COSMOS-Web: The Role of Galaxy Interactions and Disk Instabilities in Producing Starbursts at $z < 4$

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Arxiv: 2405.09619

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ABSTRACT

We study of the role of galaxy-galaxy interactions and disk instabilities in producing starburst activity in galaxies out to $z = 4$. For this, we use a sample of 387 galaxies with robust total star formation rate measurements from Herschel, gas masses from ALMA, stellar masses and redshifts from multi-band photometry, and JWST/NIRCam rest-frame optical imaging. Using mass-controlled samples, we find an increased fraction of interacting galaxies in the starburst regime at all redshifts out to $z = 4$. This increase correlates with star formation efficiency (SFE), but not with gas fraction. However, the correlation is weak (and only significant out to $z = 2$), which could be explained by the short duration of SFE increase during interaction. In addition, we find that isolated disk galaxies make up a significant fraction of the starburst population. The fraction of such galaxies with star-forming clumps ("clumpy disks") is significantly increased compared to the main-sequence disk population. Furthermore, this fraction directly correlates with SFE. This is direct observational evidence for a long-term increase of SFE maintained due to disk instabilities, contributing to the majority of starburst galaxies in our sample and hence to substantial mass growth in these systems. This result could also be of importance for explaining the growth of the most massive galaxies at $z > 6$.

- Merger or disk instability? Which lead to Star-burst (SB)?
- 387 galaxies out to z ~ 4
  - SFR, morphology, gas fraction, and star formation efficiencies ($SFE = SFR/M_{mol,gas}$)
  - Main sequence galaxies and star-burst galaxies (ΔMS)

Introduction

- Star-forming galaxies (SFGs) follow SFMS
  - An equilibrium state between gas consumption, outflow, and inflow
  - Scatter of ~0.3dex
- Star-burst galaxies have elevated SFRs by factors of 10 and more above the SFMS
  - $\sim$ 1% at $z < 0.4$; $\sim$ 2-5% at $z \sim 0.5$-1.0; higher fractions at higher redshifts depending on stellar mass
- Explanation of star-burst
  - Q1: Interactions between gas-rich galaxies lead to the inflow and compression of gas

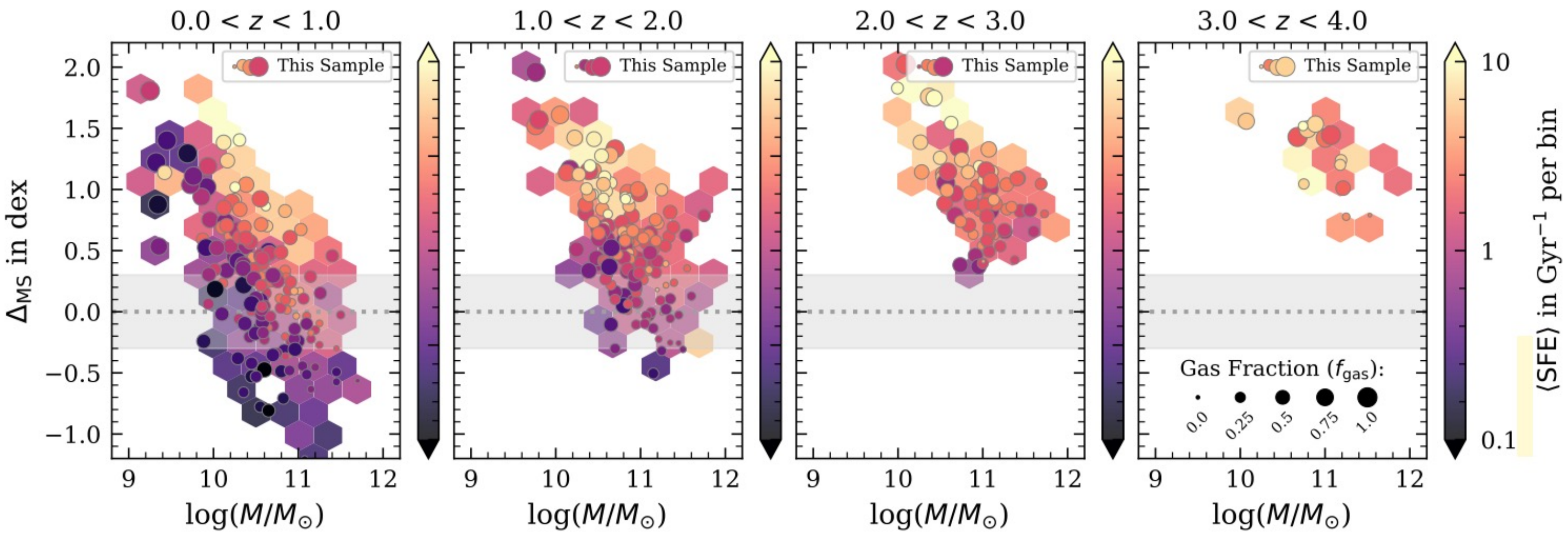
    OR/And: Disk instabilities in gas-rich galaxies without external interactions
  - Q2: Triggered by Higher gas fraction or enhanced SFE
- The origin of starbursts and The definitive link between galaxy interactions, disk structure, increased star-formation efficiency (SFE), and gas fraction out to high redshift has yet to be studied.

Sample and Basic Measurements

- 387 galaxies out to z ~ 4: sub-sample of the galaxies from *Scoville+2023* in COSMOS field
  - 1. robust measurements of total SFR from UV+far-IR Herschel
  - 2. molecular gas masses from far-IR dust continuum observations with ALMA
  - 3. stellar masses and accurate photometric redshifts from multi-band photometry
  - 4. deep sub-kpc resolution JWST rest-frame optical and near-IR imaging data
- UV and Optical Photometry from COSMOS2020 catalog → M_*, SFR, …
- JWST Imaging (for morphology) → Identifying star-forming clumps
- The infrared SFRs are measured from the total infrared luminosity via $SFR_{IR} = 8.6\times10^{-11} L_{IR}[L_\odot]$
- The molecular ISM gas masses are derived from the Rayleigh-Jeans (RJ) dust continuum (rest-frame 850 μm) calibrated over a range of galaxy types (main-sequence, starburst, luminous infrared galaxies; See *Scoville+2014*).

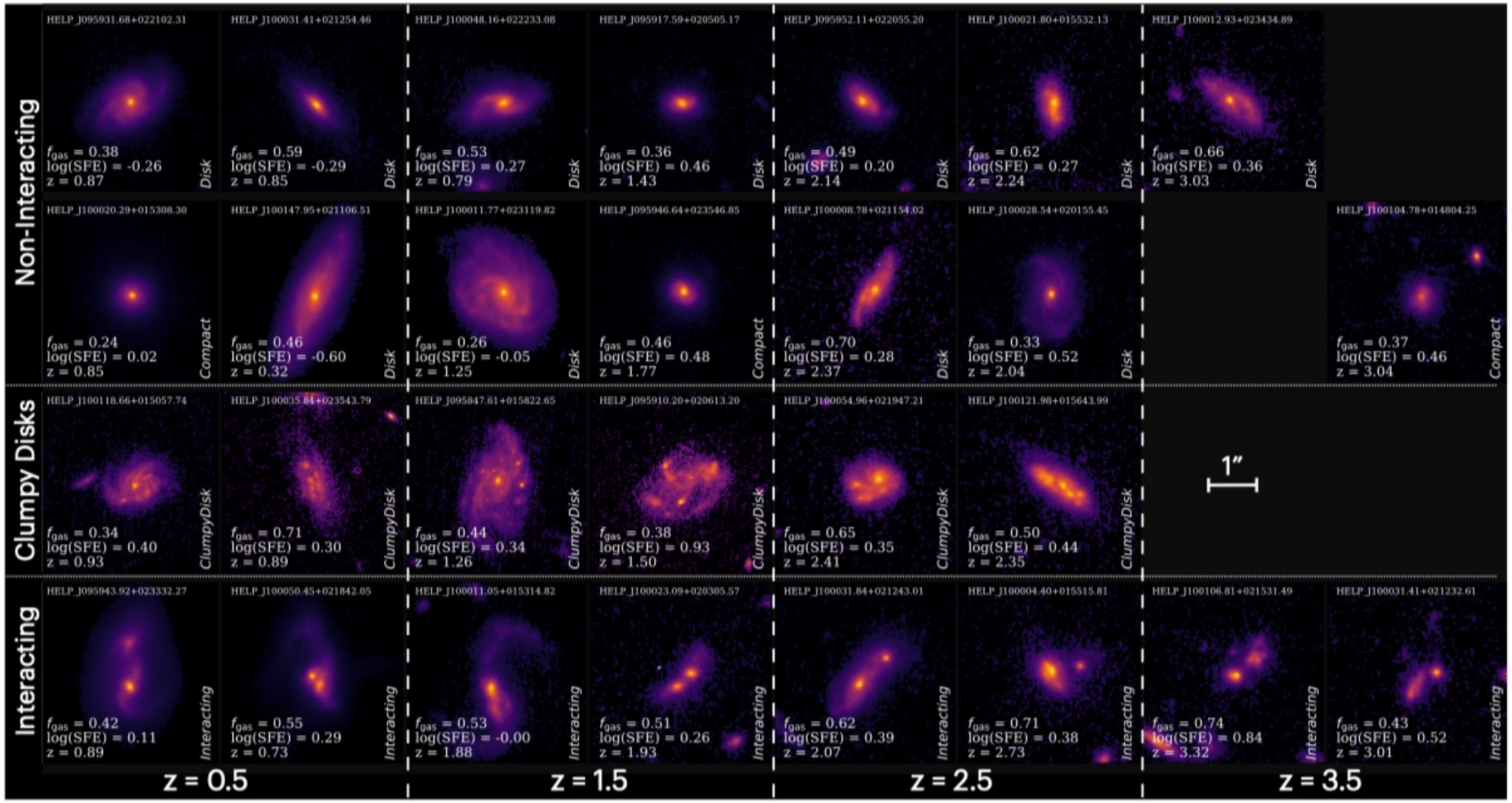
Sample and Basic Measurements

- Star formation efficiencies: $SFE = SFR/M_{mol,gas}$;
- Gas fraction: $f_{gas} = M_{mol,gas}/(M_{mol,gas} + M_*)$
- ΔMS: main-sequence parameterization from Lee et al. (2015)
  - Herschel observations are crucial for deriving robust ΔMS of starburst galaxies, often dominated by dust-obscured star formation
- The adopted mass bins in $\log(M/M_\odot)$ are [10.1,10.8] and [10.8,11.7] for z~0.5, [10.4,11.1] and [11.1,11.8] for z~1.5, [10.7,11.1] and [11.1,11.7] for z ~ 2.5, and [10.7,11.2] for z ~ 3.5



Structural Analysis

- Visual classification: Non-Interacting, Disk Galaxies, Clumpy Disks, Interacting
  - The fraction of interacting galaxies: f_{int}
  - The fraction of clumpy disk galaxies compared to the total disk galaxy population: f_{clumpy}



Results

- 1. The Impact of Galaxy-Galaxy Interaction on Starburst Activity
  - An increase of the fraction of interacting systems towards higher redshifts is found
  - Scoville+2023: Gas fraction is weakly correlated to starburst activity
  - → Not a significant correlation between f_{int} and f_{gas}. (Figure of f_{gas} and ΔMS ?)
  - Up to z = 2, a clear trend of galaxies with a higher SFE residing more frequently in interacting systems.
  - At even high-z, the different time scales between a SFE increase and visually identified merger stages → weak correlation
  - Interacting galaxies only make up at most 40% of z < 3 starburst galaxies. Non-interacting systems contribute significantly to the starburst population.

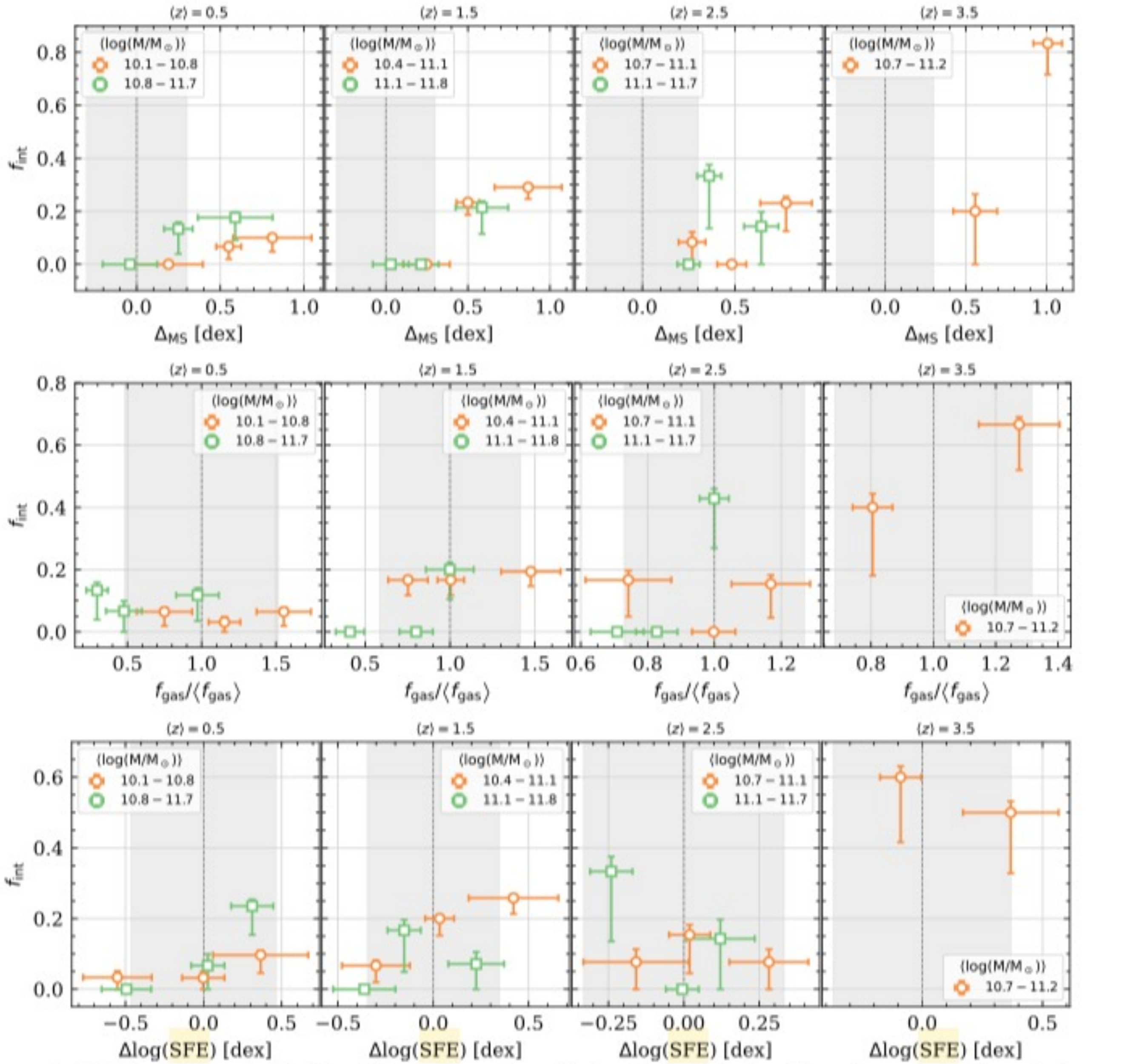


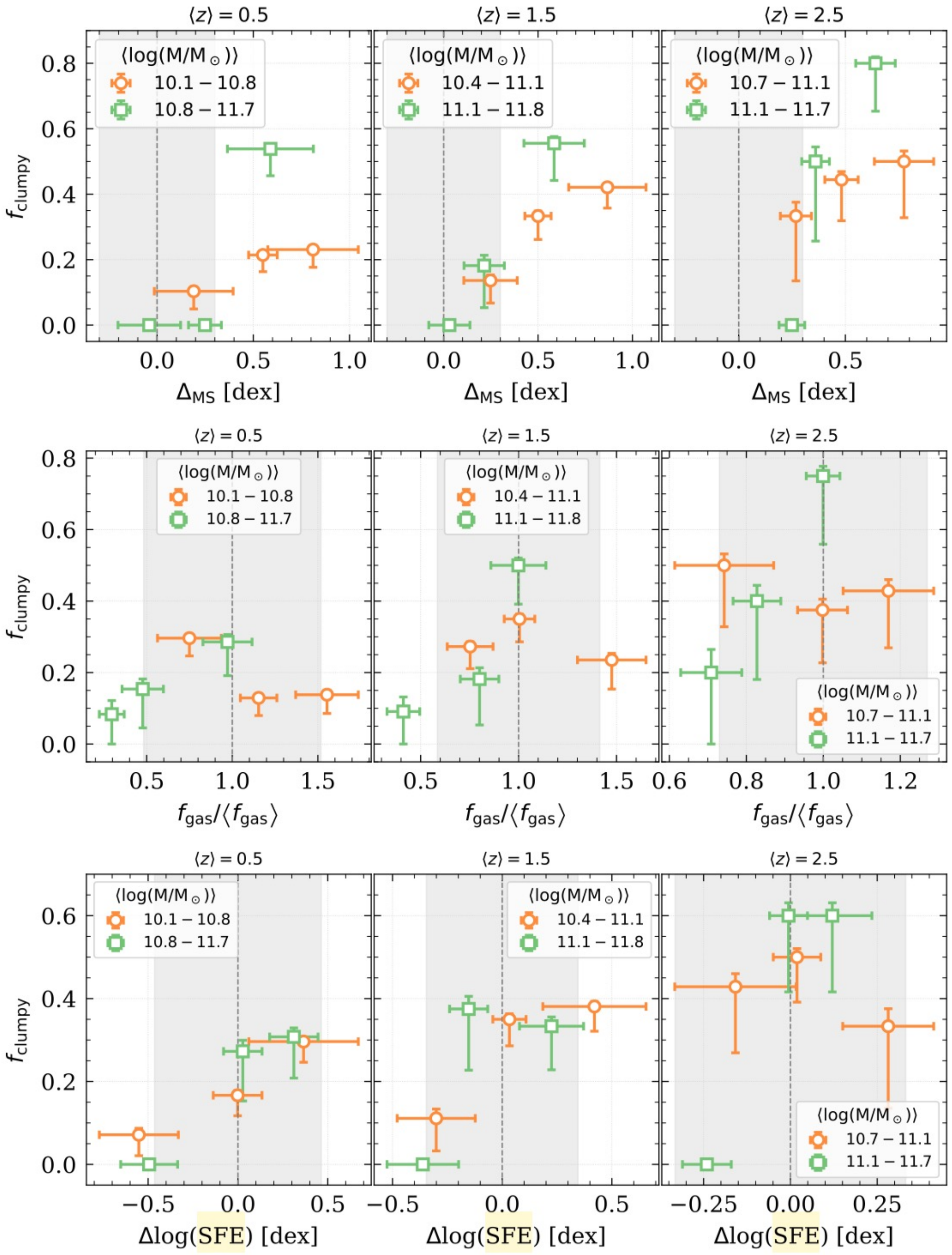
Figure 3. Relation between the fraction of interacting systems (f_{int}) and the offset from the main sequence (Δ_{MS}; top), gas fraction (f_{gas}, middle), and star formation efficiency (SFE; bottom) for different redshift ranges ($\Delta z = 1$) and two stellar mass bins. The latter two quantities are normalized to the mean of the population (width indicated by the gray region) at a given redshift and stellar mass.

Results

- 2. The Impact of Disk Instabilities on Starburst Activity

  (cannot identify clumpy at z>3, limitation of resolution and confusion with interacting systems)

  - Gas-rich streams increase the gas density of the disk, which then becomes unstable and starts to fragment into clumps.
  - An increase in the clumpy disk fraction towards the starburst regime.
  - The fraction of clumpy disks increases with both f_{gas} and SFE, while the correlation with the latter is more pronounced.



Discussion

- The former findings suggests that galaxy-galaxy interactions are a way to push galaxies into the starburst regime by increasing the efficiency of star formation in the galaxies. This has been observed at lower redshifts and is suggested by simulations.
- Galaxy-galaxy interactions may not be the prime avenue to cause starbursts at z > 2, disk instabilities could be a more common path as f_{clumpy} clearly correlates with ΔMS out to at least z = 4.

- f_{int}, f_{clumpy} vs. SFE
  - Shorter time-scale (~ 100 Myrs): An increase in star formation and SFE triggered through the compression of gas (Merger); Close mergers.
  - Longer time-scale (many 100 Myrs): infrared SFR tracers; The late and early-stage mergers; The SFE increase due to disk (compared to merger-driven enhancement)