Source plane reconstruction of the giant gravitational arc in Abell 2667: a candidate Wolf-Rayet galaxy at z~1

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Outline

- 1. Review of strong gravitational lensing
- 2. Introduction to Lenstool
- 3. Source plane reconstruction of the giant gravitational arc in Abell 2667
- 4. Conclusions and discussion
1. Review of strong gravitational lensing

Light rays are deflected by gravity.

- One consequence of Einstein’s General Theory of Relativity
\[ \gamma \sim \alpha = \frac{D_{LS}}{D_S} \frac{4GM}{\xi c^2} \]

\[ \hat{\alpha} \cdot D_{ds} = \alpha \cdot D_s \]

\[ \theta \cdot D_s = \beta \cdot D_s + \hat{\alpha} \cdot D_{ds} \]
Why GL is an important astrophysical tool?

• 1. Physical basis very well understood;

• 2. No need to make hypothesis on dynamical status of the gravitational lens (galaxy, galaxy cluster...);

• 3. No need for luminous mass tracers. （Direct evidence of Dark Matter）
- The rise of strong lensing (1979-2000)

**G2237+0305**

**Abell 2667**

**COSMOS 5921+0638**
Morphology: Change of parity across a critical line.

Note: The lensing amplification is a gain in the angular size of the sources. Allow to resolve distant sources and study their size and morphologies.

Lensed pair in AC114, $z=1.86$
2. Introduction to Lenstool

- **LENSTOOL**
- Lens modeling and source reconstruction with multiple images:
  - Making use a Monte Carlo Markov Chain (MCMC) optimization method
- Galaxy SL systems
- Galaxy-cluster SL systems
How to identify multiple images?

Color and Morphology:

Lens model can help for the identification when different solutions are possible.

Quintuple arc ($z=1.67$) in Cl0024+1654 ($z=0.39$)
Identification in a multiple images system if:
- Same color
- Same redshift
- Same features (bright knots)
- Mirrored images

The fit is good when the predicted and observed images overlap each others (within the positioning accuracy!)
Image distortion in Galaxy Cluster 0024-0414

Covone et al. (2006)
Abell 2667 is among the most luminous galaxy clusters known in the X-ray sky, with the BCG located at $z_d = 0.233$. The triple arc is determined as a galaxy at a redshift of $z_s = 1.034 \pm 0.005$. 

3. Source plane reconstruction of the giant arc in Abell2667
Observations

- Imaging data from *HST*
- Advanced Camera for Surveys (ACS; filter *F850LP*),
- WFPC2 (filters *F450W*, *F606W*, and *F814W*),
- Near-Infrared Camera and Multi-Object Spectrometer (NICMOS; filters *F110W* and *F160W*)

- *HST/ACS* high-resolution images are essential to building an accurate model of the gravitational lens, while the large multi-wavelength coverage allows us to constrain the properties.

- The central region of the galaxy cluster was observed with the VIMOS IFU (Covone et al. 2006b; Grin et al. 2007) mounted on VLT Melipal, covering from about 3900–5300 Angstrom. Covone et al. (2006b) extracted 22 galaxy spectra and the spatially resolved spectra of 3 lensed images of the gravitational arc.
Strong Lensing Mass Model
### Table 1

**Best-fit Lens Model Parameters**

<table>
<thead>
<tr>
<th>Halo</th>
<th>R.A.</th>
<th>Decl.</th>
<th>$e$</th>
<th>$\theta$ (deg)</th>
<th>$r_{\text{core}}$ (&quot;)</th>
<th>$r_{\text{cut}}$ (&quot;)</th>
<th>$\sigma_0$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>$-0.15 \pm 1.54$</td>
<td>$-0.54 \pm 1.47$</td>
<td>$0.58 \pm 0.15$</td>
<td>$-42.43 \pm 3.43$</td>
<td>$15.32 \pm 4.97$</td>
<td>$228.30 \pm 140.08$</td>
<td>$887 \pm 116$</td>
</tr>
<tr>
<td>BCG</td>
<td>0</td>
<td>0</td>
<td>$0.21 \pm 0.20$</td>
<td>$-43.52 \pm 16.89$</td>
<td>$0.85 \pm 0.28$</td>
<td>$44.30 \pm 13.48$</td>
<td>$169 \pm 43$</td>
</tr>
<tr>
<td>Gal2</td>
<td>$-12.71$</td>
<td>11.34</td>
<td>0.25</td>
<td>$-41.40$</td>
<td>…</td>
<td>…</td>
<td>$65 \pm 20$</td>
</tr>
<tr>
<td>Gal3</td>
<td>$-15.42$</td>
<td>14.66</td>
<td>0.17</td>
<td>$-9.40$</td>
<td>…</td>
<td>…</td>
<td>$123 \pm 28$</td>
</tr>
<tr>
<td>Gal4</td>
<td>$-4.53$</td>
<td>10.21</td>
<td>0.41</td>
<td>$-88.40$</td>
<td>…</td>
<td>…</td>
<td>$103 \pm 25$</td>
</tr>
<tr>
<td>L* galaxy</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>$111 \pm 28$</td>
</tr>
</tbody>
</table>

*Note. All coordinates are measured relative to the center of the BCG at [R.A., decl.] = [357.914250, $-26.084105$].*
Source reconstruction from each of the magnified images of the giant arc and their rendition into one frame with the best-fit lens model.
Surface brightness of the source galaxy in the z850 band. The dashed line is an exponential with $h_R = 0.34''$ ($r_s = 2.01$ kpc).
The apparent magnitudes of the source galaxy at different optical and NIR bands and the corresponding color profiles.
The color image of the lensed galaxy of Abell 2667 in B and R bands. It is obvious that the central bulge tends to be heavily reddened and possibly dominated by an old stellar population.
Arc spectrum of A2667 (blue spectrum) compared with the UV spectrum of the local Wolf–Rayet galaxy NGC 5253 (red spectrum). The gray shaded lines denote the EWs of Fe ii and Mg ii in the A2667 spectrum, while the orange shaded line marks the presence of the [C iii] line.
4. Conclusions and discussion

We used *HST/ACS* z850 imaging data to construct an improved lens model for the lensing cluster A2667. Using the new lens model, we reconstructed the de-lensed image of the source galaxy at $z \sim 1$.

1. The source resembles a normal disk galaxy with a bright, large central bulge, and tightly wrapped spiral arms. The smooth exponential profile supports the hypothesis of a mildly disturbed, almost face-on, disk versus a merging system, consistent with the velocity structure observed by Yuan et al. (2012).
2. After correcting for the flux magnification, the stellar mass of this spiral galaxy is $\log M^* = 10.28 \pm 0.31$. These values are close to those of disk galaxies with extended emission lines observed at $z > 1$ (Miller et al. 2011).

3. There are negative radial color gradients along the disk (i.e., the color is gradually bluer outward). The color profile becomes shallower with increasing radius. Moreover, we find that the central region of the galaxy tends to contain more metal-rich stellar populations, rather than being heavily reddened by dust due to high and patchy obscuration.
4. We further analyze the archive VIMOUS/IFU spectroscopic data and find that the spectra of the source galaxy of A2667 shows some typical features of a typical starburst WR galaxy (NGC 5253) with strong signatures from large numbers of WR stars. Marginal evidence for [C iii] 1909 emission at the edge of the grism range, as expected for a typical WR galaxy, further confirms our expectation.

However, this conclusion still needs to be checked with a high-resolution spectrum covering a different wavelength range.
SOURCE-PLANE RECONSTRUCTION OF THE GIANT GRAVITATIONAL ARC IN A2667:
A CANDIDATE WOLF–RAYET GALAXY AT z ∼ 1

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ABSTRACT

We present a new analysis of Hubble Space Telescope, Spitzer Space Telescope, and Very Large Telescope imaging and spectroscopic data of a bright lensed galaxy at z = 1.0334 in the lensing cluster A2667. Using this high-resolution imaging, we present an updated lens model that allows us to fully understand the lensing geometry and reconstruct the lensed galaxy in the source plane. This giant arc gives a unique opportunity to view the structure of a high-redshift disk galaxy. We find that the lensed galaxy of A2667 is a typical spiral galaxy with a morphology similar to the structure of its counterparts at higher redshift, z ∼ 2. The surface brightness of the reconstructed source galaxy in the z850 band reveals the central surface brightness I(0) = 20.28 ± 0.22 mag arcsec−2 and a characteristic radius r_s = 2.01 ± 0.16 kpc at redshift z ∼ 1. The morphological reconstruction in different bands shows obvious negative radial color gradients for this galaxy. Moreover, the redder central bulge tends to contain a metal-rich stellar population, rather than being heavily reddened by dust due to high and patchy obscuration. We analyze the VIMOS/integral field unit spectroscopic data and find that, in the given wavelength range (∼1800–3200 Å), the combined arc spectrum of the source galaxy is characterized by a strong continuum emission with strong UV
Thanks for your attention