Strong Lensing in Clusters of Galaxies: Using Nature's Largest Telescopes

Keren Sharon[1], Michael Gladders[1], Matthew Bayliss[1], Megan Gralla[1], Benjamin Koester[1], Eva Wuyts[1], Joseph Hennawi[2], Jane Rigby[3], Hakon Dahle[4], Felipe Barrientos[5], Mauricio Carrasco[5], Howard Yee[6], David Gilbank[7]

[1]KICP, University of Chicago, [2]MPIA, Germany, [3]Carnegie Observatories, [4]University of Oslo, Norway, [5]Universidad Catolica de Chile, [6]University of Toronto, Canada, [7]University of Waterloo, Canada

Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

The Largest Cluster-Lensing Surveys: RCS2 and SDSS Giant Arc Surveys

Our group at the University of Chicago has been leading the two largest and most successful projects to discover new cluster lenses; the SDSS Giant Arc Survey (SGAS); and the second Red-Sequence Cluster Survey (RCS-2). By mining a ~9 Gpc^3 cosmological volume covering the redshift range $0<z<1$, we have identified more than 200 cluster lenses, increasing the number of known systems by an order of magnitude. These represent some of the most spectacular examples of gravitational lensing ever discovered (see figures), and the first ever 'lensing-selected' sample of clusters, with a well-understood selection function (Gladders et al., in prep).

This sample is subject to intensive followup including observations in the optical (imaging and spectroscopy), infra-red, X-ray and SZ. It will be used to better understand mass-observable scaling relations, measure the properties of lensing clusters, cosmological arc statistics, and to study of the background universe.

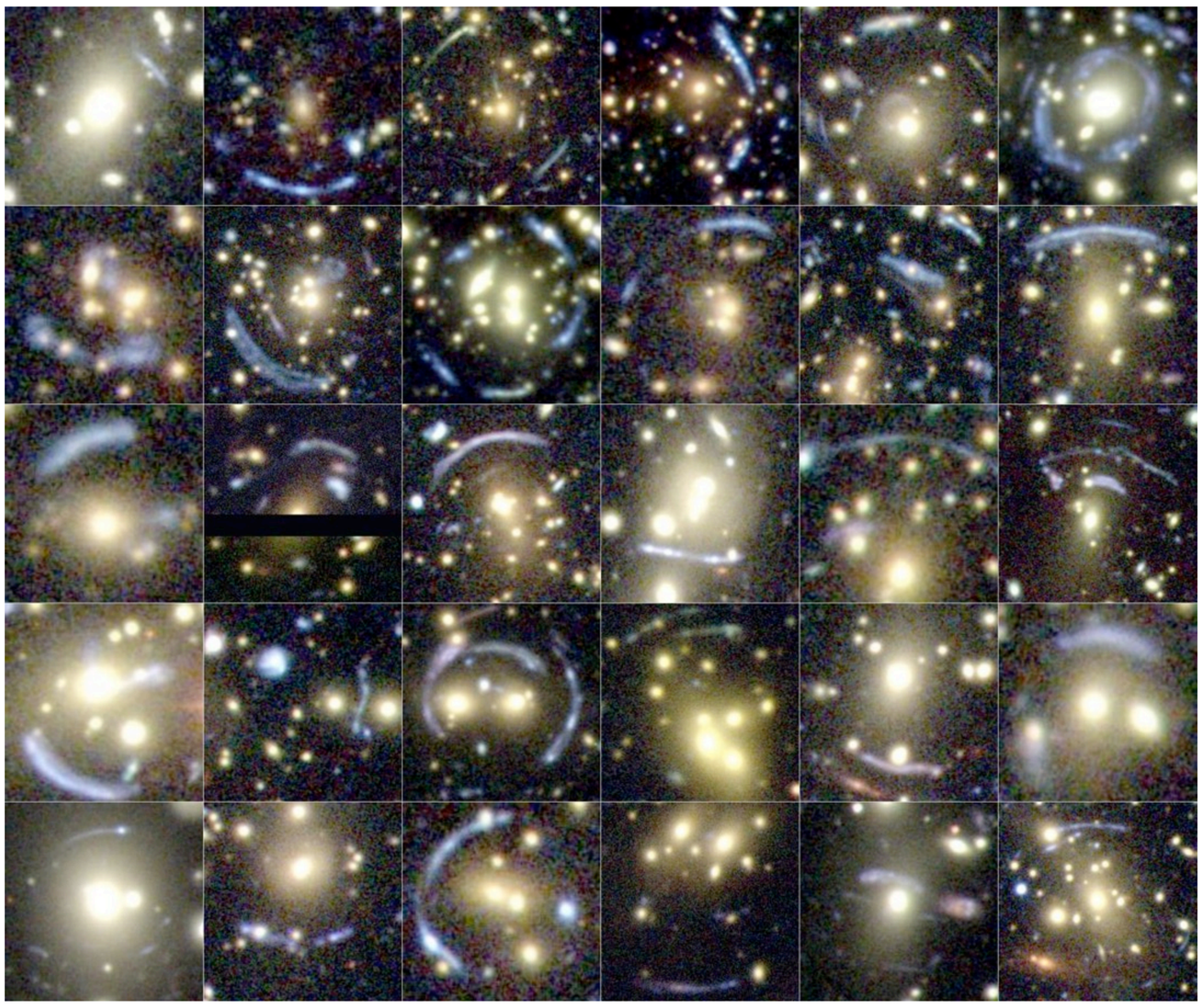
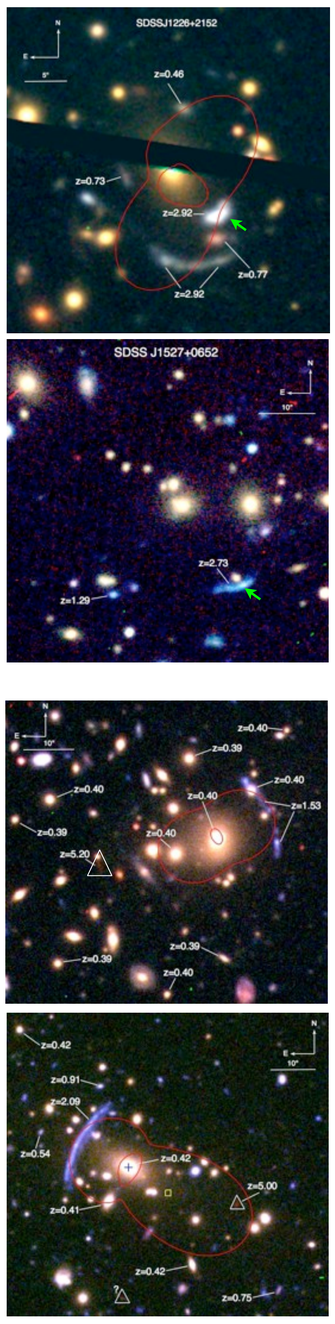


Figure 1: A small, representative sub-sample of cluster lenses that were discovered in SGAS.

The Background Universe



The deep gravitational potential of galaxy clusters makes them very efficient gravitational lenses, which distort and magnify the light coming from far away galaxies. These **natural telescopes** allow us to study the background Universe in unprecedented detail through two effects: the luminosity of the sources is magnified into our observing capability, and the high spatial magnification provides the resolution needed to study the sub-structure of these sources in great detail. A key ingredient is the construction of a reliable **lens model** that provides information about the magnification of the source, allowing us to measure their intrinsic (un-lensed) luminosities and sizes.

Galaxy evolution studies rely on quantifying the properties of galaxies as a function of redshift, many of which are measured through spectroscopy. At high redshifts, the spectra of individual galaxies, which are bright enough to be detected through photometry, would be too faint to achieve the signal-to-noise that these studies require. Researchers therefore stack information from a large sample of galaxies, discovered through dedicated surveys, and study their statistical properties instead. The few galaxies that are bright enough to be studied individually are drawn from the bright end of the luminosity function, and do not represent the true galaxy populations at high redshift. Gravitational lensing enables us to probe deep into that luminosity function, and study "normal" galaxies that would otherwise be too faint to be studied individually.

The sources on the left are among the few examples of the use of galaxy clusters as natural telescopes to study these populations of galaxies. We expect to discover dozens of similar sources in our surveys, and by compiling a statistically-meaningful sample we will be able to study the broader picture of star formation at those redshifts.

Figure 2: **Two Lensed z~3 Lyman Break Galaxies Discovered in the SDSS Giant Arcs Survey** (*Koester et al., 2010*)

Top: Gemini+GMOS-North *gri* images of the core of the clusters SDSS J1226+2152. Red lines represent the tangential and radial critical curves of the best-fit lens model, based on the observed multiply-imaged systems at z=2.92. *Bottom*: MegaCam *grz* image of SDSS J1527+0652. In both panels, the lensed LBGs (high redshift galaxies) are marked with an arrow, and spectroscopic redshifts of other background galaxies are indicated.

Figure 3: **Two Lensed Lyman-alpha Emitting Galaxies at z~5** (Bayliss et al., 2010)

Gemini+GMOS-North gri images of the cores of the clusters SDSSJ0915+3826 (top) and SDSSJ1343+4155 (bottom). The lensed LAEs, which were discovered as secondary arcs, are marked with triangles. Red lines represent the tangential and radial critical curves of the best-fit lens model for each cluster, based on the observed multiply-imaged systems. The spectroscopic redshifts of other background galaxies and cluster members are also indicated.

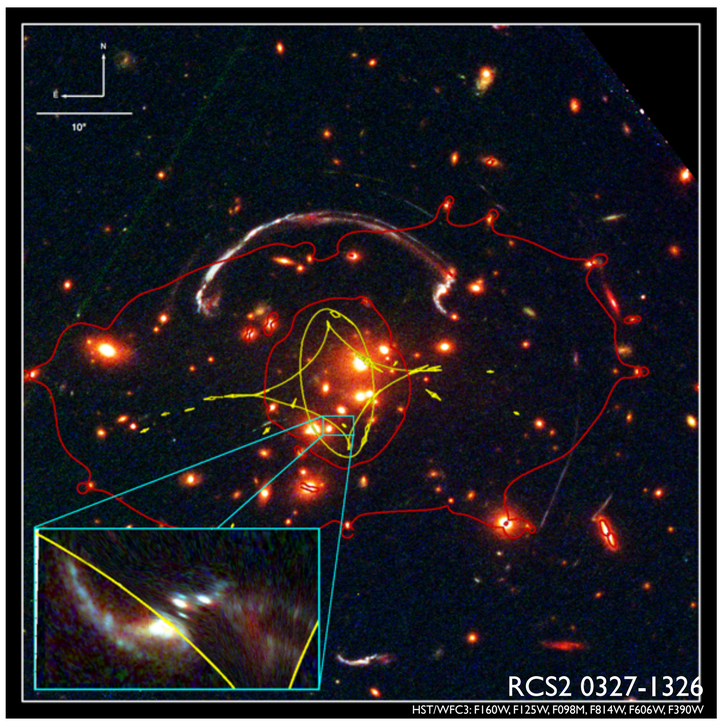


Figure 4: **The brightest known high-z arc**. (Wuyts et al. 2010; Rigby et al. 2011).

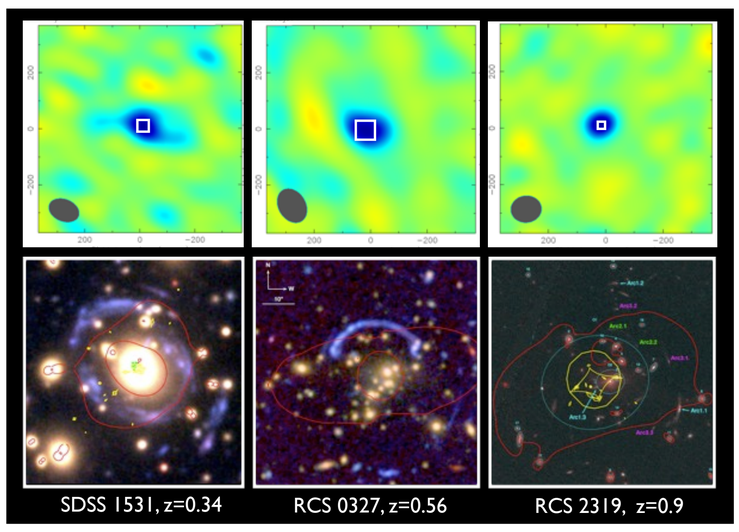
The core of RCS2 0327-1326, recently imaged with HST/WFC3. The 38''-long, z=1.7 giant arc is clearly seen at the north part of the z=0.56 cluster, with a counter image at the south. Other fainter arcs are also visible. A lens model was constructed using Lenstool (Jullo et al. 2007).

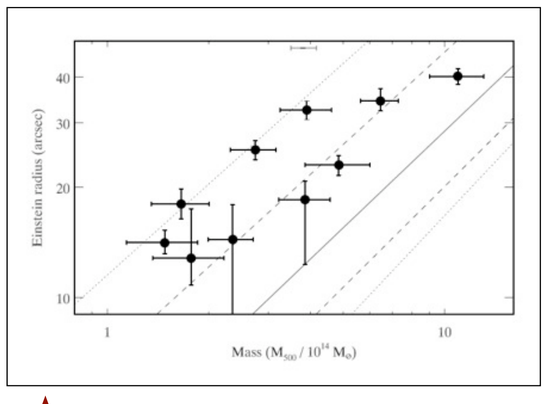
The un-lensed size and location of the source in the source plane are shown close to the center of the cluster. The inset shows a reconstruction of the source, indicating that it is likely a merger, with multiple incidents of star burst. Combined with newly acquired high resolution spectra (Keck/NIRSPEC), we are able to peer into and study these small but highly magnified areas of the galaxy which would otherwise be unaccessible.

For details see Wuyts et al. (2010) and Rigby et al. (2011).

Are Lensing Clusters Over-Concentrated?

N-body simulations in the frame of the now standard cosmology predict that dark matter halos follow a universal NFW profile (Navarro, Frenk & White 1997), with typical concentration parameter c~6 for clusters.
Some lensing clusters were reported to have c>14 (e.g., Kneib et al. 2003; Giavazzi et al. 2003; Broadhurst et al. 2005). Attempts to explain this discrepancy between theory and observations include tests of the affect of cluster triaxiality and elongation along the line of sight on lensing efficiency and cross section (e.g., Oguri et al. 2005; Hennawi et al. 2007; Oguri & Blandford 2009). A measurement of cluster concentration requires an estimate of the cluster mass on both large scale and small scale, the latter can best be derived from strong lensing, as it provides an accurate measurement of the mass enclosed in the core of the cluster. With our large lensing survey, we can now revisit this question with a robust and statistical sample.





We have recently finished analyzing a sub-sample of the first 10 lensing clusters out of RCS-GA and SGAS, with sufficient follow up information (spectroscopic redshifts for lensed sources and SZA data) for this study. We measured the clusters' M_{500} using observations from the Sunyaev Zel'dovich Array (SZA) and scaling relations derived from LoCuSS clusters; as a concentration proxy, we plot these masses against the Einstein Radii of the clusters, measured through detailed lens modeling. Figure 5 (on the left) shows a comparison between the observed values and theoretical distribution from Monte-Carlo simulation of semi-analytical models of triaxial halos (Oguri & Blandford 2009). We find that the "problem" persists in our larger sample: our measured Einstein radii are x2 larger than expected from LCDM, even after accounting for lensing bias.

Figures 5,6: Gralla et al. (2011). The Einstein radii versus M_{500} (from SZ measurements) for strong lensing clusters. The solid line shows the median of the lensing-selected theoretical halo models. The dashed (dotted) lines enclose 68% (90%) of such models. Lensing models have been scaled to a fiducial lens redshift of 0.5 and a fiducial source redshift of 2.0.
Top-right: Examples of three of the clusters, with SZ decrement map shown on the top row and the optical data and lens model on the bottom row.

How accurate is strong-lensing mass?

Given enough constraints (i.e., arcs), strong lensing provides a most accurate measurement of the *projected* mass at the cluster core, as it is insensitive to assumptions on the dynamical state of the cluster.

Problem: "enough" arcs only exist in a handful of clusters; Detailed modeling is expensive: it requires space-based resolution and many hours of 8-10m-class telescopes for spectroscopy. A detailed, A1689-like model for on order of hundreds of clusters will be challenging in the short term. However, we find that if the detailed location of the critical curve is not crucial, and the only quantity that matters is the enclosed projected mass, a crude analysis may be enough.

To test this claim we re-analyze some of the best-studied clusters, e.g., A1689, A2218, which have detailed mass models based on dozens of lensed sources in the literature to use as benchmarks. For each cluster we compiled a set of mass models, each model based on one or two families of lensed sources only. We then find the range of enclosed masses derived by these models as a function of radius. We find that even with this limited number of constraints, the disagreement between models is at the few percent level at the radius of the observed arcs (approximately the Einstein radius).

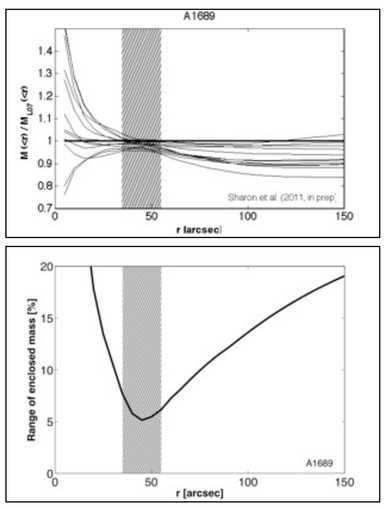


Figure 7: Range of enclosed mass as a function of distance from the BCG, relative to the best-fit model of Limousin et al. (2007). At the angular range that is constrained by arcs (shaded area), the disagreement between models is at a few percent level. The enclosed mass at small and large radii varies strongly between models. (Sharon & Gladders, in prep)

Further reading: Koester et al. (2010) ApJL723,73; Bayliss et al. (2010) ApJ720,1559; Wuyts et al. (2010) ApJ724,1182; Bayliss et al. (2011) ApJ727,26; Bayliss et al. (2011) ApJS193,8; Gralla et al. (2011) arXiv:1011.6341; Rigby et al. (2011) arXiv:1102.2441; Sharon et al., Gladders et al., in prep.