Lensing Detection of Substructures around the Post-Merger Galaxy Cluster MS0451-03

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Introduction

Galaxies clusters are the largest and rarest structures resulting from the ΛCDM hierarchical formation process. Since their properties depend on the growth of structure, clusters are ideally suited to testing cosmological models. There are approximately 80% of a cluster's mass composed by dark matter. Although this component is invisible, the total mass along a line of sight can be mapped by gravitational lensing. The distinctive signatures of strong gravitational lensing (multiple images or giant arcs) probe the mass distribution in the inner region of clusters, while weak gravitational lensing provides constraints on the cluster environment on larger scales. Combining strong and weak-lensing analyses can thus constrain the mass distribution across the entire cluster.

In this study, we use a wide-field HST/ACS imaging mosaic of 41 images (a total area of ~ 460 arcmin^2) and XMM-Newton observations to conduct a combined strong- and weak-lensing and X-ray analysis of the galaxy cluster MS 0451−03 (z = 0.54). The high angular resolution afforded by space-based imaging increases the signal-to-noise ratio (S/N) of lensing measurements.

Lensing 2D Mass Map

We preform a combined SL+WL analysis to reconstruct the projected (2D) mass distribution of MS 0451−03 using Lenstool. There are three ingredients in our mass model:

- The potential in the cluster core region are fixed by the best-fit strong-lensing mass model from Jauzac et al. (2020).
- Weak-lensing shear signals are calibrated from *pyRRG* software. Background galaxies are selected by using their photometric redshifts and color.
- Cluster members are also included as they act as small-scale perturbers in the lensing effect.

The resulting total mass distribution is shown in Fig. 1.

Features of Main Halo

From the combined SL+WL and X-ray analysis, we constrain some fundamental properties of the main dark matter halo:

- $M_{200c} = (1.65 \pm 0.24) \times 10^{15} M_{\odot}$
- $c_{200c} = 3.79 \pm 0.36$
- Axis-ratio, $q = 0.48 \pm 0.01$
- Splashback radius, $r_{sp} > 1.49$ Mpc
- Baryonic-mass fraction, $f_{b,500} = (14.6 \pm 1.4)\%$
  <—consistent with the mean cosmic baryon fraction from the Cosmic Microwave Background

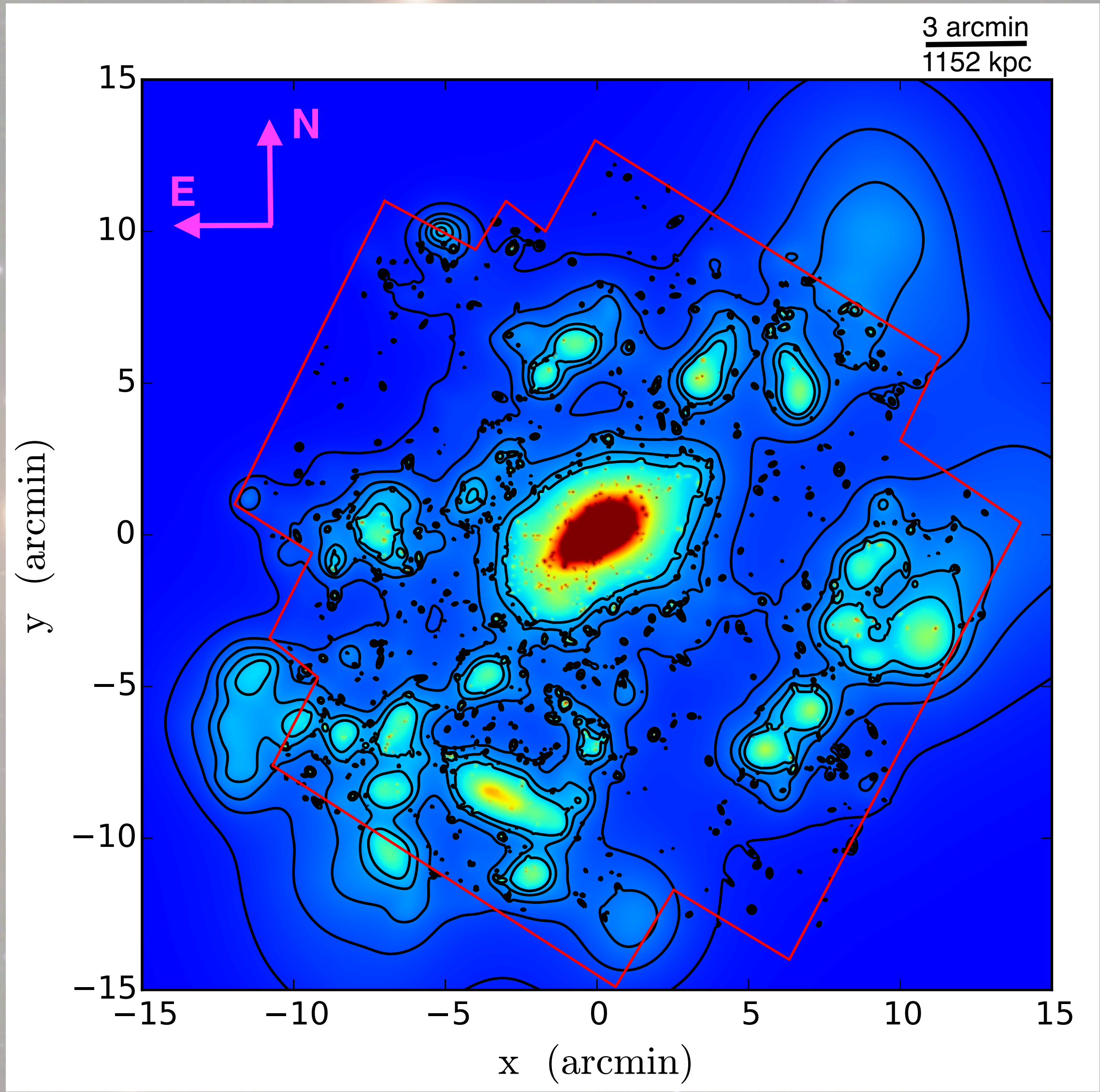

Fig. 1. The projected distribution of mass around MS 0451, inferred from our Lenstool strong+weak-lensing reconstruction and centred on the BCG (α=73.545202, δ=−3.0143863). Colours indicate the projected convergence, ϰ. The red polygon delineates the field of view of the HST/ACS imaging mosaic.

Group-Scale Substructures

In the MS 0451-03's cluster field, we detect a total of 14 weak-lensing peaks with S/N>3 integrated within circular apertures of radius R<480kpc. We found that 6 of them (labelled by red circles in Fig. 2) have optical counterparts of cluster members at the cluster redshift range, $0.48 < z < 0.61$. We thus infer that these structures are part of the extended cluster, while all others (labelled by black circles in Fig. 2) are projections of structures at other redshifts along our line of sight.

We constrained the lensing mass range of these cluster substructures:

$6.1 < M(10^{13} M_{\odot}) < 13.5$

Filaments

Based on the distribution of substructures around MS 0451, we propose that three possible filaments are connected to the cluster core (shown as green lines in Fig. 2), with mean convergence <κ> ~0.022.

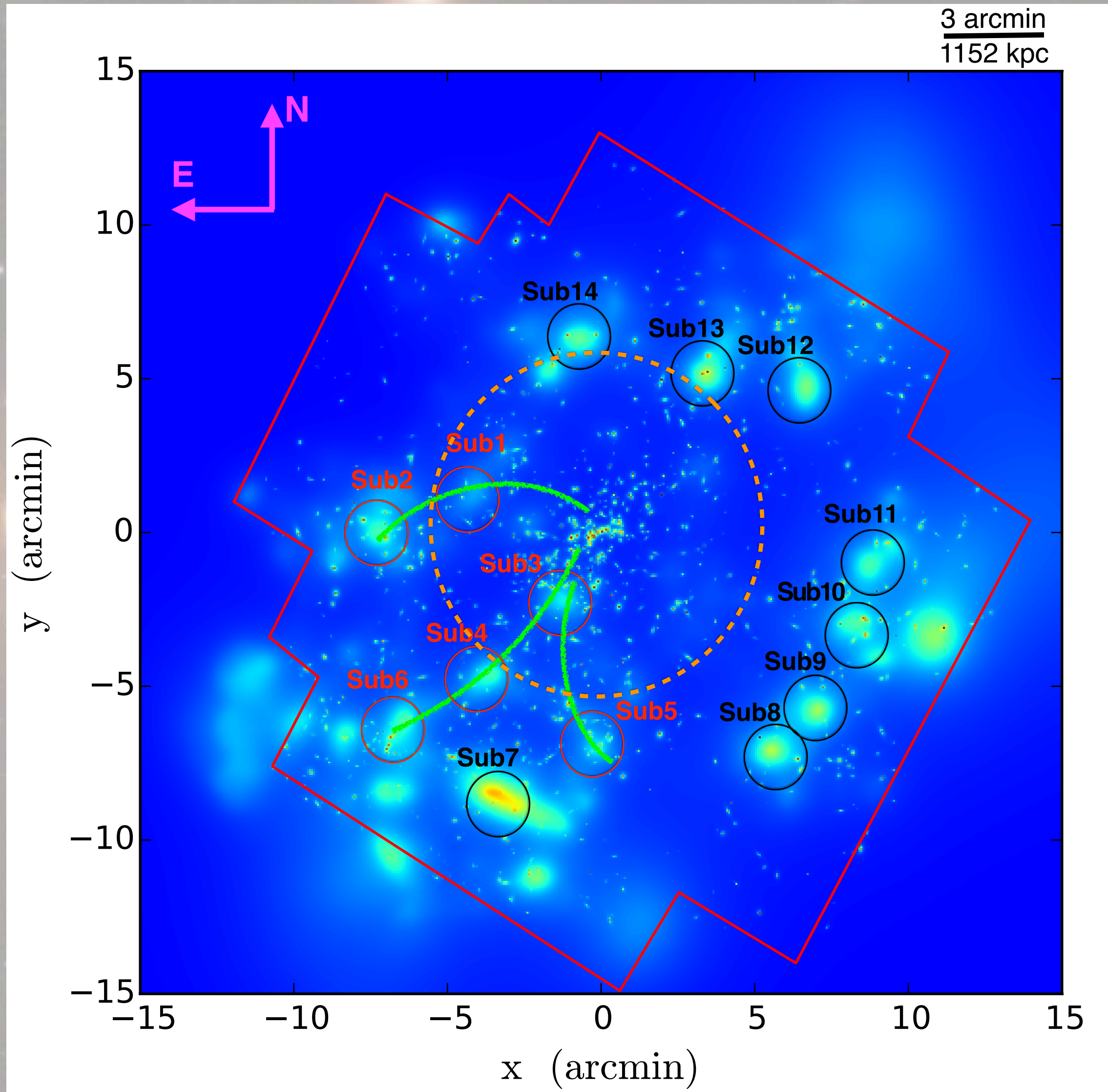

Fig. 2. The low density environment surrounding MS 0451. The colour image shows lensing convergence with SL potentials subtracted. The dashed orange circle has radius R200c = 1.99 Mpc. Red Smaller circles (with radius 480 kpc) mark cluster substructures. Green lines suggest the extent and direction of possible large-scale filaments.

Dynamical State of MS0451-03

We compare the lensing results with X-ray analysis:

- Lensing: bimodal and elongated distribution of dark matter with concentration c_{200c}=3.8±0.37

- X-ray: spherical distribution of gas with excess entropy near the core, and low concentration $c_{200c,HSE}$=2.4±0.7.

Combining these with the result of N-body and hydrodynamic simulations, we infer that MS 0451-03 is a post-merger state cluster with a major mergers 2-7Gyr after first core passage, now the two dark-matter halos approach second turnaround.

This dynamical history inferred from our analysis provides a possible explanation for the quenched star formation history observed in this system by Moran et al. 2007. They found that the star-formation in MS 0451 was abruptly quenched at redshift z=2, which is ~5 Gyr ago. This can be explained by the increased ram pressure stripping due to the major merger.

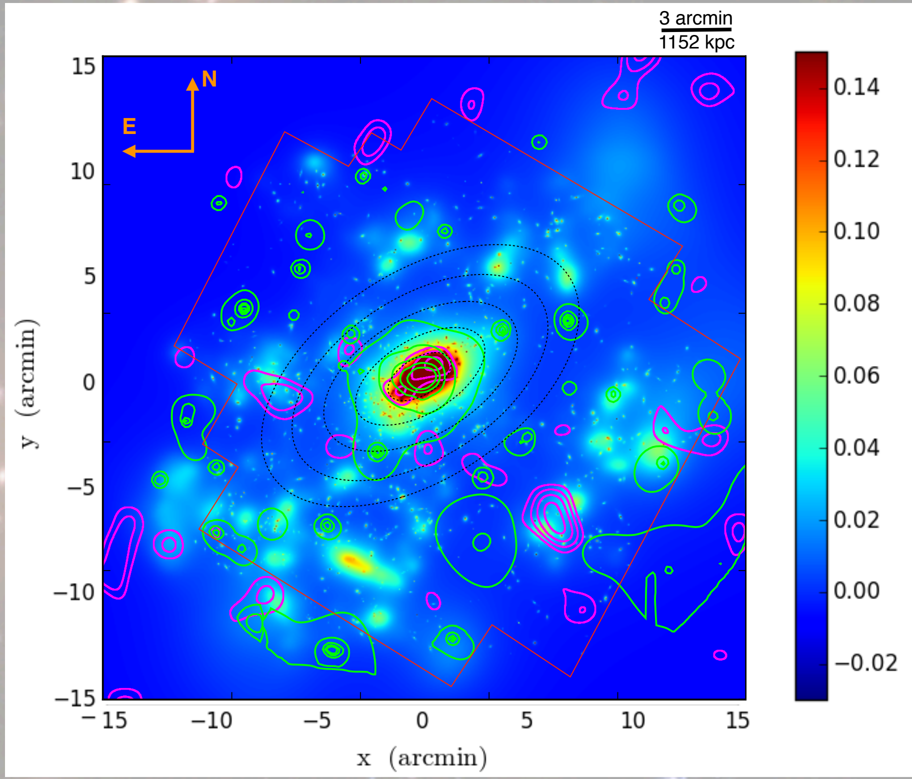

Fig.3. Alternative probes of the mass distribution around MS 0451, overlaid for ease of reference on Fig. 1. Magenta contours show weak-lensing measurements from ground-based observations (private communication N. Martinet). Green contours show the X-ray surface brightness as recorded by XMM-Newton.

Conclusion: MS 0451-03 will be a useful system for future studies of the growth of structures along filaments and late-stage evolution of bullet-type clusters.