A major galaxy cluster merger caught by eROSITA: weak lensing mass distribution and kinematic description

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ABSTRACT

We present the weak lensing mass distribution of a triple merging cluster candidate at $z_{\text{photo}} \sim 0.36$ belonging to a supercluster recently discovered during the eROSITA Performance Verification phase. Our analysis solved a previous tension in the merger classification by confirming that the cluster pair eFEDS J093513.3+004746 and eFEDS J093510.7+004910 is undergoing a major merger with a mass ratio $1.7^{+0.5}_{-0.3}$. According to our two-body kinematic description, the encounter happened $0.58^{+0.36}_{-0.20}$ Gyr ago, in a scenario that supports the observed radio relic position at the cluster outskirts. However, the same analysis showed that the companion cluster, eFEDS J093501.1+005418, is not gravitationally bound to the interacting system and therefore it is not part of the supercluster. We also checked the impact of adopting a scaling relation to determine the halo concentration $c_{200}$. At the observed merger stage, where the clusters have travelled $\sim 55$ per cent of the path to reach the apoapsis, the choice of the $c_{200}$ (whether from a scaling relation or a free parameter in the mass model) does not change significantly either the cluster masses or the kinematic description.

Key words: gravitational lensing: weak – dark matter – galaxies: clusters: general – galaxies: clusters: individual: eFEDS J093513.3+004746 – galaxies: clusters: individual: eFEDS J093510.7+004910 – galaxies: clusters: individual: eFEDS J093501.1+005418

1 INTRODUCTION

Given the large amount of energy involved ($\geq 10^{64}$ ergs; e.g., Sarazin 2004), major galaxy cluster mergers are often called astrophysical particle colliders (Harvey et al. 2015). Therefore, they are an excellent laboratory to investigate properties of the key constituents of clusters, namely the intracluster medium gas (ICM; e.g. Keshet et al. 2021), the galaxies (e.g. enhancement/quenching of star formation; Kelkar et al. 2020; Hernández-Lang et al. 2021), and the dark matter (e.g. Fischer et al. 2021), even if they are observed at late stages of a merger (e.g., Tam et al. 2020). As the ICM carries the most discernible signatures of the merger process (such as shock waves, cold fronts, and sloshing; e.g., Ha et al. 2018; Pandge et al. 2019; Ueda et al. 2020, 2021; Cho et al. 2021; Machado et al. 2022), ongoing high-quality X-ray surveys as the extended ROentgen Survey with an Imaging Telescope Array (eROSITA; Merloni et al. 2012; Predehl et al. 2021) will dramatically increase the number of identified cluster mergers.

Analysing the eROSITA Final Equatorial Depth Survey (eFEDS), Ghirardini et al. (2021, hereafter G21), reported the discovery of a supercluster at photometric redshift (photo-$z$) $z_{\text{photo}} \sim 0.36$. It consists of a chain of eight clusters spanning a length of 27 Mpc on the plane of the sky. Despite the fact that most of them present regular X-ray and optical properties, the authors identified a triple major merger candidate consisting the galaxy clusters eFEDS J093513.3+004746 (hereafter eFEDS4746; $z_{\text{photo}} = 0.367$), eFEDS J093510.7+004910 (hereafter eFEDS4910; $z_{\text{photo}} = 0.367$) and eFEDS J093501.1+005418 (hereafter eFEDS5418; $z_{\text{photo}} = 0.385$). More details of these clusters are presented in Table 1. Using LOFAR and uGMRT observations, G21 found two radio relics at the outskirts of eFEDS4746 and eFEDS4910 as well as a radio halo coincident with those clusters in projection. Radio relics are characterized by diffuse radio synchrotron emission, which are known to be good tracers of the shock wave propagating through the ICM after the pericentric passage during a merger (Zhang et al. 2020; Knowles et al. 2021), even though their origin are not yet fully understood (e.g. van Weeren et al. 2019). On the other hand, due to its regular optical and X-ray properties, together with the absence of any radio feature, G21 argued that eFEDS5418 is in a pre-merger state given its short projected distance to its companions.

In contrast with the radio observations, the major merger scenario between eFEDS4746 and eFEDS4910 does not find any support either from the estimated clusters’ richness or mass ratios, $\sim 4:1$. It is also worth mentioning that mass estimates based on the $L_X - M$ scaling relations, like those provided by G21, can be highly biased for clusters involved in a merger (e.g. Torri et al. 2004). Unfortunately, G21 stated that the shallow data from eROSITA prevented them to extract more details about the merger dynamics, because the X-ray counterparts of the radio relics cannot be detected. To solve

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1 We adopt the definition of Martel et al. (2014), and consider as major merger an event in which the mass ratio between the two most massive (in case of multiple clusters) is less than two.

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this discrepancy in the merger classification, an essential piece of information is the map of the underlying dark matter distribution from which a comprehensive description of the current merger status can be obtained.

In this work, we use the public data release of the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al. 2019) to perform the first total mass reconstruction in the field containing these clusters based on the weak gravitational lensing technique. Next, we measure the masses of individual clusters and check if the major merger scenario is feasible. We also address the kinematics of the merger through an analytical two-body description and examine whether the positions of the radio relics are consistent with the proposed merger history. Recently, Chadayammuri et al. (2022, hereafter C22) pointed that dark matter halo shapes can dramatically change during the merger event, therefore the use of a scaling relation to determining the halo concentration, \( \epsilon_{200} \), in the mass modeling could lead to an overestimate of cluster mass. To investigate the possible impact on the mass determinations and, ultimately, the verification of the correspondence between the cluster’s morphology (e.g., if the system is uni- or multi-modal) and, ultimately, the verification of the correspondence between the baryonic and dark matter, through a comparison of the projected gravitational lensing (e.g., Monteiro-Oliveira et al. 2017b, 2020; Wittman et al. 2018).

The selection of galaxies belonging to the clusters’ red sequence (Visvanathan & Sandage 1977) was done through the application of the statistical subtraction technique in the g − r versus i − z colour-colour (CC) space. Two heterogeneous regions were considered in this process: the first one centred at eFEDS4748 (a circular region with a radius of 2′) in which red cluster member galaxies are supposed to be numerically dominant, and a distant, “control” annulus (10′ ≤ radius ≤ 14′), where the counts of the field galaxies are expected to be dominant. As red sequence galaxies have similar photometric properties at a given redshift (e.g., Stott et al. 2009), we expect them to form a well-defined locus in the CC plane, as can be seen in Fig. 2. The locus boundaries become even more prominent after subtracting the contribution of the outer region, allowing for a confident CC selection. In the end, we found 765 red sequence members. Their photo-z distribution, presented in Fig. 3, shows a prominent peak around the clusters’ location, suggesting the selection was reasonably accurate. For the sake of comparison, we applied the photo-z cut introduced by Wen & Han (2013)\(^4\), finding that 3/4 of our red sequence members match this criteria.

We built the projected red sequence distribution after smoothing the discrete field with the function

\[
D(\xi) = \sum_{i=1}^{N} K(\xi_i, \sigma_\xi),
\]

which represents a sum over all \( N \) galaxies with radial coordinate \( \xi \) located inside the smoothing scale \( \sigma_\xi \), set to \( 1' \). We adopted the Epanechnikov kernel,

\[
K(\xi_i, \sigma_\xi) = \begin{cases} 
\frac{3}{4} & \frac{1}{\sigma_\xi} \left( \frac{\xi_i}{\sigma_\xi} \right)^2, \\
0 & \frac{\xi_i}{\sigma_\xi} > 1. 
\end{cases}
\]

The resulting galaxy surface density map, shown in Fig. 1, is fully consistent with the cluster positions given by G21. It clearly shows a bimodal distribution, corresponding to the pair eFEDS4748 and eFEDS4910, and a third clump reasonable away from the previous overdensity that is related to eFEDS5418. An interesting feature is the two prickle-like structures emanating from eFEDS4910, which could be the end of large scale filaments that we believe to be feeding galaxy clusters (Kuchner et al. 2022).

2.3 Shape measurements

The weak lensing effect is described in terms of two quantities, the convergence

\[
\kappa = \frac{\Sigma(\xi)}{\Sigma_{ct}},
\]

and the shear,

\[
\gamma = \gamma_1 + i \gamma_2.
\]

The former, a scalar, reflects the projected mass density of the gravitational lens and describes the change in size on background galaxies (note that the surface brightness is conserved at the same time). It is written in units of the lensing critical density,

\[
\Sigma_{ct} = \frac{c^2 D_s}{4\pi GD_{ds}D_d},
\]

\(^4\) According to these authors, cluster members correspond to all galaxies inside the slice \( \xi_{cluster} - 0.04(1 + \xi_{cluster}) \leq \xi \leq \xi_{cluster} + 0.04(1 + \xi_{cluster}) \)

\(^2\) Available at https://hsc-release.mtk.nao.ac.jp/doc/index.php/sample-page/pdr2/

\(^3\) https://hsc-release.mtk.nao.ac.jp/das_search/pdr2/
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Table 1. Summary of the cluster properties found by G21. The original $M_{500}$ were converted to $M_{200}$ assuming the halo mass density profile is well described by an NFW profile with a concentration parameter $c_{200}$ given by the $M_{200}$–$c_{200}$ scaling relation presented by Duffy et al. (2008).

| Full name                | Short name | $z_{\text{photo}}$ | Richness | $M_{200}$ ($10^{14} M_\odot$) |
|--------------------------|------------|-------------------|----------|--------------------------------|
| eFEDS J093501.1+005418   | eFEDS5418  | 0.385             | 143 ± 12 | 4.2 ± 0.8                      |
| eFEDS J093510.7+004910   | eFEDS4910  | 0.367             | 62 ± 9   | 2.2 ± 1.1                      |
| eFEDS J093513.3+004746   | eFEDS4746  | 0.367             | 208 ± 15 | 8.9 ± 1.7 [                    |

Figure 1. Composite $griz$ image showing the location of the three galaxy clusters investigated in this work (labelled in the figure). This is only part of a larger field for which the data (imaging and photometric catalogue) were extracted from the HSC-SSP PDR2. The yellow diamonds are placed at the galaxy clusters’ positions as identified by G21, based on photo-zs. The green contours show the projected density distribution of the red sequence galaxies selected through a statistical subtraction method in the colour-colour space (more details given in Section 2.2). The pair eFEDS4746 and eFEDS4910 forms a bimodal system, possibly in interaction, and, together with eFEDS5418 will have their kinematic investigated in this work in order to confirm (or not) if a triple merger is taking place. The cyan dots labeled A–F represent the positions of mass peaks identified in the weak lensing analysis presented in this work (Section 2.5). Each of the above-mentioned clusters coincides with a mass peak (A, B, and D, respectively).

where $D_s$, $D_{ds}$ and $D_d$ are, respectively, the angular diameter distances to the source\(^5\), between the lens and the source, and to the lens.

The second quantity, a spin-2 tensor, refers to the image stretching. Similar to the convergence, the shear is related to the projected gravitational potential of the lens (e.g., Umetsu 2020). The total effect caused by the lens is called the reduced shear, and involves a combination of convergence and shear,

$$g = \frac{\gamma}{1 - \kappa}.$$  \hspace{1cm} (6)

The role of the galaxy cluster is to induce a coherent distortion on the source galaxies, changing their ellipticity in the sense that, on

\(^5\) Another way to refer to background galaxies
Figure 2. Left: $i - z$ vs $g - r$ colour-colour (CC) diagram of galaxies lying in two different locations of the field. The inner region, where red sequence galaxies are expected to dominate in terms of number, was selected as a circle with radius of 2' centered at eFEDS4746. We also selected galaxies in an outer annulus, 10' ≤ radius ≤ 14' from eFEDS4746, shown in the inset. After a statistical subtraction of the CC diagrams, we defined the cluster locus (white contour) preferably inhabited by red sequence member galaxies (Section 2.2). Right: CC diagram of all galaxies in the field. The cluster locus is highlighted in green. For the weak lensing analysis, we are only interested in the galaxies located behind the cluster ($z > z_{\text{cluster}}$), and any contribution from both the red sequence and foreground galaxies ($z < z_{\text{cluster}}$) will decrease the lensing signal-to-noise (S/N). We defined an empirical foreground locus (yellow polygon) and considered as potential source candidates all galaxies located outside. The magenta points represent the final source sample selected after some quality cuts in the shape parameters (Section 2.4).

Figure 3. Photometric redshift distribution of the 765 galaxies identified as red sequence member through the statistical subtraction in the CC space. The vertical dotted (dashed) line shows the location of eFEDS4748/eFEDS4910 (eFEDS5418) as found by G21. The inset panel corresponds to those galaxies matching the selection criteria of Wen & Han (2013, i.e., $0.31 \leq z_{\text{photo}} \leq 0.44$) considering the lowest and highest redshift limits of the three clusters. This sub-sample comprises 76 per cent of the CC-selected red sequence members.

\[ \langle e \rangle \approx g . \]  

(7)

By definition, weak gravitational lensing is a statistical phenomenon which means it can only be measured over a large sample of background galaxies.

As the shape parameters of the galaxies in our region of interest are not made publicly available at the time this work was been carried out, we measured them by ourselves. We started by checking the image quality. Despite the source galaxies being the only objects carrying the gravitational lensing signal, the identification of non-saturated stars are crucial for the evaluation imaging quality and the assessment of the point spread function (PSF).

We built our own photometric catalogue of the $i$-band imaging by running the software SExtractor (Bertin & Arnouts 1996) for object identification. Then, the star/galaxy classification was done on their full width half-maximum (FWHM) as the following: objects within $0.60'' \leq \text{FWHM} \leq 0.71''$ were classified as stars (point sources) whereas those having FWHM > 0.73'' were considered as galaxies (extended objects). Our final galaxy catalogue comprises all objects matched with those from the HSC-SSP catalogue having the highest confident photo-$z$ estimations (photo-$z_{\text{CONF_BEST}} > 0.13$; Medezinski et al. 2018).

The Bayesian code im2shape (Bridle et al. 1998) was adopted to measure the ellipticity components $e_1$ and $e_2$ of stars and galaxies. It works by modelling the objects as a sum (or a single, in the case of stars) of Gaussian functions. Given that the observed unsaturated star profiles are the result of the convolution between the PSF with a delta function, the discrete set of $(e_1, e_2)$ can be spatially interpolated across the image to create an analytical description of the PSF. We accomplished this task resorting to the THIN PLACE REGRESSION (Nychka et al. 2014) function in the R environment (R Core Team 2014). The interpolation was done three times, each one removing the 10 per cent worst objects (i.e., those with the largest absolute residuals). At the end, we arrived at a tight fit as manifested by the
Figure 4. PSF modelling based on bright and unsaturated stars homogeneously distributed across the field. The 1024 black dots show the raw distribution of the ellipticity components \( e_1 \) and \( e_2 \), with \( \langle e_1 \rangle = -0.002 \pm 0.013 \) and \( \langle e_2 \rangle = -0.006 \pm 0.009 \). After removing outliers to create an analytical function to describe the PSF across the image, we found the residuals represented by the 934 red points as low as 0 ± 7 × 10^{-4} for both \( e_1 \) and \( e_2 \).

very small residuals (0.0000 ± 0.0007 for \( e_1 \) and \( e_2 \)) as shown in Fig. 4.

The galaxy ellipticities were then extracted after im2shape has performed the PSF deconvolution. For the sake of quality, we disregarded all galaxies having measured ellipticity uncertainties greater than 0.2, or showing any evidence of blending. Unfortunately, as we are not able to know a priori the shapes of the unlensed galaxies, \( e_1 \) and \( e_2 \) are at best noisy proxies of the shear field. When required, we adopted \( \sigma_{\text{int}} = 0.3 \) as the dispersion of the intrinsic ellipticity distribution of source galaxies (e.g. Leauthaud et al. 2007).

2.4 Source selection

The cluster and the foreground members have to be carefully removed from the source sample, in order not to critically dilute the weak lensing signal. To this end, we tested three selection criteria, one based on a CC cut, and two others relying on the galaxies photo-z, but excluding the cluster locus in one of them. Using the examples presented in Medezinski et al. (2010) as guidelines, we defined an empirical region in the CC diagram comprising the most probable location of foreground candidates plus the cluster locus (Section 2.2). The CC based selection process, illustrated in Fig. 2, resulted in a source density of 13.2 galaxies per arcmin^{-2}. For the photo-z based selection, we considered all galaxies beyond the upper limit suggested by Wen & Han (2013, i.e., \( z_{\text{photo}} > 0.44 \)), yielding 16.1 galaxies per arcmin^{-2}. Excluding galaxies within the cluster locus, the density decreases to 15.6 galaxies per arcmin^{-2}.

We referred to the mass aperture statistic (Schneider 1996) to create a shear signal-to-noise map,

\[
S/N = \sqrt{\frac{\sum_{i=1}^{N_{\theta_0}} e_{+}(\theta_i) Q_{\text{NFW}}(\theta_i, \theta_0)}{\sigma_{\text{int}}^2}} \left( \frac{\sum_{i=1}^{N_{\theta_0}} Q_{\text{NFW}}^2(\theta_i, \theta_0)}{\sum_{i=1}^{N_{\theta_0}} Q_{\text{NFW}}^2(\theta_i, \theta_0)} \right)^{1/2},
\]

based on the tangential ellipticity,

\[
e_{+} = -e_{1} \cos(2\phi) - e_{2} \sin(2\phi),
\]

\[
\phi = \arctan \left( \frac{y_{\text{bin}} - y_{\text{centroid}}}{x_{\text{bin}} - x_{\text{centroid}}} \right),
\]

averaged over the \( N_{\theta_0} \) galaxies inside a circular region of \( \theta_0 = 8' \) computed in each of the 1.5 × 10^2 spatial bins centred at the Cartesian coordinates \( x_{\text{bin}}, y_{\text{bin}} \). The other quantities in Eq. 8 are the radial position of the \( i \)-th galaxy \( \theta_i \) and the dispersion of the intrinsic ellipticity distribution \( \sigma_{\text{int}} \). We adopted a filter (Schirmer 2004) that roughly matches an NFW shear profile,

\[
Q_{\text{NFW}}(\theta_i, \theta_0) = \left[ 1 + e^{-a-b\chi(\theta_i, \theta_0)} + e^{-c+d\chi(\theta_i, \theta_0)} \right]^{-1} \times \frac{\tan[\chi(\theta_i, \theta_0)/\chi_C]}{\pi \theta_0^2[\chi(\theta_i, \theta_0)/\chi_C]},
\]

where \( \chi = \theta_i/\theta_0 \). Following Hetterscheidt et al. (2005), we adopted \( a = 6, b = 150, c = 47, d = 50, \) and \( \chi_C = 0.15 \).

The resultant S/N maps based on the three selection methods are presented in Fig. 5. Overall the three maps appear very similar, and all of them have the highest S/N in the same region of the clusters eFEDS4746 and eFEDS4910. When comparing the maps quantitatively within a circular region with 4' radius centred at eFEDS4746, we found that the CC based map reaches the highest S/N among the samples. The 97.5 per cent percentile (maximum) of the S/N is 7.65 (8.10), 6.61 (7.17) and 6.24 (6.92) respectively for the CC based, the CC cut and the photo-z samples. This conclusion is in line with Medezinski et al. (2018), who found that CC cuts are more efficient than photo-z’s in removing contributions from both cluster and foreground galaxies and thus maximizing the weak lensing signal. We will adopt the CC-based selection as our fiducial source sample henceforth. The 36,589 source galaxies correspond to a critical density \( \Sigma_{\text{crit}} = 2.8 \pm 0.6 \times 10^8 M_{\odot} \text{ kpc}^{-2} \) (Eq. 5). The quoted error on the critical density reflects the spread of the source redshifts, which is characterized by a mean photo-z of \( \approx 1.1 \).

2.5 Projected mass field and modelling

The Bayesian code LensEnt2 (Marshall et al. 2002) was applied to translate the source ellipticities into the cluster projected mass distribution. In a nutshell, this maximum entropy algorithm works by maximizing the evidence of the reconstructed mass field with respect to the data. Since each individual galaxy is a noisy proxy of the shear and is correlated with its neighbourhood, an intrinsic correlation function (ICF) must be applied to smooth the data. We adopted a Gaussian ICF (e.g. Monteiro-Oliveira et al. 2018, 2020, 2021) with a FWHM \( \sigma_{\text{ICF}} = 90' \). The final convergence map is presented in Fig. 1. The noise level, \( \sigma_{\text{N}} = 0.4 \), was calculated as follows. For each of 100 iterations, the mass map was computed after every galaxy orientation was rotated by a random angle in the interval \([0,180]\) to remove the lensing signal.

The convergence map is fully consistent with the mass aperture statistic S/N (Fig. 5). We identified six significant mass concentrations (i.e., \( \geq 4 \sigma_{\text{N}} \)), labelled A–F. The clumps A, B and D can be correlated respectively with the galaxy clusters eFEDS4910 (RA = 09:35:13, DEC = +00:49:38), eFEDS4746 (RA = 09:35:15, DEC = 00:47:38) and eFEDS4746 (RA = 09:35:15, DEC = +00:49:38) and the cluster eFEDS4910 (RA = 09:35:15, DEC = +00:49:38).
For all models, the halo centres were kept fixed at the position found by our algorithm.

For the models #1 and #2, we applied a flat prior \( P(\Theta) \) for the masses, \( 0 < M_{200} \leq 10^{16} \, M_\odot \), to avoid non-physical values and to accelerate the convergence. In model #3 we also added a prior on the concentration, \( 0 < c_{200} < 15 \).

The posterior in Equation 13 was sampled by the MCMC algorithm with a Metropolis sampler MCMCMETROP1R (Martin et al. 2011). Four chains of \( 10^7 \) elements plus 100 as ‘burn-in’ were generated for each model, all of which were considered convergent at the end (Plummer et al. 2006). The marginalized posteriors are shown in Table 3.

It is remarkable that, regardless of the model, the masses of all eFEDS clusters are comparable within the error bars. To select the best model, we resorted to the Akaike Information Criterion (AIC)\(^7\) and the Bayesian Information Criterion (BIC)\(^8\). Both metrics are

\[ \text{AIC} = 2k - 2 \ln \mathcal{L} \]

\[ \text{BIC} = k \ln n - 2 \ln \mathcal{L} \]

where \( k \) is the number of parameters in the considered model and \( \mathcal{L} \) is the corresponding maximum log-likelihood.

\(^6\) The total mass enclosed within a sphere whose density is 200 times the critical density of the Universe, \( \rho_c = \frac{3H^2(z)}{8\pi G} \).

\(^7\) Akaike Information Criterion (AIC)\(^7\) and the Bayesian Information Criterion (BIC)\(^8\).

\(^8\) Both metrics are
BIC statistics, model #1 was considered as the preferred one.

comparable to model #2 (Kass & Raftery 1995) whereas the BIC statistic suggests that it is
10 et al. (2018) showed that a collection of halos more massive than 

posteriors, presented in Fig. 7, shows that, in general, the param-
dentin choosing the model #1 as the fiducial one henceforth. The full

Among a finite number of models, those with the lowest AIC/BIC is

complex ones, penalising therefore those with a large number of

parameters. A small difference between the two is that BIC also takes

into account the number of data points, thus avoiding overfitting.

Among a finite number of models, those with the lowest AIC/BIC is

considered the best to describe the data.

The model #1 is the preferred according to the AIC (ΔAIC > 10; Kass & Raftery 1995) whereas the BIC statistic suggests that it is comparable to model #2 (ΔBIC < 2). These results make us confident in choosing the model #1 as the fiducial one henceforth. The full posterior plot, presented in Fig. 7, shows that, in general, the parameters are not (anti-)correlated among them, except when the nearest neighbour(s) is considered (A – B, B – E, D – F). Nevertheless, even in these cases, the anti-correlation is very weak. Another remarkable feature in the model is the considerably high mass associated with an isolated halo, labelled “C”, surpassing even the identified cluster masses. Similarly, for clumps “E” and “F”, we did not find any clear optical counterparts after computing the photo-z distribution of galaxies inside a circular region with a radius of 1.5′ (−0.5 Mpc), implying that they probably do not correspond to a single halo. Wei et al. (2018) showed that a collection of halos more massive than $10^{13} \, M_\odot$ ($z \approx 1$) can be detected at line-of-sight with a S/N $\geq 3$. We end this discussion with an important caveat: the masses in Table 3 only correspond to the “true” value if the halo redshift is the same as that considered in the modeling, $z = 0.36$.

Regarding the interacting binary system candidate, eFEDS4746 is the more massive one in 52% of the MCMC samples, as we can see in Fig. 6. Regardless of which cluster is considered the most massive, the mass ratio (i.e. the ratio between the corresponding posteriors, $R \equiv M_{\text{cluster}} / M_{\text{subcluster}}$) is $R = 1.7^{+0.5}_{-0.7}$. In 63 per cent of the samples, we found $R < 2$, suggesting that the system can be classified as a major merger, while in another 28 per cent, 2 $\leq R < 4$, suggesting that a semi-major merger class is more suitable to describe the possible interaction (Martel et al. 2014). If we consider a toy model in which eFEDS4746 and eFEDS4910 will merge within a few Gyr (e.g. Machado et al. 2015), the final cluster would have a mass of $M_{\text{MCMC}} = 5.53^{+1.24}_{-1.37} \times 10^{14} \, M_\odot$ (Fig. 6), considering the progenitors masses are conserved.

The halo concentrations are fully consistent in both models #1 and #2. When setting $c_{200}$ as a free parameter in model #3, we found comparable values within the large error bars, despite the face values being systematically smaller than those obtained by the scaling relation. The exception is eFEDS5418, with a considerably higher concentration.

Table 3. Results of the modelling. The median was taken as the representative value for each posterior, and the quoted error corresponds to the 68 per cent c.l. interval. Masses $M_{200}$ are presented in units of $10^{14} \, M_\odot$. The concentrations shown in parenthesis are those predicted by Duffy et al. (2008). Based on AIC and BIC statistics, model #1 was considered as the preferred one.

| Model | $M_{\Delta}^{200}$ | $M_{\Delta}^{200}$ | $M_{\Delta}^{200}$ | $M_{\Delta}^{200}$ | $M_{\Delta}^{200}$ | $c_{\Delta}^{200}$ | $c_{\Delta}^{200}$ | $c_{\Delta}^{200}$ | ΔAIC | ΔBIC |
|-------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|-------|-------|
| #1    | $2.63^{+0.96}_{-1.18}$ | $2.73^{+1.08}_{-1.48}$ | $4.23^{+1.53}_{-1.81}$ | $2.43^{+1.07}_{-1.30}$ | $1.27^{+0.61}_{-0.94}$ | $3.08^{+1.20}_{-1.53}$ | $(3.4)^{+0.1}_{-0.1}$ | $(3.4)^{+0.1}_{-0.2}$ | $(3.4)^{+0.1}_{-0.2}$ | 0     | 2     |
| #2    | $2.54^{+0.96}_{-1.23}$ | $3.46^{+1.28}_{-1.32}$ | $-1.52$ | $3.42^{+1.19}_{-1.35}$ | $-1.52$ | $-1.52$ | $3.4^{+0.1}_{-0.1}$ | $(3.3)^{+0.1}_{-0.1}$ | $(3.3)^{+0.1}_{-0.1}$ | 0     | 20    |
| #3    | $2.80^{+1.21}_{-1.70}$ | $3.27^{+1.44}_{-1.95}$ | $-2.32^{+0.87}_{-1.14}$ | $-2.32^{+0.87}_{-1.14}$ | $-2.32^{+0.87}_{-1.14}$ | $2.0^{+1.2}_{-1.7}$ | $2.6^{+1.0}_{-1.4}$ | $7.1^{+1.0}_{-3.9}$ | 23    | 26    |

Figure 6. Probability density function (PDF) of the sum (dashed line) and the difference ($M_{\Delta}^{200} - M_{\Delta}^{200}$, continuous line) of the posteriors of masses of individual clusters. In 52 (48) per cent of the 4 $\times 10^5$ MCMC samples, eFEDS4746 (eFEDS4910) emerges as the most massive cluster of the pair. The total mass is $5.53^{+1.24}_{-1.37} \times 10^{14} \, M_\odot$.

3 KINEMATIC ANALYSIS

Tailored hydrodynamical simulations have been proven to provide a realistic description of the merger kinematics (e.g., Molnar et al. 2020; Doudara et al. 2020; Moura et al. 2021). However, when it is not possible to utilize such a tool, we have to resort to a simplified yet still reliable analytical description of the two-body interaction, such as the Monte Carlo Merger Analysis Code (MCMAC; Dawson 2013). This is a Bayesian model designed to calculate the possible merger scenarios from the probability density function (PDF) with just a few input parameters, namely the cluster masses ($M_{200}$, Table 3), their spatial separation projected at an angle $\alpha$ from the plane of the sky ($R_p$, Fig 8) and their mean redshift ($\bar{z}$, Table 1). The great improvements offered by this code over other tools are the treatment of the clusters as spatially extended objects instead of point masses (Beers et al. 1982) and the availability of the posteriors of the quantities of interest (e.g., time since/to the pericentric passage, maximum separation). MCMAC assumes mass conservation (i.e., $M = M_1 + M_2$ constant) during the zero impact parameter merger and no angular momentum. The maximum relative velocity $V_r$ is set to be the free-fall velocity according to the cluster masses. It has two versions, one designed for post mergers (MCMAC-post) and
Figure 7. Posteriors of the parameters of model #1 (six NFW-halos) as mapped by the MCMC sampler. Dark (light) blue corresponds to 68 (95) per cent c.l.
Along the diagonal line the marginalised posteriors of each halo (A – F) are shown. We considered the median as the representative value for each distribution.

The number inside the plots shows the Pearson’s correlation coefficient for each pair.

another for pre-interaction pairs (MCMAC-pre). In the latter case, the condition for bound pairs,

$$V^2 r_p \leq 2GM \sin^2 \alpha \cos \alpha,$$

is not necessarily satisfied during the MCMC re-samplings. The probability of a system being bound (unbound) can be defined as the ratio between the number of MCMC-pre samples in which Eq. 14 is true (false) and the total number of samples, 10,000 in this work (for both MCMAC-pre/post). We adopted the cluster redshifts estimated in G21. To compute the uncertainties, we assumed a squared sum of a typical error on subcluster redshift ($\sigma_z \approx 0.007$; e.g., Monteiro-Oliveira et al. 2017a, 2018) with an uncertainty of 5 per cent corresponding to the photo-z precision of the HSC-SSP data (Tanaka et al. 2018), which will have a much larger weight on the final estimation. We also considered a realistic prior on the velocity of the merger component on the plane of sky ($v_{\text{plane}} < 1500$ km s$^{-1}$; Monteiro-Oliveira et al. 2022).

Despite the fact that MCMAC is designed to describe two-body interactions, in Monteiro-Oliveira et al. (2022) we suggested that the algorithm can be applied in more complex systems, by reducing them to one pair at a time. Although not dealing with all bodies in the system simultaneously, this approach provides a realistic chronological order for the collision events. In this sense, we use the MCMAC-pre mode to describe the potential mergers, as illustrated in Fig. 8.

We found that only the pair eFEDS4746/4910 is gravitationally bound, a scenario recovered in 81 per cent of the MCMC-pre samples. However, when either of these clusters forms a pair with eFEDS4910, a bound system is only reported by less than 41 per cent of the samples. Even when we increased the mass of the cluster to the value of the combined mass of eFEDS4746 and eFEDS4910 in our toy model, the correspondingly increased percentage (48%) is not enough to change the kinematic classification. Regarding any possible impact on the mass reconstruction described with a free $c_{200}$ parameter (model #3 in Table 3), all of the results presented in this paragraph remain consistent.

Our proposed post-merger kinematic description is presented in Table 4. MCMAC-post does not distinguish between two possible scenarios: (1) a collision that has just happened $T_{\text{SC}_0}$ Gyr ago and the members are outgoing, or (2) a system that already reached the
apoapsis and the clusters are incoming for a new encounter $TSC_1$ 5 Gyr after the last pericentric passage. This degeneracy can be broken, however, if any other age proxy is also observed. The presence of radio relics in the outskirts of eFEDS4746/4910 is itself a piece of evidence for such an event. When the drawn line is continuous (dashed) the pair is considered bound (unbound). The number below refers to the projected separation between the mass peaks (in kpc).

4 DISCUSSION

Our weak lensing mass map shows an excellent agreement with the cluster positions detected by eROSITA and Subaru (Fig. 9). Assuming that the density profile of each cluster can be satisfactorily described by an NFW profile, we found that all the clusters have similar masses (Table 3). For the last two in the Table, these estimates are in agreement with G21, considering the error bars. The most outstanding feature arising from our weak lensing analysis is the absence of a dominant cluster, contrary to the findings of G21.

| Quantity          | Unit | Median | 68 per cent c.l. |
|-------------------|------|--------|------------------|
| $M_{4746}^{200}$  | $10^{14}$ M$_{\odot}$ | 2.96 | 1.55 – 4.32 |
| $M_{4910}^{200}$  | $10^{14}$ M$_{\odot}$ | 2.74 | 1.58 – 3.85 |
| $z_{4746}$        |      | 0.367 | 0.351 – 0.382 |
| $z_{4910}$        |      | 0.367 | 0.352 – 0.382 |
| $d_{\text{proj}}$ | Mpc  | 0.71  | 0.66 – 0.75    |
| $\alpha$          | degrees | 42   | 19 – 66        |
| $v_{3D,\text{obs}}$ | km s$^{-1}$ | 1194 | 724 – 1667   |
| $d_{3D,\text{obs}}$ | Mpc  | 0.96  | 0.65 – 1.18  |
| $v_{3D,\text{col}}$ | km s$^{-1}$ | 2148 | 1747 – 2541 |
| $d_{3D,\text{max}}$ | Mpc  | 1.8   | 0.7 – 2.7    |
| $TSC_0$           | Gyr  | 0.58  | 0.38 – 0.72  |
| $TSC_1$           | Gyr  | 3.13  | 0.87 – 5.81  |

Their mass estimate for eFEDS4746 based on the $L_X - M$ scaling relation is ~ 3 times larger than our value. Even though their estimates agree with those from the Planck catalogue, we stress that the weak lensing technique does not make any assumption a priori about the cluster dynamical state (e.g., Soja et al. 2018; Umetsu 2020).

The ICM distribution is asymmetric in the interacting pair, showing a single peak related to eFEDS4746 (*X* in Fig. 9), located ~23′′ away from the corresponding mass peak. As this separation is less than the expected error on the mass peak centroid caused by the effects of shape noise and smoothing of the mass map (Dietrich et al. 2012), we cannot make any assumption about any possible spatial coincidence (or not) between the mass and gas peaks. On the other hand, the lack of an X-ray peak leads us to conclude that eFEDS4910 has temporarily lost its gas counterpart, a feature only seen in the class of dissociative mergers (Dawson 2013). Even so, such a highly asymmetric gas post-merger configuration is supported by the observed mass ratio, 1.7$^{+0.5}_{-0.3}$, as the ICM dynamics is mostly governed by the initial conditions of the gas distribution (e.g., concentration; Machado et al. 2015; Moura et al. 2021).

Since there are no spectroscopic redshift measurements for these galaxy clusters, we have to resort to their photometric redshifts estimated by G21 in order to address their kinematics. This was accomplished with an analytical two-body analysis applied to each pair to infer the possible pre- and post-merger scenarios. We confirmed that the pair eFEDS4746/4910 is highly likely bounded. On the other hand, the cluster eFEDS5418 is not gravitationally bound to either of eFEDS4746/4910 (when considered individually). This conclusion remains the same even in the case when we consider a fictional cluster formed from the merger between eFEDS4746/4910 (having the combined masses) placed midway their current positions, although
Figure 9. Summary of the analysis presented in this work. The gri image shows a zoomed-in view of the three clusters. The yellow diamonds are cluster coordinates according to G21, and the red X is the position of the single X-ray peak. Our weak lensing analysis has identified six significant mass peaks (i.e., $\geq 4\sigma_\kappa$, A–F in decreasing order of significance), whose locations are shown by the cyan points (halos C and F are outside of the current field-of-view). Three of them correspond to the known clusters, eFEDS4910 (A), eFEDS4746 (B), and eFEDS5418 (D). At the outskirts of eFEDS4746/4910, there are two radio relics (RSE and RN; magenta squares), a hint of a recent merger activity. The cyan contours represent the convergence map in units of $\sigma_\kappa$, starting from $4\sigma_\kappa$. 
the probability of the unbound scenario decreases to 52 per cent. Therefore, our analysis does not support the conjecture proposed by G21 that eFEDS5418 is a pre-merger and part of the supercluster. Regarding the last feature, this is not surprising since the selection criterion adopted by G21 is based solely on the local over-density instead of a more physically motivated one (e.g., occurrence of a future gravitational collapse; Chon et al. 2015).

Our proposed kinematic description posits that eFEDS4746 and eFEDS4910 are undergoing a major merger orientated with an axis of 42°±24°33 degrees from the plane of the sky. Despite the error bars, such a large angle can explain the absence of any brightness and temperature jumps at the positions of both radio relics, as these features can be detected even at angles as large as 30 degrees (C22). The pericentric passage happened 0.5±0.15 Gyr ago. We can also provide an alternative estimation of the merger age, by computing the time required for the shock to travel from the cluster centre (in this case the midpoint with RA = 09:35:14, DEC = +00:49:39) to the relic RNE, whose projected location to the pericentric passage (C22). Therefore, it could have an important role in the cluster mass measurement (C22) and consequently on the whole merger kinematic description, depending on whether it is determined from a scaling relation (obtained from relaxed halos; Duffy et al. 2008) or included as a free parameter in the modeling. After testing the two scenarios, we found comparable masses and therefore, similar merger histories. A possible explanation for such an agreement is, at the current merger phase (i.e., at the current time since the pericentric passage), any changes in $c_{200}$ have completely vanished. Unfortunately, a direct comparison with the temporal evolution of $c_{200}$ presented in C22 (see their Fig. 4) is not possible, as the authors presented it in terms of an arbitrary time, starting from the beginning of the simulation.

5 SUMMARY

Based on the second public data release of the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP PDR2), we present the first weak gravitational lensing reconstruction of the matter distribution in the Northern part of the eFEDS supercluster, where Ghirardini et al. (2021) found an interacting cluster pair (eFEDS4746/4910) surrounded by a companion (eFEDS4518). The masses of the clusters are found to be $2.73^{+1.08}_{-1.48} \times 10^{14}$ M$_\odot$ (eFEDS J093513.3+004746), $2.63^{+0.96}_{-1.18} \times 10^{14}$ M$_\odot$ (eFEDS J093510.7+004910), and $2.43^{+1.07}_{-1.30} \times 10^{14}$ M$_\odot$ (eFEDS J093501.1+005418), based on our analysis. Our result supports the scenario drawn from the X-ray and radio observations, in which eFEDS4746 amd eFEDS4910 are undergoing a major merger. However, eFEDS5418 does not show any evidence of being gravitationally bound to the pair. We also found no impact of the halo concentration on the mass modeling and kinematic description, irrespective of the method employed (i.e., from a scaling relation or being a free parameter of the lensing model). A spectroscopic follow-up of the cluster members can offer a complementary view of the merger dynamics and corroborate our results, which are based solely on photometric redshifts.

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To accomplish the results presented here, I used the R software. For more details, please visit https://www.r-project.org/

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DATA AVAILABILITY

All data used in this work is already publicly available. However, the processed data can be shared under request to the author.

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