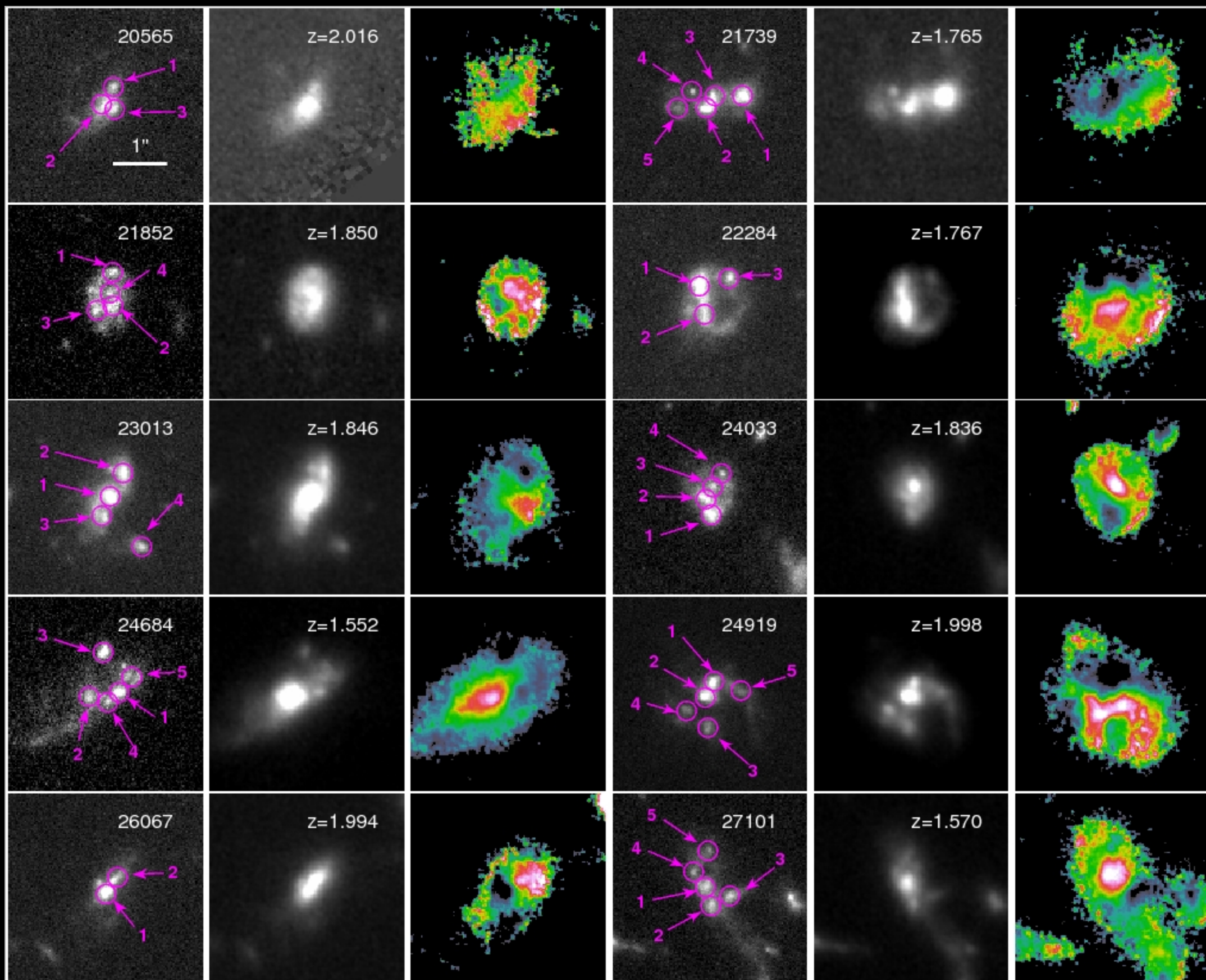
Formation and Evolution of Clumpy Galaxies at z=0.5--3

Yicheng Guo (UCO/Lick, UCSC)



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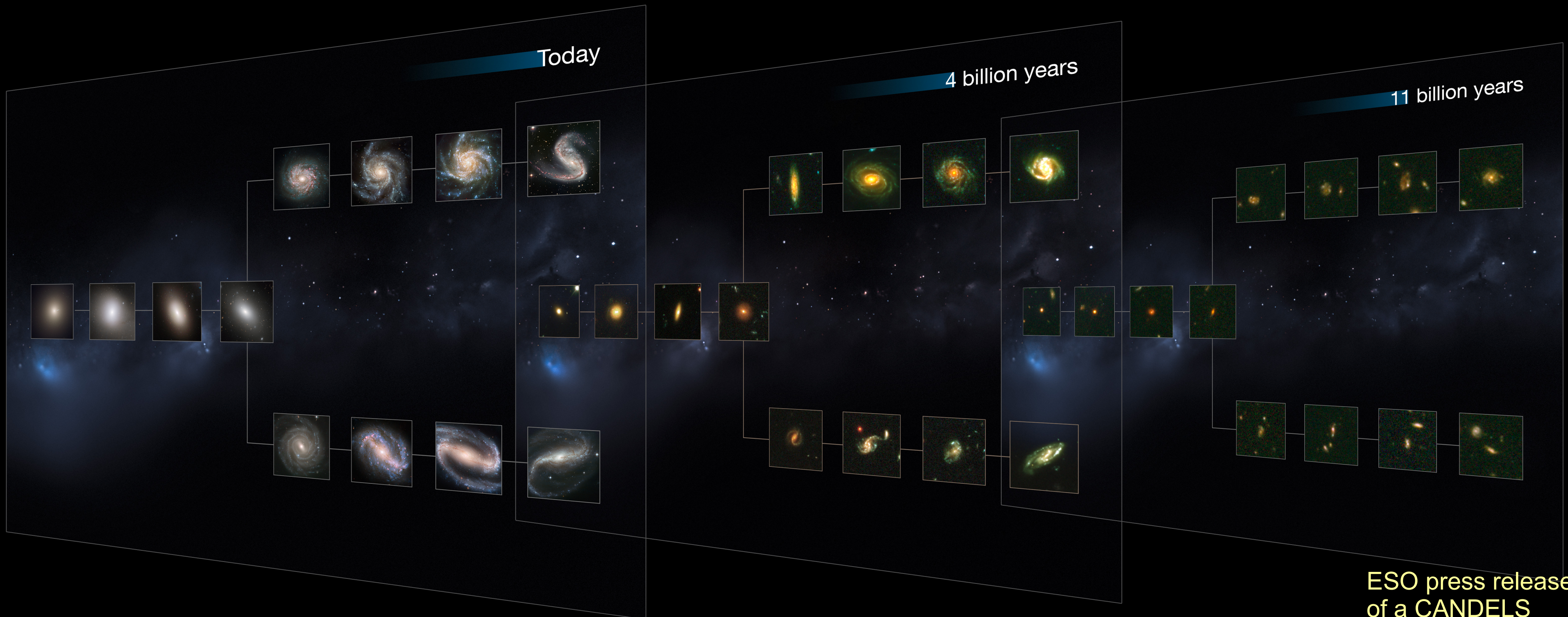
Chris Moody & CANDELS Team

Exponential Disk in Galaxies
Lowell Observatory
Flagstaff, AZ, 10/06/2014

Hubble Sequence across Cosmic Time

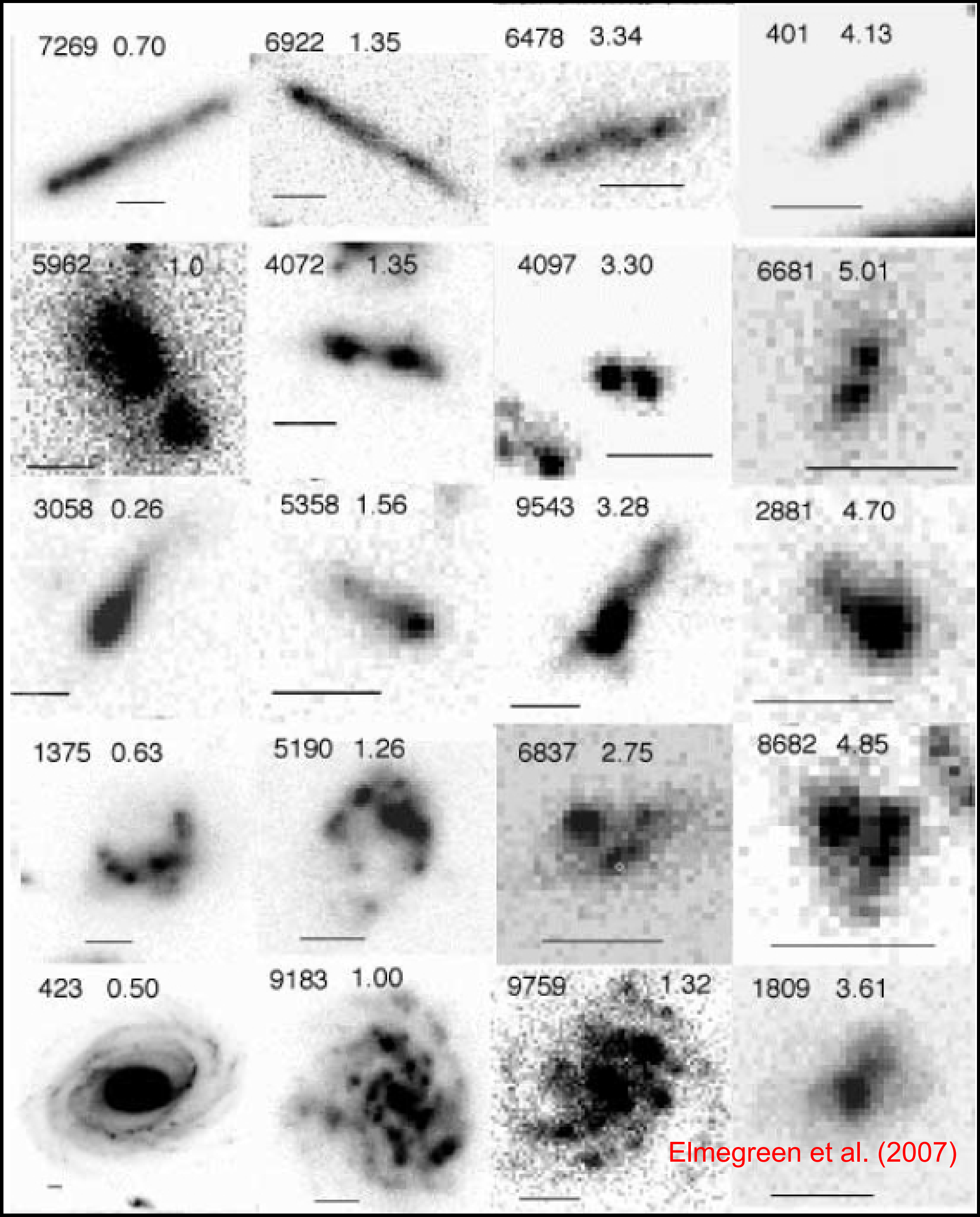


ESO press release of a CANDELS paper (Lee+2013)

- The morphology—spectral type correlation established 11 billion years ago (z=2.5)
- Galaxies are smaller at higher redshifts
- Early-type galaxies at z=2.5 look similar to those today, albeit smaller
- Late-type galaxies at z=2.5 look different to those today

Clumps: Important Feature of High-redshift 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)
- Many are in underlying disks, based on either morphological (e.g., Elmegreen+07,09) and kinematic (e.g., Genzel+11) analyses

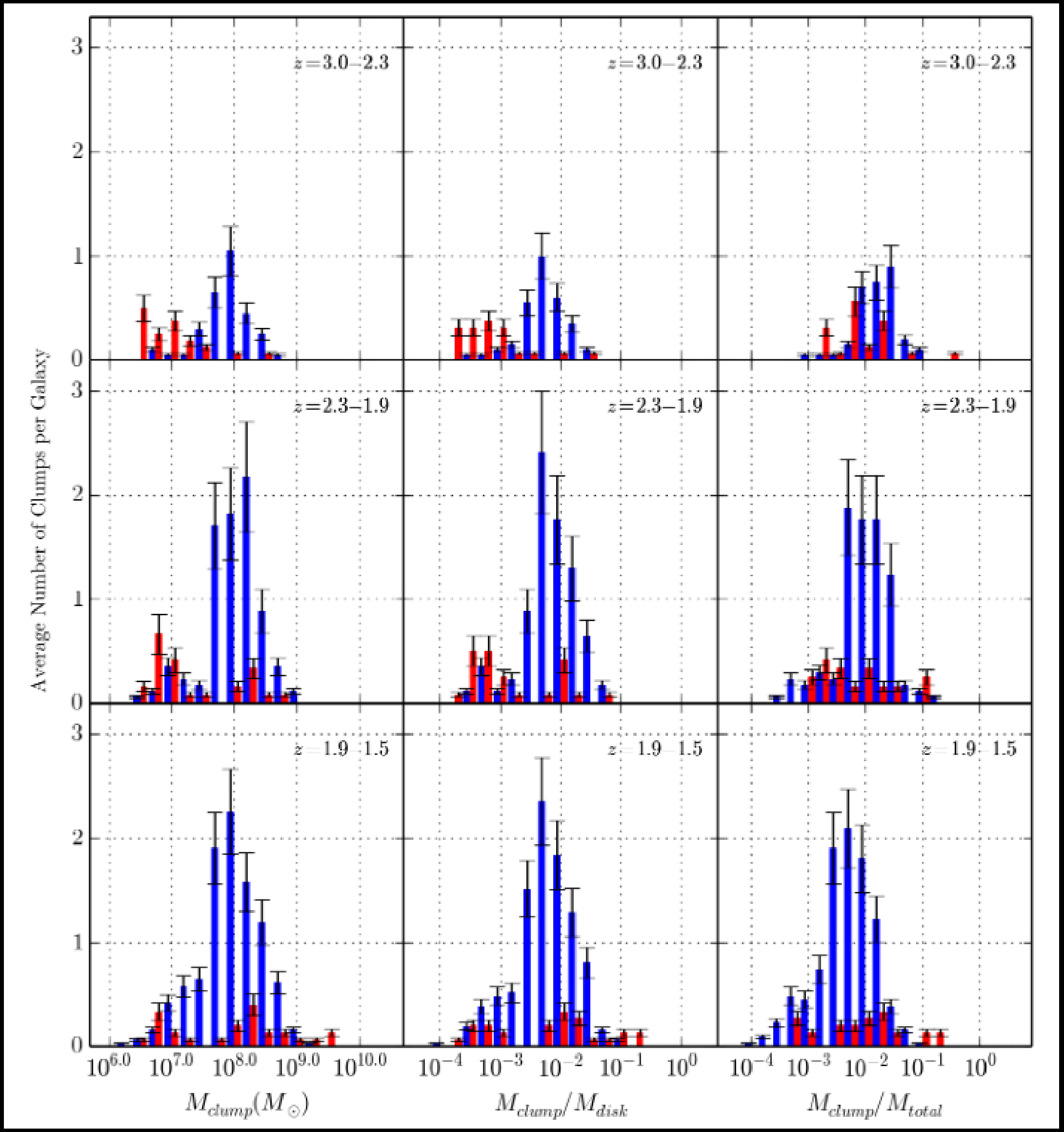


Elmegreen et al. (2007)

Why should we care about clumpy galaxies?

Clumps: Ideal Laboratory of Star Formation and Feedback

Number of clumps strongly depends on the feedback models used in numerical simulations.



Blue: supernova feedback (thermal)

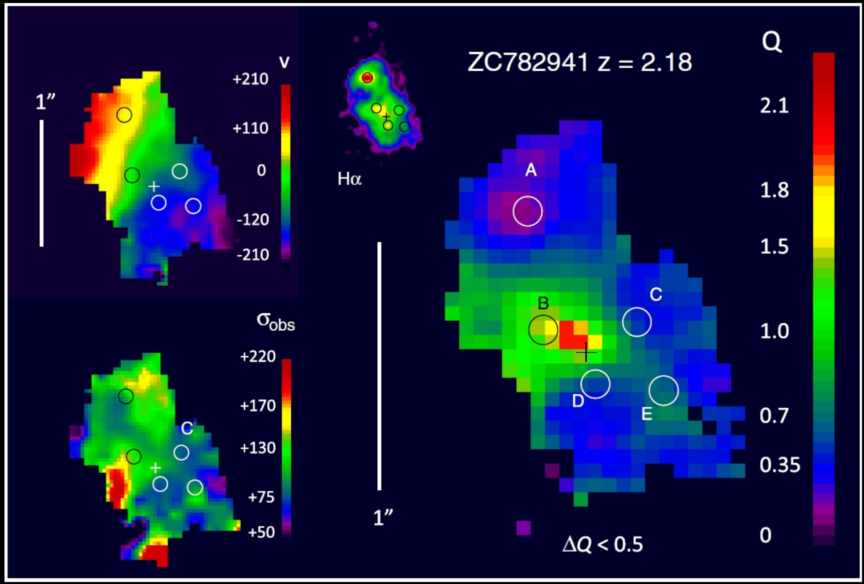
Red: supernova + radiation pressure feedback (non-thermal)

Moody, Guo, et al. 2014

Why should you care about clumpy galaxies?

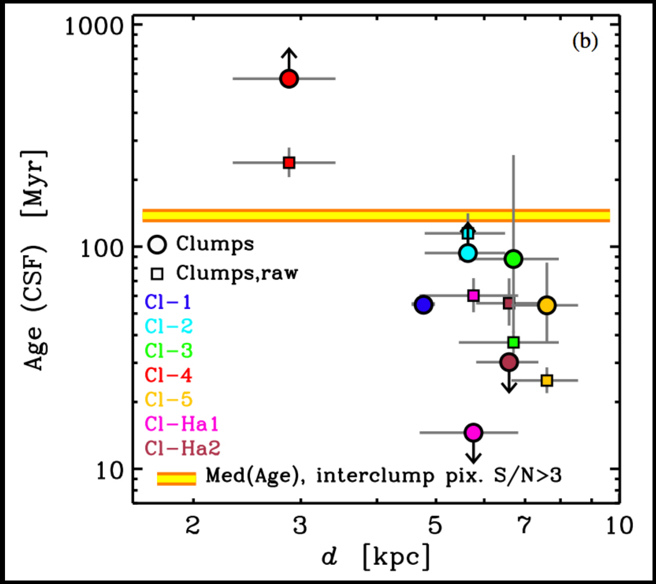
Clumps: Ideal Laboratory of Galactic Structure Formation and kinematics

- Formation:
  - (1) Violent disk instability (VDI) in gas-rich turbulent disks?
  - (2) Minor merger?
  - (3) Major merger?



Genzel et al. (2011)

- Evolution:
  - (1) Form bulge progenitors to stable the disks?
  - (2) Disrupted by feedback to form thick disks?
  - (3) Any connection between the clumpy appearance and kinematics?



Forster Schreiber et al. 2011

This Talk

- Physical properties of clumps and their variations at $z\sim2$ (Y. Guo+12)
- Clumpy fraction of star-forming galaxies from $z=3$ to $z=0.5$ (Y. Guo+14, submitted)

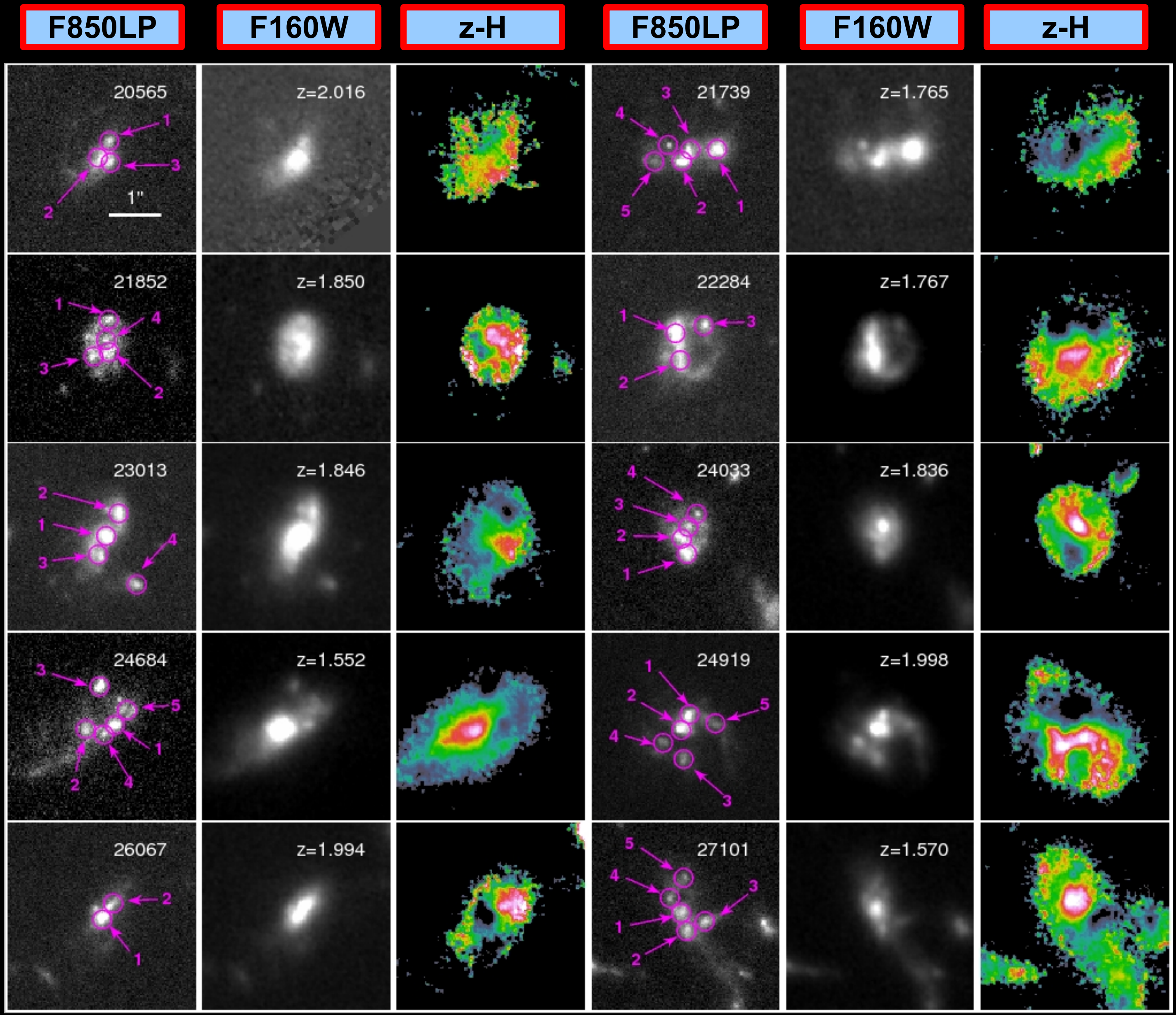
Need deep space-based surveys: high sensitivity and high spatial resolution

CANDELS: Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey, the largest program of the Hubble Space Telescope (PI: Sandra Faber & Henry Ferguson)

CANDELS observed five fields with total sky area of ~0.5 deg^2.
Observations completed August 2013 (Grogin+11; Kokermoer+11; Y. Guo+13; Galametz+13)

Part I: Physical Properties of Clumps at z~2

- 10 galaxies from HUDF
- Spec-z (1.5~2.5)
- log(M*)>10.0
- Star-forming

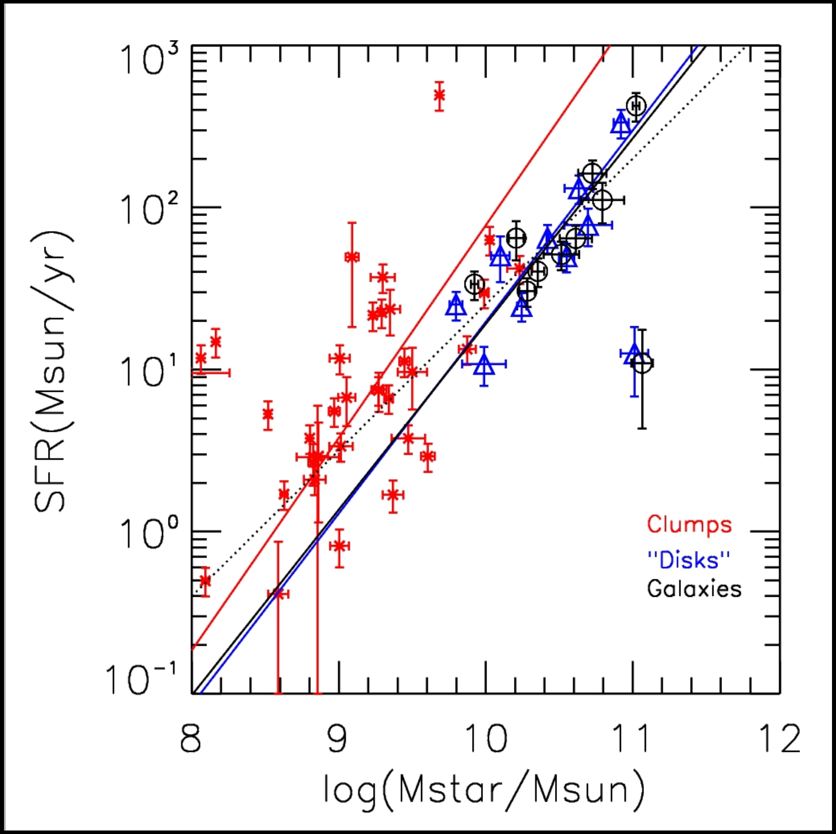


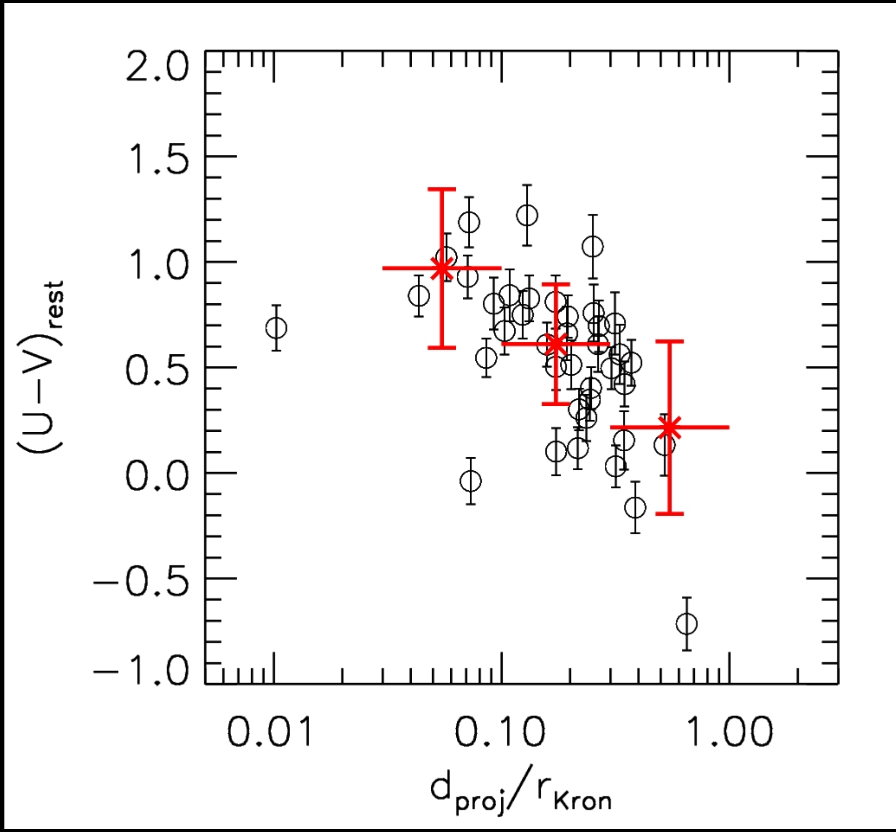
Guo+12

Physical Properties of Clumps

- Clumps are blue
- SFR of galaxies still dominated by disks
- Clumps have higher sSFR

- Clumps have radial variation of the UV—optical colors
- Central clumps are redder, outskirt clumps bluer

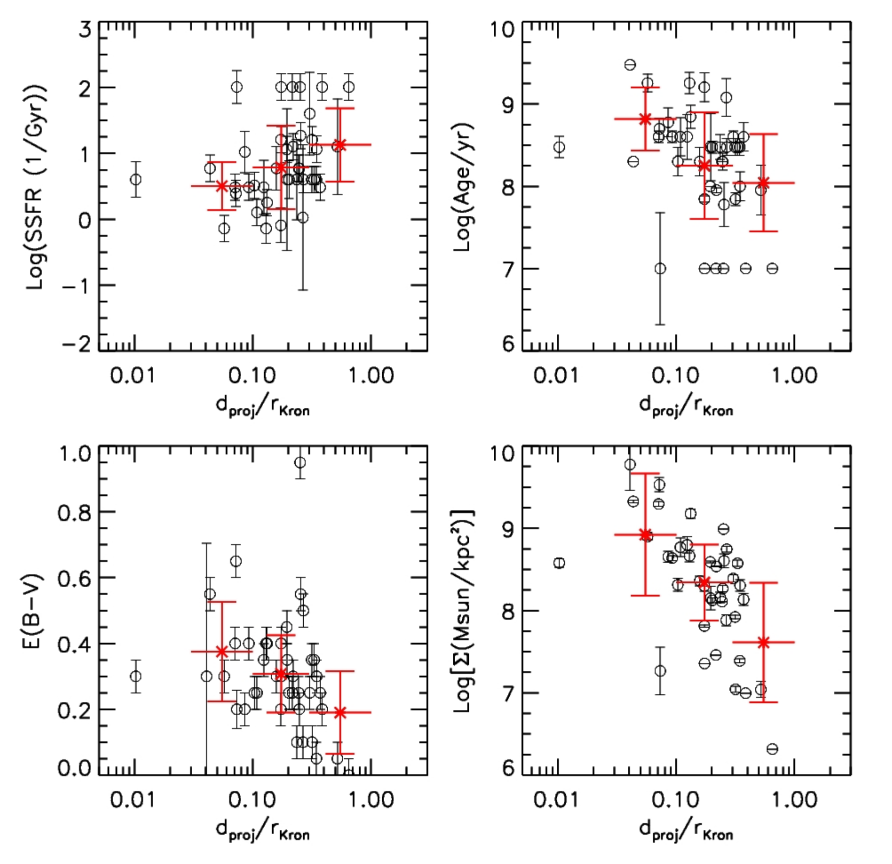




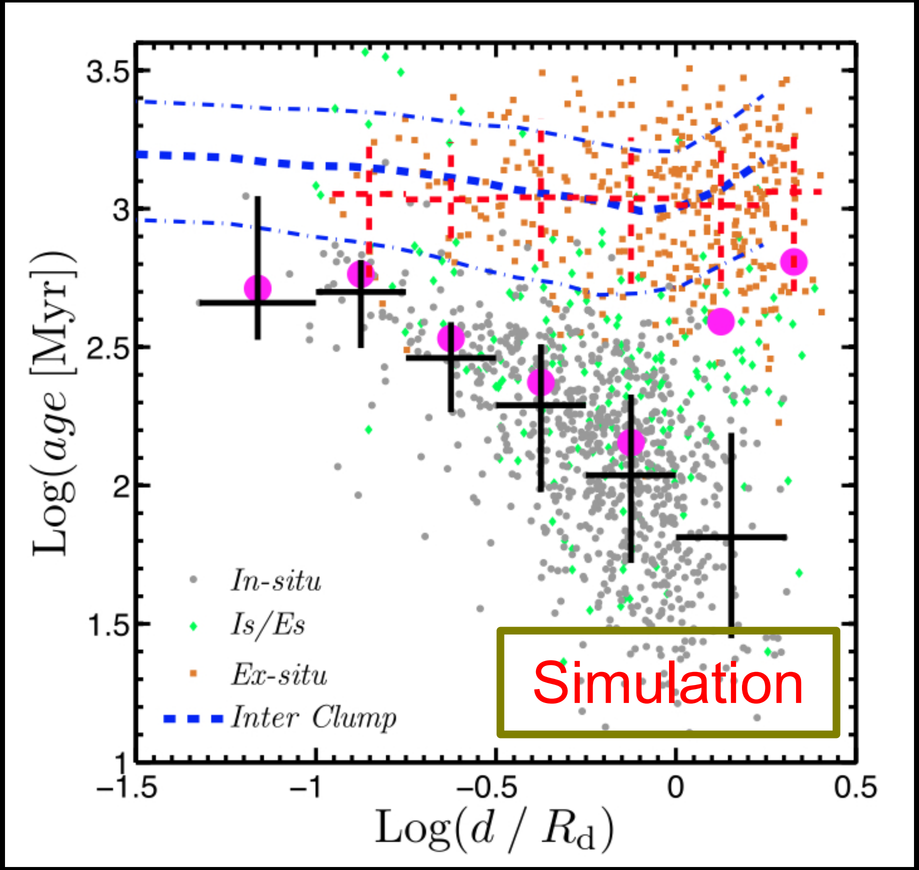
Guo+12

Radial Variations Consistent with the In-ward Migration Scenario

- Central clumps: less star formation, older, more dust, denser
- Outskirt clumps: more star formation, younger, less dust, less dense
- Similar trends seen in numerical simulations (Mandelker+14)



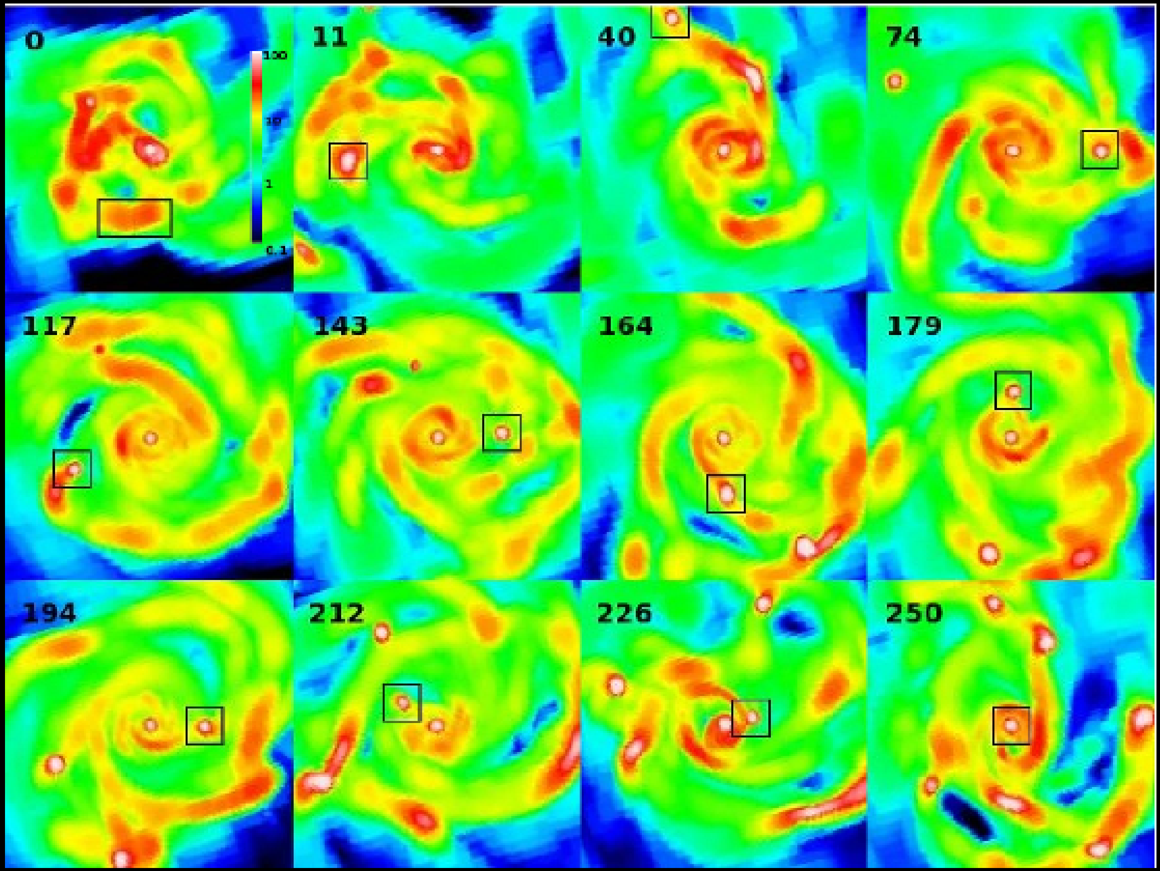
Guo+12



Mandelker+14

Radial Variations Consistent with the In-ward Migration Scenario

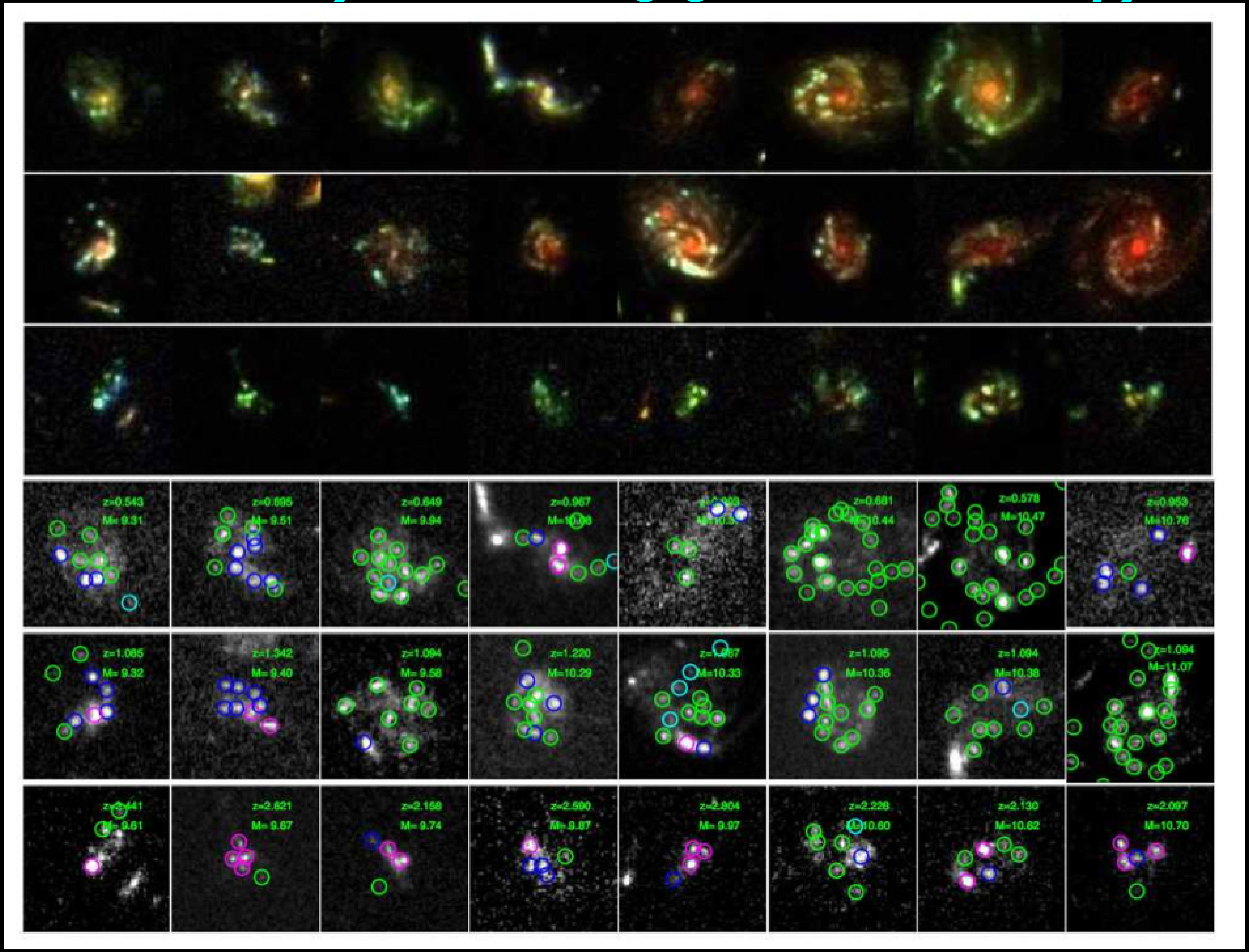
- Clumps sink to the center of galaxies to form the progenitor of bulges
- During the migration, clumps become redder, older, denser, and less star-forming
- Migration timescale: ~250 Myr



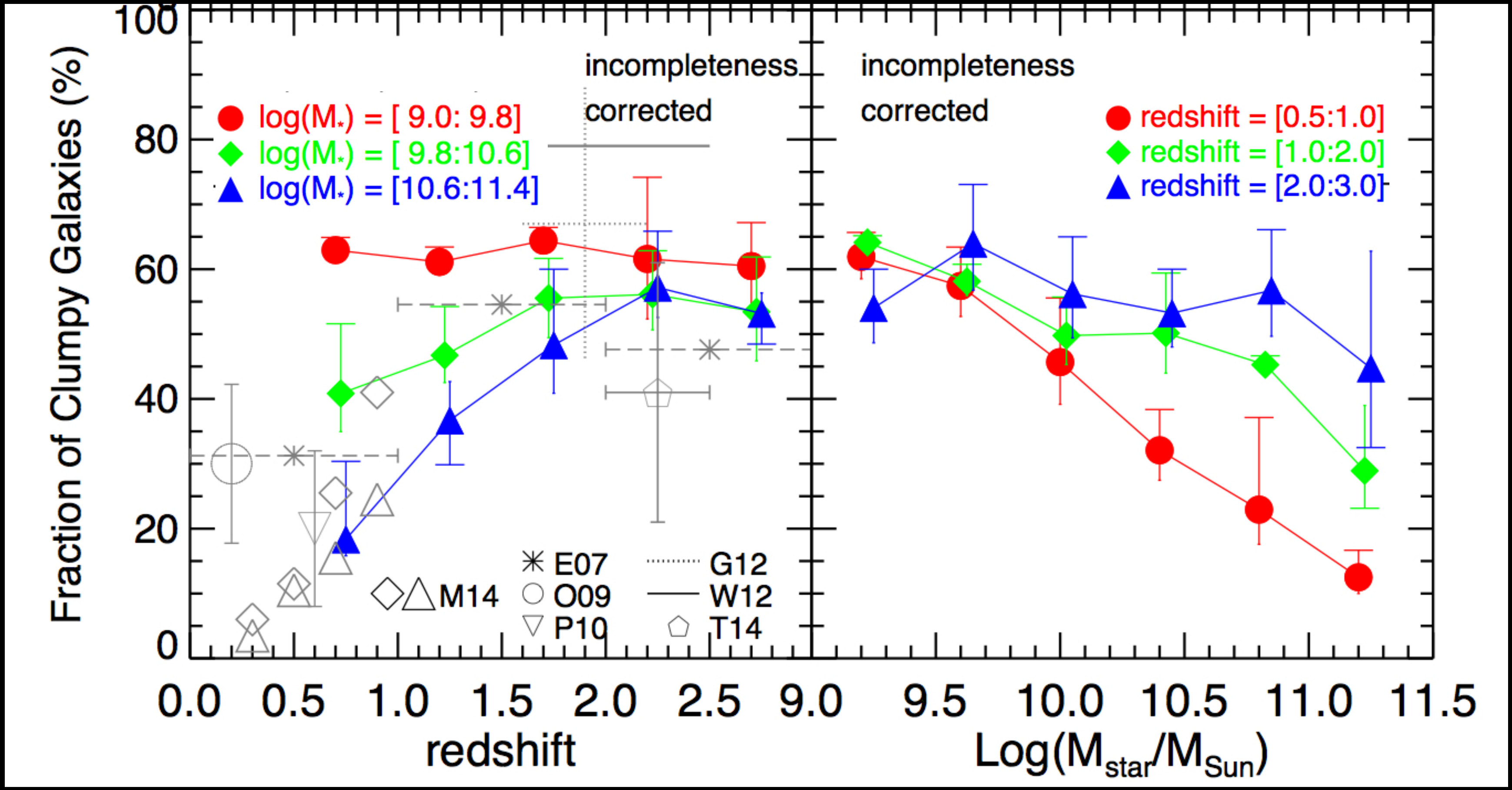
Ceverino+09

Part II: Clumpy Fraction of Star-forming Galaxies from z=3 to z=0.5

How many star-forming galaxies are clumpy?



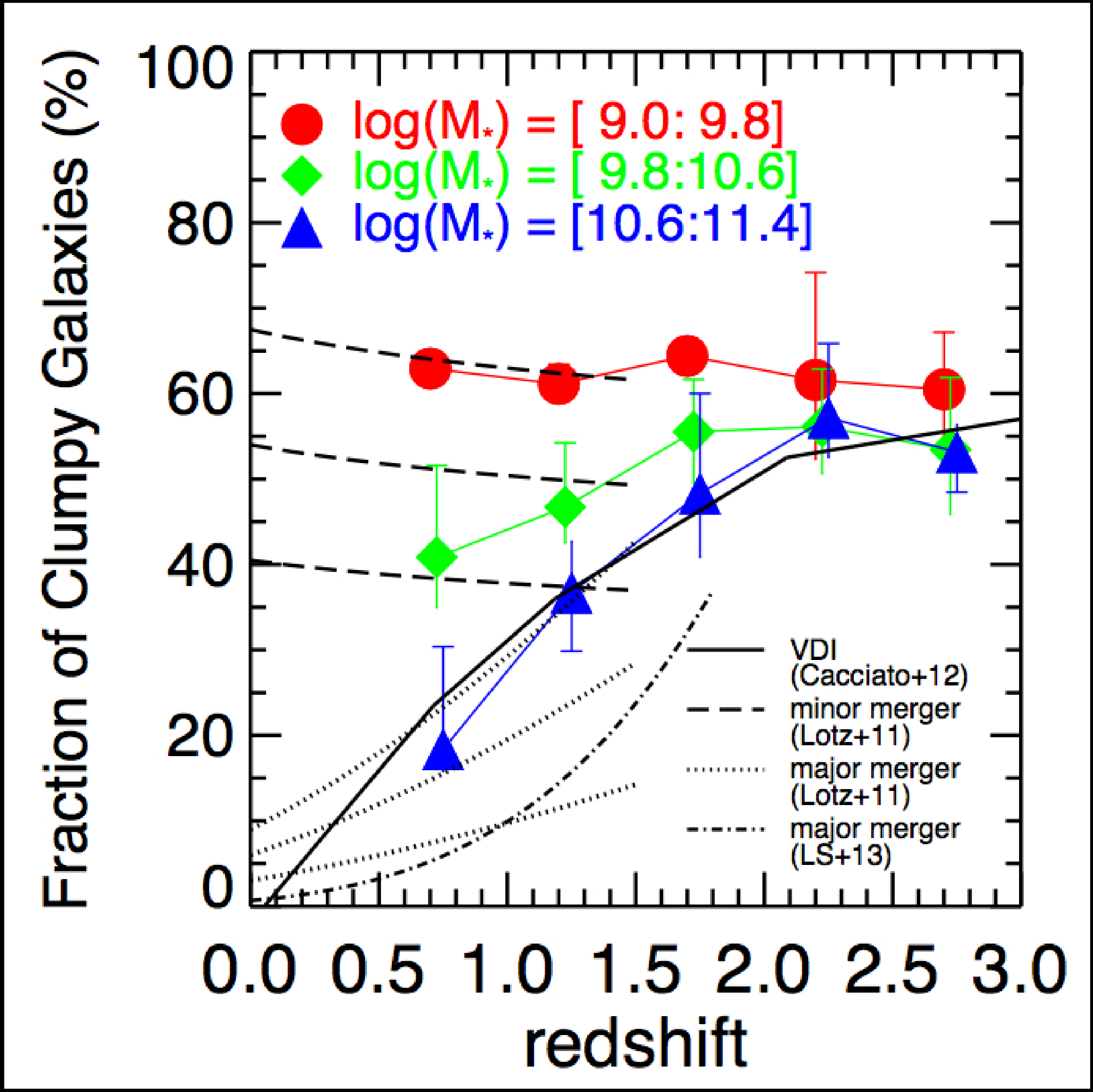
Guo+14



- A representative sample of star-forming galaxies with log(M*)>9 at 0.5<z<3
- Clump: discrete star-forming region contributing >8% of the UV light of their galaxy
- 60% of star-forming galaxies at z~3 are clumpy (containing at least one off-center clump)
- The evolution of the clumpy fraction depends on the mass of the galaxies

Possible Clump Formation Mechanisms

- VDI: the trend of its predicted v/sigma consistent with the clumpy fraction of massive galaxies
- Minor merger: merger fraction consistent with the clumpy fraction of intermediate-mass galaxies at z<1.5, given reasonable observability time-scale
- Major merger: unlikely be responsible for clump formation at z<1.5



Summary: tracing clumpy galaxies from z=3 to z=0.5

- Sub-structures of galaxies are crucial to galaxy formation and evolution

- Giant clumps: an important feature of high-redshift star-forming galaxies

- Physical properties of clumps and their variations at z~2
  (1) Clumps are blue regions with enhanced sSFR
  (2) Central clumps are redder, and outskirts clumps are bluer
  (3) Clump's radial variation is consistent with the in-ward migration scenario

- Clumpy fraction of star-forming galaxies from z=3 to z=0.5
  (1) About 60% of star-forming galaxies at z~3 are clumpy
  (2) The evolution of the clumpy fraction depends on the mass of the galaxies
  (3) Clump formation: VDI for massive galaxies, minor merger for intermediate-mass galaxies