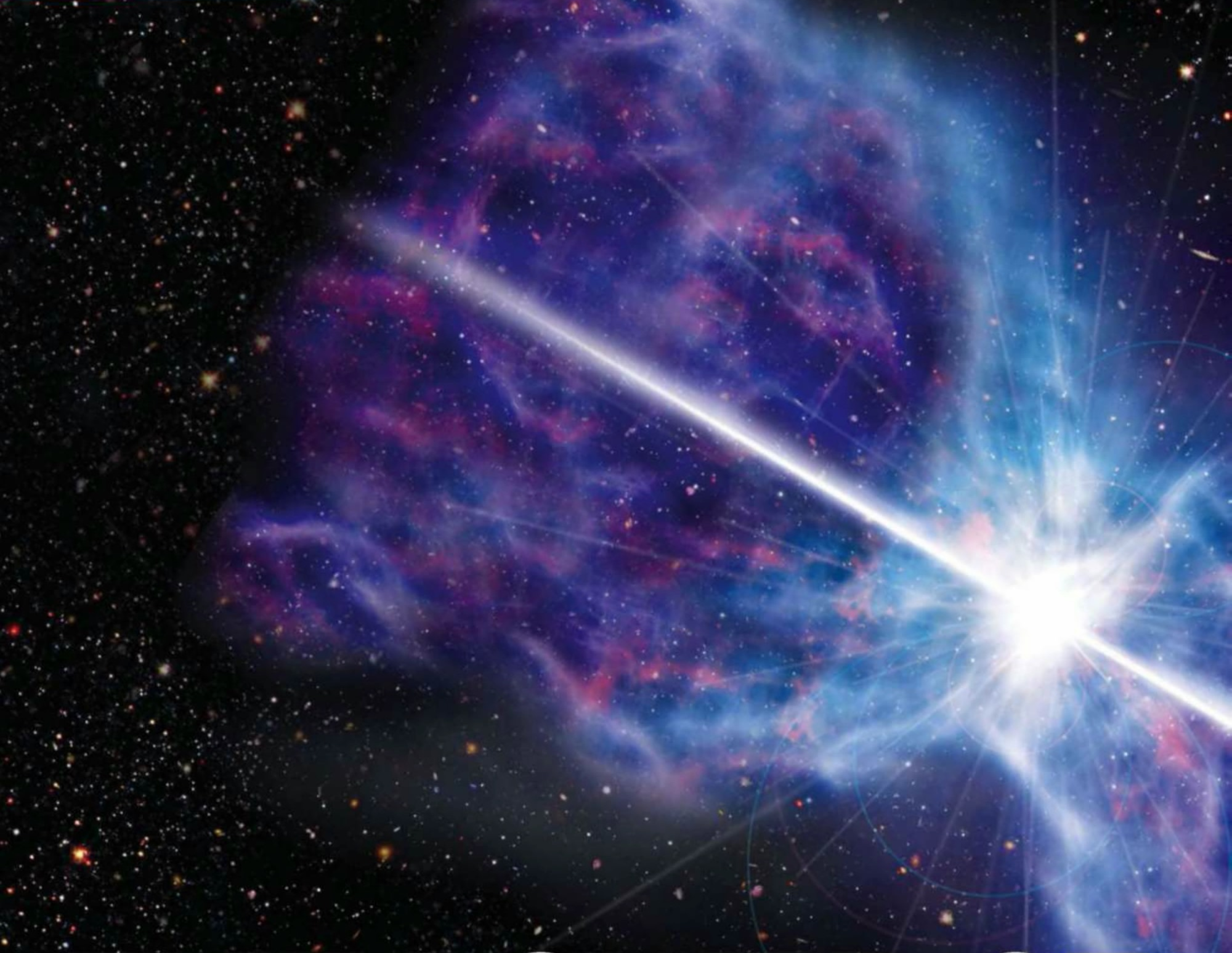


# THE POWER OF QUASARS

The brightest known objects in the universe, quasars blast light and other radiation across billions of light years of space, illuminating some of the remotest corners of the cosmos

Written by Giles Sparrow

# The power of quasars

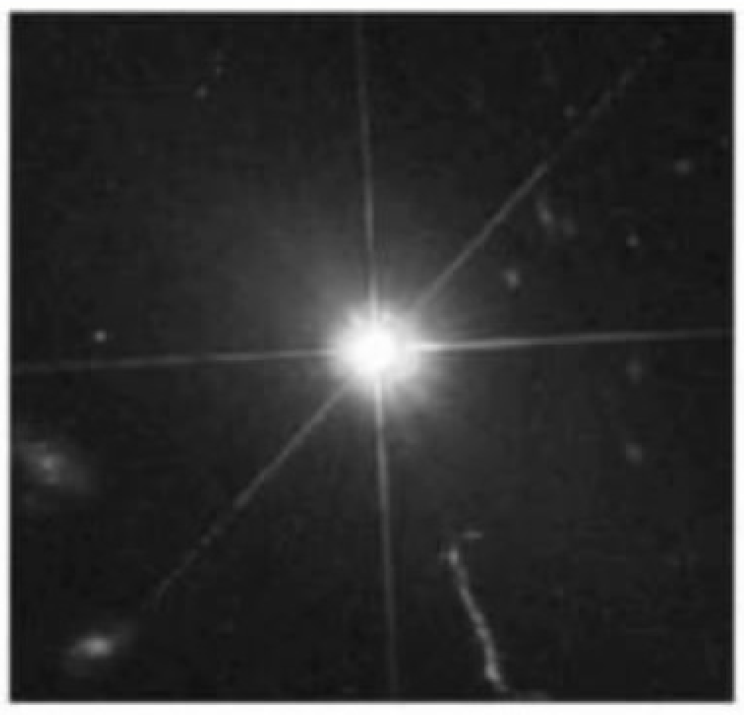
Scan a small or medium-sized telescope across the constellation of Virgo (the Virgin), to the north-east of the moderate star Eta Virginis, and you'll trace scattered chains of apparently nondescript stars.

There's little to suggest that one particular star-like point of light is any different from the rest. But, in fact, one faint object – a 'star' of magnitude 12.9, listed in catalogues under the designation 3C 273 – is extraordinary. A celestial beacon that is one of the most luminous objects ever discovered, it only appears faint because, while its neighbours in the sky are just tens or hundreds of light years away, it lies an incredible 3 billion light years from Earth. In fact, 3C 273 is a quasar – a distant galaxy with a blazing disc of white-hot matter at its heart, surrounding an enormous supermassive black hole (SMBH).

Quasars are members of a broad group of active galaxies – distinguished from normal galaxies by the fact that they have bright, variable sources of radiation at their cores (so-called active galactic nuclei, or AGNs) that cannot be accounted for by the combined brightness of their stars alone. What's more, when their light is split up into a rainbow-like spectrum, it reveals bright emission lines – peaks of intense light at certain wavelengths and energies, typically caused by the heating of interstellar matter and very different from the spectra of normal galaxies. A third telltale feature is their unusual radio emissions (which give quasars their name, short for quasi-stellar radio sources).

Aside from these common features, active galaxies vary wildly. Quasars are only seen in distant parts of the universe, and shine so brightly that they drown out the light of their 'host galaxies'. More subdued Seyfert galaxies are relatively normal spirals with AGNs that appear as unusually bright starlike points at the centre of the galaxy. Blazars, or BL Lac objects, (named after BL Lacertae, the first example to be discovered) share many of the features of quasars, but have unusual, featureless spectra. And finally, radio galaxies typically have no visible AGN, but are surrounded by enormous lobes of radio-emitting gas, often linked to the core by narrow jets of particles moving at high speeds. Needless to say, these neat categories blur in reality, with many quasars and Seyferts, in particular, displaying the jets and lobes of radio galaxies.

Today, most astronomers see all active galaxies as aspects of the same



Just another star, or an extremely distant, superluminous quasar?

## The bright discovery

Astronomers first began to discover compact radio sources above and below the plane of the Milky Way in the late-Fifties, during the compilation of the Third Cambridge (3C) Catalogue of Radio Sources. From 1960, US-based astronomers Allan Sandage of the Mount Wilson Observatory and Maarten Schmidt of Caltech began to search for visible objects associated with these sources. Sandage soon spotted a faint object corresponding to radio source 3C 48, and believed what he had was probably some kind of unusual but nearby radio star. Others soon followed, including 3C 273, the brightest such object in the sky.

In order to figure out the characteristics of these new objects, astronomers naturally turned to analysing their spectra, looking for the distinctive patterns of absorption or emission that would reveal their chemical composition. But any attempt to make sense of the spectrum proved frustrating – they didn't seem to correspond to any known lines. It was only in February 1963 that Schmidt realised the truth: the spectral lines in quasars were identical to those formed by common elements, but had been significantly redshifted.

After investigating the possible mechanisms that could cause such a huge redshift, it became clear that they were almost certainly cosmological in nature – in other words, quasars are moving away at high speed due to the expansion of the universe, and are actually superluminous objects billions of light years from Earth.

**A NASA engineer checkspart of the James Webb Space Telescope, which will be peering into distant quasars**

basic phenomenon: an AGN that consists of a blazing central region surrounded by a ring of dense gas and dust clouds, with jets emerging above and below the plane of the galaxy and billowing out to form radio lobes where they encounter intergalactic gas.

According to this model, quasars are a much brighter and more energetic equivalent of Seyfert galaxies – in both cases the galaxy is tilted or tipped towards Earth so we can see across the dust ring to the bright central 'engine' itself. Radio galaxies, in contrast, lie almost edge-on to our point of view, so their engines are hidden by intervening stars and dust, and only the jets and radio lobes are visible. Finally, blazars occur in rare cases where the jets are aligned directly towards our planet: emission lines from different parts of the jet blend into one another, as a result creating their featureless spectra.

The big question, of course, is what lies at the heart of the AGN?

> "What could be powerful enough to emit 4 trillion times the energy of the Sun?"

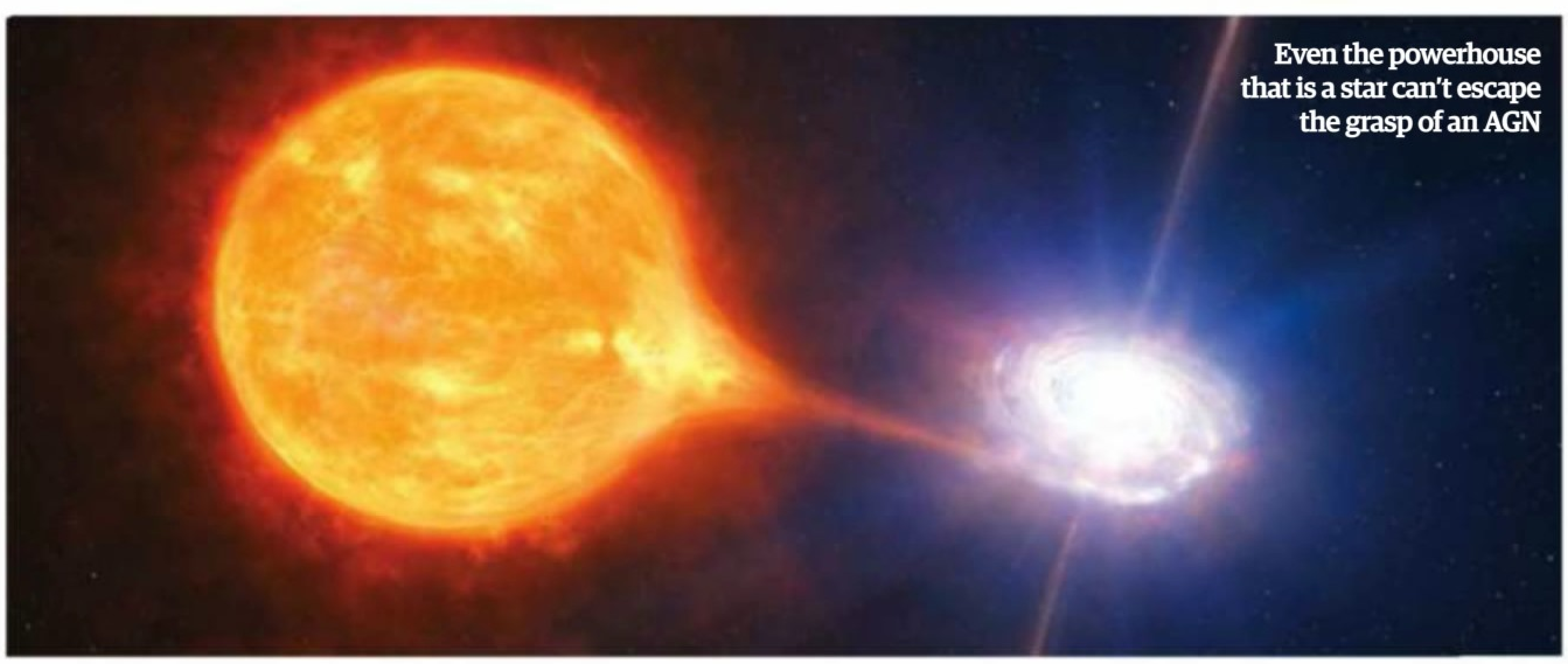
What mechanism could possibly be powerful enough to emit (in the case of 3C 273) more than 4 trillion times the energy of the Sun, and shoot beams of particles across hundreds of thousands of light years of space, at speeds close to that of light itself?

Another constraint on any proposed 'engine' is that AGNs are very small in cosmic terms: many vary their output from day to day, and since physical changes cannot possibly ripple through them faster than the speed of light, they can only be a few light hours across at most (ie about the size of our Solar System).

The need to fit such a powerful engine into such a tiny space means there's only one realistic candidate for the job: a black hole. These awesome objects, so massive and dense that even light cannot escape their grasp, produce such intense gravitational fields around them that any matter falling into their clutches is shredded and 'tidally heated' to millions of degrees. As it spirals down onto the surface of the black hole, this material develops into a superheated accretion disc that emits both visible light and higher-energy radiations such as ultraviolet and X-rays.

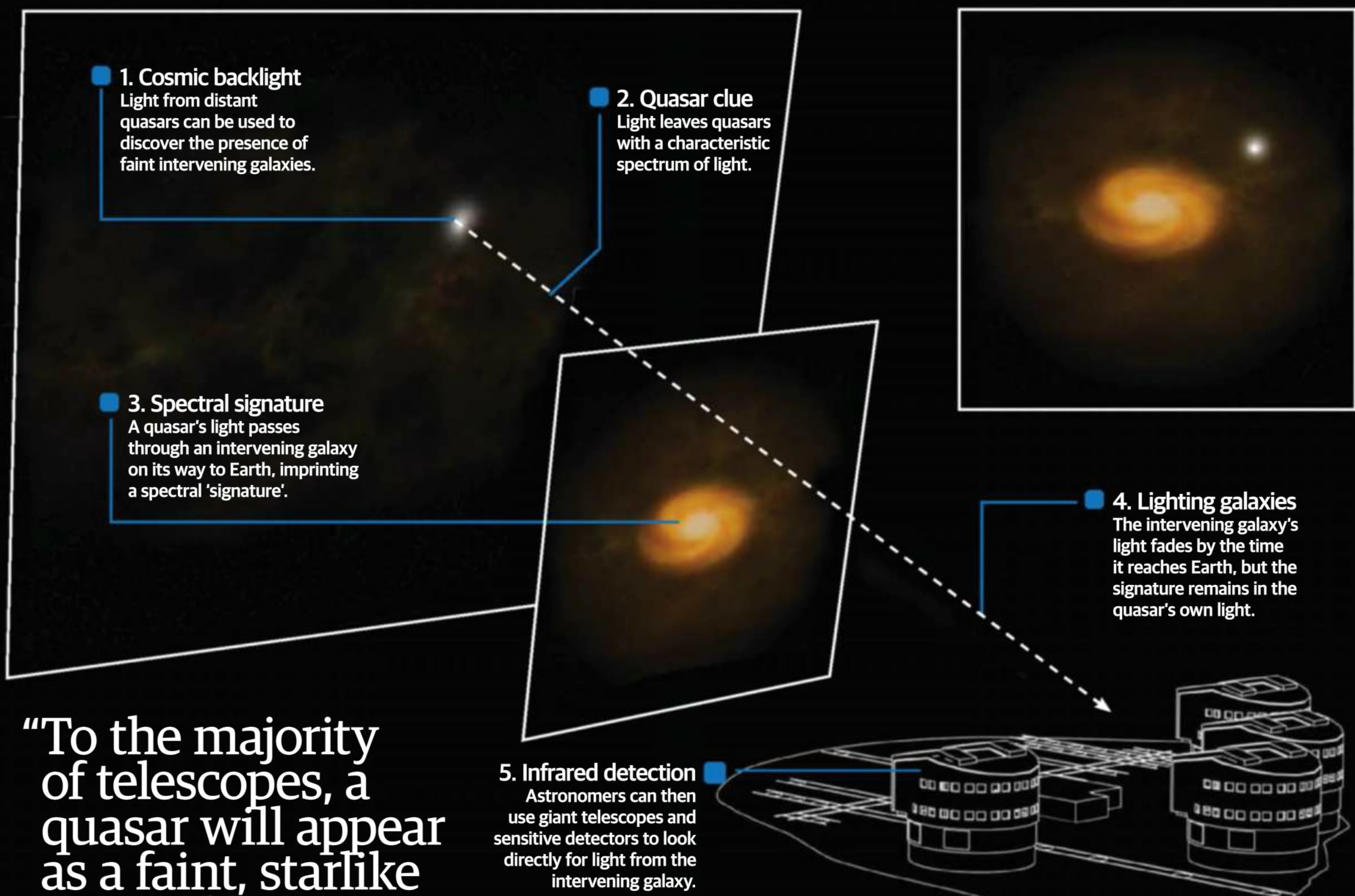
In some cases, matter close to the black hole's event horizon (the point of no return beyond which nothing can escape) is ejected by powerful magnetic fields to form jets emerging from above and below the disc.

Many of these features have been seen in stellar-mass black holes –

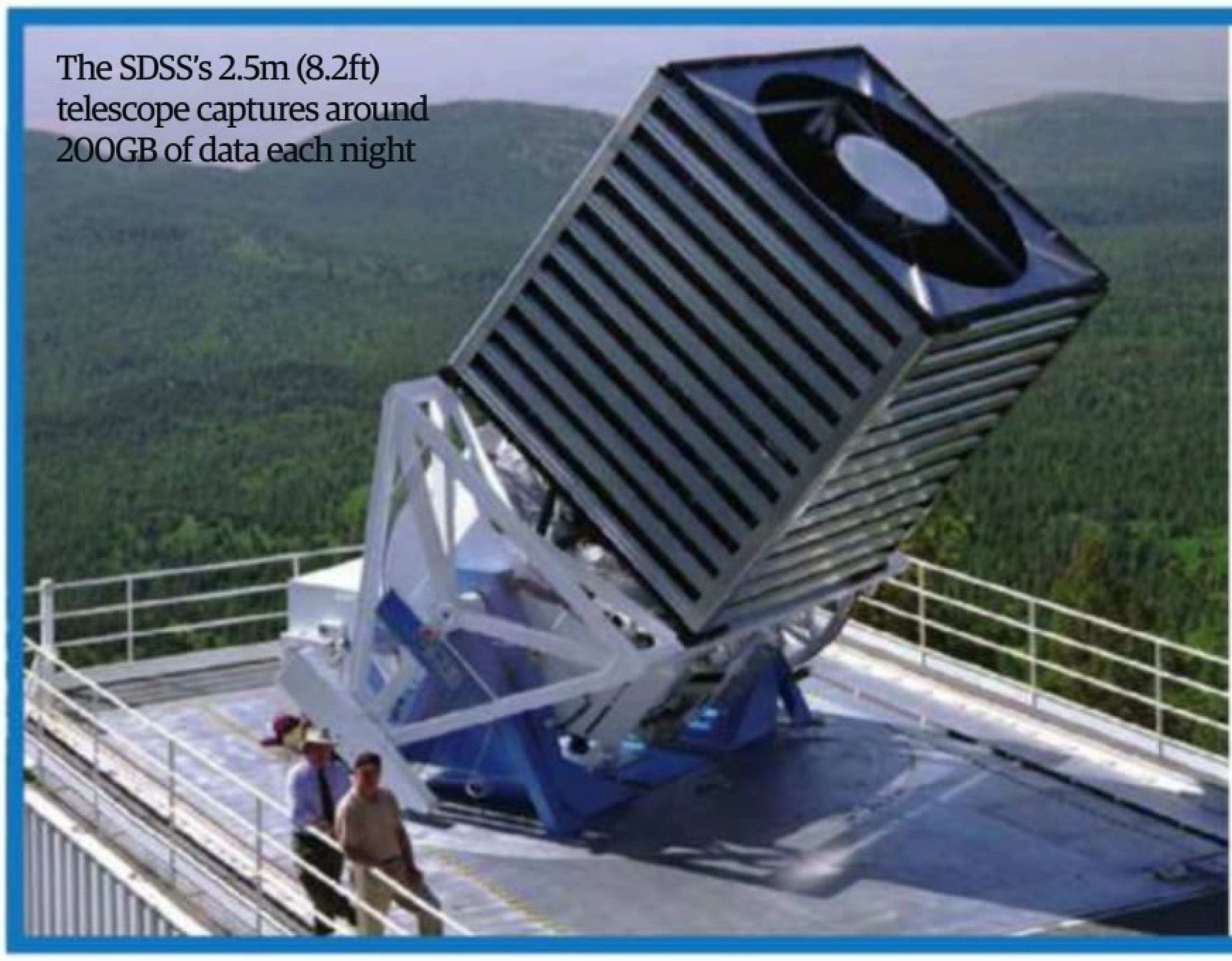


**Even the powerhouse that is a star can't escape the grasp of an AGN**

## Invisible galaxy hunting




> "To the majority of telescopes, a quasar will appear as a faint, starlike point of light"



The SDSS's 2.5m (8.2ft) telescope captures around 200GB of data each night

## Finding AGNs

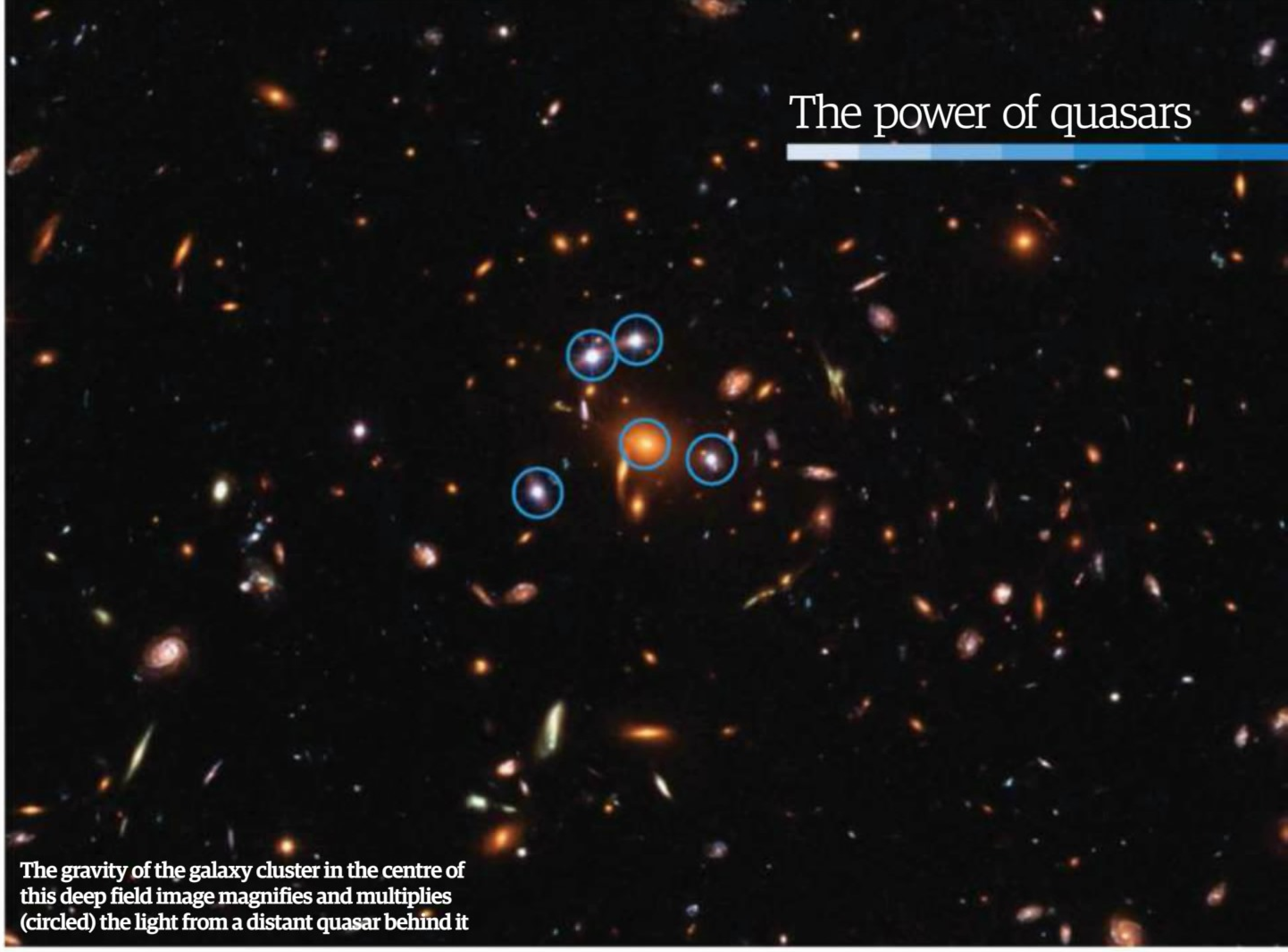
The first quasars were discovered in radio surveys of the sky, and this continues to be a common way to find them – they show up as point-like sources of radio waves, usually located above or below the galactic plane (where more diffuse radio sources in our own galaxy dominate and block out the signals from quasars beyond).

To the majority of telescopes, a quasar will appear visually as a faint, starlike point of light, varying in brightness over hours or days; the light of its host galaxy is usually drowned out by the brilliance of the central engine. However more powerful telescopes, such as the Hubble Space Telescope, have succeeded in imaging host galaxies using two techniques: either by placing a tiny 'occulting disc' over the region of the engine in order to block out its light, or by imaging the quasar in the infrared, where the engine's brightness is much reduced and the galaxy's cooler, highly redshifted outer regions get a chance to shine.

These days, quasars are largely discovered through semi-automated sky surveys. The Sloan Digital Sky Survey (SDSS), which has scanned the sky at multiple wavelengths since 2000, has so far catalogued an incredible 200,000 individual quasars.

# A close-up look at active galactic nuclei


"We're seeing them as they were several billion years ago – when the universe was significantly younger"



The gravity of the galaxy cluster in the centre of this deep field image magnifies and multiplies (circled) the light from a distant quasar behind it

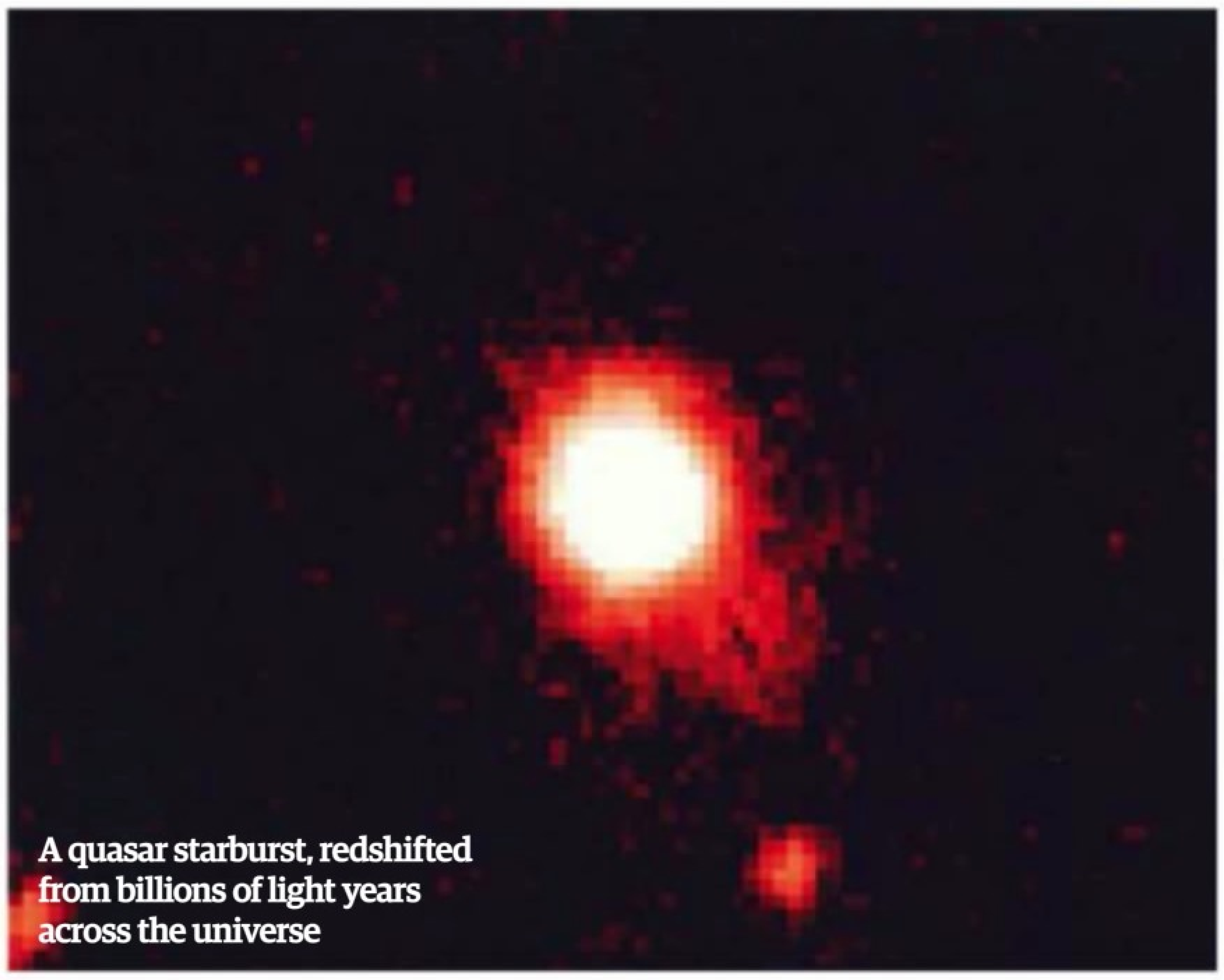
objects that are formed when the core of a dying star far more massive than the Sun undergoes a sudden and violent collapse. The resulting object typically weighs between five and 20 times as much as the Sun, and creates a powerful beacon at X-ray wavelengths. But driving an AGN requires a black hole that's off the scale compared to these stellar-mass 'tiddlers' – something with the mass of millions of Suns, feeding voraciously on gas, dust and even stray stars that come within its influence.

A key piece of evidence for the supermassive black hole theory comes from the distribution of active galaxy types. The less powerful Seyferts and some radio galaxies can be relatively nearby in space, but quasars and blazars are always, at the least, several billion light years away.

And because of the limited speed of light, this means that we're seeing them as they were several billion years ago – when the universe was significantly younger and more turbulent. So could it be that quasars are 'just a phase' that galaxies go through, and that the more sensible, middle-aged galaxies in our immediate cosmic neighbourhood – perhaps even the Milky Way itself – went through a quasar period in their wild youth?

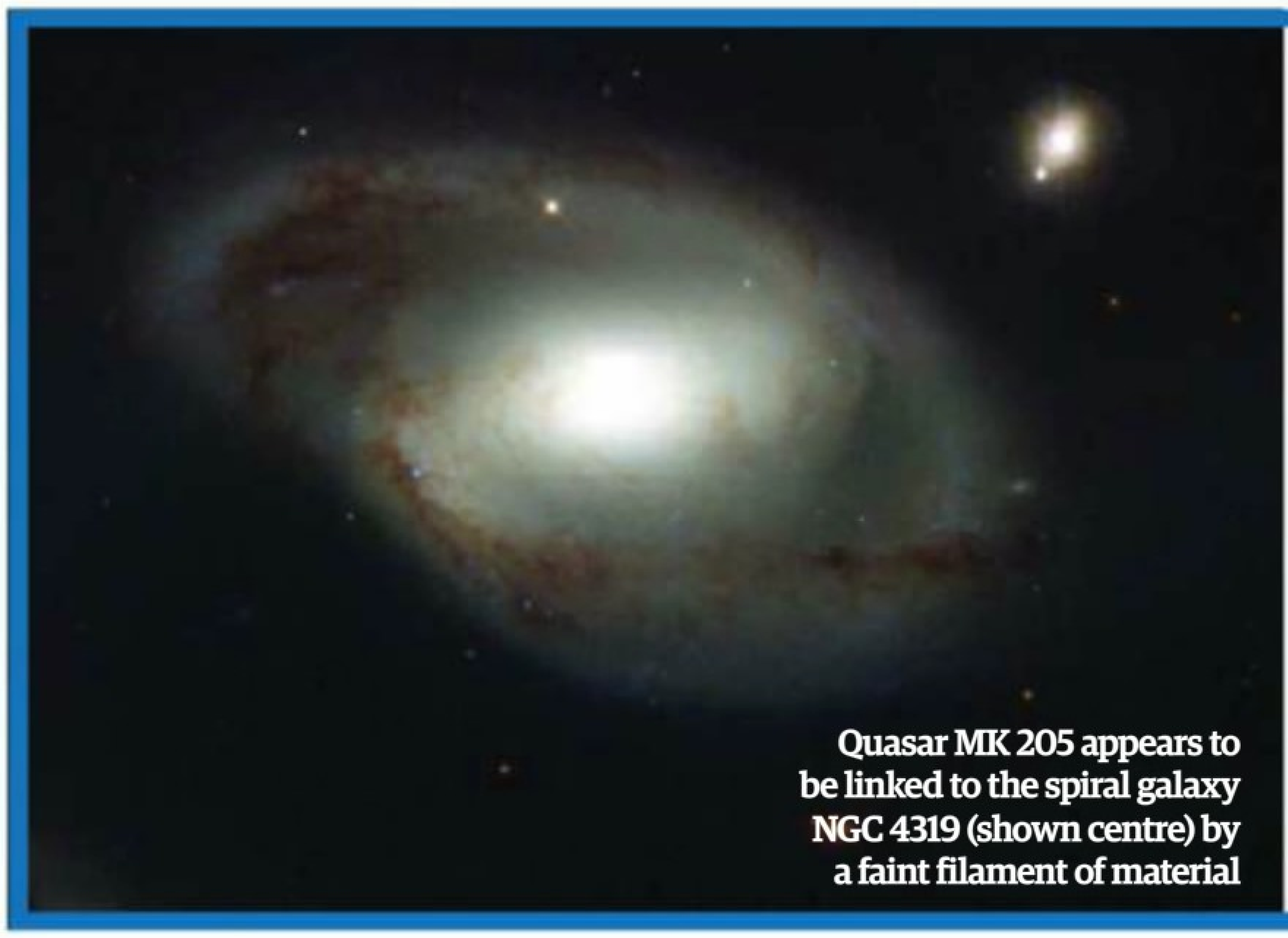
Today we know this is the case, largely because when we measure the motion of stars in the heart of nearby galaxies, they usually turn out to be orbiting around an enormous but invisible concentration of mass.

In the case of our very own Milky Way, astronomers have traced the paths of individual stars that take just a few years to orbit an object that contains 4 million solar masses of material packed into a region smaller than the Solar System. This object – named Sagittarius A* after the source of radio waves that coincides with its position in the sky – can only be a black hole: a sleeping giant at the centre of our galaxy. Amazingly, compared to the black holes confirmed in some other galaxies, Sagittarius A* seems to be on the small side.



A quasar starburst, redshifted from billions of light years across the universe

"Could it be that quasars are 'just a phase' that galaxies go through in their wild youth?"

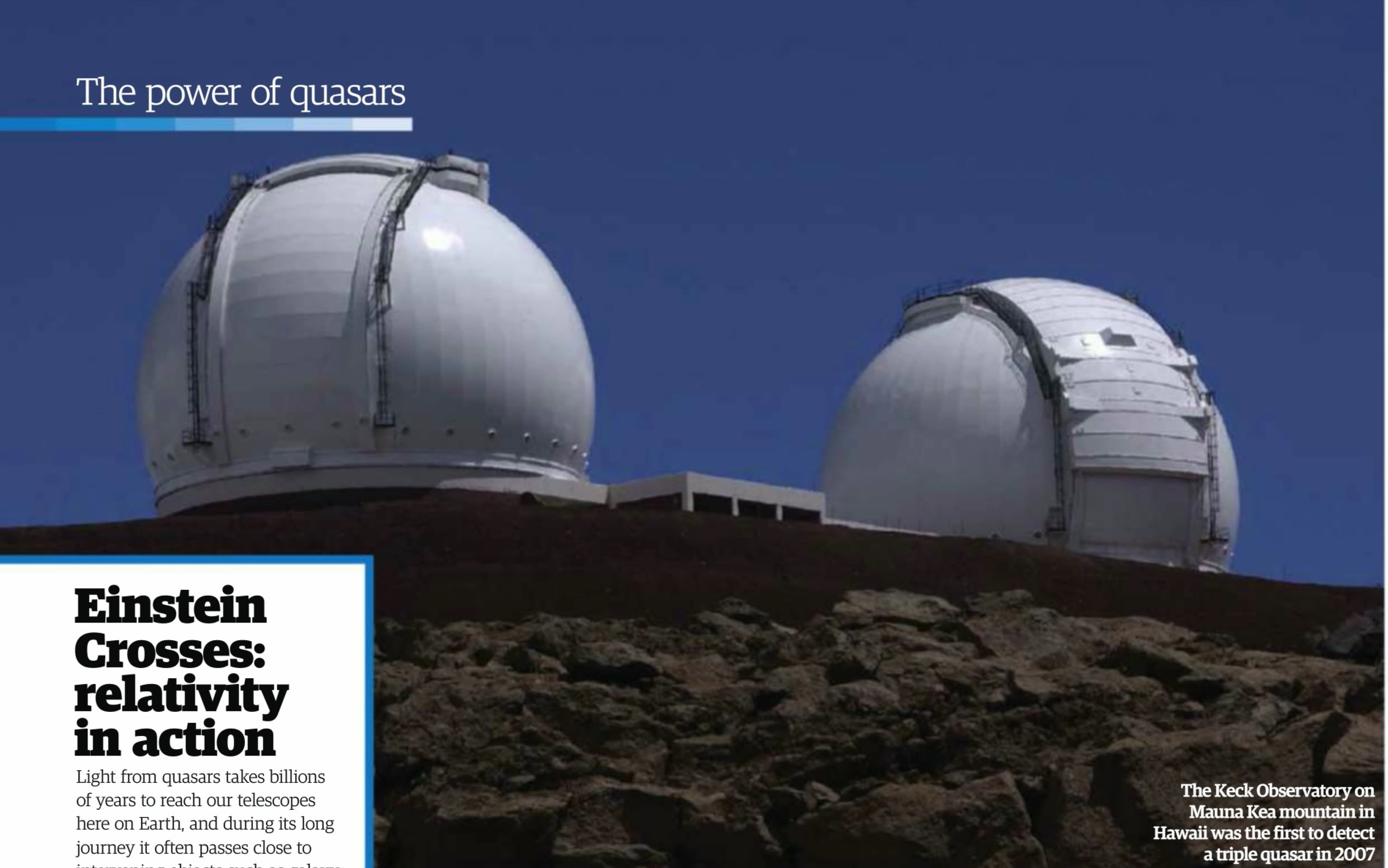


Quasar MK 205 appears to be linked to the spiral galaxy NGC 4319 (shown centre) by a faint filament of material

## Redshift controversies

In general, the astronomical establishment is agreed that the redshifts observed in quasars are a Doppler effect linked to the expansion of the universe, and therefore quasars are very distant and moving away at high speed. But there are still a few doubters, the most notable of whom is American astronomer Halton Arp, formerly of the Palomar Observatory in California and the Max Planck Institute for Astrophysics.

Arp has a formidable reputation, and compiled the first catalogue of peculiar galaxies – interacting and merging galaxies often associated with AGNs – in the Sixties. He is convinced that many quasars show physical connections to relatively normal galaxies (a good example pictured left is MK 205, which appears to be linked by a bridge of material to the spiral galaxy NGC 4319). Since the two objects show wildly different redshifts, then if they are really connected the quasar's redshift cannot be a result of cosmic expansion; instead, it must be some intrinsic property of the quasar – perhaps caused by powerful gravity.

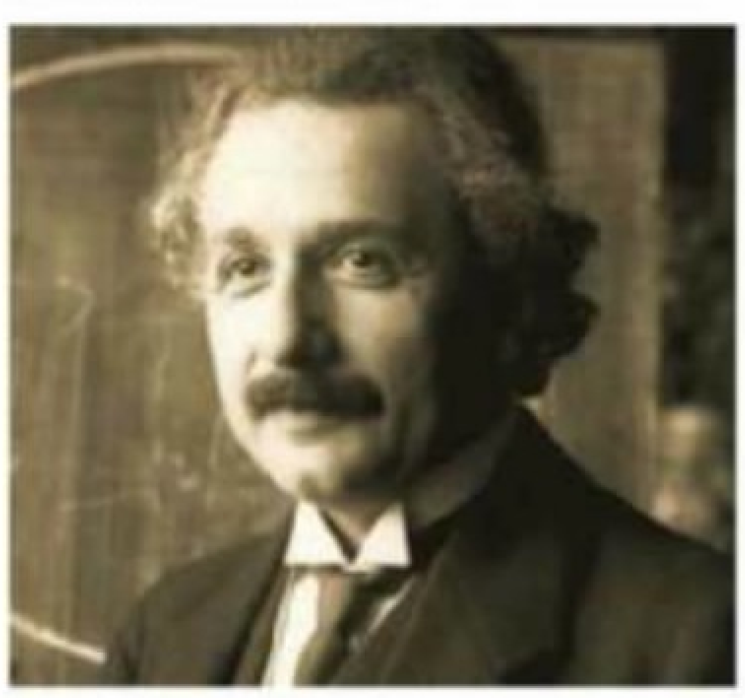


The Keck Observatory on Mauna Kea mountain in Hawaii was the first to detect a triple quasar in 2007

## Einstein Crosses: relativity in action

Light from quasars takes billions of years to reach our telescopes here on Earth, and during its long journey it often passes close to intervening objects such as galaxy clusters and individual galaxies. If the mass of such an intervening object is large enough, then according to Einstein's theory of general relativity, it should warp the space around it, deflecting the path of even massless light rays to create an effect known as gravitational lensing.

The brightness of quasars makes them ideal tests for this effect, and since the Nineties astronomers have discovered many examples of lensing in action – stunning visual proof of Einstein's theory. Depending on the precise geometry of the objects involved, the quasar's image may simply be distorted, or warped into a curve or circle. The most perfect situations can give rise to double images, or – rarest of all – the perfect quadruple image known as the Einstein Cross.



Einstein's relativity has been tested to extremes by gravitational lensing

So far, we can't apply these same techniques to quasars to prove absolutely that their AGNs are powered by giant black holes, but the circumstantial evidence still seems pretty conclusive. What's more, although the 'host galaxies' around quasars are still hard to resolve, those we can see often appear to be in a turbulent, shapeless state, suggesting that they have lots of stray matter floating around in random orbits to feed the black hole engine.

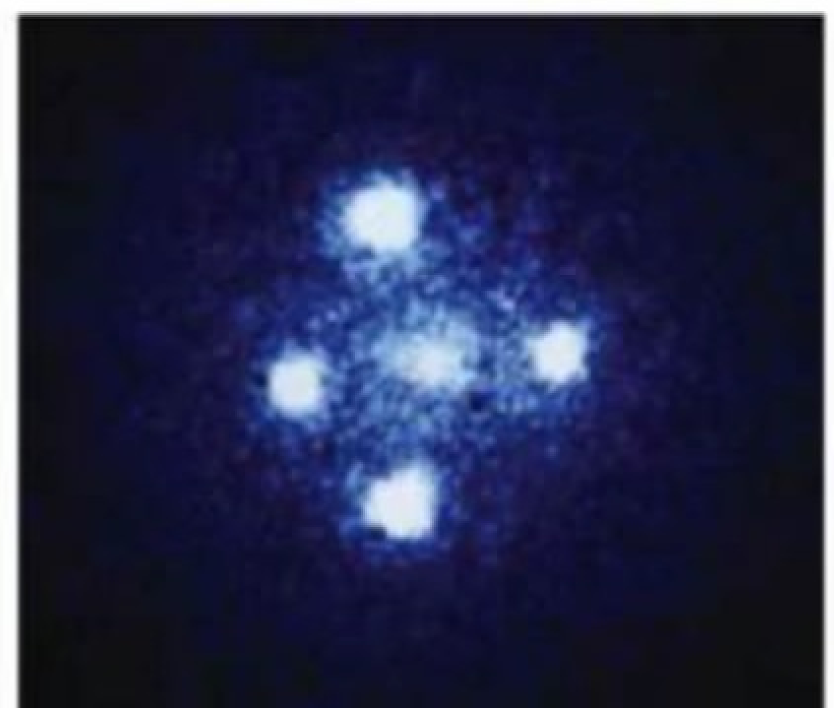
The brightest quasars of them all, meanwhile (and many nearby active galaxies) often seem to be involved in galaxy collisions and mergers. It's only as galaxies settle down into a more orderly structure that the quasars seem to dwindle away: by this point, the black hole's gravity has 'soaked up' all the fuel from its immediate surroundings, and any surviving material in the host galaxy's core will have learned to keep its distance from such a voracious monster.

So, while the mystery of quasar power sources seems to be solved, there are still some important unanswered questions. Perhaps the biggest of all is exactly how the supermassive black holes form in the first place. Do they coalesce in sudden, violent events, or develop more sedately over a longer timescale? Work on relatively faint quasars in the early universe, such as that being led by Professor Kevin Schawinski at the ETH Technology Institute in Zurich, is promising to answer some of these questions (see interview on page 24).

The brightness of quasars makes them enormously useful for astronomers studying the most distant parts of the universe – not least because until quite recently they have been the only objects visible across distances of billions of light years.

Quasar distances are usually established by measuring the redshift of their light and using Hubble's Law – the established principle that objects at greater distances are moving away from us at higher speeds and therefore exhibit greater redshifts, due to the expansion of the universe as a whole. Indeed, it was the high redshift of quasars that first convinced astronomers they were so distant and bright (see 'Discovering quasars', page 18). By measuring the redshifts of large numbers of quasars and using them as 'shorthand' for distance, cosmologists can construct three-dimensional maps of the deep universe, allowing them to discover massive structures known as large quasar groups (LQGs).

In January 2013 astronomers at the University of Central Lancashire, UK, announced the discovery of the Huge-LQG - the largest structure so far recorded in the universe, with some 73 quasars scattered over 4 billion light years of space. Such enormous objects, held together by the influence of gravity, cannot possibly have evolved



A rare, perfect Einstein Cross: a gravitationally lensed, quadruple image of quasar 8 billion light years away

in the 13.7 billion years since the Big Bang explosion believed to have spawned the universe, so their seeds must have been present – in the form of variations in the density of matter – within the Big Bang itself.

Quasars have a huge range of other cosmological uses: 'dips' in the spectrum of their light at different wavelengths can be used to discover otherwise invisible galaxies lying between them and us (see 'Galaxy hunting with quasars'); they can give us important clues to the nature of space and time themselves (see boxout on Einstein Crosses); and they can even be used as probes to investigate the mysterious dark energy that is causing the universe's expansion to accelerate. It's little wonder, then, that quasars remain a powerful weapon in the astronomer's arsenal.

The most distant X-ray jet ever observed (in part, by Hubble), 12.4 billion light years from Earth

The world's most famous space telescope, Hubble, is one of several searching for the seeds of supermassive black holes and their quasars

# Kevin Schawinski on hunting for quasars

## We talk to a professor from the ETH Technology Institute who specialises in studying faint quasars in the early universe, helping us learn how the first galaxies evolved

**First of all, can you tell us what got you interested in quasars?**
Well, they're fascinating objects in their own right! Quasars are giant black holes with about a billion times the mass of the Sun, accreting matter as fast as they can and in the process releasing truly enormous amounts of energy. These supermassive black holes are the universe's messy eaters and, when they gorge on gas and dust, they can release more energy than all the combined stars of the galaxy in which the black hole resides. Now, we also suspect strongly that some part of all this energy affects the host galaxy of the black hole, shaping its evolutionary destiny. But we don't really understand that process yet.

**Until recently we've been limited to studying only the very brightest quasars – is that right?**
It's not just a question of brightness. Of course, the brightest quasars are much easier to see with telescopes than their fainter cousins, however the universe complicates studying quasars in another way: if the central regions of a galaxy contain a large amount of gas and dust between us and where the black hole is feeding, then much of the light which is emitted by the quasar can be blocked. [To overcome this] we have to use data from ultra-deep observations by the Chandra X-ray Observatory and the infrared (IR) Spitzer Space Telescope to find these 'hidden' quasars. They emit so much energy that all that gas and dust that absorb the quasar's light get heated up, and Spitzer can pick up on the [resulting] extra 'glow'.

**Are there any fundamental differences between the brighter and fainter quasars we've detected?**
We are starting to think so. When we look at images of the galaxies in which the brightest quasars live, they look like total train wrecks: two gigantic, gas-rich galaxies crashed together igniting a luminous quasar in the process.

**...so what can we infer about the host galaxies of quieter quasars?**
We are just starting to be able to find the less luminous cousins of these brightest quasars and take images of the galaxies they [inhabit] with Hubble. And these galaxies look nothing like those train-wreck mergers. They look more or less the same as normal, star-forming galaxies in the early universe: large discs, little or no bulges, and little evidence for galaxy mergers. Clearly, these black holes are feeding for very different reasons...

**Can all this data we're gathering tell us anything about the origins of the black holes themselves?**
We can now start to piece together the why and where of black hole growth. The most massive black holes of all are the 10-billion-solar-mass monsters we find at the centre of giant elliptical galaxies like Messier 87 [54 million light years from Earth in the Virgo Cluster]. They likely grew up rapidly via the mergers of gas-rich galaxies. More normal supermassive black holes – maybe similar to the one in the Milky Way – grew in much calmer environments, feeding on random gas and dust that swirled in due to the random stirrings in the host galaxy, or the occasional infalling dwarf galaxy.

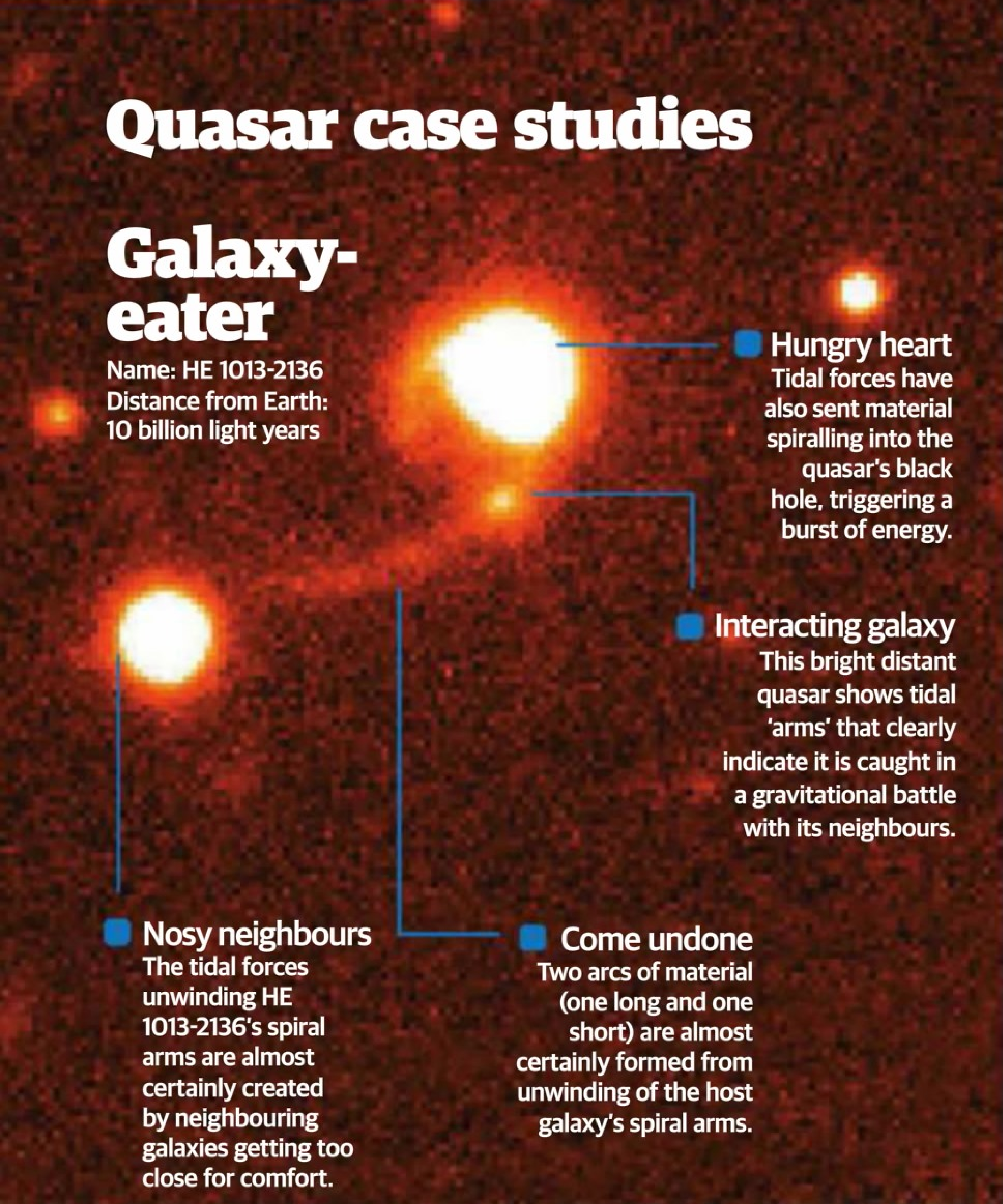
**Finally, where do you see your research taking you in the future?**
The ultimate goal is to figure out where the seeds for the supermassive black holes at the [heart] of galaxies came from, and right now, we have no idea about that. There are plenty of theoretical mechanisms, but virtually no observations yet. But I am hopeful that the teams of Hubble, Chandra and giant ground-based telescopes like the Very Large Telescope in Chile can get us there. Of course, NASA's James Webb Space Telescope, when it finally launches, [will make an impact] too.

"When we look at images of the galaxies in which the brightest quasars live, they look like total train wrecks..."

# Quasar case studies

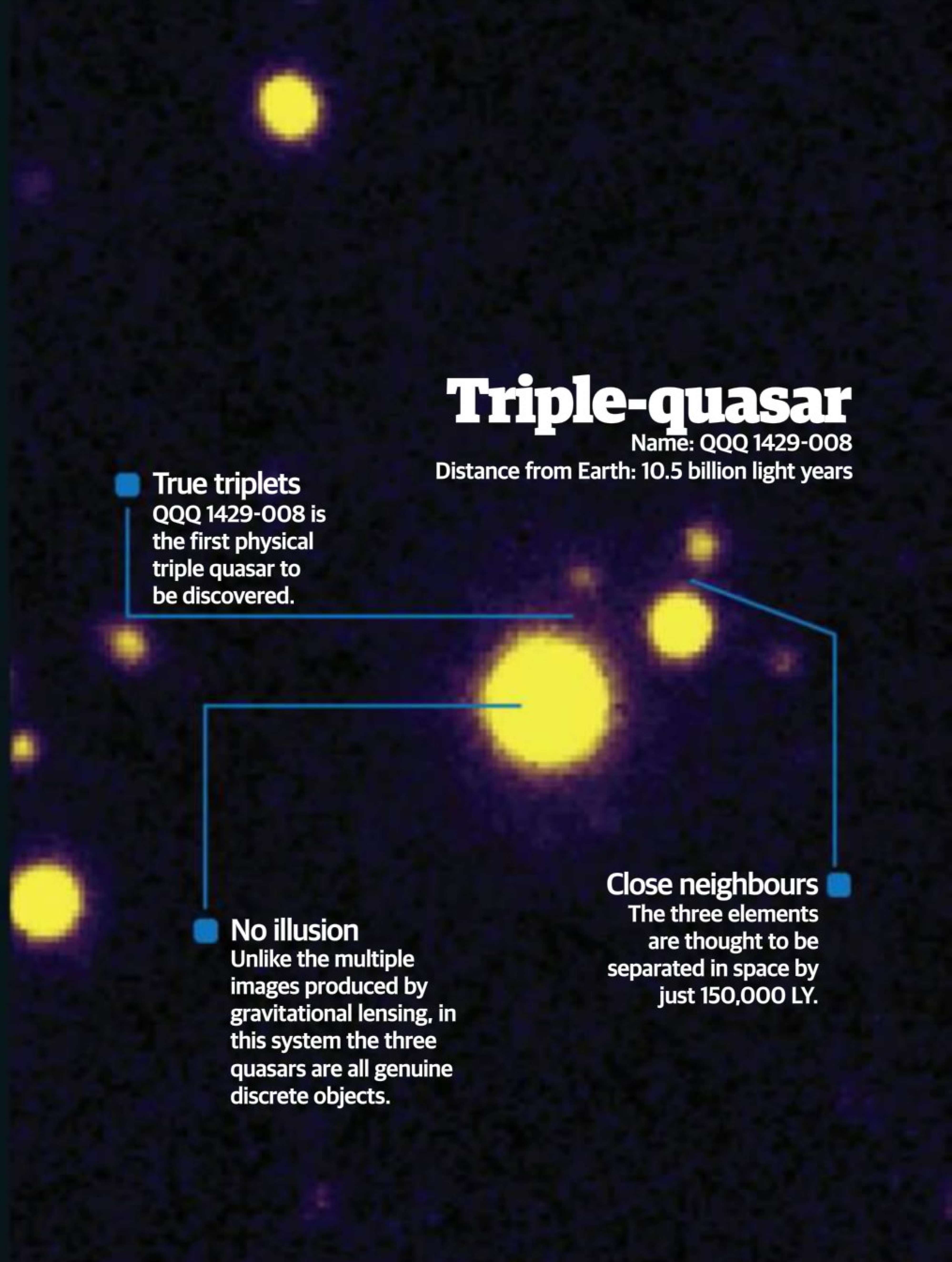
## Galaxy-eater

Name: HE 1013-2136
Distance from Earth:
10 billion light years



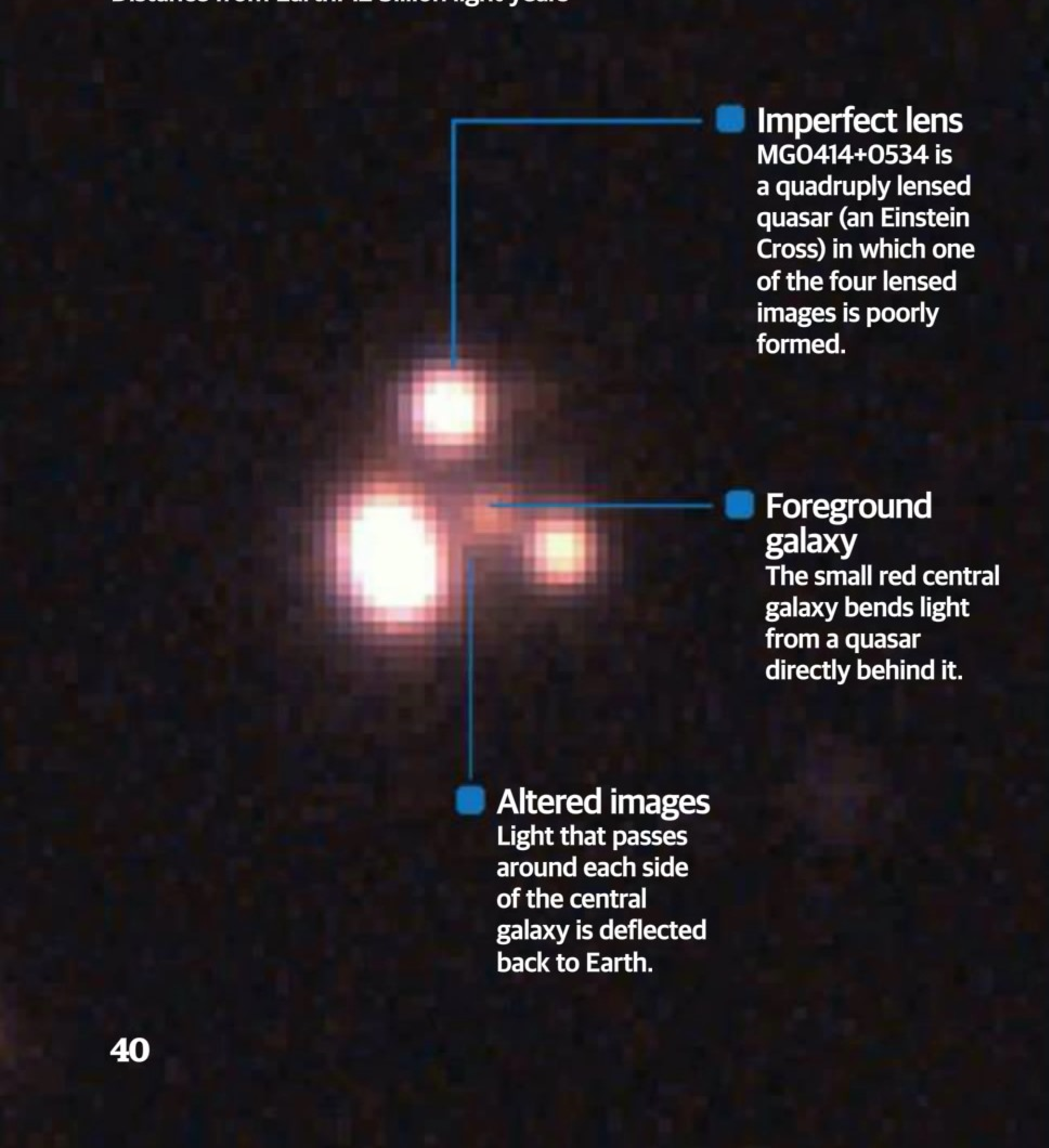

## Triple-quasar

Name: QQQ 1429-008
Distance from Earth: 10.5 billion light years




## Quadruple lensing

Name: MG0414+0534
Distance from Earth: 12 billion light years




## Stellar jets

Name: 3C 273
Distance from Earth: 3 billion light years