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# PROBING THE INNER KPC OF MASSIVE GALAXIES WITH STRONG GRAVITATIONAL LENSING

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## ABSTRACT

We examine the prospects of detecting demagnified images of gravitational lenses in observations of strongly lensed mm-wave molecular emission lines with ALMA. We model the lensing galaxies as a superposition of a dark matter component, a stellar population, and a central supermassive black hole and forecast the detection of the central images for a range of relevant parameters (e.g. stellar core and black hole mass). We find that over a large range of acceptable parameters, future deep observations of lensed molecular lines with ALMA will be able to detect the central images at $\gtrsim 3\sigma$ significance. We use Fisher analysis to examine the constraints that could be placed on these parameters in various scenarios.

*Subject headings:* black hole physics — gravitational lensing: strong — galaxies: formation — galaxies: high-redshift

## 1. INTRODUCTION

Probing the matter distribution in the innermost kpc of galaxies can answer key questions about super massive black holes (SMBH), galaxy formation, and dark matter. It is now established that almost every massive galaxy harbors a SMBH at its center with a mass that strongly correlates with the mass of the host galaxy (Kormendy & Richstone 1995; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002). In addition, the distribution of stellar populations in central regions of galaxies contains information about their past merger histories and SMBH-stellar population interactions. (e.g Barnes & Hernquist 1992; Ebisuzaki et al. 1991). Various dark matter models also predict different structures for the central regions of dark matter halos (e.g Rocha et al. 2013). Mapping the matter density in the central regions of galaxies can thus shed light on various astrophysical phenomena.

Studies of local galaxies in optical wavelengths have shown that, unlike their lower-mass counterparts, the most massive elliptical galaxies often exhibit cored stellar light profiles, with core sizes ranging from 50 to 500 pc (e.g., Ferrarese et al. 2006). These galaxies are thought to form through gas-poor mergers. In such mergers, the central structure of the resulting galaxy is dominated by the inner structure of the more concentrated progenitor. Since high-mass ellipticals are thought to form from mergers of their lower-mass counterparts, with steep profiles, the existence of cores in these galaxies represents a challenge to our understanding of galaxy mergers. Cores in massive ellipticals, therefore, should be the result of different (not merger) mechanisms. "Black hole scouring" is a plausible mechanism that can explain core-formation in these galaxies (Thomas et al. 2014).

It is thought that during a merger, the SMBHs of the two merging galaxies form a binary which sinks to the center of the potential. The two orbiting SMBHs then dissipate angular momentum through three-body interactions with nearby central stars, pushing the stars to higher orbits and "scouring out" a core. This angular momentum loss then allows the two black holes to merge (Begelman et al. 1980). Previous studies have shown that the core sizes in these galaxies scale with the mass of their SMBHs, in agreement with theoretical predictions (Kormendy & Bender 2009; Kormendy & Ho 2013). Such measurements, however have been limited to low redshifts, since both dynamical measurements to constrain the stellar and SMBH masses, and morphological measurements to constrain core sizes require very high physical resolutions.

Strong gravitational lensing is a powerful tool for probing the matter distribution in distant galaxies. Among other things, strong lenses have been used to constrain galaxy masses (e.g. ), density profiles (e.g. ), and abundance of dark matter subhalos (e.g. ). The strong lensing theory indicates that the number of lensed images should always be odd. For double and quad image configurations, a third and a fifth image are predicted to exist near the centers of lensing galaxies. Unlike the other lensed images, which are magnified, this image can be significantly *demagnified*, making its detection difficult (). It is well-understood that the magnification of the central images is very sensitive to the matter distribution in the innermost regions of lens galaxies: very steep singular density profiles significantly demagnify the central images, whereas cored or shallow profiles render them brighter. In addition to their low flux, the fact that central images coincide with the emission from lens galaxies makes their detection even harder. Distinguishing the central images from emission originating in the lens galaxies is extremely challenging. Moreover, if observed in the optical, absorption in the central dense regions of the lens can make the central images even dimmer, while the photon noise from the lens emission further reduces the sensitivity.

needs work The individual behavior () and statistical properties of central images in lens populations have been extensively studied (e.g. Wallington & Narayan 1993; Evans & Hunter 2002; Keeton 2003), suggesting that central images could have a wide range of magnifications. Observational searches for these images have found a number of candidates (e.g. Inada et al. 2005), however, only one secure detections of a central image of a galaxy-scale lens exists to date (Winn et al. 2004).(Inada:08 is a cluster?) To avoid the possibility of absorption in the lens, most studies have focused on strongly lensed radio quasars and the radio spectrum of candidate central images have been used to distinguish them from faint emission from the lens galaxies.

A new large population of strong lenses has recently been discovered in mm-bands. These systems were initially detected as bright point sources in wide area mm/submm surveys (Vieira et al. 2010; Negrello et al. 2010). Follow-up observations have confirmed that they constitute a large population of strong lenses (Vieira et al. 2013; Hezaveh et al. 2013b; Bussmann et al. 2013). In particular, ALMA observations of these sources have revealed that the background galaxies are dusty, starburst, high redshift galaxies, containing a wealth of cold molecular gas (Weiß et al. 2013). These observations showed that the extreme brightness of the sources in combination with the high sensitivity of ALMA results in very high signal to noise ratios

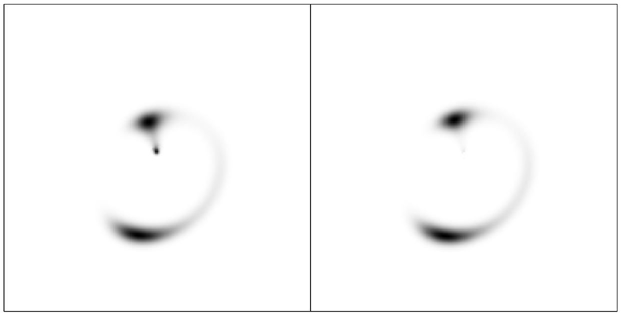

FIG. 1.— illustration of the central image in 2 cases:

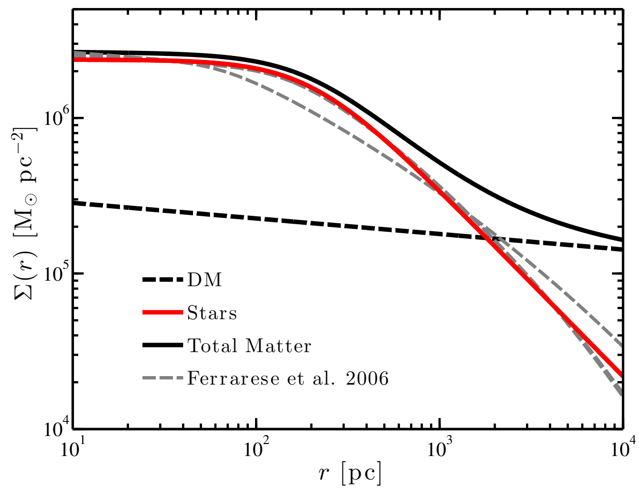


FIG. 2.— Model density profiles. The black dashed line shows the dark matter component, with a slope of 0.1, consistent with a projected NFW at the innermost regions. the grey dashed curves show cored-sersic five fits to stellar light profiles of massive galaxies from Ferrarese 2006. The red solid curve shows our cored-power-law model that we use to approximate this stellar component. The solid black line shows the total matter density (dark plus stellar) of our model.

(e.g. the lens models in Hezaveh et al. 2013b, were based on just $\sim$ 50 second long observations). Motivated by the discovery of this population and the operation of ALMA, here we revisit the issue of detecting central images. Deep ALMA observations of molecular line emission in these sources are likely to be carried out for various reasons (e.g., Hezaveh et al. 2014; Hezaveh 2014). If a central image of a lensed molecular line is detected, it will be readily identifiable since it will correspond to the redshift of the source, leaving no doubt about its origin. In addition, since these lines are in mm-bands, the line fluxes are very unlikely to be suppressed due to absorption in the lens. In contrast to lensed quasars, these sources are extended over hundreds of parsecs and can cover a larger area of the source plane. This can allow them to occupy the less demagnified regions of the source plane, allowing a higher flux for the central image (the opposite effect of magnification damping due to extended sources,, see e.g. Hezaveh & Holder 2011).

In this letter, we explore the possibility of detecting the central lensed images in such deep observations and investigate the constraints that could be placed on the core size, mass of SMBHs, and the slope of the density profiles from detection, or non-detection of such images. We also examine if binary SMBHs can possibly be detected in such observations. In Section 2 we describe the simulations, in Section 3 we present the results and discuss them, and finally conclude in Section 4. We use a flat $\Lambda$CDM cosmology with $h = 0.71$ and $\Omega_M = 0.267$.

## 2. SIMULATIONS

We generate lensed images of background sources, predict ALMA visibilities, and use them to estimate the detection significance of central images for various parameters. We simulate observations of a high-$J$ CO line. The line is assumed to have a velocity integrated flux of 1 Jy km/s and a FWHM of 400 km/s, resulting in an average flux of 2.5 mJy over a XX km/s band.

We model the lens potential as a sum of three components: dark matter, stellar population and central SMBH. The dark matter is modeled as a singular power-law with a slope of 0.1, in agreement with the projected surface mass density of the NFW profile (Golse & Kneib 2002). As by pointed out by (Keeton 2003), due to its extreme flatness in these regimes, the dark matter component has negligible influence on the central images. The stellar population is modeled as a a core power-law, $\Sigma \propto (r^2 + s^2)^\gamma$. Figure 2 shows the stellar component (red curve), dark matter component (black dashed curve) and the sum of the two (black solid curved). The grey dashed curves show a few example of core-sersic models with parameters taken from Ferrarese et al. (2006). We note that although the cored power-law model used in this work does not account for the slope of the stellar distribution below the core break, it is a close fit and a reasonable model to approximate the observed stellar light profiles. The black hole is modeled as a simple point mass at the center of the potential. In this work we assume that all the three components are concentric.

The lens mass is set to XX $M_\odot$ resulting in an Einstein radius of $\sim XX''$, in agreement with galaxy-galaxy strong lenses. We divide this mass equally (in a radius of 10 kpc) between stellar and dark matter.

To predict the visibilities we calculate the ALMA $uv$-coverage for a 5-$hr$ long observation with the most extended antenna configuration (full array), using the $simobserve$ task of Common Astronomy Software Applications package, which results in an angular resolution of $\sim 20$ $milli$-$arcsec$ at an observing frequency of 240 GHz. The visibilities for each channel are calculated by computing the 2D Fourier transform of the corresponding layer of the data cube and resampling the Fourier transform maps over the uv-coverage. The noise is estimated using ALMA sensitivity calculator for a channel width of 8 km/s at 240 GHz. We use finite differencing of visibilities to calculate the Fisher information and the parameter covariance matrix to calculate the significance of black hole mass measurement.

For simulations where we calculate the detection significance of the demagnified image, we compute the magnification at every pixel in the image plane and generate maps with and without the the demagnified flux and evaluate the detection significance of the central image by comparing the two images. In other simulations where the constrains on parameters are needed, we use a Fisher analysis to compute the full covariance of all parameters. We then marginalize over the nuisance parameters (e.g. source position, lens ellipticity) to calculate the marginalized likelihood of the relevant parameters.

## 3. RESULTS AND DISCUSSIONS

### 3.1. *Detection of central images with ALMA*

As discussed earlier, the fluxes of central images strongly depend on the slope of the lensing potential, the core size, and the mass of the central SMBHs. Figure 3 shows the detection significant of a central image for a range of these parameters in a 10-h long ALMA observation. The grey curves (dark to light) correspond to profiles with slopes of $\gamma = 0.9, 1.0, 1.1,$ and 1.2. As seen in this figure, larger stellar cores result in brighter images. When $\gamma = 1.0$ and with a core size larger than 150 pc, such observations should be able to detect the central images with more than $5\sigma$ significance. For significantly

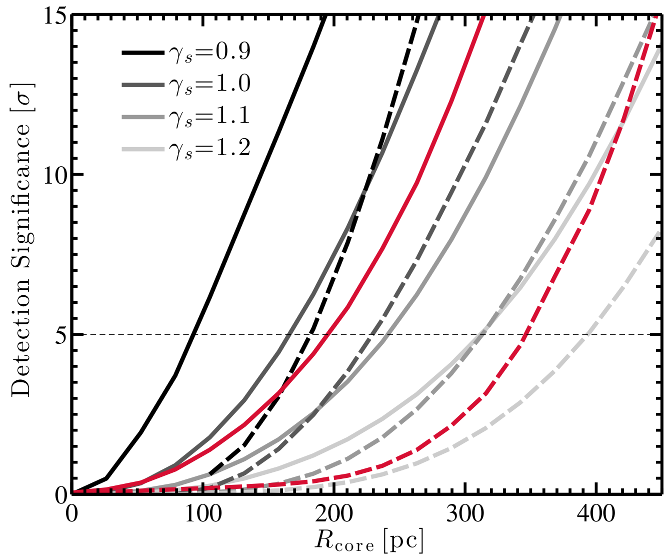


FIG. 3.— Detection significance of a central image as a function of the stellar core size for a 10-hr long ALMA observation. The gray shades correspond to different slopes for the stellar component. The solid curves correspond to a case without a SMBH while the dashed curves show the results when a $2 \times 10^8 M_\odot$ SMBH is placed at the center of the lens. The source has a Gaussian light profile with an rms of 600 pc. The red curves show the same predictions when $\gamma = 1$, for a source with rms of 300 pc.

shallower ($\gamma < 0.8$) profile slopes with larger cores, the central image is *magnified* and its detection should be trivial. The magnification and flux of central images is also influenced by SMBHs. SMBHs demagnify the images on scales comparable to the size of their Einstein radii. The dashed curves in Figure 3 show the suppression of the fluxes of central images in presence of a $2 \times 10^8 M_\odot$ SMBH.

As seen in Figure 3, and as pointed out by Keeton (2003), plausible parameters (e.g. core sizes) predict a wide range of magnifications for central images. Although for some plausible parameter combinations (e.g., $\gamma_s = 1.2$, $M_{BH} = 2e8$,$R_{core} < 300pc$ ) there is little chance of detecting the central images, over a non-negligable fraction of parameter space the central images may be detectable.

We also find that the detection significance of the central images can increase by about $3\sigma$ for an extended source with a radius of 1 kpc compared to a point source. Since extended sources cover a larger area of the source plane, which may include regions with higher magnifications, the resulting flux can be larger than the flux of more compact sources.

### 3.2. *SMBHs and the core size*

We studied the constraints that deep observations of molecular lines can place on the slope of the density profile, the size of the stellar core, and the mass of the SMBHs. We performed a Fisher analysis to examine the constrains and parameter degeneracies in simulations in which the central images are detected, as well as those in which they are below the detection limit. All model parameters were included in the Fisher matrix, and nuisance parameters were later marginalize over (e.g. intrinsic source flux and position) to obtain the marginalized likelihood of the relevant parameters. Figure 4 shows the parameter covariance for two examples with different core radii (top panel: $R_{core}$=170 pc, bottom panel: $R_{core}$=450 pc). We found that when $\gamma = 1$, cores sizes larger than 100 pc can be measured with high significance. As seen in top panel of Figure 4, the mass of SMBH is degenerate with the core size: larger cores result in brighter images, whose flux can be supressed by a more massive SMBH. This degeneracy, however, breaks when the core size is very large. Large

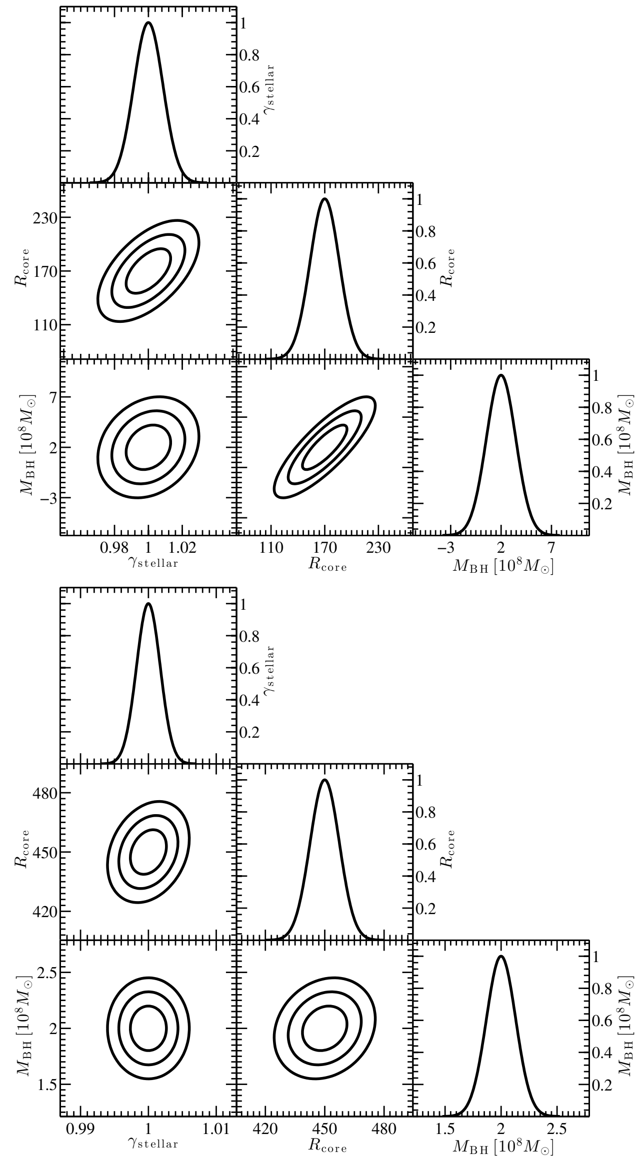


FIG. 4.— Covariance matrix of parameters for a few different scenarios.

cores produce more extended central images that are spatially resolved. The distortion caused by a SMBH can distort this image on smaller scales, resulting in a distinct dip in its surface brightness. We found that for cores $\gtrsim$ 200 pc, SMBH masses could be measured with high significance (e.g., bottom panel of Figure 4), but for smaller core sizes, only upper limits on the mass of SMBHs can be placed. We also find that when the core size is larger, the constraints on the density profile slope are stronger.

### 3.3. *Detection of Binary SMBHs*

We also investigated the possibility of detecting binary SMBHs using the perturbations that they induce on the lensed central images. We randomly placed two SMBHs in a circle with a radius of 1 kpc from the center of the galaxy and, using the Fisher analysis, computed the detection significance of their masses .

We found that in most cases, it is not possible to measure the mass of both SMBHs due to the degeneracies between their masses and their positions. However, in a few simulation, we encountered configurations that allowed a detection of both SMBH masses. The constraints in such observations come from the distortion in the resolved *shape* of the central image.

To estimate the probability of such events we simulated 200 realizations of the positions of the SMBHs for high resolution (50 mas) 40-h long observations. We used various core sizes to examine the effect of central image magnification on the binary SMBHs mass measurements.

We found that in XX% of the simulations both SMBHs were detected. Although this number may seems promising, the prospects of such measurements will be limited by the number of discovered bright central images, which based on their current dearth, may be very few. For larger core sizes and shallower profiles, which result in yet larger and brighter central images, the sensitivity to SMBHs *decreases* again, due to the size of the image becoming larger than the Einstein radius of the SMBHs (analogous to the decrease in sensitivity to subhalos due to large source sizes). If such large cores are ever detected, spectral decomposition may allow increasing the sensitivity to the effects of the SMBHs (Hezaveh et al. 2013a).

Since suitability for such measurements will depend on the core size and slope of the stellar light, future high resolution observations with thirty meter telescopes, may help select systems with the right range of morphological parameters, to be followed up.

Note that since the background source is extended, the flux subpression is *less*

## 4. CONCLUSION

We examined the prospects of detecting central, demagnified images of strongly lensed molecular lines with ALMA. We found that there is a non-negligible space of realistic and plausible parameters that result in a high significance detection of the central images. We showed that such deep observations can either allow a measurement of the mass of the central SMBH and the stellar core size, or place strong limits on them. We also studied the possibility of detecting binary SMBHs and found that under special conditions there is a non-zero probability of measuring the masses of both SMBHs, although suitable central images for such measurements may be very rare.

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