SHARP and in color: A pilot program
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Scientific background

The standard cosmological model (ΛCDM) has been remarkably successful in the large-scale linear regime, where density fluctuations are small. However, in the non-linear and high-density regime, observations and theory appear to diverge. At these scales, simulations predict a large amount of substructure, with $f_{\rm sub}$ =5–10% of the total halo mass within the virial radius being in substructures in the mass range $4\times10^{6-9}$ $M_\odot$, and with a substructure mass function of $dN/dm \propto m^{-1.9\pm0.1}$ (e.g., Diemand et al. 2007). The observed mass function of luminous satellites in the Milky Way, where the most complete investigations of substructure have been conducted, have a shallower slope ($\sim m^{-1.0}$) even after recent discoveries of low-luminosity satellites (e.g., Zucker et al. 2006a,b). These discrepant slopes lead to the well-known "missing satellites problem" on the low-mass end (e.g., Moore et al. 1999; Klypin et al. 1999) and a slight tension with excess satellites on the high-mass end of the mass function (e.g., Strigari et al. 2007). To build up meaningful statistics urgently requires that we more precisely quantify sub-galactic substructure distributions in other galaxies, not only in the Local Group, which may be a special case. Gravitational lensing provides a unique and powerful approach to this problem because it does not require the substructures to be luminous, and the lensing signal gives a *direct* measurement of the masses of any detected substructure. Thus, the lensing approach provides an excellent complement to the thorough work being done on local galaxies. Our previous NIRC2-LGS observations have shown that we can detect substructures with masses as low as $\sim 2\times10^8 M_\odot$ (see progress report), a regime where already theory and observations diverge. In this proposal we are requesting time to conduct a pilot project that uses multi-band imaging to distinguish lensing by substructure from dust extinction.

Comparison to Simulations

The characteristics of a strong gravitational lens system, whereby a massive lensing galaxy produces multiple images of a background source, depend on how the mass is distributed in the lensing galaxy, the source position, and the surface brightness distribution of the source. The lens mass distribution is most tightly constrained in the region of the lensed images, typically at an angular radius of $\sim 1''$ from the lensing galaxy. Thus, for lensing galaxies at $z \sim 0.5-1.0$, the highest sensitivity to perturbations in the mass distribution due to substructure is at projected physical radii of <10 kpc. In this region, the predicted substructure mass fraction drops to $f_{\rm sub} \leq 1\%$ due to dynamical friction and merging. Interestingly, in at least two of the small number of lens systems for which luminous substructure has been detected, the mass of the single satellite is comparable to or exceeds the expected substructure fraction. We need to move beyond small-number statistics to see if this tension between models and observations persists.

Quantifying the mass fraction and mass function through strong lensing: Simulations conducted by co-I's Vegetti and Koopmans (2009b) have shown that a Bayesian analysis of a sample of lenses that have been surveyed for substructure down to some mass threshold can provide meaningful constraints on $f_{\rm sub}$ and the slope of the mass function, α. Given a sample of several tens of lens systems, a mass detection threshold of $3\times10^8 M_\odot$ or better, and a reasonable prior on α, good constraints on $f_{\rm sub}$ are obtained (the dashed contours in Figure 1). Note that *even non-detection of substructure down to the mass limit provides useful information* for constraining $f_{\rm sub}$ and α, especially as the mass detection limit becomes smaller. As discussed in the progress report, we have detected a substructure with $M = 1.9\times10^8 M_\odot$ and we have similar quality data on over 50% of our full sample of 27 targets. Thus, we will be able to apply the powerful analysis laid out in Vegetti & Koopmans (2009b).

Clearly building up statistics on sub-galactic scale mass distributions is crucial in testing the CDM-based scenarios of galaxy formation. Until the advent of robust AO observations, investigations of substructure in cosmologically distant galaxies could only be done with expensive space-based observations. However, the combination of sensitivity provided by a large collecting area and the exquisite angular resolution provided by Keck AO provide better data than HST imaging for red objects. Combined with the power of gravitational lensing, Keck observations can dramatically push this field forward.

Detection Methodology: Gravitational Imaging

There are two main techniques to detect and evaluate the presence of substructure in a lens system. One is flux ratio anomalies, and that approach is explored in the proposal by Treu this semester. The other, which is the focus of this proposal, is gravitational imaging using lensed extended emission such as long arcs or Einstein rings. This approach takes advantage of recently developed modeling techniques that use the additional constraints provided by the extended lensed emission to break degeneracies in the modeling. An example in a more massive group-scale system is shown in Figure 2. Substructures as small as $10^8 M_\odot$ can be detected *gravitationally* if they lie close to the Einstein ring, while more distant substructures can be detected down to $10^9 M_\odot$ (Vegetti & Koopmans 2009a). We are conducting a program, the Strong lensing at High Angular Resolution Program (SHARP), that combines this modeling technique with Keck AO observations that can detect rings and arcs at high sensitivity. This program opens a whole new spectrum for conducting a census of substructure. We have successfully applied this technique to the B1938+666 system and detected a substructure with $M = 1.9 \times 10^8 M_\odot$ (see Figure 3 and our work in Vegetti et al. 2012).

Verifying the lensing signal through multiband imaging

The effect of lensing by substructure is to create a small hole in the larger arc or ring, surrounded by brighter emission. This can be clearly seen in the galaxy-group example shown in Figure 2, where the "substructure" (galaxy G4) creates a gap in the long arc, and a small-scale ring around itself. There are a couple of effects that can mimic this signal. The first is intrinsic structure in the lensed object. However, that contaminant can be easily rejected for these systems because the long arc/ring is made up of multiple images of the background source. If the lensed object has intrinsic structure, then that structure should be seen multiple times around the ring. The other effect is extinction by a clumpy dust distribution in the lensing galaxy. In our work on B1938+666, we were able to reject the dust hypothesis because we had multiband imaging of the system. However, the rest of the SHARP sample (see Progress Report) has only K' imaging. In this proposal, we are requesting time to get J and H-band imaging of two of our most promising systems, i.e., ones with bright arcs or rings. These systems are part of the subsample that is the focus of our next substructure analysis paper, and initial work indicates that at least one of them shows signs of substructure. As an ancillary benefit, the multiband data sets, each with its own angular resolution and PSF structure, can provide important independent confirmations of the gravitational signature of the substructure.

The request in this proposal represents a pilot project. We have been observing in K' because that setup typically provides the highest Strehl ratios. This pilot project will explore whether the required high image quality can be achieved in J and H with a reasonable amount of exposure time. If so, then we anticipate extending this project to that portion of the SHARP sample that shows bright arcs or rings (see Figure 4).

References

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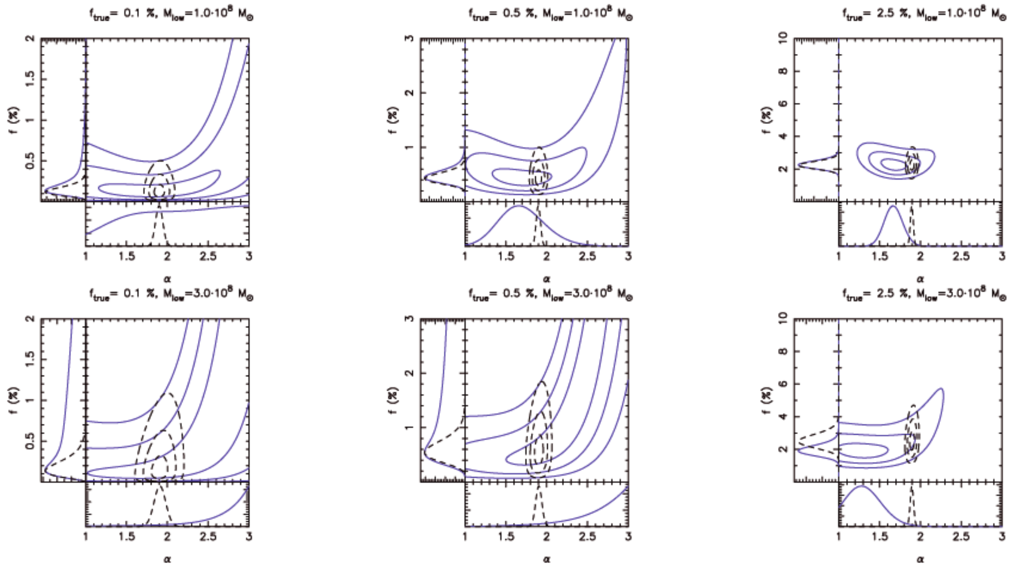

Figure 1: Predicted constraints on $f_{\rm sub}$ and α from a sample of 30 strong lens systems, from Vegetti & Koopmans (2009b). The dashed contours are the results obtained when applying a Gaussian prior on α. The top row is for a mass detection limit of $1 \times 10^8 M_\odot$, while the bottom row has $M_{\rm low} = 3 \times 10^8 M_\odot$; the detection limit obtained from our NIRC2-LGS observations of B1938+666 fall between these values. The columns represent input values of $f_{\rm sub}$ =0.1%, 0.5%, and 2.5%. Note that if $f_{\rm sub}$ is on the order of a few percent, then fewer lens systems are needed to provide meaningful constraints on $f_{\rm sub}$ and α.

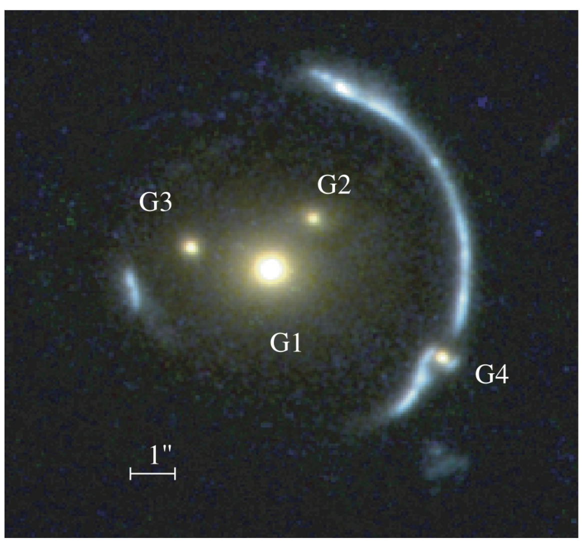

Figure 2: Demonstration of the gravitational imaging technique used to detect substructure in this program, using a group-scale massive analog. The long blue lensed arc is distorted at the location of the "substructure", G4. Even if G4 had been completely dark, its presence would still have been obvious due to the distortion in the arc. Both the location and the mass of the substructure are revealed by its gravitational effects. Image from Vegetti et al. (2010a). For galaxy-scale halos, the distortions occur on much smaller angular scales.

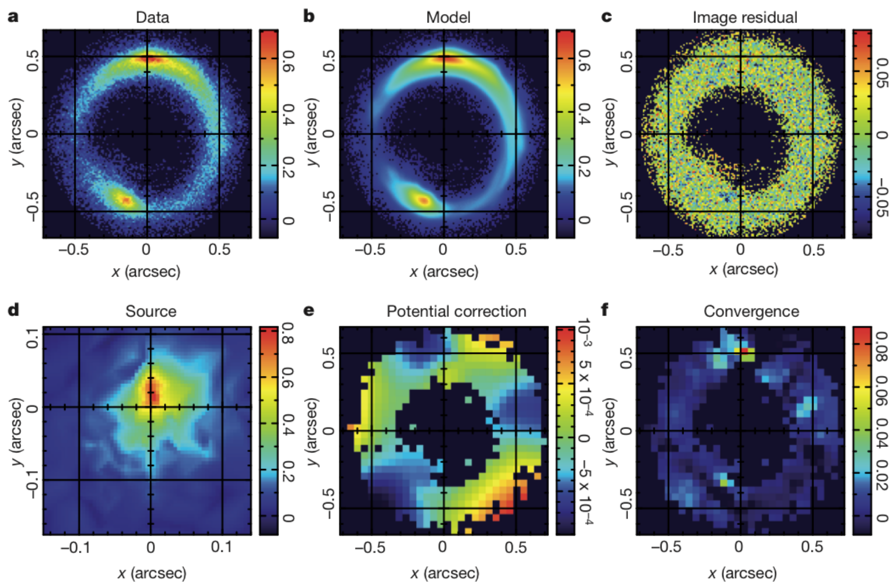

Figure 3: Detection of a substructure associated with the B1938+666 lens system. **Top row, Left:** Observed data, with lensing galaxy masked out. **Middle:** Best-fit model of the lensed emission. **Right:** Residuals. **Bottom row, Left:** Reconstructed image of the lensed object. **Middle:** Potential corrections. **Right:** Convergence map. The convergence map is essentially a correction to the mass surface density map. The newly detected dark substructure shows up as the red convergence peak at the top of the ring. Figure from Vegetti et al. (2012).

Progress Report

Observations: We took a hiatus from observations after semester 2012B in order to standardize the reduction of the full K' sample, which is now 27 systems, 25 of which are shown in Figure 4.

Analysis: During this hiatus, we have also been working on making advances in the code that now does a much more sophisticated analysis of the varying sensitivity to substructure around the ring. We have selected a subsample of the targets with the brightest rings with which to do the full substructure analysis and we have made significant progress with the new code. We are also working on an full-sample analysis of luminous substructure in this system, using a similar statistical treatment as in the gravitational imaging process.

Proof of concept: We have shown that the method of gravitational imaging can be successfully applied and used to detect low-mass substructures of cosmologically distant objects with AO imaging. Our analysis of the B1938+666 system reveals a high significance (12σ) detection of one substructure (Fig. 3) with a mass of $1.9\times10^8 M_\odot$ (Vegetti et al. 2012). This is *a factor of nearly 20 less massive* than the best result from an HST detection ($3.5\times10^9 M_\odot$; Vegetti et al. 2010b). This is not only the least massive substructure detected by the gravitational imaging technique, but it is also the most distant ($z = 0.881$ compared to $z = 0.22$ for the HST system). The substructure is also detected in archival HST/NICMOS F160W data, although at lower significance than in the K' data. The excellent angular resolution provided by Keck+AO enhances the sensitivity of these imaging observations to small perturbations caused by substructure (Bus & Koopmans, in prep). We also combined the two substructure detections to place the first constraints on the substructure fraction outside the local group, finding $< f_{\rm sub} >= 3.3^{+3.6}_{-1.8}\%$. The uncertainties on this quantity are large, but will come down as more systems are analyzed. The results from the full survey of 20 systems, when completed, will be incorporated into the Bayesian analysis and used to place observational constraints on the substructure mass fraction and mass function slope at unprecedented distances and for early-type galaxies.

PSF effects: We examined this in detail for our observations of B1938+666 the effect of varying

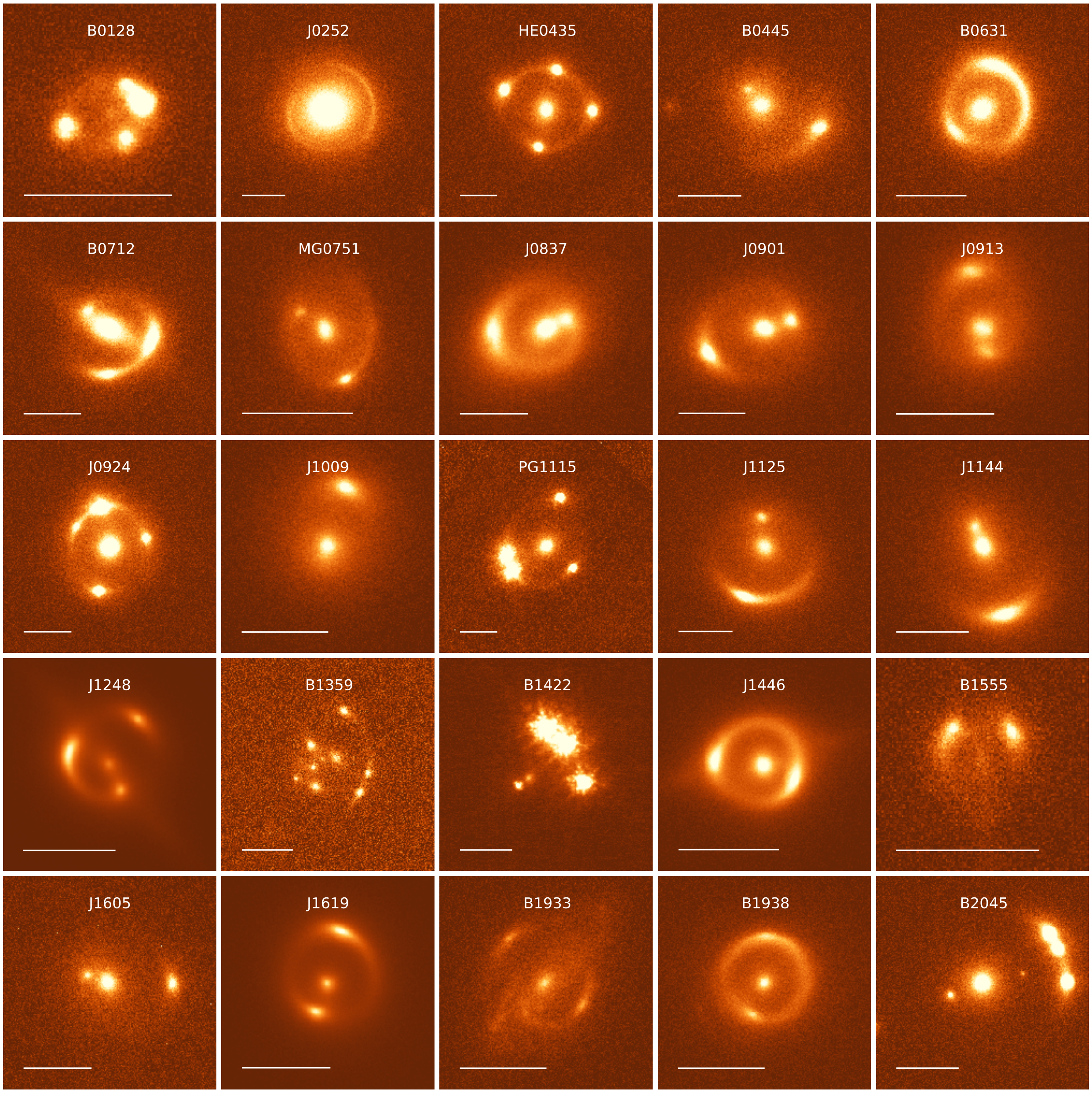

Figure 4: The K' imaging of the 25 out of 27 members of the SHARP sample that were observed with the NIRC2 Narrow camera. The other two systems were observed with the Wide camera. In all of the images, the scale bar is 1 arcsecond in length. Figure from Fassnacht et al. (in prep).

PSF on the substructure detection. Because there was no PSF star in the field, we repeated our analysis using observations of several different PSF stars. We found that both the detection of the substructure and its derived mass were robustly obtained no matter which PSF was used.

Publications from this program (to date, including pilot program)

McKean et al. 2007, MNRAS, 378, 109
Lagattuta et al. 2010, ApJL, 716, 185
Vegetti et al. 2012, *Nature*, 481, 341
Suyu et al. 2012, ApJ, 750, 10
Lagattuta et al., MNRAS, 424, 2800

Technical Remarks and Other Information

Targets and Exposures

This pilot project focuses on two of the objects for which we have high SNR detections of a full Einstein ring, B0631+519 and J0837+0801. These objects have been observed in K'-band with good Strehl, and initial analysis indicates that B0631+519 has a detected substructure. The analysis for J0837+0801 is still in progress. Multiband imaging on B1938+666 was key in assessing the validity of the substructure detection. Therefore, we propose to observe these two systems in both J and H bands. Based on our previous experience with the SHARP sample and with the AO system, we expect to obtain the required SNR for this project in roughly 3 hours per band for B0631+519 and 1 hour per band for J0837+0801, including overheads. For the pilot sample, we thus request **1 night of NIRC2-LGS time**. Given the RA distribution of the objects and the necessity of spending most of the time on B0631+519, it would be best to have the time in late December or early January.

Backup Program

In poor observing conditions, we will integrate longer on the most promising targets.

Supplementary Observations

No further supplementary data are necessary for this experiment.

Status of Previously Approved Keck Programs

The following represent all of the approved Keck programs for Fassnacht in the last five years.

2009 February – LRIS – 2 nights awarded
Title: Toward a Significant Increase in Confirmed $z > 0.35$ Gravitational Lenses
Results: The data have all been reduced, with successful measurements of the lens redshift, source redshift, or both, for seven of the eight targeted systems. The results have been published in ApJ (Lagattuta et al. 2010a).

2009B – 2012B – NIRC2-LGS – 11.5 nights awarded, 8 usable nights
Title: CDM Subhalos in Moderate-redshift Galaxies: Testing Theory with Observations (SHARP)
Results: See progress report The success of SHARP has inspired other scientific programs including this current proposal and the cosmology proposal last semester with Treu as PI.

2010B, 2011B – LRIS – 4 nights awarded, 3.3 usable nights
Title: Measuring the Universe with Gravitational Lenses
Results: One fantastic night, two decent nights, and one good night that degraded rapidly to essentially unusable. Program was to measure stellar velocity dispersions in time-delay lensing systems. The data have been reduced and velocity dispersions have been measured using two independent techniques. From those data one paper has been published (Suyu et al. 2013), another paper is in press (Suyu et al. 2014), and two more are in preparation.

2013A, 2013B – ESI – 2 nights awarded, 1 usable night
Title: The SHARP View of the Structure and Evolution of Normal and Compact Early-type Galaxies

Results: We were granted one night each in 2013A and 2013B for this purpose. The 2013A observations were obtained under good conditions and we acquired spectra for the first 50% of the sample. These data have been reduced. The 2013B night was scheduled for early January 2014, and was completely weathered out, with ice on the dome at sunset. We are re-proosing for the second night.

Path to Science from Observations

The data will be obtained and reduced by Fassnacht, Auger, and Lagattuta. The velocity dispersion measurements will be conducted by Auger, using his template-fitting code. Spiniello will do the spectral index analysis using her code, which has been tested on VLT data. The lens modeling, including the ring structure and the stellar velocity dispersion, will be conducted by Koopmans and Vegetti. The entire team will participate in the interpretation of the results and their preparation for publication.

Experience of Proposers

Fassnacht, Auger, Lagattuta, McKean, and Koopmans are experienced users of the Keck Telescopes, with many observing runs using LRIS, ESI, NIRSPEC and NIRC2-LGSAO. Auger and Spiniello have developed the software that will be used for the velocity dispersion and stellar population analyses. On the modeling side, Co-I's Vegetti and Koopmans have developed the powerful grid-based techniques and statistical analysis that will be applied to the data.

Resources and Publication Timescale

Fassnacht will cover the costs of the observing run out of a NSF grant for which these observations are a key component. We have the required computing power and storage space for the reduction.

Selected publications that are relevant for this proposal (* = Keck-based)

* "SHARP I. Models for the B1938+666 Einstein Ring from HST and Keck Adaptive Optics Imaging"
  Lagattuta, D. J., Vegetti, S., Fassnacht, C. D., Auger, M. W., Koopmans, L. V. E., & McKean, J. P.
  MNRAS, 424, 2800

* "Disentangling Baryons and Dark Matter in the Spiral Gravitational Lens B1933+503"
  Suyu, S. H., Hensel, S. W., McKean, J. P., Fassnacht, C. D., Treu, T., Halkola, A., Norbury, M., Jackson, N., Schneider, P., Thompson, D., Auger, M. W., Koopmans, L. V. E., & Matthews, K.
  2012, ApJ, 750, 10

* "Gravitational Detection of a Low-mass Dark Satellite at Cosmological Distance"
  Vegetti, S., Lagattuta, D. J., McKean, J. P., Auger, M. W., Fassnacht, C. D., & Koopmans, L. V. E.
  2012, *Nature*, 481, 341

* "A Compact Early-type Galaxy at $z = 0.6$ Under a Magnifying Lens: Evidence for Inside-out Growth"
  Auger, M. W., Treu, T., Brewer, B. J., Marshall, P. J.
  2011, MNRAS, 411, 6L

* "Adaptive Optics Observations of B0128+437: A Low-mass, High-redshift Gravitational Lens"
  Lagattuta, D. J., Auger, M. W., & Fassnacht, C. D.
  2010, ApJL, 716, 185L.

* "Lens Galaxy Properties of SBS1520+530: Insights from Keck Spectroscopy and AO Imaging"
  Auger, M. W., Fassnacht, C. D., Wong, K. C., Thompson, D. Matthews, K. & Soifer, B. T.
  2008, ApJ, 673, 778

* "High Resolution Imaging of the Anomalous Flux-ratio Gravitational Lens System CLASS B2045+265: Dark or Luminous Satellites?"
  McKean, J. P., Koopmans, L. V. E., Flack, C. E., Fassnacht, C. D., Thompson, D., Matthews, K., Blandford, R. D., Readhead, A. C. S., & Soifer, T.
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