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Physics

Quantifying Clumpy Galaxies: Inferring Turbulent Jeans Mass from Galaxy Imaging

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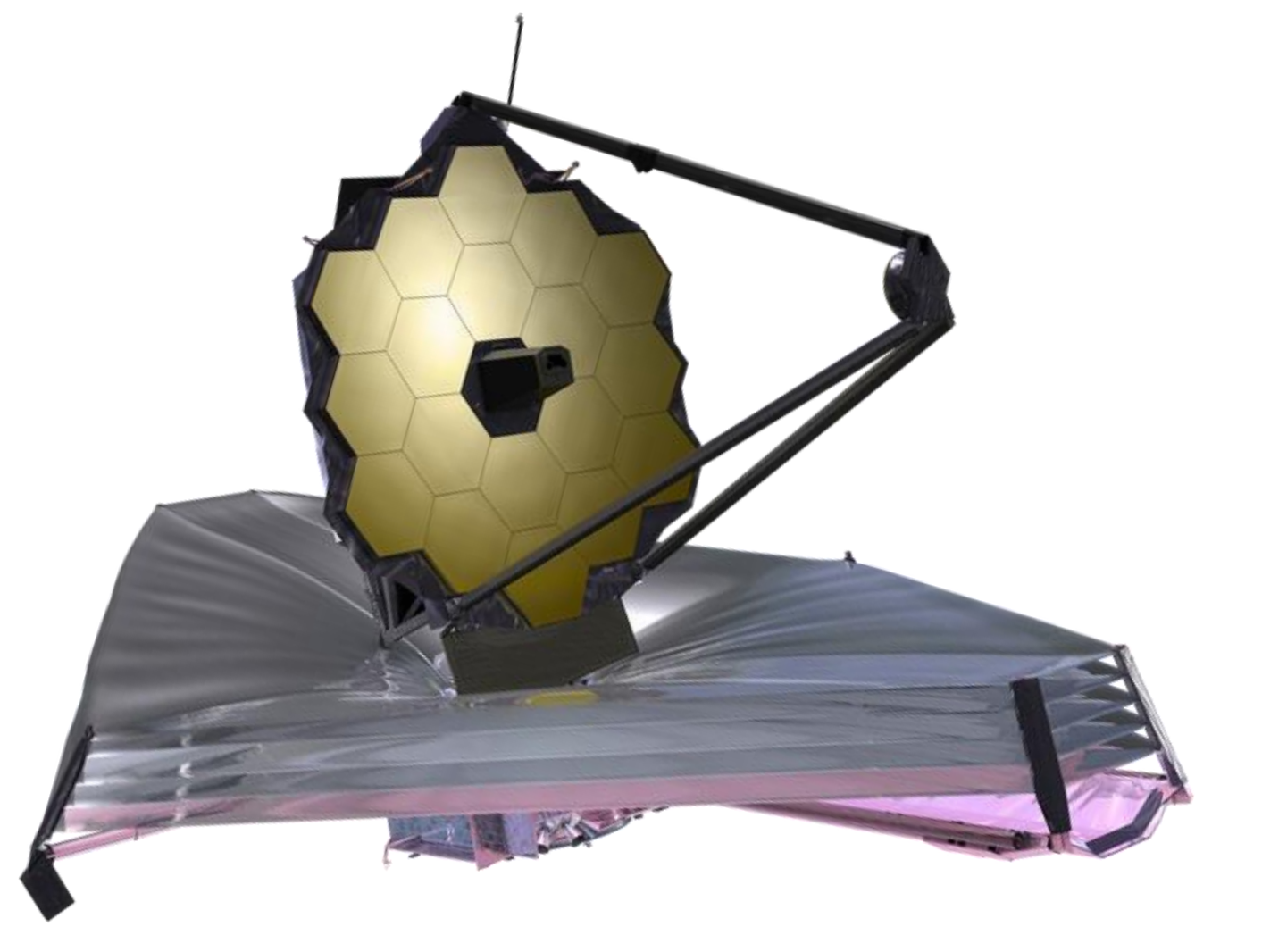

Introduction

- High-redshift galaxies (around z~1-3) often exhibit clumpy, irregular structures unlike the smooth disks seen in the local universe. Redshift z, is a measure of how much the expansion of the universe has stretched the light's wavelength between the moment it was emitted and the moment it reaches our telescopes.
- These clumps are massive star-forming regions formed due to high gas density, turbulence, and gravitational instability.
- Understanding clumpy galaxies is key to explaining how galaxies grow, form stars, and evolve over time.

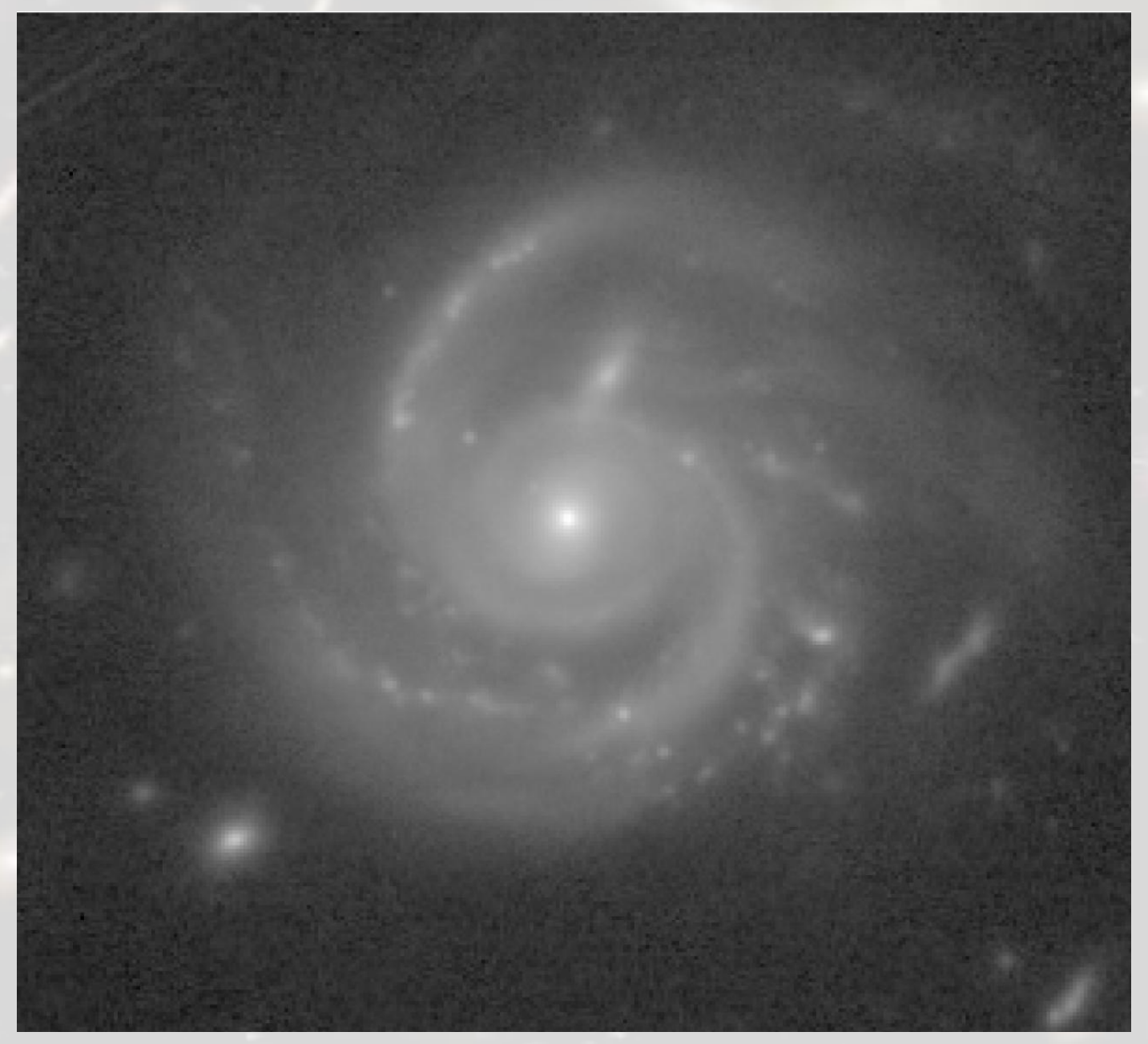

Figure 1: Image of Clumpy Galaxy from JWST NIRcam 6

- Traditional methods describe clumpiness morphologically but do not directly connect it to underlying physical conditions.
- This study aims to link observable galaxy structure to physical properties by inferring turbulent Jeans mas from imaging data.

Theory

- Gravitational instability in galaxy disks is described by the competition between self-gravity and internal support (pressure, turbulence, and rotation).
- The turbulent Jeans mass M_J defines the characteristic mass scale for collapse in gas-rich, turbulent disks: $M_J = \frac{\sigma^4}{\mathrm{G}^2 \Sigma_{gas}}$, where σ is velocity dispersion and G is the gravitational constant.
- Star formation is linked to gas content through the Kennicutt–Schmidt law, relating gas surface density Σ_{gas} to star formation rate density : $\Sigma_{\mathrm{SFR}} = A\Sigma_{\mathrm{gas}}^N$, where A is a normalization constant and N is represents the sensitivity of star formation to gas density. A value of $N \approx 1.4$ is the standard value used for most galaxies.
- Disk stability is quantified using the Toomre Q parameter, which determines whether a rotating disk will fragment: $Q = \frac{\kappa\sigma}{\pi G \Sigma_{\mathrm{gas}}}$, where κ is the epicyclic frequency. A galaxy with a global Q-value of 1-20 is considered unstable and a galaxy with a global Q-value of 20-80 is considered stable.
- Together, these relations connect observable quantities (imaging-based properties) to physical conditions governing clump formation in high-redshift galaxies.

Method

- Selected a sample of 24 high-redshift galaxies ($0.83 \leq z \leq 3.1$) from JWST NIRCam F200W imaging (CEERS survey).
- Created postage-stamp images and segmentation maps using Python (**Photutils**) to isolate galaxy structures.
- Modeled galaxy light profiles with **GALFIT** to extract structural parameters (e.g. effective radius (R_e), Sérsic index).
- Estimated star formation rate surface density using the Kennicutt–Schmidt relation, and then converted SFR surface density into gas surface density.
- Used empirical redshift-based relations to estimate velocity dispersion (σ) in absence of spectroscopy: $\sigma(z) \approx \sigma_0(1+z)^n$, where σ_0 is the typical dispersion at $z = 0$ (surveys find $\sigma_0 \approx$ 15-20 km/s. The scaling exponent n (usually 0.5-1.0) describes how strongly σ grows as z increases.
- Calculated the Toomre Q parameter to quantify global disk stability and then computed $\mathrm{M_J}$ to estimate characteristic clump-forming scales.
- Binned galaxies by Q to compare physical properties across stability regimes.

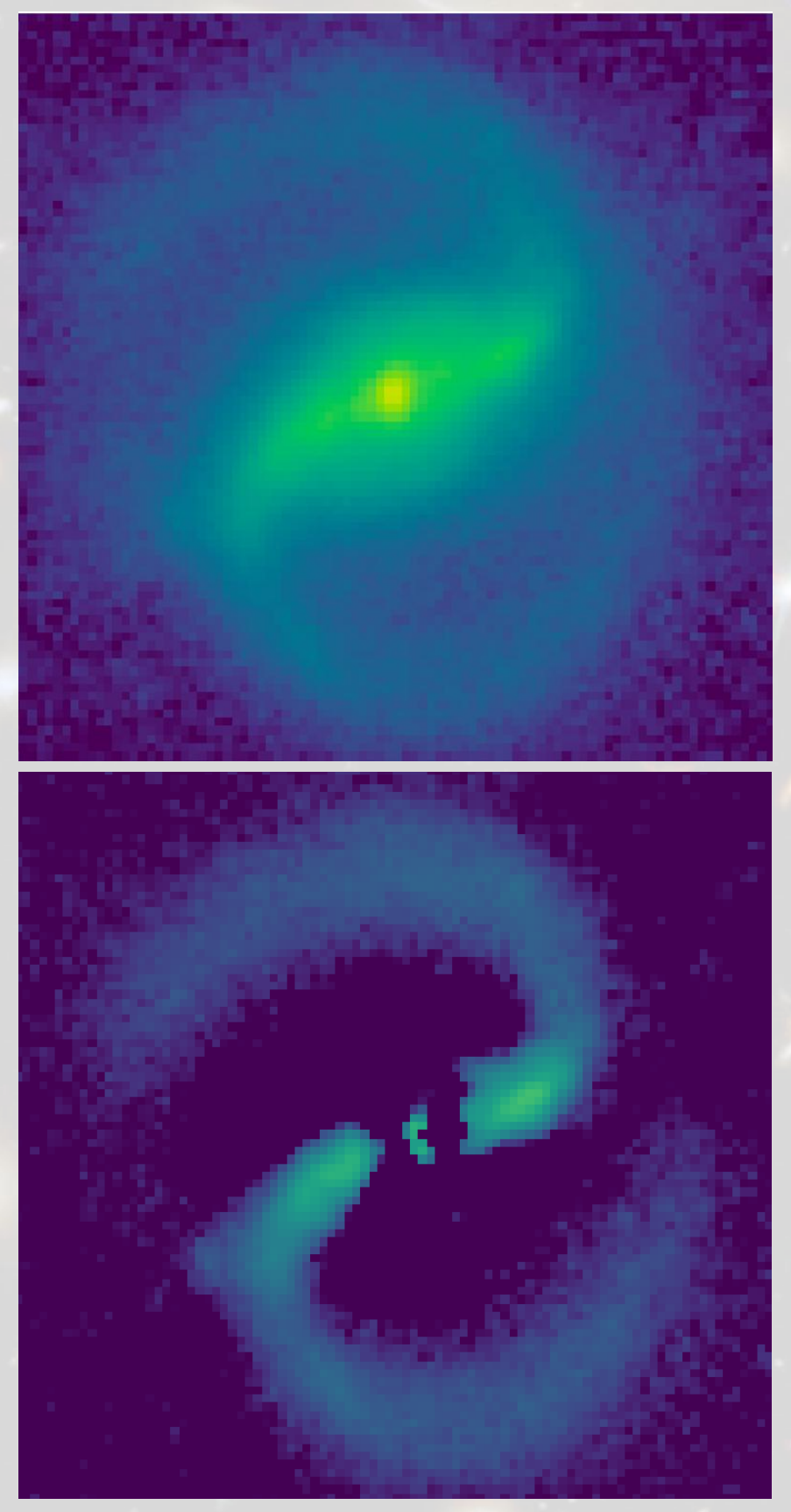

Figure 2: Original galaxy (top) compared to modelled galaxy using GALFIT (bottom).

Results: Key Trends

- Star formation rate surface density Σ_{SFR} and gas surface density Σ_{gas} both increase with redshift (Fig. 3 and 4, respectively), indicating more gas-rich and actively star-forming galaxies at earlier cosmic times.

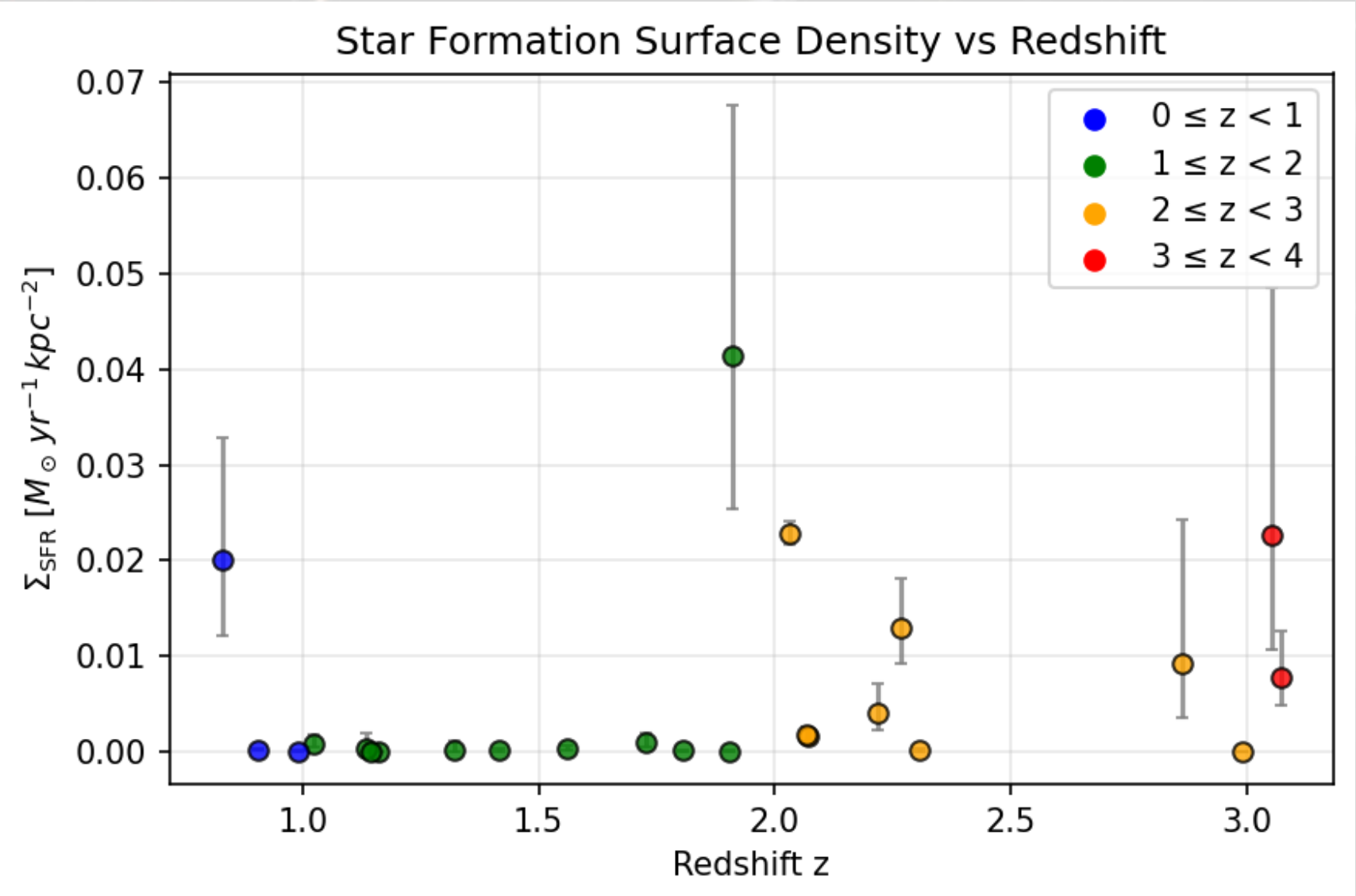

Figure 3: Graph of Σ_{SFR} vs z

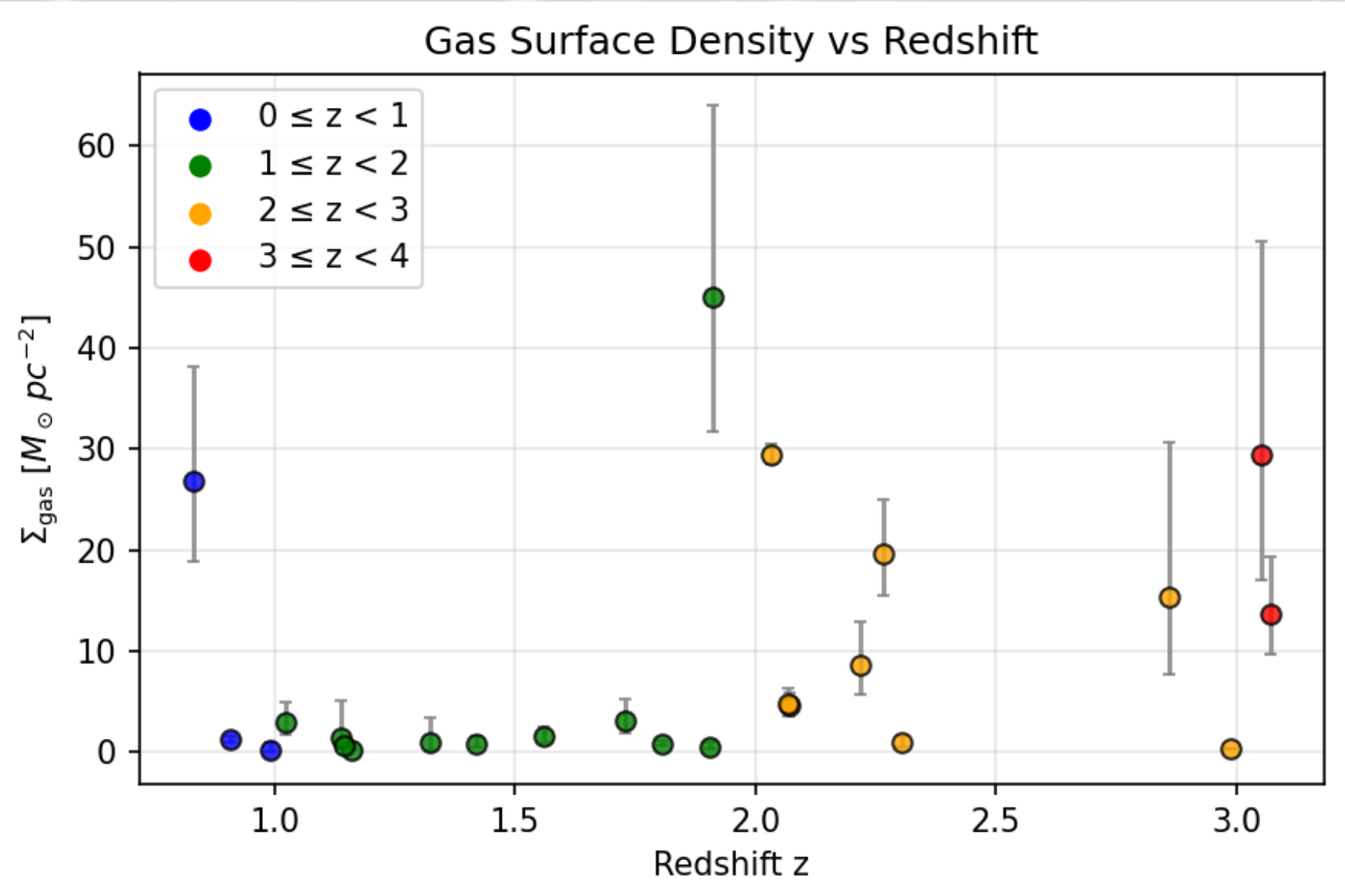

Figure 4: Graph of Σ_{gas} vs z

- Galaxies with lower Toomre Q ($Q \approx$ 1–20) show higher gas densities and enhanced star formation, consistent with gravitational instability.
- Higher- Q systems (more stable disks) show significantly reduced star formation activity and smoother morphologies.
- Turbulent Jeans mass increases with disk stability, suggesting larger characteristic collapse scales in more stable systems.
- These trends support the idea that clump formation is driven by instability in gas-rich, turbulent disks.

Results: Morphology & Physical Interpretation

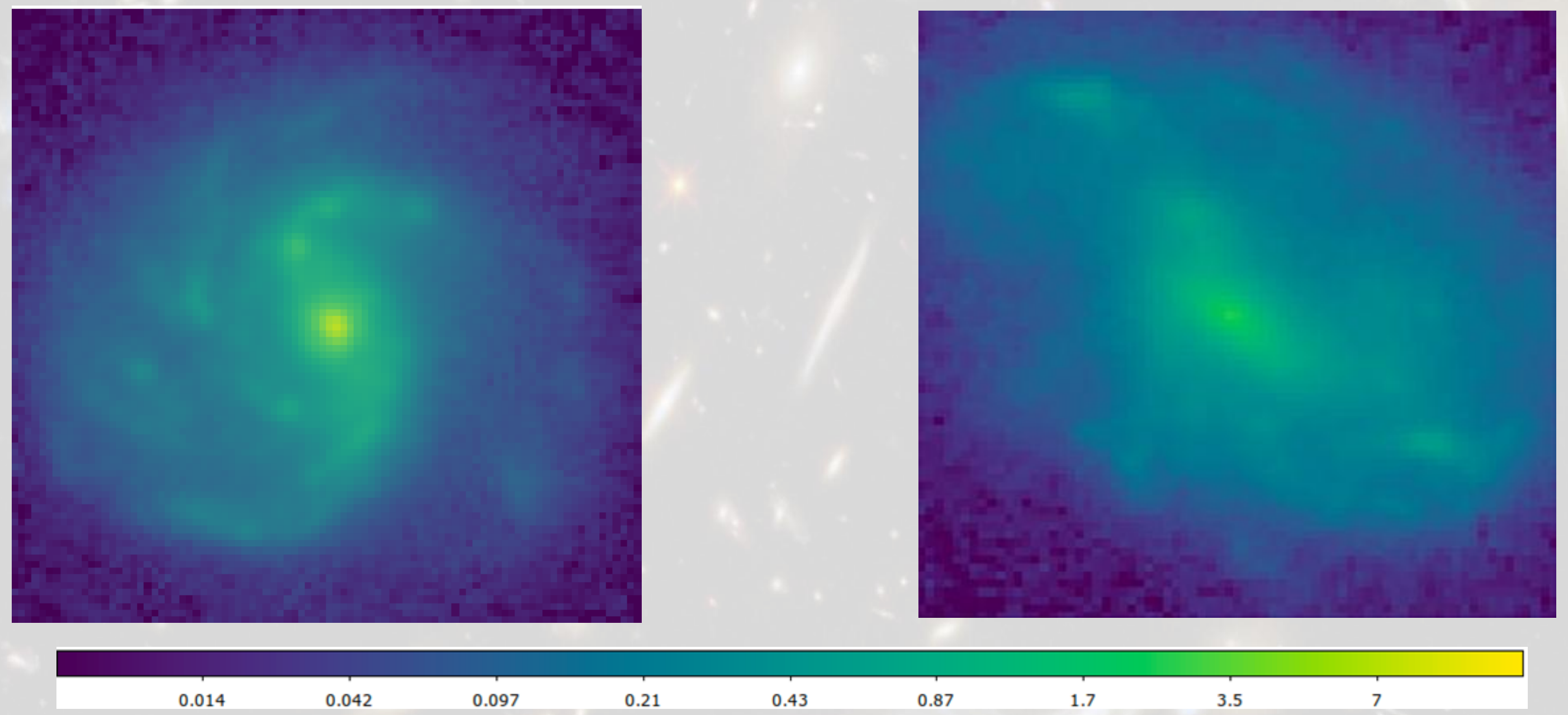

Figure 5: JWST NIRcam F200W images of galaxy 44 ($Q = 11.63, z = 2.069$, left) and galaxy 11 ($Q = 51.04, z = 1.804$, right)

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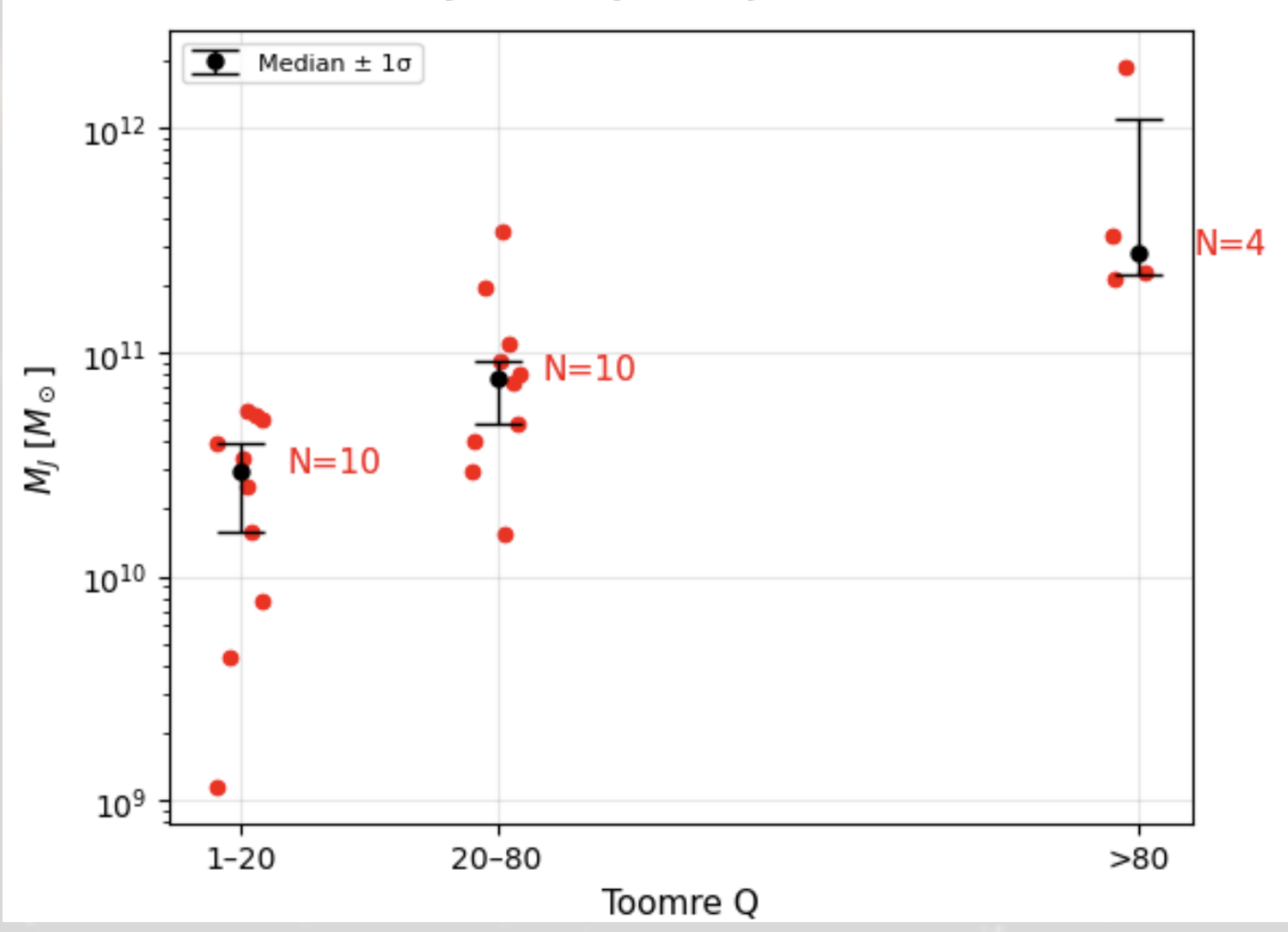

Figure 6: Median M_J of galaxy subsamples binned by Toomre stability parameter Q

Conclusion

- Clump formation in high-redshift galaxies is driven by gravitational instability in gas-rich, turbulent disks.
- Lower Toomre Q systems exhibit higher star formation rates and more pronounced clumpy morphologies.
- Higher-Q galaxies are more stable, showing smoother structures and suppressed star formation activity.
- The turbulent Jeans mass sets the characteristic scale of collapse and matches observed clump masses (~10^{10} $\mathrm{M}_\odot$).
- Observable properties from imaging can be used to reliably estimate underlying physical conditions in galaxies.
- This study provides a reproducible, physically grounded framework linking galaxy morphology to disk instability and evolution.

Future Work

- Extend the sample size to include a larger number of galaxies across a wider redshift range to improve statistical significance.
- Incorporate spectroscopic measurements of velocity dispersion to validate and refine the empirical $\sigma(z)$ relation used in this study.
- Investigate local (spatially resolved) variations in Toomre Q within galaxies to better understand where clumps form.
- Explore machine learning or automated methods to connect galaxy morphology with physical parameters more efficiently.
- Refine assumptions in the method by incorporating more accurate gas surface density estimates (e.g., beyond the Kennicutt–Schmidt relation) to reduce systematic uncertainties.
- Improve structural modeling by testing alternative fitting approaches (e.g. multi-component or non-parametric methods) to better capture complex, clumpy galaxy morphologies.

Acknowledgments

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