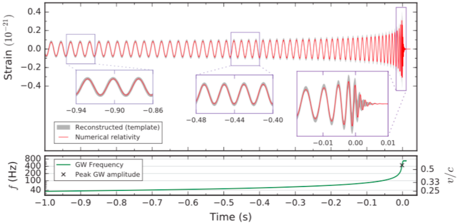
LIGO: The first event



This was loud. The strains from the two detectors were consistent with the time of flight.

LIGO: Both events





The left shows the first event, the right the second event (the Boxer day event). The second was much lower mass- many more cycles were observed.

LIGO: parameters

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	$0.09^{+0.03}_{-0.04}$

Primary black hole mass	$14.2^{+8.3}_{-3.7} M_\odot$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_\odot$
Chirp mass	$8.9^{+0.3}_{-0.3} M_\odot$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_\odot$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_\odot$
Radiated gravitational-wave energy	$1.0^{+0.1}_{-0.2} M_\odot c^2$
Peak luminosity	$3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s
Final black hole spin	$0.74^{+0.06}_{-0.06}$
Luminosity distance	440^{+180}_{-190} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

They can pull out many parameters from their data, including masses, spins, and distances.

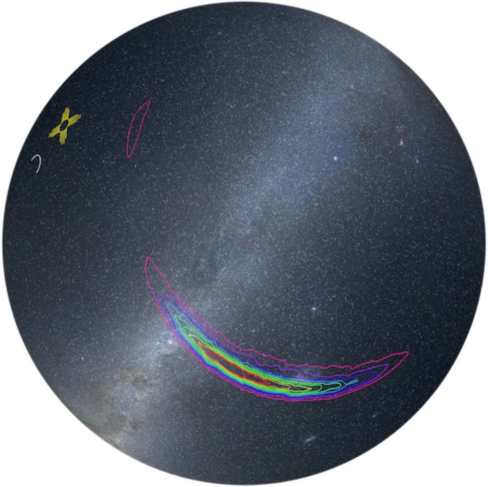
LIGO: what did they hear?

Lets see a simulation of the first LIGO event.

Astronomy: what would I see?

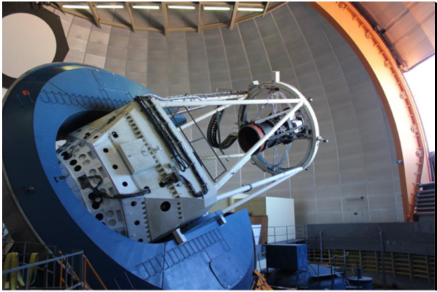
Let's put a ring of glowing matter around a BH, in our plane, and take a look. It looks bright, but at 400 Mpc it would be too dim to see.

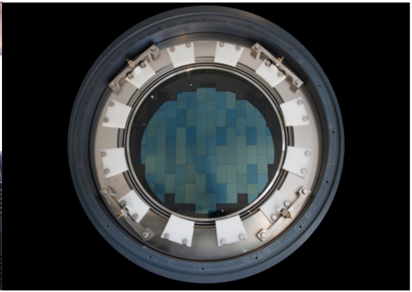
Astronomy: Can LIGO tell where it was?



LIGO provides a sky localization based on triangulation with two detectors. It isn't very good. Half the entire sky is shown.

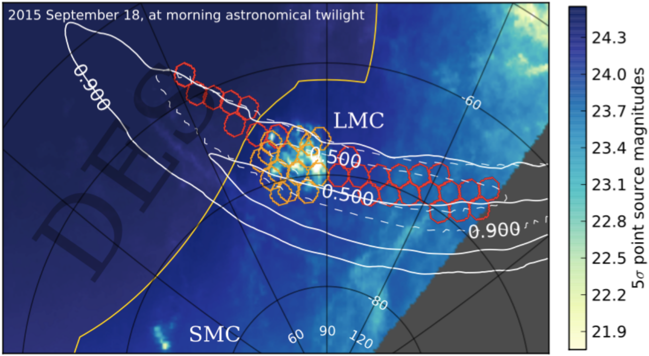
Astronomy:DECam





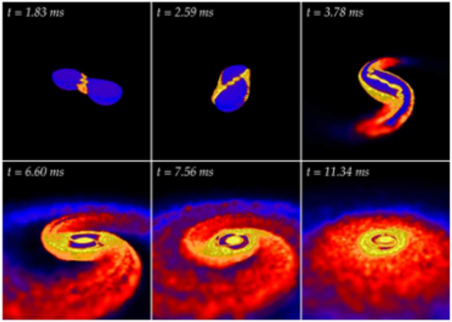
The DESgw group at Fermilab uses DECam: a 62 ccd camera with a 3 sq-degree field of view for the Blanco 4m telescope at CTIO in Chile.

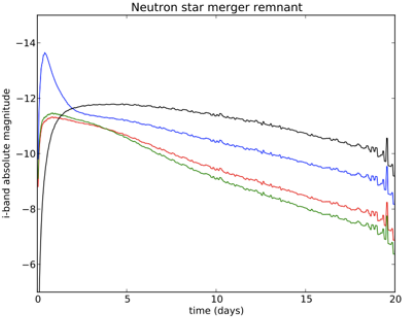
Astronomy: following up GW150914



We covered 38% of the localization map, before they shifted the map. In the end we covered 11% of the map. We really don't expect to see anything.

Astronomy: kilonova





We really are looking for neutron star mergers, which have a rich and fascinating matter physics. They blow up and are visible in the optical via r-process element decay energy.

Astronomy: cosmology

The reason we are in this is to learn about the cosmological metric. LIGO measures the distance to the event in meters. If we can find the redshift to the event, by identifying it or by statistically associating galaxies to the events, we are measuring the metric.

Over the next two years we hope to make a measurement of the Hubble Constant, the size of the universe, with these events.

Summary

- The measurements made by LIGO this year are important because they both opened up gravitational wave astronomy and because they are listening in detail to black holes.
- Black holes are not matter but a feature in the spacetime geometry
- Most of the exotica of black holes are associated with the gravitational time delay near the horizon, and the existence of the horizon
- LIGO measures moving curvature perturbations (gravity waves) using a pair of laser interferometers.
- We use a big telescope and large silicon array to look for optical counterparts to BH mergers. Unlikely we'll see anything, but we'll look at the next few anyway.

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