MERGING CLUSTERS OF THE DARC SAMPLE: studying the formation of galaxy clusters

Marisa Girardi, Rafael Barrena, and Walter Boschin

(1) Dip. di Fisica, Univ. di Trieste – Trieste – Italy; (2) I.A.C.; (3) INAF-TNG

Abstract

Extended, diffuse radio emissions (halos and relics) embedded in galaxy clusters are rare phenomena. Here I present a few results of the DARC program, aimed to study the internal Dynamics Analysis of "Radio"-Clusters mainly based on a TNG program (spectroscopic data for 20 clusters at z=0.1-0.3). The study of kinematics of member galaxies show that DARC clusters are examples of very substructured systems and allow us to detect and weight the intervening subclusters as well as to determine their relative motions and projected geometry. The observational scenario, reinforced by X-ray data too, agrees with the DARC clusters being in the phase of the formation through a major merger. I present here some interesting examples.

1 Introduction

Merging processes constitute an essential ingredient of the evolution of galaxy clusters (Feretti et al. 2002). An interesting aspect of these phenomena is the possible connection between cluster mergers and extended ($\sim$ 1 Mpc), diffuse radio sources: halos and relics. The synchrotron radio emission of these sources demonstrates the existence of large-scale cluster magnetic fields and of widespread relativistic particles. Cluster mergers have been proposed to provide the large amount of energy necessary for electron reacceleration to relativistic energies and for magnetic field amplification (Tribble 1993). Radio relics, which are polarized and elongated radio sources located in the cluster peripheral regions, seem to be directly associated with merger shocks (e.g., Ensslin et al. 1998). Radio halos, unpolarized sources that permeate the cluster volume in a similar way to the X-ray emitting gas (intracluster medium, hereafter ICM), are more likely to be associated with the turbulence following a cluster merger (e.g., Cassano & Brunetti 2005). However, the precise radio halos/relics formation scenario remains unclear because diffuse radio sources are quite uncommon and one has been able to study these phenomena only recently on the basis of a sufficient statistics (few dozen clusters up to $z \sim 0.4$, e.g., Feretti et al. 2011). It is expected that new radio telescopes will largely increase the statistics of diffuse sources (e.g., LOFAR).

From the observational point of view, there is growing evidence of the connection between diffuse radio emission and cluster merging, above all from X-ray observations (Casano et al. 2010; Feretti et al. 2011).

Optical (photometric and spectroscopic) data on cluster galaxies are a powerful way to investigate the presence and the dynamics of cluster mergers, too (e.g., Girardi & Biviano 2002). The optical information is really complementary to X-ray information since galaxies and the ICM (i.e. $\sim$ collisionless and collisional cluster components) react on different time-scales during a merger.

2 The DARC project

In the above context, we are conducting an intensive observational and data analysis program to study the internal dynamics of clusters with diffuse radio emission by using member galaxies (see also the web site of the DARC project: $http://adlibitum.oat.ts.astro.it/girardi/darc$).

The DARC project is mainly based on spectroscopic data acquired at the 4m class Italian telescope, TNG, which, equipped with DOLORES/MOS instrumentation, is well suited to study the internal dynamics of clusters exhibiting radio halos/relics having redshift in the range of z=0.1-0.3, i.e. a large part of known clusters exhibiting these phenomena.

For each DARC cluster we sampled a significant fraction of the cluster virial region with about 100 galaxies having redshifts, magnitudes, and colors. Additional information comes from the equivalent width (EW) of the relevant lines for basic spectral characteristics and from the analysis of the cluster outskirts, as obtained from large-field multiband-photometry at the wide field camera of the INT telescope or available in the Sloan Digital Sky Survey.

For each cluster, we obtain: a) the estimate of global optical and dynamical properties; b) the detection and significance of optical substructures; c) the membership and dynamical properties of individual substructures. In the specific case of major cluster collisions we can estimate: d) the projected direction of the merger axis; e) the projected separation of subclusters; f) the individual mass of the subclusters and thus the mass ratio of the merger; g) the line-of-sight (LOS) velocity difference between the subclusters.

For each cluster, information about the ICM hot component is available in public literature or obtained from data in public archives. The comparison between X-ray and optical data (and results from numerical simulations) is very useful to estimate the age of the merger. We discuss our findings in the framework of a multiwavelength approach, i.e. cf. with X-ray, radio, and gravitational lensing results.

3 Results

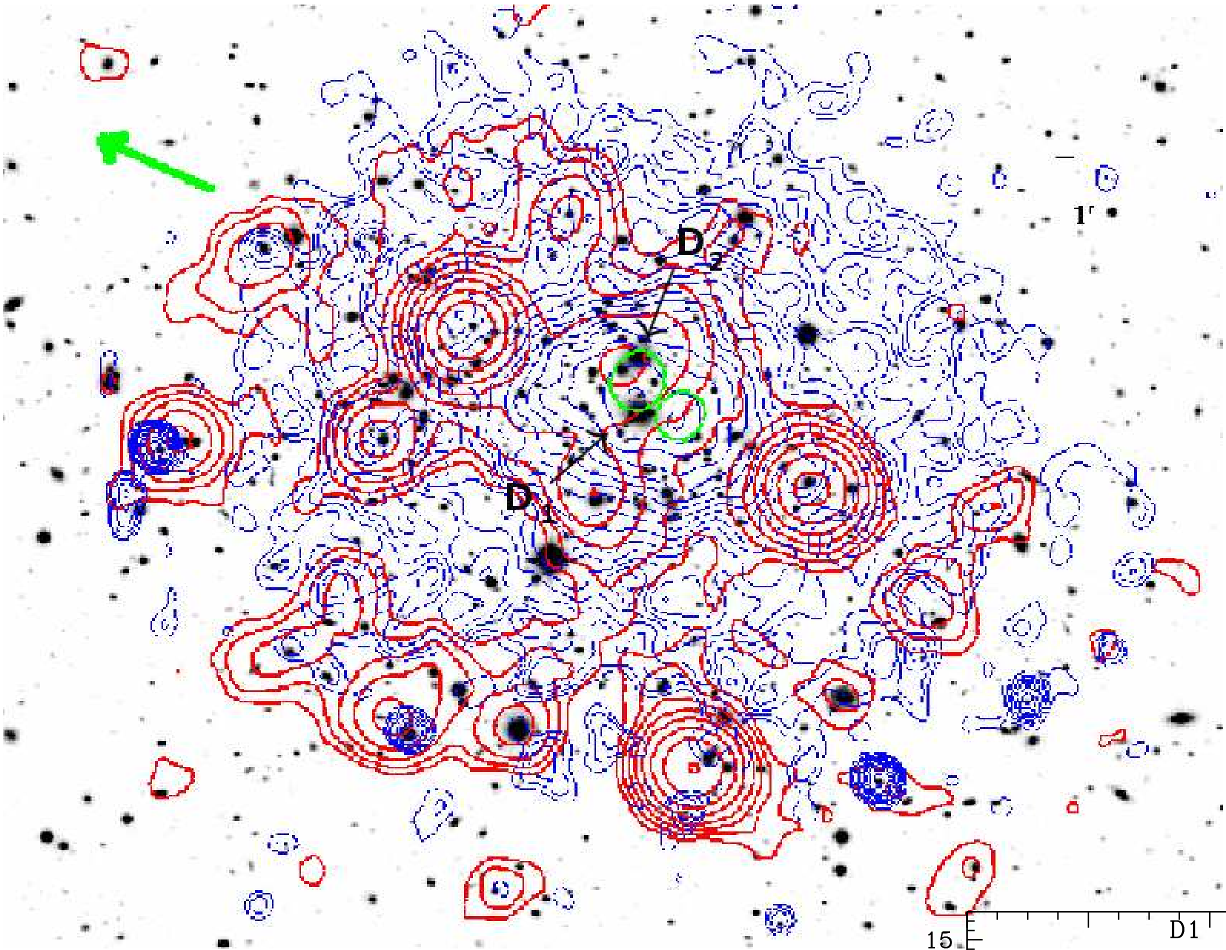
In the context of the DARC project we have already analyzed 18 clusters (Abell 115, 209, 520, 545, 610, 697, 725, 796, 773, 959, 1240, 1914 1995, 2219, 2254, 2294, 2345, 2744) and the study of other two clusters (ZwCl2341+00 and Abell 1351) is going on. Our results can be summarized as:

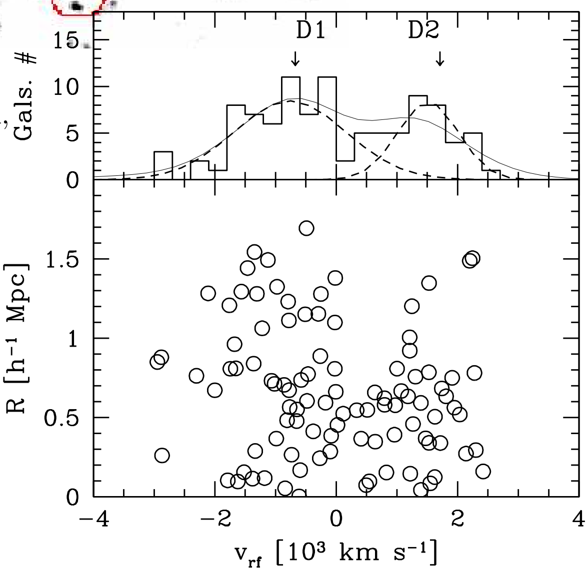
- **DARC clusters have a high gravitational mass ($M \sim$ 1-4 $\times 10^{15}$ h_{70}^{-1} $M_{\odot}$ within R_{200}).**
- **DARC clusters show the presence of strong substructure and, in most cases, we can detect the intervening subclusters. In the well studied cases, the observational scenario agrees with the DARC clusters being in a post-merger phase, few Gyr after the core-core passage, and with the rest-frame velocity difference between the subclusters of the order of 1000-4000 km s^{-1}. Our conclusion supports the view of the connection between extended radio emission and energetic merging phenomena in galaxy clusters.**
- **We find that the subclusters are (very often) traced by their brightest/dominant galaxies (BCGs) and that the evolution of galaxy systems is parallel to the evolution of their BCGs. Two distant - in space and/or in velocity - BCGs correspond to two well distinct subclusters. We interpret two close BCGs or one very elongated BCG as due to a more advanced phase of merger.**

Hereafter we show a few examples of DARC clusters: A520 (Girardi et al. 2008, A&A, 491, 379); A545 (Barrena et al. 2011, A&A, 529, A128); A697 (Girardi et al. 2006, A&A, 455, 45); A773 (Barrena et al. 2007, A&A, 467, 37); A1240 (Barrena et al. 2009, A&A, 503, 357); A1995 (Boschin et al. 2012, A&A, accepted); A2254 (Girardi et al. 2011, A&A, 356, 89).

Abell 773: a line-of-sight merging cluster with a radio halo.

The velocity distribution of the cluster galaxies shows two peaks at $v \sim$65000 and $\sim$67500 km s^{-1}, corresponding to the velocities of the two dominant galaxies D1 and D2. Our analysis of Chandra data shows the presence of two very close peaks in the core and the elongation of the X-ray emission in the ENE-WSW direction. **Our results suggest we are looking at a one, likely two groups in advance phase of merging with a main cluster with an impact velocity is $\Delta v_{\rm rf} \sim 2500$ km s^{-1}.**





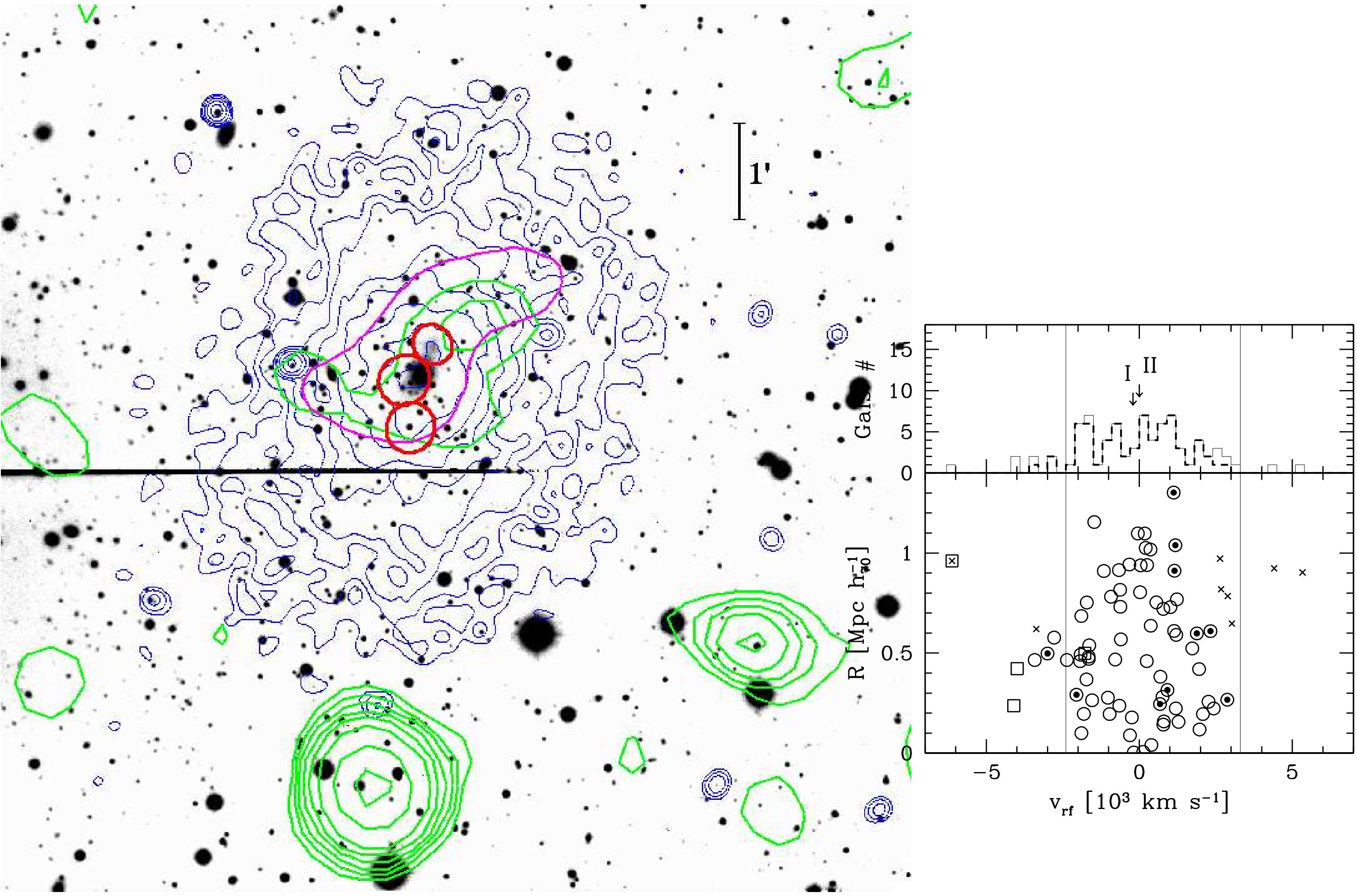
UPPER PANEL: INT *R*-band image of the cluster A773 with, superimposed, the contour levels of the Chandra image (blue) with the two separated peaks (green), and the contour levels of the Radio image (red). The direction of the close cluster A782 is also shown. North is at top and East to left.

RIGHT PANEL: velocity distribution of the cluster galaxies, where the two peaks are centered around the velocities of the two dominant galaxies.

Abell 697: an advanced phase of a complex merger?

We compute the line-of-sight (LOS) velocity dispersion of galaxies, $\sigma_{\rm v} = 1334^{+114}_{-95}$ km s^{-1}, in agreement with the high average X-ray temperature $T_{\rm X}$ =(10.2±0.8) keV recovered from Chandra data, as expected in the case of energy-density equipartition between galaxies and gas. Further investigations find that A697 is not fully relaxed, as shown by the non Gaussianity of the velocity distribution, the elongation of the X-ray emission, and the presence of small-size substructures in the central region.

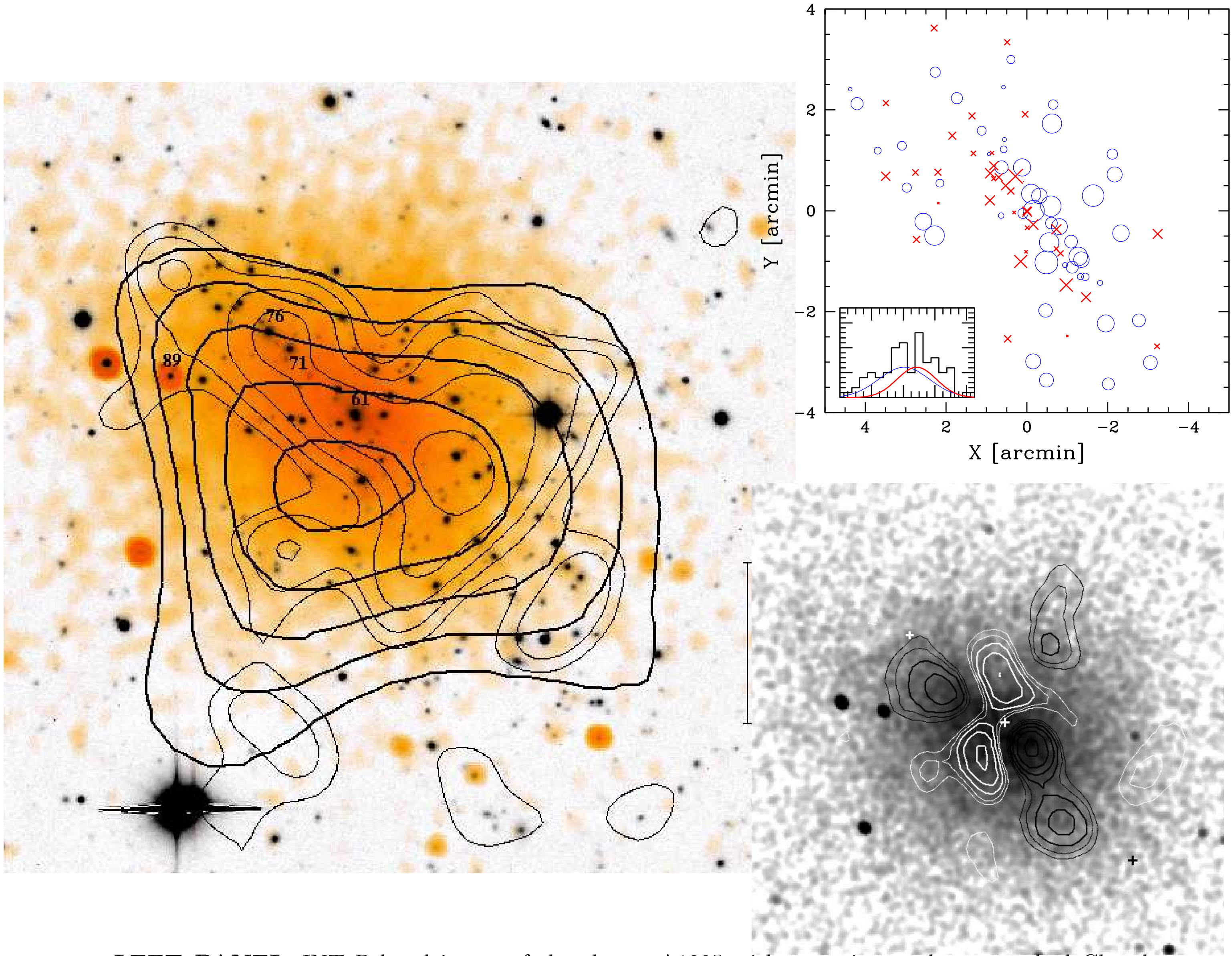
Our results suggest that we are looking to a cluster undergone to a complex cluster merger occurring roughly mainly along the LOS, with a transverse component in the SSE-NNW direction. The dominant galaxy has a main and a secondary nuclei - I and II - close in velocity.



LEFT PANEL: *R*-band image of the cluster A697 with, superimposed, the contour levels of the Chandra image (blue contours) and NVSS radio image (green contours). Red ellipses identify structures detected by Wavdetect. To avoid confusion, only one isodensity contour of the spatial distribution of the (likely) cluster members is shown (magenta). North is at the top and East to the left. **RIGHT PANEL**: velocity distribution of the cluster galaxies, where I and II indicate the two nuclei of the BCG. In the lower panel the distribution of the cluster galaxies in the velocity-radius plot is shown.

Abell 1995: a merging cluster with an elongated radio halo

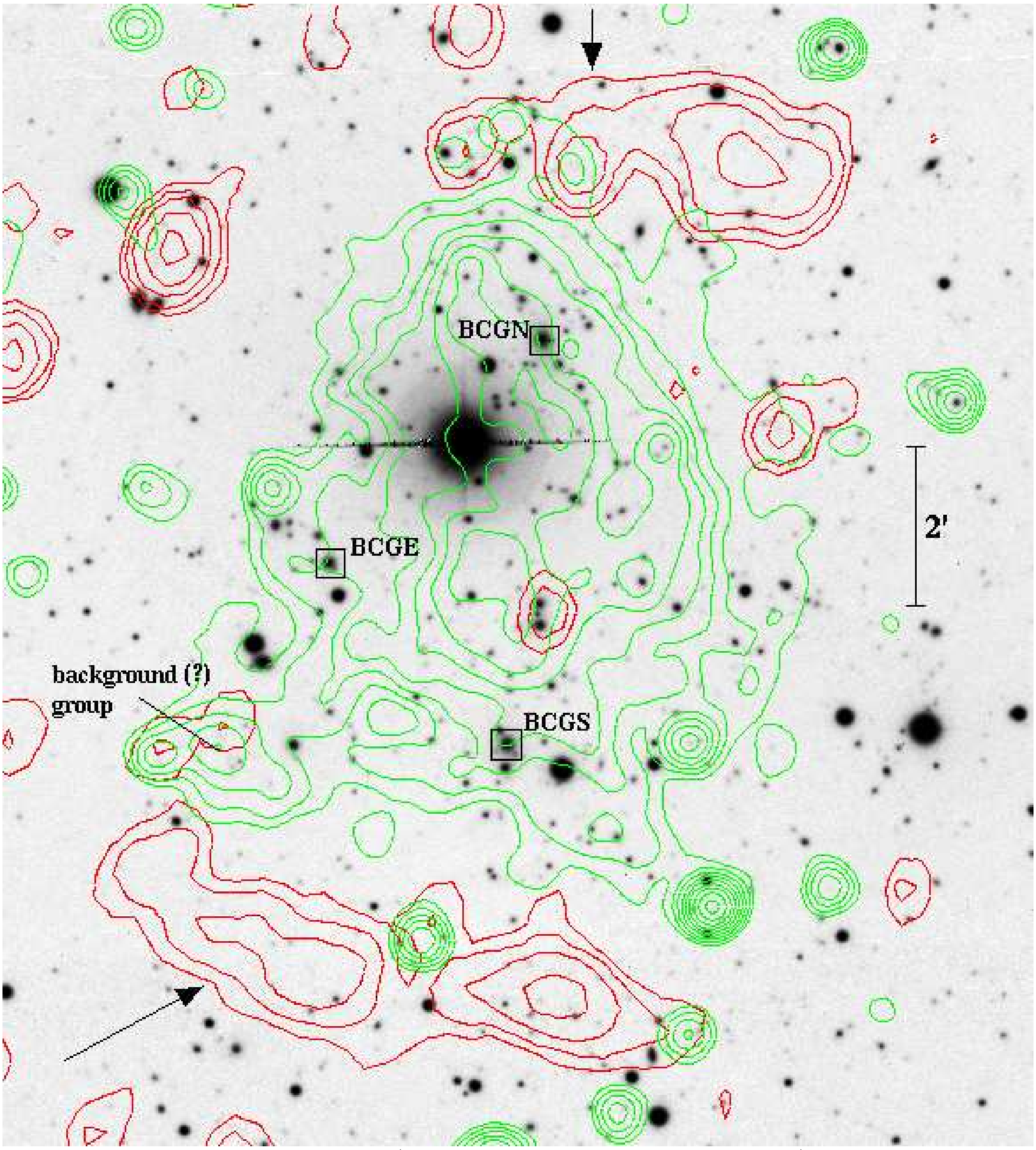
We compute the line-of-sight (LOS) velocity dispersion of galaxies, $\sigma_V = 1302^{+107}_{-71}$ km s^{-1}. Our analysis shows the presence of two galaxy-clumps and a velocity gradient along the NE-SW direction, the same of the radio halo elongation. The BCG lies in the middle of the two peaks of the velocity distribution. As for the X-ray analysis, we confirm the NE-SW elongation of the X-ray isophotes and find evidence of three peaks. Two X-ray peaks are offsetted and lie between the two optical subclusters, thus suggesting a bimodal merging catched in a phase of post core-core passage. The third X-ray peak lies between the NE galaxy peak and a third, minor galaxy peak suggesting a more complex merger. **In this scenario, the remaining puzzling point concerns the dark matter distribution, which is quite circularly symmetric (Dahle et al. 2002; Holhjem et al. 2009) with respect to the quite elongated galaxy and gas distribution we analyze.**



LEFT PANEL: INT R-band image of the cluster A1995 with, superimposed, a smoothed Chandra image (orange) and the contours of the of a VLA radio image (thin lines, Giovannini et al. 2009, the radio halo) and the mass distribution contours reconstructed from the weak-lensing analysis (thick contours, Holhjem et al. 2009). **UPPER RIGHT PANEL**: the 2D and velocity distribution of the two subclusters detected through our 3D optical analysis. **LOWER RIGHT PANEL**: X–ray emission with, superimposed, the contour levels of the positive (black) and negative (white) smoothed elliptical β-model residuals. Big crosses indicate the centers of the two main optical clumps detected from the 2D optical analysis.

Abell 1240: a cluster with symmetric double radio relics.

We estimate a LOS $\sigma_V \sim 870$ km s^{-1}. Abell 1240 is shown to have a bimodal structure with two galaxy clumps, each dominated by a brightest cluster galaxy, BCGN and BCGS, roughly aligned along the N-S direction, the same as defined by the elongation of its X-ray surface brightness (peaked between the two galaxy subclusters, Chandra archive data) and the axis of symmetry of the relics. A minor clump is likely associated with the third bright galaxy (BCGE). The two-body model agrees with the hypothesis that we are looking at a cluster merger that occurred largely in the plane of the sky, the two galaxy clumps being separated by a rest-frame velocity difference $V_{\rm rf} \sim 2000$ km s^{-1} at a time of 0.3 Gyr after the crossing core. **This estimate of the merging time and that the merging axis is perpendicular to the radio relics strongly support the "outgoing merger shocks" model.**

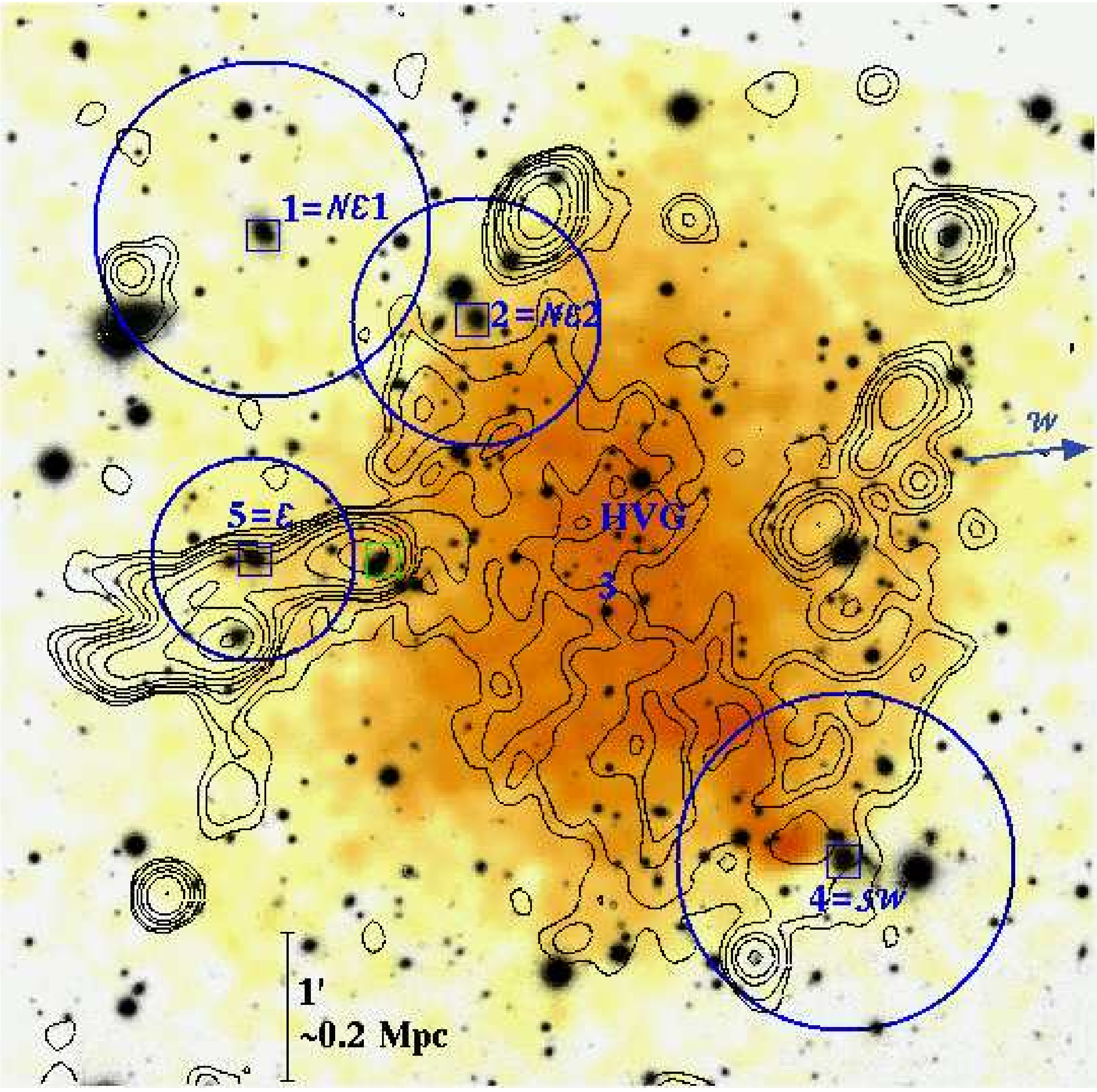


INT R-band image of the cluster A1240 (North at the top and East to the left) with, superimposed, the contour levels of the Chandra image (green contours) and the contour levels of a VLA radio image at 1.4 GHz (red contours; Bonafede et al. 2009). Arrows show the positions of the two radio relics. Boxes highlight the brightest galaxies of A1240: BCGN, BCGS, and the third, minor BCGE.

Abell 520: a cluster at the crossing of three LSS filaments.

Our analysis is based on redshift data for 293 galaxies in the cluster field. We detect the presence of a high velocity group (HVG) with a rest-frame relative LOS velocity of $v_{rf} \sim 2000$ km s^{-1} with respect to the main system (MS). We also find that the MS shows evidence of subclumps along two preferred directions. The main, complex structure $\mathcal{NE}1$+$\mathcal{NE}2$ and the $\mathcal{SW}$ structure (at $v_{rf} \sim +1100$ km s^{-1}) define the NE-SW direction, the same of the merger suggested by X-ray and radio data. The $\mathcal{E}$ and $\mathcal{W}$ structures define the E-W direction. Moreover, we find no dynamical trace of the lensing dark core suggested by Mahdavi et al. (2007), see aldo Jee et al. (2012). Rather, the HVG and a minor MS group, having different velocities, are roughly centered in the same position of the lensing dark core, i.e. are somewhat aligned along the line-of-sight.

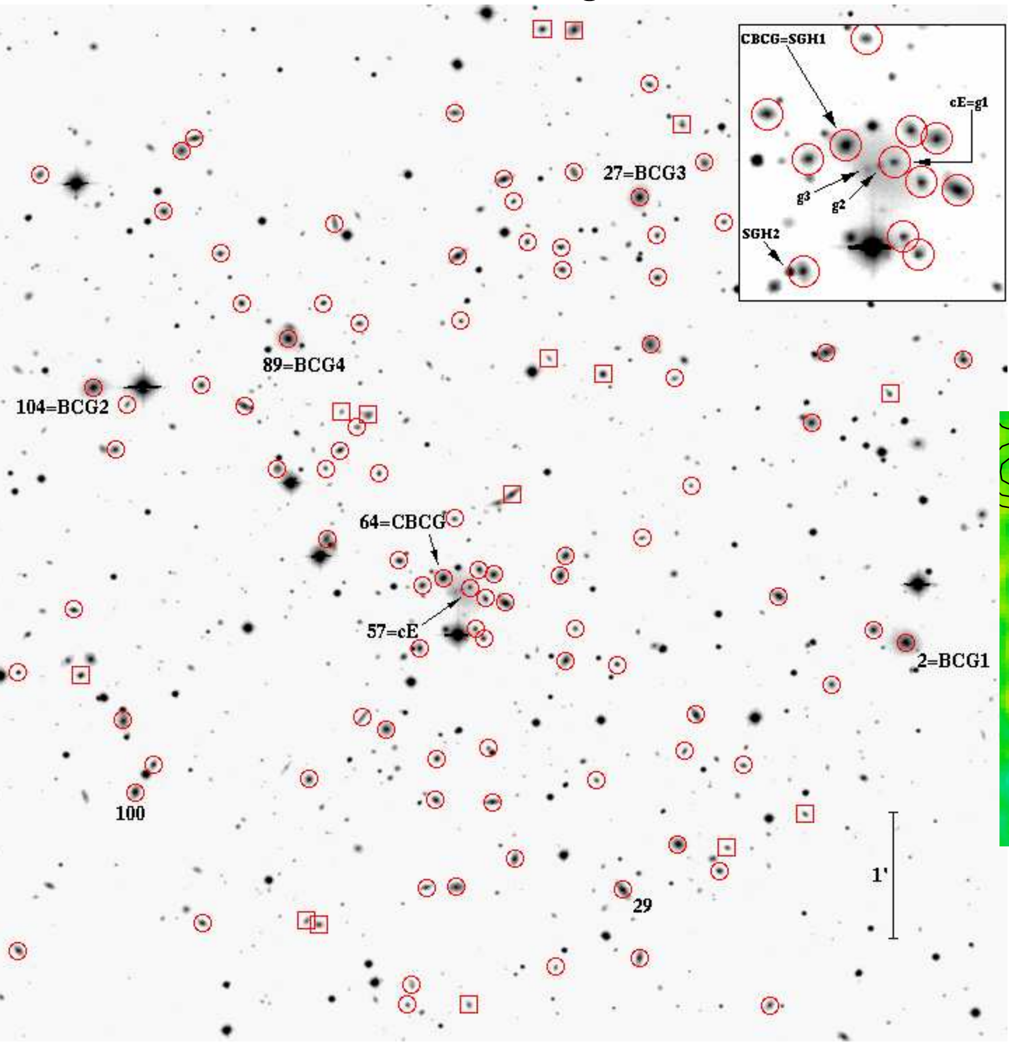
Our results suggest that we are looking at a cluster forming at the crossing of three filaments of the large scale structure, each intervening subclump having its BCG.

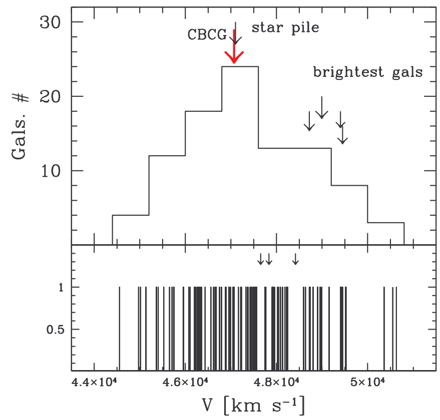


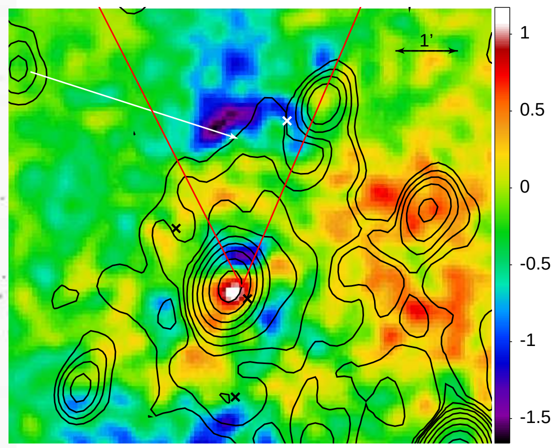
Multiwavelength picture of A520 (North is at the top and East to the left). A smoothed Chandra image (orange and yellow colors) of the central region of A520 (by Markevitch et al. 2005) is superimposed to a r'-band image taken with the WFC camera of the INT. The contour levels of a VLA radio image at 1.4 GHz (by Govoni et al. 2001) are shown, too. Main structures recovered by our analysis are highlighted. Label HVG indicates the center of the high velocity group having a relative LOS velocity of $v_{rf} \sim 2000$ km s^{-1} with respect to the main system (MS). Blue squares indicate the BCGs for each subcluster.

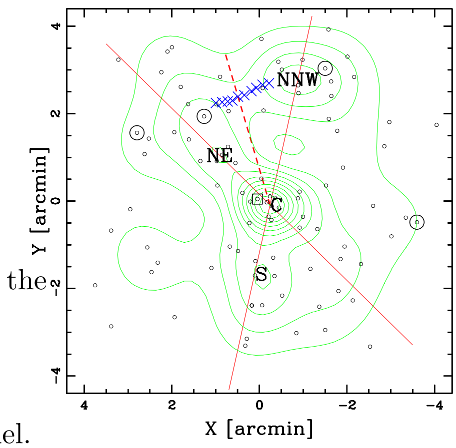
Abell 545: a merging cluster with a forming BCG?

Optical data reveal three main galaxy clumps (one at the center hosting the peak of X-ray emission; one at NNW, and one at NE). There is not a dominant galaxy and the four brightest galaxies avoid the cluster core. The analysis of the X-ray surface brightness distribution (XMM archive data) provides us evidence of a disturbed dynamical phase: the strong NNW-SSE elongation, a western excess, and a sharp discontinuity in the northern region which is the possibly signature of a shock. Located in the central region there is a bright, red diffuse very bright intracluster light (star pile) and a bright galaxy (CBCG). We show that the ICL, which has a previously determined redshift (Salinas et al. 2007), has a similar redshift to that of the CBCG and that of the cluster. The emerging picture of Abell 545 is that of a massive, $M(R < 1.6\ h_{70}^{-1}\mathrm{Mpc}) = (1.1\text{–}1.8) \times 10^{15}\ h_{70}^{-1}\ M_{\odot}$, very complex cluster with merging occurring along two directions. **The intracluster light "star pile" is likely due to the process of a brightest galaxy forming in the cluster core, is related to the accretion along the NE direction.**





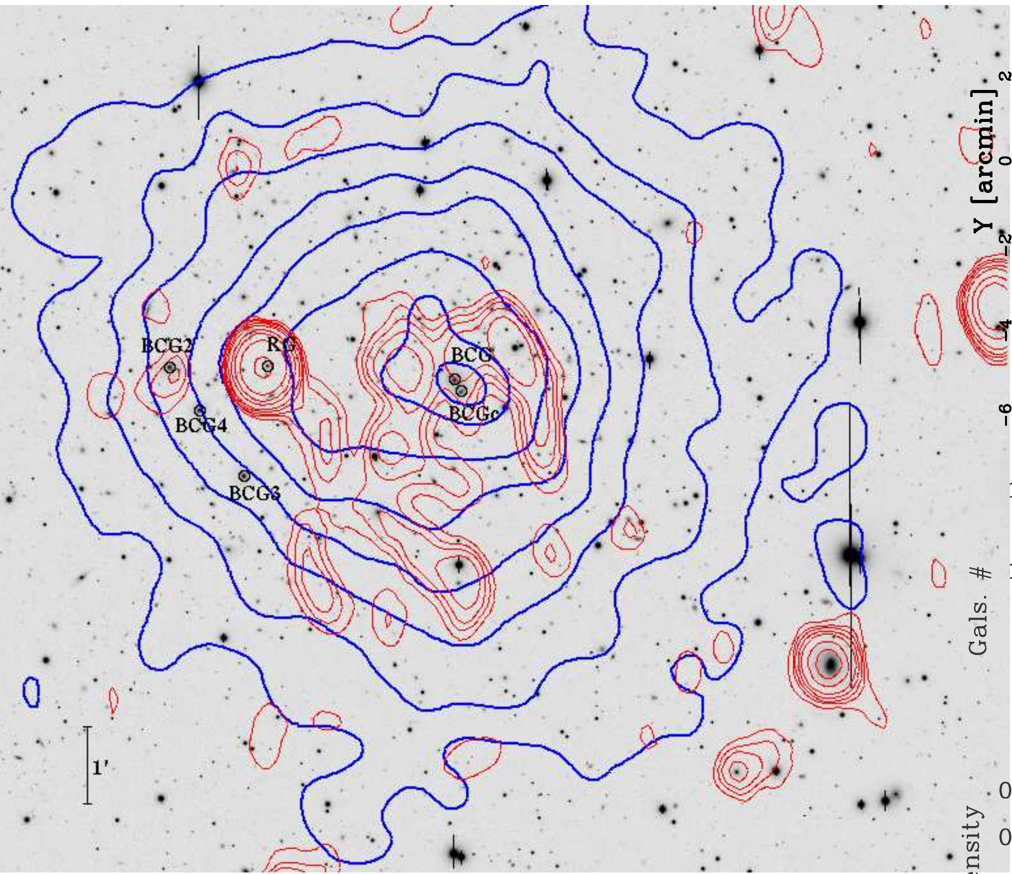


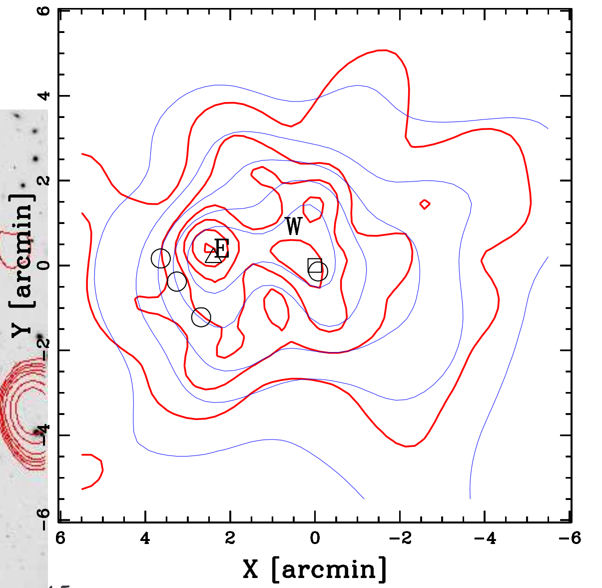


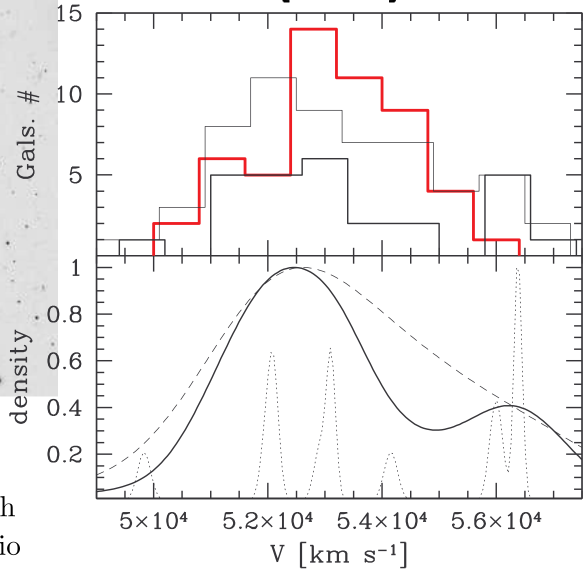
LEFT PANEL: INT r'-band image of the cluster A545. Circles and squares indicate spectroscopically cluster members and non-members. In the inset figure the corresponding IDs of Salinas et al. (2007) are given, too. **TOP-RIGHT PANEL**: velocity distribution of the cluster galaxies. **MIDDLE-RIGHT PANEL**: residuals of the X-ray surface brightness map (XMM-data) after subtraction of the best fitting elliptical beta model. The black contours show the extended radio emission (Bacchi et al. 2003). The arrow indicates the position of the North surface brightness jump, possibly a signature of a shock. **BOTTOM-RIGHT PANEL**: spatial distribution and isodensity contours. Circles and square indicate the four brightest galaxies and the CBCG. The two red lines indicate the two likely merging directions. Blue crosses indicate the sharp discontinuity detected in the X-ray surface brightness.

Abell 2254: a merging cluster with a clumpy radio emission

We estimate the line-of-sight (LOS) velocity dispersion, $\sigma_{\rm V} \sim 1350$ km s^{-1} , and the X-ray temperature $kT \sim 6.4$ keV. 2D and 3D analyses show the presence of a eastern high velocity ($\Delta V_{\rm rf,LOS} \sim 3000$ km s^{-1}). The main system is likely substructured, too. The X-ray analysis (XMM archive data), based on power ratios, centroid shifts, and concentration parameter, confirms that Abell 2254 is a dynamically disturbed cluster. The X-ray isophotes are elongated toward the eastern direction, in agreement with a merger in the post core-crossing phase. **The E-subcluster does not contain any bright galaxy and is a low mass ($\sigma_{\rm V} \sim 200$–500 km s^{-1}) group. This might explain why no secondary X-ray peak is detected, being the E-group completely stripped of its gas content.**







LEFT PANEL Subaru V-band image of the cluster A2254 with (blue) contours of the XMM-image and (red) contours VLA radio image (Govoni et al. 2001).

UPPER-RIGHT PANEL: spatial distribution and isodensity contours of two samples of Subaru photometric cluster members with $i' \leq 20.5$ and with $i' \leq 21.5$ (blue and red contours, respectively). **LOWER-RIGHT PANEL**: velocity distributions of the galaxies in the western and eastern samples (red and black lines, respectively). The velocity distribution of a subsample of the eastern sample, i.e. the 27 galaxies within a radius of 1.5′ from the E-peak (E1.5-sample), is also shown (black thick line). In the lower panel, the velocity galaxy density, as provided by the DEDICA adaptive-kernel reconstruction method for the E1.5 sample (solid line).