# ***AstroTalk: Behind the news headlines of May 2016***

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## ***Supernovae and gravitational lenses: A true match made in heaven!***

During the last week of May 2016, I organized an international conference at the International Space Science Institute in Beijing. The meeting's main aim was to update our understanding of the different, cutting-edge techniques we now use routinely to determine accurate distances to a wide variety of objects across the Universe. At the end of the week, I looked back with great satisfaction at a series of very high-quality presentations by some 45 scientists from around the world and numerous in-depth discussions, all conducted in a constructive, friendly atmosphere. Indeed, I consider this workshop to have been one of the most successful and pleasant meetings I have ever been responsible for, while also having rekindled old friendships and making many new friends, too.

A large subset of the presentations offered exciting new results, leaving me with the impression that we are truly on the verge of a new era of precision distance determination in astronomy. However, one presentation in particular left me truly awe-struck. My colleague and friend Sherry Suyu, affiliated with both the Academia Sinica Institute for Astronomy and Astrophysics (Taiwan) and the Max-Planck Institute for Astrophysics (Germany), told us about her team's work on using so-called 'gravitational lenses'—massive foreground objects that bend light, but more about how this works below—as distance tracers. Her team had serendipitously discovered a supernova—an exploding massive star at the end of its life—that had been gravitationally lensed into multiple images. This allowed them not only to determine the entire system's distance framework, they even managed to predict almost exactly when a new image of the supernova would appear. And their calculations proved to be correct! This, on its own, was a major, ground-breaking result, but it also provided strong confirmation of Albert Einstein's Theory of General Relativity—which, of course, was proved once and for all by the detection of gravitational waves late last year. Awesome—I truly have no other words to express my feelings about these results.

But let me take you along on a step-by-step journey to explain why I was so impressed. Supernovae are among astronomers' most important tools for exploring the history of the Universe. Their frequency allows us to examine how active star formation was, how heavy elements have developed, and to determine the distances to galaxies. Yet even these titanic explosions are only so bright, and there's an effective limit on how far we can detect them with the current generation of telescopes. However, this limit can be extended with a little help from gravity.

Over the past several decades, astronomers have come to realize that the sky is filled with magnifying glasses that allow the study of very distant and faint objects usually barely visible with even the largest telescopes.

Albert Einstein's General Theory of Relativity predicts that dense concentrations of mass in the Universe will distort space and bend light like a lens, magnifying objects behind the mass when seen from Earth. While first postulated in 1924, and proposed for galaxies by the Swiss–American astronomer Fritz Zwicky in 1937, the effect wasn't observed until 1979 when a distant quasar, a highly energetic core of a distant galaxy, was split in two by the gravitational disturbances of an intervening cluster of galaxies.

Today, lensing provides a new window into the extremely faint Universe shortly after its birth 13.8 billion years ago. But in doing so based on supernova searches, astronomers must look for these events in a different manner than most other supernova searches. These searches are generally limited to the visible portion of the spectrum, the portion we see with our eyes, but due to the expansion of the Universe, the light from these objects is stretched into the near-infrared portion of the spectrum where few surveys to search for supernovae exist.

But one team, led by Rahman Amanullah at Stockholm University in Sweden, has conducted a survey using the Very Large Telescope in Chile to search for supernovae lensed by the massive galaxy cluster Abell 1689. This cluster is well-known as a source of gravitationally lensed objects, making visible some galaxies that formed shortly after the Big Bang.

In 2009, the team discovered one supernova that was magnified by this cluster that originated 5–6 billion light-years away. In the mean time, the team discovered an even more distant supernova, nearly 10 billion light-years distant. This event was magnified by a factor of 4 from the effects of the foreground cluster. From the distribution of energy in different portions of the spectrum, the team concluded that the supernova was an implosion of a massive star. The distance of this event puts it among the most distant supernovae yet observed.

More recently, while looking through infrared *Hubble Space Telescope* images taken on 10 November 2014, Patrick Kelly, a University of California Berkeley astronomer, discovered that one of these lenses—a massive galaxy within a known cluster of galaxies, both of which are gravitationally bending and magnifying light—had created four separate images of a supernova at almost the same distance.

> "*These gravitational lenses are like a natural magnifying glass. It's like having a much bigger telescope*," Kelly said. "*We can get magnifications of up to 100 times by looking through these galaxy clusters*."

The four supernova images detected by *Hubble* were part of the Grism Lens-Amplified Survey from Space (GLASS) programme. GLASS acquires near-infrared spectra of massive galaxy clusters with the primary goals of studying faint galaxies near the edge of the observable Universe and spatially resolved galaxies closer to Earth, as well as characterizing the cluster galaxy population.

This supernova is the first that was seen multiple times thanks to gravitational

lensing. Kelly and his collaborators dubbed the distant supernova SN Refsdal in honour of Sjur Refsdal, the late Norwegian astrophysicist and pioneer of gravitational lensing studies. It is located about 9.3 billion light-years away, near the edge of the observable Universe, while the lensing galaxy is about 5 billion light years from Earth.

> "*Basically, we get to see the supernova four times and measure the time delays between its arrival in the different images, hopefully learning something about the supernova and the kind of star it exploded from, as well as about the gravitational lenses themselves*," said Kelly. "*That will be neat*."

When light from a background object passes by a mass, such as an individual galaxy or a cluster of galaxies, the light is bent. When the path of the light is far from the mass, or if the mass is not especially large, 'weak lensing' will occur, barely distorting the background object. When the background object is almost exactly behind the mass, however, 'strong lensing' can smear extended objects (like galaxies) into an 'Einstein ring,' surrounding the lensing galaxy or cluster of galaxies. Strong lensing of small, point-like objects, on the other hand, often produces multiple images—an Einstein cross—arrayed around the lens.

> "*It's a wonderful discovery*," said Alex Filippenko, University of California Berkeley professor of astronomy and a member of Kelly's team. "*We've been searching for a strongly lensed supernova for 50 years, and now we've found one. Besides being really cool, it should provide a lot of astrophysically important information*. *We have seen many distant quasars appear as Einstein crosses, but this is the first time a supernova has been observed in this way*," Filippenko continued. "*This short-lived object was discovered only because Pat Kelly very carefully examined the Hubble data and noticed a peculiar pattern. Luck comes to those who are prepared to receive it*."

The galaxy that is splitting the light from the supernova into an Einstein cross is part of a large cluster, called MACS J1149.6+2223, which has been known for more than 10 years.

In 2009, astronomers reported that the cluster had created the largest known image of a spiral galaxy ever seen through a gravitational lens. SN Refsdal is located in one of that galaxy's spiral arms, which also appears in multiple images around the foreground lensing cluster. The supernova, however, is split into four images by a red elliptical galaxy within the cluster.

> "*We get strong lensing by a red galaxy, but that galaxy is part of a cluster of galaxies, which is magnifying it more. So we have a double lensing system*," Kelly said.

After Kelly discovered the lensed supernova while looking for interesting and very distant supernova explosions, he and his team examined earlier *Hubble* images and saw it in images taken as early as 3 November 2015, although it was

very faint. In the mean time, the *Hubble Space Telescope* has taken several dozen images of it using the Wide Field Camera 3 infrared camera.

> "*By luck, we have been able to follow it very closely in all four images, getting data every two to three days*," he said.
>
> "*The longer the path length, or the stronger the gravitational field through which the light moves, the greater the time delay*," noted Filippenko.

Kelly hoped that measuring the time delays between the phases of the supernova in the four images will enable constraints on the foreground mass distribution and on the expansion and geometry of the Universe. And indeed, his wish came true.

> "*While studying the supernova, we realised that the galaxy in which it exploded is already known to be a galaxy that is being lensed by the cluster*," explains Steve Rodney from the University of South Carolina and co-author of the study. "*The supernova's host galaxy appears to us in at least three distinct images caused by the warping mass of the galaxy cluster*."

These multiple images of the galaxy presented a rare opportunity. As the matter in the cluster—both dark and visible—is distributed unevenly, the light creating each of these images takes a different path with a different length. Therefore the images of the host galaxy of the supernova are visible at different times.

Using other lensed galaxies within the cluster and combining them with the discovery of the Einstein Cross event in 2014, astronomers were able to make precise predictions for the reappearance of the supernova. Their calculations also indicated that the supernova appeared once before in a third image of the host galaxy in 1998—an event not observed by any telescope. To make these predictions they had to use some very sophisticated modelling techniques.

> "*We used seven different models of the cluster to calculate when and where the supernova was going to appear in the future. It was a huge effort from the community to gather the necessary input data using Hubble, the MUSE instrument on the Very Large Telescope, and the Keck Observatory, and to construct the lens models*," explains Tommaso Treu, lead author of the modelling comparison paper, from the University of California at Los Angeles, USA. "*And remarkably all seven models predicted approximately the same time frame for when the new image of the exploding star would appear*."

Since the end of October 2015 Hubble had been periodically peering at MACS J1149.5+2223, hoping to observe the unique rerun of the distant explosion and prove the models correct. On 11 December SN Refsdal finally made its predicted, but nonetheless show-stopping, reappearance. The exact date is uncertain by approximately one month, the interval between two consecutive *Hubble* observations.

"*Hubble has showcased the modern scientific method at its best,*" commented Kelly. "*Testing predictions through observations provides powerful means of improving our understanding of the cosmos.*"

The detection of SN Refsdal's reappearance served as a unique opportunity for astronomers to test their models of how mass—especially that of mysterious dark matter—is distributed within this galaxy cluster. Astronomers are now eager to see what other surprises the ongoing *Hubble Frontier Fields* programme will bring to light.

**Figures:**

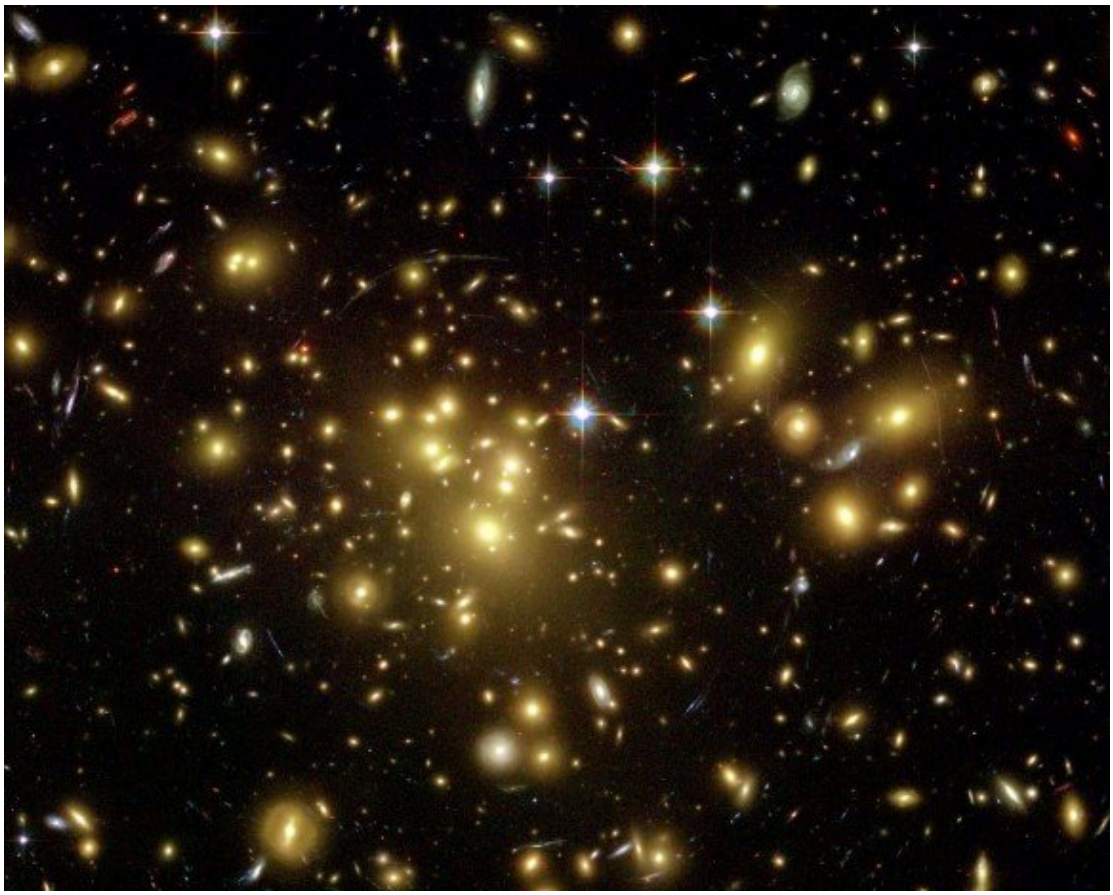

Figure 1: Galaxy Cluster Abell 1689

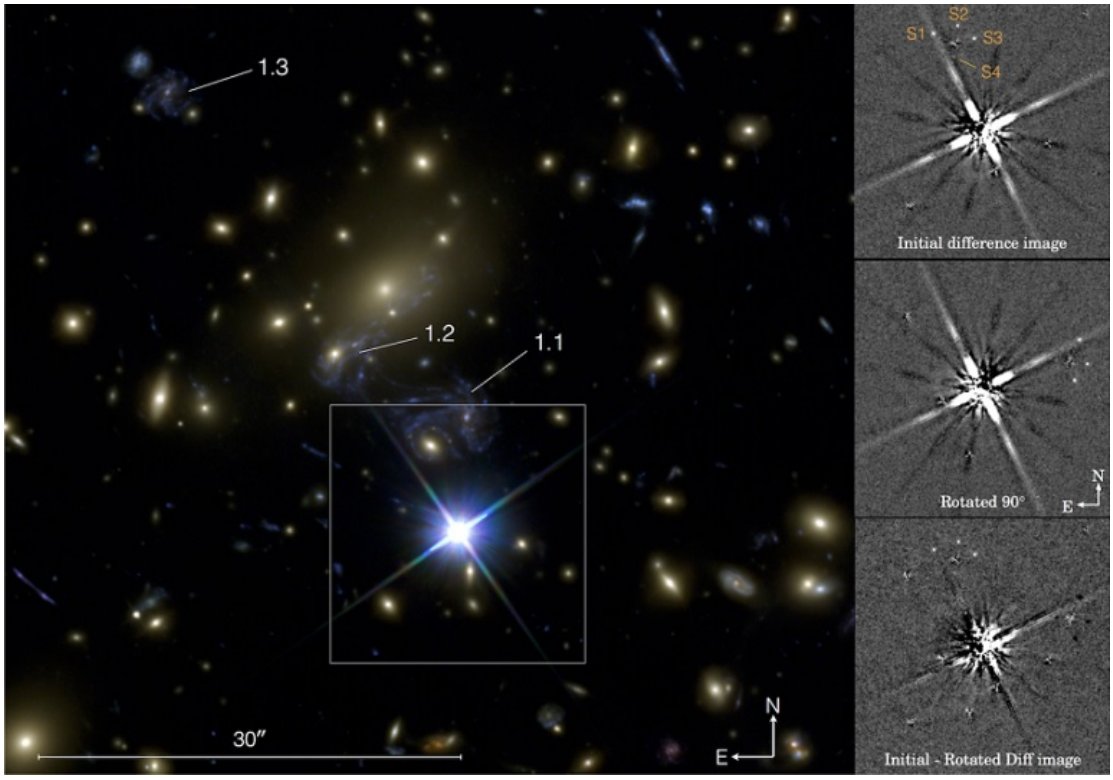


Figure 2: The MACS J1149.6+2223 field, showing the positions of the three primary images of the SN Refsdal host galaxy (labeled 1.1, 1.2, and 1.3). SN Refsdal appears as four point sources in an Einstein Cross configuration in the southeast spiral arm of image 1.1. The highlighted box is shown at the same scale in panels on the right-hand side, which illustrate the removal of contaminating diffraction spikes from a difference image. Each difference image is centered on the location of the contaminating star (top panel), then rotated clockwise by 90 degrees (middle panel). The rotated difference image is then subtracted from the initial difference image, removing most of the flux from the contaminating diffraction spike at the location of the SN Refsdal point sources (bottom panel). *(Credit: Steven A. Rodney et al., 2015.)*

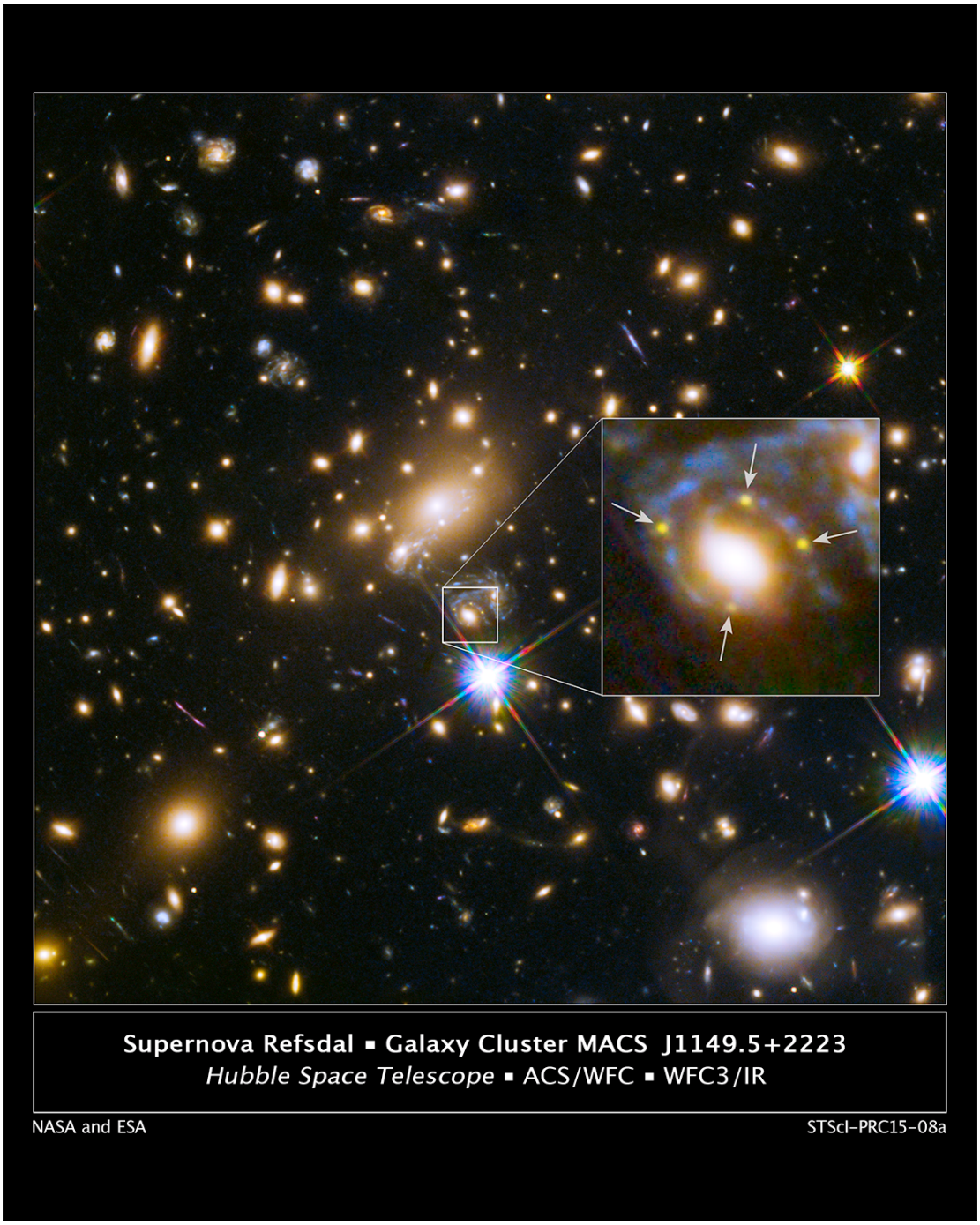


Figure 3: The many red galaxies in this *Hubble Space Telescope* image are members of the massive MACS J1149.6+2223 cluster, which strongly bends and magnifies the light of galaxies behind it. A large cluster galaxy (center of the box) has split the magnified light from an exploding background supernova into four yellow images (arrows), which form an Einstein Cross. *(Credit: Image courtesy of Z. Levay at NASA's Space Telescope Science Institute and ESA. Patrick Kelly and Alex Filippenko at UC Berkeley contributed to the discovery and analysis.)*

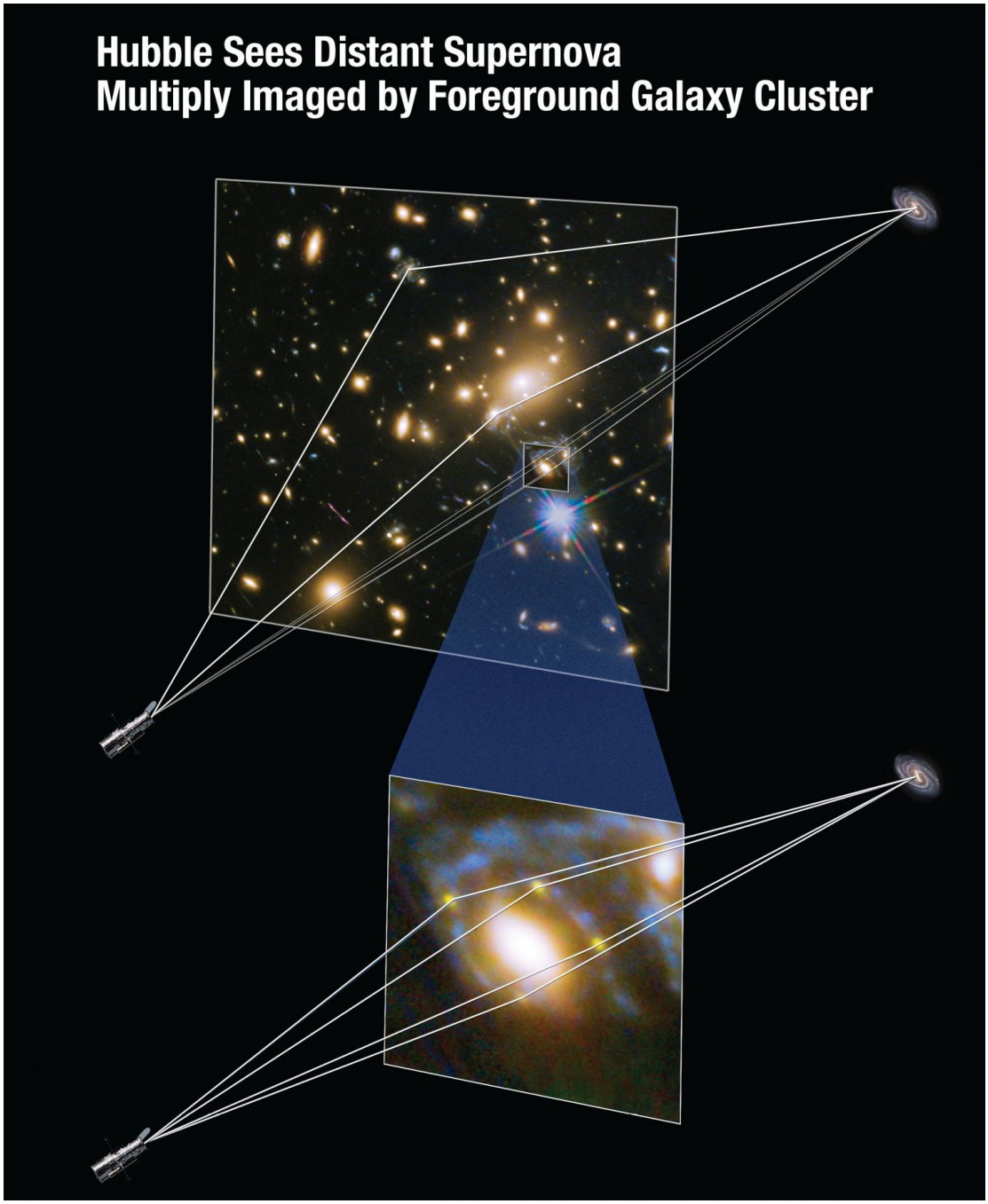


Figure 4: The light from the underlying supernova is deflected by the gravity of a large collection of galaxies and an elliptical galaxy, which thus acts like a magnifying glass and amplifies the light from the distant supernova. This special phenomenon, called gravitational lensing effect, works like Nature's own giant telescope and the supernova appears 20 times brighter than its normal brightness. *(Credit: NASA/ESA/GLASS/FrontierSN team)*

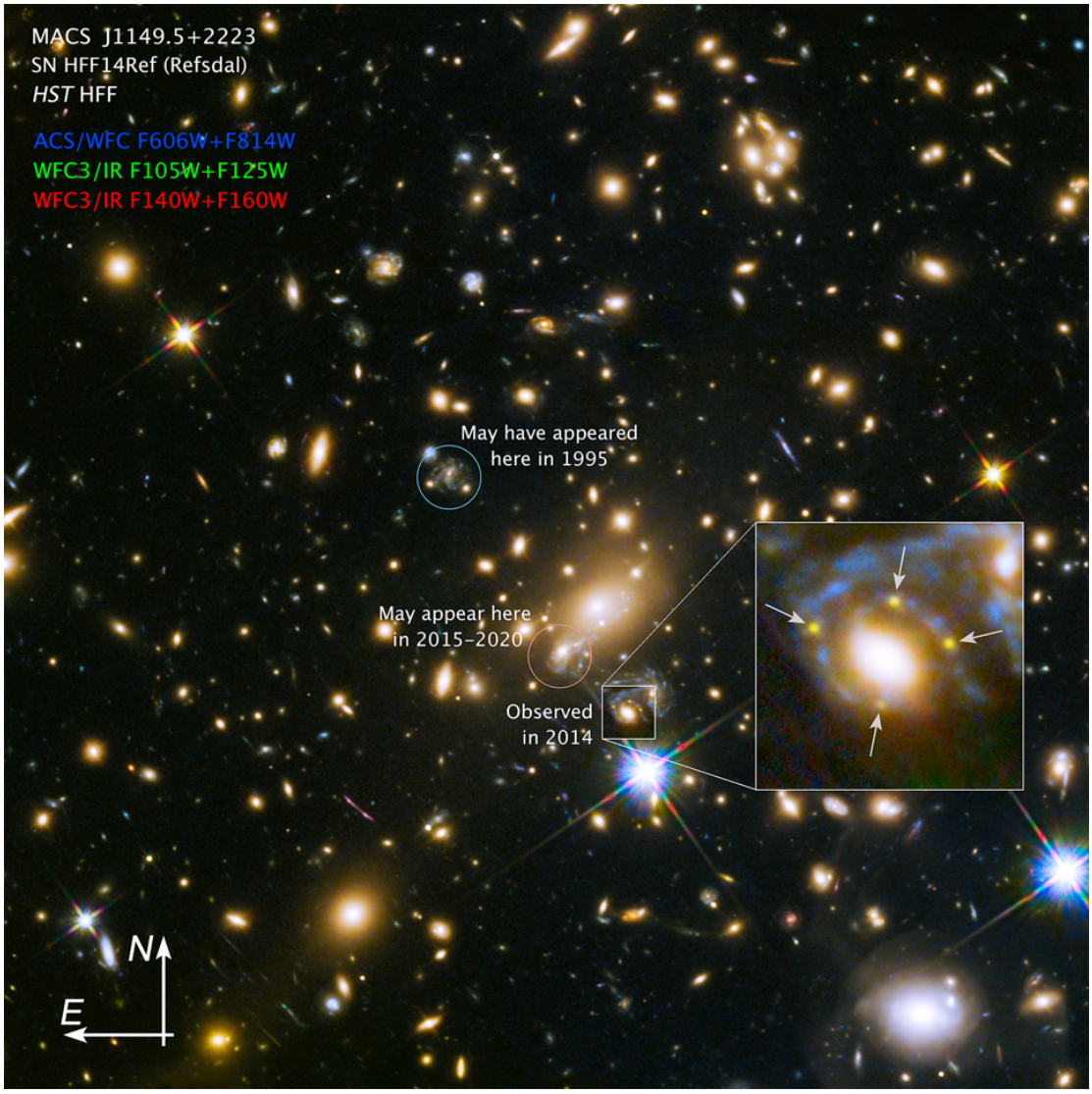


Figure 5: In the large square to the right in the image you see the four light representations of the supernova that was spotted on 11 November 2014. The blue circle shows another location in the galaxy cluster where you probably would have been able to see a single image of the supernova 20 years ago and the red circle shows where the supernova would appear again, according to calculations. This gave the astronomers a rare opportunity to get a backward glance at the supernova and will also enable the researchers to improve their calculations of the amount and distribution of dark matter—both in the galaxy cluster and in the one elliptical galaxy. *(Credit: NASA/ESA/GLASS/FrontierSN team)*

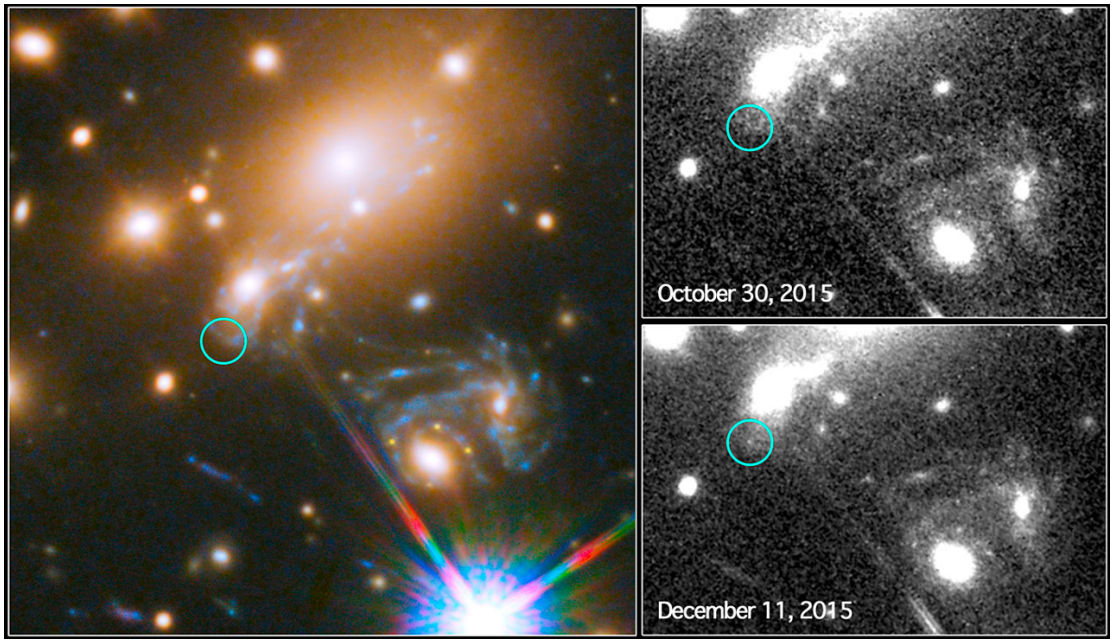


Figure 6: This image composite shows the search for the supernova, nicknamed SN Refsdal, using the NASA/ESA *Hubble Space Telescope*. The image to the left shows a part of the deep-field observation of the galaxy cluster MACS J1149.5+2223 from the Frontier Fields programme. The circle indicates the predicted position of the latest appearance of the supernova. To the lower right the Einstein cross event from late 2014 is visible. The image on the top right shows observations by *Hubble* from October 2015, taken at the beginning of observation programme to detect the newest appearance of the supernova. The image on the lower right shows the discovery of the Refsdal Supernova on 11 December 2015, as predicted by several different models. *(Credit: NASA & ESA and P. Kelly, University of California, Berkeley)*