Review of Theory

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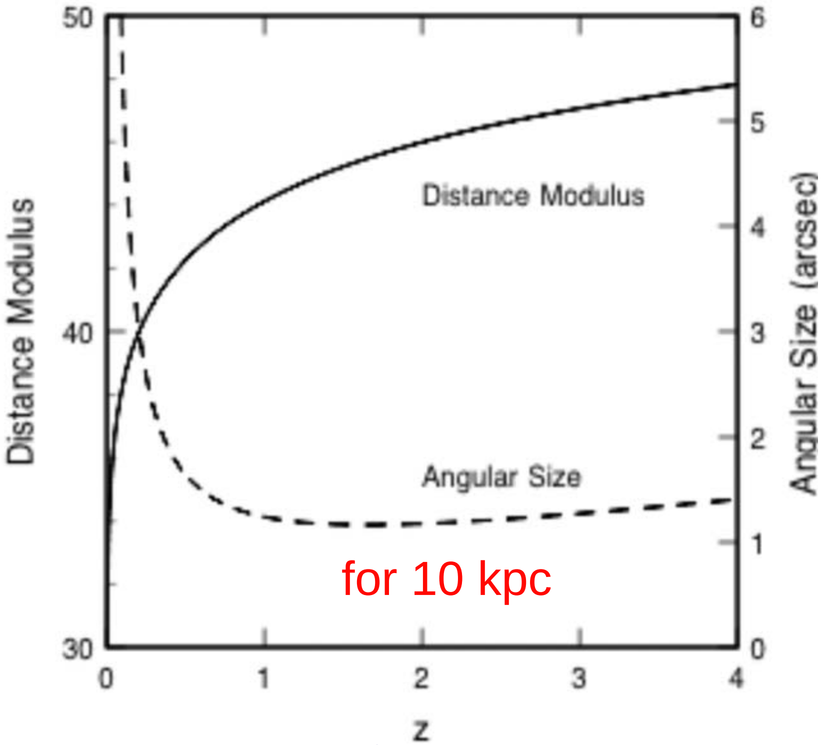
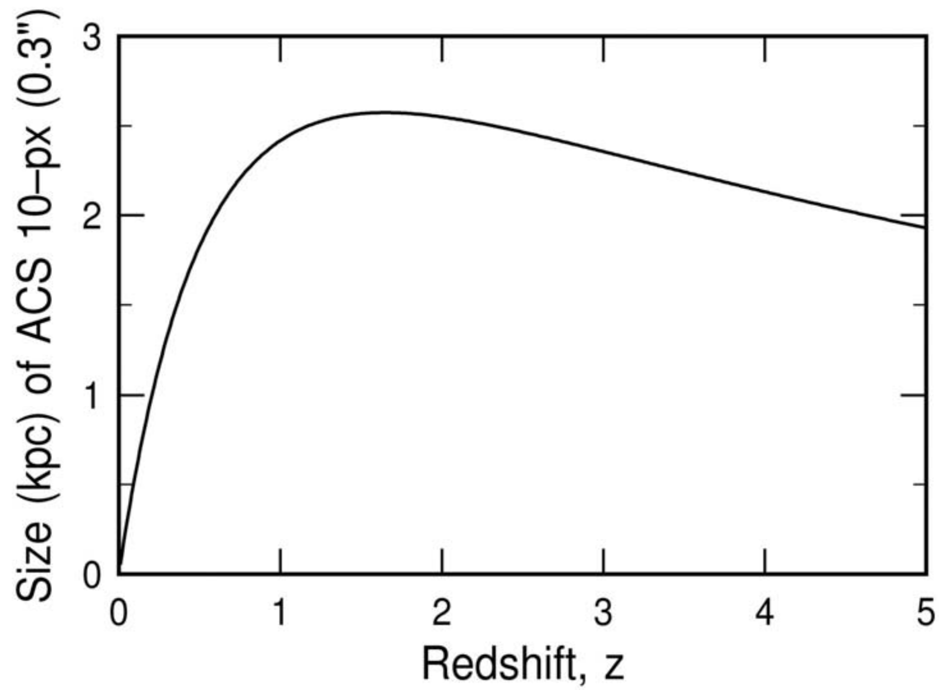
based on a collaboration with Debra Meloy Elmegreen

Local Star Formation: Many Modes

- Gravitational instabilities in the ISM
  - swing amplified stellar and gaseous spiral arms with knots of SF
  - beads on a string from parallel gas instabilities in stellar spiral arms & modes
  - pure gas instabilities (flocculent spirals)
  - feathers/spurs from parallel gas instabilities in thin SDW shocks
  - characteristic mass ~ 10^7 M_O
- Secondary instabilities inside the 10^7 M_O clouds
  - GMCs, GMC cluster-forming cores, etc.
- Gravitational instabilities inside swept-up shells, layers, comets, …
- Direct compression of globules and residual cloud clumps
  - HII regions, winds, supernovae, pre-main sequence winds and jets, …
- Gravitational instabilities in compressed regions between colliding clouds
  - shock-shock collisions in a turbulence framework
- Gravitational instabilities inside turbulence-compressed and shocked regions,
- your other favorites ….

What can we see at high redshift?





Size vs z for ΛCDM model: 3 pixels of ACS ~ 700 pc from z=1-4

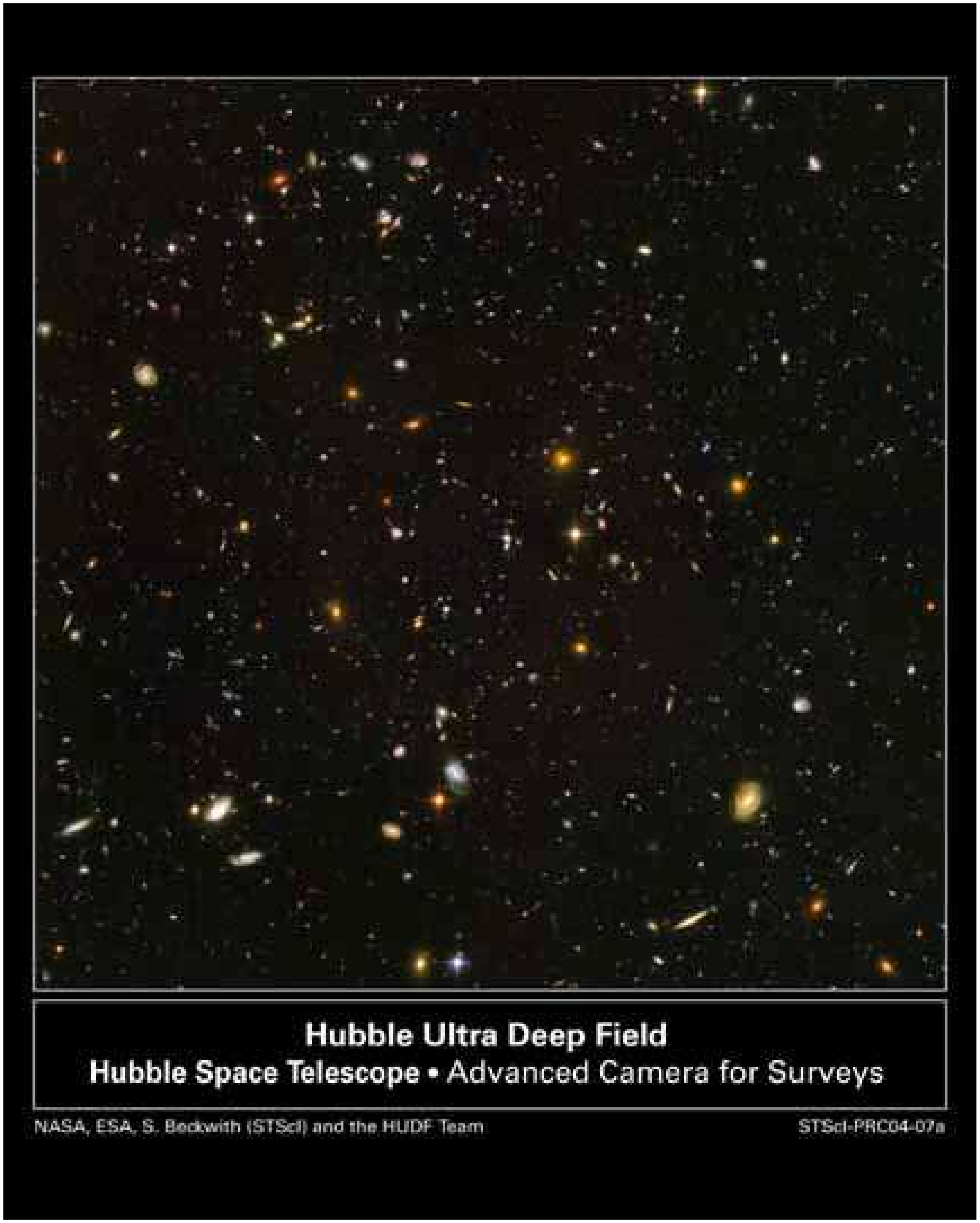
…. cannot see shells, supershells, comets, turbulence

can only see kpc-scale instabilities if there are any

The Ultra Deep Field

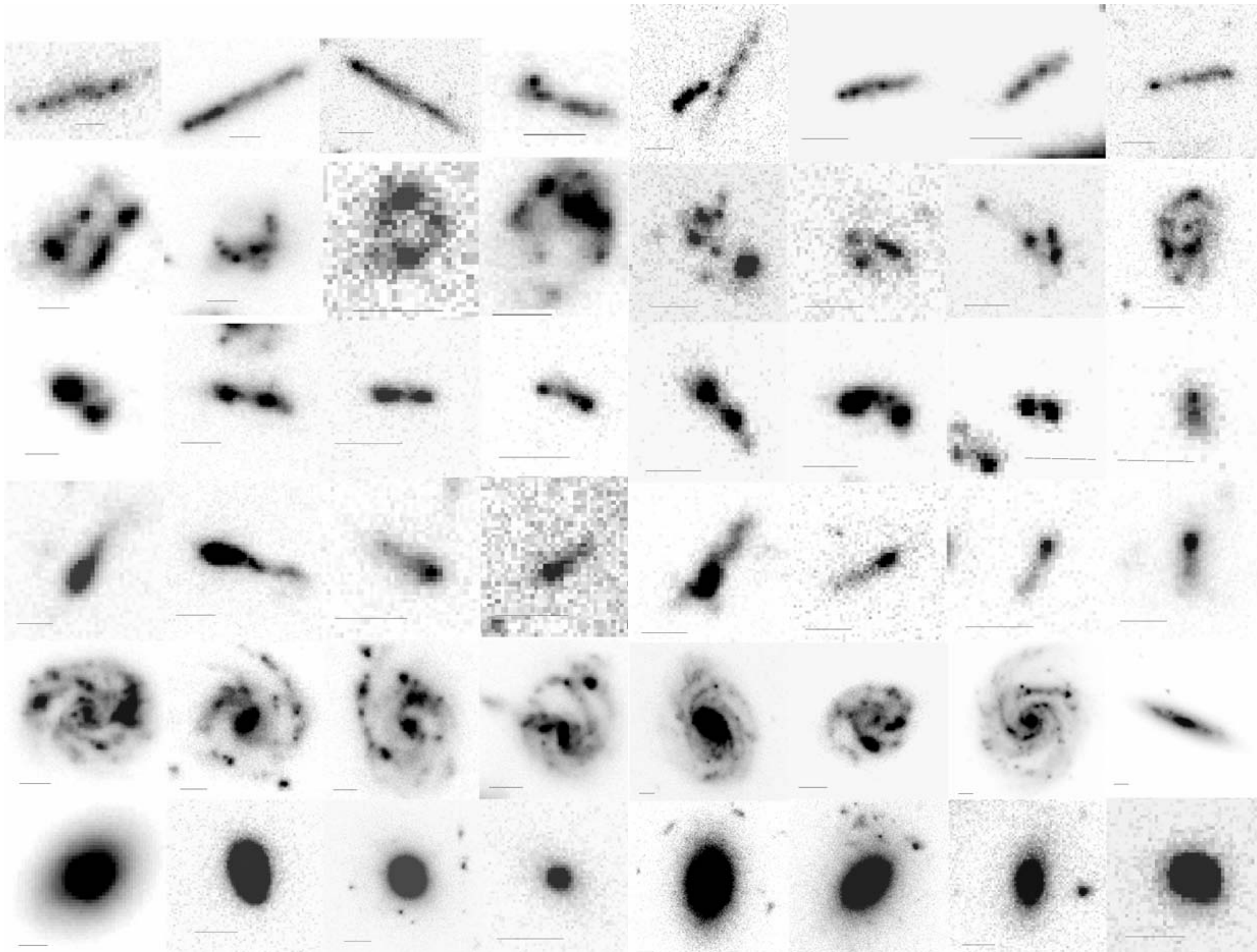
The UDF is 270 hours of exposures in 4 wavelength intervals (B,V,i,z; 350 orbits)

The deepest high resolution image ever taken by Hubble



Resolved Galaxies are more clumpy in the UDF

- Chain
- Clump cluster
- Double
- Tadpole
- Spiral
- Elliptical



—— = 0.5”

(E,E, Rubin, Schaffer 05)

UDF Morphologies

- Among all UDF galaxies with diameters>10px and surface brightness < 26.0 mag arcsec^{-1} (2-sigma), there are
  - 121 chains
  - 192 clump clusters
  - 134 doubles
  - 114 tadpoles
  - 313 spirals
  - 129 ellipticals

- All are unusually clumpy, even the ellipticals
- Chains/clump clusters are apparently precursors of spirals

The clumps are star forming regions

•**Chain**

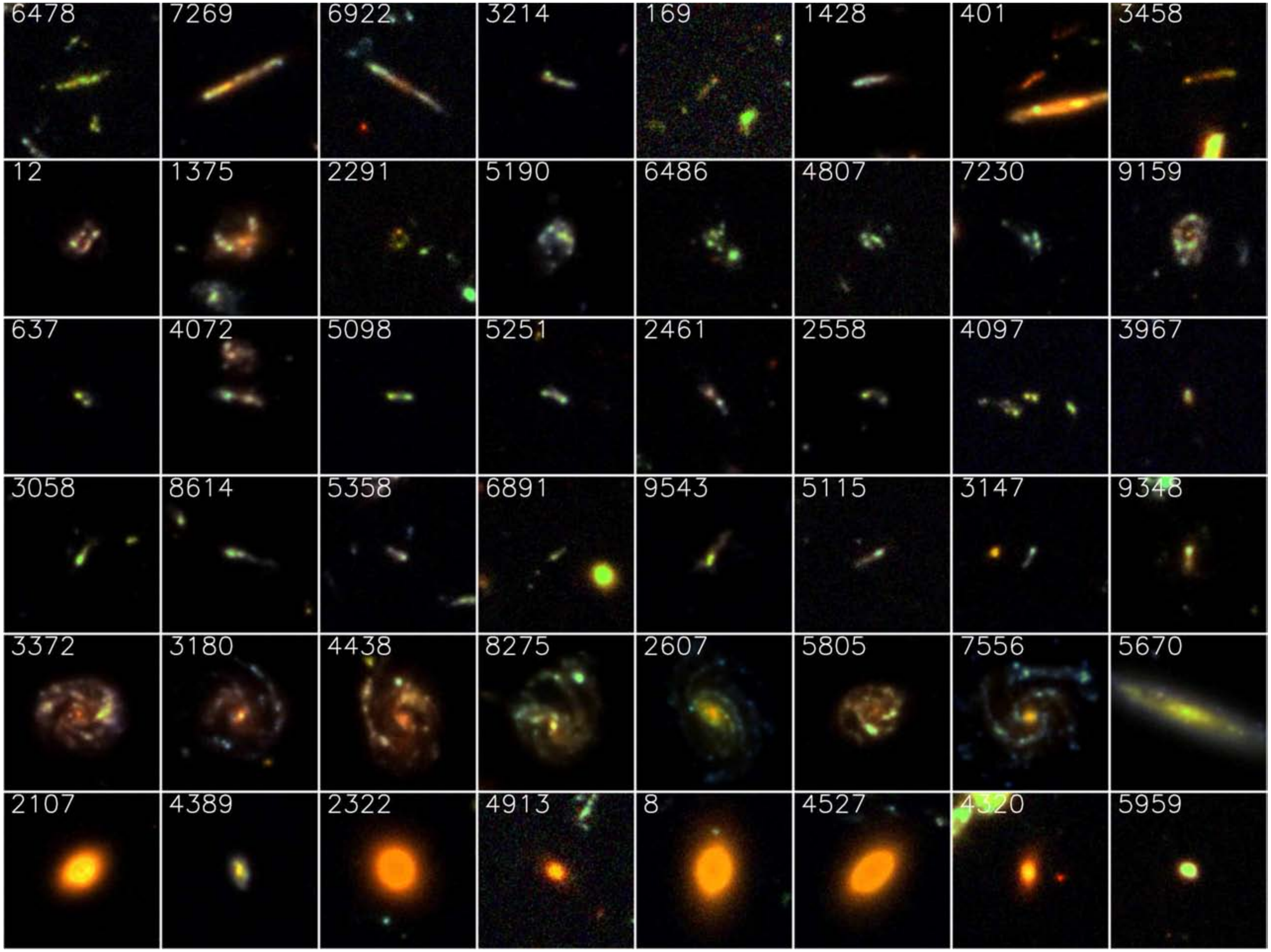
•**Clump cluster**

•**Double**

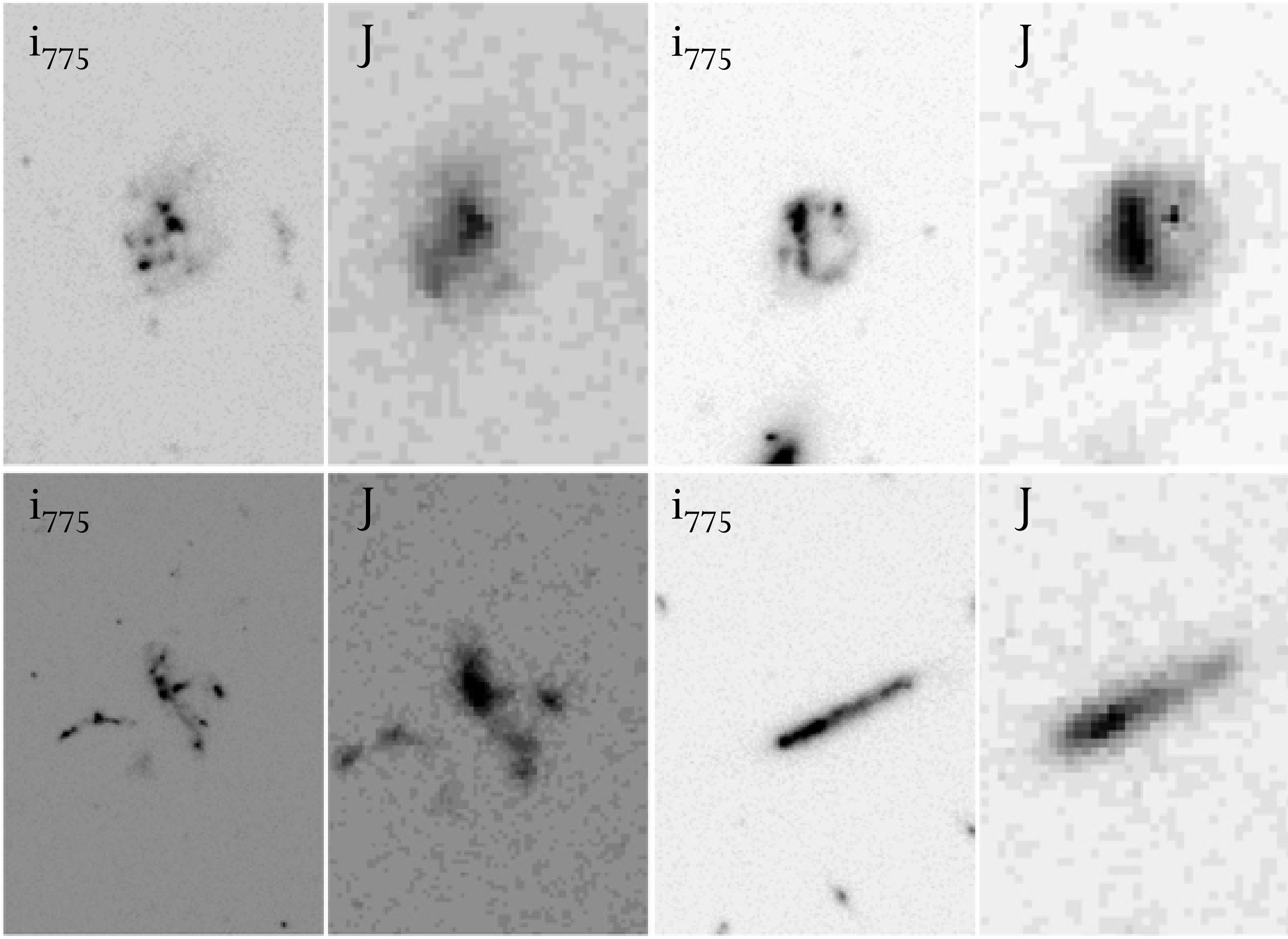
•**Tadpole**

•**Spiral**

•**Elliptical**



(color images from Steve Beckwith, private comm.)

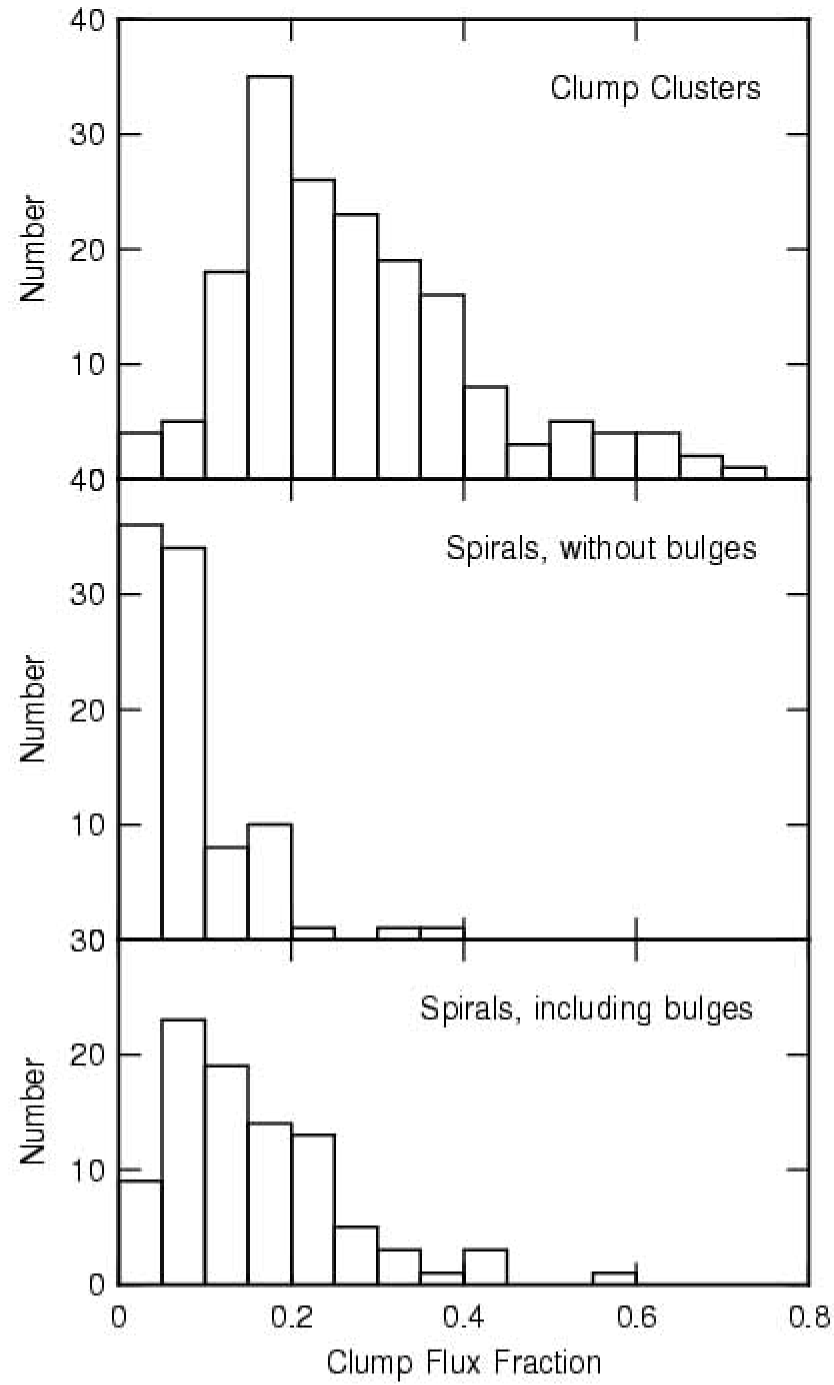


(Elmegreen, Elmegreen, Ravindranath, Coe 2007a)

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

<u>The clumps are not just uv patches in a uniform disk.</u>

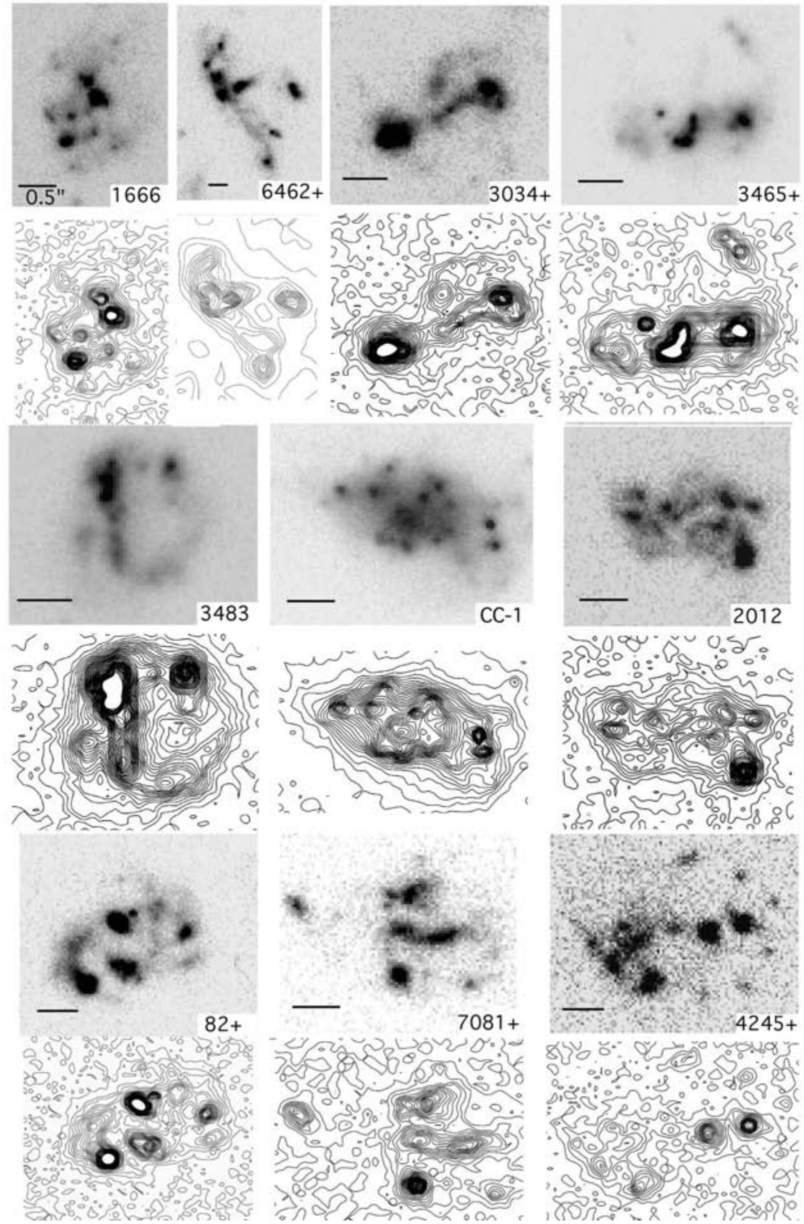
Clumps are a much higher fraction of the light in clump clusters than in spirals.



Elmegreen,Elmegreen, Vollbach, Foster & Ferguson 05

Clump Properties: 10 Cases

- Photometric z (<z>~2.3)
  - Bruzual & Charlot '03
  - Rowan-Robinson dust (and x2, x4)
  - Madau '95 intergalactic H absorption
  - Calzetti/Leitherer extinction
- Average clump:
  - Stellar 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:
  - Stellar M_{gal} ~ 6×10^{10} M_O,
  - D_{gal} ~ 20 kpc, V_{rot} ~ 150 km s^{-1}

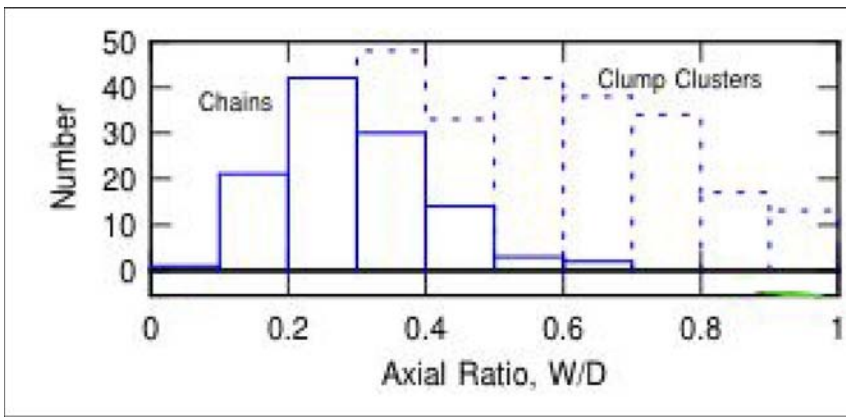


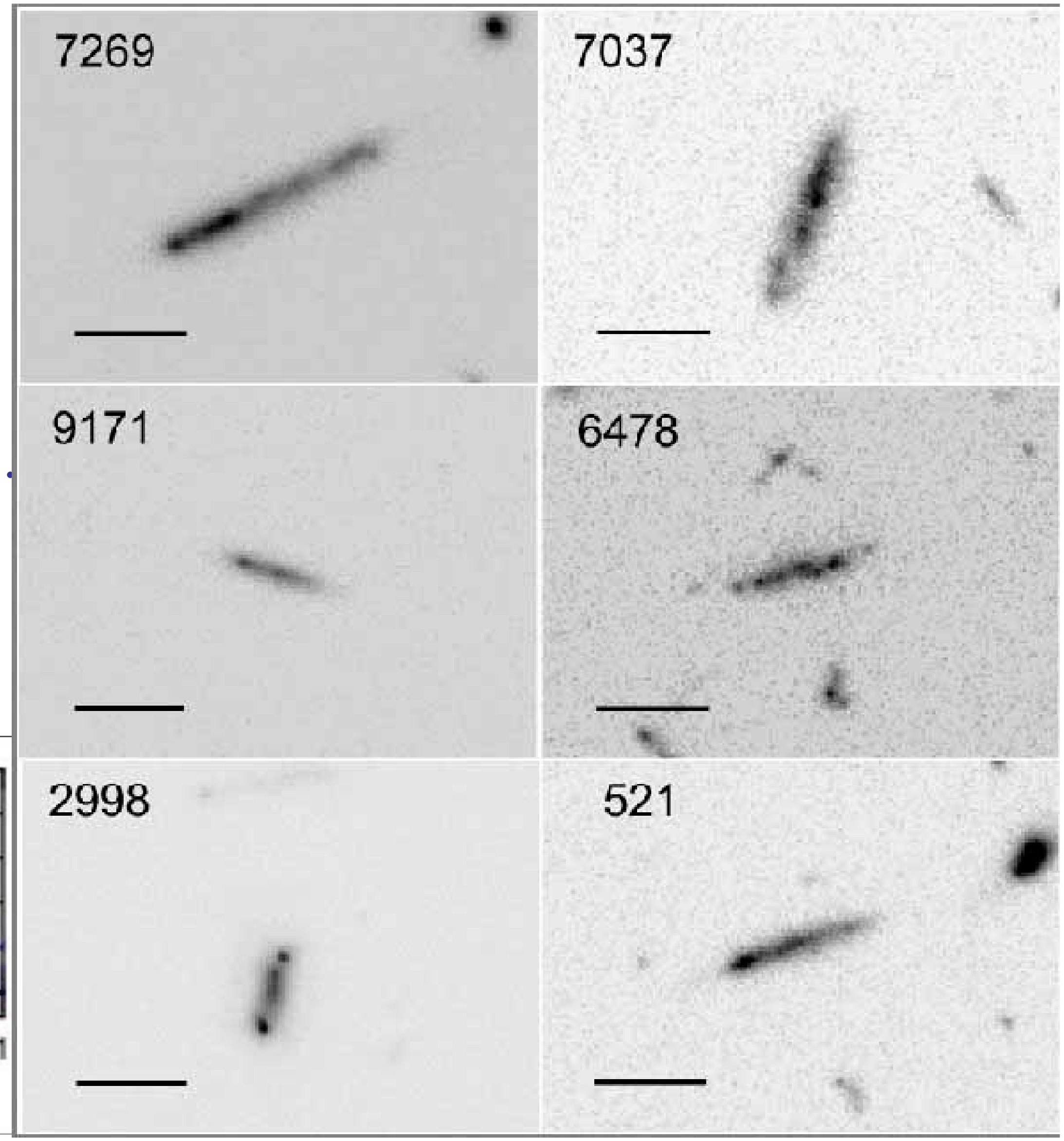
— =0.5" (Elmegreen & Elmegreen 05)

Chain galaxies are edge-on clumpy disks:

-Clump & galaxy properties are the same (mag,color,size,z).

-Axial ratio distribution for combined population is flat





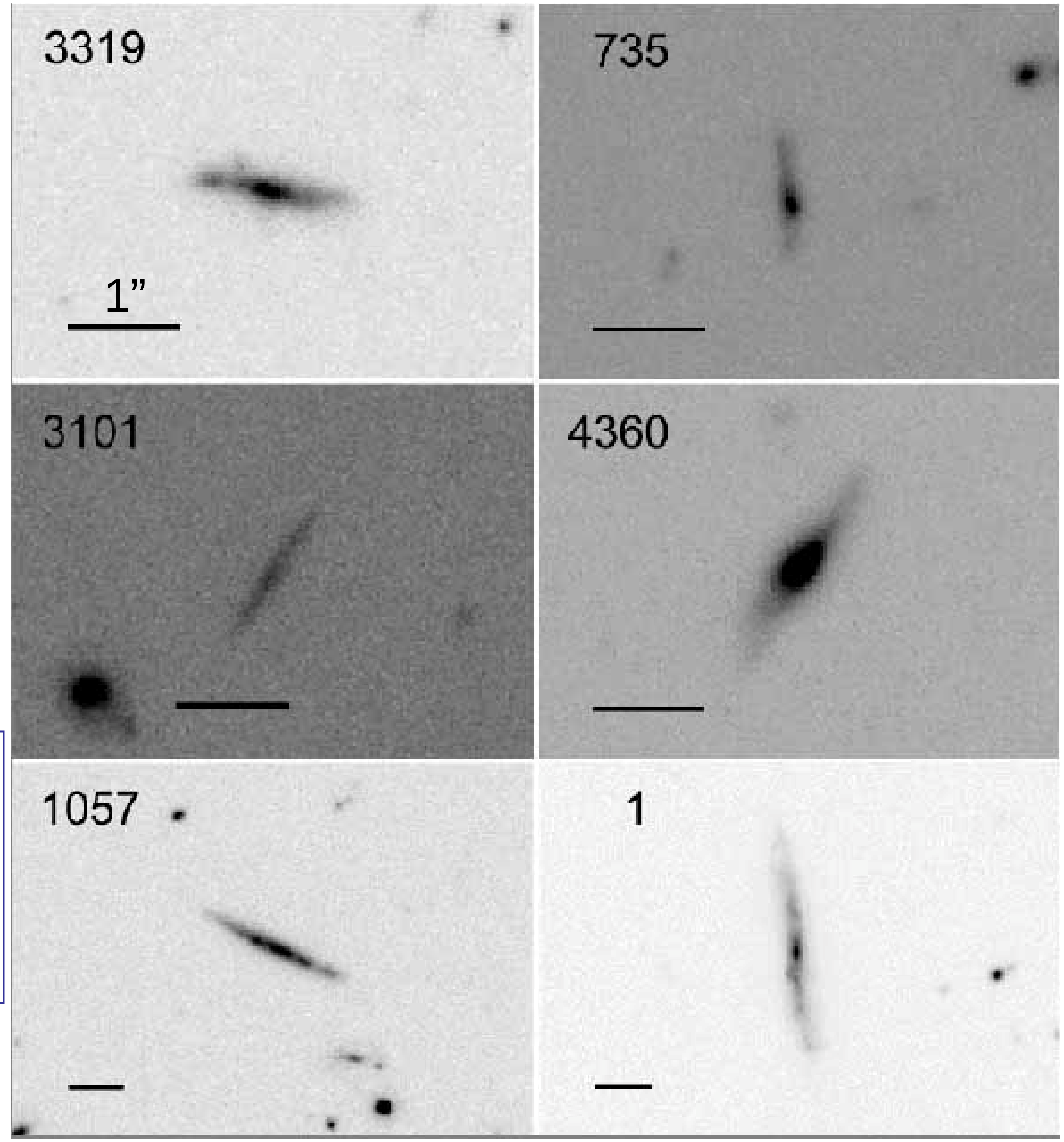
Often there is no nucleus.

Elmegreen et al. 05, 06

Edge-on spirals look different than chains:

They have nuclei, bulges and tapered (exponential) disks

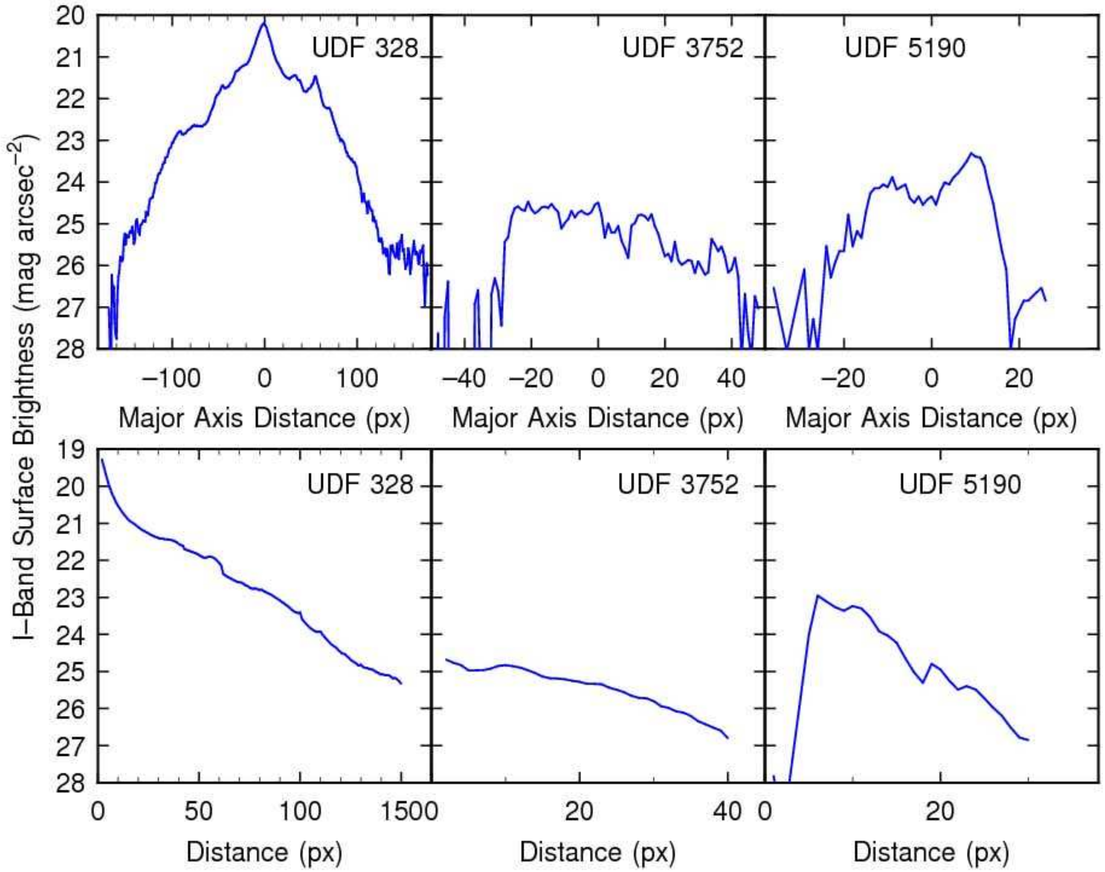
Do chain and clump cluster galaxies evolve into spirals?

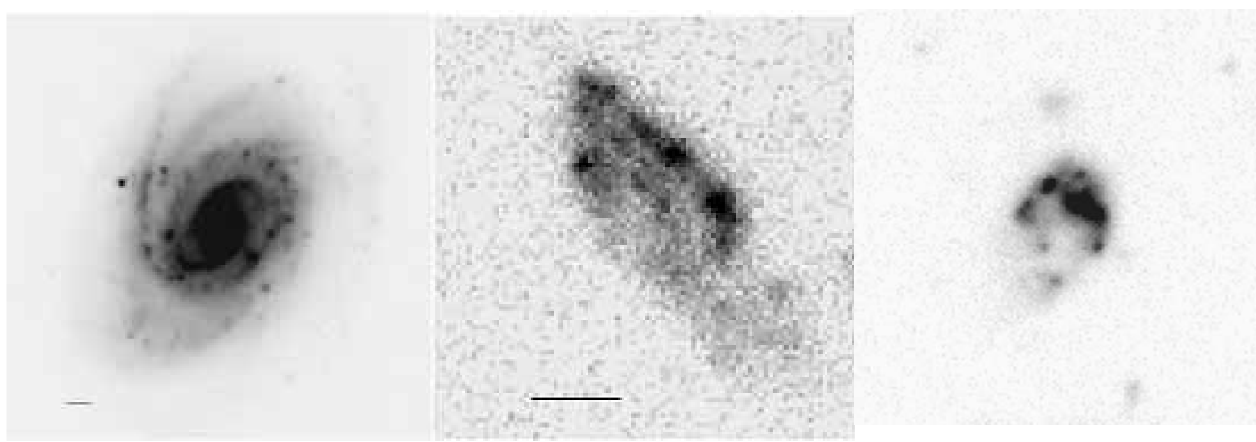


Elmegreen & Elmegreen 06

Major axis profiles and ellipse fit radial profiles of spirals are exponential.

Major axis profiles of clumpy galaxies are irregular. Ellipse fit profiles are somewhat exponential.





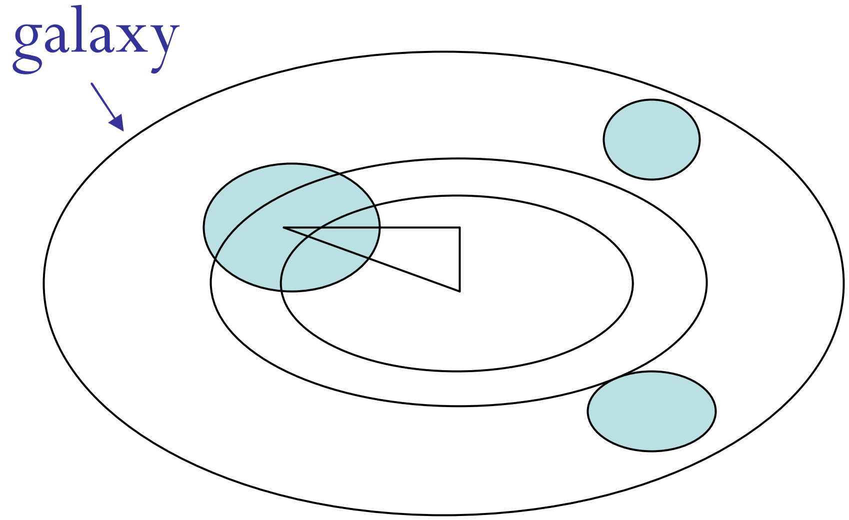
Elmegreen, Elmegreen, Vollbach, Foster & Ferguson 05

Still, the average radial profiles of the clumps are exponential.

Measure every clump position and brightness.

Find the deprojected radius (assuming the galaxy is a circle) divided by the galaxy radius

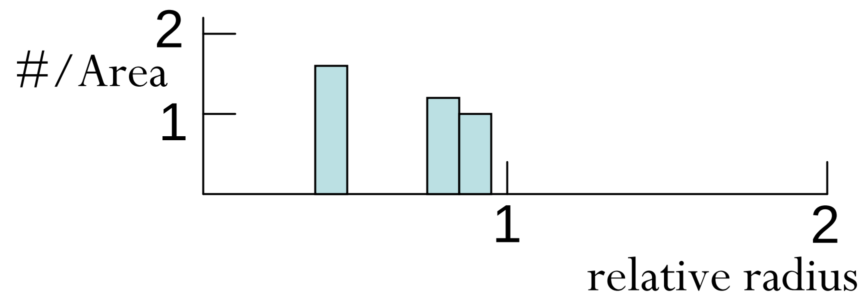
Plot the total number per unit area in each relative radial interval versus the relative radius

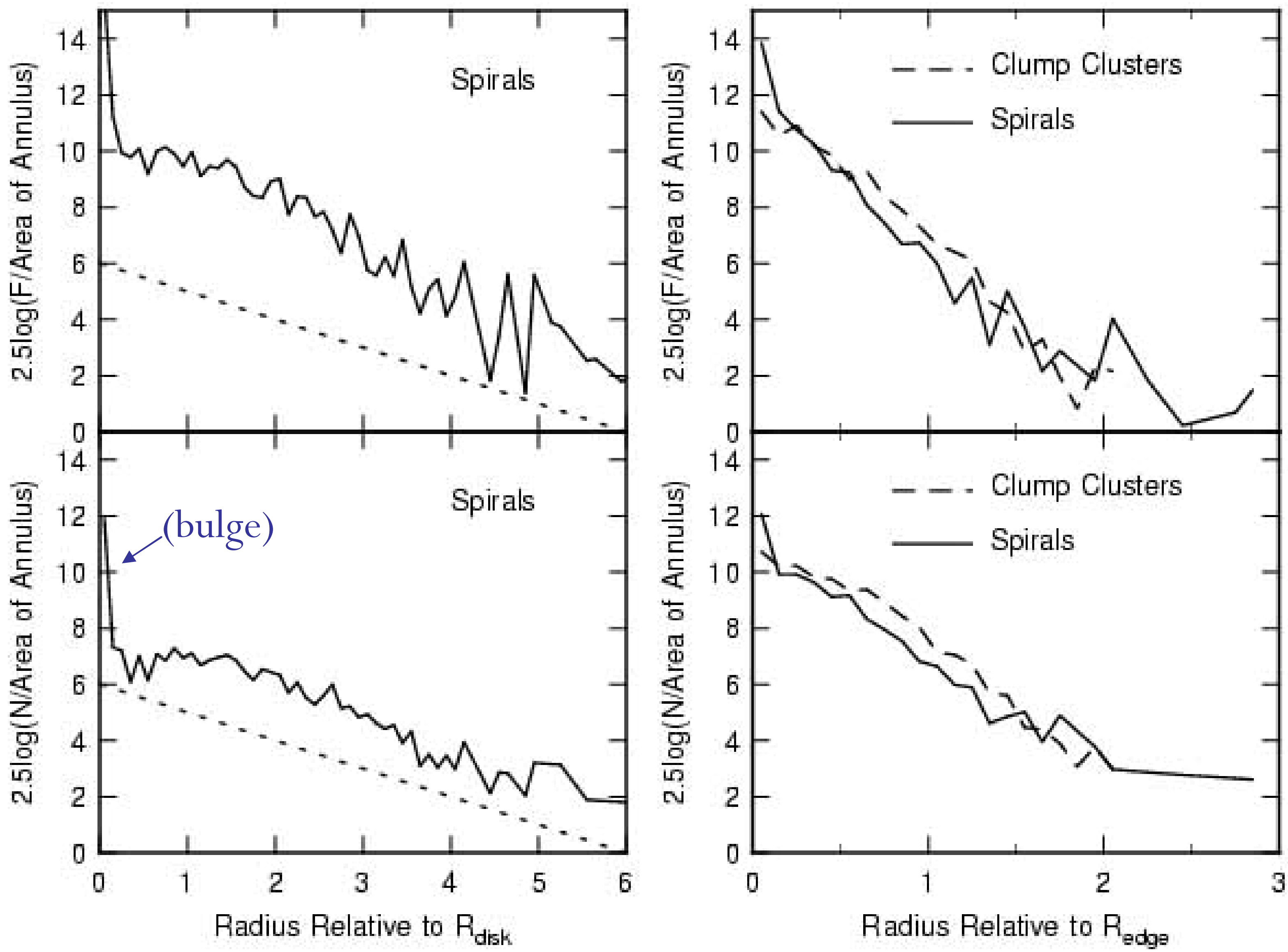


e.g., number per radial interval = 1 for relative radius = 0.4

other clumps at 0.8 and 0.9 rel.radii

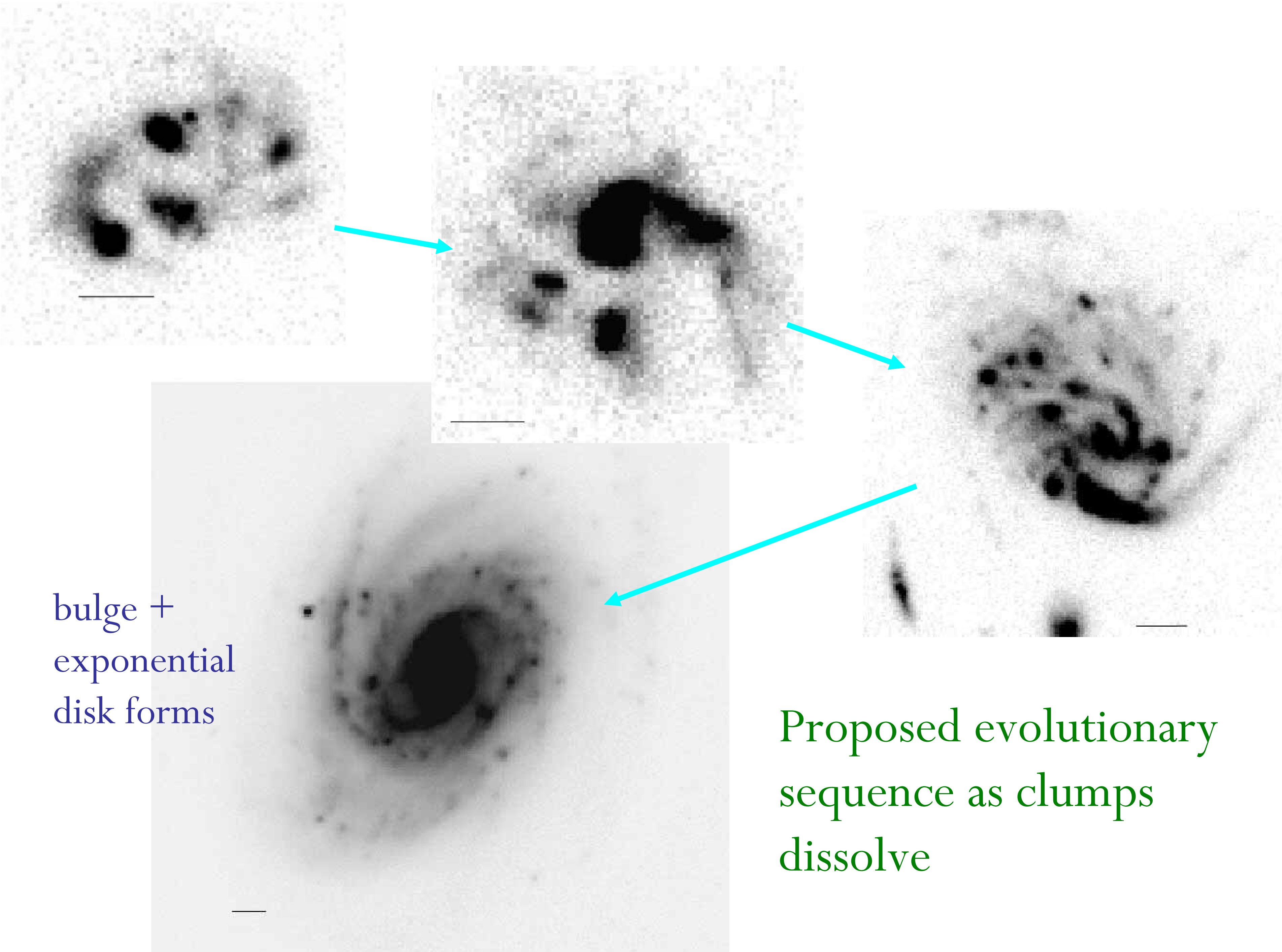
Resulting contribution to plot:





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

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

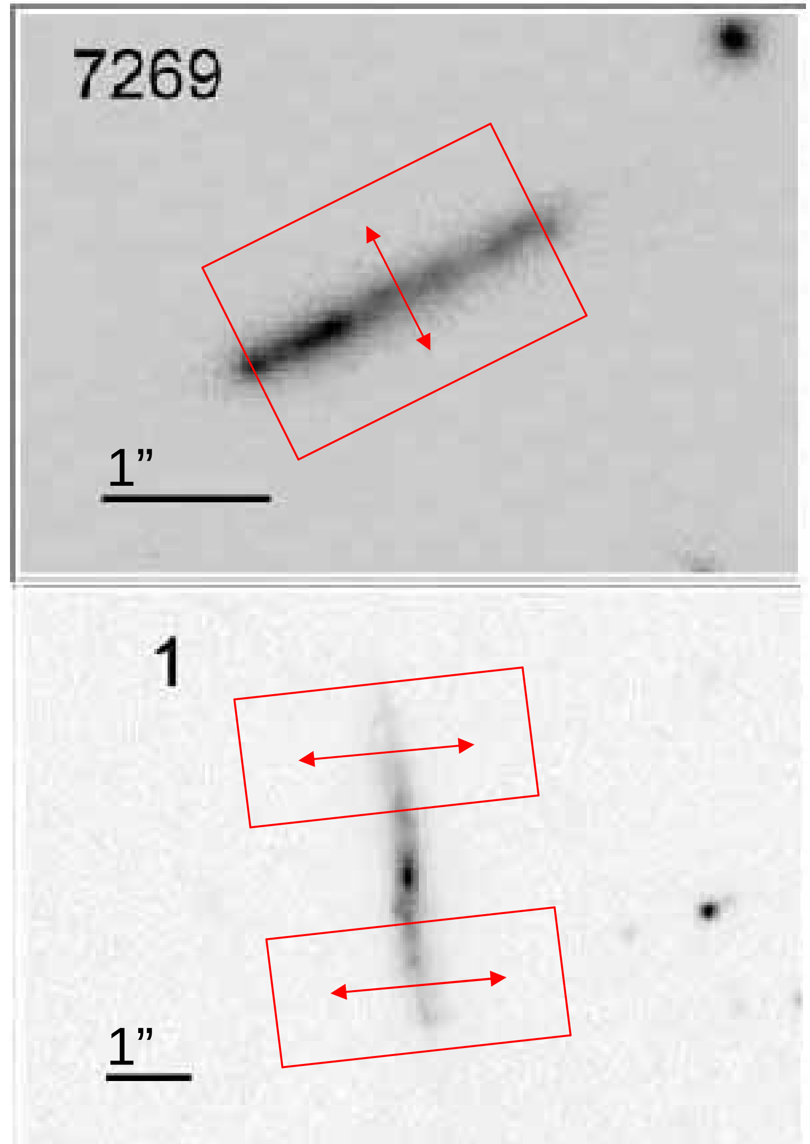


bulge +
exponential
disk forms

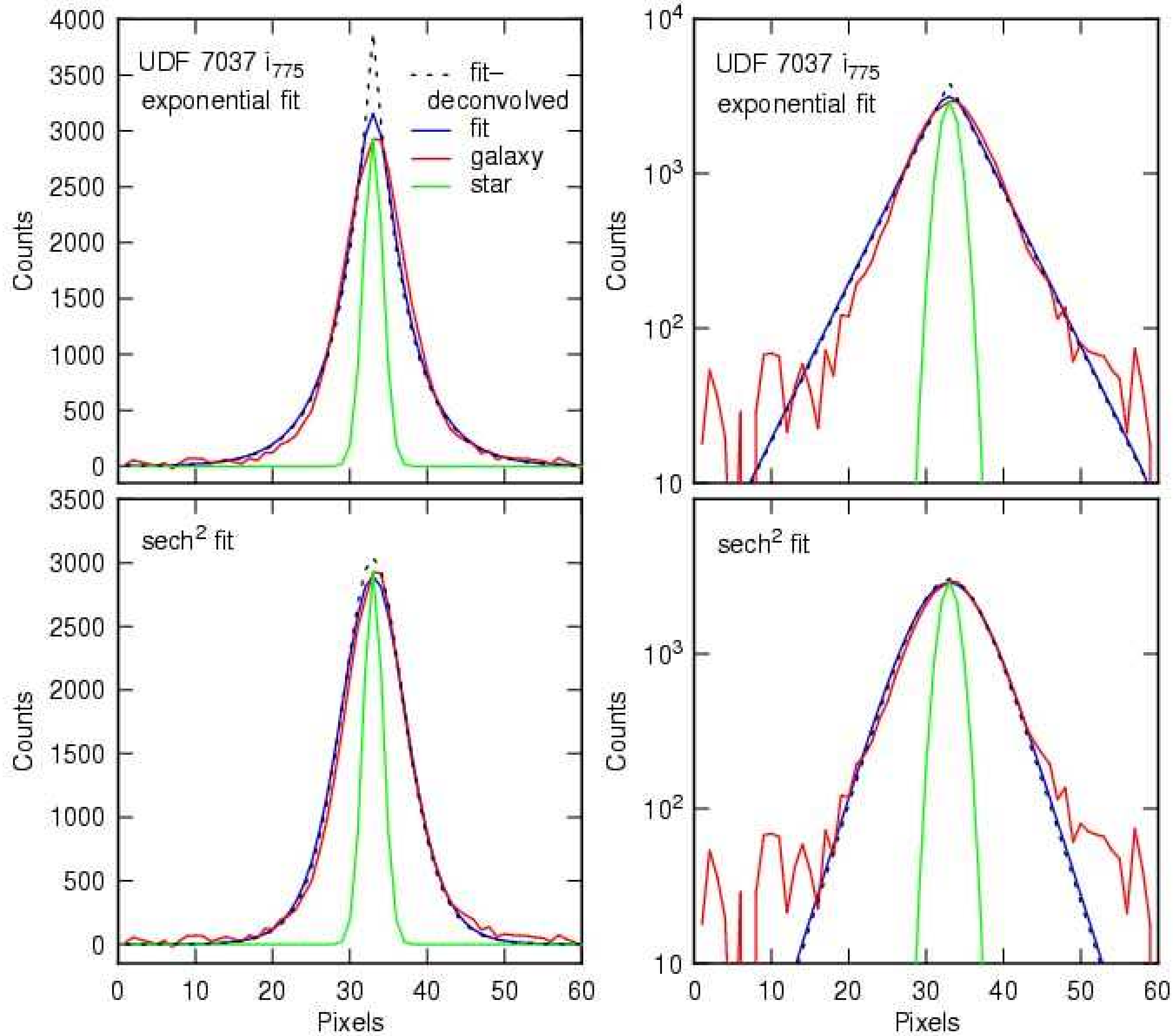
Proposed evolutionary sequence as clumps dissolve

UDF galaxies have relatively thick disks.

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



Deconvolve stars, fit to sech^2 profiles



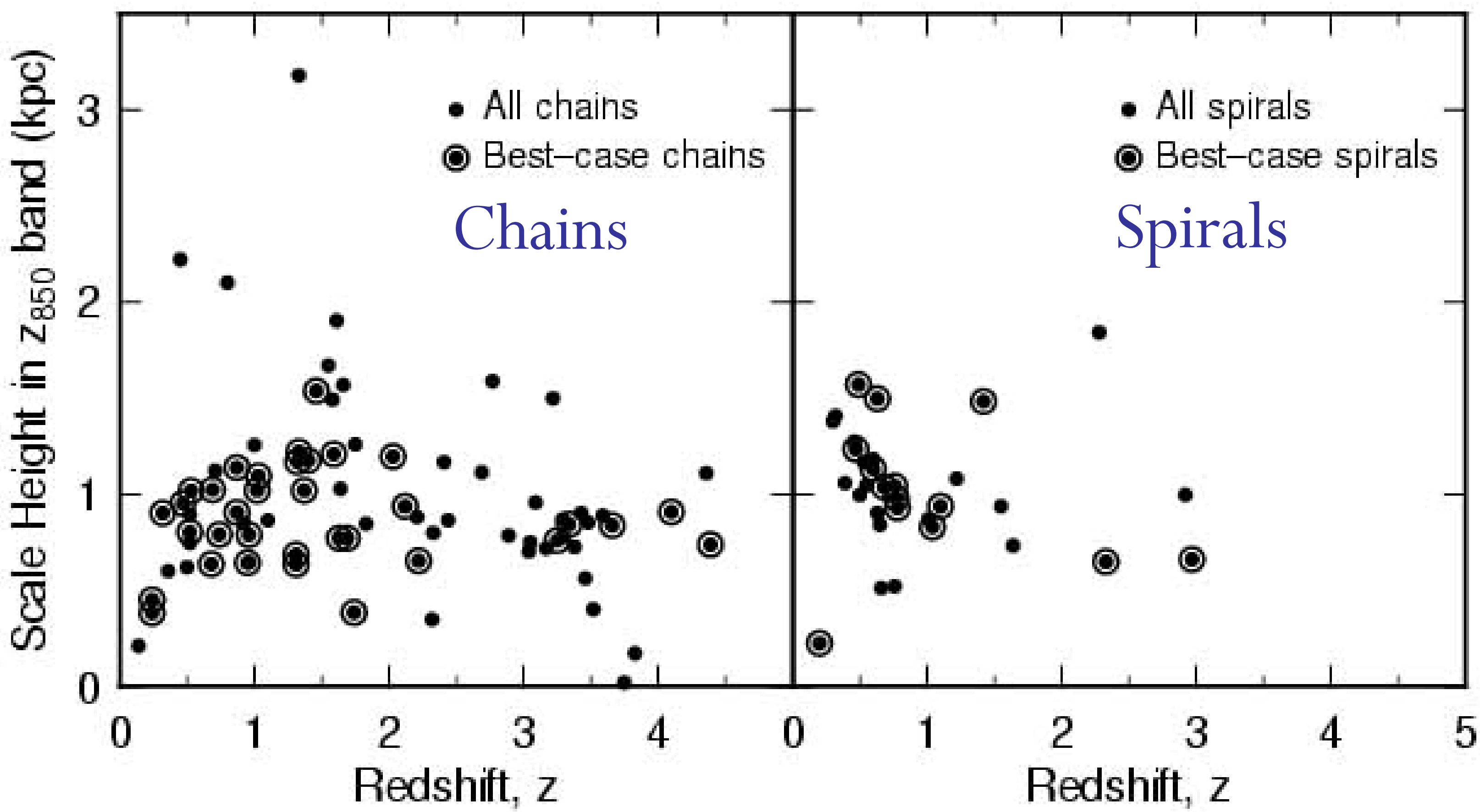
$\mathrm{sech}^2(z/z_0)$ is the equilibrium solution to the perpendicular profile of an isothermal self-gravitating disk

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

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

Σ = mass column density

EE06

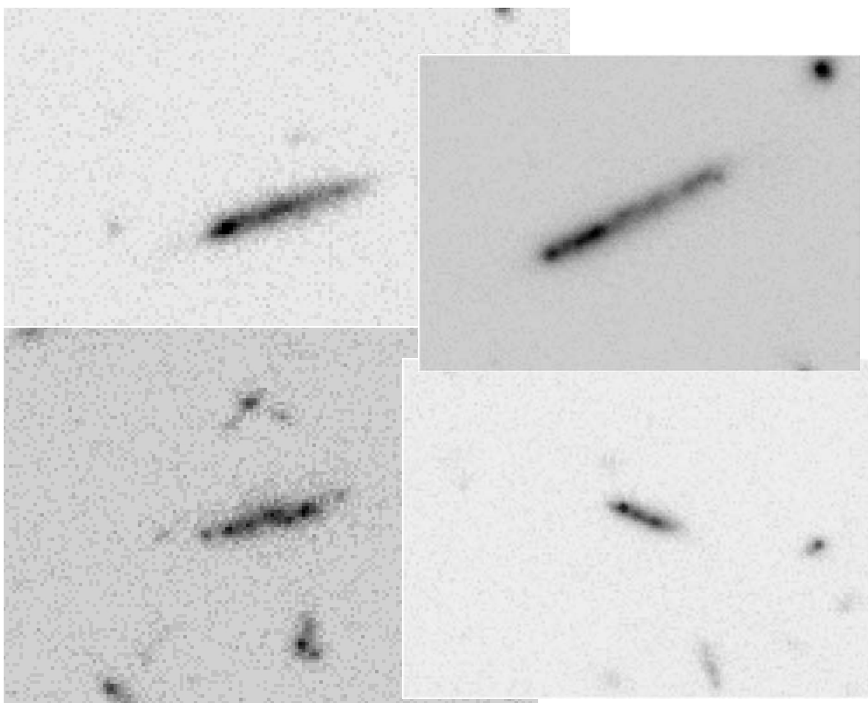


$z_0 \sim 0.9$ kpc for all redshifts

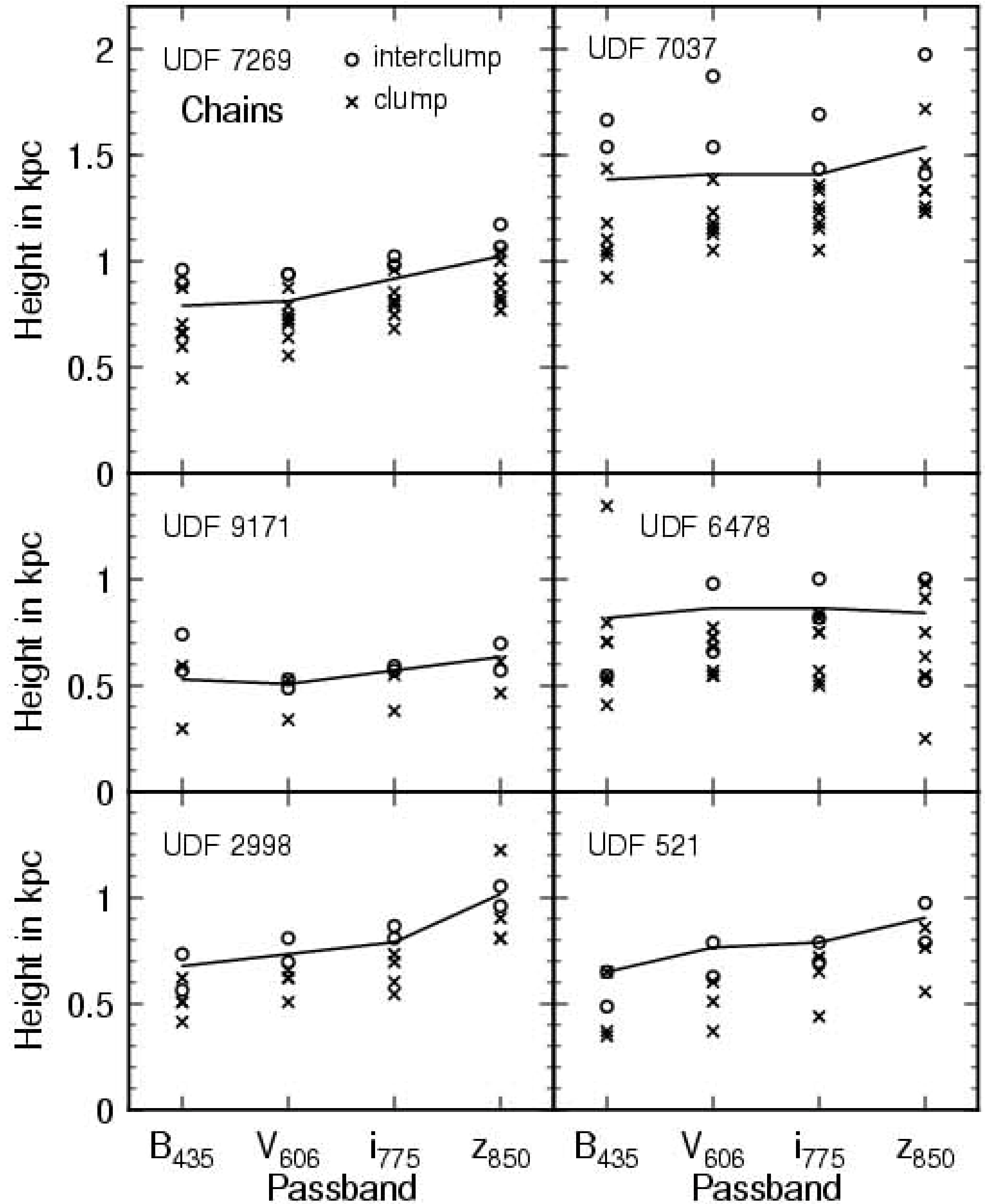
EE06

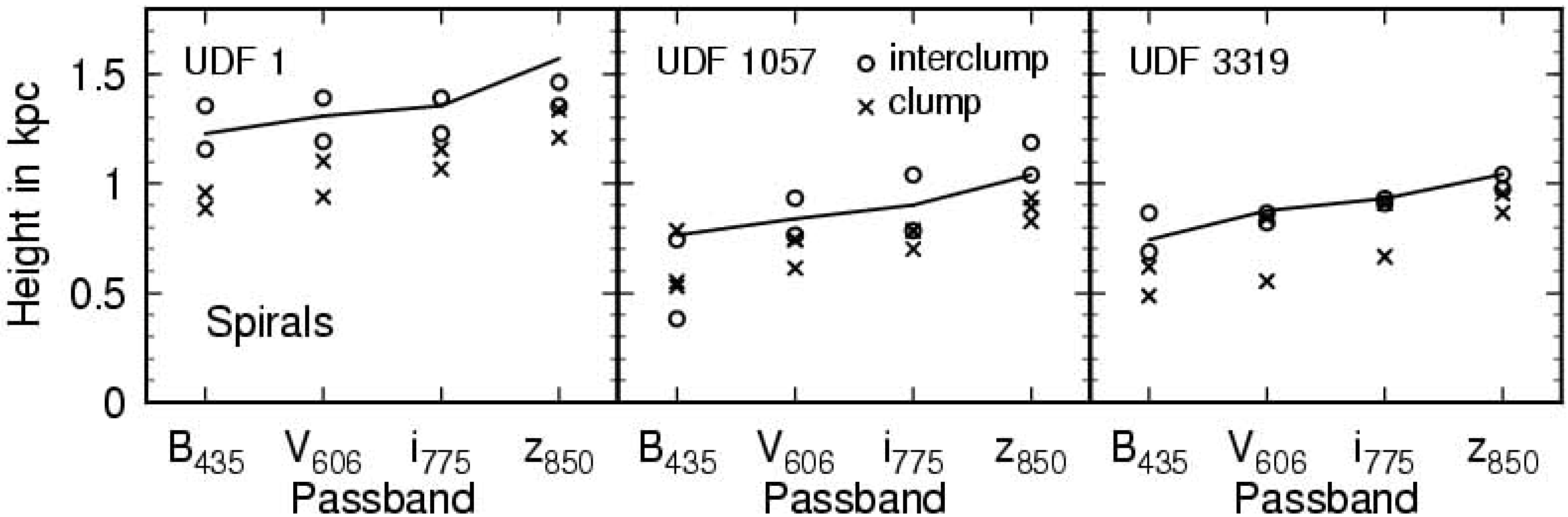
Now fit sech^2 to clumps and interclump regions

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



EE06



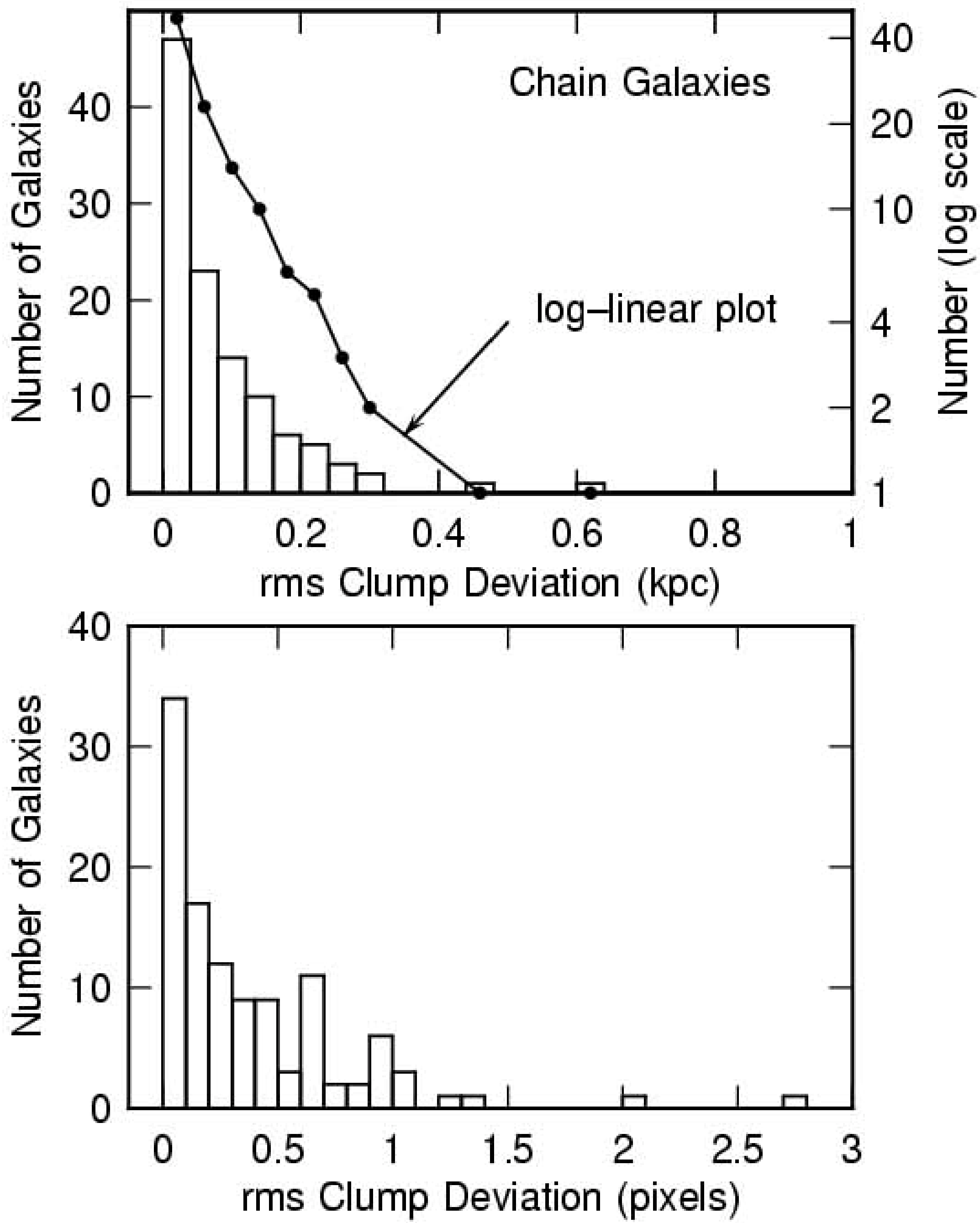


the same for spiral thick disks

The clumps in chain galaxies are also <u>highly confined to the midplanes</u>.

This <u>confinement</u> makes the clumps look like <u>gravitational instabilities</u> rather than accretion blobs.

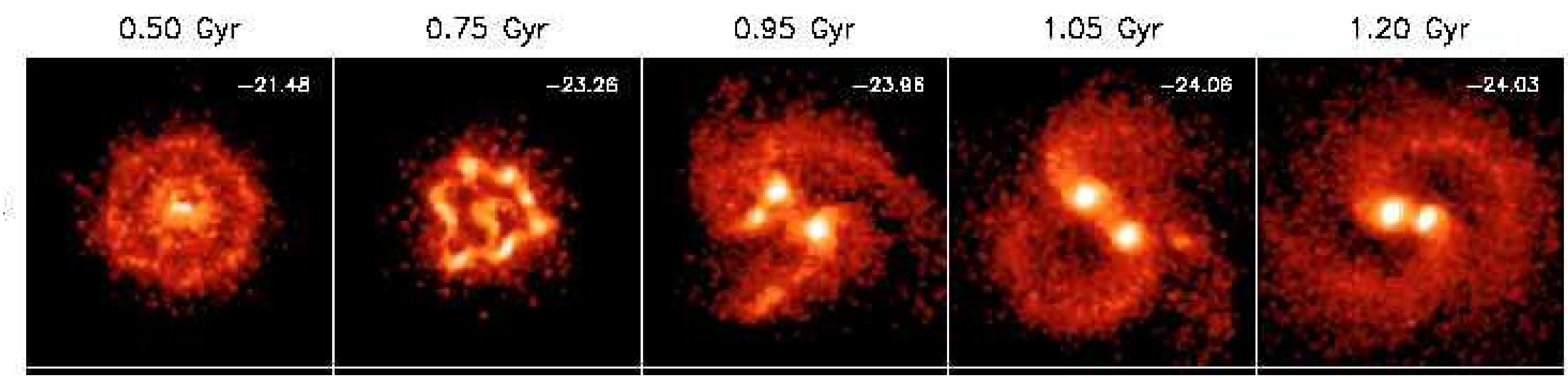
EE06



Clump Formation by Gravitational Instabilities

- Requires cosmological accretion to disk in a smooth flow (e.g., Murali et al. '02; Westera et al. '02, Sommer-Larsen, Gotz &Portinari '03, Keres et al. '04)
- Simulations by Noguchi (1999) and Immeli et al. (2004) show massive clump formation and interaction, with coalescence into a bulge.

(Immeli et al. 04)

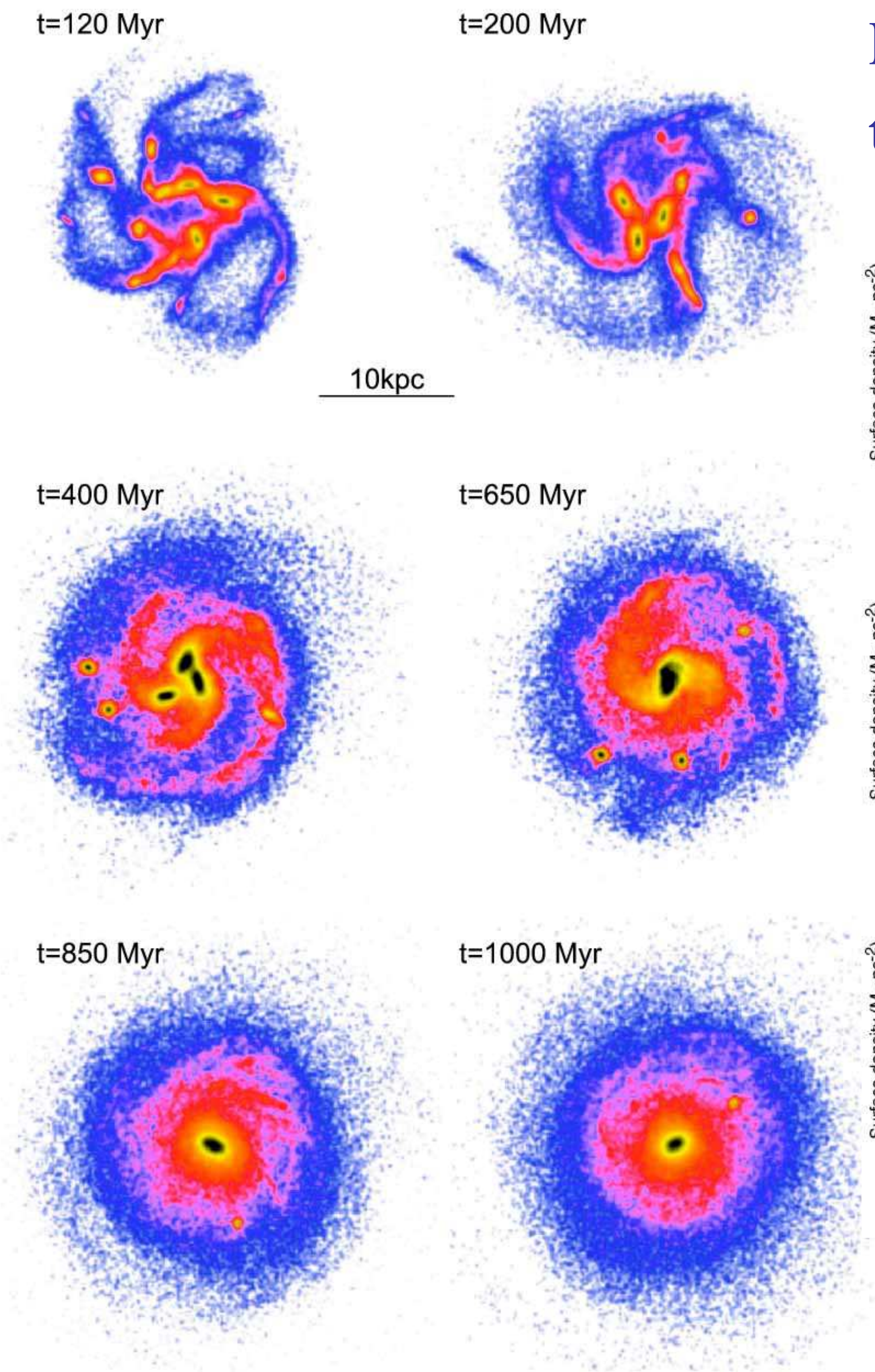


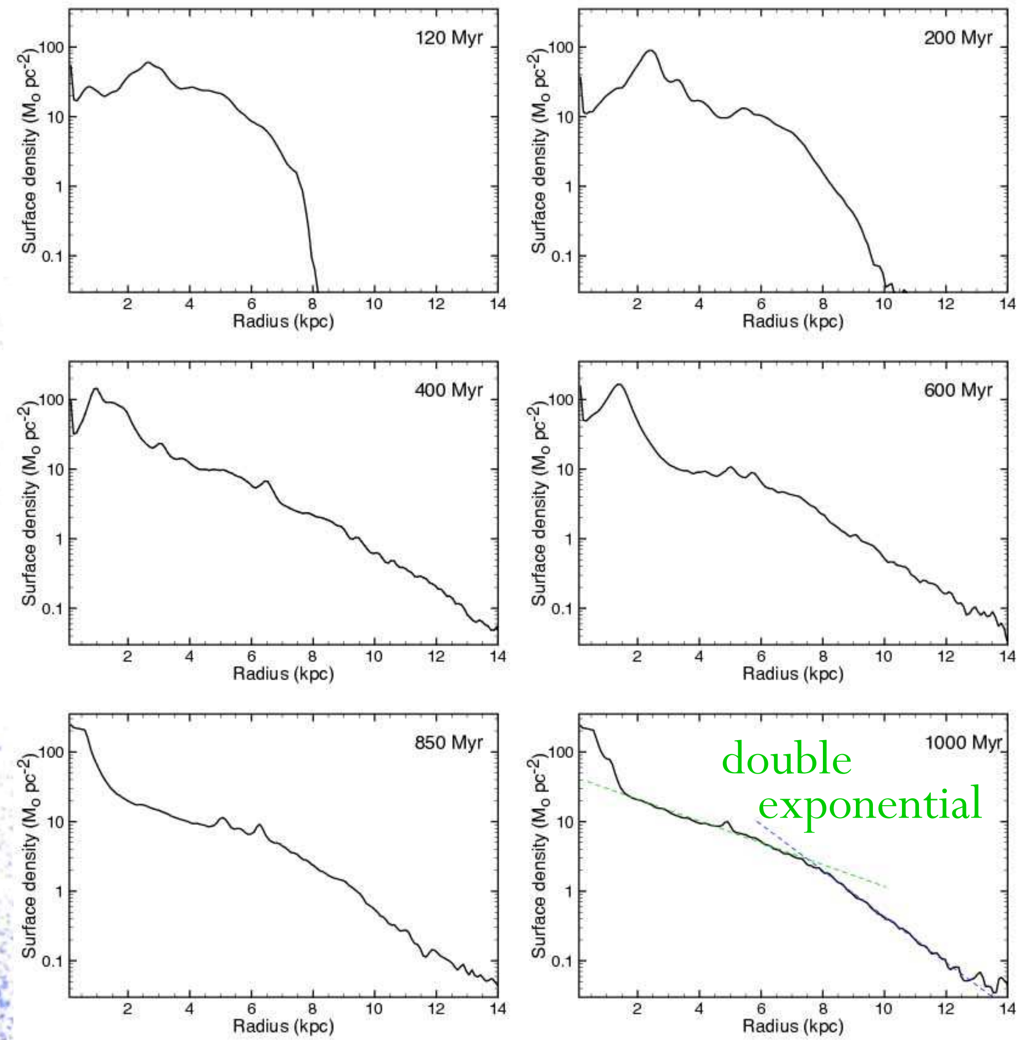
New Simulations of Clump Cluster Evolution

(Bournaud, Elmegreen & Elmegreen 07)

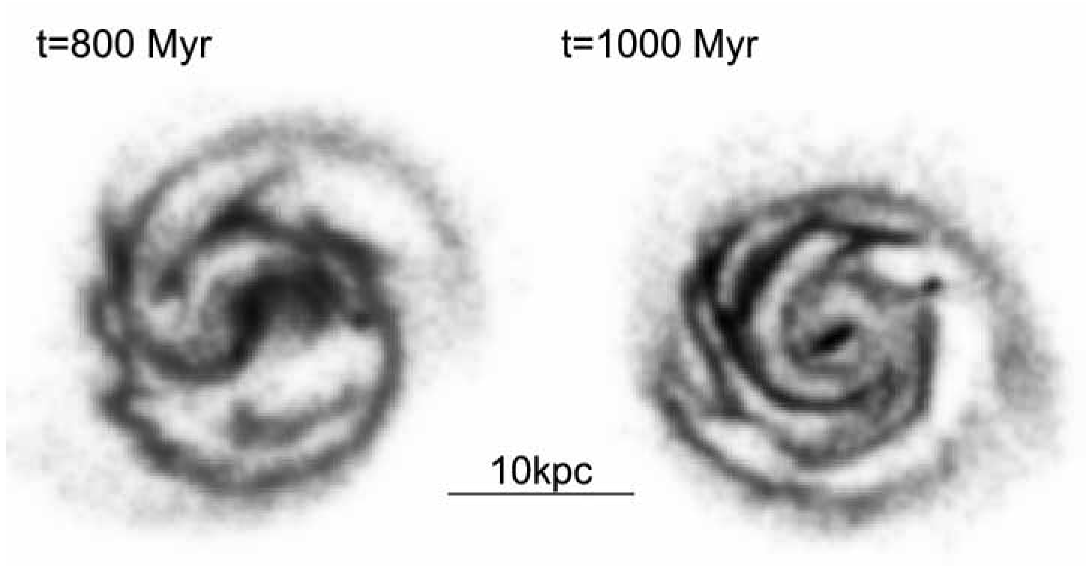
- Particle-mesh, sticky particle gas (β=0.7)
  - grid resolution 110 pc
  - 10^6 particles each for halo, stars, gas
    - halo = Plummer sphere with scale length 15 kpc
- Schmidt-law star formation
  - probability particle converts to a star is proportional to the local density to the power 1.4
- Initial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

Initially flat disk evolves to a kpc-thick <u>exponential disk with a bulge</u>

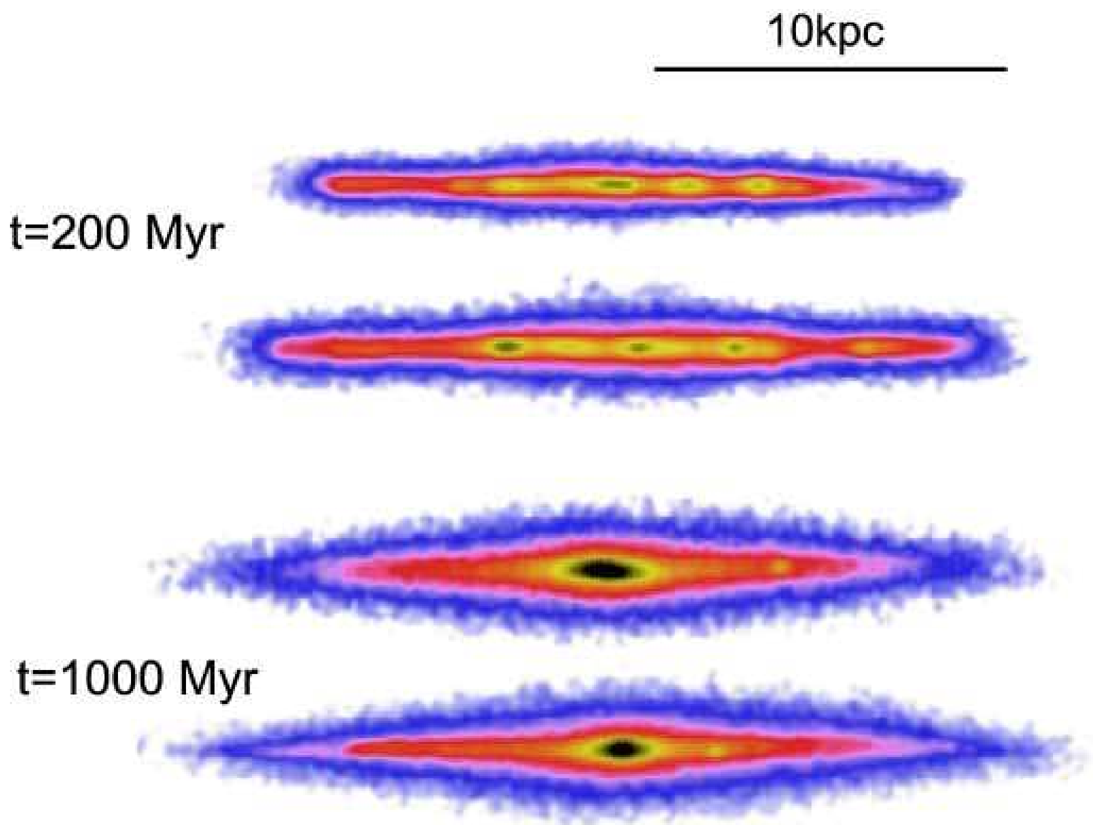




Bournaud, Elmegreen & Elmegreen 07



Late-time gas distribution is typical for a spiral galaxy

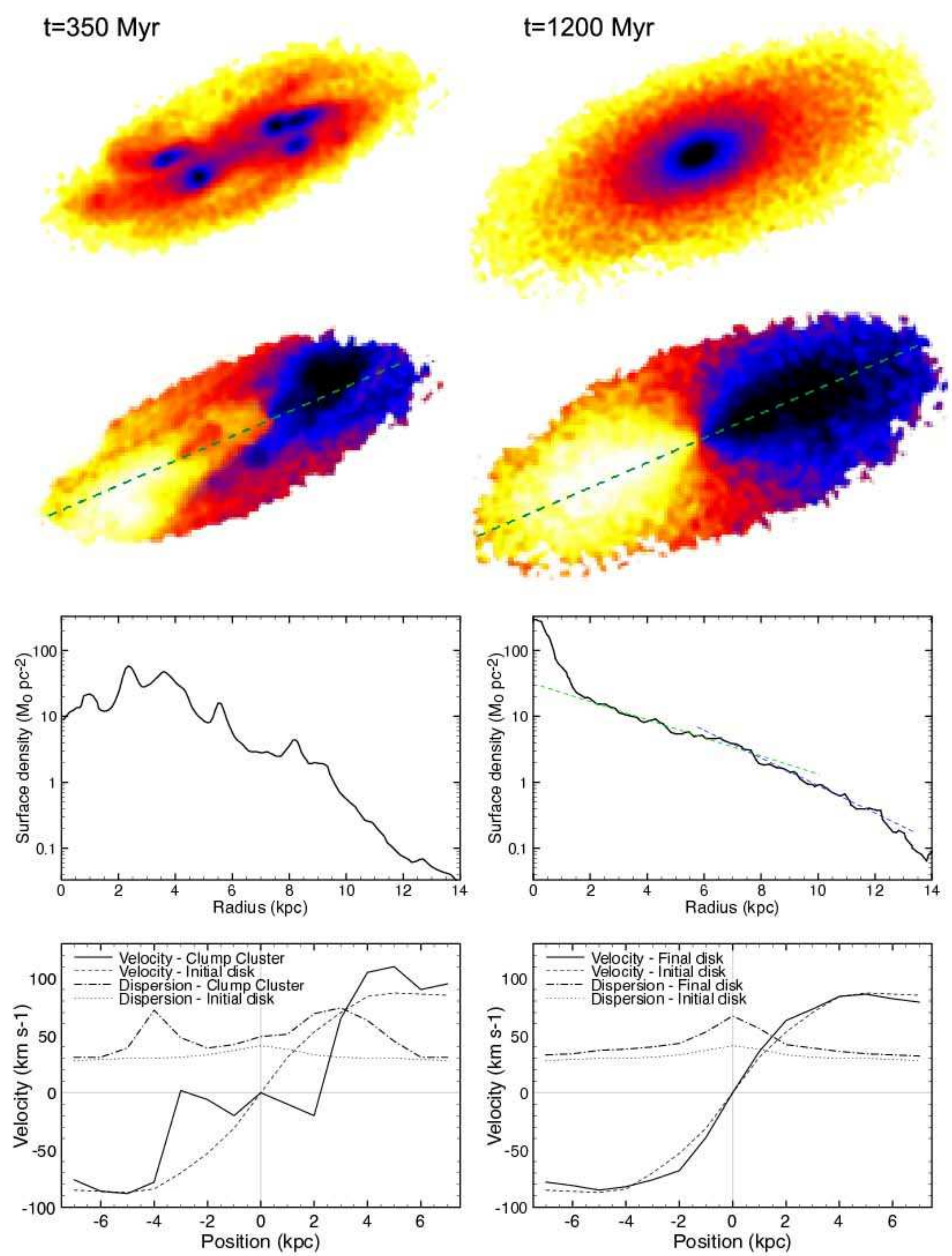


Edge-on disks go from chain galaxies
to normal bulge-centered spirals

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

Weiner et al. 06 finds rotation in only ~30% of chain galaxies. Early studies found no rotation (Bunker et al. 00, Erb et al. 04). High velocity dispersions found in clumpy galaxies (Forster Schreiber et al. (2006) and Genzel et al. (2006)

Bournaud, Elmegreen & Elmegreen 07



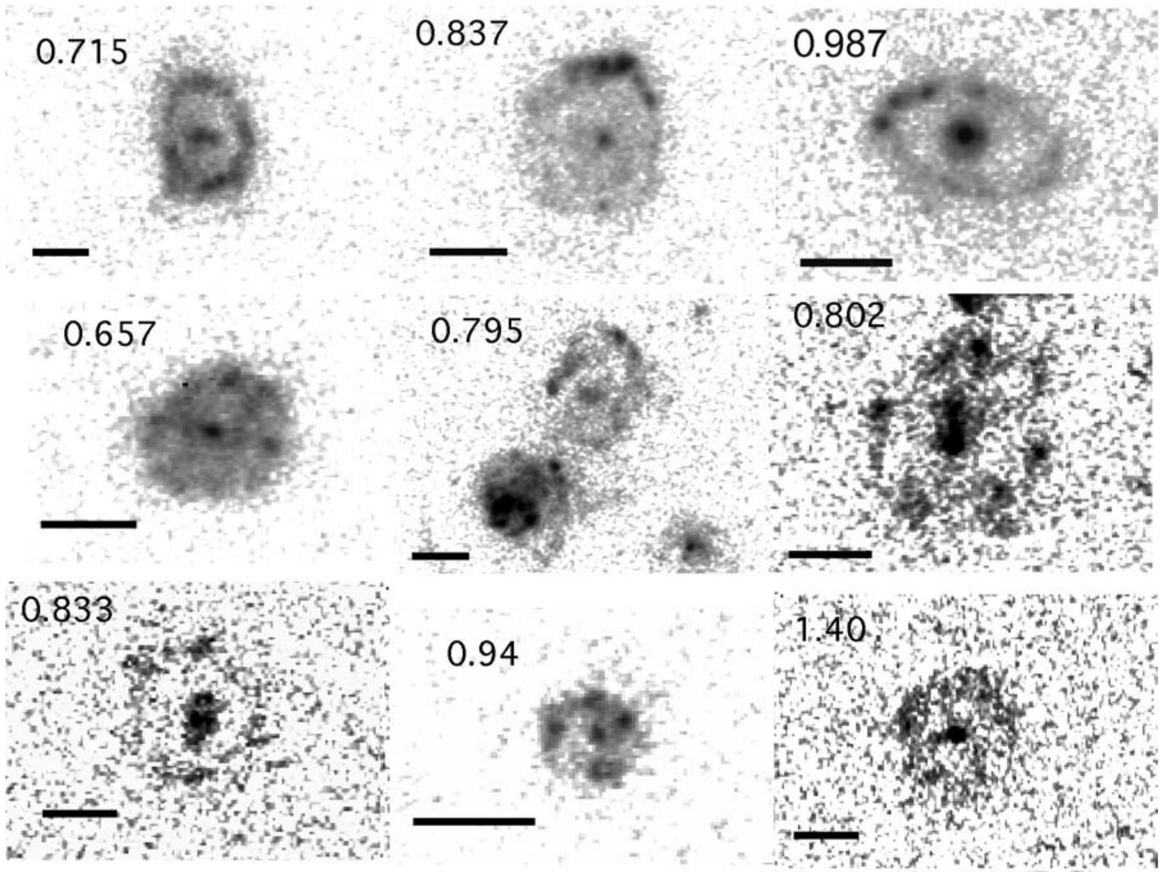
Summary: evidence for clump formation by gravitational instabilities:

- Clump size ~ disk thickness (~1 kpc): both are a Jeans length: $L \sim a^2/\pi G\Sigma \sim 2$ kpc
- Clump mass is then the Jeans mass, $M \sim \Sigma L^2 \sim 2 \times 10^8\ M_\odot$
  - requires turbulent disk a~40 km/s, and high column density of gas, $\Sigma \sim 50\ M_\odot/pc^2$
- Clump positions centered on midplane
- Clump peak star formation rates comparable to dynamical rates
  - color ages ~ 10^8 yrs, so average SFR ~ few $M_\odot$/yr in each clump
  - dynamical rate = $0.1a^3/G \sim 1.5\ M_\odot$/yr for a=40 km/s

Other evidence for clump formation by gravitational instabilities:

- clumps in interaction ring galaxies
- tidal dwarf formation
- clumps in tidal arms
- clumps in strong spiral arms,
  - typical $M \sim 10^7$-$10^9\ M_\odot$, spacing ~1-2 kpc

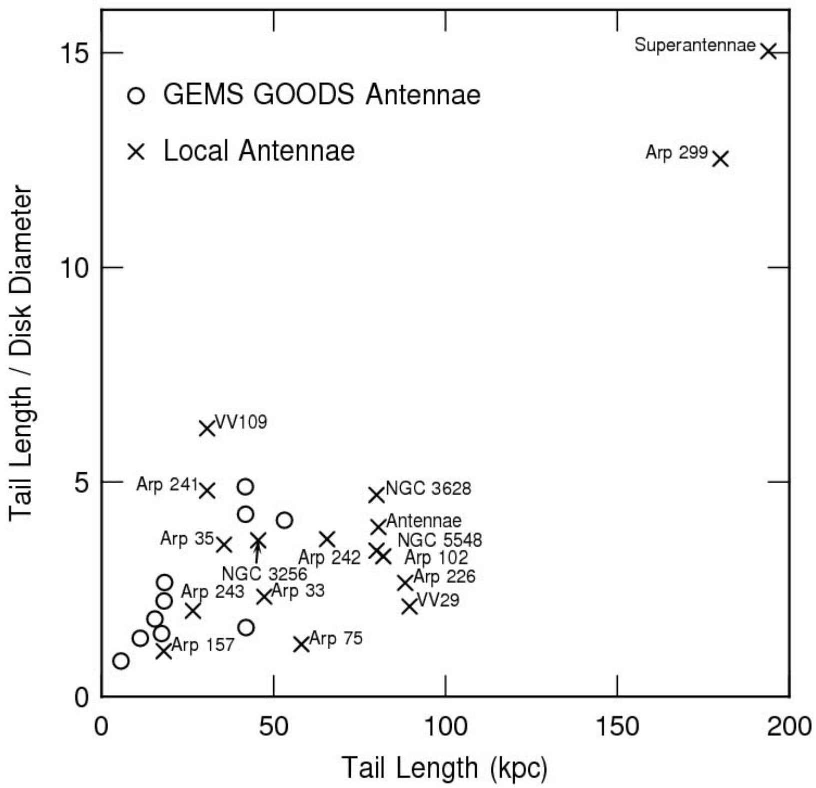
Big Clumps in Ring Galaxies in GOODS and GEMS: regularity suggests instabilities, not blob accretion



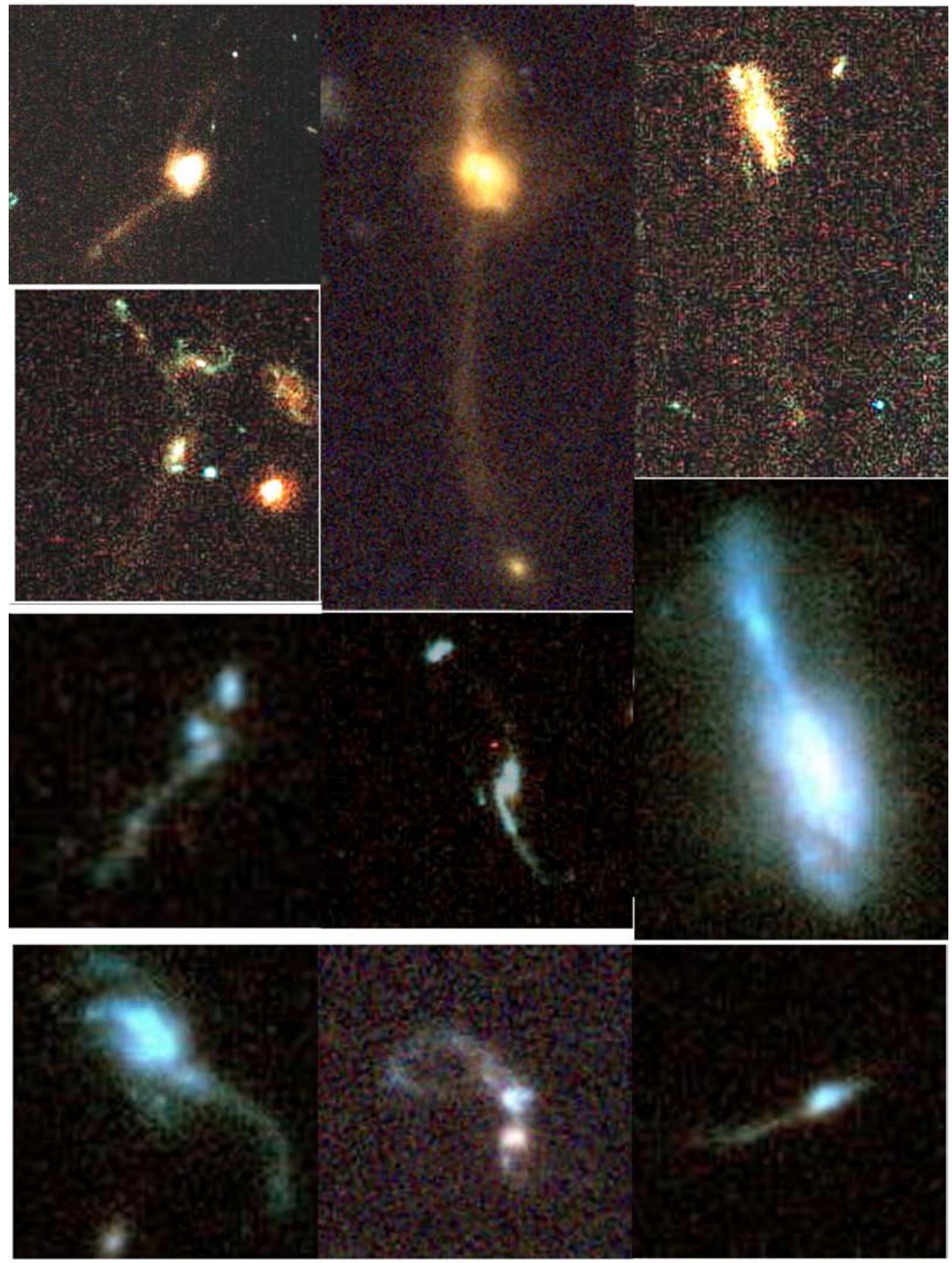
Elmegreen & Elmegreen 2007

1”

Antennae (GEMS+GOODS)
Tidal dwarfs form by GI
in the gas (e.g. Wetzstein, Naab,
Burkert 07)



Elmegreen, Elmegreen,
Ferguson, Mullan 2007



Diffuse interactions:
First example of GI
in the stars

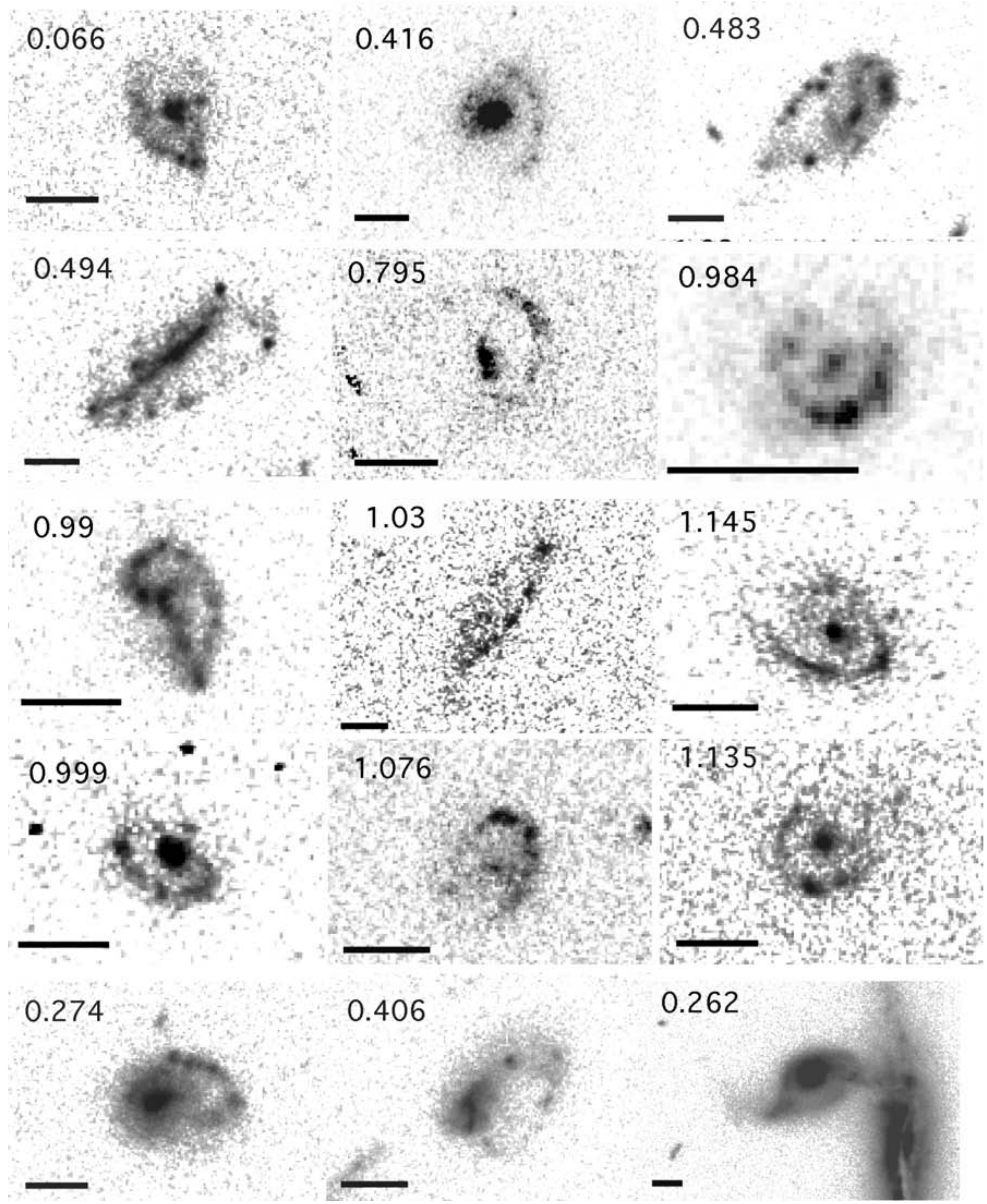
Note big diffuse tidal
clump.

Elmegreen, Elmegreen,
Ferguson, Mullan 2007

Partial Rings

Regularly spaced
beads on a string

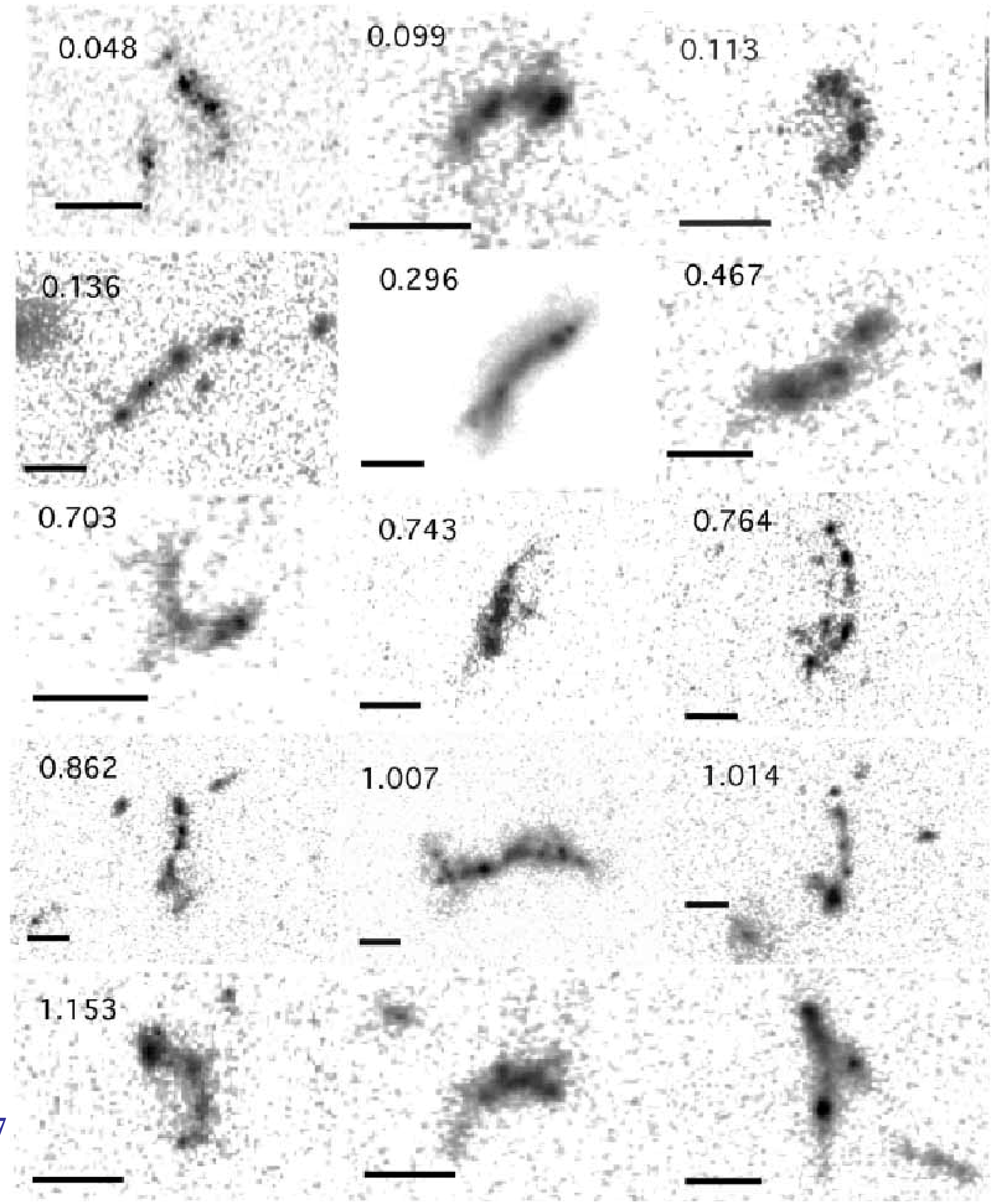
1”



Elmegreen & Elmegreen 2007

Bent Chains

Regularly spaced
beads on a string

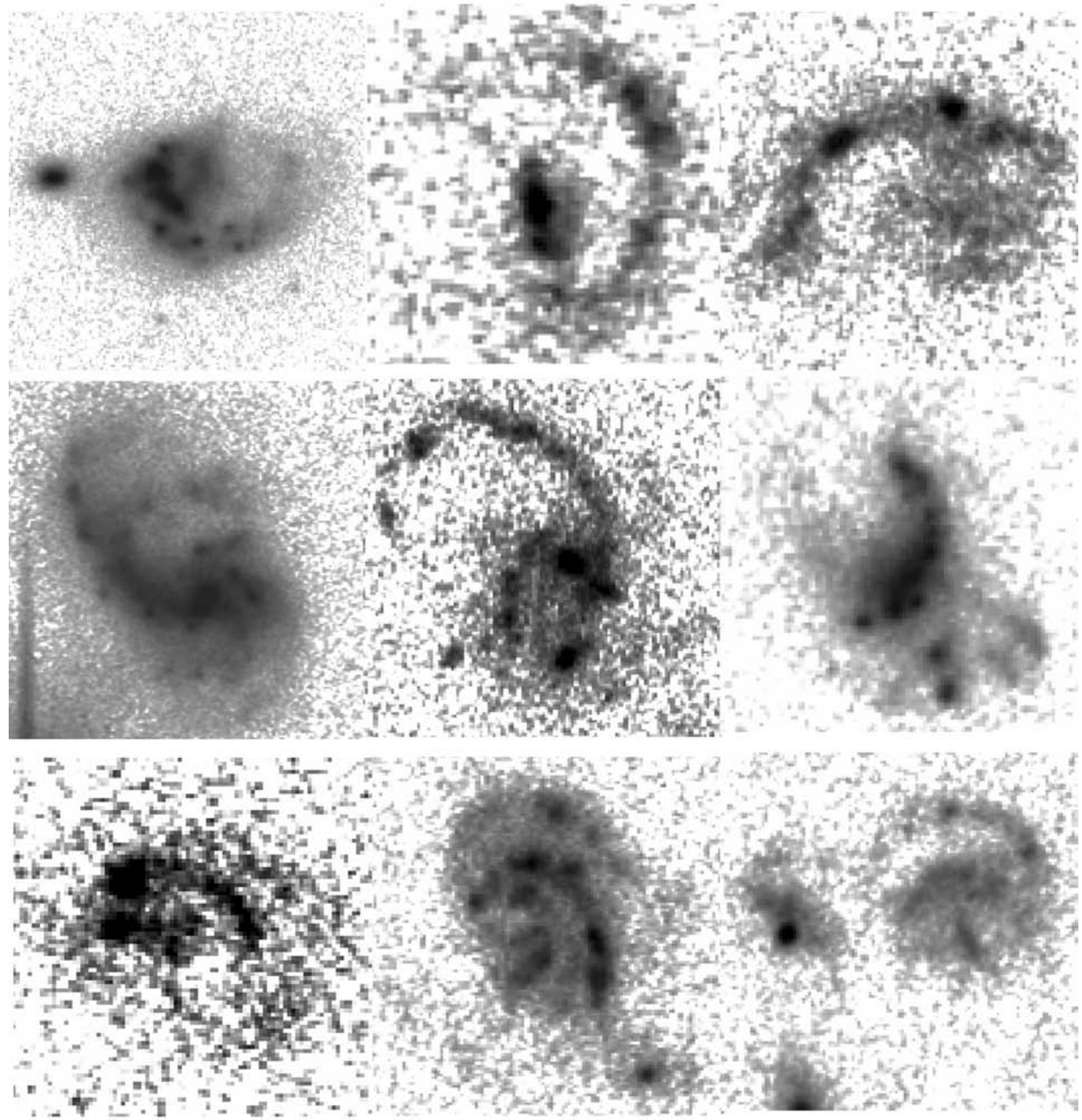


—— 1”

Elmegreen & Elmegreen 2007

“Shrimps”

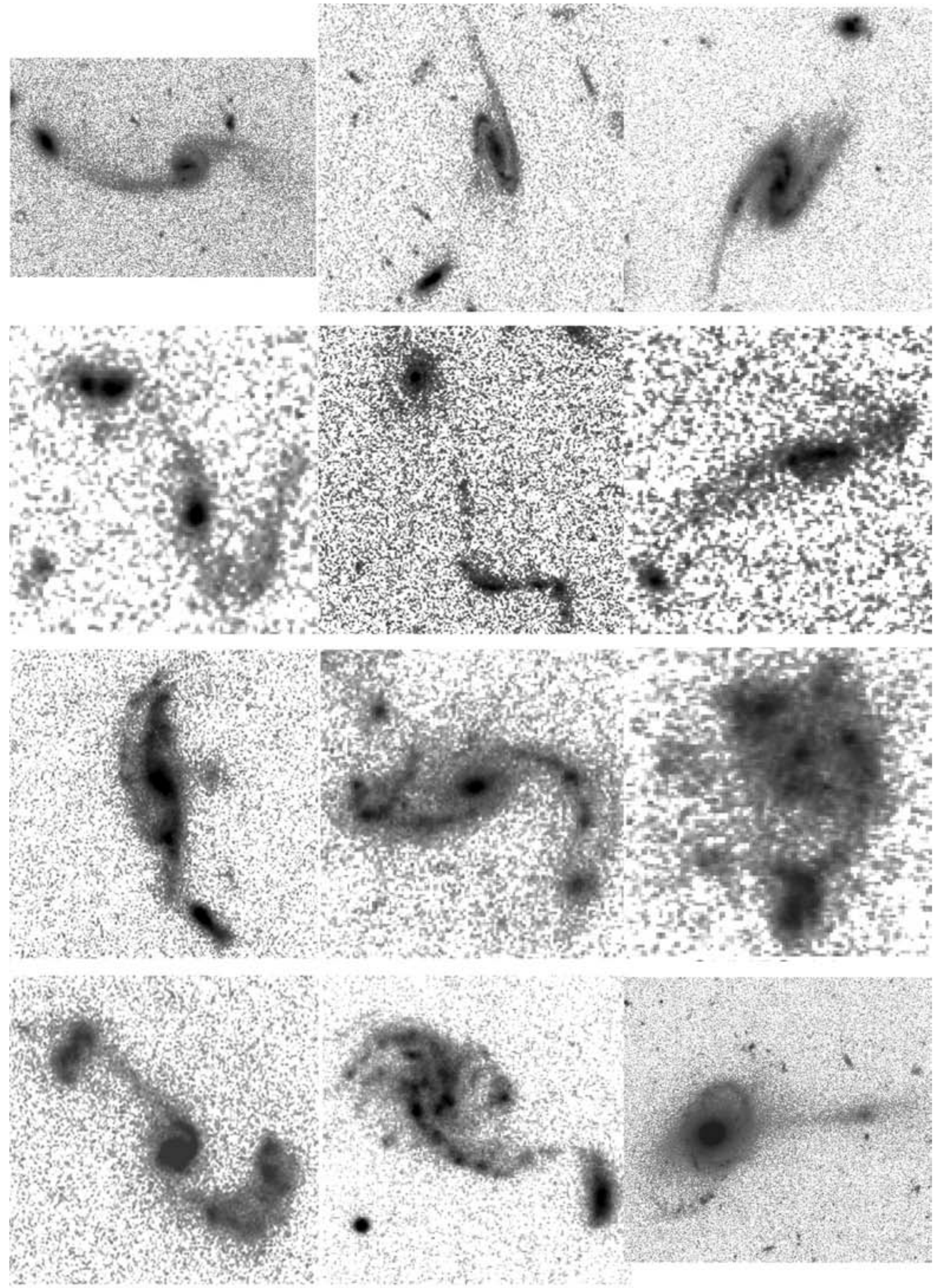
GI are a violent mode of SF, dominating processes in highly unstable gas



Elmegreen, Elmegreen, Ferguson, Mullan 2007

M51 types

material arms that fragment



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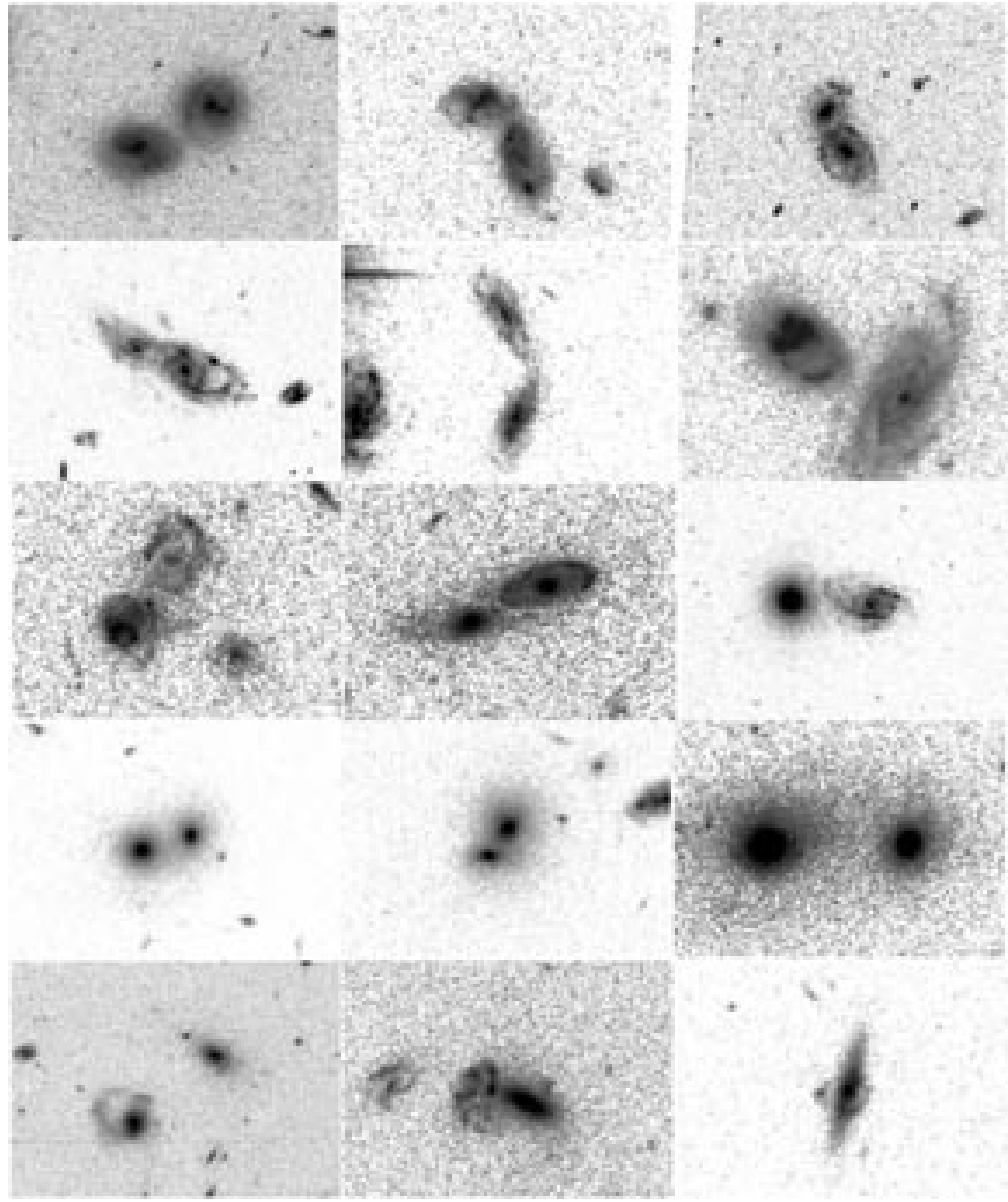
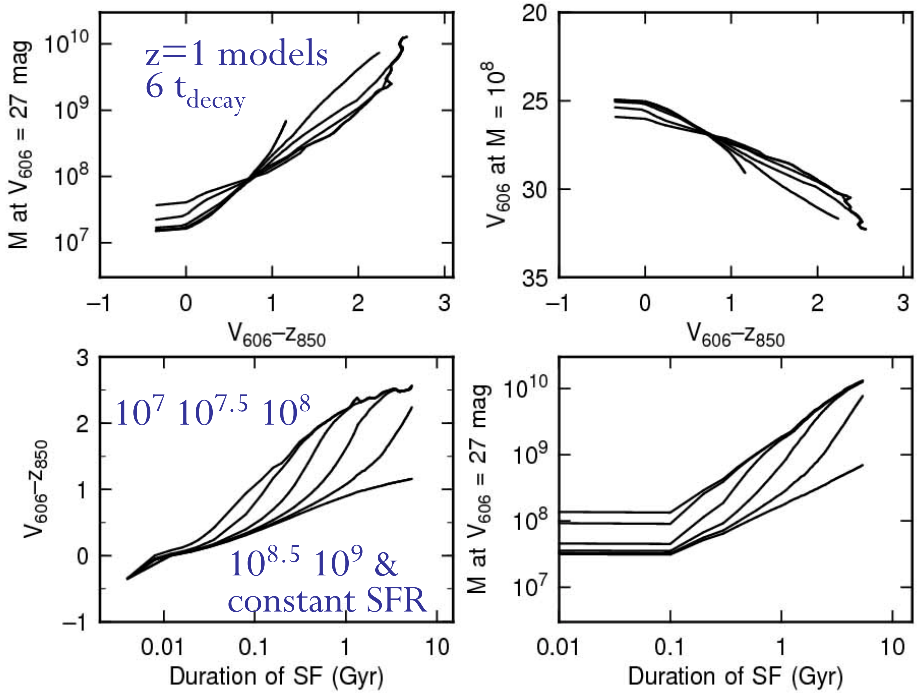
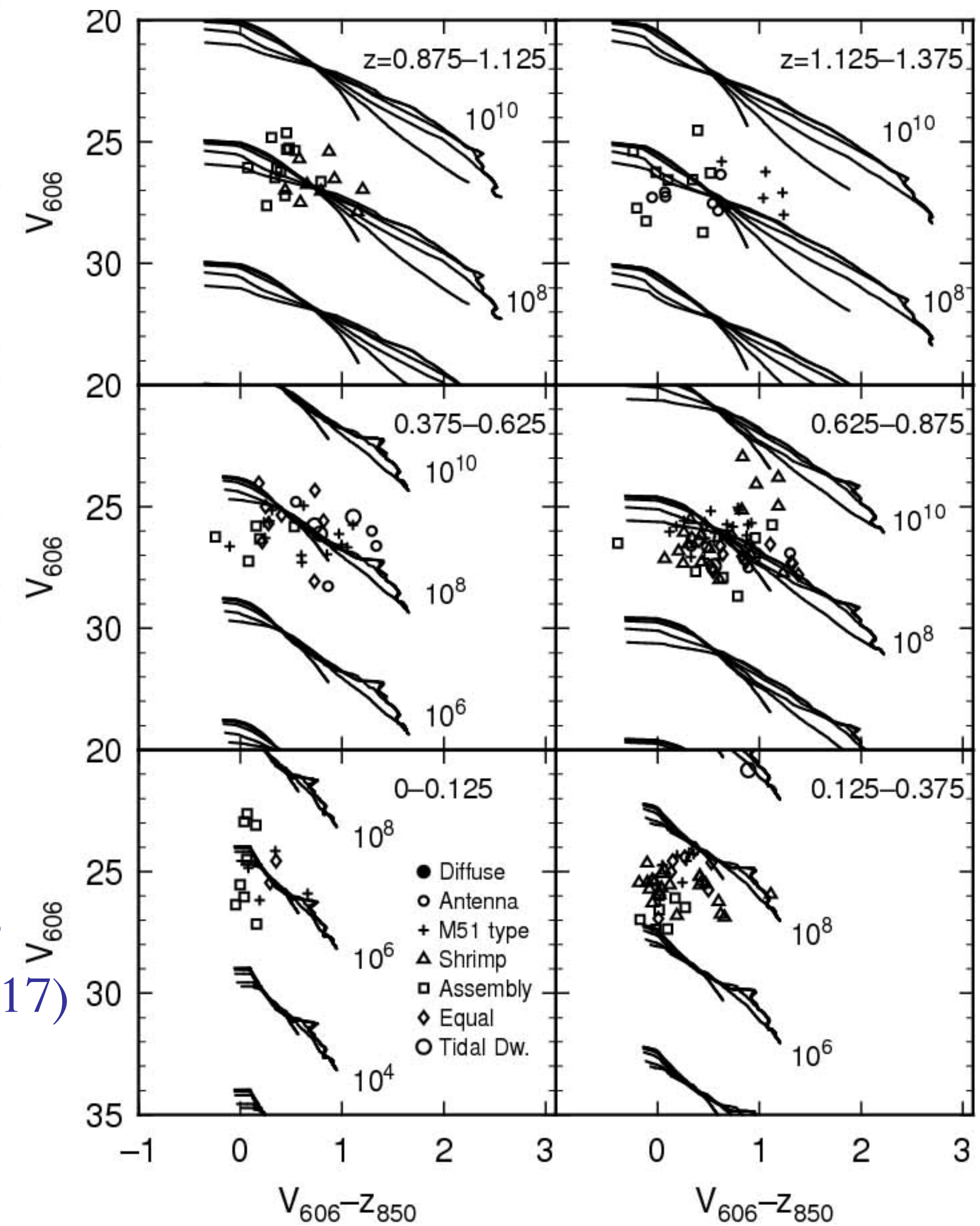
Equal-mass pairs

Weak interactions, normal spirals, not so violent



Elmegreen, Elmegreen, Ferguson, Mullan 2007



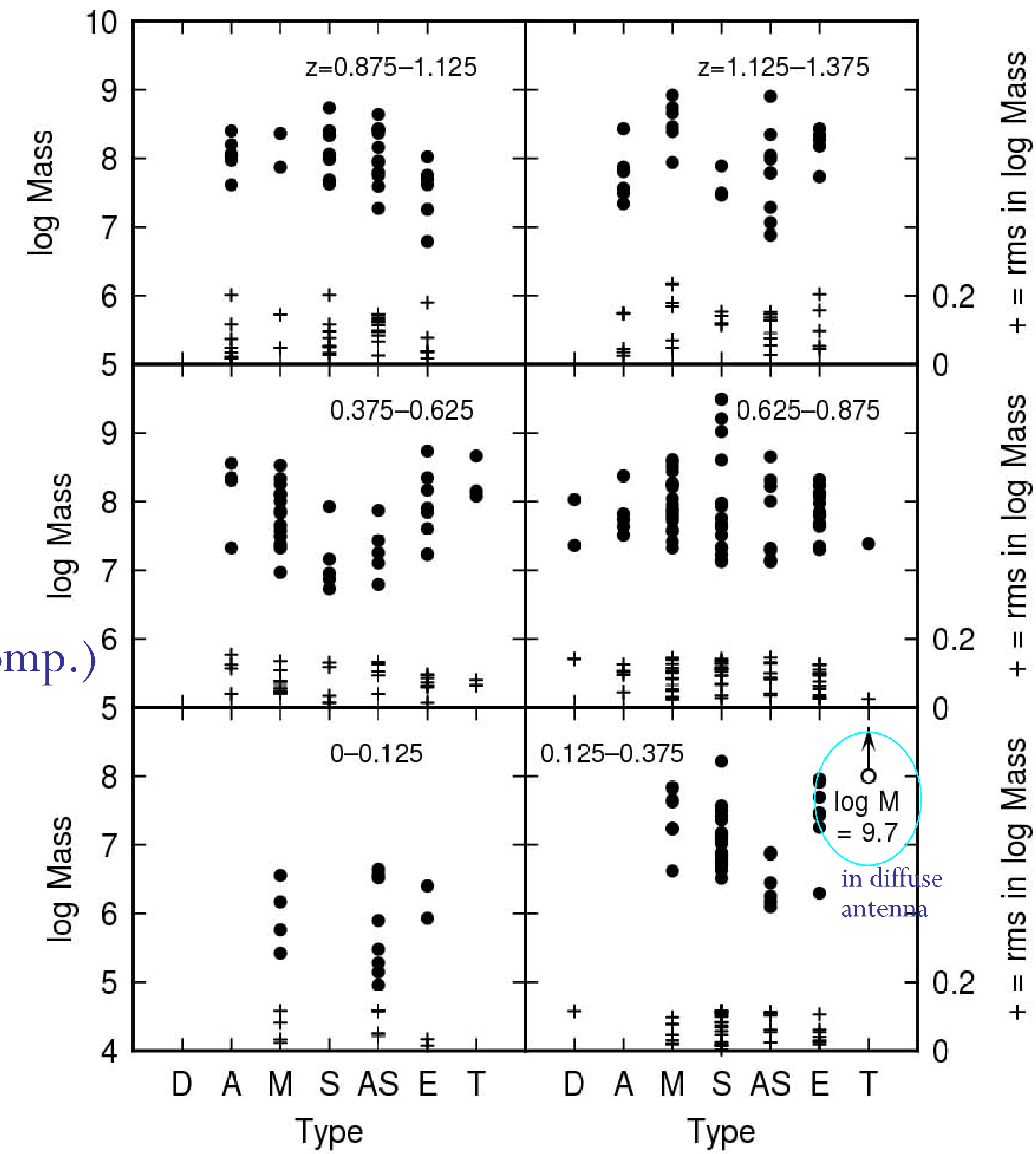


GEMS has 2 ACS filters: V and V-z
These are enough to estimate the mass given a photometric redshift (COMBO17)

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 each redshift



D=diffuse antennae

A=normal antennae

M=M51 types

S=shrimps (one-arm, no comp.)

AS = assemblies (later…)

E=equal pairs

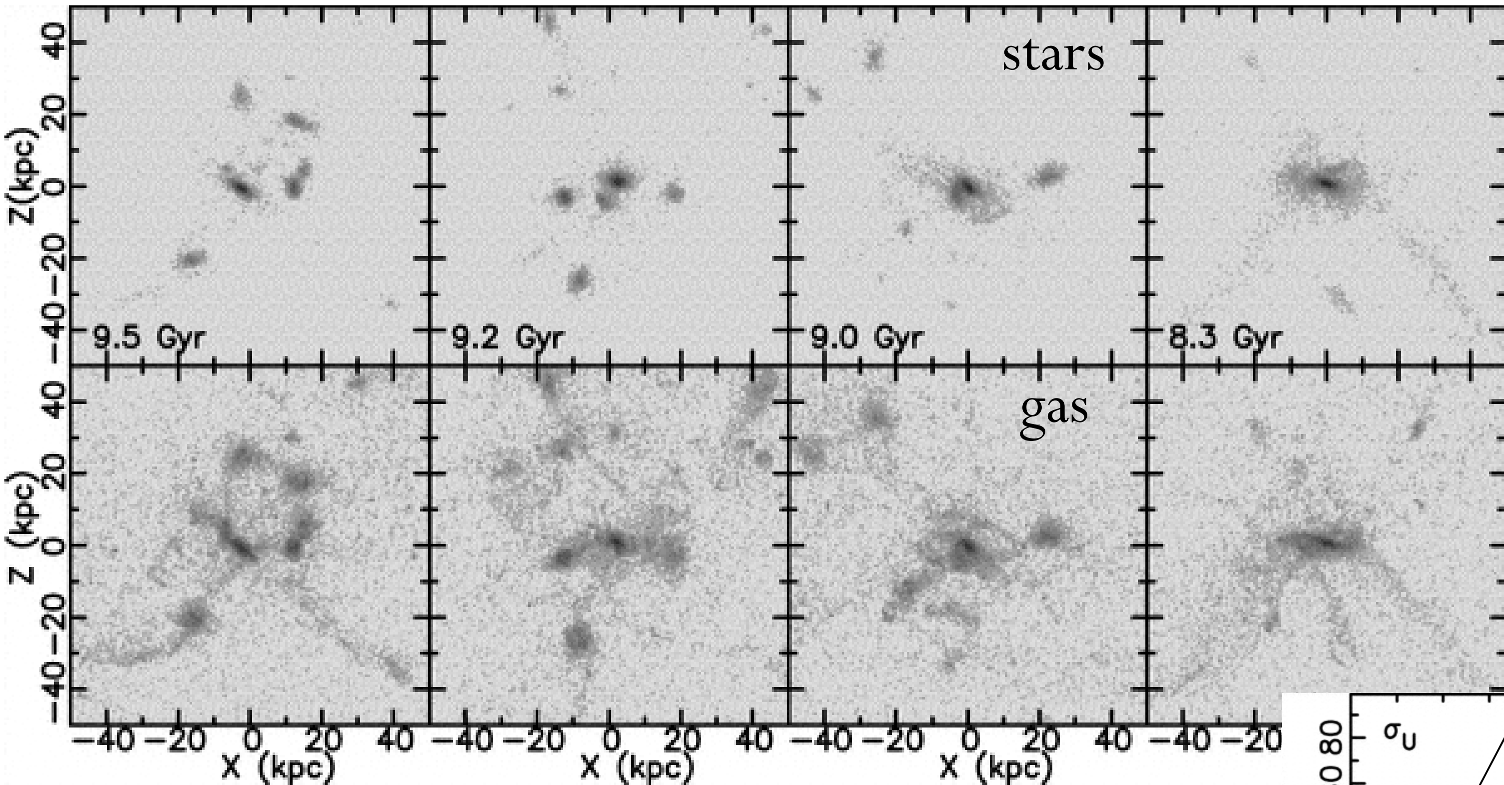
T=tidal dwarfs

Elmegreen, Elmegreen, Ferguson, Mullan 2007

However,

It is possible some clumpy young galaxies have clumps coming in from the outside.

Instabilities and clumping happens in the accreting gas

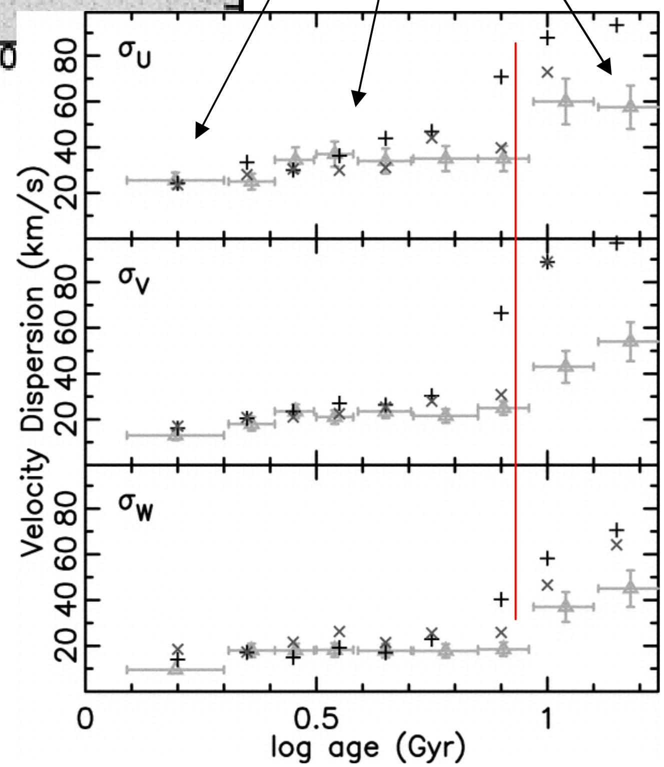


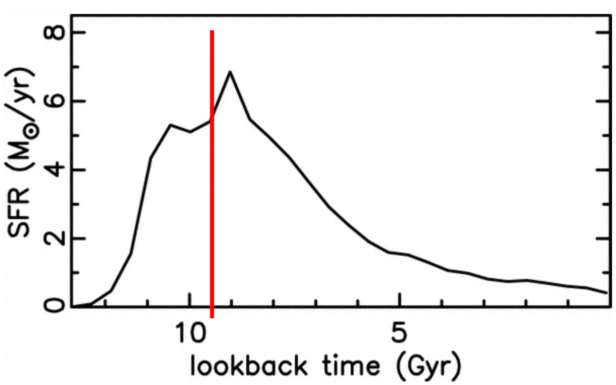
Profile of stars (top) and gas at epoch of thick disk formation

young thin disk

old thin disk

thick disk

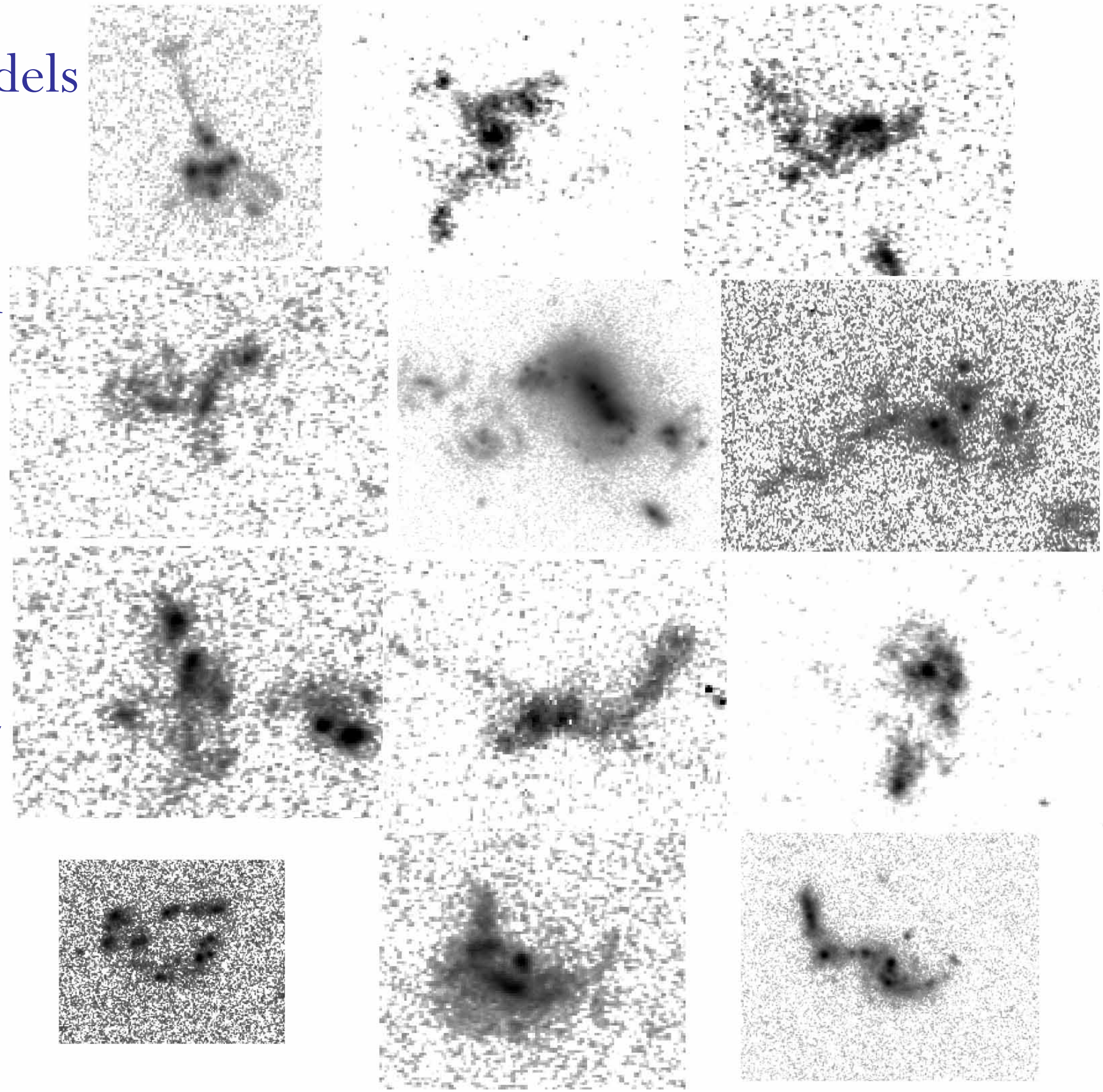




Thick disk turbulence stirred by clumpy gas impacts ~10 Gyr ago

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

The Brook models look like these loose clump clusters, which appear to be recent "assemblies"



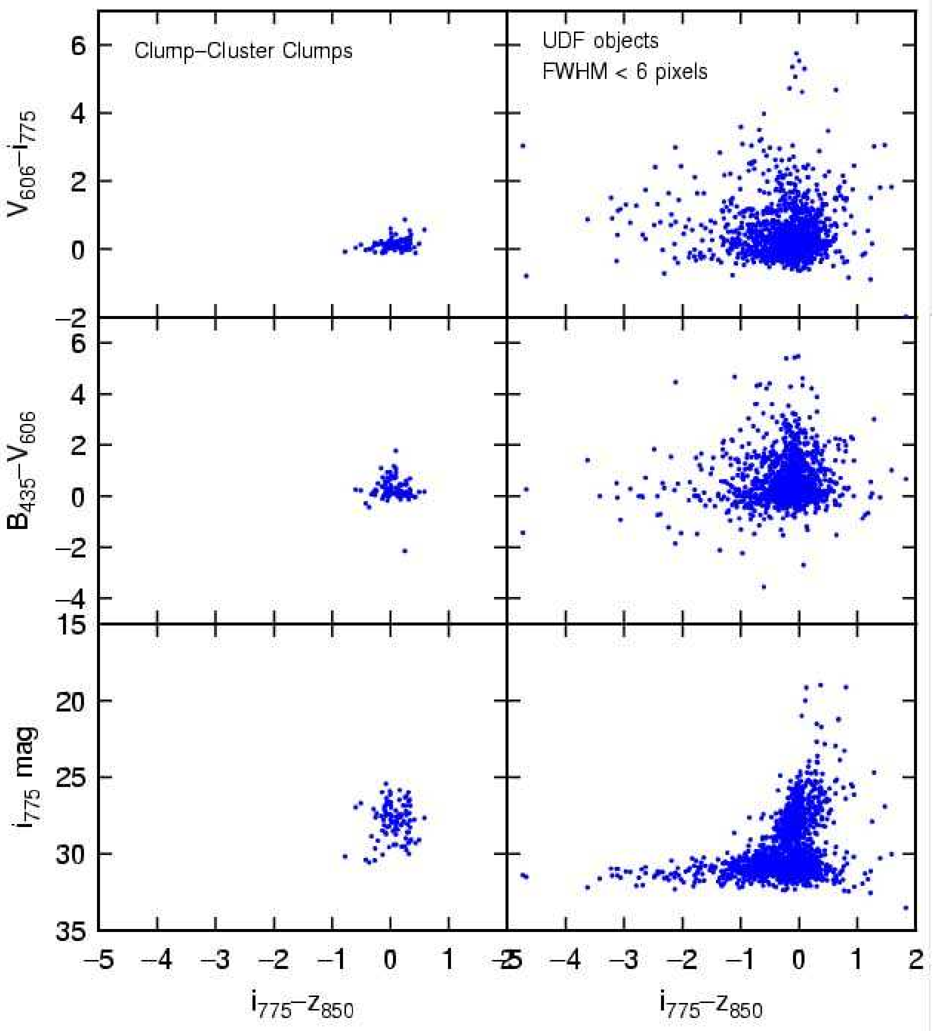
z from 0.093 to 1.309
<z> = 0.71 in GEMS/ GOODS

Elmegreen et al. 2007b

Also, the clumps in clumpy galaxies resemble small field galaxies in the UDF

- CMD for clumps in 10 UDF clump clusters vs 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)
- EXCEPT most clumps are confined to the midplanes of chains, and to the rings and spiral arms

- ANALOGY: SF regions in local dwarfs are about the same sizes and colors as SF regions in local spirals
  - velo. dispersions same, Σ_g same



(EE05)

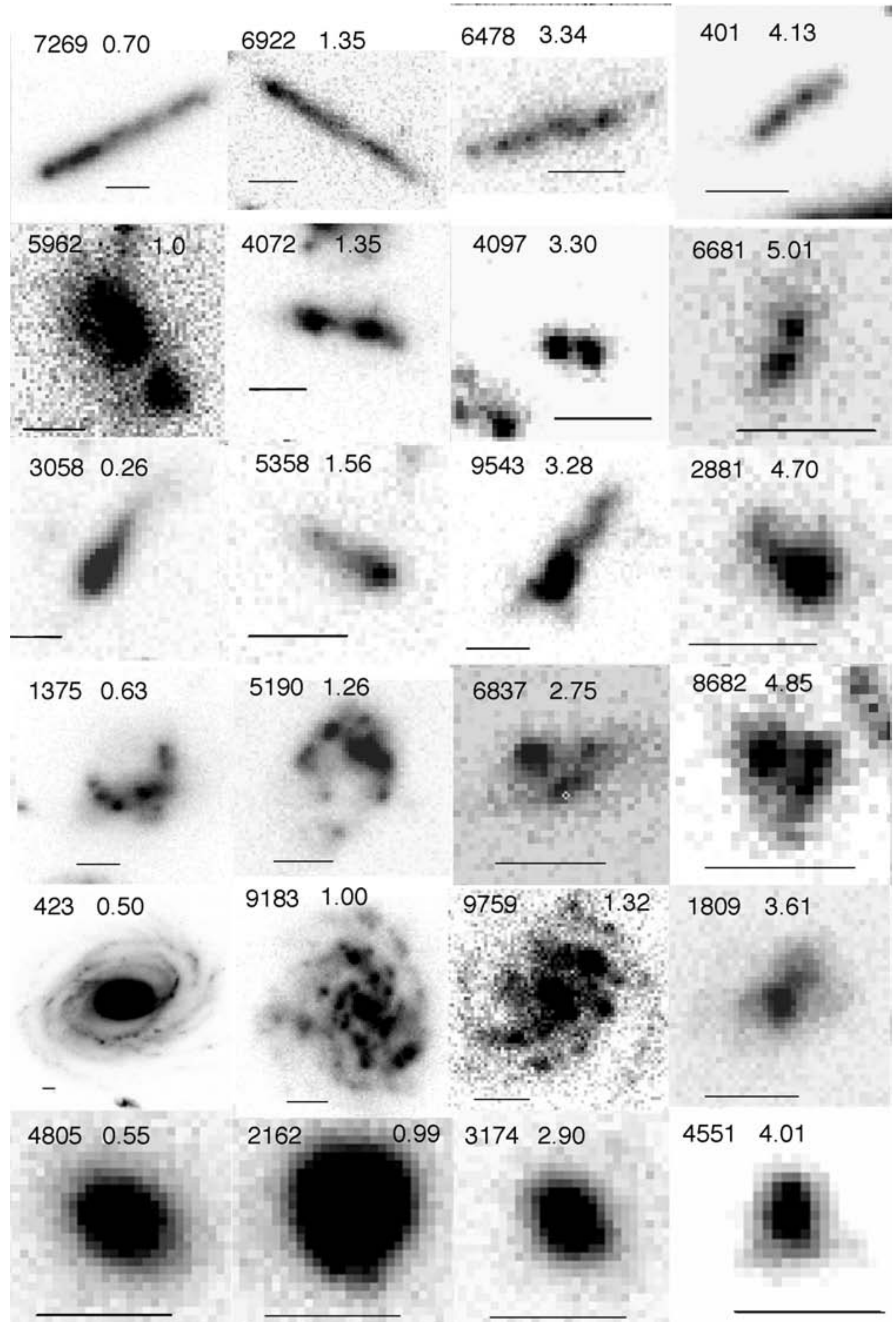
Can we follow the evolution of star and disk formation over cosmic time?

- The redshift distribution of morphologies in the ACS shows that <u>clumpy disks are the first types to form</u>
- They form early enough ($z \sim 5$) to <u>account for red disks and ellipticals</u> (via mergers) by $z \sim 2.5$
- They appear to form <u>continuously</u> because their dynamical times (evolution to exponential/bulge galaxies) and their star formation times (both ~1 Gyr) are shorter than their local Universe ages
- Transition cases from $z=1$ to 0 are now found (in prep.)

- Observations suggest <u>most star formation occurs in disks</u>

Photometric redshifts from Coe et al.

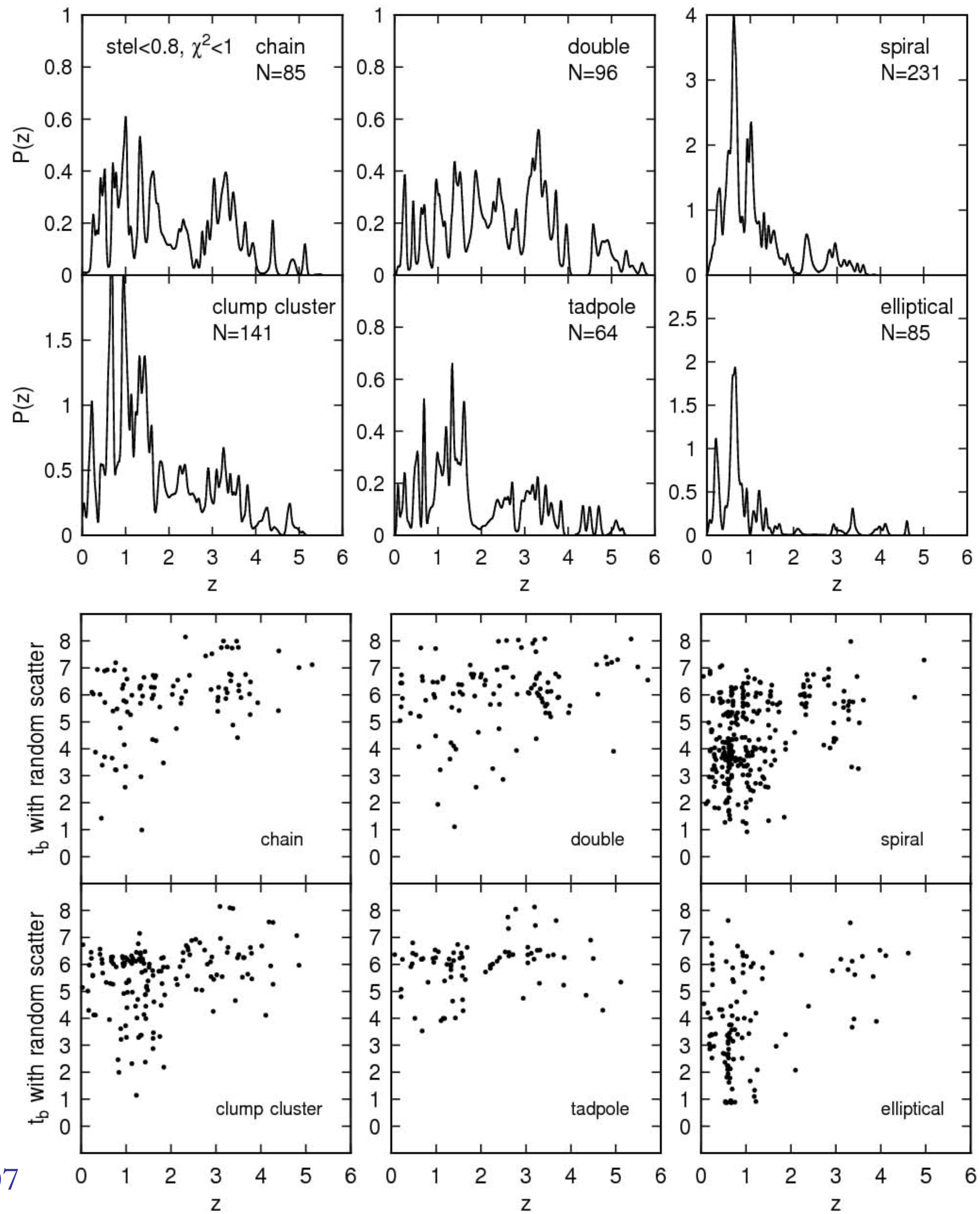
Uncertainty: $\Delta z \sim 0.04(1+z)$,
include only $\chi_{mod}^2<1$ and stel<0.8



Elmegreen, Elmegreen, Ravindranath, Coe 2007a

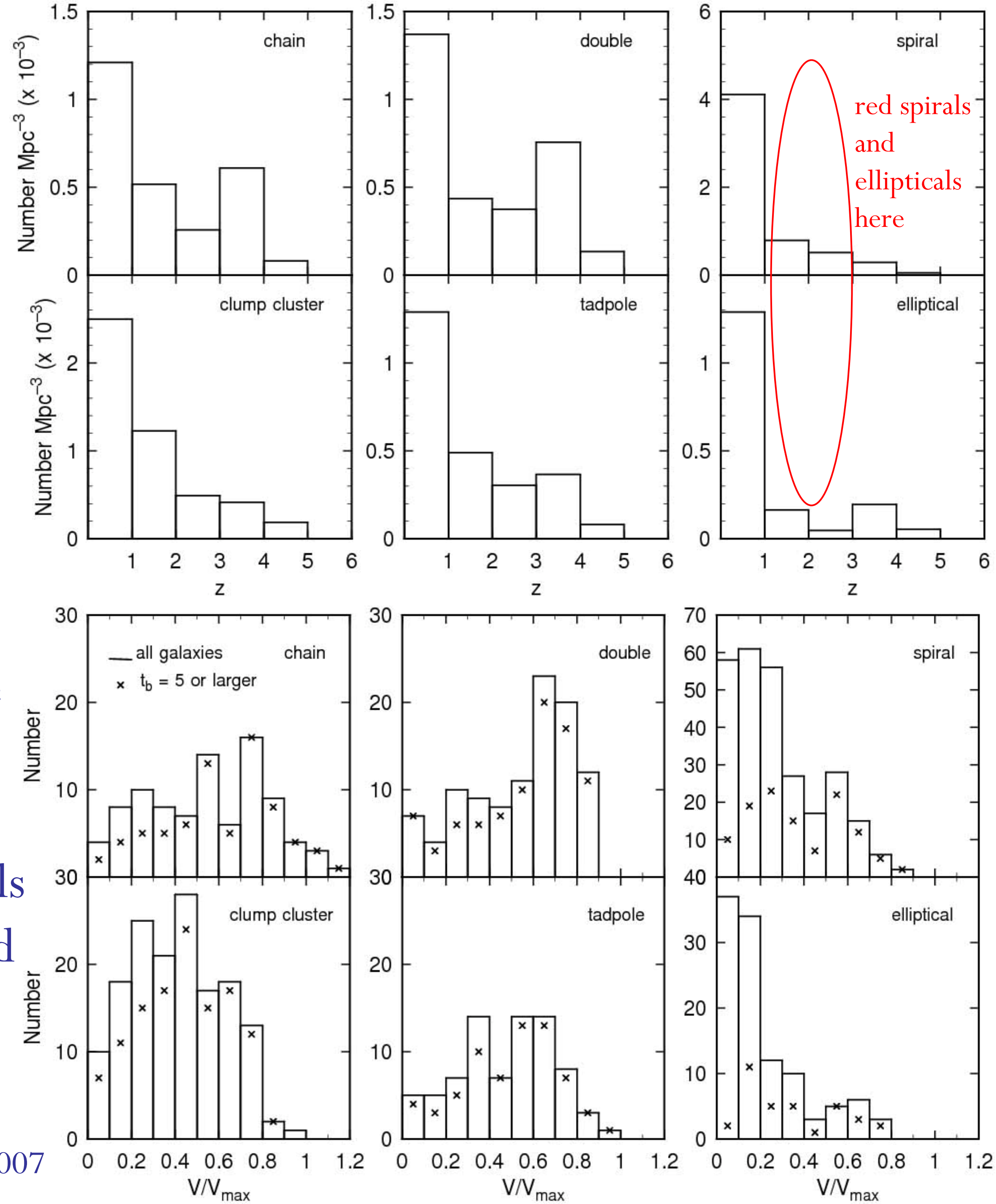
Spirals and Ellipticals restricted to z<2 (a result of bandshifting of red disks out of the ACS z filter)

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.



Elmegreen, Elmegreen, Ravindranath, Coe 2007

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

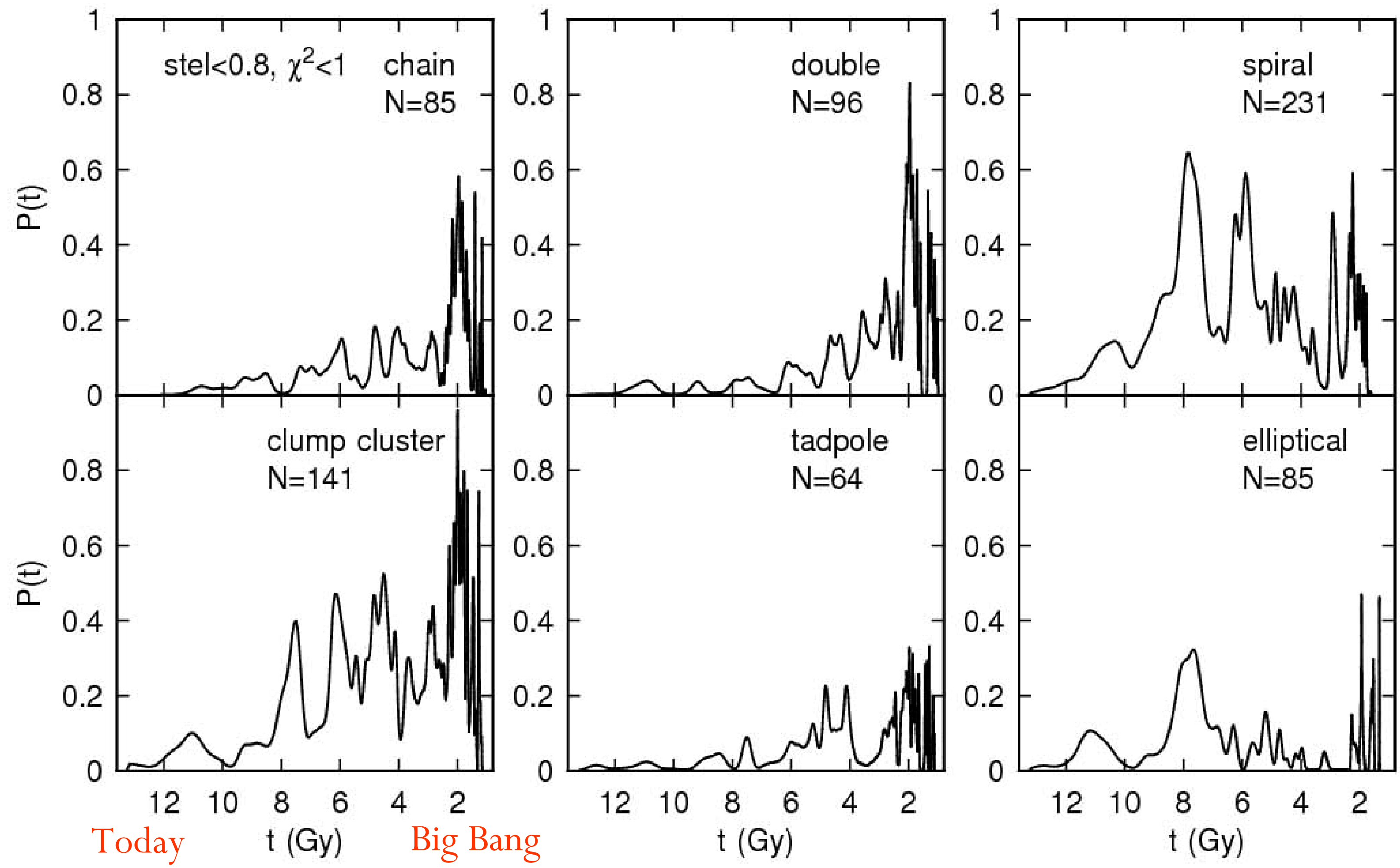


All spirals and ellipticals from z~3 to today could have begun as c-c/chain galaxies

- isolated ones made spirals
- coalescence makes ellipticals

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

Elmegreen, Elmegreen, Ravindranath, Coe 2007



Clumpy types dominate the early Universe and continue for ~8 Gyr with super-starburst rates. But τ_{SF}~ 1Gyr and $\tau_{clump\text{-}coalesc}$~1Gyr: Most likely, these non-nucleated clumpy disks continuously form.

Elmegreen, Elmegreen, Ravindranath, Coe 2007; Bournaud, Elmegreen & Elmegreen 2007

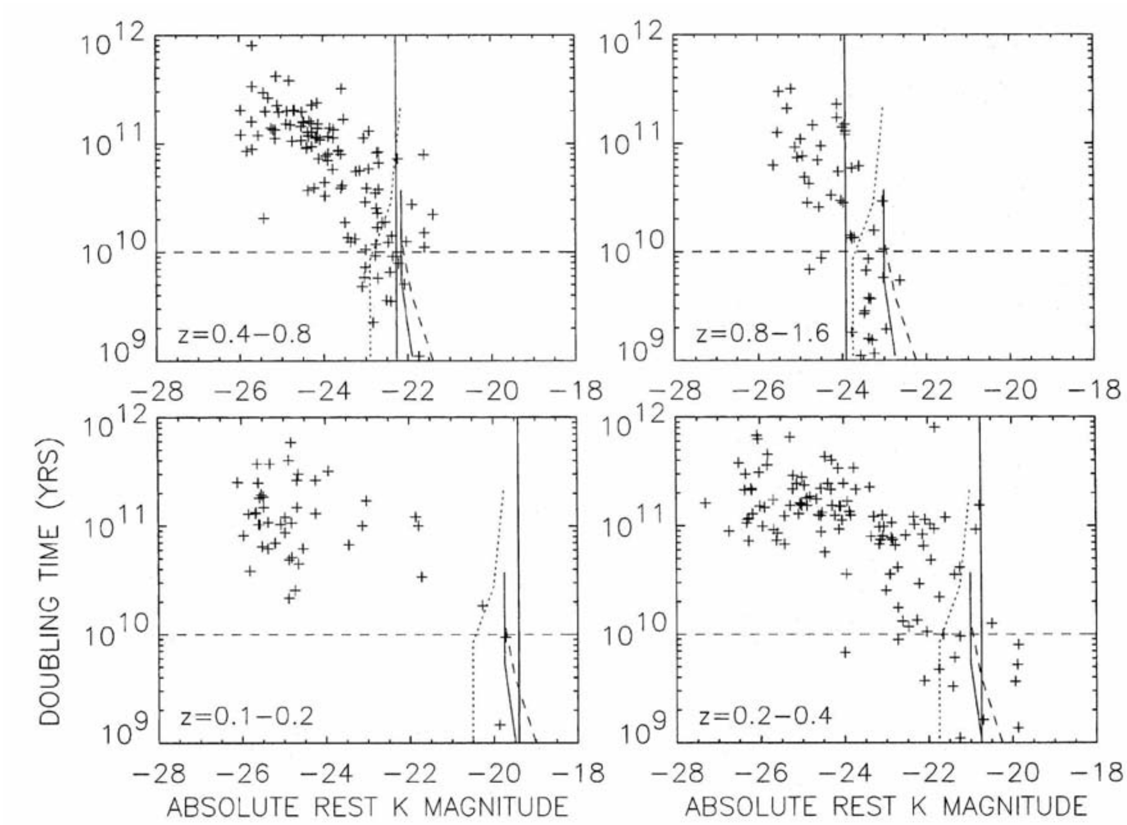
More on Continuous Formation: Downsizing

Cowie et al. 1996:

Measured K, I, B mags and sp. redshifts of 393 galaxies in 2 Hawaii deep survey fields.

Considered restframe U-K<1.3 to be "forming" because M/(dM/dt)<10 Gyrs

"Forming" galaxies get lower M at decreasing z



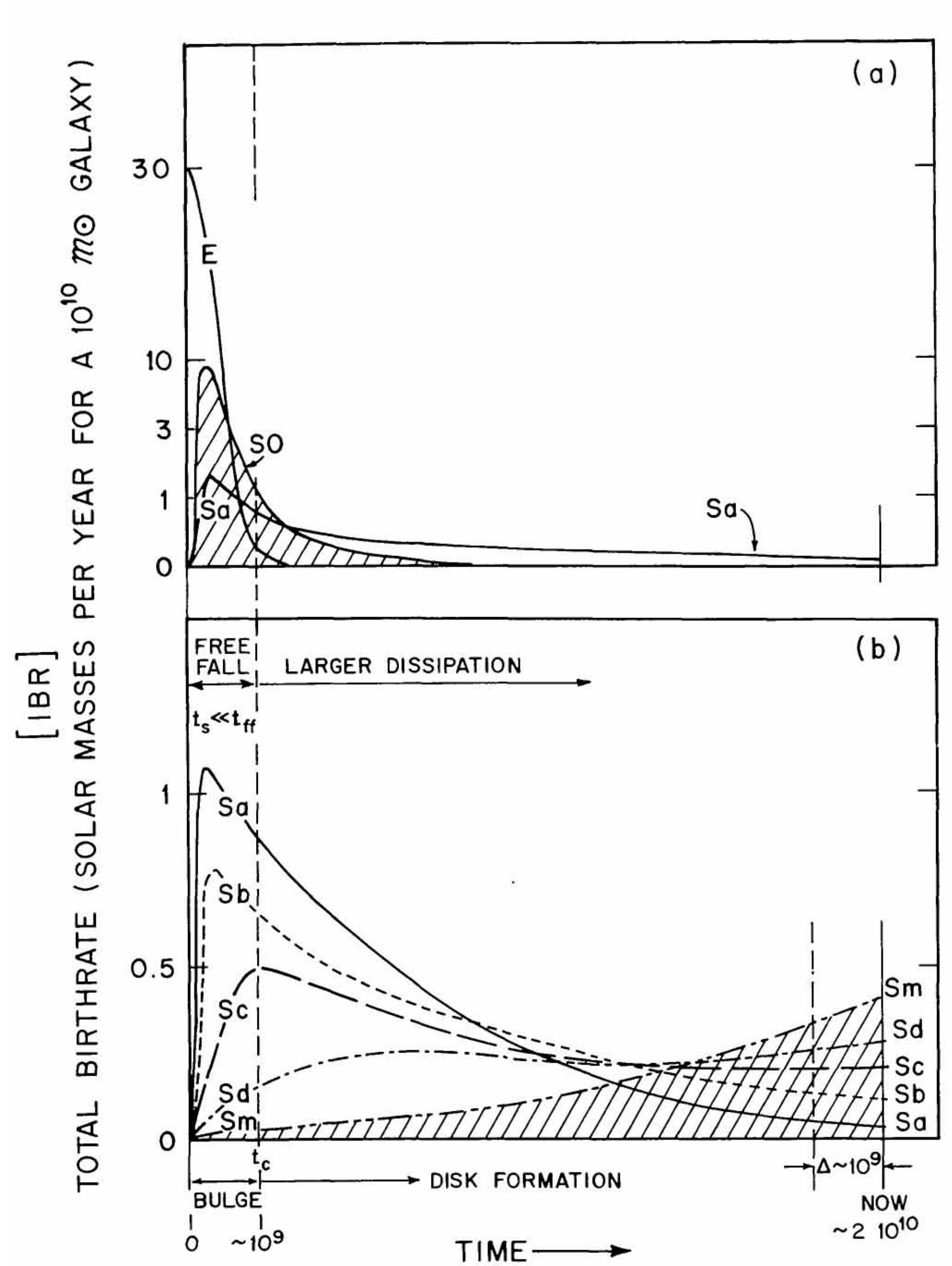
Sandage 1987

and others recognized these general trends too in today's galaxies.

Massive galaxies are red, low mass galaxies blue.

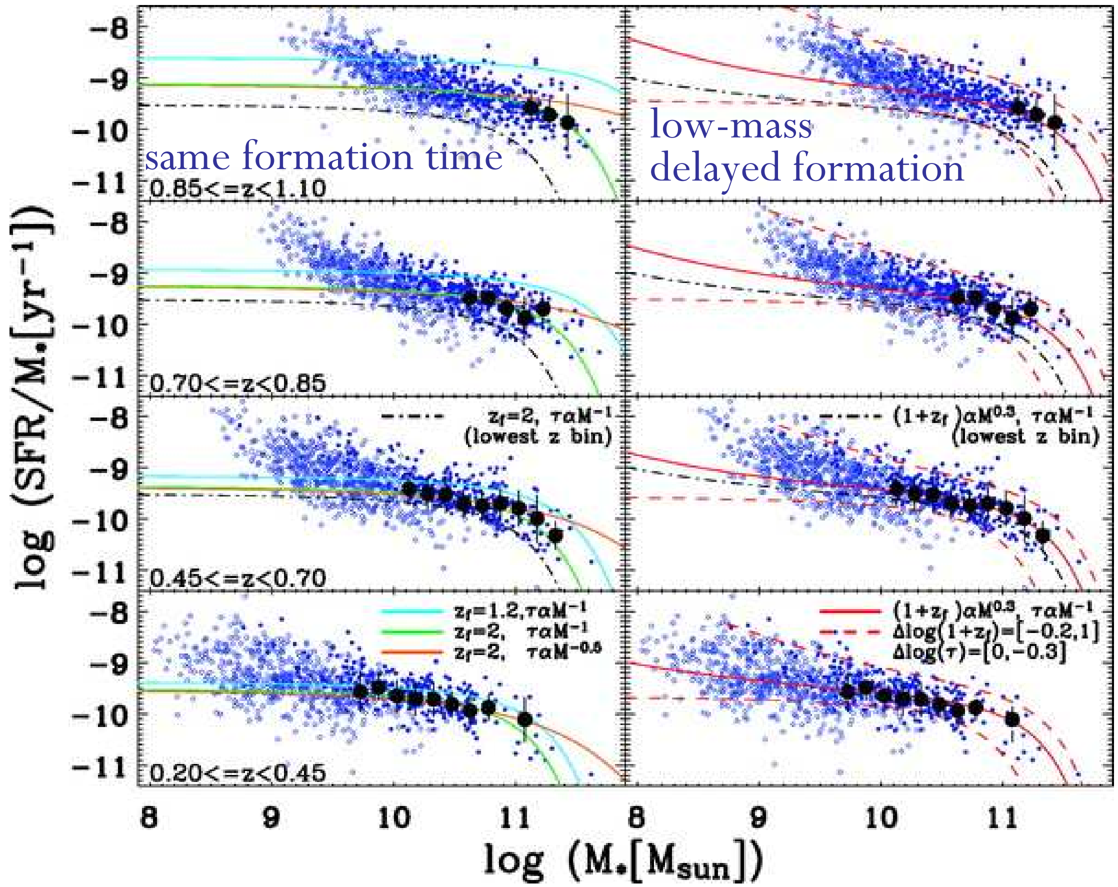
Hubble type is a sequence of mass and color.

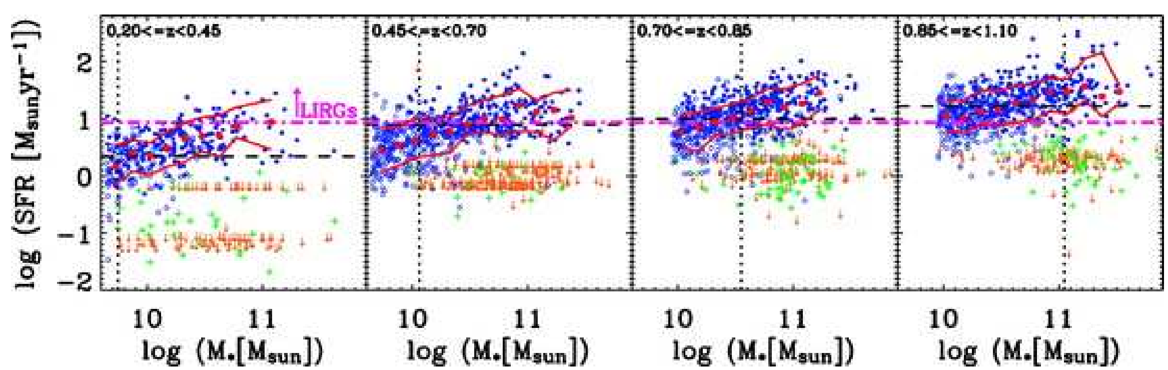
Standard model has all galaxies form at the same time and evolve at HT-dependent rates



Noeske et al. 07a,b suggest small galaxies form late and decay by simple gas consumption.

SF in late Hubble Types (= low mass, low density) starts late and proceeds slowly, as expected for processes dominated by gravitational instabilities.





Noeske et al. 07a,b

Conclusions - I

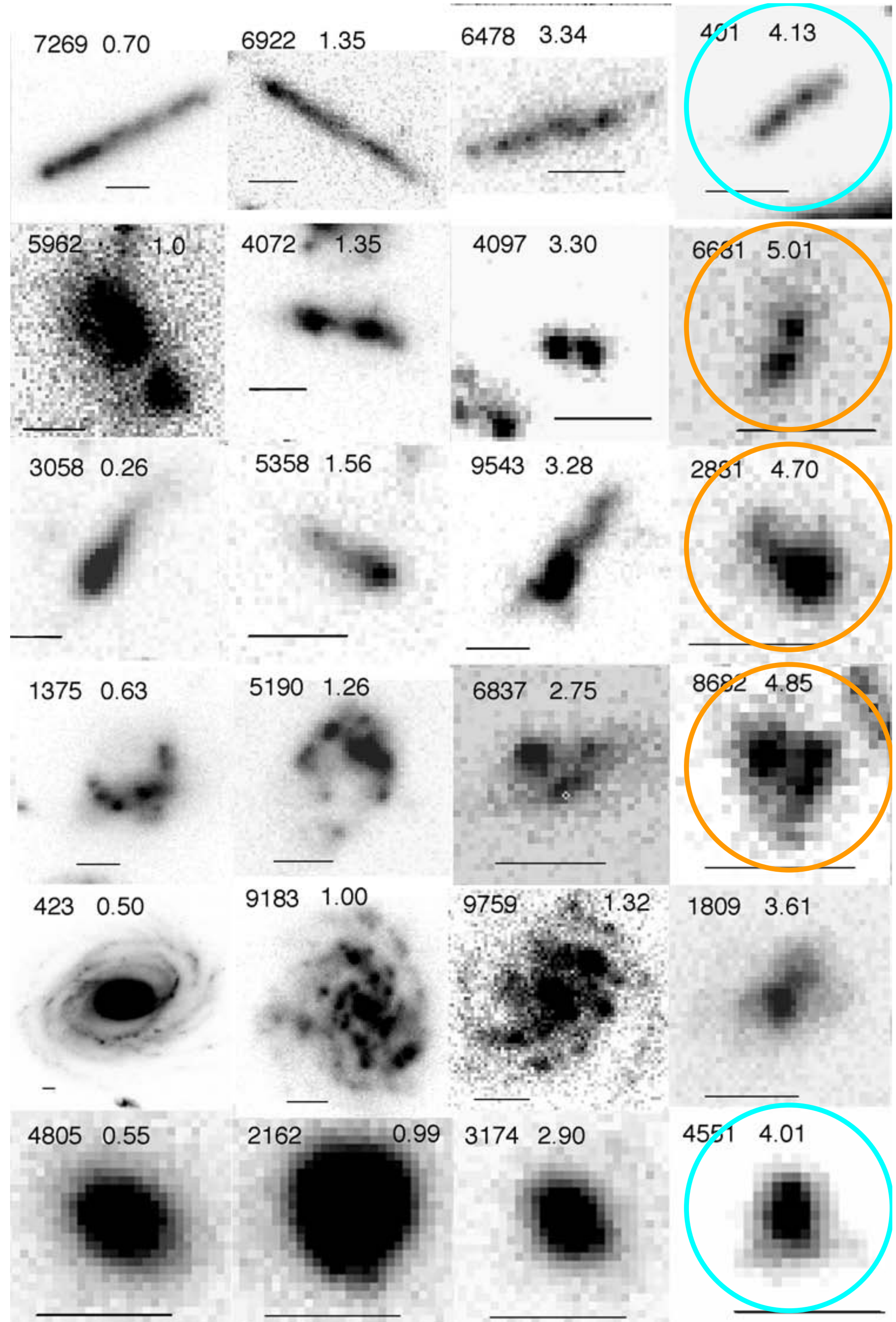
- Star formation at $z=0-5$ can be observed directly using the high resolution of the ACS camera (250 pc/px).
- Most galaxies (>10 px) have star formation in giant clumps in disks
  - The dominant morphology at $z=1-2$ is a clump cluster
  - At $z>2$, combined clumpy types outnumber spirals+ellipticals by factor of 2
  - starbursting spirals dominate at $z<1$, but even then their total count only equals the sum of the chains and clump clusters
  - sub-mm galaxies are dusty SF systems, Lyman break galaxies are intense SF systems, but most are outside the UDF and have not been resolved*
- Red galaxies tend to be standard Hubble types (spirals & ellipticals) and although they bandshift out of the ACS at $z>2$, IR surveys show their comoving count really does drop $z>1.5$ (Daddi et al. 05, Cassata et al. 05, Franceschini et al. 06), long before the clumpy types disappear.
- <u>The earliest and most persistent SF morphology is a clumpy disk</u>. Apparently, most SF is in disks. Disks that avoid major mergers become spirals, those that don't become ellipticals.

Lyman Break Drop-out Galaxies[a]

B-band drop-outs					
UDF	SFR[b]	UDF	SFR[b]	UDF	SFR[b]
65(C)	7.9	141(T)	9.5	401(C)	21
631(E)	8.4	985(D)	5.7	2394(C)	3.7
3001(C)	2.0	3458+3418(C)	13	3778(CC)	19
4313(D)	4.1	4548(T)	7.7	4551(E)	16
4685(D)	14	4765+4795(CC)	21	5548(CC)	12
6137(D)	2.3	6209(D)	1.5	6450(C)	3.8
6543(D)	15	6709(C)	1.1	6808(D)	4.8
7036(S)	77	7044(T)	3.1	8092(C)	16
8419(D)	6.6	9085+8865(C)	9.7	9310(T)	1.8
C7(C)	7.1	E19.47(E)	15	CC11(CC)	61
V-band drop-outs					
1796(D)	6.2	2350(CC)	42	2881(T)	58
3377+3398(D)	30	5225(C)	48	5928(D)	6.5
6139(D)	63	6681(D)	24	7328(CC)	465
8326(D)	18	8664(D)	23	8682(CC)	50
D11(D)	9.9				

B-band drop outs

V-band drop outs



Elmegreen, Elmegreen, Ravindranath, Coe 2007a

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Conclusions - II

- Most stars form in giant uv clumps, 10^7-10^9 M_O, kpc scales, 100-300 Myr timescale
  - mass, size, timescale, morphology consistent with formation by gravitational instability
  - turbulence triggering, shells, comets, etc., hierarchical star formation, SSC, OB associations, etc., may be clump substructures, but cannot be resolved yet
  - no evidence for explosive "quenching." Death by gas consumption instead.
- Simulations and observations suggest that exponential galaxy disks and bulges build up as clumps dissolve
  - happens very quickly, few dynamical times
  - Nuclear Black Holes then have to be made in the clumps and brought to the nuclei by interaction torques and dynamical friction when the bulge forms (BEE07)
- Redshift distributions and rapid evolution times (EERC07, BEE07), as well as SF rates and masses (Noeske et al. 07), suggest that galaxies form continuously, with low mass galaxies forming late and slow, and high mass galaxies forming early and fast.

Questions

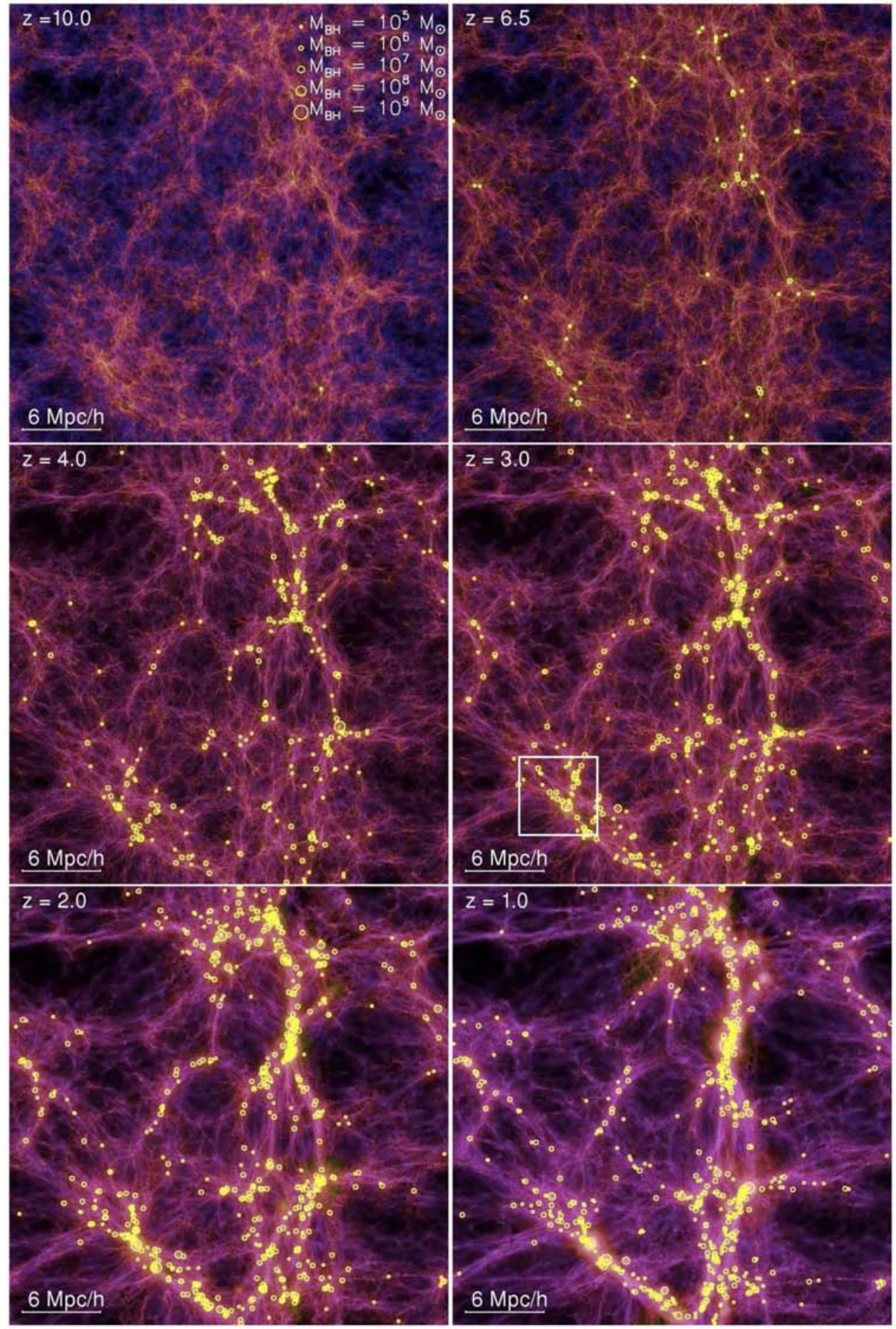
- Are super starburst cases ULIRGs etc. the same physical processes?
  - dynamical SF: SF rate ~ $0.1\Delta v^3/G \sim 24(\Delta v/100\text{km/s})^3\ M_O/\text{yr}$
  - timescale ~ $GM/\Delta v^3 \sim 40\text{Myr}*(M/10^{10}M_O)(\Delta v/100\text{km/s})^{-3}$
- Are all ellipticals and messy 3D starbursts major mergers?
  - mixed up disks with maximum SF rates from GI
- Are there several bulge formation mechanisms?
  - dissolved bars and inner dynamical instabilities among stars
  - nuclear, highly turbulent star formation
  - coalesced disk clumps
  - mini-mergers (bare bulges)
- Can simulations produce the observed galaxy morphologies?

DiMatteo et al. 07 study Black Hole growth with SPH using sink particles.

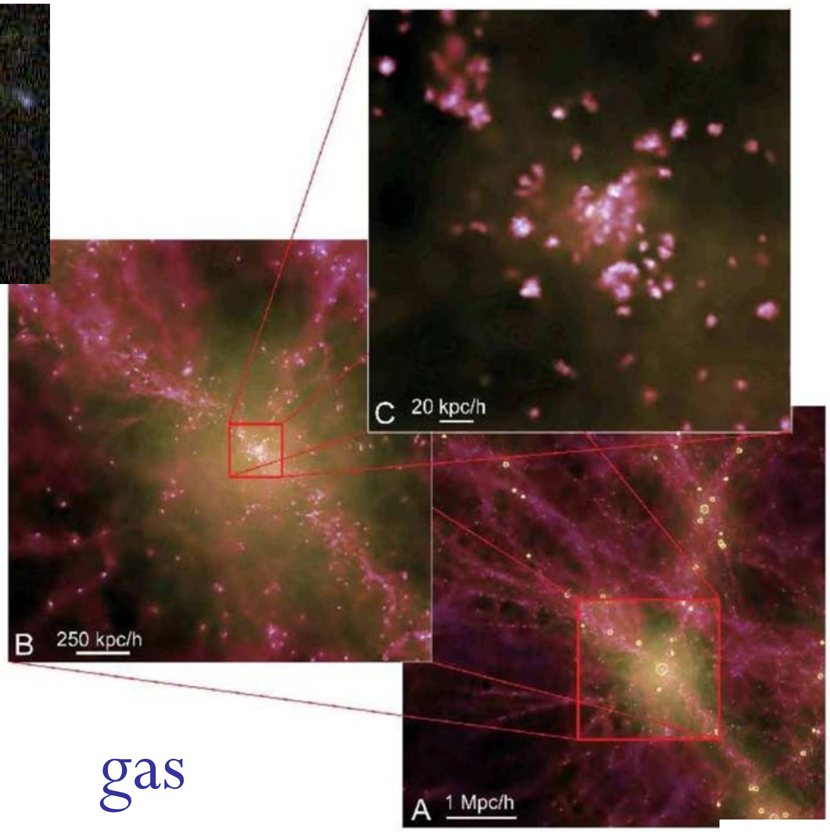
Code has cloud formation from thermal instability and star formation in the cool clouds.

Stars heat the gas with supernovae, evaporate cool clouds, and form a steady state.

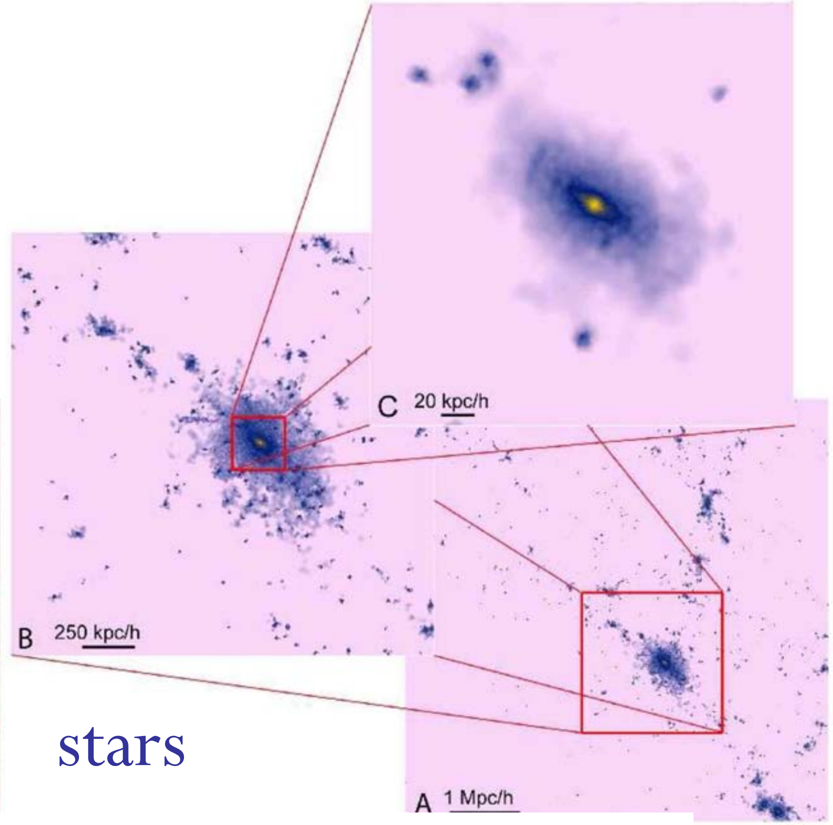
Unrealistic SF prescription may not matter, but <u>high SPH shear viscosity may… disk versus nuclear accretion.</u>



UDF1666 (not a bad match in the uv)



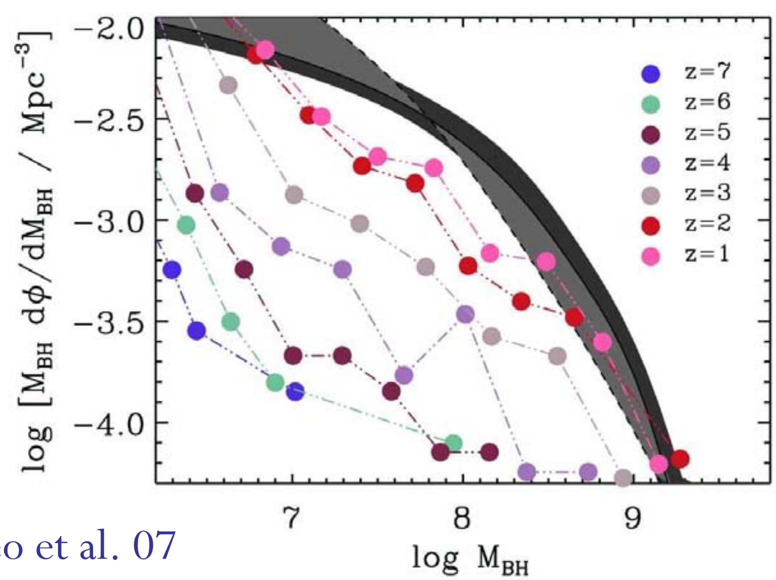
gas



stars

Distributions at z=3

BH Mass function versus z: high mass BH finished forming by z=2, and lower mass BH continue to form later: <u>downsizing in BHs</u>



DiMatteo et al. 07

Direct observations of star formation in high redshift galaxies reveal the dominant physical processes involved and may illustrate the formation of galaxy disks.

Most studies consider only galaxy-integrated properties, not morphology, but the key to understanding processes is the morphology.

Computer simulations could be tuned better to reproduce the observed morphologies.

The End