Fraction of Clumpy Star-forming Galaxies in CANDELS/GOODS-S

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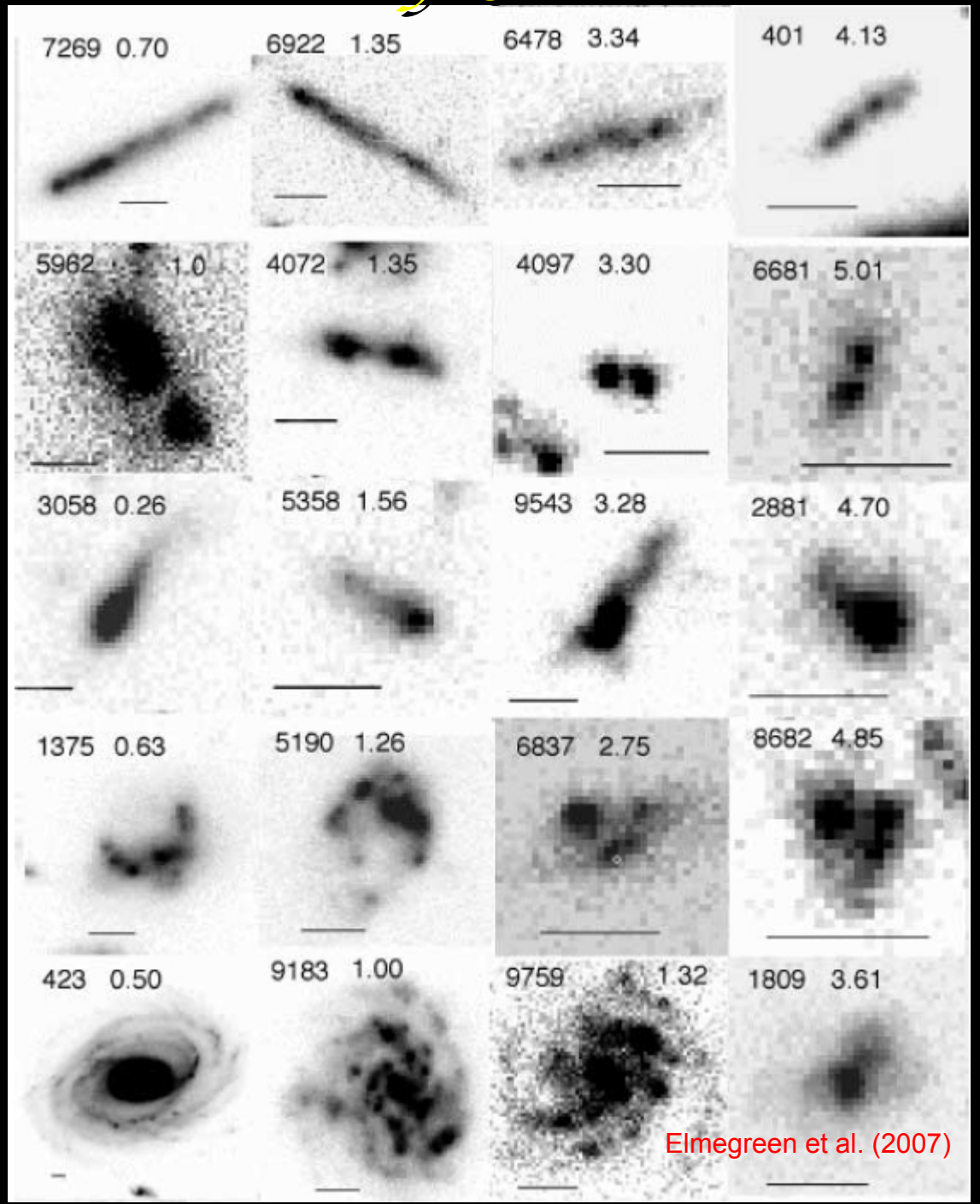
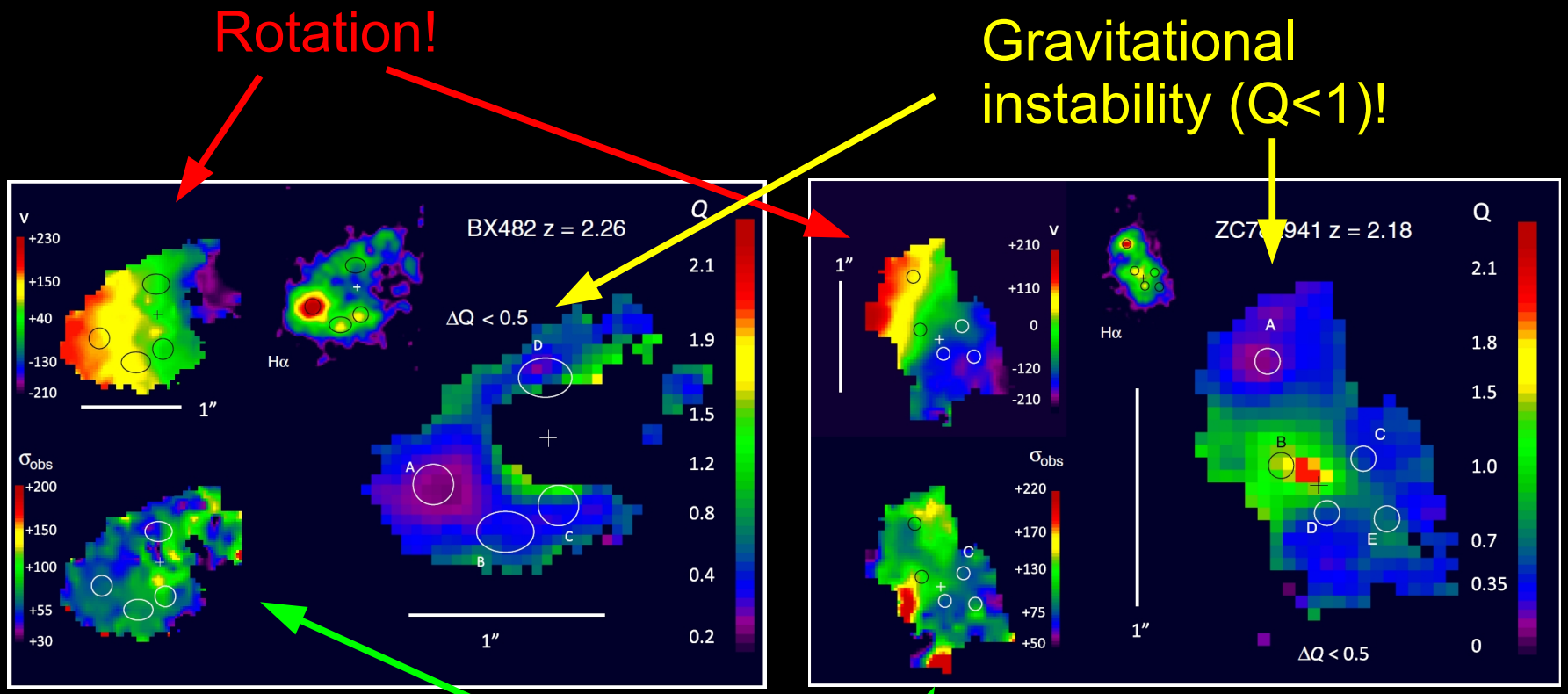
Clumps: Important Feature of Galaxies

- Seen in deep rest-frame UV (e.g., Elmegree+07, 09, Guo+12), rest-frame optical images (e.g., Forster Schreiber+11, Guo+12), and emission line maps (e.g, Genzel+08, 11)
- Span a wide redshift range: 0.5<z<5
- Typical stellar mass: 10^7~10^9 Msun, typical size: ~1 kpc
- Regions with blue UV—optical color and enhanced specific SFR (e.g., Guo+12, Wuyts+12)
- Have underlying disks, based on either morphological (e.g., Elmegreen+07,09) and kinematic (e.g., Genzel+11) analysis



Clumps: Ideal Laboratory of Star Formation, Feedback, and Structure Formation

- **Formation:** gravitational instability in the gas-rich turbulent disks (VDI)

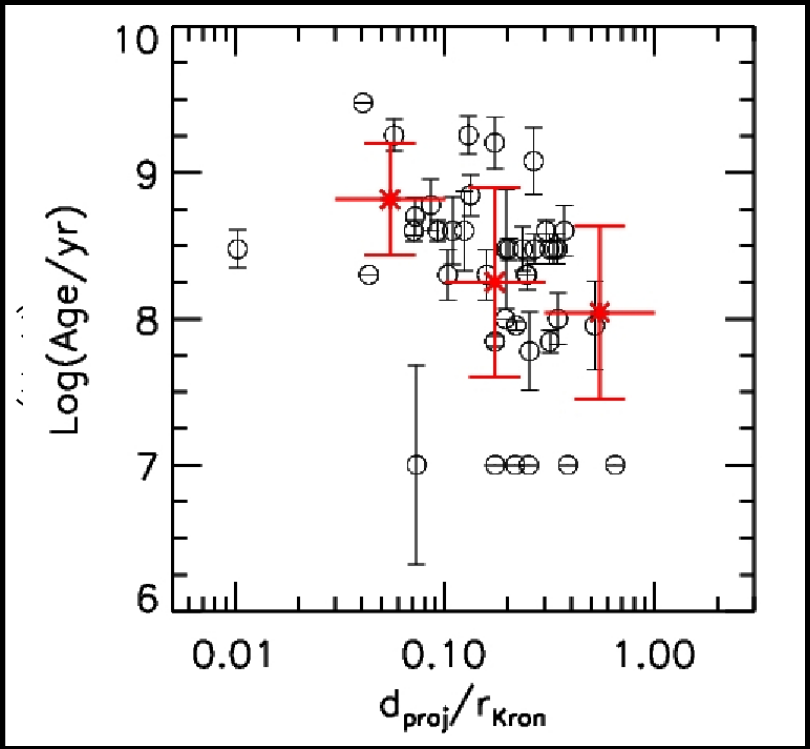


Genzel et al. (2011)

Clumps: Ideal Laboratories of Star Formation, Feedback, and Structure Formation

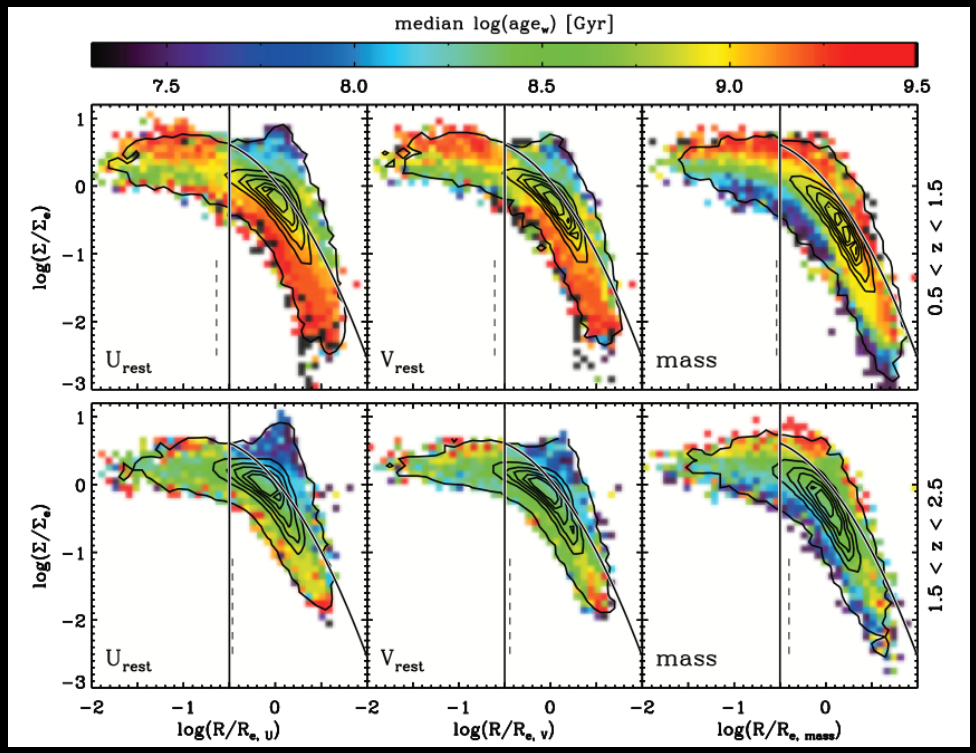
Fate:

- In-ward migration towards the center to coalesce into bulges



Guo et al. (2012)

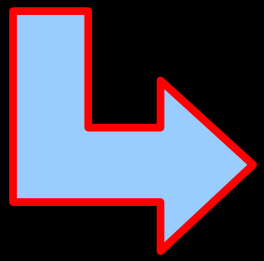
- Quick disruption by tidal force or feedback



Wuyts et al. (2012)

One Key Question Still Remains Unclear:

$$\text{Fclumpy}\,(M^*, z) = \frac{\text{Number of Clumpy Galaxies with } (M^*, z)}{\text{Number of Galaxies with } (M^*, z)}$$



Probability of galaxies undergoing VDI, linked with the macro-physics of star formation

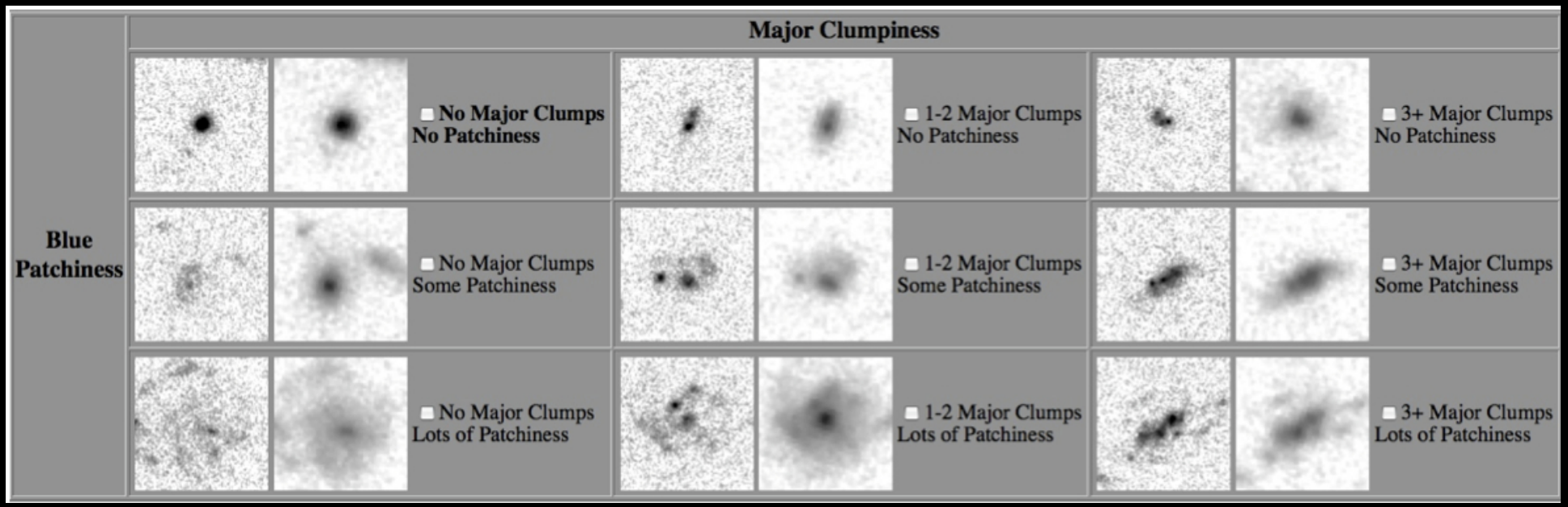
This work

Measuring Fclumpy of star-forming galaxies in CANDELS/GOODS-S

Sample

I. $0<z<3.5$
II. $\log(M^*)>9$
III. SSFR>0.1/Gyr

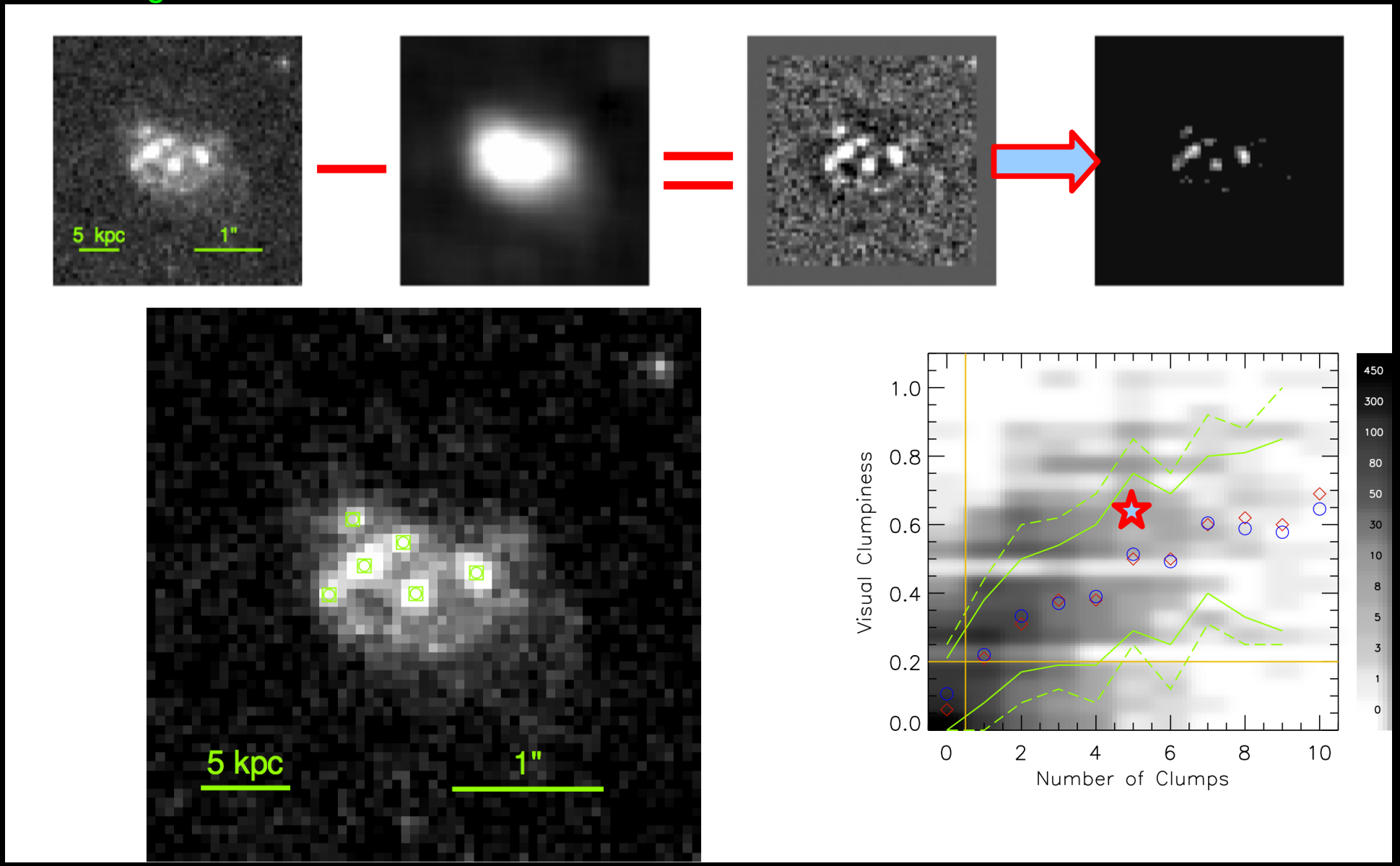
Identifying Clumpy Galaxies: I. Visual Classification



- Visual classification done by CANDELS astronomers
- Each galaxy inspected by 3—5 different people
- 3X3 grid of (major clumps, blue patches) in V and H bands
- Diagonalized, normalized, and averaged:
  - 0.00 - no clumpy/no patches
  - 0.25 - 1-2 clumps/no patches OR no clumps/some patches
  - 0.50 - 3+ clumps/no patches OR 1-2 clumps/some patches OR no clumps/Lots of patches
  - 0.75 - 3+clumps/some patches OR 1-2 clumps/lots of patches
  - 1.00 - 3+ clumps/lots of patches

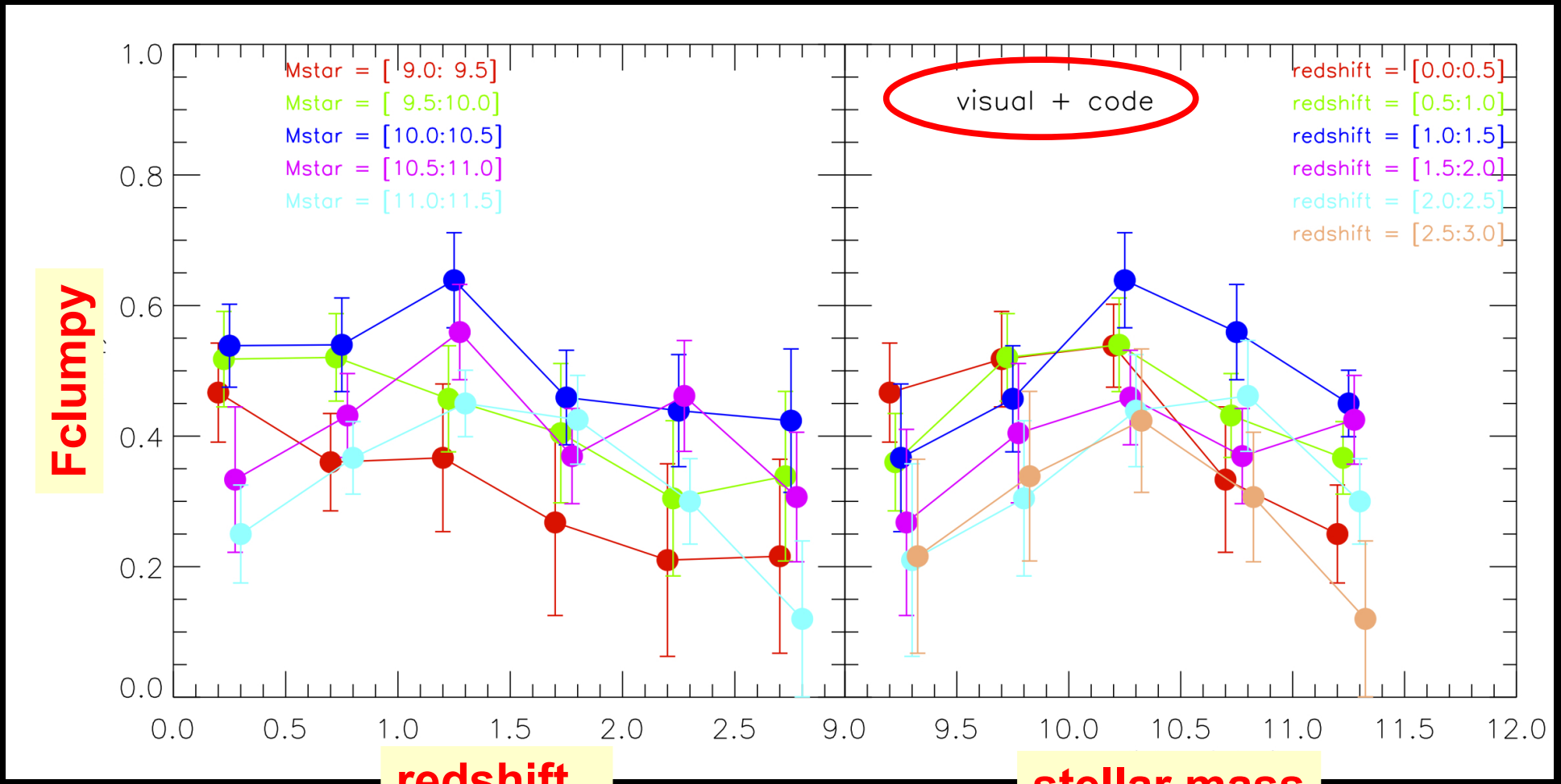
- Limited only to H<24 AB galaxies
- Cannot tell clump positions

Identifying Clumpy Galaxies: II. Clump Finder



- Combining both: visual classification primary, clump finder secondary

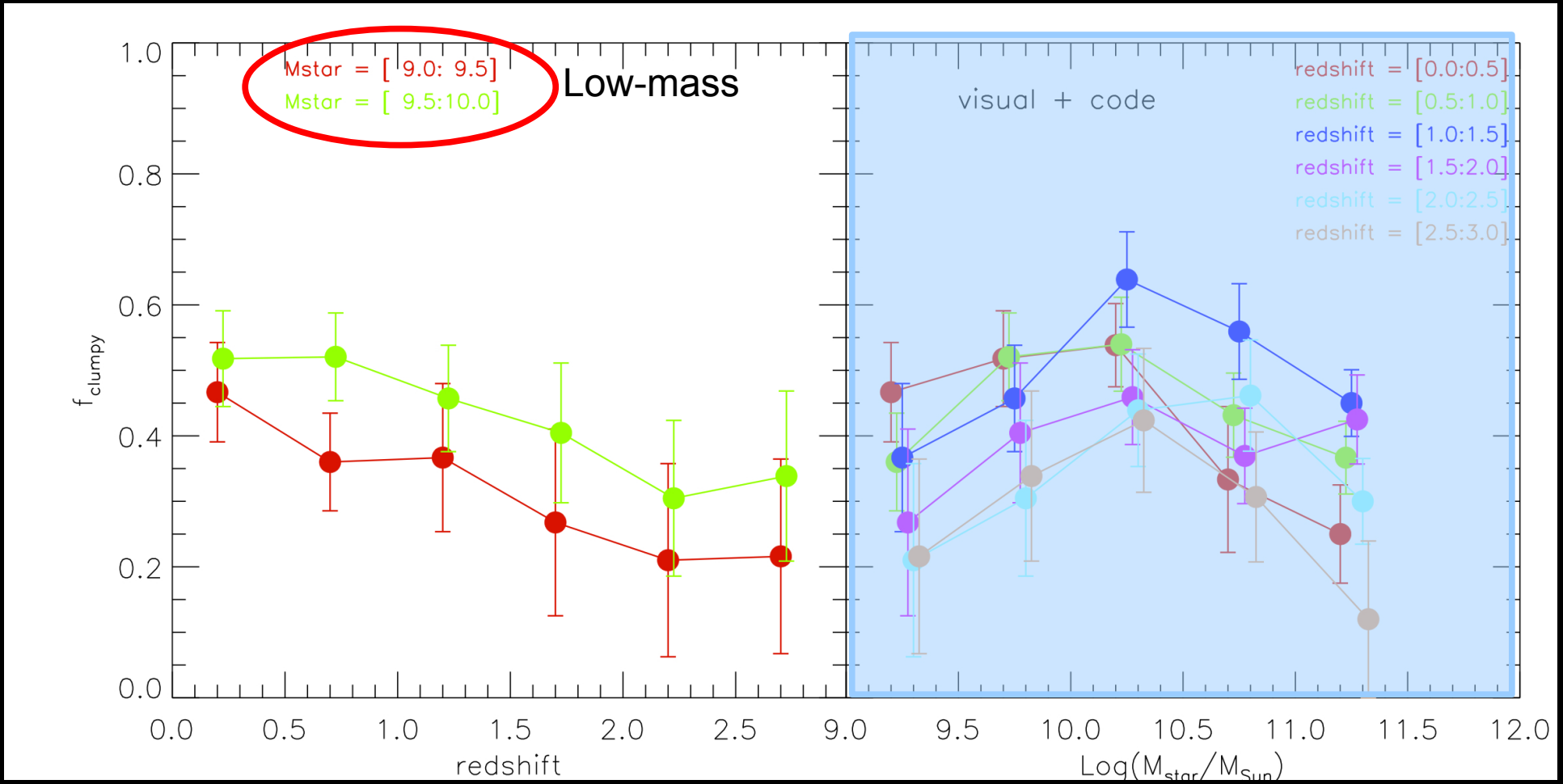
Fraction of Clumpy Galaxies



General results:

- I. Fclumpy between 20% and 60% for different (M*, z) bins
- II. Fclumpy vs. redshift differs for different mass bins
- III. Fclumpy peaks at Log(M*)=10—10.5 for all redshift bins

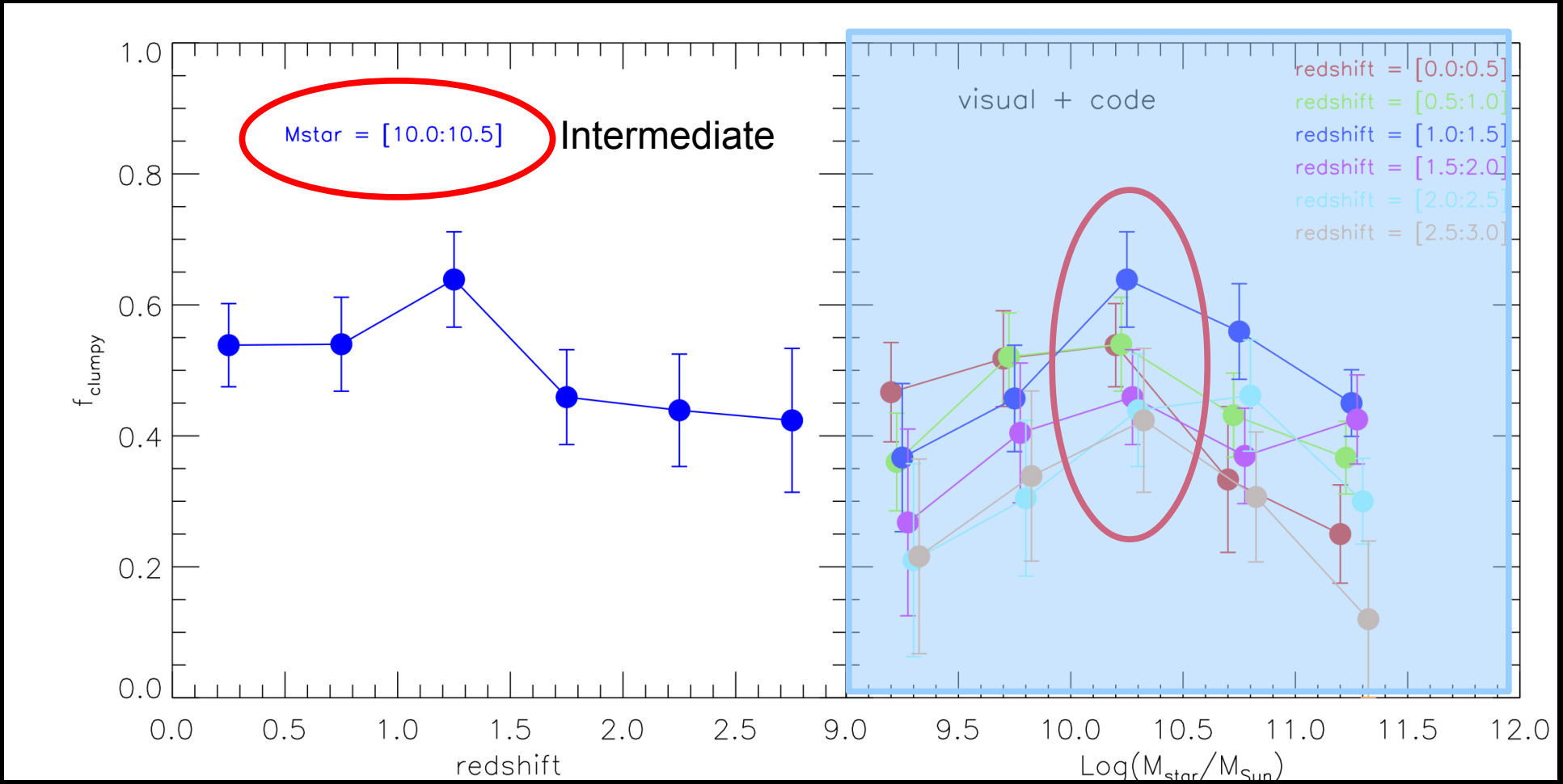
Fraction of Clumpy Galaxies



Low-mass End:

- Fclumpy increases toward low z
- Violent disk instability occurs later in low-mass galaxies
- Observational bias (cosmological dimming) flattens but does not eliminate the trend

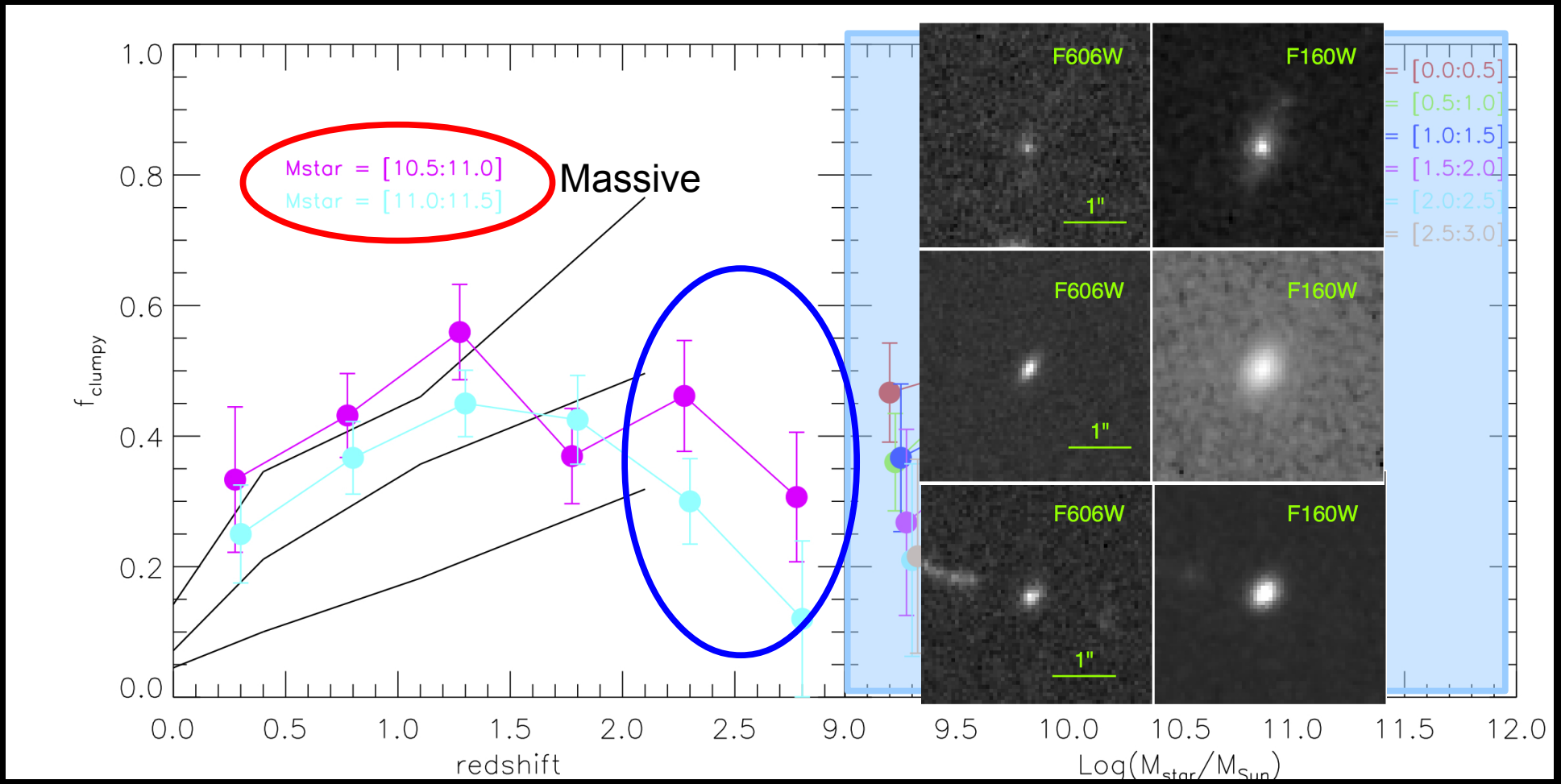
Fraction of Clumpy Galaxies



Intermediate:

- Fclumpy changes mildly along redshift
- Clump formation most efficient in this M* bin: the highest Fclumpy among all redshift bins

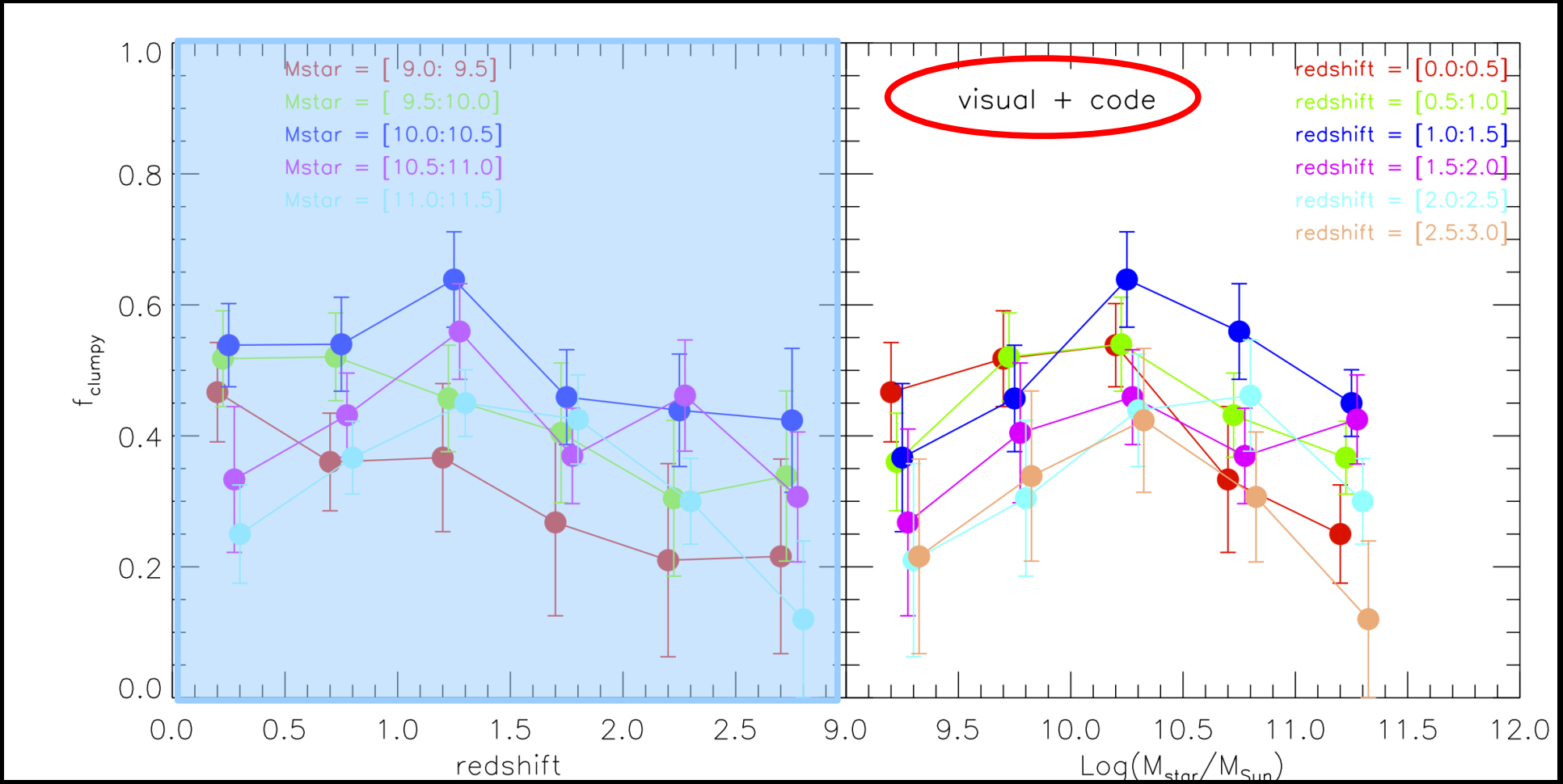
Fraction of Clumpy Galaxies



Massive End:

- Fclumpy peaks during z=1.0—1.5
- Low-z end: disk stabilized (Dekel+09, Cacciato+12, Forbes+13), gas accretion rate dropped (Dekel+09), and low gas fraction (Geach+11)
- High-z end: disk stabilized by bulge or collapsed to nugget?

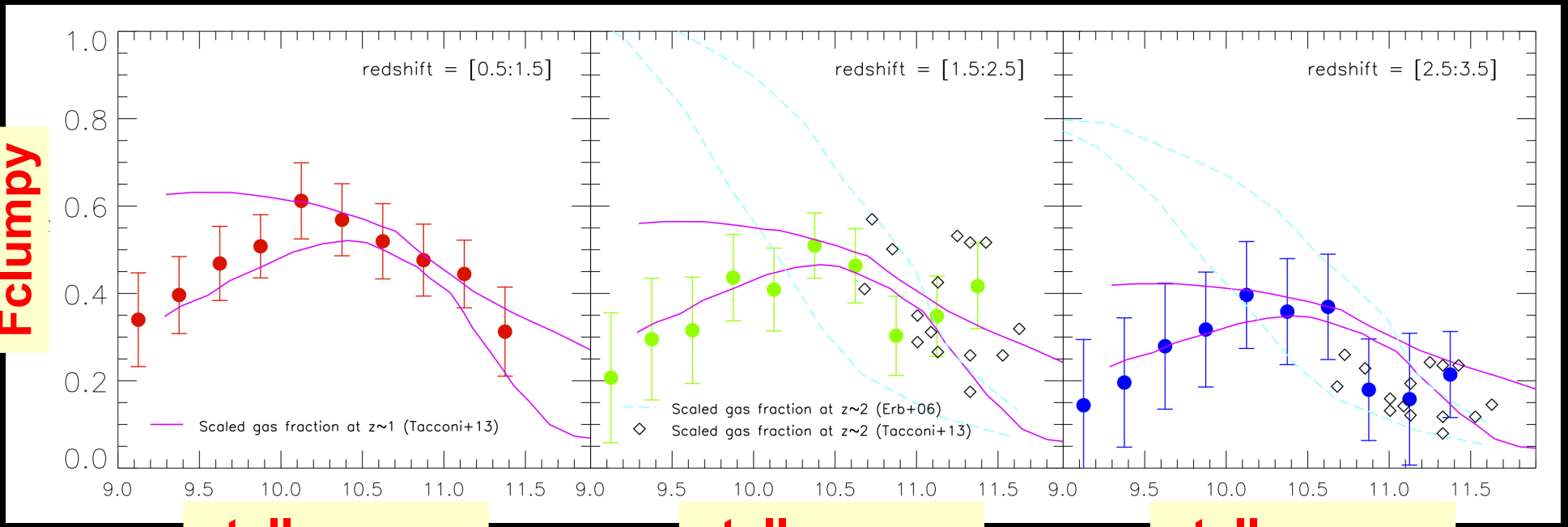
Fraction of Clumpy Galaxies



Fclumpy vs. M*:

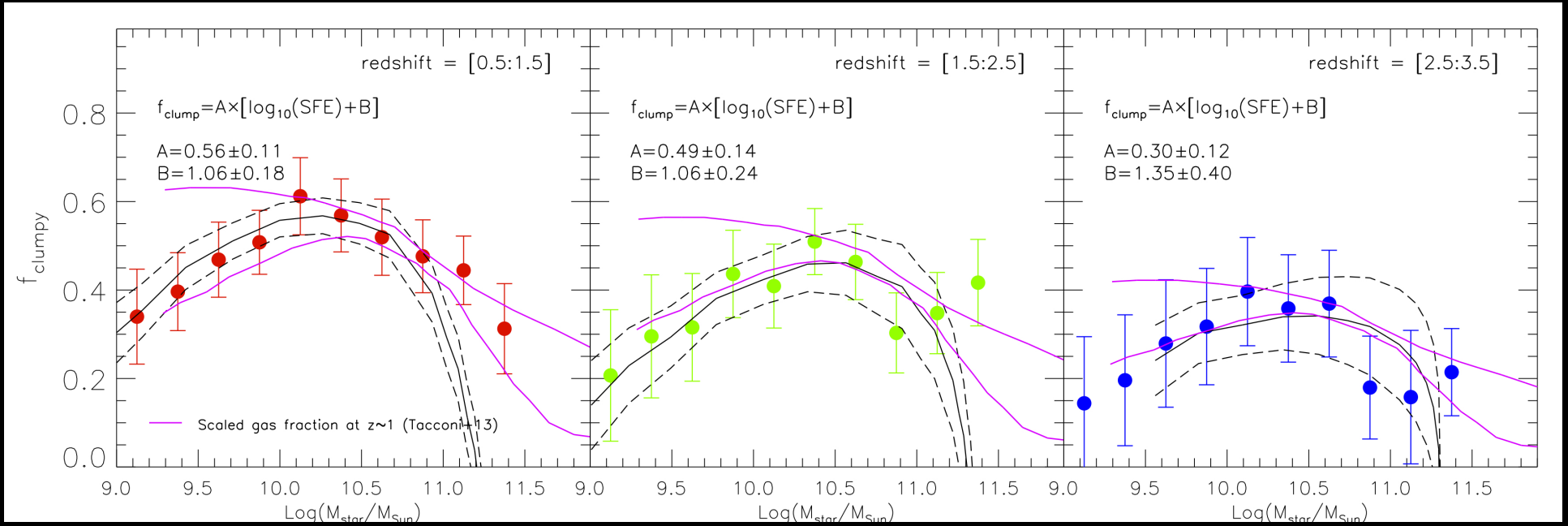
- Fclumpy peaks at Log(M*)=10—10.5 for all redshift bins
- Observational biases (if any) mainly change the amplitude not the trend

Fraction of Clumpy Galaxies vs. Gas Fraction



- Both fractions drop at the massive ends with same trend at z~1
- Galaxies need to be gas-rich to form clumps
- At the low-mass end, clumpy fraction drops more quickly than gas fraction: need mechanisms (e.g. radiative feedback) to prevent clump formation or destroy clumps

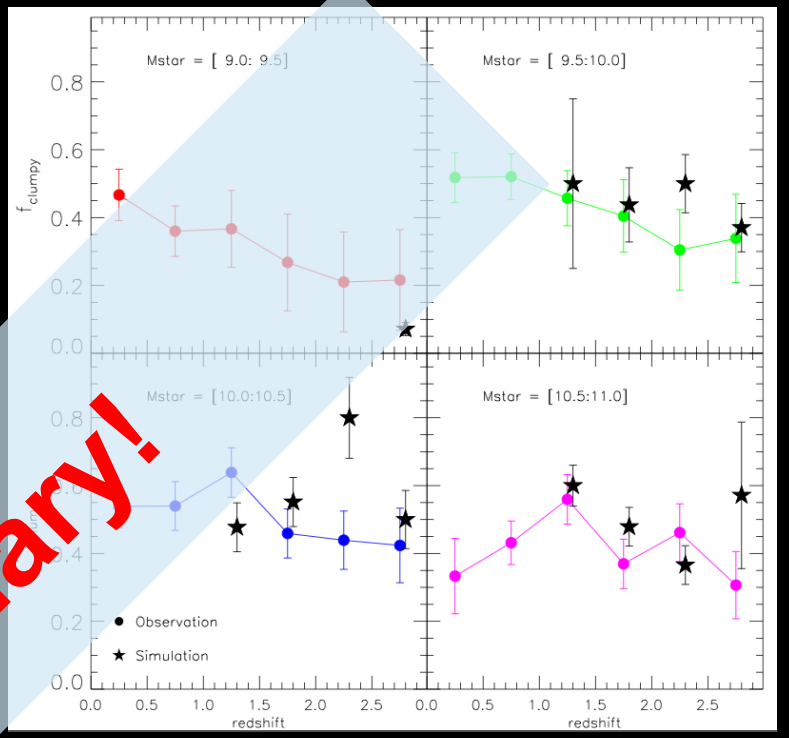
Fraction of Clumpy Galaxies vs. SFE

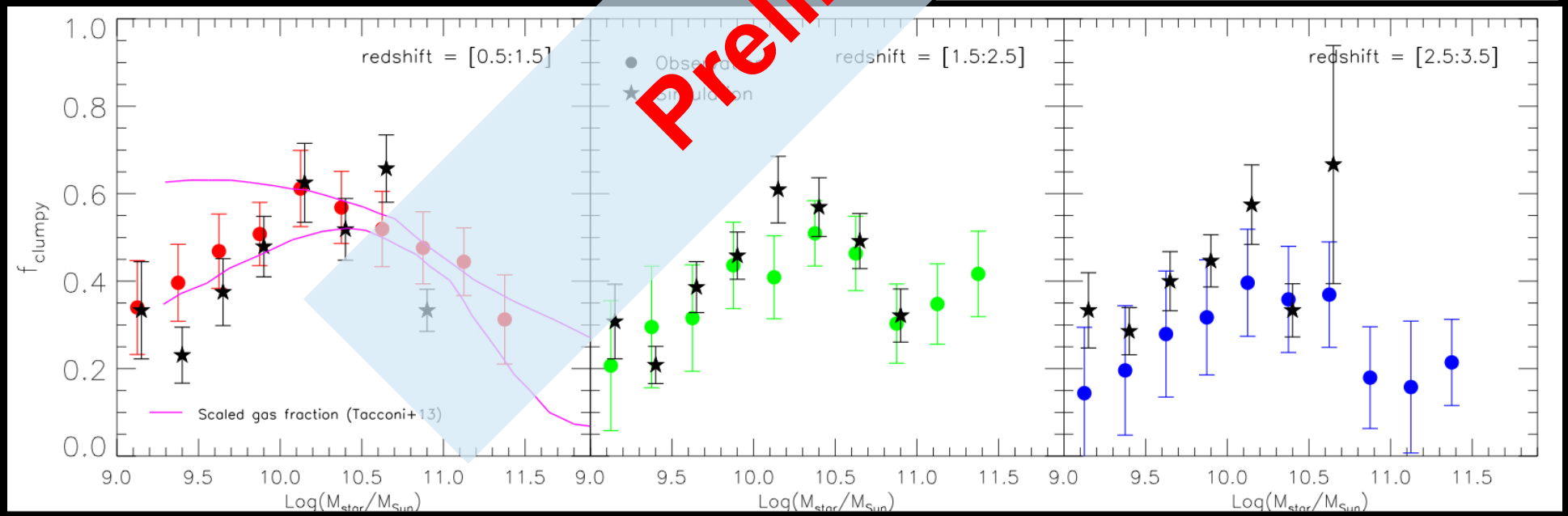


- SFE = SFR / Baryon Accretion Rate (Behroozi+12, 13)
- Good correlation at the low-mass ends
- Deviation at the most massive ends: something (AGN?) affecting SFE dose not affect Fclumpy
- Or quiescent galaxies dominate the most massive ends

Comparison with Simulation

- Zoom-in hydro cosmological simulations of 29 galaxies (Ceverino & Klypin 09, Ceverino+11, Deke+13)
- Clumps identified from 3-D gas snapshots (Mandelker+13)
- Only clumps with Mclump/Mdisk>0.01 (both in-situ and ex-situ) counted
- Good agreement between observation and simulation





Preliminary!

Summary

- A key question: the fraction of clumpy galaxies with (M*, z)
- Visual classification + clump finder on star-forming galaxies in CANDELS/GOODS-S
- Fclumpy between 20% and 60% for different (M*, z) bins
- Fclumpy vs. redshift differs for different mass bins
- Fclumpy peaks at Log(M*)=10—10.5 for all redshift bins
- Fclumpy vs. M* shows the same trend of gas fraction for massive galaxies at z~1
- Correlation between Fclumpy and SFE for low-mass galaxies
- Comparison with simulation: still on-going, but good preliminary agreement