Kinematics of the SN Refsdal host revealed by MUSE:

a regularly rotating spiral galaxy at z ≃ 1.5

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ABSTRACT

We use Multi Unit Spectroscopic Explorer (MUSE) observations of the galaxy cluster MACS J1149.5+2223 to explore the kinematics of the grand-design spiral galaxy (Sp1149) hosting the SN “Refsdal”. Sp1149 lies at z ≃ 1.49, has a stellar mass $M_* \approx 5 \times 10^9 M_\odot$, a star-formation rate SFR ≃ 1 – 6 $M_\odot$ yr$^{-1}$ and represents a likely progenitor of a Milky-Way-like galaxy. All the four multiple images of Sp1149 in our data show strong [O ii]-line emissions pointing to a clear rotation pattern. We take advantage of the gravitational lensing magnification effect ($\approx 4\times$) on the [O ii] emission of the least distorted image to fit 3D kinematic models to the MUSE data-cube and derive the rotation curve and the velocity dispersion profile of Sp1149. We find that the rotation curve steeply rises, peaks at $R \approx 1$ kpc and then (initially) declines and flattens to an average $V_{\text{flat}} = 128^{+29}_{-19}$ km/s. The shape of the rotation curve is well determined but the actual value of $V_{\text{flat}}$ is quite uncertain because of the nearly face-on configuration of the galaxy. The intrinsic velocity dispersion due to gas turbulence is almost constant across the entire disc with an average of 27 ± 5 km/s. This value is consistent with z ~ 0 measurements in the ionized gas component and a factor 2-4 lower than other estimates in different galaxies at similar redshifts. The average stellar-to-total mass fraction is of the order of one fifth. Our kinematic analysis returns the picture of a regular star-forming, mildly turbulent, rotation-dominated (V/σ ~ 5) spiral galaxy in a 4 Gyr old Universe.

Key words: galaxies: kinematics and dynamics — galaxies: high-redshift — gravitational lensing: strong — galaxies: clusters: individual: MACS J1149.5+2223

1 INTRODUCTION

MACS J1149.5+2223 (hereafter MACS1149, Ebeling et al. 2007) is a well-known galaxy cluster at $z = 0.542$. It has been targeted by several observational programs, including the Cluster Lensing And Supernova survey with Hubble (CLASH, Postman et al. 2012), the Hubble Frontier Fields (HFF, Lotz et al. 2014) and the Grism Lens-Amplified Survey from Space (GLASS, Schmidt et al. 2014; Treu et al. 2015) with the Hubble Space Telescope (HST). MACS1149 shows numerous strong-lensing features, like multiply imaged galaxies and elongated arcs, and lensing models have been developed in several studies (e.g., Smith et al. 2009; Zitrin et al. 2011; Johnson et al. 2014; Oguri 2015; Grillo et al. 2016; Jauzac et al. 2016). This cluster has also revealed a magnified image of...
one of the youngest-known galaxies at $z \approx 9.6$ (Zheng et al. 2012) and the first case of a multiply-imaged, spatially-resolved supernova (SN), commonly referred to as SN “Refsdal” (Refsdal 1964), in a background magnified spiral galaxy (Kelly et al. 2015; 2016; Rodney et al. 2016; Treu et al. 2016).

The SN Refsdal exploded in a spiral galaxy (Sp1149, hereinafter) at $z = 1.49$ behind MACS1149. Thanks to the lensing magnification effect provided by the cluster, we can study this spiral galaxy with a level of detail comparable to that reached at $z \approx 0.1$ (Smith et al. 2009; Karman et al. 2016). The galaxy reveals itself in four (two full and two partial) multiple images (Figure 1, left-hand panel) that are highly magnified (a factor $\mu = 4 \cdot 20$, depending on the image, e.g. Zitrin & Broadhurst 2009; Grillo et al. 2016) and has been studied in several works well before the appearance of the SN Refsdal. Sp1149 is a nearly face-on disc-dominated galaxy with a stellar mass $M_* \approx 10^{10.5-11.5} M_\odot$ and bulge-to-total light ratio $B/T \approx 0.4 - 0.5$ (rest-frame B-band, Smith et al. 2009), showing at least four extended and prominent spiral arms that host several star-forming regions sized 50-100 pc (Adamo et al. 2013). Rest-frame UV (V$_{1553}$ band, Smith et al. 2009) and Hx observations (Livermore et al. 2012) revealed a normal star-formation rate (SFR) of $1 - 6 M_\odot$ yr$^{-1}$. Sp1149 almost perfectly lies on the galaxy main sequence (i.e. SFR-M, relation) at $1 \leq z \leq 2$ (e.g. Speagle et al. 2014) and represents a likely progenitor of a Milky Way-like galaxy in the local Universe (Behroozi et al. 2013; van Dokkum et al. 2013).

The large magnification factor allows us to trace the kinematics of Sp1149 with an accuracy otherwise unachievable for a galaxy at $z \approx 1.5$. The kinematic properties of young star-forming galaxies are still controversial, although the number of high-$z$ studies has been quickly increasing in the last decade (e.g. Förster Schreiber et al. 2009; Gnerucci et al. 2011; Contini et al. 2012; Wisnioski et al. 2015; Stott et al. 2016). The current understanding is that high-$z$ galaxies are settled in turbulent disk structures, namely marginally-stable rotating discs with a significant contribution of random motions to the dynamical support of the system (see, for example, the review of Glazebrook 2013). The mechanisms that generate such a high turbulence (i.e. high velocity dispersion) are still debated (e.g., Green et al. 2010; Swinbank et al. 2012) and it is not clear how high-$z$ galaxies evolve into the lowly-turbulent and rotation-dominated systems that we observe in the local Universe (e.g., Bournaud et al. 2009). In general, estimating the intrinsic kinematics of high-$z$ galaxies is challenging because observations have very low spatial resolution and signal-to-noise ratios (S/N). The low spatial resolution makes it difficult to derive meaningful kinematic maps and disentangle rotation velocity from velocity dispersion because of the well-known “beam smearing” effect (e.g., Bosma 1978; Epinat et al. 2010). In particular, the high values of velocity dispersion derived for many high-$z$ galaxies could be, at least partially, due to an instrumental bias (line broadening) and not to an intrinsically high velocity dispersion of the gas (see e.g., Davies et al. 2011; Di Teodoro et al. 2016). In this context, gravitational lensing helps to improve both the S/N and the linear spatial resolution through magnification (e.g. Jones et al. 2010a; Newman et al. 2015; Leethochawalit et al. 2016; Yuan et al. 2017), minimizing the impact of beam smearing.

The former attempts to derive the kinematics of Sp1149 returned conflicting results. Yuan et al. (2011) used the integral field spectrograph (IFS) OSIRIS (Larkin et al. 2006) on the Keck Telescope to trace the Hx-[N$\alpha$] emission in one of the multiple images (M1 in Figure 1) of Sp1149 and found a maximum rotation velocity $V_{\text{max}} = 210$ km/s (assuming an inclination of 45$^\circ$), with a rotation-to-dispersion ratio $V/\sigma \approx 4$. The same OSIRIS observations led instead Livermore et al. (2015) to estimate a $V_{\text{2,2}} = 59$ km/s with a $V/\sigma < 2$, where $V_{\text{2,2}}$ is the rotation velocity at 2.2 times the scale length of the exponential disc. These studies were however not targeted at accurately defining the kinematics of Sp1149 and their results could be biased by the very low S/N of OSIRIS observations, the non-negligible distortion of the M1 image due to gravitational lensing and an improper account for beam smearing. In a more recent paper, Mason et al. (2017) presented the first results of the KMOS Lens-Amplified Spectroscopic Survey (KLASS), a survey with the KMOS IFS (Sharples et al. 2013) aimed at investigating the kinematics of lensed galaxies at $1 \leq z \leq 3$, including Sp1149. They have $\text{[O} \text{II}]$ observations of both the M1 and M3 images: their 3D modelling of M1 returned a $V_{\text{max}} = 227$ km/s with an inclination of 12$^\circ$ and a low gas velocity dispersion $\sigma = 15$ km/s ($V/\sigma \approx 15$). M3 is not spatially resolved in their data and they just set an upper limit to the velocity dispersion of about 50 km/s.

In this paper we try to nail down the kinematic properties of Sp1149 by using high-quality IFS data from the Multi Unit Spectroscopic Explorer (Bacon et al. 2010, MUSE) on the Very Large Telescope (VLT). We modelled the $\text{[O} \text{II}]$ data-cube of the least magnified and least distorted image of Sp1149 (M3 in Figure 1) using an updated version of the 3D{\text{B}arolo} code (Di Teodoro & Fra-ternali 2015). Unlike other 2D techniques based on the modelling of kinematic maps, 3D{\text{B}arolo} works directly in the 3D observational space and is essentially unaffected by beam smearing issues. This means that, as long as a galaxy is resolved, the spatial resolution does not significantly affect the derived kinematic properties. Three-dimensional fitting codes, such as 3D{\text{B}arolo} or GalPaK3D (Bouché et al. 2015), currently provide the most advanced kinematic modelling of low spatial resolution observations (see e.g. Bacon et al. 2015; Schroetter et al. 2015; Contini et al. 2016).

The paper is organized as follows. In Section 2 we summarize the MUSE observations used in this work. Section 3 and Section 4 describe the stellar mass estimates and the kinematic modelling procedure, respectively. We show and discuss our findings in Section 5, comparing them to those published in the literature in Section 6 and drawing our conclusions in Section 7. Throughout this work, we use a flat $\Lambda$CDM cosmology with $\Omega_{\text{m}0} = 0.27$, $\Omega_{\Lambda0} = 0.73$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. In this cosmology framework, 1 arcsec corresponds to 8.7 kpc and the look-back time is 9.5 Gyr at $z = 1.5$. 2 DATA

MACS1149 was observed with MUSE at the VLT under the program ID 294.A-5032 (P.I.: C. Grillo). The total integration time is 4.8 hours, divided in 12 exposures of 24 minutes each. Ten exposures are taken under a seeing lower than 1.1″, two exposures have worse observational conditions and a seeing of about 2″. Observations are centered at coordinates $\alpha = 11:49:35.75$, $\delta = +22:23:52.4$ (J2000) and have one single pointing. MUSE guarantees a wide field of view (FOV) of 1 arcmin$^2$, meaning that the four multiple images of Sp1149 lie all inside our data. In Figure 1 (left panel), we show a composite RGB image of the central regions of MACS1149 (CLASH survey, Postman et al. 2012). The image extends about two thirds of the MUSE FOV. The four images of Sp1149, labelled M1-M4, clearly stand out thanks to the blue-UV light from the young stellar populations in the spiral arms.

For a comprehensive description of MUSE observations and data reduction process we refer to Grillo et al. (2016) and Karman et al. (2015), respectively. Our final data-cube has a pixel scale of

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\[ \frac{r}{a} = 0.2'' \text{ and a spectral channel width of 1.25 Å.} \]

\[ \text{The whole spectroscopic coverage of data spans from 4750 Å to 9350 Å, corresponding to a rest-frame range} \]
\[ -1910 - 3750 Å \text{ for Sp1149 at} \]
\[ z = 1.49. \]

\[ \text{The [O} \text{] doublet represents the strongest emission feature from the ionized gas component in this range.} \]

\[ \text{The four multiple images of Sp1149 in our data show strong [O} \text{] emission lines.} \]

\[ \text{Out of four multiple [O} \text{] detections of Sp1149, M2 and M4 are severely distorted and not ideal to be kinematically modelled before a complicated reconstruction on the source plane.} \]

\[ \text{The last image, M3, lies at} \]
\[ \sim 20 \text{ arcsec from the central core of the cluster and it is the least magnified one, with an almost isotropic and constant distortion over its entire surface (e.g., Zitrin & Broadhurst 2009).} \]

\[ \text{In the HST zoom-in of the M3 image (Figure 1, top-left map in the right panels), we show the gravitational lensing effect in terms of magnification and stretching predicted by the best-fit MLV-G12F median model by Grillo et al. (2016) with} \]
\[ \text{Grux.} \]

\[ \text{Red ellipses represent how a circular source with radius} \]
\[ r = 1 \text{ pixel} = 0.065'' \text{ is lensed in different regions of the M3 image.} \]

\[ \text{The magnification factor is} \]
\[ \mu \sim 4, \text{ which means that ellipses have} \]
\[ \text{semi-major axes} \]
\[ a = r \mu^{0.5}. \]

\[ \text{The ellipticity of the ellipses exemplifies the anisotropic distortion effect, which is very small and does not significantly vary across the Sp1149 disc.} \]

\[ \text{The M3 image offers therefore the favourable chance of studying the kinematics of a magnified galaxy without the need of reconstructing the image on the source plane.} \]

\[ \text{We stress that, thanks to full 3D modelling of the data-cube, the loss of magnification with respect to the other images does not reduce our capability of deriving a reliable kinematics.} \]

\[ \text{Our VLT/MUSE data provide for the first time valuable and spatially-resolved integral field observations of the M3 image, which we use to derive the kinematics of Sp1149 with unprecedented accuracy. Moreover, we use the M1 image, which has higher magnification than M3 and hence higher physical spatial resolution, to test the reliability of the inferred kinematics in the inner parts of the galaxy.} \]

\[ \text{The high-quality of the MUSE data-cube can be appreciated in Figure 2, where the blue contours trace the [O} \text{] emission in the M3 image at different wavelengths (the so-called “channel maps”).} \]

\[ \text{In the right panels of Figure 1, we also show moment maps derived by fitting a double Gaussian function to each spatial pixel in the [O} \text{] data-cube of the M3 image.} \]

\[ \text{The velocity field shows a strong velocity gradient along the major axis that points to a manifest rotation.} \]

\[ \text{The values of velocity dispersions in the dispersion field are not beam-smearing corrected and are completely dominated by instrumental effects. We stress that we do not make use of these moment maps in our kinematic modelling (see Section 4).} \]

\[ \text{We measured the Point Spread Function (PSF) of our observations from the bright star visible in the} \]
\[ \text{left panel of Figure 1.} \]

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1 Lens modelling software developed by A. Halkola and S. H. Suyu (Suyu & Halkola 2010; Suyu et al. 2012).
We fitted a 2D Gaussian function to the integrated map of the star-forming galaxy like Sp1149. In this case, the fit would typically yield unphysical solutions (e.g., extremely young stellar populations), especially if the rest-frame UV continuum is sampled more finely by the photometry than the rest-frame optical-NIR. Here we instead used a rising SFH based on the evolution of the M–SFR relation, using the parametrization of Sargent et al. (2014). This main sequence SFH starts at $z=10$ and has one free parameter, a seed mass which we let vary between $10^8$ and $10^{10} M_\odot$. For this model we also assumed an evolving stellar metallicity, computed at each time step from a gas metallicity based on the fundamental mass-metallicity relation of Mannucci et al. (2010) (see Gobat & Hong 2016, for more details). We bracketed it by the metallicity range of the templates (0.005–2.5 $Z_\odot$), for more details). We bracketed it by the metallicity range of the templates (0.005–2.5 $Z_\odot$) within each aperture are listed in Table 1.

### 3 STELLAR MASS ESTIMATES

We measured cumulative stellar mass values within each aperture considered in the kinematic modelling (see Section 4) by fitting the galaxy spectral energy distribution (SED), obtained in the 12 reddest CLASH HST bands, with stellar population models based on Bruzual & Charlot (2003) single-burst (SSP) templates. We note that, since the global star formation rate of galaxies reaches a maximum at $z=1–2$, the commonly used declining, delayed or truncated star formation histories (SFHs) might not apply to a $z=1.5$ star-forming galaxy like Sp1149. In this case, the fit would typically yield unphysical solutions (e.g., extremely young stellar populations), especially if the rest-frame UV continuum is sampled more finely by the photometry than the rest-frame optical-NIR. Here we instead used a rising SFH based on the evolution of the M–SFR relation, using the parametrization of Sargent et al. (2014). This main sequence SFH starts at $z=10$ and has one free parameter, a seed mass which we let vary between $10^8$ and $10^{10} M_\odot$. For this model we also assumed an evolving stellar metallicity, computed at each time step from a gas metallicity based on the fundamental mass-metallicity relation of Mannucci et al. (2010) (see Gobat & Hong 2016, for more details). We bracketed it by the metallicity range of the templates (0.005–2.5 $Z_\odot$) within each aperture are listed in Table 1.

### 4 KINEMATIC MODELS

We derived the kinematic parameters of Sp1149 by using a modified version of 3DBarolo (Di Teodoro & Fraternali 2015), an algorithm that fits 3D tilted-ring models to emission-line data-cubes. 3DBarolo basically produces a disc model and shapes it into a 3D simulated observation by building a line profile in each spatial pixel. Instrumental effects are taken into account by convolving the model with the PSF and the LSF of the observations. The model-cube is eventually compared pixel-by-pixel to the observed data-cube. This 3D methodology allows us to overcome the well-known difficulty of deriving galaxy kinematics from 2D maps in low spatial resolution observations (e.g., Newman et al. 2013). Extensive tests with simulated and local galaxies have shown that 3DBarolo is very effective in recovering the intrinsic kinematics whenever the disc is resolved with at least 3 independent resolution elements across the major axis (see, in particular, Fig. 7 and Fig. 8 in Di Teodoro & Fraternali 2015). Moreover, unlike 2D techniques, where the kinematic models may depend on the way velocity and dispersion fields are derived from the data-cube, our approach directly applies on the original dataset and does not require the extraction of any additional kinematic maps.

3DBarolo builds a kinematic model assuming that a disc galaxy can be decomposed in a certain number of rings, each of which is defined by six parameters: 1) the galaxy centre coordinates $(x_0,y_0)$, 2) the inclination angle $i$ of the galaxy with respect to the plane of the sky, 3) the position angle $\phi$ of the major axis, taken anticlockwise from the North direction, 4) the redshift $z$ of the galaxy, 5) the rotation velocity $V_\text{rot}$ and 6) the intrinsic velocity dispersion $\sigma_\text{gas}$ of the gas. All these parameters can in principle vary ring by ring.

The standard version of 3DBarolo works on single emission lines. In order to exploit the entire kinematic information in our data, we updated the algorithm to fit both lines of the [O\text{II}] doublet at once. In our modified version, the line profile $I(\lambda)$ in each spatial pixel is built by adding the contribution of two Gaussian components $G_1$ and $G_2$: $I(\lambda) = G_1(A_1, m_1, \sigma_1) + G_2(A_2, m_2, \sigma_2) = G_1(A_1, m_1, \sigma_1) + \Delta(\lambda, \sigma)$, where $A_n, m_n$ and $\sigma_n$ are the amplitude, mean and standard deviation of the $n=1,2$ component. In Equation 1, we assume that $G_2$ is scaled by factor $\kappa = A_2/A_1$, has an offset of $\Delta \lambda = m_2 - m_1$ from $G_1$ and equal standard deviation $\sigma = \sigma_1 = \sigma_2$. For the [O\text{II}] doublet, we set $\Delta \lambda = 2.7(1+z)$ Å = 6.7 Å, where 2.7 Å is the wavelength separation at rest of the two lines in the doublet, and we estimated $\kappa = 1.62$ from the total spectrum of Sp1149 (see Figure 3, bottom panel). The standard deviation $\sigma$ of the Gaussian functions is a combination of the gas velocity dispersion $\sigma_\text{gas}$, which is a parameter of the model, and the instrumental LSF $\sigma_\text{Instrumental}$. We tested the updated algorithm with simulated galaxies (following the procedure described in Section 4 of Di Teodoro & Fraternali 2015) and found that the performance of 3DBarolo with emission line doublets is fully comparable to the single emission line case.

Although the algorithm is able to simultaneously fit up to six parameters per ring, this is not recommendable in low-resolution data. We decided to fit only the kinematic parameters ($V_{\text{rot}}$ and $\sigma_{\text{gas}}$), while the other parameters were evaluated a priori and then kept fixed in the modelling step. We estimated these parameters as follows:

- **Galaxy centre.** HST observations of MACS1149 are publicly available from various surveys (e.g. HFF, CLASH). We made use of HST combined images from CLASH in F150W/F814W/F225W bands to estimate the galaxy centre. We fitted a Sérsic profile (Sérsic 1963; Caon et al. 1993) to the galaxy surface-brightness by using the software imfit (Erwin 2015) and we found $(x_0,y_0) = (x=11:49:36.819, y=22:24:08.80) (J2000)$, with 1σ uncertainties of 0.1". The adopted centre is shown as a cross in the zoom-in panel of Figure 1. We note that the [O\text{II}] total intensity (top-right map) well matches the stellar light distribution and that the centre estimated from the HST images coincides with the central peak of the [O\text{II}] emission.
- **Redshift.** We fitted a 1D double Gaussian function to the [O\text{II}]
Inclination. The galaxy appears to be nearly face-on, which makes it challenging to estimate its actual inclination. Yuan et al. (2011) and Livermore et al. (2015) quote $i = 45^\circ$, coming from a kinematic fit of the Hα velocity field of the M1 image. The M3 HST image and the M3 [O ii] intensity map suggest however a slightly lower inclination angle. Our imfit fit on the M3 HST image returns $i_{\text{HST}} = (37 \pm 6)^\circ$. We also used an algorithm, implemented in $^{3D}$Barolo, that fits a PSF-convoluted model map to the observed intensity map and we found $i_{\text{OII}} = (32 \pm 7)^\circ$. We eventually decided to set $i = 35^\circ$ as our best guess in the following kinematic modelling. However, given the wide range of acceptable values and having no further information to constrain the real inclination angle, we decided to calculate the uncertainties on rotation velocity and velocity dispersion by fitting two additional models: a nearly face-on disc at 25$^\circ$ and, for consistency with former studies, a more inclined disc at 45$^\circ$ (see below for a discussion on the error estimate).

• Position angle. We extracted a velocity field by fitting a 1D double Gaussian function with fixed $\Delta \lambda = 6.7$ Å to each spatial pixel of the [O ii] MUSE data-cube (Figure 1, right panels). The characteristic velocity $V(x, y)$ along the line-of-sight at a given position $(x, y)$ was calculated from the offset of the first Gauss-
sian function from the redshifted [O\textsc{ii}]-$\lambda$3726Å line, such that \(V(x,y) = c(m - A_x)/A_y\), where \(m\) is the mean of the Gaussian, \(c\) is the speed of light and \(A_x = A_0(1 + z) = 9274\) Å. We estimated the position angle \(\phi\) by finding the straight line passing through the galaxy centre and along which the gradient on the velocity field is maximum. This procedure is directly provided by \textsc{3dbarolo}. We found \(\phi = (227 \pm 6)^\circ\). The adopted position angle is shown as a straight line on the Sp1149 velocity field in Figure 1.

During the fitting procedure, the MUSE data-cube was masked through a S/N threshold cut equal to 2.5, i.e. we blanked all those regions where the [O\textsc{ii}] flux is lower than 2.5 times the noise level on a channel-by-channel basis. We calculated the noise level as the root mean square (RMS) in five different emission-free regions of each channel of the data-cube. Estimating the RMS at each wavelength separately prevents a particularly noisy channel from invalidating the goodness of the fit. We stress however that the noise level in our MUSE data is consistently constant over the wavelength range covered by the [O\textsc{ii}] lines, with an average value \(\sigma_{\text{noise}} = 2.0 \times 10^{-20} \text{erg s}^{-1}\text{cm}^{-2}\text{Å}^{-1}\). In addition to the S/N cut, we manually masked a 1.3" circular region centred at \((x=11:49:36.970, \delta=+22:24:10.83)\), where we detected the continuum emission of the foreground galaxy located North-West from Sp1149 M3 image (see HST image in the right panel of Figure 1).

We built kinematic models by using ring widths of 0.4", a value that is twice the pixel size and about half the FWHM of the PSF. Models were normalized azimuthally, i.e. we calculate and impose a constant gas surface density along each ring. We also checked that a fit with the local normalization used in Di Teodoro et al. (2016) returned consistent best-fit values for \(V_{\text{rot}}\) and \(\sigma_{\text{gas}}\). A \(\cos(\theta)\) weighting function, being \(\theta\) the azimuthal angle, was applied to the residual calculation in order to give more importance to the pixels lying closer to the major axis (\(\theta=0\)). Errors in \textsc{3dbarolo} are calculated through 1000 Monte Carlo realizations of the model, where the parameters are randomly drawn from a Gaussian distribution centred on the best-fit values (see Di Teodoro & Fraternali 2013, for further details). In this process, all the parameters are varied, including those kept fixed during the fit. The largest uncertainties on the kinematic parameters, in particular on the rotation velocity, comes from the inclination angle: Sp1149 is seen nearly face-on \((i = 45^\circ)\) and a more inclined model \((i = 25^\circ)\) and a more face-on model \((i = 25^\circ)\) and a more inclined model \((i = 45^\circ)\). The best-fit values at \(i = 25^\circ\) and \(i = 45^\circ\) were used to quantify upper and lower limits to the rotation velocities and the velocity dispersions of Sp1149. In this way, we can account for an effective variation of the inclination \(\Delta i = \pm 10^\circ\) from our fiducial model at \(i = 35^\circ\), a range sufficiently large to embody also possible lensing uncertainties.

The kinematic analysis was performed on the M3 image of the galaxy with no prior lensing reconstruction. Rotation curve and velocity dispersion profile were derived as a function of the angular distance in the image-plane from the galaxy centre, which was afterwards traced back to source-plane radii using the MLV-G12F median lensing model by (Grillo et al. 2016). We stress however that our best-fit values of rotation velocity and intrinsic velocity dispersion are not dependent on the assumed lensing model, which instead exclusively affects the conversion between a radius in the image plane to a radius in the source plane.

5 RESULTS AND DISCUSSION

Figure 2 compares the M3 MUSE data-cube to our best model-cube at \(i = 35^\circ\) in the whole wavelength range where the [O\textsc{ii}] doublet is detected. The upper panels refer to the [O\textsc{ii}]-3726Å line, the lower panels to the [O\textsc{ii}]-3729Å line. The data is shown in the top row (blue contours), the model in the middle row (red contours) and the data-minus-model residuals in the bottom row (green contours). Our model is completely symmetric both in surface density and kinematics. The model nicely traces the kinematic behaviour of the galaxy and, in particular, the channel maps at the extremest wavelengths (\(\lambda = 9269.76\) Å and \(\lambda = 9283.51\) Å), which carry information on the maximum rotation velocity, are well reproduced. The strong residuals visible in the top and bottom left corners of all channel maps come from the continuum emission of two nearby galaxies, members of the cluster (see Figure 1). We also extracted position-velocity diagrams (PVs), namely slices through the spectral dimension of the data-cube, to check that the model is consistent with the observations. In Figure 3 (top panel), we show PVs taken along the major (top) and minor (bottom) axes of the galaxy. We plot PVs of data, model and residuals in the left, middle and right columns, respectively. Residuals show that the model replicates the bulk of the [O\textsc{ii}] emission in the galaxy disc. The vertical strip in the left part of the major axis and the residual emission in the left side of the minor axis are due to the continuum from the top-left galaxy and the bottom-left galaxies visible in Figure 2, respectively. Some residual emission emerges at high velocities in the
very central regions both on the major and minor axes. These features can be either a high-velocity $\text{[O} \text{II]}$ emission component or the galaxy continuum, which has not been subtracted in this work and might be stronger in the galaxy center. In the first case, the high-velocity central emission can be reproduced either by a very high gas surface density and rotation velocity ($\sim 250$ km/s) in the inner region of the galaxy or by non-circular motions (outflows, e.g. Bradshaw et al. 2013). In the bottom panel of Figure 3, we finally show that the model well matches the overall kinematic properties of the galaxy by comparing the 1D global spectra of data (blue) and best-fit model (red dashed).

The derived rotation curve and velocity dispersion profile are reported in Figure 4. Radii in arcsec units in these plots are measured on the image-plane and then converted to source-plane physical radii by using the magnification factors from Grillo et al. (2016) listed in Table 1. Uncertainties in $R$ are propagated from the statistical errors of the lensing model: best-fit uncertainties on the magnification factors are always lower than 0.2, thus we used a conservative value of 0.2 to compute errors on delensed radii. In both plots we show the best-fit values of the model with $i = 35^\circ$ (red points with errorbars) and a “safety” strip (red region) where we include the uncertainties on the inclination angle in a very conservative way. The lower (upper) boundaries of this region are calculated as the minimum (maximum) between the best-fit values of the $i = 35^\circ$ model minus (plus) the error and the values obtained from the $i = 25^\circ$ and $i = 45^\circ$ models. The rotation curve (left panel of Figure 4) of Sp1149 peaks at 148 km/s around 1 kpc from the galaxy centre, it shows a slight decline and then flattens to an average value $V_{\text{rot}} \approx 128$ km/s, where the average is calculated over all the points but the innermost one. The actual value of $V_{\text{rot}}$ is however strongly affected by the inclination uncertainty and it could raise to 157 km/s for $i = 25^\circ$ or drop to 109 km/s for $i = 45^\circ$. As a benchmark, the local stellar-mass Tully-Fisher relation for a galaxy with $\log(M_*/M_\odot) = 9.7$ predicts a rotation velocity $V_{\text{rot}} \approx 125$ km/s (e.g. McGaugh & Schombert 2015). This velocity is fully compatible with the value we found for our fiducial model at $i = 35^\circ$, within the errors. The flat shape of the outer rotation curve is similar to that observed in low-$z$ spiral galaxies and conflicts with recent claims of declining rotation curves at $z \sim 1–2$ (Genzel et al. 2017; Lang et al. 2017). The central peak of the rotation velocity implies a very steep rise of the curve within a 0.2″ radius and suggests a strong concentration of matter in the inner kpc (e.g. Sofue et al. 1999), consistent with the size of the bulge-like structure in the galaxy centre (see HST images in Figure 1).

The velocity dispersion (middle panel of Figure 4) is nearly constant across the galaxy disc, with an average value of 27 ± 5 km/s. We note that the uncertainties on the measured velocity dispersions do not depend on the inclination angle assumed and the limits of the confidence strip are mostly set by the error obtained in the fit at $i = 35^\circ$. Our value of 27 km/s is in good agreement with the ionized gas velocity dispersions of local star-forming galaxies (e.g. Andersen et al. 2006; Epinat et al. 2010) and recent 3D determinations at $1 \lesssim z \lesssim 2$ (Di Teodoro et al. 2016; Mason et al. 2017), while it is generally lower than 2D measurements at similar redshifts: in particular, our velocity dispersion is about half of the average values found by Stott et al. (2016) at $z \approx 0.9$, by Epinat et al. (2012) at $z \approx 1.3$ and by Wisnioski et al. (2015) at $z \approx 2$ and a factor 4–5 lower than the dispersions quoted by Förster Schreiber et al. (2009) at $z = 2$. We stress that the combination of lensing magnification, low inclination of the galaxy and 3D modelling allows us to minimize the impact of instrumental and projection effects and to robustly derive the intrinsic velocity dispersion of the gas. Since the velocity dispersion is a measure of non-ordered random motions (turbulence), we conclude that Sp1149’s disc is not significantly more turbulent than today spiral galaxies with similar SFR. Sp1149’s disc may nonetheless be thicker than local discs because of the shallower potential of the galaxy. The low velocity dispersion is also consistent with the existence and the survival of the prominent spiral arm features in Sp1149 (Elmegreen & Elmegreen 2014; Yuan et al. 2017).

We can roughly estimate the stellar-to-total mass fractions $M_*/M_{\text{tot}}$ at different radii. The total dynamical mass in a spherically symmetric system can be inferred from the rotation curve: the mass contained inside a radius $R$ is $M_{\text{tot}}(< R) = RV_{\text{rot}}^2(R)/G$, where $V_{\text{rot}}(R)$ is the rotation velocity at $R$ and $G$ is the gravitational constant. Given the low velocity dispersion, we can neglect the contri-
bution of random motions to the dynamical support of the galaxy (asymmetric drift, Oort 1965). We calculated dynamical masses inside each radius and we compared them to the stellar masses derived in Section 3. In the right panel of Figure 4 we show the cumulative trends with radius of the derived stellar masses (blue stars), total dynamical masses (gray points) and stellar-to-total mass fractions (purple triangles). The average stellar-to-total mass fraction is \( M_*/M_{\text{tot}} \approx 0.2 \pm 0.1 \), meaning that gas and dark matter contribute to about 80% of the total mass budget. This value is on the low stellar-to-total mass fraction side but still consistent with those of recent studies at similar redshifts (e.g., Yuan et al. 2011; Livermore et al. 2015) and Mason et al. (2017). Yuan et al. and Livermore et al. used AO observations with the Keck/OSIRIS IFU of the Hα and [N II]λ6548 – 6583Å emission lines in the M1 image, with total exposure time of 4.75 hours. Mason et al. used seeing-limited (median seeing ∼ 0.6 arcsec) VLT/KMOS IFU observations of the [O III] – [S II] emission line in the M1 and the M3 images with 2.25 hours of integration time on each source. The kinematics derived in these three studies and that presented in this work do not agree. The discrepancies cannot be ascribed to the use of different emission features because Hα, [N II], [O II] and [O III] lines arise from the warm ionized gas and are reasonably expected to trace the same kinematics.

6 COMPARISON WITH FORMER STUDIES

The kinematics of the galaxy Sp1149 has been studied in three previous papers, namely Yuan et al. (2011), Livermore et al. (2015) and Mason et al. (2017). Yuan et al. and Livermore et al. used AO observations with the Keck/OSIRIS IFU of the Hα and [N II]λ6548 – 6583Å emission lines in the M1 image, with total exposure time of 4.75 hours. Mason et al. used seeing-limited (median seeing ∼ 0.6 arcsec) VLT/KMOS IFU observations of the [O III] – [S II] emission line in the M1 and the M3 images with 2.25 hours of integration time on each source. The kinematics derived in these three studies and that presented in this work do not agree. The discrepancies cannot be ascribed to the use of different emission features because Hα, [N II], [O II] and [O III] lines arise from the warm ionized gas and are reasonably expected to trace the same kinematics.

The paper of Yuan et al. (2011) focused on the metallicity gradient in Sp1149 and a proper kinematic modelling is beyond their goals. They estimated a value for the rotation velocity by fitting a model velocity field (Jones et al. 2010b) to the observed velocity field of the M1 image after reconstruction on the source plane based on the lens model of Smith et al. (2009). Beam smearing is not taken into account. They quote a rotation velocity \( V_{\text{rot}} \sin(i) \approx 150 \pm 15 \) km/s. An inclination angle of 35° would lead to \( V_{\text{rot}} \approx 260 \) km/s, a value which is hardly compatible with our rotation curve. It is difficult to assess the goodness of Yuan et al.’s kinematics because their model is not shown in the paper. A direct comparison with our kinematic estimate is also difficult because they do not specify at which radius the rotation velocity is measured. Our data however seem to rule out the possibility of a value of 150 km/s for the line-of-sight velocity: in such case, the combined effect of rotation velocity, velocity dispersion and instru-
mental smearing would have made the galaxy to spread its emission in channels with velocities well beyond those detected in our data-cube (for example, in the first channel of Figure 2).

Livermore et al. (2015) included the dataset from Yuan et al. (2011) in a broader study on the kinematics of a sample of lensed galaxies. Similarly to Yuan et al., they fitted the deflected 2D kinematic velocity map with an arctangent model of the rotation curve (Courteau 1997) without any correction for beam smearing and galaxies. Similarly to Yuan et al., they fitted the delensed 2D kine-
cube (for example, in the first channel of Figure 2).
in channels with velocities well beyond those detected in our data-
velocity field in their Fig. 1). This is likely due to a combination
model does not satisfactorily reproduce their data (see the residual
smearing. Finally, we stress that the Livermore et al.'s kinematic
This value is however strongly a
lower spatial resolution than OSIRIS data, our rotation curve seems
to exclude such a low rotation velocity at 1.32 kpc (Figure 4, Fig-
thermodynamical) mass fraction.

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