The problem(s) with binaries

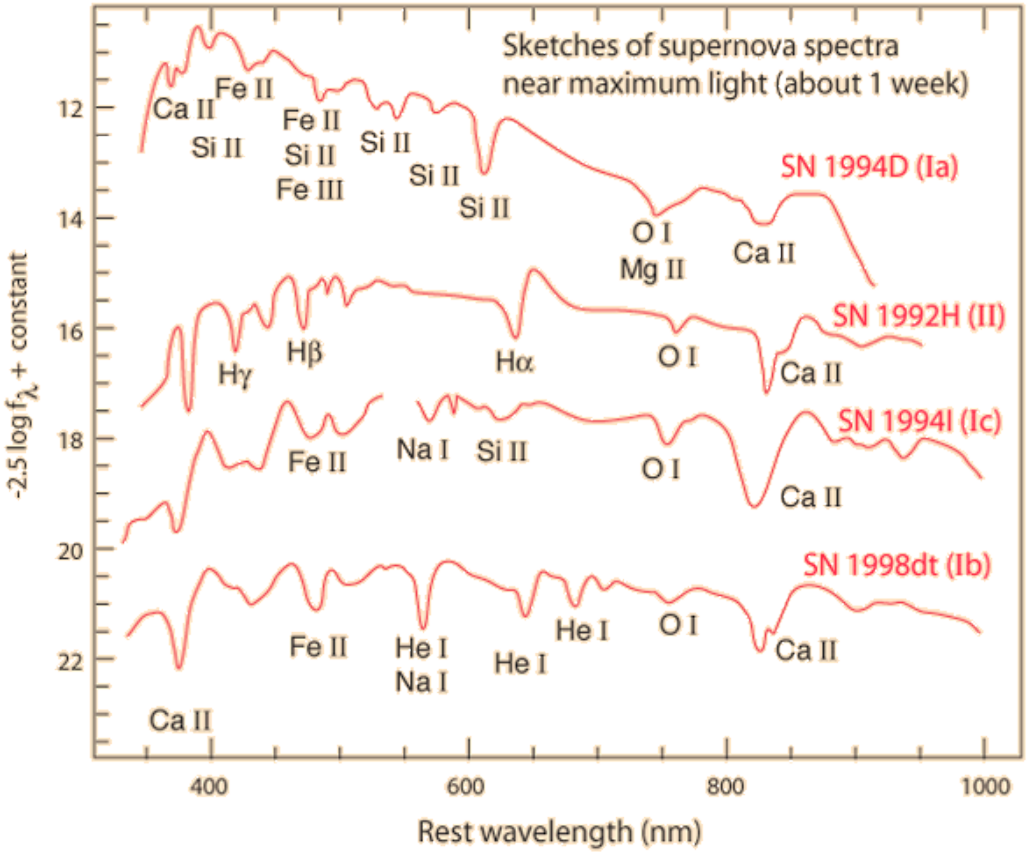
– *Type Ia SNe and the LIGO binaries*

THE UNIVERSITY OF SYDNEY

Type Ia supernovae

In lecture 9, we discussed core-collapse supernovae, formed at the end of a massive star's life.

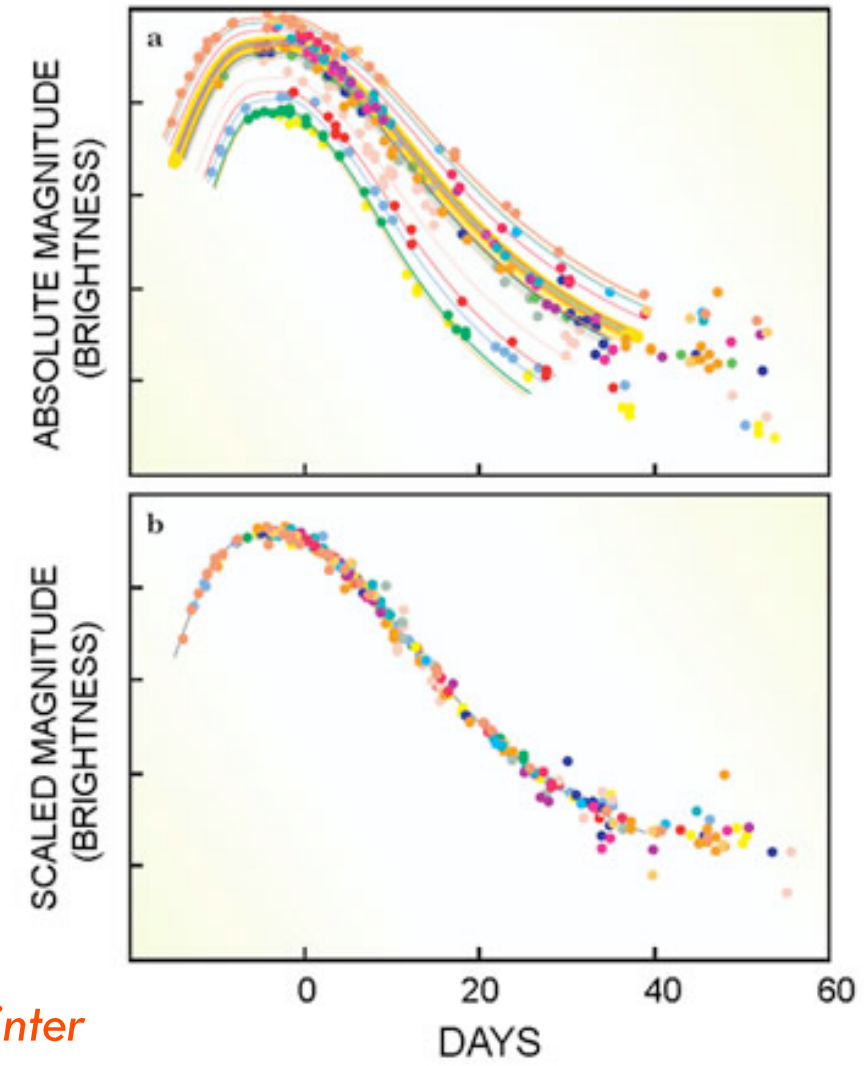
There is a second important class of supernovae, called Type Ia. These are recognised because they show no hydrogen in their spectrum, and they don't have the characteristic "bump" in their light curve from the decay of radioactive elements.



Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

Type 1a supernovae are remarkably homogeneous. With a correction for the colour (weaker explosions being less luminous, redder, and having a faster decline than more energetic events), their brightness and light curves are almost identical.

⇒ use as *standard candles*.

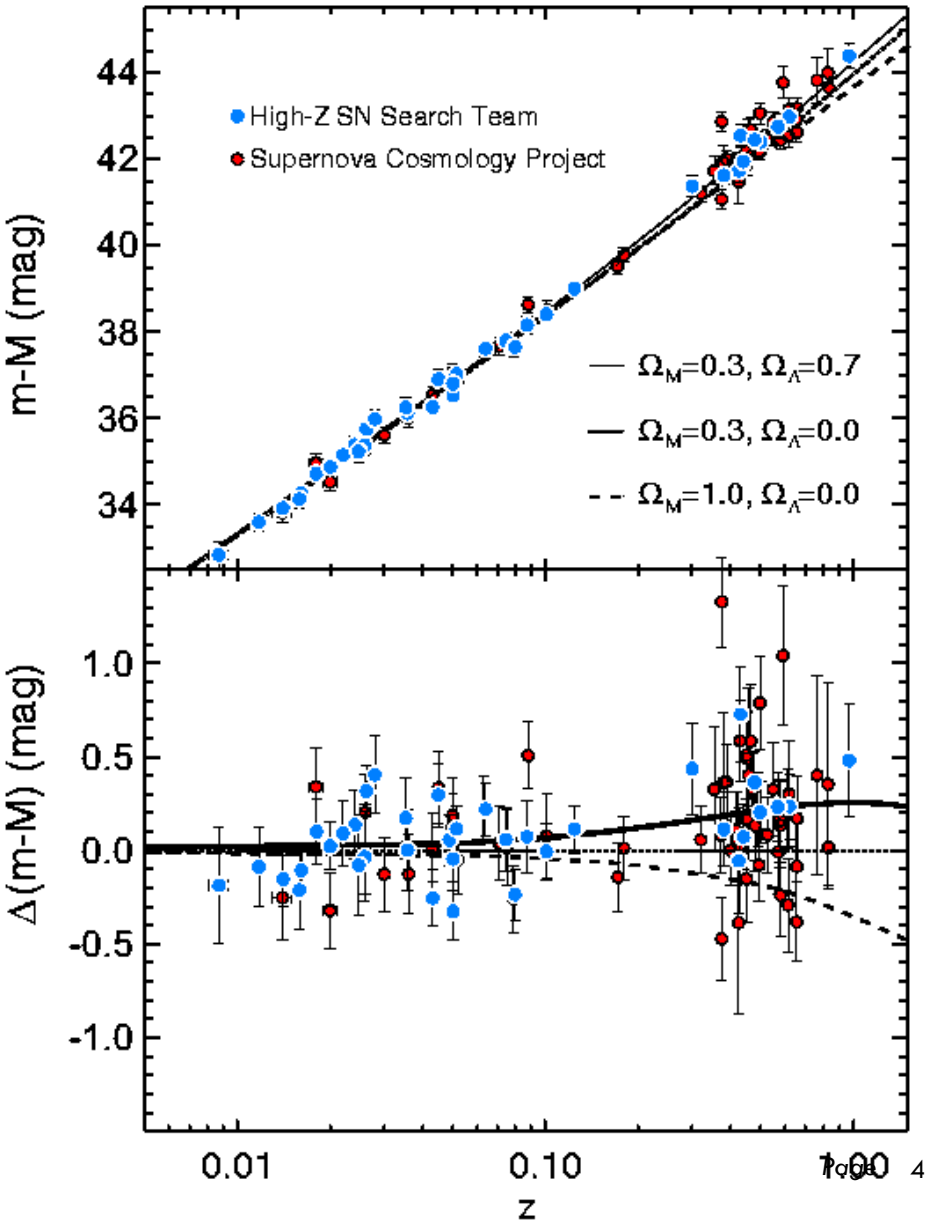


Brighter supernovae are found to take longer to fade than fainter ones; a single correction can make all the light-curves match

The 2011 Nobel Prize was awarded to two teams for their discovery of the accelerating universe using SN 1a.

Both teams found that supernovae at high redshift were dimmer than expected.

This means that instead of re-collapsing, slowing down or coasting, the expansion of the universe was *accelerating*.



So having used SN Ia to discover the fate of the universe, it would be nice if we knew how they work.

The fact that all the explosions have exactly the same brightness strongly suggests they involve the collapse of a Chandresekhar-mass white dwarf.

Unlike the core of a collapsing massive star, the white dwarf is made of carbon and oxygen, and this ignites during the collapse.

The resulting explosion results in the complete destruction of the star:

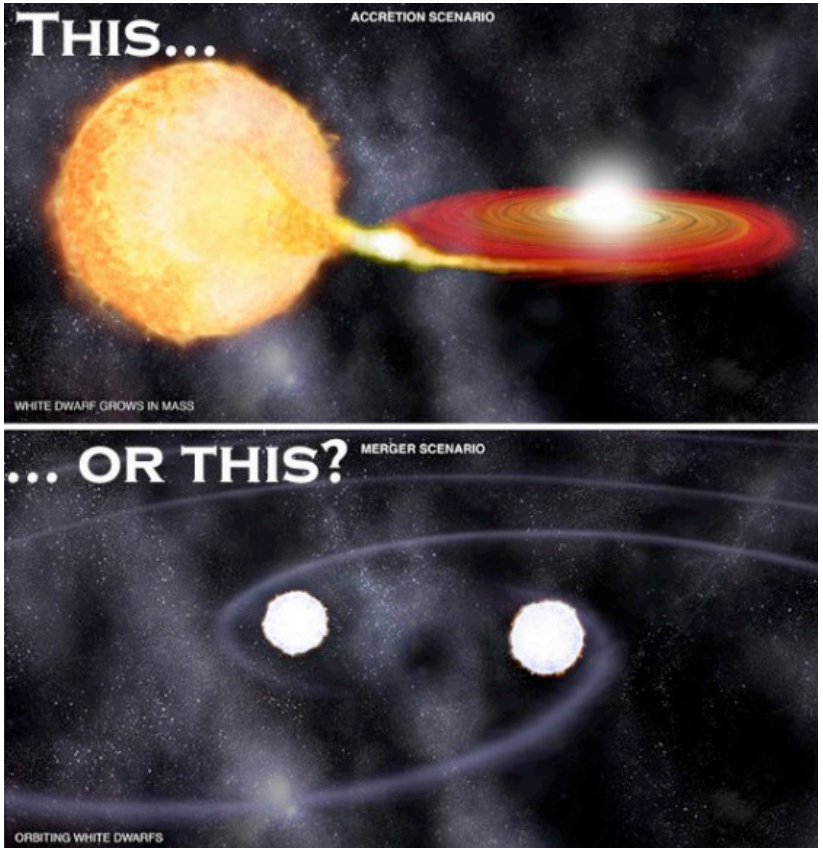
- E(binding) of 1.4 $M_\odot$ WD ~ 5×10^{43} J
- E(nuclear) of 0.6 $M_\odot$ C+O $\rightarrow {}^{56}Ni$ ~ 1×10^{44} J

All the explosions emit the same amount of energy because all the white dwarfs are the same mass.

The problem is that we don't know how to take a WD away from stable equilibrium and lead it to mass growth, ignition, and explosion. In other words, we do not know the identity and nature of the systems that explode as SNe Ia. This is the "SN Ia progenitor problem."

The two most likely contenders for the progenitors are

- the *single-degenerate* scenario, where a white dwarf accretes matter from a companion; or
- the double-degenerate scenario, where two white dwarfs merge.

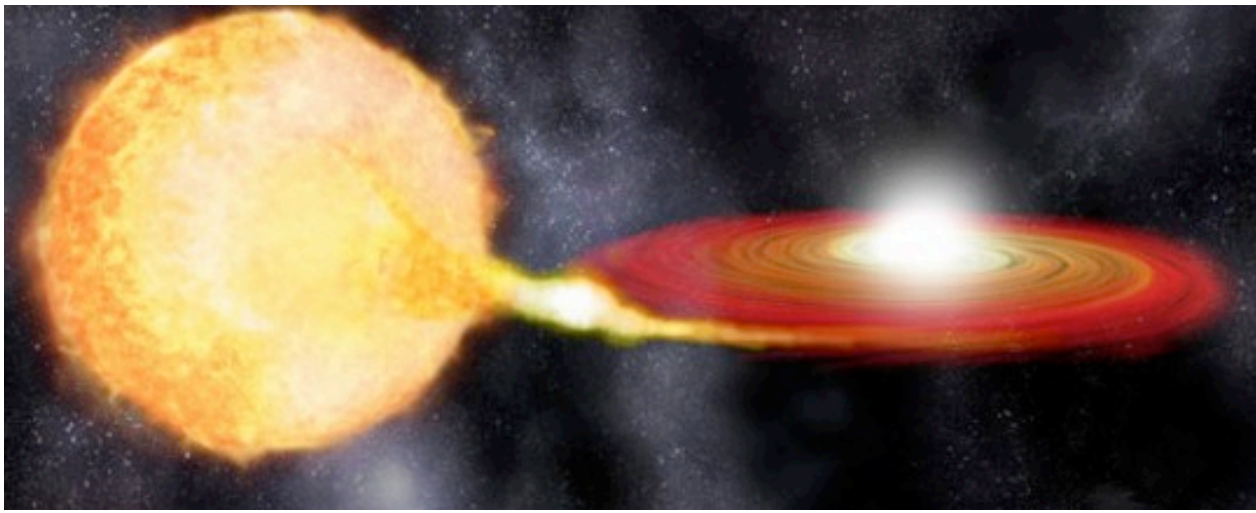


The single-degenerate scenario

Both scenarios have major problems.

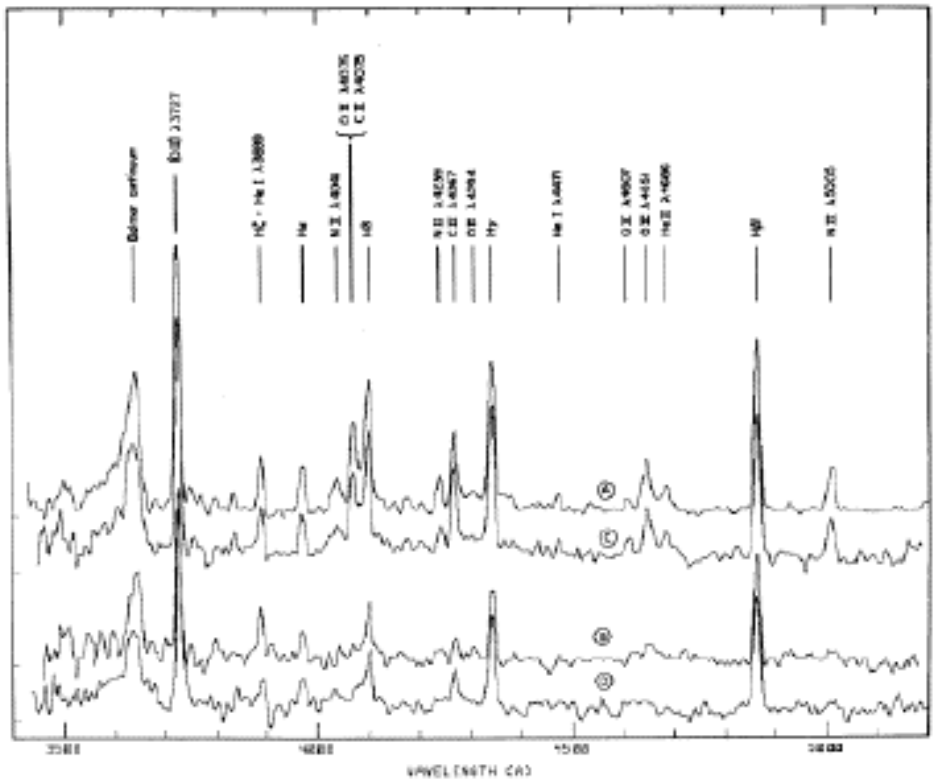
In the *single-degenerate scenario* the white dwarf is accreting matter from a companion star, i.e. it is a cataclysmic variable.

But then why do we see no hydrogen in the spectrum of the supernova?



Even worse: how do you get a white dwarf near the Chandrasekhar mass? Why isn't the material consumed in repeated nova explosions instead?

In ordinary nova explosions, the white dwarf loses a little mass each time: so how does it grow large enough to reach the Chandrasekhar mass?



Spectrum of the shell of DQ Her, taken in 1978, 44 years after the nova outburst: from the original paper by Williams et al. 1978, ApJ 224, 171

The *recurrent novae* seemed for a long time to be the most likely candidates for the progenitors for SN Ia.

The short recurrence time implies the white dwarf is very massive (high surface gravity), plus they must be accreting matter very rapidly (to get it to explode sooner).

These are exactly the conditions where the white dwarf is likely to reach the Chandrasekhar mass and explode.

U Sco is a recurrent nova, which erupts roughly once ten years; it has long been seen as one of the most likely progenitor systems for SN Ia.

However, measurements during the 2010 outburst showed that the white dwarf seems to have *lost* mass instead of gaining it.

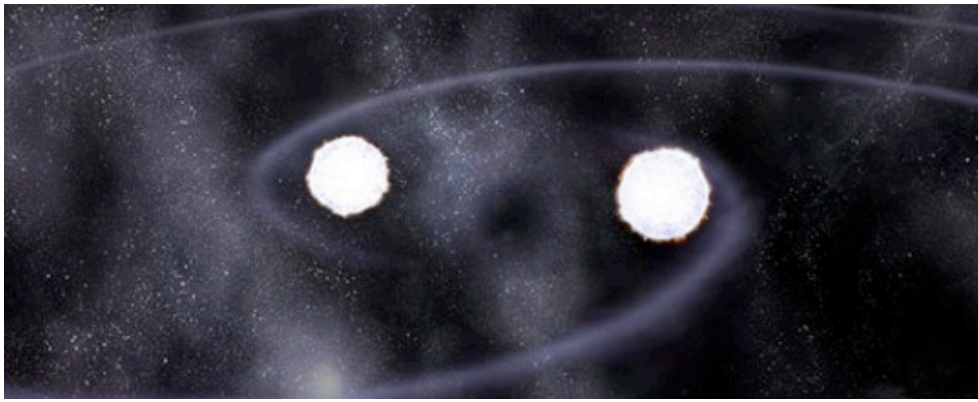
So the single-degenerate model, despite being the favoured model for a long time, is looking problematic.

The double-degenerate scenario

– In the *double-degenerate scenario* two white dwarfs merge, so there is no hydrogen.

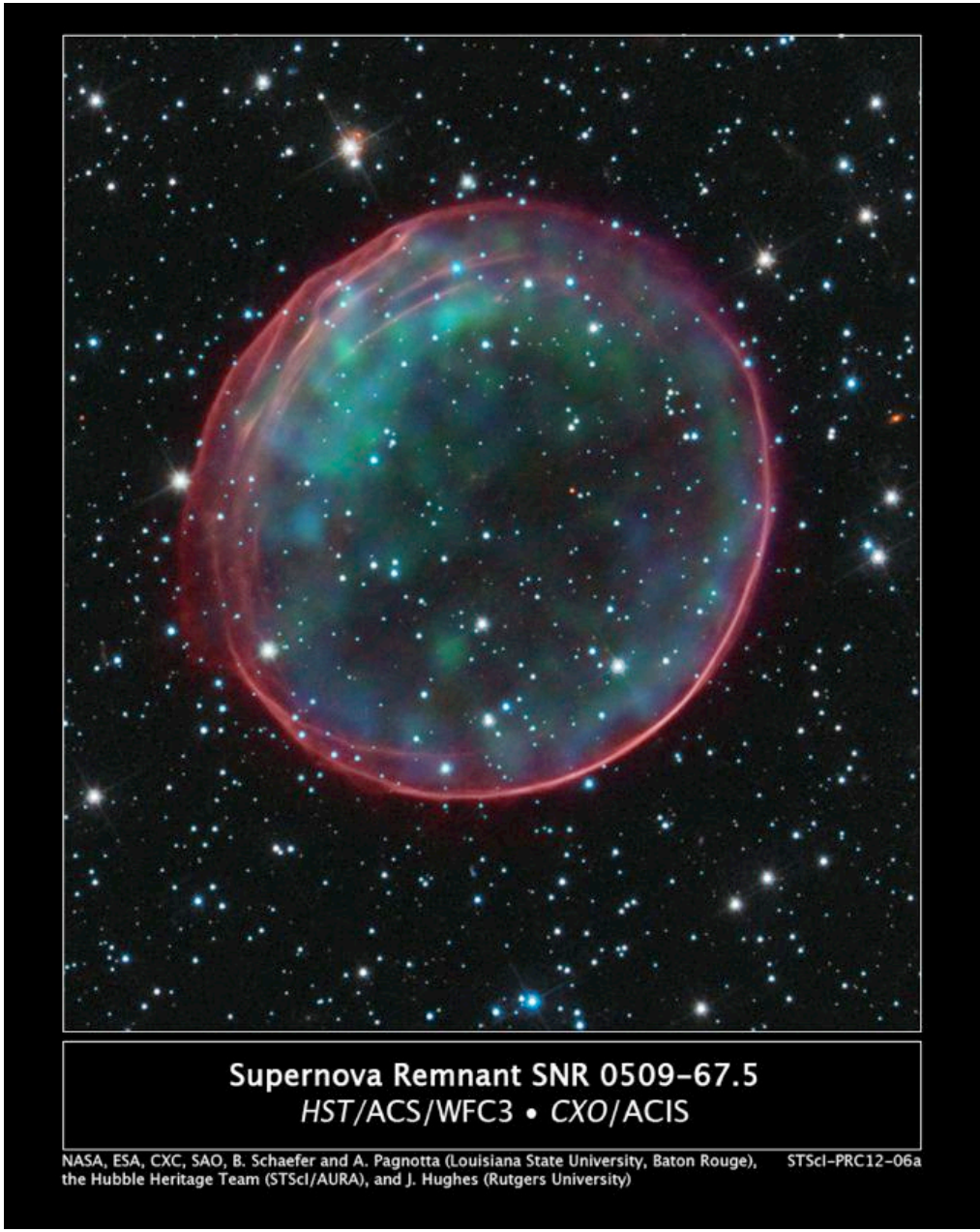
But if you are merging two random white dwarfs, why do all the explosions have the same brightness?

Even worse, we know of very few white dwarf binaries which will merge within a Hubble time, and *no* white dwarf binaries where the sum of the masses is greater than the Chandresekhar mass.



Try addressing the question observationally, by looking at the site of past SN Ia explosions.

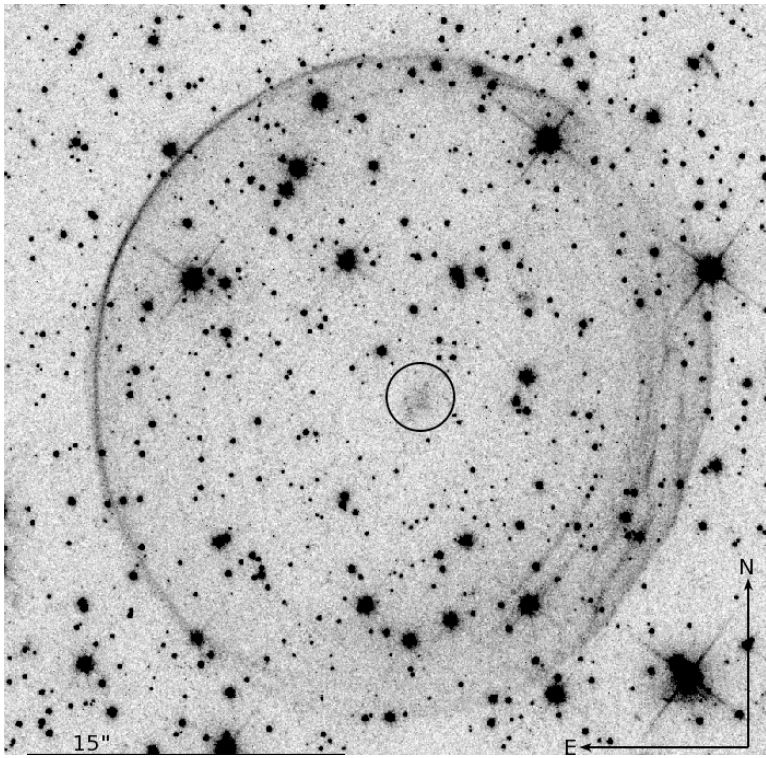
In the single-degenerate scenario, the companion star would still be there. In the double-degenerate scenario, both stars are obliterated in the explosion.



SNR 0509-67.5 in the Large Magellanic Cloud, which must have exploded about 400 years ago.

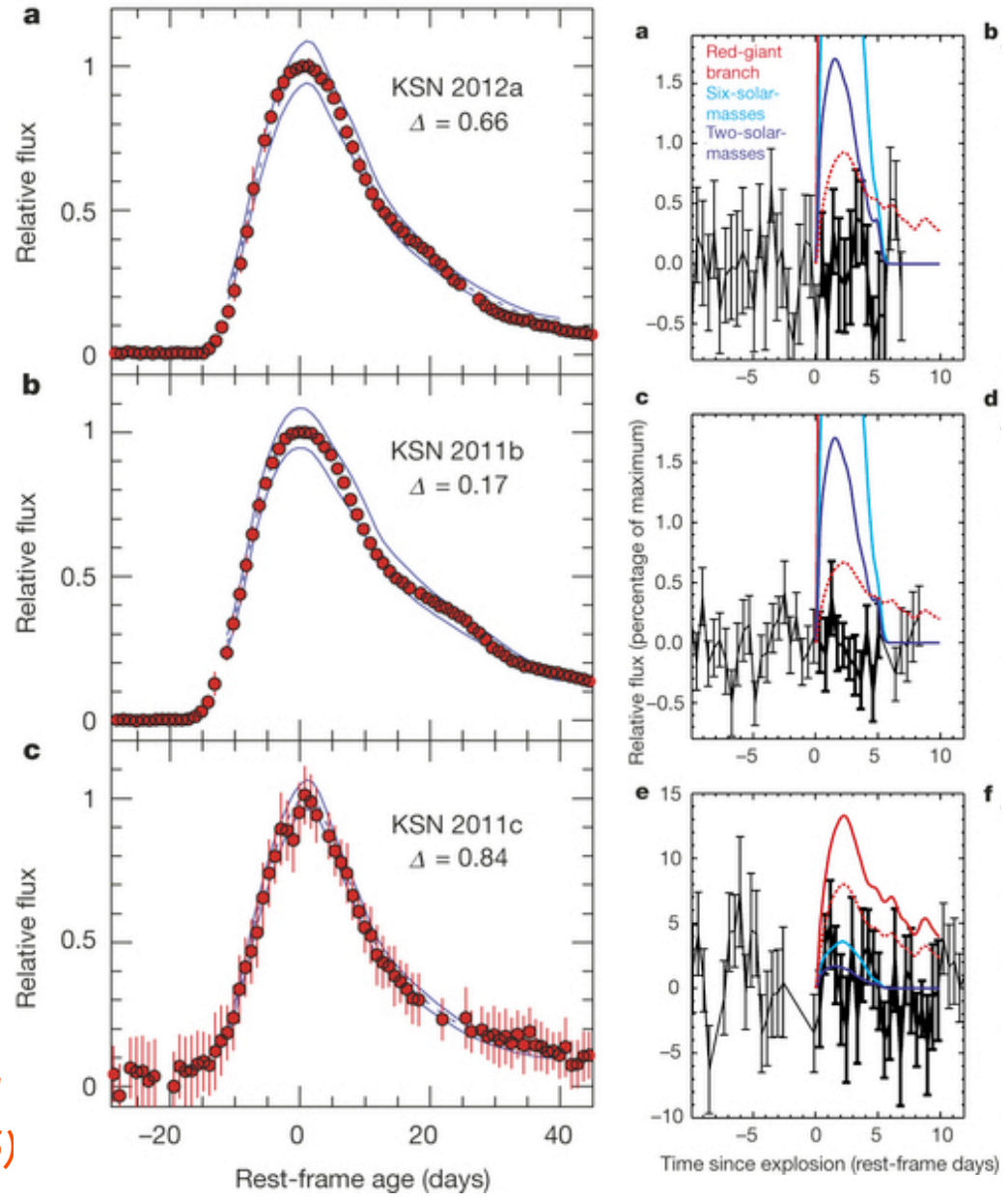
No stars in the central region of any of the remnants, so any surviving companion star must be very faint.

This limit rules out all possible classes of progenitors except for the close pair of white dwarfs.



Recent work has used the very accurate light curves from Kepler to look for the interaction of the supernova ejecta on a companion star. They found no signatures of the supernova ejecta interacting with nearby companions, suggesting the supernovae arose from merging white dwarfs.

Some authors suggest these observations *also* rule out two merging white dwarfs.



Kepler light curves for three supernovae, plus close-ups of the start: the solid curves show the brightening expected for a red giant and two main-sequence stars (Olling et al. Nature 2015)

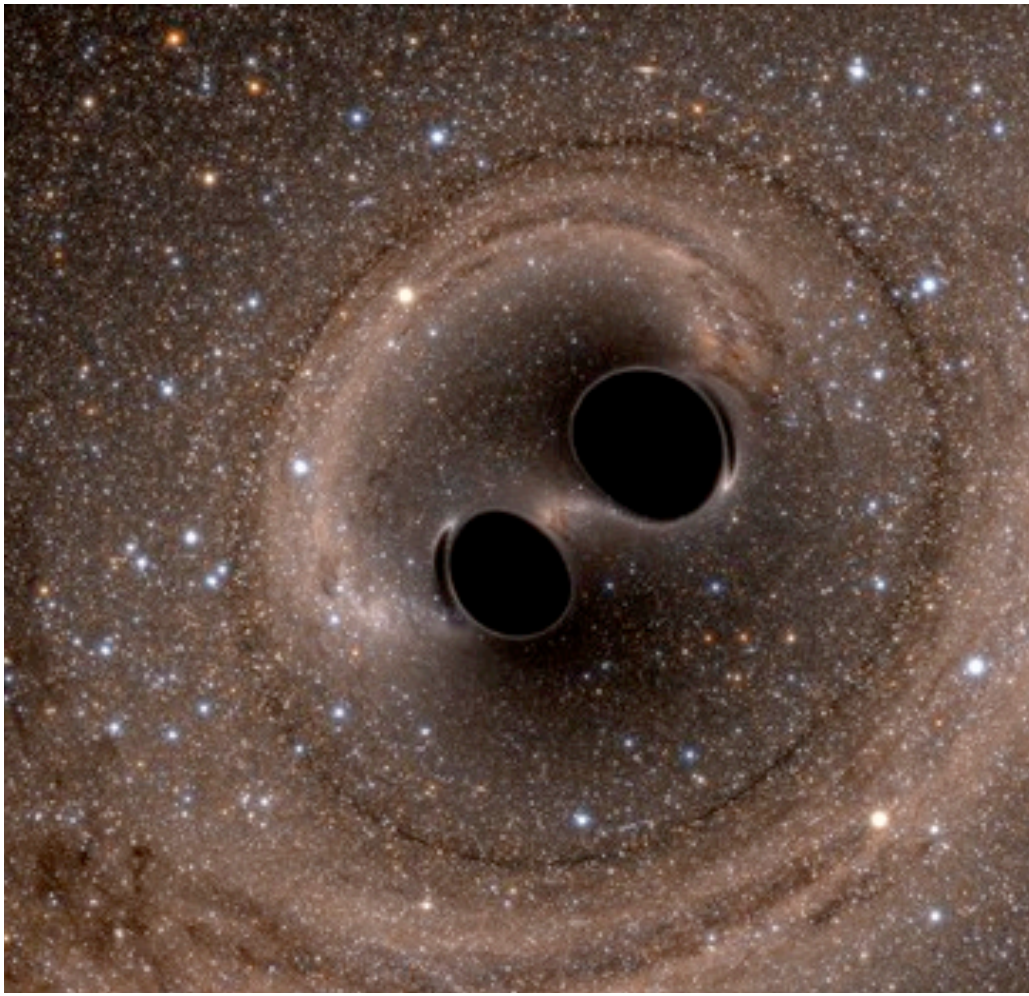
So we still don't know what the progenitor systems for Type Ia supernovae are.

"We *know* that Type Ia supernovae (SN Ia) result from binary evolution. The only caveats are that 1) there is no observational evidence for this statement, and 2) there is no generally accepted theory for the evolution."

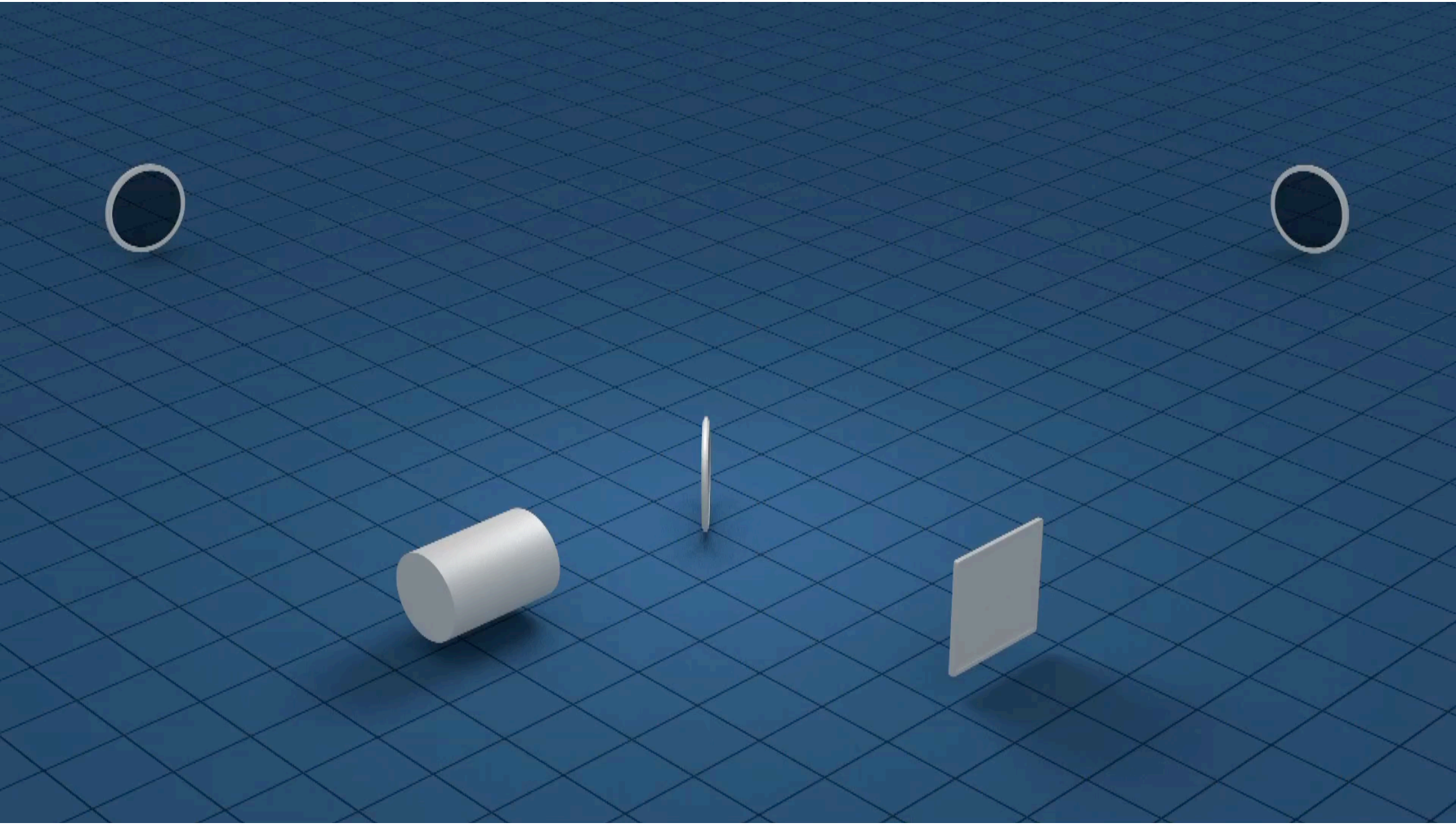
– *J. Craig Wheeler(1995)*

The LIGO binary black hole merger GW150914

On 14 September 2015 a signal was detected by the two arms of the *Laser Interferometer Gravitational-Wave Observatory* (LIGO).

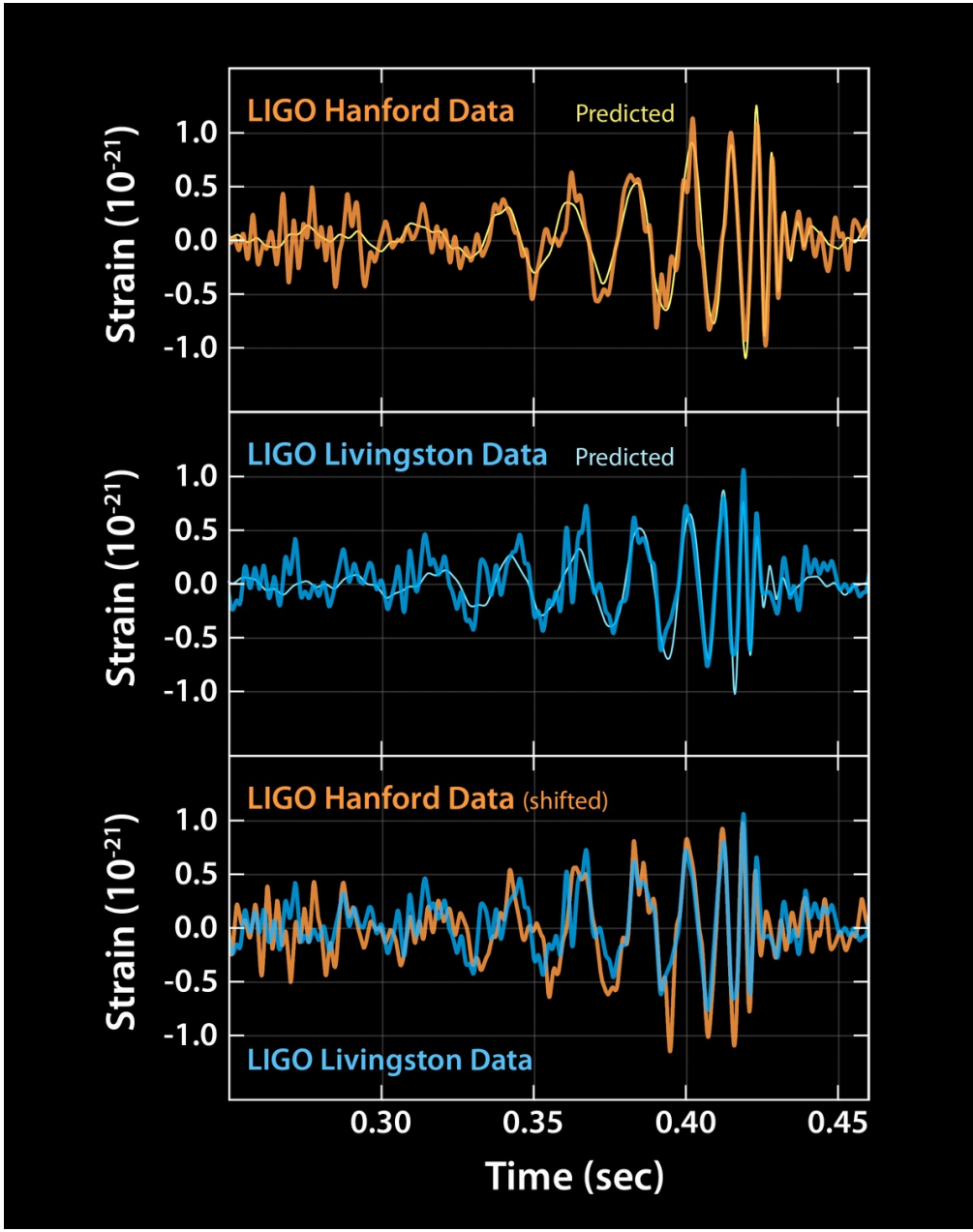


The LIGO "observatory" is made up of two identical and widely separated interferometers situated in sparsely populated, out-of-the-way places: LIGO Hanford in southeastern Washington State, and LIGO Livingston, 3002 km away near Baton Rouge, Louisiana. Each arm is 4 km long.

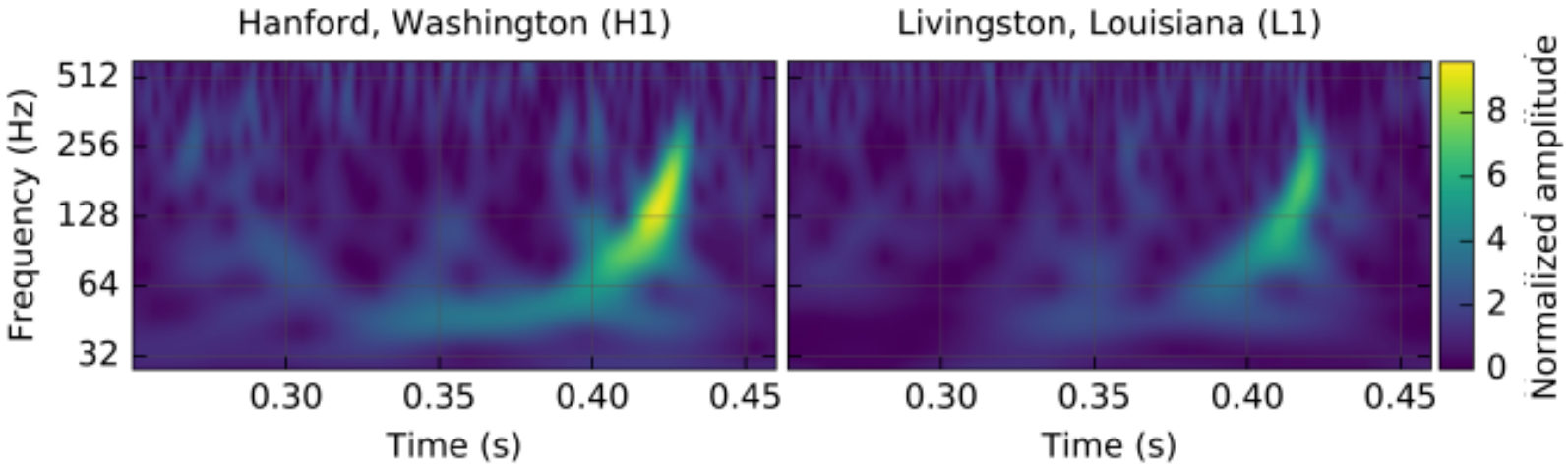


The gravitational wave event seen by the two LIGO detectors. Top two plots show the measured strain, compared to a numerical relativity waveform for two merging black holes.

The third plot shows the data from both detectors, with the data from H1 shifted by 6.9 ms and inverted.



Over 0.2 s, the signal increases in frequency and amplitude in about 8 cycles, from 35 to 150 Hz (the “chirp”). The most plausible explanation for this signal is the inspiral of two orbiting masses due to gravitational wave emission.



Derive the "chirp mass":

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5},$$

The observed frequency and frequency derivative give $\mathcal{M} \sim 30\ M_\odot$.

You showed that one object cannot be a neutron star, so both objects must be black holes.

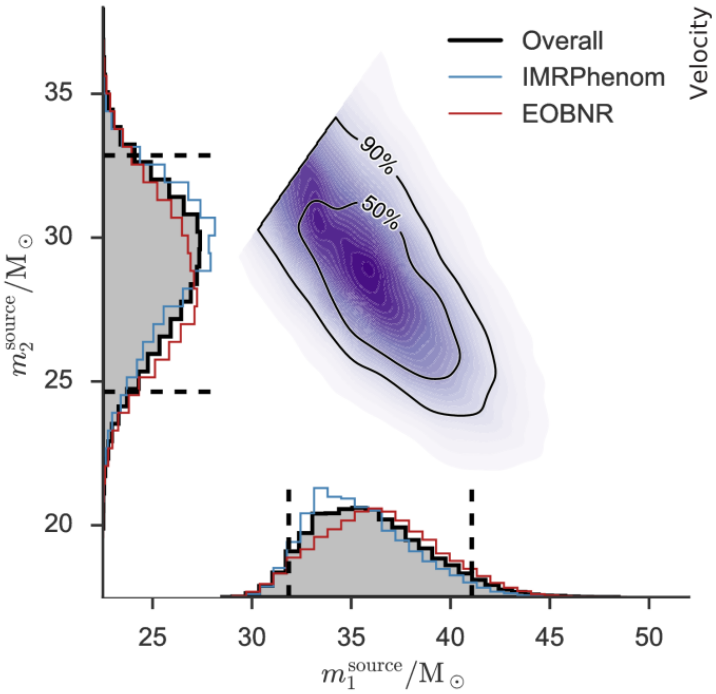
Best estimate for masses:

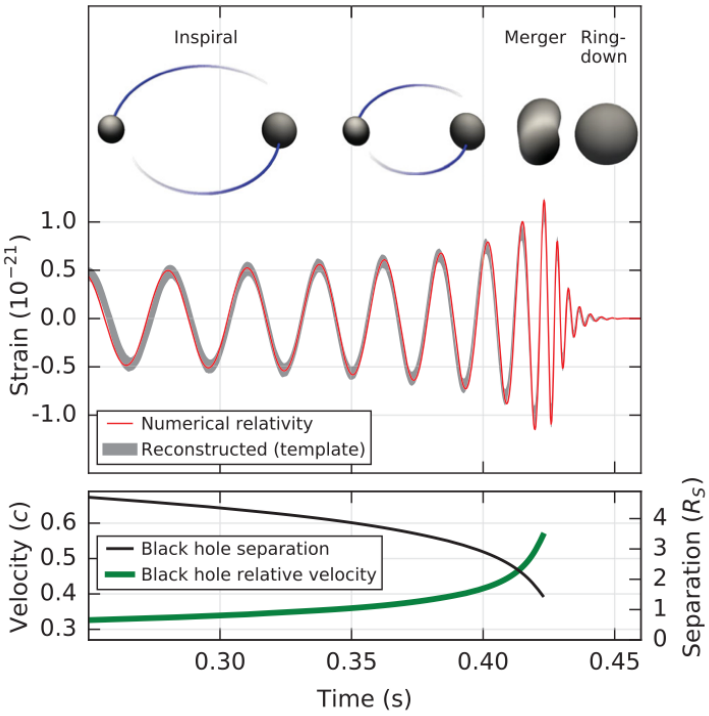
$$36^{+5}_{-4} M_\odot \text{ and } 29^{+4}_{-4} M_\odot$$

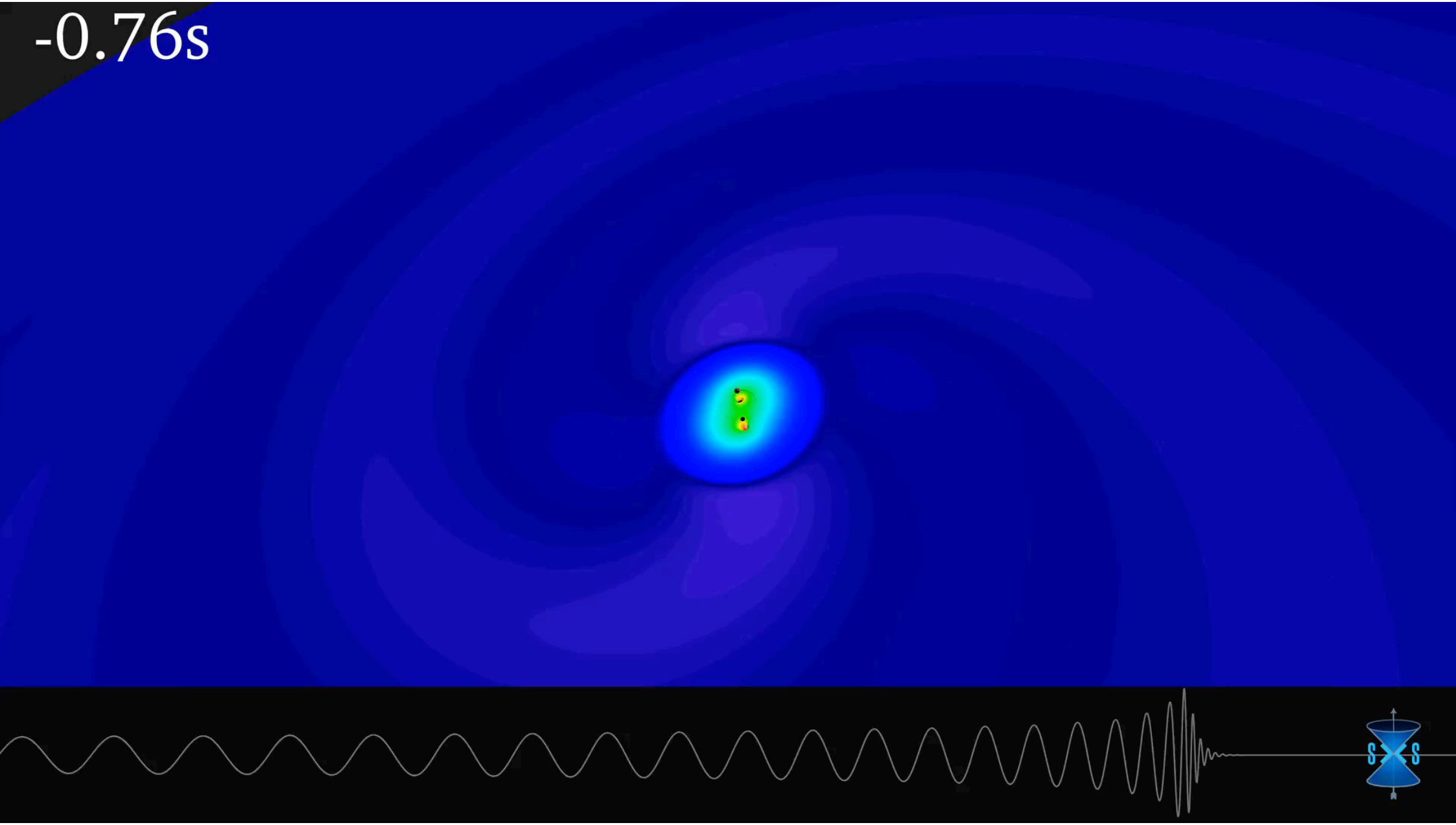
Final BH mass:

$$62^{+4}_{-4} M_\odot$$

so $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated away as gravitational waves.






-0.76s
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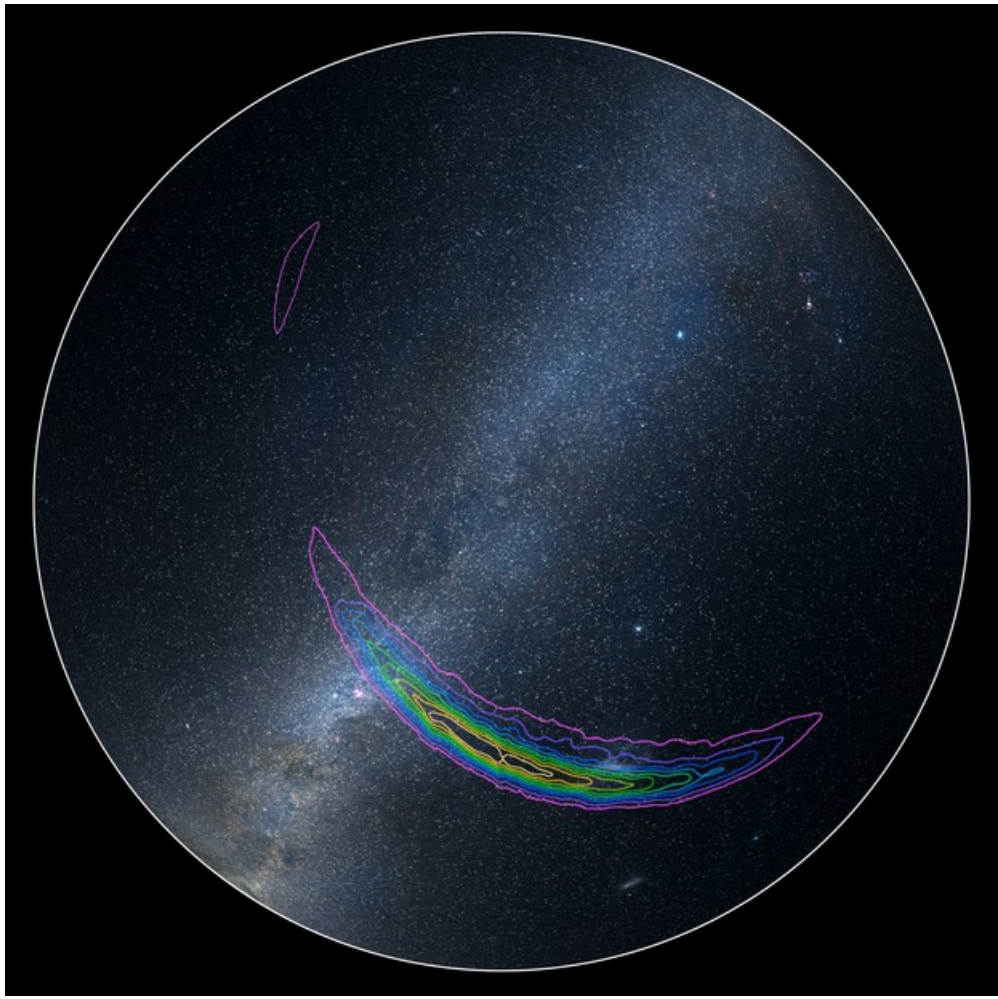
From strength of signal, get weak limits on position and distance of source: the source is localised to a 600 deg^2 area in the Southern hemisphere, and the distance to the source is about 400 Mpc.



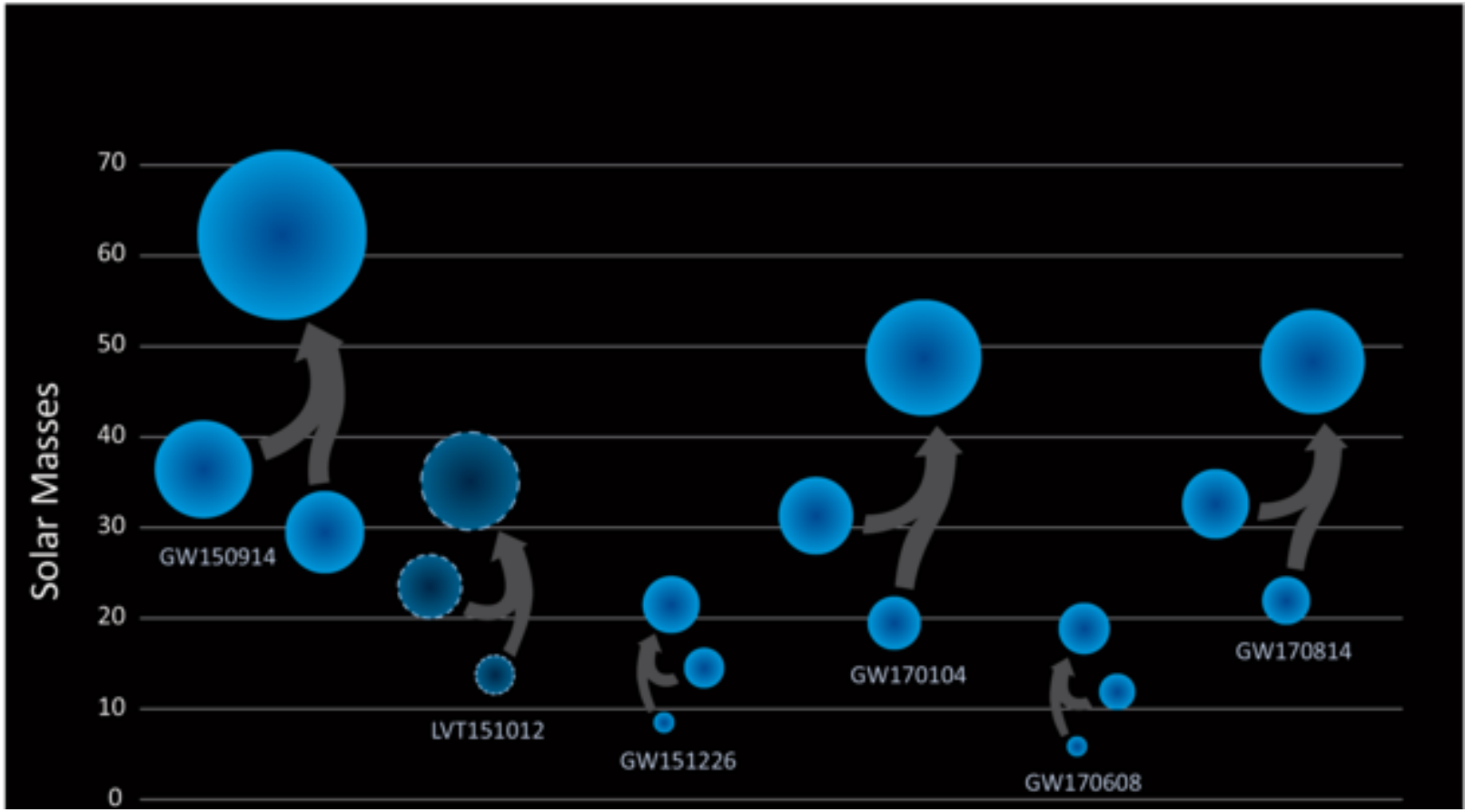
The GW150914 binary is

– most massive stellar-mass BH

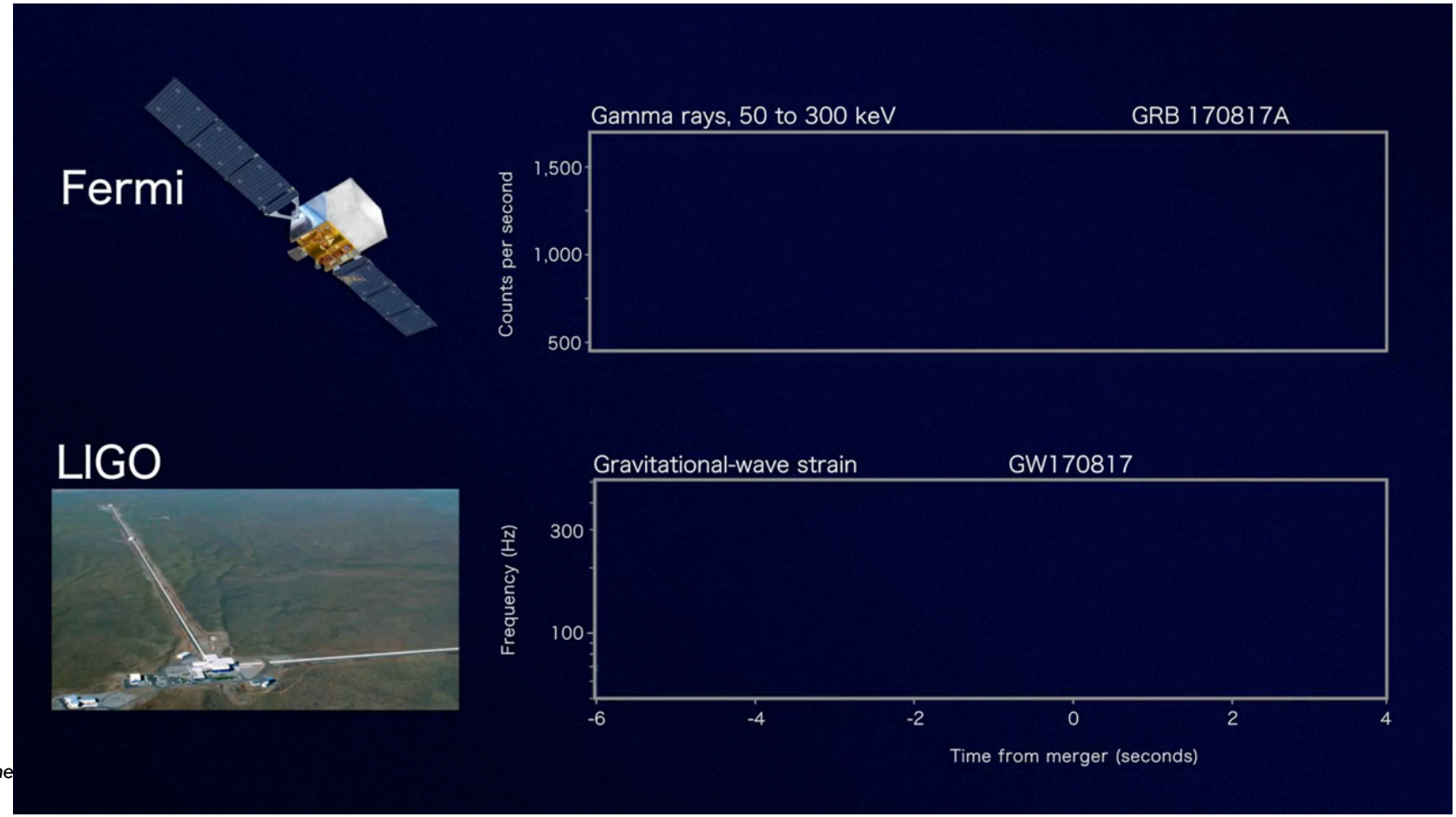
– first BH binary

– sensitive test of GR

LIGO has now detected several more black hole mergers, the latest in collaboration with the VIRGO detector in Italy.

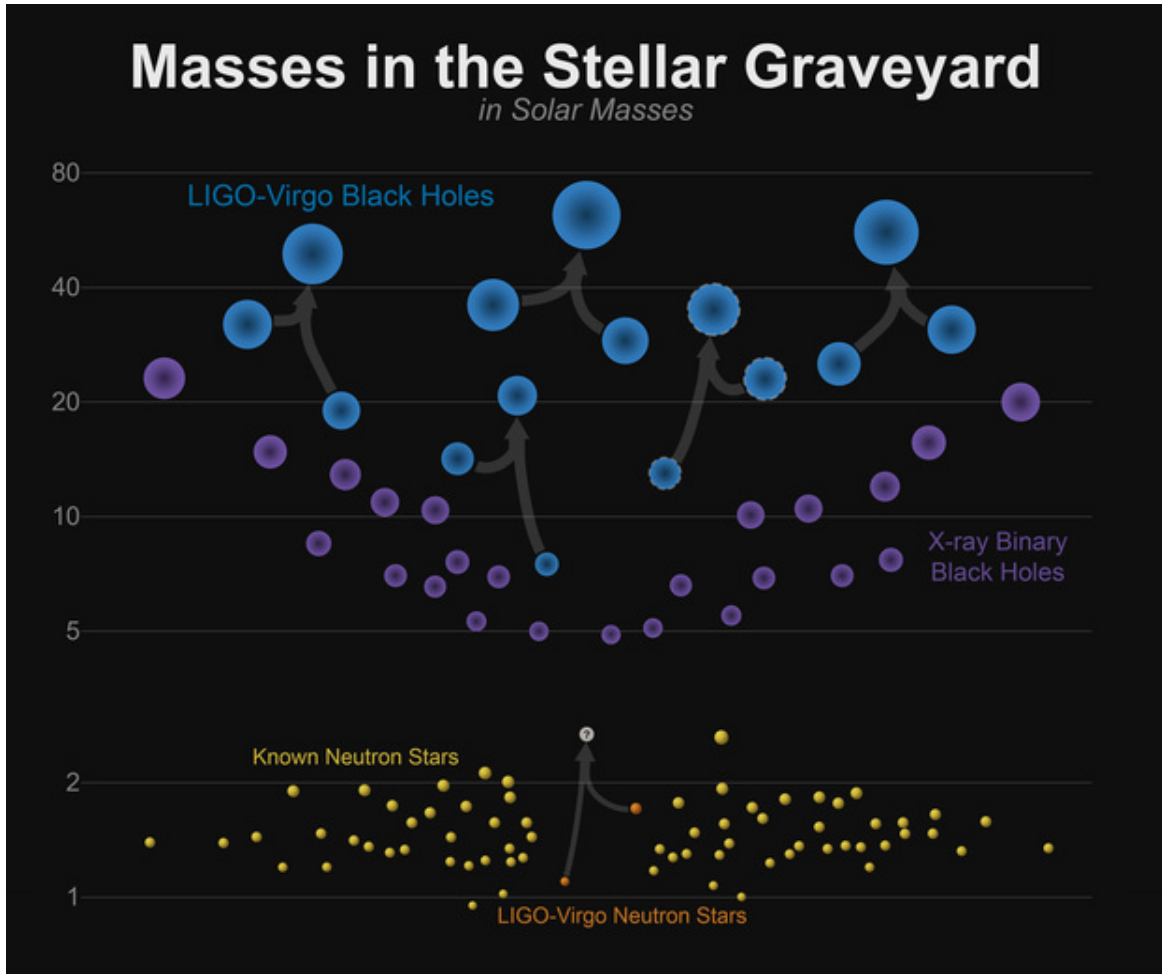


In August 2017, LIGO + Virgo and the Fermi gamma-ray satellite discovered the first neutron star-neutron star merger event



RIPPLES OF GRAVITY,
FLASHES OF LIGHT:
WORLD'S OBSERVATORIES
WITNESS A COSMIC CATACLYSM

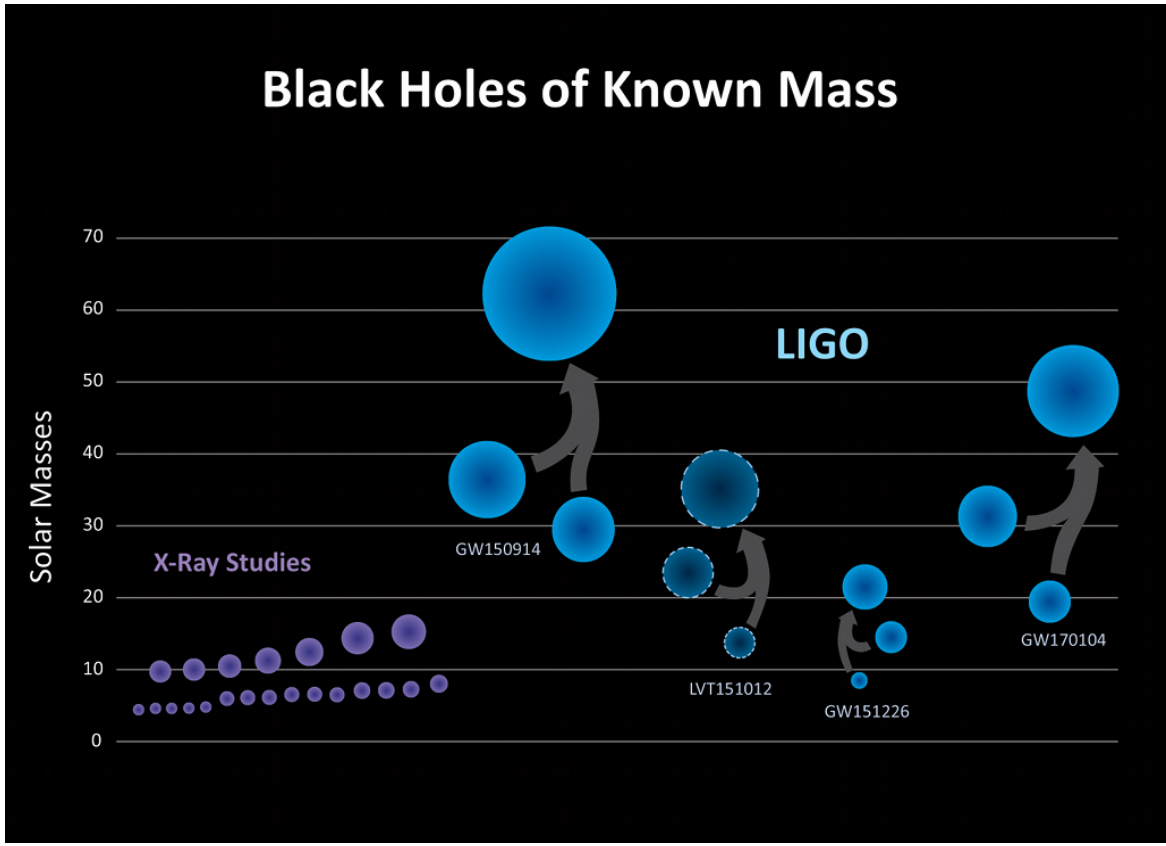
What was left behind after merger? Massive neutron star or light black hole?



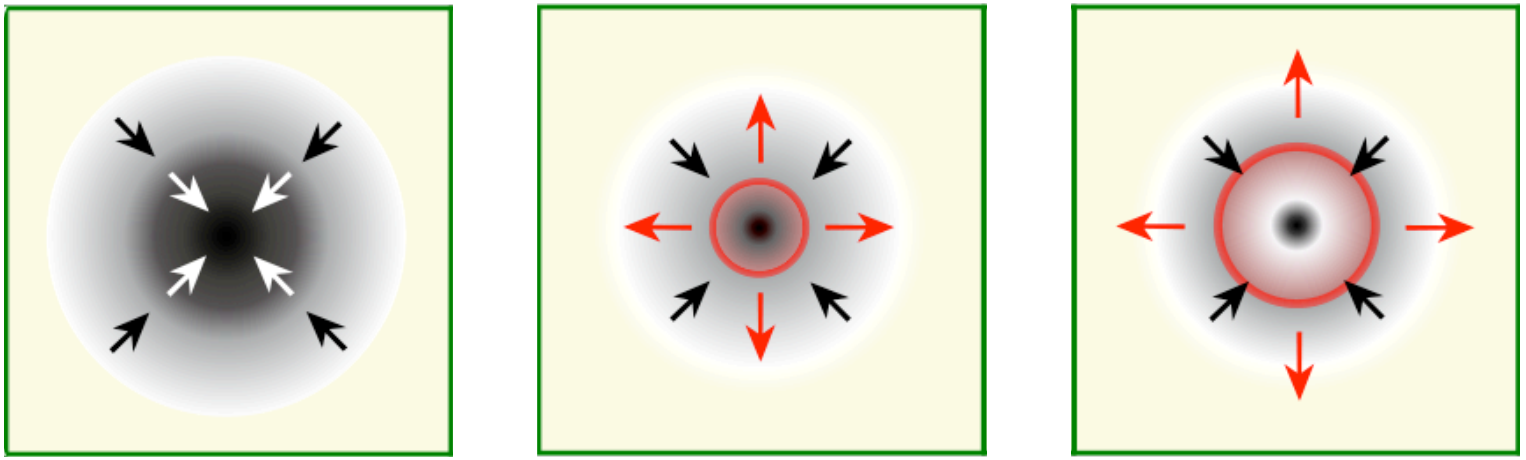
What about the binary?

The black holes detected by LIGO are significantly more massive than any other black holes we have yet measured in binaries.

Where did they come from?



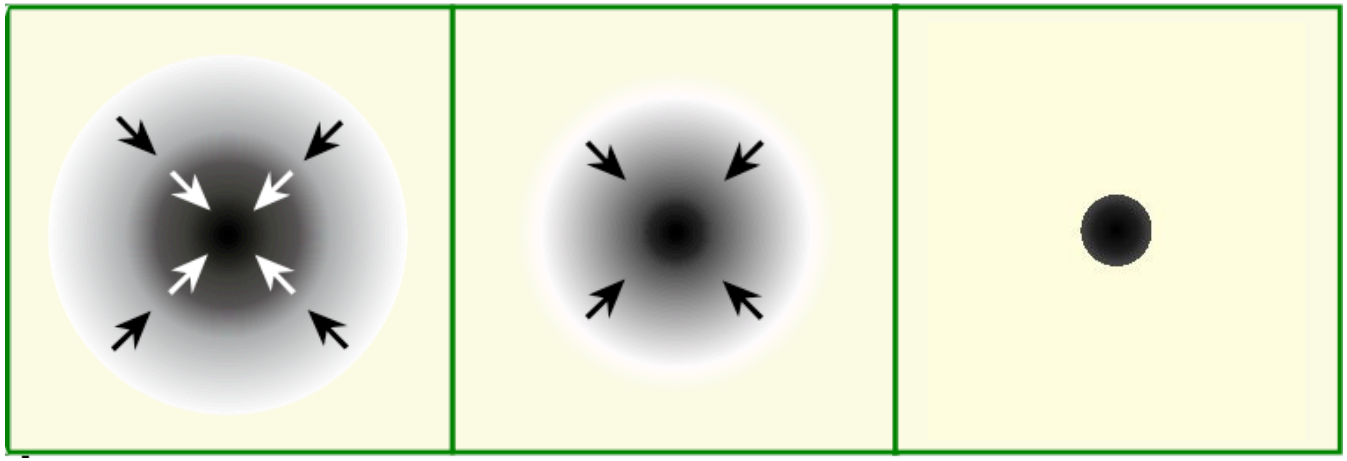
Recall our discussion about supernova explosions. Once a massive star has formed an iron core bigger than the Chandrasekhar mass, the pressure can no longer support the weight of the star, and the core begins to collapse. When the collapsing core reaches nuclear densities, it forms a proto-neutron star, and the rebound drives a shock outwards through the star, which explodes the outer layers in a supernova explosion.



What if the shock *doesn't* re-start? Then the outer layers, instead of being exploded outwards, will collapse onto the proto-neutron star, forming a black hole.

What would we see from the outside?

No-one is really sure. There could be an explosion, if there is a successful shock but the black hole forms after more material falls onto the core. Or if the shock never forms (or stalls before it gets to the surface), the star might just disappear.

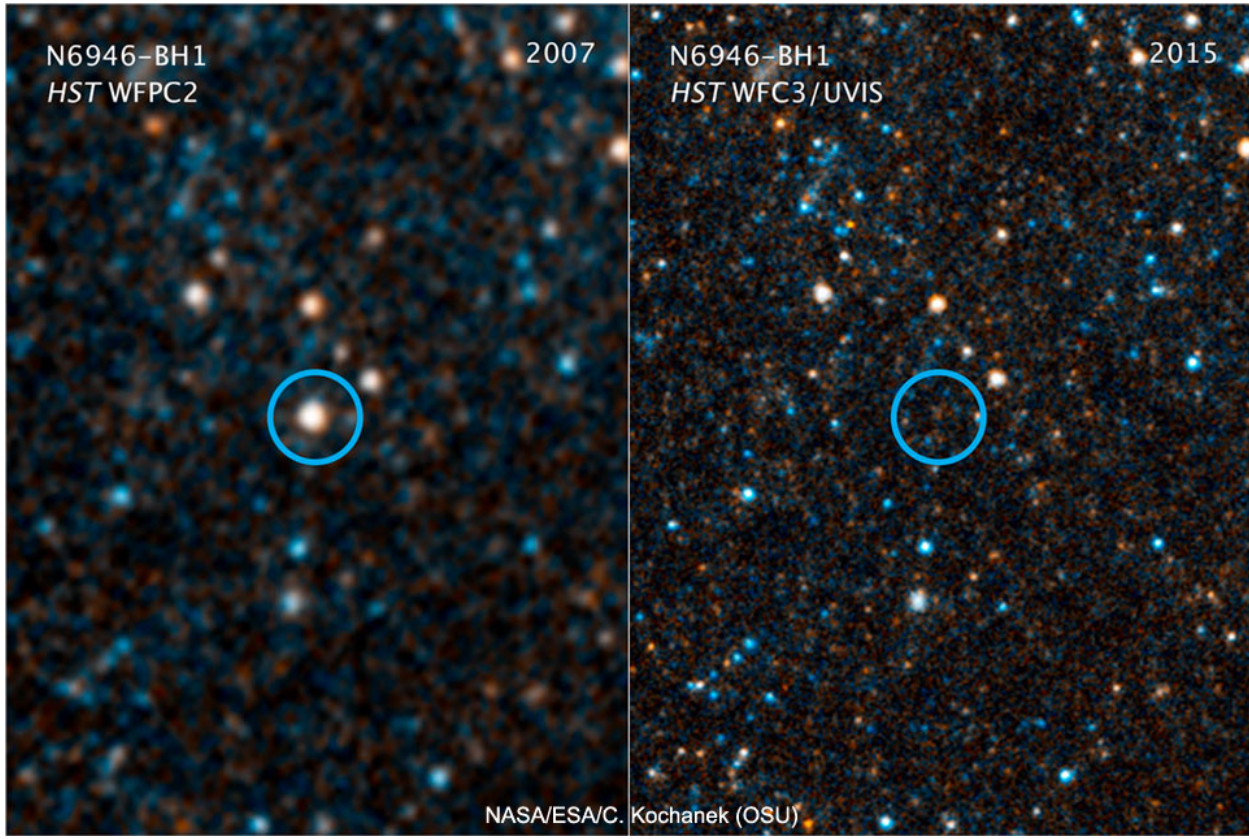


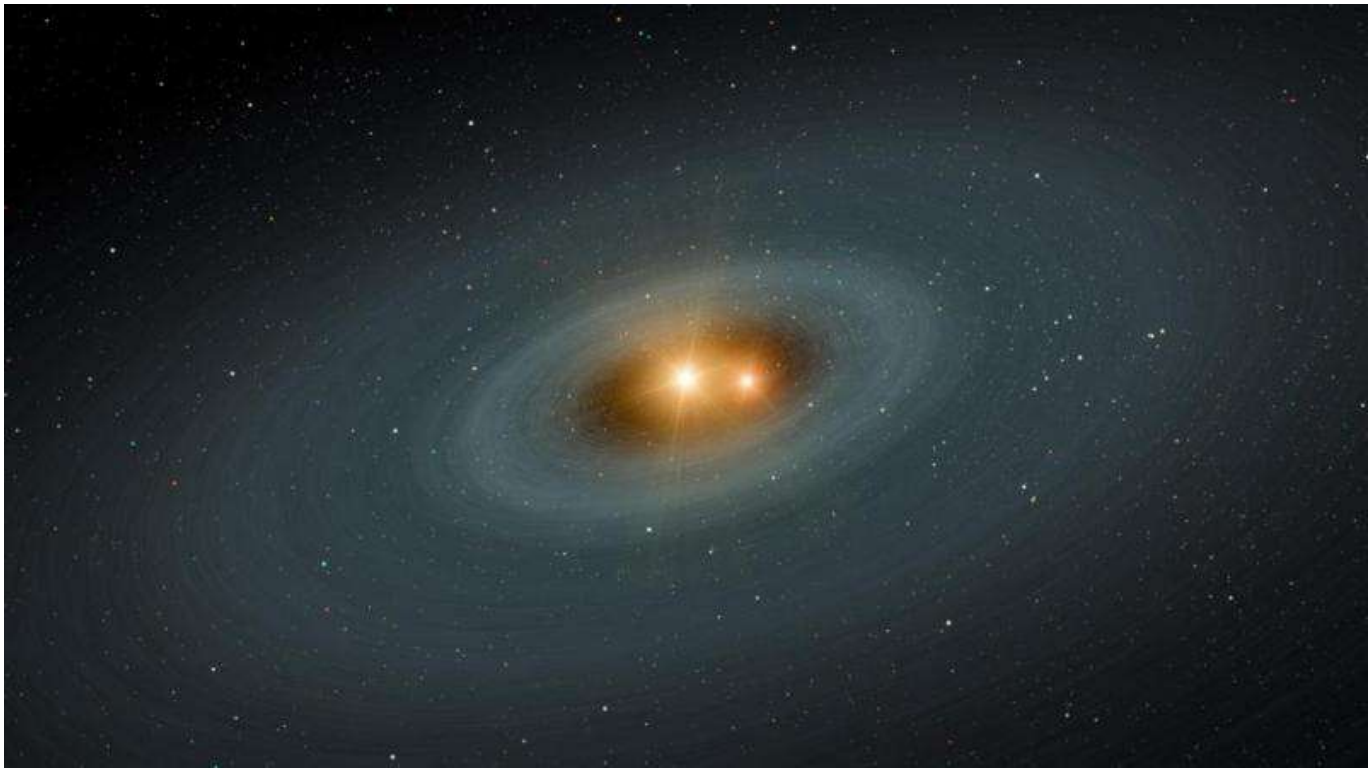
"Despite intense theoretical and computational efforts, it is difficult to simulate the evolution of any star with realism, and most attempts to produce SNe fail… the theoretical effort is focused on making SNe succeed (particularly for M~10 $M_\odot$) because they are observed, without significant constraint on whether nature is any more successful at producing explosions than theorists."

– *Kochanek et al. 2008 (ApJ 684, 1336)*

Several teams have looked for these “failed supernovae” (or “unnovae”) by looking in nearby galaxies for stars that disappear.

One star that disappeared without bright supernovae has been found.



If a large fraction of massive stars (M > 18–20 solar masses) end by imploding directly to black holes, then there should be many sources for LIGO to observe.

And who knows what else we will find?