

# What we learn from the Frontier Fields cluster MACS J0416.1–2403

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**Abstract.** The Frontier Fields cluster MACS J0416.1–2403 with its extensive imaging and spectroscopic data sets provides a great opportunity to study the mass distribution of the galaxy cluster and members, the high-redshift Universe and cosmology. By taking advantage of the observations in the 16 *Hubble Space Telescope* imaging bands of the Cluster Lensing And Supernova survey with Hubble (CLASH) survey and our large spectroscopic follow-up program with the VISIBLE Multi-Object Spectrograph (VIMOS) on the Very Large Telescope (VLT), we have been able to identify and obtain the spectroscopic redshifts of 10 important strong lensing systems in this cluster. Furthermore, we have selected and modeled the mass distribution of 200 candidate cluster members residing in the inner regions of the cluster. We present the results on the model-predicted central mass profile and subhalo population, which are detailed in Grillo *et al.* (2015). Work is underway to quantify the effects of line-of-sight structures. These are essential elements to make progress in our understanding of the dark matter distribution in massive galaxy clusters and of the distant Universe within the current Frontier Fields initiative and before the advent of the *James Webb Space Telescope*.

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## 1. Introduction

Observations of galaxy clusters provide powerful ways to probe the assembly of mass structure. Under the current  $\Lambda$ CDM paradigm, structures form hierarchically with massive systems in dark matter halos forming later through the accretion and mergers of smaller, self-bound “subhalos” of dark matter (e.g., Tormen 1997; Moore *et al.* 1999; Klypin *et al.* 1999; Springel *et al.* 2001). From an observational point of view, more studies of galaxy clusters are needed to answer key questions on the formation and evolution of the subhalos. How much mass of subhalos is stripped as they fall into the host potential? What are the mass and spatial distributions of the subhalos? Highly accurate studies of galaxy clusters are only becoming possible now, thanks to the substantially improved quality of the available photometric and spectroscopic data.

The *Hubble Space Telescope* (HST) Multi-Cycle Treasury program Cluster Lensing And Supernova survey with Hubble (CLASH; P.I.: M. Postman; Postman *et al.* 2012), complemented with the spectroscopic campaign carried out with the Very Large Telescope (VLT) (the CLASH-VLT Large Programme; P.I.: P. Rosati; Rosati *et al.* 2014), has been a major step forward in acquiring exquisite imaging and spectroscopic data sets on galaxy clusters. The current Hubble Frontier Fields (HFF; P.I.: J. Lotz) initiative will further provide the deepest-ever images of up to six massive galaxy clusters, achieving

a depth of  $\approx 29$  mag (AB). The HFF data provide a great opportunity to study the structure of the dark matter halos hosting these clusters.

In this proceeding, we focus on the HFF cluster MACS J0416.1–2403 (hereafter MACS 0416) that was first discovered in the X-rays by Mann & Ebeling (2012) as part of the Massive Cluster Survey (MACS). Building upon previous studies of MACS 0416 (e.g., Zitrin *et al.* 2013; Johnson *et al.* 2014; Richard *et al.* 2014; Jauzac *et al.* 2015; Diego *et al.* 2015), we perform a detailed strong lensing analysis of MACS 0416 containing (1) a large number of spectroscopic redshifts of strongly lensed background sources obtained through our CLASH-VLT program, (2) a robust approach of selecting cluster galaxies based on multi-color information calibrated on 113 spectroscopic members in the *HST* field of view, and (3) a detailed mass model that tests various methodological assumptions. Using our mass model, we compare the distribution of the cluster galaxies with those of the cluster subhalos from  $N$ -body simulations to probe with unexampled accuracy the substructure properties of a galaxy cluster.

We refer to Grillo *et al.* (2015) for details of these data sets and lens mass modeling. In the next section, we briefly describe the main modeling results.

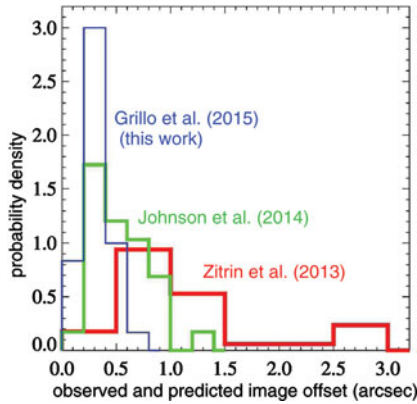
## 2. Lens modeling results

We use GLEE, a software developed by A. Halkola and S. H. Suyu (Suyu & Halkola 2010; Suyu *et al.* 2012), to model the lens mass distribution of MACS 0416. We describe the mass distribution of MACS 0416 with simply parameterized mass profiles for the cluster galaxies and dark matter halos. In particular, we use truncated isothermal spheres for the cluster galaxies with their masses scaled by the observed luminosity, and explore various scaling relations. For the cluster dark matter, we employ two cluster halo components with either cored pseudo-isothermal profiles or prolate Navarro-Frenk-White profiles (Navarro *et al.* 1996). To constrain the parameters of our lens mass model, we use the spectroscopic redshifts of the 10 background sources measured by CLASH-VLT and the positions of 30 corresponding lensed images from CLASH (see Table 3 of Grillo *et al.* 2015).

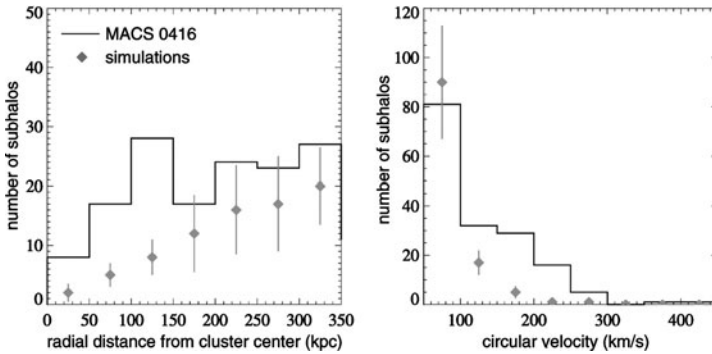
Of the six lens mass profile parameterizations that we have explored, the lens mass model which fits best to the observed multiple image positions is the one represented by cored elliptical pseudo-isothermal mass distributions for the cluster halos and truncated isothermal spheres with a mass-to-light scaling relation reflecting the tilt of the Fundamental Plane for the cluster members. The suite of models that we have considered allows us to obtain a realistic estimate of systematic uncertainty due to lens mass assumptions. The total enclosed mass within the Einstein radius is measured accurately to within  $\sim 5\%$ , including the systematic uncertainties. We stress that the knowledge of cluster membership based on extensive spectroscopic information and the use of multiple-image systems with spectroscopic redshifts are key to reconstructing robustly the cluster mass distribution.

In Figure 1, we show the offset in distance (in arcsec) between the observed and best-fitting model-predicted positions of the multiple images for our best-fitting model in comparison to those of Zitrin *et al.* (2013) and Johnson *et al.* (2014)<sup>†</sup>. Our model reproduces the observables with unprecedentedly high accuracy. More quantitatively, the

<sup>†</sup> These are the only two previous studies that presented the necessary numbers for this comparison. For the distribution of the image offsets for Johnson *et al.* (2014) we consider exactly our 10 multiple image systems. For Zitrin *et al.* (2013) we use 34 multiple image positions from 13 different sources (23 images of 8 sources are in common with ours).



**Figure 1.** Comparison of strong lens mass models: the probability distribution function of the offset in distance (in arcsec) between the observed and best-fitting model-predicted positions of the multiple-image systems considered by the models.



**Figure 2.** Subhalo distribution in terms of the projected distance from the cluster center (left) and of their circular velocity value within a two-dimensional aperture of 420 kpc (right). The histograms are based on our lens model of MACS 0416, and the points with bars show the median values with the  $1\sigma$  uncertainties obtained from  $N$ -body simulations.

rms offset is  $0.36''$  in our case,  $0.51''$  in Johnson *et al.* (2014),  $0.68''$  in Jauzac *et al.* (2015), approximately  $0.8''$  in Richard *et al.* (2014), and  $1.37''$  in Zitrin *et al.* (2013)‡.

From our mass model of MACS 0416, we can compare the mass and radial distribution of the cluster members with the subhalos of similar clusters extracted from  $N$ -body simulation. We refer to Bonafede *et al.* (2011), Contini *et al.* (2012) and Grillo *et al.* (2015) for more information on the simulations and the identification of cluster subhalos. In Figure 2, we compare, in projection along the line of sight, the observed number of cluster galaxies in MACS 0416 (histogram) and the number of simulated subhalos (points).

The number of subhalos in simulated clusters is underpredicted on all radial scales, as shown in the left-hand panel, especially in the inner  $\sim 150$  kpc of galaxy clusters. In the right-hand panel, we group the substructures in terms of their circular velocities  $v_{\text{circ}}$  (i.e., masses) irrespective of their locations within the clusters. For the low-mass cluster members with  $v_{\text{circ}} \lesssim 100 \text{ km s}^{-1}$ , the observed number is in good agreement with the predicted number from the  $N$ -body simulations. For cluster members with  $v_{\text{circ}}$

‡ we remark however that different analyses use different sets of multiple image systems

between  $\sim 100 \text{ km s}^{-1}$  and  $\sim 300 \text{ km s}^{-1}$ , the simulated clusters have fewer substructures compared to the observations.

These comparisons suggest that massive subhalos are not formed/accreted into the simulated clusters as rapidly as observed, or that tidal strippings of simulated massive subhalos are more efficient than observed, or both of these effects. We remark that the simulations are dark-matter only and do not contain baryons. The inclusion of baryons into subhalos would likely make the subhalos more tightly bound, which would make tidal stripping less effective and result in a higher number of simulated subhalos. This could perhaps explain in part the lower number of subhalos in simulations, although the baryonic effect might have little impact on the number of massive subhalos. We defer the comparison of substructure distributions in hydro simulations to future work which will provide insights on the formation of galaxy clusters and the role of baryons.

### 3. Summary and outlook

Through the exquisite observations from the CLASH and CLASH-VLT programs, we have performed a detailed strong lensing study and compared the central distribution of cluster members with dark-matter-only cosmological simulations in MACS 0416. Our lens mass model reproduces the observed multiple image positions within  $\sim 0.3''$  that is unprecedented. We find that MACS 0416 contains substantially more cluster galaxies in comparison to simulated galaxy clusters of similar total mass.

HFF clusters are massive clusters, with typically multiple structures projected along the line of sight to the background sources, as evident from the spectroscopic redshifts collected through the CLASH-VLT program. Current strong lens models of clusters incorporate explicitly only the cluster members, although various studies have estimated the effects of line-of-sight structures (e.g., D'Aloisio & Natarajan 2011; Caminha *et al.*, in prep.). Work is underway to include line-of-sight structures into our mass modeling that will allow us to characterize even better the inner mass distribution of clusters.

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