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# A strong-lensing elliptical galaxy in the MaNGA survey

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**ABSTRACT**

I report discovery of a new galaxy-scale gravitational lens system, identified using public data from the Mapping Galaxies at Apache Point Observatory (MaNGA) survey, as part of a systematic search for lensed background line emitters. The lens is SDSS J170124.01+372258.0, a giant elliptical galaxy with velocity dispersion $\sigma = 256\ \mathrm{km\,s^{-1}}$, at a redshift of $z_\mathrm{l} = 0.122$. After modelling and subtracting the target galaxy light, the integral-field data cube reveals [O II], [O III] and H$\beta$ emission lines corresponding to a source at $z_\mathrm{s} = 0.791$, forming an identifiable ring around the galaxy centre. If the ring is formed by a single lensed source, then the Einstein radius is $R_\mathrm{Ein} \approx 2.3$ arcsec, projecting to ∼5 kpc at the distance of the lens. The total projected lensing mass is $M_\mathrm{Ein} = (3.6 \pm 0.6) \times 10^{11}\ \mathrm{M_\odot}$, and the total *J*-band mass-to-light ratio is $3.0 \pm 0.7$ solar units. Plausible estimates of the likely dark matter content could reconcile this with a Milky Way-like initial mass function (IMF), for which $M/L \approx 1.5$ is expected, but heavier IMFs are by no means excluded with the present data. An alternative interpretation of the system, with a more complex source plane, is also discussed. The discovery of this system bodes well for future lens searches based on MaNGA and other integral-field spectroscopic surveys.

**Key words:** gravitational lensing: strong – galaxies: elliptical and lenticular, cD.

## 1 INTRODUCTION

Strong gravitational lensing provides the most precise and accurate means to determine absolute masses for distant galaxies (Treu 2010). Such measurements yield valuable constraints on the structure of dark matter haloes, and on the normalization of stellar mass estimates, independent of assumptions for the stellar initial mass function (IMF; e.g. Auger et al. 2010).

Numerous methods have been developed to identify strong-lensing galaxies in a systematic fashion, e.g. via their characteristic arc morphologies (Bolton et al. 2006), from unusual colour configurations in catalogue data (Gavazzi et al. 2014), exploiting amplification above an underlying population e.g. for sub-mm galaxies (Negrello et al. 2010), or through searches for multiple components in the spectra of survey target galaxies (Bolton et al. 2006).

In the SNELLS (SINFONI Nearby Elliptical Lens Locator Survey) project, Smith, Lucey & Conroy (2015) adapted the spectroscopic method to apply to integral-field unit (IFU) data. The specific aim of SNELLS was to discover strong-lensing galaxies at low redshift, where (all other factors being equal) the Einstein radius is smaller, relative to the stellar effective radius, than in distant systems. Lensing masses for such galaxies are subject to smaller fractional dark matter contributions, and so provide especially robust limits on the stellar mass-to-light ratio, and hence the IMF (Smith & Lucey 2013). However, since massive galaxies are intrinsically rare, the probability that any nearby galaxy acts as a lens to a *bright* background source is very small. To tackle this challenge, our method exploits the combined spatial and spectral contrast of IFU data to detect *faint* background emission lines, and hence finds less spectacular, yet still scientifically valuable lens systems. For SNELLS, we applied this method to targeted infrared IFU observations of 27 very massive elliptical galaxies at $z_\mathrm{l} \lesssim 0.06$, discovering multiply imaged background sources behind two of them, and recovering another previously known low-$z$ lens.

Despite these efforts, there are still very few known lenses with $z_\mathrm{l} \lesssim 0.1$, and consequently the low-redshift lensing approach to the IMF is uncomfortably dependent on the properties of the three galaxies discussed in Smith et al. (2015). The advent of large galaxy surveys conducted using instruments with multiple deployable IFUs promises to enlarge significantly the available sample of nearby strong lenses. The two leading surveys of this kind are SAMI (Sydney–Australian-Astronomical-Observatory Multi-object Integral-Field Spectrograph; Bryant et al. 2015) at the Anglo-Australian Telescope, and MaNGA (Mapping Galaxies at Apache Point Observatory; Bundy et al. 2015), which is part of the fourth-generation Sloan Digital Sky Survey (SDSS). Both will gather IFU data for thousands of galaxies, with samples that are weighted towards large, fairly low-$z$ galaxies, and hence suitable for finding stellar-mass-dominated lenses. The wide wavelength coverage (0.36–1.00 µm) of MaNGA is especially advantageous for probing background emitters over a large redshift range.

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In this Letter, I report a strong-lensing galaxy discovered from the first public MaNGA data (Law et al. 2016), from SDSS Data Release 13 (DR13; Sloan Collaboration 2016). Although this particular system is probably too distant to provide very robust constraints on the IMF, it is a useful demonstration of the power of multiple-IFU surveys to identify strong lenses which were (as in this case) not discovered in previous generation single-fibre data for the same galaxy. I briefly describe the data processing and search methods used in Section 2, and the properties of the first newly discovered lens system in Section 3. Some preliminary analysis and comparison with other lenses is made in Section 4, and summarized in Section 5. A more thorough description of the MaNGA strong-lens search will be presented in a future paper, while detailed study of the system reported here will require follow-up observations.

## 2 SEARCH METHOD

For this preliminary study, I restricted the analysis to the 81 galaxies in MaNGA DR13 having SDSS single-fibre velocity dispersion $\sigma > 250$ km s$^{-1}$. This is a small enough sample that all targets could be carefully inspected visually, and because the lensing cross-section scales approximately as $\sigma^4$, the total lensing probability for the survey is weighted heavily to these most massive galaxies.[1]

As with the original SNELLS method, the broad approach is to extract an average spectrum for the primary target galaxy, use this as a simple model to remove the target light from each pixel in the data cube, and then to examine suitably noise-normalized residual images by eye. For MaNGA, initial explorations showed that the combined data cubes from DR13 are affected by small reconstruction artefacts, causing abrupt changes in the spectrum shape on a pixel-by-pixel basis. These features seem to arise from imperfect relative flux calibration, combined with masking of pixels affected by cosmic rays. This leads to excessive spurious features in the residual data cube, especially near the galaxy centres, which would badly hamper detection of real emission lines.

Thus, for this analysis, I instead work from the ‘row-stacked spectra’ data products, which contain the individual input spectra and associated masks, in order to handle the lens galaxy subtraction prior to any interpolation between fibres. The mean galaxy signal was subtracted from each spectrum after modulation by a continuum fit to account for sensitivity and broad colour variations, and the residuals in each wavelength channel were normalized by the median absolute deviation of all pixels in that channel. Finally, I reconstructed the residuals to a new data cube defined on a square-pixel oversampled grid. Specifically, the output pixels are 1 arcsec, but each is an average of the residual flux over a 2 × 2 arcsec cell, hence neighbouring pixels are correlated. The residual data cube was then also output as an ‘unwrapped cube’ (pseudo-long-slit) format, which is convenient for visual inspection.

In most cases the ‘inspection images’ are fairly featureless. Residuals from strong sky lines are usually present, but largely suppressed by the noise normalization. Where target galaxies have spatially varying spectra, e.g. strong emission lines, or evident rotation, the effects are visible in the inspection images, but easily distinguished from the localized background emission signal being sought here.

Background line-emitters are detected in the inspection images for around a quarter of all targets considered. In almost all cases, multiple lines are visible to confirm the source redshift, while for one distant [O II] emitter the identification was clear based on the resolved doublet structure. From the DR13 $\sigma > 250$ km s$^{-1}$ sample, all but one of the background emitters were located at large $\gtrsim$5 arcsec from the primary target, and hence unlikely to be multiply imaged. Curiously, several targets have two background galaxies at a common or very similar redshift, but the separation is so large in most cases that they must be multiple sources, e.g. in a background group.

Only one system was discovered among this sample that can be confidently classified as lensed, based on the MaNGA data alone, as described in the next section.

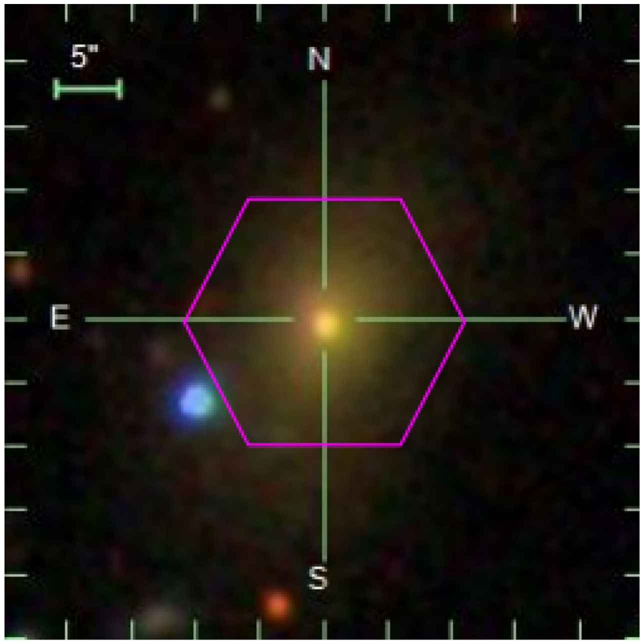


**Figure 1.** The MaNGA lens galaxy J1701+3722. The lensed source is not visible in this SDSS broad-band image, but the faint feature just inside the south-east corner of the MaNGA field is the ‘southern source’ at the same redshift as the lensed galaxy. The bright blue object outside the IFU is a foreground star.

## 3 A BRIGHT EINSTEIN RING IN J1701+3722

A strongly lensed background line-emitter was discovered in the residual data cube for target SDSS J170124.01+372258.0 (hereafter J1701+3722),[2] which is a giant elliptical galaxy with $\sigma = 256 \pm 8$ km s$^{-1}$ and redshift $z = 0.122$. The SDSS image and MaNGA IFU field for this target are shown in Fig. 1. The galaxy image appears smooth and without any peculiarities. The original SDSS single-fibre spectrum exhibits a pure continuum spectrum, characteristic of an old stellar population, with no emission lines to indicate ongoing star formation or nuclear activity.

Fig. 2 shows an extract from the MaNGA inspection image for this galaxy, which reveals prominent emission lines that are consistent with [O II] 3727 Å, H$\beta$, [O III]4959 Å and [O III] 5007 Å, at a redshift of $z = 0.791$. As with some other objects found in this project (as mentioned above), the emission is clearly broken into several spatial parts. The upper section itself displays two bright regions separated by a fainter section. The uppermost part is clear

[1] Galaxies with $\sigma > 250$ km s$^{-1}$ account for ~40 per cent of $\sum\sigma^4$ for MaNGA DR13.

[2] Also identified as MaNGA ID 1-136292, and MaNGA plate–ifu number 8606-6102.

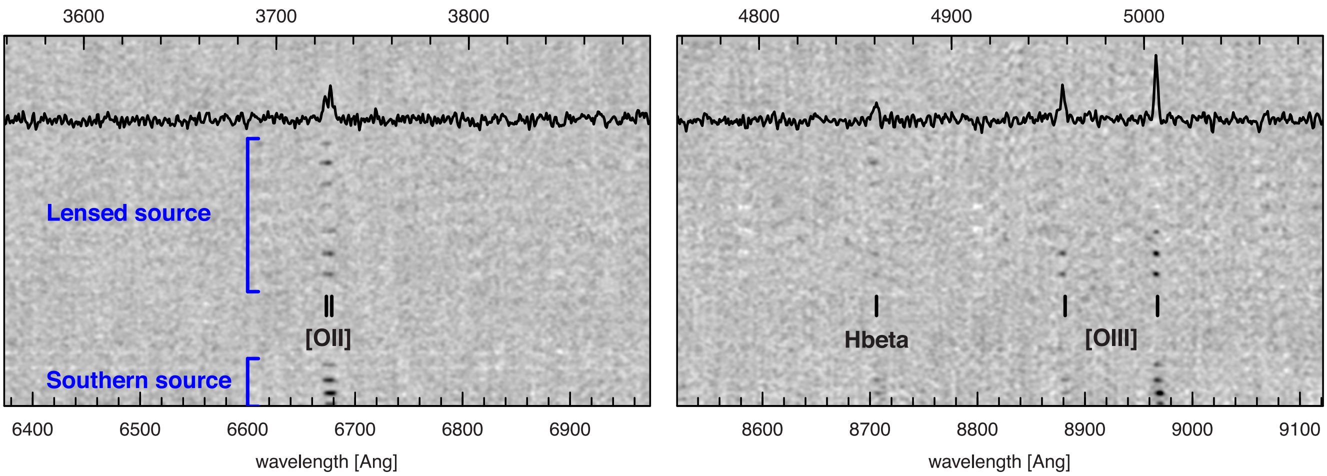


**Figure 2.** Extracts from the 'inspection image' for the MaNGA lens galaxy J1701+3722. This is an unwrapped cube or pseudo-long-slit spectrum, after removing the $z = 0.122$ target galaxy signal, and normalizing by the noise spectrum. Positive signals (emission lines) are dark in this image. The vertical direction follows the spatial raster, with the north of the field at the top. The wavelength scales are as observed (lower) and at rest for $z = 0.791$ (above). The trace shows the noise-normalized residual spectrum extracted from the brightest part of the lensed source.

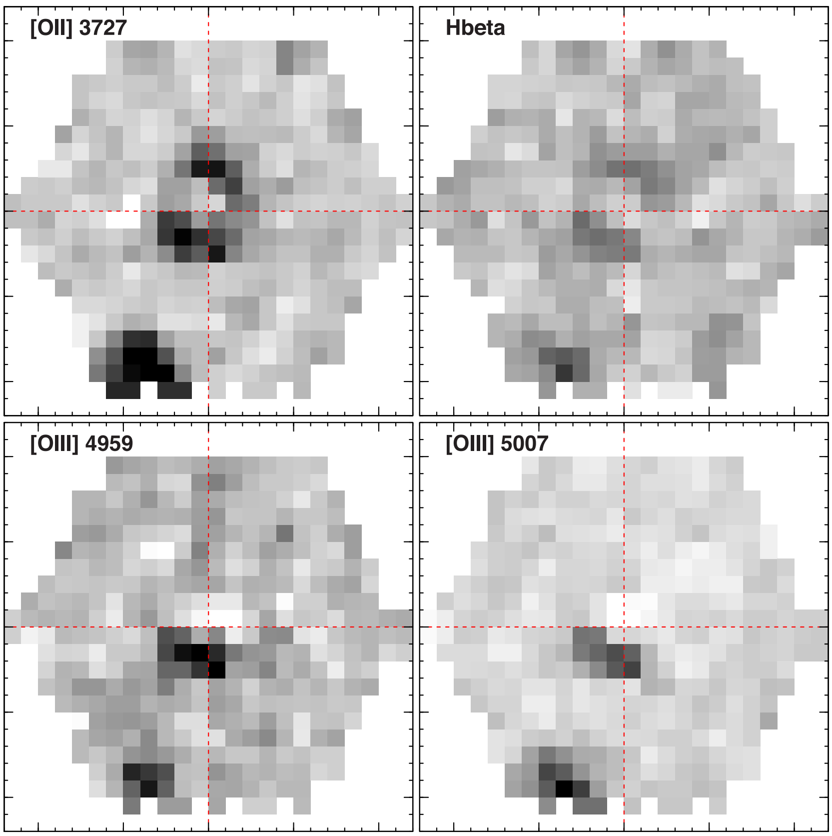


**Figure 3.** Spatial structure of the four detected $z = 0.791$ background emission lines in J1701+3722. The panels are 24 arcsec on each side, with 1 arcsec pixels, with the same orientation as Fig. 1. The colour scaling is slightly adjusted in each panel to emphasize the main features. An apparent Einstein ring configuration is seen in the upper panels, but only one 'arc' is bright in [O III]. The 'southern source' at the same redshift is seen in the corner of the field.

only in [O II], but also faintly visible in H$\beta$. The [O II] doublet line profile is identifiable throughout both sources; the redshift is unambiguous.

Fig. 3 shows the spatial structure of the $z = 0.791$ emission, from the four brightest lines. The brightest part of the emission corresponds to a separate object at the same redshift, well to the south of the target galaxy. This source is faintly visible in the SDSS imaging. In the [O II] line, the northern part of the emission seems to form a near-complete ring, with radius ∼2.3 arcsec around the centre of J1701+3722. The ring is possibly broken into two 'arcs', though the detailed morphology should not be over-interpreted at this stage, given the low resolution of the reconstructed image, and the processing steps applied. Within the ring, [O III] 5007 Å is the brightest line, peaking at ∼$1.5 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ per MaNGA fibre, while [O III] 3727 Å reaches ∼$1.0 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ per MaNGA fibre. Curiously, the emission morphology appears to be different in the [O III] lines, where only the southern 'arc' is visible, both 'arcs' are seen in the weak H$\beta$ line.

## 4 DISCUSSION

The newly discovered lens occupies an interesting redshift niche, being substantially more distant than the SNELLS galaxies (at $z = 0.03$–$0.05$), but at near end of the range probed by the SLACS (Sloan Lens Advanced Camera for Surveys) sample of Bolton et al. (2008) ($z = 0.10$–$0.35$). The velocity dispersion is smaller than that of the SNELLS lenses, but higher than average for the closest lenses in SLACS. The background source in J1701+3722 is so bright that it may be surprising it was not detected from the single-fibre SDSS spectroscopy: the [O II] line can, with hindsight, be clearly seen as a residual peak in the original spectrum, but the other lines cannot. The [O II] and [O III] lines *are* both seen, however, in a 3-arcsec 'aperture' constructed from the deeper observation for MaNGA.

Assuming the simplest interpretation for the system, i.e. an Einstein ring formed by a single source (but see below), the total projected mass can be estimated from the Einstein radius, using the symmetric lens approximation.

Adopting $R_{\rm Ein} = 2.3 \pm 0.2$ arcsec, together with the angular diameter distances computed with the same Komatsu et al. (2011) cosmological parameters as used in Smith et al. (2015), this yields $M_{\rm Ein} = (3.6 \pm 0.6) \times 10^{11}$ M$_{\odot}$. Again following Smith et al. (2015) for consistency, I estimate the luminosity in the $J$ band, from 2MASS (the 2-Micron All-Sky Survey; Skrutskie et al. 2006). J1701+3722 has $J = 14.8 \pm 0.2$ in the 2.3-arcsec aperture, corresponding to $L_{\rm Ein} = (1.2 \pm 0.2) \times 10^{11}$ L$_{\odot}$. Hence the total mass-to-light ratio inside the Einstein aperture is $3.0 \pm 0.7$. For comparison, the total mass-to-light ratio of the three SNELLS lenses was 1.8–2.1 in the same band. According to the Maraston (2005) models, the expected value for old stellar populations alone (i.e. no dark matter) is ∼1.5 with a Kroupa (2001) IMF, or ∼2.3 with a Salpeter (1955) IMF.

The contribution of dark matter to the lensing mass in J1701+3722 will be larger than in the SNELLS galaxies, because the lens is more distant, so the Einstein radius projects to a larger physical scale: ∼5.0 kpc, compared to ∼2 kpc for SNELLS. The method applied in Smith et al. (2015), based on projected dark matter halo profiles in simulations (Schaller et al. 2015), yields an estimate of $M_{\rm DM} = (1.2 \pm 0.2) \times 10^{11}$ M$_{\odot}$, within $R_{\rm Ein}$, i.e. ∼33 per cent of the total. Thus, the total mass-to-light ratio obtained here is consistent with the SNELLS results favouring a Milky Way-like IMF, but given the large present uncertainties, they are also quite compatible with Salpeter or heavier IMFs.

The estimates above should be treated with caution until the lens can be better characterized with improved data. Two factors in particular suggest that the simple lens model might be inappropriate for J1701+3722. First, the radius of the observed 'ring' is 50 per cent larger than the expected Einstein radius for an isothermal mass distribution with $\sigma = 256$ km s$^{-1}$, given the lens and source redshifts. Second, there is the different appearance of the system in the [O III] versus the [O II] lines. This disparity is probably physical, rather than caused by artefacts in the observations or data processing, since both [O III] lines are affected similarly, while H$\beta$ follows the same structure as [O II]. An alternative interpretation would be that the arcs correspond to two *different* sources at the same redshift, each being either singly imaged or having a faint counter-image at smaller radius which is not detectable in the present data. This scenario would imply a smaller Einstein radius, resolving the apparent discrepancy with the measured velocity dispersion.[3]

Future observations at higher spatial resolution are essential to distinguish between these possibilities.

## 5 SUMMARY AND OUTLOOK

In this Letter, I have presented the discovery of a strongly lensed emission-line galaxy behind a $z = 0.122$ elliptical observed in the MaNGA survey. The survey data allow a crude initial estimate of the Einstein radius and total lensing mass, under the simplest assumptions, but improved data will be necessary to characterize the lensing configuration properly.

The discovery of such a bright example, from just the first few dozen MaNGA observations analysed, augurs well for identifying numerous strong lenses with the new generation of multi-IFU surveys. I am currently extending this initial study to search for lenses among MaNGA galaxies with lower velocity dispersion, and also conducting an equivalent programme using data from the SAMI survey. While the method can certainly detect much fainter background sources than that in J1701+3722, most such systems will require follow-up observations to confirm the candidates. None the less, this approach is a promising means to enlarge the sample of low-redshift, stellar-mass-dominated lenses.


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[3] I am grateful to Tom Collett for proposing this interpretation.

of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University and Yale University.

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