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DÉJÀ VU ALL OVER AGAIN: THE REAPPEARANCE OF SUPERNOVA REFSDAL

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ABSTRACT

In *Hubble Space Telescope (HST)* imaging taken on 10 November 2014, four images of supernova (SN) 'Refsdal' ($z = 1.49$) appeared in an Einstein-cross–like configuration (images S1–S4) around an early-type galaxy in the cluster MACS J1149.5+2223 ($z = 0.54$). The gravitational potential of the cluster creates three full images of the star-forming host galaxy of the SN. Almost all lens models of the cluster have predicted that the SN should reappear within approximately one year in a second host-galaxy image, offset by $\sim 8''$ from the previous images. In *HST* observations taken on 11 December 2015, we find a new source that we interpret as a new image of SN Refsdal. This marks the first time the appearance of a SN at a particular time and location in the sky was successfully predicted in advance! We use these data and the light curve from the first four observed images of SN Refsdal to place constraints on the relative time delay and magnification of the new image (SX), compared to images S1–S4. This enables us, for the first time, to test lens model predictions of both magnifications and time delays for a lensed SN. We find that the timing and brightness of the new image are consistent with the blind predictions of a fraction of the models. The reappearance illustrates the discriminatory power of this blind test and its utility to uncover sources of systematic uncertainty in the lens models. From planned *HST* photometry, we expect to reach a precision of 1–2% on the relative time delay between S1–S4 and SX.

Subject headings: gravitational lensing: strong, supernovae: general, individual: SN Refsdal, galaxies: clusters: general, individual: MACS J1149.5+2223

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1. INTRODUCTION

Background sources strongly lensed by galaxies and galaxy clusters that show flux variations in time can be used as powerful probes, because they make it possible to measure the relative time delays between their multiple images. As Refsdal (1964) first suggested, time delays are useful, because they depend sensitively on both the cosmic expansion rate as well as the gravitational potential of the lens. While the positions of the images of lensed galaxies depend on the derivative of the potential, time delays are directly proportional to differences in the potential.

Refsdal (1964) examined the utility of time-delay measurements from a multiply imaged supernova, but a strongly lensed SN with multiple resolved images was not found in the following five decades. Several SN with significant lensing magnifications have been observed behind galaxy clusters (Goobar et al. 2009; Patel et al. 2014a; Nordin et al. 2014; Rodney et al. 2015), though none has been close enough to the cluster core to be multiply imaged. In a similar case with a galaxy-scale lens, Chornock et al. (2013) discovered a bright H-poor SN at redshift $z = 1.38$, which was later shown to be a strongly lensed SN (Quimby et al. 2013, 2014), but multiple images could not be identified.

Although strongly lensed SN have eluded detection for 50 years, the discovery of multiply imaged quasars beginning in the 1970's (Walsh et al. 1979) has made it possible to measure time delays for more than twenty systems (see, e.g., Kundic et al. 1997; Fassnacht et al. 1999; Tewes et al. 2013). For a subset of multiply imaged quasars with simple, early-type galaxy lenses, it has been possible to precisely predict the delay arising from the potential and thereby to measure an absolute distance scale and H_0 geometrically (e.g., Paraficz & Hjorth 2010; Suyu et al. 2013, 2014). Although they are more difficult to find, strongly lensed SN hold great promise as tools for time delay cosmography (Kolatt & Bartelmann 1998; Holz 2001; Bolton & Burles 2003; Oguri & Kawano 2003). Relative to quasars, a SN light curve is comparatively simple, and, for SN Ia (Phillips 1993) and some SN IIP (e.g., Kirshner & Kwan 1974), the peak luminosity can be calibrated absolutely, thus providing a measurement of lensing magnification.

Kelly et al. (2015) reported the discovery of SN Refsdal, the first strongly lensed SN resolved into multiple images, in the MACS J1149.5+2223 (Ebeling et al. 2001, 2007) galaxy cluster field on 11 November 2014 in *Hubble Space Telescope (HST)* images collected as part of the Grism Lens-Amplified Survey from Space (GLASS; PI: Treu; GO-13459; Schmidt et al. 2014; Treu et al. 2015b). Those exposures revealed four resolved images of the background SN, arranged in an Einstein cross configuration around an elliptical cluster member. Models of the complex potential of the galaxy cluster and early-type galaxy lens suggest that three of the four images are magnified by up to a factor of ∼10–20 (Kelly et al. 2015; Oguri 2015; Sharon & Johnson 2015; Diego et al. 2015; Grillo et al. 2015; Jauzac et al. 2015; Kawamata et al. 2015; Treu et al. 2015a).

In addition to the Einstein-Cross–like configuration caused primarily by the galaxy-scale lens, SN Refsdal is also being strongly lensed by the gravitational potential of the MACS J1149.5+2223 cluster. This larger lens produces multiple images of the SN Refsdal host galaxy (Smith et al. 2009; Zitrin & Broadhurst 2009). Lens models produced soon after the SN discovery consistently predicted that a fifth image of SN Refsdal should appear within several years in another image of the host, approximately 8″ from images S1–S4 (Kelly et al. 2015; Oguri 2015; Sharon & Johnson 2015; Diego et al. 2015). We adopt the identifier 'SX' for this new image, following Oguri (2015). In these models, the galaxy-cluster gravitational potential is constrained by varying combinations of strong-lensing constraints, including the positions and redshifts of multiply imaged background galaxies, the positions of the SN Refsdal images S1–S4, and locations of bright clumps within SN Refsdal's host galaxy. The potential (or surface mass density) is also parameterized in a variety of ways, often using the positions or light distributions of cluster galaxies as constraints.

Given the complexity of the cluster potential, it is unlikely that measurement of time delays between the SN Refsdal images can be used for precision cosmology, as suggested by Refsdal (1964). However, if one adopts a fixed set of cosmological parameters, then time delays and magnification ratios can be used to measure the difference in the potential and its derivatives between the positions of multiple images, thus providing a powerful local test of lens models.

To sharpen this test, several lens modeling teams have refined their predictions for the relative time delay and magnification of image SX. Treu et al. (2015a) identified an improved set of multiply imaged galaxies using additional data collected after the discovery of the SN. Systems were discovered or confirmed from *HST* WFC3 G102 and G141 grism spectra (PI: Treu), thirty orbits of G141 grism spectra taken to determine the spectroscopic type of the SN (PI: Kelly; GO-14041; Kelly et al., in prep.; Brammer et al., in prep.), deep VLT-MUSE observations (PI: Grillo; Grillo et al. 2015, submitted), Keck/DEIMOS observations (PI: Jha), as well as Frontier Fields observations of the MACS J1149.5+2223 field that began shortly after discovery (PI: Lotz; GO-13504). The spectroscopic data provided 429 spectroscopic redshifts in the field of MACSJ1149.5+2223, including 170 spectroscopic cluster members and 23 multiple images of 10 different galaxies. With the improved dataset, Treu et al. (2015a) organized 5 independent lens modeling teams which produced 7 separate predictions for the time delays. In a parallel effort, Jauzac et al. (2015) used new Gemini GMOS and part of the VLT-MUSE data (PI: Grillo), as well as Frontier Fields photometry to generate improved constraints on the cluser potential and new predictions for the time delay and magnification of image SX.

These revised models consistently favor delays of less than one year, except for the model by Jauzac et al. (2015). Image SX is also predicted to be significantly fainter than images S1–S3, by a factor of 3-4. Together these predictions indicated that image SX could plausibly have been detected as soon as *HST* could observe the MACS J1149.5+2223 field beginning on October 30 2015. From late July through late October, it had been too close to the Sun to be observed. Importantly, all of these modeling efforts were completed before the first realistic opportunity to detect image SX on October 30

2015, making these truly *blind* predictions.

Here we present a direct test of these lens model predictions, as we revisit the MACS J1149.5+2223 field and identify the appearance of the anticipated fifth image of SN Refsdal. In this work, Section 2 presents the data processing and photometry on the new *HST* images. In Section 3 we derive joint constraints on the relative time delay and magnification and compare these to the published predictions from the lens modeling community. We briefly discuss our results in Section 4 and conclude in Section 5. Throughout this paper, magnitudes are given in the AB system (Oke & Gunn 1983), and a concordance cosmology is assumed when necessary ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, H_0= 70 km s^{-1} Mpc^{-1}).

2. METHODS

We processed the WFC3 imaging data using a pipeline constructed from the `DrizzlePac` software tools.[26] The images were resampled to a pixel scale of 0.06″/pixel using `AstroDrizzle` (Fruchter, A. S., et al. 2010) and registered to a common astrometric frame using `TweakReg`. Template images in each band were constructed by combining all available WFC3 IR imaging collected prior to 30 Oct, 2015, comprising observations from the GLASS program, the Cluster Lensing And Supernova survey with Hubble (CLASH, GO-12068; PI:M. Postman, Postman et al. 2012), the Hubble Frontier Fields (HFF, DD/GO-13504; PI: J. Lotz), the FrontierSN program (GO-13790; PI: S. Rodney), and the SN Refsdal Follow-up program (DD/GO-14041; PI: P. Kelly). We generated difference images by subtracting these template images directly from the search epoch images, without applying any smoothing algorithm (Alard & Lupton 1998), owing to the excellent stability of the *HST* point spread function (PSF).

To measure the SN flux from the difference images, we used the `PythonPhot`,[27] software package (Jones et al. 2015) which employs a PSF-fitting photometry procedure based on the `DAOPHOT` algorithm (Stetson 1987). We measure photometric uncertainties by planting and recovering 1000 fake stars (copies of the model PSF) in the vicinity of the SN position.

3. RESULTS

In Figure 1, we present the *F125W* and *F160W* images taken on 11 December 2015 that show a new image of SN Refsdal in its redshift $z = 1.49$ host galaxy. The location of this image SX in J2000 coordinates is R.A., Decl. = 11:49:36.02, +22:23:48.1.[28] This locates SX at 6.2″ North and 3.9″ East of image S1. Table 1 reports the measured fluxes and uncertainties. The upper limits are measured from the recovery of fake stars. We measure an *F125W* - *F160W* color of 0.2±0.3 for image SX, which is consistent with that reported for of S1–S4 at discovery.

Figure 2 shows simultaneous constraints on the time delay and magnification ratio between image S1 discovered in 2014, and the newly discovered image SX, and comparisons with model predictions from several teams reported by Treu et al. (2015a), and independent predictions by Jauzac et al. (2015). In Figure 3, we show a comparison between the coordinates of the new image SX and several published model predictions, which shows a good agreement.

Table 1
PHOTOMETRY OF IMAGE SX

Obs. Date (MJD)	Filter	Exp. Time (s)	Magnitude (AB)
57325.8	F125W	1259	27.4 ± 0.4
57340.9	F125W	1259	27.3 ± 0.4
57367.1	F125W	1259	26.56 ± 0.16
57325.9	F160W	1159	27.4 ± 0.6
57341.0	F160W	1159	26.29 ± 0.15
57367.1	F160W	1159	26.24 ± 0.16

4. DISCUSSION

Lensed SN provide a powerful means to test the accuracy of the lens models of the foreground deflector, or to provide additional input constraints (e.g. Riehm et al. 2011). Previous tests have been based on SN that are magnified but not multiply imaged (Patel et al. 2014b; Nordin et al. 2014). Recently, Rodney et al. (2015) discovered a Type Ia SN magnified by a factor of ∼2× by a galaxy-cluster potential, and found that its calibrated luminosity was in tension with some – but not all – models of the cluster potential.

With SN Refsdal we have for the first time been able to test predictions for both the lensing time delay as well as the magnification. This is important because the time delay depends on the difference in gravitational potential, while magnification depends on a combination of second derivatives, and therefore the two observables test different aspects of the potential. In principle, time delays are much less sensitive than magnification ratios to milli and microlensing and should therefore be more robustly predicted.

It is important to keep in mind that all of these tests are local, and thus a larger sample is needed to assess the global goodness-of-fit of every model. Nevertheless, these tests are an extremely valuable probe of systematics. In fact, as discussed by Treu et al. (2015a), the uncertainties reported by modelers do not include all sources of systematic errors. For example, systematic uncertainties arising from unmodeled milli-lensing, residual mass-sheet degeneracy, and multiplane lensing, are very difficult to calculate and are thus not included. The lensed-supernova tests provide estimates of the amplitude of the unknown uncertainties. Other known sources of errors are not included either. For example, a 3% uncertainty on the Hubble constant (Riess et al. 2011) implies a 3% uncertainty on time delays, i.e. approximately 10 days for a year-long delay. Furthermore the uncertainties are typically highly non-Gaussian so that the 95% confidence interval is not simply twice as wide as the 68% one.

5. CONCLUSIONS

We have detected the reappearance of SN Refsdal in a different multiple image of its host galaxy from the one where the event was originally discovered in 2014. Keeping in mind the caveats given in the previous section, we can reach two major conclusions. First, SN Refsdal

[26] `http://drizzlepac.stsci.edu`
[27] `https://github.com/djones1040/PythonPhot`
[28] The coordinates are registered to the astrometric system used for the CLASH, GLASS, and HFF images and catalogs `http://www.stsci.edu/hst/campaigns/frontier-fields/`

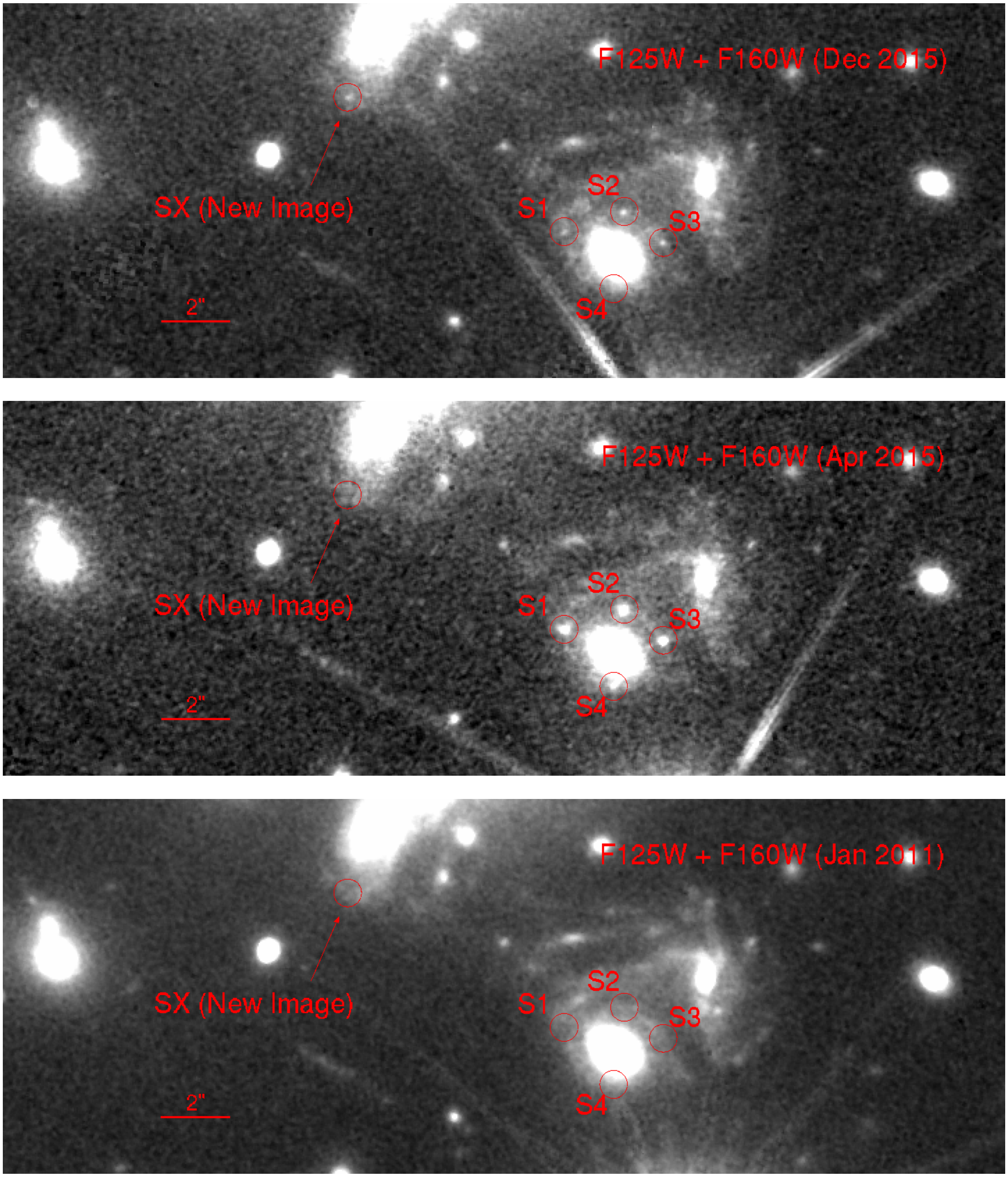

Figure 1. Coadded WFC3-IR *F125W* and *F160W* exposures of the MACS J1149.5+2223 galaxy-cluster field taken with *HST*. Top panel shows images taken on 11 December 2015 which reveal the new image SX of SN Refsdal. The middle panel shows images taken on 20 April 2015 where the four images forming the Einstein cross are close to maximum brightness, but no flux is evident at the position of SX. Bottom panel shows images acquired in 2011 without images of the SN.

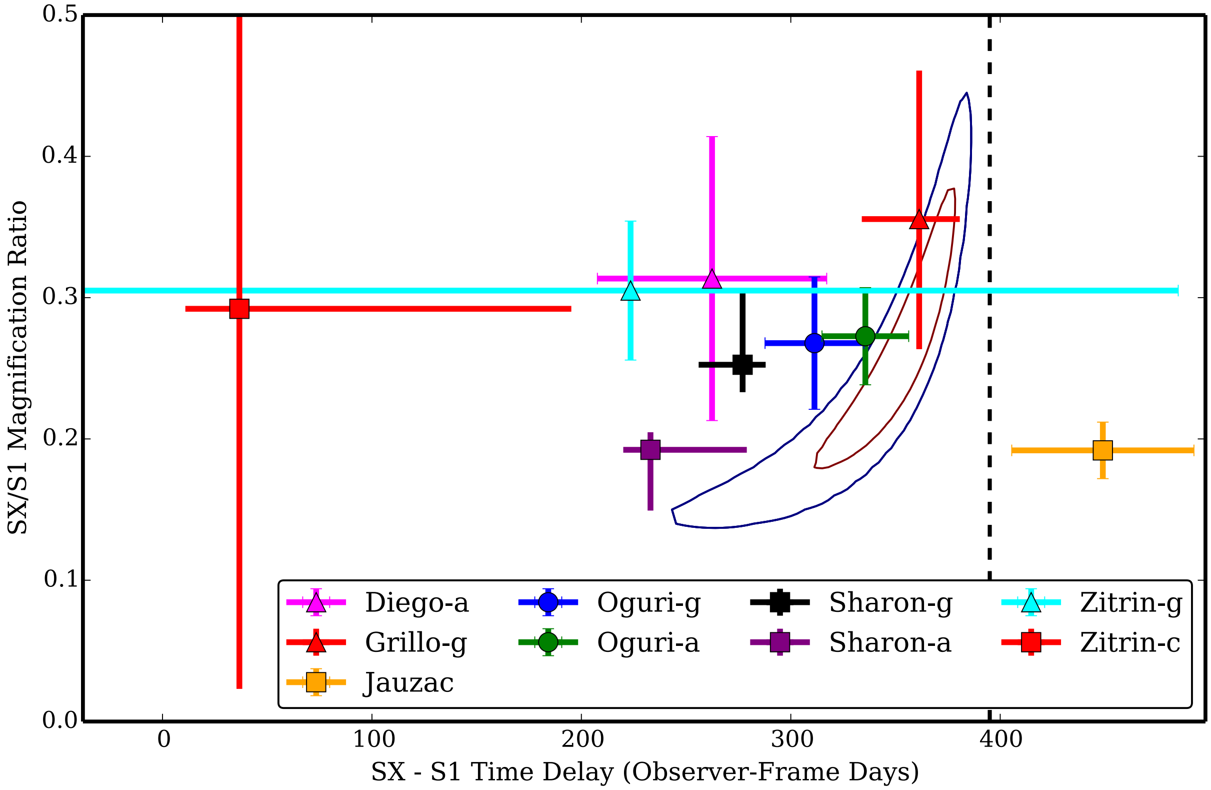

Figure 2. Simultaneous constraints on the relative time delay between S1 and SX from the measured magnitude of SX. The two-dimensional contours show the 68% and 95% confidence levels, while the model predictions plot 68% confidence levels. The *F160W* (approximately rest-frame *R*) light curve of SN Refsdal is reasonably well-matched by that of a slowly evolving SN similar to 1987A (Kelly et al., in prep.). We use separate second-order polynomial fits to the *F125W* and *F160W* light curves of image S1 of SN Refsdal as models for the light curves of SX to compute joint constraints on the time delay and the magnification ratio between S1 and SX, for comparison with model predictions. Except for the Jauzac et al. (2015) prediction, labels refer to models presented in Treu et al. (2015a). While all other plotted predictions were made in advance of the *HST* Cycle 23 observations in Fall 2015, 'Zitrin-c' is a post-blind prediction that supercedes the 'Zitrin-g' model; in this model the lens galaxy was left to be freely wighted to reassure is critical curves pass between the four Einstein-cross images. We note that many of the lensing predictions are not Gaussian distributed, and 68% limits do not imply that are necessarily inconsistent with the measurements. The greater the S1-SX delay, the earlier we currently are in the light curve of SX. The black dashed line marks the delay beyond which we lack data on the light curve of SN Refsdal. Our model for the light curve at earlier epochs is an extension of the second-order polynomial.

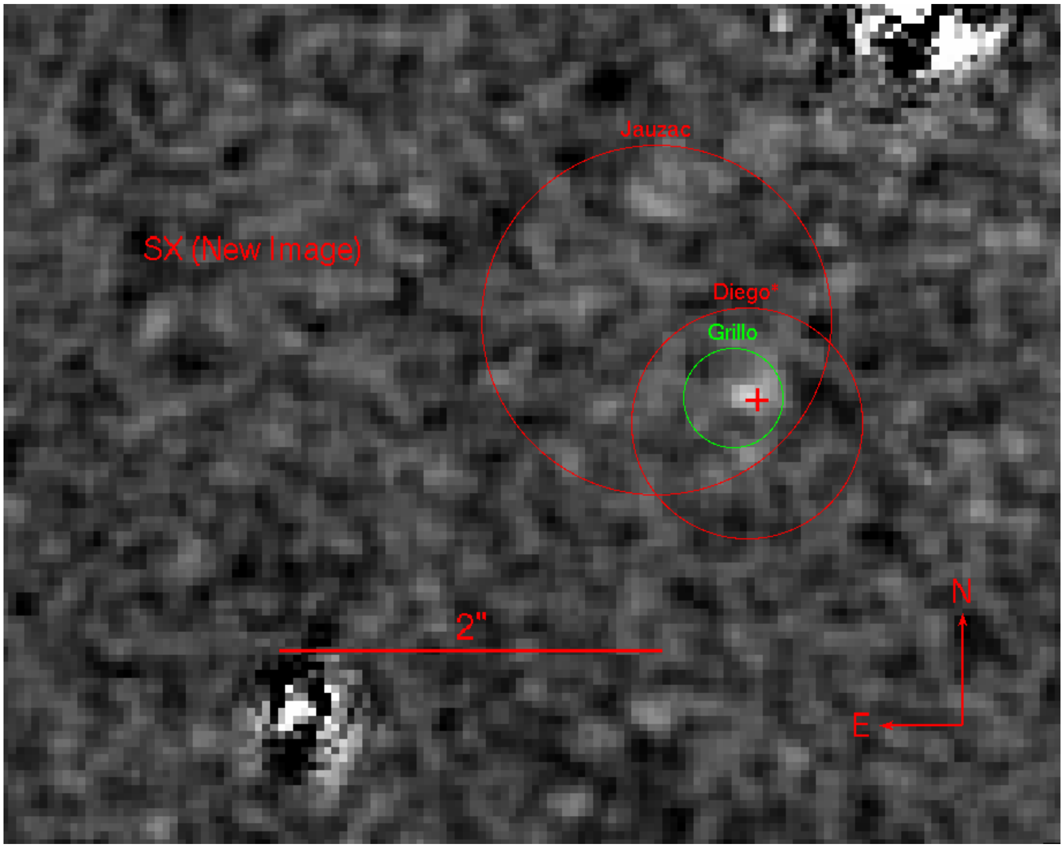

Figure 3. Comparison between the position of image SX and published predictions. Coordinates are overplotted on the combined *F125W* and *F160W* difference image from the 11 December 2015 and template imaging acquired in 2011. The Jauzac et al. (2015) and Grillo et al. (2015) positions both agree within the rms scatter reported between input and best-fit positions in each paper. An uncertainty was not available for the Diego et al. (2015) prediction and we show an annulus with a $0.6''$ radius.

indeed reappeared approximately as predicted, implying that the unknown systematic uncertainties are not substantially larger than the random uncertainties, at least for some models. This is a remarkable and powerful validation of the model predictions specifically and of general relativity indirectly. The second conclusion is that already this first detection provides some discriminatory power: not all models fare equally well. Grillo-g, Oguri-g, Oguri-a, and Sharon-a appear to be the ones that match the observations most closely. In general most models seem to predict a slightly higher magnification ratio than observed, or shorter delays. A detailed statistical analysis of the agreement between the model predictions and the observations will have to wait for the actual measurement of the magnification and time delays, which will require analysis of the full light curve past its peak during 2016.

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