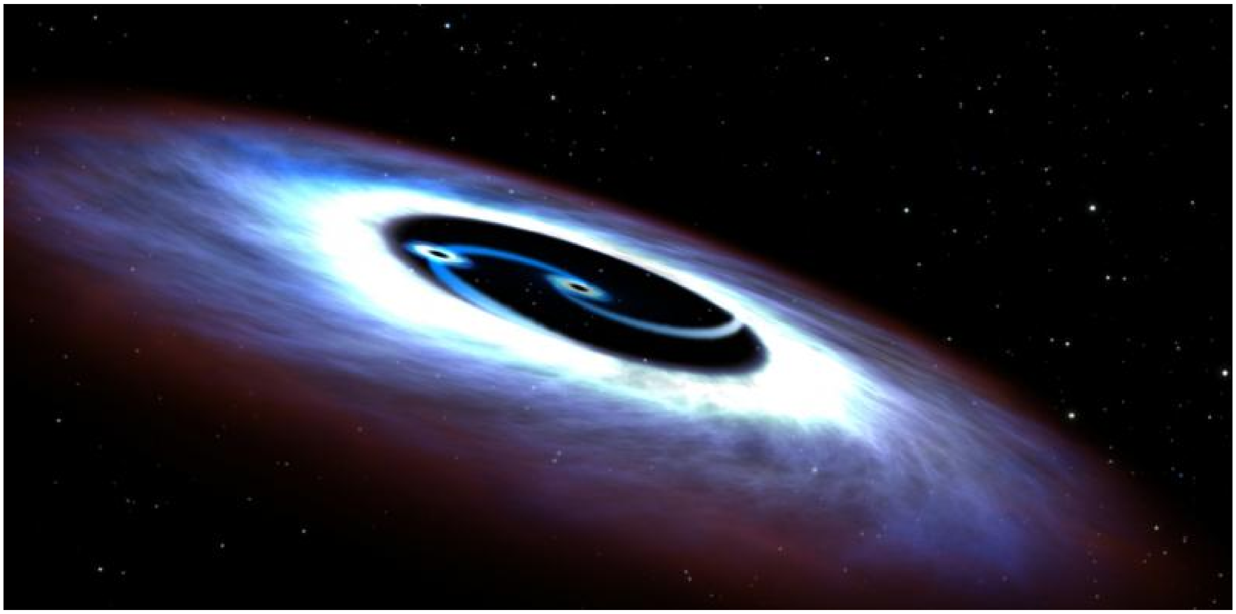
When black holes meet—inside the cataclysms that cause gravitational waves

February 12 2016, by David Blair, University Of Western Australia



Binary black holes come in a variety of forms, but they are all astounding. Credit: NASA, ESA, and G. Bacon (STScI)

It has long been predicted that when two black holes merge, they ought to give out a staggering amount of energy in the form of gravitational waves.

To put the breathtaking scale of this outburst into perspective, it's been caclulated to be equivalent to the power output of 10^{23} of our suns.

That's 100,000,000,000,000,000,000,000 suns!

Most of this stupendous burst of gravitational energy is given out in the last few orbits, as the black holes merge into a single rotating hole.

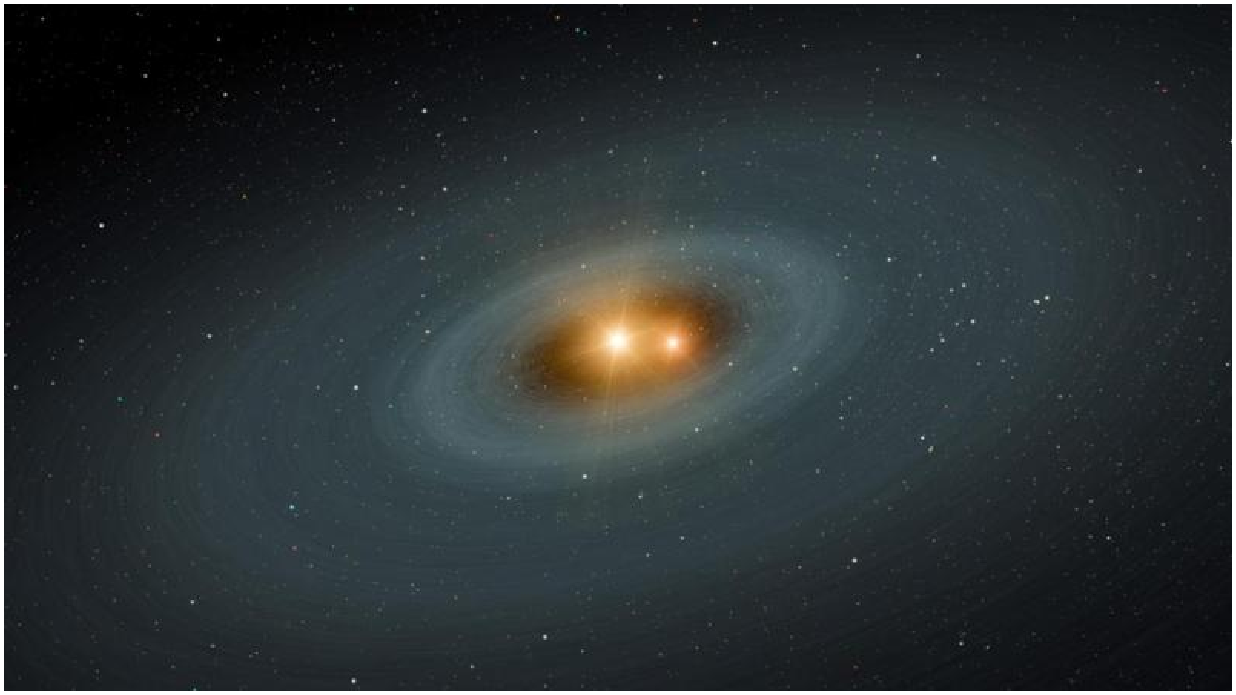
So binary black holes are like gravitational time bombs. They announce their existence in a pure gravitational explosion. The countdown timer for the explosion is set by the initial spacing of the two black holes. And only gravitational wave astronomy can reveal their existence.

Cosmic relics

Black hole pairs can be formed in a few different ways.

The first pathway to a binary black hole starts with pairs of stars born together. This is not uncommon; between one third and one half of the stars in the universe are members of binary pairs.

These stars will evolve together, and if they are massive enough, they will live fast and die young. In only a million years, both stars will have evolved, exploded and collapsed, leaving behind a pair of black holes.



If the stars are massive enough, they could collapse into black holes. Credit: NASA/JPL-Caltech

Spinning around each other like gravitational egg beaters in the sky, binary black holes tend to clear away the stars around them. Their masses could be 20 to 100s of times the mass of our sun. We call these systems co-evolved binary black holes.

Co-evolved binaries are likely to be tidally locked, meaning the spin of each star is matched to its orbital rotation, causing the pair of black holes to have their spin axes lined up like most of the planets in the solar system.

Co-aligned spin is the key signature of binary black holes that were born together. The signature can be measured in gravitational wave signals.

Cosmic rogues

A binary black hole system can form in another way. Two black holes, born individually in a relatively dense cluster of stars, can capture each other.

The sling-shot effect, which space agencies use to take energy from planets to sling spacecraft out of the solar system, plays a crucial role here.

Globular clusters can also be the birthplace of binary black holes. Credit: ESA/Hubble & NASA, Acknowledgement: Judy Schmidt

Stars passing near the black holes get random sling-shots as they drift through the cluster. Black holes from the early universe, which are normally expected to be at least 20 times as massive as normal stars, tend to lose energy to the stars they pass, and so they slowly sink towards the centres of their star cluster.

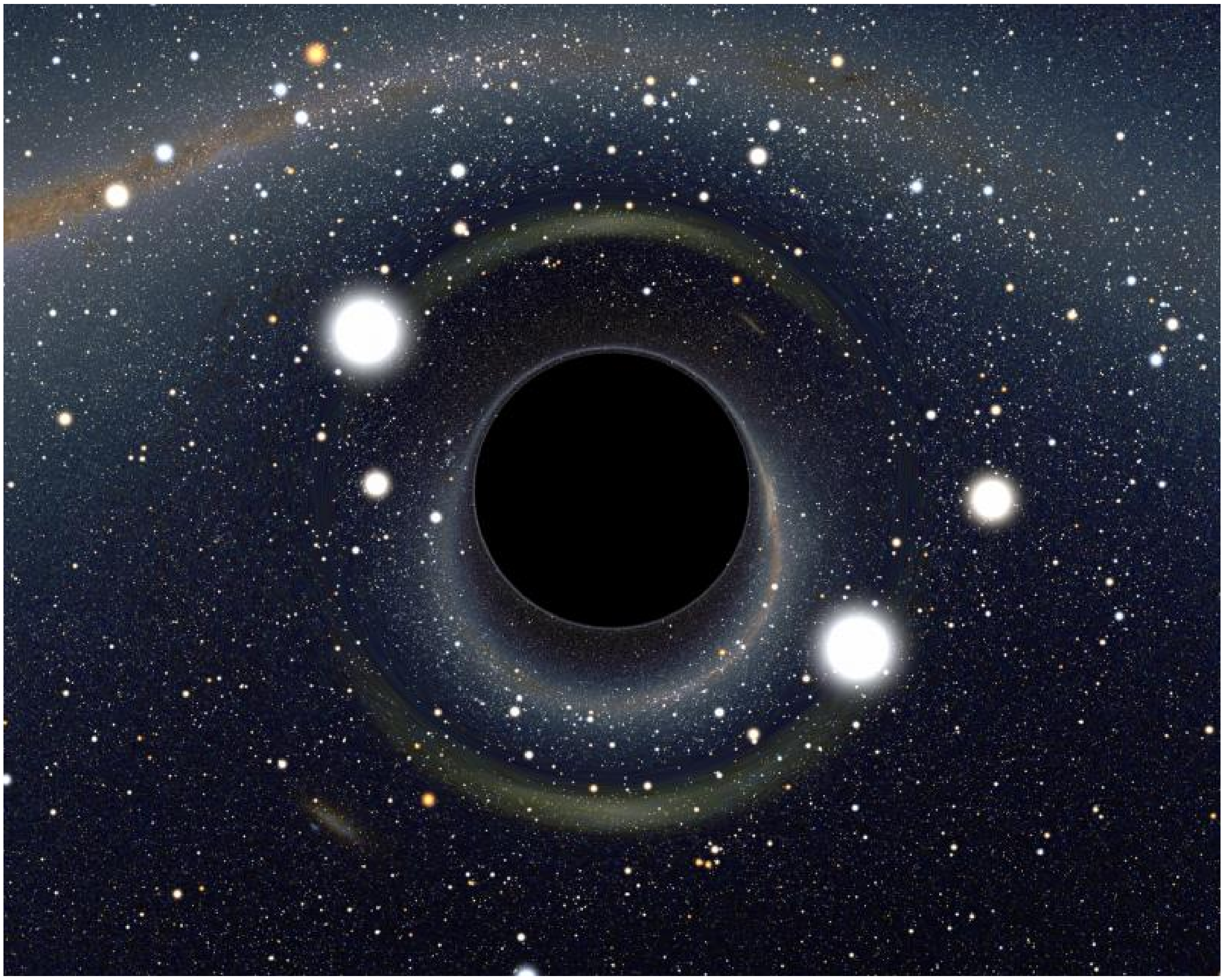
Over billions of years, as more massive black holes sink towards the centre of globular clusters, the density increases until the typical spacing between stars and black holes is about as close as the distance between the sun and Pluto.

In these super-dense conditions, black holes can capture other black holes. Once a black hole pair has formed, it again acts like an egg beater, which transfers energy to passing stars.

Each interaction tends to cause the black hole binary to shrink, while the whole binary simultaneously gets a forward kick, which is usually strong enough to throw the binary right out of the cluster into intergalactic space.

These "capture binaries" have two significant differences when compared to co-evolved binaries: their spin axes will be randomly oriented, because the black holes themselves were born separately. These signatures can also be measured in gravitational waves.

Galactic captives



Gravitational waves can give direct evidence of the existence of black holes. Credit: Alain Riazuelo, IAP/UPMC/CNRS, CC BY-SA

Sling-shot interactions with other stars can also take energy from widely spaced binaries, so as to reduce the time to coalescence, and also can create black hole binaries near the centres of galaxies.

But galaxies have much stronger gravity than globular clusters. This means it's much less likely the black holes will be flung into interstellar space.

In these different ways, black holes born from the first stars end up as binary pairs: some captured near the centres of galaxies; some still near their birthplace; and others drifting through empty space for billions of years.

These are gravitational time bombs. They are all spiralling together towards coalescence. The time setting depends on their proximity.

Billions of binaries across the universe will be creating a random background of gravitational waves, ripples on a cosmic sea of space-time. But when each finally merges, they emit a vast explosion of gravitational energy, triggering a cosmic tsunami.

Countdown to coalescence

The gravitational wave emission from black hole binaries is like waves created by a moving ship. They take away energy, causing the binary to spiral inexorably towards merger.

In the emptiness of interstellar space, they can only emit electromagnetic waves if they encounter gas or comets, which could trigger weak X-ray emission. They are so small and so distant that conventional astronomy is unlikely to ever be able to detect them.

Each black hole system is like a countdown timer. Each one set to a different time according to its starting conditions. In the chaotic conditions of a collapsing gas cloud we would expect a range of time settings.

Likewise all other formation scenarios will create binaries with various time settings. Some will have times set longer than the age of the universe. Others will coalesce in an moment of cosmic time.

Only those binaries with their gravitational countdown timer set to match our place and time in the universe are useful to us. These are like cosmic time capsules that release their data in the form of a vast explosion of gravitational energy, detectable by the LIGO gravitational wave detectors.

Are there enough of these binaries, with their correct time clock setting that we can detect these gravitational explosions? Today we know that the answer is *yes*. See the remaining articles about the historic detection of gravitational waves by LIGO to find out more!

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