Lives of the Stars Lecture 10: Interacting binaries

– Type Ia supernovae, and gravitational waves from black hole binaries

Presented by
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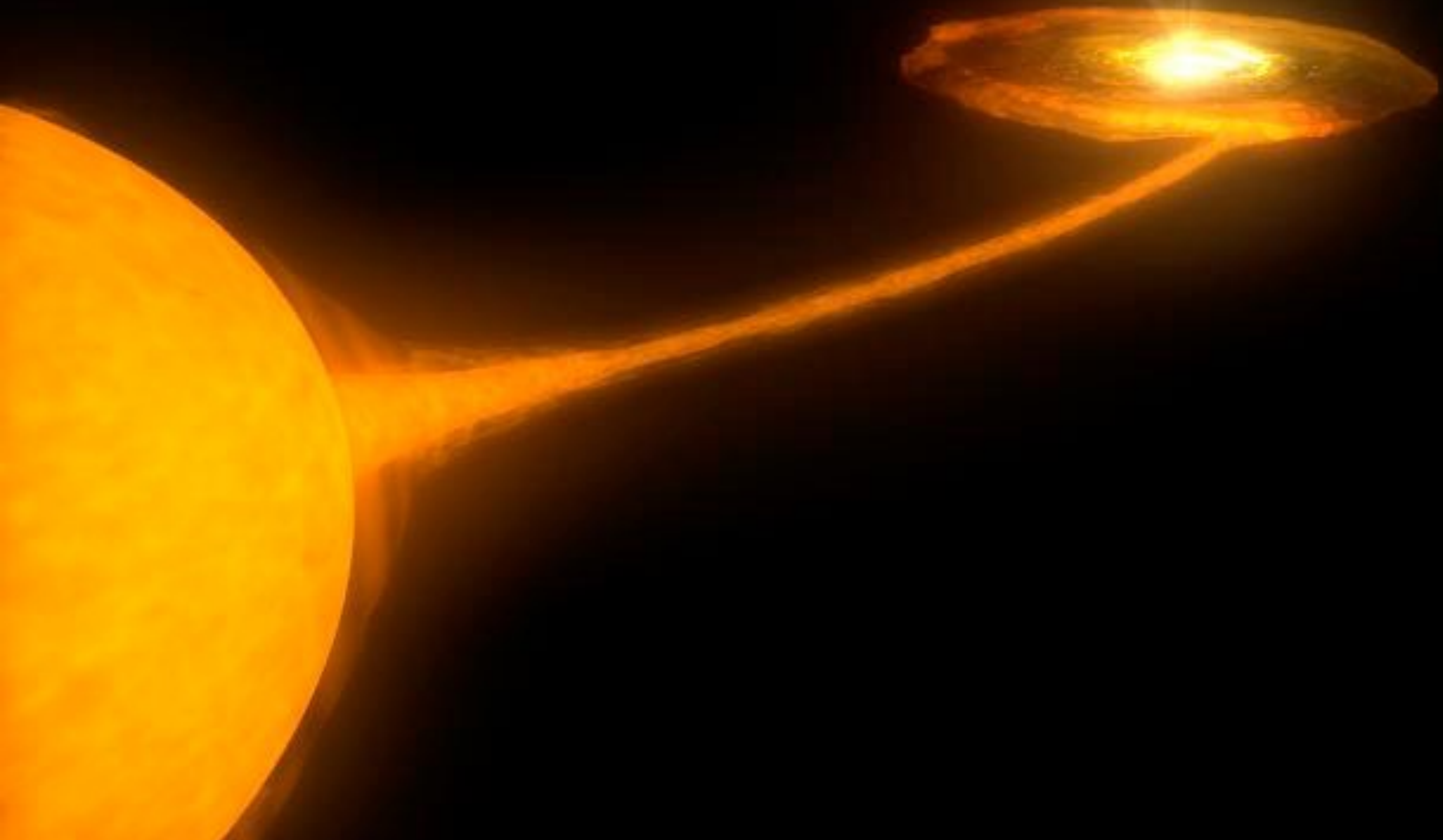
THE UNIVERSITY OF SYDNEY

In tonight's lecture

- Interacting binaries
  – *the interacting binary zoo*
- The type Ia supernovae problem
  – *the progenitor problem*
- The gravitational wave binary GW150914
  – *a major discovery; but what about the binary?*

Interacting binaries



- If the stars in a binary are far enough apart, they will have little or no effect on each other.
- However, if they are close, then stellar evolution can have a major effect as each star's radius changes with time.
- The observed properties of some binaries are inexplicable without taking this into account.
  - e.g. some compact binaries, containing a white dwarf, have orbital periods $P < 2$ hours, implying orbital separations $a < R_\odot$.

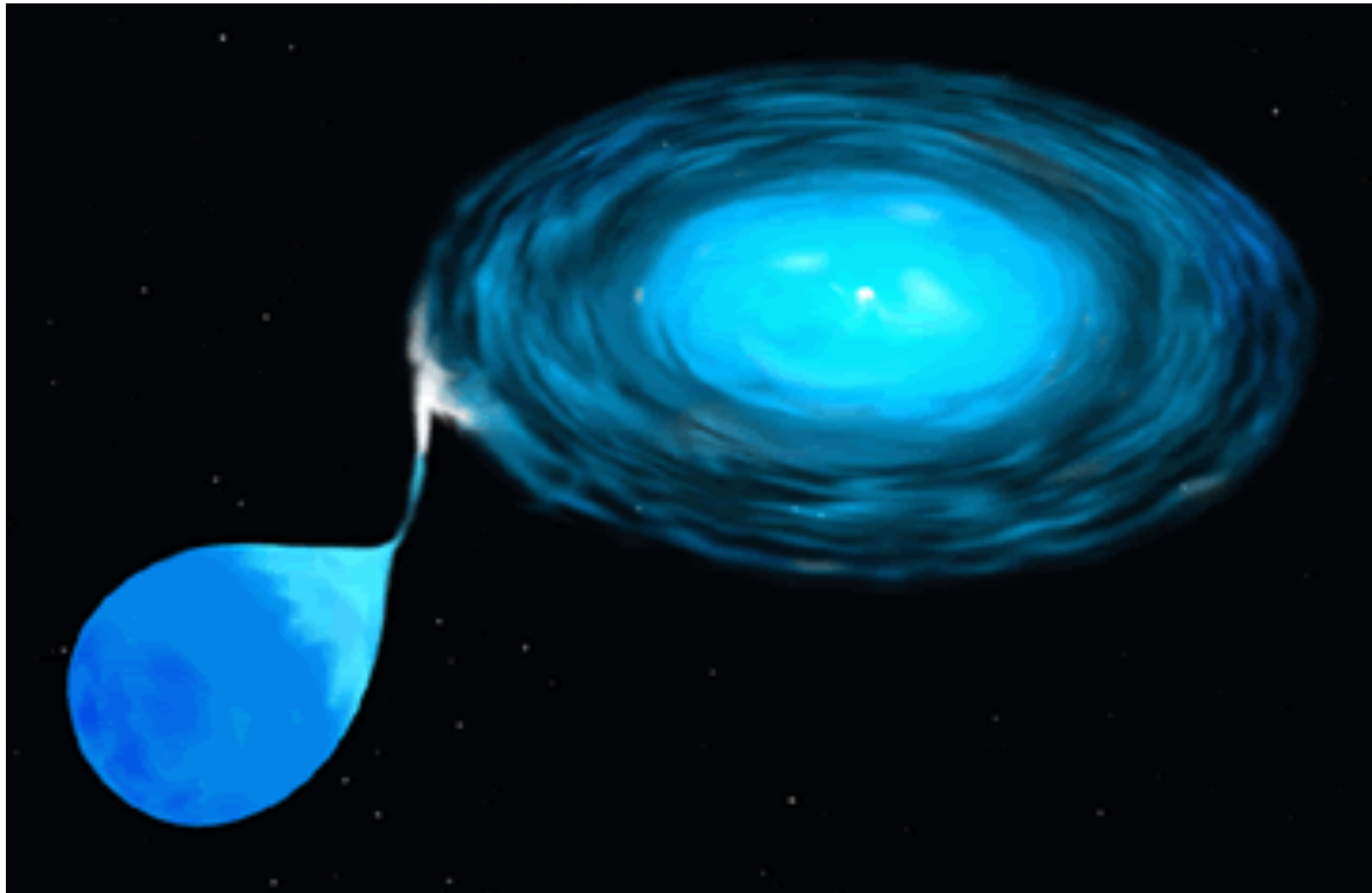
The Algol paradox

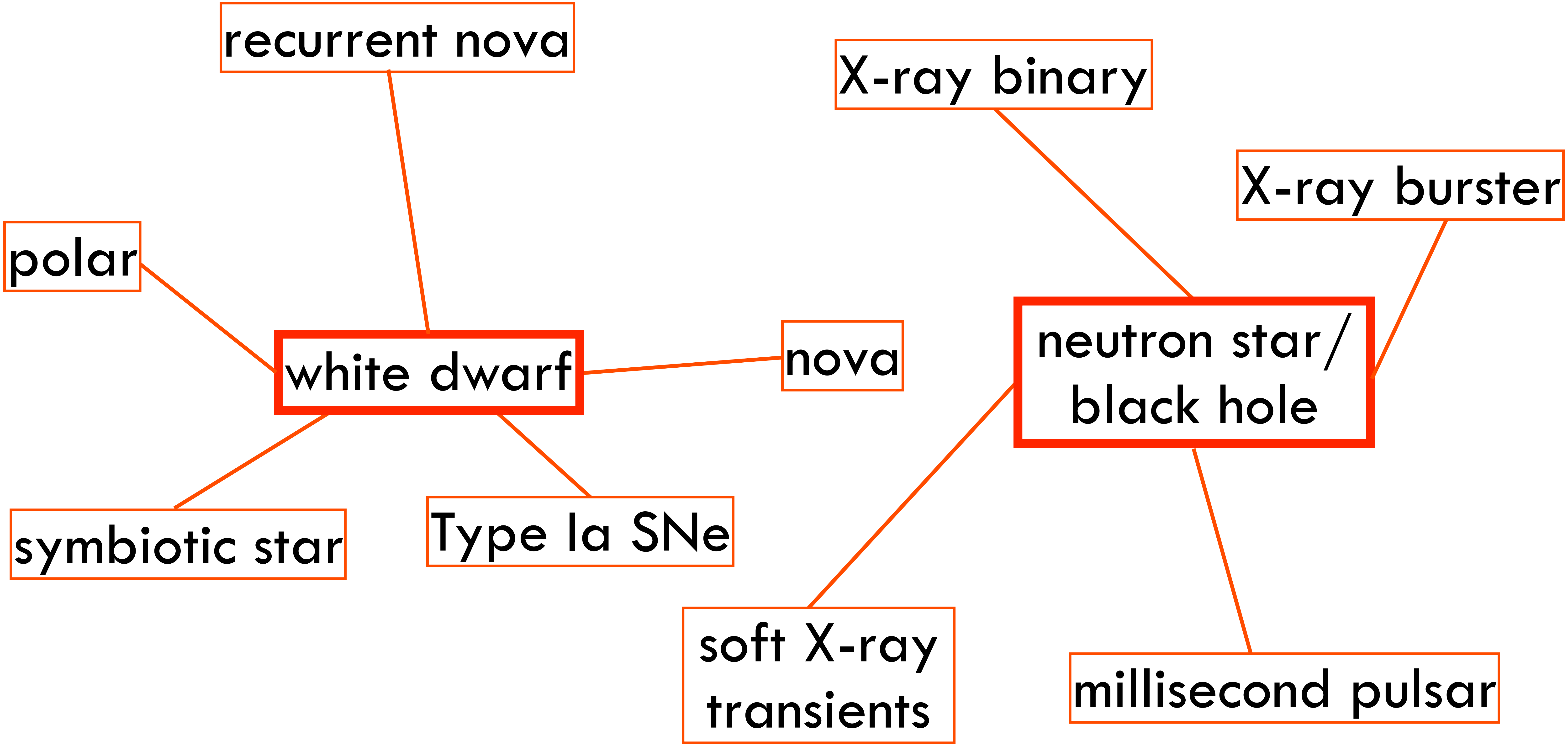
Algol consists of a main-sequence B star with $M = 3.5M_{\odot}$, plus a giant K star, with $M = 0.81M_{\odot}$.

How can the less massive star be further advanced in its evolution?

Algol is an example of an *interacting binary*. The K-star was indeed originally the more massive star. As it evolved, it expanded and then transferred mass to the companion star. So much mass was transferred that it became the less massive star.

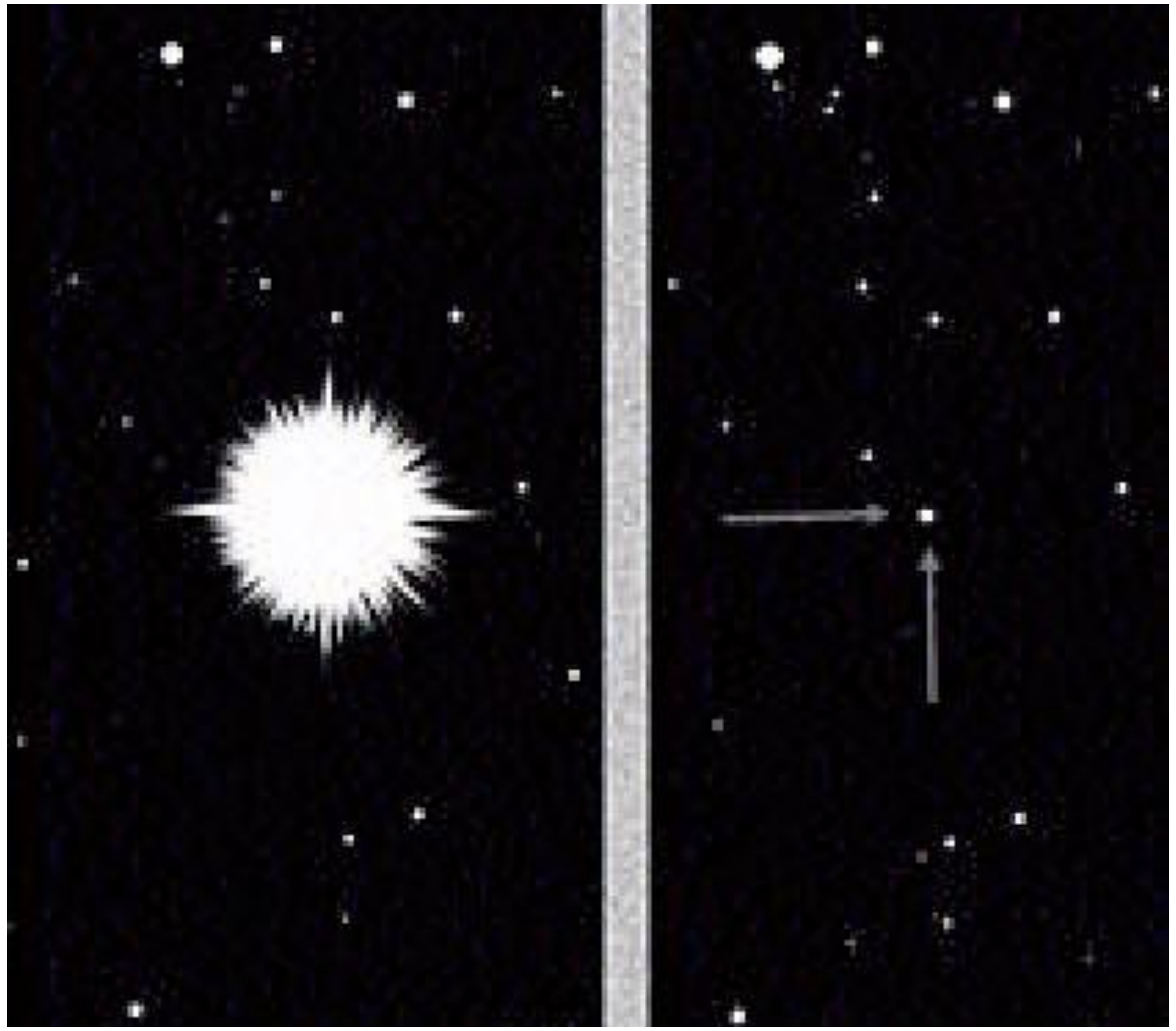
Interacting binaries can appear in many forms: the *binary zoo*.




recurrent nova
X-ray binary
X-ray burster
polar
white dwarf
nova
neutron star/
black hole
symbiotic star
Type Ia SNe
soft X-ray
transients
millisecond pulsar

Novae

Novae are (apparently) "new" stars, which suddenly brighten by a factor of 50,000 or more.

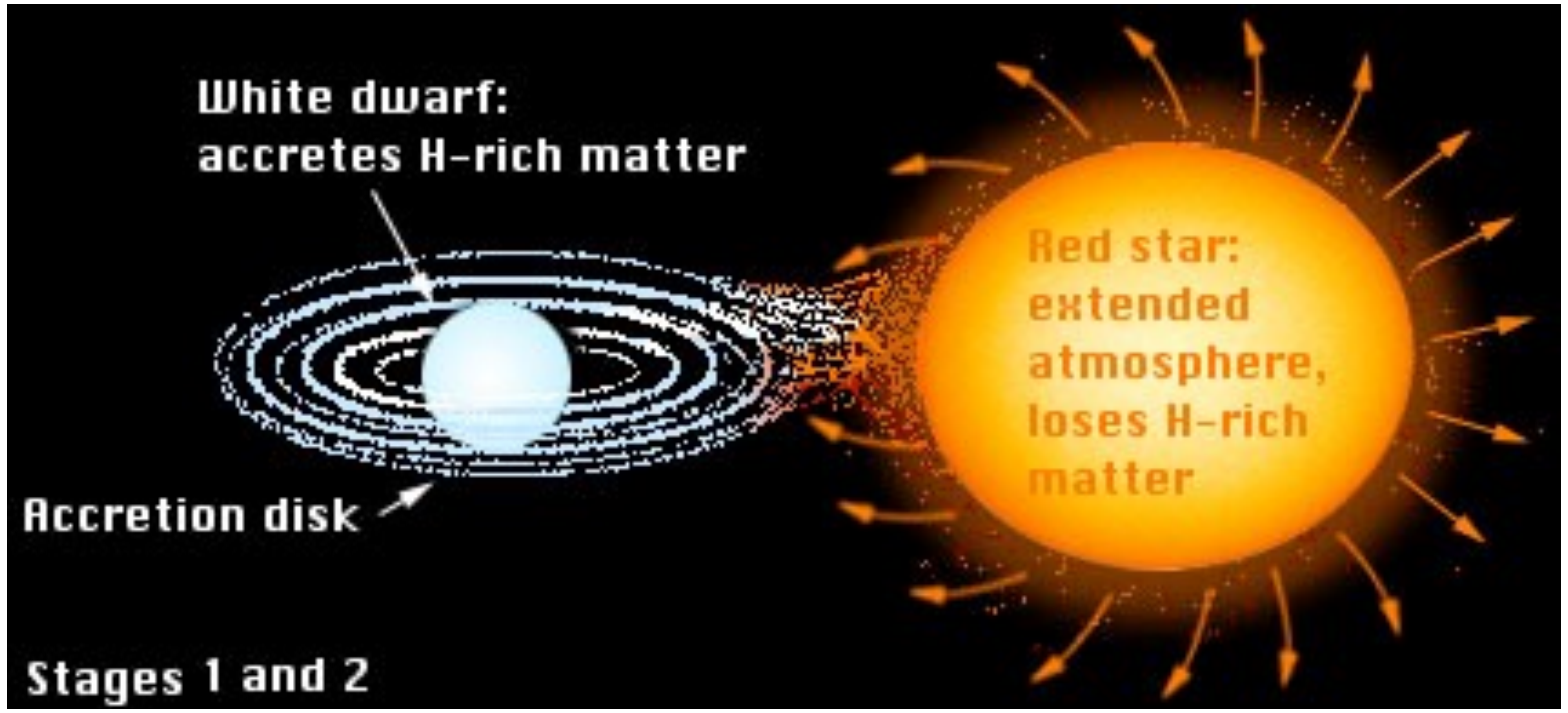


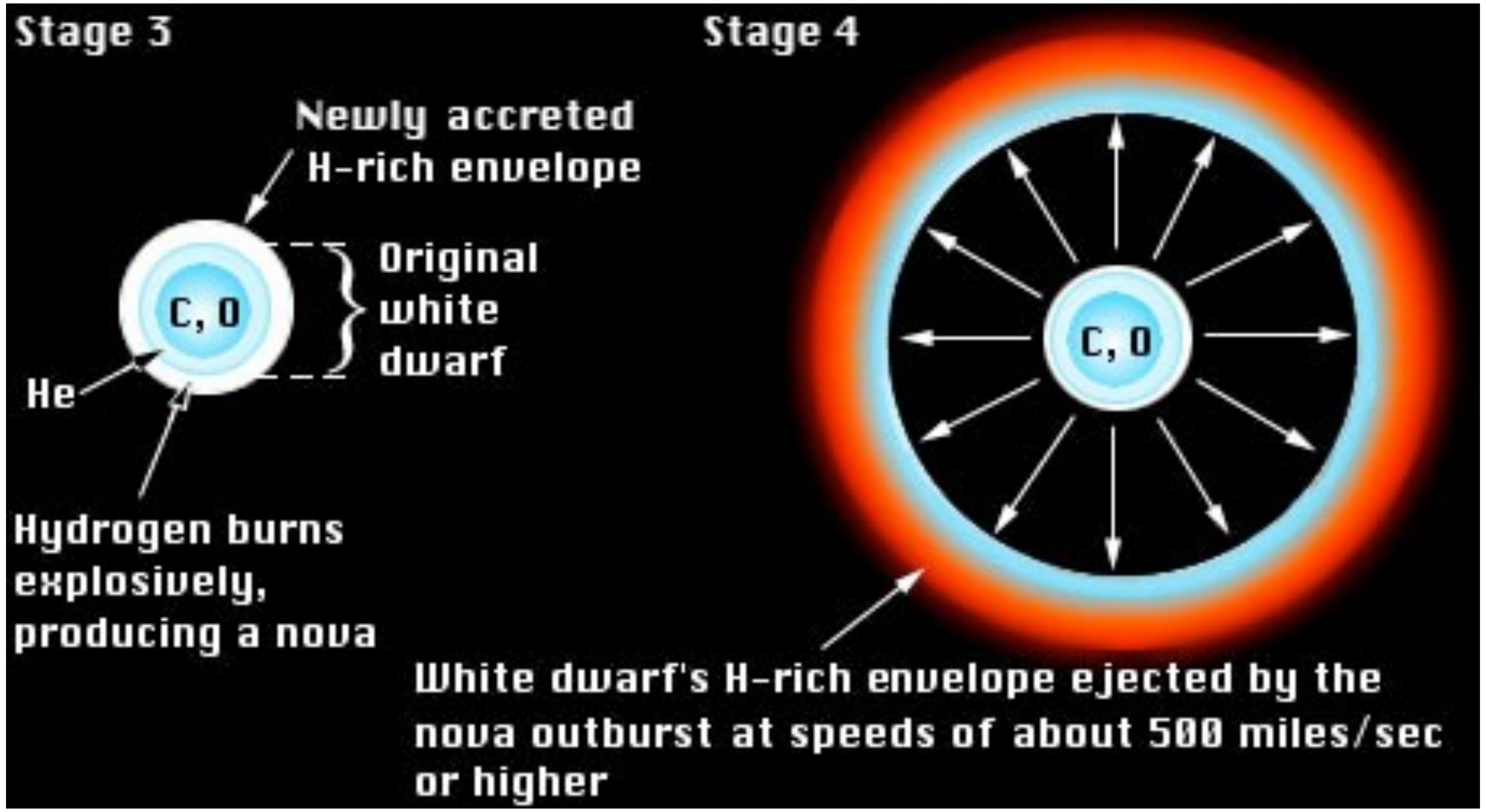
Nova Herculis 1934, before and during outburst, when it brightened by a factor of 60,000.


Nova Cen 2013
Beta Cen
Alpha Cen
Centaurus

Hydrogen transferred from the companion star accumulates on the surface of the white dwarf.

When the base of this layer reaches a critical temperature, the whole layer explodes.





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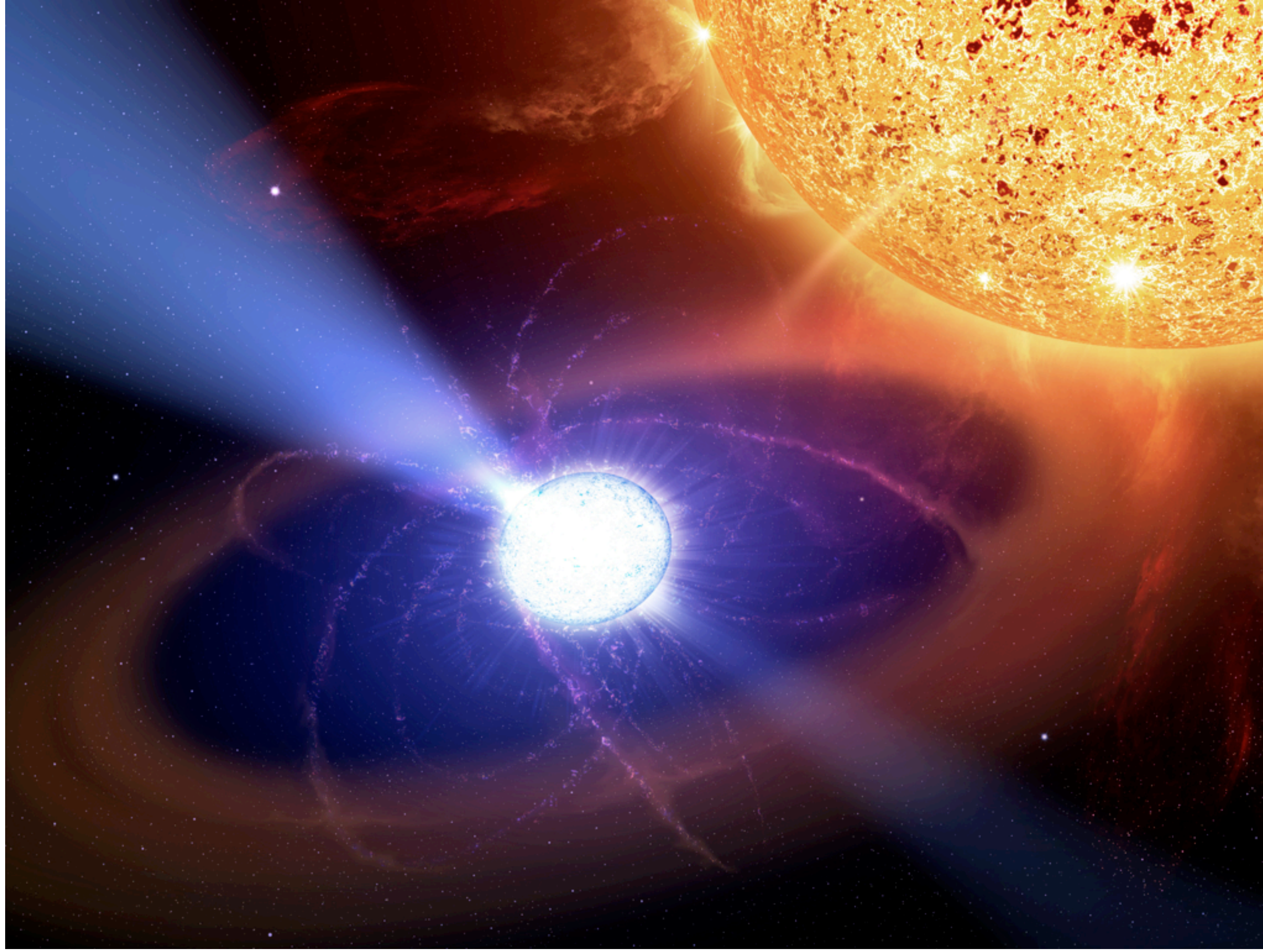
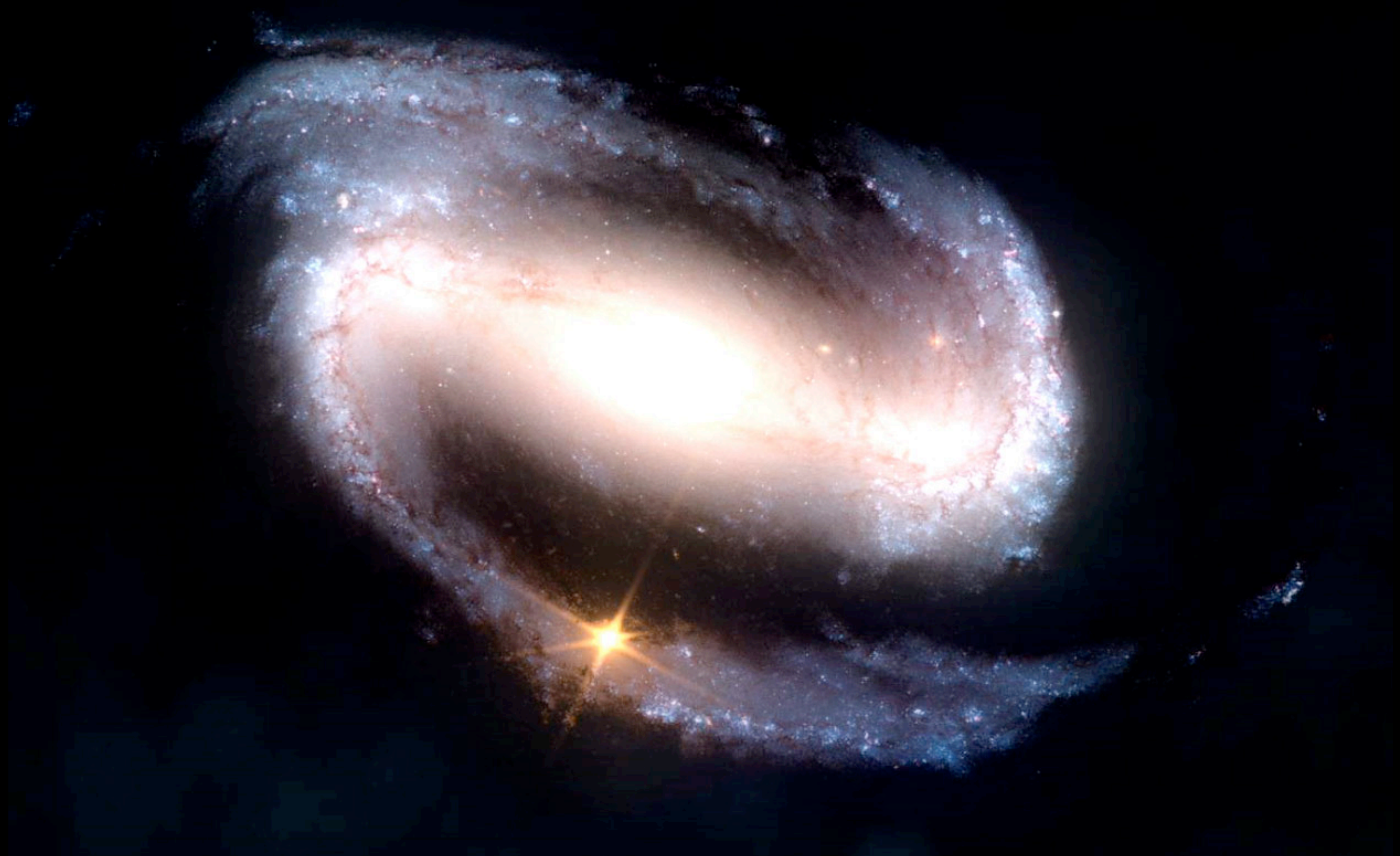
Most novae have only been seen to erupt once, but there are ten known *recurrent novae* which have had more than one recorded eruption. The time between eruptions can be anything from 10 to 80 years. So any ordinary nova might be a recurrent nova, but on a longer timescale than this.



Type Ia supernovae



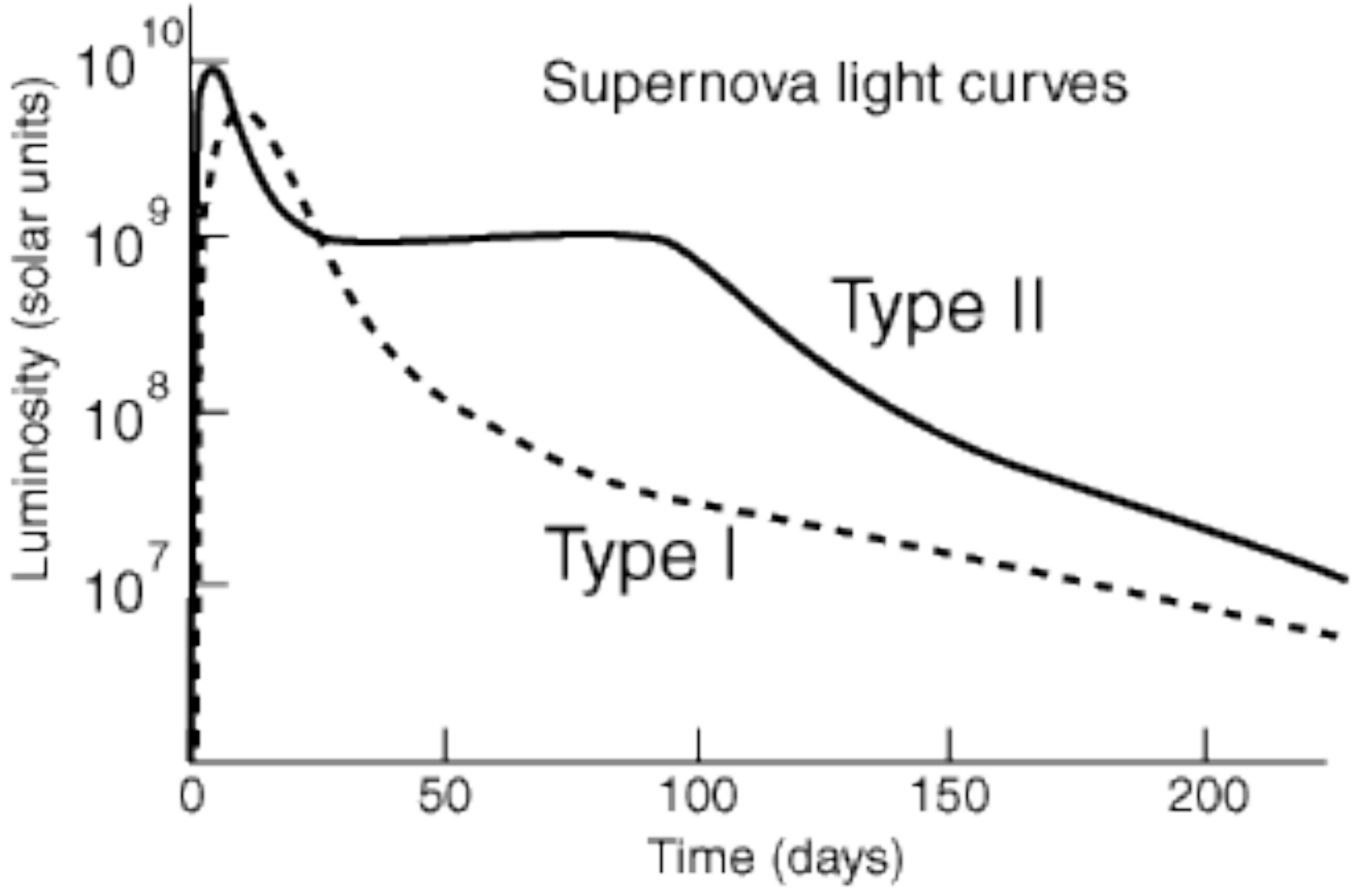
Supernovae

We spoke about *core-collapse supernovae* resulting from the deaths of massive stars. These explosions involve the complete destruction of the star.

Type Ia supernovae

There is a second type of supernova explosion.

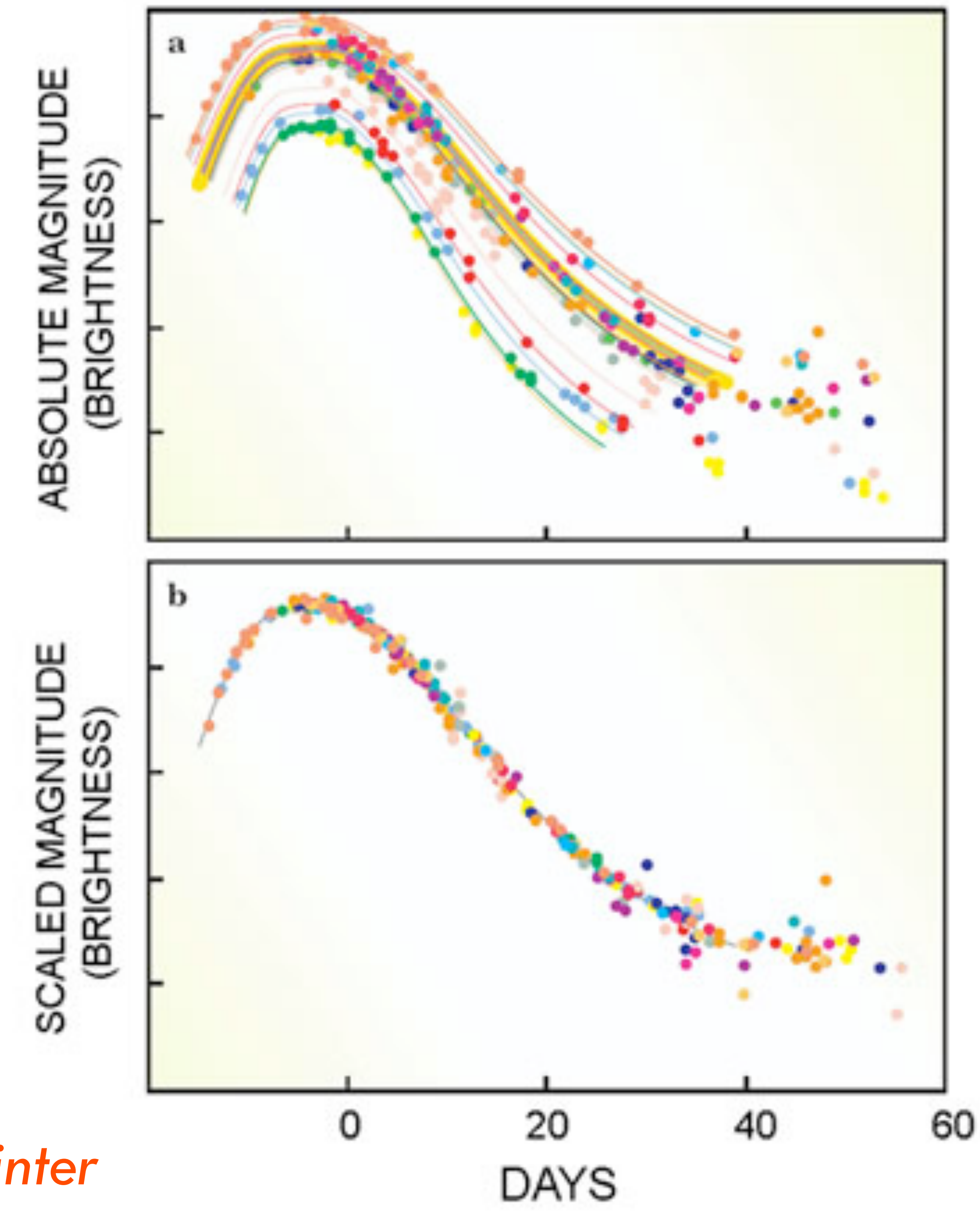
Type Ia supernovae have no hydrogen in their spectrum, and lack the characteristic "bump" in their light curve from the decay of radioactive elements.



Adapted from Chaisson & McMillan

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*.

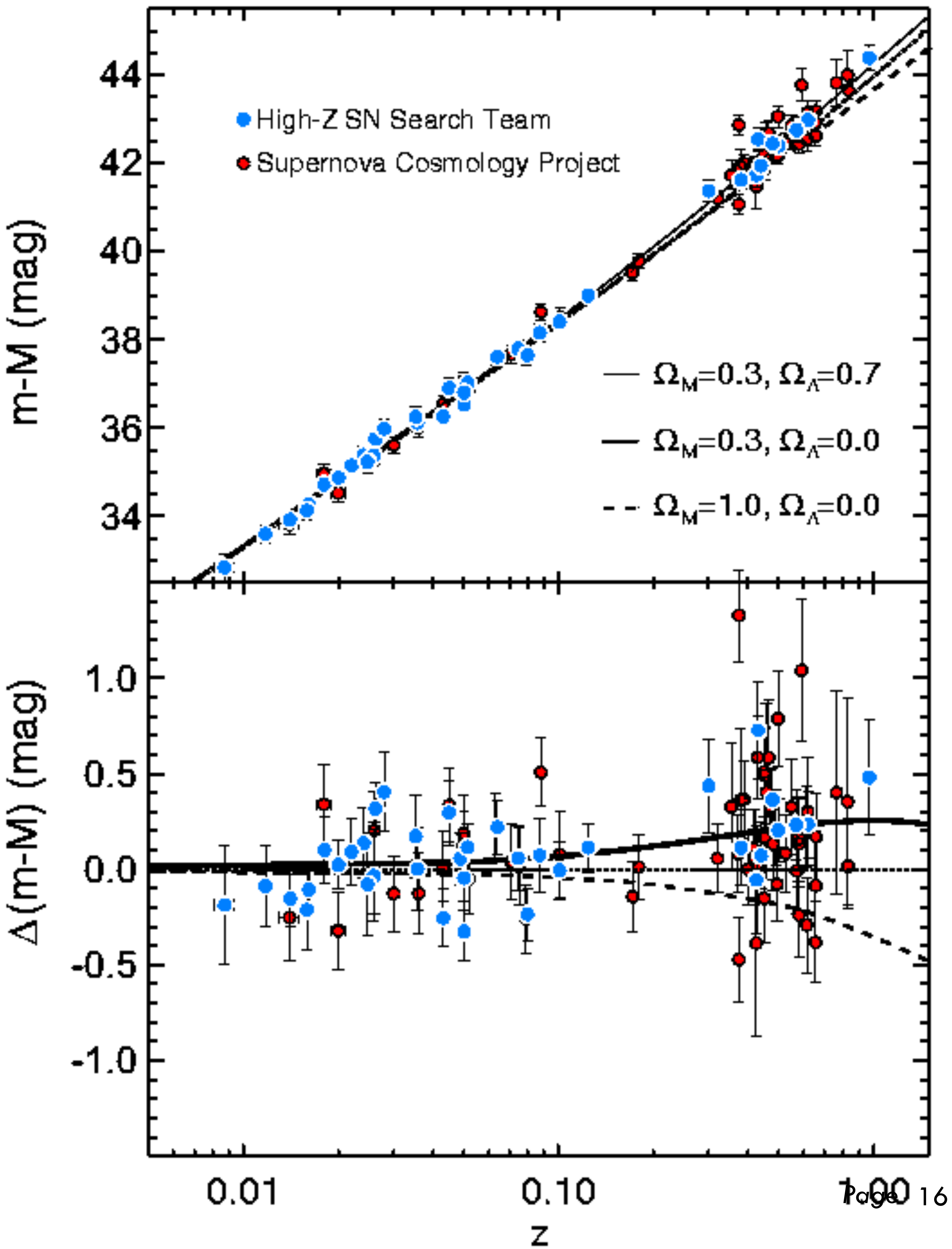


Brighter supernovae are found to take longer to fade than fainter ones; a single correction can make all the light-curves match

The *2011 Nobel Prize for Physics* 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*.



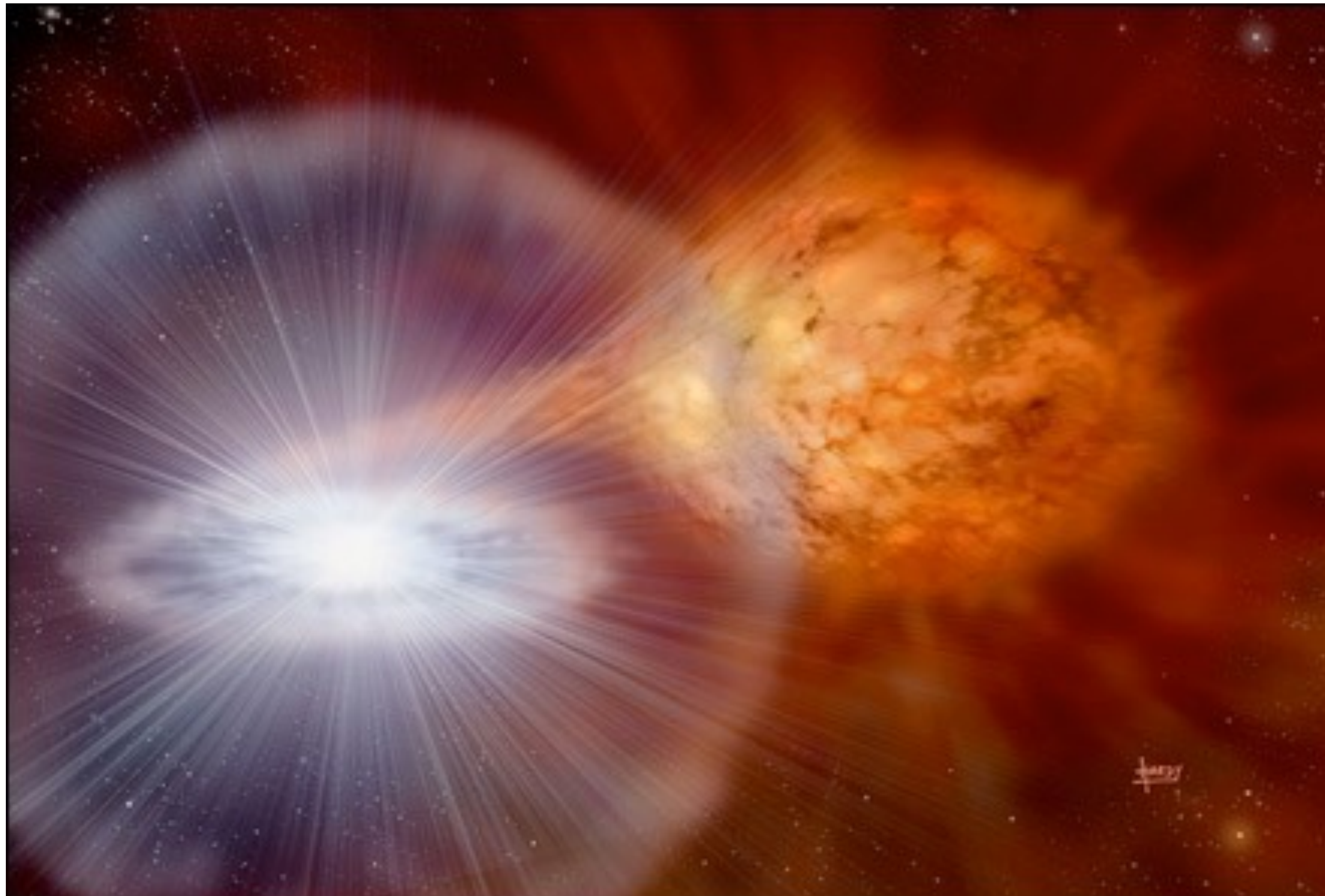
So having used SN Ia to discover the fate of the universe, it would be nice if we knew how they work.

"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 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.



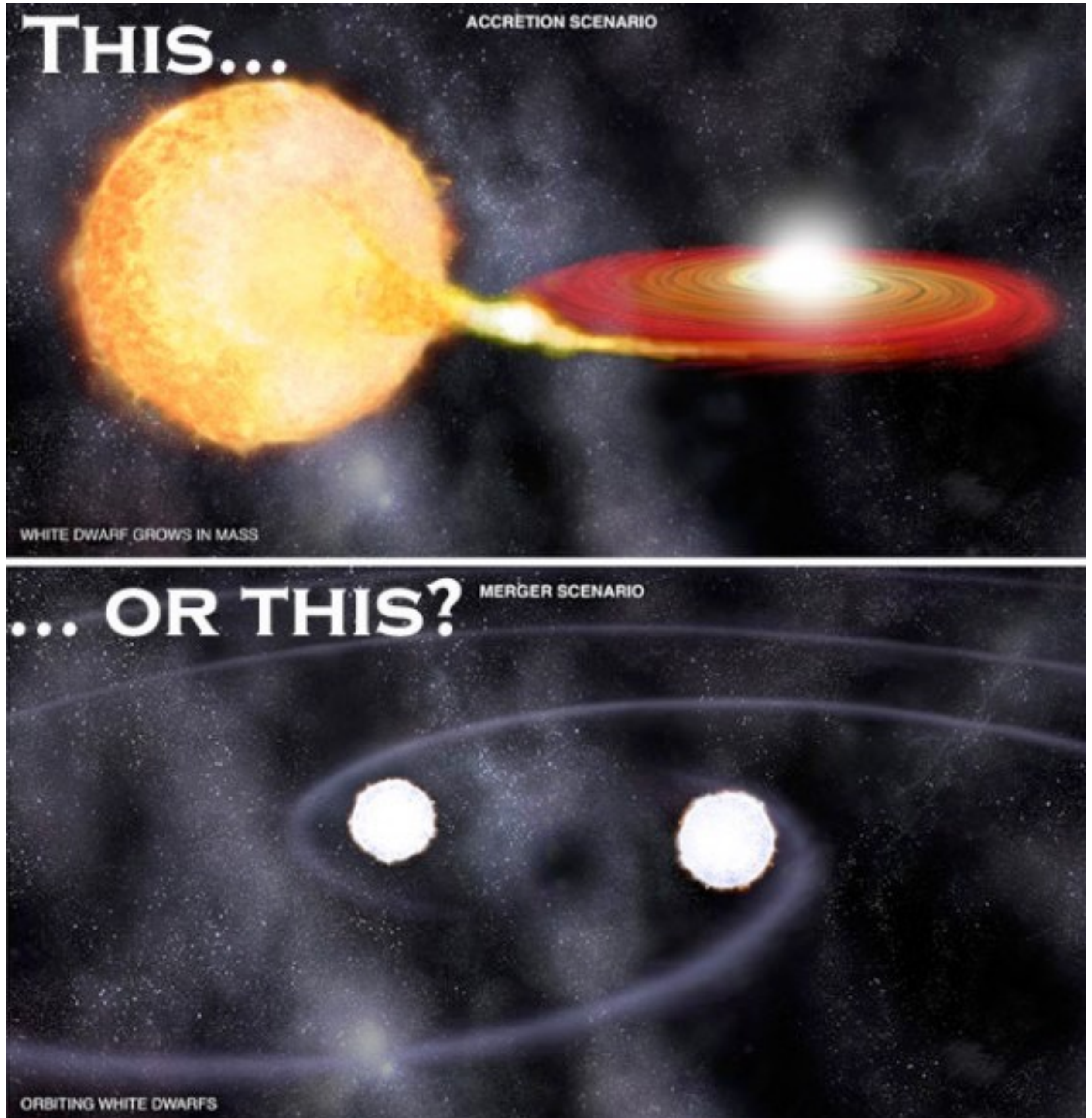
The resulting explosion results in the complete destruction of the star.

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

The problem is that 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.

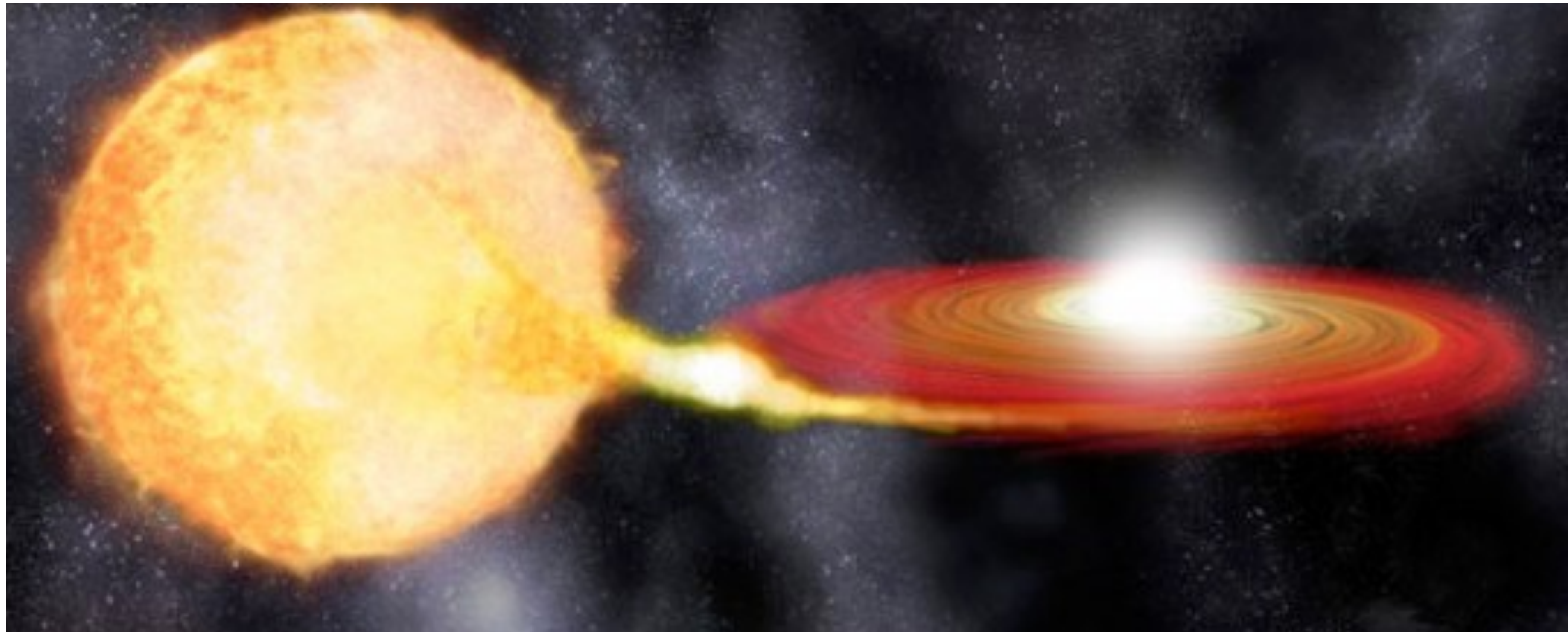


The single-degenerate scenario

Both scenarios have major problems.

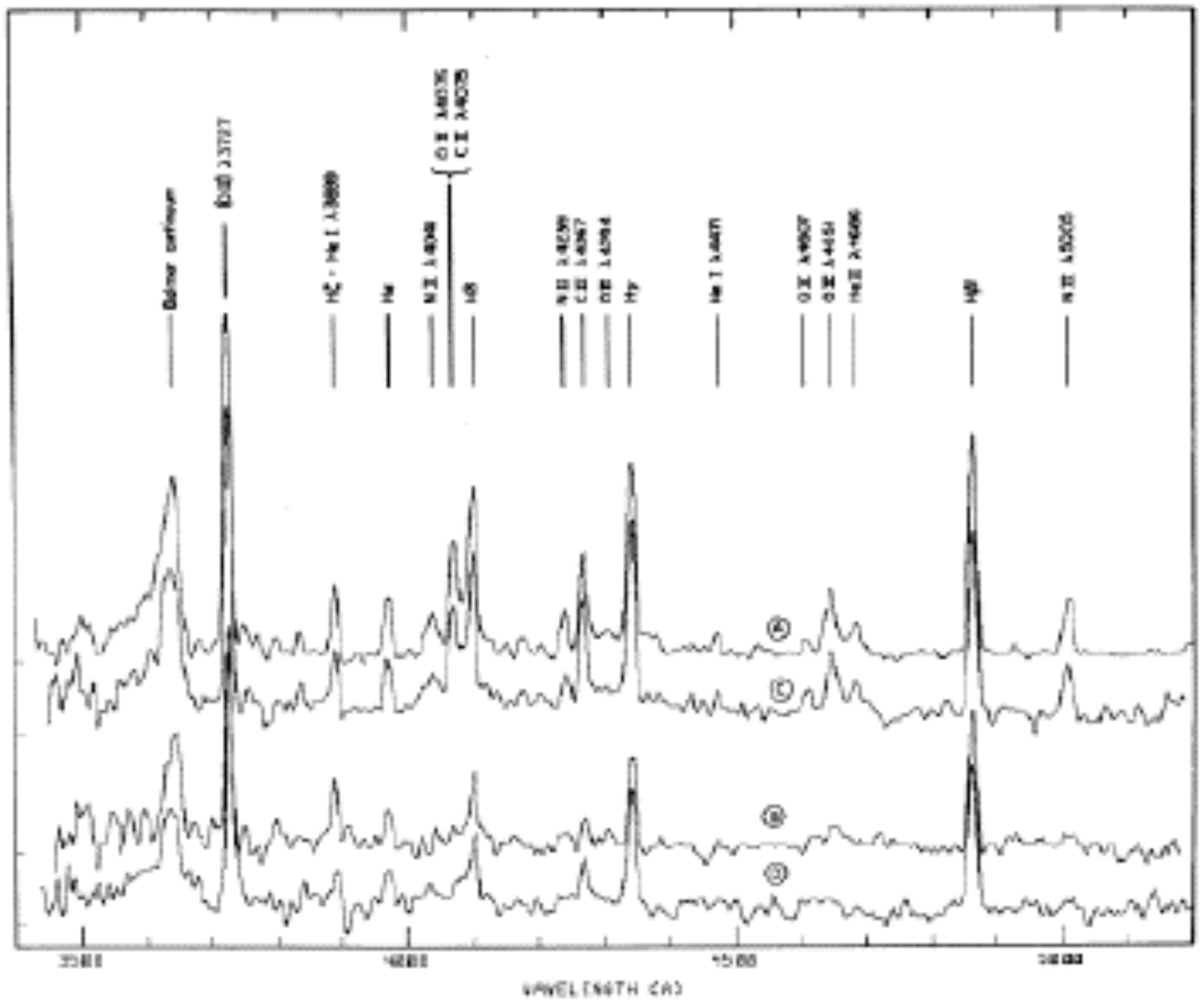
In the *single-degenerate scenario* the white dwarf is accreting matter from a companion star, i.e. it is a cataclysmic variable.

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 problem is that

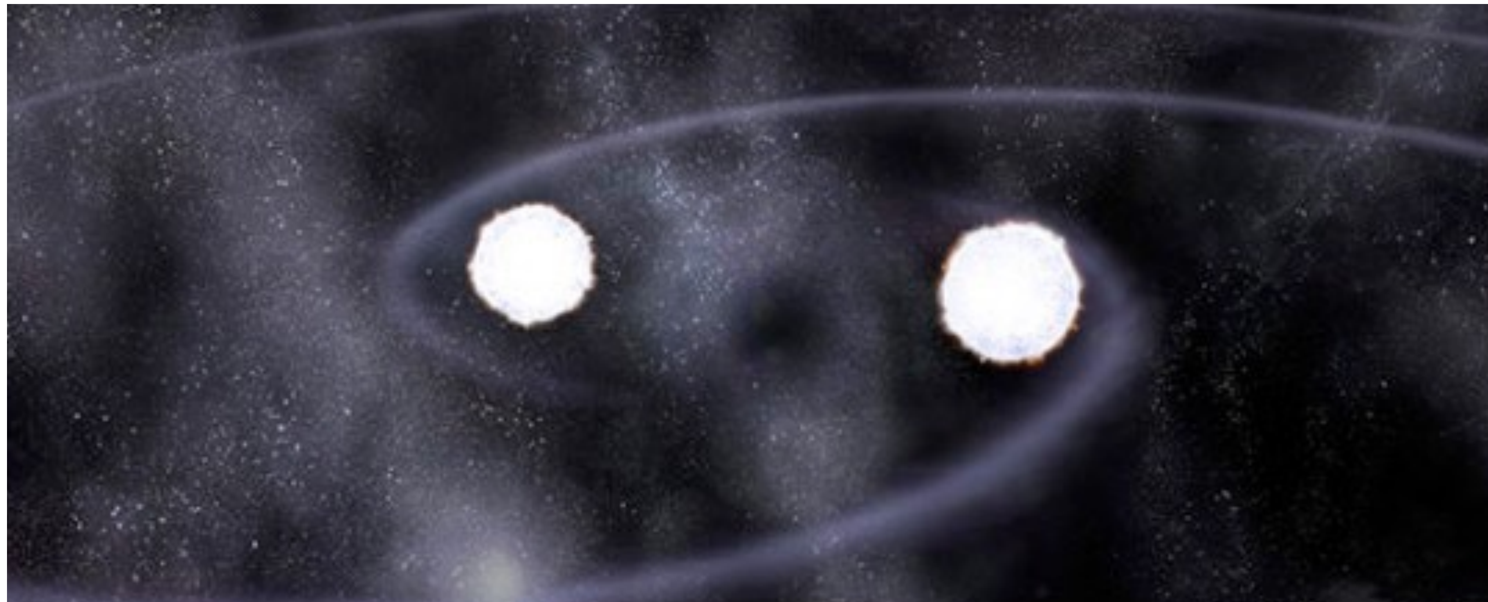
"all accretion rates of hydrogen from zero to infinity are ruled out by various constraints" (Wheeler 1995).

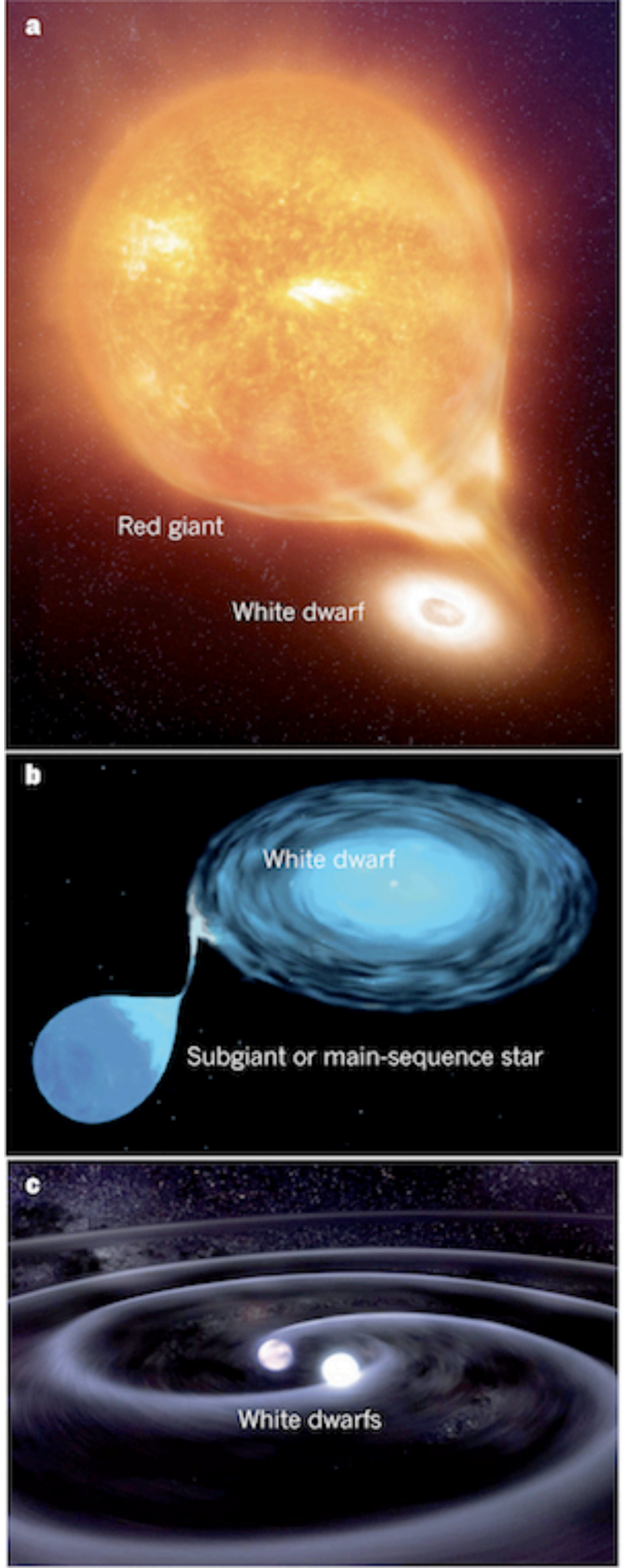
The double-degenerate scenario

– 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.





Three main cases:

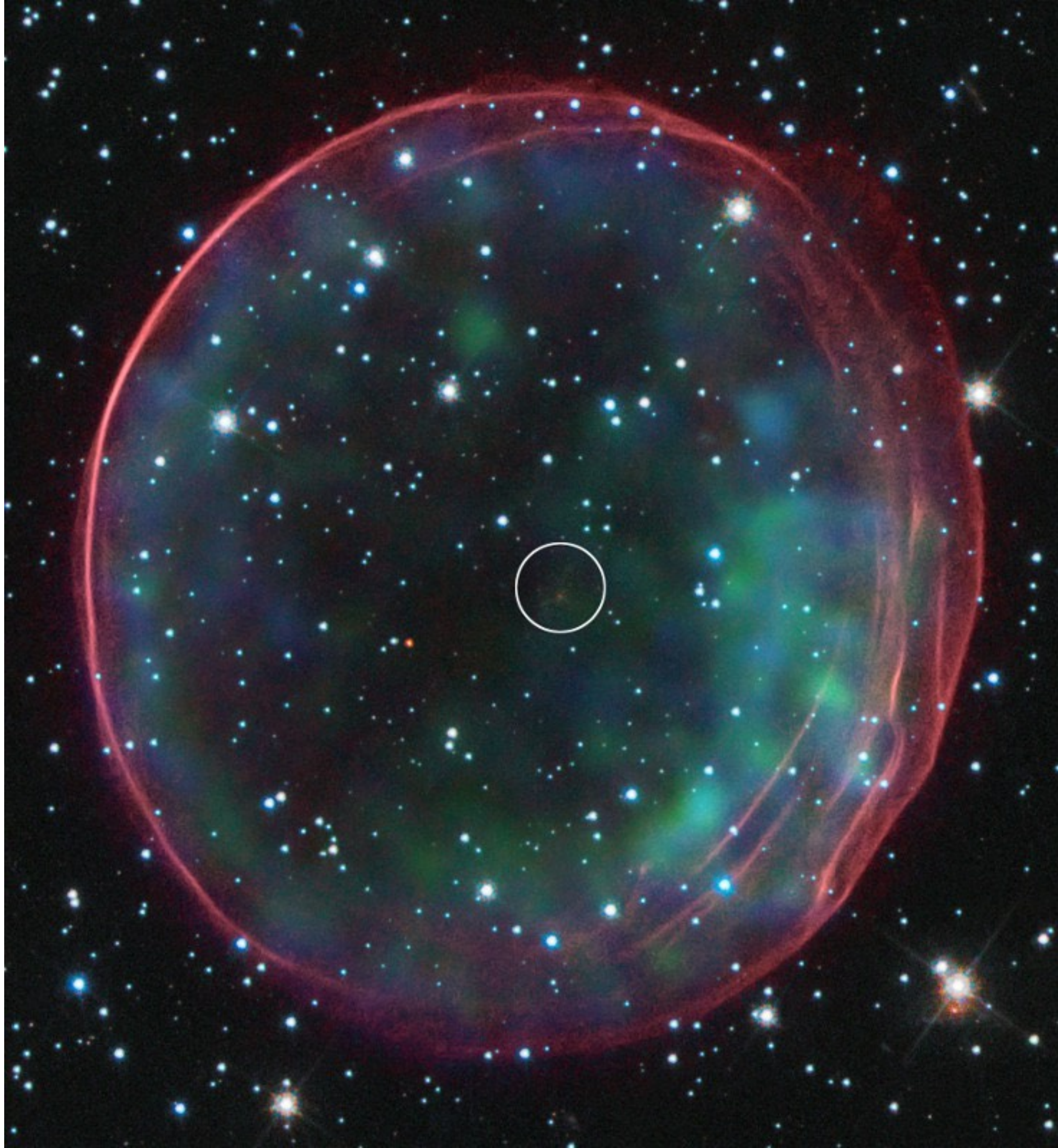
- case A: red giant + white dwarf
- case B: main-sequence star + white dwarf
- case C: two white dwarfs

Observational test: look for companion star either after the explosion, or before.

Look at the site of past SN Ia explosions.

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

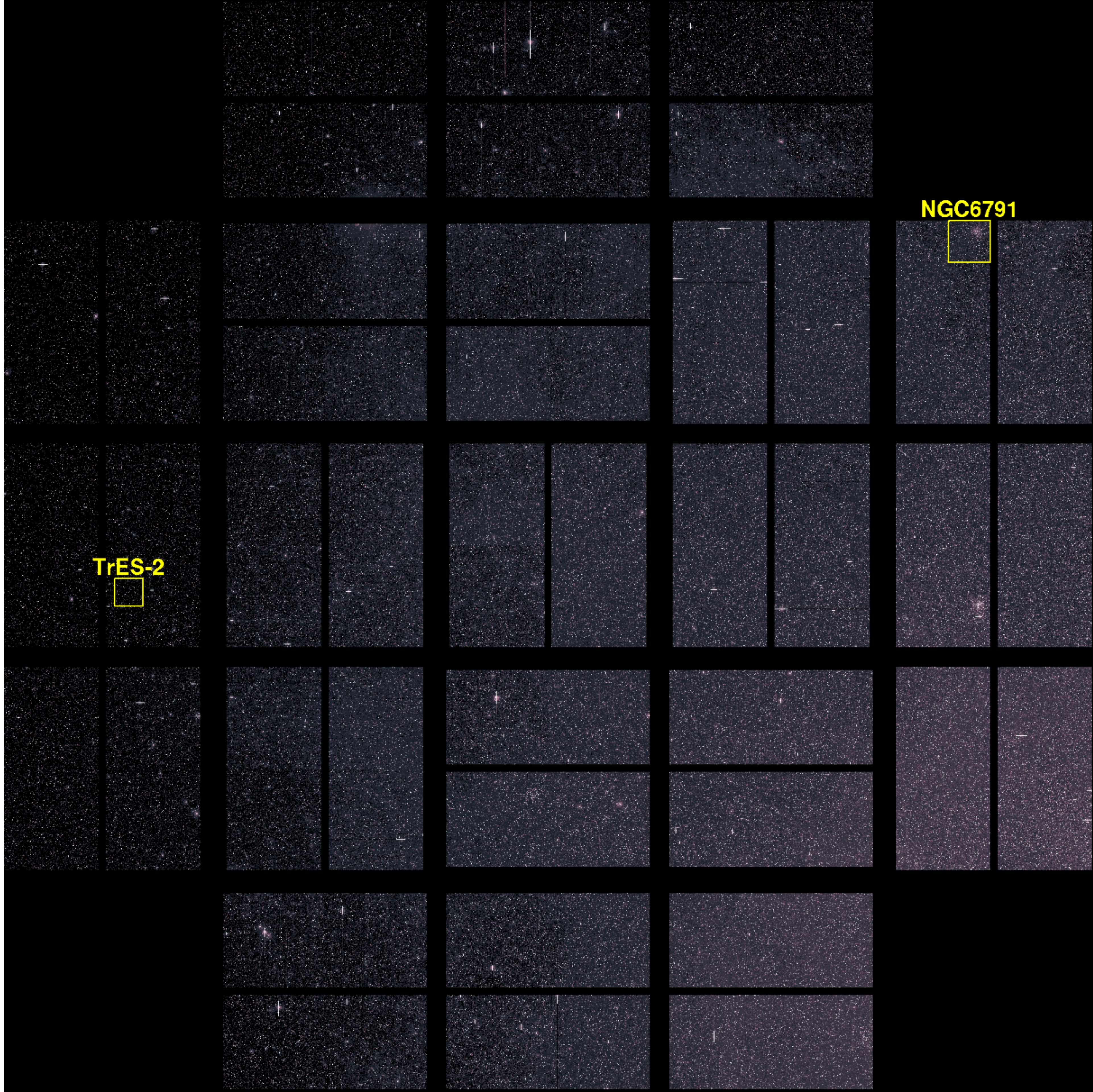
This limit rules out all possible classes of progenitors except for the close pair of white dwarfs.



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

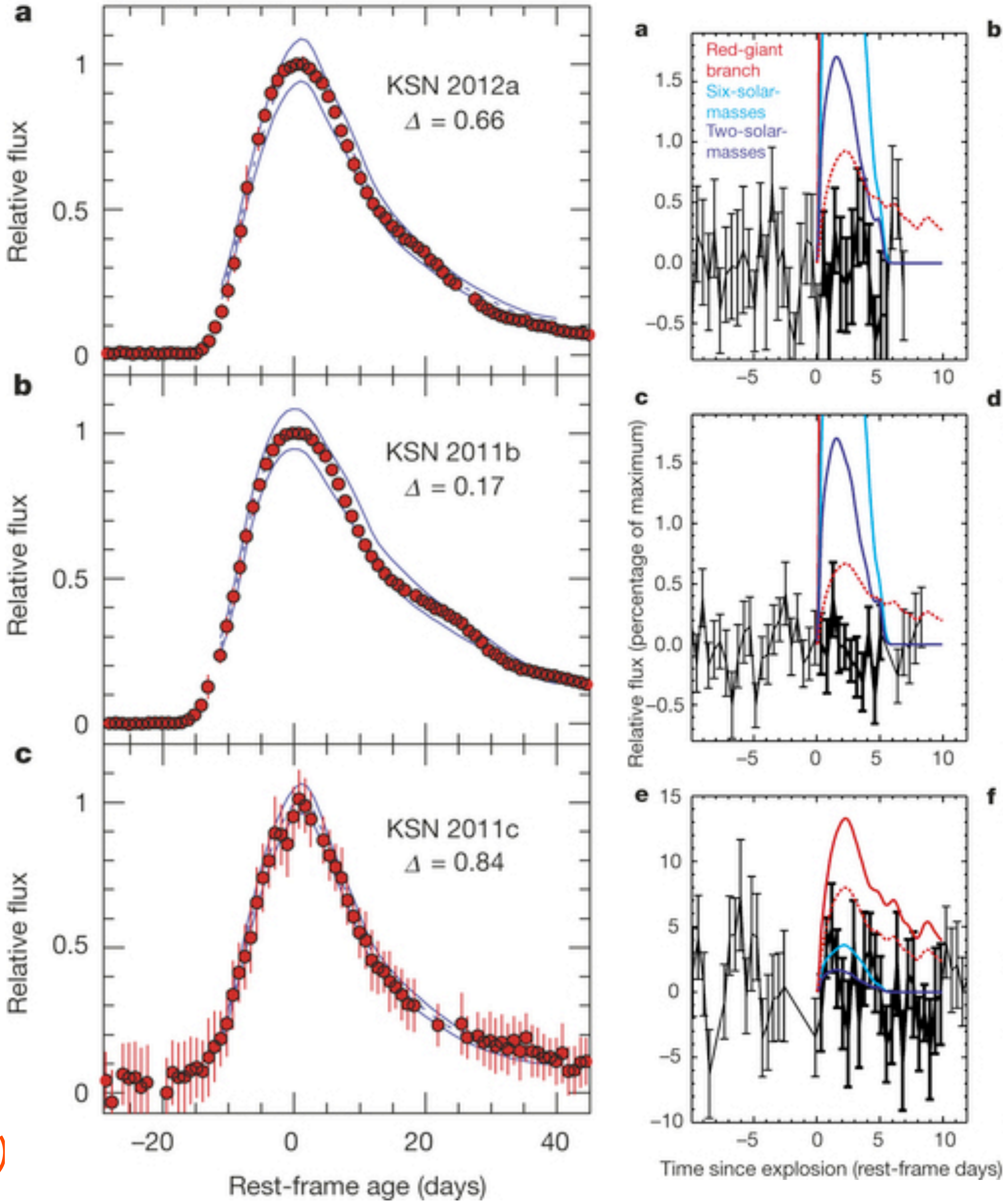
The *Kepler* spacecraft spent four years staring at one patch of sky, looking for exoplanets.

The patch contains 500,000 stars, but also many galaxies. Several of these galaxies had supernova explosions while Kepler was monitoring them: we can look for the impact of the explosion on the companion (if any).



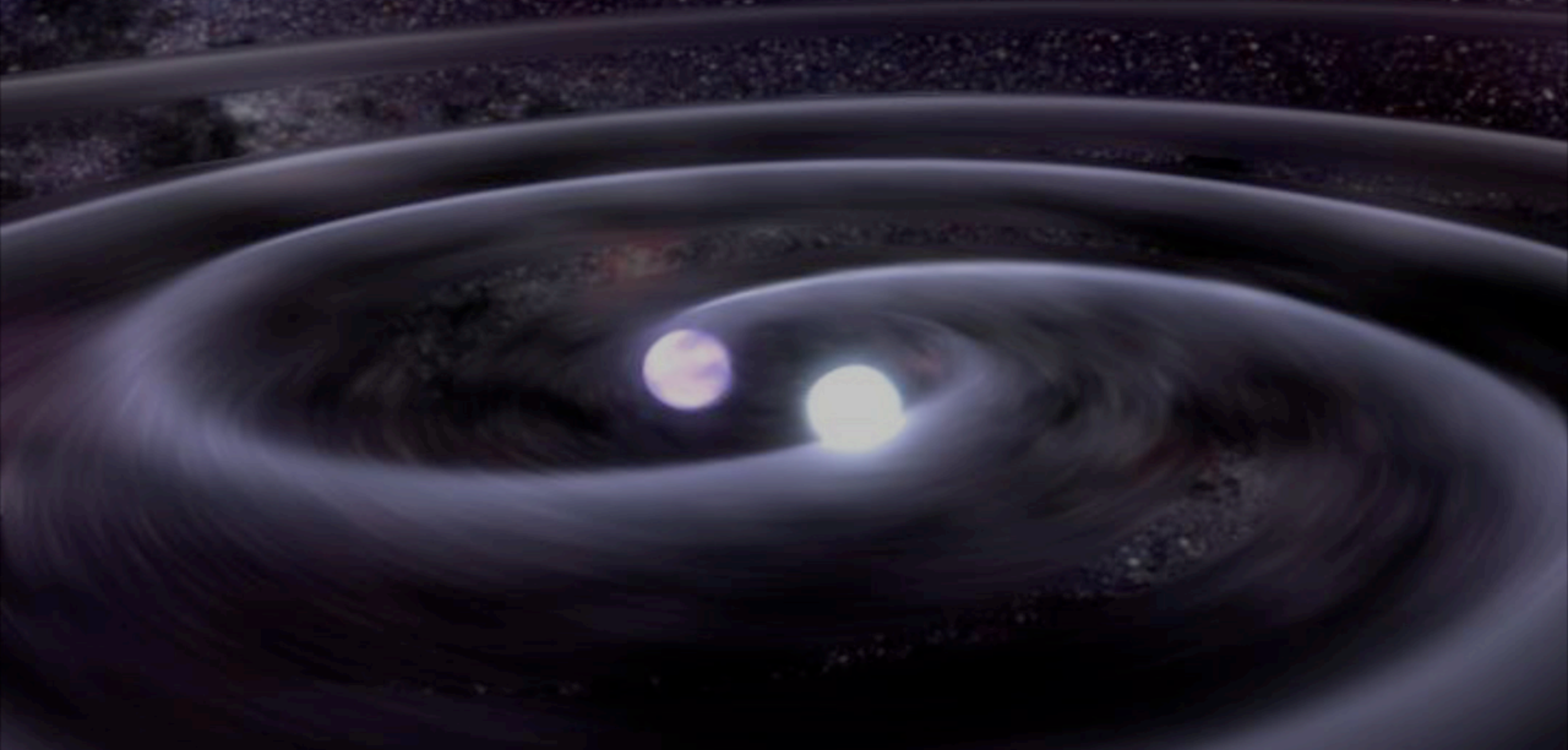
The authors found *no* signatures of the supernova ejecta interacting with nearby companions, suggesting the supernovae arose from merging white dwarfs.

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)

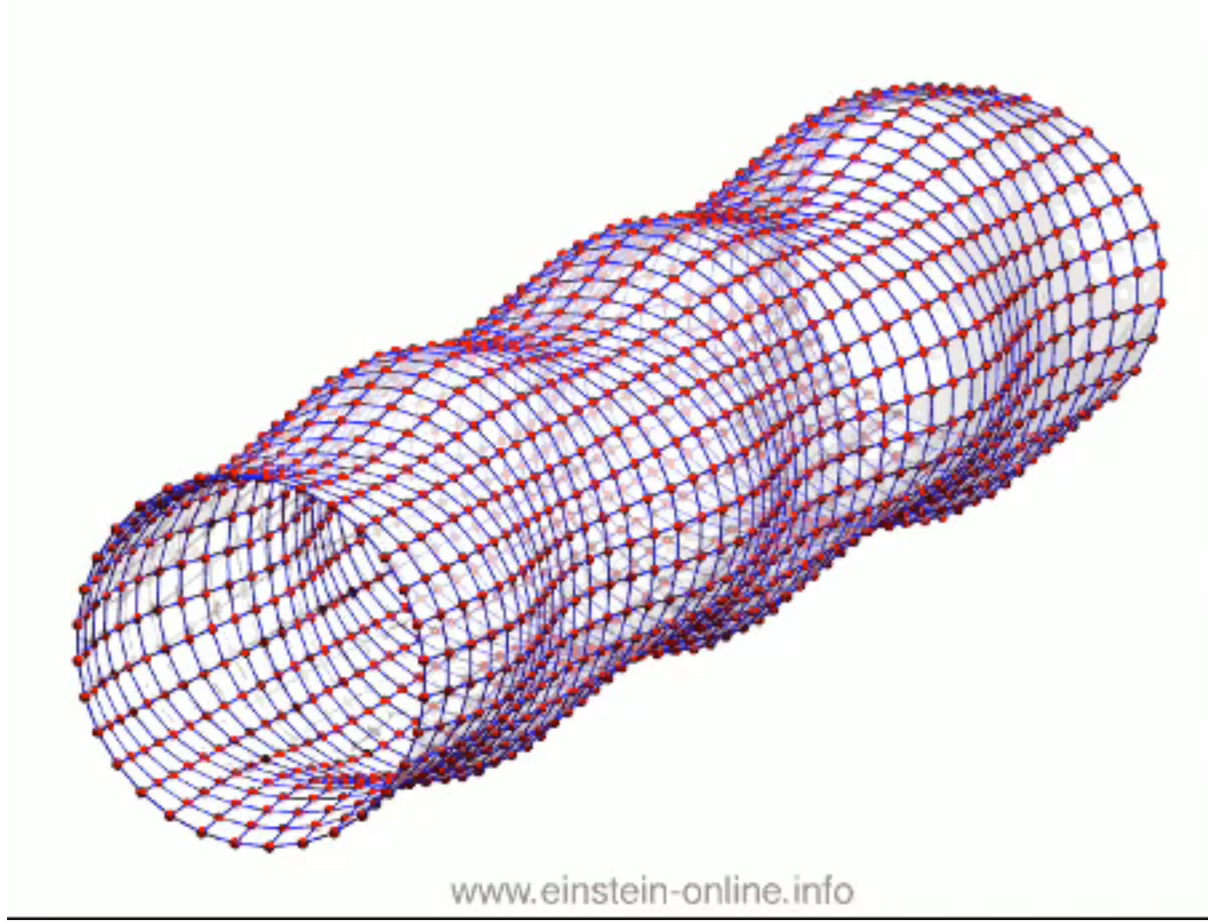
Gravitational waves from binaries



Gravitational waves

Last lecture, we discussed that general relativity predicts the existence of *gravitational radiation*: fluctuations in space-time which propagate as a wave.

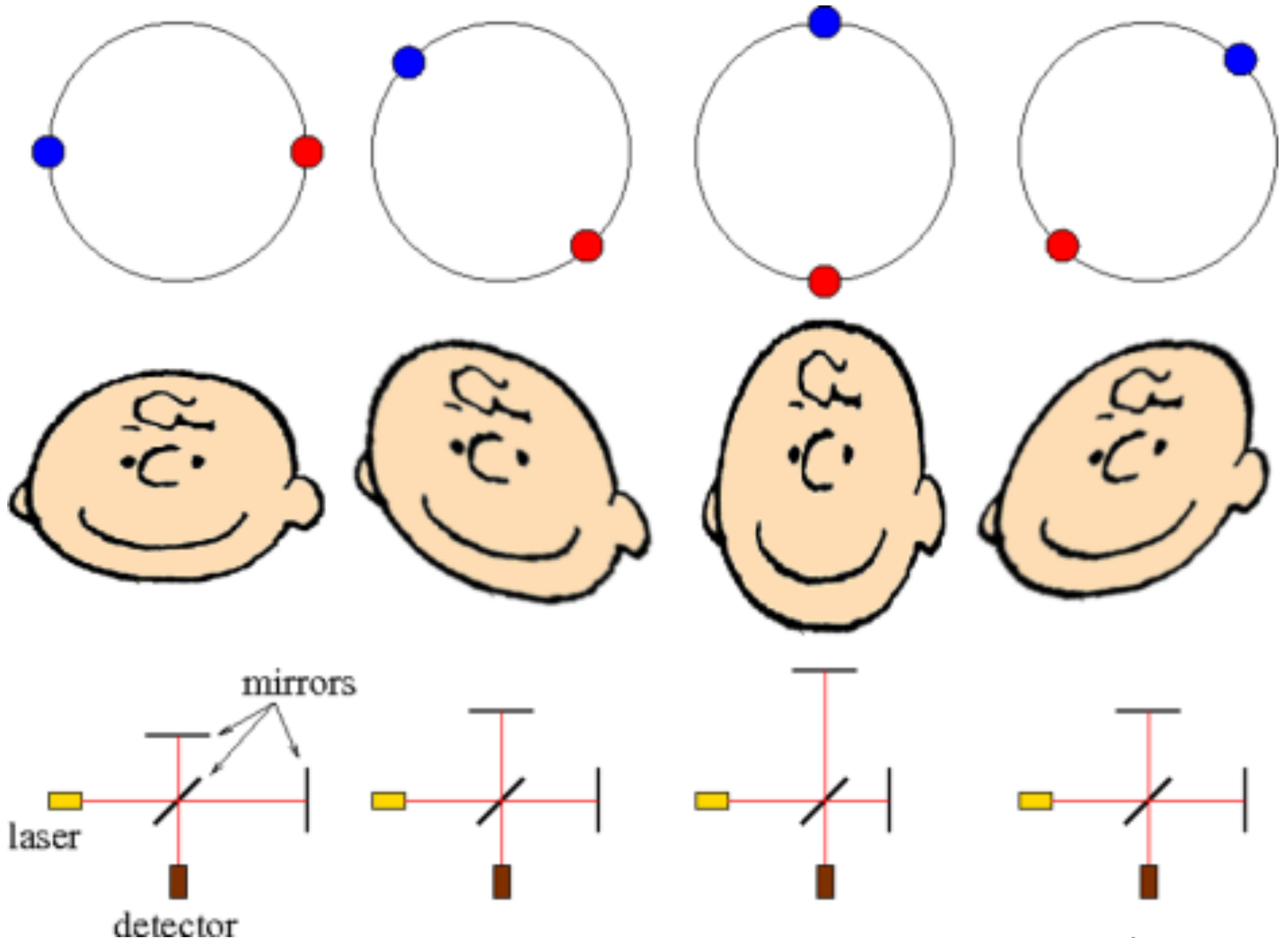
Gravitational waves are detected by detecting a change in lengths, e.g. the change in the distance between two objects.



Detecting gravitational waves emitted by a binary pulsar by measuring a distortion (image by Matthew Francis)

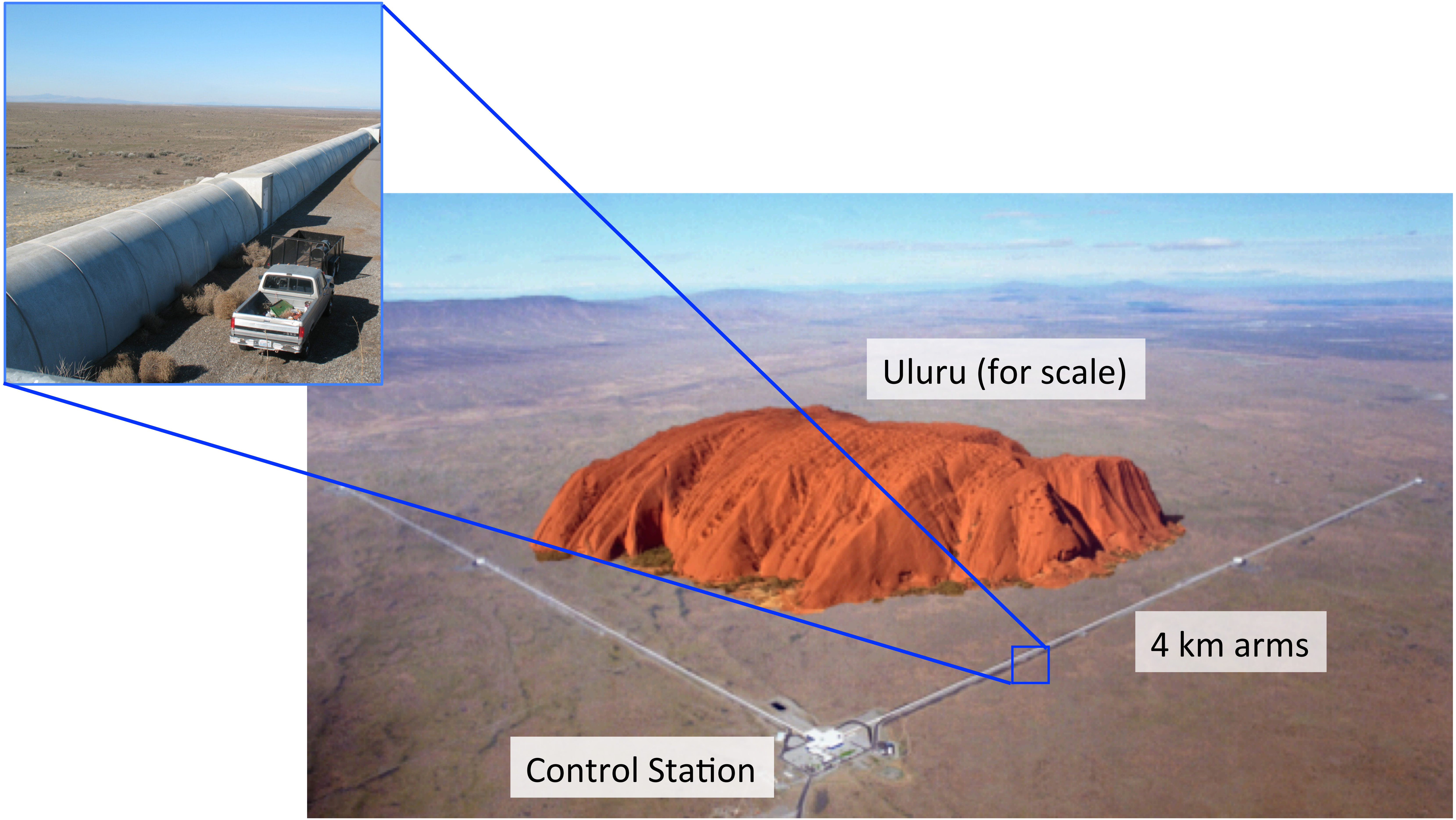
Gravitational waves are detected by detecting a change in lengths, e.g. the change in the distance between two objects.

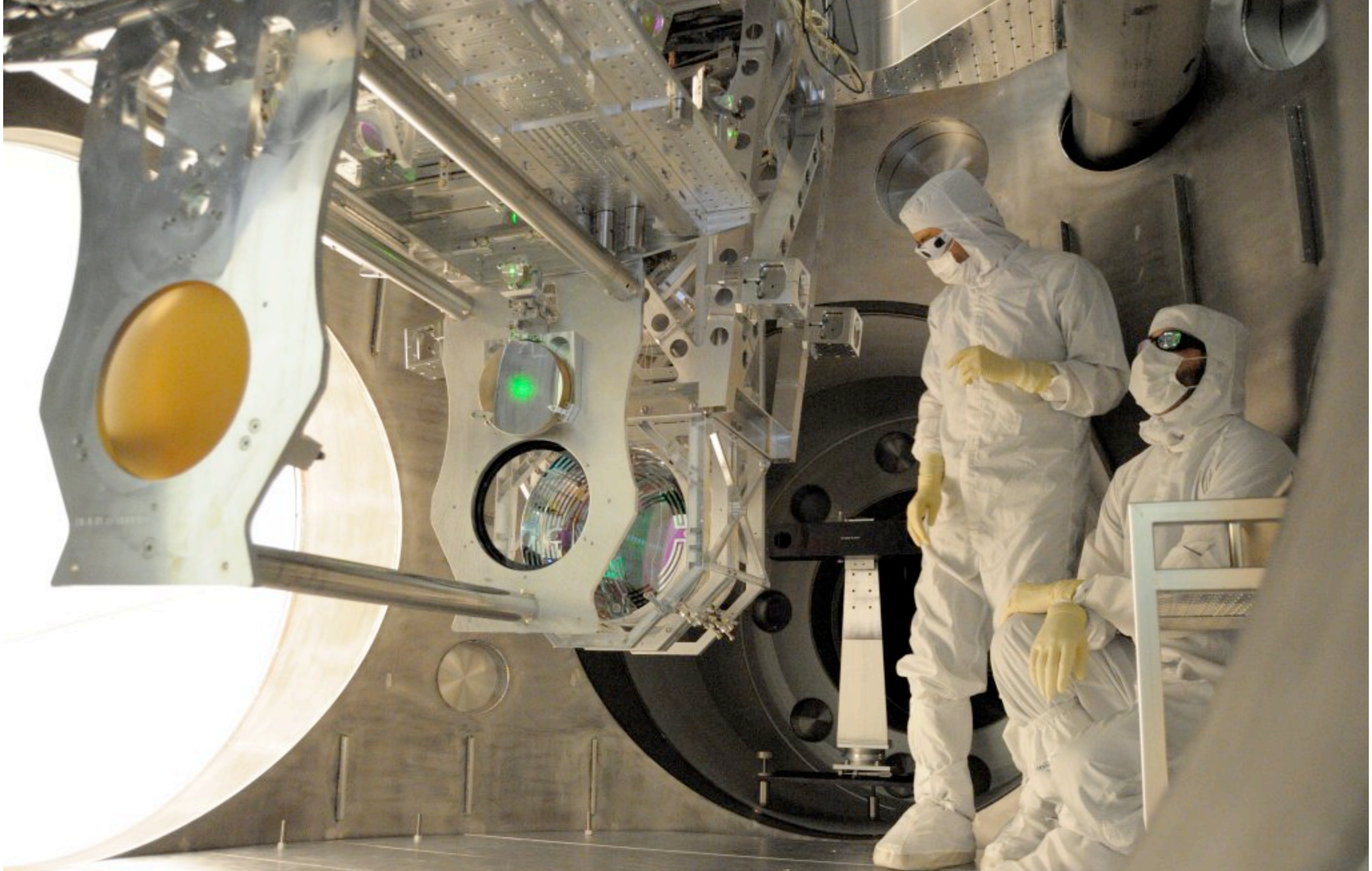
The effect is *extremely* weak: the most violent event produces changes of about 1 part in 10^{21}. To measure this, you need to be able to measure the change in length equal to 0.1% x diameter of a proton over 4 km.

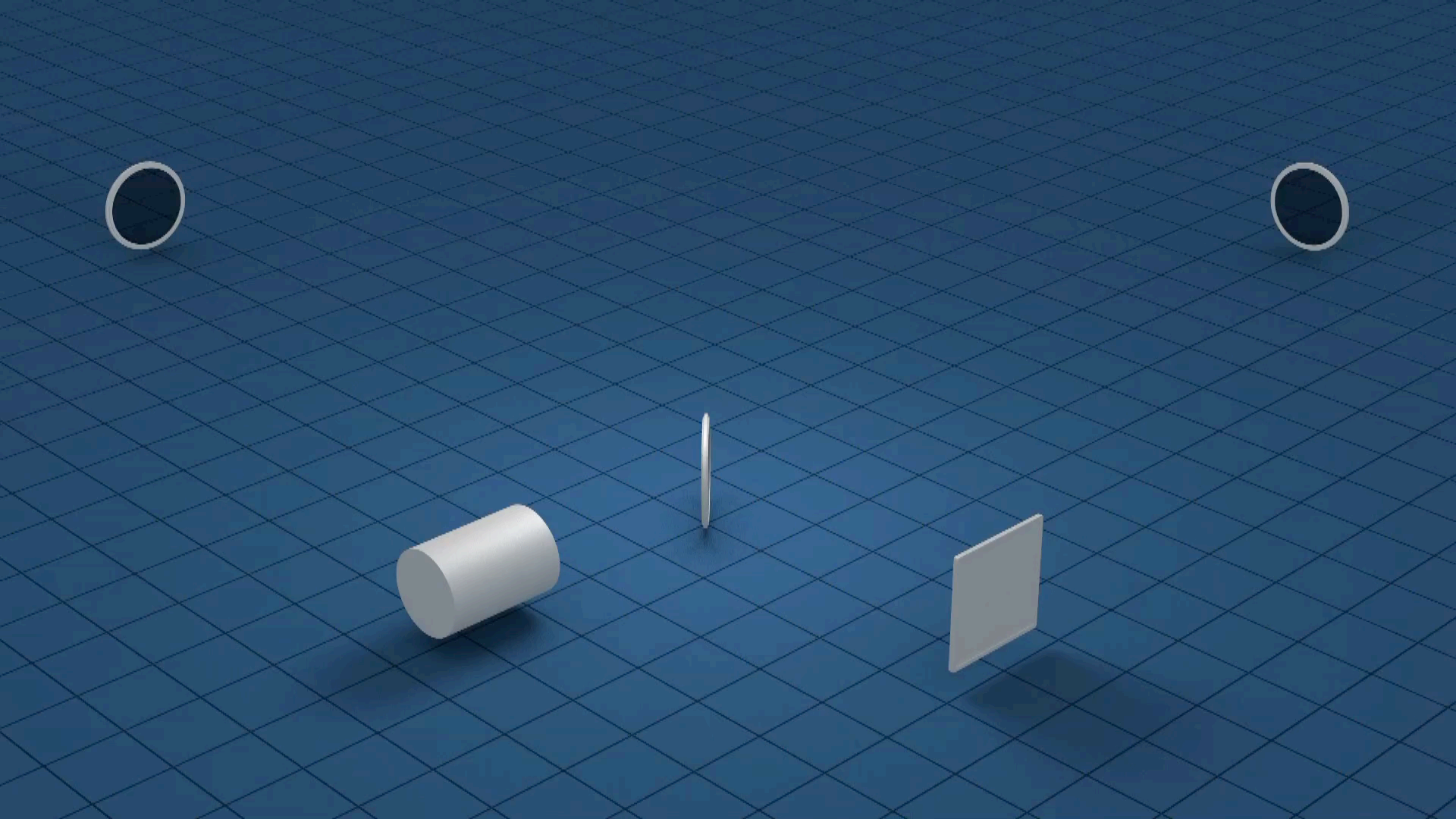


Detecting gravitational waves emitted by a binary pulsar by measuring a distortion (image by Matthew Francis)

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.

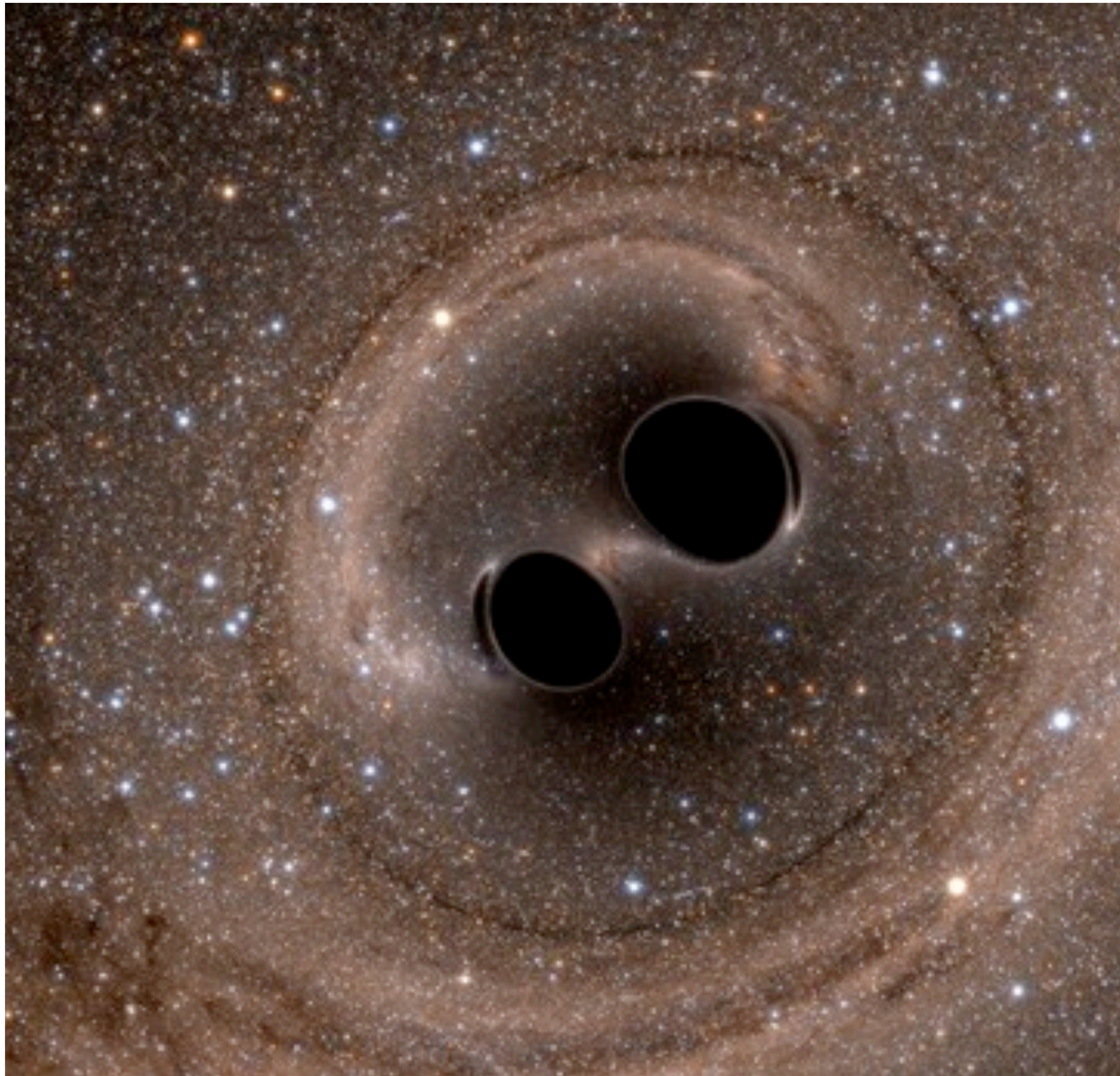

Uluru (for scale)
4 km arms
Control Station





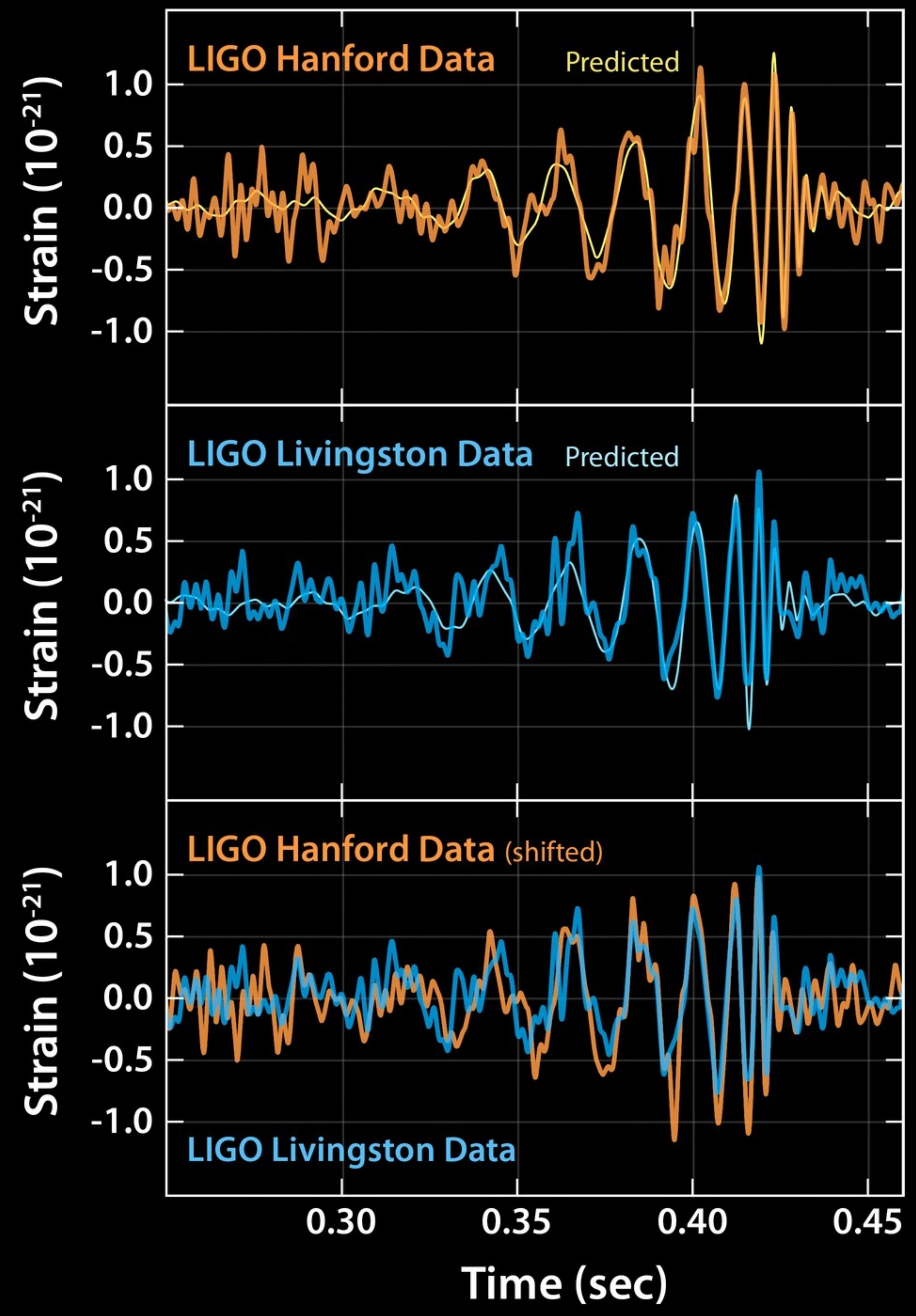
The LIGO binary black hole merger GW150914

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

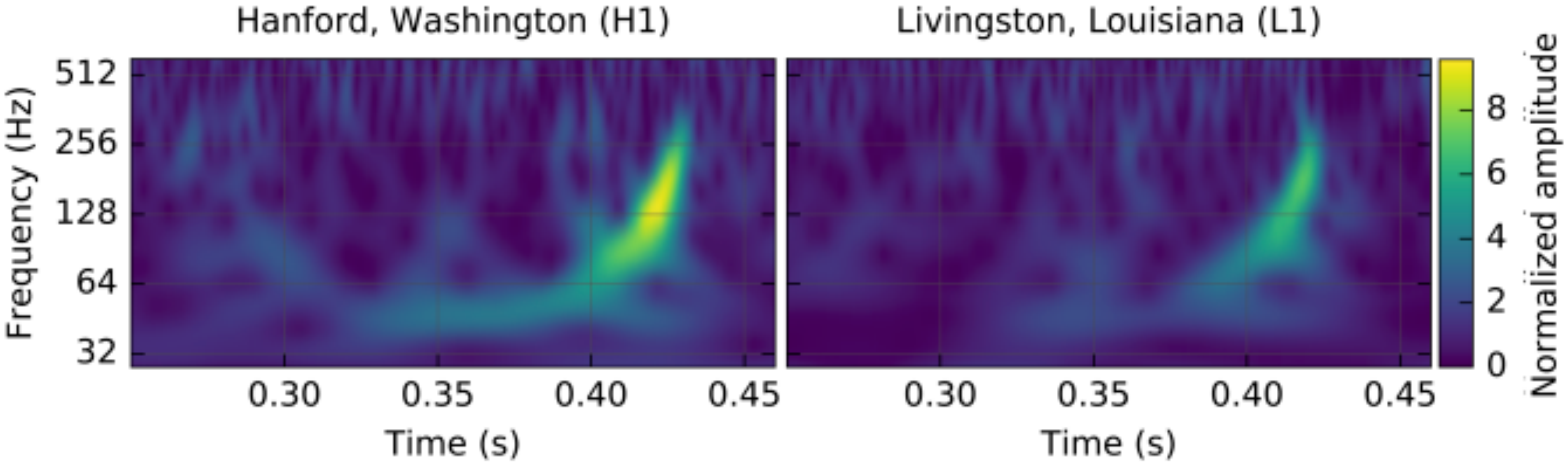


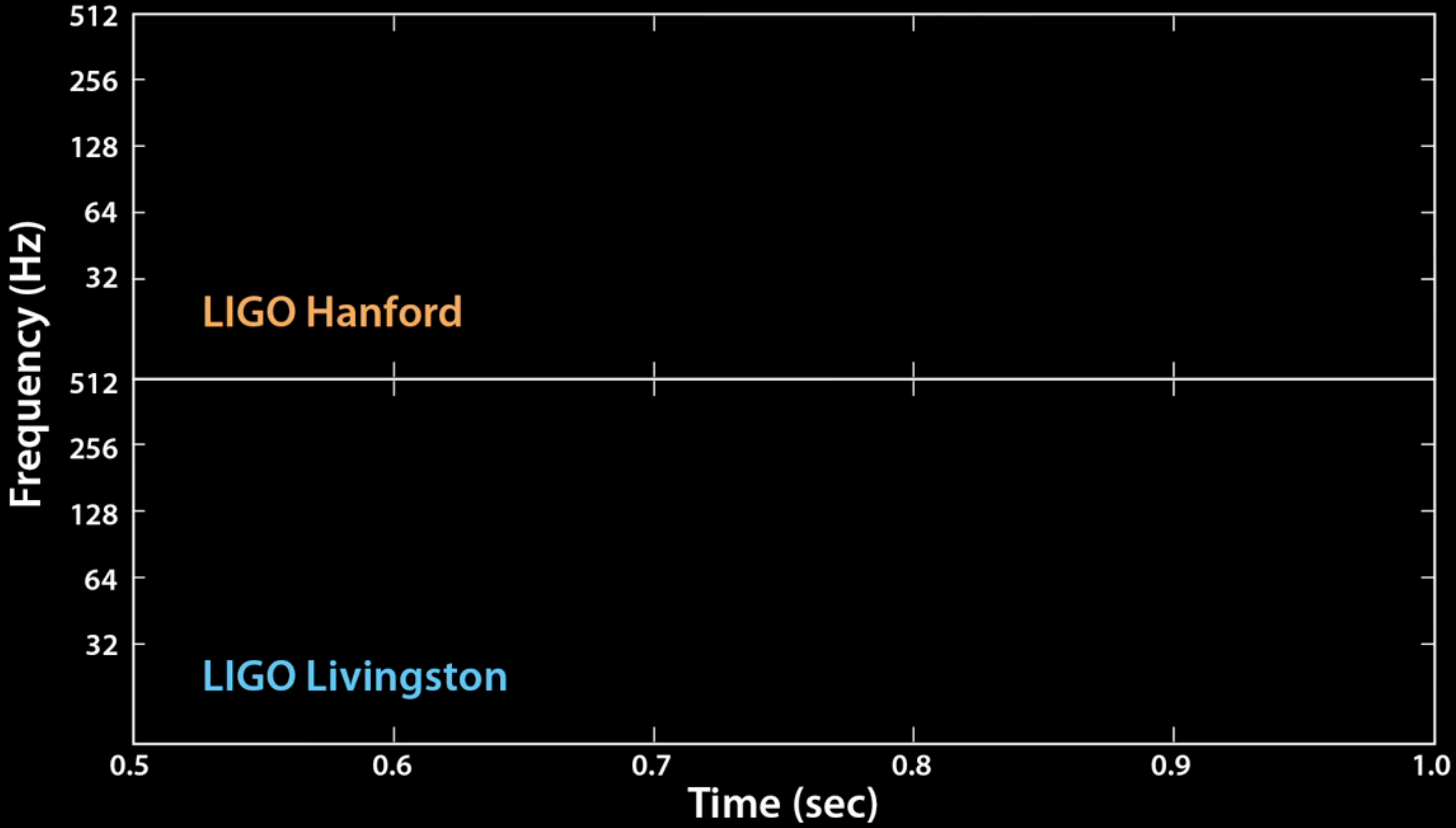
The gravitational wave event seen by the two LIGO detectors. Top two plots show the measured strain, compared to a numerical relativity waveform for two merging black holes.

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.




Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

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 $\mathcal{M} \sim 30\ M_\odot$.

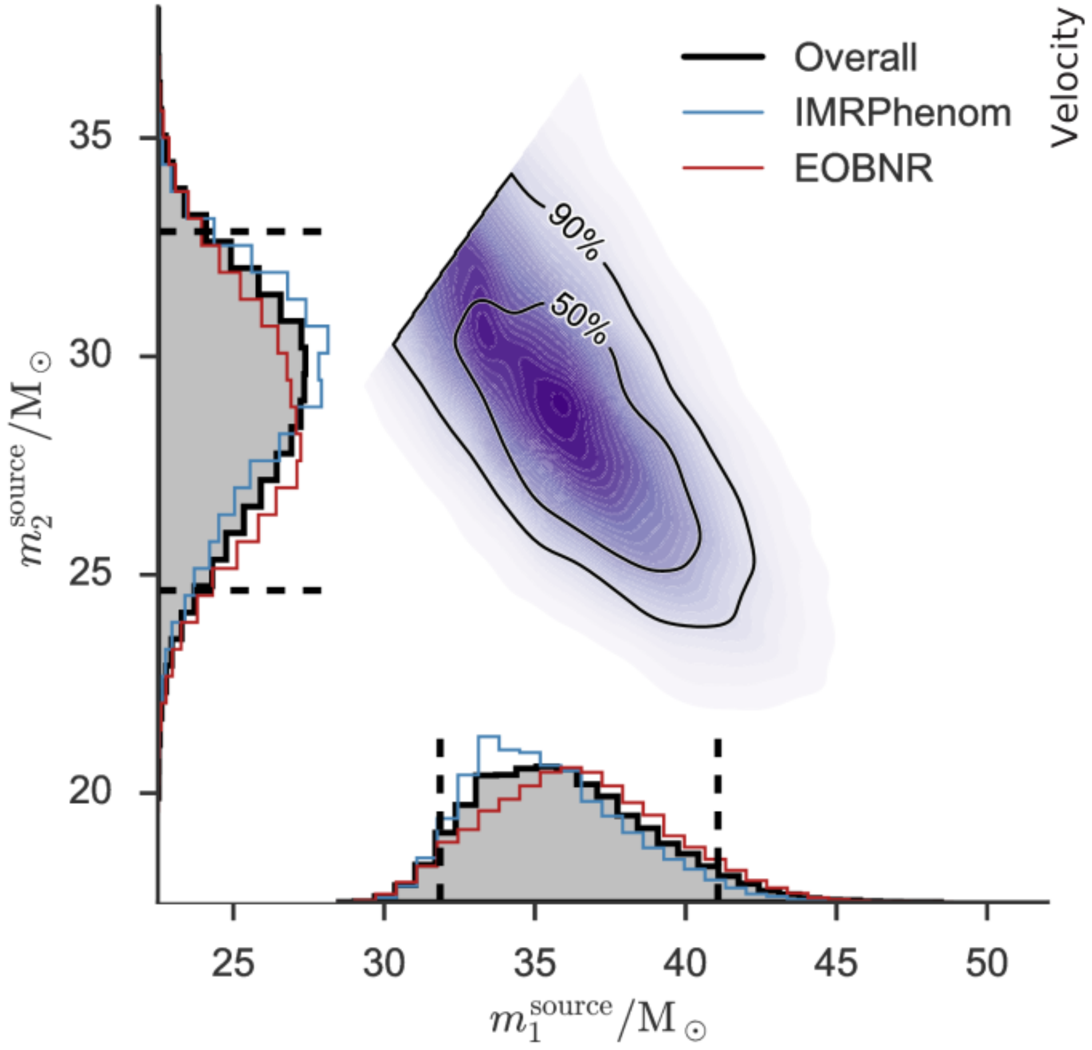
We can rule out one object being a neutron star, so both objects must be black holes.

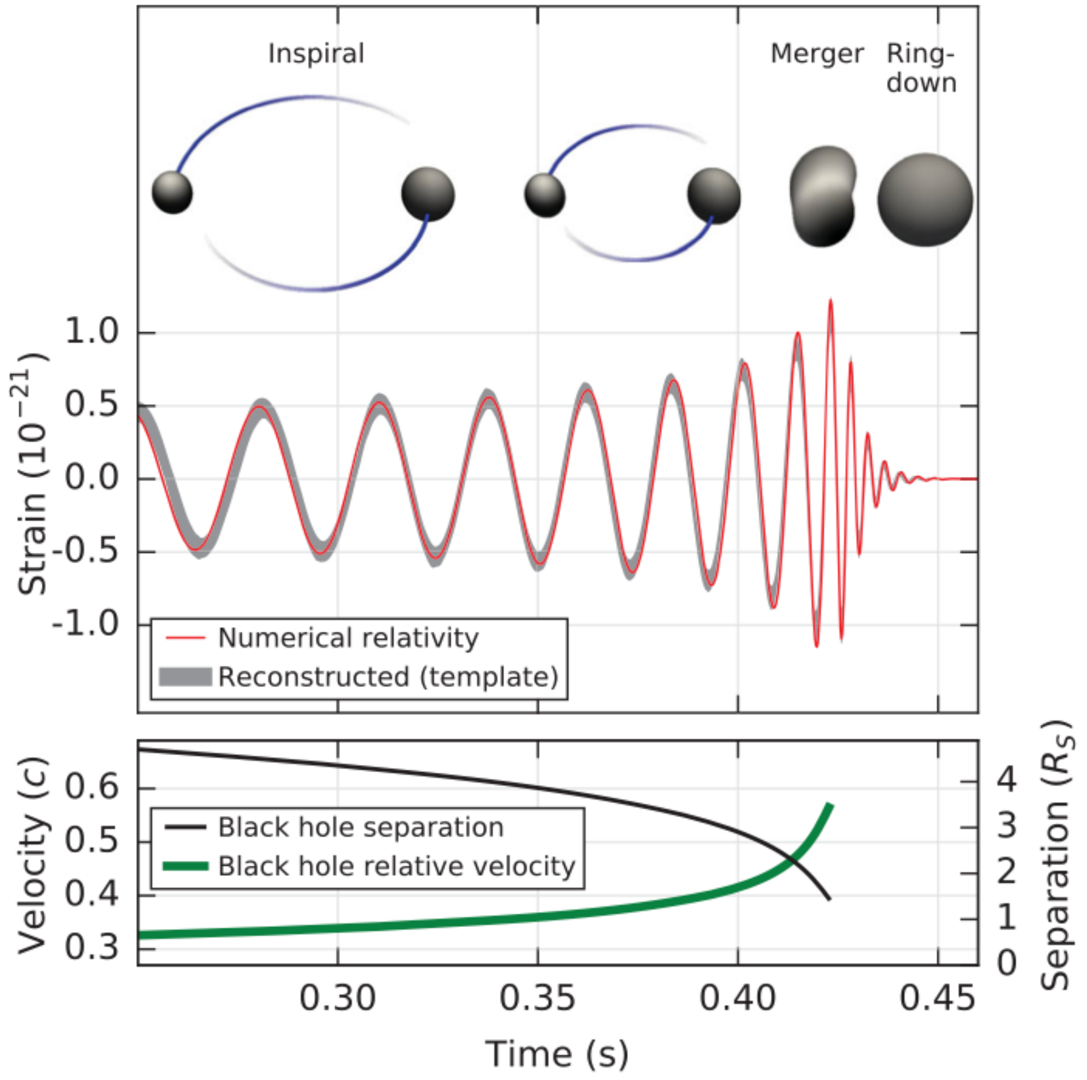
Best estimate for masses:

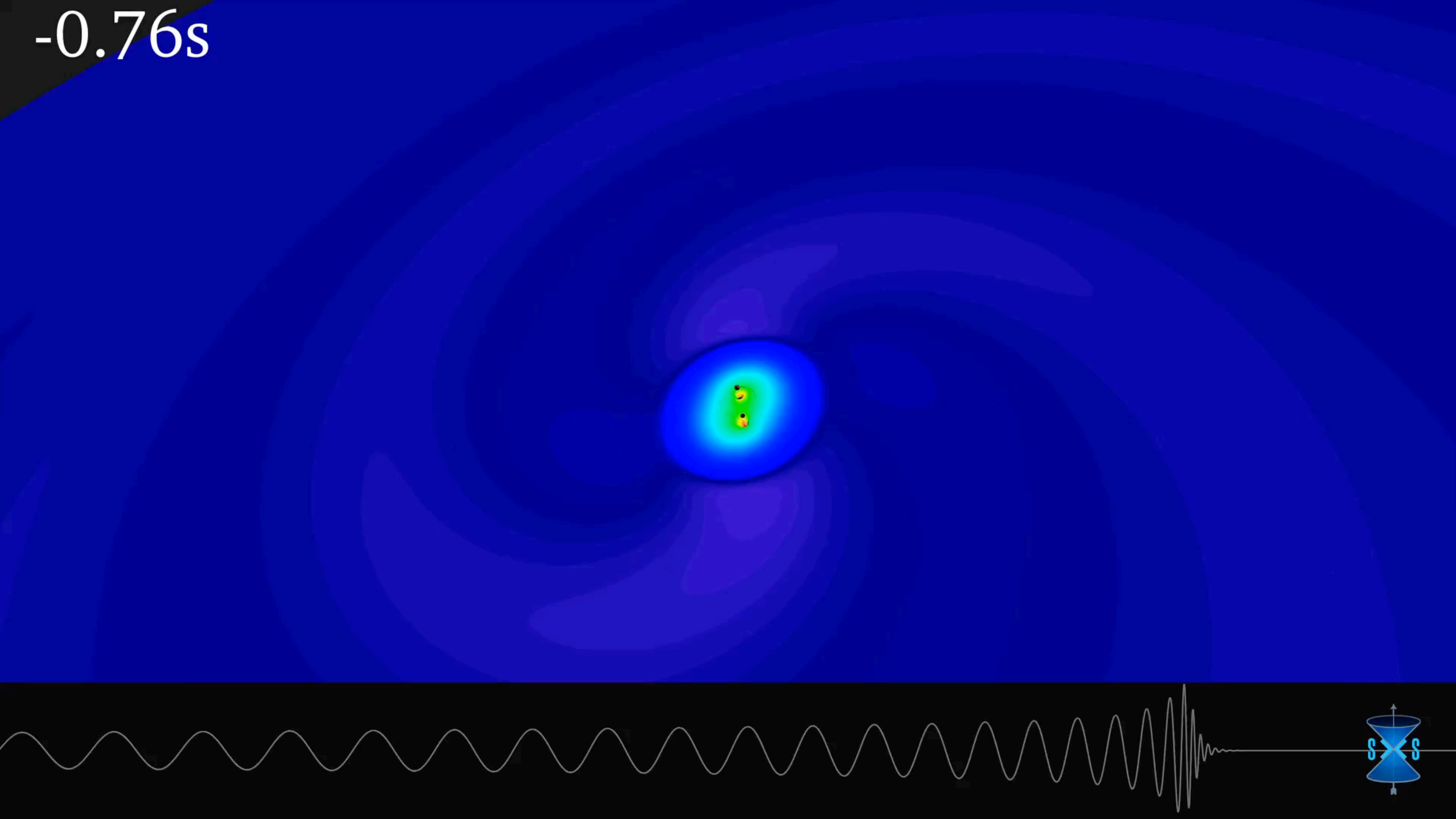
$$36^{+5}_{-4} M_\odot \text{ and } 29^{+4}_{-4} M_\odot$$

Final BH mass: $62^{+4}_{-4} M_\odot$

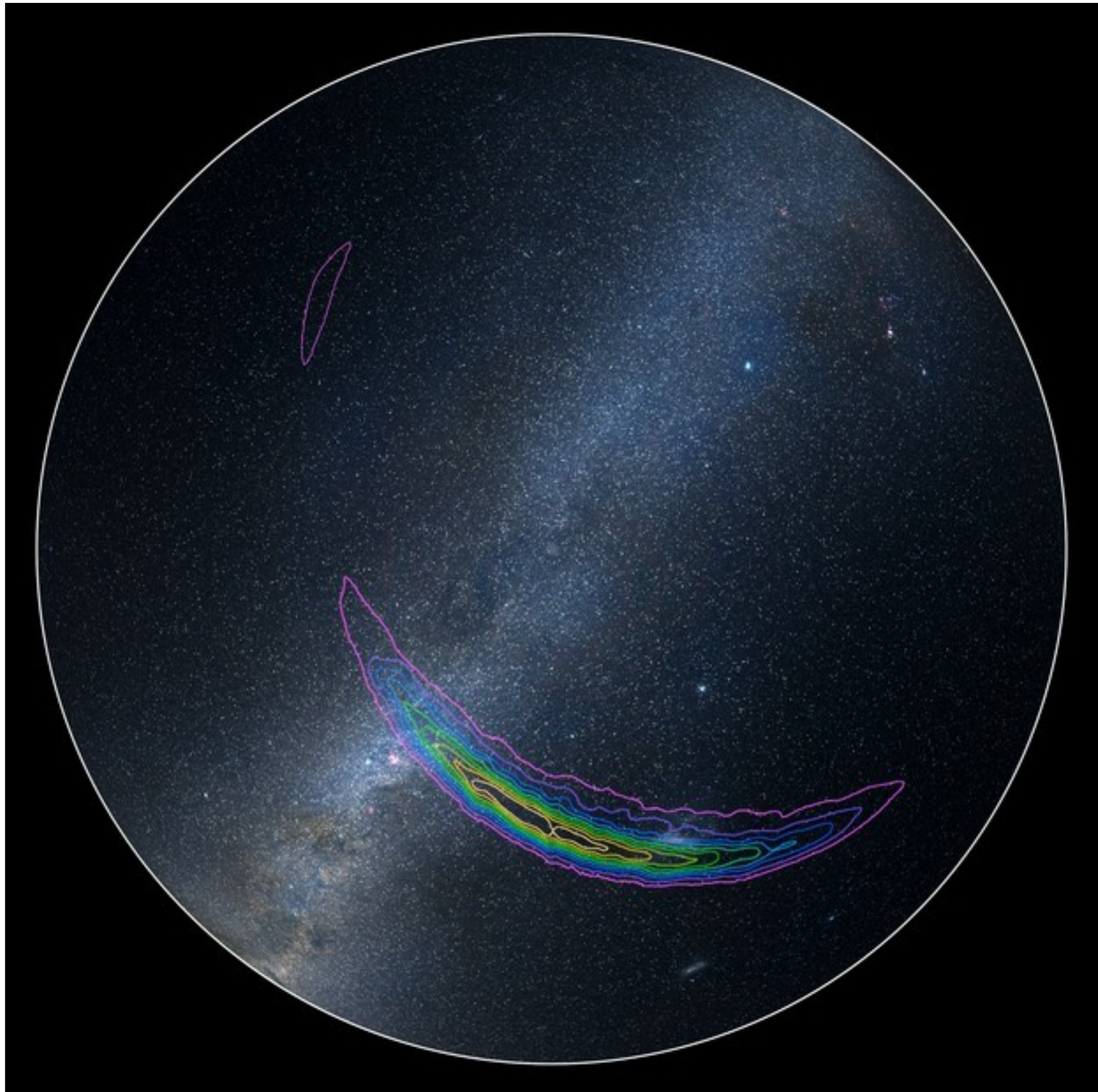
so $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated away as gravitational waves.





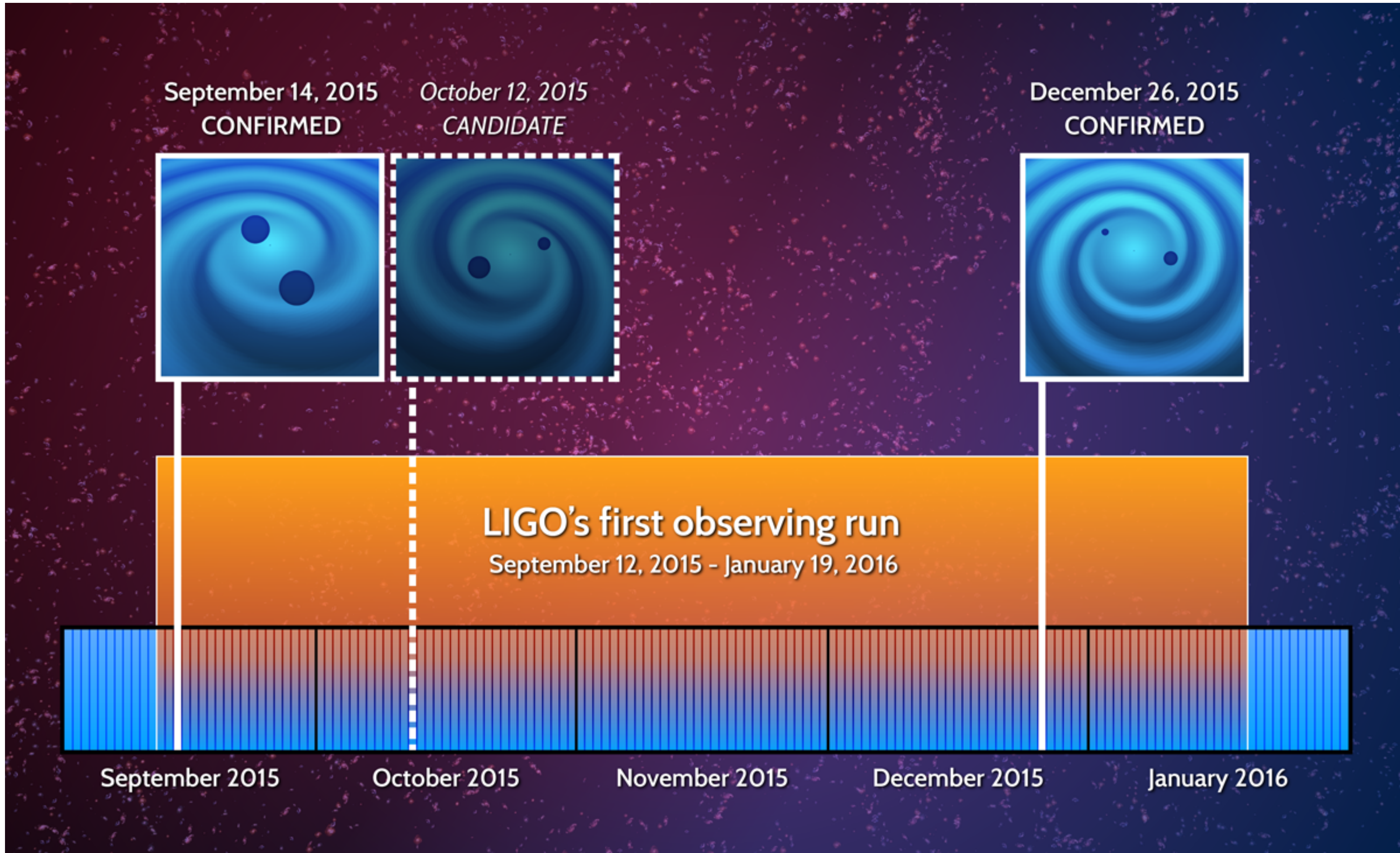

-0.76s

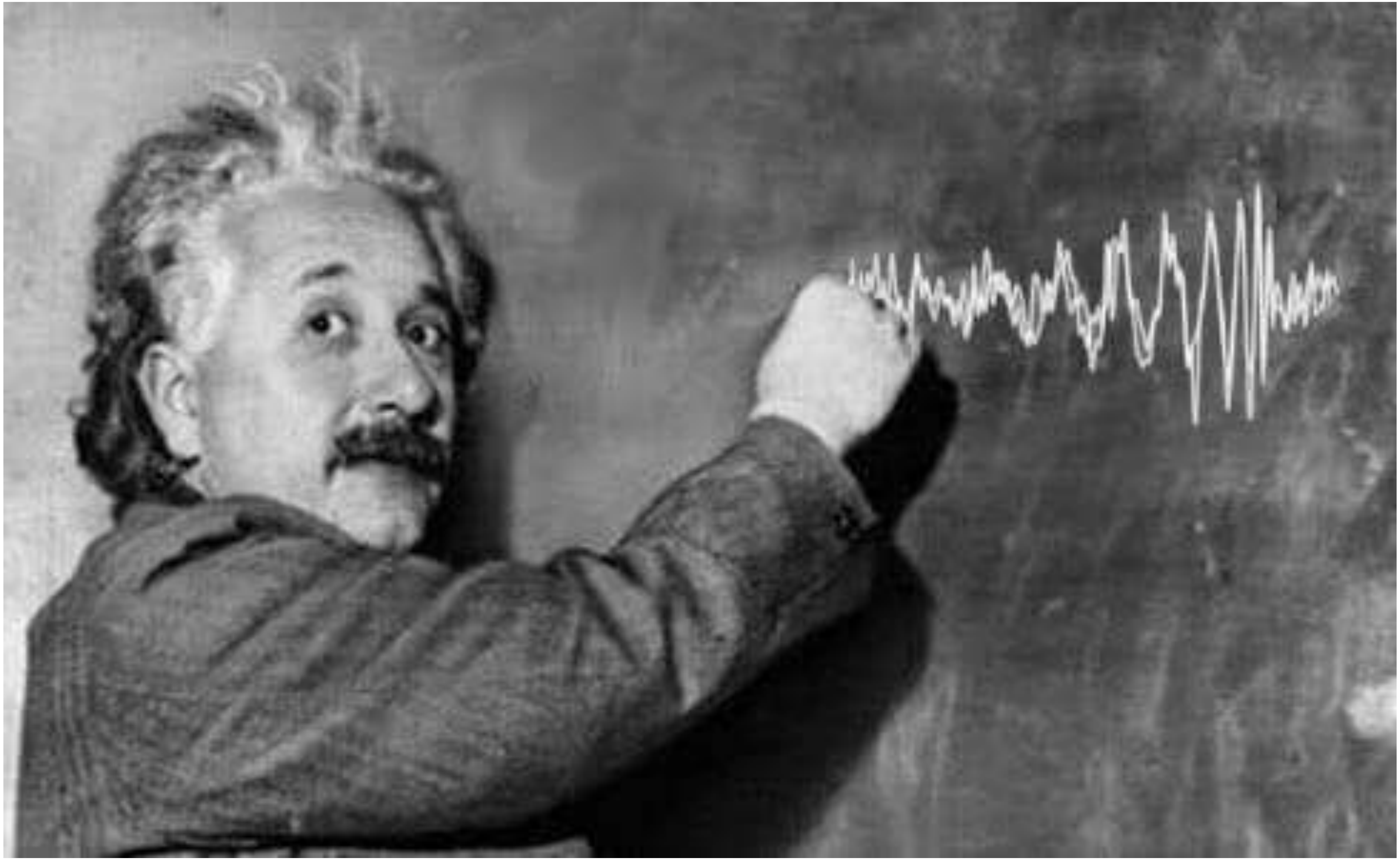
From strength of signal, we get weak limits on position and distance of source: the source is localised to a 600 deg^2 area in the Southern hemisphere, and the distance to the source is about 400 Mpc.



At least one more BH-BH merger (total mass 22 solar masses) has been detected (the “Boxing Day event”).

LIGO’s second run started on Nov 30.

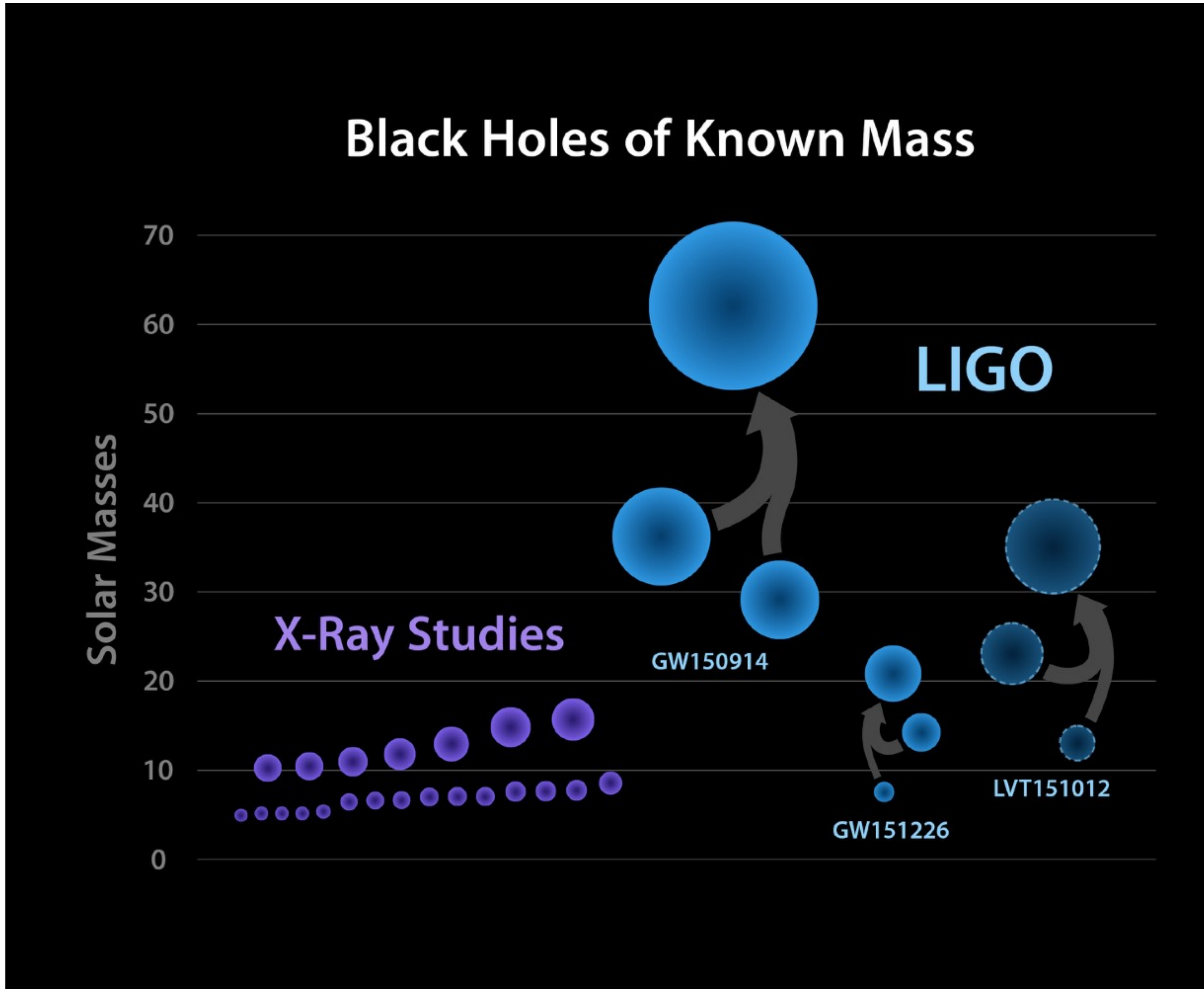




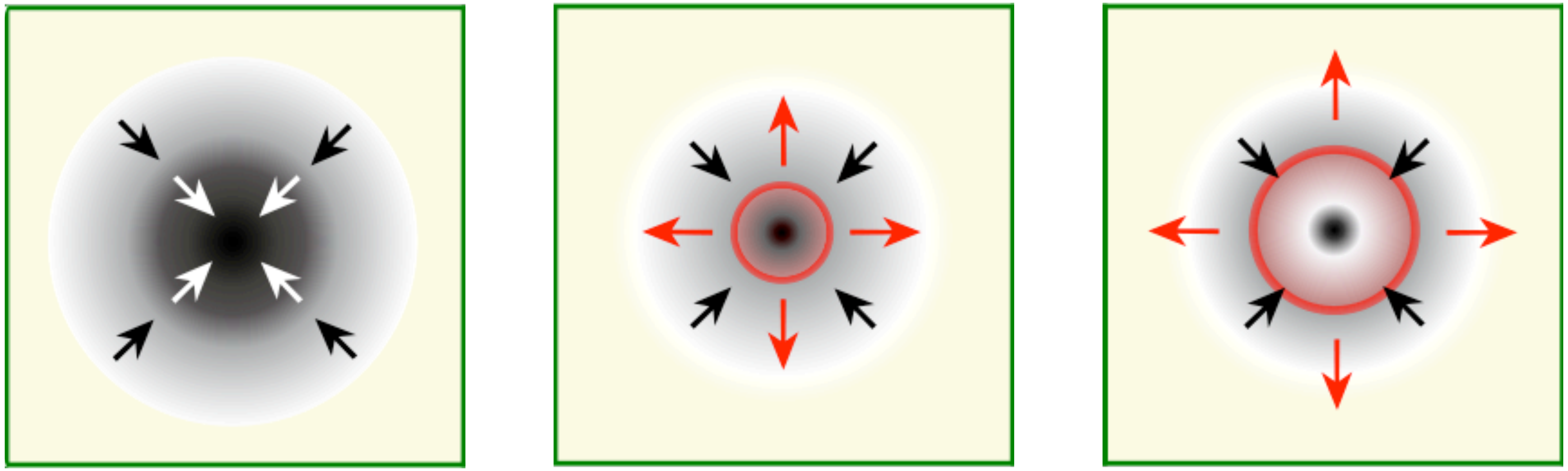
What about the binary?

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?



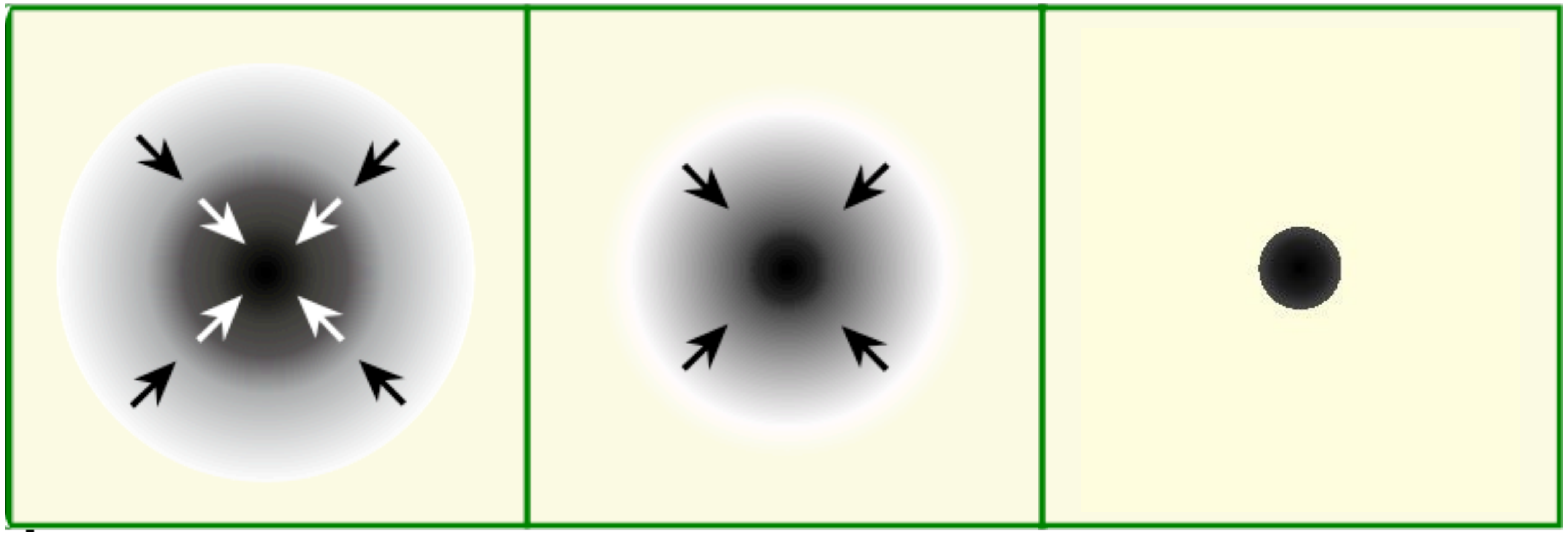
Recall our discussion about supernova explosions. Once a massive star has formed an iron core bigger than the Chandrasekhar mass, the pressure can no longer support the weight of the star, and the core begins to collapse. When the collapsing core reaches nuclear densities, it forms a proto-neutron star, 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.

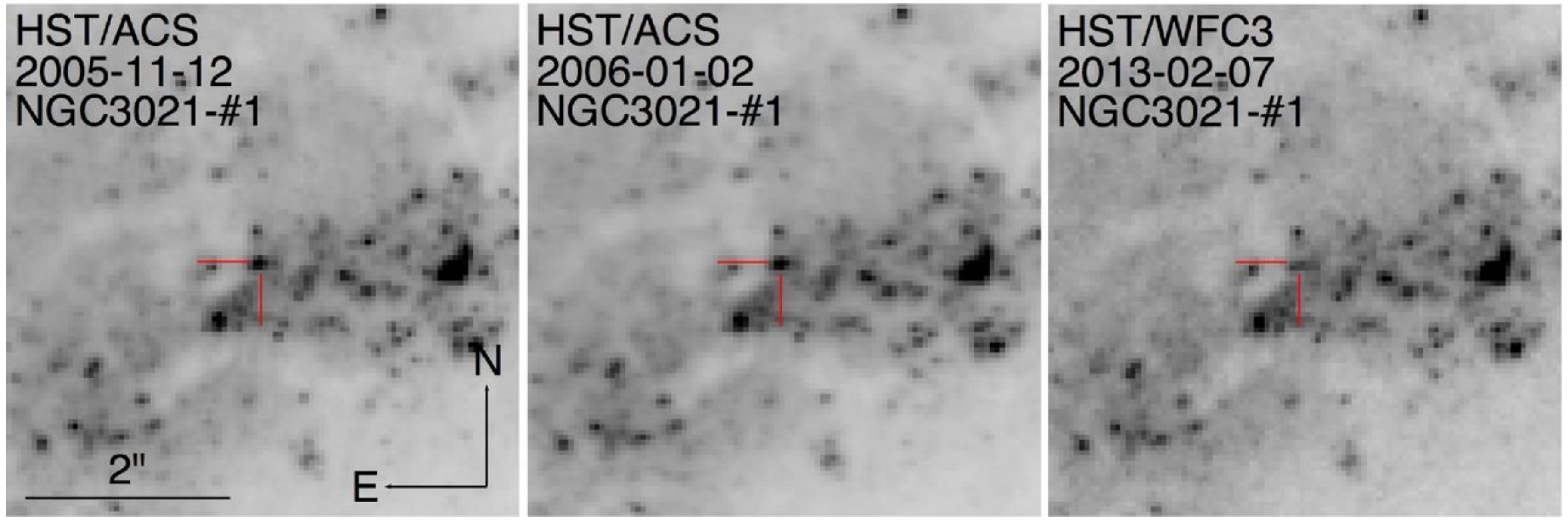
What would we see from the outside?

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.



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

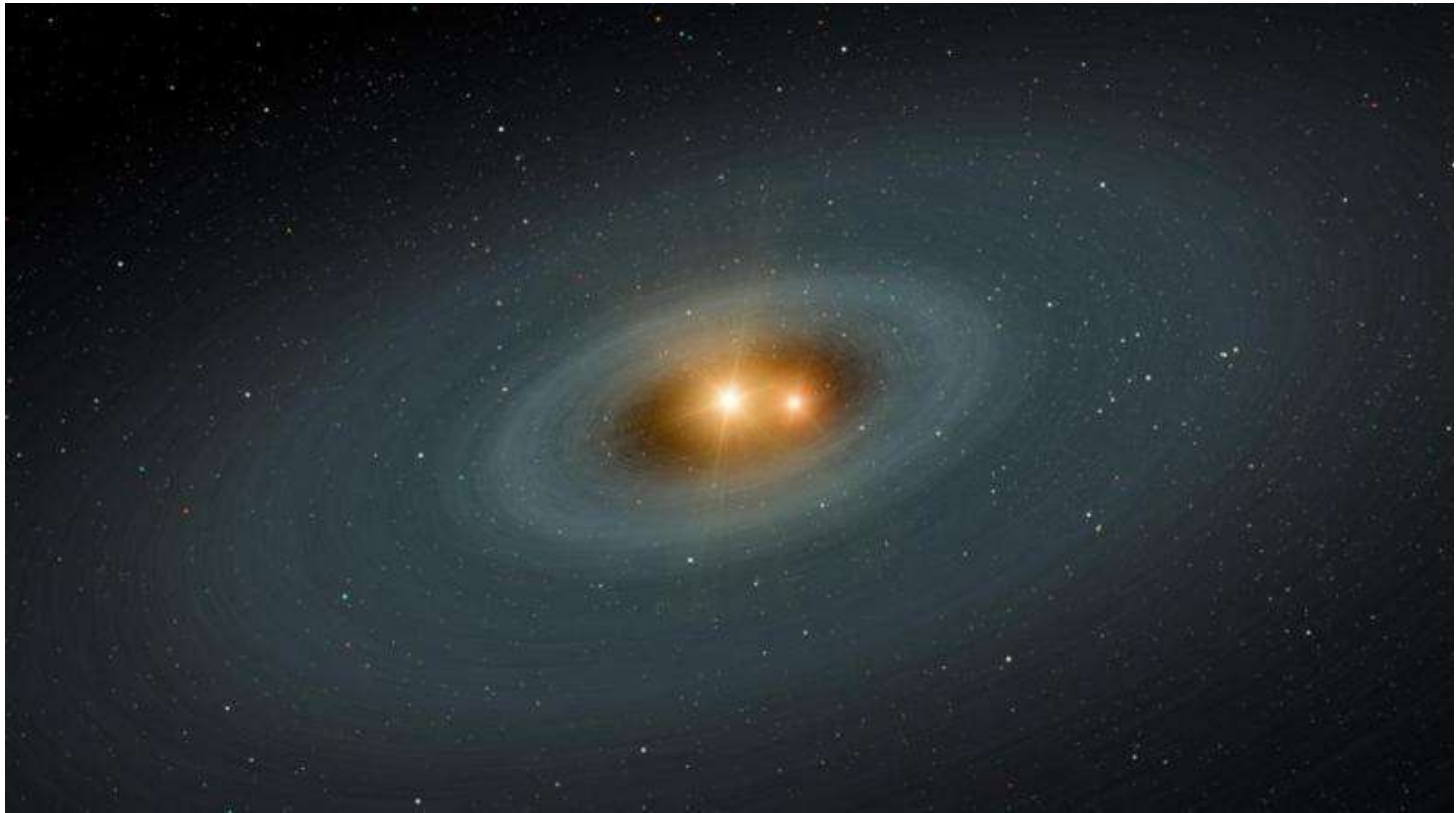
Two stars that disappeared without bright supernovae have been found.



Candidate failed supernova in the galaxy NGC 3021 (indicated by tick marks)

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?



There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

– Donald Rumsfeld, 2002

To infinity and beyond!

- Read "Astronomy Picture of the Day" for all the best astronomy images and news http://http://apod.nasa.gov/apod/

- Read an astronomy blog, like "Bad Astronomy" http://www.slate.com/blogs/bad_astronomy.html or "Snapshots from Space" http://www.planetary.org/blogs/emily-lakdawalla/

- Join a local astronomical club: see listing at the Astronomical Society of Australia page http://www.astronomy.org.au/ngn/engine.php?SID=1000022&AID=100136

Sign up for the “Sydney Ideas” lectures

http://sydney.edu.au/sydney_ideas/

which have lectures about a vast range of topics, including astronomy.

Particularly watch out for the “Professor Walter Stibbs Lectures”, a public lecture on astronomy each year in about April.

– 2016: Natalie Batalha, “A planet for Goldilocks”
– 2015: Andrea Ghez, “The monster at the heart of our Galaxy”
– 2015: Fulvio Melia, “Cracking the Einstein Code"

The 2017 lecture will be given by David Reitze, director of the Caltech LIGO lab:

"LIGO, Gravitational Waves, and the Final Ballet of a Pair of Black Holes: The Birth of a New Kind of Astronomy"

on Tuesday, 11 April 2017,
6–7:30 pm, Messel LT

And, of course, attend more Continuing Education courses! Future courses include

Voyage to the Planets

A look at the solar system in the era of space exploration

Introduction to Astronomy

from the solar system to distant galaxies

plus occasional other courses, such as

Eyes on the Prize

A history of astronomical discoveries which have been awarded the Nobel Prize

That’s all, folks!

Further reading

- Only tangentially related to what we were talking about tonight, but "**The 4% Universe: Dark matter, dark energy, and the race to discover the rest of reality**" by Richard Panek (Oneworld, 2011) is a rollicking good read, describing the race to find the acceleration of the Universe using observations of Type Ia supernovae.

- "**Black Hole Blues**" by Janna Levin (Knopf, 2016) tells the story of the behind the creation of LIGO. I can only assume she had the whole book, then managed to add a postscript about the first discovery, in order to get the book out so fast!

- LIGO discoveries can be followed at http://ligo.org/ and https://www.ligo.caltech.edu/

Sources for images used:

- X-ray binary: from http://xraypulsars.aip.de/
- Artist's impression of the Algol system: from The Electronic Sky, http://www.glyphweb.com/esky/stars/algol.html
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