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ROTATION ON SUB-KPC SCALES IN THE STRONGLY LENSED Z~ 3 'ARC&CORE' AND IMPLICATIONS FOR HIGH-REDSHIFT GALAXY DYNAMICS

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1 IFU observations of gravitationally lensed and field galaxies at z$\sim 2-3$

Redshifts z$\sim$2$-$3 represent the cosmologically most important epoch of star formation and galaxy evolution. Detailed studies of individual galaxies during this epoch are now possible with integral-field spectrographs (IFUs). The emerging picture is however far from simple. Even adaptive optics (AO) assisted observations reach resolutions of only $\sim$ 1 kpc, making it difficult to infer even the basic physical mechanism driving the kinematics. Forster Schreiber et al. (2006) (hereafter FS06) argue that at least a subsample of blue, star-forming galaxies at somewhat lower redshifts, z$\sim$ 2.5, may show the signs of large, spatially-extended, rotating disks. Law et al. (2007) emphasize however that UV selected z$\sim$2$-$3 galaxies have irregular kinematics, which are likely not dominated by large-scale gravitational motion, but may be more related to merging or gas cooling. Moreover, none of these scenarios may be easily generalized to the overall population of high-z galaxies. To ensure observational success, only bright and large sources are being targeted with IFUs. This bears the risk that the targets will not be good representatives of the overall high-z galaxy population, but may be biased towards the most actively star forming and disturbed galaxies such as (minor and major) mergers.

To investigate whether this worry is substantiated we compare IFU samples of z$\sim$2$-$3 galaxies with galaxies at similar redshifts, where the observational constraints are alleviated by the additional boost of a gravitational lense. We do this in two steps: (1) Detailed comparison of a lensed and unlensed z$\sim$ 3 LBG with rest-frame optical IFU data. (2) A comparison of rest-frame optical line widths in unlensed z$\sim$2$-$3 galaxies with IFU data and lensed galaxies. Both comparisons suggest that existing IFU samples may be seriously biased.

2 The "arc&core": The first z$\sim$3 galaxy with a rotation curve on sub-kpc scales

Due to a fortuitous lensing configuration of the z=3.2 strongly lensed LBG (SLLBG) 'arc&core', we see a zoom into the inner $\sim$ 1 kpc and several more peripheral patches magnified by factors $\sim$ 20. Most strikingly, [OIII]λ5007 line emission reveals a smooth velocity gradient of 190 km s^{-1} at a spatial resolution of $\sim$ 200 pc in the source plane (Nesvadba et al. 2006), that resembles rotation curves of spiral galaxies at low redshift (Fig. 1). Line widths are uniform and relatively narrow, decreasing from σ=97$\pm$9 km s^{-1} in the inner 'core' to σ=62 $\pm$ 15 km s^{-1} in the outer 'arc'. The overall properties of the 'arc&core' appear rather average compared to samples of LBGs in the field, raising confidence that rotation on sub-kpc scales is not uncommon for high-z galaxies, and consistent with inside-out disk formation scenarios. Such scales are significantly smaller than what is found from IFU observations of unlensed galaxies at slightly lower redshifts.

An important measure to quantify the amount of random to ordered motion in galaxies is the ratio between velocity gradient v and Gaussian line width σ, v/σ. For the arc&core, v/σ $\sim$3, while the galaxies of FS06 have $v/\sigma \sim 1$, suggesting that field galaxies studied with IFUs are kinematically more strongly disturbed. This may be a result of somewhat different selection criteria (the z$\sim$ 2.5 sample has a UV color selection, but not strictly the Lyman-break technique). However, even the z=3.2 LBG Q0347-383 C5 (a classical LBG) shows the same trend. C5 consists of two separate, unresolved line emitting clumps with a relative velocity shift of 33

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km s^{-1}, but much greater line widths $\sigma \sim 85$ km s^{-1} (Fig. 1), perhaps indicative of a merger of two subunits. The co-moving space density of bright LBGs like C5 is consistent with theoretically predicted merger rates (Nesvadba et al. 2008).

A comparison based on only two galaxies cannot be conclusive, but the number of strongly lensed LBGs at z$\sim$2$-$3 with deep IFU data sets is small, and the arc&core is the only SLLBG in the literature with a spatially resolved rotation curve. We thus compare with the integrated line widths of 5 z$\sim$ 3 SLLBGs with near-IR spectroscopy in the literature. We find significantly more narrow lines in the integrated spectra of SLLBGs compared to the spatially resolved maps of FS06. The spatial resolution of the field galaxies approximately corresponds to the size of the lensed galaxies in the source plane, so we compare spectra extracted from similarly large regions. Similarly to the above detailed comparison of two LBGs with IFU data, this may suggest that great care is warranted when generalizing IFU observations to the overall population of high-z galaxies.

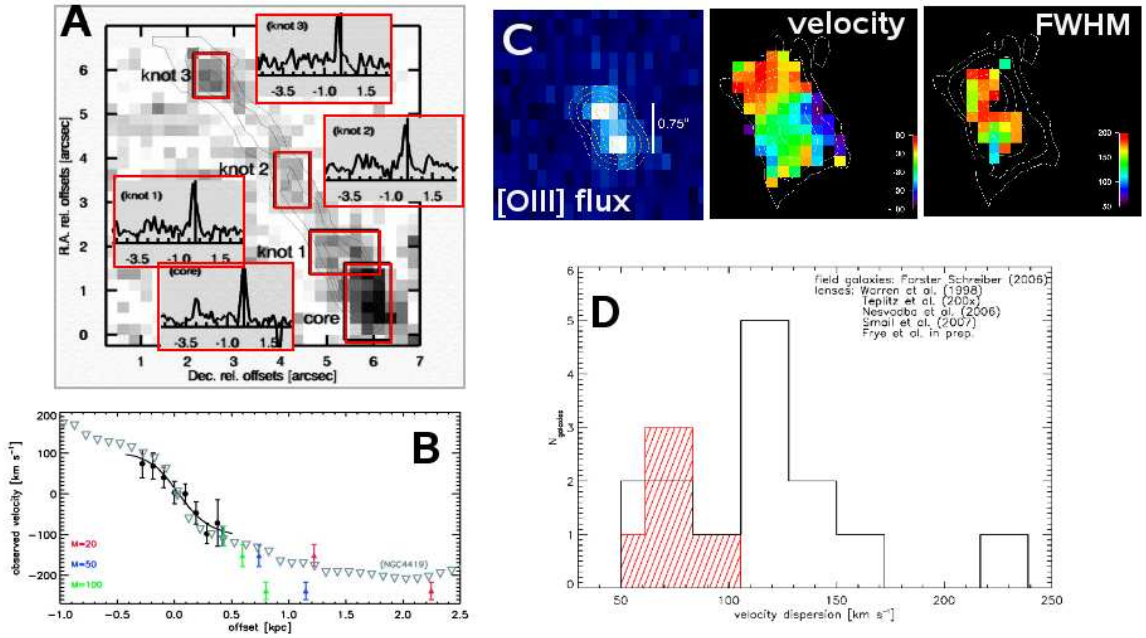

Fig. 1. *(A) [OIII]λ5007 line image of the 'arc&core'. Insets show spectra extracted from the apertures highlighted in red. (B) Relative velocities within the "core" (black dots) and the "arc" (red,blue and green triangles) closely resemble the rotation curve of a* $\leq 10^{10}$ $M_{\odot}$ *disk galaxy (black line: model, gray upside-down triangles: Rotation curve of the* $\mathcal{L}^*$ *sprial galaxy NGC4419 in the Virgo cluster). (C) (left to right) [OIII] morphology, velocities and FWHMs of the bright, unlensed LBG Q0347-383 C5. Morphology and kinematics are consistent with two interacting subunits. (D) Comparison of the line widths in lensed galaxies (red hatched histogram) with the sample of z$\sim$ 2.5 galaxies with IFU data (FS06). The lensed galaxies have widths in the lower tail of the unlensed sample.*

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