

A High Incidence of Central Star Formation Inferred from the Color Gradients of Galaxies at $z > 4$

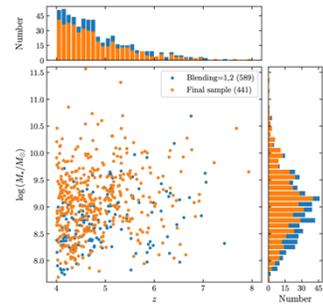
[Previous study related to color]

- local galaxies : negative gradient (redder in the center and bluer in the outskirts) (Muñoz-Mateos et al. 2007; Kelvin et al. 2012)
- $1 < z < 2$: negative gradient, but weaker strength of gradient and larger scatter (Suess et al. 2019; Miller et al. 2023; van der Wel et al. 2024)
- $3 < z < 5$: negative gradients in massive quiescent systems (Ji et al. 2025)
- $z > 4$: little evidence for color gradients (if anything, more likely positive instead of negative) (Ono et al. 2024, Morishita et al. 2024)

- There are differences in sample selection methods
- Their correlation with physical quantities is not yet clear.

[Data]

- JWST/NIRCam 7band image (CEERS program)
- rest frame UV-optical color gradient
- Redshift: $4 < z < 8$
- 441 galaxies
- [Sample filtering conditions]
 1. Remove galaxies that are blended by a contaminating source.
 2. Remove galaxies R_e (effective radius) $< 0.06''$ in one of the 7 bands (if $R_e < 0.06''$, the uncertainty is large)
 3. Apply magnitude limit of F150W ≈ 28 (Not clear reason. In paper: "After some experimentation, we find that a magnitude limit of F150W ≈ 28 also needs to be imposed.")

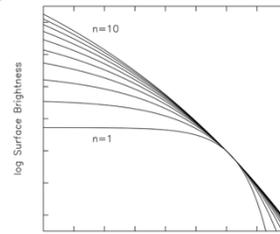


- blue data: filtered sample
- orange data: selected sample

[Difference with previous studies]

- Use galaxy 3 color parameters to interpret color gradients
- Sérsic function: surface brightness distribution of galaxy

$$\mu(R) = \mu_e \exp \left[-\kappa \left(\left(\frac{R}{R_e} \right)^{1/n} - 1 \right) \right]$$



- R_e : effective radius (radius at which half of the total light of a galaxy is emitted)
- μ_e : surface brightness at R_e
- K : $\sim 2n - 1/3$
- n : Sérsic index
 - large n : concentrate on center
 - small n : spread more evenly

$$\mathcal{N} = \frac{n^b}{n^r}$$

Parameter 1. wavelength variation of the Sérsic index:

- n^b and n^r : the Sérsic index measured in the blue and red band.
- ex) For galaxies with redder centers: the value of n is larger at longer wavelengths $\rightarrow n^r > n^b \rightarrow \mathcal{N} < 1$
- How to measure n values: Using the galaxy light distribution fitting code 'GalfitM' (Haußler et al. 2013; Vika et al. 2013, 2015)

Parameter 2. wavelength variation of the effective radius: $\mathcal{R} = \frac{R_e^b}{R_e^r}$

- R_e^b and R_e^r : effective radius measured in blue and red band

Parameter 3. color gradient: $\nabla = \frac{\Delta(\mu^b(R) - \mu^r(R))}{\Delta \log R}$

- $\mu^b(R)$ and $\mu^r(R)$: surface brightness profiles as a function of radius R in blue and red band
- $\rightarrow d(\mu^b(R) - \mu^r(R))/d(\log R)$: Color gradient at a point with radius R
- Red band: Band closest to the 5000 Å rest frame
- Blue band: Band closest to the 2000 Å rest frame

[Result]

1. Color Gradients at $z > 4$

Galaxy with blue center and red outskirts:

- $z \lesssim 1$: 10% of galaxies
- $1 < z < 3$: 20% of galaxies
- $z > 4$: 50-60% of the 441 galaxies in this paper

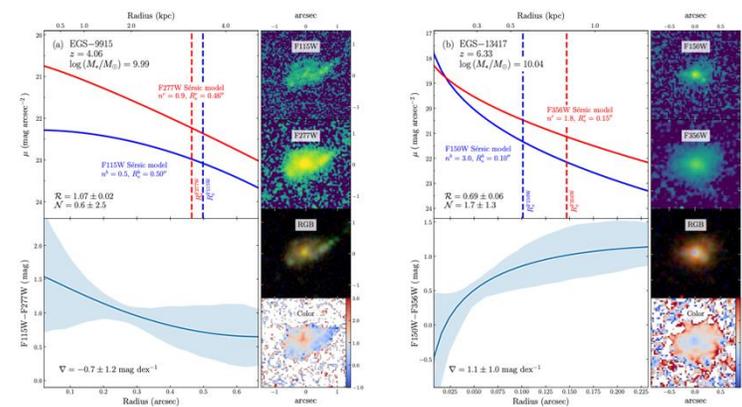


Figure 5. Example of galaxies with (a) negative and (b) positive color gradient in our sample. In each panel, the left column shows the best-fit Sérsic model profile for the rest-frame UV and optical bands (top) and the UV-optical color profile (bottom), where the blue shaded area shows the 16th and 84th percentile of the color profile derived by sampling the structural parameter according to its uncertainty. The right column of each panel shows the two-dimensional visualizations of the color gradients: from top to bottom, the panels show the science images from the rest-frame UV and optical, the pseudo-color image (red = F444W, green = F277W, blue = F150W), and the PSF-matched UV-optical color image.

2. Changes of color parameters depending on the redshift

- R and \mathcal{N} do not change depending on the redshift
- The larger the redshift, the more galaxies with positive ∇ (gradient) (= blue center)

Table 1. Redshift Evolution of Color Gradient

Redshift Range	Median Redshift	Number	\mathcal{R}	\mathcal{N}	∇ (mag arcsec $^{-1}$)
(1)	(2)	(3)	(4)	(5)	(6)
$4 \leq z < 4.4$	4.20	151	$1.02^{+0.10}_{-0.07}$	$1.30^{+0.38}_{-0.36}$	$0.28^{+0.39}_{-0.43}$
$4.4 \leq z < 5.0$	4.67	152	$0.96^{+0.09}_{-0.10}$	$1.29^{+0.51}_{-0.47}$	$0.29^{+0.55}_{-0.59}$
$5.0 \leq z < 8.0$	5.58	138	$1.00^{+0.09}_{-0.10}$	$1.38^{+0.42}_{-0.65}$	$0.50^{+0.62}_{-0.32}$

NOTE— Col. (1): Redshift range. Col. (2): Median redshift. Col. (3): Number of galaxies. Cols. (4)–(6): Median value of \mathcal{R} , \mathcal{N} , and ∇ and the 16th and 84th percent of their distributions.

3. 3 color parameters vs. galaxy size, stellar mass, UV-optical color

- R_e^{opt} : effective radius measured in the optical band nearest to the rest-frame of 5000 Å
- Result for 1st column:
 - Larger the galaxy \rightarrow the redder center and blue outer regions
- Result for 2nd column:
 - Massive galaxies \rightarrow red centers and blue outer regions

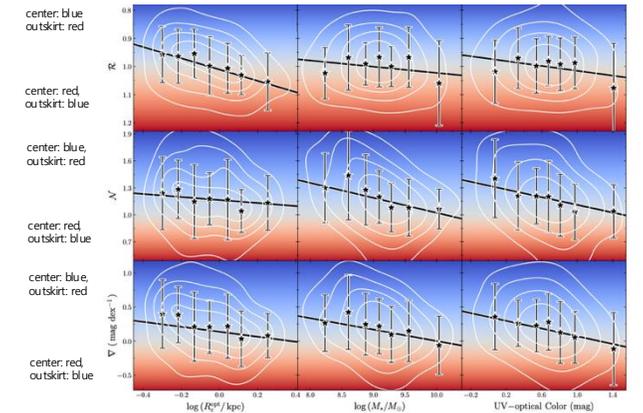


Figure 7. Dependence on galaxy properties of the color gradient, quantified using the variation of the effective radius \mathcal{R} (Equation 3, top), variation of the Sérsic index \mathcal{N} (Equation 2, middle), and the color gradient ∇ (Equation 4, bottom). From left to right, the columns show the dependence on galaxy optical effective radius (R_e^{opt}), stellar masses (M_*), and the rest-frame UV-to-optical color. The white contours denote the density distribution of the data points, the stars show the running median of the data binned so that each bin contains at least 60 galaxies, and the error bars indicate the standard deviation. The solid line gives the best-fit linear regression of the individual measurements. The background gradient denotes the region where the color gradient is positive (blue) or negative (red).

4. Stellar mass vs. sSFR & galaxy size vs. 3 color parameters

- 1st row and 1st column graph:
 - At the same stellar mass, the larger the galaxy's size (R_e^{opt}), the redder its center becomes.
- 2nd row and 2nd & 3rd column graph:
 - At the same stellar mass, the greater the star formation activity (sSFR), the center of galaxy become bluer

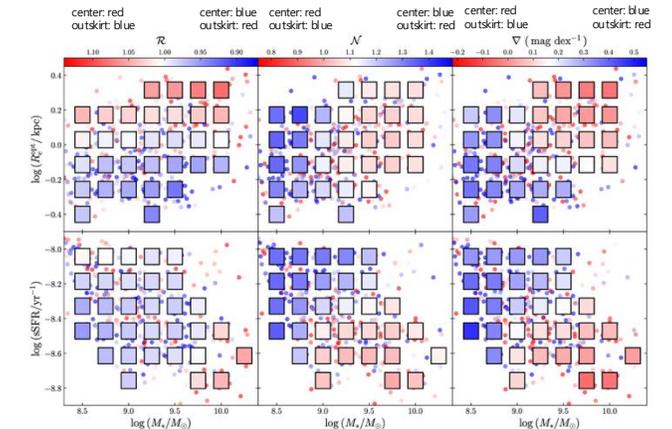


Figure 8. The stellar mass versus size and stellar mass versus specific SFR (sSFR) distributions of our sample. From left to right, the columns quantify the color gradient using \mathcal{R} , \mathcal{N} , and ∇ , whose strength is indicated by the color bar on the top. The squares denote median values of at least five objects within a box of size 0.25 dex in $\log M_*$ and 0.11 dex in $\log R_e^{\text{opt}}$ or 0.13 mag in rest-frame UV-to-optical color, after performing a locally weighted regression smoothing using the Python package LOESS (Cappellari et al. 2013).

5. ∇ (color gradient) vs dust extinction

- A_V from Bagpipes SED fitting
- The number of galaxies with $A_V > 1$ mag is very small (11/441)
- Most galaxies have low dust extinction (396/411)
- Although there is a negative correlation, it is difficult to say that there is an overall trend.

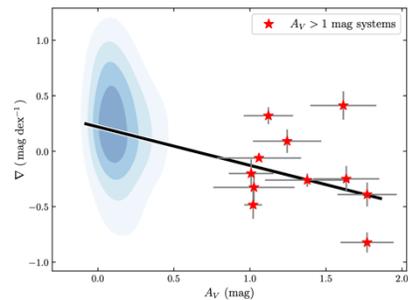


Figure 9. The correlation between dust attenuation and ∇ in our sample. Dusty systems ($A_V > 1$ mag) are highlighted in red stars. The blue contours display the distribution of all sample galaxies, with the black solid line indicating the best-fit linear regression.

[Possible causes of the outside-in growth]

To create a young star → cold gas flows rapidly into the center → angular momentum dissipation allows the gas to flow into the center

- Mechanisms that can cause angular momentum loss:
 - Galaxy merger
 - Gravitational instability

[Summary]

- low-redshift: center red, outskirts blue (negative gradient)
- high-redshift: center blue, outskirts red (positive gradient)
- without strong contribution from dust extinction and AGN.
- Feature of center blue and outskirts red galaxy:
 - centrally concentrated star formation or outside-in growth
 - lower stellar mass
 - smaller size
 - bluer spectral energy distribution
 - high sSFR
- (All features are identical to low-mass galaxies in Yun's work)
- Not related to cosmic noon epoch