Star Formation in High Redshift Galaxies

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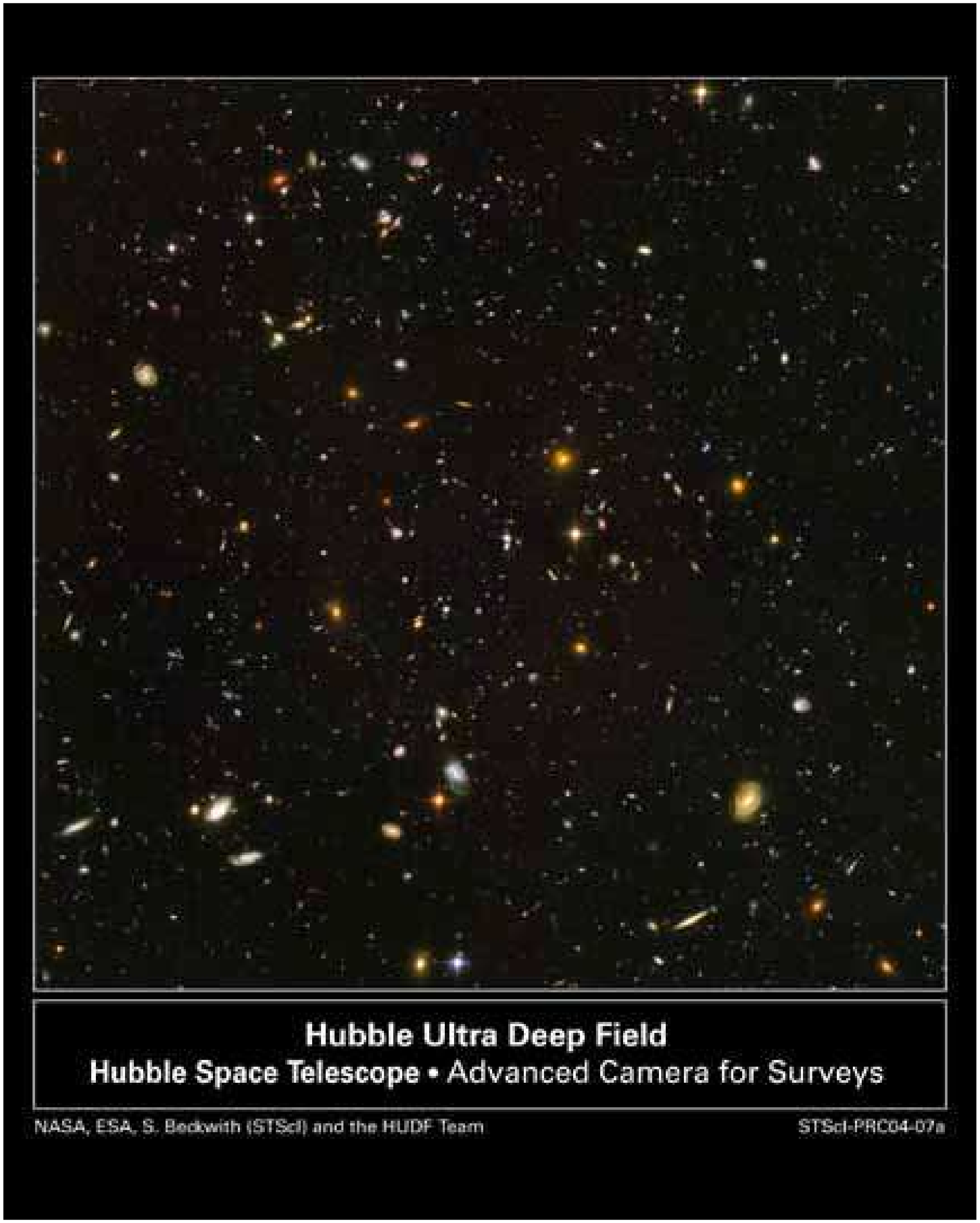
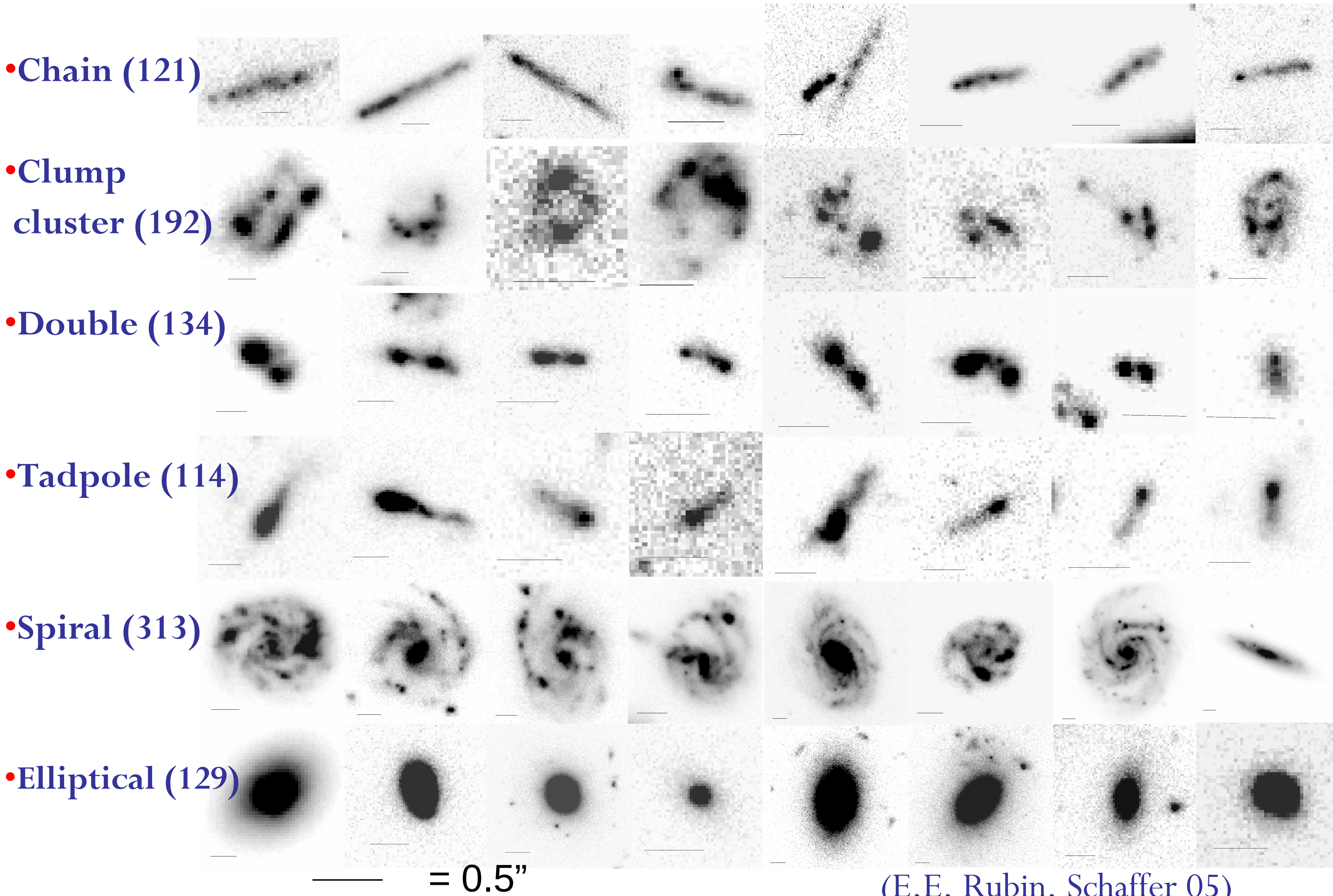
The Ultra DeepField

The UDF is 270 hours of exposures in 4 wavelength intervals (B,V,i,z; 350 orbits)

The deepest high resolution image ever taken by Hubble

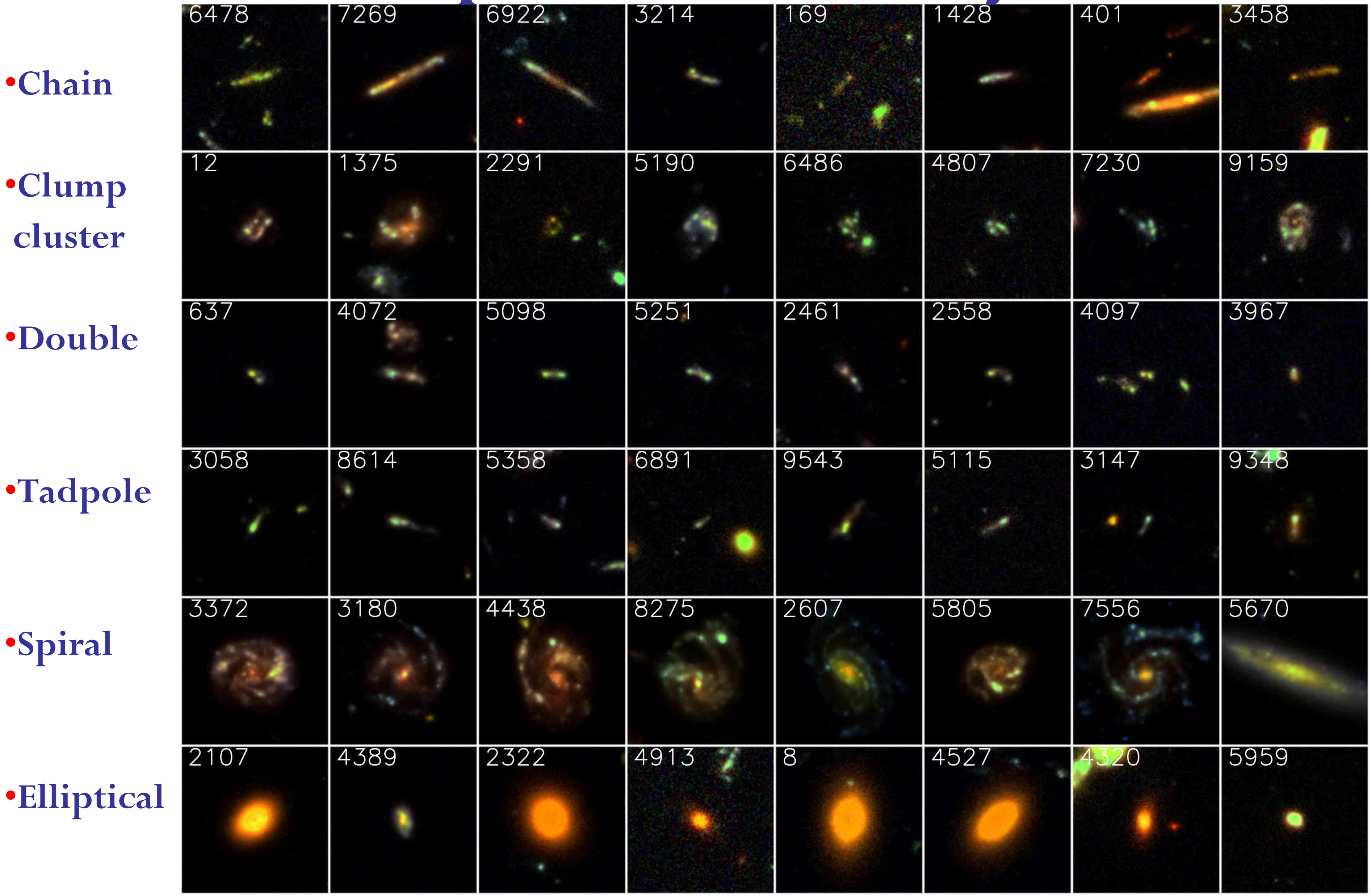


Galaxies look different in the UDF

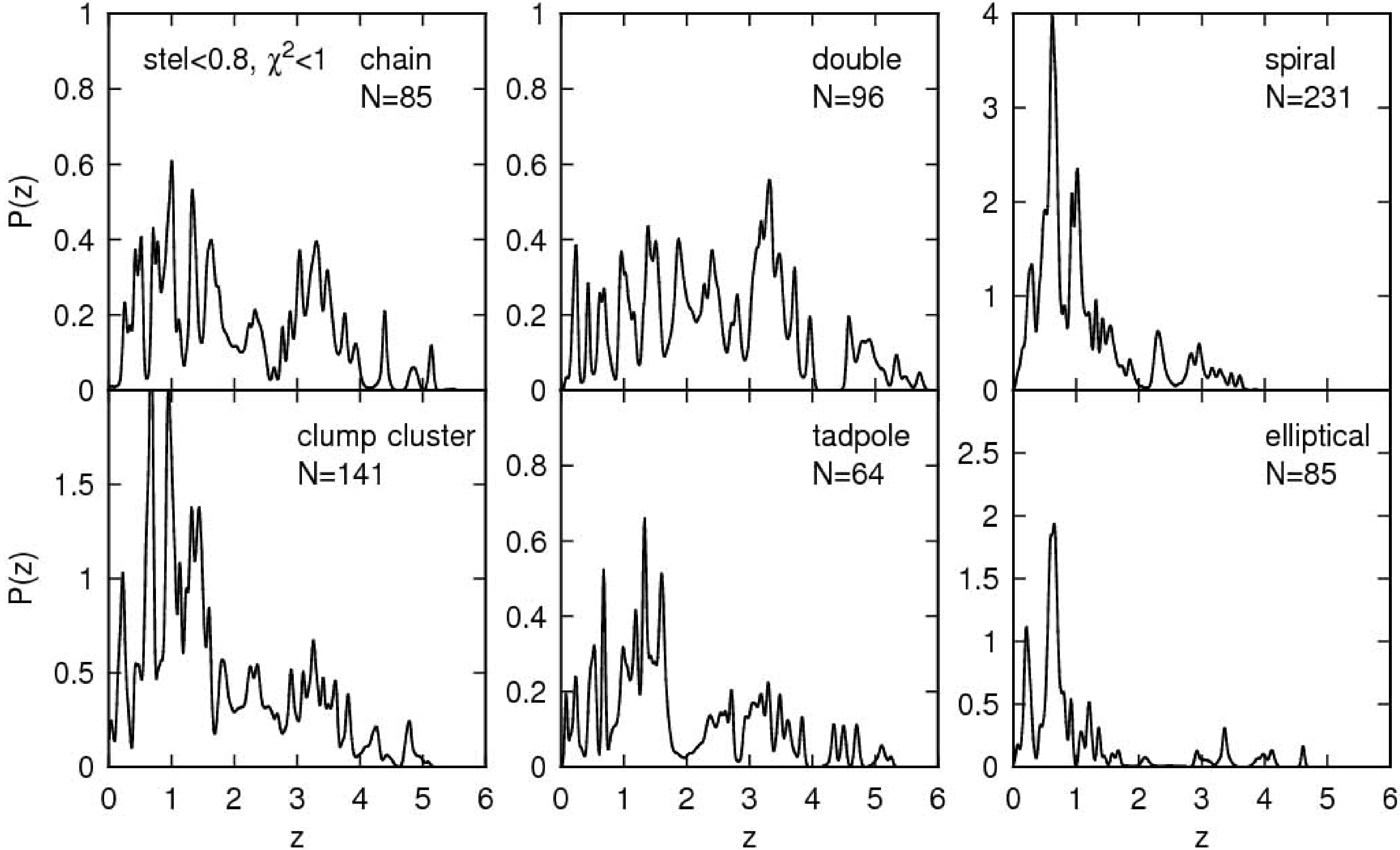


(E,E, Rubin, Schaffer 05)

The clumps are relatively blue

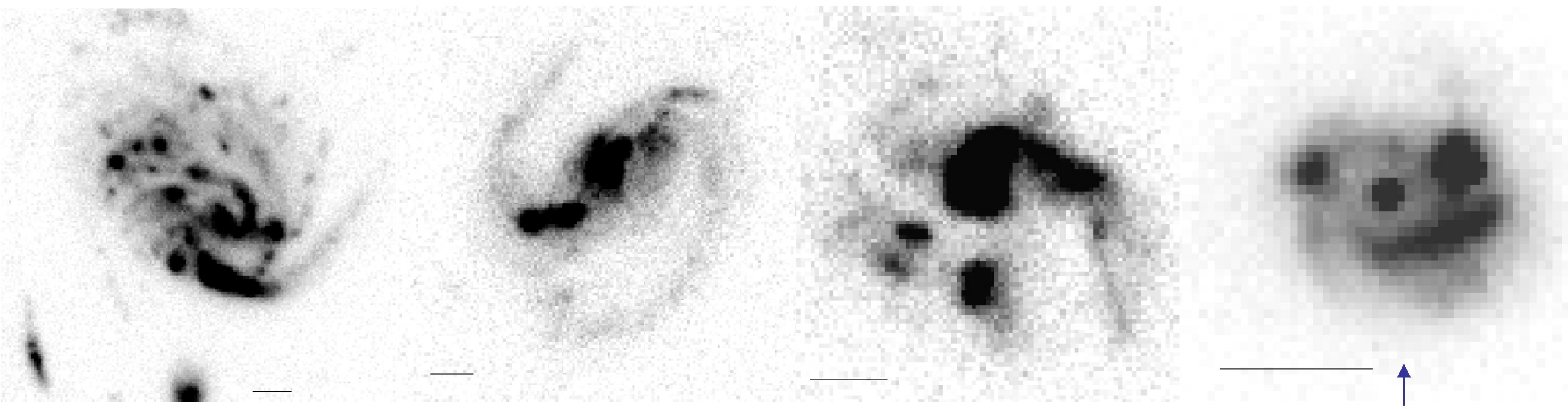


(from Steve Beckwith, private comm.)



Photometric redshifts from Coe et al.
Uncertainty: $\Delta z \sim 0.04(1+z)$,
include only cmod2<1 and stel<0.8

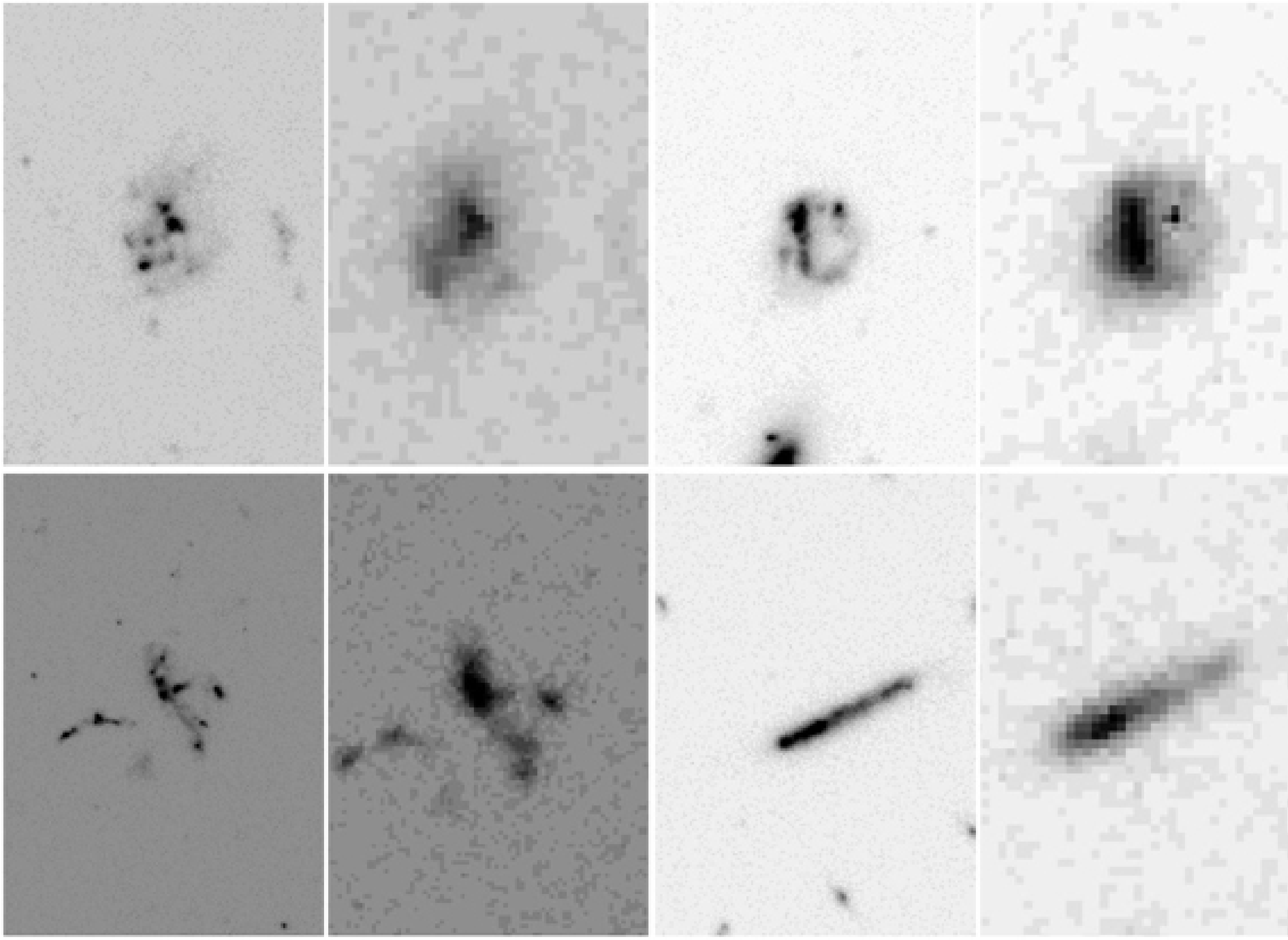
Spiral galaxies are more clumpy and asymmetric than local spirals



Kermit
(with cigar)

—— =0.5"

(E,E, Rubin, Schaffer 05)



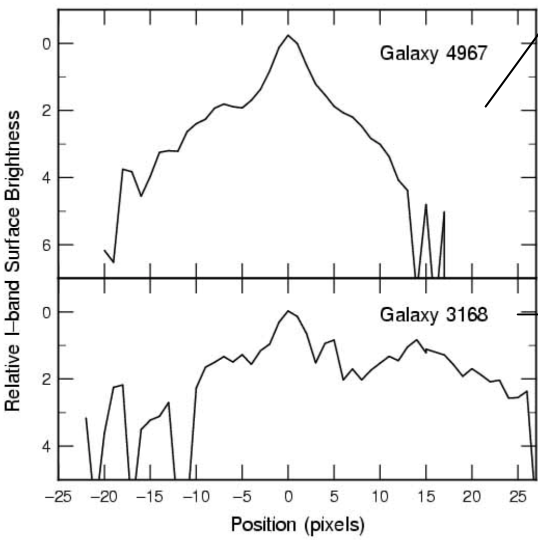
(Elmegreen, Elmegreen, Ravindranath, Coe 2007a)

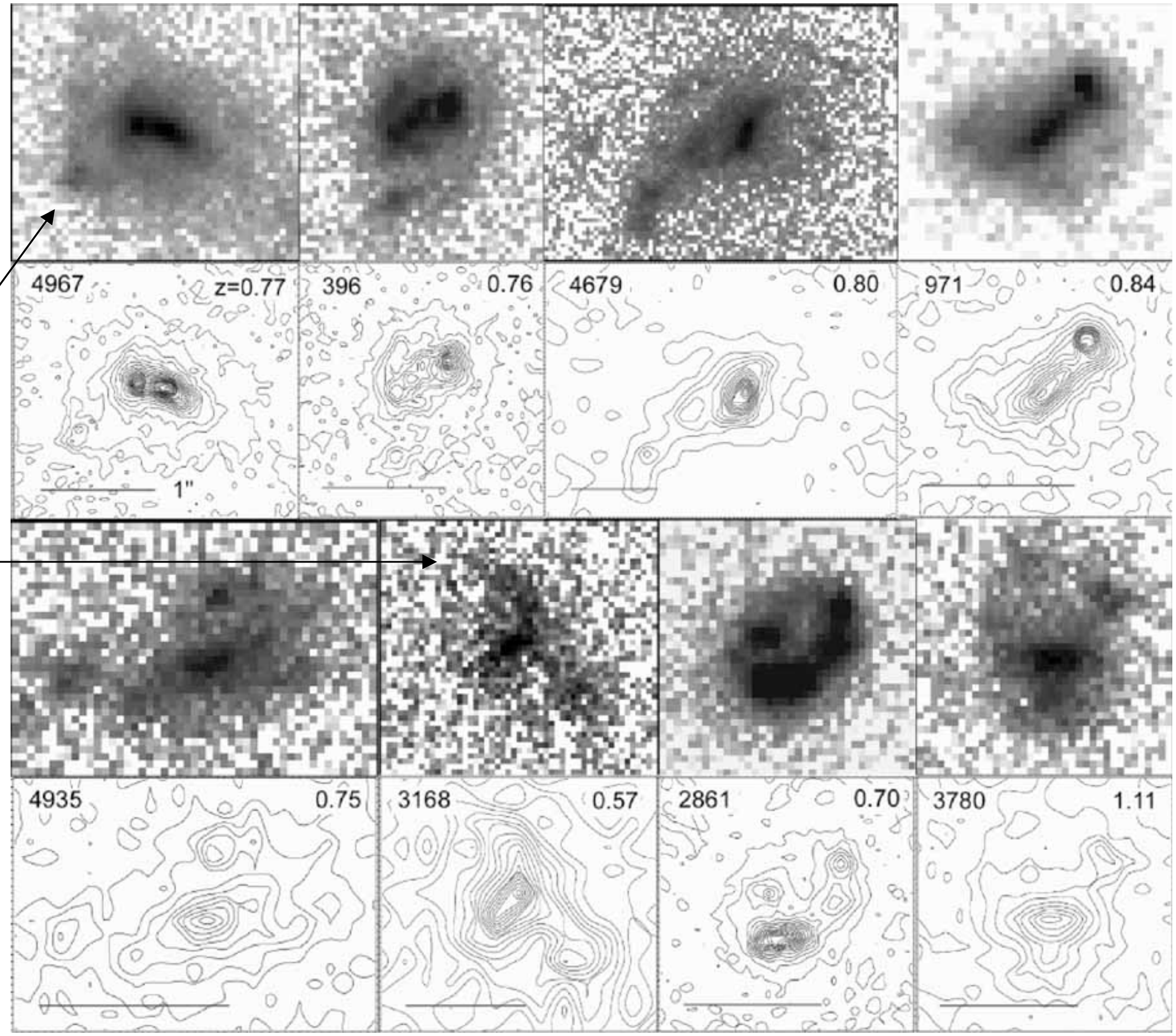
i_{775} and NICMOS J band images of clump clusters and a chain.

The clumps are not just uv patches in a uniform disk.

Clumpy bars in exponential disks

Do bars form in gas?

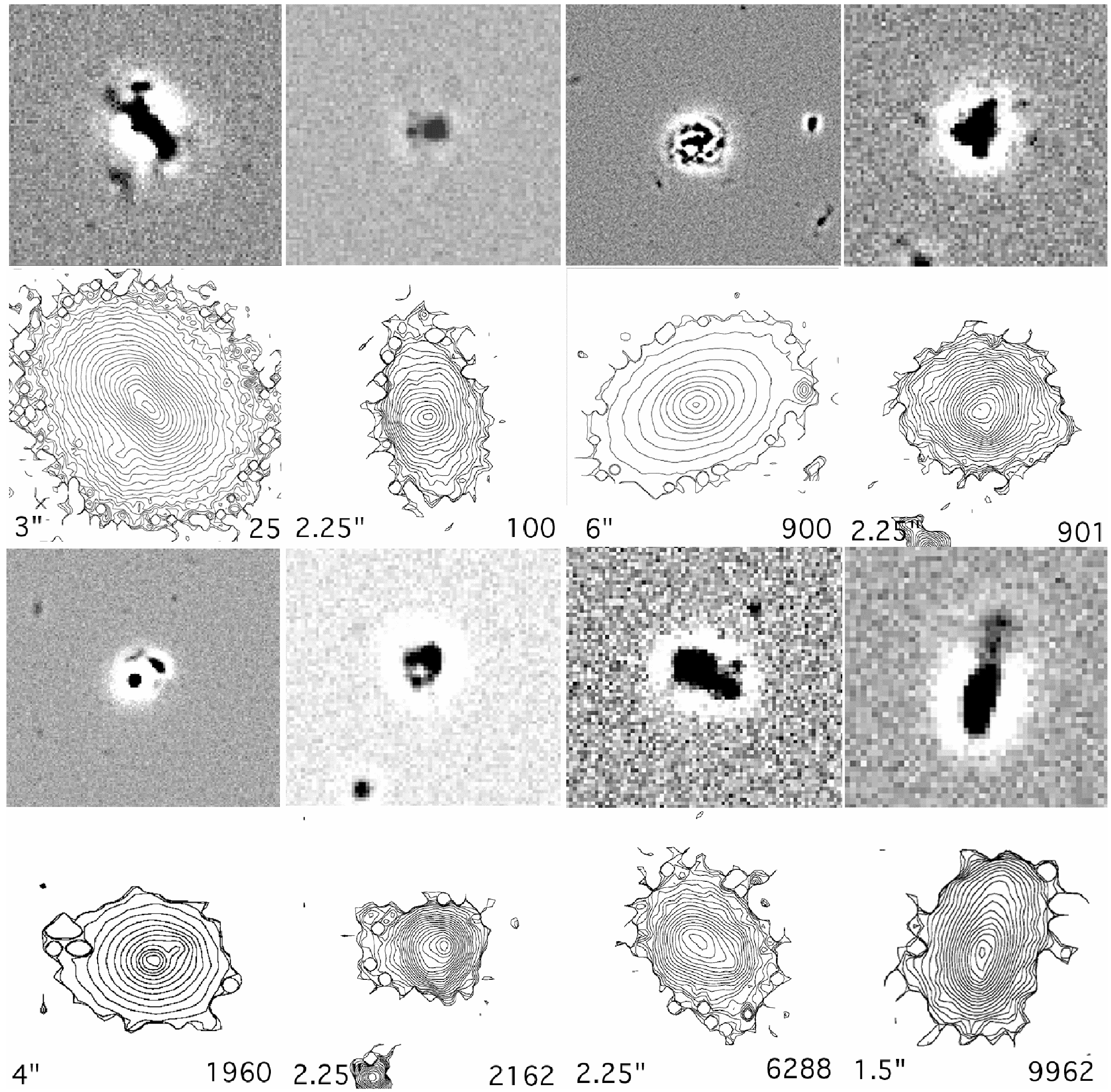




Bars in clump-clusters

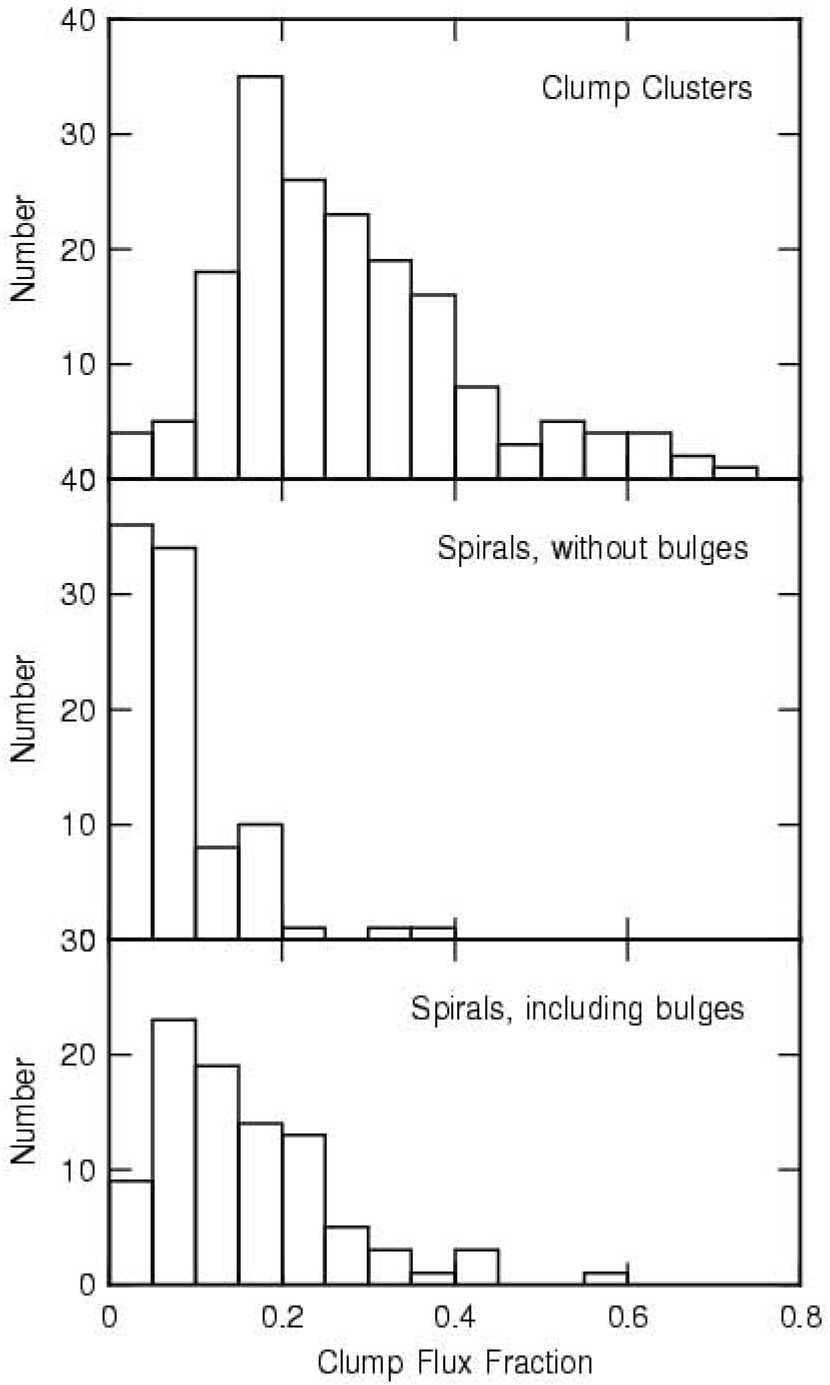
(Elmegreen, Elmegreen & Hirst 2004)

30% of UDF ellipticals also have central blue clumps



(Elmegreen et al. 2005)

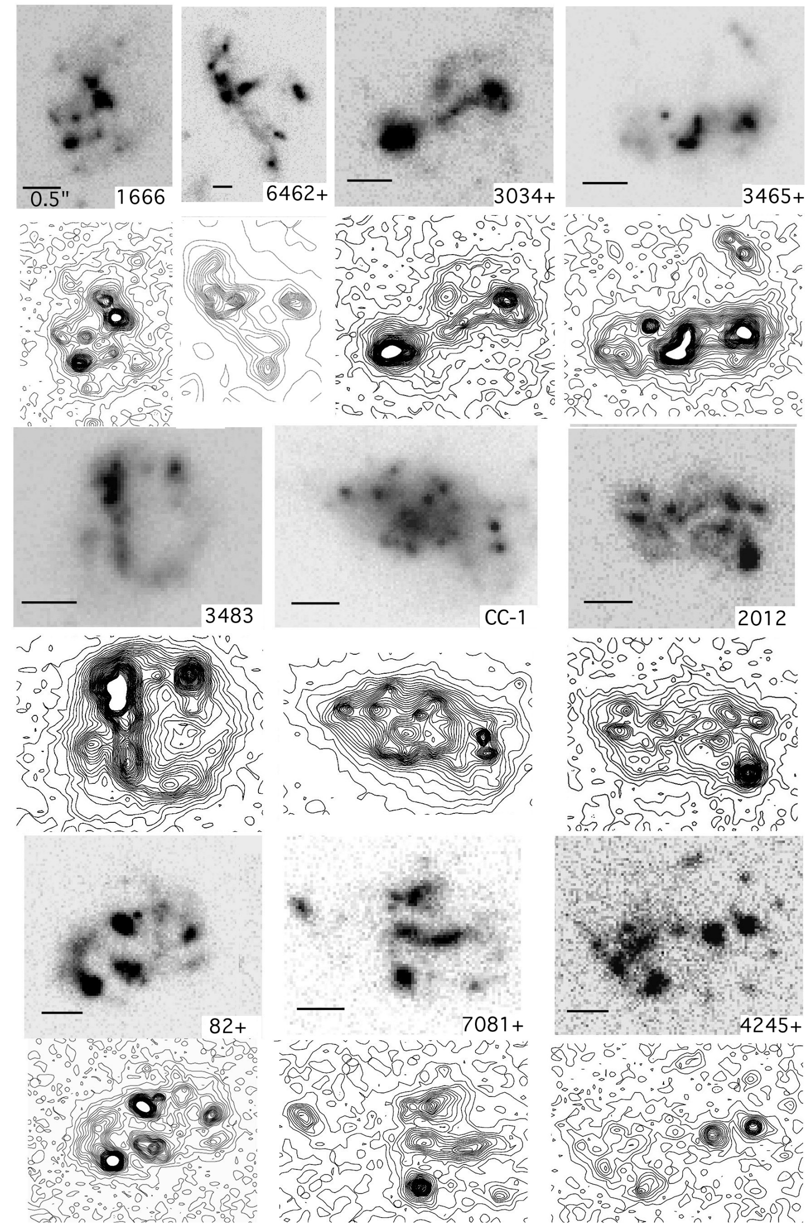
Clumps are a much higher fraction of the light in the clump clusters than in spirals.



Elmegreen,Elmegreen, Vollbach, Foster & Ferguson 05

Some galaxies are nearly pure clumps

- Photometric z (<z>~2.3)
  - Bruzual & Charlot '03
  - Rowan-Robinson dust (and x2, x4)
  - Madau '95 intergalactic H absorption
  - Calzetti/Leitherer extinction
- Average clump:
  - Mass ~ 6×10^8 M_O,
  - Diameter ~ 1.8 kpc,
  - age ~ 300 Myr, τ_{decay}~100 Myr
  - SFR ~ 20 M_O/yr(peak), 2 M_O/yr(ave)
- Average galaxy:
  - M_{gal} ~ 6×10^{10} M_O,
  - D_{gal} ~ 20 kpc, V_{rot} ~ 150 km s^{-1}

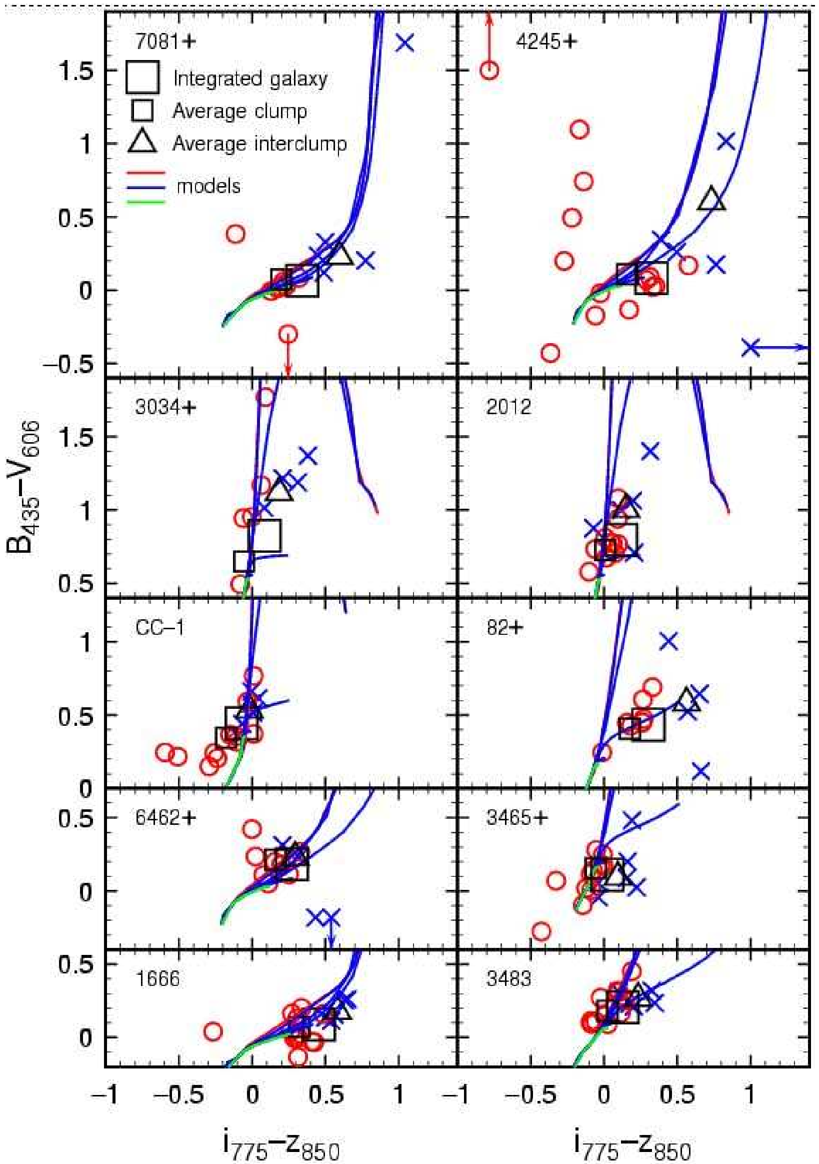


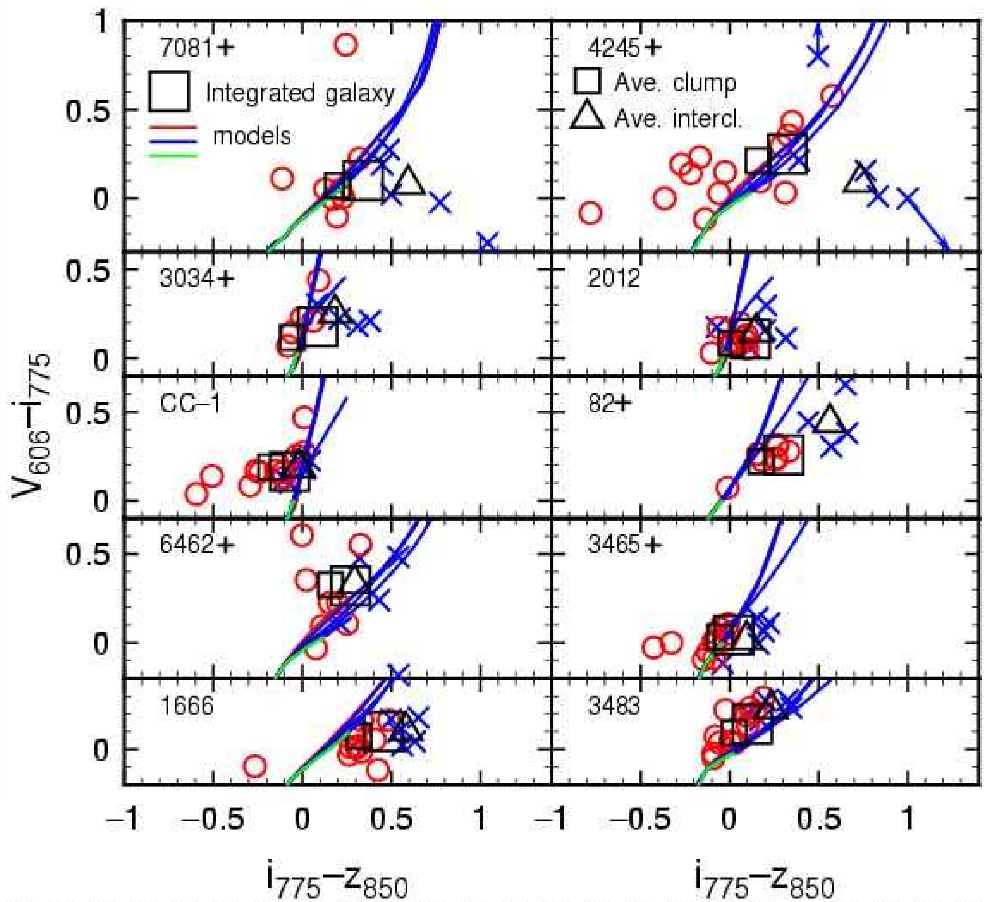
— =0.5" (Elmegreen & Elmegreen 05)

Photometric models

o=clumps, x=interclump

curves=SF decay logτ=7.5,8,8.5,9

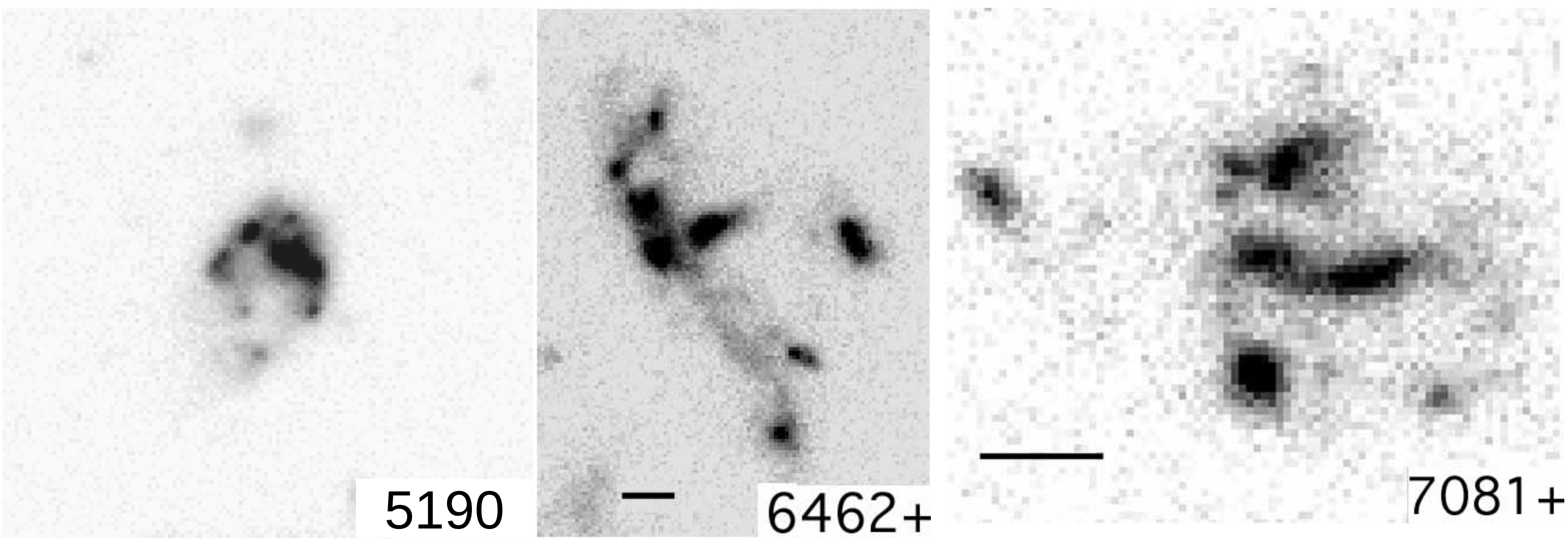




(EE05)

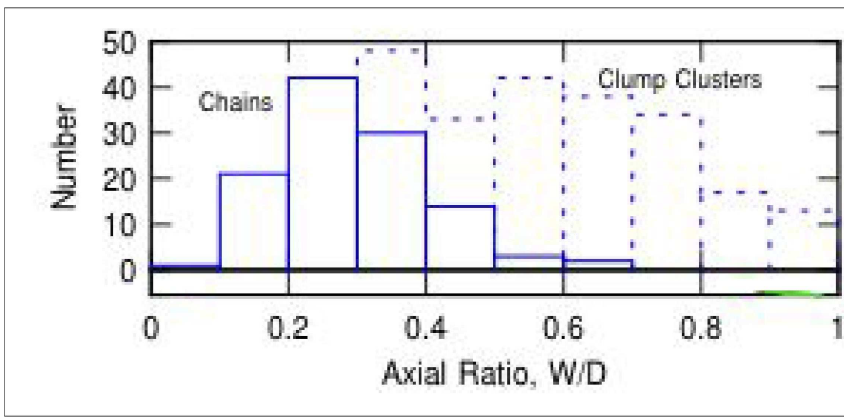
– t_{dyn} ~ 40 Myr ~ 0.1 clump age → bound super clusters
– $t_{dyn} * V_{rot} / D_{gal} \sim (\rho_{tidal}/\rho_{internal})^{1/2} \sim 0.3$ → tidal forces important
– (Need gas measurement to get total clump mass)

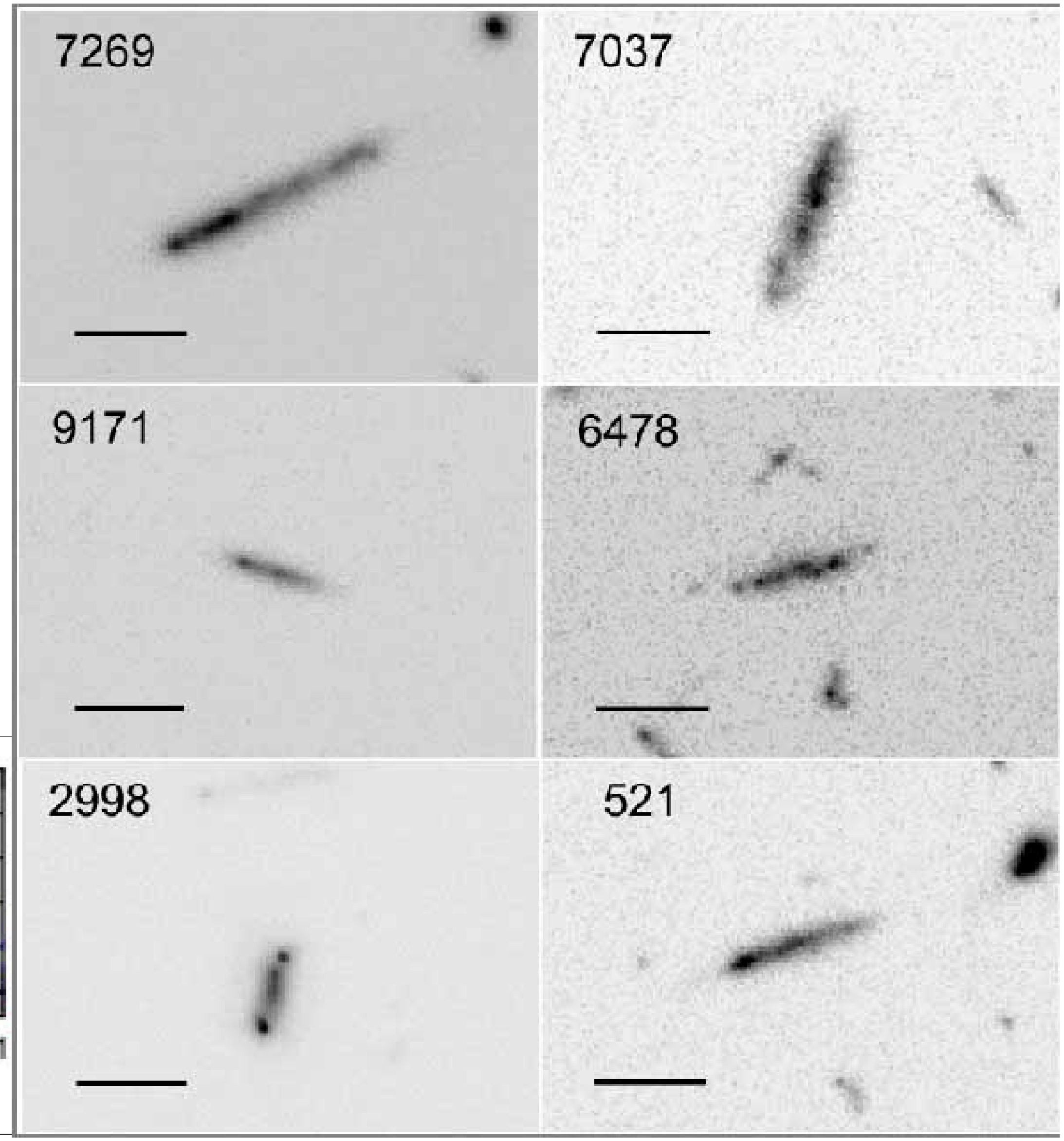
- Clumps should disperse by tidal forces and <u>form a smooth disk</u>



(EE05)

"Chain" galaxies in the UDF could be edge-on clumpy disks

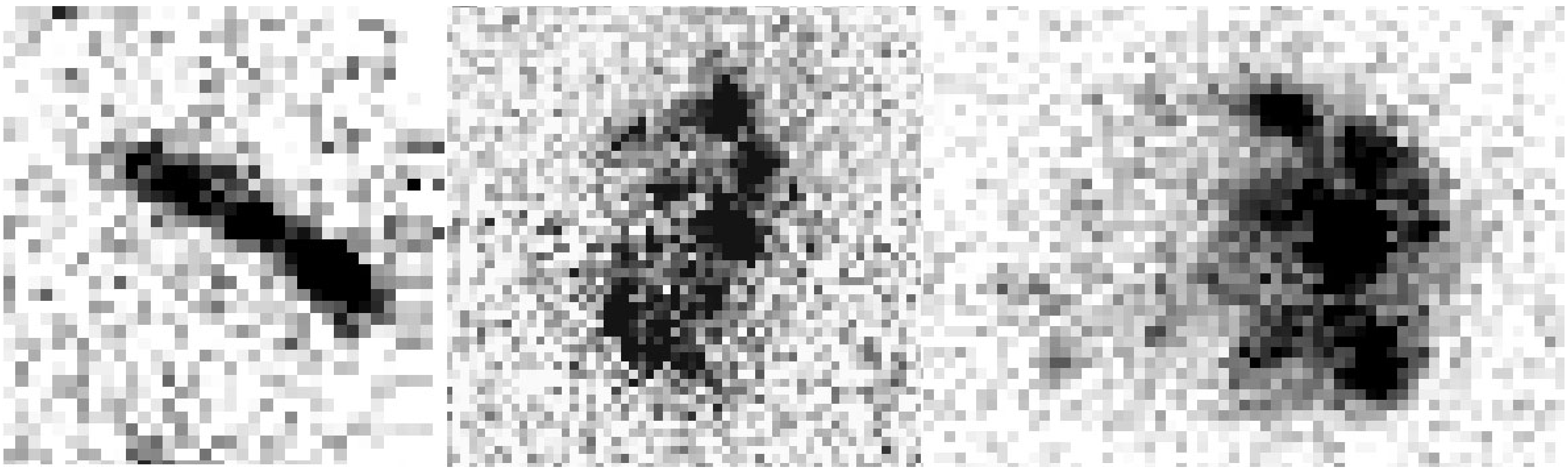




Axial ratio distribution is ~ constant, as it is for randomly oriented circles

Elmegreen et al. 05, 06

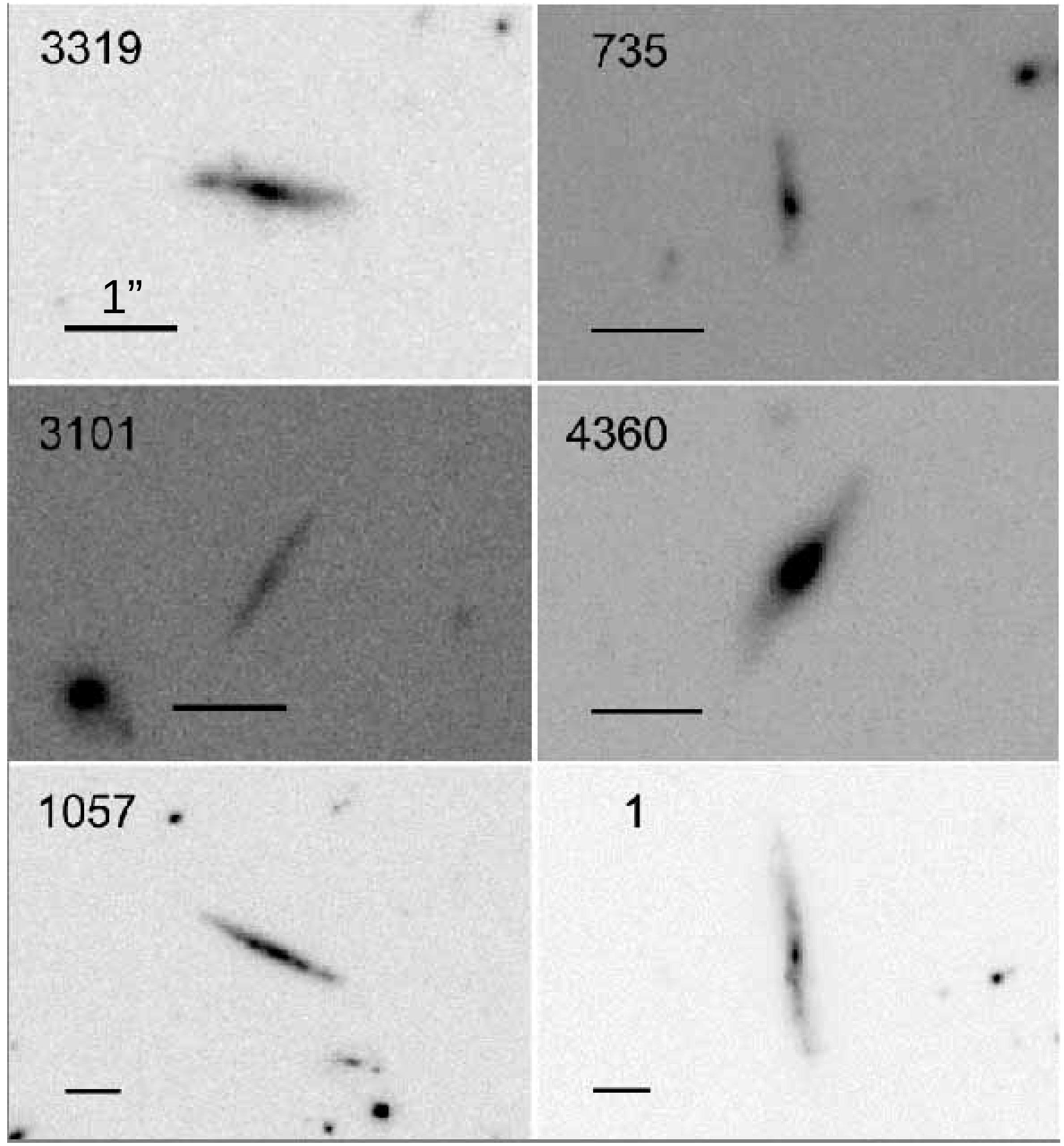
This means the chain and clump cluster galaxies are just different viewing aspects of disks systems



(E,E, & Hirst 04)

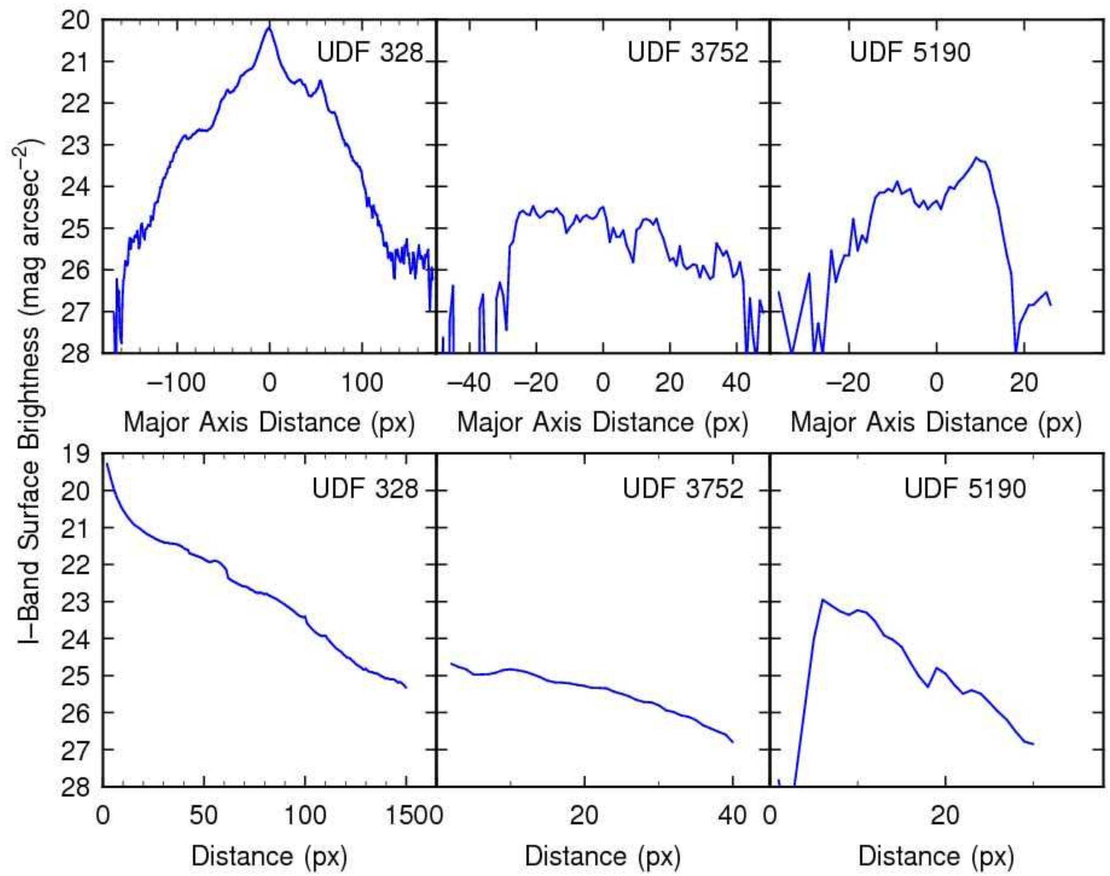
Edge-on spirals look different than chains:

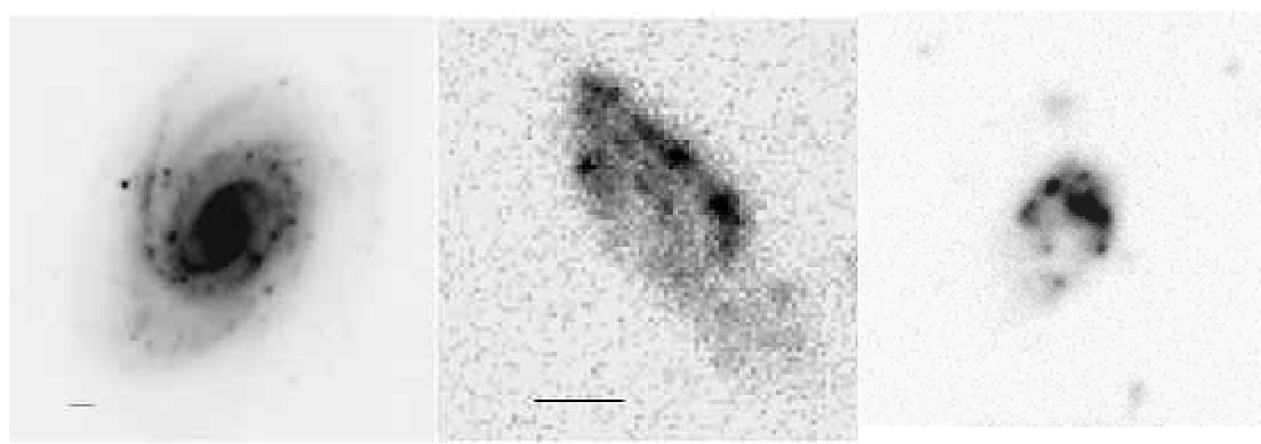
they have bulges and tapered (exponential) disks like local spirals



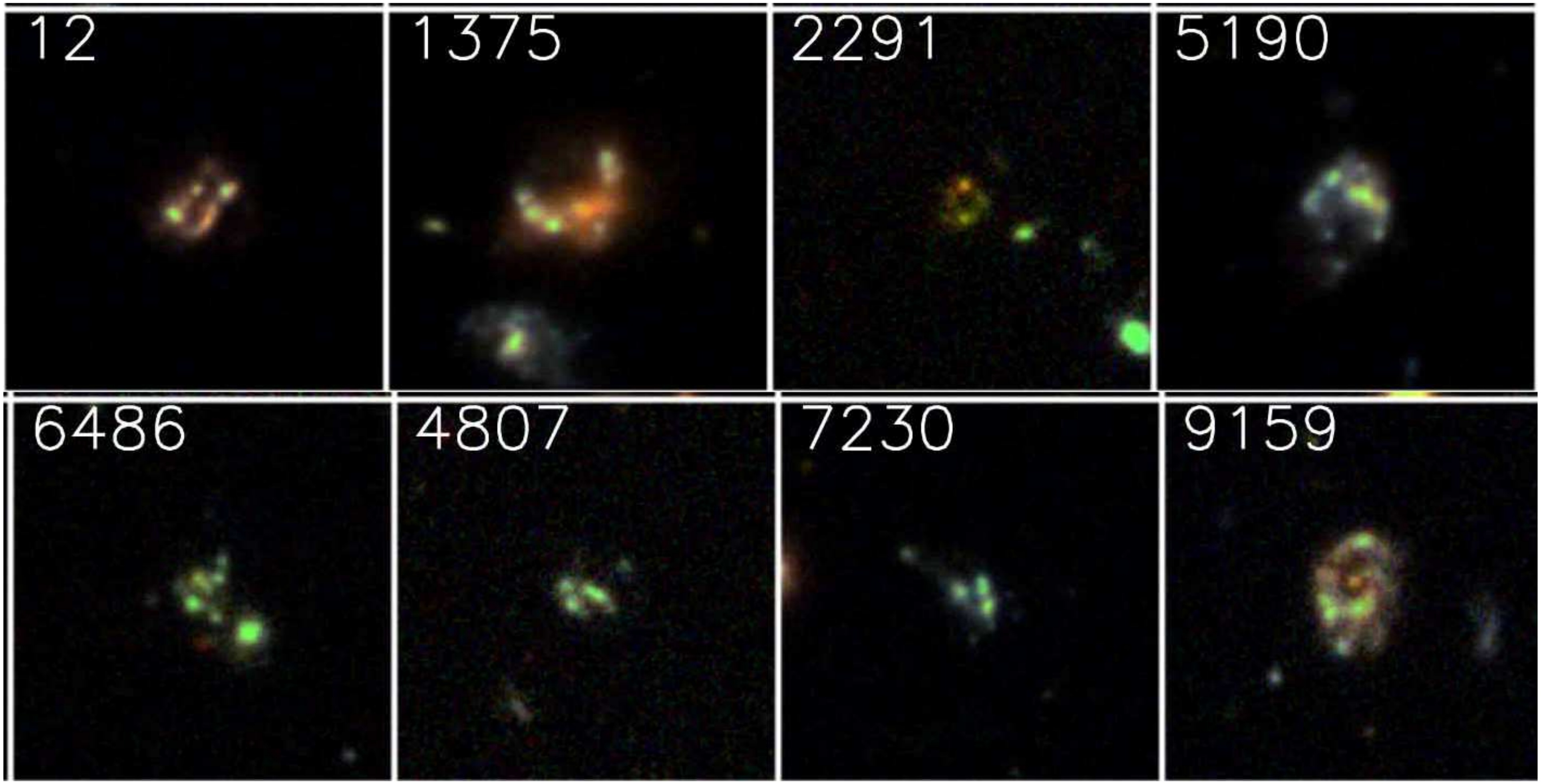
Elmegreen & Elmegreen 06

Radial profiles of clumpy galaxies are irregular, whereas profiles for spirals are exponential



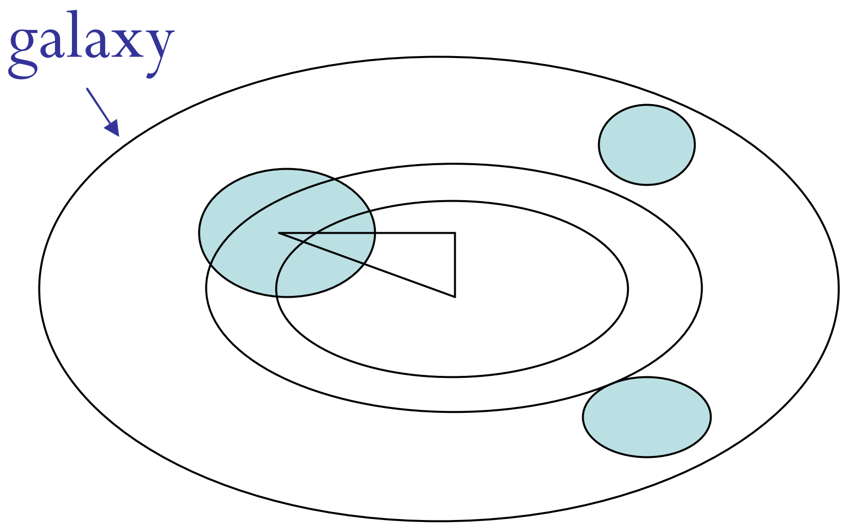


Elmegreen, Elmegreen, Vollbach, Foster & Ferguson 05



What would a clumpy galaxy look like if we smoothed over all the clumps? What is the average radial profile of the clumps?

(color: Beckwith 05)



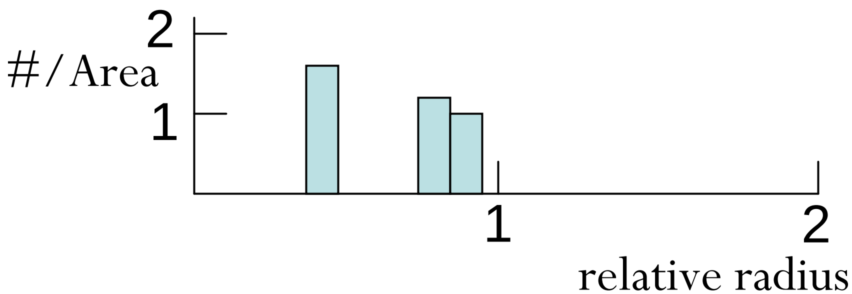
To find the average profile of clumps, we measure every clump position and brightness.

Then find the deprojected radius (assuming the galaxy is a circle) divided by the galaxy overall radius

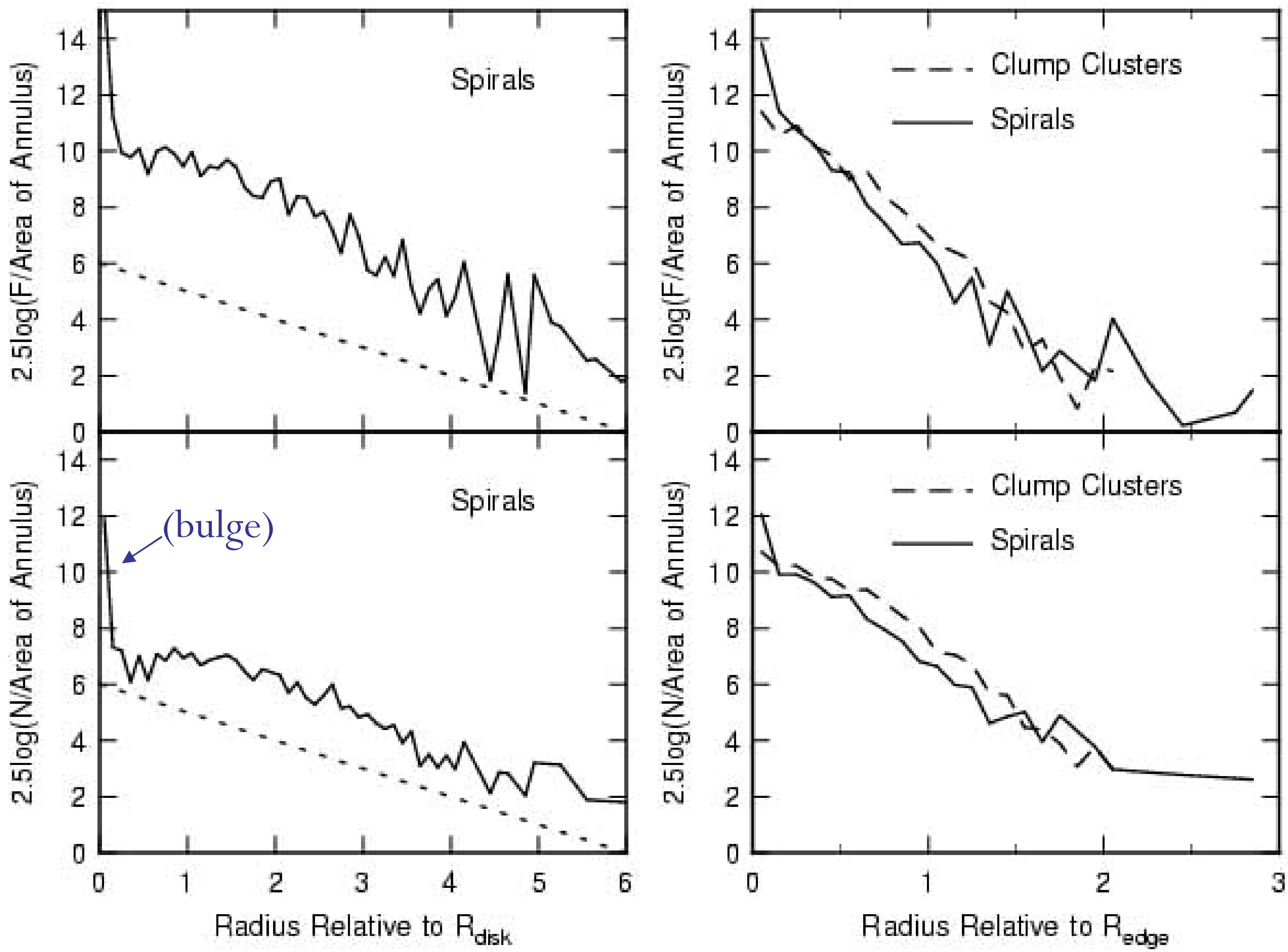
e.g., number per radial interval = 1 for relative radius = 0.4

other clumps at 0.8 and 0.9 rel.radii

Resulting contribution to plot:

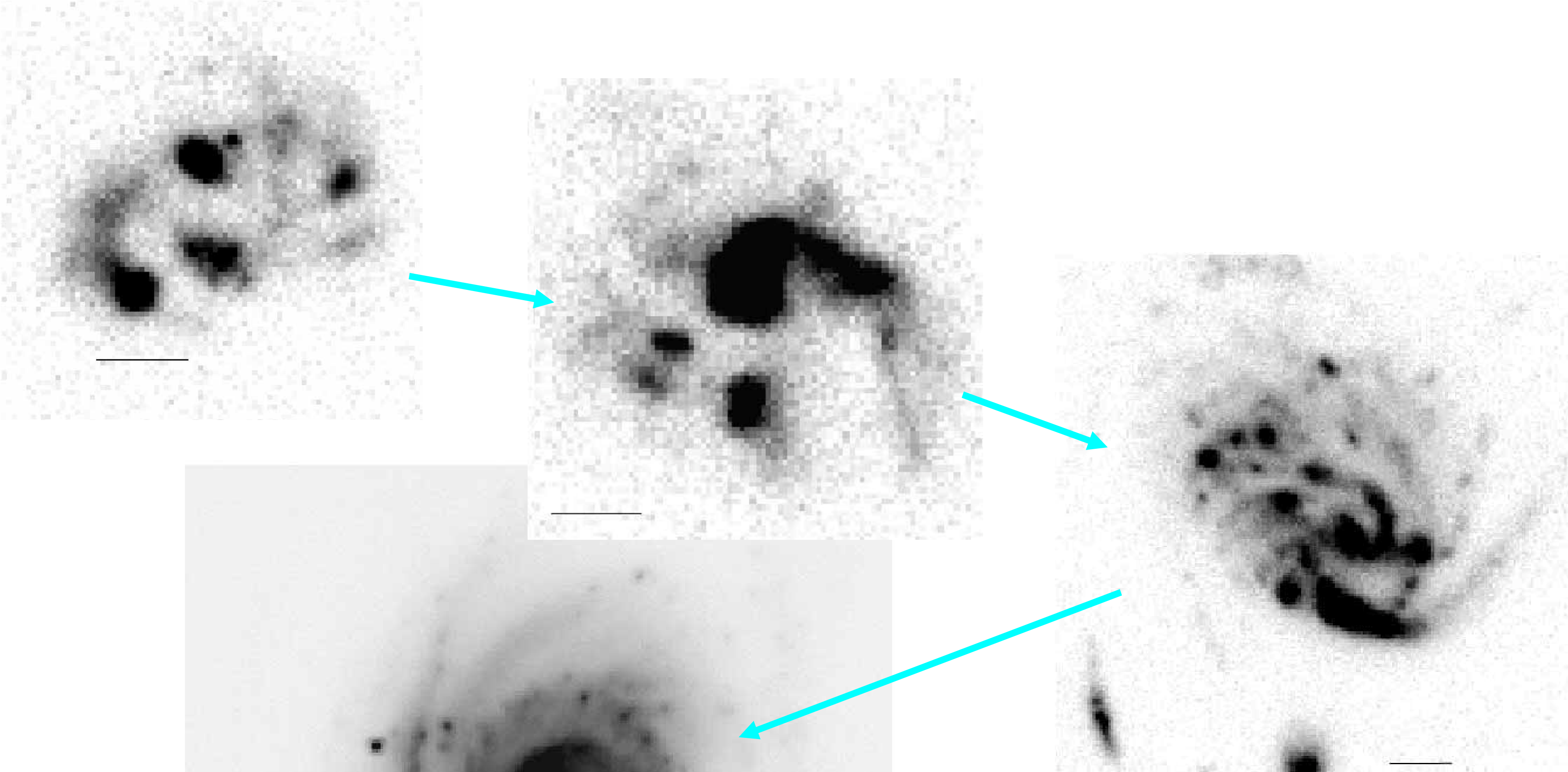


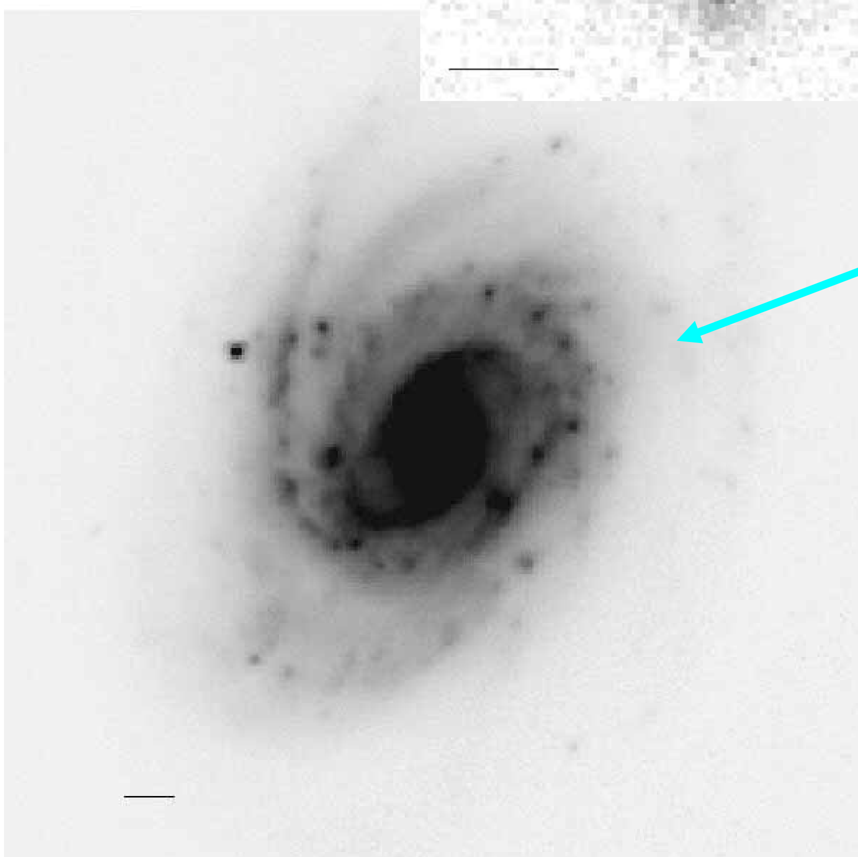
and plot the total number per unit area in each relative radial interval versus the relative radius



The average radial positions of the clumps in the clump-cluster galaxies is the same as the smooth radial profiles of spirals: exponential

(E,E, Vollbach, Foster & Ferguson 05)





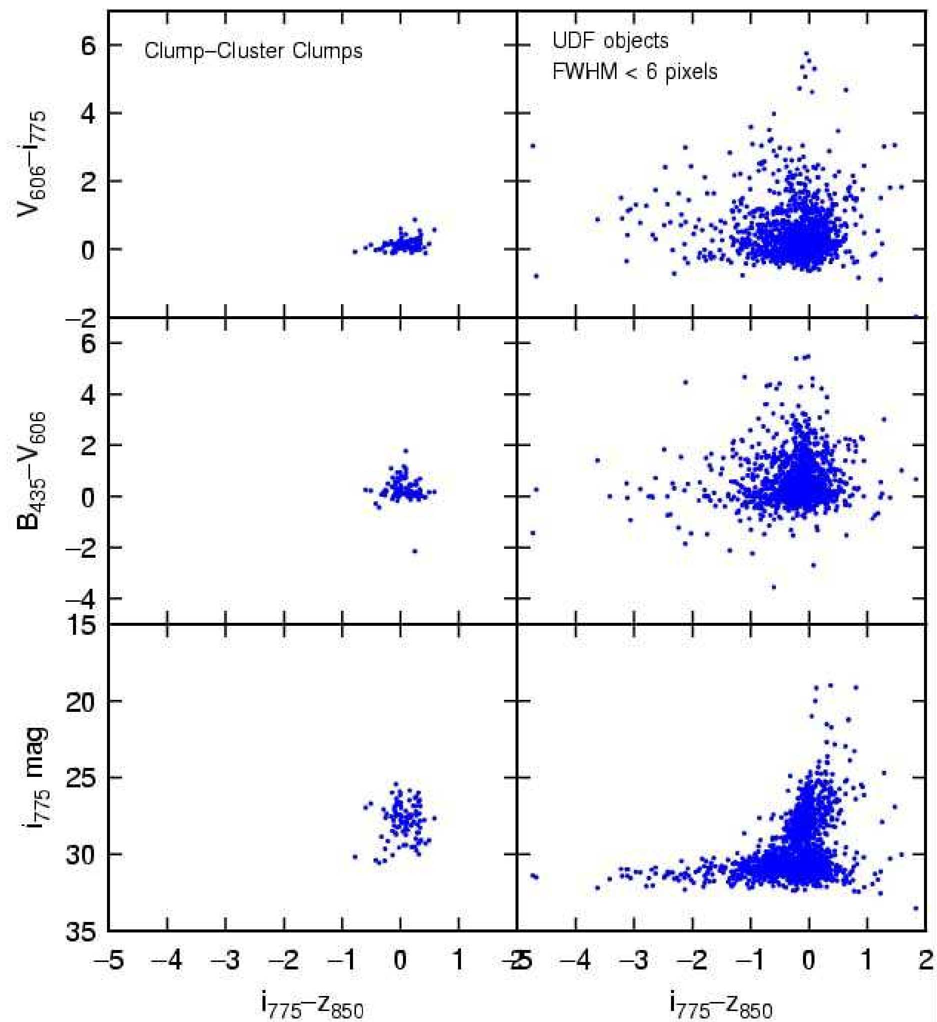
Proposed evolutionary sequence as clumps dissolve

Clump Origins

- Come from outside?
  - resemblance to extragalactic clumps of the same size
  - existence of even looser clump clusters
- Form inside gas disk?
  - Clump separations and masses could be from gravitational instabilities in a highly turbulent gas disk: $L \sim a^2/\pi G\Sigma \sim 2\text{-}3$ kpc; $M \sim \Sigma L^2 \sim 2 \times 10^8\ M_O$ requires
    - $a \sim 5$x normal, $\Sigma \sim a^2 = 25$ times normal
      - (gives L the same as normal, but M higher by $a^2=25$)
  - Clumps lie in the midplane

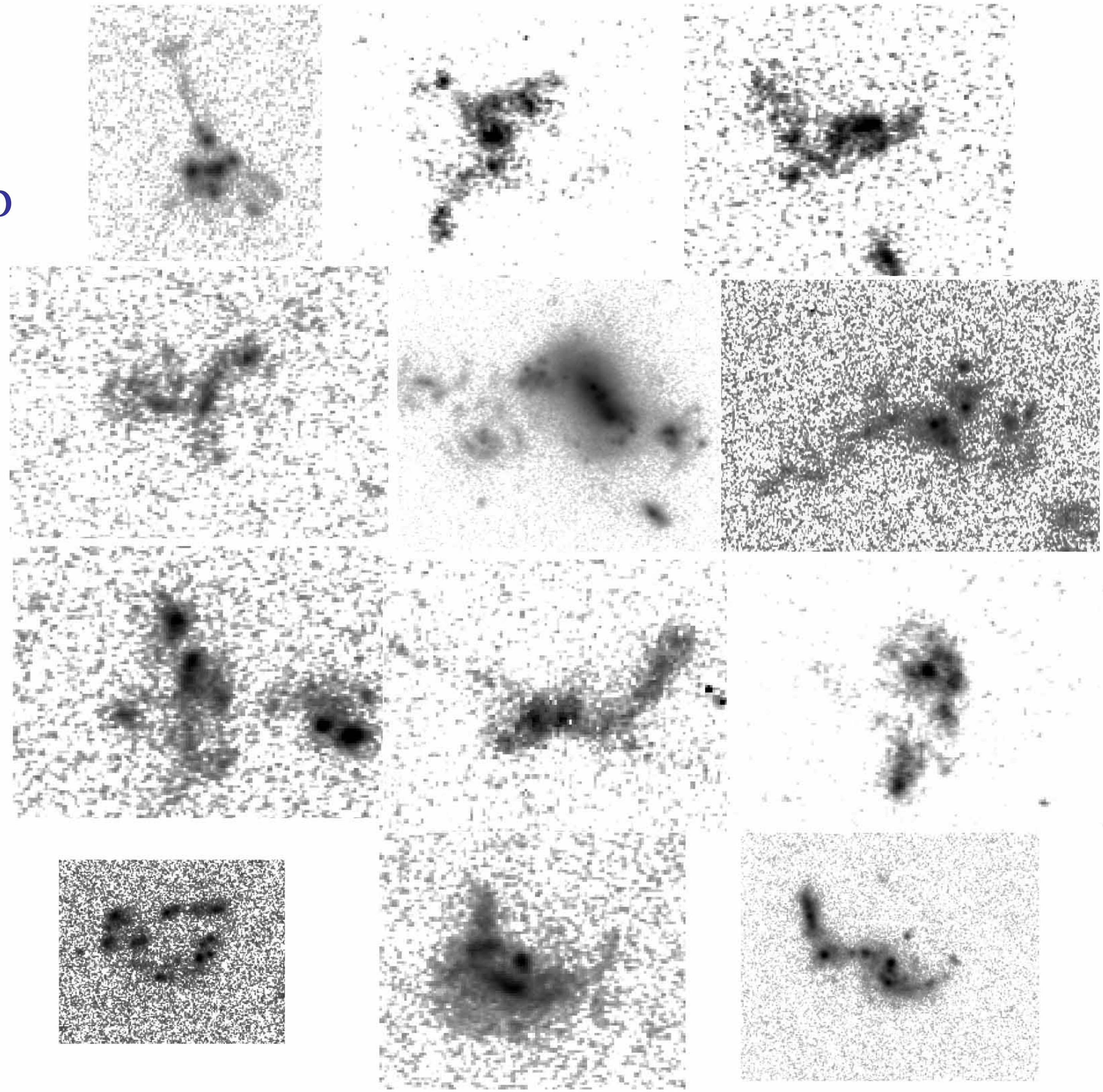
Clump resemblance to small galaxies outside?

- Figure compares CMD for clumps in these 10 UDF clump clusters with equally small UDF field objects
  - distributions are the same
- Clumps could be accreted as intergalactic gas+star blobs
  - (Walker, Mihos & Hernquist '96; Abadi et al. 2003)
- Or accreted as gas clouds and then compression-triggered into star formation
  - (Brook et al. '04)

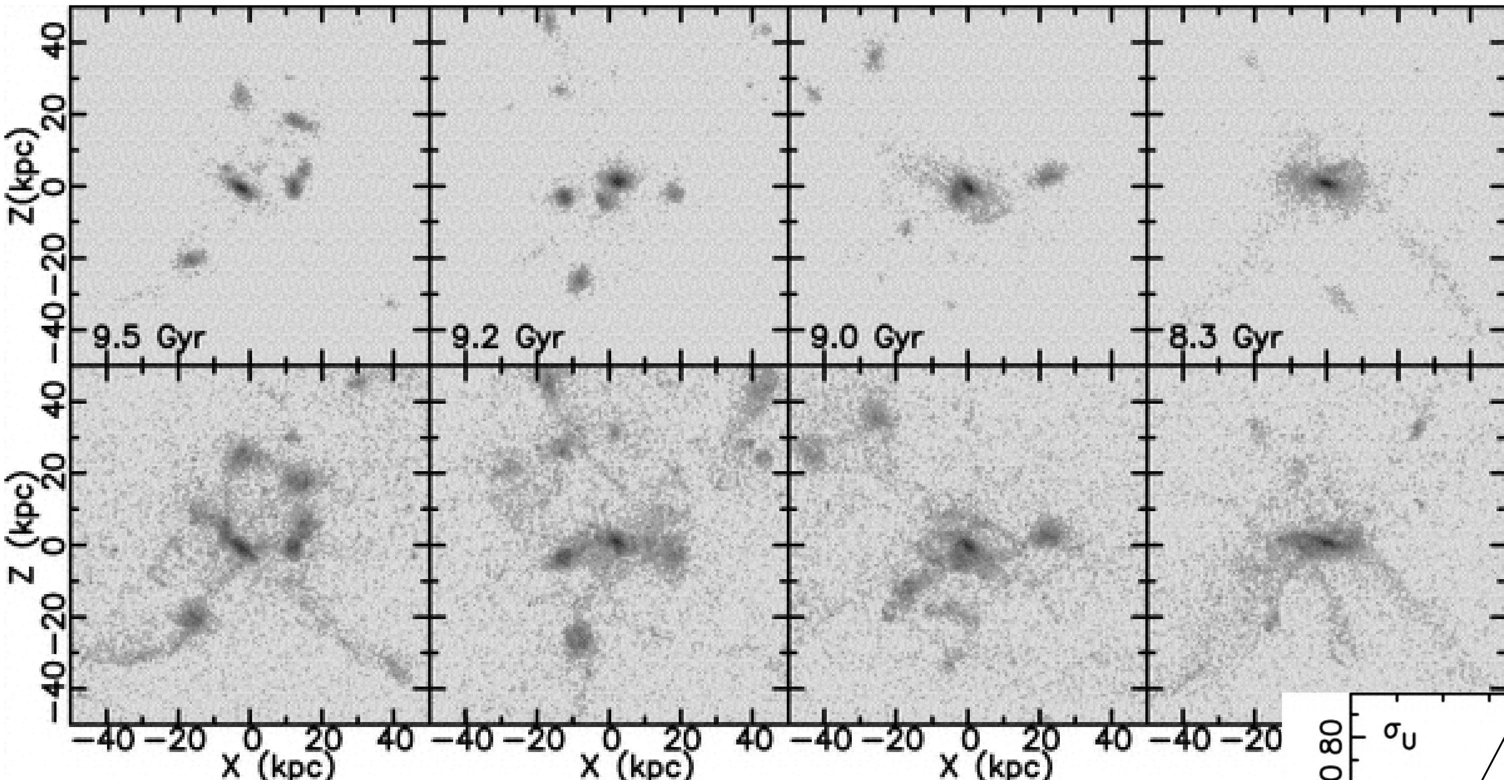


(EE05)

Loose clump clusters: appear to be recent assemblies.

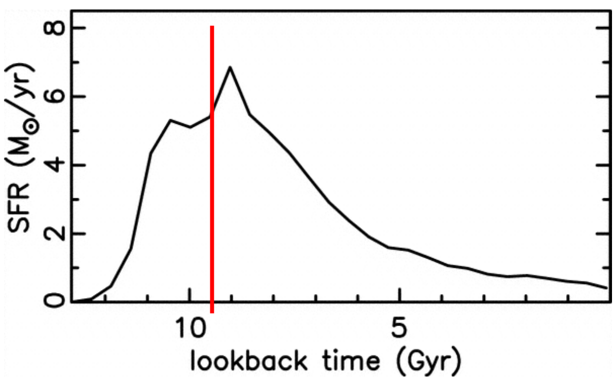


Elmegreen et al. 2007b

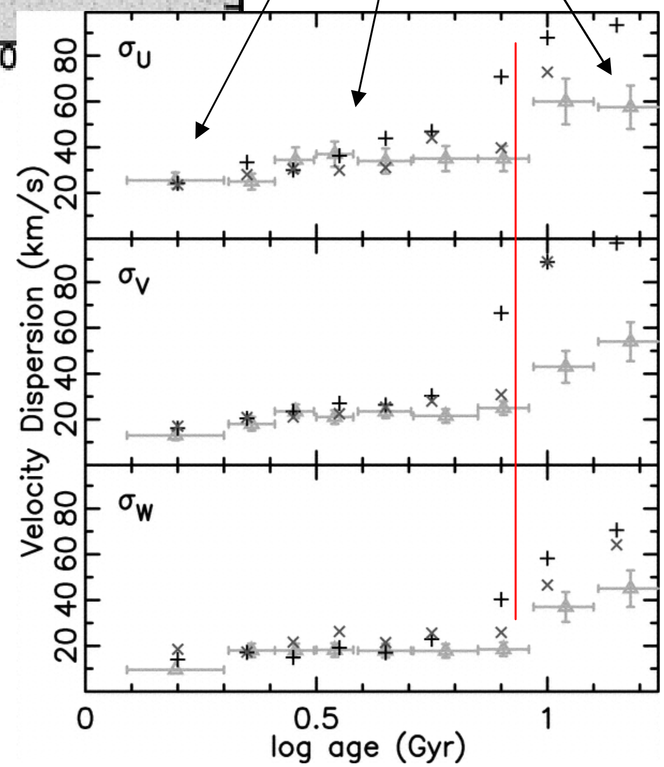


Profile of stars (top) and gas at epoch of thick disk formation

young thin disk
old thin disk
thick disk



Thick disk turbulence stirred by clumpy gas impacts ~10 Gyr ago



Brook et al. 2004 simulation of collapsing protogalaxy with initial density perturbations. $z_{collapse}=1.8$, solid body rotation $\lambda=0.0675$

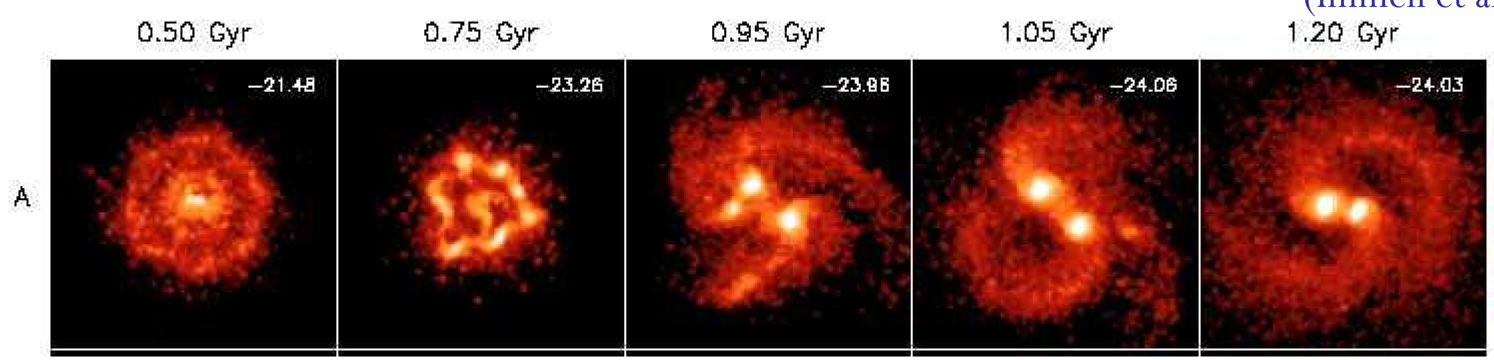
But Gravitational Instabilities can make clumps too:

- For 10 clump cluster galaxies, M and R imply high internal velocity dispersions,
  - $\Delta v \sim 24\ \mathrm{km\ s^{-1}}$ on average

- Need fast ISM turbulence if formation by <u>gravitational instability</u> (Noguchi '99, Immeli et al. '04)
  - Consistent with thick disks
  - Pre-collapse turbulent energy may be from accretion
    - need $\Delta v \sim 0.16\ v_{rot}$
    - expect $v_{impact} \sim 0.4 v_{circular}$ if accretion from filaments (Keres et al. 04)
    - and $\Delta v \sim 0.5 v_{impact}$ (shock jump condition)

- Instability model follows if gas accretes to disk in a <u>smooth flow</u>, as in many formation models (e.g., Murali et al. '02; Westera et al. '02, Sommer-Larsen, Gotz &Portinari '03, Keres et al. '04)

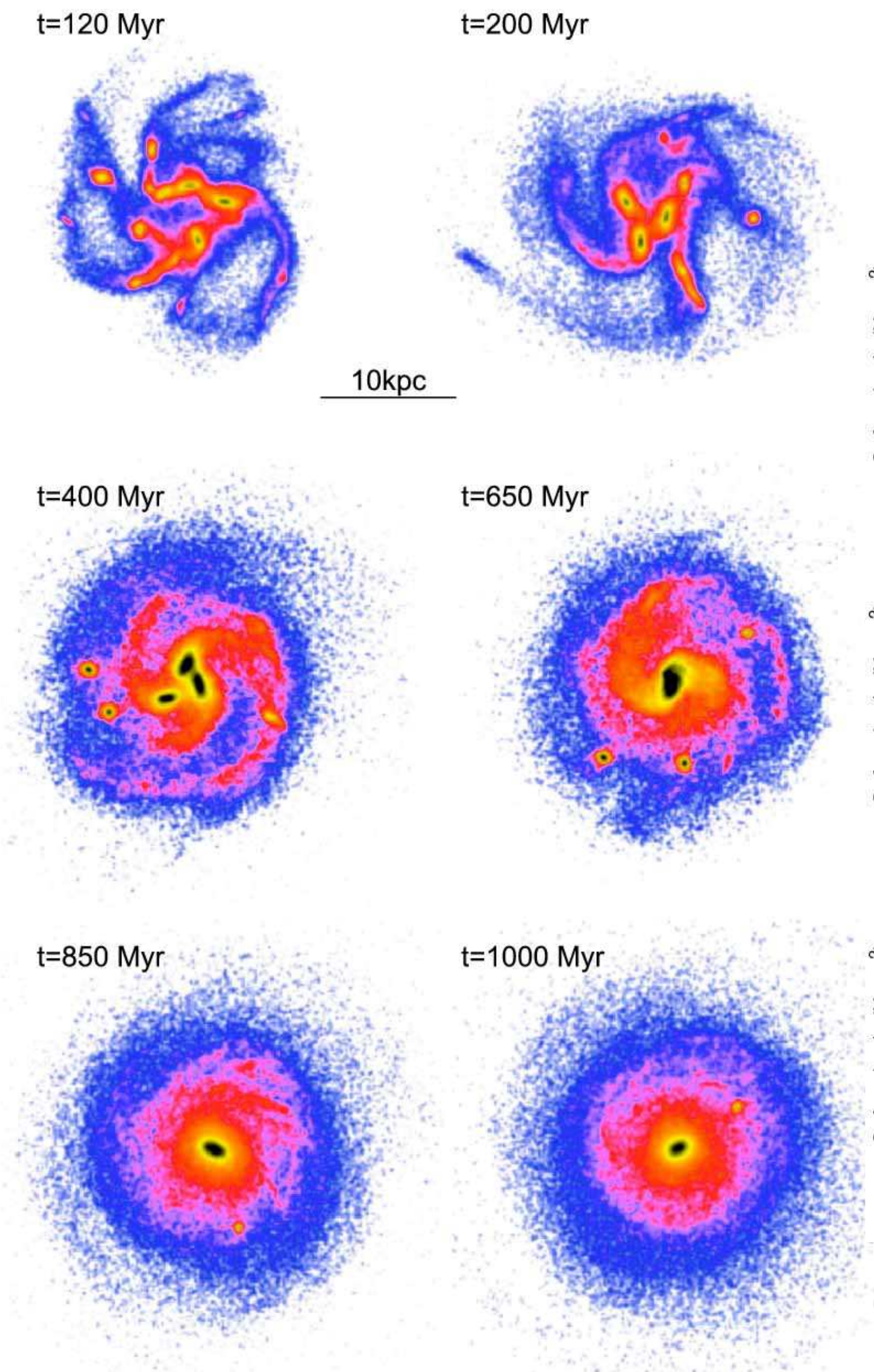
(Immeli et al. 04)



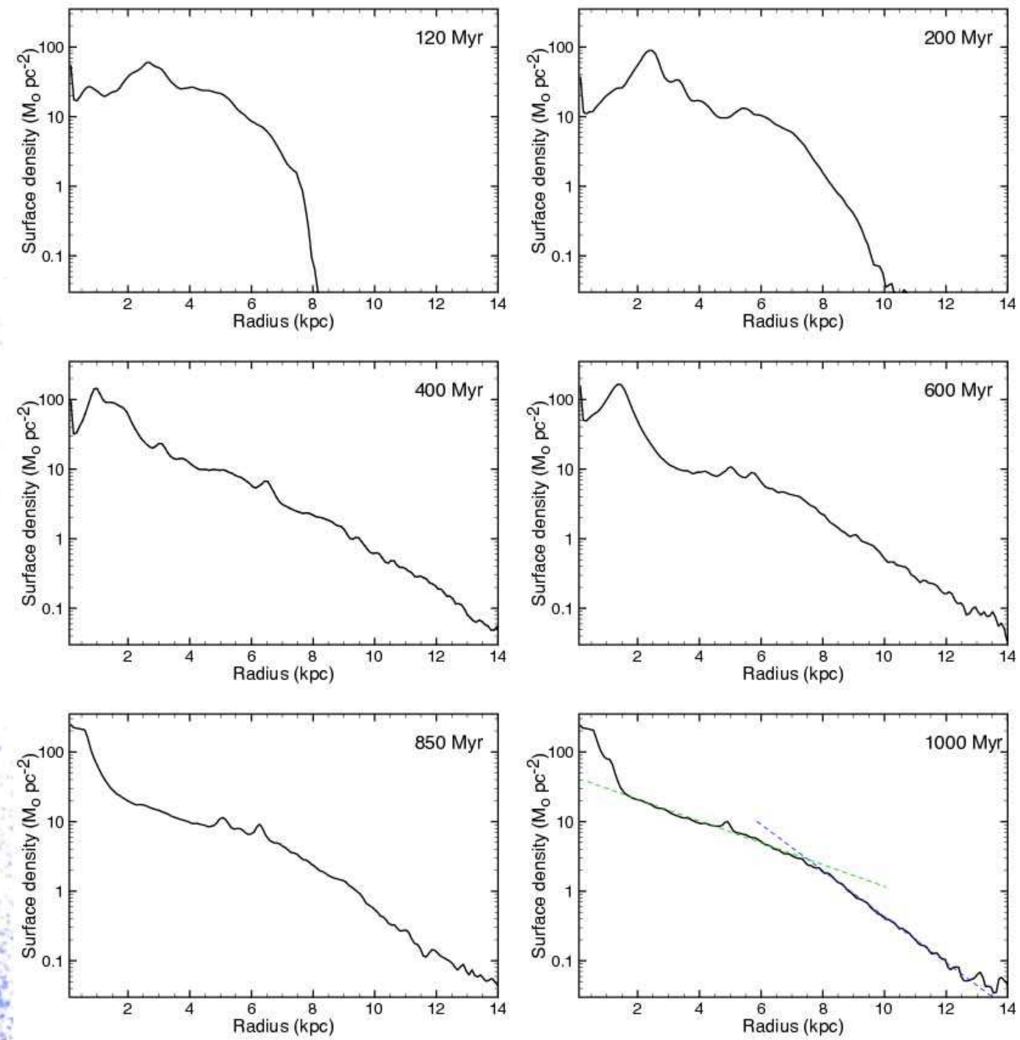
New Simulations of Clump Cluster Evolution

(Bournaud, Elmegreen & Elmegreen 07)

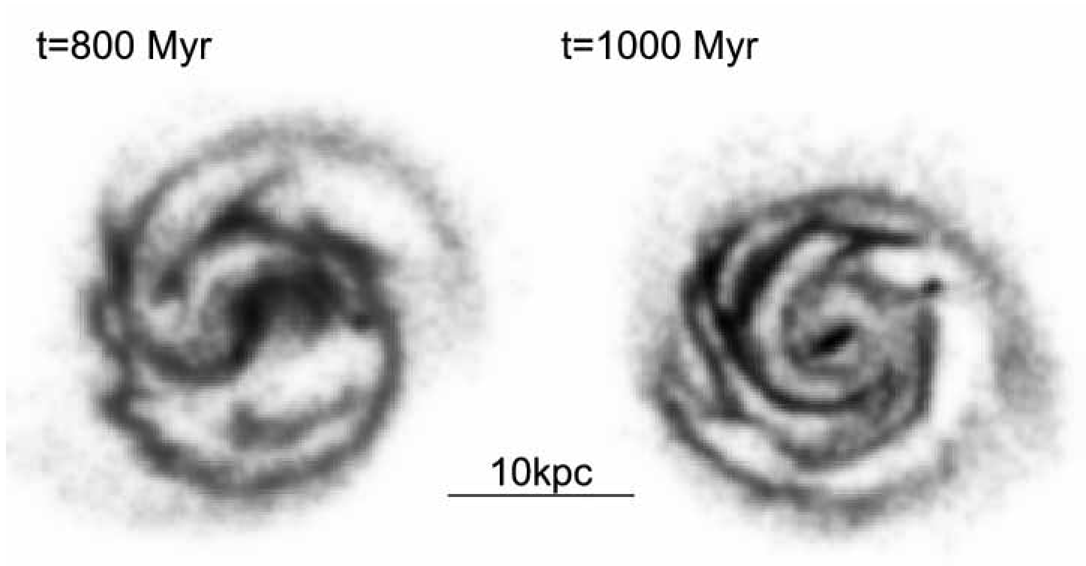
- Particle-mesh, sticky particle gas (β=0.7)
  - grid resolution 110 pc
  - 10^6 particles each for halo, stars, gas
    - halo = Plummer sphere with scale length 15 kpc
- Schmidt-law star formation
  - probability particle converts to a star is proportional to the local density to the power 1.4
- Initial disk flat profile, bulgeless, 6 kpc radius, 7×10^{10} M_O total disk
- Initial Q_{star}=1.5
- Example here: 50% disk gas fraction initially, disk/halo inside disk=2



New models show evolution to <u>exponential disk & bulge</u>

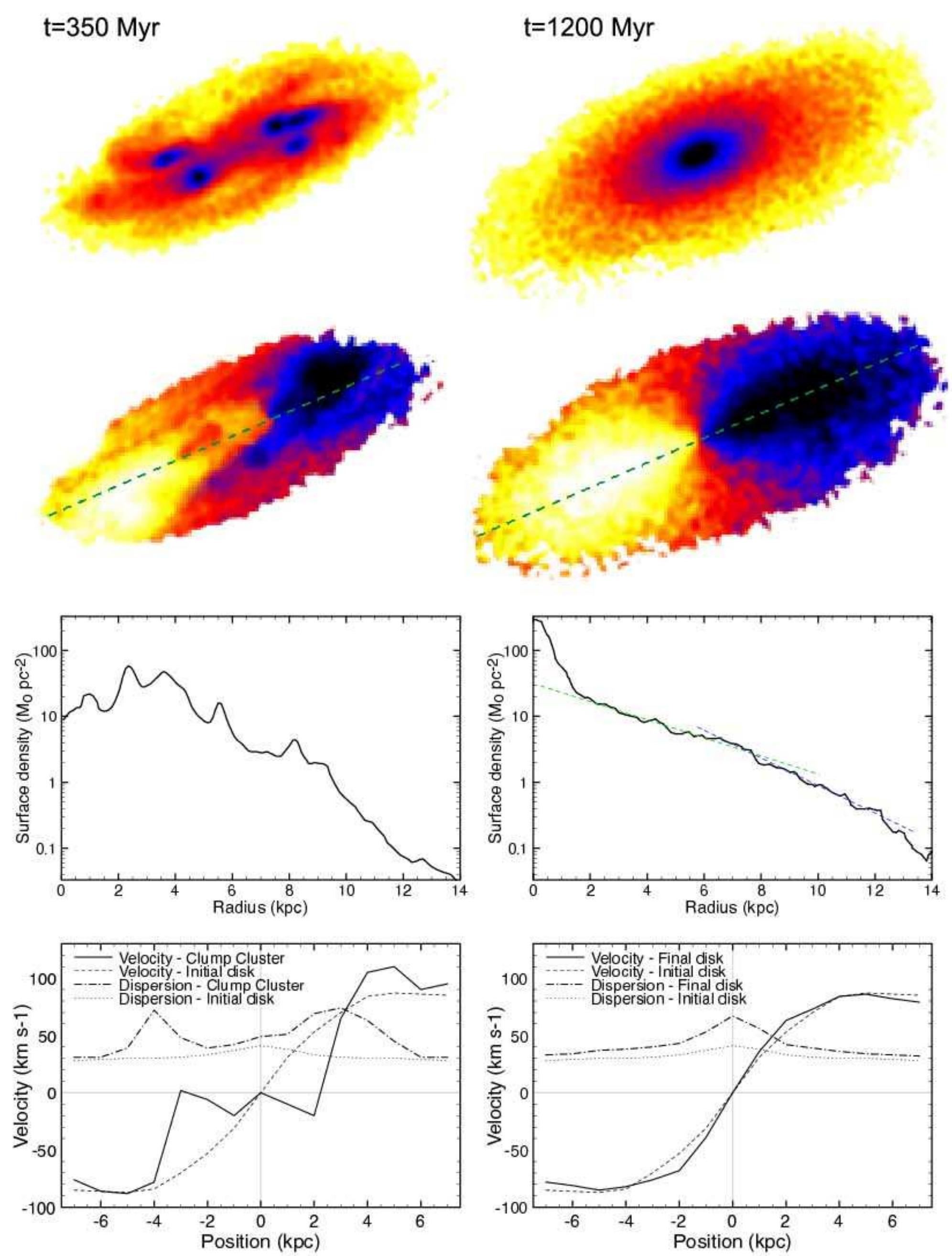


Bournaud, Elmegreen & Elmegreen 07

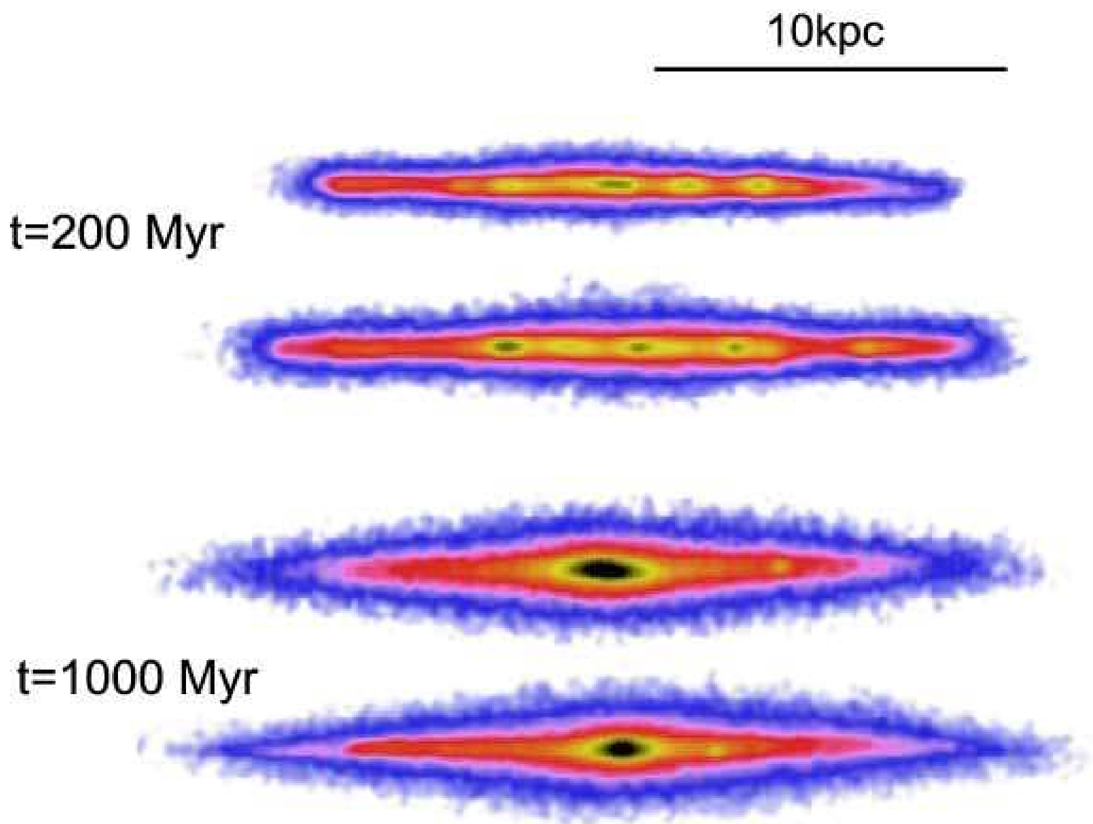


Late-time gas distribution is typical for a spiral galaxy

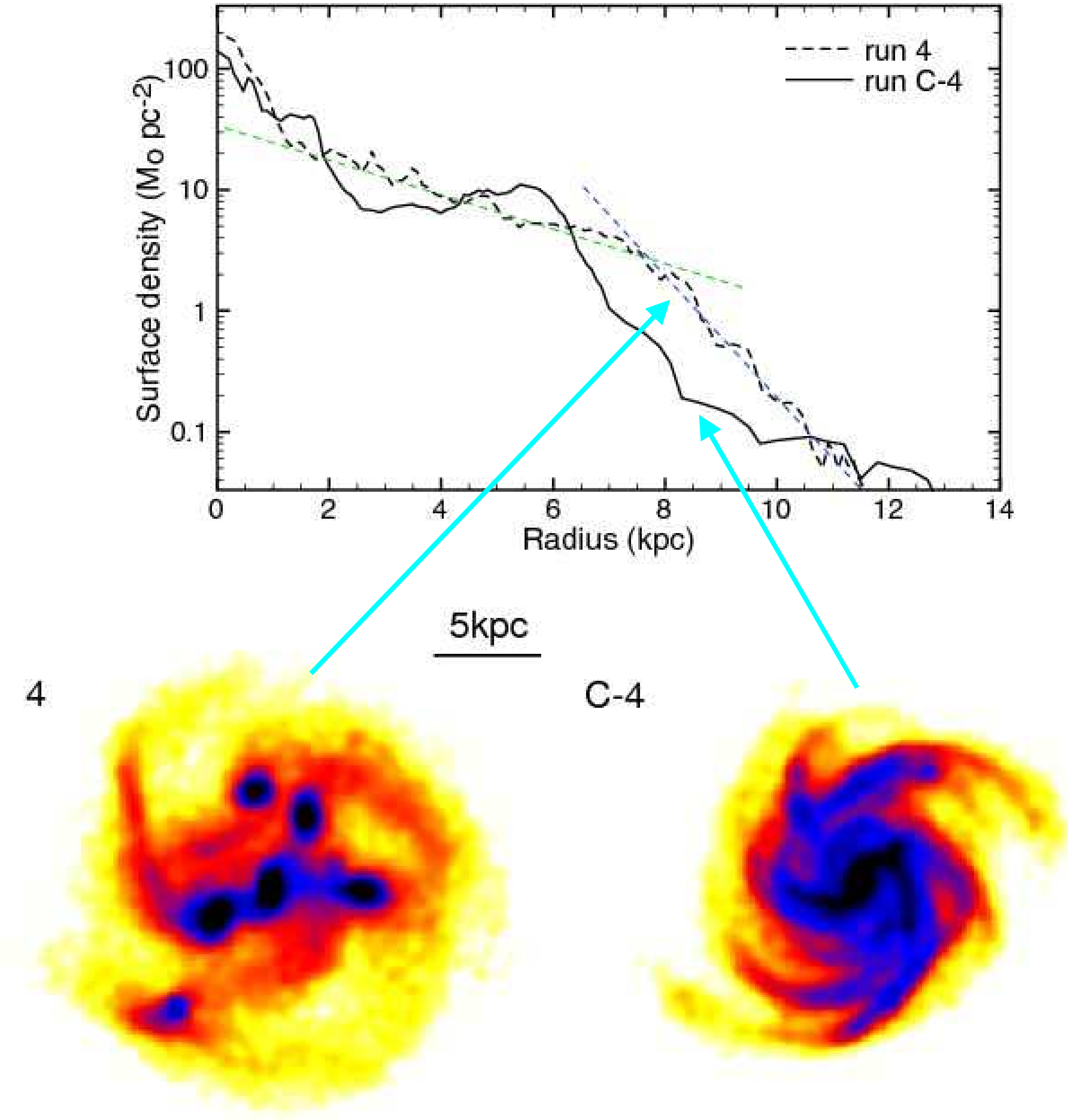
Rotation curve goes from irregular to flat and velocity dispersion goes from highly turbulent to relaxed



Bournaud, Elmegreen & Elmegreen 07



Edge-on disks go from chain galaxies
to normal bulge-centered spirals



1 Gyr structure for initially unstable disk (left) versus initially stable disk.

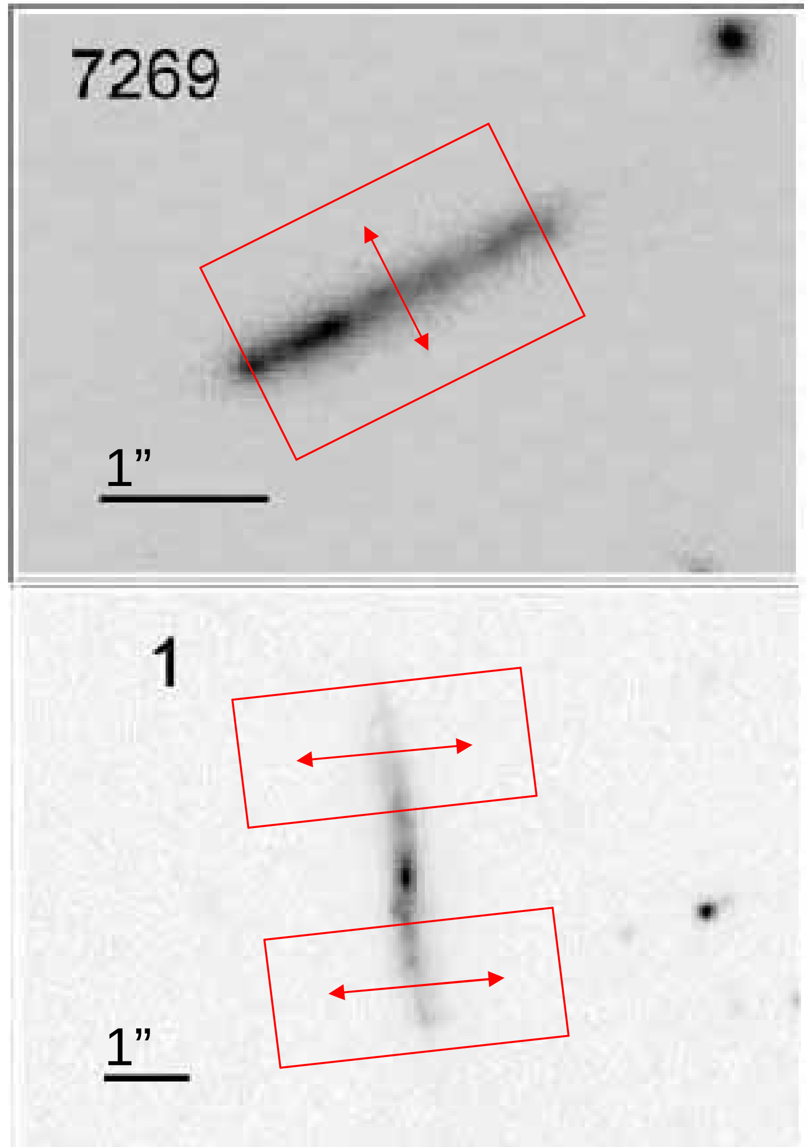
Instabilities promote exponential disk formation.

Perpendicular Profiles of Spirals and Chains suggest instabilities

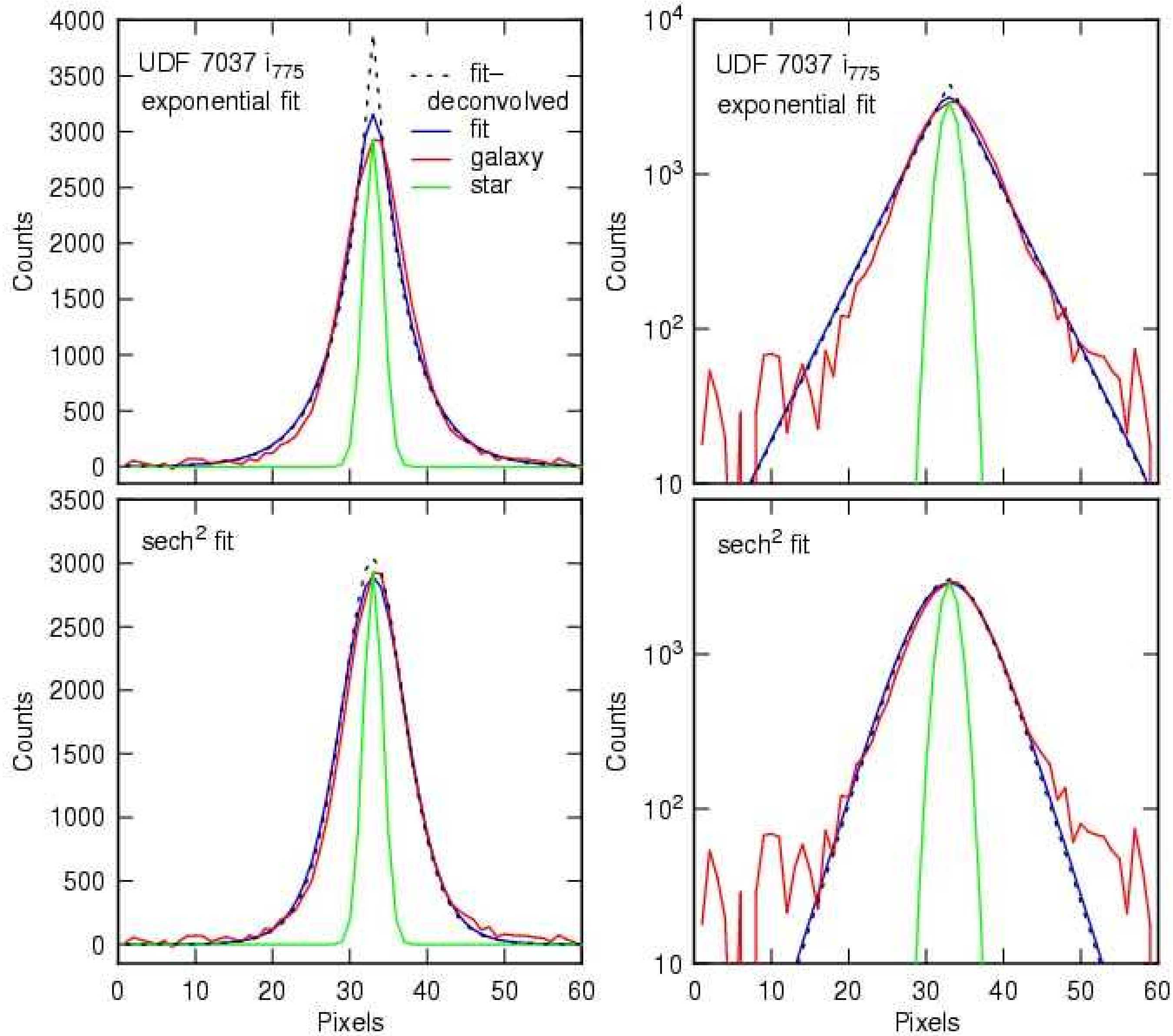
- All high redshift spirals and chains (clump clusters) have <u>thick</u> disks [$z_0 \sim 1$ kpc for $\text{sech}^2(z/z_0)$ profiles]
- Clumps have sizes ~ disk thicknesses
- Clumps lie in the midplanes
  - they look like they formed there and did not accrete

All distant galaxies are found to have relatively thick disks.

Measure the average perpendicular profiles through chains and edge on spirals, avoiding the bulge



Deconvolve stars, fit to exp or sech^2 profiles



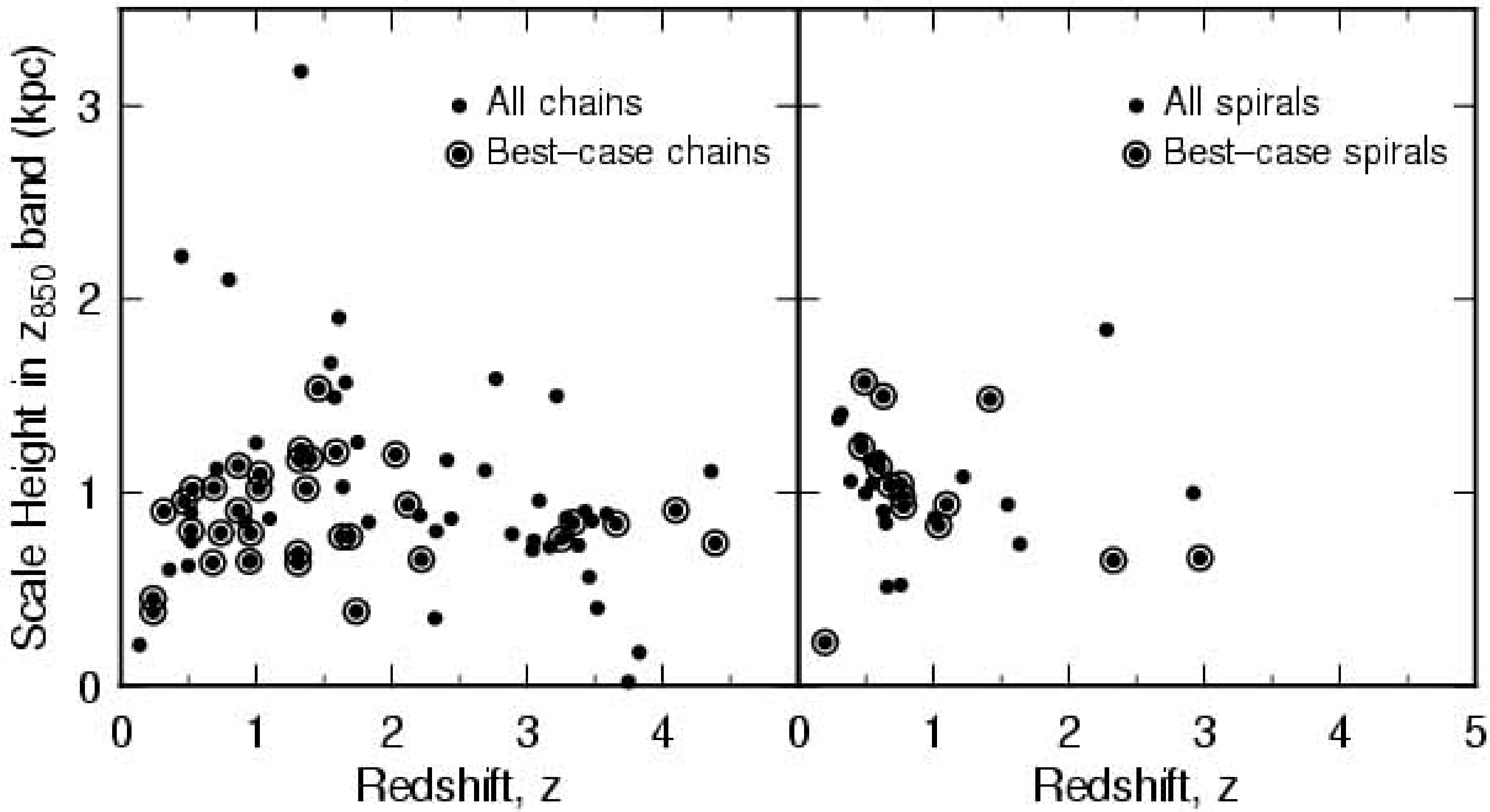
$\mathrm{sech}^2(z/z_0)$ is the equilibrium solution to the perpendicular profile of an isothermal self-gravitating disk

$z_0 = a^2 / \pi G \Sigma$

$a^2 = P/\rho$ (velocity dispersion)

Σ = mass column density

EE06

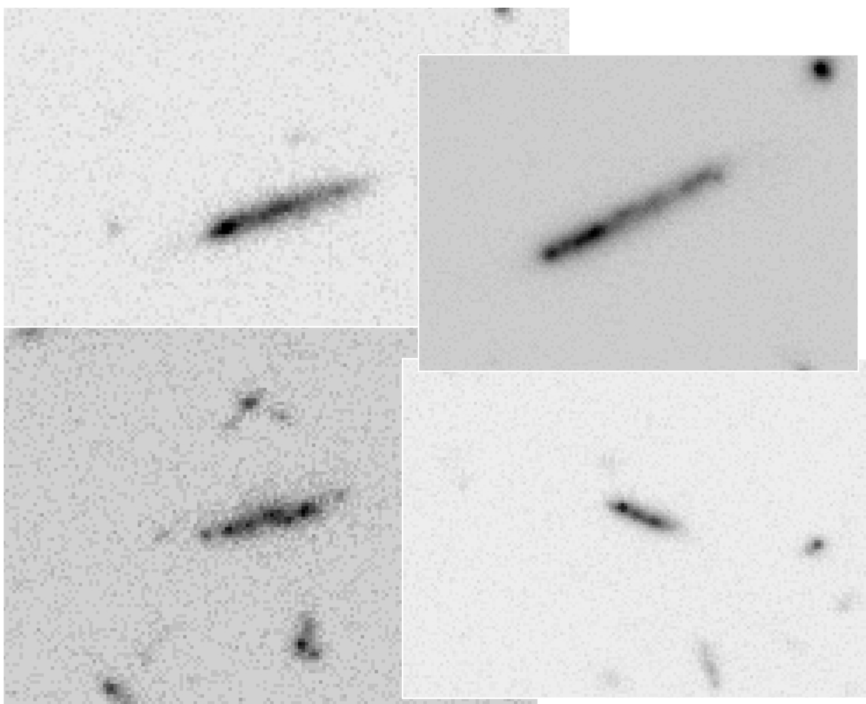


$z_0 \sim 0.9$ kpc for all redshifts

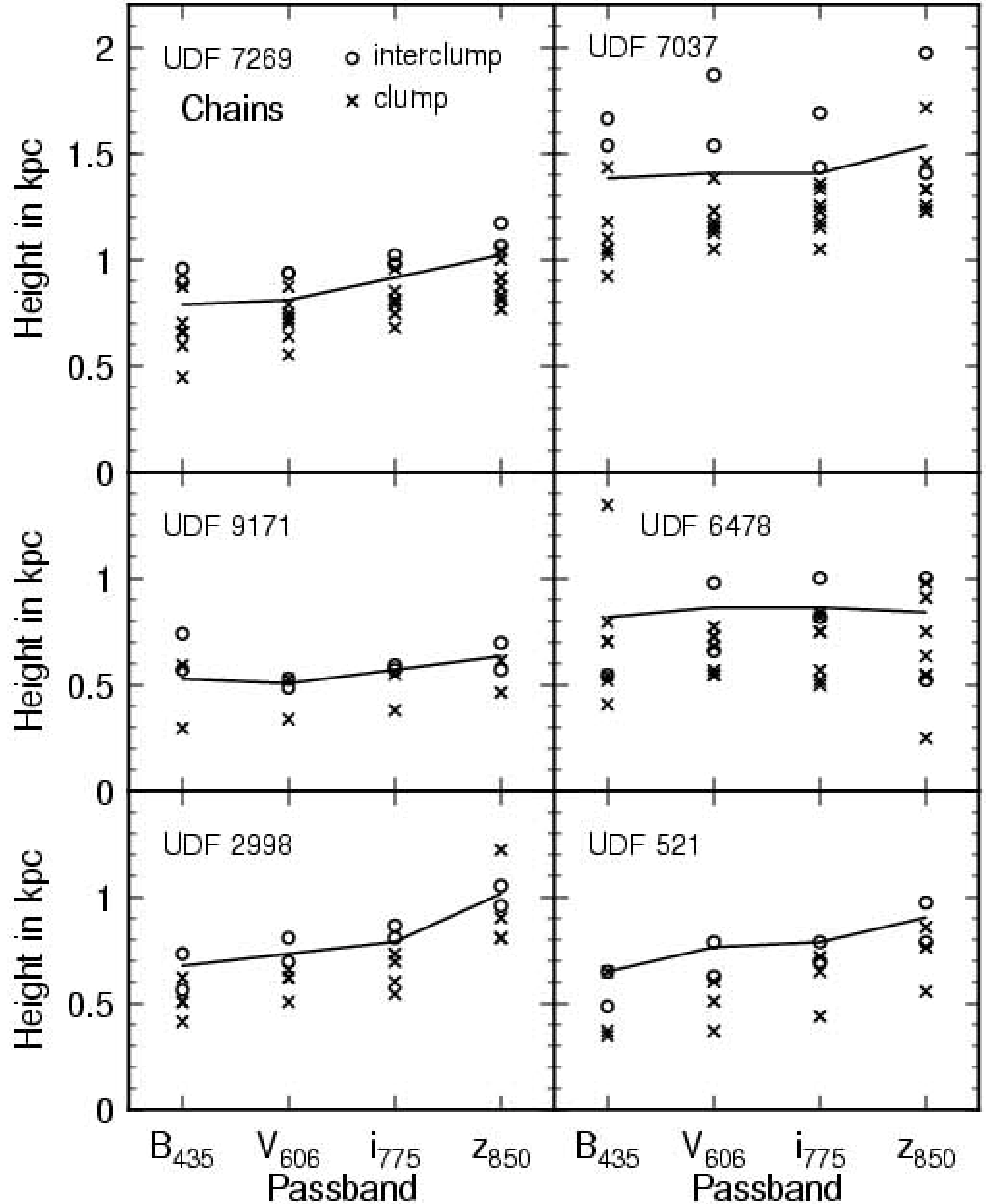
EE06

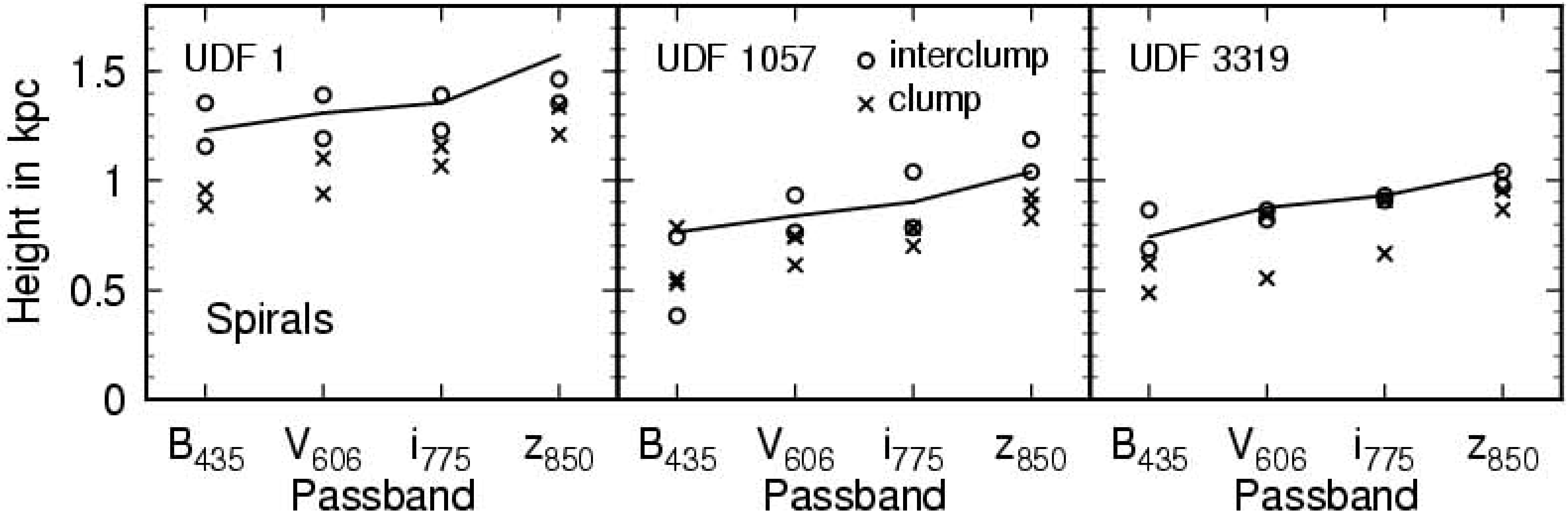
Now fit sech^2 to clumps and interclump regions

Find that clumps are big, 80% of the average height



EE06

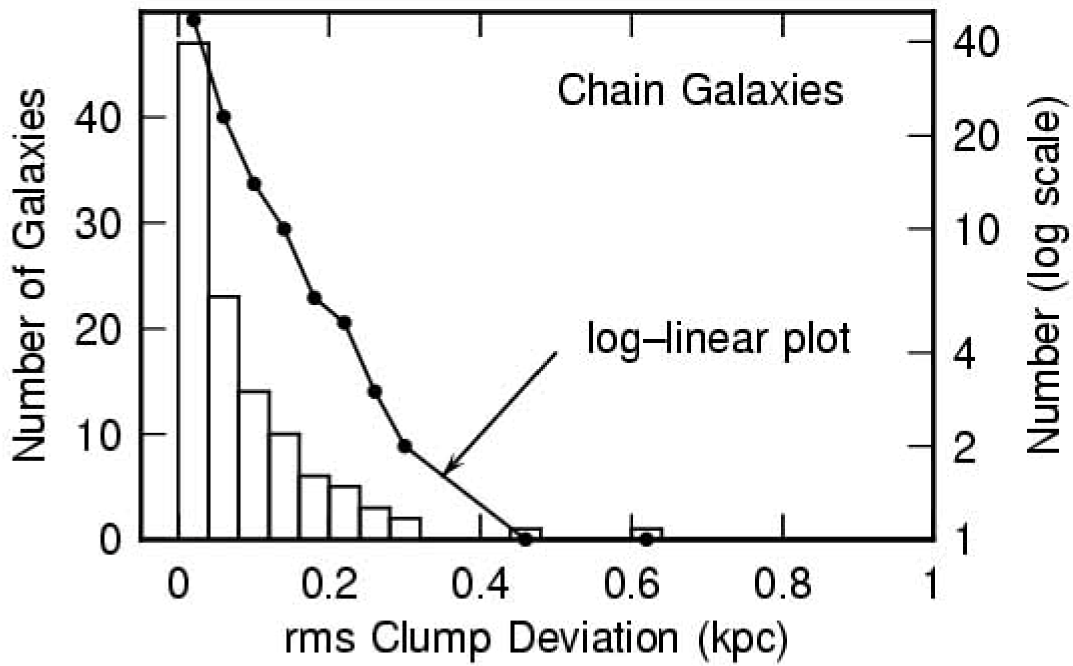


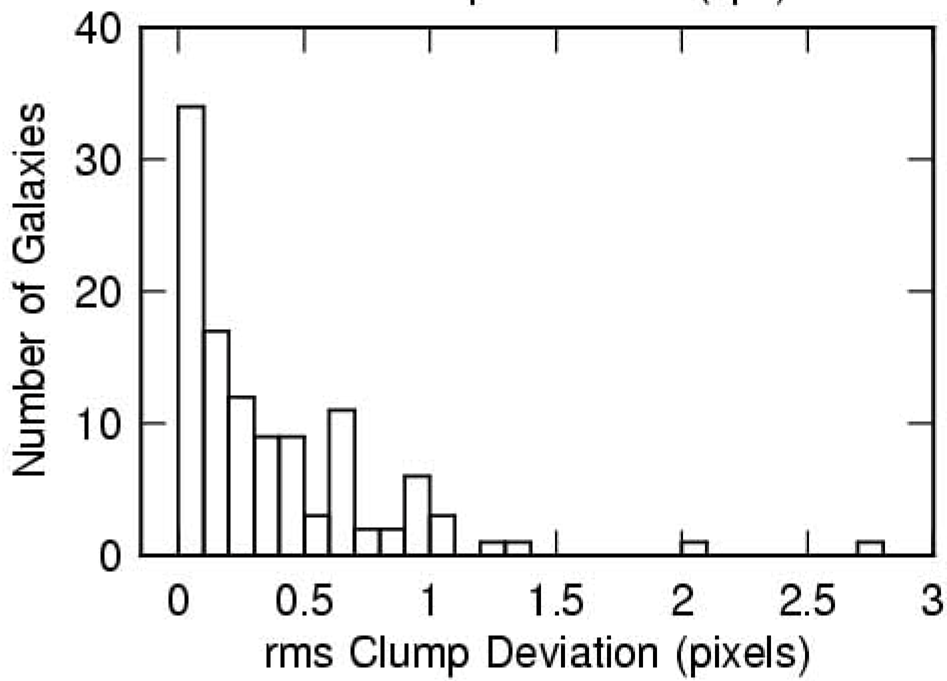


the same for spiral thick disks

The clumps in chain galaxies are also highly confined to the midplanes.

This confinement, more than anything else, makes the clumps look like gravitational instabilities.





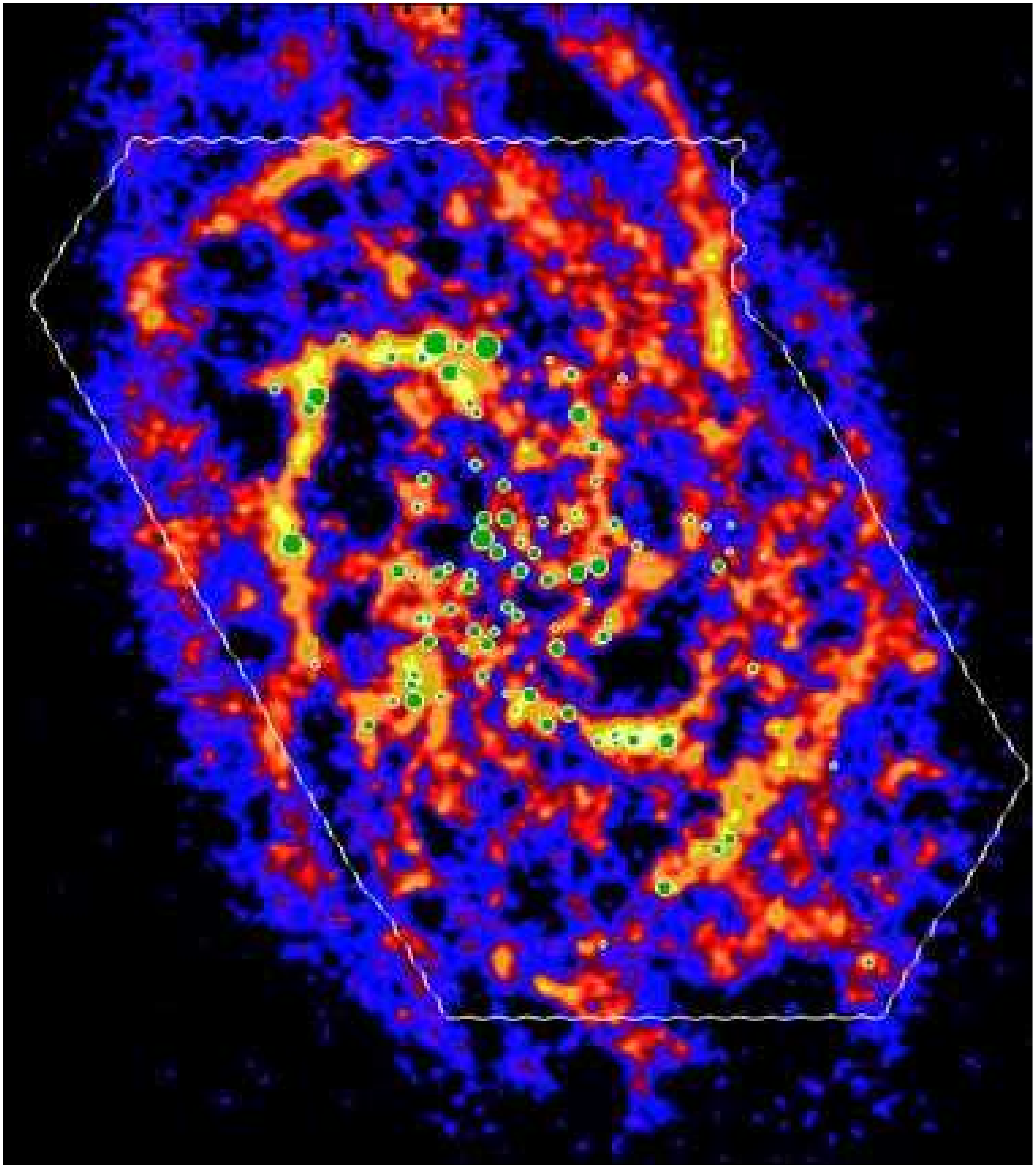
EE06

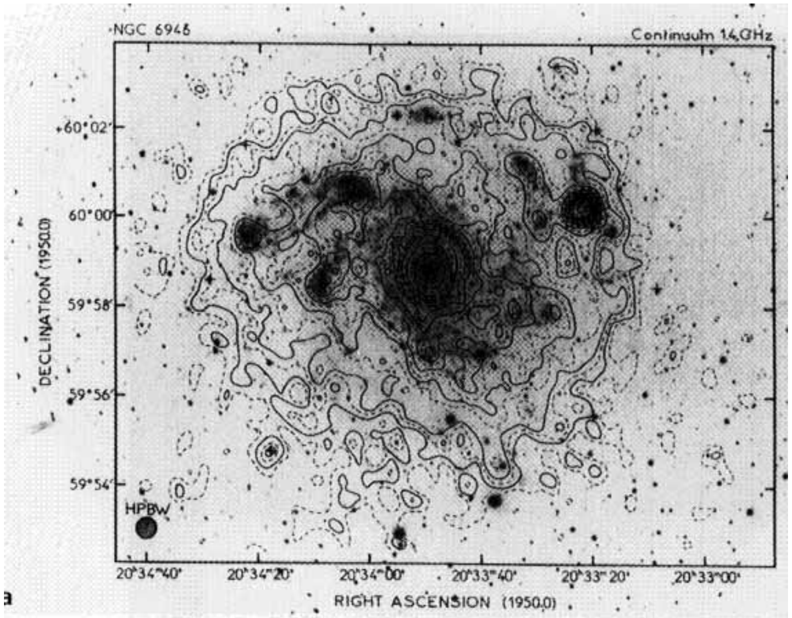

Recall what a gravitational instability
looks like in local galaxies
M33 - Jacoby

CO clouds in M33 are the cores of giant HI clouds.

Giant molecular clouds form by the condensation of giant HI clouds, which probably form by GI ($M \sim 10^7\ M_O$).

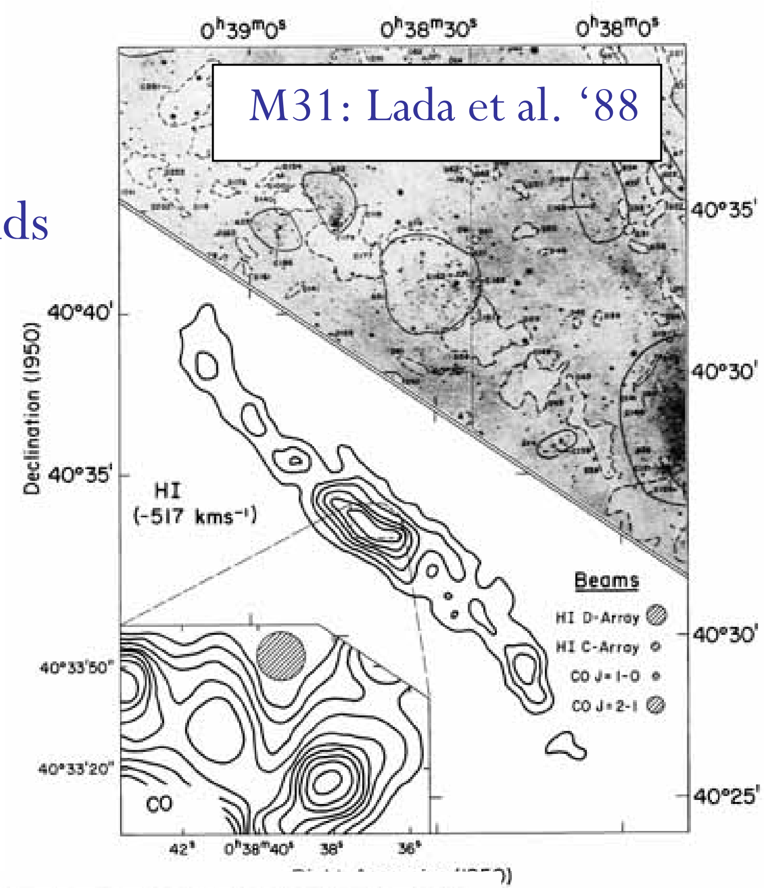
Engargiola et al. 2004



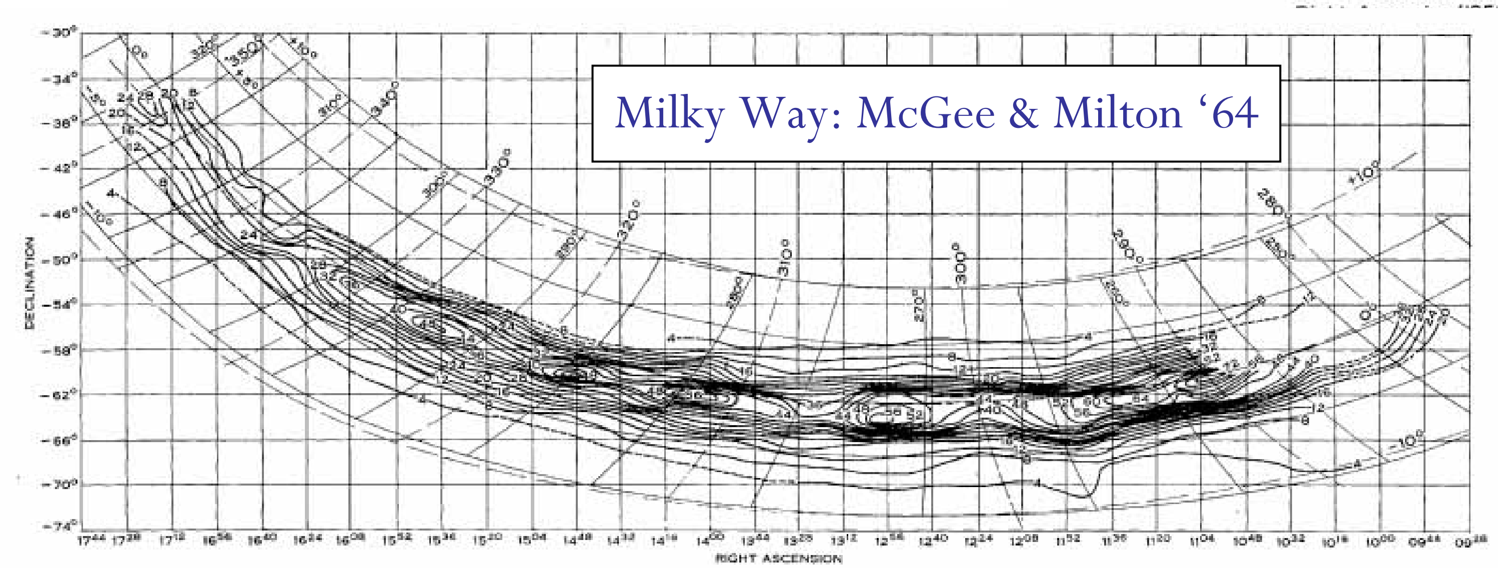


NGC 6946: Boulanger & Viallefond '92

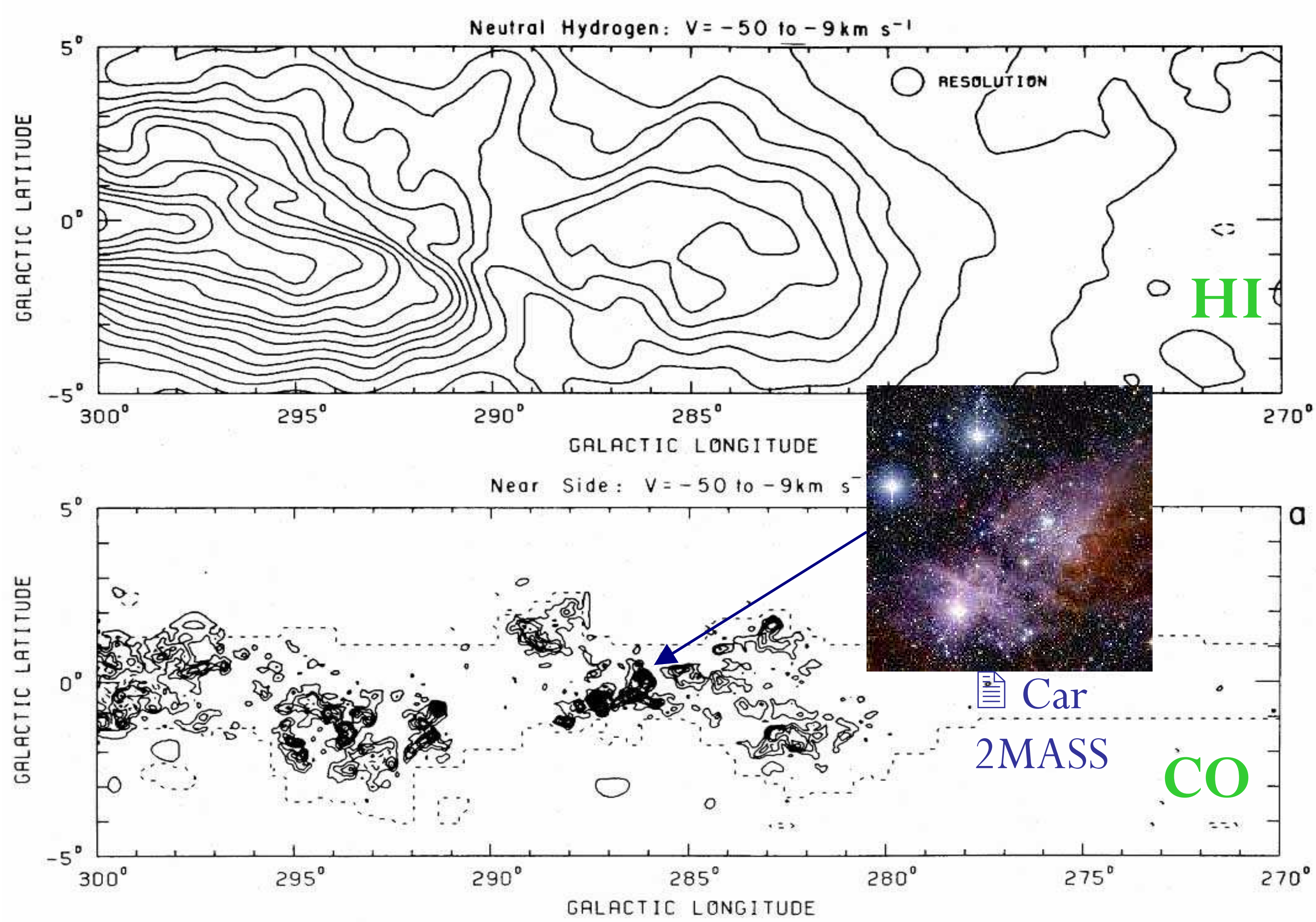
Giant HI clouds have been associated with SF for 40 years.



M31: Lada et al. '88

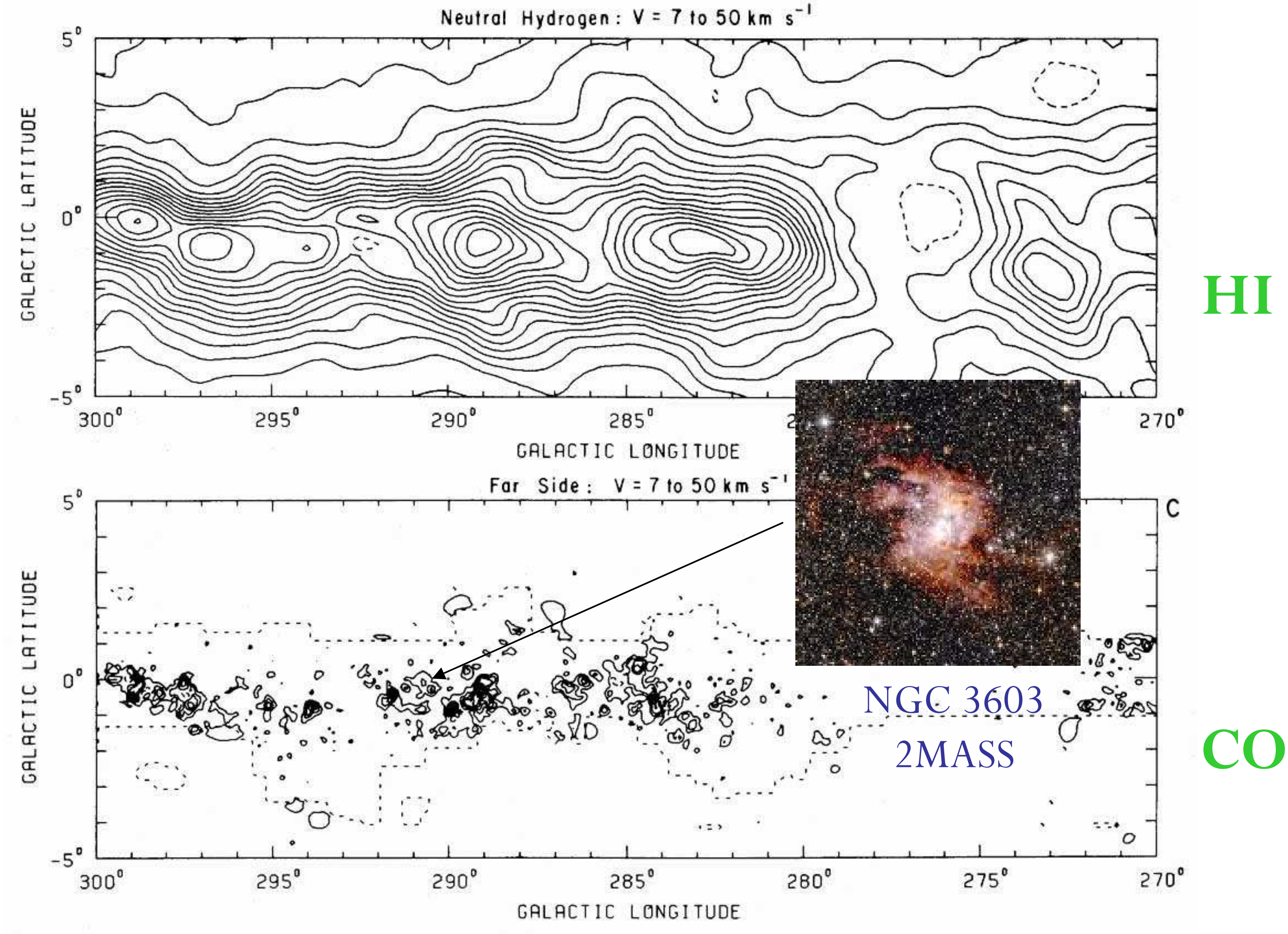


Milky Way: McGee & Milton '64



Atomic clouds with GMC cores line up on the Sagittarius-Carina arm of the Milky Way

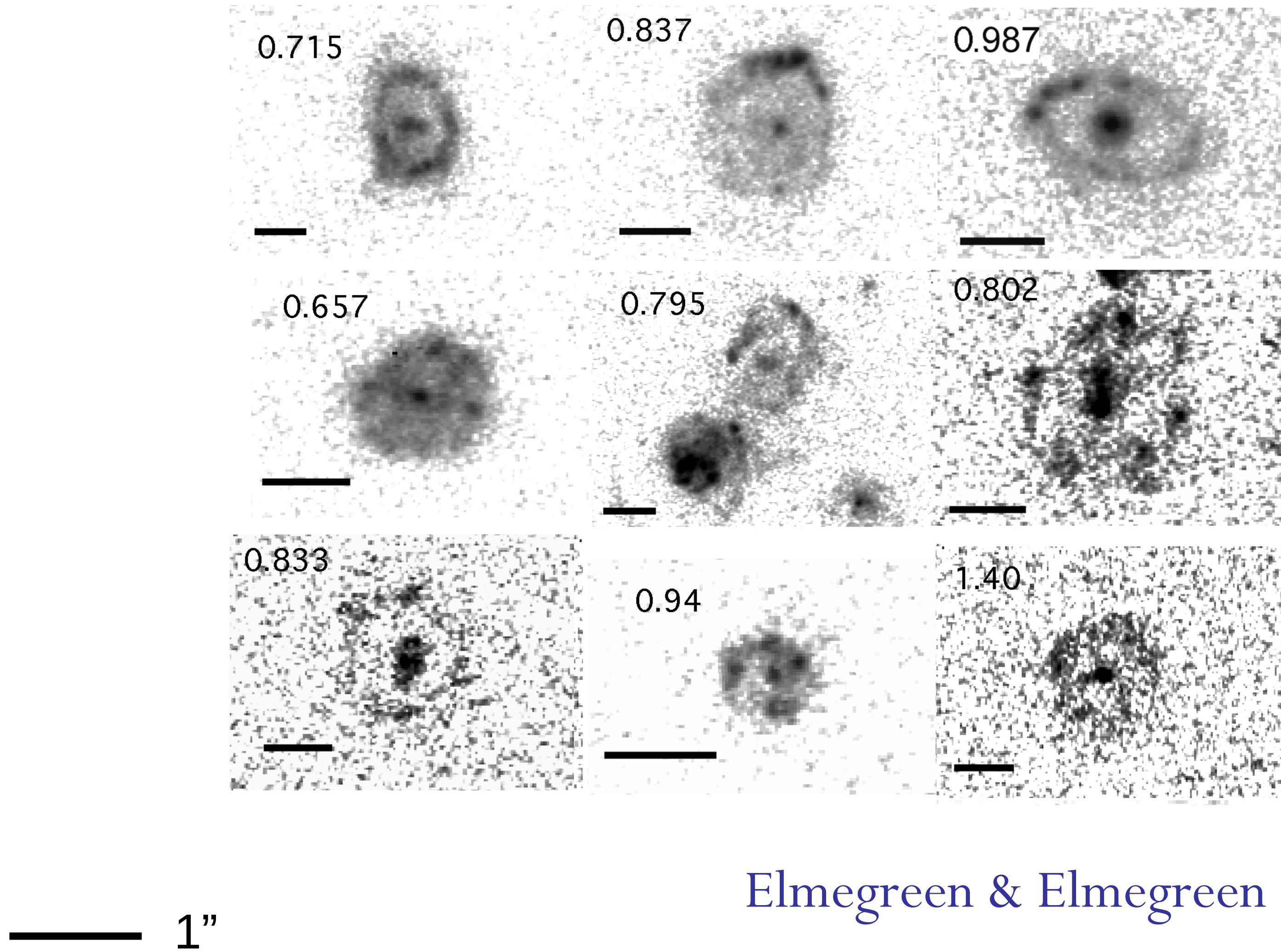
Grabelsky et al. 1987



Most Star Formation in the Milky Way begins in $10^7\ M_O$ clouds

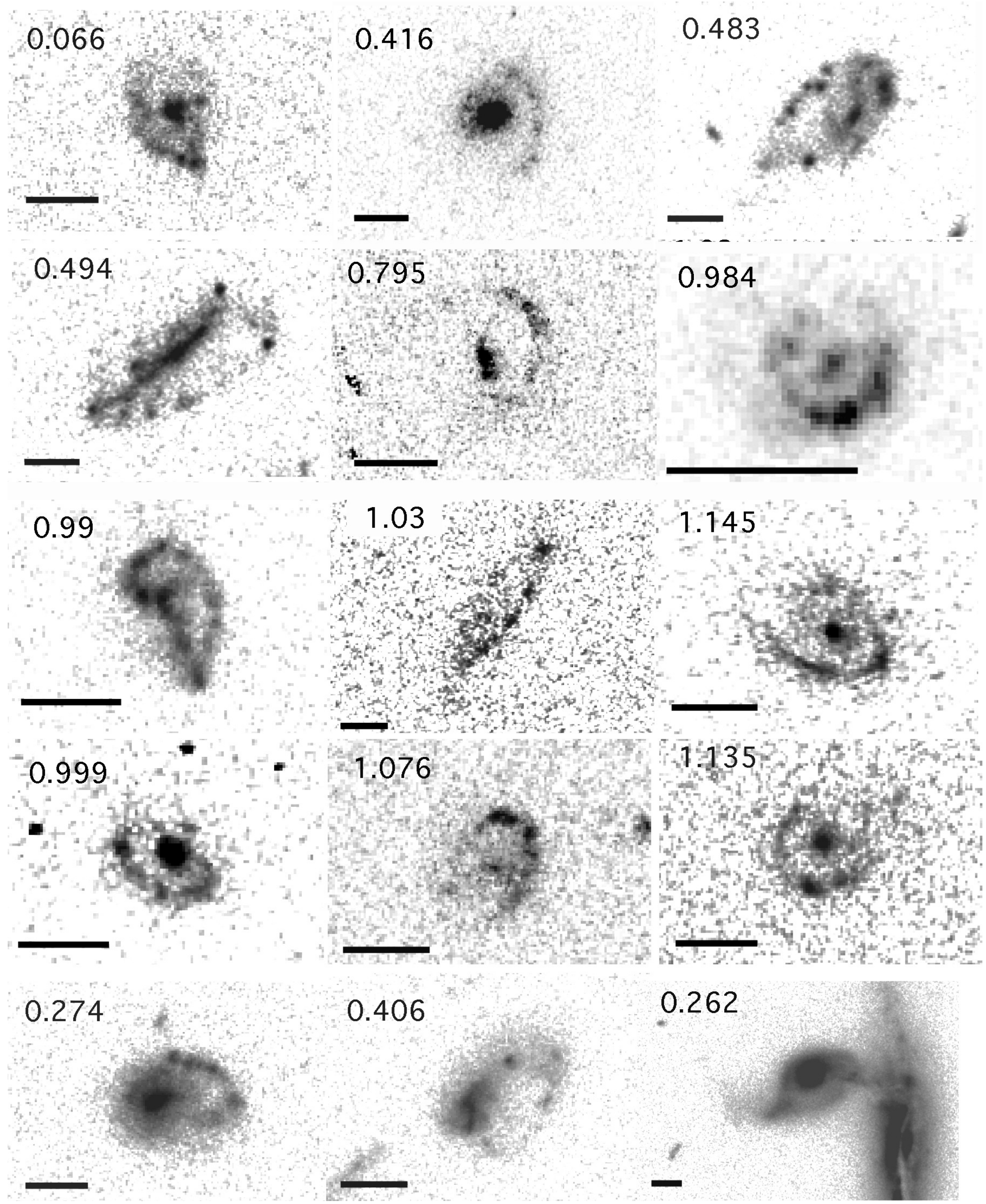
- In high redshift galaxies, the clumps look similar to those in local galaxies, but they are much more massive and there are fewer clumps/galaxy at high-z
  - probably just the result of a higher turbulent velocity dispersion for the instability
- Still, they are star clusters, forming in the midplane, and they apparently dissolve to build up a smooth exponential disk

Big Clumps also in Ring Galaxies in GOODS and GEMS: these are instabilities, not accretions



Elmegreen & Elmegreen 2007

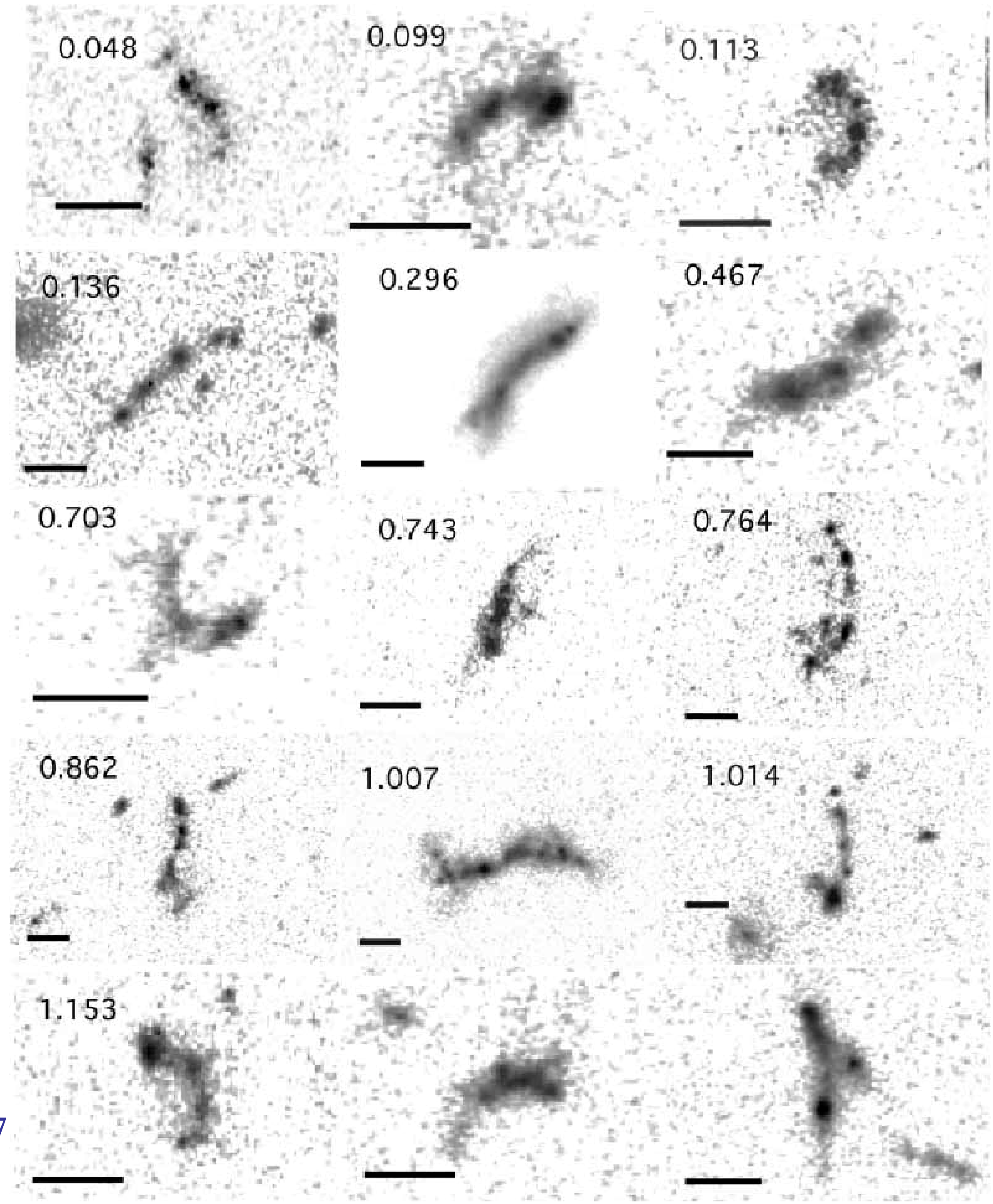
Partial Rings



1”

Elmegreen & Elmegreen 2007

Bent Chains



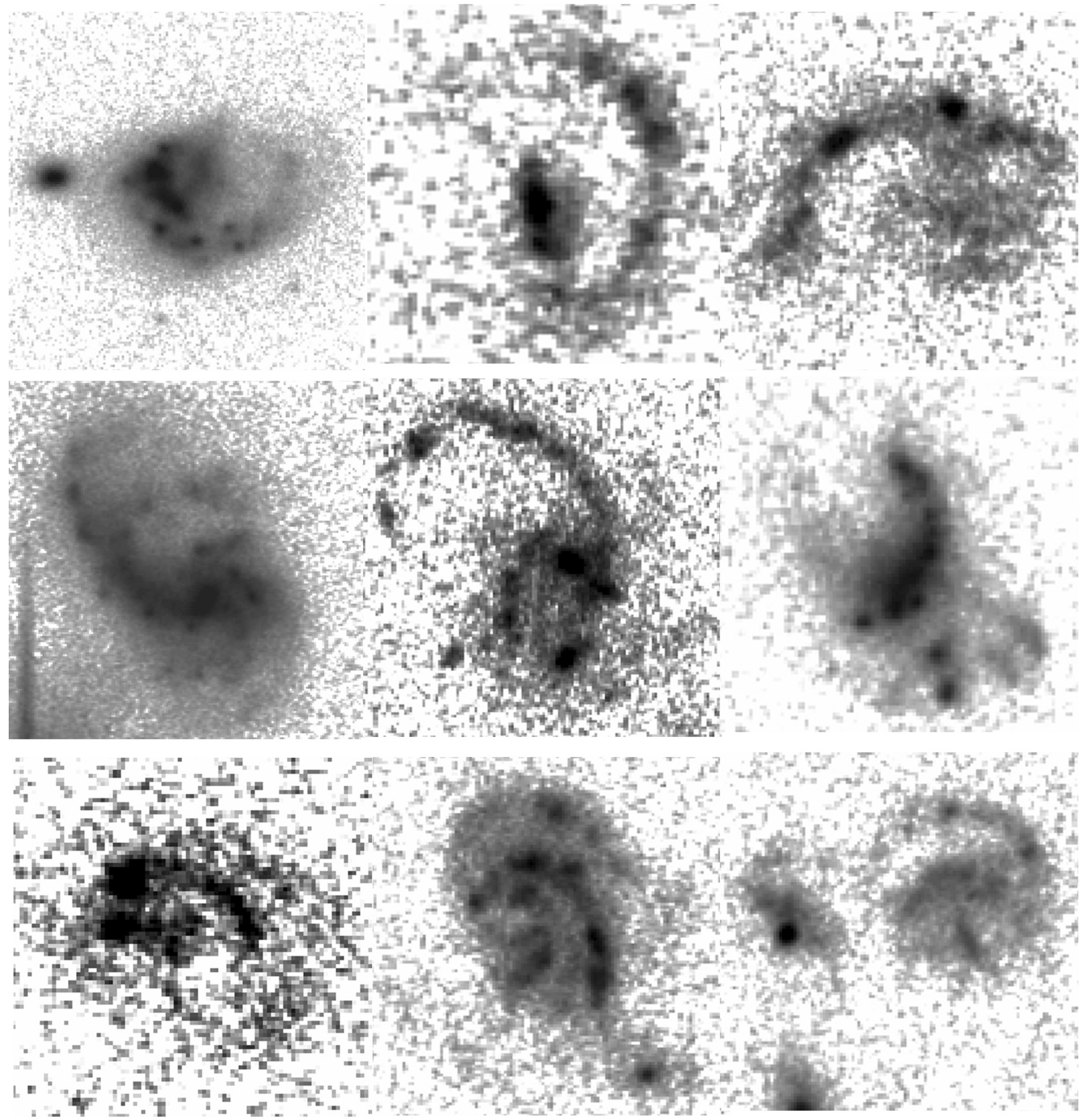
1”

Elmegreen & Elmegreen 2007

“Shrimps”

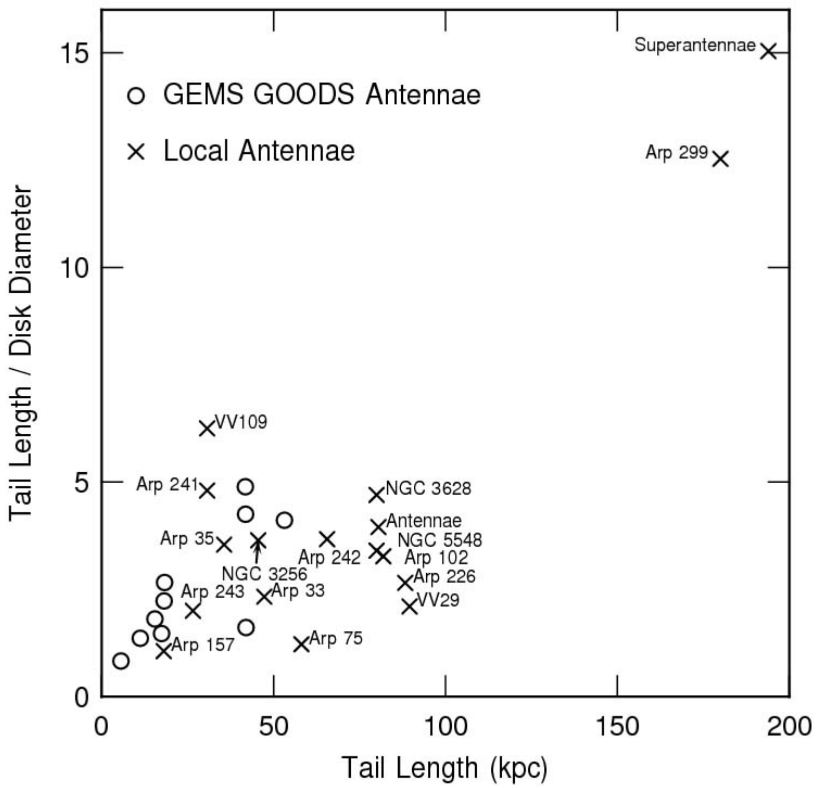
Mass & separation of clumps gives velocity dispersion and column density of gas.

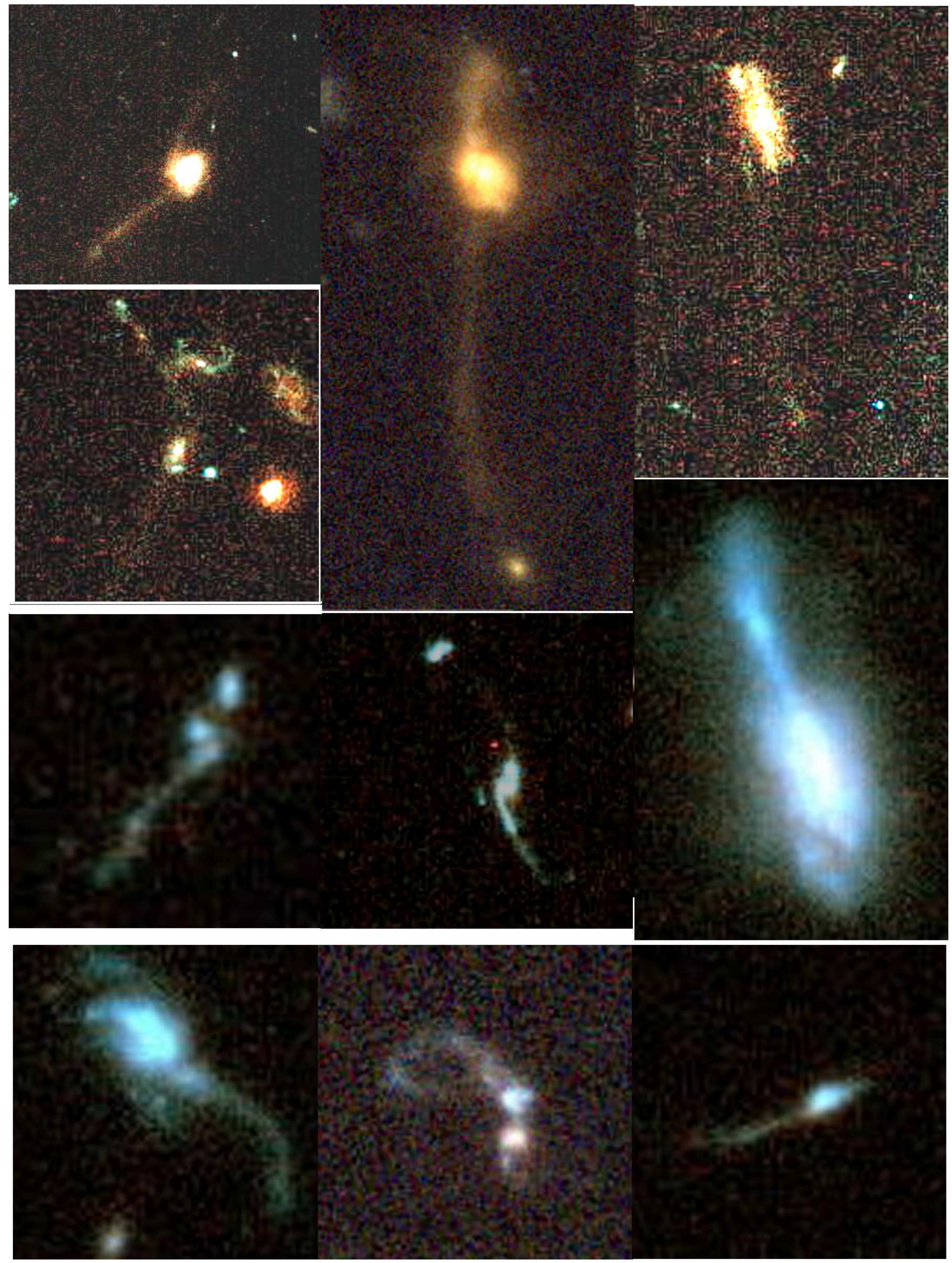
x5, and x25 of local gal.



Elmegreen, Elmegreen, Ferguson, Mullan 2007

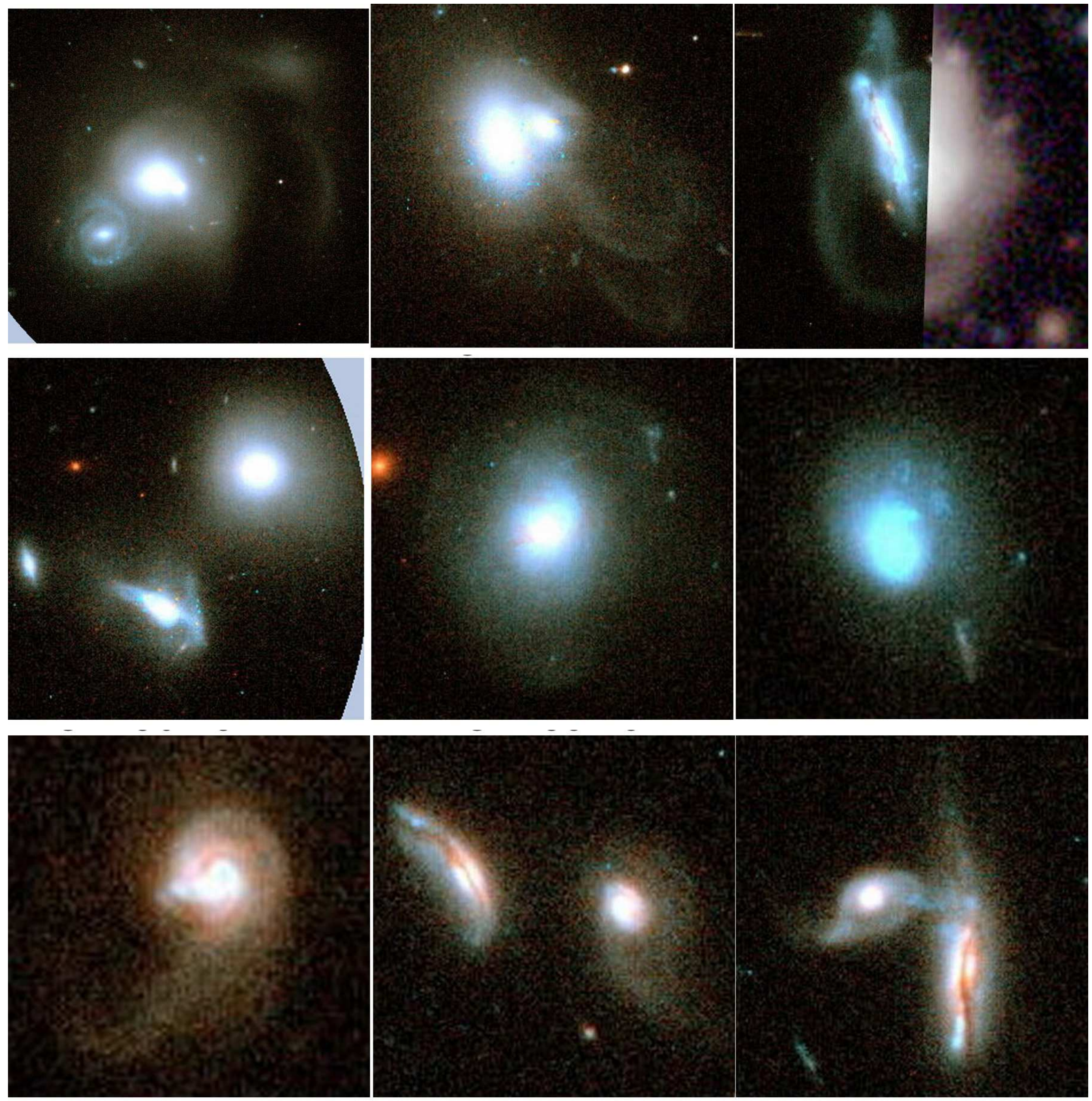
Antennae





Elmegreen, Elmegreen, Ferguson, Mullan 2007

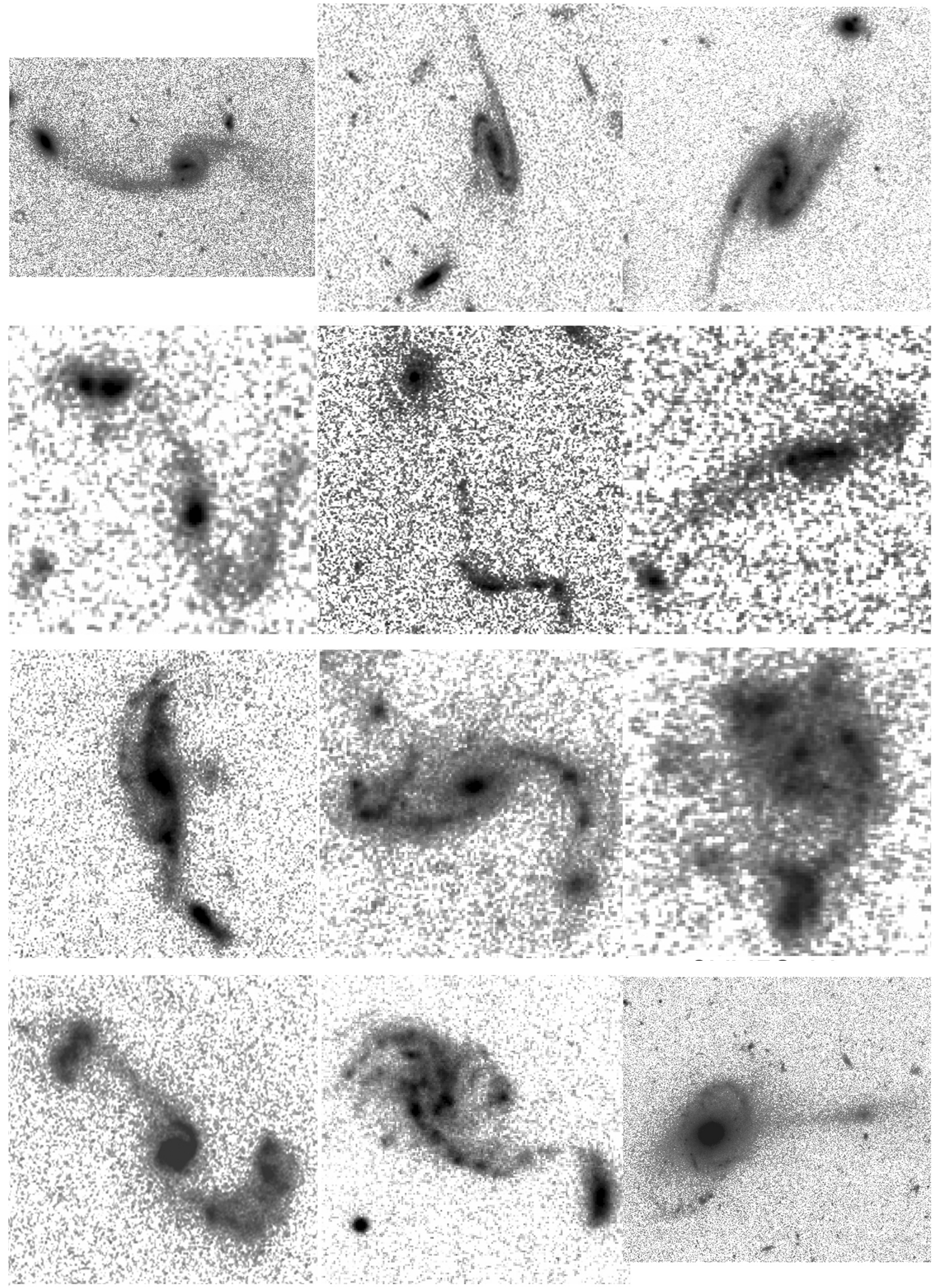
Diffuse interactions



Note big diffuse tidal clump. First example of tidal dwarf formation in a pure stellar tail

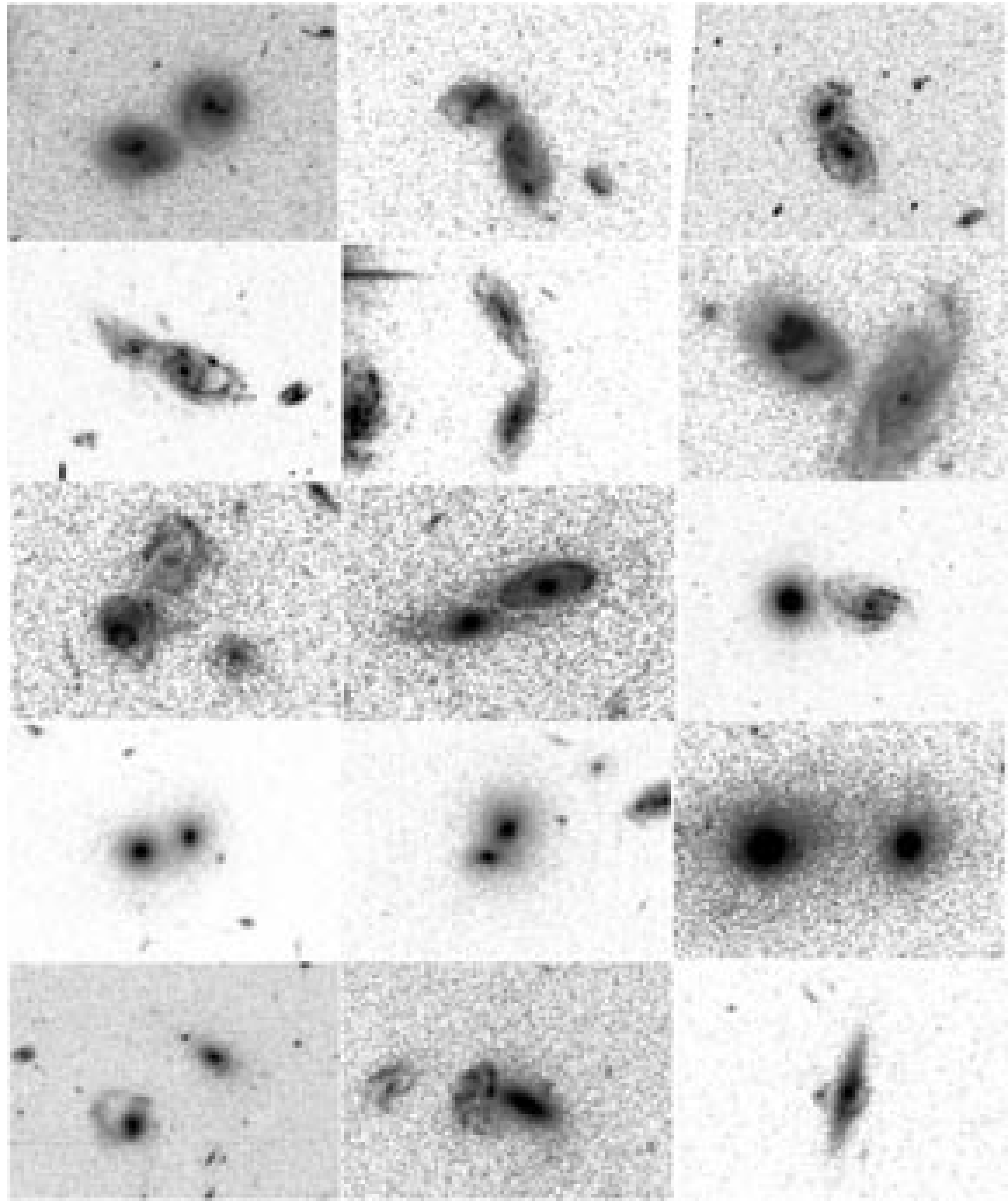
Elmegreen, Elmegreen, Ferguson, Mullan 2007

M51 types

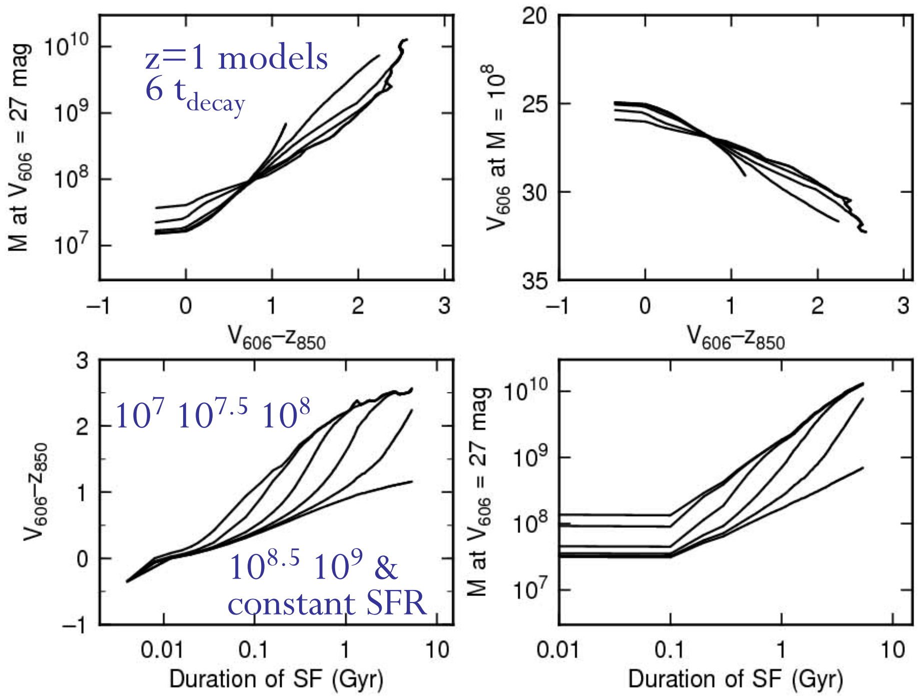


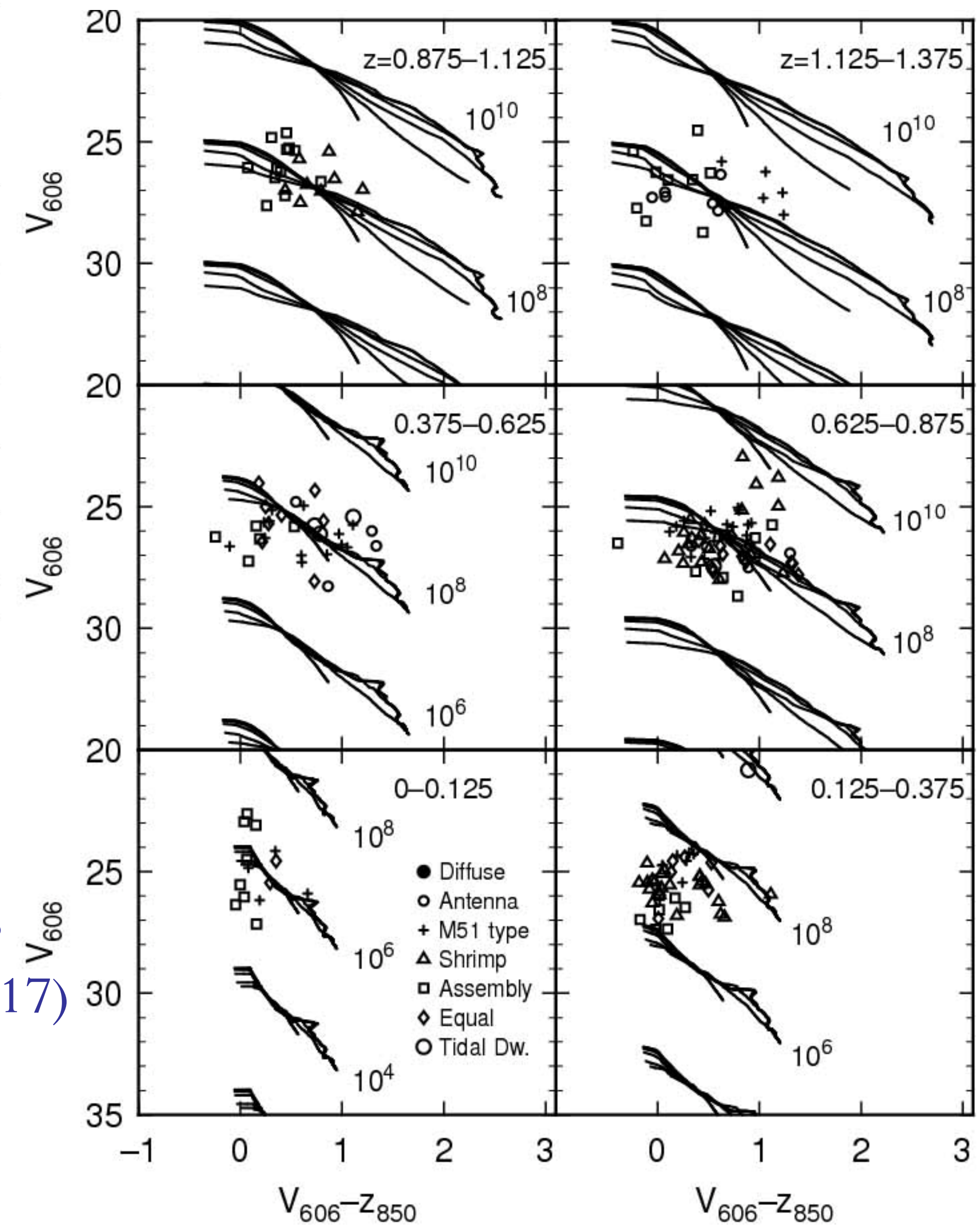
Elmegreen, Elmegreen, Ferguson, Mullan 2007

Equal-mass pairs



Elmegreen, Elmegreen, Ferguson, Mullan 2007





GEMS has 2 ACS filters: V and V-z

These are enough to estimate the mass given a photometric redshift (COMBO17)

evolution from Bruzual & Charlot ‘03

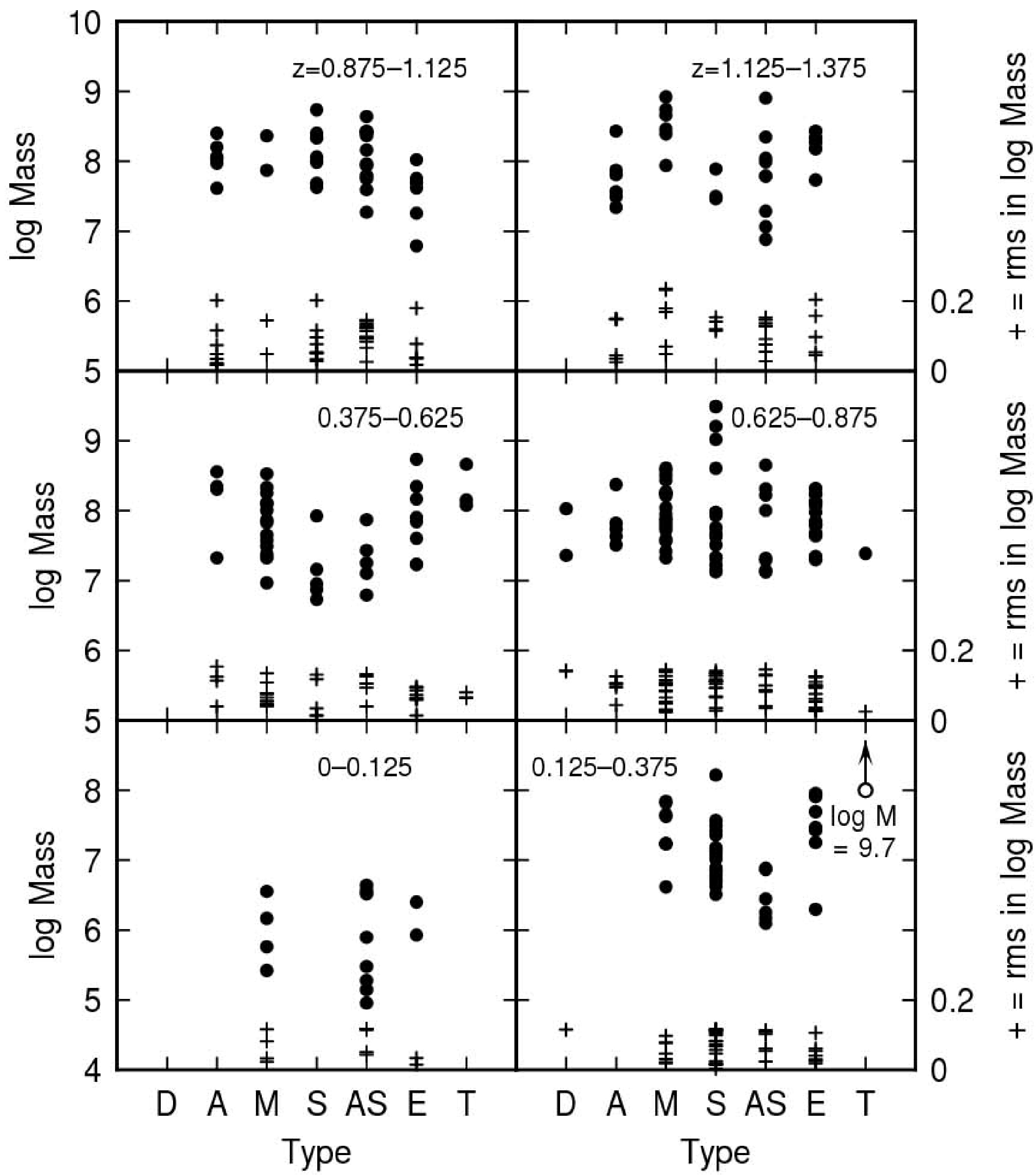
Rowan-Robinson (2003) extinction

Madau ’95 intergalactic H absorption

Calzetti/Leitherer extinction curve

Elmegreen, Elmegreen, Ferguson, Mullan 2007

Clump masses for each type for redshift bins



Elmegreen, Elmegreen, Ferguson, Mullan 2007

UDF Galaxies and star formation vs. z

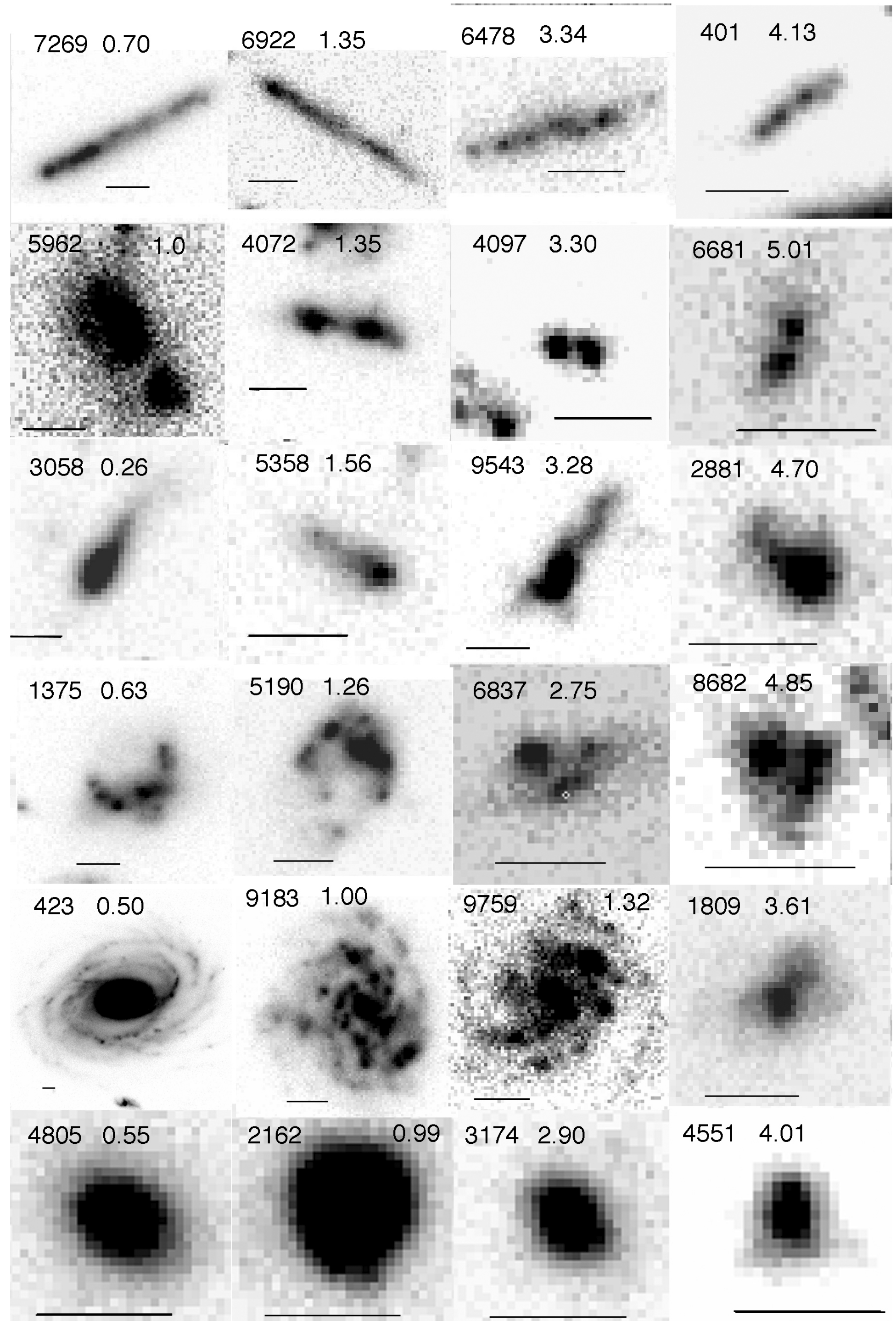
Consider only galaxies with diameters>10px and surface brightness < 26.0 mag arcsec^{-1} (2-sigma)

121 chains, 134 doubles, 192 clump clusters, 114 tadpoles, 313 spirals, and 129 ellipticals

Use photometric redshifts from Coe et al.

Uncertainty: $\Delta z \sim 0.04(1+z)$, include only $\chi_{mod}^2<1$ and stel<0.8

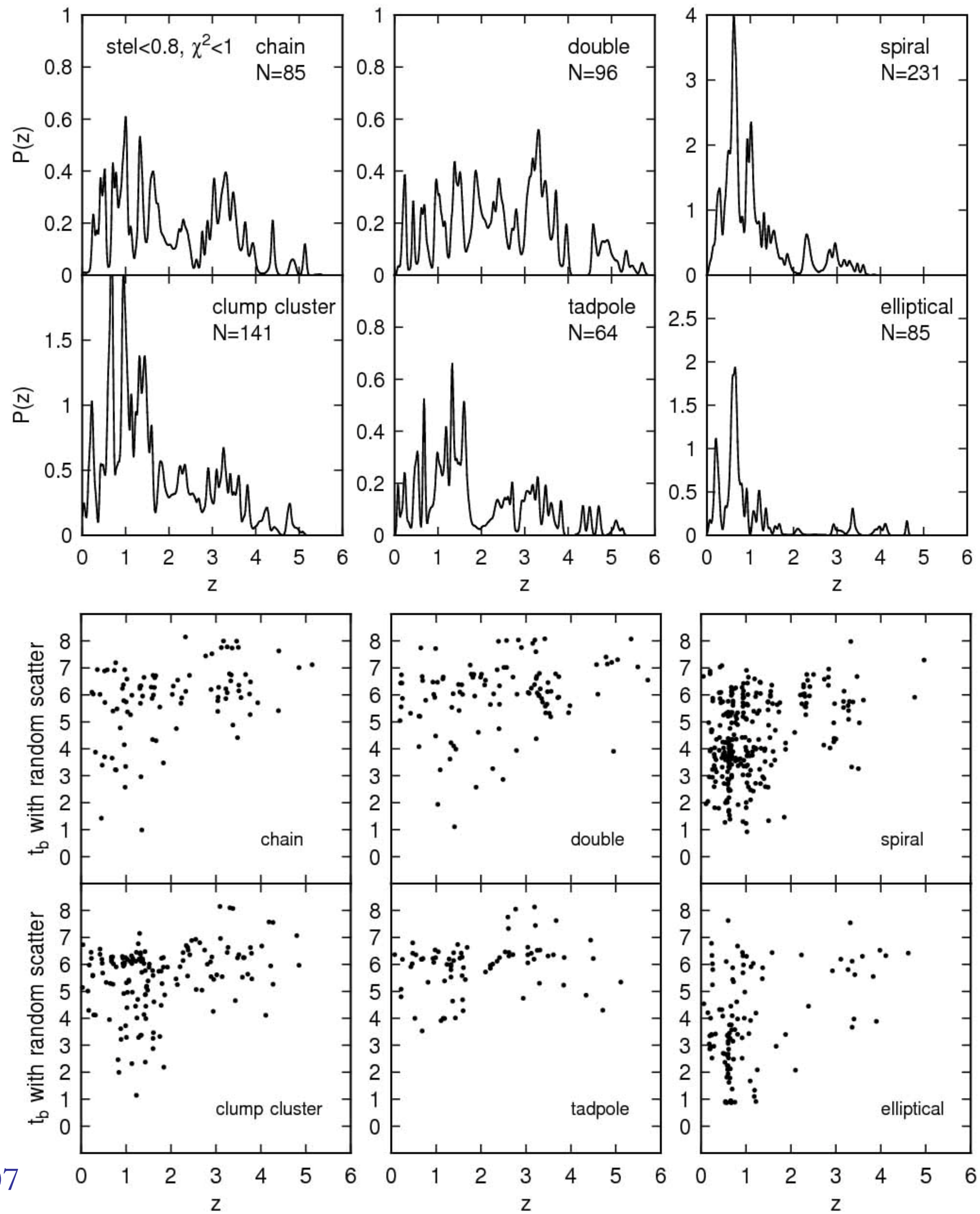
Elmegreen, Elmegreen, Ravindranath, Coe 2007a



Spirals and Ellipticals restricted to z<2 (a result of bandshifting of red disks out of the ACS z filter)

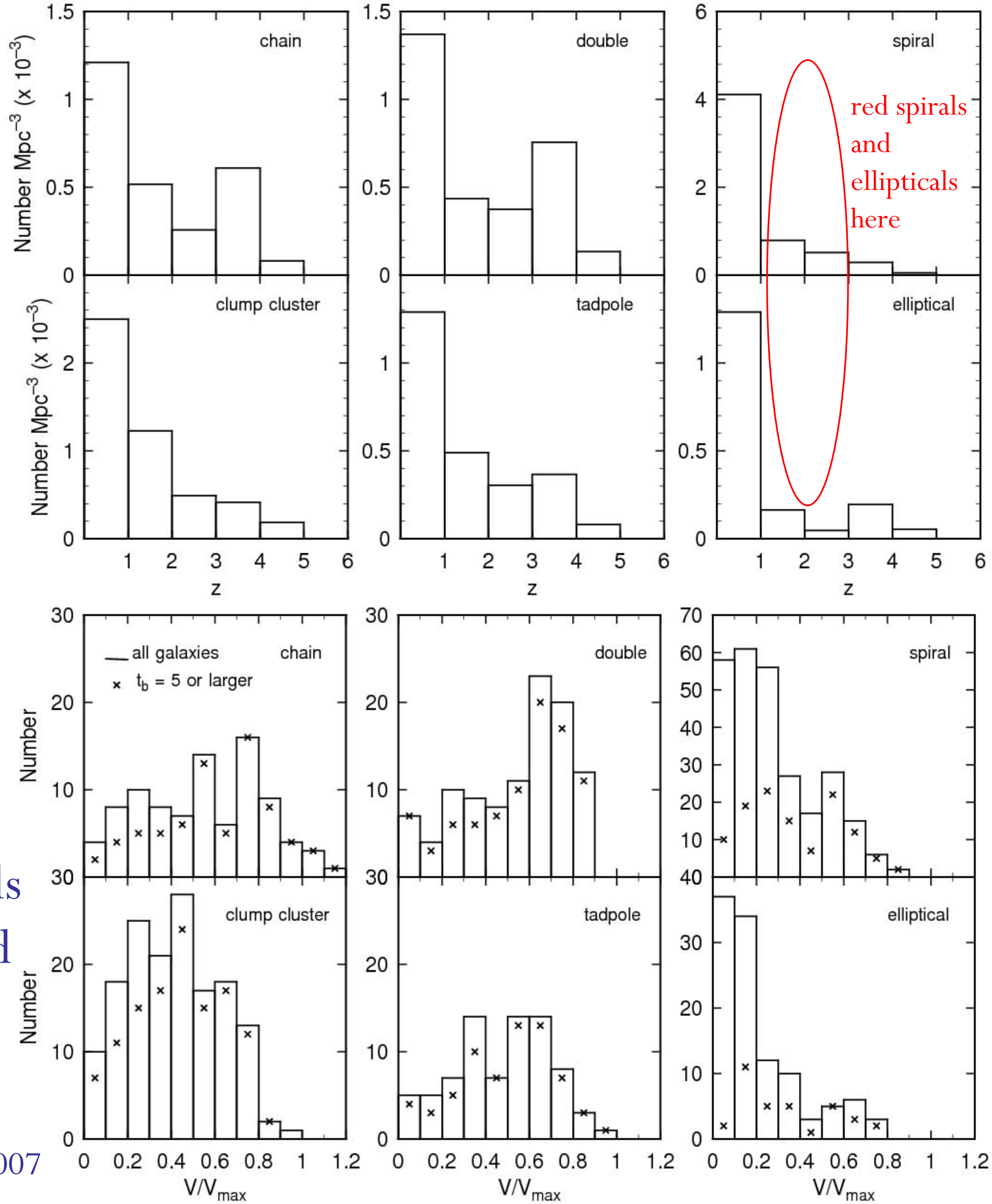
Clumpy types are highly starbursting and remain visible in the ACS out to z~5. Only the starbursting spirals and ellipticals are visible at z~5.

Starbursting & clumpy (= "forming" galaxies) occur for a wide range of z.



Elmegreen, Elmegreen, Ravindranath, Coe 2007

Spirals and Ellipticals fall off quickly with z or V/Vmax, but the clumpy types remain.



All spirals and ellipticals from z~3 to today could have begun as c-c/chain galaxies

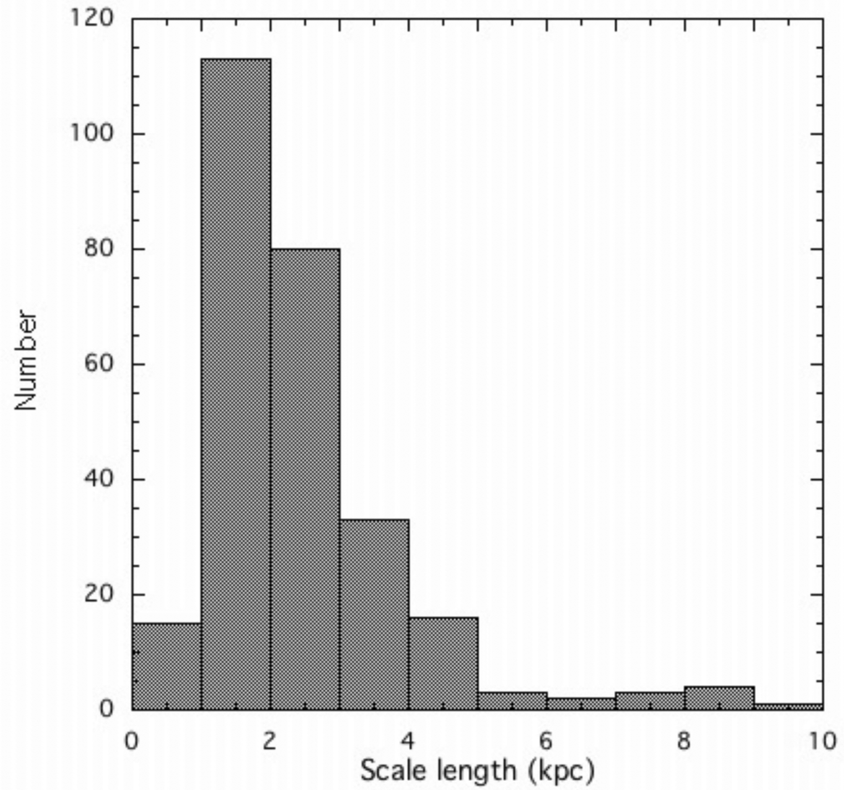
- isolated ones made spirals
- coalescence makes ellipticals

Oldest galaxies: massive & red at z~4 (Rodighiero et al 07)

Elmegreen, Elmegreen, Ravindranath, Coe 2007

Linear spiral scale lengths

UDF



Nearby

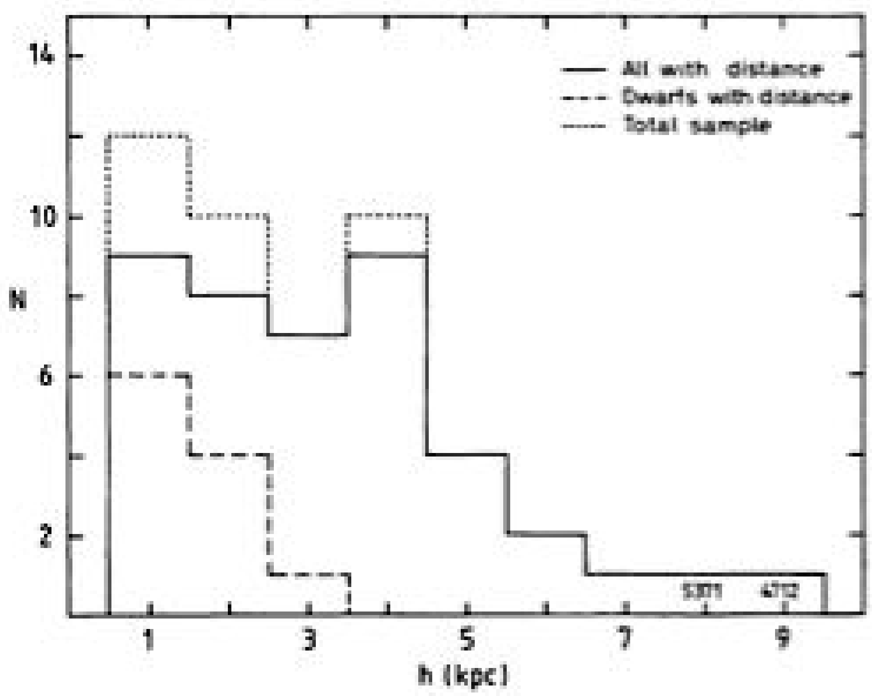
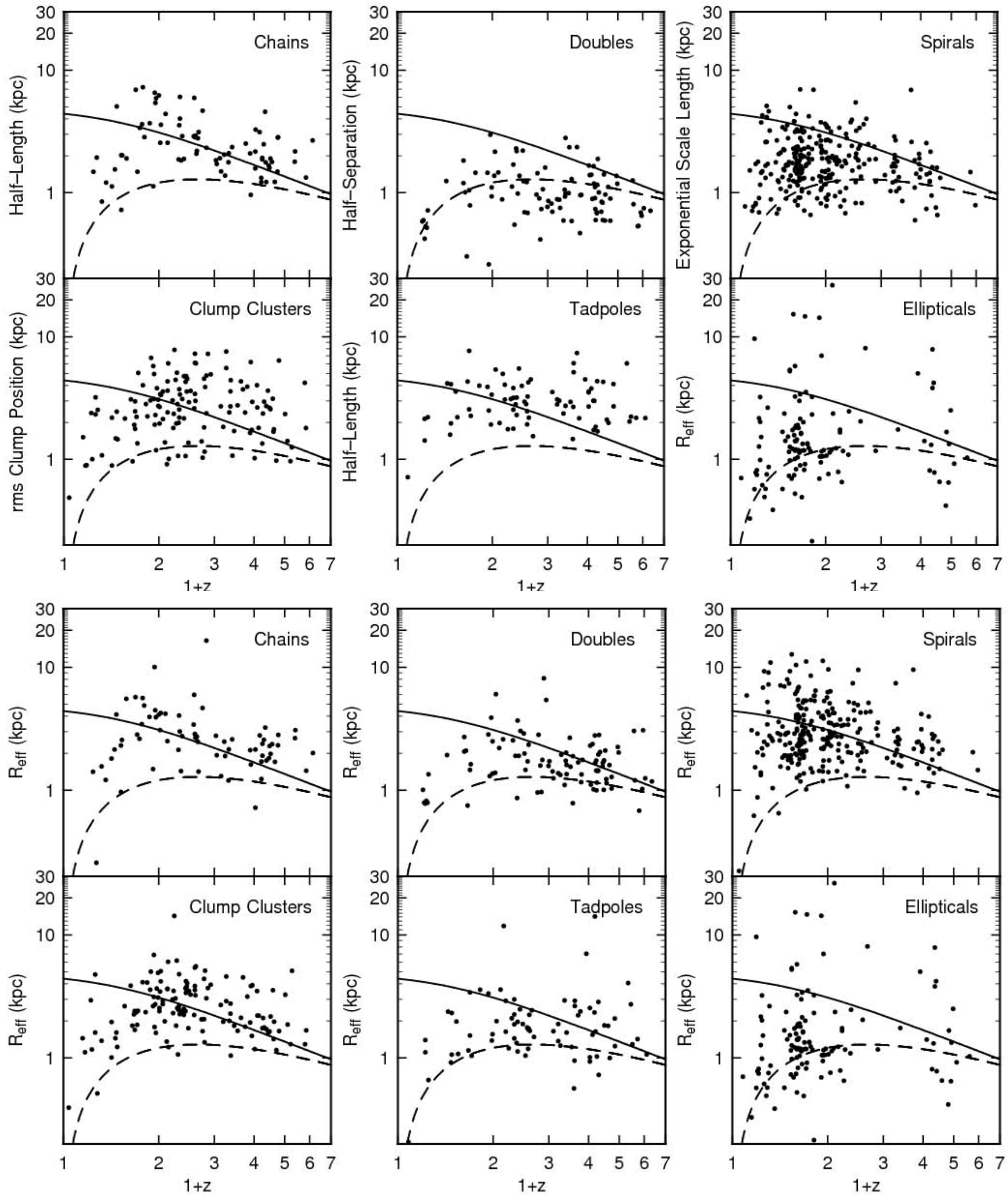


Fig. 8. Histogram of the distribution of scalelengths in the sample. The full-drawn lines refer to the subsample for which radial velocities are available and the dwarfs in this sample have been indicated with the dashed lines. The dotted lines indicate the distribution for the remaining galaxies in the sample using estimated distances. NGC 5371 and 4712 have disks that are only exponential over a small range of scalelength

van der Kruit 1987 A&A, 173, 59

Spirals and Chains get smaller with z. Other types don't show clear evidence for changes here.

Small spirals at high z means inner parts of disks (i.e., dense), not like today's dwarfs



Elmegreen, Elmegreen, Ravindranath, Coe 2007

Conclusions

- High z galaxies include spirals and ellipticals (both unusually clumpy) as well as nearly pure-clump galaxies (chains, clump-clusters, tadpoles, doubles)
- Some clumps may enter a galaxy from outside, but most appear to form by gravitational instabilities
  - clump masses are large because the turbulent speeds are large (25-50 km/s)
  - evidence for GI: clump sizes~disk thicknesses, midplane position, rings, spirals
- Dispersal of clumps builds the first exponential disk and the bulge
- Clumpy disks may go back in z further than any other type
  - suggest ellipticals at z~2-3 form by mergers of clumpy disks
  - suggest spirals evolve from isolated clumpy disks
  - suggest all star formation occurs in disks (no 3D "monolithic collapse" mode)