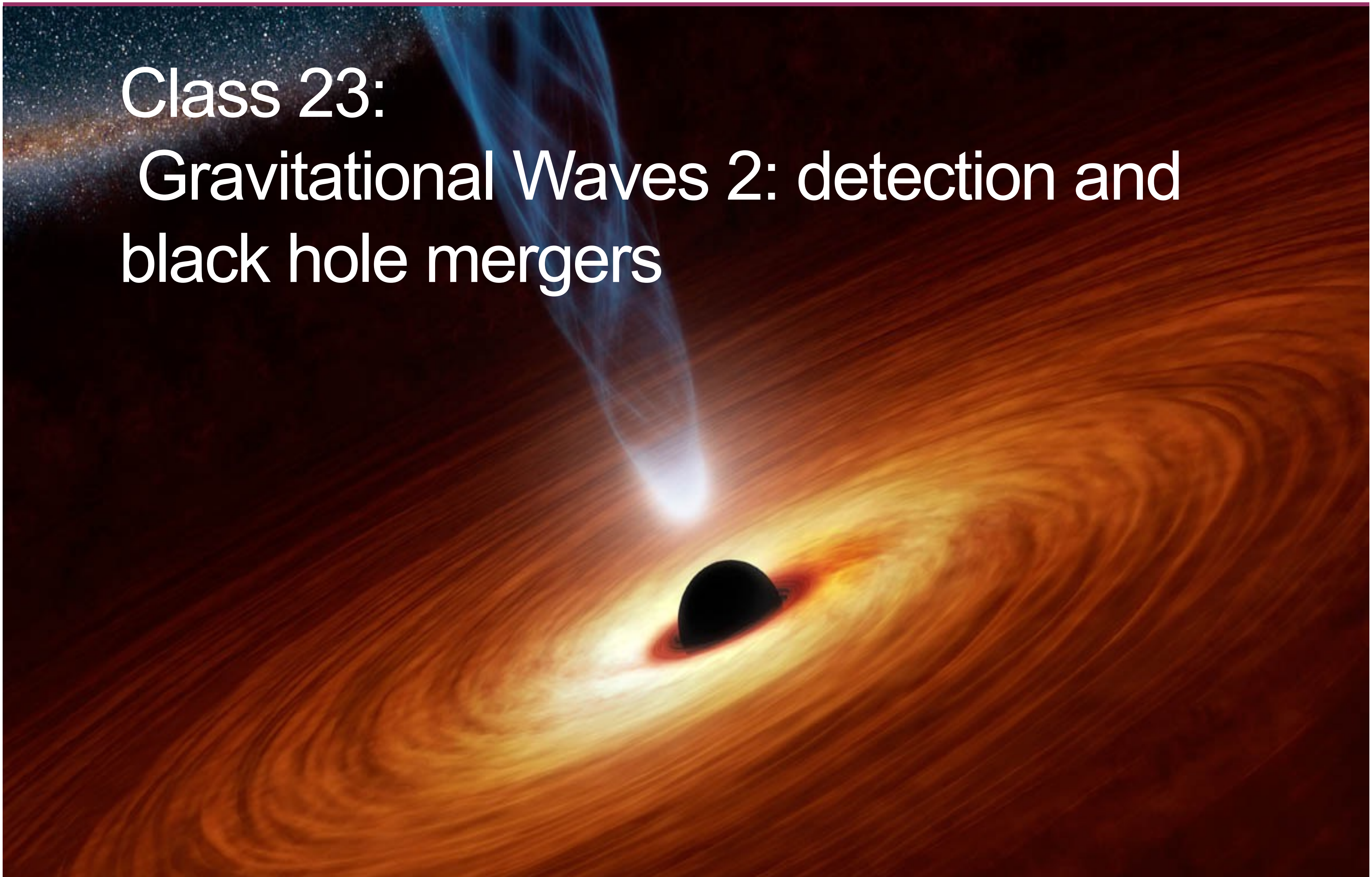


Class 23:
Gravitational Waves 2: detection and black hole mergers

ASTR350 Black Holes (Spring 2022)

Cole Miller

Recap

- Gravitational waves are ripples in spacetime predicted by Einstein's theory of General Relativity
- When GWs go by, they change the distances between things. However, the distance change is ludicrously tiny unless the GWs are caused by massive things moving really fast, and not too far away
  Black holes and neutron stars!

This Class

- Even for "big" gravitational waves at Earth, the distance changes are really, really, small (often less than the diameter of a proton)
- How do we detect them?
- And what kind of sources make gravitational waves?
  Relation to black holes

Direct detection of gravitational waves

- How do you search for gravitational waves?
- Small distortions in space-time curvature show up as weak oscillatory tidal forces
- Pioneered by Joseph Weber (former UMd Professor)
  - Thinking about binary neutron stars, he estimated wave frequency (10,000Hz)
  - Looked for resonant "ringing" in a metal bar caused by passage of gravitational wave.
  - Weber claimed detection in early 1970s
    - but his sensitivity was $dL/L \sim 10^{-17}$
    - too low to detect the signals we now know exist
  - Never verified – but Weber held out to the end…

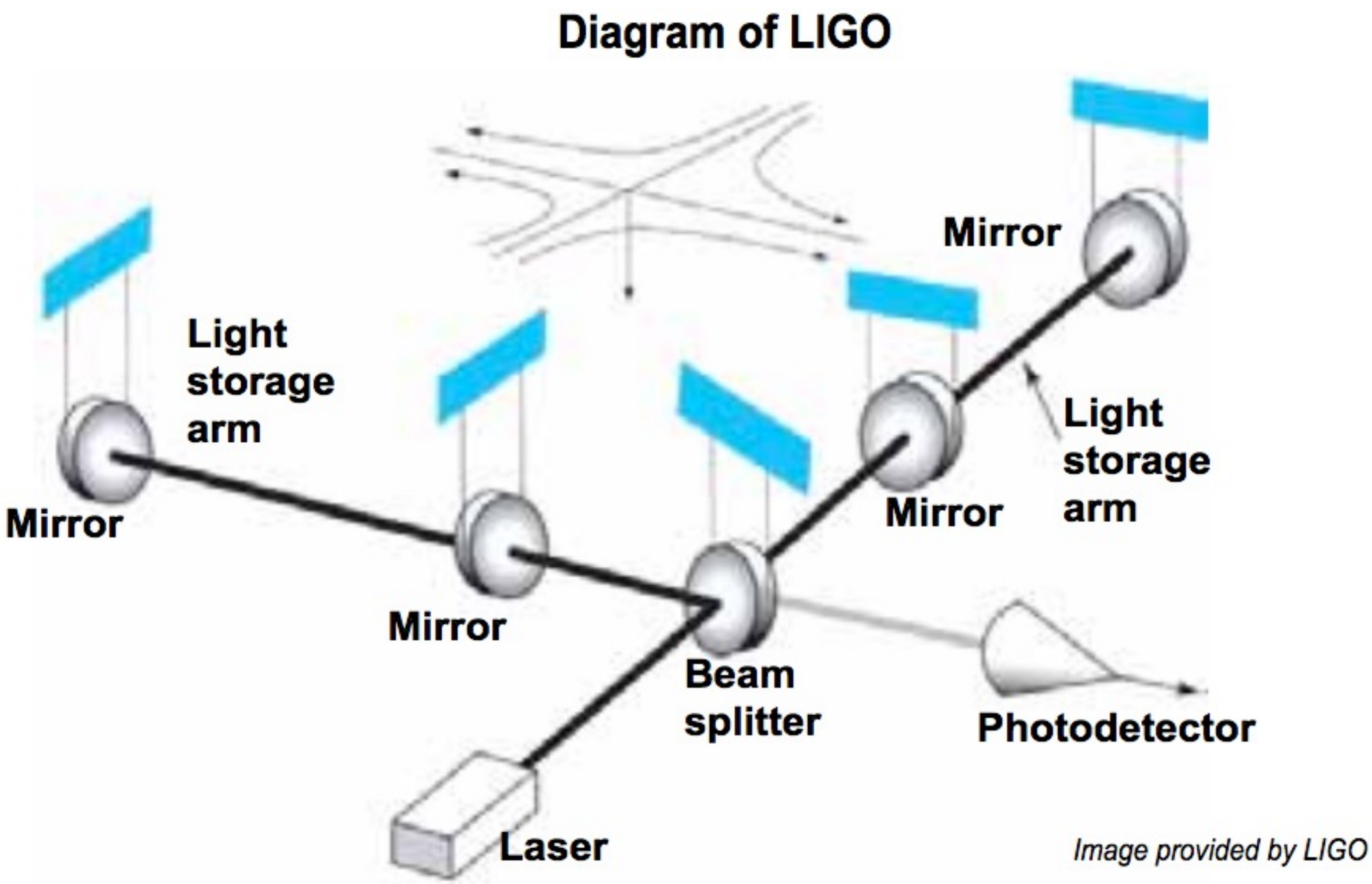
AIP Emilio Segrè Visual Archives

Weber Bars Outside of PSC

HOW WE LOOK FOR (AND HAVE DETECTED!) MERGING BLACK HOLES….LIGO

$h \leq 10^{-22}$; can build $L = 4$ km;
must measure $\Delta L = h L \leq 4\times10^{-19}$ m

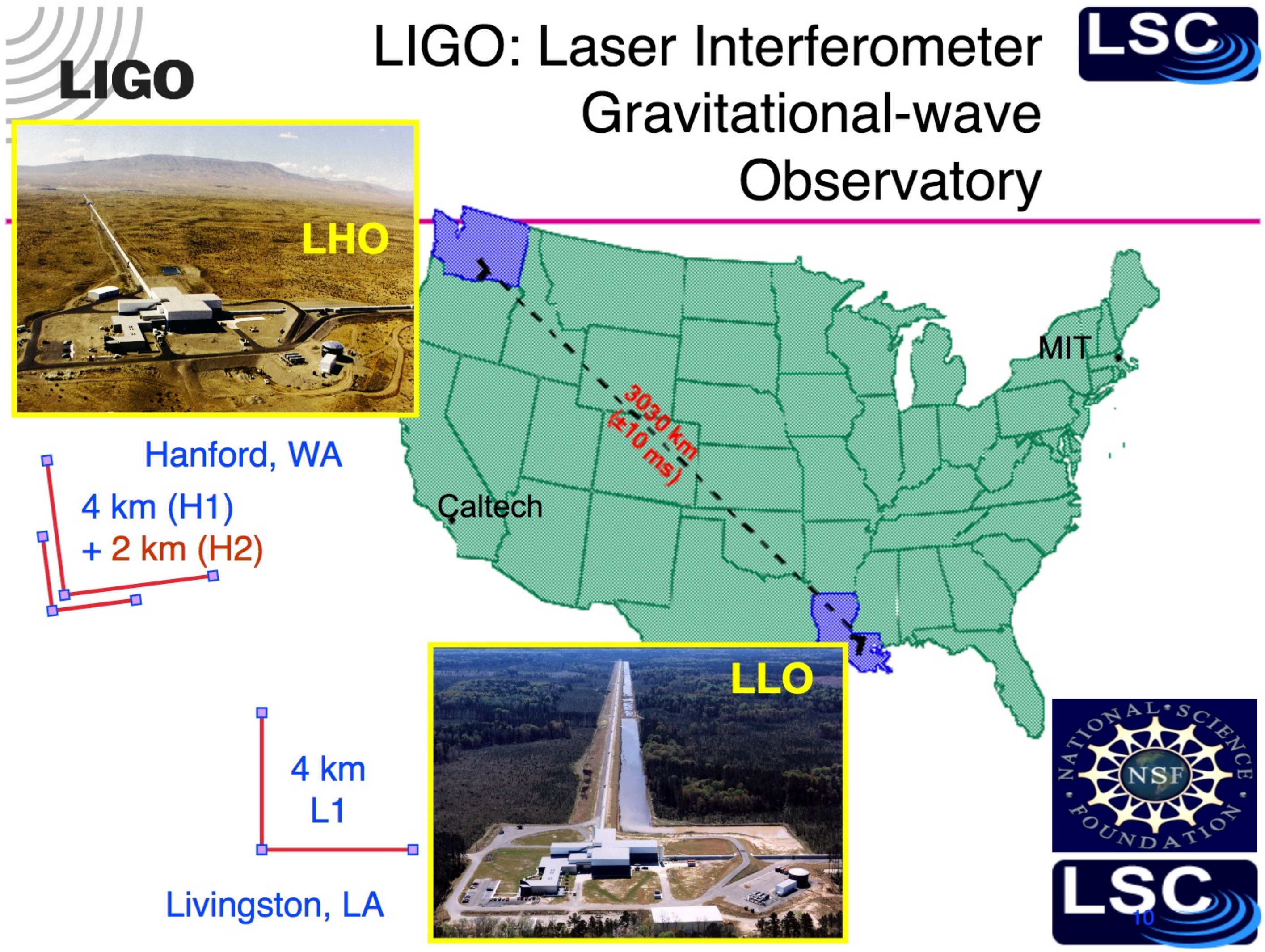
LIGO is an interferometer



The LIGO interferometers

- The difference between the two arm lengths is proportional to the strength of the passing gravitational wave, referred to as the **gravitational-wave strain**, and this number is VERY small. For a gravitational wave typical of what is expected the strain is ~1/10,000th the width of a proton!
- However LIGO's interferometers are so sensitive that they can measure even such tiny amounts.

Two Sites Operating - allows better positions and reduction of false detections



Detection of GRAVITATIONAL WAVES

.

LIGO researchers sensed a wave that stretched space by **one part in 10^{21}**, making the entire Earth expand and contract by 1/100,000 of a nanometer, about the width of an atomic nucleus

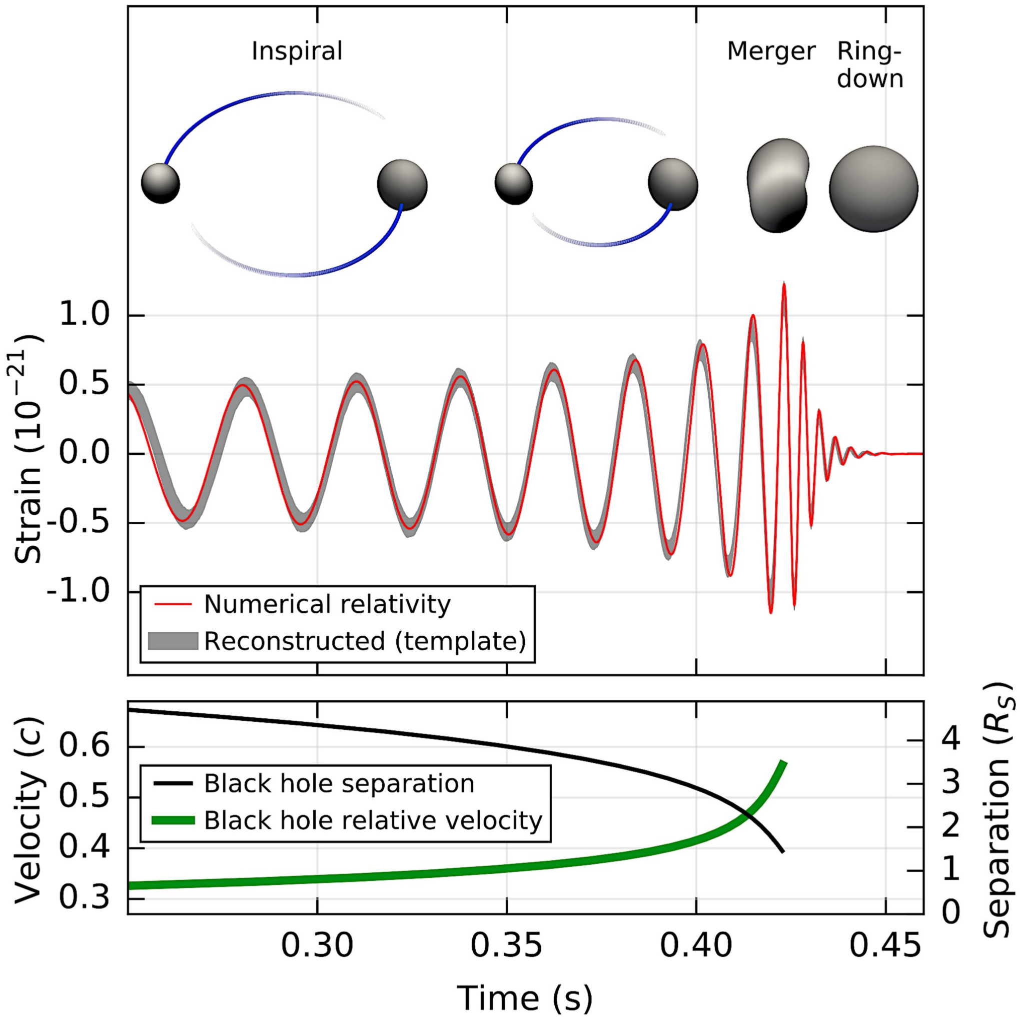
Incredibly small! Detectable using the advanced instrumentation of LIGO (and Virgo and KAGRA), but you need a little more help...

Numerical relativity

Because the GW signal is so weak, one has to develop very sophisticated algorithms to detect them in the presence of (lots) of noise

LIGO uses the idea of 'matched filtering'- e.g. look for a signal that 'looks like' a GW wave- called a template.

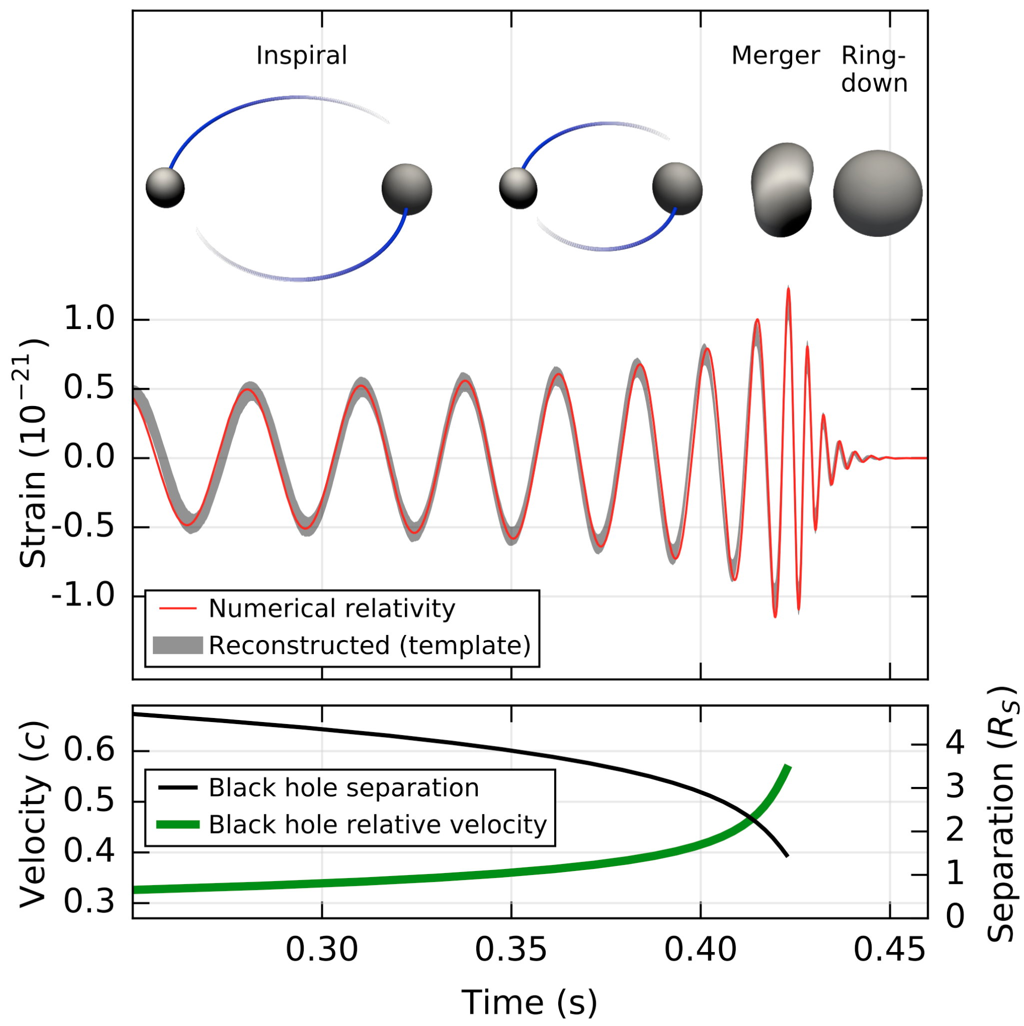
How do you know that this looks like?- **Numerical relativity**



Numerical relativity

One has to develop templates that cover a wide range of parameters

- ratio of the two masses
- spin of the black holes
- velocity of BHs



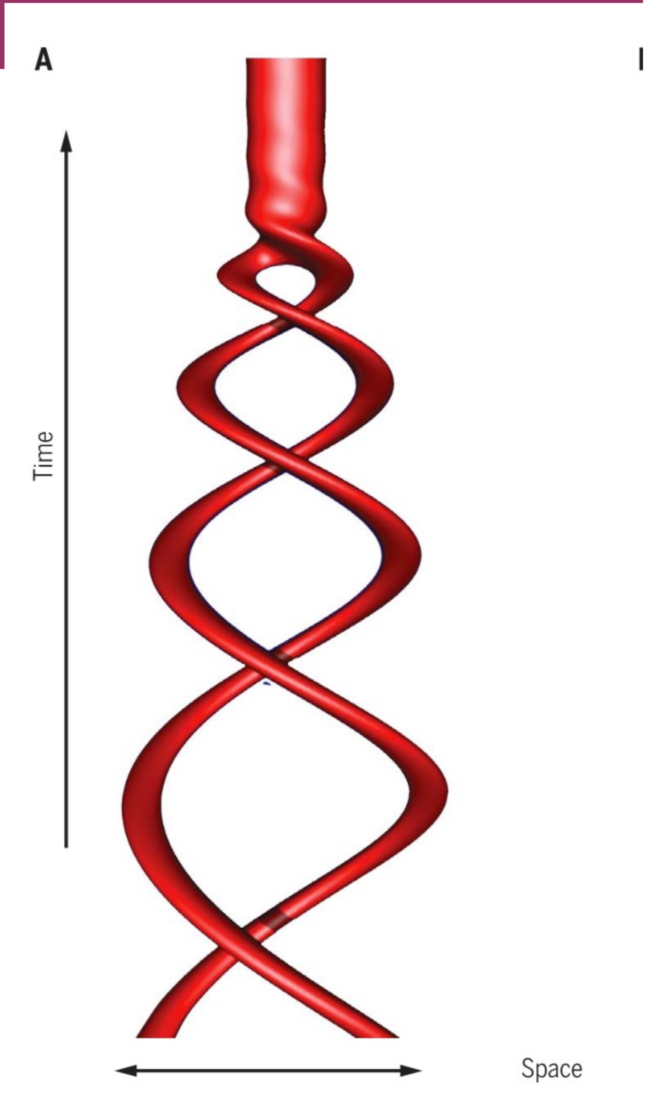
This generation of templates is NOT EASY

to quote from Centrella et al 2010:

for many years, numerical relativists attempting to model these mergers encountered a host of problems, causing their codes to crash after just a fraction of a binary orbit could be simulated.

Numerical GR

- For numerical implementations, the first step is to write the Einstein equations as a well-posed system of partial differential equations(PDEs) for the metric.
  - 10 coupled, nonlinear PDEs for the 10 independent components of the metric
- a typical numerical relativity simulation for a binary coalescence, representing just a single data point in a template catalog, take ~1 month on 1000 to 10,000 cores of a supercomputer.

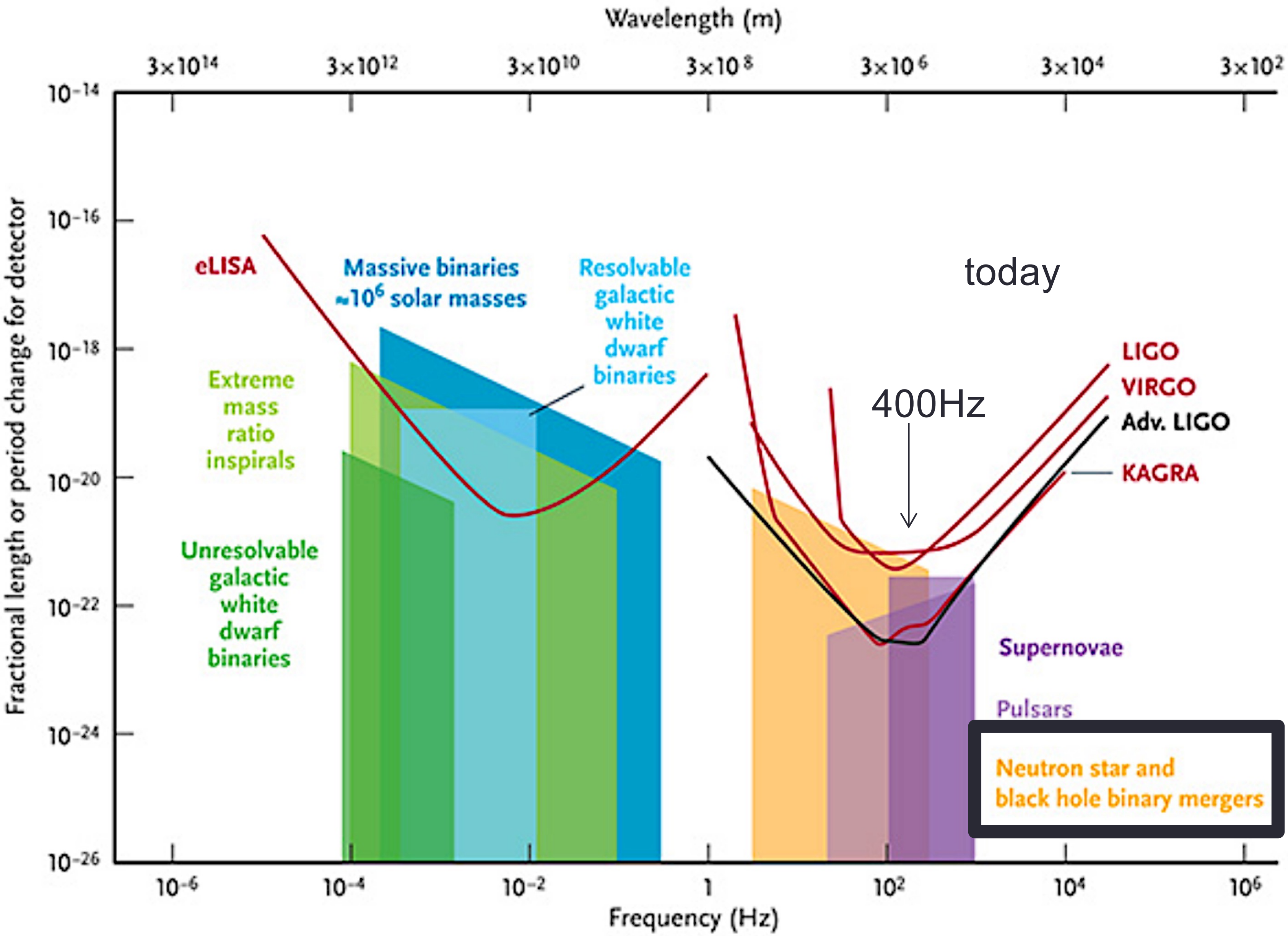


space time diagram of a merger

III: Gravitational Waves and Black Holes

- Suppose that there is a binary star system where both stars are quite massive…
  - The more massive star goes supernova ➔ black hole
  - May have an X-ray binary phase
  - Second star goes supernova ➔ black hole
  - We now have a binary black hole system!
  - Black holes orbit around common center of mass
  - They gradually lose energy to gravitational waves
  - Eventually, they will merge together
- Final gravitational wave pattern is complicated and needs computer simulations. Such simulations have only been possible for past 12 years!

Phase Space of Compact Object Mergers that Produce Gravitational Waves



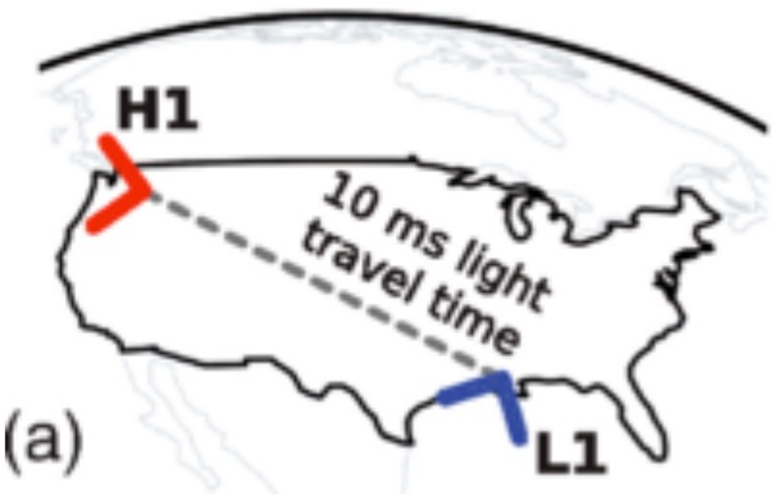
V: Detection of GW150914

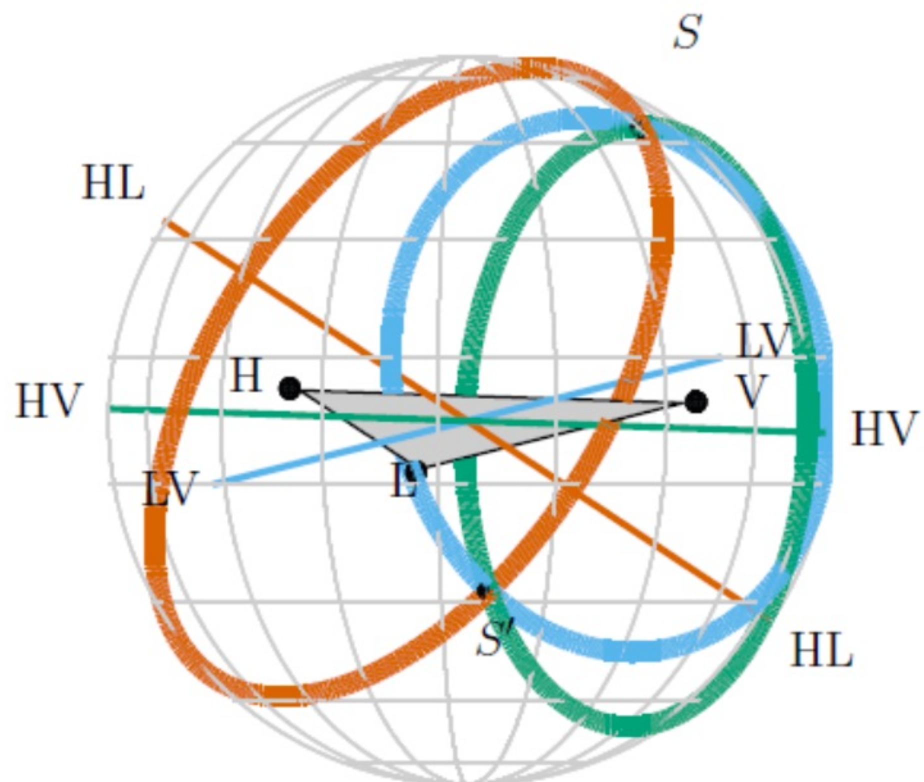
- LIGO detected its first GW signal on 14th Sept 2015 (announced on 11th February 2016)
  - 36 M_{sun} + 29 M_{sun} ➔ 62 M_{sun} (interesting? Add the two initial masses...)
  - Peak power ~4×10^{49}W
    - total energy $5.3(+0.9/-0.8)\times10^{47}$ Joules $=3.0(+0.5/-0.5)\ c^2\ M_{\odot}$

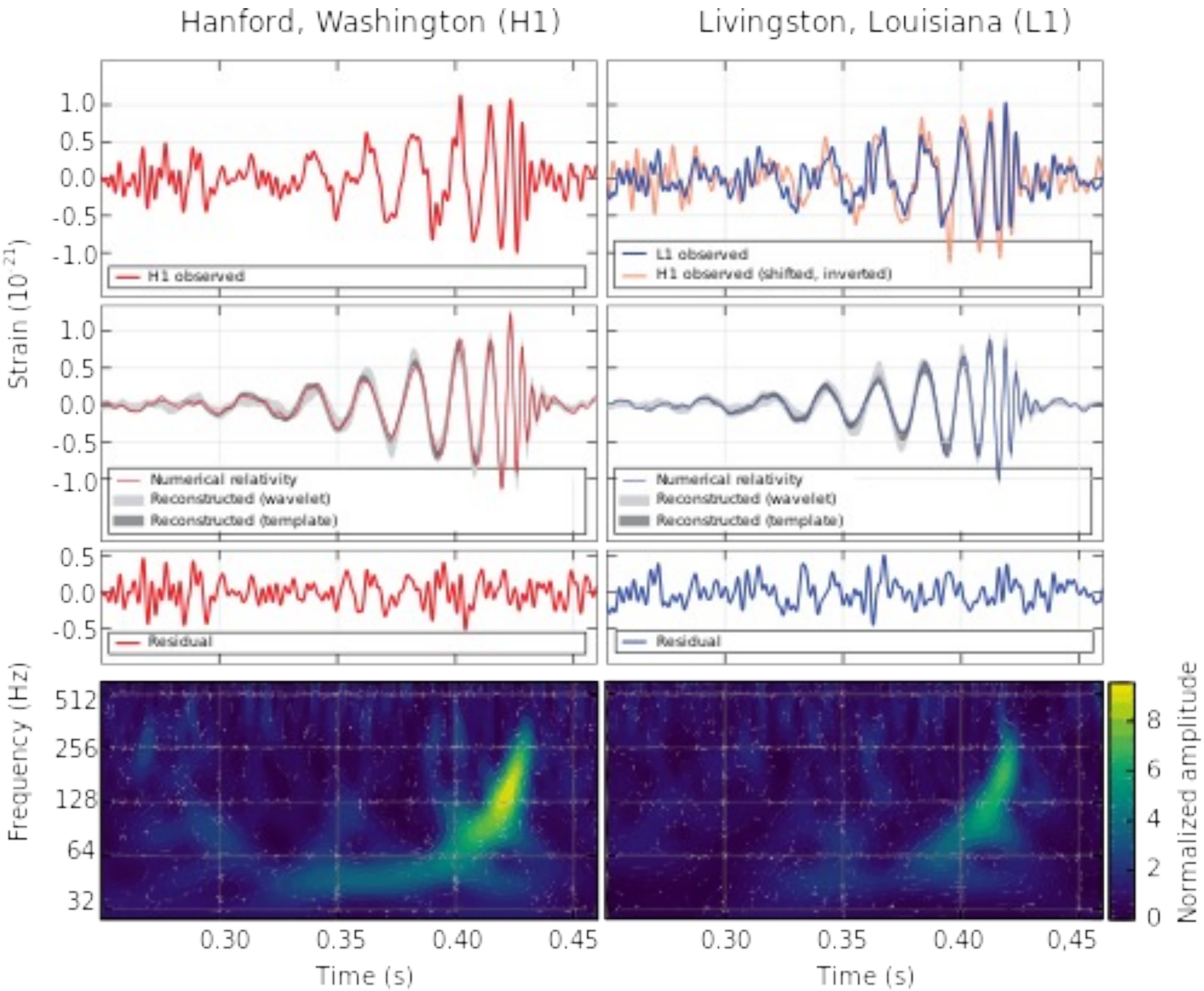
      3 solar masses were converted into gravitational wave energy
  - Distance 440Mpc (redshift 0.093)
  - Hard to localize on the sky

Sky localization (RA, DEC)

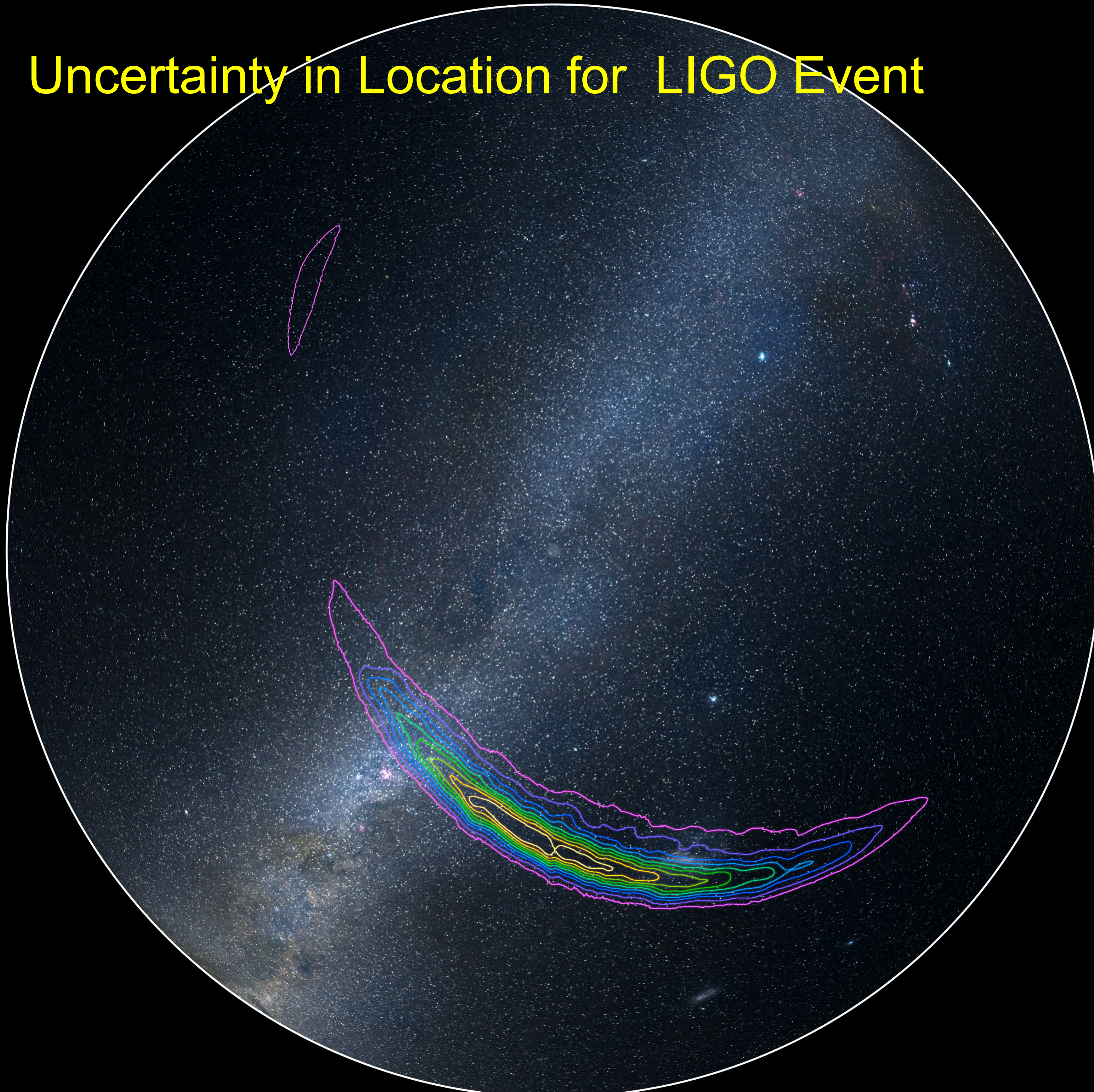
Measured by time delay between two detectors
(+ phase, + amplitude)



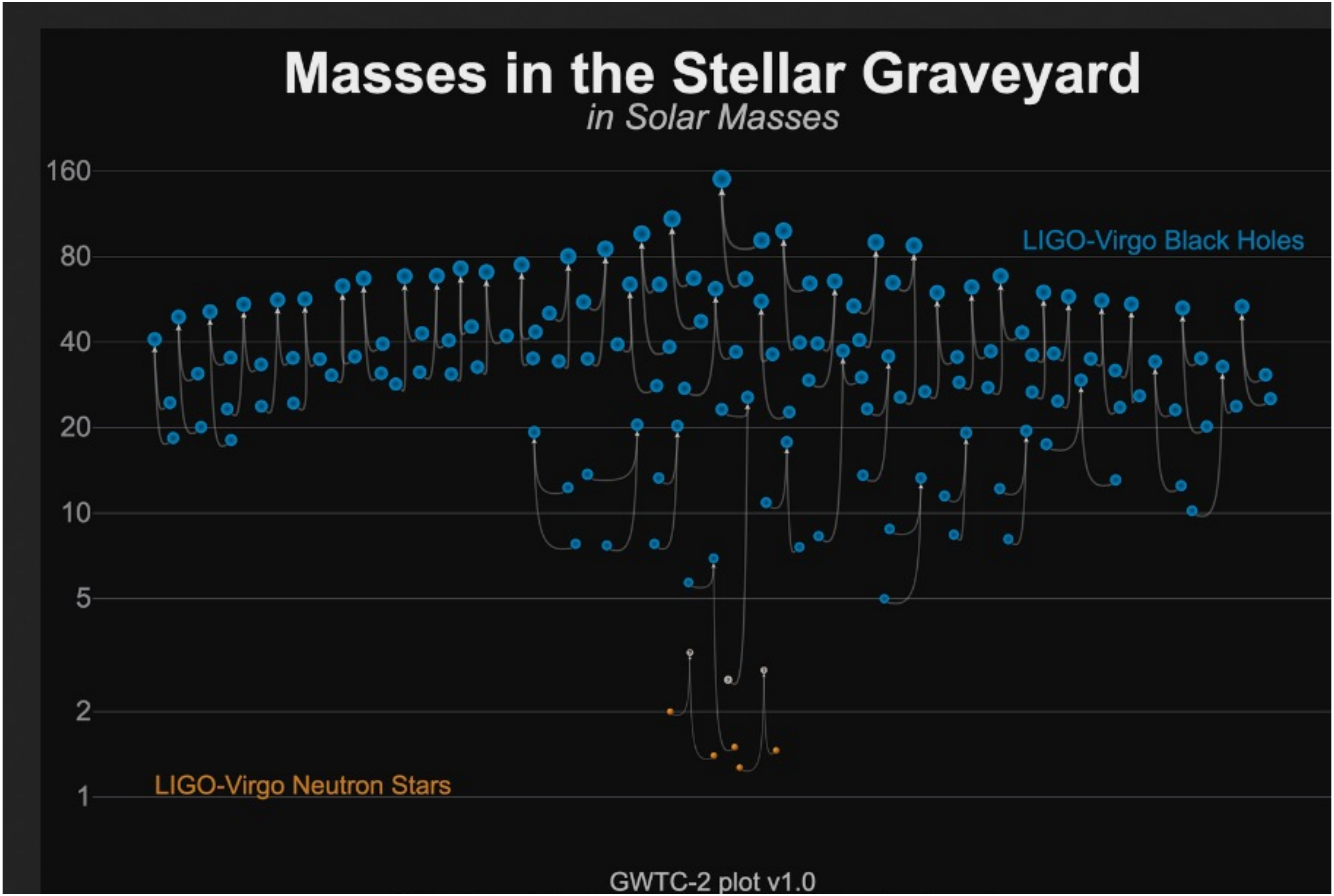



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)

Uncertainty in Location for LIGO Event



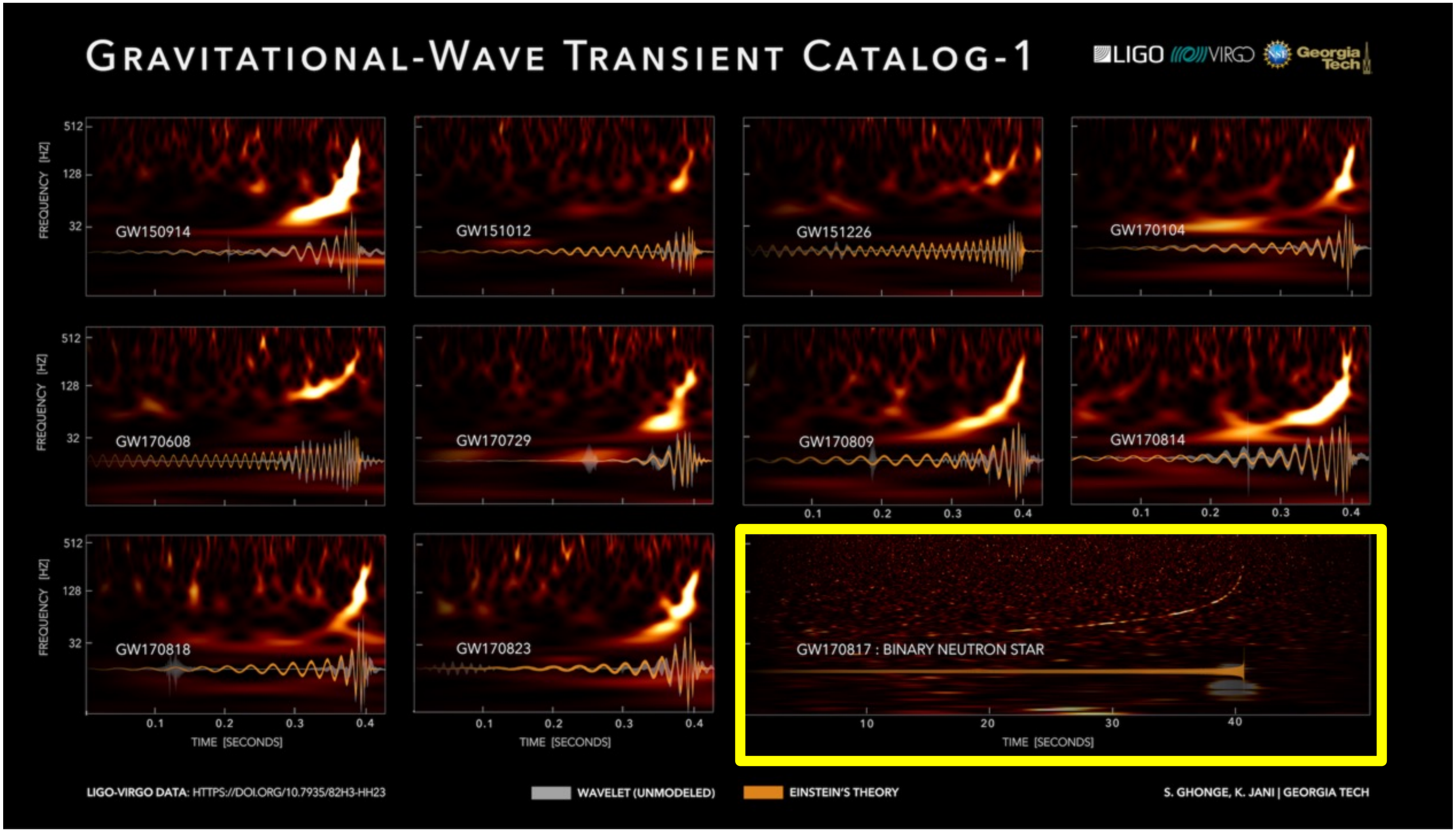
New LIGO Detections- 40 BH Mergers, 2 NS Mergers



The only electromagnetic counterpart!

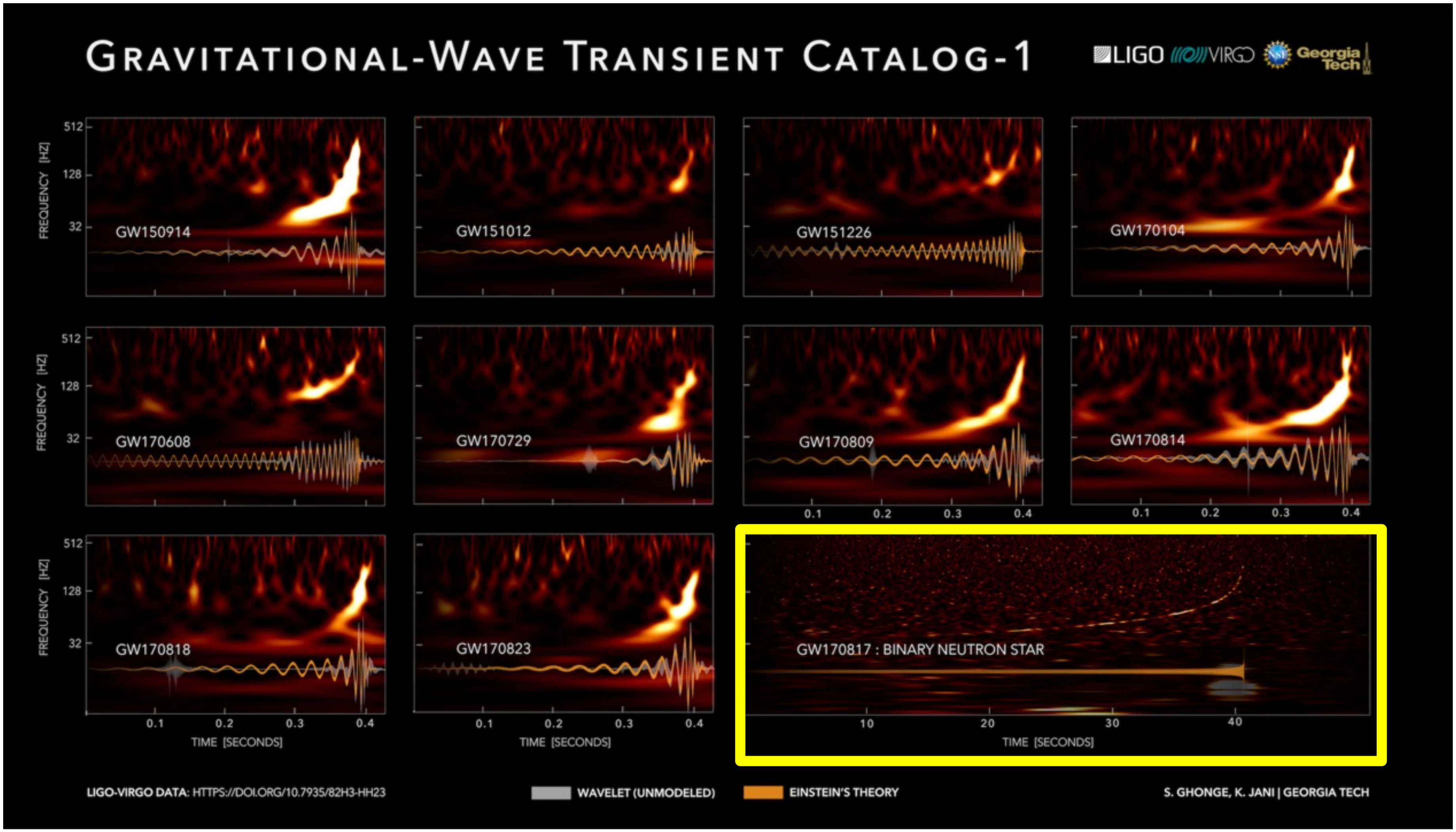
So far the only GW signal that has a counterpart is the merger of two **neutron stars**....GW1708017

The gravitational wave signal is due to the collision of two neutron stars with a total mass of 2.82(+0.47/−0.09) $M_\odot$ notice the very different waveform and timescale



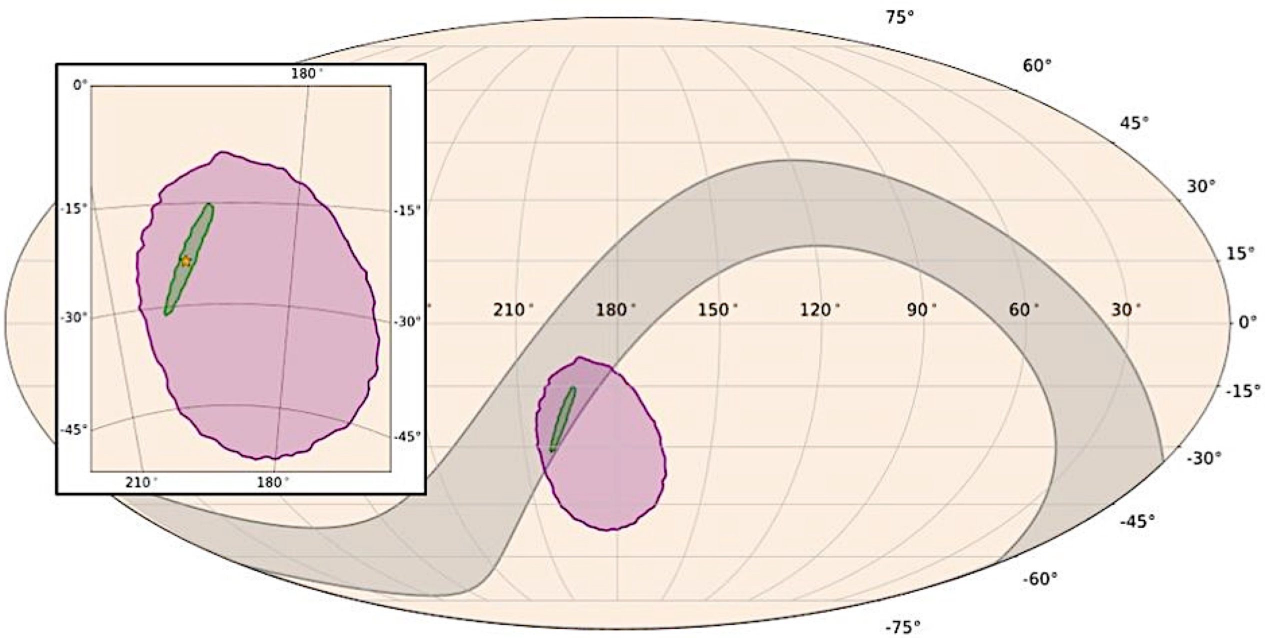
The only electromagnetic counterpart!

The source was 40Mpc away and positional uncertainty was only 16 sq degrees- VERY DIFFERENT than other GW signals



Lucky and Good

- Within 2 sec of the GW event a gamma-ray burst occurred in more or less the same part of the sky
- This was the closest GRB that has ever been seen -40Mpc
- Radically different than the other GW signals
- This allowed a optical counterpart to be identified



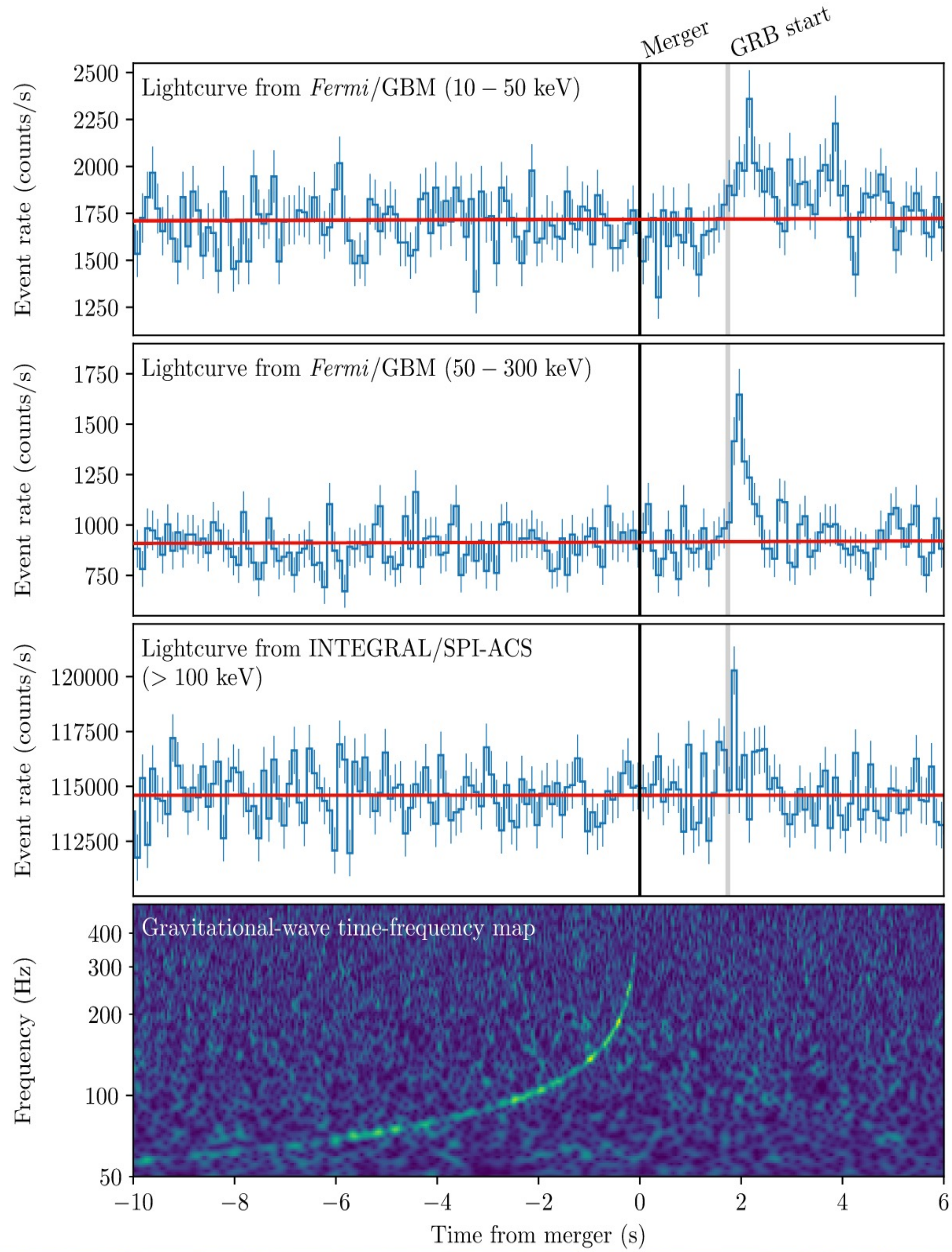
Green is GW positional uncertainty **16 sq degrees**
Purple is GRB uncertainty

Gamma-Ray Burst and GW Event

GRB occurred 2 sec after merger- it was a short GRB, which had been predicted to be produced by merger of 2 NS

The gamma ray burst comes after the gravitational waves because first you have to smash the objects together, then the material is warmed up, and then you get the radiation. So you would expect to see the gravitational waves first.

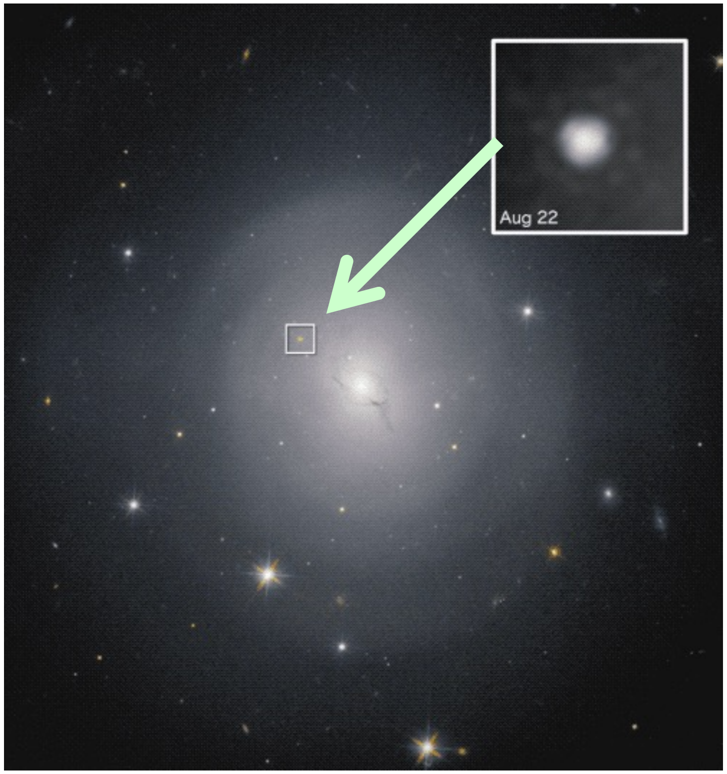
GW signal indicated that this indeed was the case



Identification of Optical Counterpart

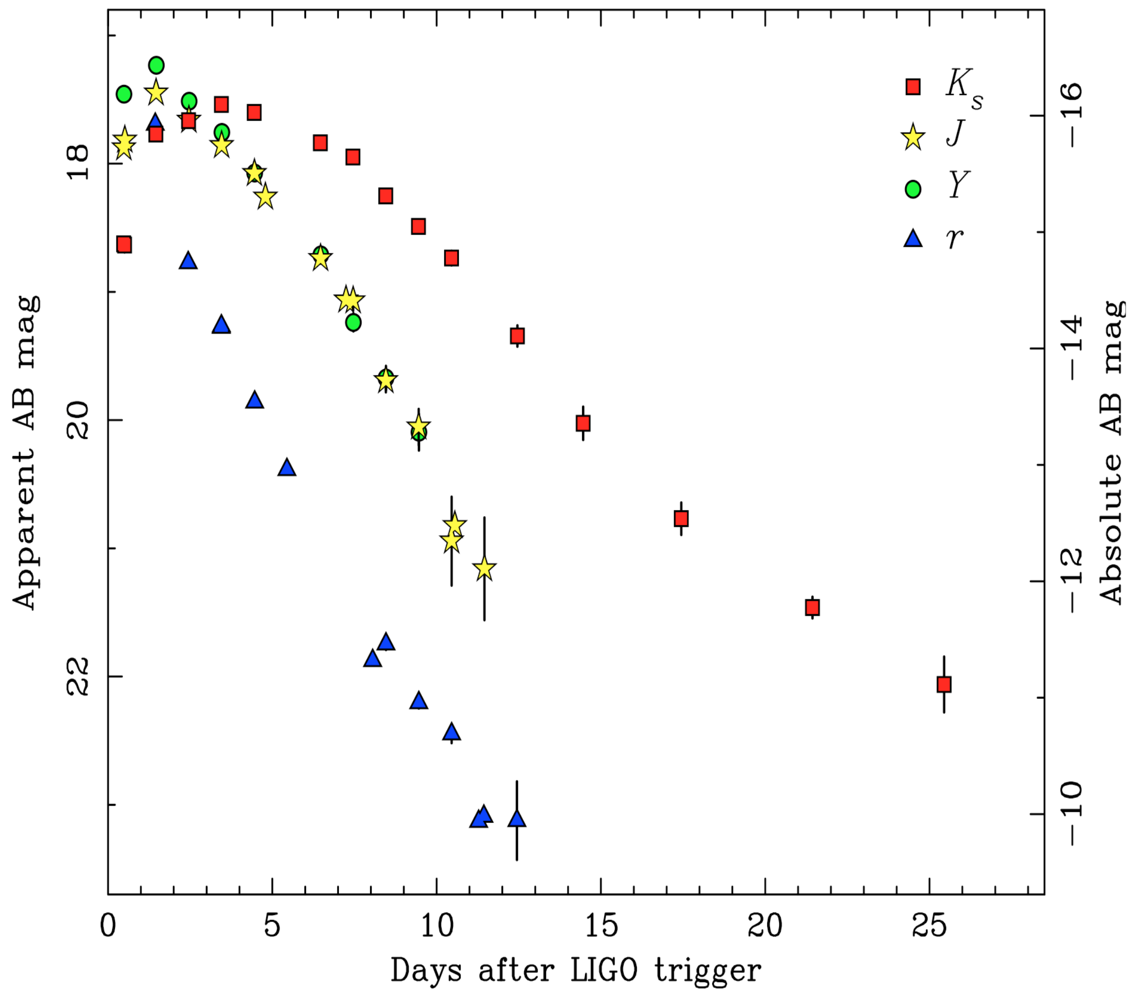
The GW positional uncertainty of 16 square degrees was much smaller than any previous or following event allowing a search for a counterpart in optical, x-ray and radio.

The GW signal indicated a distance to the source of ~40Mpc and thus a focused search on massive galaxies at the 'right distance' and right position revealed a 'new' transient in the galaxy NGC 4993



Afterglow

The optical source faded rapidly and had a optical-IR spectrum different than anything seen before- but was very similar to theoretical predictions of what a NS-NS merger would look like (a kilonova). The optical afterglow is powered by radioactive decay of very heavy elements (including gold and platinum) very different than a type I SN



It was detected in the X-rays 9 days later and 16 days later in the radio.

This is so far the only GW event with an electromagnetic counterpart!

LIGO Results

- Confirms that black holes really do exist — at least as the perfectly round objects made of pure, empty, warped space-time that are predicted by general relativity.
- Confirms that mergers between two black holes proceed as predicted e.g. gravitational waves are radiated as the two black holes start to spiral towards each other.
- Gravitational waves travel at the speed of light
- Allows the estimate of the masses (so far 18-130$M_{\odot}$) of the 2 objects merging, spins and their distance from us.
  - Based on LIGO sensitivity one can detect merger of massive BHs out to ~5000Mpc
  - So far almost all the mergers of been of roughly equal mass BHs
  - One NS-NS merger with an optical counterpart-new type of object a kilonova

BREAKTHROUGH OF THE YEAR

Cosmic convergence

The merger of two neutron stars captivated thousands of observers and fulfilled multiple astrophysical predictions

On 17 August, scientists around the world witnessed something never seen before: One hundred and thirty million light-years away, two neutron stars spiraled into each other in a spectacular explosion that was studied by observatories ranging from gamma ray detectors to radio telescopes. The blast confirmed several key astrophysical models, revealed a birthplace of many heavy elements, and tested the general theory of relativity as never before. That first observation of a neutron-star merger, and the scientific bounty it revealed, is *Science*'s 2017 Breakthrough of the Year.

Especially remarkable was the way the event was spotted: by detecting the infinitesimal ripples in space itself, called gravitational waves, that the spiraling neutron stars radiated before they merged. Scientists first detected such waves just 27 months ago, when the Laser Interferometer Gravitational-Wave Observatory (LIGO) sensed a space tremor from two massive black holes spiraling together in an invisible cataclysm. The discovery of gravitational waves was *Science*'s 2016 Breakthrough of the Year.