HST FRONTIER FIELDS PRELIMINARY MAP MODELING

CATs Team (Clusters As Telescopes)

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RECONSTRUCTION METHODOLOGY

Producing a magnification map involves solving the lens equation for light rays originating from distant sources and deflected by the massive foreground cluster. This is ultimately an inversion problem for which several sets of codes and approaches have been developed independently (see recent review by Kneib & Natarajan 2010). Our collaboration uses *LENSTOOL*[1], an algorithm developed collectively by us over the years. *LENSTOOL* is a hybrid code that combines observational strong- and weak-lensing data to constrain the cluster mass model. The total mass distribution of clusters is assumed to consist of several smooth, large-scale potentials that are modeled either in a parametric form or non-parametrically, along with contributions from many (typically N > 50) individual cluster galaxies that are modeled using physically motivated parametric forms. For lensing clusters a multi-scale approach is optimal, in as much as the constraints resulting from this inversion exercise are derived from a range of scales. Further details of the methodology are outlined in Jullo & Kneib (2009) and have been extended to the weak-lensing regime (Jauzac et al. 2012).

At present, the prevailing modeling approach is to assign a small-scale dark-matter clump to each major cluster galaxy and a large-scale dark-matter clump to prominent concentrations of cluster galaxies (Natarajan & Kneib 1997). This technique has proven very reliable and results in mass distributions that are in reasonably good agreement with theoretical predictions from high-resolution cosmological N-body simulations (Natarajan et al. 2007). This explicit one-to-one correspondence between mass and light is less accurate, however, in the outer regions of clusters where the galaxy distribution is sparser, and strong-lensing constraints are unavailable.

In its current implementation in *LENSTOOL,* the optimization of the combined parametric and non-parametric model is computationally time intensive. Both the multi-scale and the parametric models are adjusted in a Bayesian way, i.e., we probe their posterior probability density with a MCMC sampler (Jullo et al. 2007). This process allows us to easily and reliably estimate the errors on derived quantities such as the amplification maps and the mass maps. The described procedure automatically produces amplification maps as well as robust accompanying error maps. We provide these maps for all six HFF clusters.

We have used *LENSTOOL* to generate preliminary magnification maps and error maps for all six HFF clusters. All models have been produced for the concordance cosmological model with

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[1] *LENSTOOL* – Gravitational lensing software for modeling galaxies and clusters has been developed and honed over more than a decade. The publicly available version of our code with ample documentation, illustrations, and installation information, as well as an active developers wiki can be found at: http://projects.lam.fr/projects/lenstool/wiki

H_0 = 70 km/s/Mpc, Ω_Λ = 0.7 and Ω_M = 0.3. We and the CLASH team also provided cluster galaxy catalogs that were used in the modeling and shared with all other teams (Ebeling, Ma & Barrett 2013, in prep.; Balestra et al. 2013, in prep.).

All data were shared amongst the five selected preliminary map modeler groups. However, we clearly identify the spectroscopic data obtained and contributed by our group.

FORMAT FOR THE PRELIMINARY HSTFF MAP FILES

For each cluster we provide the following list of files (as input and output files in *LENSTOOL* format):

(1) File with best-fit parameters

(2) File with list of multiple images included as modeling constraints:
Format is ID, Right ascension (degrees), declination (degrees), elliptical shape (fixed a,b,theta, not used in the modeling), redshift, magnitude (fixed not used in the modeling).

(3) File with best output magnification map for sources at z = 1, 2, 4, and 9 (FITS format with WCS information aligned with HLSP images. 0.2" pixel scale)

(4) File with κ and γ maps (convergence and shear, not normalized by the DLS/DS distance ratios, same scale and WCS as (3)) to allow computation of magnification at any redshift

(5) Deflection maps: x and y, not normalized by DLS/DS.

DESCRIPTIONS OF PRELIMINARY CLUSTER MAGNIFICATION MAPS

Abell 2744 (z = 0.308, Abell 1958)
RA = 00:14:23.4 **DEC =** −30:23:26

Magnification maps have been created using 17 orbits of existing publicly available HST ACS data and shared spectroscopic redshifts obtained by us with VLT/FORS2 (Richard et al. 2013, in prep.).

The best-fit model for A2744 consists of four large potentials with velocity dispersions in excess of 600 km/s for the central region and includes the potentials of 150 contributing cluster galaxies. All potentials are modeled with Pseudo Isothermal Elliptical Mass Distribution (PIEMD) profiles. This best-fit model for A2744 includes 17 families of multiple images of which two have measured spectroscopic redshifts of z = 2.0 and z = 3.6.

<u>MACSJ0416.1−2403</u> (z = 0.397, Mann & Ebeling 2012)
RA = 04:16:08.4 **DEC** = −24:04:21

Magnification maps have been created by us using the following imaging data sets: 15 orbits of existing HST ACS + WFC3IR, and public CLASH MCT data. We have measured a spectroscopic redshift of z = 1.9 with Keck/LRIS and VLT/XSHOOTER (Christensen et al. 2012) for one system.

The best-fit model for MACSJ0416 consists of three large potentials with velocity dispersions in excess of 700 km/s to model the central region and includes the potentials of 219 contributing cluster galaxies. All potentials are modeled with Pseudo Isothermal Elliptical Mass Distribution (PIEMD) profiles. This best-fit model for MACSJ0416 includes 17 families of multiple images of which seven now have spectroscopic redshifts (Balestra et al. 2013, in prep.; Grillo et al. 2013, in prep.)

<u>MACSJ1149.5+2223</u> (z = 0.543, Ebeling et al. 2007)
RA = 11:49:35.7 **DEC** = 22:23:55

Magnification maps have been created using the following data sets: 17 orbits of existing HST ACS + WFC3IR data, and public CLASH MCT data. Previously published spectroscopic data from Keck/LRIS and Gemini/GMOS in Smith et al. (2009) were also used. An earlier version of the *LENSTOOL* model has been published in Smith et al. (2009).

The best-fit model for MACSJ1149 consists of two large-scale potentials (one with velocity dispersion in excess of 1000 km/s and another with velocity dispersion in excess of 600 km/s) and three potentials with velocity dispersions in excess of 300 km/s to model the central region. In addition it includes the potentials of 217 contributing cluster galaxies. All potentials are modeled with Pseudo Isothermal Elliptical Mass Distribution (PIEMD) profiles. This best-fit model for MACSJ1149 includes 12 families of multiple images of which three have published spectroscopic redshifts.

<u>MACSJ0717.5+3745</u> (z = 0.545, Ebeling et al. 2007)
RA = 07:17:35.6 **DEC** = +37:44:44

Magnification maps were created using the following imaging data sets: 18 orbits of existing HST ACS + WFC3IR data, and the public CLASH MCT data. In addition to shared data, spectroscopic redshifts obtained by our group from Keck/LRIS and LBT/MODS were used. An earlier version of the *LENSTOOL* model has been published in Limousin et al. (2012).

The best-fit model for MACSJ0717 consists of four large-scale potentials (two with velocity dispersions in excess of 900 km/s and two with velocity dispersions of 500-900 km/s) for the central region. In addition, it includes the potentials of 226 contributing cluster galaxies. All potentials are modeled with Pseudo Isothermal Elliptical Mass Distribution (PIEMD) profiles. This best-fit model for MACSJ0717 includes 14 families of identified multiple images of which five have spectroscopic redshifts.

<u>AS1063</u> (z = 0.348, Abell, Corwin & Olowin 1989)
RA = 22:48:44.3 **DEC** = −44:31:48

Magnification maps were created using the public CLASH MCT data. Spectroscopic data obtained by us on Magellan/LDSS3 (one system) and VLT/FORS2 (four systems) were shared and will be published in Boone et al. (2013, submitted) and Richard et al. (2013, in prep.).

The best-fit model for AS1063 consists of one large-scale potential with a velocity dispersion in excess of 1300 km/s for the central region and includes the potentials of 105 contributing cluster galaxies. All potentials are modeled with Pseudo Isothermal Elliptical Mass Distribution (PIEMD) profiles. This best-fit model for AS1063 includes 14 families of identified multiple images of which five have spectroscopic redshifts between z=1.2 and z=6.1.

<u>Abell 370</u> (z = 0.375, Abell 1958)
RA = 02:39:52.8 **DEC** = −01:34:36

Magnification maps were created using the following imaging data sets: 12 orbits of existing HST ACS + WFC3IR data. Identified multiple-image systems in this cluster have ground-based spectra from CFHT and VLT/FORS2. A previous version of the *LENSTOOL* model has been published in Richard et al. (2010). One additional unpublished redshift procured after the publication of Richard et al. (2010) was shared with all modeling groups and used to derive the most up-to-date lens model provided here (Richard et al. 2013, in prep.).

The best-fit model for A370 consists of two large-scale potentials with a velocity dispersion in excess of 800 km/s for the central region and includes the potentials of 95 contributing cluster galaxies. All potentials are modeled with Pseudo Isothermal Elliptical Mass Distribution (PIEMD) profiles. This best-fit model for A370 includes 11 families of identified multiple images of which three have measured spectroscopic redshifts.

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