A Free-Form Prediction for the Reappearance of Supernova Refsdal in the Hubble Frontier Fields Cluster MACSJ1149.5+2223.

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ABSTRACT

The massive cluster MACSJ1149.5+2223\(z=0.544\) displays five very large lensed images of a well resolved spiral galaxy at \(z_{\text{spect}}=1.491\). It is within one of these images that the first example of a multiply-lensed supernova has been detected recently in deep Hubble Frontier Field imaging. The depth of this data also reveals many HII regions within the lensed spiral galaxy which we identify between the five counter-images. Here we expand the capability of our free-form method to incorporate these HII regions locally, with other reliable lensed galaxies added for a global solution. This improved accuracy allows us to estimate when the Refsdal supernova will appear within the other lensed images of the spiral galaxy to an accuracy of \(\sim 7\%\). We predict the reappearance of this supernova in one of the counter-images (RA=11:49:36.025, DEC=+22:23:48.11, J2000) on November 1\(^{st}\) 2015 (\(\pm 25\) days), offering a unique opportunity to study the early phases of this supernova and to examine the consistency of the mass model and the cosmological model that have an impact on the time delay prediction.

Key words: galaxies:clusters:general; galaxies:clusters:MACSJ1149.5+2223; dark matter

1 INTRODUCTION

The unprecedented data quality of Hubble Frontier Fields (HFF) program requires a higher standard of strong lensing analysis. The HFF images contain many tens of multiply lensed images that are not easily recognised, but require the guidance of a reliable model. This is because of the complexity of the cluster chosen for the HFF in order to maximise lensing. During a major merger the critical curves can be "stretched" between the mass components enhancing the critical area with elongated critical curves (Zitrin et al. 2013). This effect results in a relatively large sky area subjected to very large magnification and hence to the detection of unusually bright lensed galaxies. Galaxies as distant as \(z\approx 10\) have been identified through the HFF program (Zitrin et al. 2014, Zheng et al. 2014, Oesch et al. 2014, Coe, Bradley & Zitrin 2015, Ishigaki et al. 2015) with the potential to reach \(z\approx 12\) given the spectral coverage of the HFF data.

The HFF program may in fact be probing already the edge of the observable universe at near-IR wavelength as so far there as yet no examples of galaxies beyond \(z\approx 10\) in the HFF data. This lack of higher redshift galaxies may be supported by the recently updated value for the mean redshift of reionization calculated from the inferred value of the optical depth, \(\tau\) obtained by the Planck mission data for which a surpassingly low redshift to be \(z\approx 8.8\) (for instantaneous or mean redshift of reionization) has been estimated, Planck Collaboration et al. (2015). This has implications for the assumptions regarding the spectral index of the ionising
radiation, and the extrapolation of the galaxy UV luminosity function to undetected luminosities together with the escape fraction of ionising radiation from high-z galaxies. Despite these considerable uncertainties, consistency has been claimed between the recent low value of \( \tau \) from Plank and the sketchy first measurements of the UV selected luminosity density of z>9 galaxies (Robertson et al. 2015; Bouwens et al. 2015). The initially claimed "steep decline" in the integrated UV luminosity density of galaxies at z>9 would seem to empirically support this z~9 epoch as marking the beginning of galaxy formation (Oesch et al. 2012, 2014) and interestingly this is not obviously reconciled with the many predictions made for \( \Lambda \)CDM with ever smaller galaxies naturally expected to higher redshift, in a scale free way, limited only by the relatively large Jeans scale for metal free star formation (McKee & Ostriker 2007; Barkana 2006). A lower redshift of galaxy formation is anticipated for CDM in the form of light bosons limited by a Jeans scale for the Dark Matter generated by quantum pressure of bosons in the ground state (Peebles 2000; Hu, Barkana & Gruzinov 2000). The first simulations of this form of CDM normalised to fit local galaxy DM cores predict the first galaxies at z\approx 12 in a 30Mpc volume (Schive, Chiu & Broadhurst 2014) and hence this interpretation of CDM is more viable than heavy fermionic WIMPs that are increasingly undetected in the laboratory. The HFF may provide considerably more clarity in deciding between these two very different interpretations of CDM by providing sufficient z>9 galaxies with lower luminosities than field surveys, by virtue of the high levels of lens magnification.

Another important reason to study the HFF clusters is for the constraints that may be derived from the level of any self-interaction within the dark matter, as those clusters are caught in the act of collision. Although relaxed clusters seem to agree well with predictions from \( \Lambda \)CDM models (Newman et al. 2013), recent results on non-relaxed clusters show interesting deviations in the density profiles in the central regions when compared to predictions from standard \( \Lambda \)CDM. In particular, shallow profiles have been identified by several authors in HFF clusters and more in agreement with self-interacting dark matter expected for purely collisionless dark matter (Diego et al. 2014; Lam et al. 2014; Diego et al. 2015). Other possible, and less exotic, interpretations may be related to projection effects, overlapping of cluster cores and uncertainties in the reconstruction of the central regions. More data and better hydrodynamical modelling of the HFF clusters may help resolve these questions. It is imperative therefore that free-form modelling of these lenses is achieved to reliably establish the density of background sources detected as a function of redshift.

In this paper we explore the remarkable MACSJ1149(z=0.544) for which 5 very large well resolved images of a spiral galaxy were recognised as multiple images (Zitrin & Broadhurst 2009; Smith et al. 2009) and subsequently explored more thoroughly with the CLASH program (Rau, Vegetti & White 2014; Zitrin et al. 2015). These models demonstrate that the magnification is large over the full critical area of this cluster because of the flatness of the central density profile which lies close to the critical value for lensing in the central strong lensing region and is hence optimal for creating high magnification. Indeed a very high redshift galaxy has been identified by the CLASH team (Zheng et al. 2012) at z=9.6, which has a high magnification. The power of this lens has led to its selection for the HFF program in the search for more higher redshift lensed galaxies. The depth of the HFF data allows now many internal HII regions within 5 spiral galaxy images to be identified and matched between the counter images. Moreover, the distribution of the multiple counterimages map the central region in a semi-continuous fashion from distances \( R = 13.12' \) (or \( R = 84.62 \) kpc) to only \( R = 1.26' \) (or \( R = 8.12 \) kpc) from the centre of the dominant BCG. In addition, a supernova is observed multiply lensed 4 times around a cluster member galaxy (Kelly et al. 2015). This supernova is observed in only one of the counterimages to date. The corresponding supernova event in the other counter images has either occurred in the past of will happen in the future. Time delays between the different counterimages have been computed by different authors but with estimates varying in general by several years between the different authors (Oguri 2015; Sharon & Johnson 2015; Kelly et al. 2015). The time delay between the counterimages depend on the lens model, position of the background source and cosmology (in particular the Hubble constant). Having an accurate time delay for this supernova will be useful to plan an observing campaign of the future supernova. This will offer the rare opportunity to study the supernova from the very early phases and provides a test of competing lensing models and a consistency check of cosmological models.

Here we implement an enhancement to our free-form method, WSLAP+ (Diego et al. 2005a; 2007; Sendra et al. 2014), which is largely motivated by the uniqueness of the particularly large lensed images generated by MACSJ1149+2223 (z = 0.544) and we calculate the corresponding time delays for the Supernova event. The paper is organized as follows. We describe the Hubble data in section 2. The X-ray data is described in section 3. The lensing data is described in section 4. In section 5 we give a brief

**Figure 1.** MACS1149 as seen by HST with *Chandra* contours overlaid on top. The field of view is 1.6'.
description of the reconstruction method with the new improvements that are applied to the data for the first time in this work. Section 5.2 describes six different scenarios that are assumed to reconstruct the lens and to study the uncertainties and variability in the solutions. Section 6 presents the results of the lensing analysis, focusing on the reproducibility of system 1, the 2-dimensional mass distribution, the projected mass profile and the time delays for the Refsdal SN. We conclude in section 7.

Throughout the paper we assume a cosmological model with $\Omega_M = 0.3$, $\Lambda = 0.7$, $h = 70$ km/s/Mpc. For this model, 1" equals 6.45 kpc at the distance of the cluster.

2 HFF DATA

In this paper we use public imaging data obtained from the ACS (filters: F435W, F606W and F814W) and the WFC3 (F105W, F125W, F140W and F160W), retrieved from the Mikulski Archive for Space Telescope (MAST). The data used in this paper consists of $\approx 1/3$ of the data to be collected. Part of the data comes from CLASH (Postman et al. 2012). This release includes the first 70 orbits of observations of MACS1149 from the Frontier Fields program ID 13504 (P.I. J. Lotz) but also including archival ACS and WFC3/IR data from programs 13790 (P.I. S. Rodney), and 14041 (P.I. P. Kelly). In the IR bands we use the background corrected images, corrected for a time-dependent increase in the background sky level (see for instance Koekemoer et al. (2013)). From the original files, we produce two sets of color images combining the optical and IR bands. The first set is based on the raw data while in the second set we apply a low-pass filter to reduce the diffuse emission from member galaxies and a high-pass filter to increase the signal-to-noise ratio of small compact faint objects. The second set is particularly useful to match colors in objects that lie behind a luminous member galaxy.

3 X-RAY DATA

To explore the dynamical state of this cluster, we produce an X-ray image using recent public Chandra data on this cluster. In particular we use data with the following Obs IDs, 1656, 3589, 16238, 16239, 17595, 17596, 16306, 16582 (P.Is Vaspeybroeck, Jones, Murray) totallying 363.4 ks. The X-ray data is smoothed using the code ASMOOTH (Ebeling, White & Rangarajan 2006). The smoothed X-ray map is compared with the distribution of galaxies in figure 1.

A significant offset is observed between the peak of the X-ray emission and the BCG indicating that this cluster shows the effect of collision. The X-ray emission is elongated in the diagonal direction and, as discussed later, the same elongation is found in the distribution of matter although the peak of the mass distribution is also found to be offset with respect to the peak of the X-rays and more in agreement with the position of the BCG.

4 LENSSING DATA

For the lensing data we add the previous multiple-image system identifications from CLASH data (Zitrin et al. 2015). In particular, we use the reliable systems 1,2,3,4,5,6 and 8. For systems 5 and 6 we use only two of the counterimages as the remaining third counterimage is not regarded as reliable (various candidates are consistent with being the counterpart of the third images, 5.3 and 6.3). Further HFF data will soon help clarify these and uncover other systems. Systems 1,2, and 3 have spectroscopic redshifts. The redshift of systems 4,5,6 and 8 are matched to the redshift preferred by the lens models (see below) which constrain the position of the critical curve. We should note that the redshifts for systems 4,5,6 and 8 may differ from estimates used by other authors. This may result in small differences in the mass model. In particular, for systems 1,2,3,4,5,6 and 8 we adopt the following redshifts; 1.491, 1.894, 2.497, 2.5, 1.9, 1.9, and 2.5 respectively. The systems are shown in Fig. 2. For comparison purposes we also show the critical curve for one of our models for a source at redshift $z = 3$.

In addition to the position of these lensed systems, for some of them we use the position of knots readily identified in the different counterimages thanks to the depth of the data (see Fig. 3). The large image 1.1 (in the notation of Zitrin & Broadhurst (2009)) is the largest, most magnified image of system 1 (and displays the 4 SN images) with many internal features that we label in Figure 3. Lensed systems 3 and 8 are also morphologically resolved allowing us to identify a few individual knots and these are also included in our new reconstruction algorithm. In order to take full advantage of the resolved geometry of system 1 (and to a lesser extent of systems 3 and 8), we introduce two enhancements to our code that are described in the next section.

Figure 2. MACS1149 with a typical critical curve ($z = 3$) for one of our models (case 5, see text). The images used in the reconstruction are marked with yellow IDs. The field of view is 1.6'.
Figure 3. Knots for system 1 used to do the mass reconstruction. Only two of the counterimages of system 1 are represented here.

Figure 4. Example of a multiresolution grid (352 grid points). The peaks of the individual Gaussians are located at the positions of the crosses. The width of the Gaussians are adjusted to guarantee a smooth constant distribution when the amplitudes are equal. This distribution is suited to the increasing strong lensing data density towards the center.

5 LENSING RECONSTRUCTION AND IMPROVEMENTS TO THE CODE

We use the method, WSLAP+, that we have been developing to perform the lensing mass reconstruction with the lensed systems and internal features described above. The reader can find the details of the method in our previous papers (Diego et al. 2005a, 2007; Sendra et al. 2014). Here we give a brief summary of the most essential elements.

Given the standard lens equation,

\[
\beta = \theta - \alpha(\theta, \Sigma),
\]

where \( \theta \) is the observed position of the source, \( \alpha \) is the deflection angle, \( \Sigma(\theta) \) is the surface mass density of the cluster at the position \( \theta \), and \( \beta \) is the position of the background source. Both the strong lensing and weak lensing observables can be expressed in terms of derivatives of the lensing potential.

\[
\psi(\theta) = \frac{4GD_lD_s}{c^2D_{ls}} \int \, d^2\theta' \Sigma(\theta') \ln(|\theta - \theta'|),
\]

where \( D_l, D_s, \) and \( D_{ls} \) are the angular diameter distances to the lens, to the source and from the lens to the source, respectively. The unknowns of the lensing problem are in general the surface mass density and the positions of the background sources in the source plane. As shown in Diego et al. (2005a, 2007), the strong and weak lensing problem can be expressed as a system of linear equations that can be represented in a compact form,

\[
\Theta = \Gamma X,
\]

where the measured strong lensing observables (and weak lensing if available) are contained in the array \( \Theta \) of dimension \( N_\Theta = 2N_{SL} \), the unknown surface mass density and source positions are in the array \( X \) of dimension \( N_X = N_c + N_g + 2N_s \) and the matrix \( \Gamma \) is known (for a given grid configuration and fiducial galaxy deflection field) and has dimension \( N_\Theta \times N_X \). \( N_{SL} \) is the number of strong lensing observables (each one contributing with two constraints, \( x, y \)), \( N_c \) is the number of grid points (or cells) that we use to divide the field of view. Each grid point contains a Gaussian function. The width of the Gaussians are chosen in such a way that two neighbouring grid points with the same amplitude produce a horizontal plateau in between the two overlapping Gaussians. \( N_g \) is the number of deflection fields (from cluster members) that we consider. In this work we set \( N_g \) equal to 3. The first deflection field contains the BCG galaxy, the second contains a prominent elliptical galaxy near the image 1.2 and the third deflection field contains the remaining galaxies from the cluster that are selected from the red-sequence. \( N_s \) is the number of background sources (each contributes with two unknowns, \( \beta_x, \beta_y \)) which in our particular case is \( N_s = 7 \). The solution is found after minimising a quadratic function that estimates the solution of the system of equations (3). For this minimisation we use a quadratic algorithm which is optimised for solutions with the constraint that the solution, \( X \), must be positive. Since the vector \( X \) contains the grid masses, the re-normalisation
Two improvements are implemented that resolve some of the problems of the original code was the biases introduced in the previous version of the code. One of the issues found in the earlier work was the introduction of spurious artifacts in the reconstructed solution when using a multiresolution grid. The bias was the consequence of sharp changes in resolution between neighbouring cells (or Gaussians). The difference in size between two cells of different resolutions was a factor 2\(^n\) which introduced spurious artifacts in the space dividing two resolutions. We have mitigated this problem by introducing a more gradual change between neighbouring cells. An example of the new scheme for the multiresolution grid is shown in figure 4. The use of the multiresolution grid with increased resolution around the BCG has the advantage of allowing for a more complex mass distribution in the central region where the density of lensed image constraints is higher and in particular it allows for a better and more flexible way of parametrising the elongation of the dark matter halo in the central region.

A second improvement is related with the original assumption that the sources are very compact. This assumption is normally a good approximation but in cases like system 1, this assumption would result in bad solutions that produce a very small area for system 1 in the source plane. This pathological problem was extensively discussed in our earlier work (Diego et al. 2005a, 2007; Fonente & Diego 2011) and the solutions derived from it were referred to as the point source solution. Information related to the shape of the galaxies in the source plane can be easily integrated in the algorithm. Based on a solution that is obtained after stopping the minimization before it starts producing very small sources, it is possible to produce a good guess for the shape of the galaxy in the source plane. If several knots are identified in the image plane, these knots can be projected back in the source plane. The knots in the source plane define a set of displacements, \(\delta \beta\) with respect to the central knot. These relative displacements can be incorporated in the algorithm as additional constraints. We found that this second improvement solves one of the problems in the original algorithm. The minimization process converges to a solution that is stable and does not produce unphysical solutions (like the point source solution discussed in our earlier work). A similar behaviour was observed when introducing the deflection field from the member galaxies as part of the lens model as they act as an anchor for the solutions, better constraining the range of possible solutions. In figure 3 we show the knots identified in system 1. Some knots are observed in all counterimages and some others are seen only in some counterimages. A future improvement of the code will include a penalty function for those models that predict images (knots) at positions that are not observed. This approach was already initially explored in Diego et al. (2005a) with promising results.

5.2 Models

To account for uncertainties and variability in the solutions, we explore a range of cases where we change the assumptions for the two main components of our method: the member galaxies and the grid definition. In particular we consider six types of models (or cases) described briefly below.

- Case 1. We use a standard grid of 16 \(\times\) 16 = 256 cells in our field of view. Each member galaxy is assigned an NFW profile where its total mass is taken proportional to its luminosity in the 814W filter band. The scale radius of the NFW is derived from the mass assuming a scaling \(M^{1/3}\). The concentration parameter is fixed to \(C = 8\).
- Case 2. Like Case 1 but instead of a uniform regular grid we use a multiresolution grid with 280 cells similar to the one shown in figure 4.
- Case 3. Like Case 2 but instead of a multiresolution grid with 280 cells we increase the resolution and use a grid with 576 cells.
- Case 4. Like Case 1 but we divide the scale radius by a factor 2 making the galaxies more compact.
- Case 5. Like Case 2 but we divide the scale radius by a factor 2 making the galaxies more compact.
- Case 6. Like Case 3 but we divide the scale radius by a factor 2 making the galaxies more compact.
6 RESULTS

For each one of the six cases discussed in section 5.2, we derive a solution. The minimization is stopped once the solution has converged to a stable point. We use the same number of iterations to derive the six solutions. A first comparison between the different solutions is made by contrasting the reconstructed shape of the original (unlensed) galaxy of system 1 in the source plane. Figure 5 shows the predicted shape of the galaxy of system 1 in the source plane based on image 1.3. We find that changing the scale radius of the member galaxies has no significant effect on the deflection field around image 1.3. This is not surprising as 1.3 lies in a region of the cluster with no major member galaxies. Consequently, the delensed images of Cases 1, 2, and 3 are virtually indistinguishable from those of Cases 4, 5, and 6 respectively. Comparing the different cases in Fig. 5, increasing the resolution of the grid seems to result in an elongation of the galaxy in the vertical direction. The right panel in the same figure, shows the corresponding solution for the case where no prior information about the shape of the galaxy is included and the algorithm reconstructs an unphysically small galaxy in the source plane. This is the solution that would have been derived with a very large number of iterations in our previous version of the code. A further assessment of the quality of the solution can be tested by comparing the observed and predicted counterimages in the image plane. We focus on system 1 as this is the most interesting one in terms of complexity and also due to its proximity to the centre of the cluster. Figure 6 shows the challenging cases of images 1.2, 1.4 and 1.5 (for the model corresponding to Case 5 described in the previous section). For this example, we use 1.1 as a template for the source that is delensed and relensed by our lens model to predict the other counterimages. The agreement between the observed and predicted images is in general very good with typical distances between observed and predicted features smaller than 1".

The prediction for all six models is shown in figure 7. In general all models reproduce the observed image reasonably well. Image 1.4 is the most challenging and some significant deviations can be appreciated in some of the models. In particular, models 1, 3, 4 and 6 predict an additional counterimage for the nucleus that is not observed in the current case. In addition to these cases, we briefly consider the equivalent of Case 1 but in our previous implementation of the code where no information about the spatial extent of system 1 is used and the galaxy in the source plane is assumed to be very compact. We refer to this case as the singular case. In all cases, we assume three deflection fields for the galaxies as described in the previous section. Most of the galaxies are contained in one deflection field. The BCG and the elliptical next to image 1.2 are treated as independent deflection fields and their masses are re-scaled by the algorithm in the minimization process. For the remaining cluster members, their masses are also re-scaled but all by the same factor.

Figure 7. Predicted images using the delensed 1.1 as a template of the source for the six different cases discussed in section 5.2. Note how models 1, 3, 4 and 6 predict an extra counterimage for the nucleus that is not observed. The scale and centre of the images are the same as the left panel of Fig. 6.
data although it cannot be ruled out that the counterimage for the nucleus is lost in contrast with the central glare of the BCG. The upcoming deeper optical data from the HFF program (specially the UV band where the BCG will be relatively faint) will certainly help in testing for the existence of this possible additional image of the bulge of system 1. Knot number 8 (see figure 3) in image 1.2 seems to be reproduced better (closer to the BCG) in the case of the regular grid with the more extended (i.e larger scale radius) galaxies (case 1) suggesting that the mass distribution stretches and flattens in the direction connecting the BCG with the elliptical galaxy next to 1.2.

The result for the counterimage 1.3 is shown in figure 8 for case 5. As in the previous case, 1.1 is used to delens and relens the galaxy. The agreement is again very good, with the exception of the appearance of the supernova that appears 4 times, separated by about 0.3″ but this is due, in part, to the fact that the elliptical in between the SN is modeled as a spherical halo. Future improvements to the lens model will include a halo based on teh elongation of the luminous matter. The predicted images 1.3 for the six models are shown in figure 9. All images are centered on the same position as the left panel of figure 8 and have the same scale. The agreement for all models is also excellent, with some models like cases 3 and 6 (high resolution grid) showing some distortion in the northern part of the galaxy. Cases 1 and 4 (regular grid) show an elongation in the di-angle direction. These distortions may be connected with the fact that the spiral galaxy in the north-east (possibly a cluster member) was not included in our set of cluster members as it is not included in the red-sequence. Due to the proximity of this spiral galaxy to image 1.3, a small distor tion in the deflection field might be expected. Cases 2 and 5 (intermediate resolution grid) seem to best reproduce image 1.3.

The solutions show some sensitivity to the redshifts of systems with photo-z. In particular to images 4.3 and 8.3. Excluding images 4.3 and 8.3 from our analysis produces more smooth solutions and a rounder critical curve. These solutions (without 4.3 and 8.3) reproduce better the image pairs 4.1, 4.2 and 8.1, 8.2 with a lower redshift. Imminent new optical data from the HIFF should improve photo-z esti-mates and provide new systems that will help constrain the solution better. This will be explored in a future paper.

6.1 Mass profile and mass distribution

The 2-dimensional distribution of the soft component (grid) for the mass is shown in Fig. 10 and is compared with the position (and shape) of the input galaxies and with the X-ray emission from Chandra. A few interesting conclusions can be derived from this plot. First, the peak of the soft component lies close to the position of the BCG. The small misalign-ment may be natural since the BCG may not be at rest with respect to the projected center of mass or this may be a conse-quence of our assumption of a spherical halo for the BCG while clearly the HST data suggests an elongation for this halo. The location of the peak and the elongation of the soft component around the BCG seems to correct for this wrong assumption by adding an elongation to the global mass distribution (or deflection field). Interestingly, this elongation points in the direction of the X-ray peak that is offset from the BCG by ≈ 50 kpc. Also, in the direction of the X-ray peak there is another prominent member galaxy that was not fitted independently in our model. Better constraints around this massive galaxy derived from the imminent new HFF optical data will help constrain this galaxy in an inde-pendent way. The offset between the X-ray and mass peaks confirms the disturbed nature of this cluster.

The mass profiles for the six models are shown in Fig. 11. A general good agreement is found between the six models. For comparison we show the profile derived recently by Zitrin et al. (2015) from the CLASH survey. A small shift is observed between the parametric solution of Zitrin et al. (2015) and our free-form solution. The origin of this small discrepancy may be the fact that for systems 4 and 8 we use a redshift that is different than the one assumed in Zitrin et al. (2015). In contrast with our previous work on HFF clusters (A2744, MACS0516 and MACS0717), no plateau is observed in the profile beyond the outer radius of the central galaxy. We find a good agreement between our derived profile and a low concentration NFW profile expected for massive clusters. According to results from simulations (Meneghetti et al. 2014), and recent observations on clusters (Merten et al. 2014), massive galaxy clusters are well reproduced by NFW profiles with relatively low values of the concentration parameter, $C \approx 3 - 4$, with somewhat larger values are derived for well defined relaxed clusters from the CLASH program (Umetsu et al. 2014; Zitrin et al. 2015).
the particular case of MACS1149, we find that a NFW profile with a concentration $C = 3$ produces a good match to the observed projected profile, consistent with the dynamical state of this cluster which from our comparison of the gas and dark matter distribution (Fig. 10) is evidently not suffering a first core passage of a major merger, but is not yet well relaxed.

6.2 Time delays

Here we use our free form model to obtain the 2D-time delay surface for this cluster. Image 1.1 hosts a quadruply lensed supernova (and named in honour ofRefsdal for his pioneering interest in this regard, Refsdal (1964)). Several authors have predicted the time delays between the 4 supernova counterimages in 1.1 and the predicted position of the supernova in images 1.2 and 1.3. Oguri (2015) predicts the SN in 1.3 appeared 17 years ago while one in 1.2 will appear in 1-3 years. In Sharon & Johnson (2015), the authors predict the SN in 1.2 will appear in $\approx 0.65$ years (around early July 2015 with $\approx 1$ month uncertainty) after the SN is observed in 1.1. The same model predicts the SN in 1.3 occurred $\approx 11.6$ years before the SN in 1.1 was observed (with $\approx 1$ year uncertainty). The suite of models produced by the method of Zitrin & Broadhurst (2009), Zitrin et al. (2015) as presented in Kelly et al. (2015) also predicts time delays consistent with these predictions.

We compute time delays from our 6 models and estimate the mean and dispersion from these 6 models. The time delay is defined as

$$t(\theta) = \frac{1 + z_d}{c} \frac{D_d D_s}{D_ds} \left[ \frac{1}{2} (\theta - \beta)^2 - \psi(\theta) \right] .$$

(4)

Figure 12 shows the average time delay from our models. The counterimages in 1.2, lies in the future by approximately 1 year with respect to the observed SN. If the model prediction is correct, the SN should appear again by the end of 2015. The counterimage of the SN at image 1.3 is predicted to have occurred approximately 9 years ago. These predictions are similar to those derived by Sharon & Johnson (2015). Also, a visual comparison of our Fig. 12 with the bottom-left panel of Fig. 4 in Sharon & Johnson (2015) reveals a similar structure in the 2-dimensional distribution of the time delay. The agreement between our free-form prediction and their parametric predictions favours strongly a window around July-December 2015 to observe the SN in image 1.2 at RA=11:49:36.025, DEC=+22:23:48.11 (J2000). A measurement of the time delay in the near future can be used to impose tight constraints in the lens model. Small differences between models result in small changes in the balance between the terms $(\theta - \beta)^2$ and $\psi(\theta)$ which are later magnified by the factor $\frac{1 + z_d}{c} \frac{D_d D_s}{D_ds}$. This factor typically takes values of $\sim 1$ Gyr. A discrepancy in the time delay prediction of one year between models is possible with small changes of order $10^{-9}$ in the difference shown in brackets in Eq. 4. Note that these models do not predict the time of explosion of the supernova, which is estimated empirically to be about 3 weeks prior to the November 2014 NIR observations in which it was discovered [Kelly et al. (2015)].

November the 1st, and with an uncertainly 25 days If the supernova is in fact observed in the near future in image 1.2, this observation could be used to improve the constraints in the lens model and perhaps even cosmological parameters like the Hubble constant. For the current paper, we have adopted the value $h = 0.7$ for the Hubble constant. While the strong-lensing constraints are not sensitive to $h$ (due to the degeneracy in $h$ between the geometric factor and the cluster mass), the time delay exhibits a different dependency with the Hubble constant. Accurate estimations of the mass...
based on strong lensing constraints can be used to derive precise predictions of the time delay that scale as $h^{-1}$ and when contrasted with measurements of these time delays, derive a constraint on $h$ (Oguri 2007).

In the particular case of WSLAP+, time delay constraints can be easily incorporated if one makes the approximation that the change in position of the background source is small (in relation to the typical deflection angles) when time delays constraints are incorporated in the reconstruction. In this case, the unknown variable $\beta$ in the quadratic term $(\theta - \beta)^2$ can be expressed as a fixed term, $\beta_0$, plus a small perturbation, $\delta \beta$.

$$(\theta - \beta)^2 = (\theta - (\beta_0 + \delta \beta))^2 = (\theta - \beta_0)^2 + \delta \beta^2 - 2(\theta - \theta_0) \delta \beta \approx C - 2(\theta - \theta_0) \delta \beta$$

(5)

where $\beta_0$ is the source position as inferred from the arc positions in the standard strong lensing analysis, $\delta \beta$ is the offset (with respect to $\beta_0$) of the new source position when time delays are included, $C$ is a known variable (constant) that can be pre-computed and we make the approximation that the term $\delta \beta^2$ is much smaller than the other terms so it can be neglected. This assumption is good if in fact the offset between the new source position and that inferred from the strong lensing constraints is indeed small when compared with the typical deflection angles. When computing $\delta \beta$ for our 6 solutions, we find that the relative change between the six models is indeed very small (less than one arcsecond). Hence, if time delays are able to discern between different models (like the ones used in this work), the approximation that $\delta \beta^2$ is very small is valid. Under this approximation, Eq. [3] can be linearized in the unknown variables (mass and source position) and solved using the same fast optimization algorithm (system of linear equations). Fixing $\beta_0$ requires solving the problem in an iterative way where each time the value of $\beta_0$ is updated. The convergence of the algorithm when time delays are included will be tested in a future work.

7 CONCLUSIONS

We apply our improved lensing reconstruction algorithm to the HFF cluster MACS1149. The new enhancements in the code to incorporate the internal structure of the large spiral galaxy images, in which the Refsdal SN was found, result in solutions that are more stable and precise. The increased precision in the solutions allows us to reproduce the observed images with unprecedented detail for a free-form method. Our best fitting mass distribution shows a somewhat disturbed but single cluster well fitted radially by an NFW profile with a low concentration value, $C = 3$, typical for large unrelaxed clusters (Neto et al. 2007). We confirm an offset between the X-ray and mass maxima, that is similar to the offset observed between the centre of the cluster BCG and the X-ray peak. The peak of the diffuse mass distribution extends towards the position of the X-ray peak suggesting that the lensing data may be sensitive to the X-ray plasma, a possibility already suggested by our earlier HFF work on A2744 and MACS0416 (Lam et al. 2014; Diego et al. 2015).

Our improved model allows us to compute precise time delays for the observed Refsdal SN. Our results are in agreement with previous estimates and places the future occurrence of the SN somewhere between early October 2015 and early January 2016 (assuming a value for the Hubble constant of $h=0.7$). A significant deviation from this prediction will result in changes in the lens model and/or the cosmological model (in particular $h$). The inclusion of a future observation of this time delay can be easily incorporated in our reconstruction algorithm and will be exploited in future work. The planned deep optical observations of this cluster as part of the ongoing HFF will reveal new multiply lensed images that will help in constraining better this cluster, in particular the halos of the perturbing central member galaxies including the BCG, for which currently the data are still very ambiguous.

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