

Multiple Images of a Highly Magnified Supernova Formed by an Early-Type Cluster Galaxy Lens

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We report the discovery of the first multiply-imaged gravitationally-lensed supernova. The four images form an Einstein cross with over $2''$ diameter around a $z = 0.544$ elliptical galaxy that is a member of the cluster MACS J1149.6+2223. The supernova appeared in *Hubble Space Telescope* near-infrared exposures taken on 3-20 November 2014 UT, as part of the Grism Lens-Amplified Survey from Space. The images of the supernova coincide with the strongly lensed arm of a spiral galaxy at $z = 1.491$, which is itself multiply imaged by the cluster potential. A measurement of the time delays between the multiple images and their magnification will provide new unprecedented constraints on the distribution of luminous and dark matter in the lensing galaxy and in the cluster, as well as on the cosmic expansion rate.

The possibility that the light from an exploding supernova (SN) could follow more than a single path around an intervening strong galaxy lens to the observer was first explored exactly fifty years ago (1). Many decades of transient searches, however, have not identified an example of a SN visible at multiple positions around a gravitational lens. Here we report the discovery of the first strongly lensed SN found in resolved multiple images, which we identified in the MACS J1149.6+2223 (2) galaxy cluster field on 11 November 2014¹.

The detection of a multiple-image transient provides the opportunity to measure two quantities of great cosmological interest. First, the difference in arrival time, owing to the difference in geometric and gravitational time delay (3), is directly proportional to the so-called time-delay distance and thus inversely proportional to the Hubble constant and weakly dependent on other cosmological parameters (1, 4–6). Second, for an assumed cosmological model, the time delays are a direct measurement of the difference in gravitational potential between the multiple images and thus greatly improve the reconstruction of the mass distribution in the deflector. Furthermore, if the lensed SN were of Type Ia, light-curve calibration (7, 8) would make it possible to infer the intrinsic brightness of the explosion with $\sim 10\%$ precision. Comparison of the SN intrinsic brightness and its apparent brightness would then enable an estimate of the absolute magnifications experienced by the SN across the multiple images (9, 10). This in turn provides separate, powerful constraints on the lensing mass distribution (11, 12), and the cosmic expansion and geometry (13), breaking the mass-sheet degeneracy (14).

This supernova (hereafter ‘SN Refsdal’) is the first multiply imaged SN discovered to date. It was recently shown that PS1-10afx (15) is a redshift $z = 1.38$ SN Ia strongly magnified (a factor of ~ 30) by an intervening galaxy at $z = 1.12$ (16, 17). Follow-up spectroscopy after the light from the SN had faded showed emission and absorption features produced by the $z = 1.12$ galaxy lens. Since PS1-10afx was discovered and monitored

¹UT dates are used throughout this paper

with ground-based telescopes, the available imaging had insufficient resolution to separate multiple potential images of the SN, and thus none of the applications described above could be pursued. For SN Refsdal, the four images are instead clearly resolved with an image separation of over $2''$, thus presenting an ideal opportunity to carry out for the first time the experiment suggested 50 years ago by Refsdal (1).

The Grism Lens-Amplified Survey from Space (GLASS) program (GO-13459; PI Treu) is a 140-orbit *Hubble Space Telescope* (*HST*) program that is obtaining near-infrared grism spectra of massive galaxy clusters with the primary goals of studying faint high-redshift ($z \gtrsim 6$) galaxies (18), spatially resolved intermediate-redshift galaxies (19), and characterizing the cluster galaxy population. Wide-band near-infrared *F105W* and *F140W* exposures are taken using the Wide Field Camera 3 (WFC3) to align and calibrate the grism data, and we have been promptly searching these images for transient sources.

In the *F140W* GLASS images acquired on 10 November 2014, we detected the four component images of a quadruple lens system, which we label S1–S4. Figure 1 shows coadditions of 3–20 November 2014 *F105W*, *F125W*, and *F140W* images, as well as the difference between these images and pre-explosion exposures of the field acquired in 2010 and 2011. The fluxes we measure at the positions of S1–S4 from *F105W* (3, 8, and 11 November 2014), *F125W* (20 November 2014), and *F140W* (10 and 20 November 2014) exposures are shown in Figure 2. While sources S1 and S2 do not show substantial changes in their fluxes, S3 exhibits a clear rise in brightness. The light curve of S4 is difficult to characterize with the currently available data, since it is comparatively faint.

Table 1 shows the coordinates of the variable sources. In Figure 3, the color-composite image shows the red galaxy lens at $z = 0.544$ (20) surrounded by an Einstein ring formed by light from the distorted spiral host galaxy with $z = 1.491$ (21), whose nucleus is offset by $\sim 3.3''$ from the center of the lensing elliptical galaxy.

The transient images are not coincident with the nucleus of the spiral host galaxy, making nuclear activity in the host an unlikely explanation. Indeed, the early-type galaxy lens only multiply images the tip of one of the spiral arms. A search of archival WFC3 *F105W*, *F110W*, *F140W*, and *F160W* images of MACS J1149.6+2223 acquired across ten separate *HST* visits beginning on 4 December 2010 finds no evidence for previous variability. Figure S1 shows several epochs of registered and coadded *F140W* imaging having no significant variation — seven archival epochs of *F160W* imaging likewise show no significant changes. Imaging without evidence for variability supports the hypothesis that the lensed source is an explosive transient, and not a flare from an active galactic nucleus (AGN) which would be expected to show long-term variability. We note that the transients detected on November 11 are several magnitudes above the upper limits obtained at previous epochs of ~ 28.5 mag AB. The amplitude of this variation would be very unusual for an AGN, whose light curves typically vary at the level of a few tenths of a magnitude over these time scales (22–24).

A separate possibility would be that the lensed source is an AGN not associated with the distorted spiral galaxy. However, if the hypothetical AGN had a different redshift

from the spiral galaxy, the Einstein cross formed by the lensed sources would not be coincident with the Einstein ring formed by the blue light from the spiral (see Figure S2). Furthermore, such an AGN would likely have sufficient brightness for detection in the many previous exposures. Figure S1 reveals no point-like sources in earlier exposures spatially coincident with the multiple images we detect.

Given the configuration and the image separation, a significant fraction of the strong gravitational lensing potential is contributed by the massive galaxy. Because of its location near the critical lines of the cluster itself (25), there is also an important contribution from the overall cluster potential. This makes modeling of the system particularly complex, and owing to the time-critical nature of this report, full modeling is deferred for future studies.

In order to obtain a rough estimate of the time delay and magnification ratios between the images, we constructed fourteen preliminary mass models, by modeling the system with variations of a single power-law ellipsoid mass distribution plus an external shear. As expected for this symmetric configuration (26), the time delays are relatively short and the magnification ratios are of order one-to-a-few. As one example, the simple model consisting of a single isothermal ellipsoid embedded in a strong external shear (26) yields time delays of the order of several tens of days. S1 is generally the leading image, typically followed by S2, S3, and then S4. Magnifications are of the order 2 for the least magnified source S4 and of the order ~ 10 for the other images. These magnifications do not include the additional contribution from the cluster, which is expected to be significant. Earlier modeling has found a relatively flat, nearly convergent central mass distribution, evident from the nearly undistorted shape of the spiral images (25). Adding a sheet of high-density matter and hence convergence onto our simplistic galaxy-lens model is expected to boost magnifications. Our cluster lens model shows typical magnifications of ~ 20 – 30 in the area in which the lens galaxy is embedded (27). The short predicted time delays and small magnification ratios are consistent with our identification of the system as a multiply imaged SN, because we expect the luminosity of the SN not to vary dramatically over the time scale of less than a week in the rest frame.

The spiral host galaxy itself is multiply imaged by the galaxy cluster (21, 25), so the SN may be detected at future epochs, or may have already appeared elsewhere in the cluster field. A search of archival HST imaging in both the optical (*F606W*, *F814W*, and *F850LP*) and infrared (*F105W*, *F125W*, *F140W*, and *F160W*) at the locations of the multiple images of the presumed host galaxy has revealed no evidence for SN Refsdal when these data were taken. Our cluster lens model predicts that the SN will appear in the central image of the spiral host galaxy, at an approximate position of $\alpha=11^{\text{h}}49^{\text{m}}36.01^{\text{s}}$, $\delta = +22^{\circ}23'48.13$ (J2000.0), at a future time (about a decade from now).

Due to a favorable coincidence, Frontier Fields program observations (GO-11504; PI Lotz) of the MACS J1149.6+2223 galaxy cluster field began on 20 November 2014 and run through January 2015 with WFC3 *F105W*, *F125W*, *F140W*, and *F160W* broadband filters, supplemented with additional observations from the FrontierSN program (GO-13386,13790; PI Rodney), to sample the SN light curve with a reasonable cadence. These anticipated

data will make it possible to measure the time delays among the multiple images from the light curve. If a spectrum having sufficient signal-to-noise ratio can be obtained using a ground- or space-based instrument, it will provide a useful constraint on the phase of the SN light in each image independent of measurements of its light curve. A *HST* Director’s Discretionary time program (GO-14041; PI Kelly) will obtain multiple band optical data on the SN to constrain its spectroscopic type from its wide-band spectral energy distribution.

This is the first discovery of a SN whose light is bent by an intervening lens to form multiple, resolved images. Measurements of the time delays between the phase of the SN in the pairs of images will enable constraints on the foreground mass distribution, and on the expansion and geometry of the universe. If the SN is of Type Ia, separate, even stronger limits on both the matter distribution and cosmological parameters become possible.

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Name	R.A. (J2000)	Dec (J2000)
S1	11:49:35.574	+22:23:44.26
S2	11:49:35.451	+22:23:44.84
S3	11:49:35.369	+22:23:43.95
S4	11:49:35.472	+22:23:42.62

Table 1: Coordinates of the transient point sources detected around the cluster galaxy lens, in J2000 Right Ascension and Declination.

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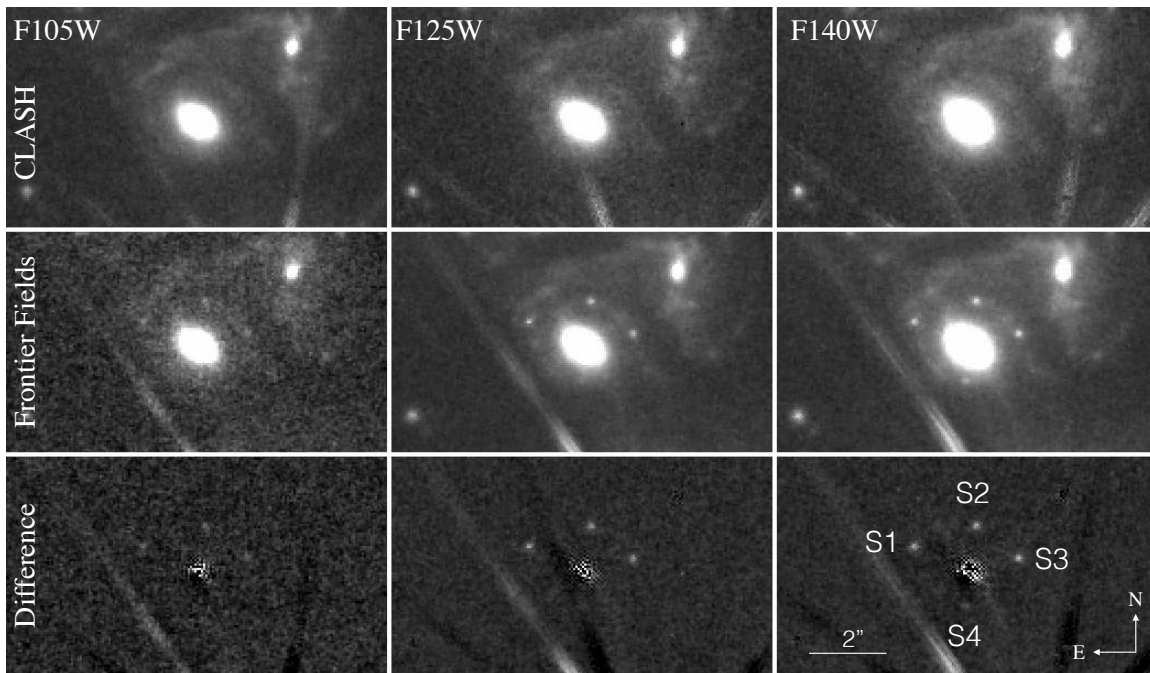


Fig. 1: *HST* WFC3-IR images showing the simultaneous appearance of four point sources around a cluster member galaxy. From left to right the columns show imaging in the *F105W* filter (Y band), *F125W* (J), and *F140W* (JH). From top to bottom the rows show archival imaging from the CLASH program, discovery epoch images from GLASS and the Hubble Frontier Fields programs, and the difference images. The template imaging in the top row comprises all available archival WFC3-IR imaging in these filters, collected from 05 December 2010 through 10 March 2011. The middle row of images are the composite of all available HST imaging collected between 3 November and 11 November 2014 (for *F105W*, at left), on 20 November 2014 (*F125W*, middle), and between 10 November and 20 November 2014 (*F140W*, right). The sources S1, S2, S3, and S4, which form an Einstein cross, are absent from all images obtained at earlier epochs, and therefore are clearly detected in the difference images along the bottom row. The line segments below S4 and in the lower-right corner are diffraction spikes from a nearby bright star in the foreground.

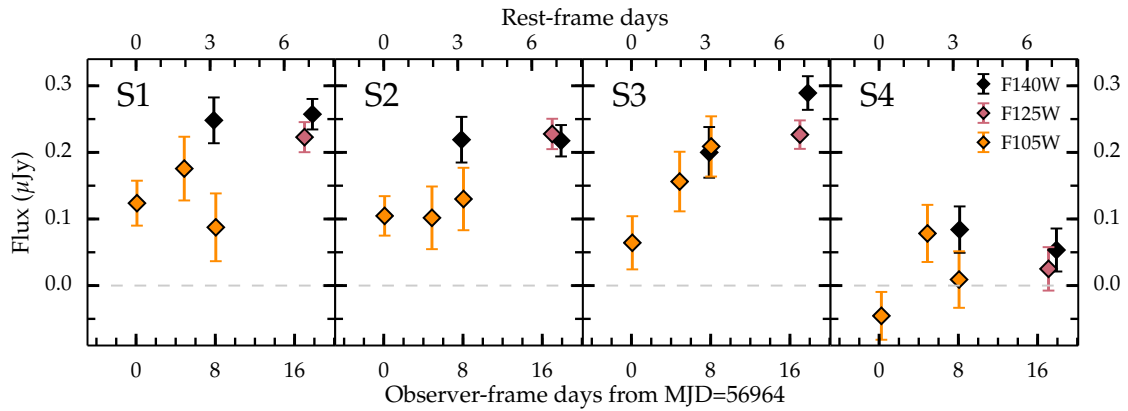


Fig. 2: Light curve of the images S1–S4 of the strongly lensed SN taken from 3 November 2014 through 20 November 2014. Rest-frame days assume the supernova is at the redshift of the multiply imaged spiral galaxy ($z=1.491$). We plot the fluxes measured in the WFC3 *F105W*, *F125W*, and *F140W* images of the MACS J1149.6+2223 galaxy cluster field. The expected time delays between images of days to weeks suggest that the transient must evolve over a timescale similar to that of a SN. A generic prediction of our lens models is that images S2, S3, and S4 are predicted to be delayed relative to S1, which is consistent with the early photometry.

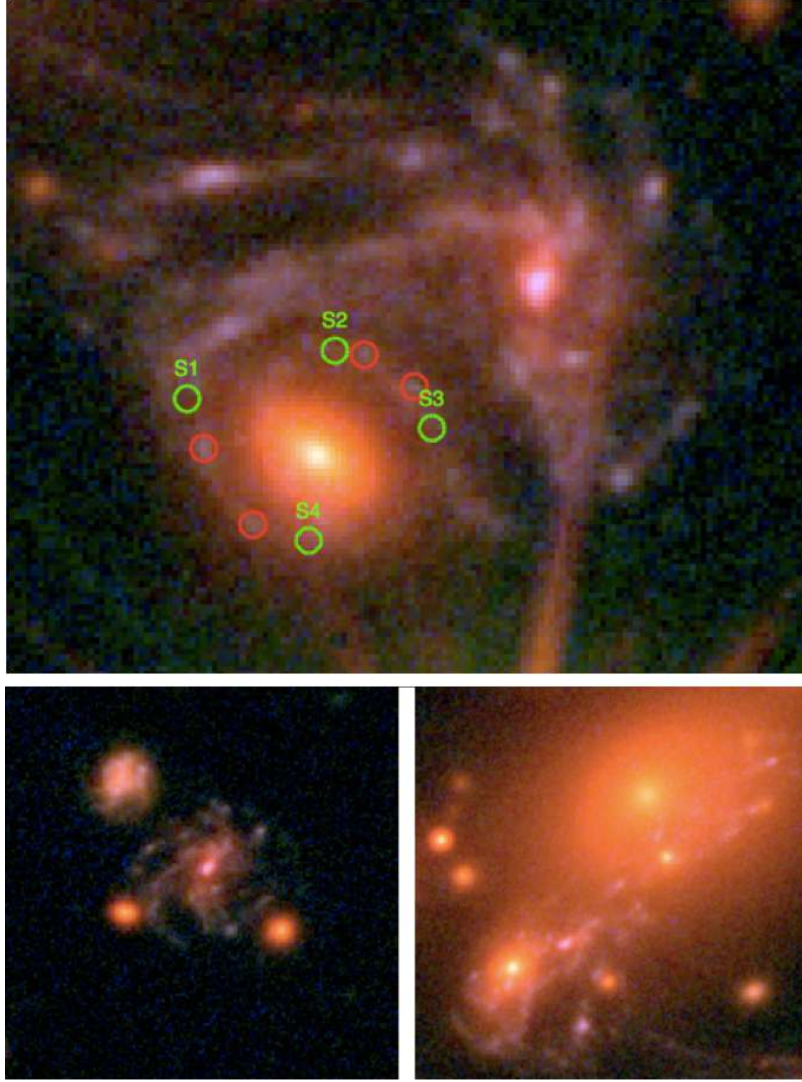


Fig. 3: Color-composite image of lensing elliptical galaxy and distorted background ($z = 1.491$) host spiral (top). The nucleus of the bluer host galaxy is offset by $\sim 3.3''$ from the red lensing elliptical galaxy ($z = 0.544$), suggesting the detected sources are separate from any possible nuclear activity in the host spiral galaxy. The green circles show the locations of images S1–S4, while another quadruply imaged segment of the spiral arm is marked in red (28). The orange line segments at the bottom of the upper panel are diffraction spikes from a nearby star. The spiral galaxy itself is known to be multiply imaged by the cluster (21, 25). The bottom panels show two additional lensed images of the spiral host galaxy visible in the galaxy cluster field.

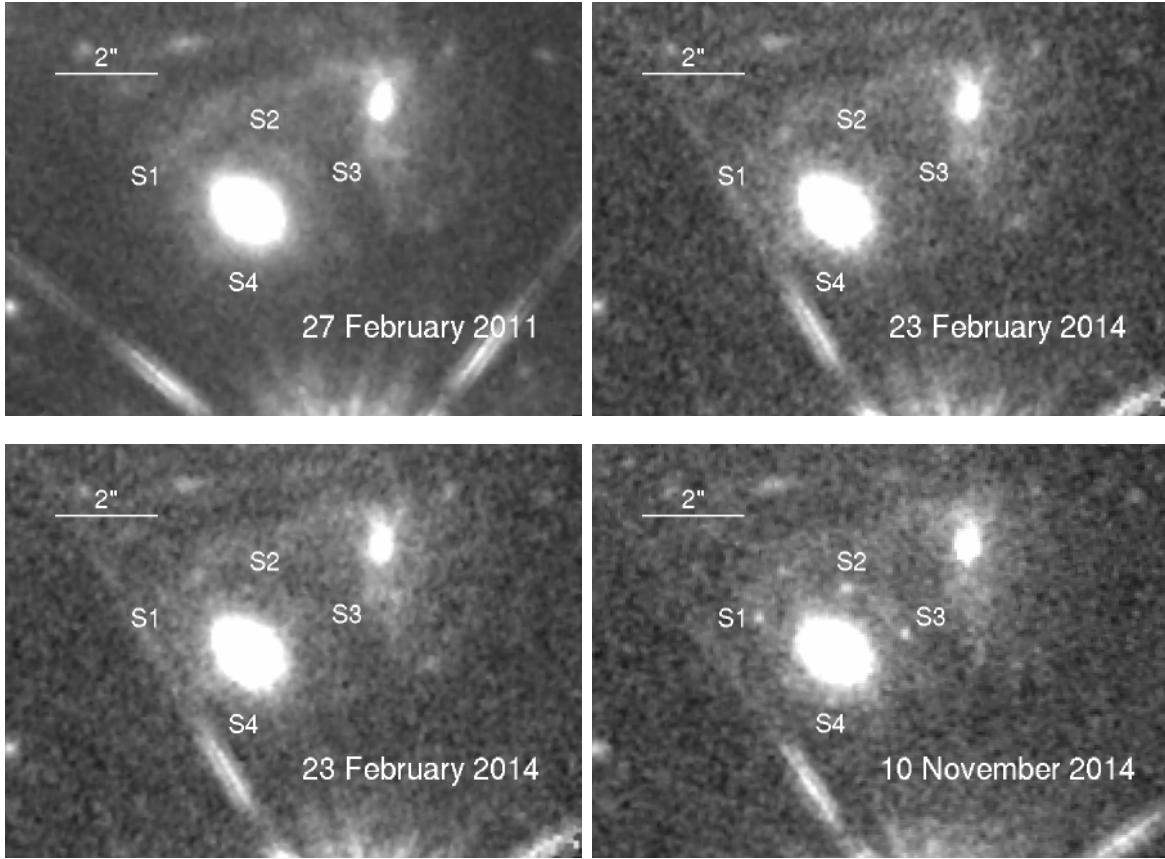


Fig. S1: Images of the lensing system from archival *HST* WFC3-IR observations in the *F140W* filter. All exposures obtained prior to 3 November 2014 show no evidence for variability at any of the positions associated with SN Refsdal.

Supporting Online Material

Previous and Future Appearances of SN Refsdal in Multiple Images of its Host Galaxy Our cluster lens model (27) predicts that SN Refsdal might have appeared some ~ 20 years ago in spiral image labeled 1.1 in Zitrin & Broadhurst (2007; hereafter ZB07). The SN may additionally have appeared a couple of years ago in spiral images ZB07 1.3/1.4 (25, 28), or, alternatively, will appear there in approximately a decade. Our model also suggests that SN Refsdal could have appeared some ~ 40 -50 years ago in spiral image ZB07 1.5 (25), although the SN position is believed not to be present in this multiple image (28). These estimates are highly approximate, because time delays on these cluster scales depend very sensitively on the exact expected position, and a fraction of the images are only partial.

Date	MJD	Filter	Exposure Time (sec)	<i>HST</i> Program ID
2004 Apr 22.7	53117.7	<i>F814W</i>	4590	9722
2006 May 25.5	53880.5	<i>F814W</i>	2184	10493
2010 Dec 04.9	55534.9	<i>F850LP</i>	1032	12068
2010 Dec 05.0	55535.0	<i>F125W</i>	1509	12068
2010 Dec 05.0	55535.0	<i>F160W</i>	1006	12068
2011 Jan 16.0	55577.0	<i>F110W</i>	1509	12068
2011 Jan 16.0	55577.0	<i>F606W</i>	1032	12068
2011 Jan 16.0	55577.0	<i>F850LP</i>	1044	12068
2011 Jan 16.1	55577.1	<i>F160W</i>	1006	12068
2011 Jan 30.6	55591.6	<i>F850LP</i>	1032	12068
2011 Jan 30.7	55591.7	<i>F105W</i>	1509	12068
2011 Jan 30.7	55591.7	<i>F140W</i>	1006	12068
2011 Feb 13.3	55605.3	<i>F625W</i>	1015	12068
2011 Feb 27.0	55619.0	<i>F850LP</i>	1032	12068
2011 Feb 27.1	55619.1	<i>F775W</i>	994	12068
2011 Feb 27.1	55619.1	<i>F160W</i>	1509	12068
2011 Feb 27.1	55619.1	<i>F110W</i>	906	12068
2011 Feb 27.5	55619.5	<i>F606W</i>	1032	12068
2011 Feb 27.6	55619.6	<i>F140W</i>	1306	12068
2011 Feb 27.7	55619.7	<i>F105W</i>	1306	12068
2011 Mar 09.8	55629.8	<i>F160W</i>	1509	12068
2011 Mar 09.8	55629.8	<i>F625W</i>	1032	12068
2011 Mar 09.8	55629.8	<i>F775W</i>	1053	12068
2011 Mar 09.9	55629.9	<i>F125W</i>	1006	12068
2013 Nov 02.1	56598.1	<i>F160W</i>	5508	13504
2014 Feb 23.4	56711.4	<i>F105W</i>	762	13459
2014 Feb 23.7	56711.7	<i>F140W</i>	762	13459
2014 Feb 23.9	56711.9	<i>F105W</i>	406	13459
2014 Feb 25.6	56713.6	<i>F105W</i>	762	13459
2014 Apr 14.7	56761.7	<i>F814W</i>	5246	13504

Table S1: Past epochs of *HST* imaging on the MACS J1149.6+2223 field. In a visual inspection of difference images constructed from these data, no evidence for any transient source in any image of the SN Refsdal host galaxy was found.

Absence of Variability in Prior Imaging. To check for past episodes of variability from this source, we performed a visual search of difference images constructed from archival HST imaging in both the optical ($F435W$, $F606W$, $F814W$, and $F850LP$) and IR ($F105W$, $F125W$, $F140W$, and $F160W$). We found no evidence of any transient sources prior to 3 November 2014 at any of the positions S1-S4 identified with SN Refsdal. There is also no variable source apparent at the locations of any of the multiple images of the presumed host galaxy elsewhere in the cluster field. A subset of the available IR images from previous *HST* observations are shown in Figure S1, and the full list of prior imaging epochs we evaluated in this search is given in Table S1.

Association of the SN with the Strongly Distorted Spiral Galaxy. Figure S2 shows that the broad-band spectral energy distribution (SED) of the Einstein ring that surrounds the four images of the SN matches that of the $z = 1.491$ spiral galaxy, after subtracting contaminating light from the underlying elliptical galaxy lens. The subtraction is accomplished by scaling the SED of the early-type galaxy lens until its $F140W$ flux matches that measured for the Einstein Ring, and removing the scaled SED.

In Figure S3 we show a spectrum from the location of the Einstein Ring, collected with the Keck telescope in Hawaii on 20 November 2014. An emission feature at 9727 \AA is observed from knots in the Einstein Ring that are distinct from the supernova source positions, but spatially associated with the same ring feature. We identify this as [O II] $\lambda\lambda 3727$, giving further confirmation that the ring around the lensing galaxy is at $z = 1.49$, the same redshift as the presumed spiral galaxy host behind the cluster. No emission from SN Refsdal is apparent in this spectrum.

Photometry of Multiple Images of the SN In Table S2, the magnitudes of the sources are shown for the three $F105W$, single $F125W$, and two $F140W$ visits, measured using point spread function fitting photometry.

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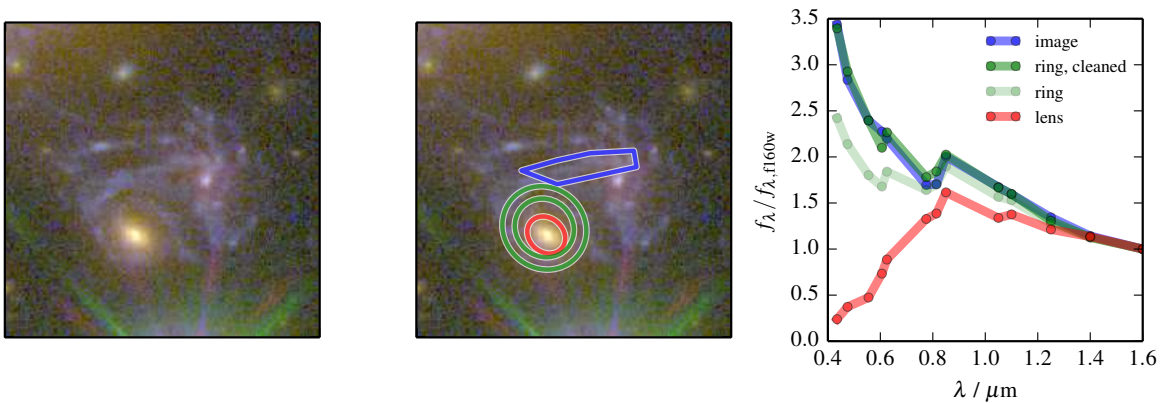


Fig. S2: Spectral energy distributions (SEDs) of the $z = 1.491$ spiral host galaxy, Einstein ring, and elliptical galaxy lens measured from pre-explosion *HST* imaging. After subtracting the underlying light from the red, elliptical galaxy lens, the SED of the Einstein ring matches that of the strongly distorted $z = 1.491$ spiral galaxy. This indicates that the SN, whose images are embedded in the Einstein ring, is spatially coincident with the spiral galaxy. Lens modeling also strongly suggests that the ring is associated with the main lensed galaxy (25). The blue polygon is an aperture enclosing the spiral host galaxy light, the green elliptical annulus aperture encloses the Einstein ring where the multiple SN images appeared, and the red elliptical aperture encloses the lens. All of the SEDs are normalized to the *F160W* flux.

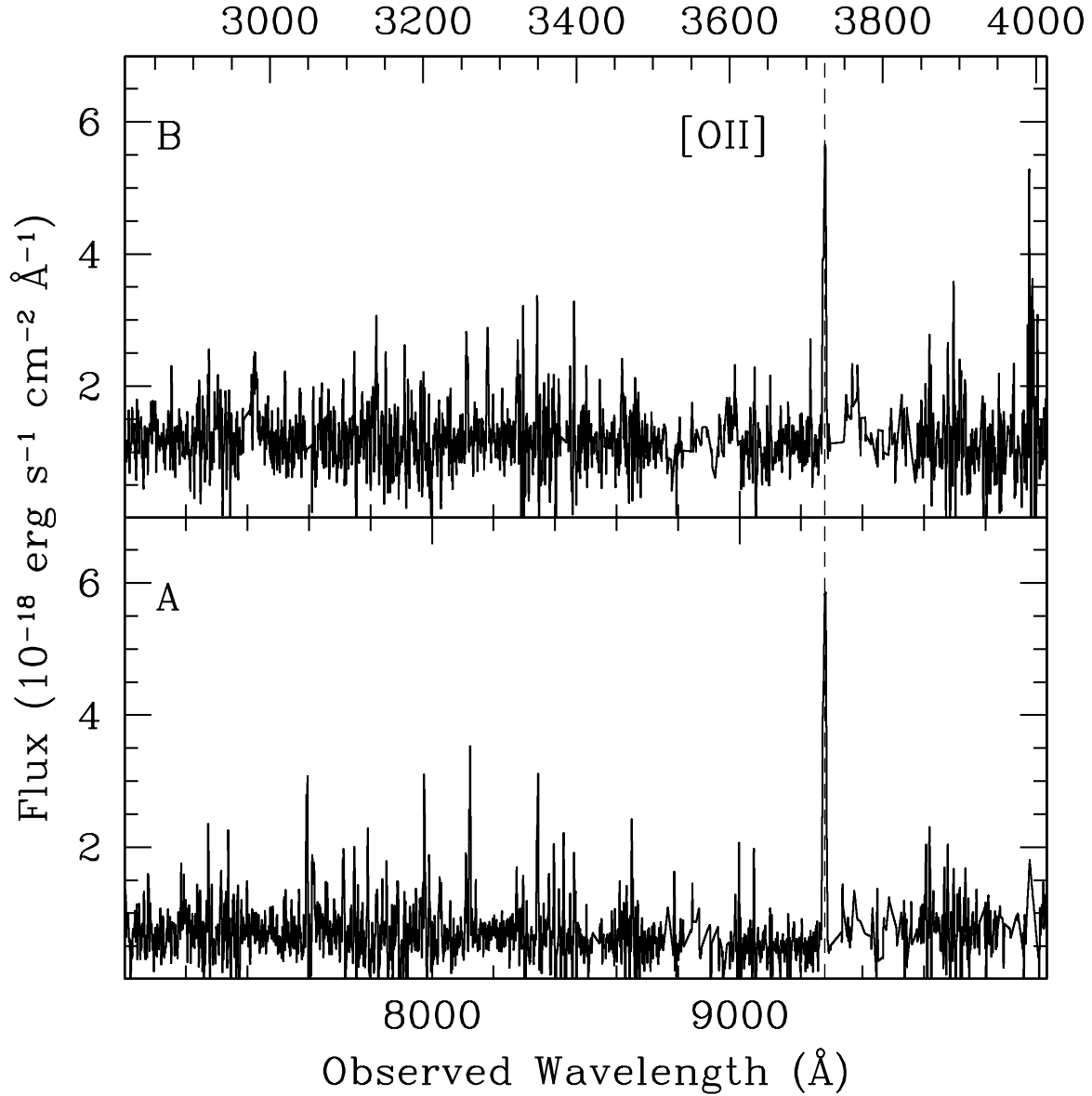


Fig. S3: A spectrum of the SN Refsdal host galaxy, taken with the Keck telescope’s Low Resolution Imaging Spectrometer (LRIS) on 20 November 2014. For these observations the LRIS long slit was aligned along a portion of the Einstein ring, between the positions of sources S1 and S2. The [O II] $\lambda 3727$ emission line is clearly detected at an observer-frame wavelength of 9727 \AA , confirming the redshift of the Einstein Ring at $z=1.49$. The top axis marks the rest-frame wavelength in Angstroms for this redshift solution.

Source	MJD	Filter	Flux (μJy)	Flux Err	AB Mag	Mag Err
S1	F140W	56971.9	0.248	0.034	25.41	0.16
S1	F140W	56981.8	0.257	0.023	25.38	0.14
S1	F125W	56981.0	0.223	0.023	25.53	0.18
S1	F105W	56964.1	0.124	0.034	26.16	0.30
S1	F105W	56968.9	0.176	0.048	25.79	0.28
S1	F105W	56972.1	0.087	0.051	26.46	0.43
S2	F140W	56971.9	0.219	0.034	25.54	0.17
S2	F140W	56981.9	0.217	0.024	25.55	0.12
S2	F125W	56981.0	0.228	0.023	25.50	0.15
S2	F105W	56964.1	0.105	0.030	26.33	0.30
S2	F105W	56968.9	0.102	0.047	26.44	0.40
S2	F105W	56972.1	0.130	0.047	26.03	0.36
S3	F140W	56971.9	0.200	0.038	25.65	0.21
S3	F140W	56981.8	0.289	0.025	25.26	0.12
S3	F125W	56981.0	0.227	0.021	25.51	0.14
S3	F105W	56964.1	0.064	0.040	26.93	0.62
S3	F105W	56968.9	0.156	0.045	25.90	0.32
S3	F105W	56972.1	0.209	0.045	25.67	0.27
S4	F140W	56972.1	0.084	0.035	26.59	0.45
S4	F140W	56981.9	0.053	0.032	27.08	0.66
S4	F125W	56981.1	0.025	0.033	27.90	1.41
S4	F105W	56964.2	-0.045	0.036	26.70	...
S4	F105W	56968.9	0.078	0.043	26.66	0.59
S4	F105W	56972.1	0.009	0.042	29.01	5.10

Table S2: *HST* WFC3-IR photometry. The observed fluxes were measured with point spread function fitting on difference images using template images constructed from all WFC3-IR images collected prior to November 2014. In cases where the source is not detected and noise from the sky results in a measurement of negative flux, we report the magnitude as a $3\text{-}\sigma$ upper limit.