LIGO and the Extreme Side of Gravity

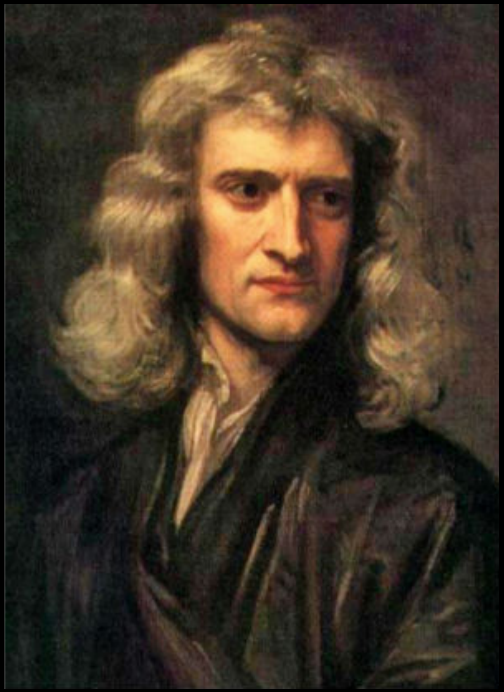
Outline

- Gravity : Newton vs Einstein
- The extreme side of spacetime : gravitational collapse and black holes
- But do black holes *really* exist?
  - black hole collisions and gravitational waves
- LIGO and the search for gravitational waves
  - how we can interpret the first few signals LIGO measured as coming from black hole collisions

Newtonian Gravity

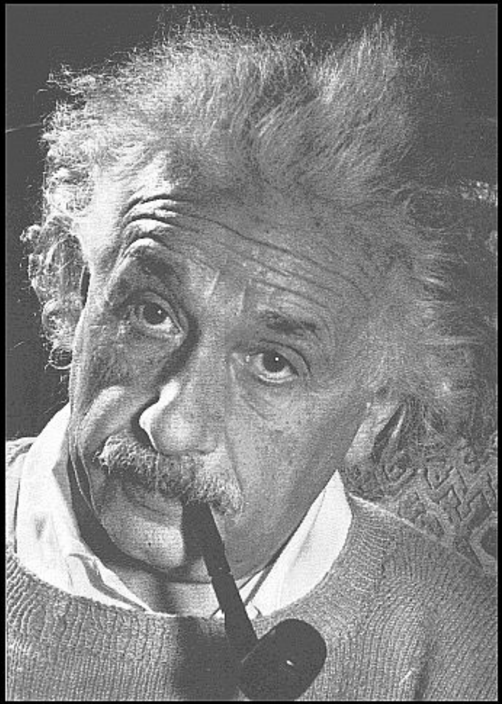
- Published in 1687, Newton postulated that gravity is a *force*, mathematically described by his universal law of gravitation

  any two objects in the universal feel an instantaneous force of attraction between them, in strength proportional to the product of their masses, but diminishing by the square of the distance between them



- Highly successful theory : explains why objects fall to earth with the same acceleration independent of their mass, can derive Kepler's laws of planetary motion, etc.

Einsteinian "Gravity"



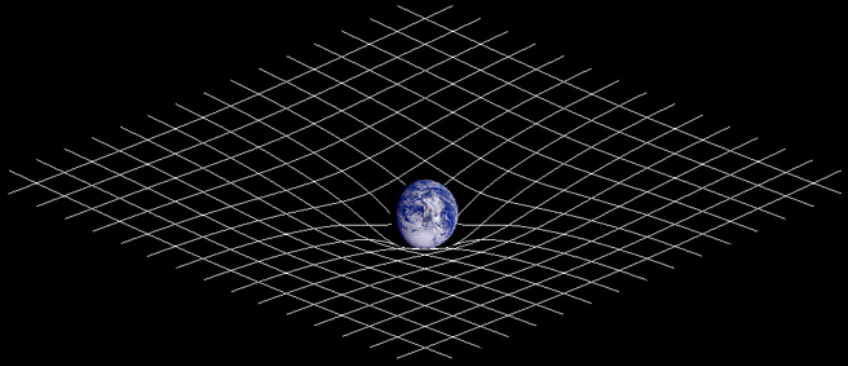
- Einstein's theories of relativity are theories about the structure of space and time, or *spacetime*
- Both the special and general theories posit that spacetime can be described by the mathematics of geometry
  - In special relativity, this geometry is given by fiat, and is flat and unchanging
  - In general relativity, the geometry can by curved and dynamical

Special Relativity

- With the following assumptions/postulates:
  - spacetime has a given, static geometric structure (Minkowski spacetime)
  - without external forces acting on them, *inertial* (free-fall) observers follow *geodesics* of the spacetime
  - there is no preferred inertial observer; the geometry of spacetime looks *identical* to all inertial observers
  - the speed of light c is a universal constant of nature as seen by any observer
- interesting (and certainly not obvious!) consequences arise:
  - energy and mass are intimately related concepts, quantified by the famous formula $E=mc^2$
  - nothing can travel faster than light
  - time-dilation and length-contraction of the other party is perceived when there is relative motion between two observers

General relativity

- Einstein immediately realized Newton's theory of gravity was inconsistent with special relativity, as it allowed instantaneous propagation of gravitational fields. This lead him (after almost a decade of effort) to general relativity, published in 1915
  - general relativity, as special relativity, is a theory about the geometric structure spacetime, but now spacetime becomes a *dynamical* entity
    - observers still follow geodesics, but now their mass/energy can *curve*, or *bend* spacetime
    - the details of this bending are described by the *Einstein field equations*; very complicated, but the bottom line is the more massive an object, the more it curves spacetime



  - curved geometry together with the geodesic hypothesis is enough to completely describe what we think of as the "force of gravity"

Extreme Gravity

- Newton : how strong can the gravitational force be, and what happens when it becomes “very” strong?

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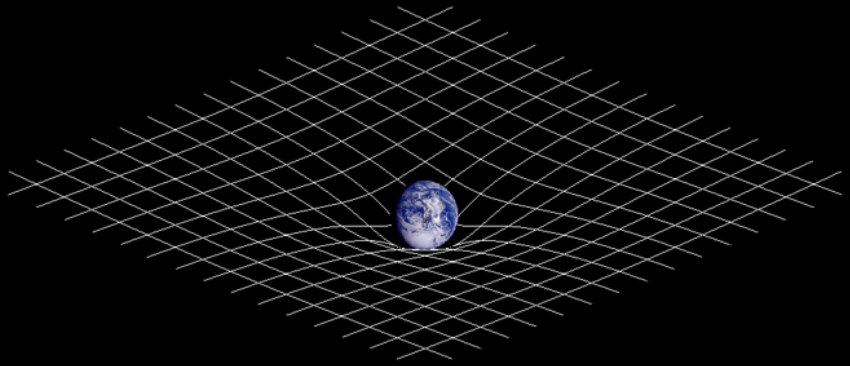
  Arbitrarily strong, but nothing qualitatively changes; the force is just that much stronger

Extreme Gravity

- Einstein: how curved can spacetime become, and what happens when it becomes "very" curved?

- Here it is useful to think of one aspect of how we experience curved spacetime : *gravitational time dilation*

  – if you hover near a massive object, a distance observer will see your clock running slower than theirs



  – this can be related to the Newtonian notion of force, in that how much slower time flows is related to the *non-gravitational* force you'd have to exert to *hover*; i.e. to *not* follow the natural, free-fall geodesic.

Extreme Gravity

- Einstein: how curved can spacetime become, and what happens when it becomes “very” curved?

  (*if Einstein and Newton are just different mathematical descriptions of the same phenomenon, don’t we already now the answer?:*

  > *Gravitational time dilation can become arbitrarily large, but nothing qualitatively changes; clocks just seem to run that much slower)*

Extreme Gravity

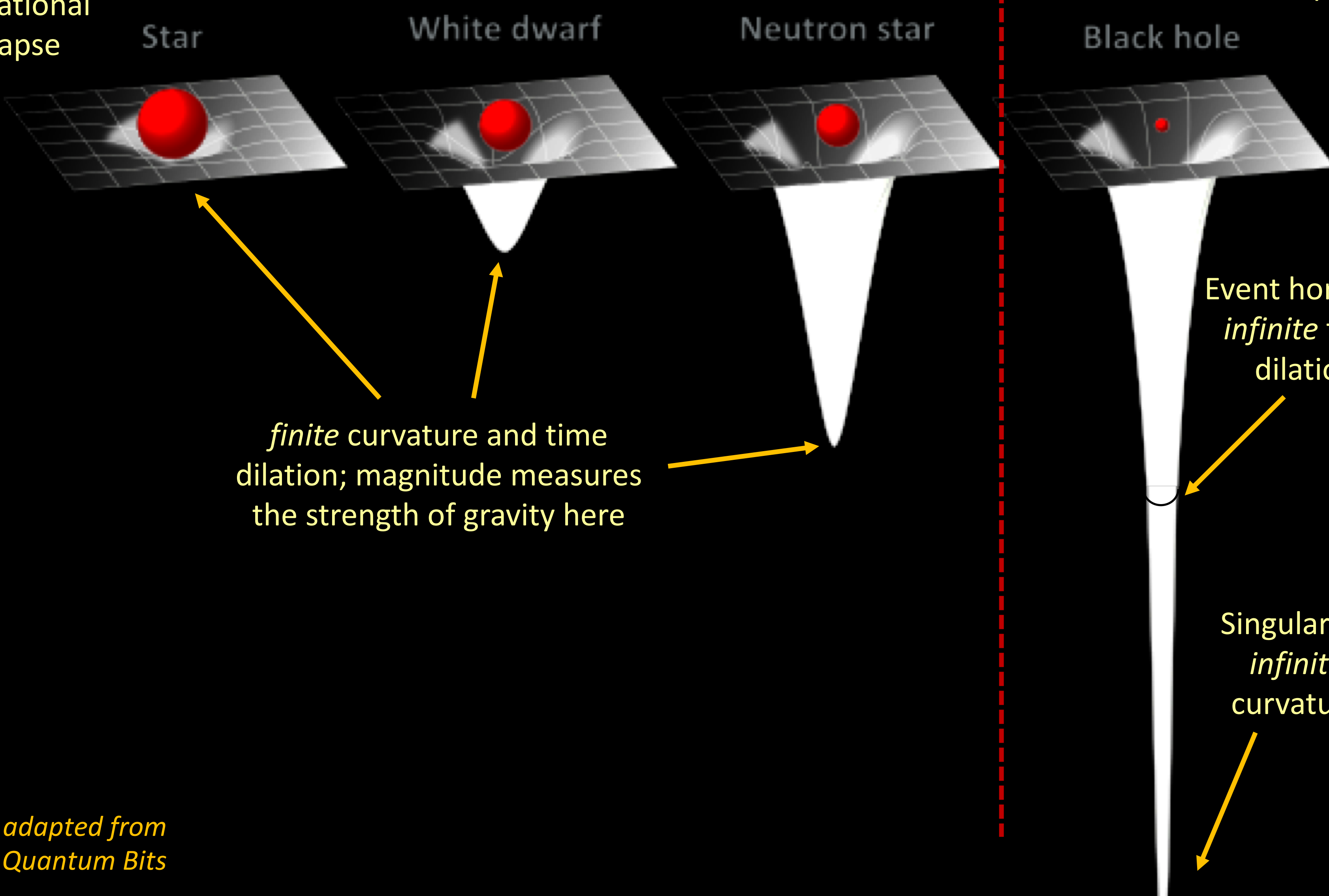
- Einstein: how curved can spacetime become, and what happens when it becomes “very” curved?

  Gravitational time dilation can become arbitrarily large, but this happens well before curvature becomes arbitrarily large. Moreover, the nature of spacetime also changes *qualitatively*, undergoing what is called *gravitational collapse,* and forming a *black hole.*

Gravitational Collapse

Before gravitational collapse

After gravitational collapse



finite curvature and time dilation; magnitude measures the strength of gravity here

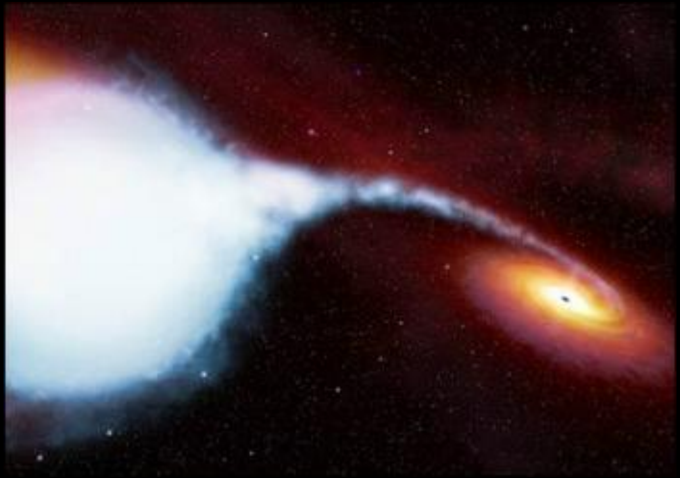
Event horizon : *infinite* time dilation

Singularity: *infinite* curvature

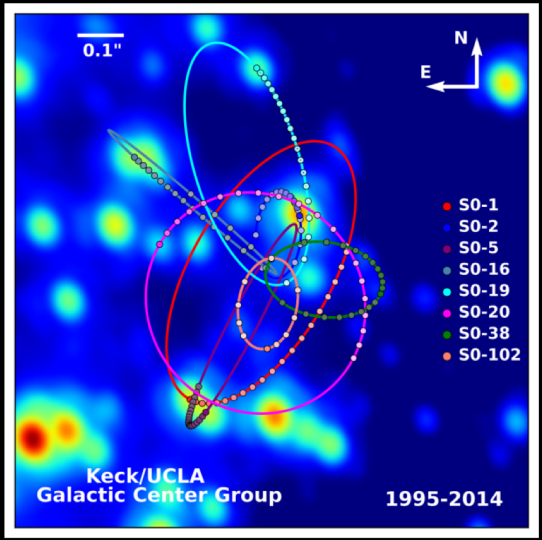
Image adapted from Quantum Bits

Do black holes really exist?

- I.e., are there really regions of spacetime out there undergoing gravitational collapse, causally disconnecting themselves from the rest of the universe, and flowing to singularities where Einstein’s field equations don’t make sense anymore?
  - It seems so:



Artists impression of Cygnus X-1, a candidate stellar mass black hole



Orbits of stars about SgrA, the putative supermassive black hole at the center of our galaxy*

  - But these are extraordinary claims, and so we should demand an extraordinary level of evidence

Black hole collisions and gravitational waves

- To get *direct* evidence for black holes, we need signals coming from the curvature of spacetime itself: *gravitational waves*

- In general relativity, the best source of a gravitational wave is the collision of two black holes (a single black hole in isolation doesn't radiate at all)

  - The structure of the wave encodes precise details about the strong curvature regime near the colliding horizons, and thus can give evidence for (or against!) the general relativistic description of black holes, at least exterior to the horizon

Gravitational Waves in General Relativity

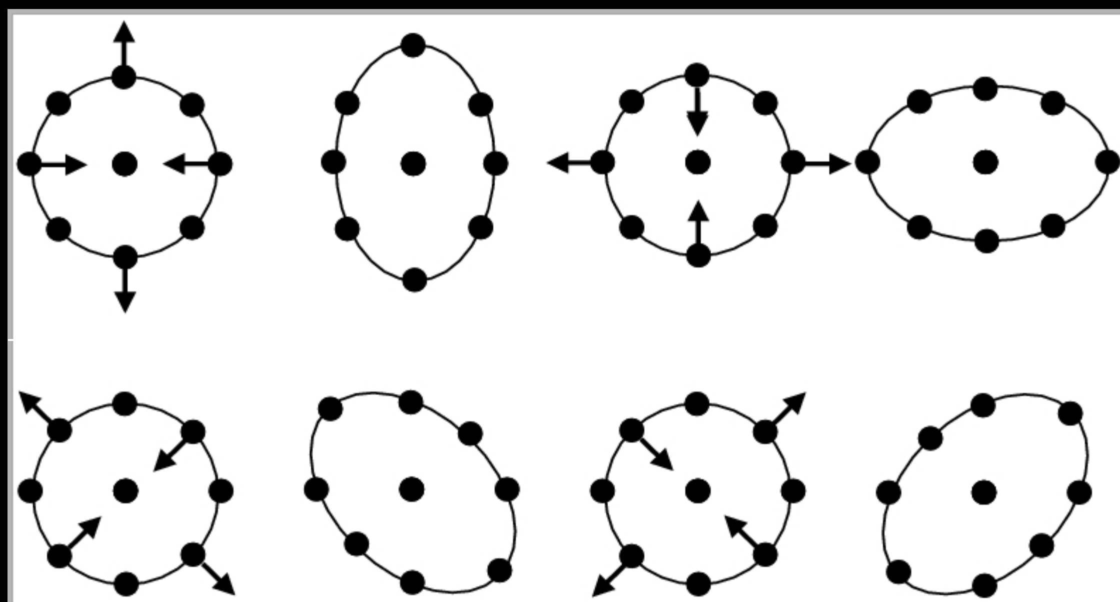
- Gravitational waves are localized disturbances, or ripples in the geometry of spacetime that propagate at the speed of light
  - matter/energy that undergoes accelerated motion can produce gravitational waves
  - spacetime is very "stiff" however, and *huge* concentrations of *exceedingly* dense matter accelerating *very* rapidly are needed to produce gravitational waves that are strong enough to detect
    - terrestrial source/receiver set-ups unfeasible
    - need to look to the universe for sources from extreme events : black hole collisions, neutron star collisions, supernova, etc.

Weak field nature of gravitational waves

- Far from the source, the effect of a gravitational wave is to cause distortions in distance transverse to the direction of propagation

- Two linearly independent polarizations (+ and x)

  – schematic effect of a wave, traveling into the slide, on the distances between an initially circular ring of particles:



+

time

x

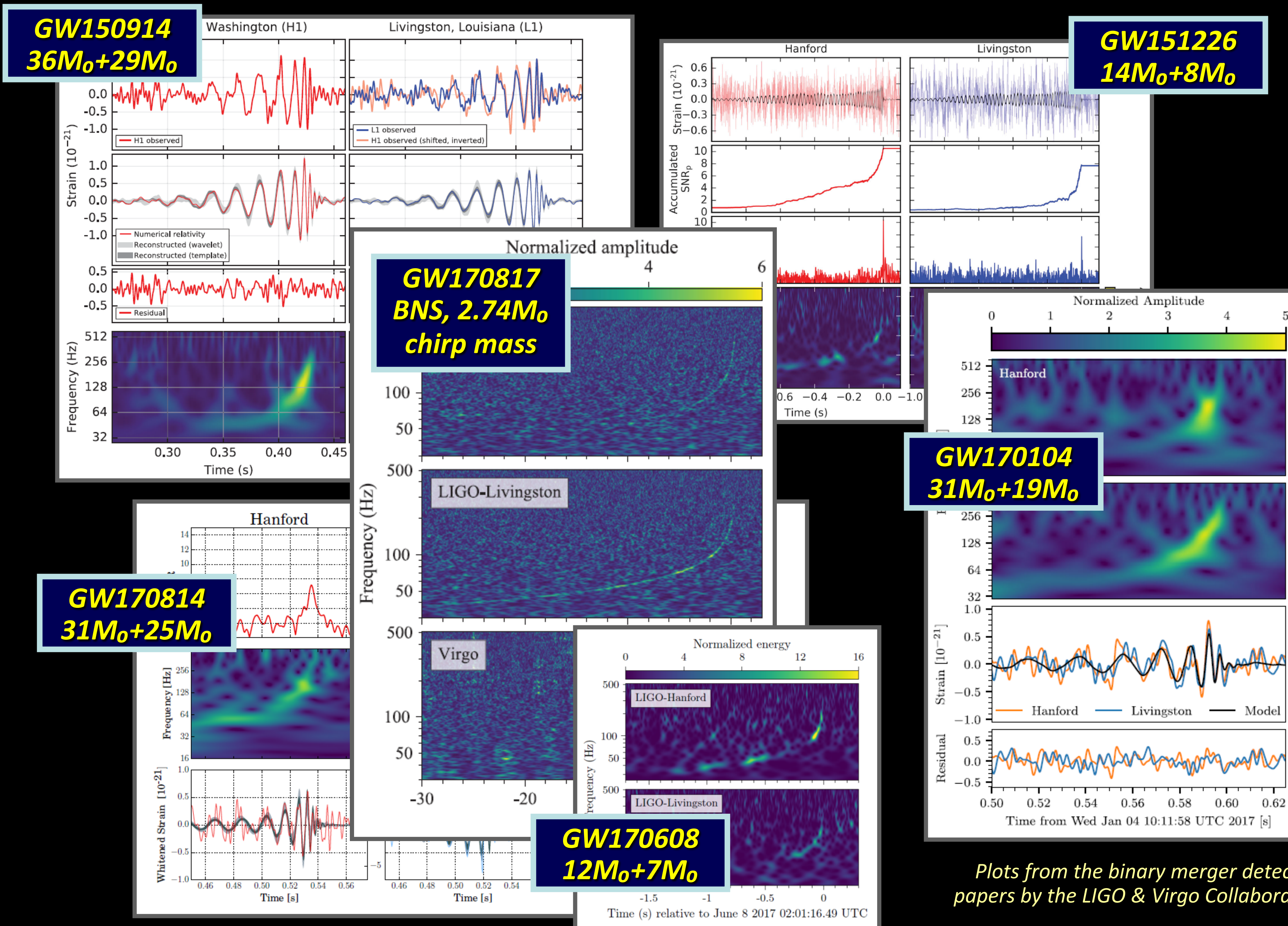
  – this basic property of gravitational waves underlies all direct detection efforts

The LIGO gravitational wave detectors

LIGO Hanford

LIGO Livingston

The new era of GW observation of the universe



Plots from the binary merger detection papers by the LIGO & Virgo Collaboration

Black Holes of Known Mass

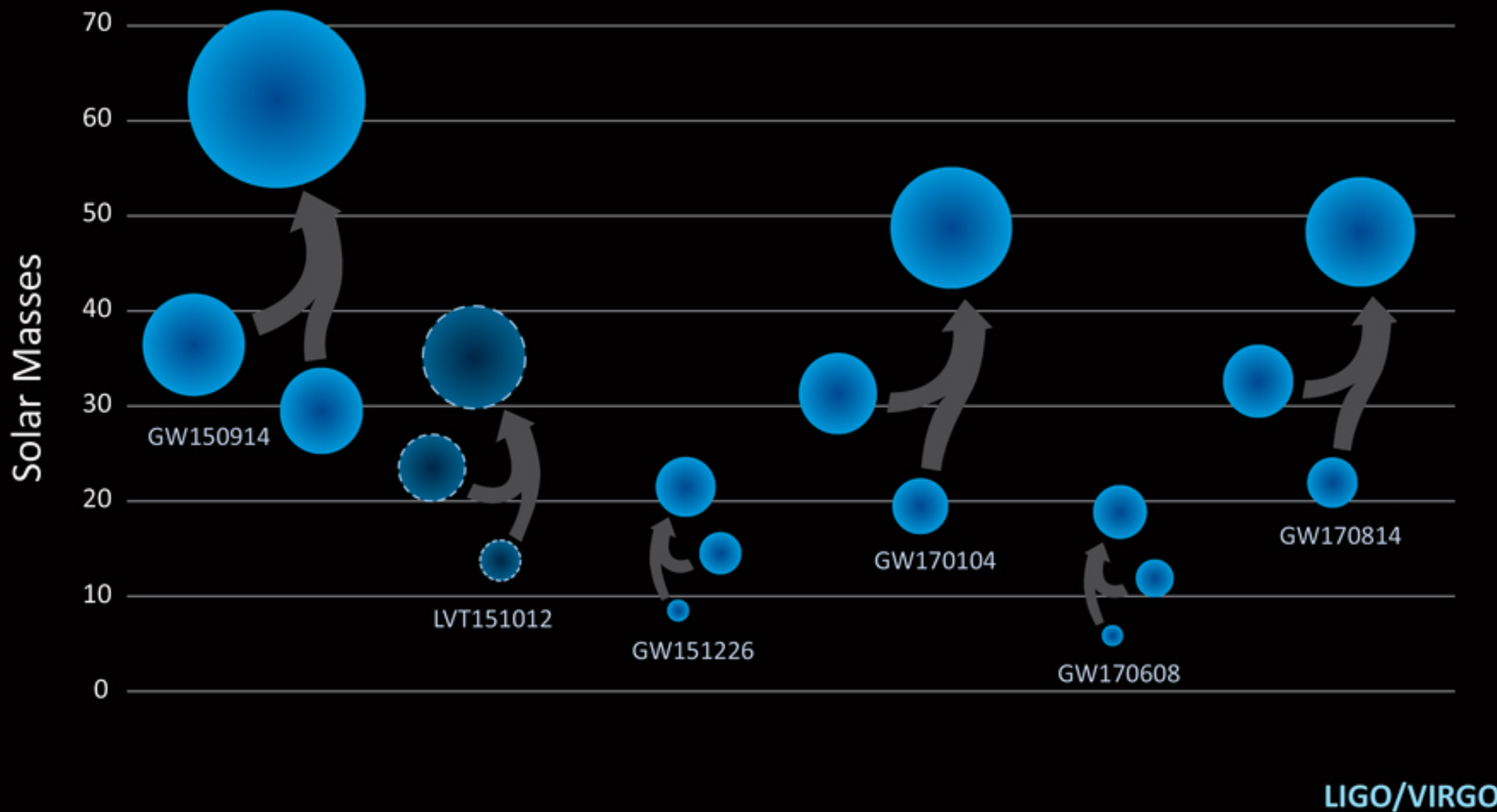


Image from LIGO website

Black holes in orbit

- Two sufficiently massive stars in a binary orbit will each eventually collapse to a black hole, leading to a binary black hole system

- In general relativity, all binary orbits are *unstable* :

  - the orbital motion produces gravitational waves, that carry energy away, causing the orbit to decay

  - this is a run-away process : the tighter the orbit, the faster the motion, leading to even stronger gravitational wave emission, hence faster orbital decay, …

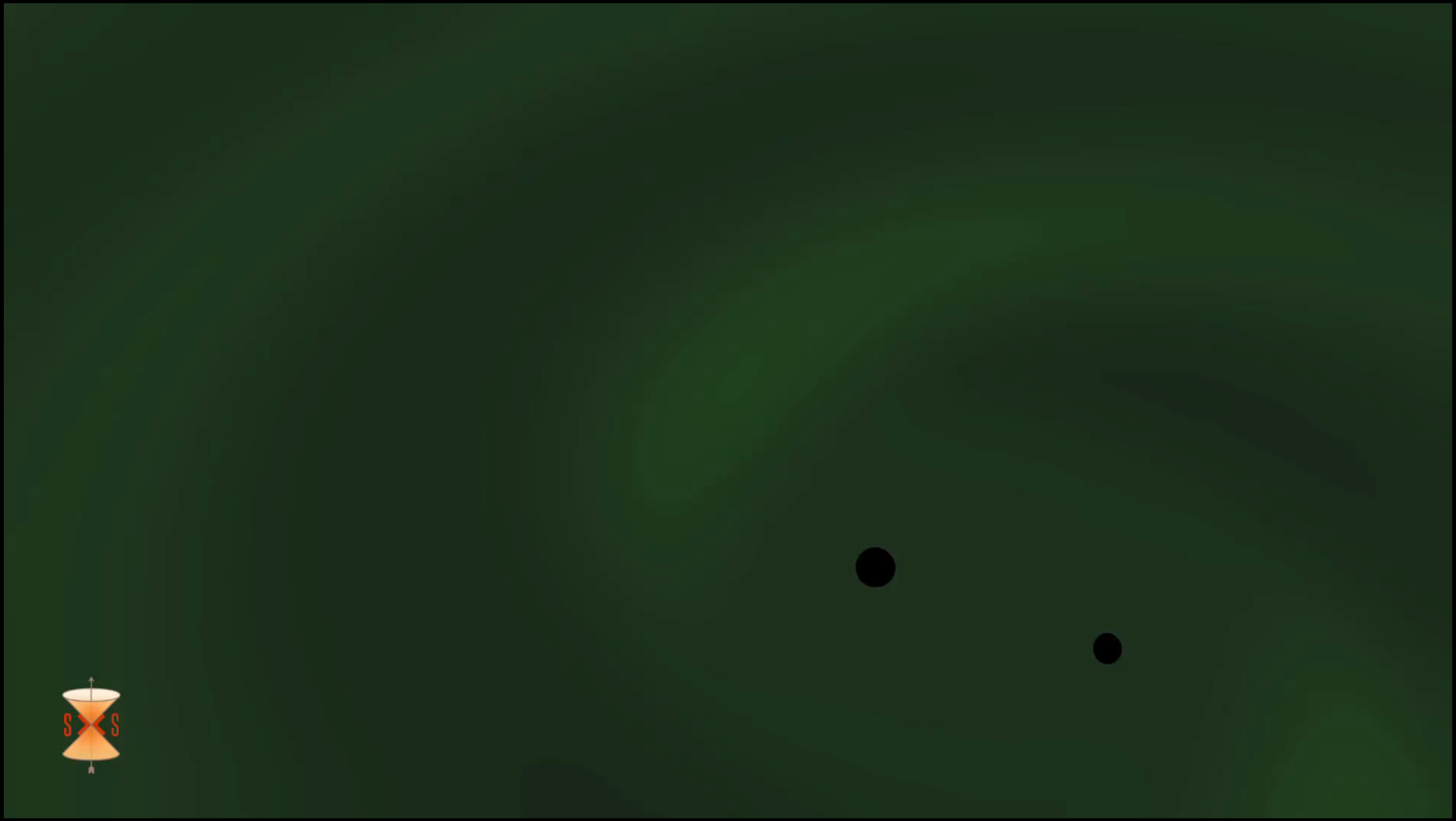
  - for black holes, this process ends when the two horizons meet, merging into a single horizon

  - initially the merged horizon is highly distorted and rotating, and continues to emit gravitational waves, but the emission rapidly quenches in a process called *quasi-normal ring down*

Gravitational waves from a simulation of GW150914

Slowed down by about 100x (total “real time” duration ~20ms)

~1000km (~600 miles)

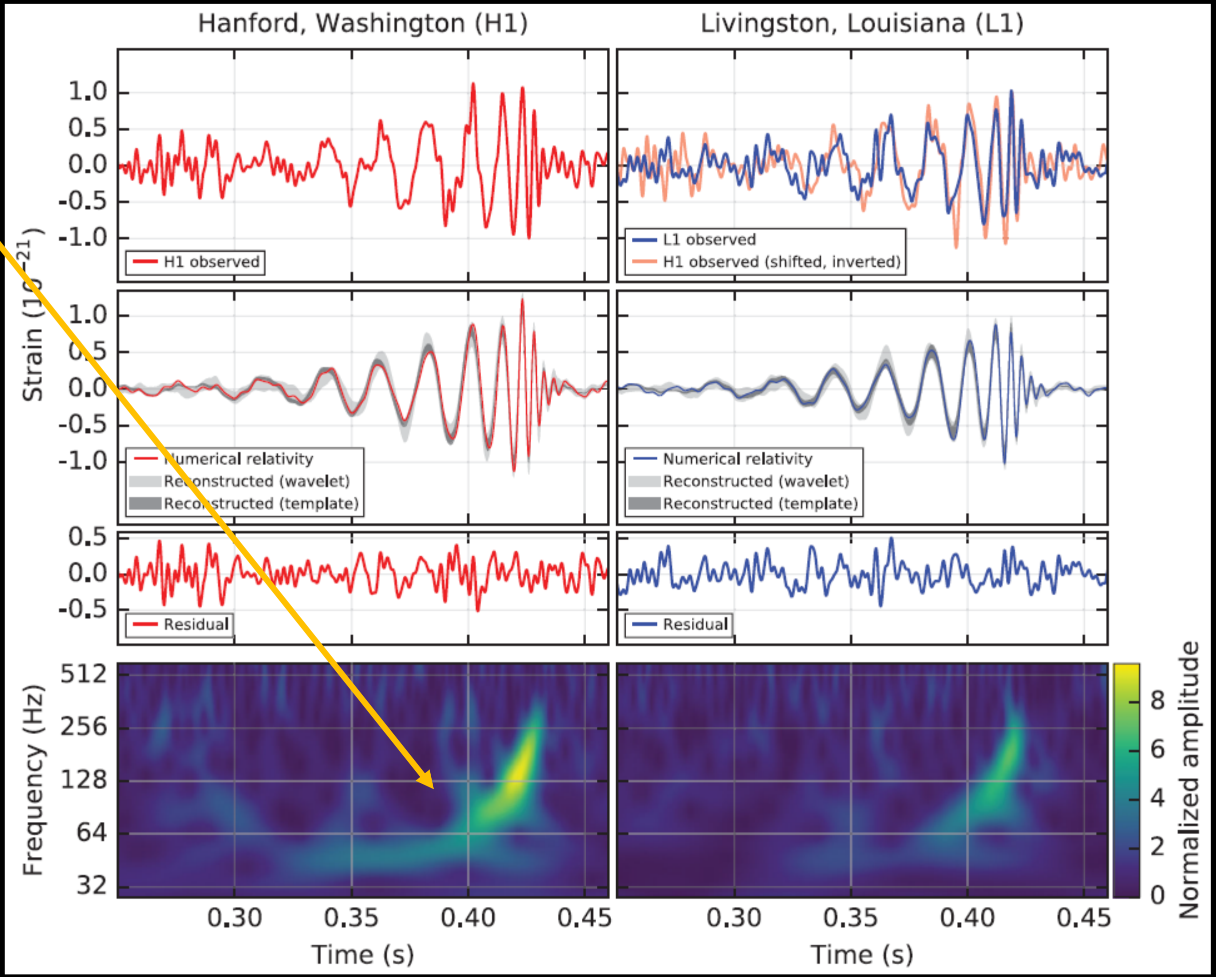


From the SXS collaboration (Caltech, Cornel, CITA, …)

Features of a black hole merger encoded in the signal of GW150914

The "chirp" is a characteristic of a runaway inspiral.

How fast the chirp ramps up in amplitude and frequency is related to the mass of the binary

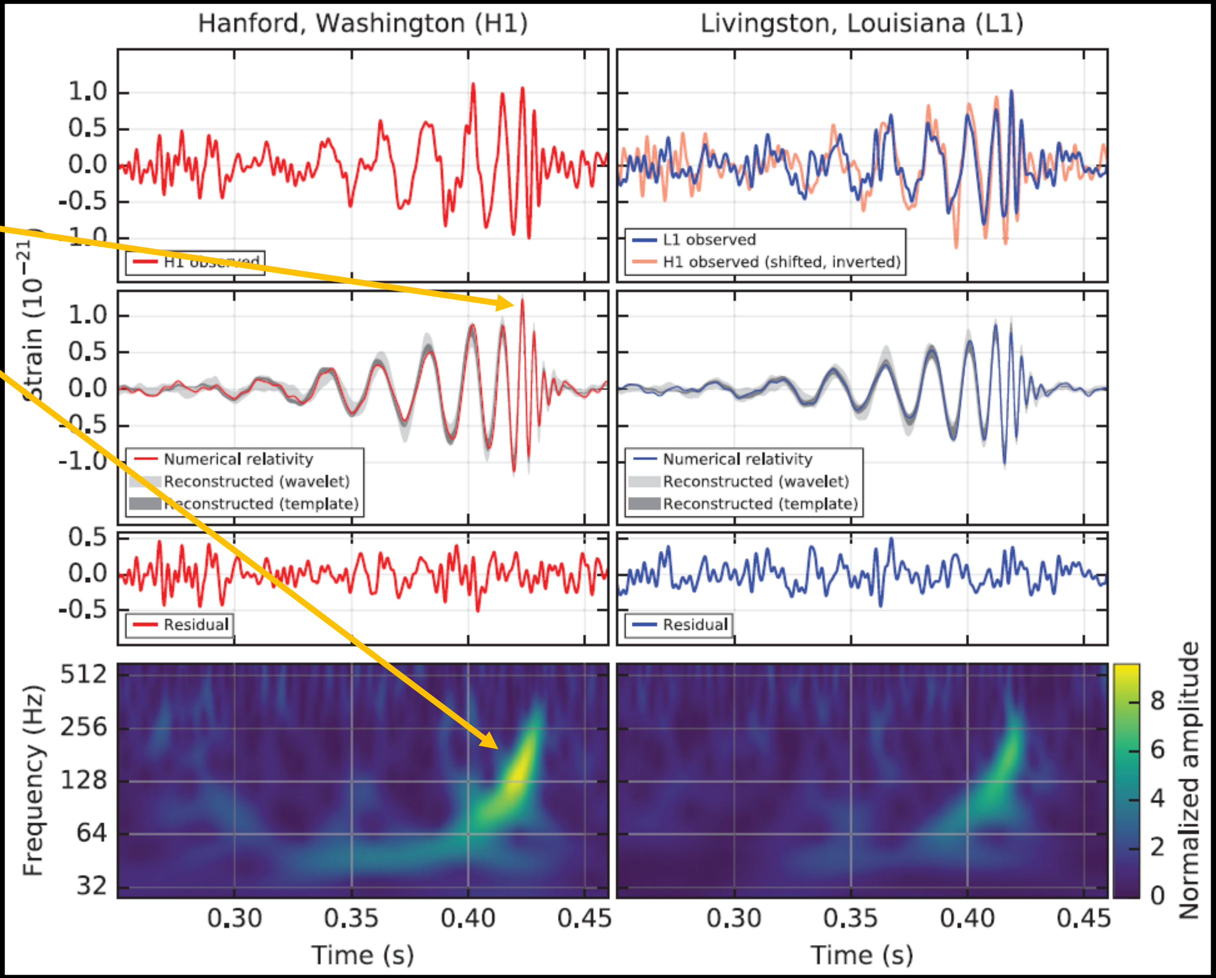


Plot by the LIGO & Virgo Collaboration

Features of a black hole merger encoded in the signal of GW150914

The frequency at peak amplitude can be related to the size of the two objects as they touched.

Combined with the chirp, this tells us two objects, with a total mass *65 times* that of the sun, were so compact they didn't touch until they were both contained within a diameter of ~1000km

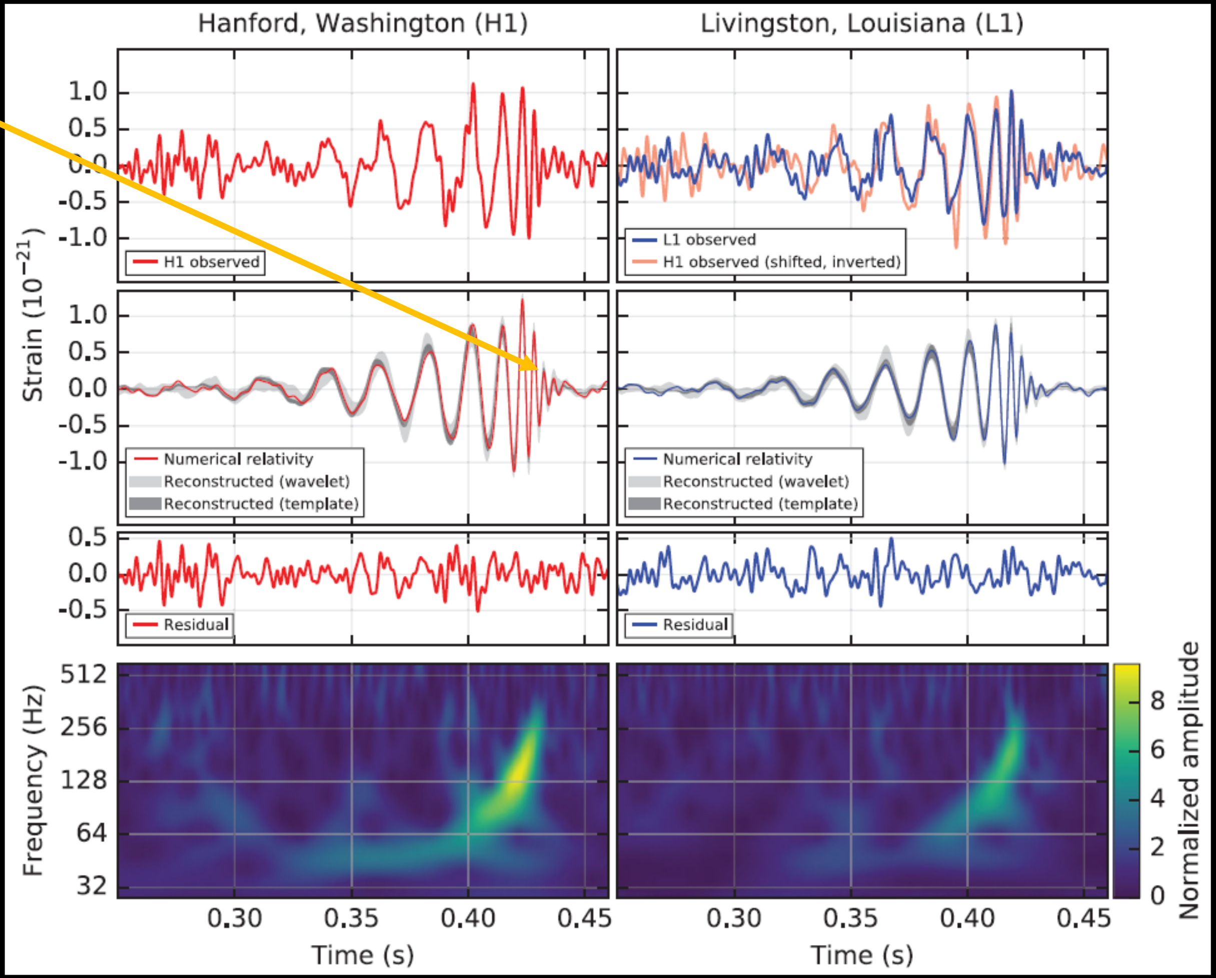


Plot by the LIGO & Virgo Collaboration

Features of a black hole merger encoded in the signal of GW150914

The rapid quenching of the signal is a hallmark of the quasi-normal ringdown of a black hole. Moreover, the frequency and decay rate tells as the mass (and spin) of the remnant; here it turns out to be 62 times that of the sun.

3 solar masses worth of energy were lost to gravitational waves in a few milliseconds!

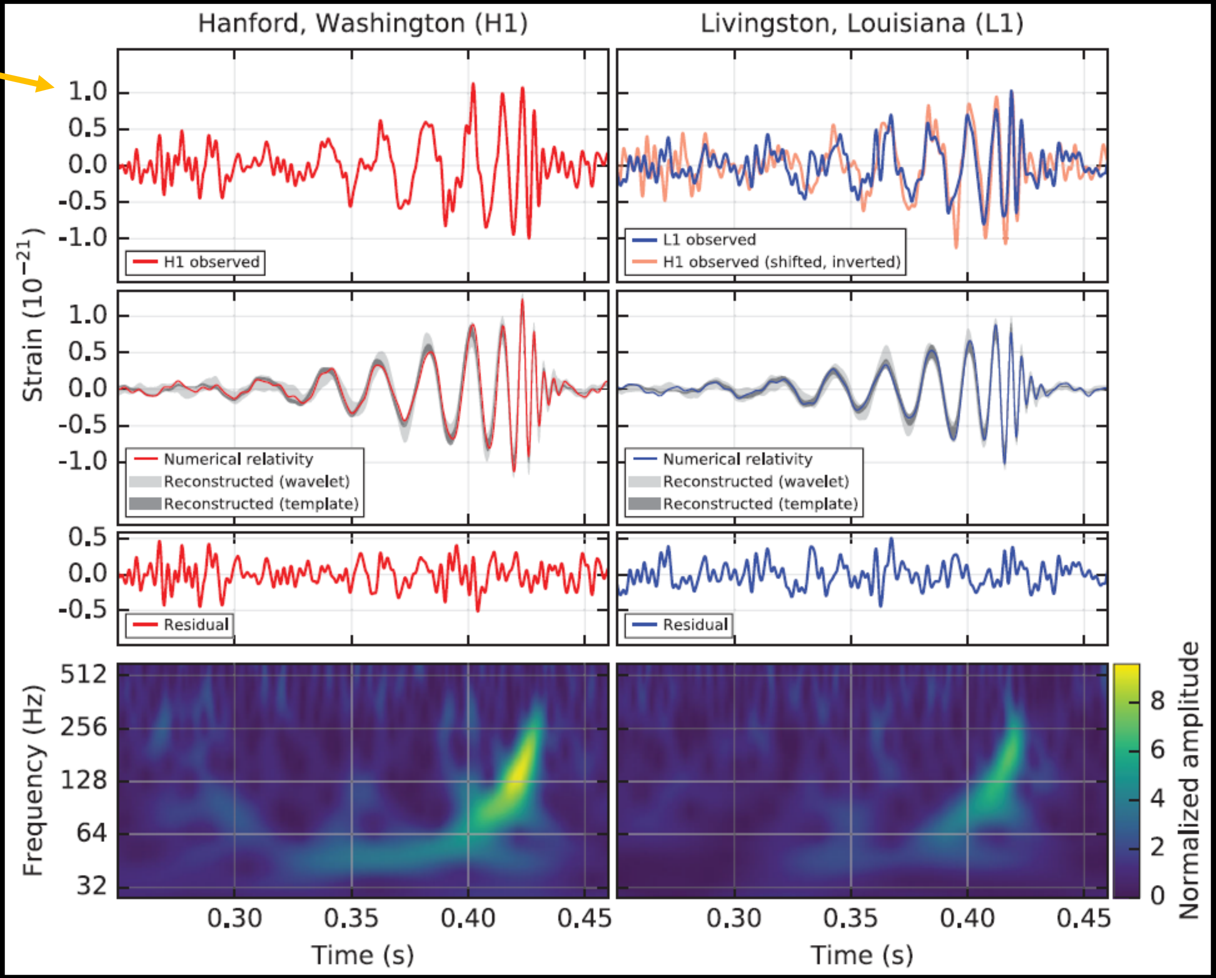


Plot by the LIGO & Virgo Collaboration

Features of a black hole merger encoded in the signal of GW150914

The measured amplitude of the gravitational wave here on earth tells us how far away the merger happened.

This event occurred about 1.2 billion light years away



Plot by the LIGO & Virgo Collaboration

Conclusion

- Black holes are one of the most bizarre and remarkable predictions of general relativity
  - the contrast between the scientific community's acceptance of them comparing the first to second half-centuries of general relativity is stark :
    - before the 60's they were dismissed by most as mathematical curiosities irrelevant to the real universe
    - after the 70's they become a part of our description of the universe people almost take for granted, despite only circumstantial evidence for their reality
- In 2015, 100 years after Einstein's publication of general relativity, LIGO has finally given us direct evidence that the black holes of the theory do exist
  - it's not a precise confirmation yet, but these are the early days of the new era of gravitational wave astronomy, and the best is yet to come!