Calibrating galaxy clusters as natural telescopes

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Clusters as natural telescopes

- massive clusters magnify large area of sky behind the clusters
- allow us to study faint and/or distant galaxies with help of lensing magnifications ("natural telescopes")
- need accurate cluster mass models to recover correct galaxy property
HST Frontier Fields (HFF)

• >100 multiple images for each cluster led to significant progress in cluster strong lens study!
Spec-z revolutions

- spec-z’s for many multiple images
  → secure identifications & more constraints!
HFF mass models (v3, v4)

- LENSTOOL
  - CATS
    - Sharon Caminha
- GLAFIC
- LENSMODEL
  - Keeton
  - (also GLEE by Grillo, Suyu+)
- LTM
  - Zitrin
- WSLAP+
  - Diego Bernstein
  - Grale
  - Williams
  - SWUnited
  - Bradac

https://archive.stsci.edu/prepds/frontier/lensmodels/
Figure 1.1: Example of lens equation solving for point sources. I use square grids (thin black lines) to adaptively refine near critical curves to derive image positions for a given source. Upper panels show image planes, and lower panels are corresponding source planes. Critical curves and caustics are drawn by blue lines. Positions of sources and images are indicated by red triangles. Left panels show an example from a simple model that consists of NFW and SIE profiles. A source near the center is producing 7 lensed images. In right panels, I add small galaxies to the primary NFW lens potential. This time 5 lensed images are produced.

http://www.slac.stanford.edu/~oguri/glafic/

• public software for strong lensing analysis (“parametric” modeling)
• adaptive grid to solve lens equation efficiently
• support many kind of lens potentials
• see Kawamata, MO+ ApJ 819(2016)114 for details of our HFF mass modeling
Quantify goodness of mass models

- **RMS of multiple image positions**
  root-mean-square of differences of multiple image positions btw obs and model

- **mock challenge**
  blind test from mass modeling of mock strong lensing clusters

- **lensed supernovae**
  blind test from magnifications and time delays of lensed supernovae
RMS of multiple image positions

- difference of image positions between best-fit model and observation
- in cluster strong lensing, typically RMS $\sim 1''$, much worse than meas. errors ($\lesssim 0.1''$ for HST)
- due to complex mass dist. of clusters (e.g., substructure)
RMS in HFF

- despite large numbers of multiple images, RMS improved to \(~0.4\)" in HFF

- reasons?
  - less misidentification
  - improved modeling method
  - improved method to explore likelihood

\[ \Delta_x / \text{arcsec} \]

Kawamata, MO+2016
Improvements of RMS

- mass modeling of clusters w/ ≳50 multiple images
- plotted data not complete
- RMS getting better….

HFF started
Improvements of RMS

- mass modeling of clusters w/ \( \geq 50 \) multiple images
- plotted data not complete
- RMS getting better….

HFF started

zero by \( \sim 2020 \)?
Improvements of RMS

- mass modeling of clusters w/ \( \approx 50 \) multiple images
- plotted data not complete
- RMS getting better....

![Graph showing improvements of RMS over years.](image-url)
Mock challenge

• create HFF-like mock strong lensing cluster data, people analyze the mock data without knowing the answer

• this allows us to assess how accurate the reconstructed mass distributions are
Figure 3. Color composite images of Ares and Hera (left and right panels, respectively). In the upper panels, we overlay to the optical images the surface density iso-contours. In the central panels, we show the critical lines for $z_s = 1$ (red) and $z_s = 9$ (white). In addition, we display the location of the multiple image systems (numbered yellow circles). The galaxies identified as cluster-members are indicated by white circles in the lower panels.
Result: convergence map (Ares)

Convergence maps ($z_s=9$) of Ares. The first nine panels show the results of the reconstructions, beginning with the free-form methods (panels 1-4) and concluding with the parametric models (panels 5-9). The lower left panel shows the true convergence map, for comparison.
The key results of this phase of the comparison exercise of lens mapping methodologies can be summarized as follows.

- Parametric methods are generally better at capturing two-dimensional properties of the lens cores (shape, local values of the convergence and of the magnification). The free-form methods are as competitive as the parametric methods to measure convergence and mass profiles. It is worth mentioning, however, that, in both Ares and the Hera, the cluster galaxies were good tracers of the cluster mass distributions.

- The accuracy and precision of strong lensing methods to measure the mass within the Einstein radius (or more generally within the region probed by the strong lensing constraints) is very high. The measured profiles deviate from the true profiles by only a few percent at these scales. Of course, larger deviations are found at radii larger and smaller than the Einstein radius. The determination of the mass enclosed within the Einstein radius was extremely robust for all methods.

- The largest uncertainties in the lens models are found near substructures and around the cluster critical lines. For some of the parametric models, the total mass around substructures (identified by cluster galaxies) is constrained with an accuracy of $\sim 10\%$. However, other methods have much larger scatter. Uncertainties on the magnification grow as a function of the magnification itself and are therefore more pronounced near the cluster critical lines. For the best performing methods, the accuracy in the magnification estimate is $\sim 10\%$ at $\mu_{\text{true}} = 3$ and degrades to $\sim 30\%$ at $\mu_{\text{true}} = 10$.

- Switching from Ares to Hera, i.e. from a purely parametric to a more realistic lens mass distribution, the gap between parametric and free form methods becomes smaller. Algorithms such as that used by the GLAFIC team, which include third order multi-poles in the lens mass distribution, have extra degrees of freedom which allow them to better reproduce asymmetries. These asymmetries, and possible variations of the halo ellipticity as a function of radius, seem to be the strongest limitations of parametric methods. The adoption of an hybrid approach, where parametric and free-form methods are combined also to describe the large-scale component...

GLAFIC performs best!
Lensed supernovae

• provide totally new constraints beyond image positions
  – magnification factor
    Type Ia only, but even for single image
  – time delay
    when multiply imaged

• serve as a blind test of mass models made before the supernova explodes
SN HFF14Tom

- lensed Type Ia at $z=1.3457$ (single image)
optical imaging from HST+ACS already being provided by the ACS G800L grism, supplementing the rapid-cadence campaigns. The FrontierSN observations provided WFC3-(PI:Rodney, HST-PID:13386), which aims to discover the locations of the cluster center, the SN, and the optical and IR imaging campaigns are separated by F606W and F814W) and 4 infrared (IR) bands (WFC3-). Each field is observed in 3 optical bands (ACS F435W, F555W, and F814W).

Figure 1. Upon discovery, HST target-of-opportunity observations were obtained. The left panel shows a UV/Optical/IR color composite image constructed from all collected data. The right panel shows a close-up view with a yellow circle marking the SN location with an arrow. (Left panel image credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer.)

The most probable host galaxy for SN HFF14Tom is located at J2000 Coordinates of HFF14Tom, host, and cluster.

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<th>Fr. Par.</th>
<th>strong</th>
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<td>CATS(v1)</td>
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In Section 6.1 we found that SN HFF14Tom is on a small systematic bias apparent. All but two of the lensing magnifications are given filled markers. The top half, with points in black, shows predictions from lens models. The vertical blue line shows the median magnification, the host galaxy, and the intergalactic medium.

It is often the case in SN surveys that redshifts are assigned, but nearly universal bias. We first consider whether a misinterpretation of the data on the SN itself can account for the tension between the measurement and the models. There is no evidence for any redshifts from the SN itself: we find a consistent redshift from both the SN spectrum (Section 4.2) and the tension between the measurement and the models. It is important to emphasize that SN HFF14Tom only samples a single line of sight through the cluster, and this bias to higher magnifications is minor. Nevertheless, a systematic shift of +2 is significant different from 0. This appears to be a solid and self-consistent picture, so the evidence strongly disfavors any redshift beyond 1.5.

In Section 7.1 we analyze the possible errors in supernova analysis. 7.1.1. Redshift Error

We have adopted the most precise redshift of z = 1.3457 from the host galaxy as our baseline for the magnitude. This appears to be a solid and self-consistent representation of the model.
SN Refsdal

- lensed SNcc at $z=1.49$
- four Einstein cross SN images
- a new SN image predicted ~1 year after the 4 images!

(MO 2015; Sharon & Johnson 2015; Diego+2016; Jauzac+2016; Treu+2016; Grillo+2016)
before SN image S1-S4 appears (late 2014) fifth image appears (late 2015)
Reappearance of SN Refsdal

- some models correctly predicted reappearance (incl. GLAFIC mass model!)

Figure 3. Simultaneous constraints on the time delay and magnification of image SX relative to image S1 from photometry of image SX listed in Table 1. The two-dimensional contours show the 68% and 95% confidence levels, and model predictions plot 68% confidence levels.

Since many of the lensing predictions are not Gaussian distributed, the 68% limits do not imply that they are necessarily inconsistent with the measurements. Except for the Jauzac et al. (2015) prediction, labels refer to models presented by Treu et al. (2016). While all other plotted predictions were made in advance of the HST Cycle 23 observations beginning on 30 October 2015, “Post Blind Zitrin-c” and “Post Blind Jauzac” were updates made at a later date. “Post Blind Zitrin-c” is an update of the “Zitrin-g” model where the lens galaxy was left to be freely weighted to assure that its critical curves pass between the four Einstein-cross images. For “Post Blind Jauzac,” the authors compute a common position for images S1–S4 in the source plane and recompute the time delays analytically using their LENSTOOL model.

It is important to keep in mind that all of these tests are local, and thus a larger sample is needed to assess the global goodness of fit of every model. Nevertheless, these tests are an extremely valuable probe of systematics. In fact, as discussed by Treu et al. (2016), the uncertainties reported by modelers do not include all sources of systematic errors. For example, systematic uncertainties arising from unmodeled millilensing, residual mass-sheet degeneracy, and multiplane lensing are very difficult to calculate and are thus not included. The lensed-SN tests provide estimates of the amplitude of the unknown uncertainties. Other known sources of errors are not included either. For example, a 3% uncertainty in the Hubble constant (Riess et al. 2011) implies a 3% uncertainty in time delays (i.e., \( \pm 10 \) days for a year-long delay). Furthermore, the uncertainties are typically highly non-Gaussian, so the 95% confidence interval is not simply twice as wide as the 68% one.

5. CONCLUSIONS

With models of the MACS J1149.5+2223 galaxy-cluster potential, the appearance of SN Refsdal in November 2014 as an Einstein cross became an augury of its future arrival \( \approx 800 \) away in a different image of its host galaxy. The detection of the reappearance here shows the power of modern-day predictions using models of the distribution of matter in galaxy clusters and the general theory of relativity. The timing and brightness of light from SN Refsdal in image SX is approximately in agreement with predictions, implying that for most models, unknown systematic uncertainties cannot be substantially larger than random uncertainties. At the same time, this first detection provides some discriminating power: not all models fare equally well. Grillo-g, Oguri-g, Oguri-a, and Sharon-a appear to be the ones that match the observations most closely. In general, most models seem to predict a slightly higher magnification ratio than observed, or shorter delays.

From the light curves of images S1–S4 of SN Refsdal, we can already anticipate how the brightness of image SX will evolve. An HST imaging program will continue to measure the light curve of image SX past peak brightness.
Summary

• rich dataset provided by HFF significantly advanced our understanding of cluster strong lens mass modeling

• various independent tests with mock challenge and lensed supernovae indicate that we are on the right track to improve mass modeling

• further improvements? line-of-sight effect, caustic crossing, …