Star Formation in Clumpy Disks at High Redshift



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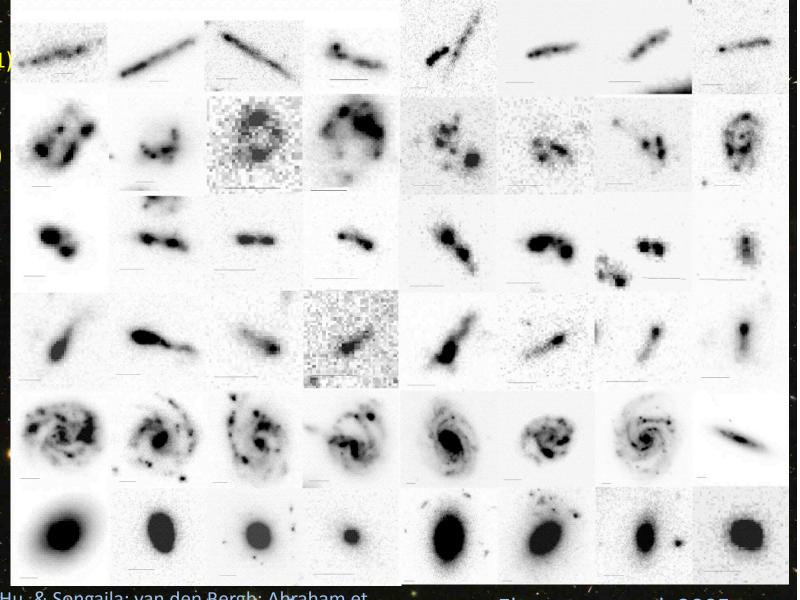
with Bruce Elmegreen (IBM)

and students

J. Lemonias, X. Fernandez, M. Marcus, K. Shahinyan, A. Yau, M. Petersen

UDF ZOO: 1003 galaxies > 10 px in UDF to z~5

- Chain (121
- Clump
 Cluster (192)
- Double (134)
 - Tadpole (114)
- Spiral (313)
- Elliptical (129)

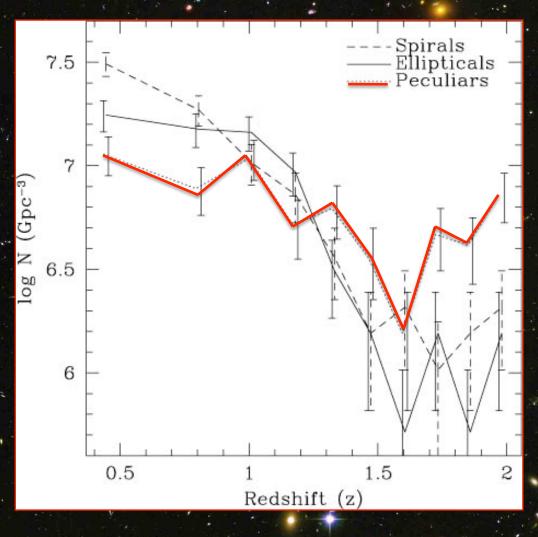


(see also Cowie, Hu, & Songaila; van den Bergh; Abraham et al.; Williams et al.; Conselice; Lotz)

Elmegreen et al. 2005

Clumps are relatively blue (star-forming) Chain Clump Cluster Double Tadpole Spiral Elliptical (from Steve Beckwith, private comm.)

Peculiar galaxies dominate beyond z=1.5

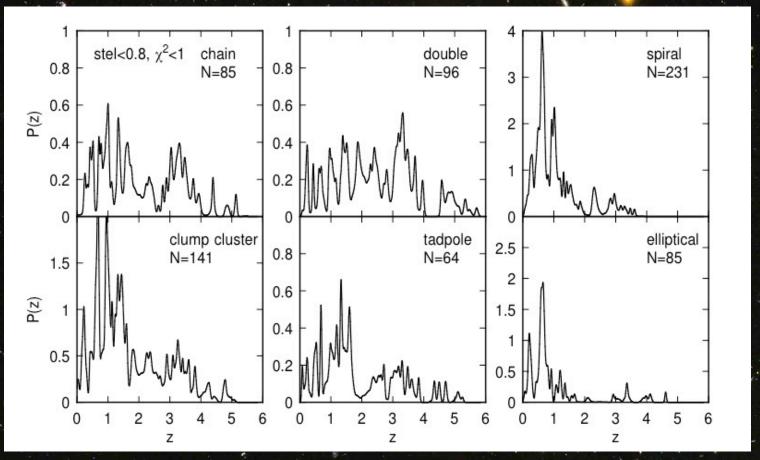


Hubble Deep Field

Conselice 2004

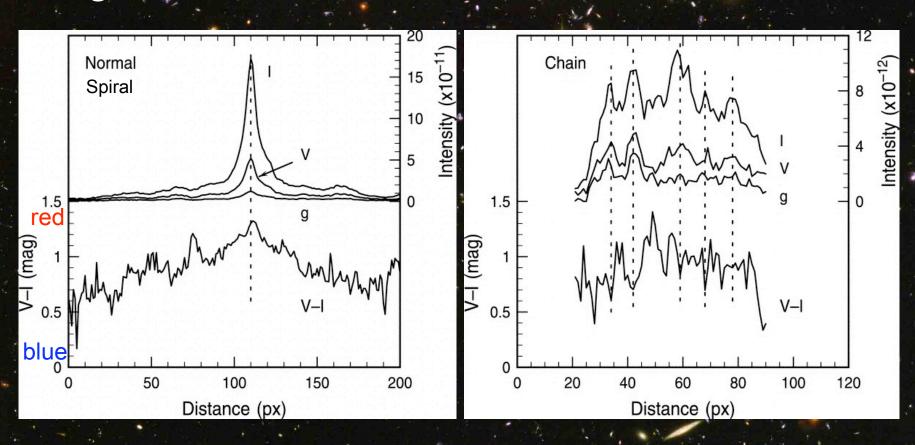
Distant UDF galaxies are mostly clumpy types

 selection against red galaxies at high z (incl. spirals and ellipticals)



Elmegreen, Elmegreen, Ravindranath, Coe 2007

Chain galaxies are not edge-on spirals – only spirals have exponential radial profiles and color gradients; chain clumps have higher contrast

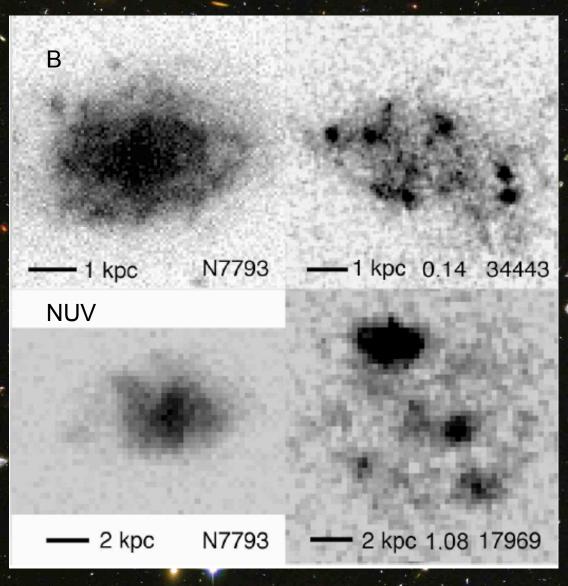


Elmegreen, Elmegreen & Sheets 2004

Comparison of two Clump Clusters with a local flocculent galaxy

Left, right have same rest wavelengths and same physical resolution

Clump Clusters
have higher clump
contrast, more
massive clumps,
and no central
concentration

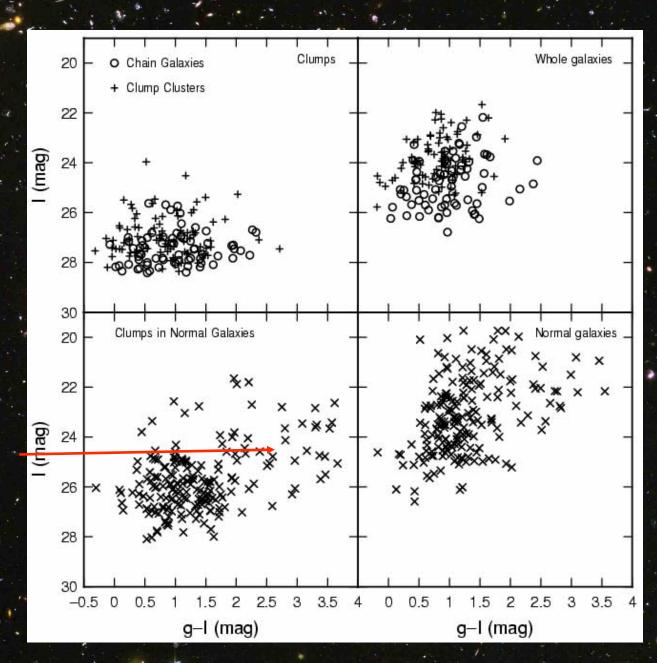


GOODS clump cluster

GOODS clump cluster

Tadpole field:

Chain and clump cluster CMDs are similar; spirals have red bulges



Elmegreen, Elmegreen & Hirst 2004

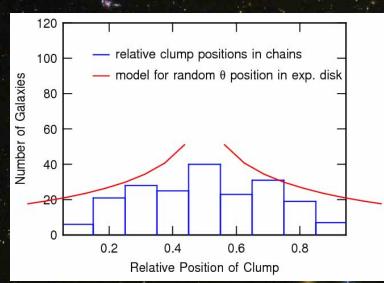
Chain galaxies are edge-on clump clusters:

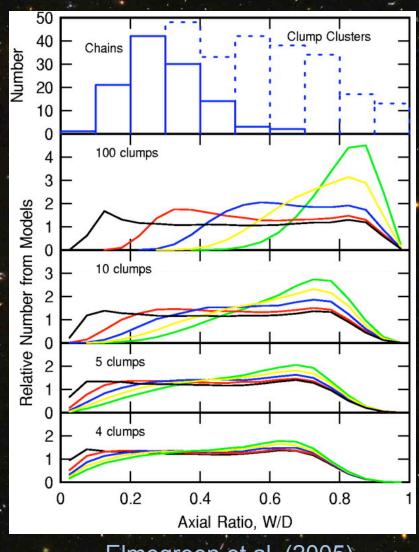
Their combined axial ratio distribution is flat

Circular disks

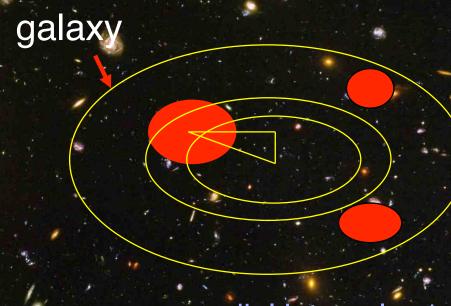
Models show W/D distribution for randomly oriented pure-clump "galaxies"

flattening Z/D=0.1 (black), 0.3 (red) 0.5 (blue), 0.7 (yellow), 1 (green).





Elmegreen et al. (2005)



e.g., no. per radial interval = 1 for relative radius = 0.4,

0.8 and 0.9 here

Clump disk locations: measure every clump position & brightness

Determine deprojected radius (assuming galaxy is a circle) divided by galaxy overall radius

Plot total number per unit area in each radial interval versus the relative radius

Result: cumulative clump number and clump flux vs. radius are exponential in spirals as well

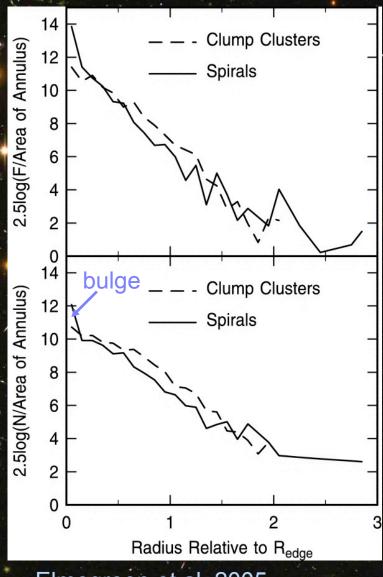
as in clump clusters

clumps disperse to make the disk

Clump flux density vs. radius

Clump number density vs. radius

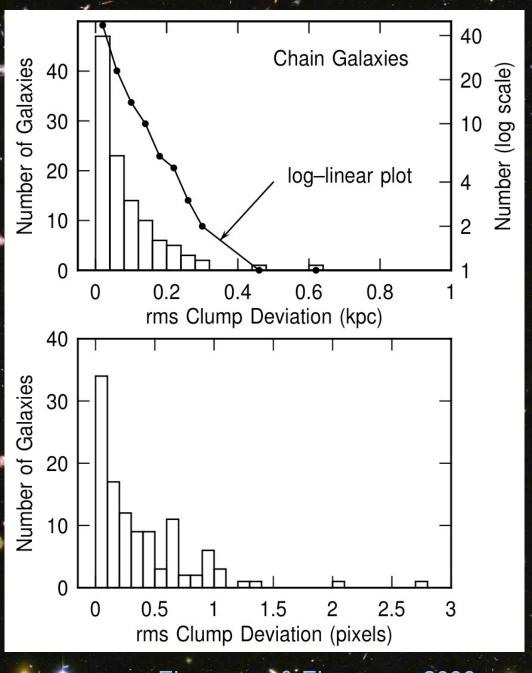
(For all galaxies, averaged together)



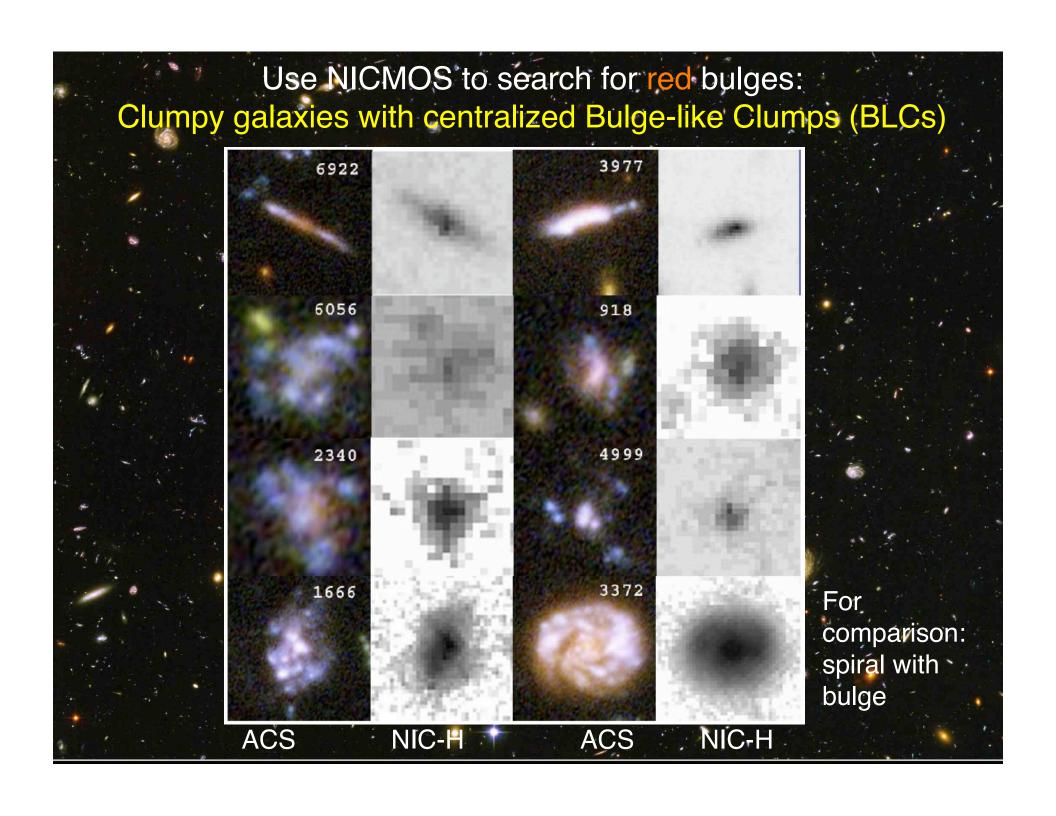
Elmegreen et al. 2005

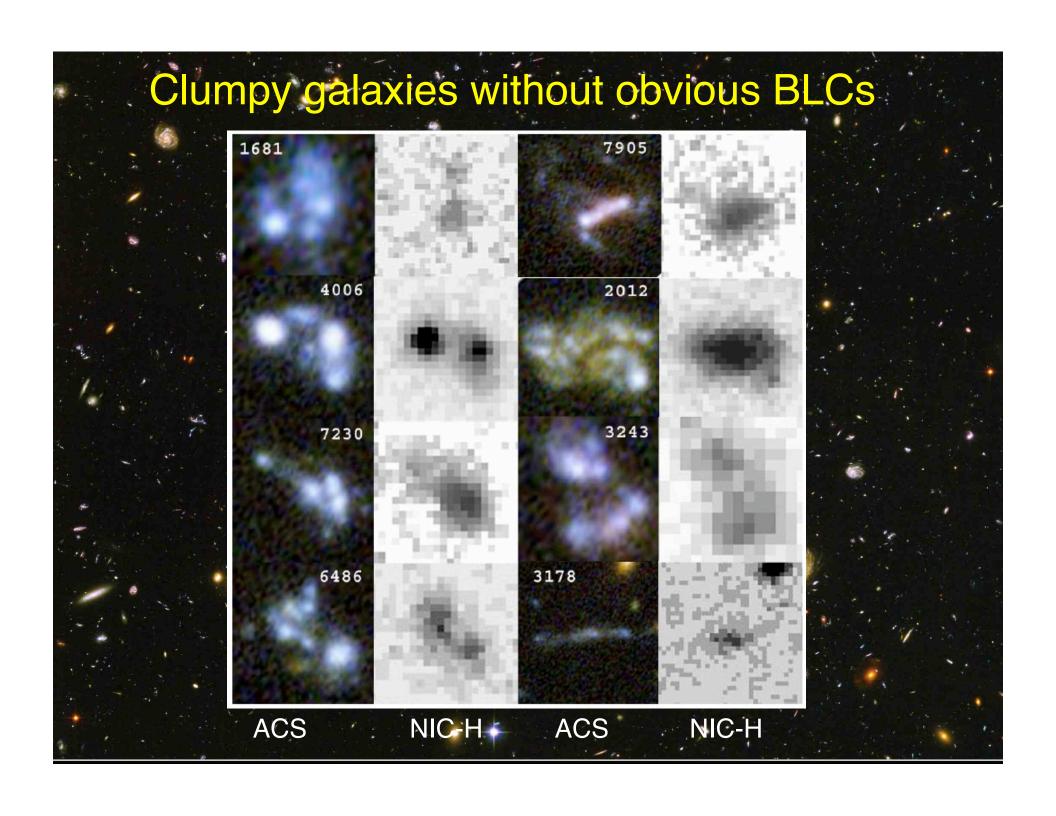
Deviations of chain clump centers from midplane are small

suggests in situ
 formation of
 clumps rather
 than accretion



Elmegreen & Elmegreen 2006





Photometry of large clumps

- Fit SEDs to bandshifted Bruzual & Charlot '03 models with variable age, SF exponential decay time, and extinction
 - Include Madau '95 intergalactic H absorption,

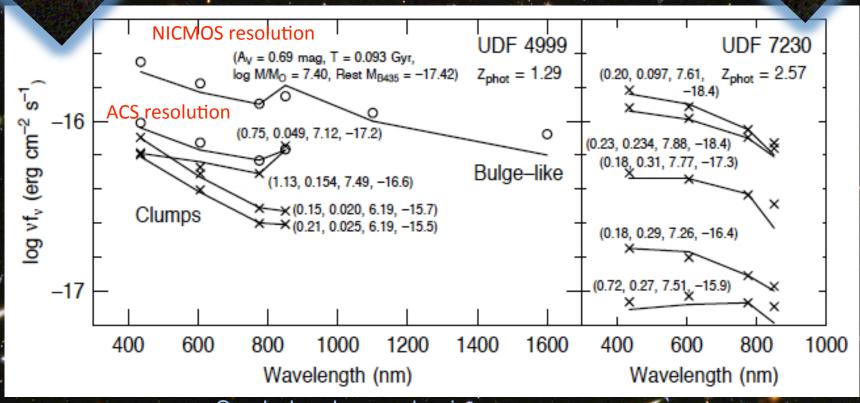
Calzetti / Leitherer extinction

- Assume metallicity is 0.4 solar
- Determine clump masses from ages and magnitudes
 - mass and age dependency on metallicity is small.
 - (0.02 solar → 1.5x age, 1.1x mass)

SEDs of galaxies with and without bulge-like clumps (UDF)

Clump cluster with bulge-like clump

Clump cluster without BLC



Symbols: observed points

Lines: Population synthesis models

rms deviations between model & ob-

rms deviations between model & observed colors are ~ 0.1 mag

UDF: Clump masses from model fits

Bulges:

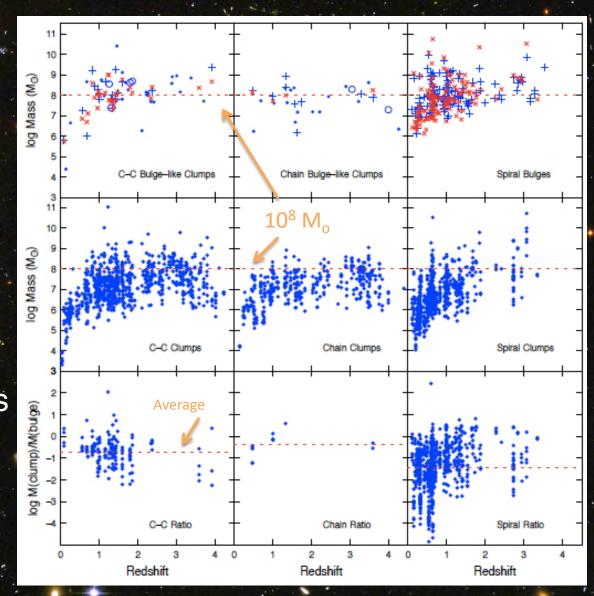
 $10^8 - 10^9 \, \mathrm{M}_{\mathrm{O}}$ (up to $10^{10} \, \mathrm{M}_{\mathrm{O}}$ in spirals)

SF clumps:

•/ 10⁷-10⁸ M_O

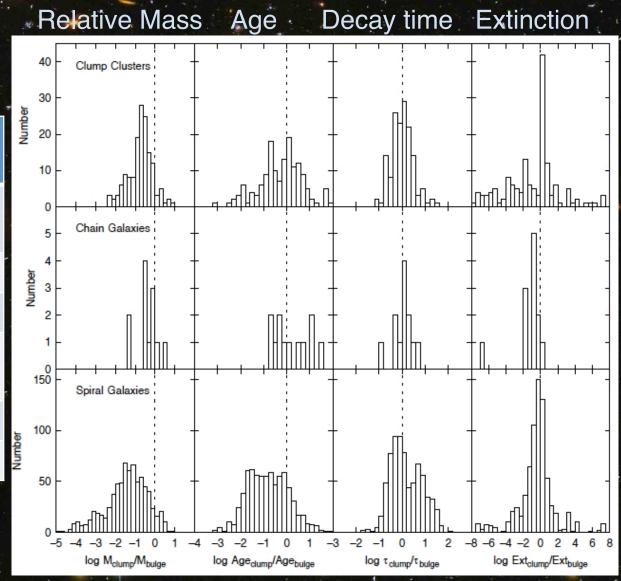
Ratio: clump/bulge

- ~ 1/26 for spirals
 - ~ 1/3 for cc's & chains
- → BLCs are more similar to star-forming clumps in clumpy galaxies than bulges are to SF clumps in spirals



Comparison of bulge and clump parameters

| | Log Mass | Log Age |
|--------------------|-------------|------------|
| Clumpy galaxies | | |
| SF clumps | 7.5±1 | 8±1 |
| BLCs | 8±0.5 | 8±1 |
| Spiral galaxies | | |
| SF clumps | 7.5±1 | 8±1 |
| bulges | 9±1 | 9±1 |



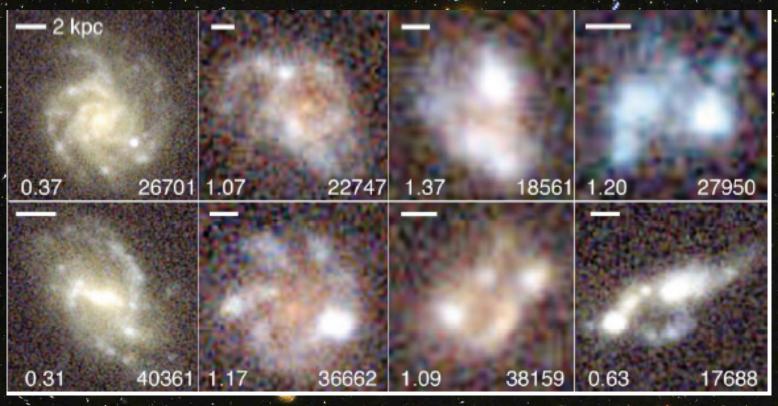
Summary from UDF

- 30-50% of clumpy galaxies in UDF have bulgelike clumps
- Bulges in spirals are older and more massive than star-forming clumps in spirals
- Bulge-like clumps in chains and clump clusters have similar masses and ages as star-forming clumps
- Chains and clump clusters with BLCs are in transition as they evolve into spirals



- several hundred galaxies in sample

Disk galaxies have a range of morphologies



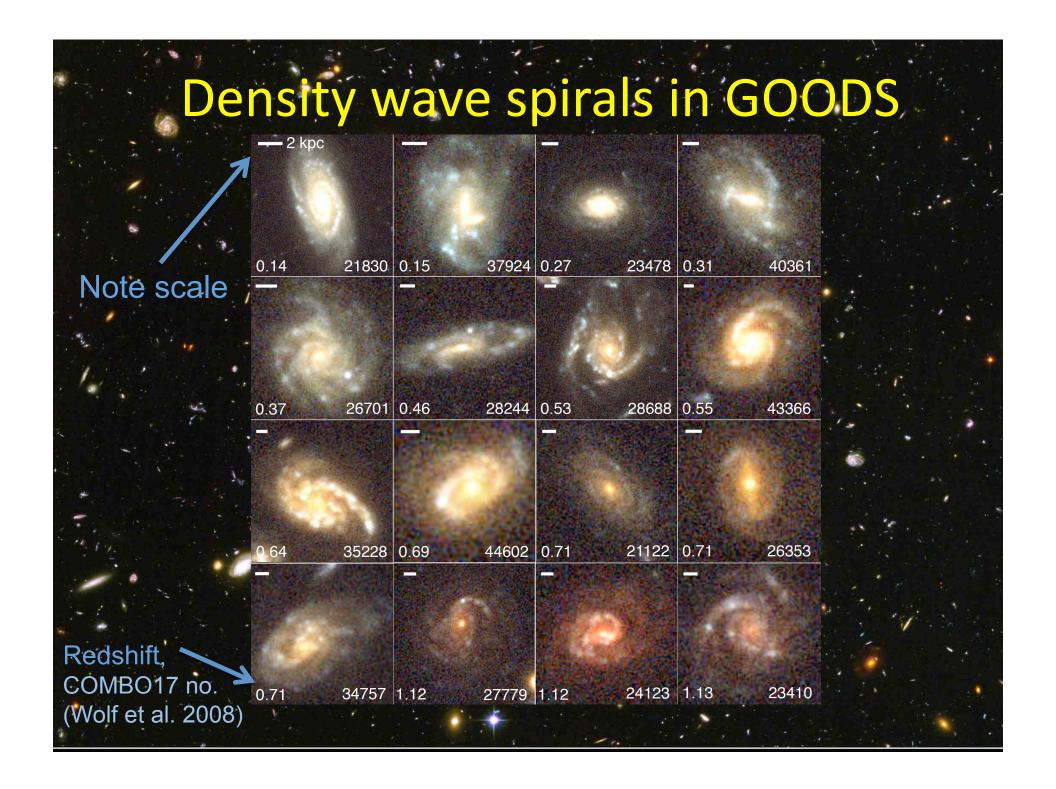
spiral

flocculent spiral

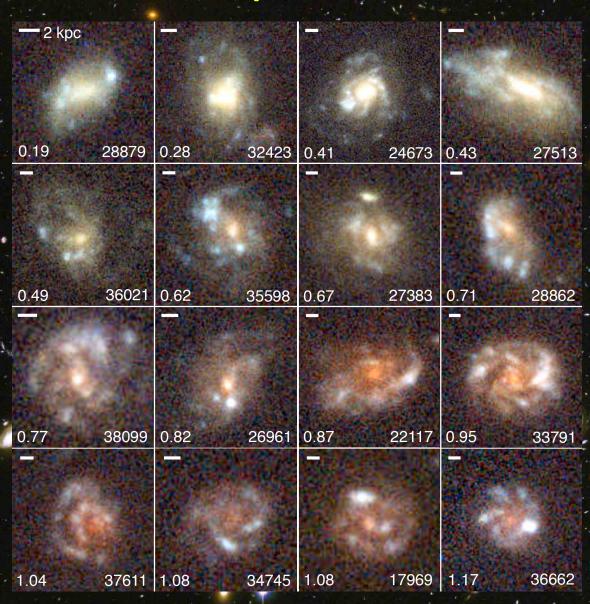
clump cluster red underlying disk

clump cluster no red disk

Elmegreen, Elmegreen, Marcus, Shahinyan, Yau, Petersen 2009



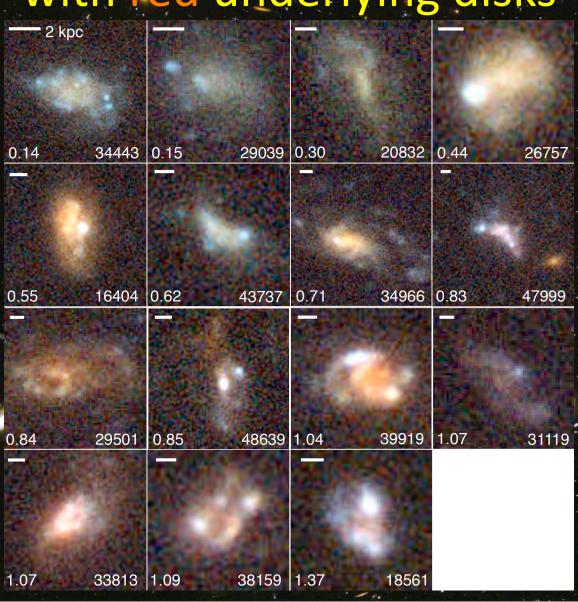
Flocculent spirals in GOODS



Redshift,

COMBO17 no.

Clumpy galaxies with red underlying disks



Clump Clusters with no red underlying disks 26313 0.13 23000/22986 0.10 28751 0.11 43681 0.13 44365 0.18 39638 0.20 31809 0.20 34721 33576 0.35 48259 0.63 17688 0.87 29727 30509 1.09 21768 1.20 1.02 44885 1.05 27950

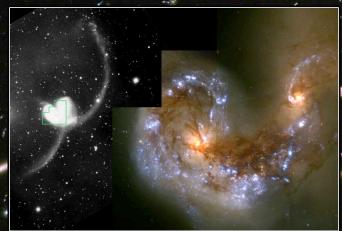
Implications for clump clusters

- Clumpy appearance is not due to bandshifting since they occur at same redshifts as spirals
 - Clump clusters are intrinsically clumpy, even in restframe B and V

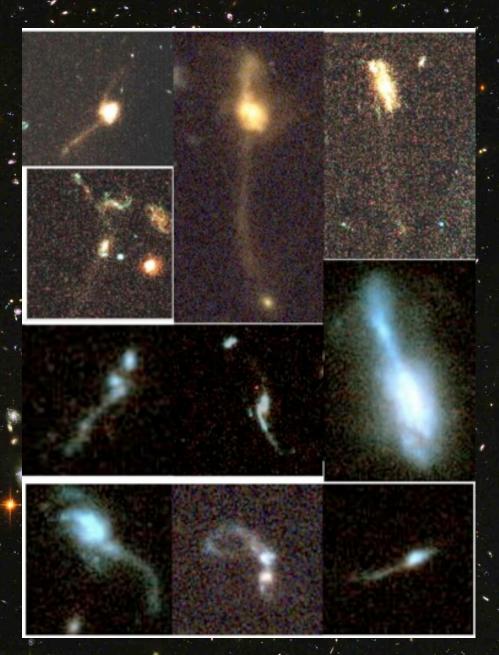
Also,

• Clumpy appearance in general is not due to interactions since tidal features can be seen in obvious interactions at same z:

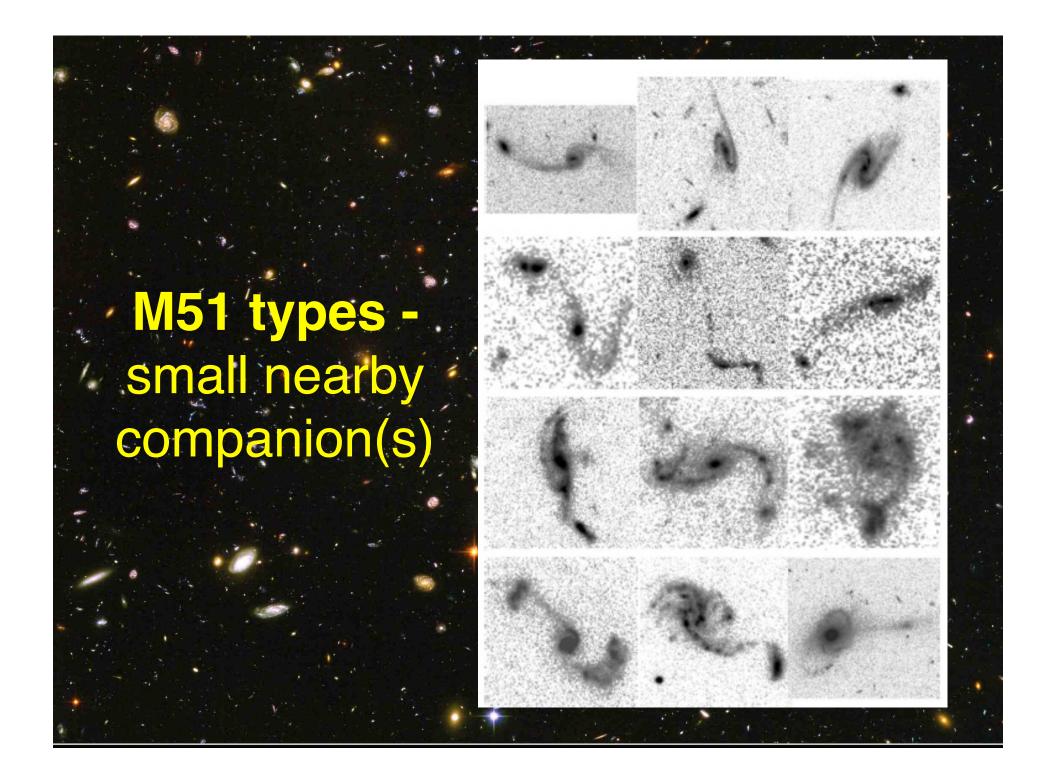
Interactions: Antennae in the GEMS and GOODS fields



Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2
PRC97-34a • ST Scl OPO • October 21, 1997 • B. Whitmore (ST Scl) and NASA



Elmegreen, Elmegreen, Ferguson, Mullan 2007



GEMS & GOODS: Clump mass

Left:

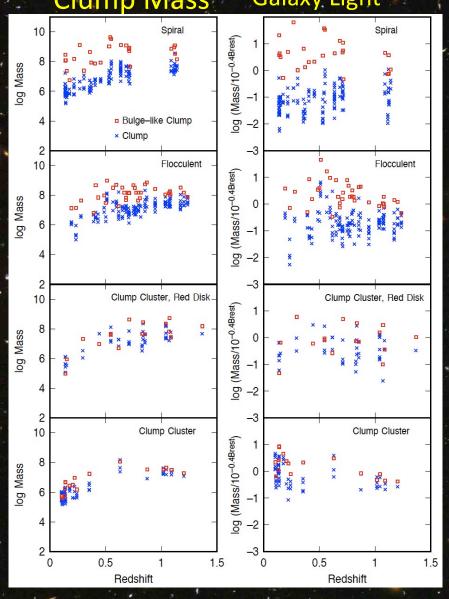
Bulges 16x mass of clumps in spirals;
2x mass of clumps in clump clusters

Right: *

Clump mass per unit galaxy light ~ independent of redshift; ~ 100x local galaxies

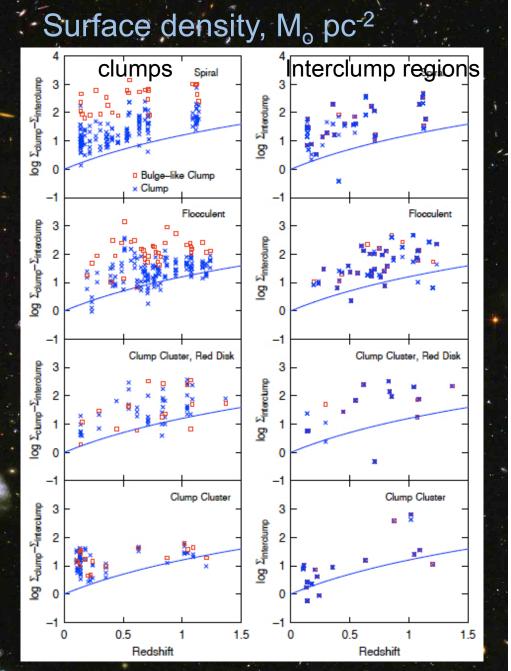
Red=bulges or BLCs
Blue=non-bulge clumps





Surface density

- Bulge surface density compared to clump surface density is 8x in spirals, but only 1x in clump clusters
- Interclump surface density
 2x higher in spirals than clump clusters
- Evolution of bulges and interclump medium towards higher surface densities as clump clusters convert into spirals



Red=bulges or BLCs Blue=non-bulge clumps

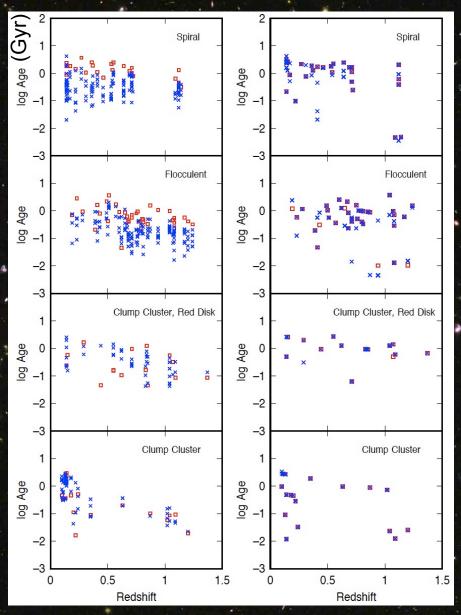
Age

(left) Bulges 10x older than clumps in spirals. BLCs ~same ages as clumps in clump clusters.

(right) Interclumps are 3x older than clumps in spirals and CC's with red underlying disks, but same age as clumps in CC's without red underlying disks

→ Evolution from clumps to older interclumps and bulges



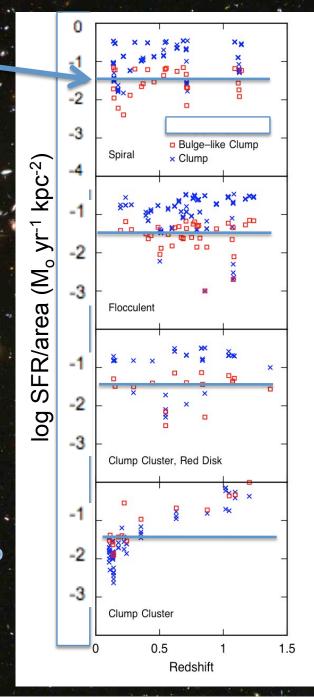


Milky Way star complex

SFR per unit area in clumps ~ 10x that in star-forming complexes in local galaxies

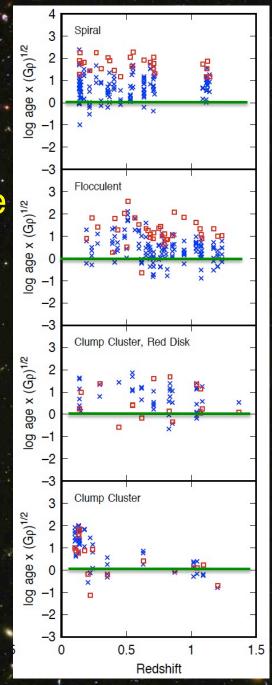
(clumps $\sim 0.1-1 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$)

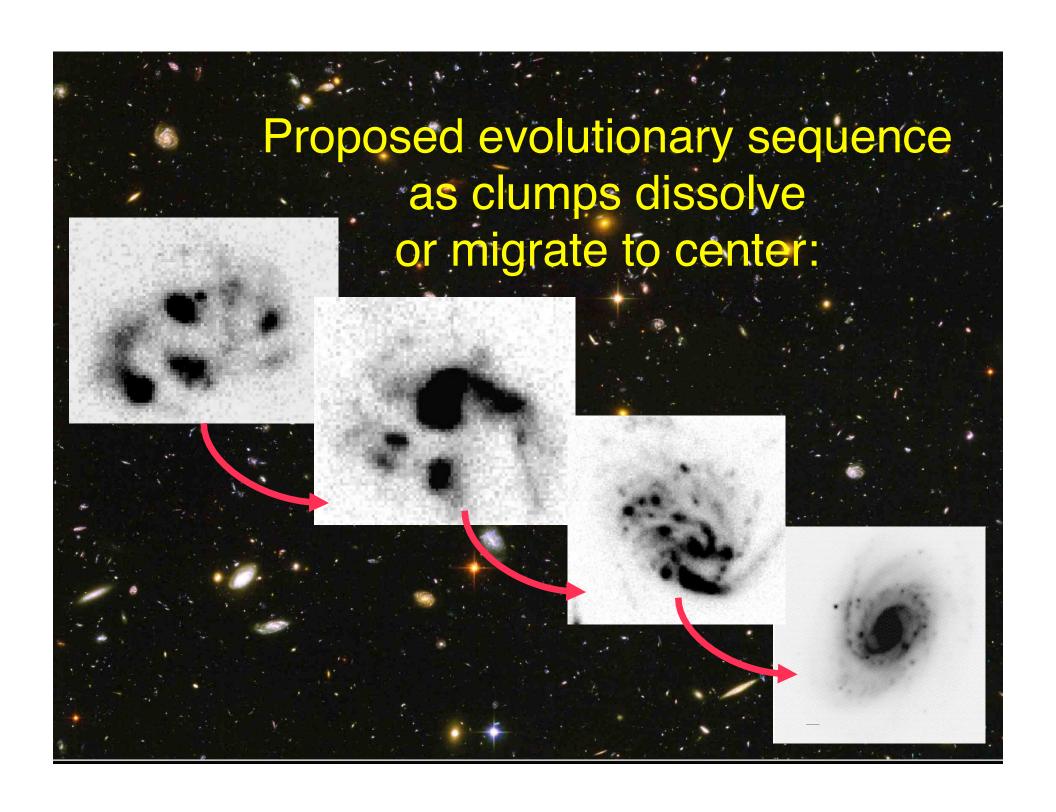
Use local complex of $5x10^5$ M_o (e.g. 5% efficiency in 10^7 M_o cloud), radius 300 pc, age $5x10^7$ yr = 0.035 M_o yr⁻¹ kpc⁻²



Dynamical rate

- Ratio of clump age to dynamical time
- ~1-10 for clumps,
- ~1-10 for BLCs in clump clusters, and
- ~10-100 for bulges in spirals
- Bulges and some clumps are gravitationally bound.
- Clumps have recent star formation.





Conclusions

- Clumpy galaxy morphology is due to in-disk star formation
- Star-forming clumps are more massive in high redshift galaxies than in local galaxies by 100x
- Bulges resemble clumps in clumpy galaxies but are older and more massive than clumps in spirals
- Interclump density 2x higher in spirals than in clump clusters

clump clusters evolve into spirals as clumps dissolve to form the disk while the bulge grows