Subaru Telescope LGS-AO imaging of Gravitationally Lensed Quasars
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Well-defined sample of gravitationally lensed quasars: Since the discovery of the first gravitationally lensed quasar Q0957+561 (Walsh et al. 1979), more than 100 strongly lensed quasars have been discovered. They are now considered as an immensely useful astrophysical tool, which has been providing unique insights into a broad range of scientific problems including the fine structure of quasar accretion disk, the structure and evolution of massive galaxies, and cosmology. However, a caveat is that the population of lensed quasars is quite biased in several ways, due to the "rare" nature of strong lensing. For a specific example, it has been argued that lensing galaxies should reside in denser environments than non-lensing galaxies of similar luminosities, because a large amount of dark matter associated with the dense environment boosts strong lens optical depths (Oguri et al. 2005). The fact, in turn, suggests that the mass-to-light ratios or cosmological parameters estimated by these strong lenses can similarly be biased.

One can get around such lensing biases by working on a well-defined homogeneous lens sample whose selection function is fully understood. The current largest homogeneous lens sample is provided by the Sloan Digital Sky Survey quasar lens search (SQLS; Oguri et al. 2006, 2008; Inada et al. 2008), a large lens survey conduced by Dr. Oguri and his collaborators. We have discovered ~ 40 new lensed quasars to date (e.g., Inada et al. 2009; Kayo et al. 2010), which constitute a significant fraction of lensed quasars known. The selection function has been studied extensively using simulated SDSS images (Oguri et al. 2006), allowing an accurate estimate of lensing biases inherent to the lens sample.

Importance of High-Resolution Images: High-resolution imaging of these quasar lenses is the key to turning each lens into a highly useful astrophysical and cosmological probe. This is because the typical size (image separation) of a galaxy-scale strong lenses is $\sim 1'' - 2''$, which is comparable to the seeing size of ground-based imaging. The high-resolution imaging is necessary for accurate astrometry and photometry of all lens components, two or four quasar images accompanied by the lensed host galaxy, plus lens galaxies in between the quasar images, all of which are confined inside $\sim 1'' - 2''$ diameter. Here we highlight only two of the many applications enabled by the high-resolution images:

• Quasar host galaxies: It is very difficult to study the properties of $z > 1$ quasar host galaxies even with Hubble Space telescope (HST) because of the cosmological surface brightness dimming. Lensed quasars are enormously helpful to this problem, because the lensing magnification increases both the total flux and the apparent size of quasar host galaxies. Indeed, Peng et al. (2006) was able to study the evolution of the black hole to bulge mass relation out to $z \sim 4$ by using HST images of lensed quasars (Fig. 1). The inherent idea behind such study is two-fold: First, to infer virial masses for the central black holes from published spectra; second, to use lens modeling in order to extract the luminosity of the resolved host galaxy from under the much brighter but unresolved quasar component.

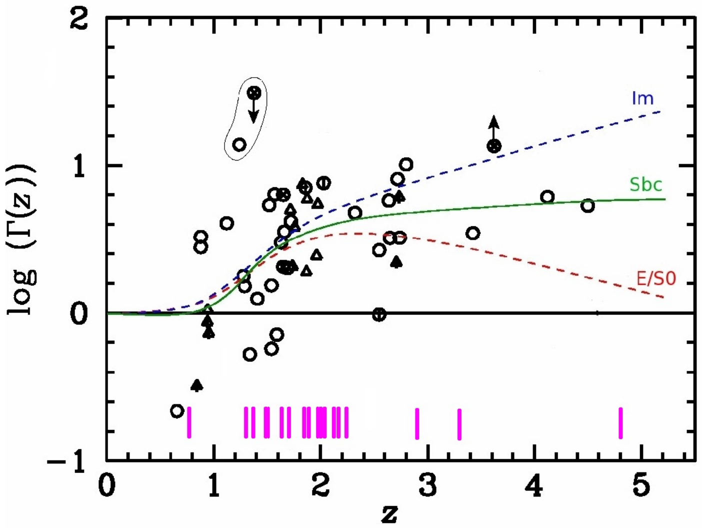

Figure 1: The ratio $\Gamma(z)$ of the measured black hole to stellar mass ratio $M_{\rm BH}/M_*$ at redshift z to that of the local ($z = 0$) value, obtained from gravitationally lensed quasar host galaxies (Peng et al. 2006). The Sbc template was used as a default template for computing K-correction; effects of changing the template are shown by dashed lines. The Figure shows $\log(\Gamma(z)) > 0$ at high redshifts, indicating that black holes were more massive (for a given stellar mass) in the past. Vertical bars (magenta) show the redshifts of our complete list of 25 targets.

• Structure and evolution of massive galaxies: Strong gravitational lensing provides a robust mass measurement within the Einstein radius, and hence a robust measurement of the mass-to-light ratio for each lens. This leads to unique constraints on the fundamental plane relation of early-type galaxies using gravitational masses (e.g., Kochanek et al. 2000). In addition, the ensemble of strong lenses constrain enclosed masses at different radii, which allow us to derive the mean radial mass profile for massive early-type galaxies (e.g., Rusin & Kochanek 2005). Clearly, accurate astrometric constraints to the mass model are essential for these applications, as well as accurate surface photometry for the lensing galaxies.

Proposed Observation: High-resolution images necessary for the applications discussed above have mainly been supplied by the HST. However, recent progress of adaptive optics (AO), especially the utilization of laser guide star (LGS), makes it possible to obtain high-resolution images using ground-based telescopes. Due to the smaller diffraction limit, NIR imaging with Subaru Telescope AO should achieve *three times* the spatial resolution of HST.

The current proposal is complementary to an already accepted GT proposal with the same title. For the GT observations we focus on lenses with complicated morphology, aiming mainly to constrain dark matter substructures and explain flux ratios anomalies. On the other hand, here we focus on the evolutionary studies described above, for which large samples of targets are necessary.

We therefore propose LGS-AO imaging of a large number (25 in total, 12 in S11A) of quasar lenses discovered by the SQLS, using Subaru LGS (see Fig. 2, and also Table in the Technical Details).

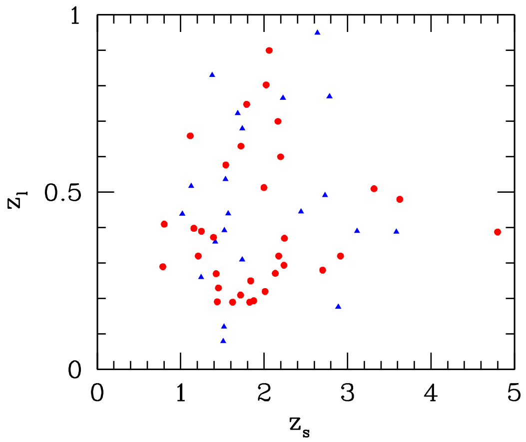

Figure 2: The source (z_s) and lens (z_l) redshift distributions of the 56 SQLS lenses. Blue filled triangles indicate lenses with high-resolution images already available (mostly from Hubble Space Telescope), whereas red filled circles are those without any high-resolution images; for these lenses, we only have ground-based images taken in a typical seeing size of $\sim 0.9''$. We select our targets among these objects.

All our targets have only ground-based images taken with a typical seeing size of $\sim 0.9''$, and therefore imaging with LGS-AO will greatly improve relative astrometry and surface photometry. Among 56 SQLS lenses, 22 lenses have received high-resolution images to date. The proposed Subaru observations will virtually double this number, significantly increasing the sample of SQLS lenses with high-resolution imaging. We plan to conduct reasonably deep imaging ($\sim$ 20 min or more) for each target in order to search for lensed host galaxies down to $K \sim 21$ mag or more, a factor of $\lesssim 1/10$ fainter than the quasar component which is typical for lensed host galaxies (Peng et al. 2006). In Figure 1 we show the source redshift distribution of some of our proposed targets, which suggest that our targets will probe the very interesting redshift range of $1.4 \lesssim z \lesssim 2.4$, where the scaling relation appears to evolve quickly, as well as higher redshifts, where the uncertainty in the relation is large.

To emphasize the critical importance of high-resolution imaging for our study, in Figure 3 we show simulated images of a typical lensed quasars, with and without AO. The power of high-resolution imaging is quite obvious from this Figure; with AO, each component can be detected and studied much more robustly and cleanly. To summarize, our proposed observations will be an important step toward enabling full use of the unique SQLS lens sample.

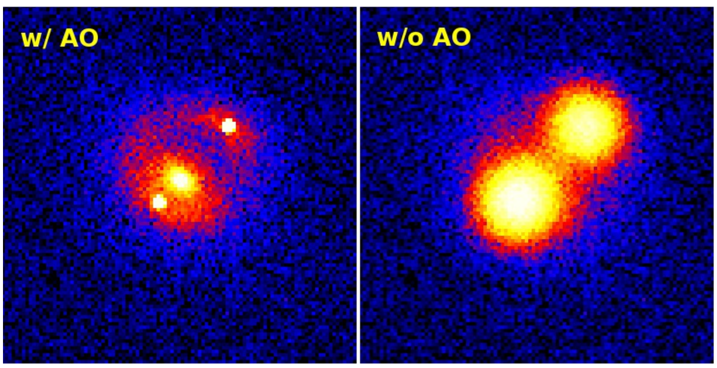

Figure 3: Simulated images of a typical two-image SQLS lens with an image separation of $\theta = 1.5''$. Left and right panels show simulated images with (PSF FWHM $0.07''$) and without AO (PSF FWHM $0.7''$), respectively. In the left panel, we can see not only the shape of a lensing galaxy very clearly, but also a lensed host galaxy forming tangential arcs. Without AO it is hard to study these features, hidden under the bright quasar components.

References

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