

KEN-ICHI TADAKI¹¹Faculty of Engineering, Hokkai-Gakuen University, Toyohira-ku, Sapporo 062-8605, Japan

ABSTRACT

We study bulge formation in 16 massive dusty star-forming galaxies at $z \sim 2$ by combining JWST MIRI F770W imaging, NIRCam imaging in eight bands, and ALMA 870 μm data. At the median redshift of $z = 2.18$, the F770W band probes the **rest-frame 2.4 μm light**, close to the rest-frame K band, and traces the stellar mass distribution with little effect from dust attenuation. The effective radii measured in F770W agree with those of the 870 μm dust emission, with a median ratio of 0.95, and are typically 23% smaller than those in F444W. The rest-frame K -band imaging is therefore essential to measure the **true extent of the stellar mass, which is as compact as the dusty star-forming regions**. In stacks of the 16 galaxies at a matched resolution, the **870 μm and F770W profiles agree closely out to 8 kpc**, and a bulge plus disk decomposition of the F770W stack gives a bulge-to-total ratio of 0.50. Fitting the SEDs in radial bins with CIGALE, we find that the attenuation decreases from **$A_V = 2.6$ mag at the center** to 1.5 mag at $r \gtrsim 7$ kpc, while the specific star formation rate profile is flat. In these galaxies the **bulge is already in place**, and the whole system grows toward compact quiescent galaxies within about 1 Gyr. In two galaxies, by contrast, the 870 μm emission is 3 to 6 times more compact than the F770W light, which suggests that they are still in the bulge-building compaction phase. Our sample may thus catch massive galaxies in several phases of bulge formation.

Introduction

- When and how **bulges** formed in galaxies?
 - Massive quiescent galaxies at $z \sim 2$ already have bulges comparable to those of local massive galaxies.
- Proposed scenarios:
 - External: gas-rich mergers
 - Internal: clump migration
- The central SF (and the bulge) is expected to be **heavily obscured by dust**.
- So, the rest-frame UV/optical observation is strongly affected by dust attenuation.
 - Recent JWST/NIRCam studies indicate radial gradient of dust attenuation.
- This work utilizes JWST/MIRI **F770W data (rest-frame K-band)** which is much less sensitive to dust.

Sample

- 16 massive ($M_* \sim 10^{11-11.5} M_\odot$) dusty star-forming ($SFR_{\text{IR}} \sim 180\text{--}1400 M_\odot/\text{yr}$) main-sequence galaxies in CANDELS UDS at $1.95 < z < 2.53$ drawn from Tadaki+20.

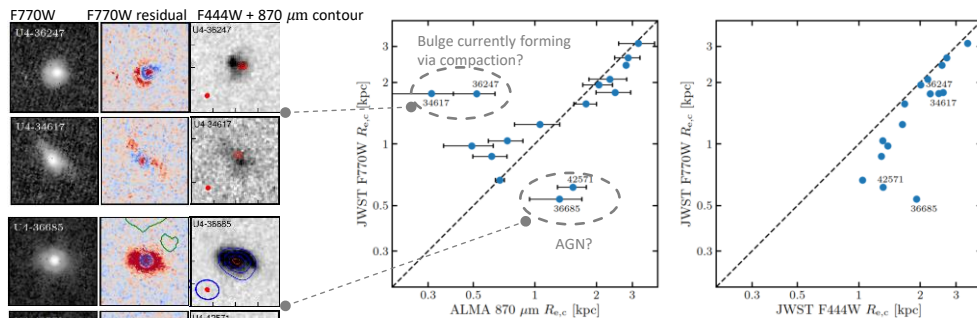


Figure 3. Circularized effective radii of the F770W emission (this work, $n = 1$) compared with those of the 870 μm dust continuum (Tadaki et al. 2020, left panel) and those of the F444W emission (Tadaki et al. 2023, right panel) for the 16 galaxies. The dashed lines show the one-to-one relations. The F770W error bars are the statistical uncertainties from the empty-sky perturbation analysis (Section 3.2) and are mostly smaller than the symbols. The four outliers discussed in the text are labeled.

Individual analysis

- F770W size estimation w/ single Sersic component using GALFIT
- F770W vs. ALMA 870 μm (Tadaki+20) that traces dust extent (and obscured SF) (Fig3, left):
 - **Excellent agreement** in sizes (median ratio = 0.95) and centroids (median separation ~ 0.31 kpc), with 4 outliers (two bulge-forming and two AGN-hosting).
 - **→ Old stars and dust have similar spatial distributions.**
- F770W vs. NIRCam **F444W** (Tadaki+23) that traces younger stellar populations (Fig3, right):
 - $R_e(\text{F770W})/R_e(\text{F444W}) \sim 0.77$
 - **→ It implies even F444W is affected by dust attenuation, especially at the central region.**

Stacking analysis

- Image stacking of 16 galaxies in 9 JWST bands + 870 μm .
 - Remarkably similar to the 870 μm profile. (Fig4, left)
 - **→ Dust and old stars spatially coincide well beyond the PSF scale.**
 - Shorter bands tend to be more extended.
- **Bulge+disk decomposition** of the stacked galaxy in F770W
 - $R_{e,\text{bulge}} \sim 0.8$ kpc, B/T ~ 0.50
 - **→ 50% of the stellar mass is already in the compact bulge.**
- **SED fitting in radial bins** of the stacked galaxy using CIGALE. (Fig7)
 - ΣM_* and ΣSFR follow resolved MS, decreasing toward the outskirts.
 - The central ΣM_* is comparable to QGs.
 - sSFR is almost flat ($\sim 1.5 \text{ Gyr}^{-1}$)
 - Since the flat sSFR cannot produce B/T=0.5 structure, the bulge must have formed earlier.
 - At the current sSFR, the galaxy will be comparable to compact quiescent galaxies within 1 Gyr ($z \sim 1.6$).
 - $A_V \sim 2.6$ mag at the center
 - ~ 0.7 mag at $1.4 \mu\text{m}$ whereas ~ 0.3 mag at $2.4 \mu\text{m}$
 - NIRCam bands, even the longest F444W, are indeed affected by dust.

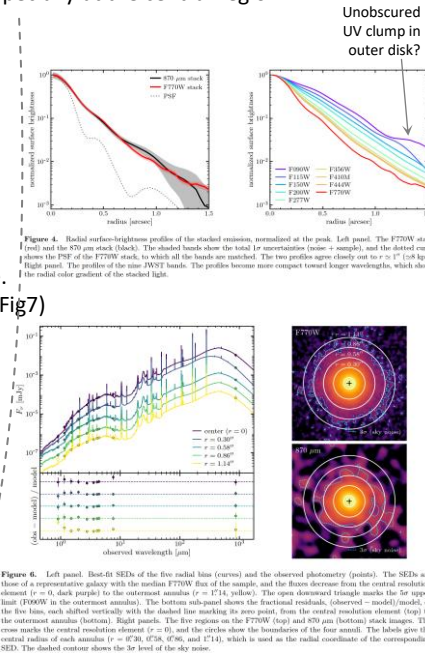


Figure 4. Radial surface-brightness profiles of the stacked emission, normalized at the peak. Left panel: The F770W stack (red) and the 870 μm stack (black). The shaded bands show the total ($\pm$ uncertainty) (solid + sample), and the dotted curve shows the PSF of the F770W stack, in which all the bands are matched. The two profiles agree closely out to $r = 1''$ (1.4 kpc). Right panel: The profiles of the nine JWST bands. The profiles become more compact toward longer wavelengths, which shows the radial color gradient of the stacked light.

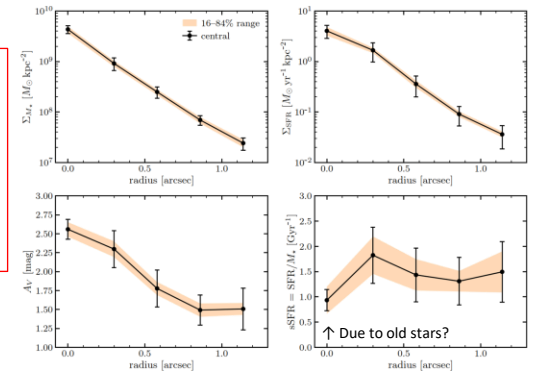


Figure 7. Radial profiles of the stellar mass surface density (top left), the SFR surface density (top right), the attenuation A_V (bottom left), and the sSFR (bottom right) from the CIGALE fits to the radial-bin SEDs. The error bars show the Bayesian uncertainties of the fits, and the shaded bands show the 16-84% spread of the 50 bootstrap realizations, which we adopt as the parameter errors. The sSFR is the ratio of two fitted parameters, and its error bars show the SFR uncertainty after the stellar-mass uncertainty is subtracted in quadrature, because the amplitude uncertainty is common to the two parameters and cancels in the ratio. The stellar mass and SFR surface densities are those of a representative galaxy with the median F770W flux of the sample.

- Rest-frame 2.4 μm *truly* traces the stellar mass distribution with minimal impact from dust attenuation.
- Majority of the sample (dusty SFGs) at $z \sim 2$ has already formed well-developed bulges and is expected to evolve into compact quiescent galaxies within 1 Gyr.