

# DARC

## - DYNAMICAL ANALYSIS OF “RADIO” CLUSTERS

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### Abstract

Extended, diffuse radio emission (halos and relics) in galaxy clusters is a rare phenomenon. The origin of these radio sources and their connection with cluster mergers is still being debated. Here we present the results of the DARC program, aimed to the internal Dynamics Analysis of “Radio” Clusters and mainly based on a long-term TNG-INT program (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 interveining subclusters, as well as to obtain information about their relative motions and the merger geometry. The multiwavelength observational picture of DARC clusters is well interpreted in a scenario of a recent, major cluster merger.

## 1 Introduction

Merging processes constitute an essential ingredient of the evolution of galaxy clusters (see Feretti et al. 2002 and refs. therein). 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., Giovannini et al. 2009). 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 (Feretti 2008 and refs. therein).

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://adlbitum.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 (e.g., Girardi et al. 1998); 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 (e.g., the Chandra archive). The comparison between X-ray and optical data (and results from numerical simulations) is very useful to estimate the age of the merger.

Applying the two-body model we also obtain an estimate of the angle of view of the merger and therefore we can suitably deproject observed distances and impact velocities of the subclusters.

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 14 clusters (Abell 115, 209, 520, 610, 697, 725, 796, 773, 959, 1240, 2219, 2294, 2345, 2744 and the study on other 6 clusters is going on).

To date our results can be summarized as:

- Most DARC clusters have a relatively high gravitational mass, i.e.  $\sim 1\text{--}4 \times 10^{15} h_{70}^{-1} M_{\odot}$  within  $R_{200}$ ).
- All DARC clusters show presence of strong substructure and for most of them 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  $1000\text{--}4000 \text{ km s}^{-1}$ . 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 traced by their brightest/dominant galaxies (BCGs) and that the evolution of galaxy systems is parallel to the evolution of their BCGs: i.e., i) two distant - in space and/or in velocity - BCGs correspond to two well distinct subclusters; ii) two close BCGs - or one elongated BCG - correspond to a substructured cluster where the intervening subclusters (or more likely their remnants) are detectable with difficulty. We interpret these two families of clusters with two different merger stages (less and more advanced, respectively).

Hereafter we show a few examples of DARC clusters.

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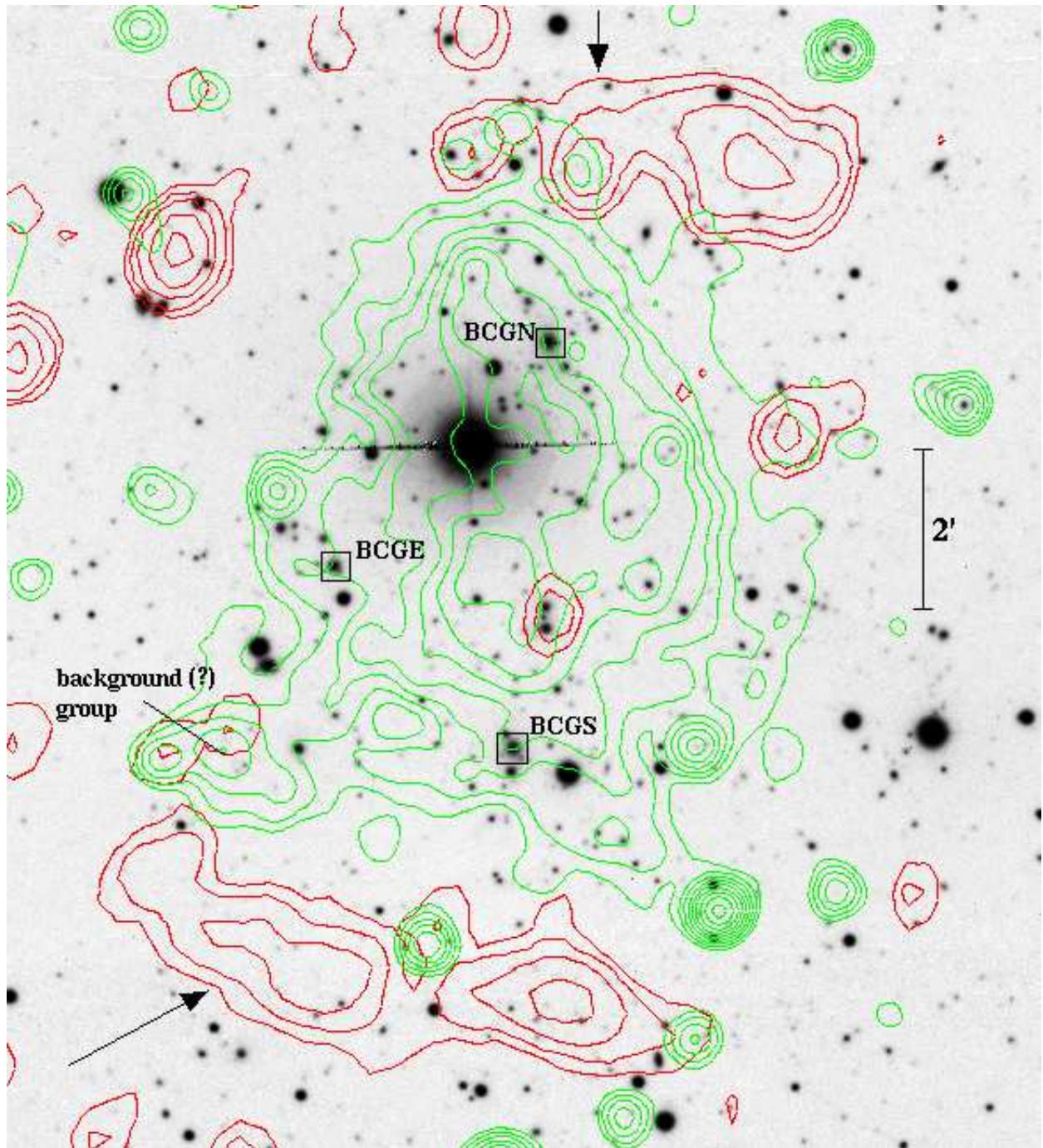
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## Abell 1240: a cluster with symmetric double radio relics

We estimate a LOS  $\sigma_V \sim 870 \text{ km s}^{-1}$ . Abell 1240 is shown to have a bimodal structure with two galaxy clumps, each dominated by a BCG, 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.

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  $V_{\text{rf}} \sim 2000 \text{ km s}^{-1}$  at a time of 0.3 Gyrs after the crossing core. The merging axis is perpendicular to the radio relics strongly supporting support the “outgoing merger shocks” model.

See Barrena et al. (2009, A&A, 503, 357) for other details.



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.

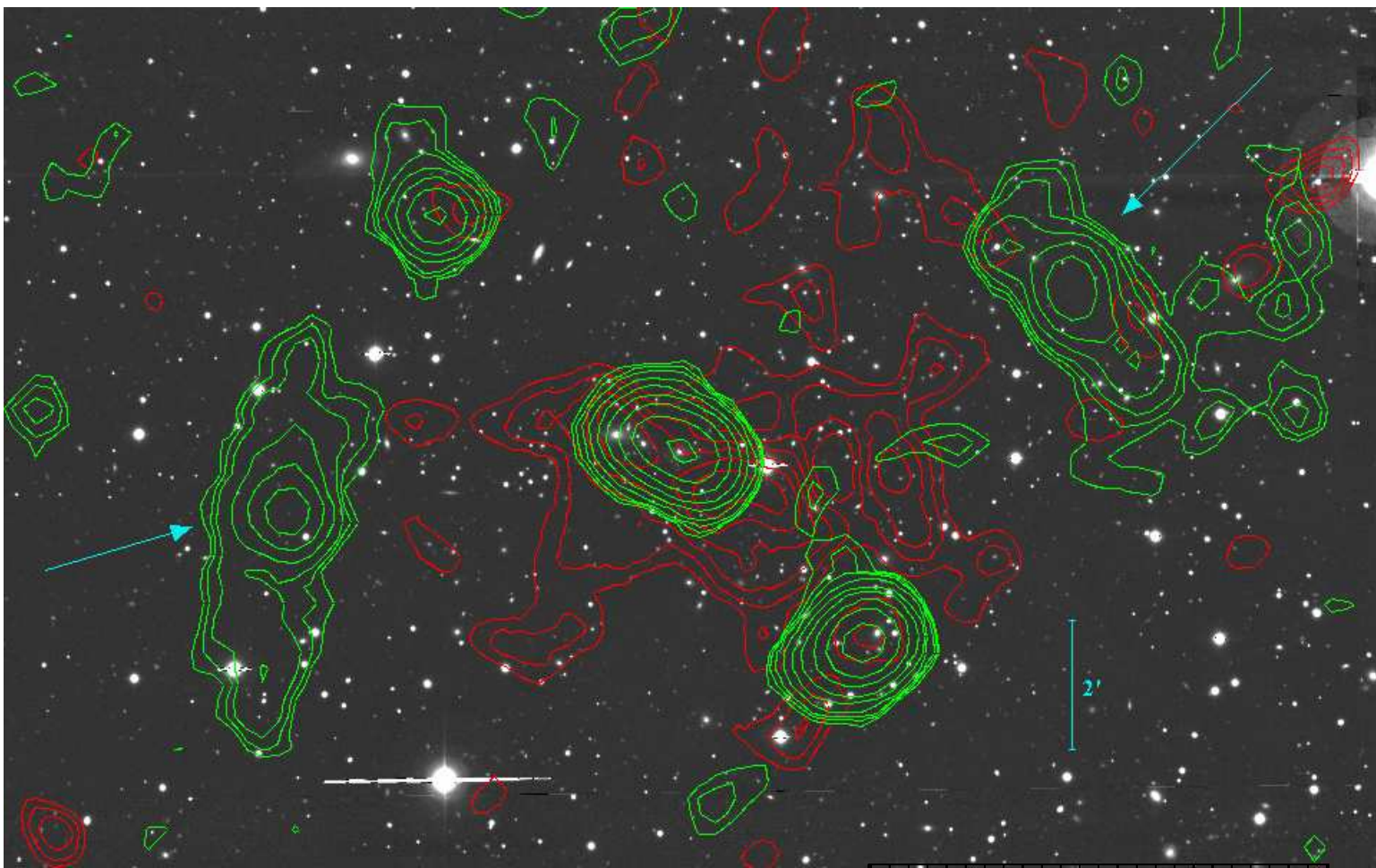


# Abell 2345: a cluster with two non-symmetric radio relics

The photometric and spectroscopic catalogs reveal the presence of, at least, three galaxy subclumps, the E-, SW-, and NW- clumps). The SW- and NW-clumps have similar mean velocities, while the E-clump has a larger mean velocity ( $\Delta V_{\text{rf}} \sim 800 \text{ km s}^{-1}$ ). The ROSAT X-ray data also show a very complex structure, mainly elongated in the E-W direction, with two (likely three) peaks in the surface brightness distribution, which, however, are off-set from the position of the peaks in the galaxy density.

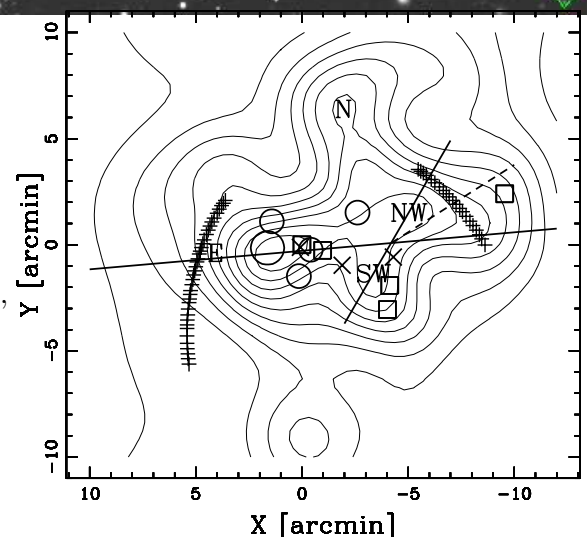
The observed phenomenology agrees with the hypothesis that we are looking at a complex cluster merger occurring along two directions: a major merger along the  $\sim$ E-W direction and a minor merger in the western cluster regions along the  $\sim$  N-S direction. The eastern radio relic is elongated in the direction perpendicular to that of the major merger, while the peculiar, western radio relic is elongated in the direction perpendicular to the bisecting of the two merger directions.

See Boschin et al. (2010, A&A, forthcoming paper) for other details.



UPPER: INT  $r'$ -band image of the cluster A2345 (North at the top and East to the left) with, superimposed, the contour levels of the ROSAT/HRI archival image (red contours) and the contour levels of a VLA radio image at 1.4 GHz (green contours, see Bonafede et al. 2009). Arrows highlight the contour levels of the two radio relics.

RIGHT: Isocontours of the 2D galaxy distribution. X-ray peaks, DM peaks, and more luminous galaxies are indicated by crosses, circles, and squares.



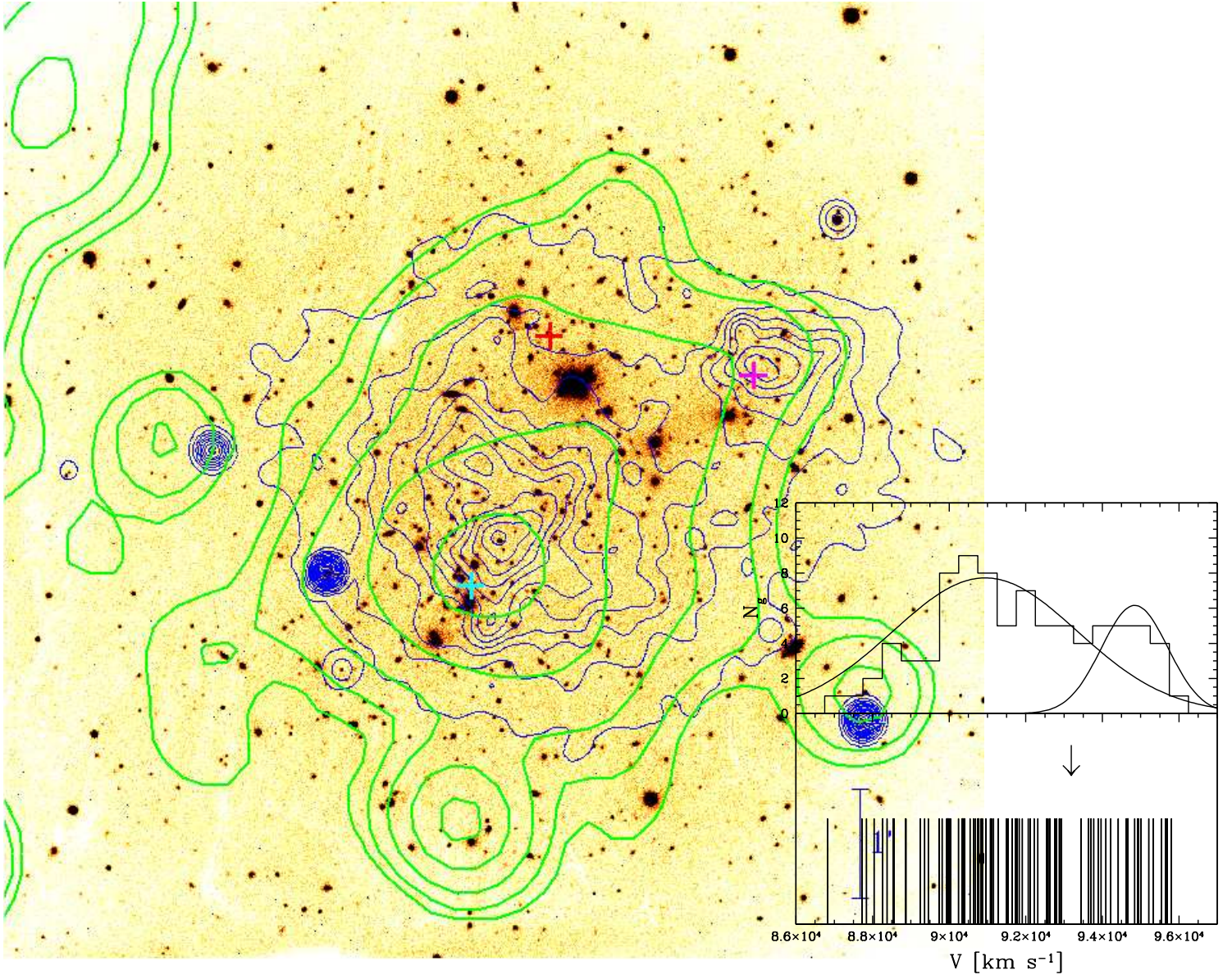


# Abell 2744: a LOS cluster merger with halo+relic

We compute the line-of-sight (LOS) velocity dispersion of galaxies,  $\sigma_V = 1767^{+121}_{-99}$  km s<sup>-1</sup>, which is significantly larger than what is expected in the case of a relaxed cluster with an observed X-ray temperature of 8 keV. Our analysis shows the presence of two galaxy-clumps of different mean LOS velocities  $\Delta V \sim 4000$  km s<sup>-1</sup>. We detect a main, low-velocity clump with  $\sigma_V \sim 1200$ -1300 km s<sup>-1</sup> and a secondary, high-velocity clump with  $\sigma_V = 500$ -800 km s<sup>-1</sup> and located in the S-SW cluster region.

**Our results suggest a merging scenario of two clumps with a mass ratio of 3:1 and a LOS impact velocity of  $\Delta V_{\text{rf}} \sim 3000$  km s<sup>-1</sup>, likely observed just after the core passage.**

See Boschin et al. (2006, A&A, 449, 461) for other details.



LEFT: NTT R-band image of the cluster A2744 with, superimposed, the contour levels of the Chandra archival image ID 2212 (blue contours, see Kempner & David 2004) and of a VLA radio image at 1.4 GHz (green contours by Govoni et al. 2001). The X-ray image shows the central and the NW peaks, as well as the north and south secondary peaks. The radio image shows the powerful radio halo and (partially) the NE relic. The three gray crosses indicate the position of the three peaks detected in the 2D galaxy distribution of the likely cluster members according to the photometric redshifts. North is at top and east to left.

RIGHT: Velocity distribution of cluster galaxies, where the two peaks are centered around the velocities of the two BCGs.

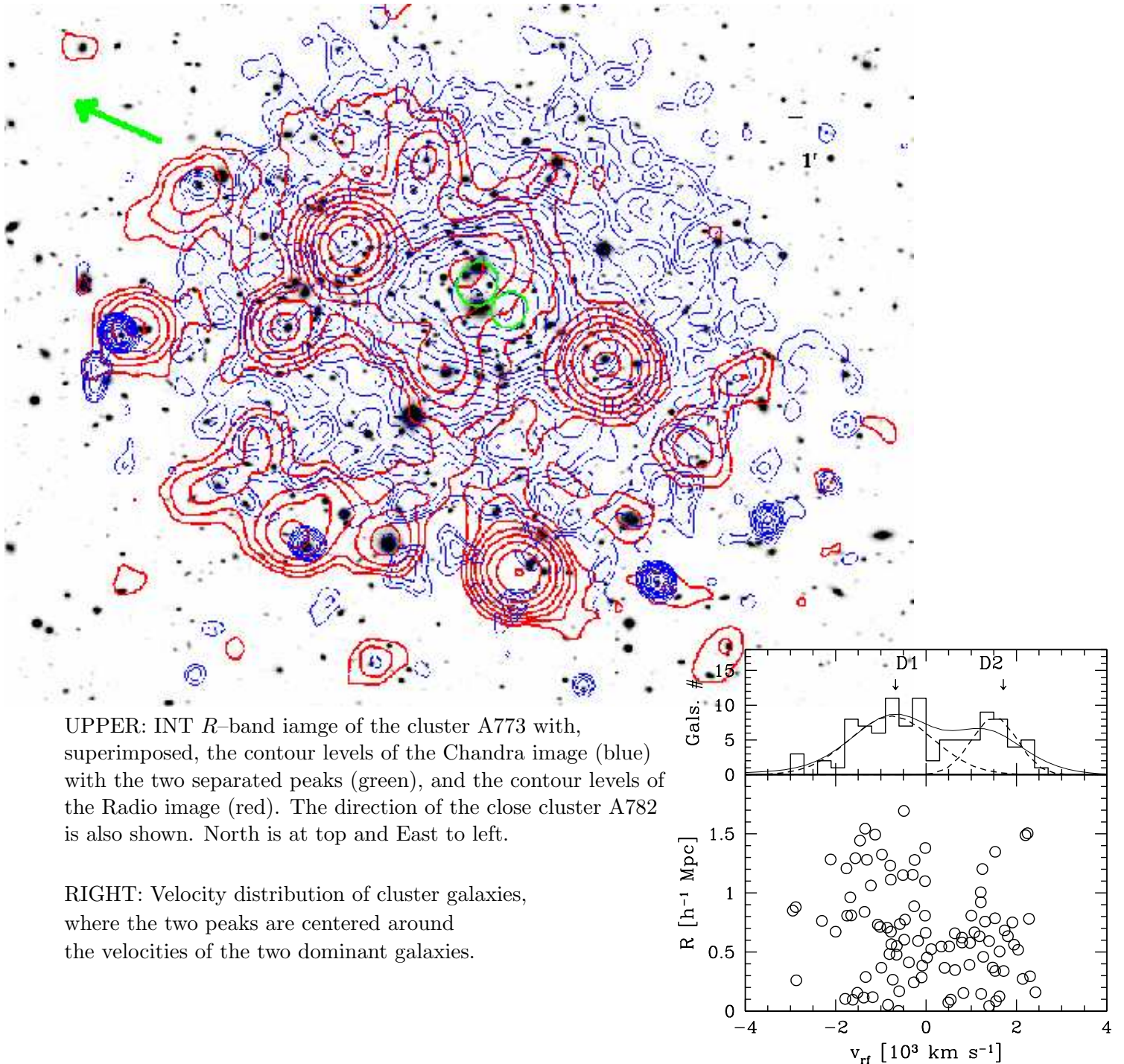


# Abell 773: a LOS cluster merger with radio halo

The 2D galaxy distribution shows two significant peaks separated by  $\sim 2'$  along the EW direction with the main, western one closely located to the position of the two dominant galaxies and the X-ray peak. The velocity distribution of cluster galaxies shows two peaks at  $v \sim 65000$  and  $\sim 67500$   $\text{km s}^{-1}$ , in correspondence of the velocities of the two dominant galaxies. 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  $\Delta v_{\text{rf}} \sim 2500$   $\text{km s}^{-1}$ .**

See Barrena et al. (2007, A&A, 467, 37) for other details.





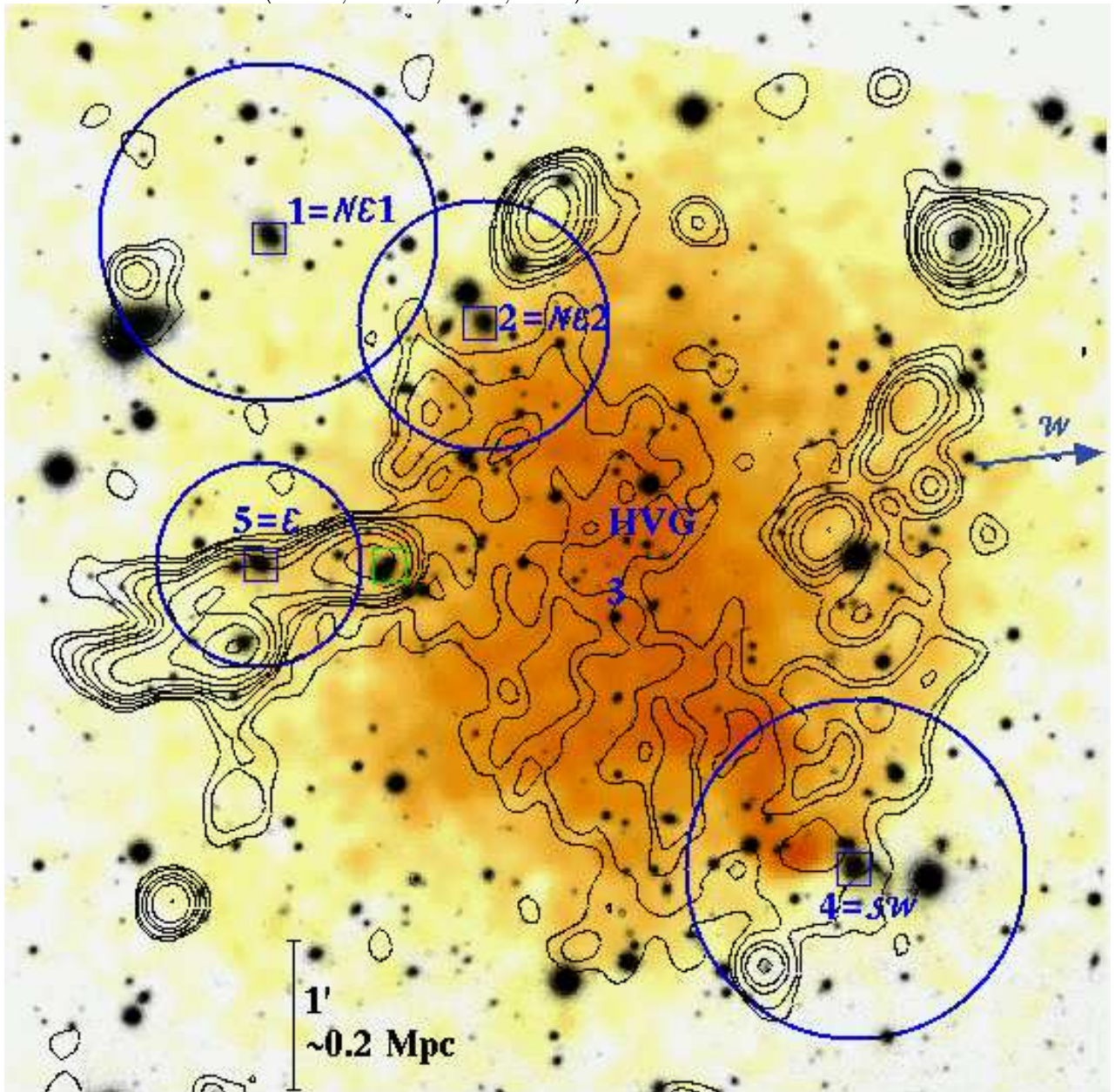
# Abell 520: a cluster at the crossing of three LSS filaments

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  $v_{\text{rf}} \sim 2000 \text{ km s}^{-1}$  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  $v_{\text{rf}} \sim +1100 \text{ km s}^{-1}$ ) 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). 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 with the LOS.

**Our results suggest that we are looking at a cluster forming at the crossing of three filaments of the large scale structure.**

See Girardi et al. (2008, A&A, 491, 379) for other details.



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  $v_{\text{rf}} \sim 2000 \text{ km s}^{-1}$  with respect to the main system (MS).

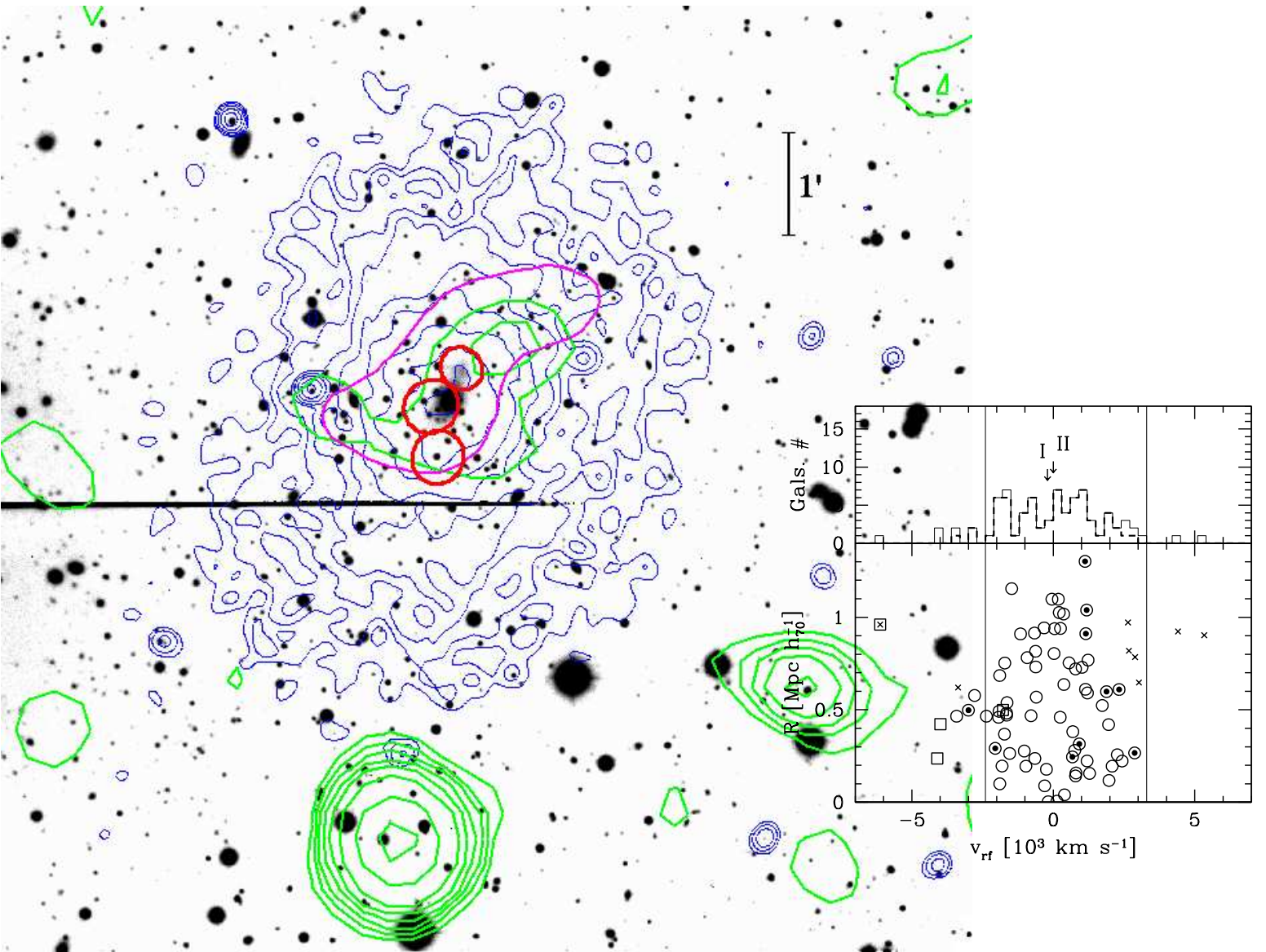


# Abell 697: an advanced phase of a complex merger?

We compute the line-of-sight (LOS) velocity dispersion of galaxies,  $\sigma_v = 1334_{-95}^{+114}$  km s<sup>-1</sup>, in agreement with the high average X-ray temperature  $T_X = (10.2 \pm 0.8)$  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.

See Girardi et al. (2006, A&A, 455, 45) for other details.



LEFT: *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: Velocity distribution and “caustics” of cluster galaxies.