The evolution of the size-mass relation at z=1-3 derived from the complete Hubble Frontier Fields data set

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We measure the size-mass relation and its evolution between redshifts 1< z <3, using galaxies lensed by six foreground Hubble Frontier Fields clusters. The power afforded by strong gravitation lensing allows us to observe galaxies with higher angular resolution beyond current facilities. We select a stellar mass limited sample and divide them into star-forming or quiescent classes based on their rest-frame UVJ colors from the ASTRODEEP catalogs. Source reconstruction is carried out with the recently-released `lenstruction` software, which is built on the multi-purpose gravitational lensing software `lenstronomy`. We derive the empirical relation between size and mass for the late-type galaxies with $M_* > 3\times10^9 M_\odot$ at $1< z <2.5$ and $M_* > 5\times10^9 M_\odot$ at $2.5< z <3$, and at a fixed stellar mass, we find galaxy sizes evolve as $R_{\rm eff} \propto (1+z)^{-1.05\pm0.37}$. The intrinsic scatter is < 0.1 dex at z < 1.5 but increases to ~ 0.3 dex at higher redshift. The results are in good agreement with those obtained in blank fields. We evaluate the uncertainties associated with the choice of lens model by comparing size measurements using five different and publicly available models, finding the choice of lens model leads to a 3.7% uncertainty of the median value, and ~ 25 % scatter for individual galaxies. Our work demonstrates the use of strong lensing magnification to boost resolution does not introduce significant uncertainties in this kind of work, and paves the way for wholesale applications of the sophisticated lens reconstruction technique to higher redshifts and larger samples.

重力レンズを利用した銀河のsize進化

- 銀河のタイプ (色・形態) によってsize進化が異なる → 銀河とそれを取り巻くハローの mass assembly 史がタイプによって異なることを示唆。
- 重力レンズを使った銀河の size 推定 → field より compact という結果。
  - strong lens (μ>10) によって compact 銀河にバイアスしていた (magnification bias)。
- Stellar mass選択でより faint (low μ?) な銀河まで complete にサンプル。

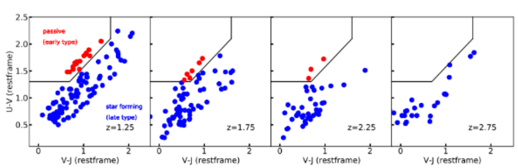
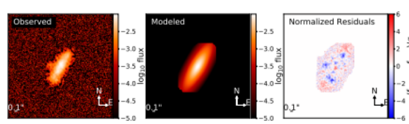
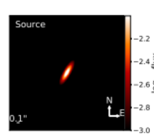


Figure 1. The rest-frame UVJ color diagram for four redshift bins (each Δz=0.5 wide). Galaxies are classified into two types, passive (early-) or star-forming (late-type). The solid black lines in each panel indicates the selection criteria from (Williams et al. 2009), which is used in this work.

↑ Figure 1: UVJ colorでタイプ分類
6つのレンズ銀河団領域のHFF ASTRODEEPカタログから$1<z_{\rm phot}<3$, $M_s>3e9M_{\rm sun}$,で抽出された255個の銀河。



(a) From left to right, we show the observed lensed images, the modeled lensed images, and the normalized residuals (i.e., divided by uncertainty)



(b) Reconstructed source surface brightness distribution with lens models from Brada.

Figure 3. Demonstration of the modeling results of the singly-imaged system using `lenstruction`/LENSTRONOMY.

Figure 3: image reconstruction → by lenstronomy/lenstruction

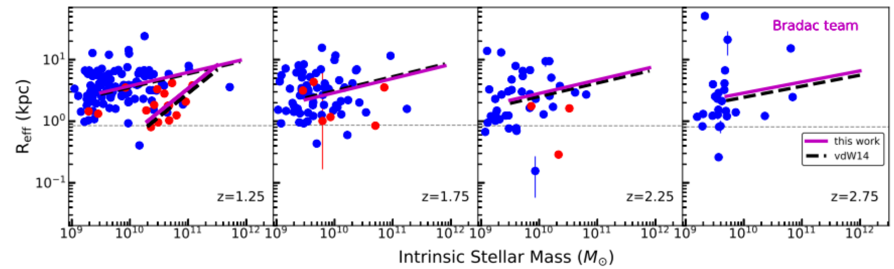


Figure 5. Size-mass distribution of early- (red) and late-type (blue) galaxies at redshifts 1< z <3 assuming the fiducial lens model from the Bradač team. The magenta lines indicate the fits to the data points (see also Table 2) while the black dash lines show the fitting results from van der Wel et al. (2014). The grey dash lines demonstrate the angular resolution limitation of the WFC3/IR.

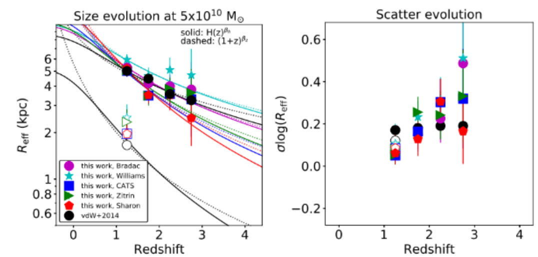


Figure 6. Redshift evolution of galaxy sizes (left) and intrinsic scatter (right) and the former's parameterizations for each of the lens models used in this work. The filled and open symbols represent the results of the late-type and early-type galaxies, respectively, while the different colored lines represent the fitting results for different lens models while black lines show the results of van der Wel et al. (2014), for comparison. Strong evolution is seen for the sizes of late-type galaxies and we parameterize such evolution as a function of $H(z)$ and $(1+z)$ shown by solid and dashed lines, respectively. For the intrinsic scatter, our uncertainty is too large to conclude whether there is evolution as a function of redshift.

- ↑ Figure 5: size-M_s関係
- ← Figure 6: size進化 (@M_s=5e10$M_{\rm sun}$)
どちらもfield銀河(not lensed) の結果とよく一致。
→lensを用いた手法の妥当性・有用性を証明。

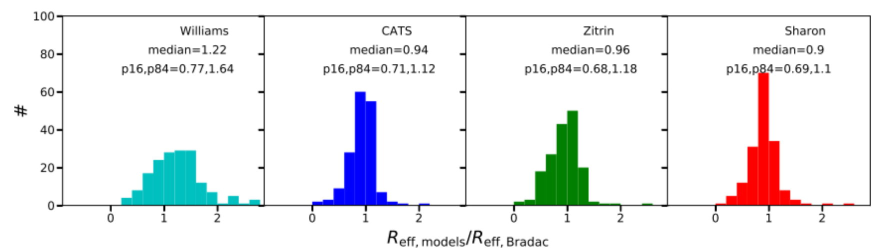


Figure 9. Distribution of the ratio between the size measured using the Bradač lens model and the other lens models used in this work. In each panel, we indicate the median size and the 16th and 84th percentiles of the distribution.

↑ Figure 9: 重力レンズモデルによる推定sizeの違い：Williamsを除けば、medianのバラつきは~3.7%と小さい。

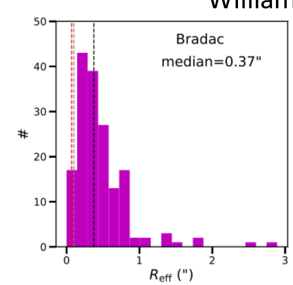


Figure 10. Size distribution in units of arc-second of our sample reconstructed via the Bradač model. The grey and red dash lines demonstrate the angular resolution of HST-WFC3/IR and JWST (0.07 arcsec at 2μm).

Figure 10. 今回のサンプルのsize分布：
Small, faint (less massive) 銀河は光度関数のfaint-end を担う＝数が多い。
→ 再電離源として重要な種族となり得る。
→ JWST (0.07"@2um) + lens によって、z>7 のfaint-end slopeやsize分布を精度よく決定できるだろう。