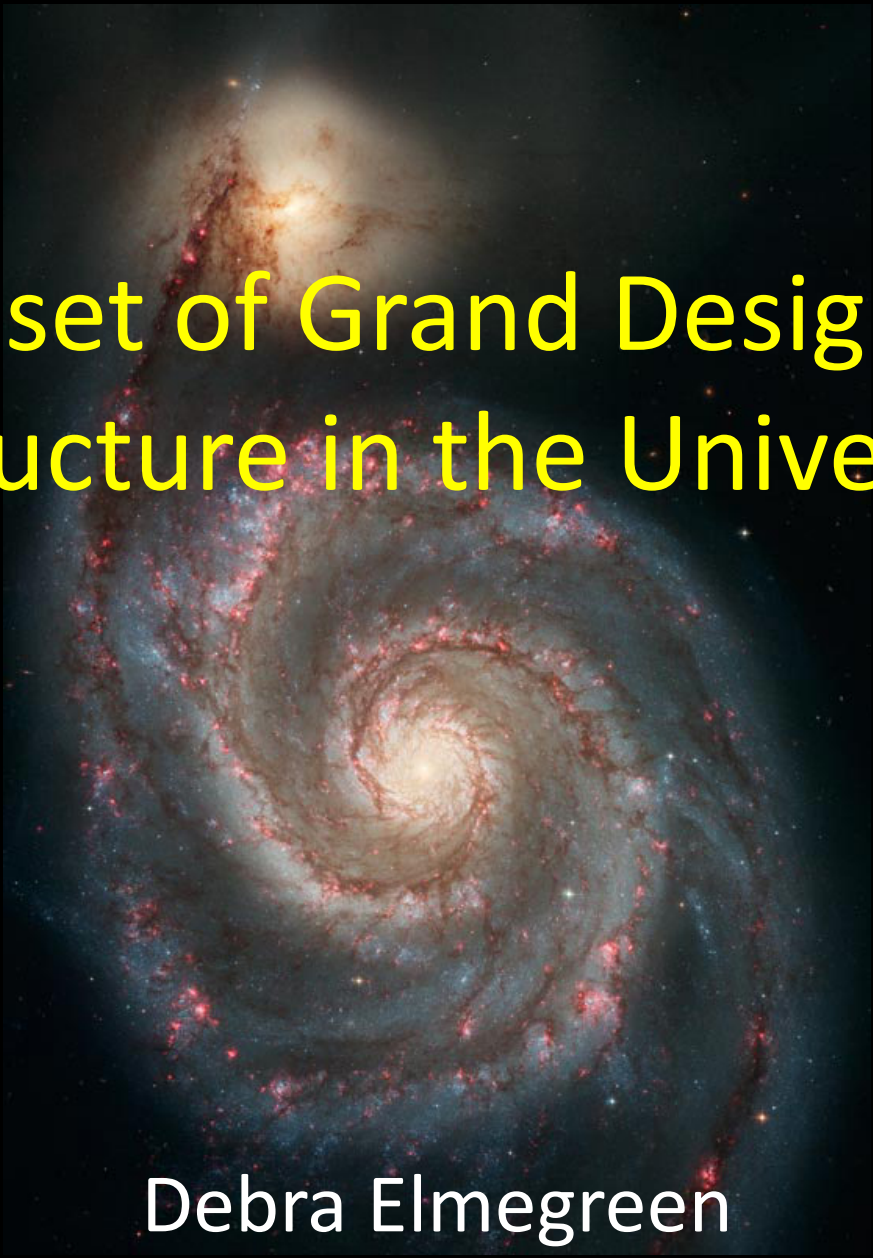


# The Onset of Grand Design Spiral Structure in the Universe



Debra Elmegreen  
Vassar College, New York, USA

The Lin-Shu Symposium – Beijing – June 2013

# Overview of high redshift galaxies

- General morphology: statistics
- Properties: star formation, radial profiles, kinematics
- Evolution to spirals: hot disks and bar structure

# Lin and Shu density waves

THE ASTROPHYSICAL JOURNAL, Vol. 155, March 1969

ON THE SPIRAL STRUCTURE OF DISK GALAXIES

III. COMPARISON WITH OBSERVATIONS\*

C. C. LIN AND C. YUAN

Massachusetts Institute of Technology

AND

FRANK H. SHU

Harvard College Observatory

Received June 21, 1968; revised August 16, 1968

As emphasized before (Oort 1962; Lin and Shu 1967; Lin 1968), the primary purpose of our theory is to attempt to explain the *grand design* over the whole disk, and in particular to explain its persistence.

The waves described by the dispersion relationship (eq. [3.2]) have the following properties:

a) They extend essentially over a range of the galactic disk for which the conditions

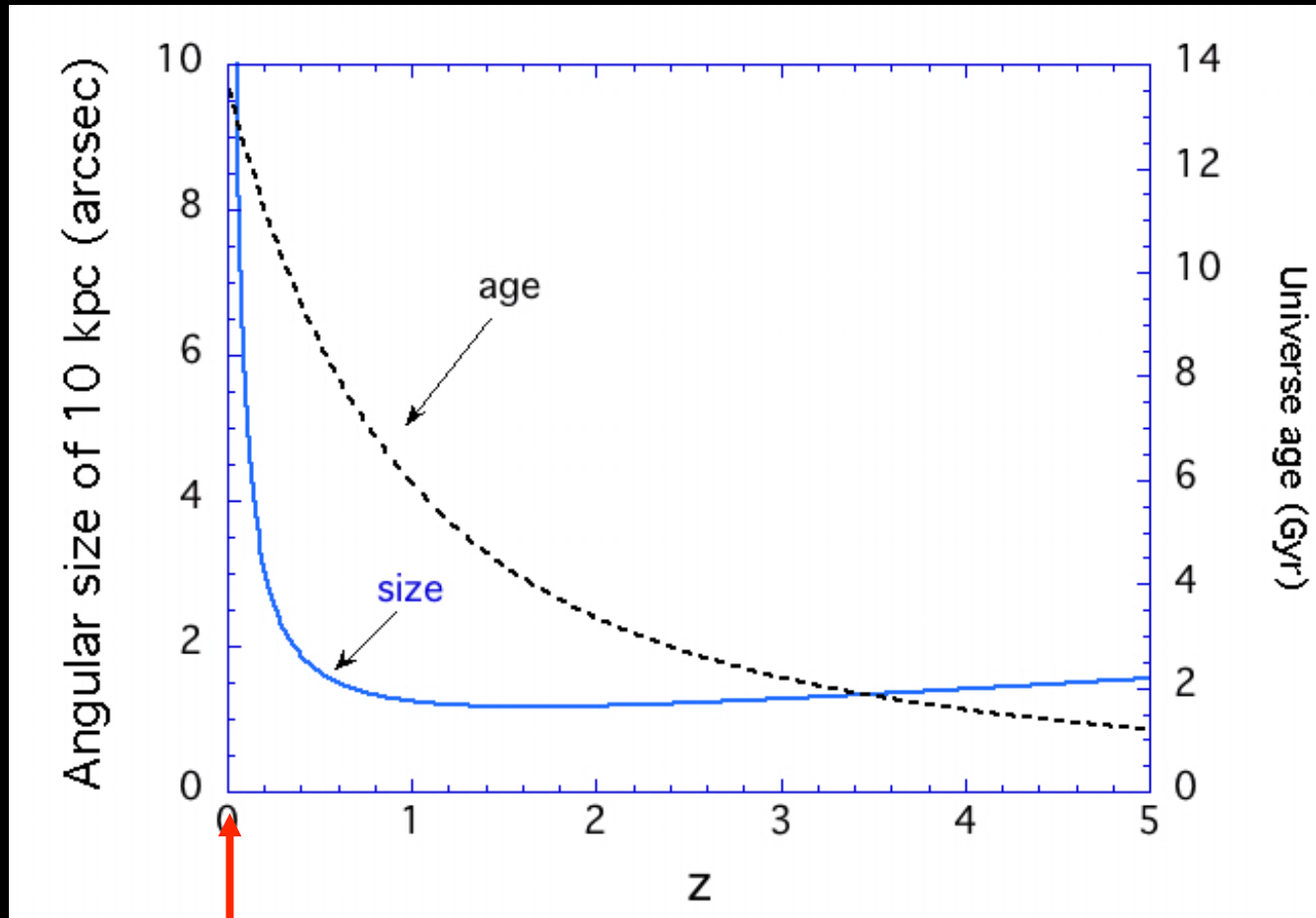
$$\Omega - \frac{\kappa}{m} < \Omega_p < \Omega + \frac{\kappa}{m} \quad (3.5)$$

*all spirals have two arms* (or only one arm), for the rotation curves are qualitatively the same. Note that the argument no longer holds for the outer part of a galaxy, leaving the possibility open for the existence of “multiple-armed” galaxies such as M101, which has still a well-defined two-armed structure in the interior parts.

# Galaxy morphology at high $z$

# Distant galaxies: resolved out to $z > 4$

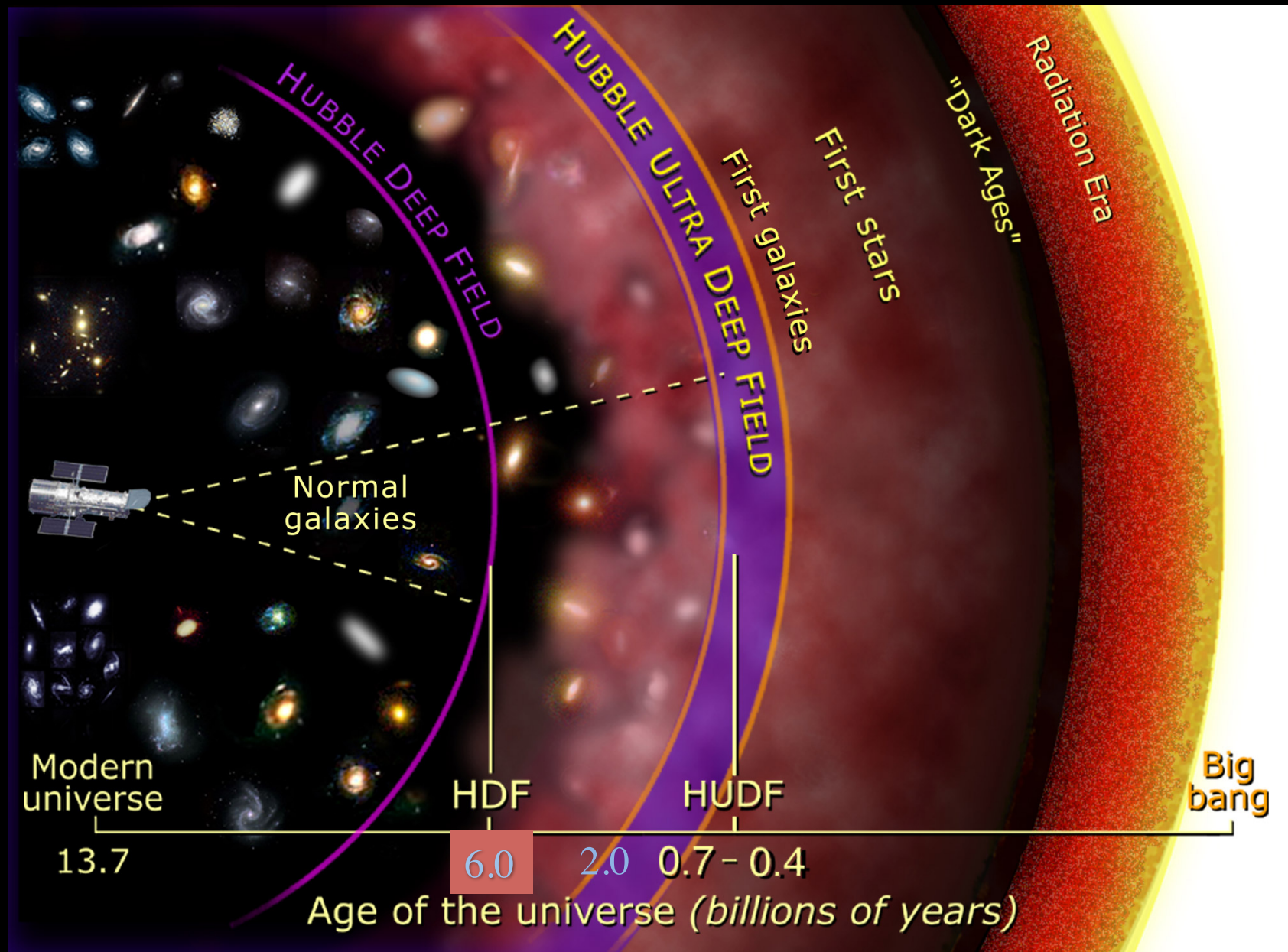
< 2 billion years after the Big Bang



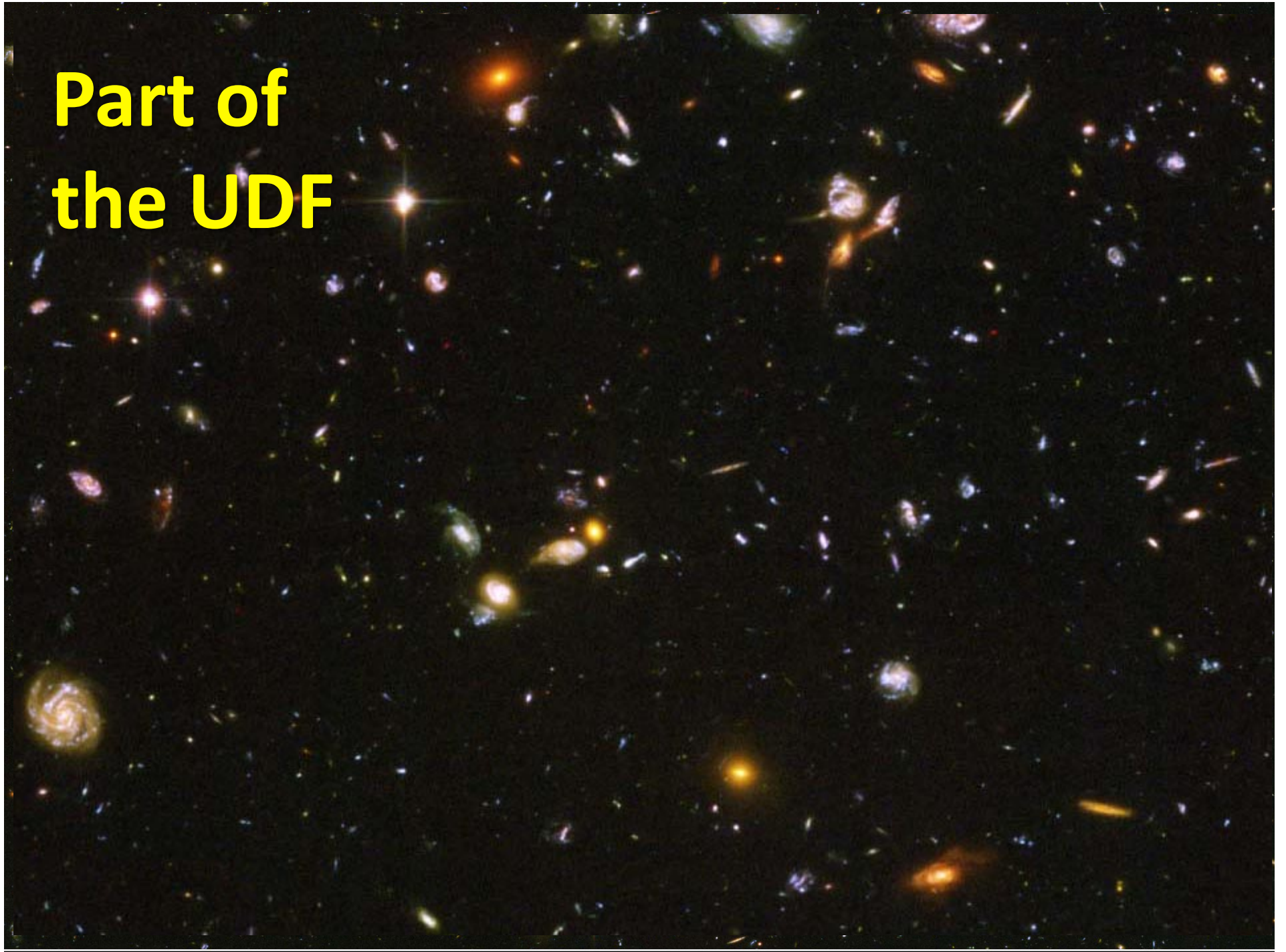
Current age  $\sim$  13.7 billion years

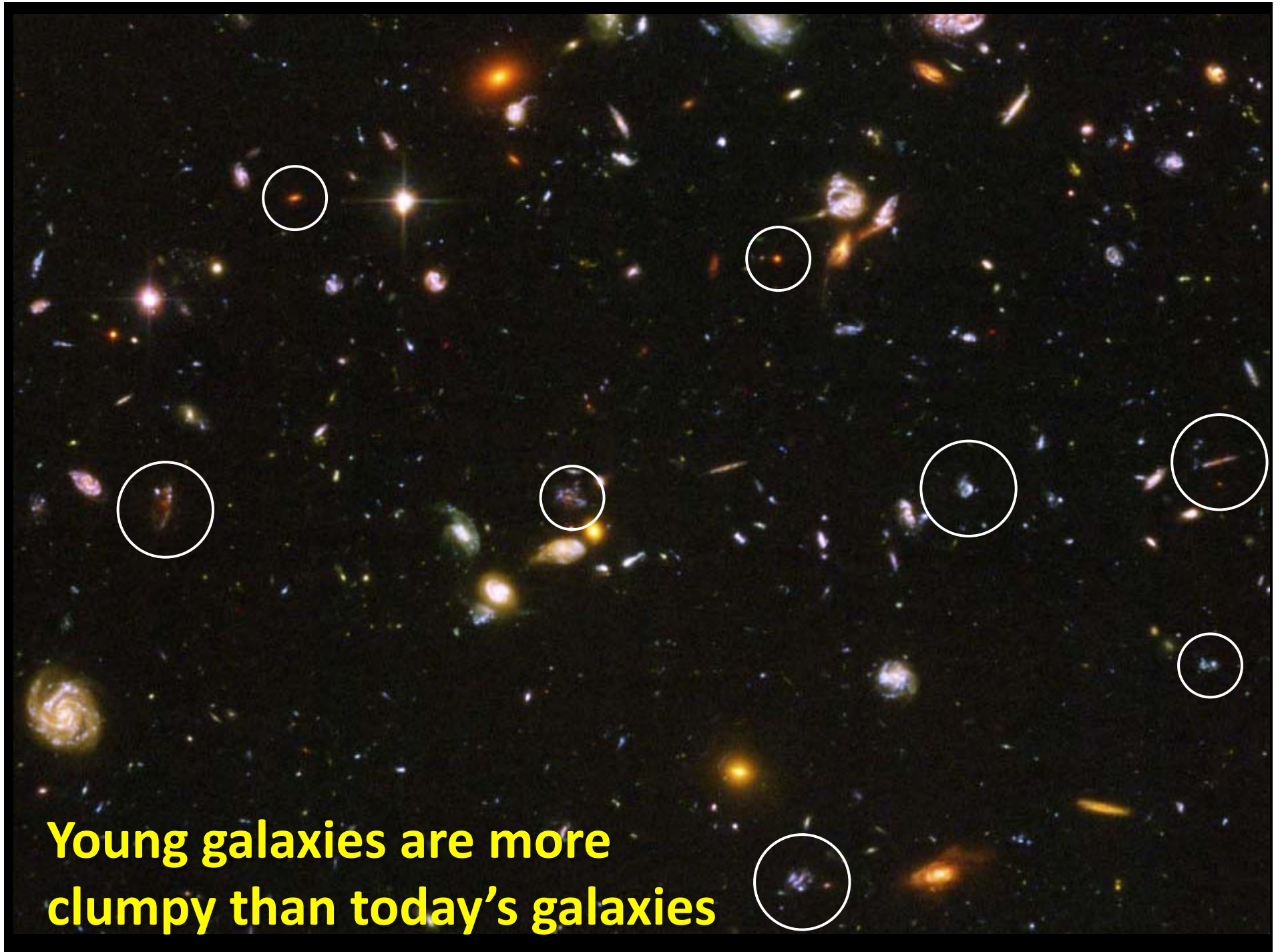
$\Lambda$ CDM model, Spergel 2003

# Timeline



# Part of the UDF





**Young galaxies are more  
clumpy than today's galaxies**

# UDF zoo: classified all 1003 galaxies > 10 px in UDF to $z \sim 5$

Chain (121)

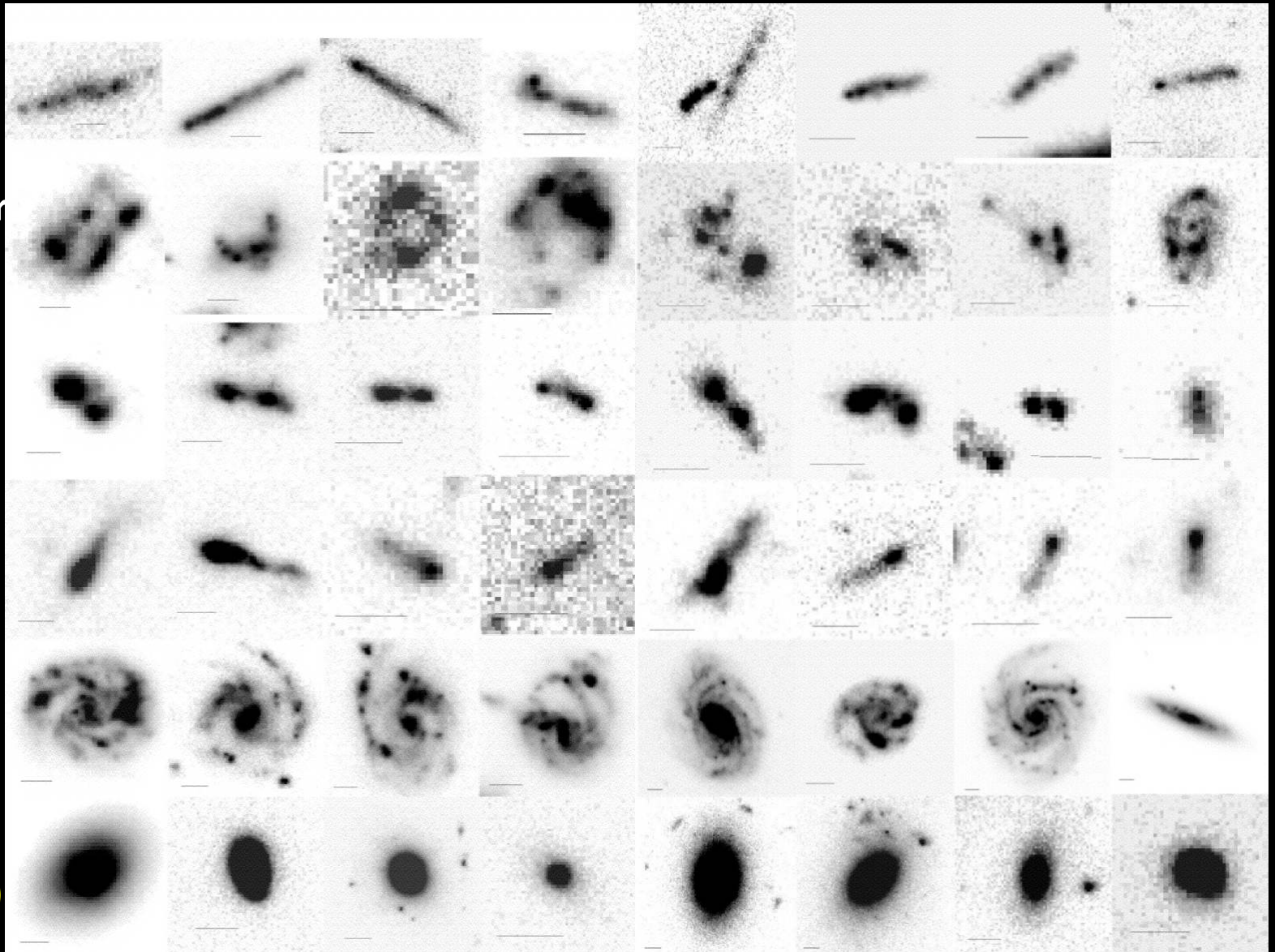
Clump Cluster  
(192)

Double (134)

Tadpole (114)

Spiral (313)

Elliptical (129)

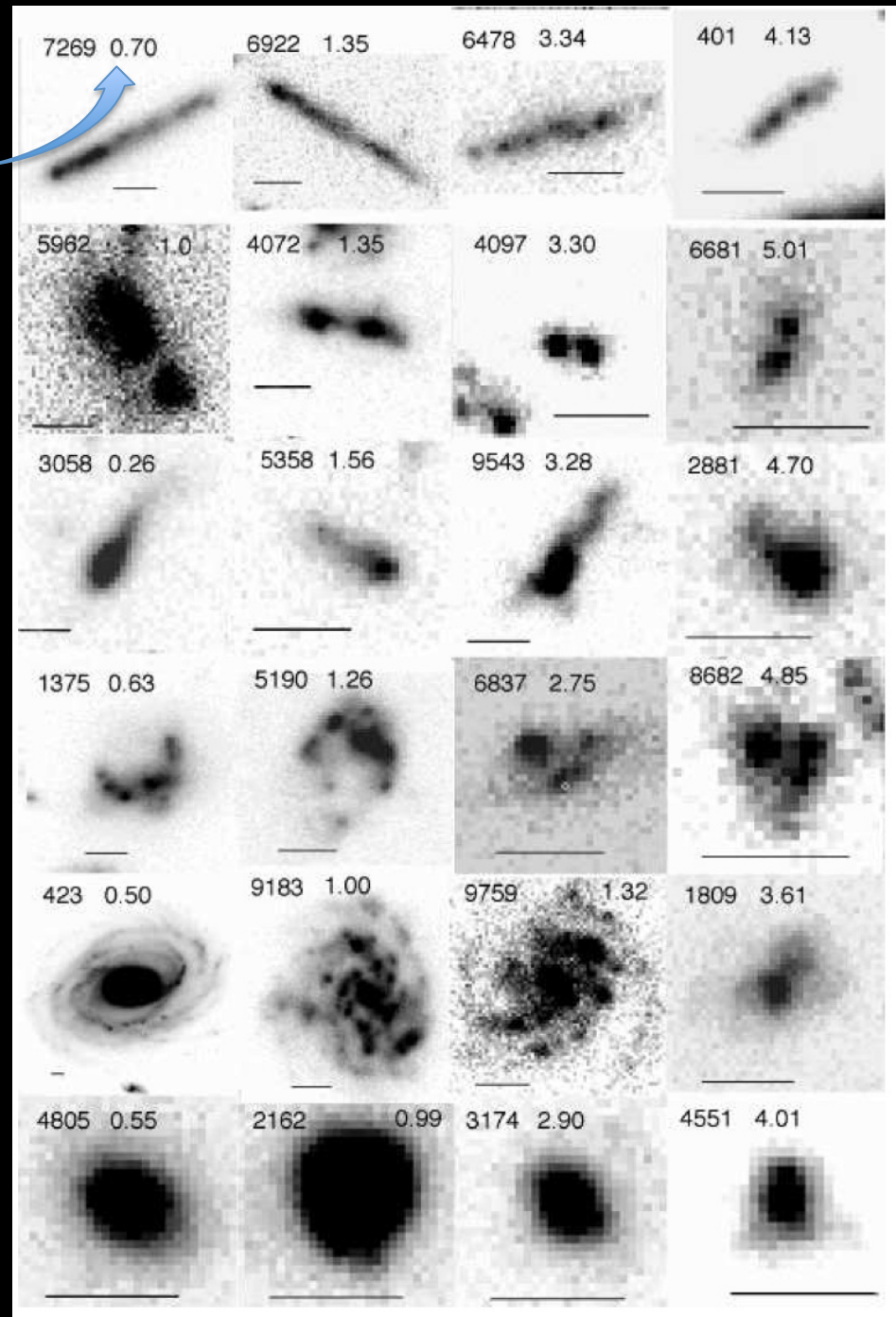


(see also Cowie, Hu, & Songaila; van den Bergh; Abraham et al.; Williams et al.; Conselice; Lotz)

Elmegreen et al. 2005

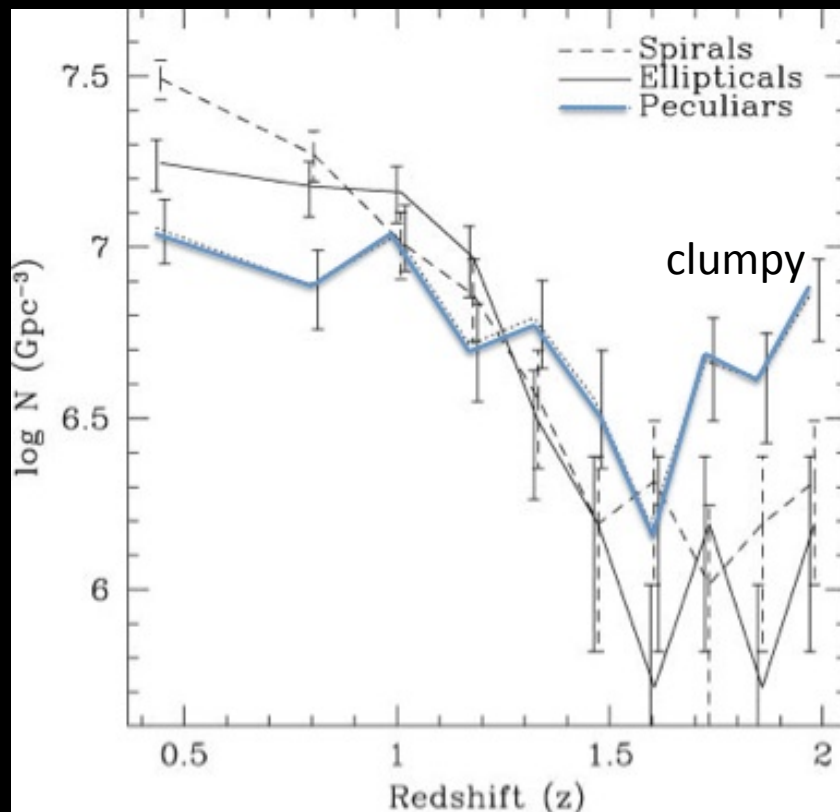
redshift

UDF types  
exist over a  
wide range of  
redshifts

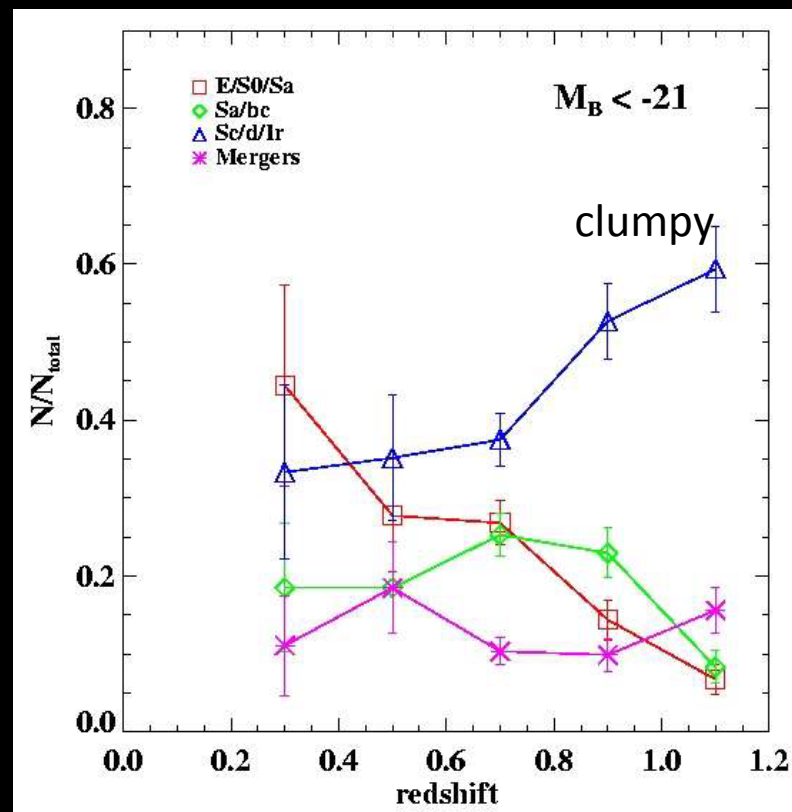


Elmegreen, Elmegreen,  
Ravindranath & Coe 2007

# Clumpy galaxies dominate beyond $z=1.5$ in the Hubble Deep Fields and beyond $z=0.7$ in the Extended Groth Strip

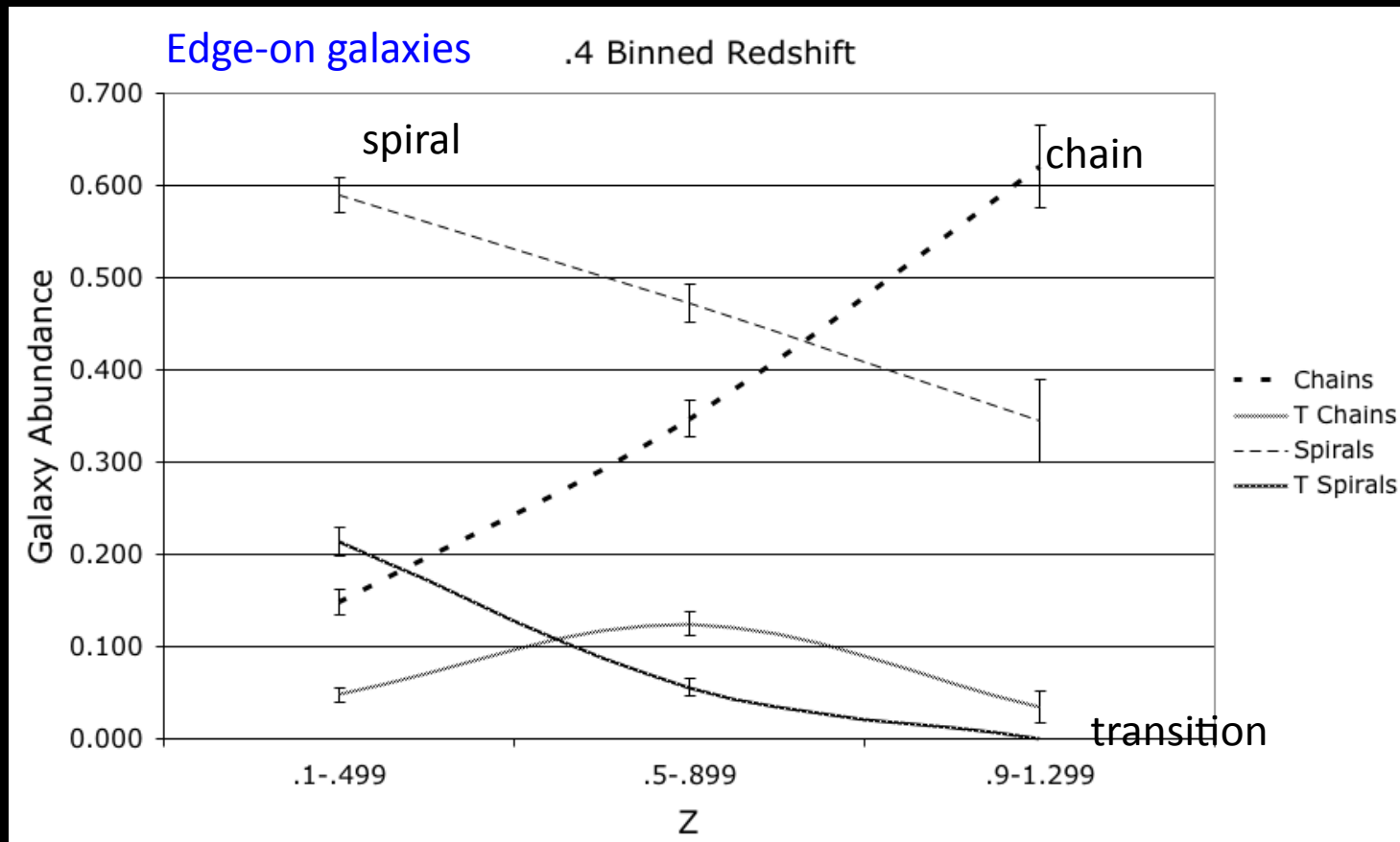


Conselice 2004



Lotz et al. 2006

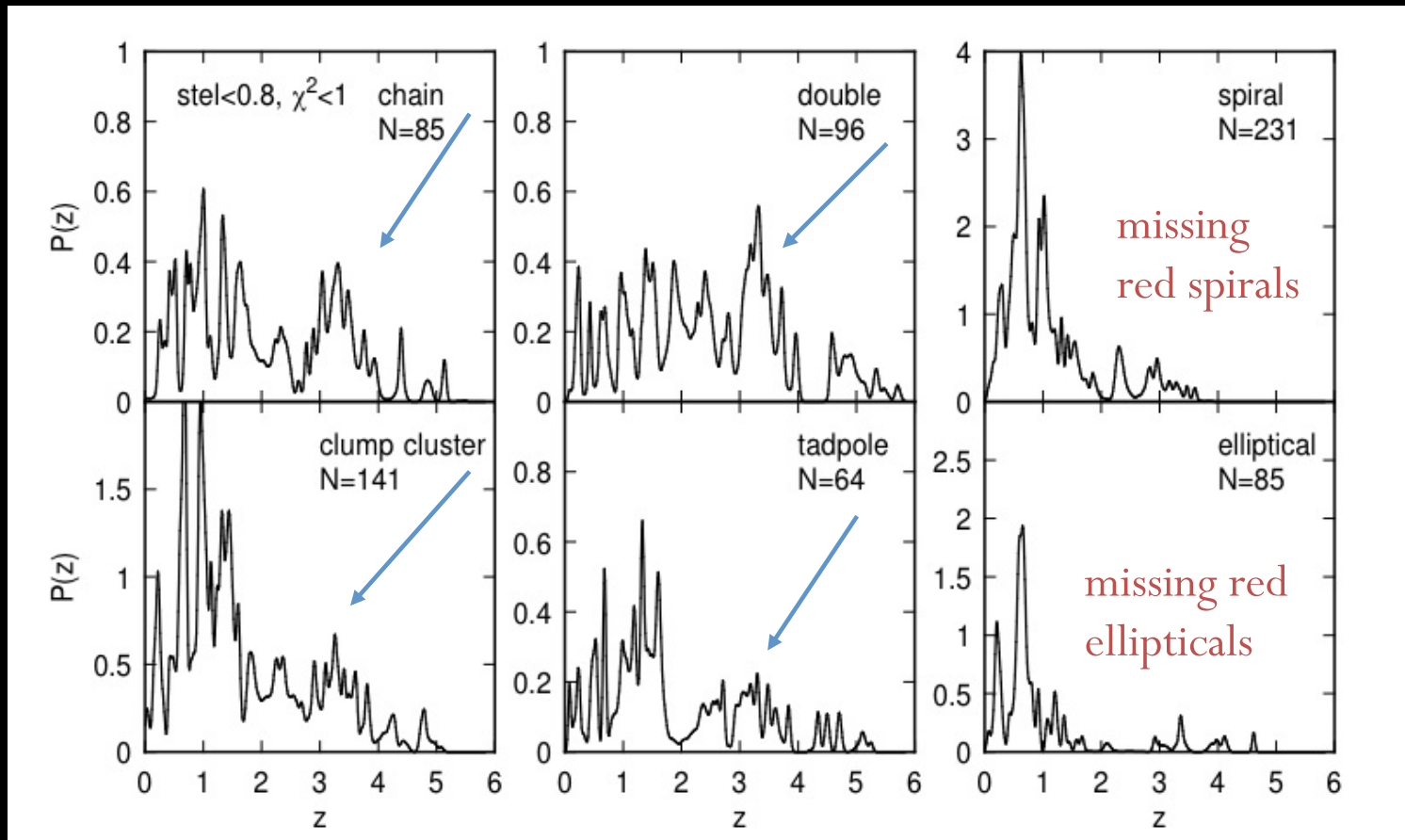
# The fraction of edge-on clumpy galaxies increases beyond $z \sim 1$



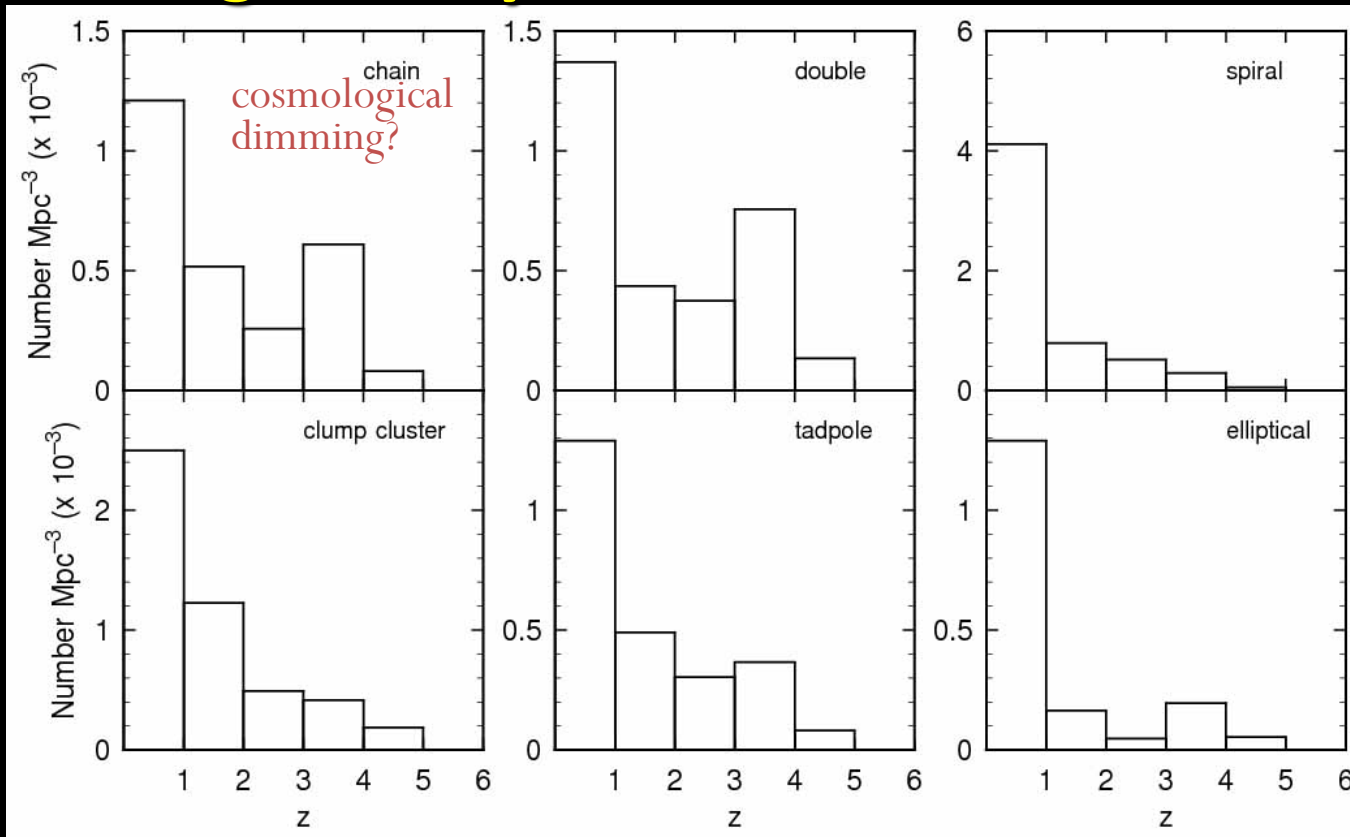
Elmegreen et al. 2008

# Redshift distribution for each type in UDF

- $z > 2$  galaxies are mostly clumpy types
- selection against **red** galaxies at high  $z$  (incl. spirals and ellipticals)



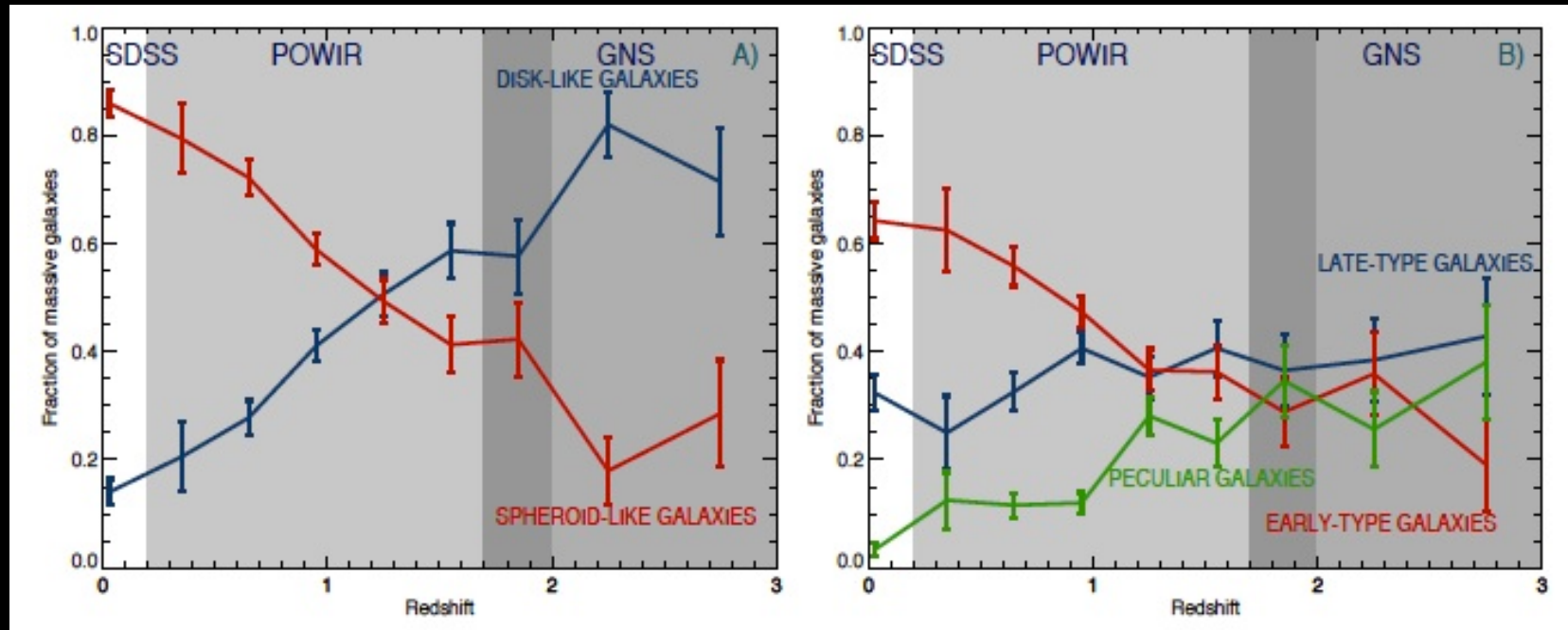
# Co-moving density of starbursts in the universe:



Chains+clump clusters exceed spirals by a factor  $> 2$  at  $z > 1$

→ all spirals could pass through a clumpy phase

# Fractions of spheroidal and disk-like massive galaxies in SDSS

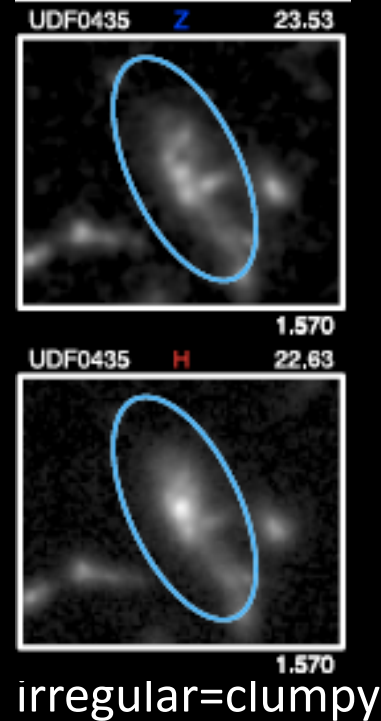
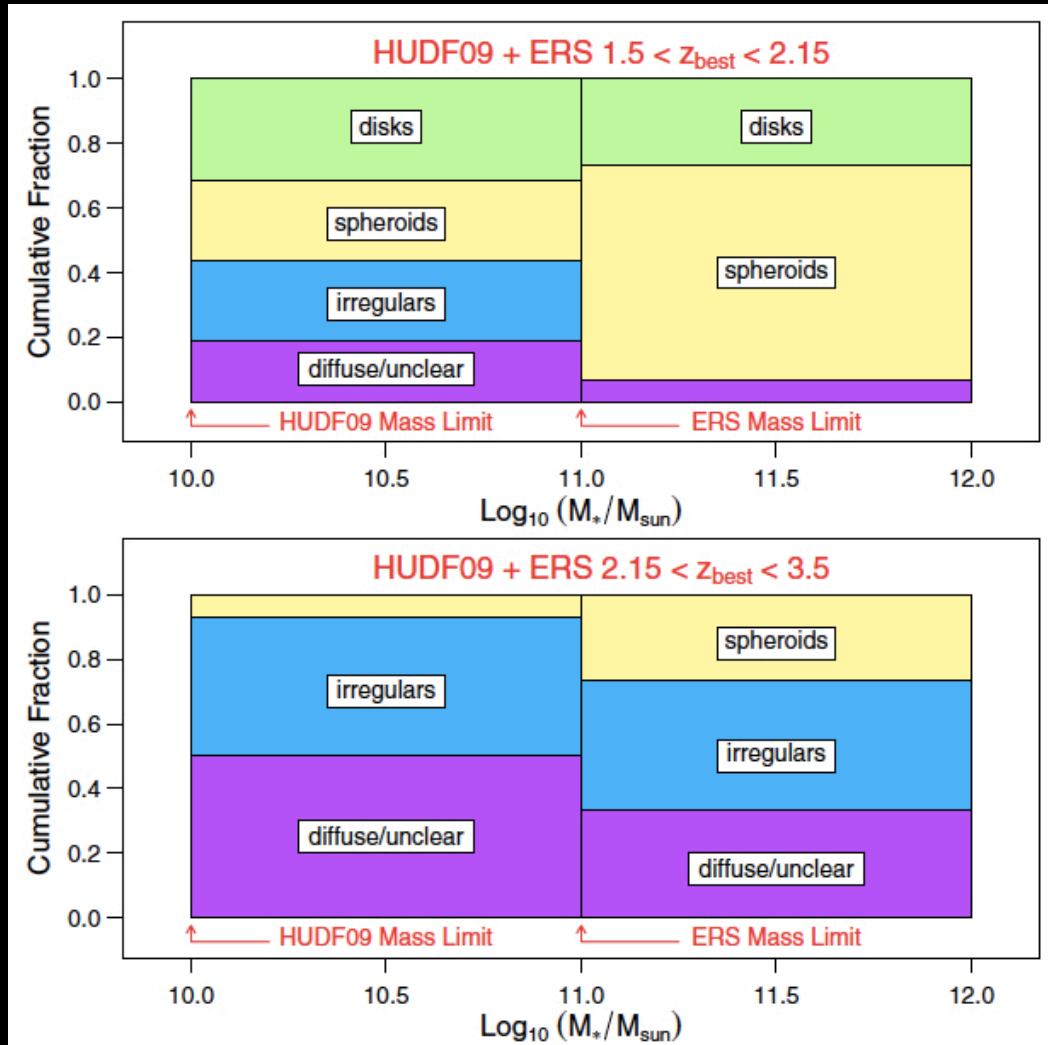
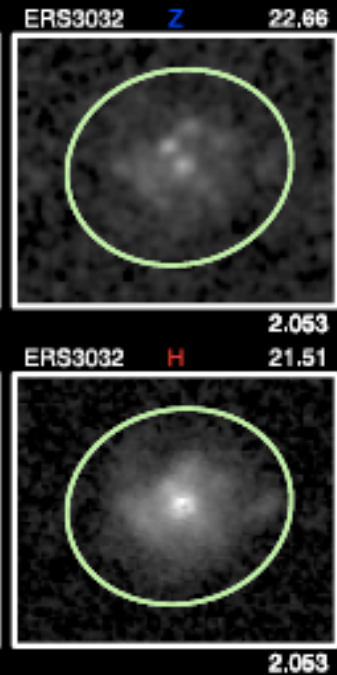


Buitrago et al. 2013

In galaxies more massive than  $10^{11} M_{\odot}$ , **disk-like** galaxies dominate in early universe; spheroids dominate at  $z < 1$  (based on Sersic fits and visual morphological classifications for 1100 galaxies)

# HUDF09 and Early Release GOODS-S: Disk (=spiral) galaxies only begin to be significant by redshift $\sim 2$ ; “irregular” (clumpy) dominate earlier

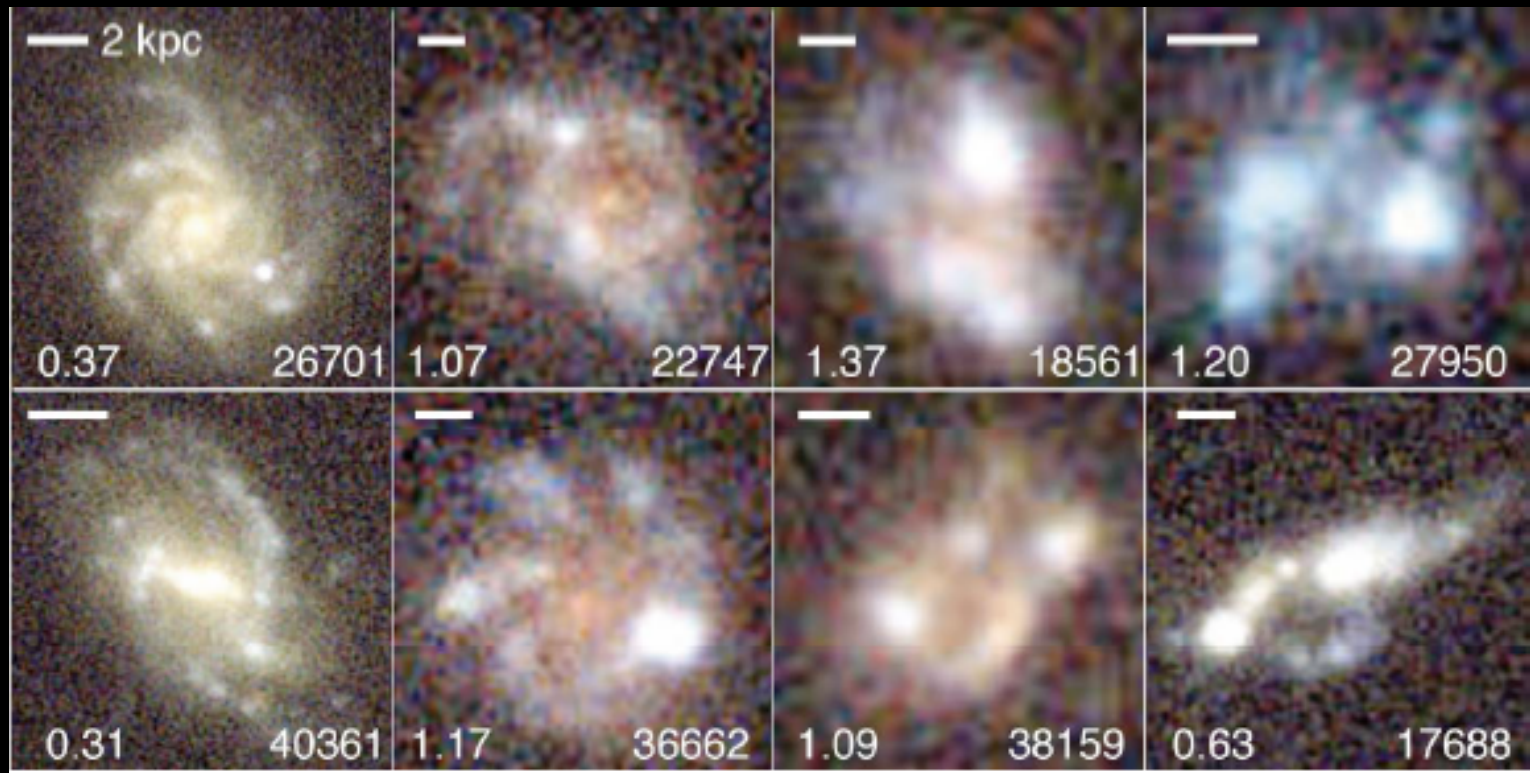
disk=central bulge



**Conclusion:** spirals can form  
by  $z \sim 2$

**When can grand design  
spirals form?**

# Disk galaxies in GOODS have a range of morphologies



density wave  
spiral

flocculent  
spiral

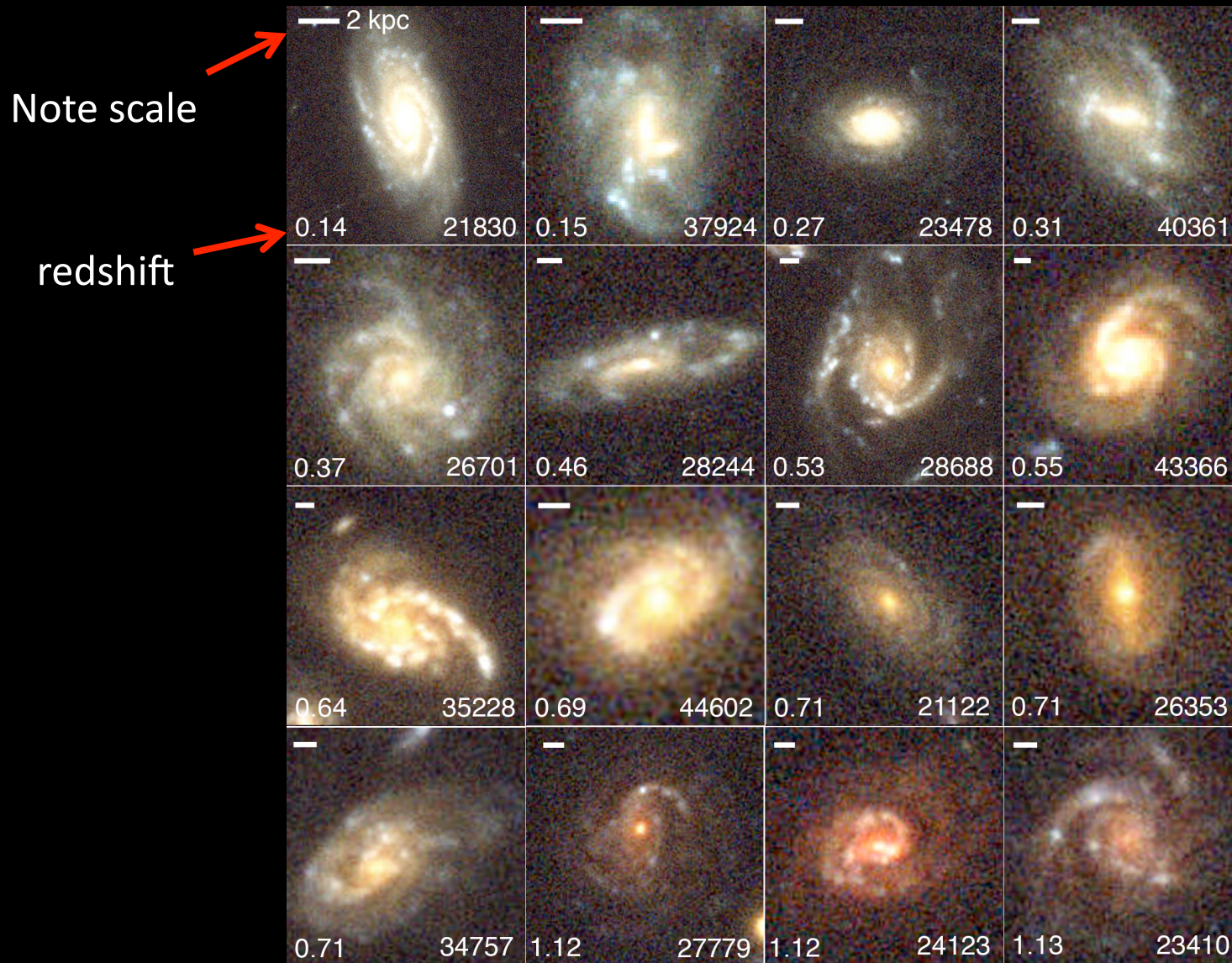
clump cluster  
red disk

clump cluster  
no red disk

Redshift, COMBO17 no.  
(Wolf et al. 2008)

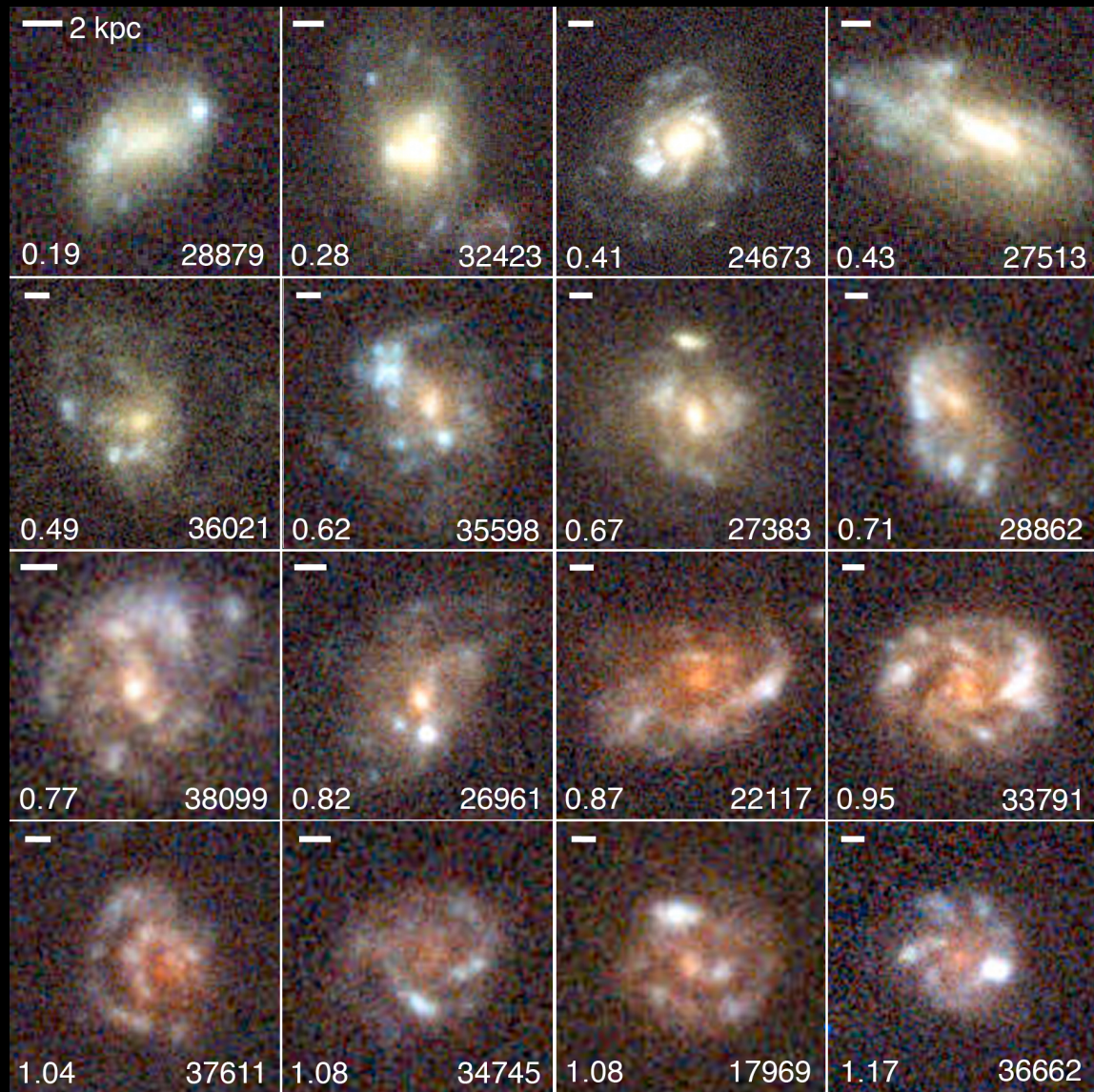
Elmegreen et al. 2009

# Density wave spirals in GOODS



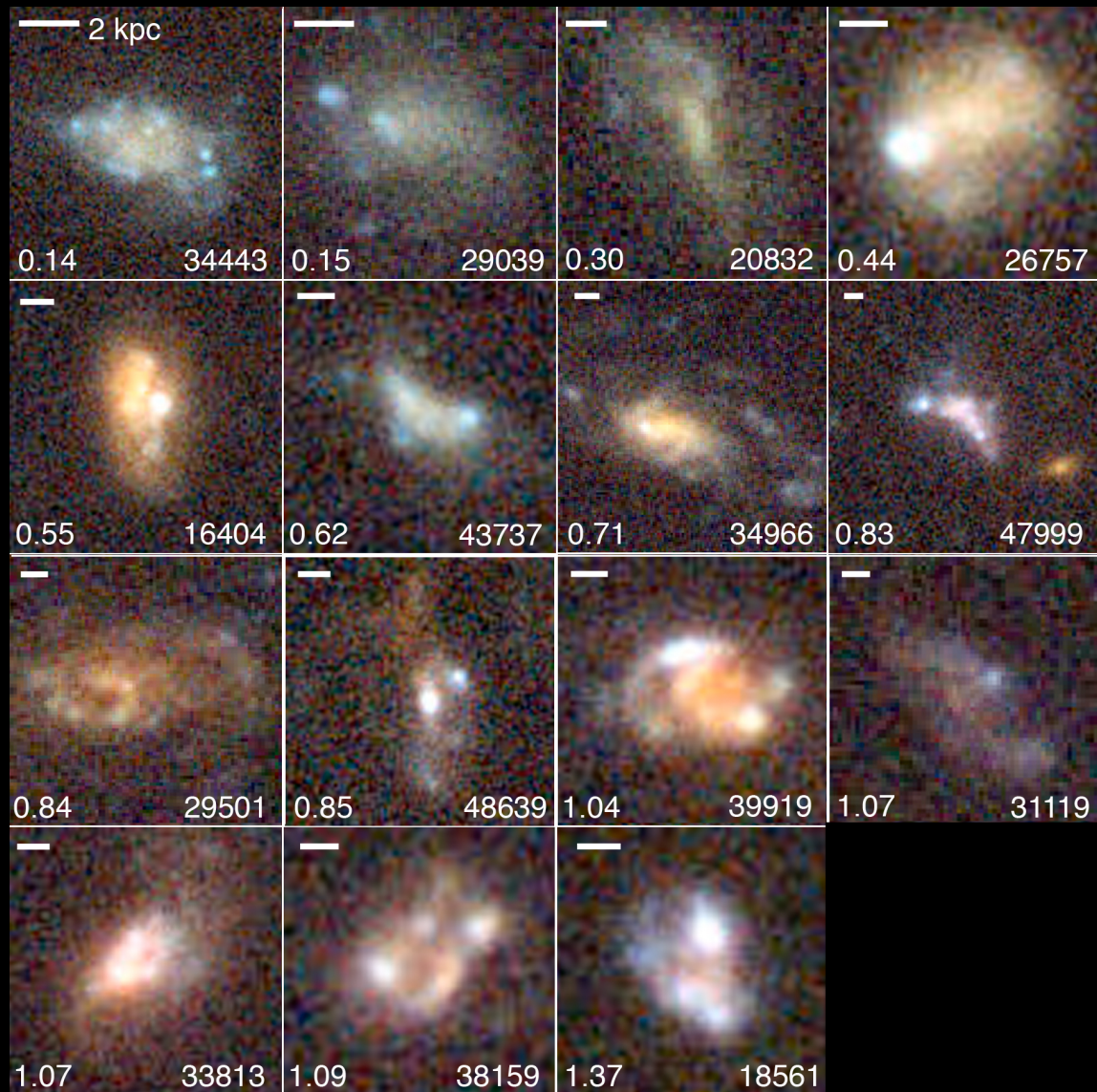
26 in sample

# Flocculent spirals in GOODS



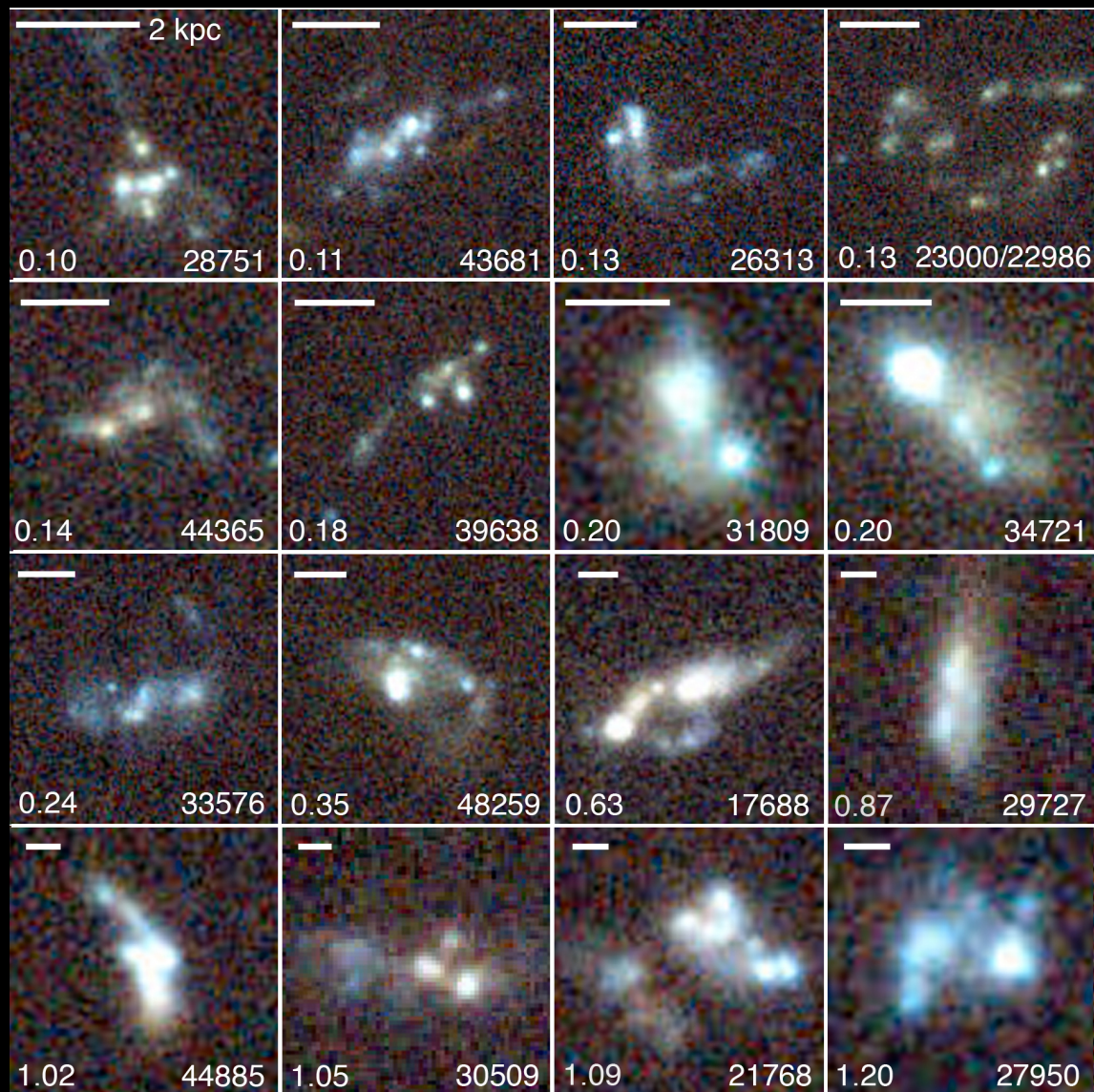
35 in sample

# Clumpy galaxies in GOODS with red underlying disks



15 in sample

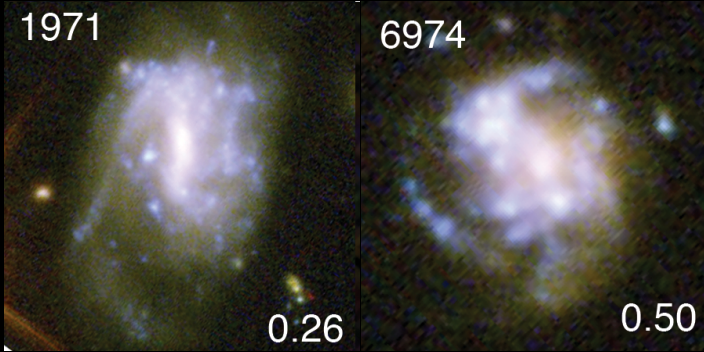
# Clumpy galaxies in GOODS with no red underlying disks



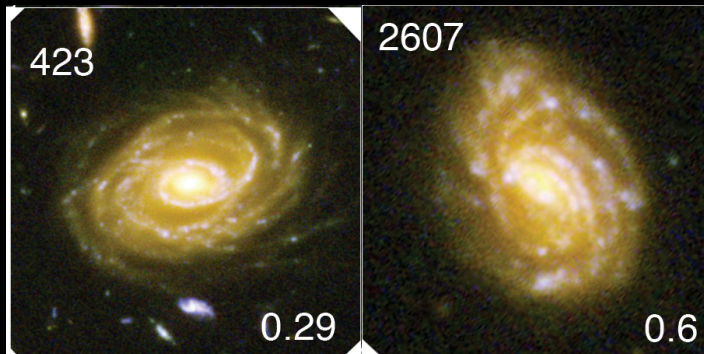
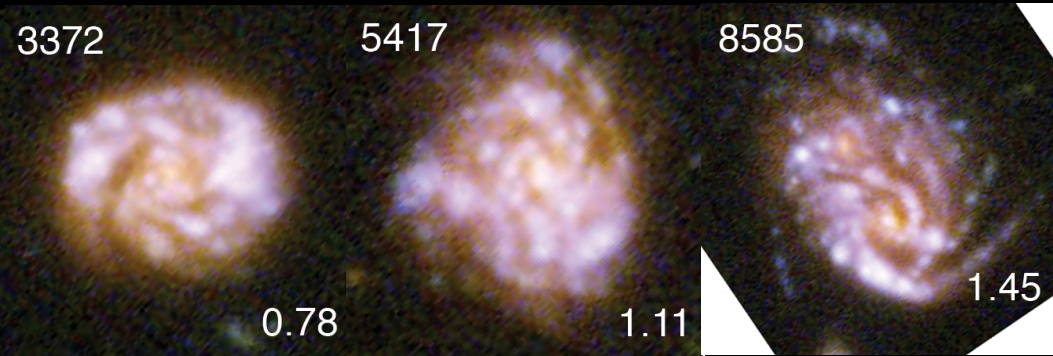
17 in sample

# Galaxies in the UDF

## Flocculent spirals

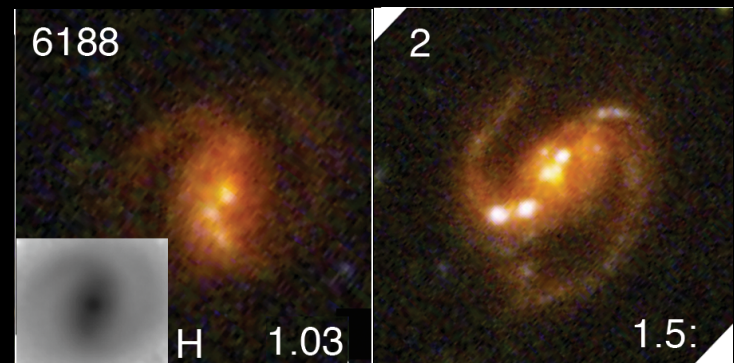


## Clumpy multiple arm spirals



## Multiple arm spirals

## Grand design 2-arm spirals

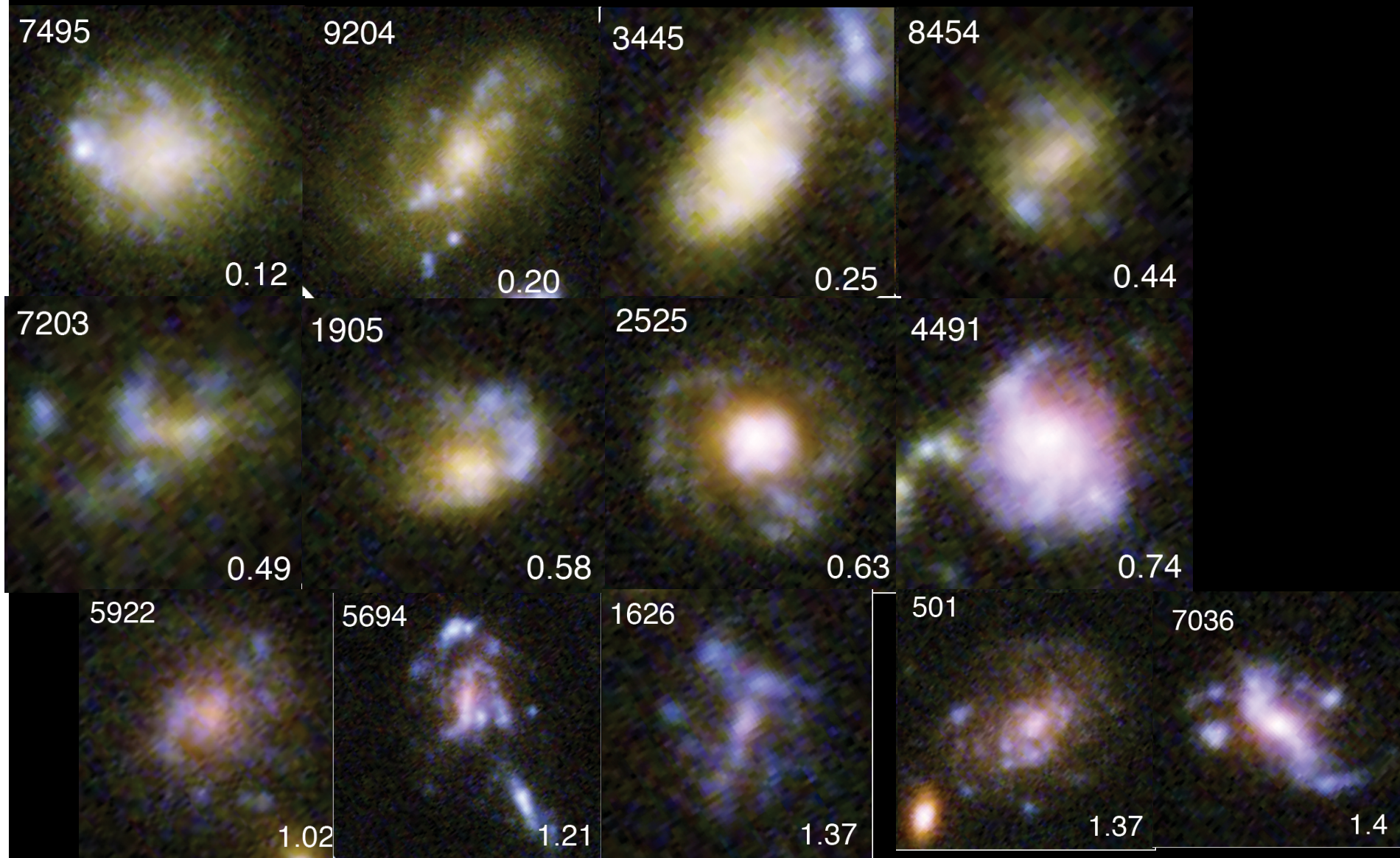


## The 3 largest star-forming clumps, compared with the total galaxy:

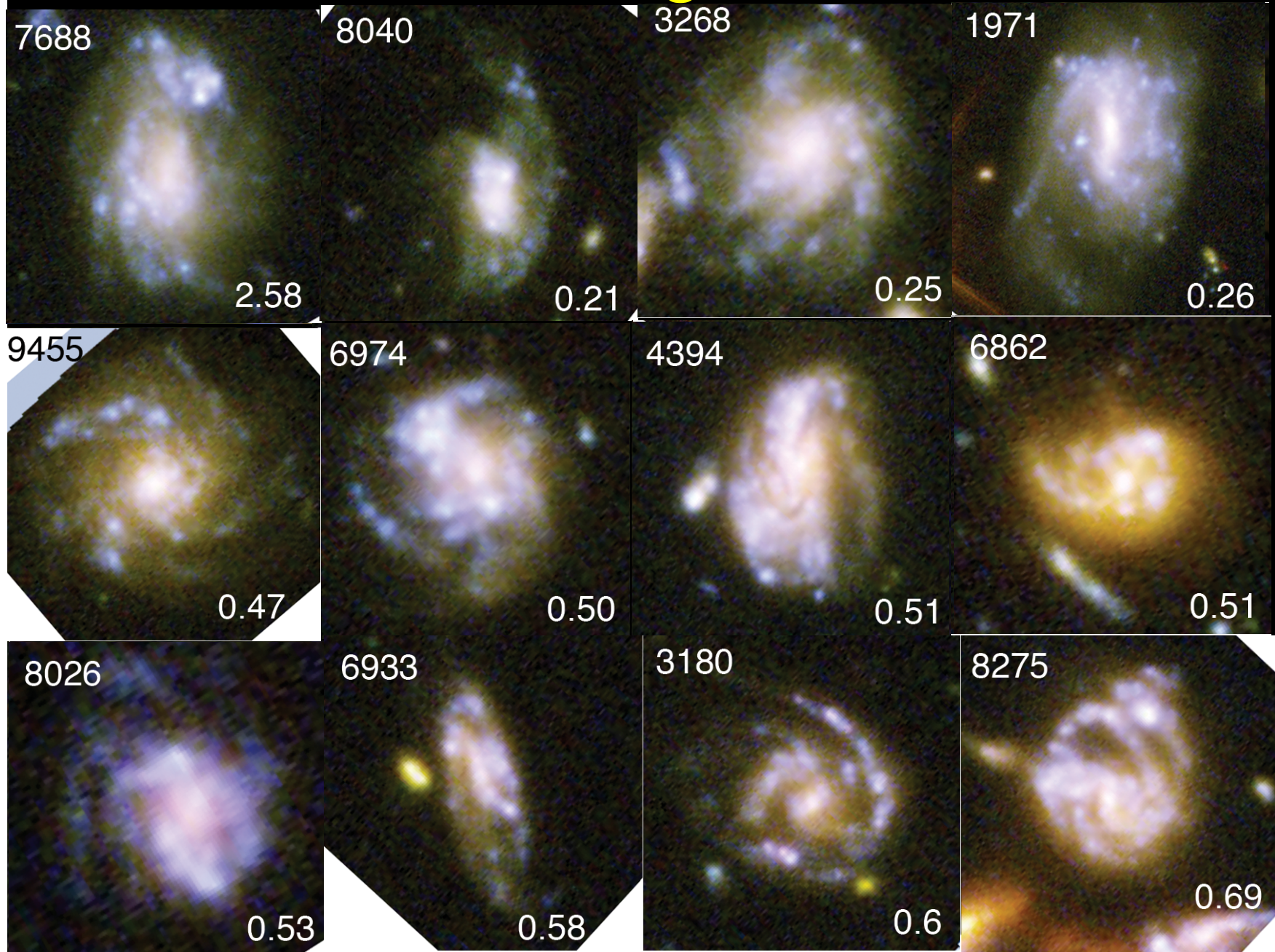
- in clumpy multiple arm spirals contribute 5-15% of the total galaxy luminosity in I band, 10-25% in B band
- in multiple arm spirals contribute 0.5-2% in I band, 3-5% in B band



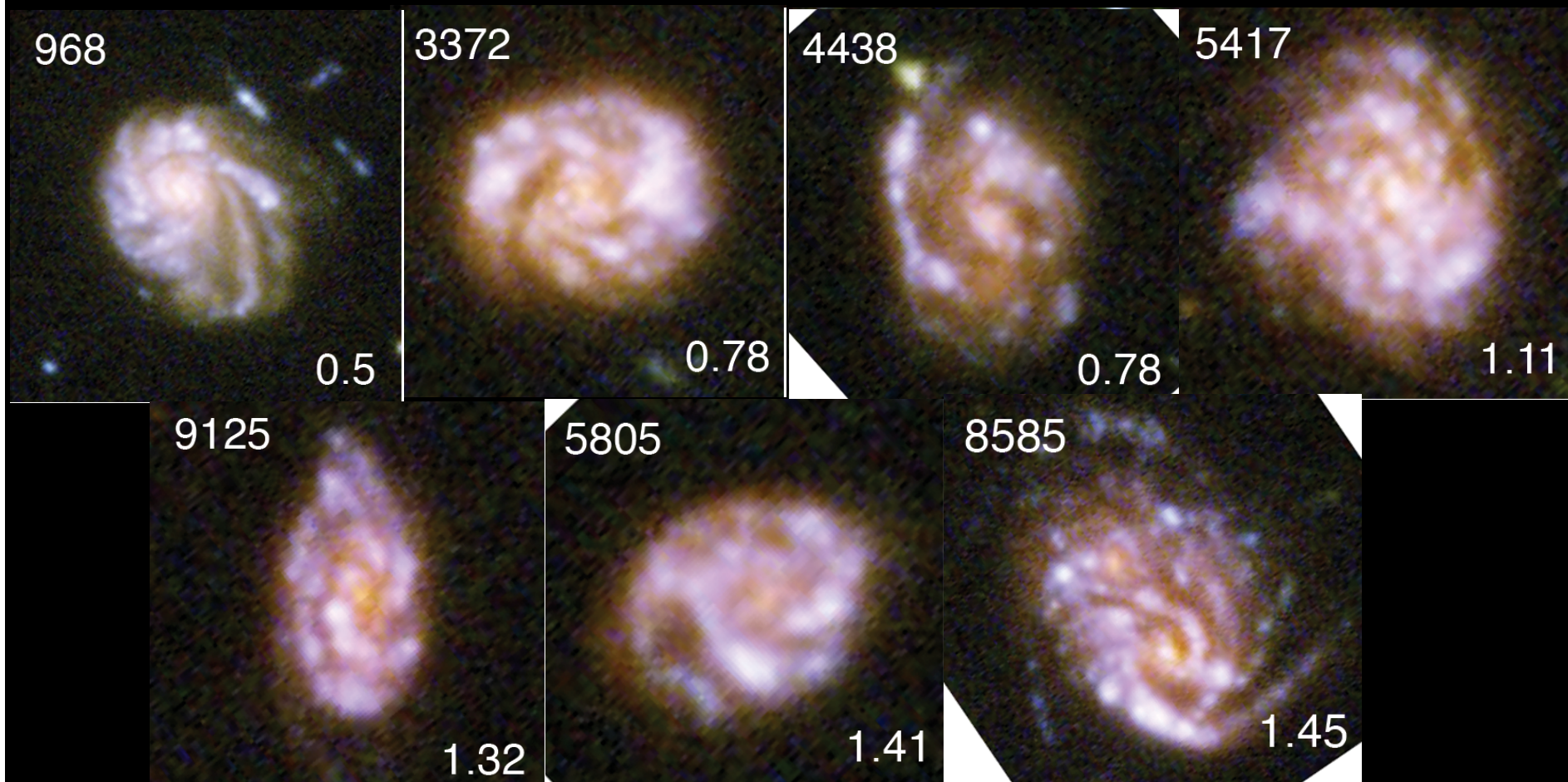
# More examples: Flocculent galaxies in the UDF



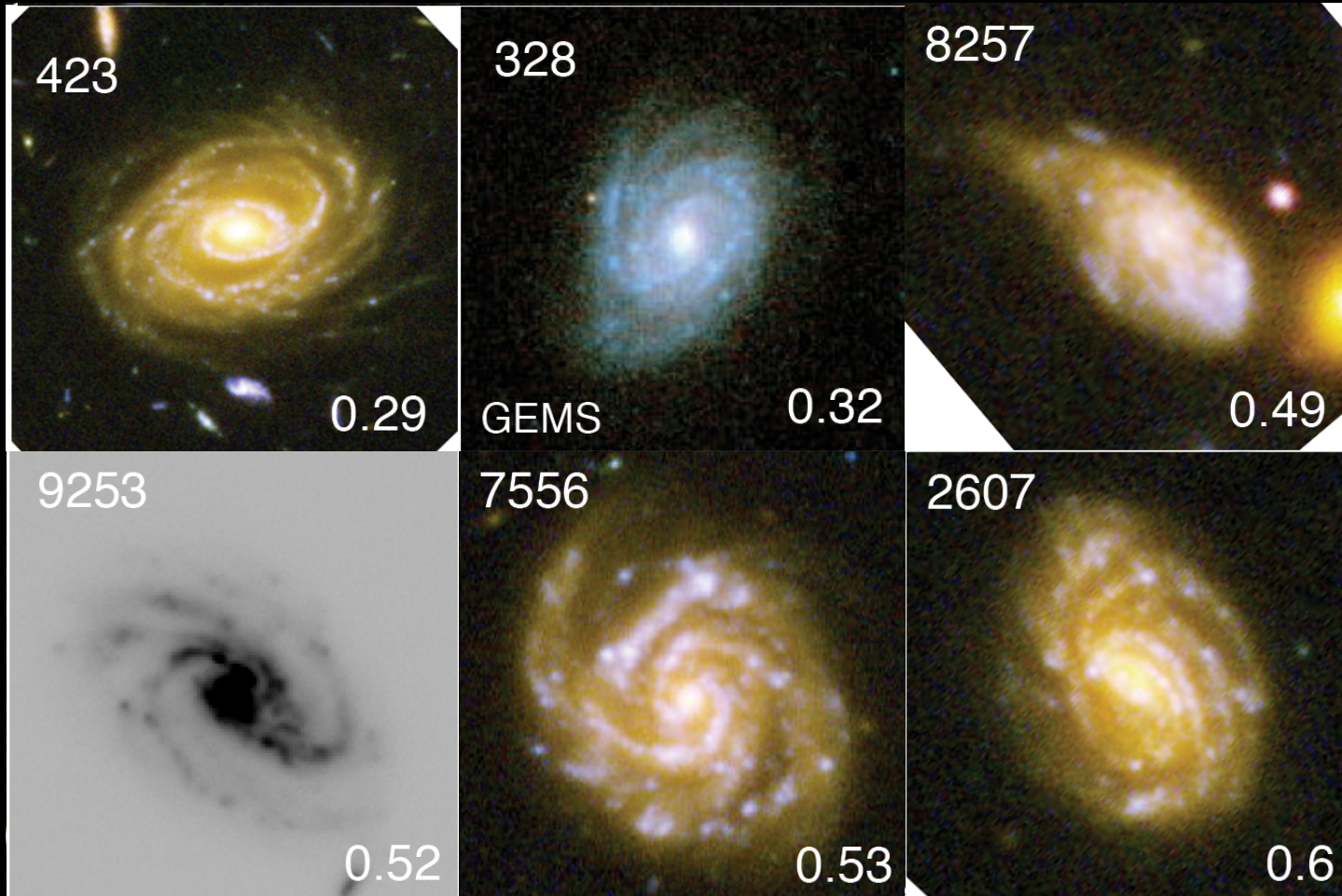
# ...some with long arms



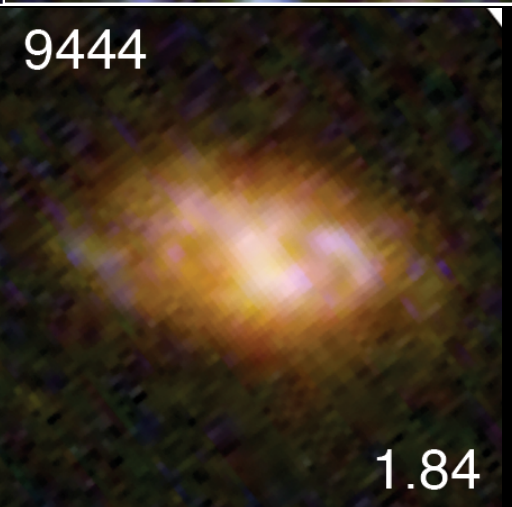
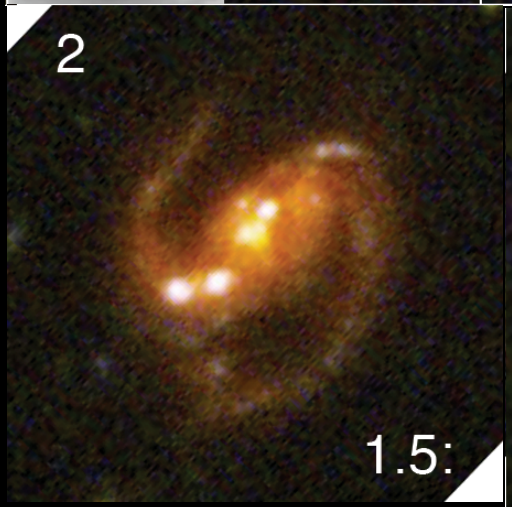
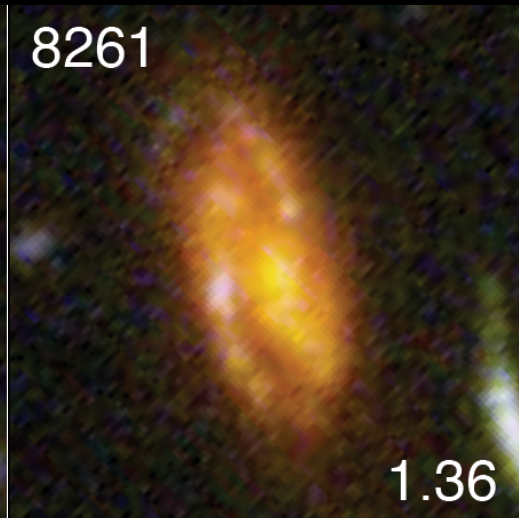
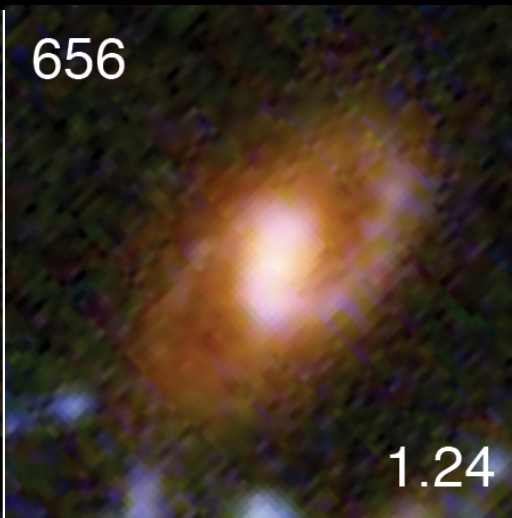
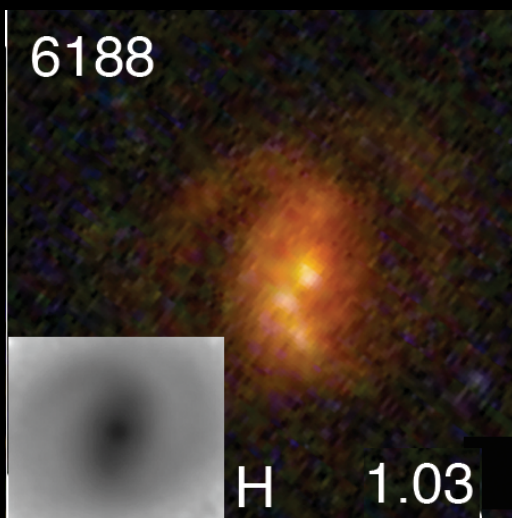
# Clumpy multiple arm spirals



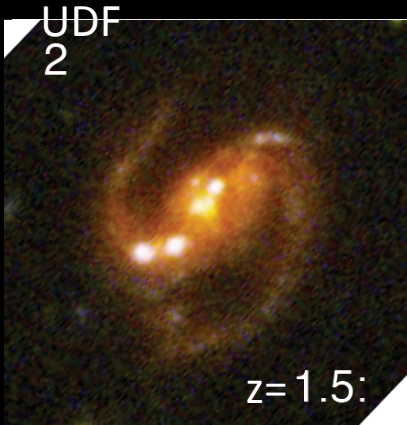
# Multiple arm spirals



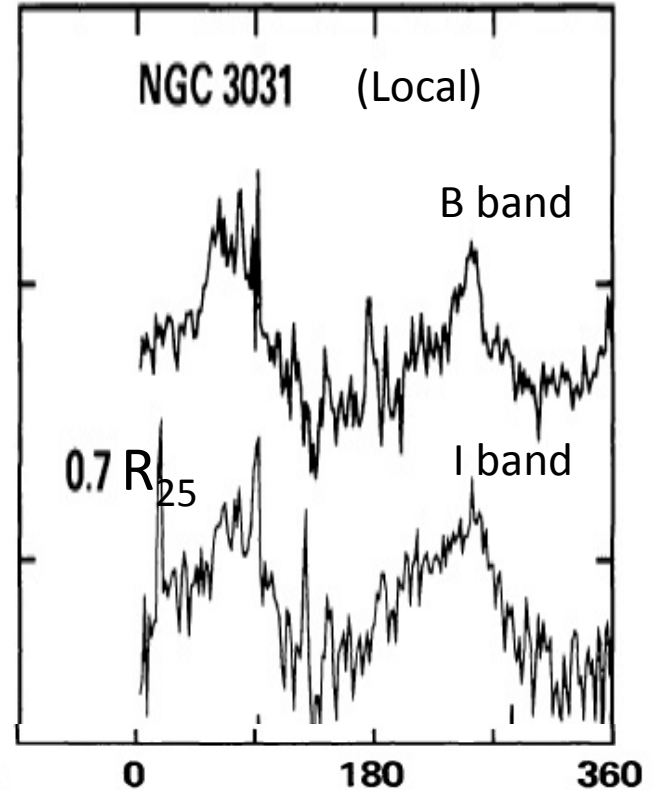
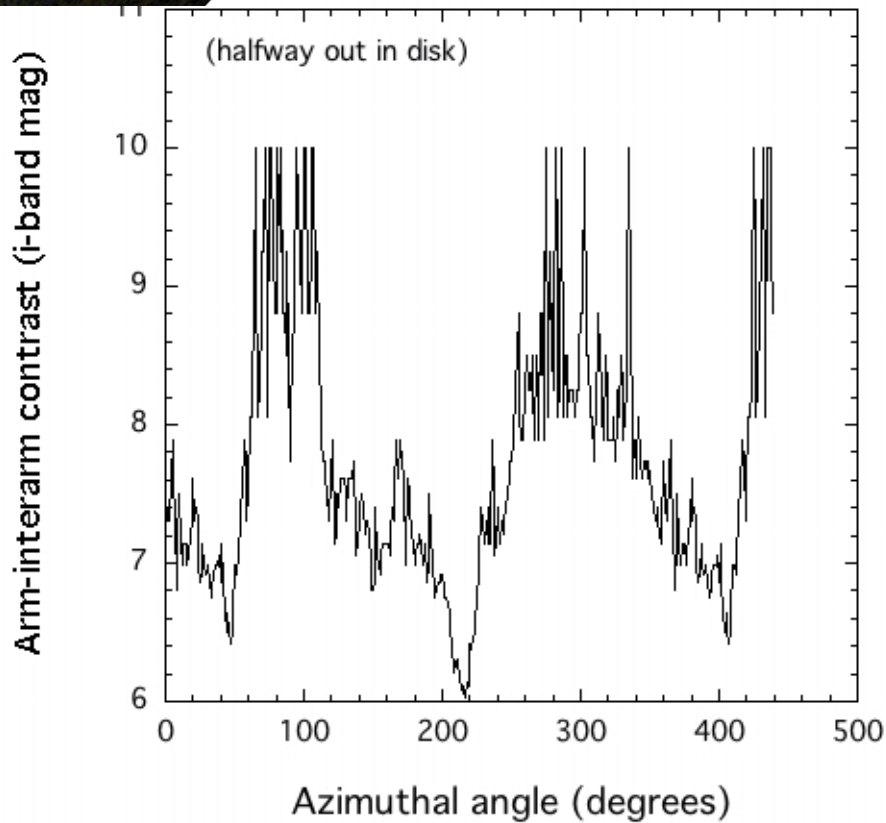
# Two-arm spirals



...in place by  
 $z \sim 1.8 = 4 \text{ Gyr}$   
after Big Bang

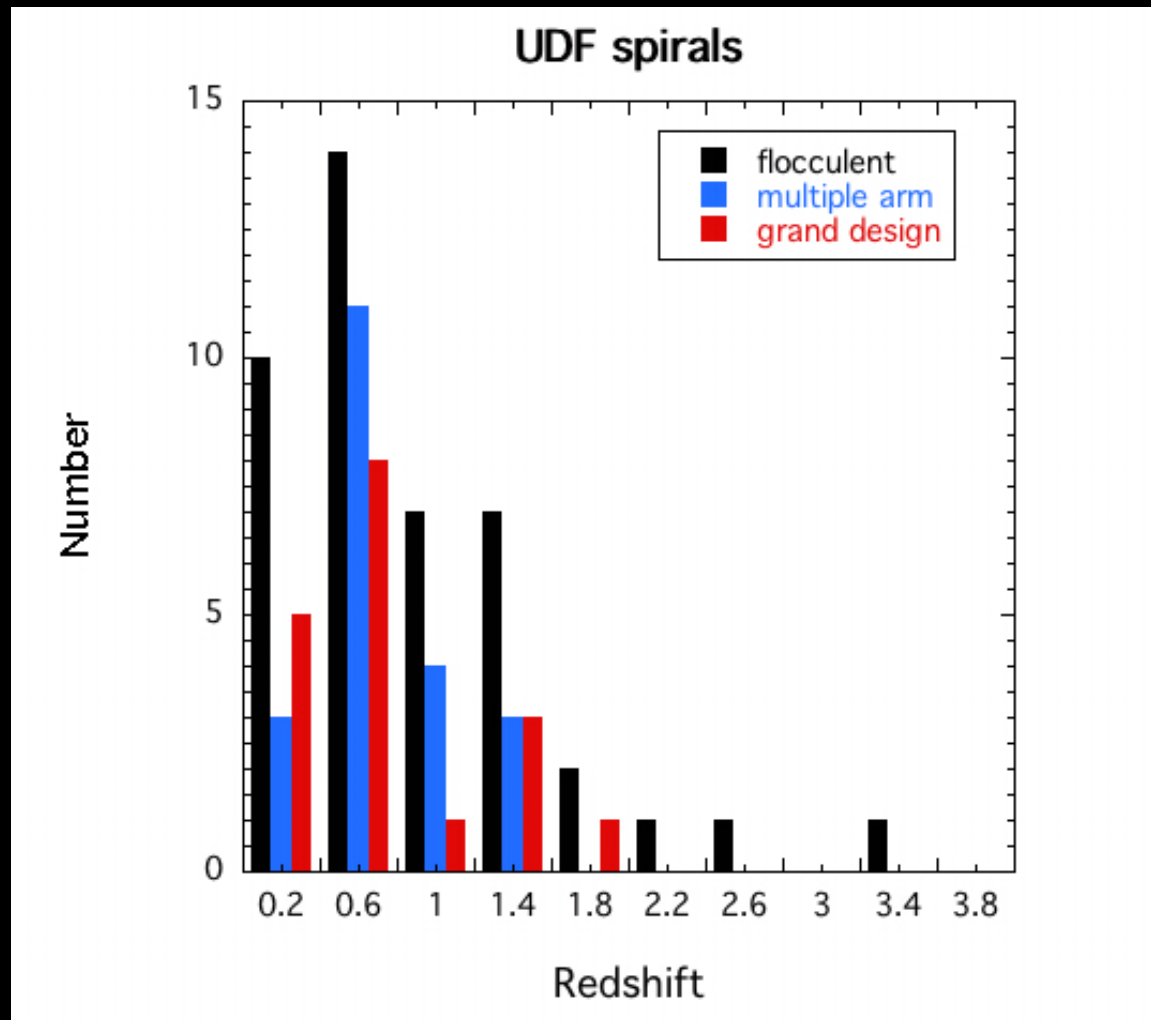


# Arm-interarm contrast in z=1.5 galaxy



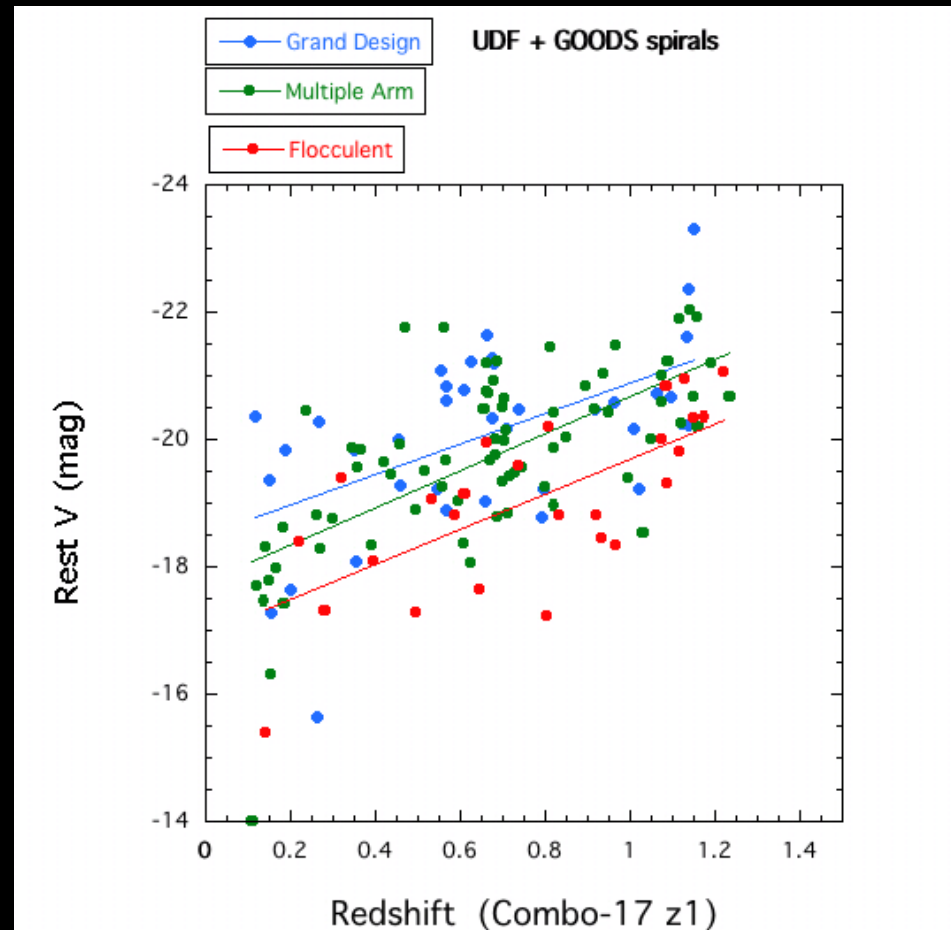
UDF contrast looks similar to local grand design galaxies, 1-2 mag

# Statistics of UDF spirals



# Flocculent, grand design spirals in UDF and GOODS

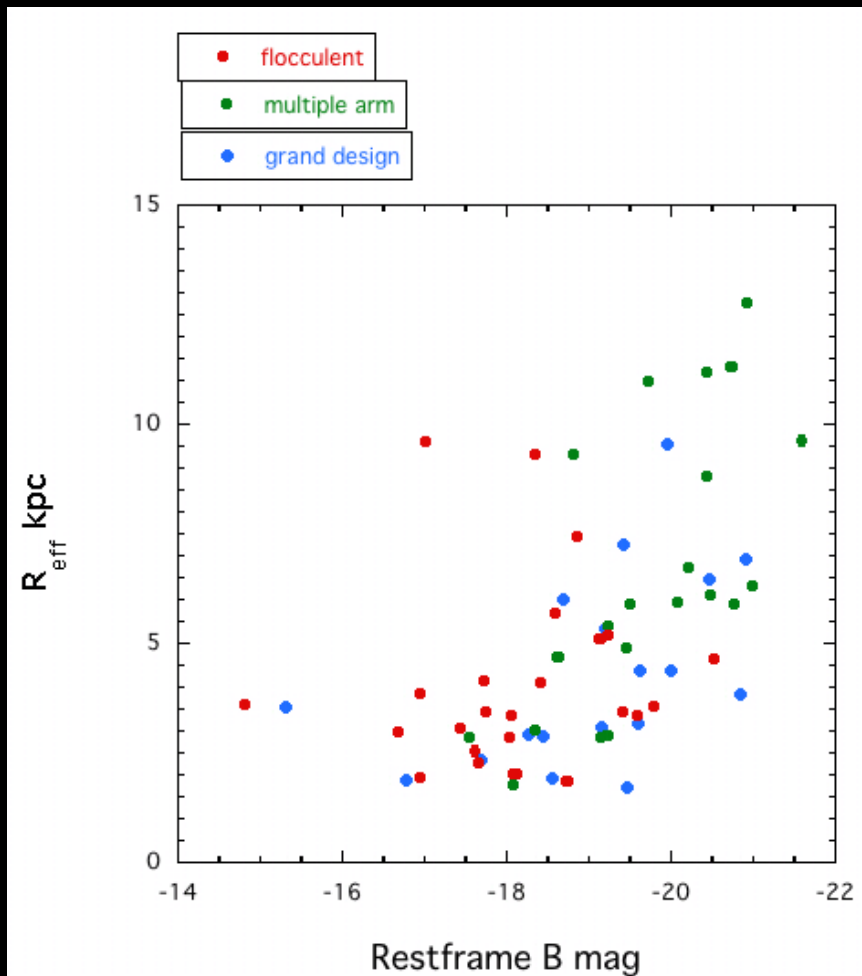
Elmegreen &  
Elmegreen 2013, in  
prep



At a given  $z$ , galaxies with well-organized structure average 1-2 mag **brighter** than flocculent spirals

# Effective radius:

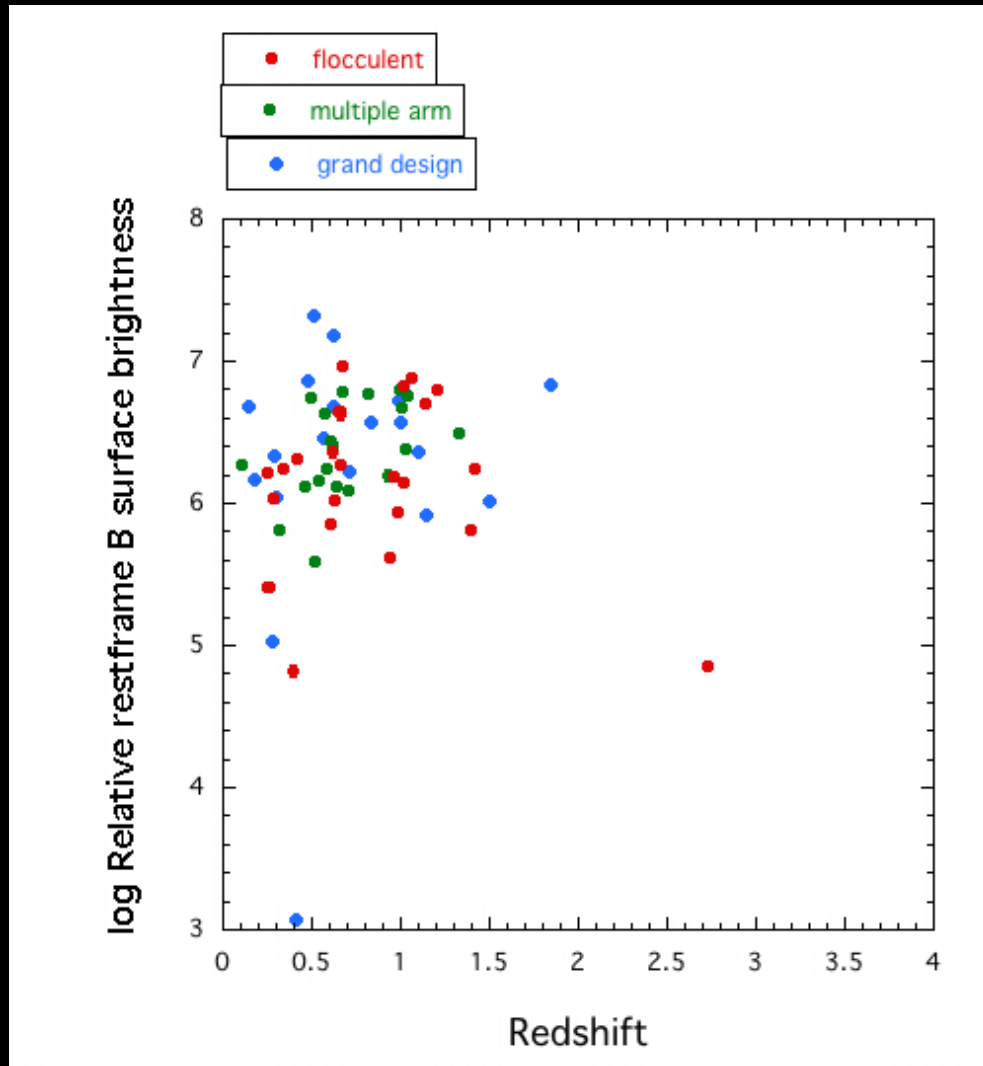
flocculents are smaller than G, M on average



Arm class	$\langle R_{\text{eff}} \rangle$ (kpc)	$\langle \text{Scale length} \rangle$ (kpc)
Flocculent	$3.71 \pm 1.88$	$2.16 \pm 1.07$
Multiple arm	$6.37 \pm 3.10$	$2.77 \pm 1.13$
Grand design	$4.13 \pm 2.16$	$2.32 \pm 1.42$

Locally, grand design galaxies are 1.5x larger than flocculents within a given Hubble type (Elmegreen<sup>2</sup> 1985)

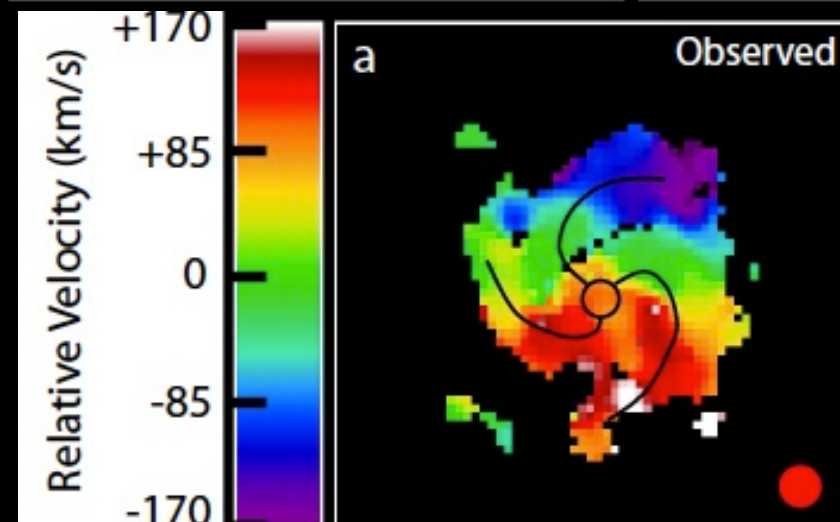
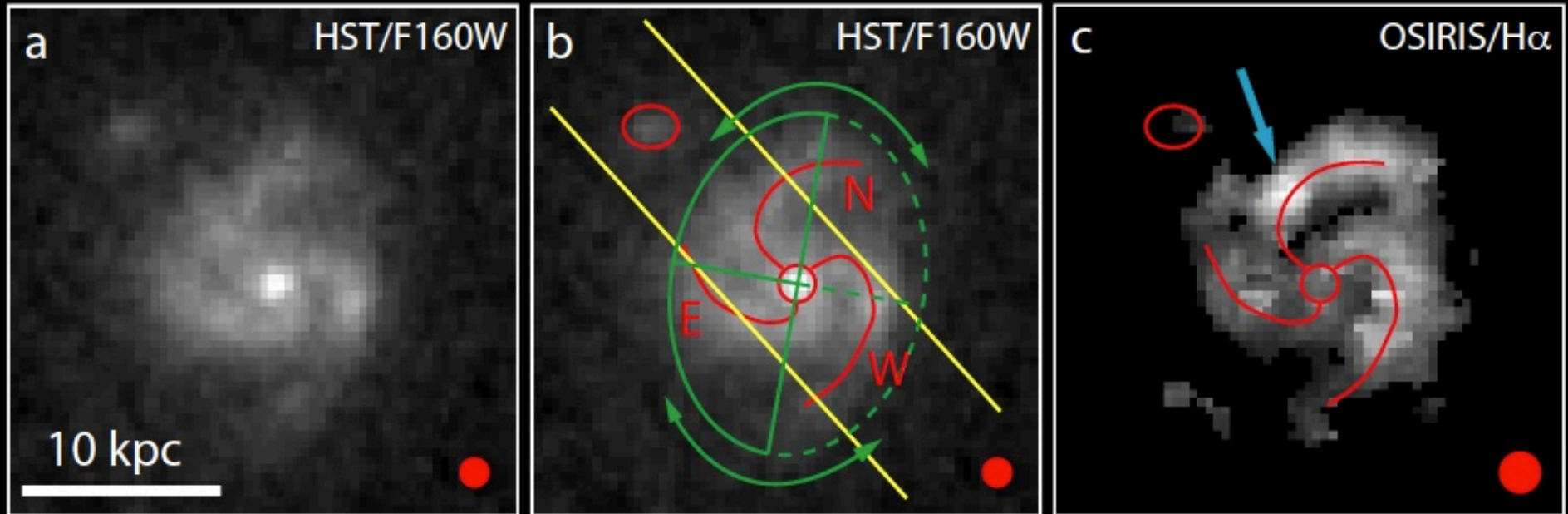
# Relative restframe surface brightness



Elmegreen<sup>2</sup> in prep

~ constant with  $z$ , so bigger galaxies are brighter

# 3-arm spiral (BX442) at $z=2.18$



Law et al. 2012

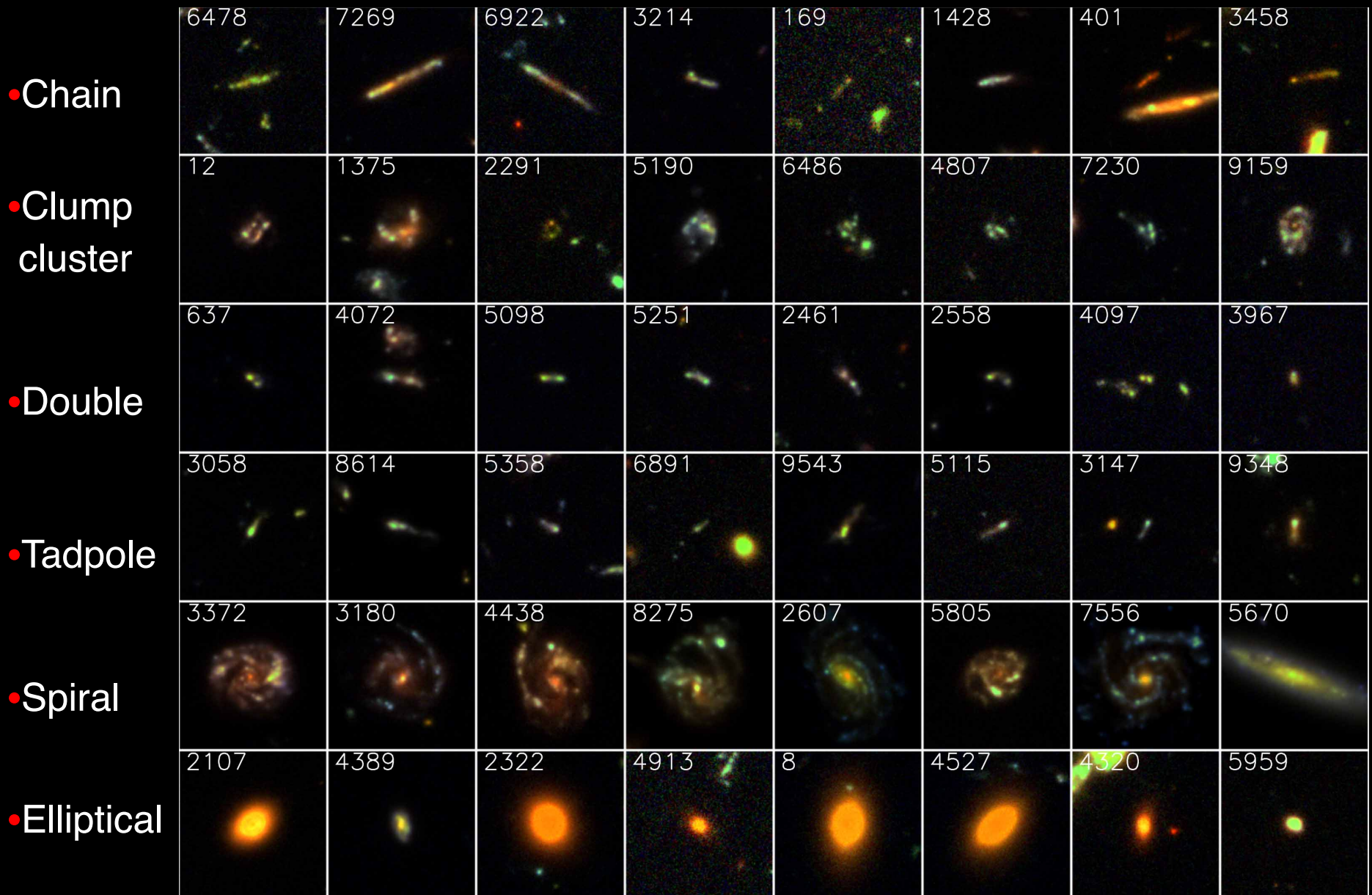
- $V \sim 230$  km/s,  $\sigma \sim 70$  so hot disk
- $Q < 1$  so susceptible to spiral
- But may be merger

## Conclusions:

- Grand design spirals can form as soon as flocculent spirals, around  $z=2$ , but
- Grand design galaxies tend to be larger at a given  $z$  than flocculents

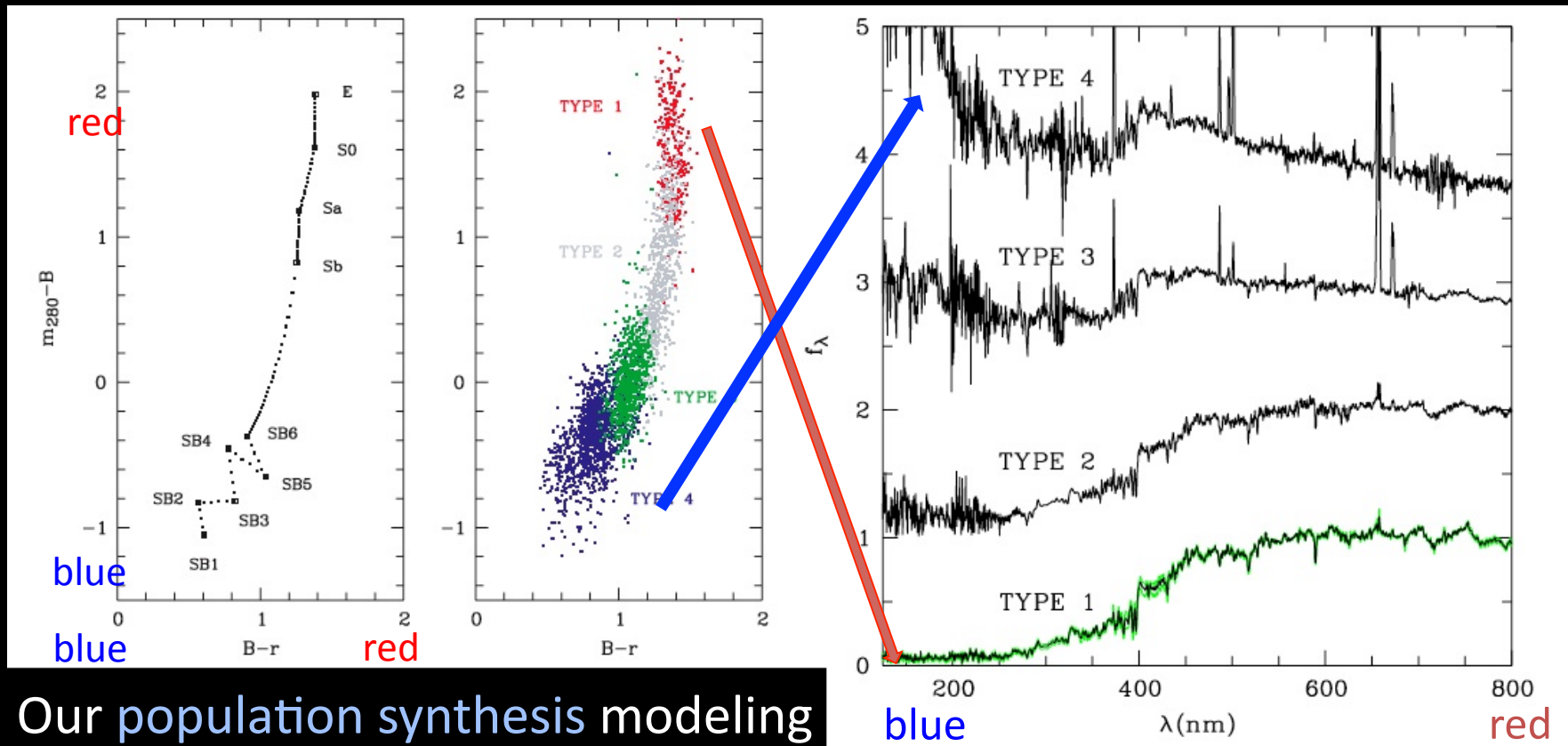
How do the properties of spirals and clumpies compare?

# Star formation: Clumpy types are relatively blue



(from Beckwith, private comm.)

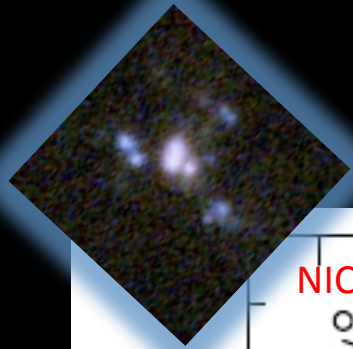
# Templates of galaxy SEDs for comparison with high z



Our population synthesis modeling includes Bruzual & Charlot 03 models, Calzetti/Leitherer extinction, Madau 95 intergalactic H absorption, and redshift corrections

Wolf et al. 2003

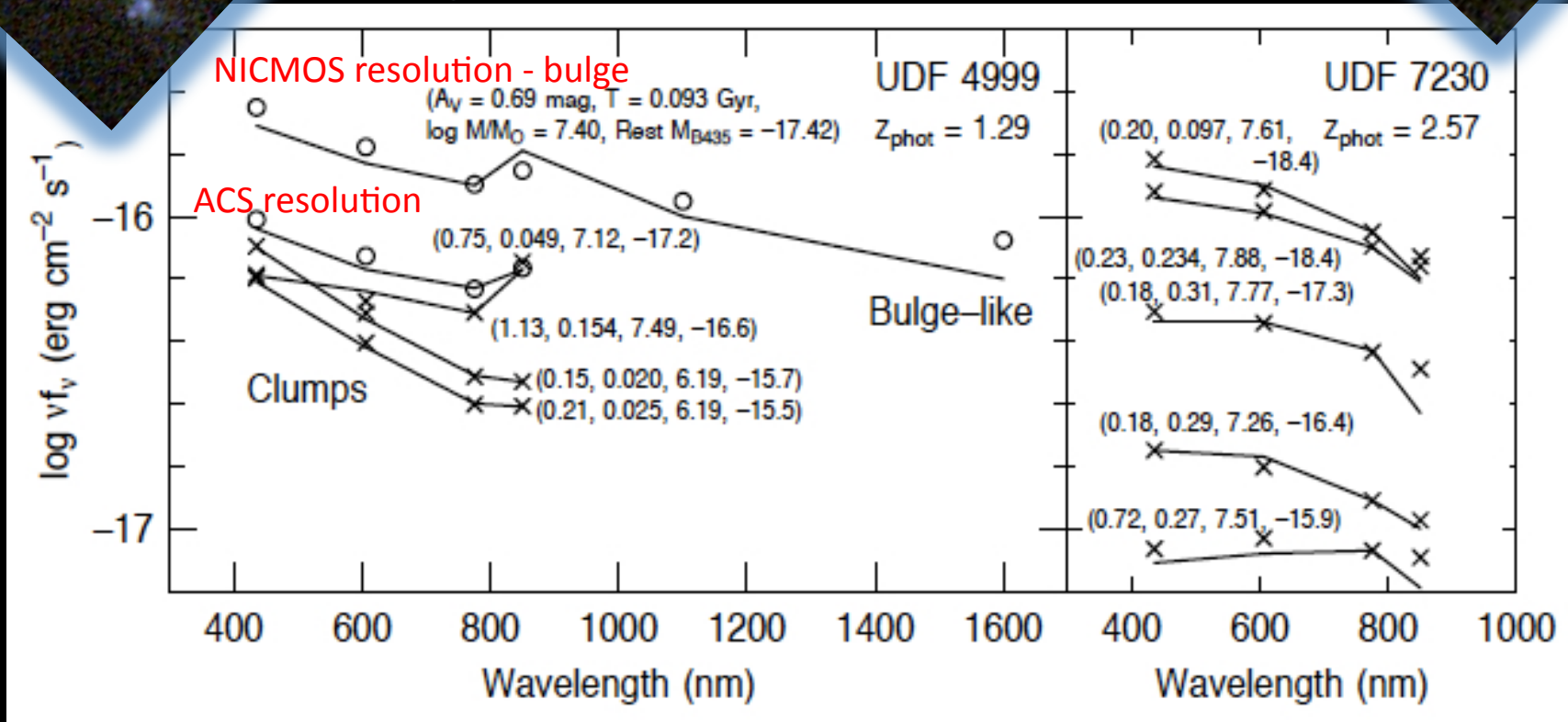
# SEDs of UDF galaxies with and without bulge-like clumps



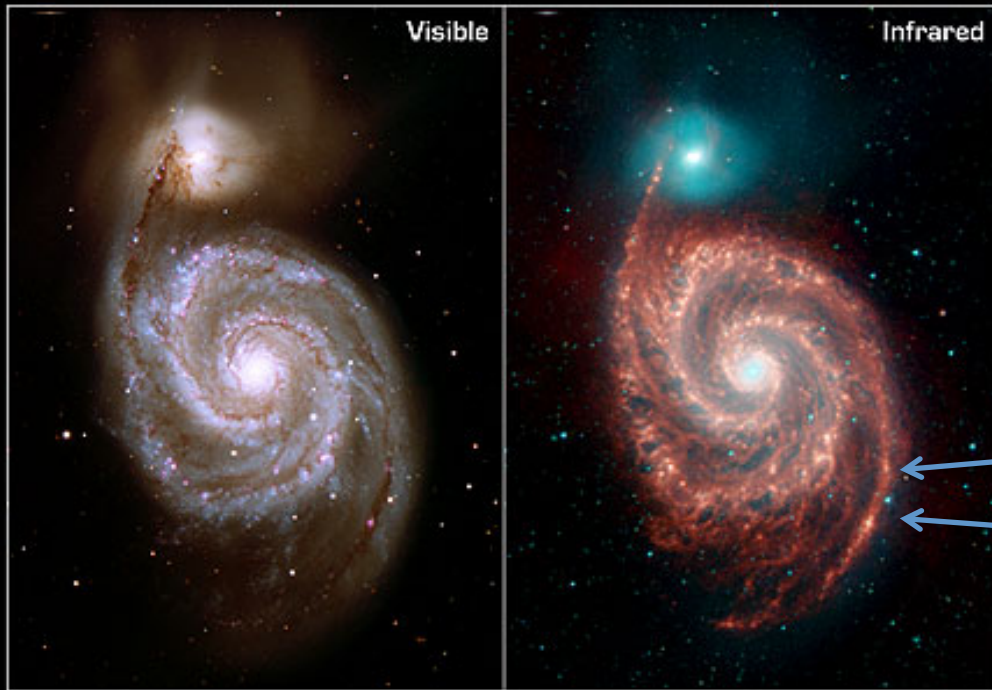
Clumpy  
with bulge-like clump



Clumpy  
without BLC



**Symbols: observed** Lines: Population synthesis models  
 rms deviations between model & observed colors are  $\sim 0.1 \text{ mag}$



**Star-forming  
complexes in local  
galaxies, up to  
 $10^4$ - $10^6 M_{\odot}$  over 1 kpc**

Spiral Galaxy M51 ("Whirlpool Galaxy")  
NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)

Spitzer Space Telescope • IRAC  
ssc2004-19a



IC2163/2207 HST, Spitzer



Elmegreen et al. 2001, 2006

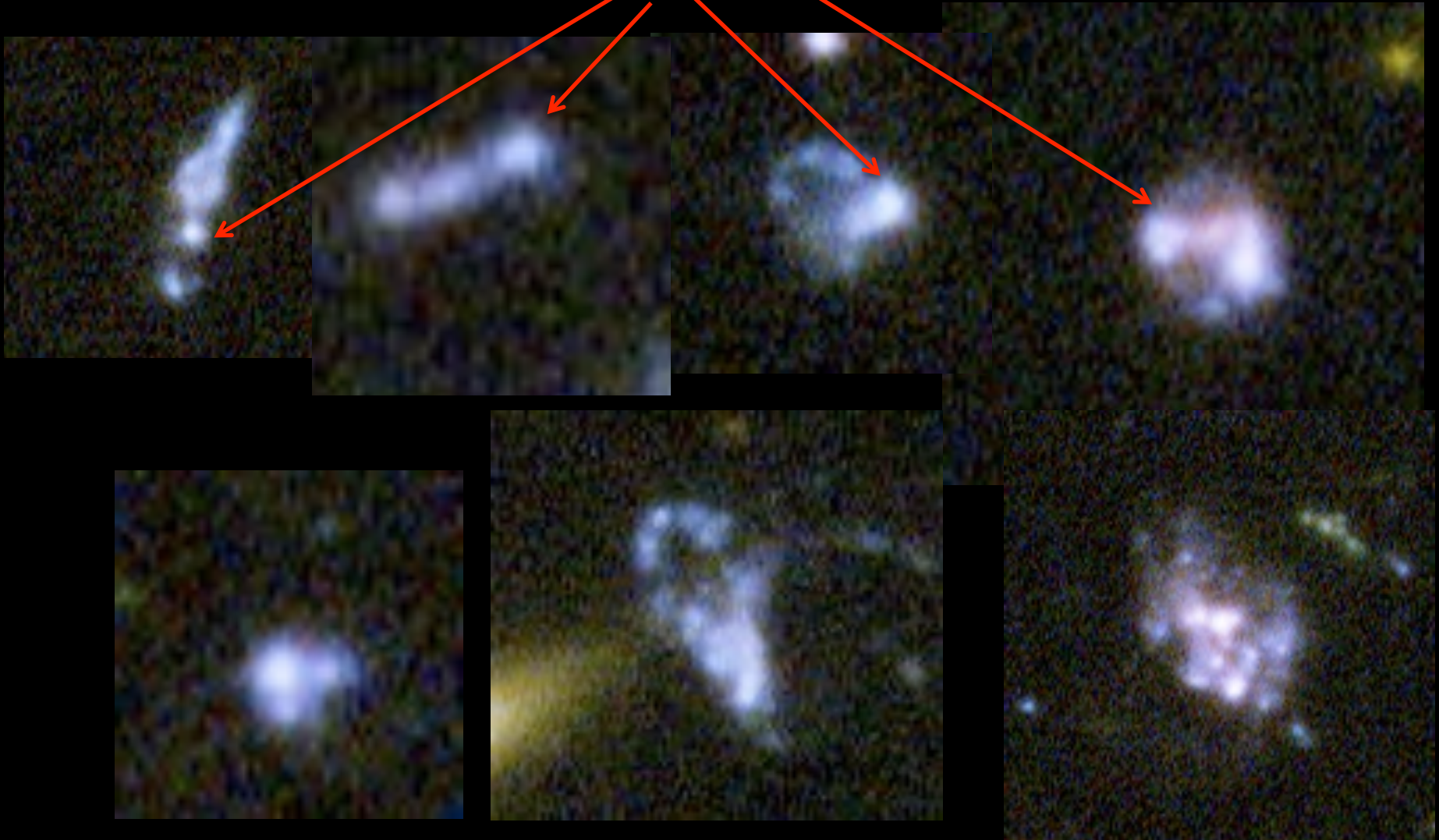
**Spirals at  $z \sim 0.2-1$  have more massive complexes  
( $>10^7 M_{\odot}$ )**

→ gas in disk is more turbulent



Hubble Ultra Deep Field

**Clumpy galaxies' complexes are also  $>10^7 M_{\odot}$**   
(higher gas fraction, more turbulent)



Hubble Ultra Deep Field

# Comparison with nearby galaxies

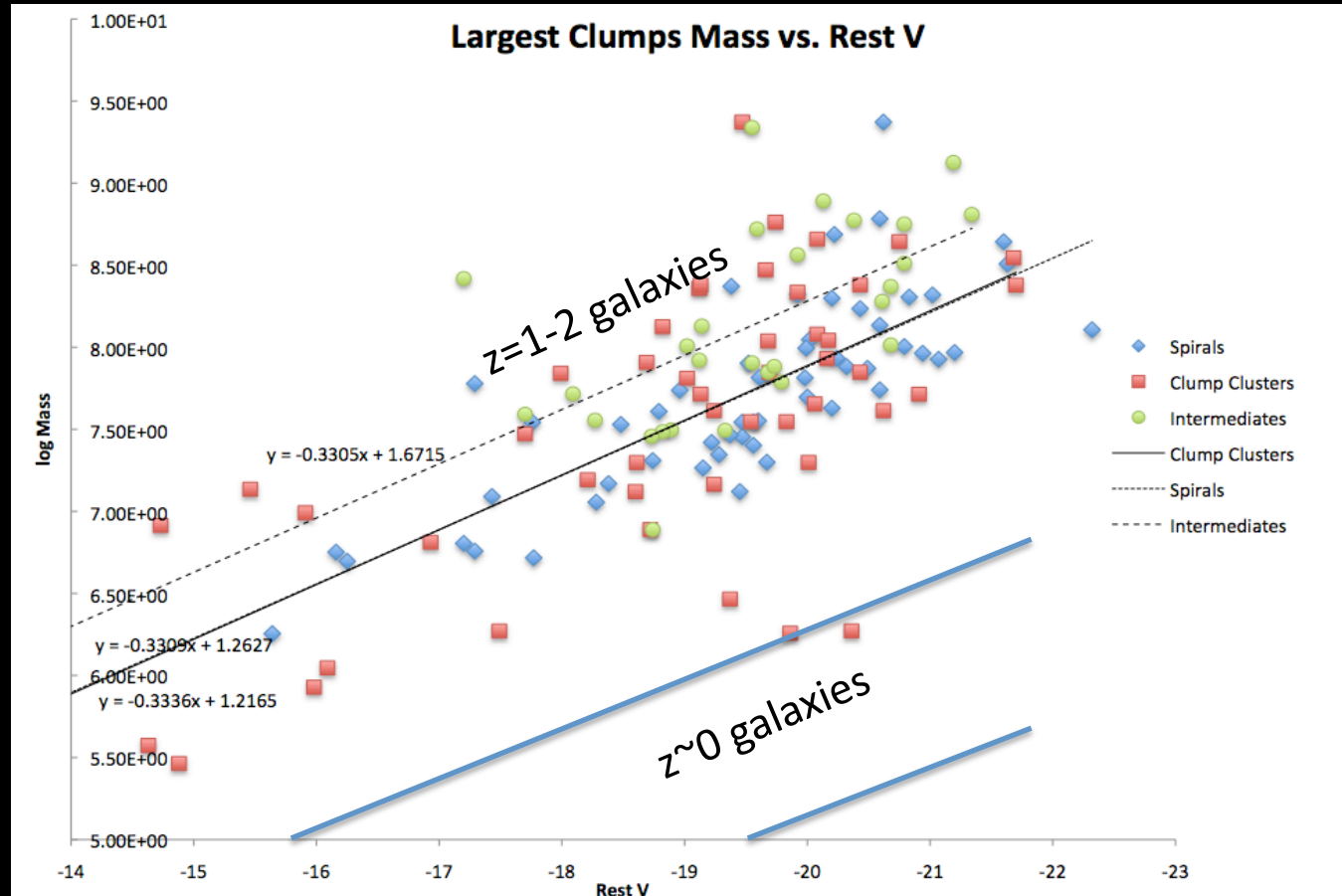
→ clump mass scales with galaxy mag, and complexes were more massive in the past

Clump  
Mass

$10^9 M_{\odot}$

$10^7$

$10^5$



Galaxy restframe magnitude

High z: Elmegreen et al. 2009; Local: Elmegreen et al. 2013 submitted

## Summary of UDF bulge and clump results

Galaxy type	Log Mass	Log Age
Clumpy		
SF clumps	$7.5 \pm 1$	$8 \pm 1$
bulge-like clumps	$8 \pm 0.5$	$8 \pm 1$
Spiral		
SF clumps	$7.5 \pm 1$	$8 \pm 1$
bulges	$9 \pm 1$	$9 \pm 1$

→ bulges are not well-formed yet in clumpies

# Mass fractions of clumps

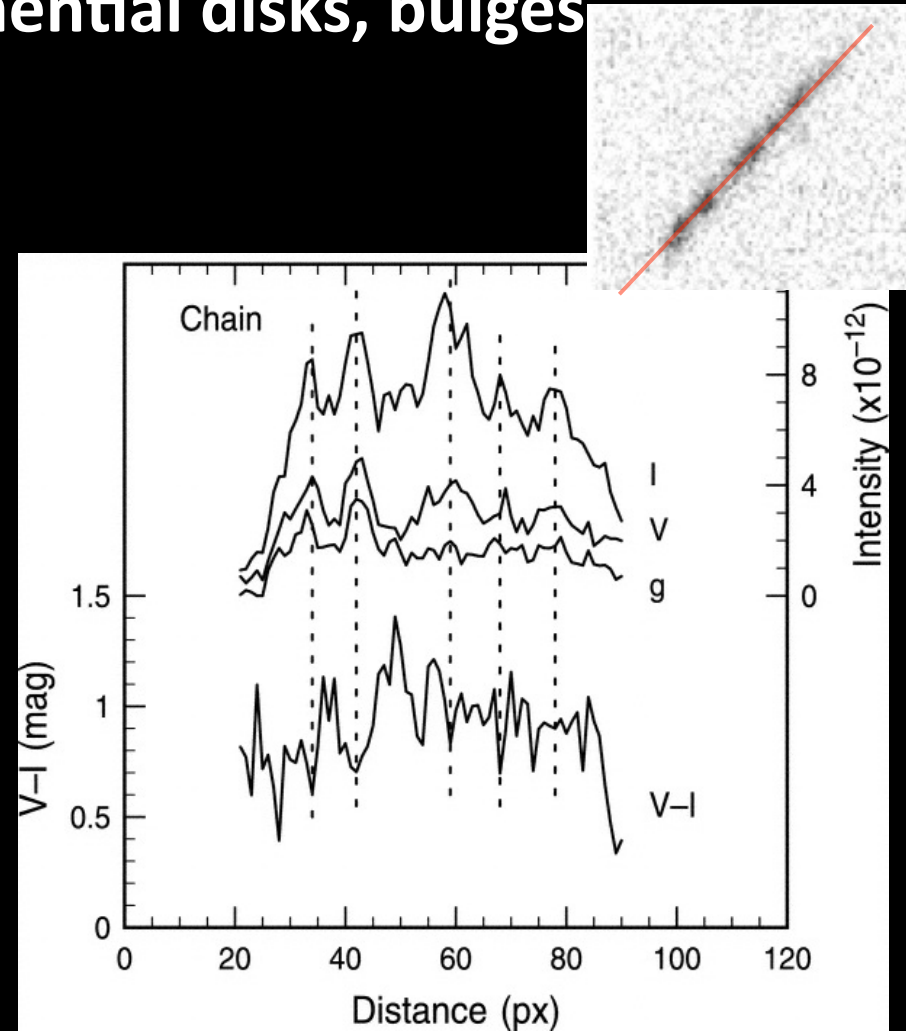
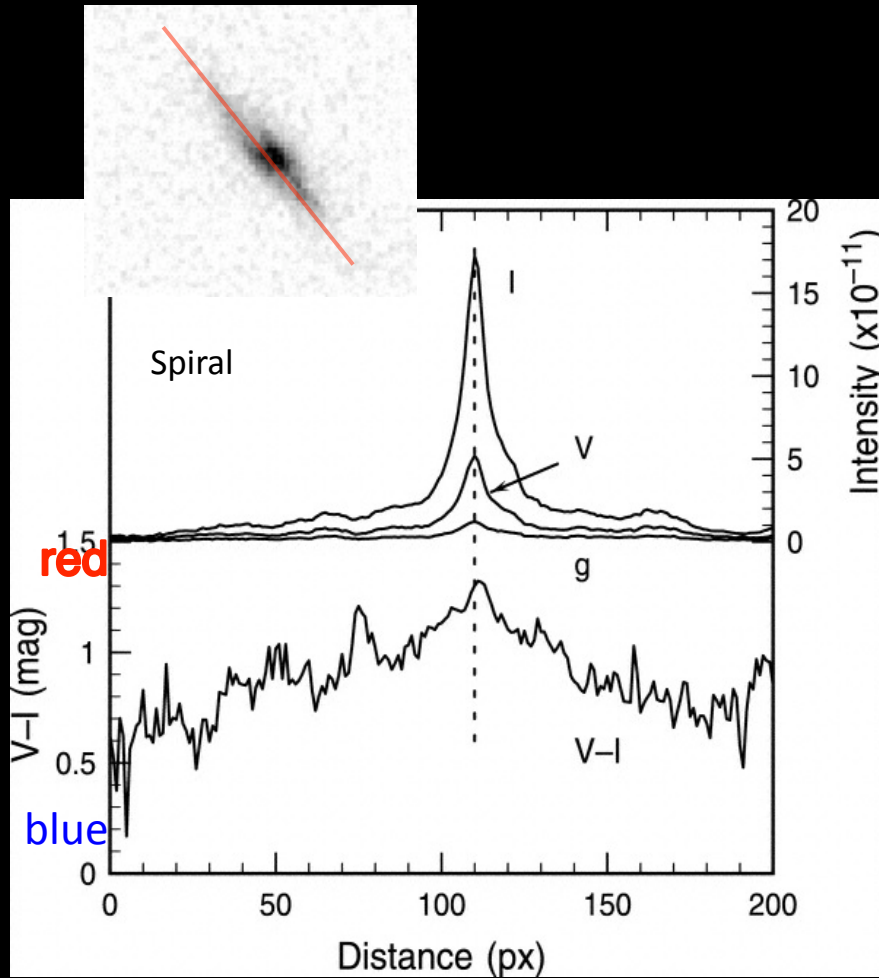
(Wuyts et al. 2012)

- **Fraction of star-forming galaxies (SFG) that are clumpy** on mass maps (clumpy means the clump fraction  $> 5\%$  of total)
  - 15% of  $z=0.5-1.5$ ,      41% of  $z=1.5-2.5$
- **fraction of stellar mass in the clumps** for all SFG:
  - 2% at  $z=0.5-1.5$ ,      7% at  $z=1.5-2.5$
- **fraction of stellar mass in clumps** in clumpy SFG:
  - 15% at  $z=0.5-1.5$ ,      16% at  $z=1.5-2.5$
- **clump ages**: 400 Myr at  $z\sim 1$ , 150 Myr at  $z\sim 2$ 
  - 1-2 orbit times

These results are consistent with our UDF studies

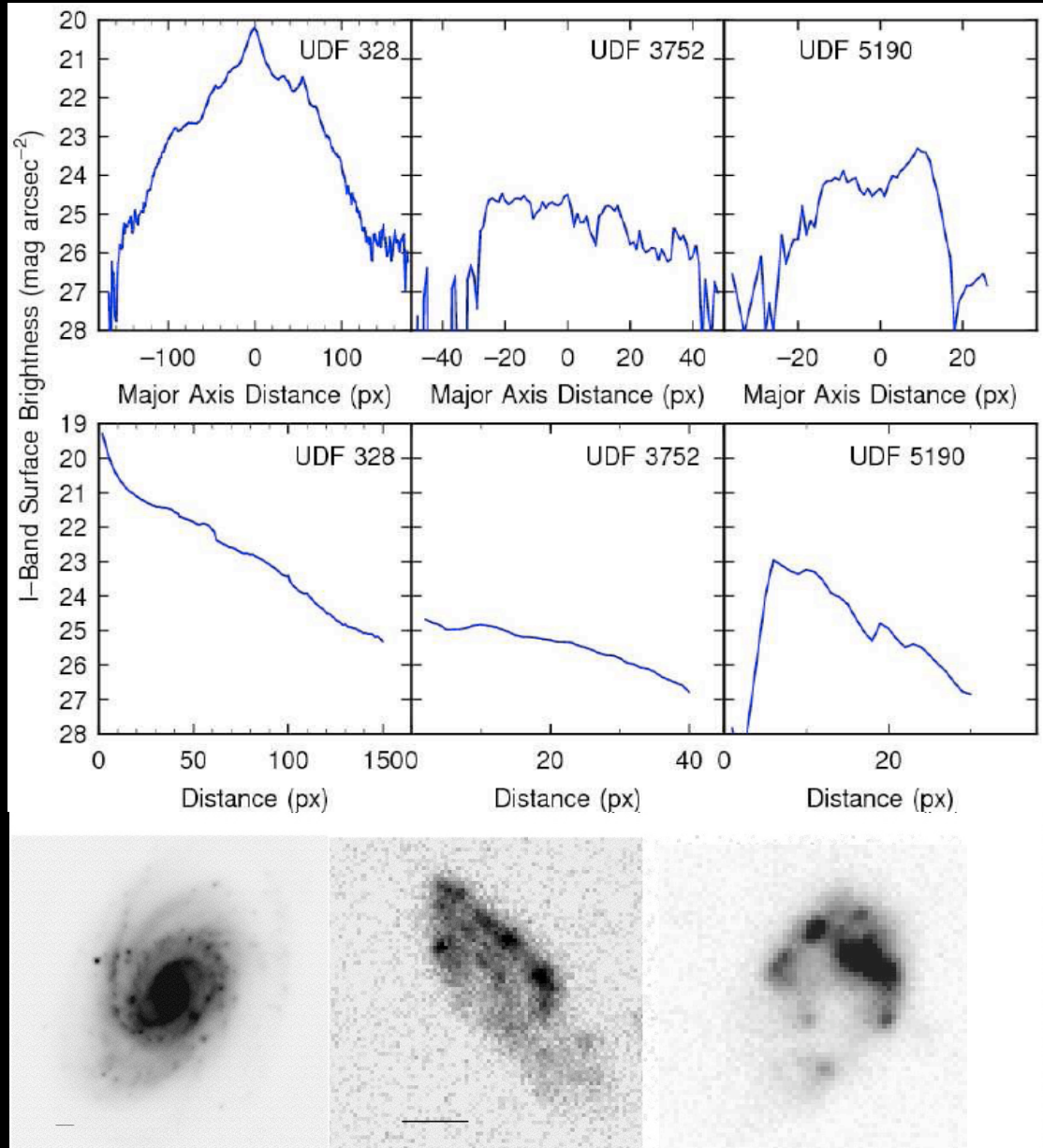
# Radial Profiles

Chain galaxies are not just edge-on spirals;  
only spirals have exponential disks, bulges



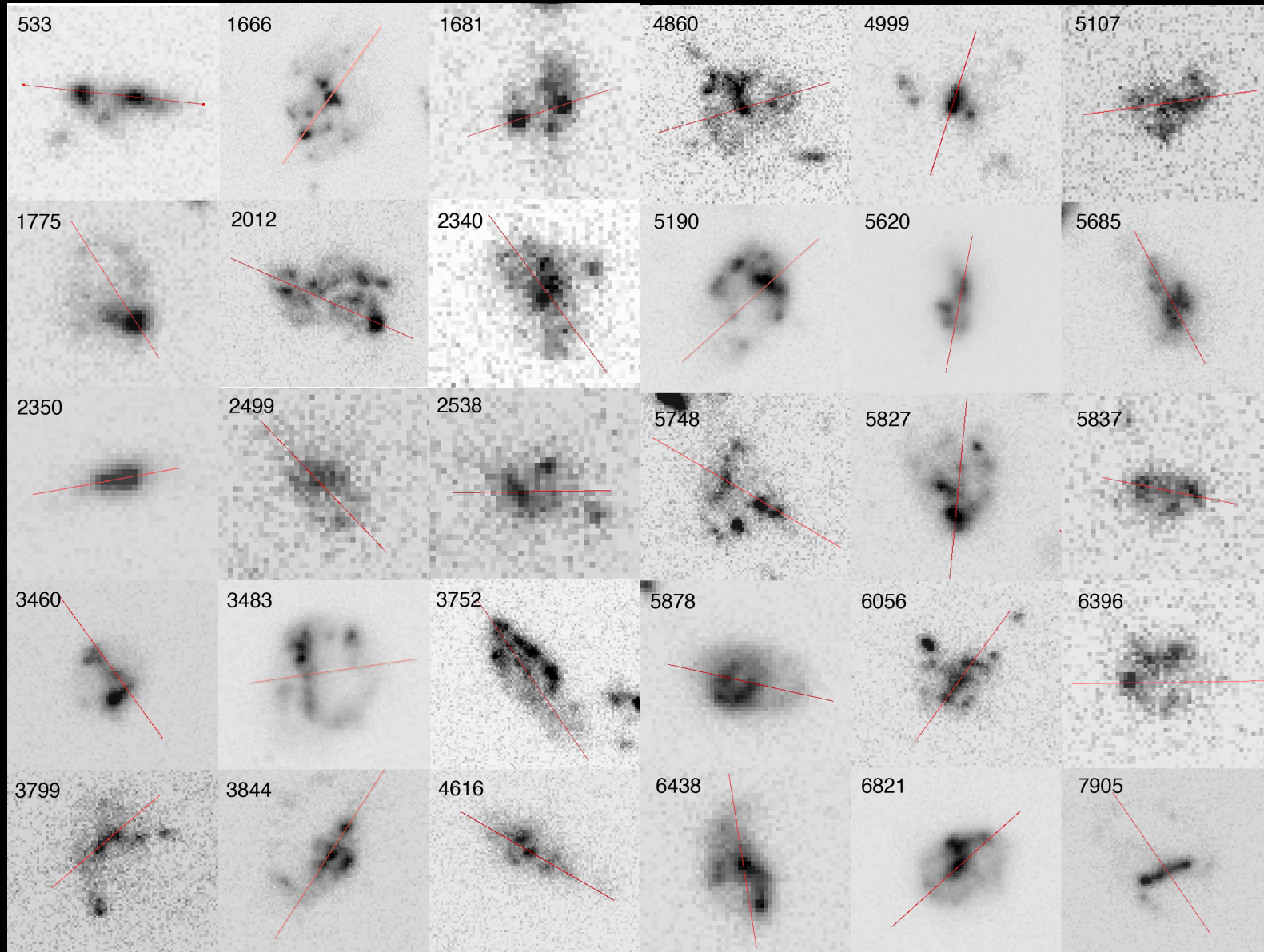
Elmegreen, Elmegreen & Sheets 2004

**Radial profiles of spirals differ from clump clusters too**

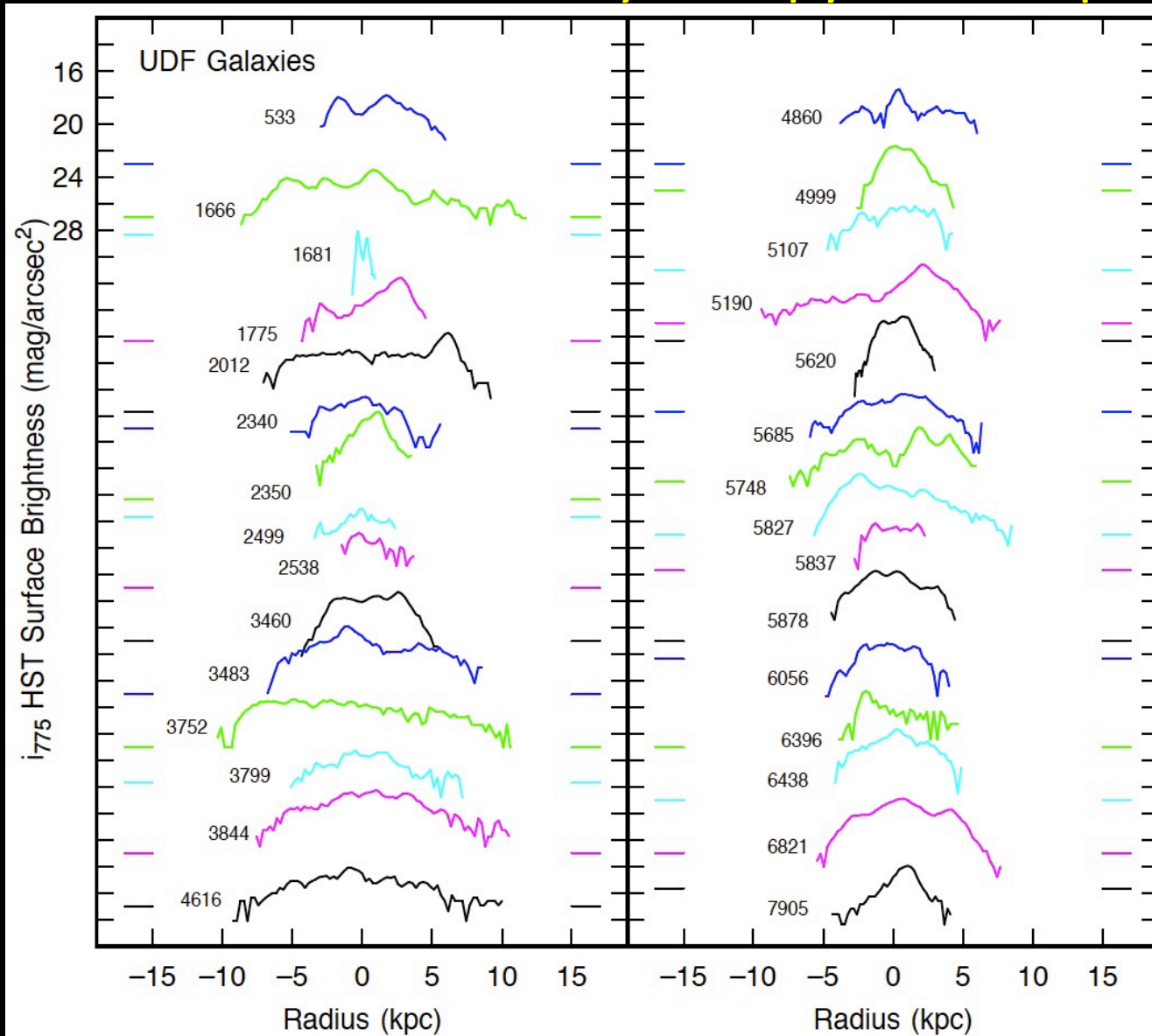


Elmegreen, Elmegreen & Hirst 2004

# UDF clumpies have a mixture of irregular and pseudo-spiral shapes



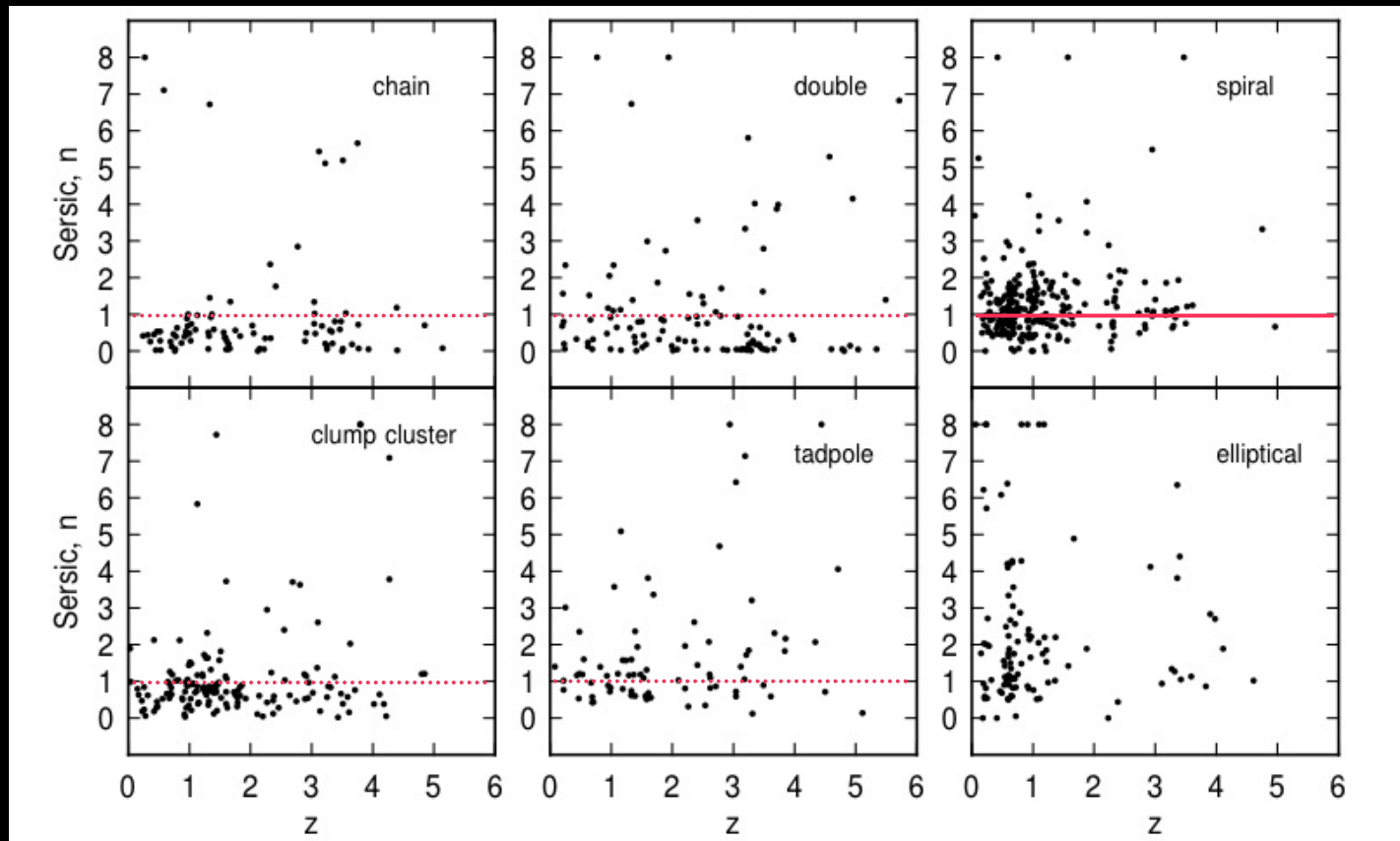
# UDF radial cuts show mostly clumpy and flat profiles



Elmegreen et al. 2013 submitted

## UDF : Sérsic $n$ vs. $z$ (from GALFIT; $I \propto \exp(-r^{1/n})$ )

- clumpy galaxies have flat profiles
- spiral galaxies have  $\sim$  exponential profiles (scale length avg  $\sim$   $\frac{1}{2}$  today's spirals)
- ellipticals have wide range of profiles



$n: 1 = \text{exponential}, 4 = \text{de Vaucouleurs } r^{1/4}; >2.5 \text{ spheroid-dominated}$

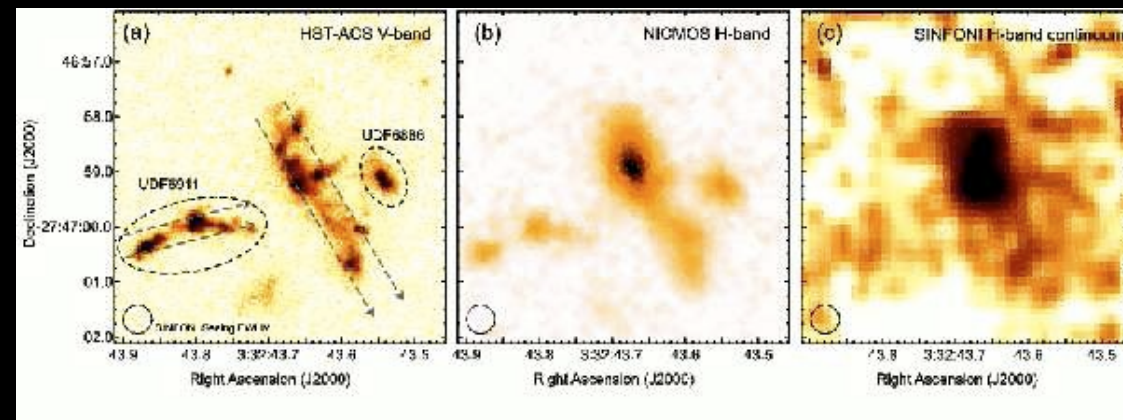
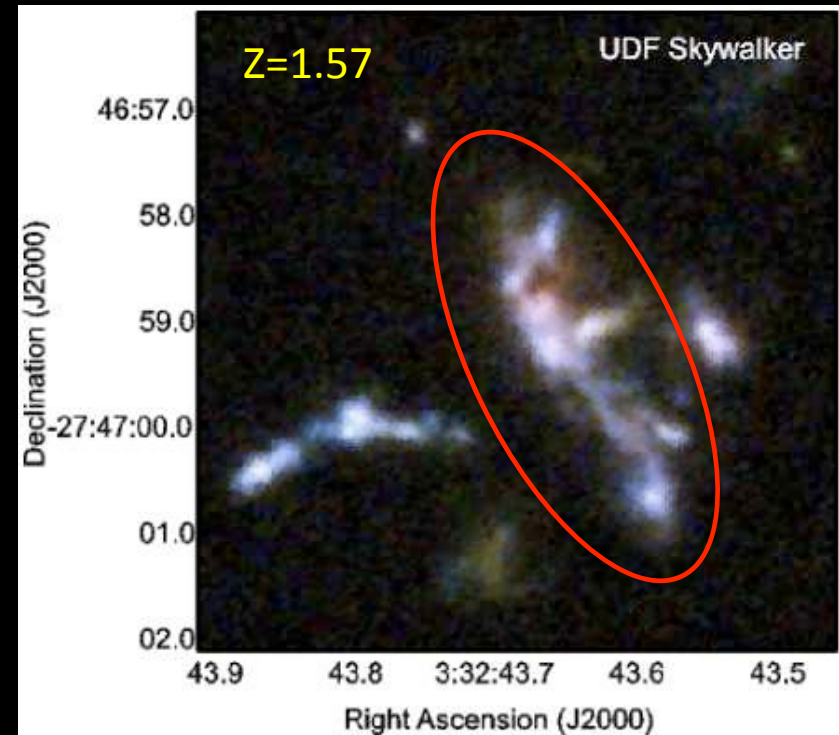
(see also Aceves, Velazquez, & Cruz 2006 for merger ellipticals; Ravindranath et al. 2006 for GOODS)

# Kinematic information

- **Kinematics of disks at intermediate redshifts show irregular structures** (Erb + 04; Yang + 08)
- **Turbulent motions can be large compared to rotation speed...** (Forster-Schreiber + 06; Weiner + 06; Genzel + 06, 08; Puech + 07)
- **...although there can be underlying systematic rotation too** (e.g. Bournaud + 08; Forster-Schreiber +09)

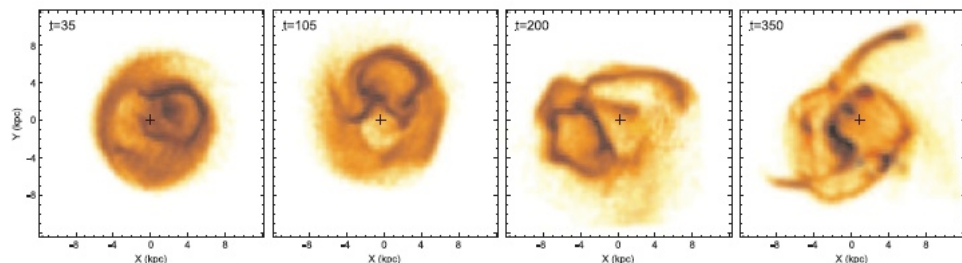
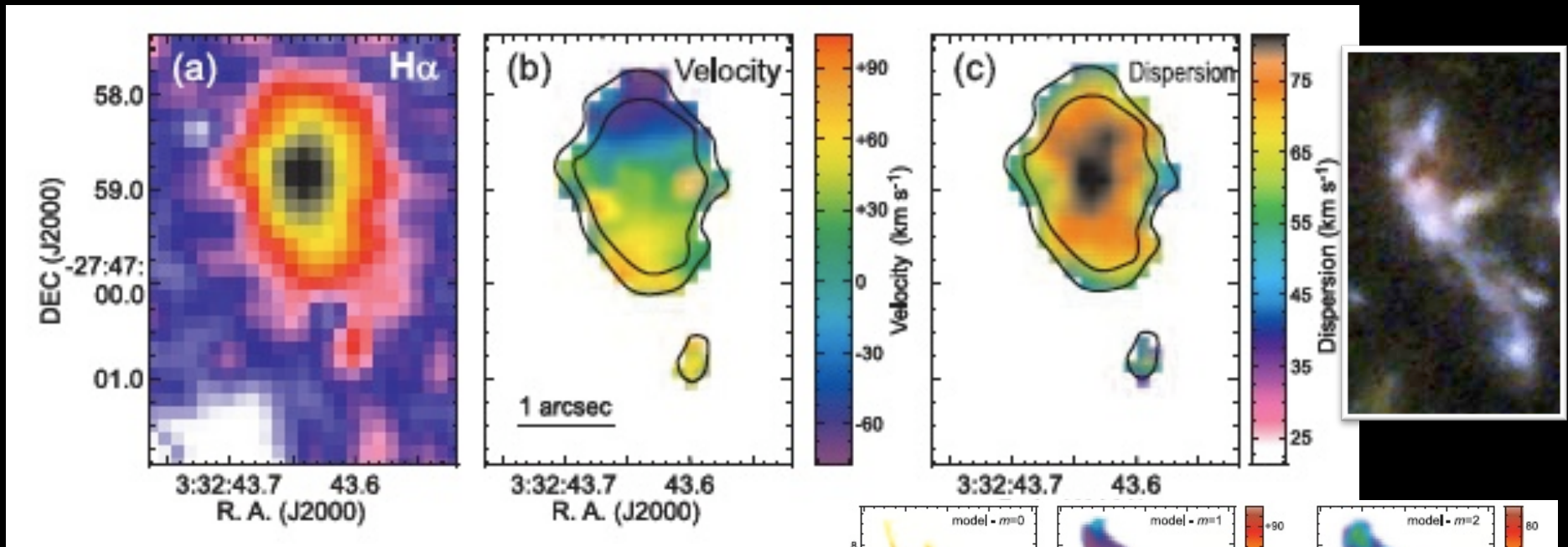
## Kinematics of a CC:

SINFONI VLT spectroscopic observations of UDF6462 show a clumpy rotating disk, also reproduced in simulations

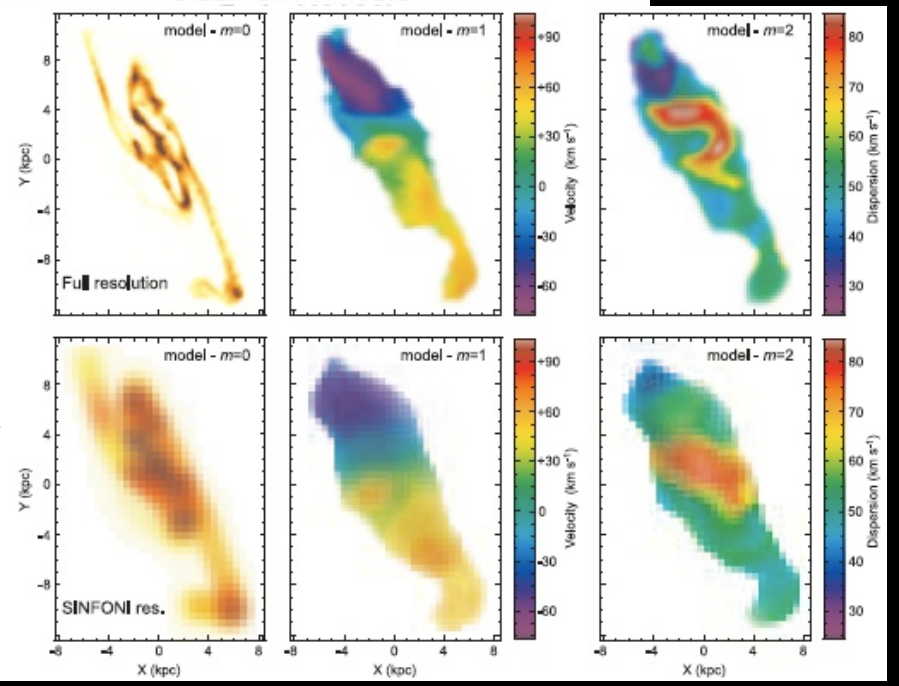


Bournaud, Daddi, Elmegreen et al. 2008

# SINFONI moment maps for H $\alpha$



models

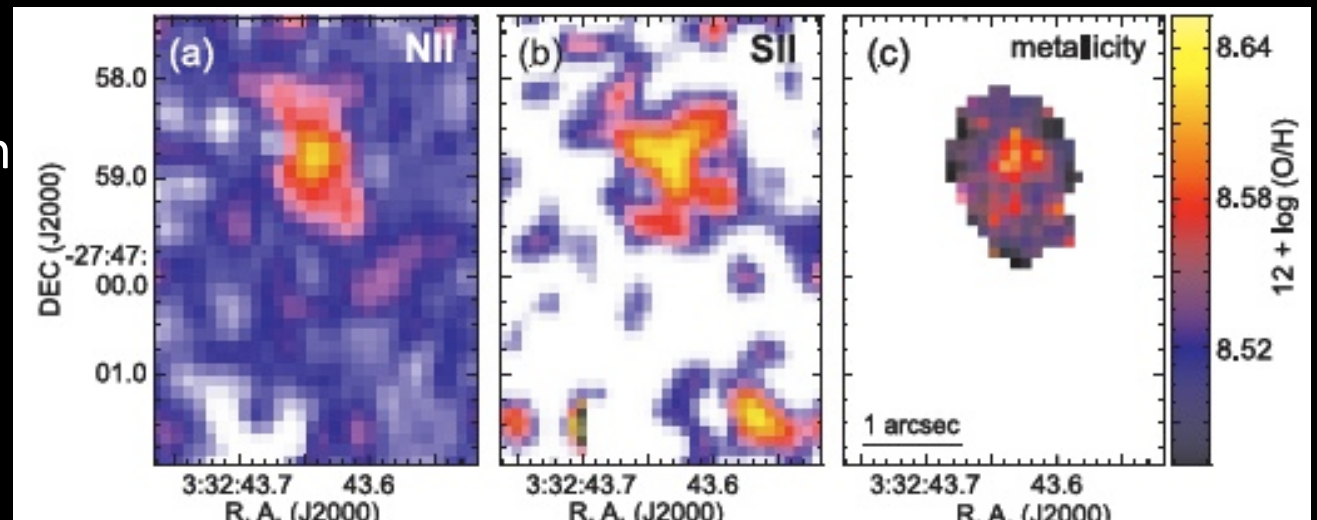
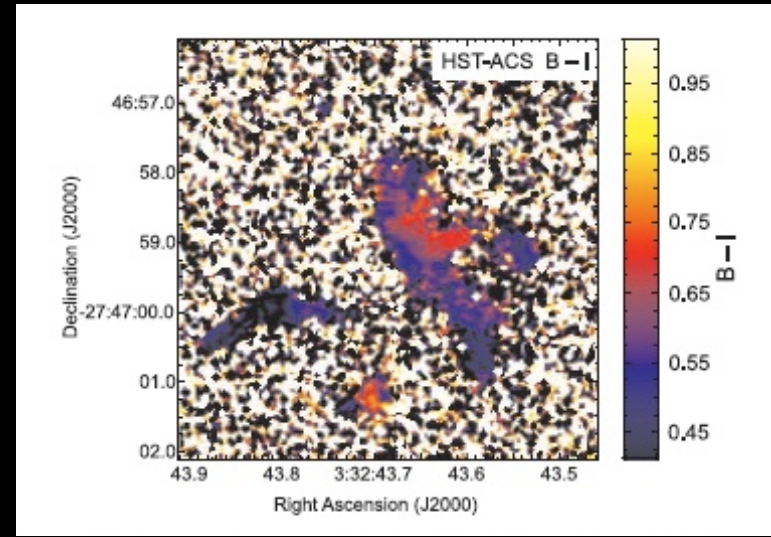


# Star formation and metallicity also indicate a disk:

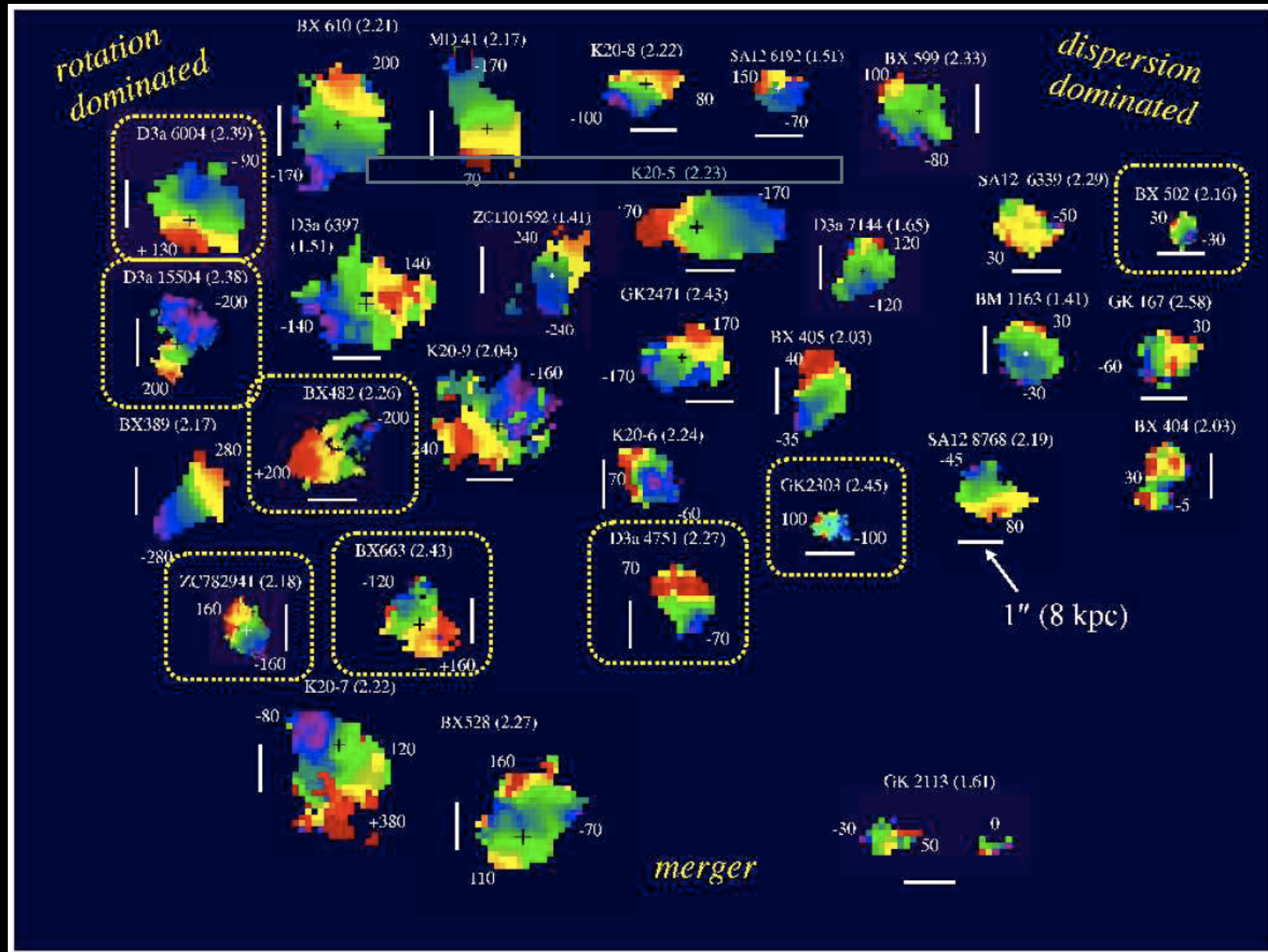
UV extinction-corrected SFR is  $50 M_{\odot} \text{ yr}^{-1}$  (starburst)

$H\alpha$ , [N II], [S II] lines  $\rightarrow$  centrally concentrated metallicity gradient

$Z \sim 0.5 Z_{\odot}$ ; agrees with mass-metallicity relation (Erb 2006) for  $z \sim 2$  galaxies

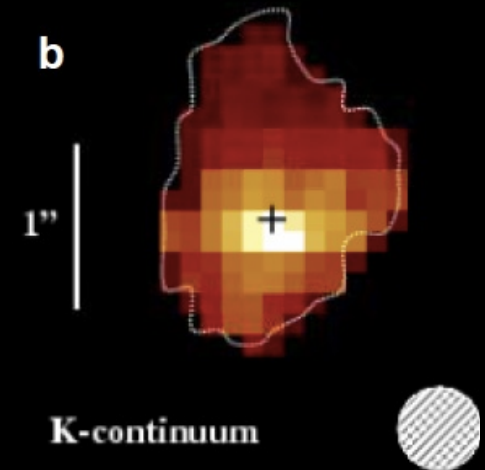


# SINS survey: kinematics for a broad sample of $z \sim 2$ galaxies

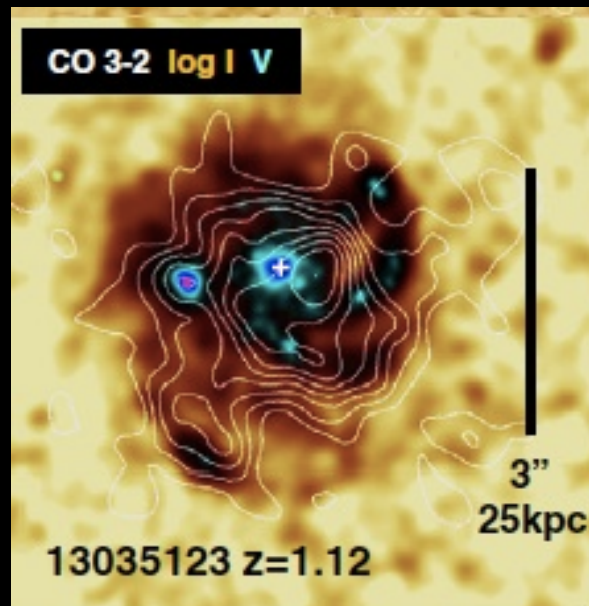
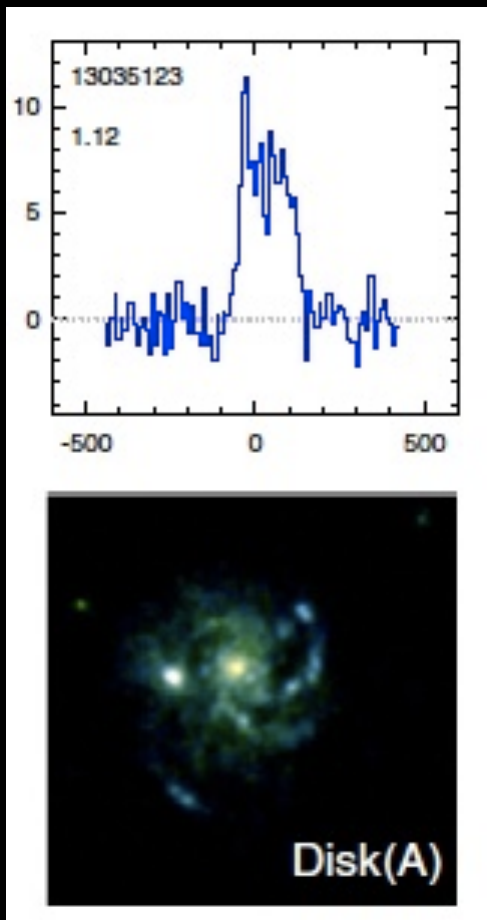


# Genzel et al. (2009) BzK sample

- protodisks in place by  $z=2-3$
- BzK15504 massive rotating (proto)disk at  $z\sim 2$ 
  - Scale length 4.5 kpc
  - Mass  $1.1 \times 10^{11} M_{\odot}$  out to  $R=8$  kpc
  - $V_{\text{circ}}=230$  km/s,  $v/\sigma \sim 2-4 = \text{hot disk}$   
(local spirals  $v/\sigma \sim 10-50$ )
  - $2-10 \times 10^8 M_{\odot}$  clumps



# CO detections



CO (3-2) detected in 52 galaxies,  $z=1-2$

**Gas fraction:** 33% at  $z=1$   
47% at  $z=2$

Tacconi et al. 2013

## Conclusions:

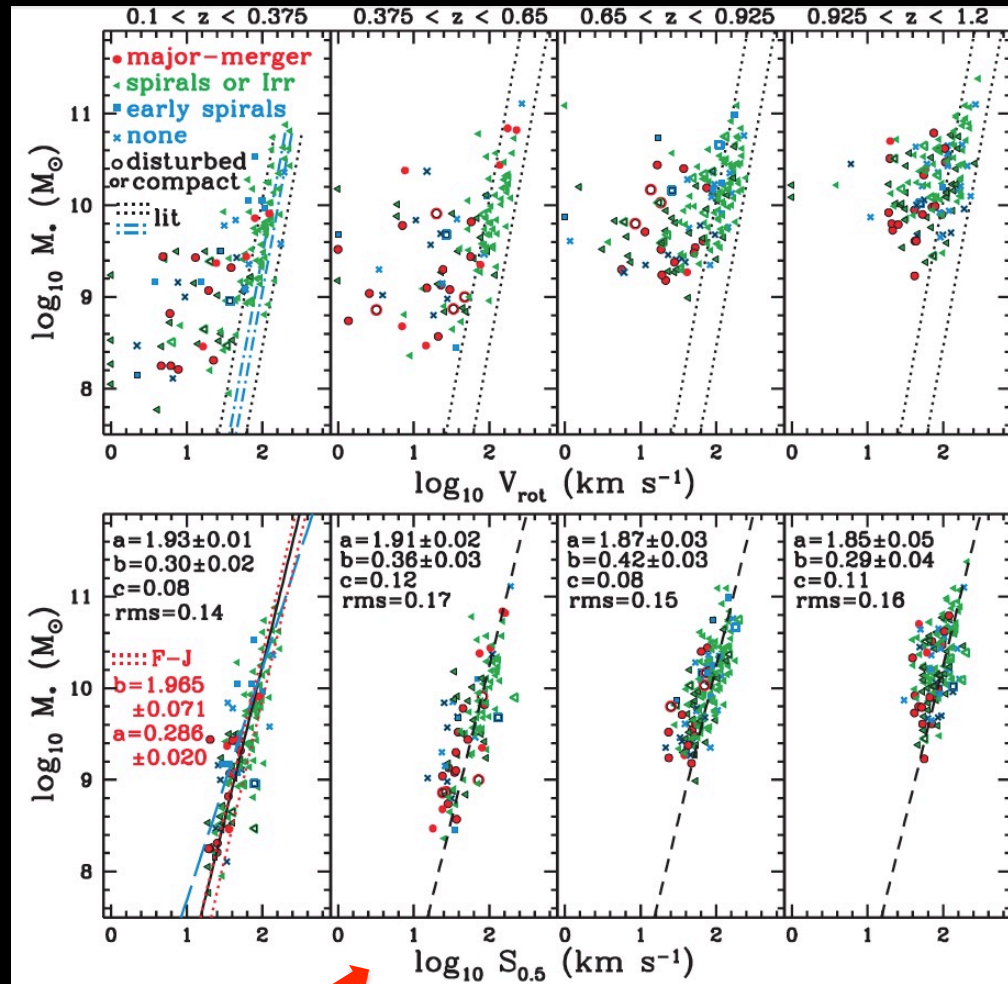
- high  $z$  spirals and clumpy galaxies have more massive complexes than local spirals
- clumpy galaxy bulges are younger and less massive than in spirals
- clumpy galaxies have higher gas fractions than local spirals
- clumpy galaxies have flatter profiles than spirals
- clumpy galaxies have rotating disks but high dispersions

When can bars (which help form grand designs) develop?

# Stellar mass Tully-Fisher relations

All-wavelength Extended Groth Strip International Survey (AEGIS)

544 emission  
line galaxies  
from  $0.1 < z < 1.2$



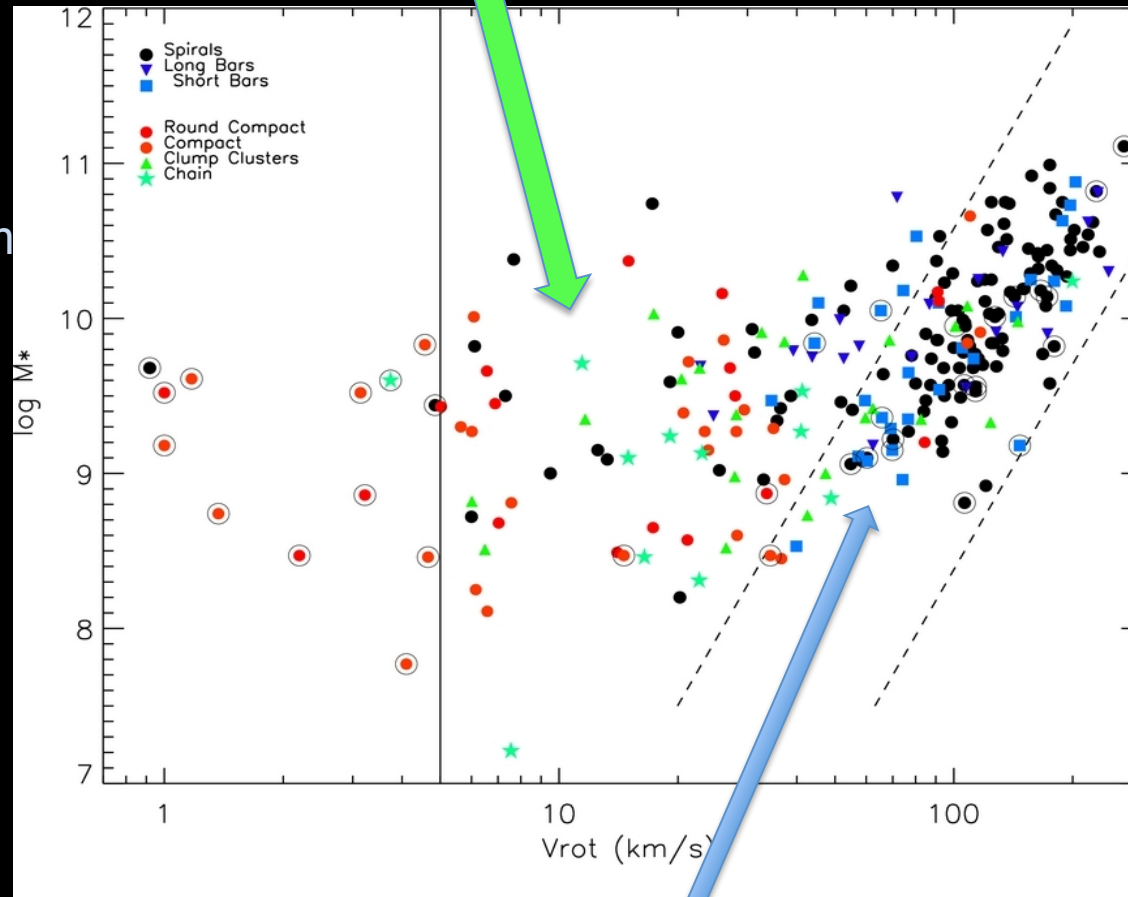
$$S_{0.5} = (0.5V_{\text{rot}}^2 + \sigma_g^2)^{1/2}$$

Kassin et al. 2007

Must include velocity dispersion too to get good T-F fits for non-spirals

Barred galaxies out to  $z=0.8$  lie on the T-F relation. Clumpy galaxies often do not  $\rightarrow$  high velocity dispersions.

257 galaxies from  
 $0.1 < z < 0.84$  in  
Extended Groth  
Strip and DEEP2

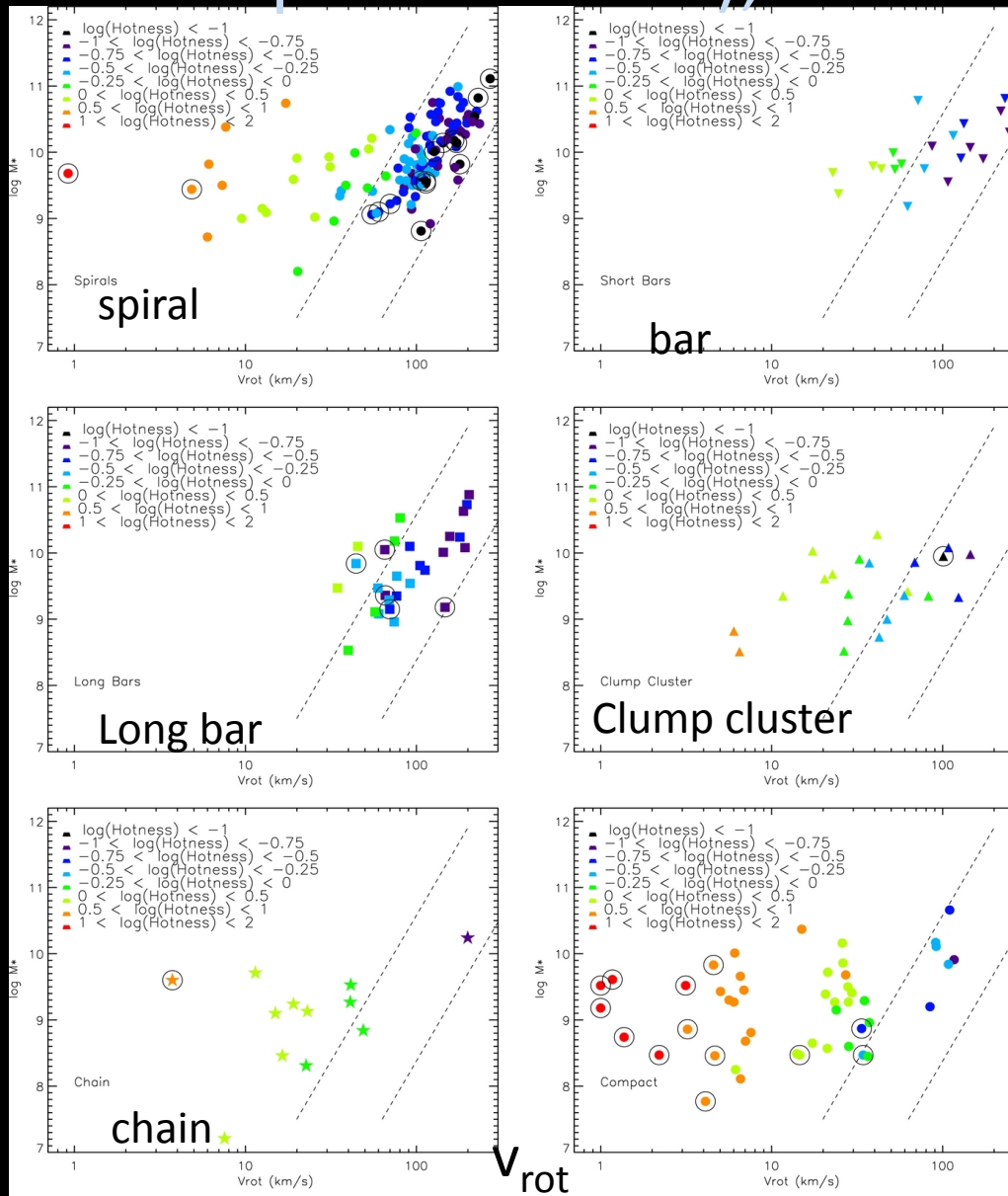


Sheth, Melbourne,  
Elmegreen et al. 2012

Barred galaxies in blue

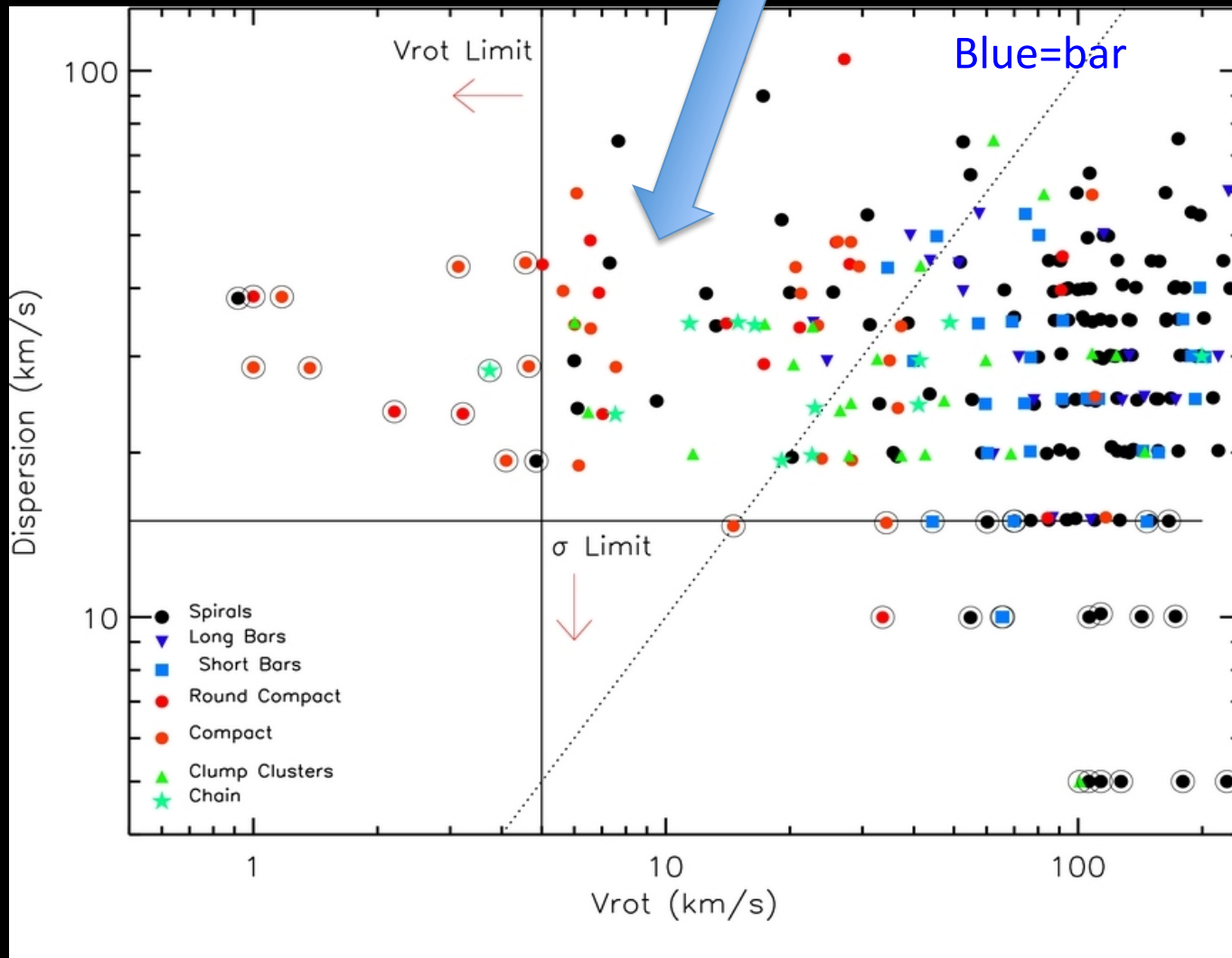
# Breakdown of types: clumpies are dynamically hot (but some spirals are too); bars are not

Log Mass



Sheth et al. 2012

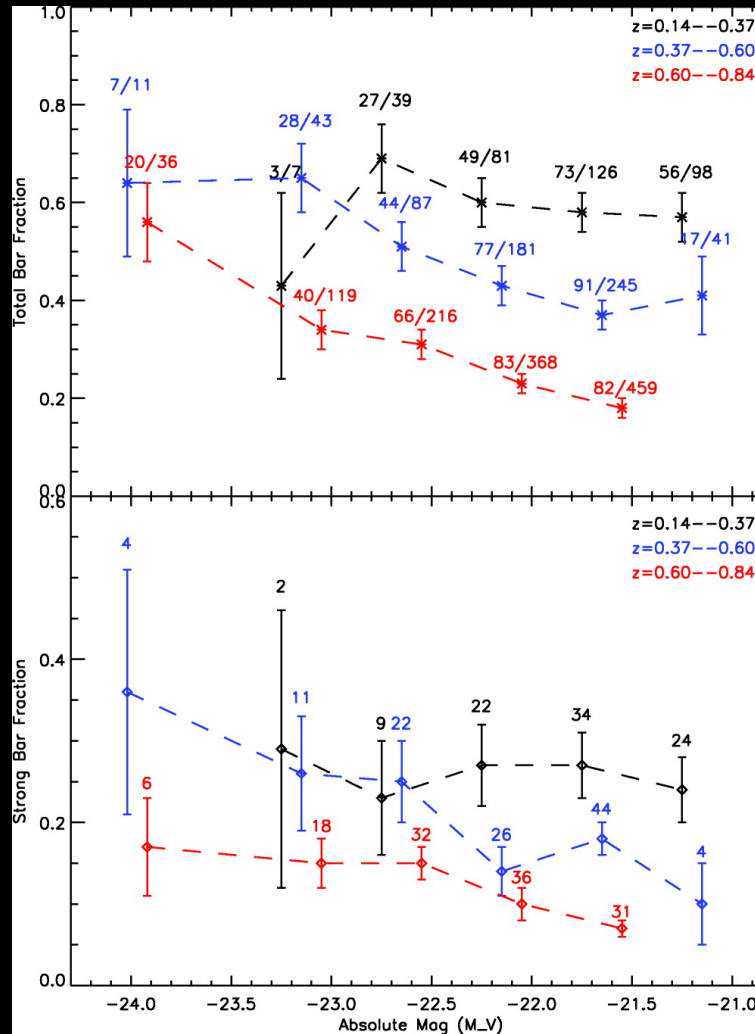
# Inhibition of bar formation and predominance of clumpy galaxies in dispersion-dominated galaxies:



Sheth et al. 2012

# Evolution of the Bar Fraction in COSMOS

2157  
luminous  
galaxies from  
COSMOS  
between  
 $0.2 < z < 0.84$

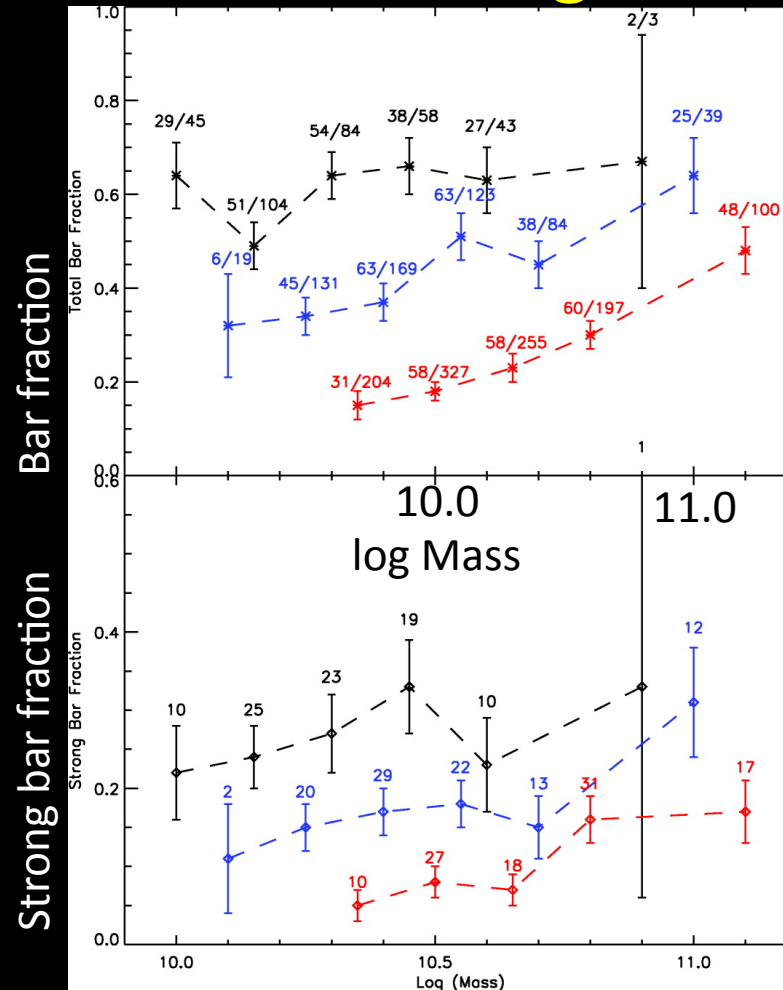


$z=0.14-0.37$   
 $z=0.37-0.60$   
 $z=0.60-0.84$

Sheth, Elmegreen et al. 2008

The fraction of **all** bars decreases with increasing redshift; the fraction of **strong** bars falls off less steeply

# Bar fraction decreases with redshift more for lower mass than higher mass galaxies



$z=0.14-0.37$   
 $z=0.37-0.60$   
 $z=0.60-0.84$

Sheth, Elmegreen et al. 2008

→ Massive galaxies are more dynamically evolved sooner than less massive galaxies

# Conclusions

- Bar fraction decreases with higher  $z$ ,  
but
- More massive galaxies form bars earlier  
(fraction changes less with  $z$ )
- Clumpy galaxies tend not to be barred and to  
lie off T-F

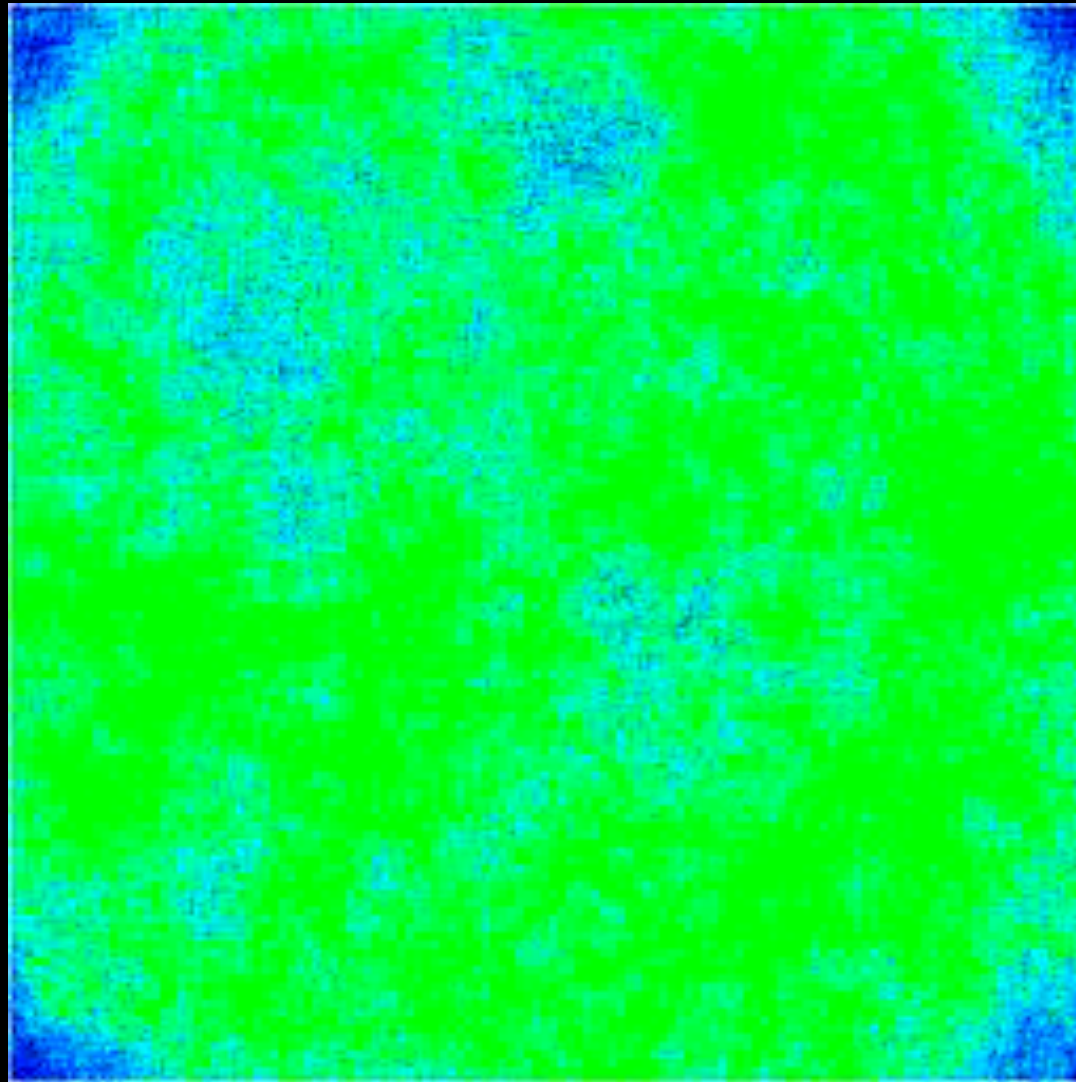
How might clumpies evolve to spirals?

# A Scenario for Hierarchical Build-up and Evolution

- Dark matter halos form
- Small halos merge to bigger halos
- Gas forms disk via cold flows
- Disk begins to grow and form stars
- Clumps merge to form bulge
- Disk grows more through gas accretion
- Mergers and interactions occur
  - Major merger → deplete gas → elliptical, or
  - Minor merger → build up spiral halo

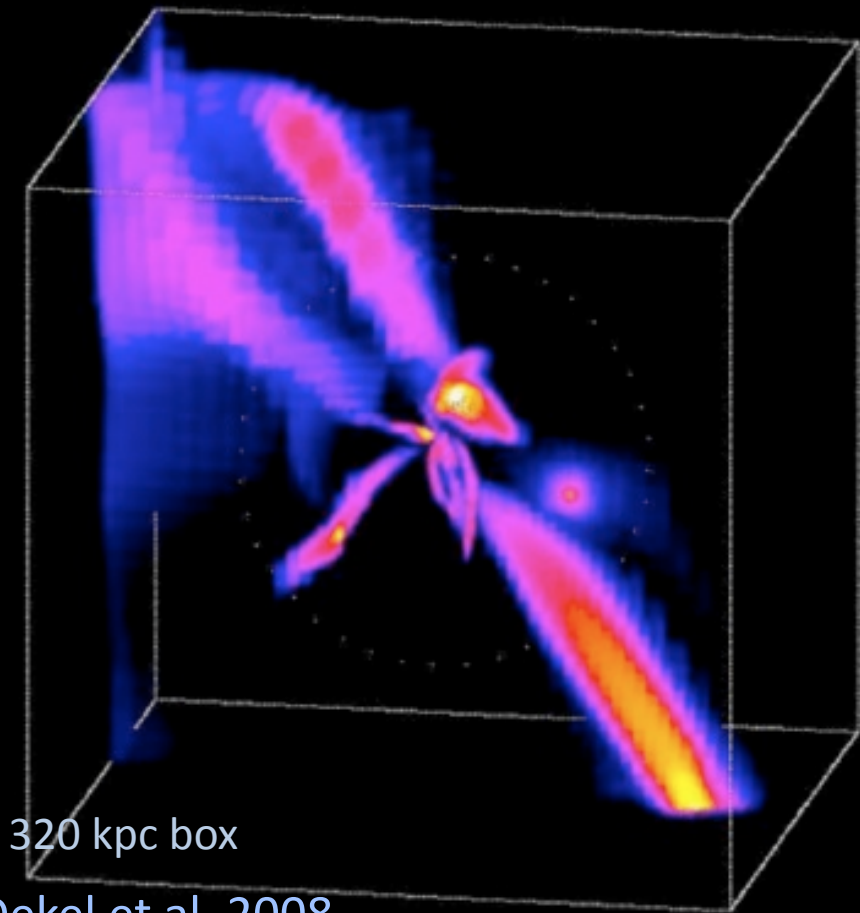
These processes may occur over a wide range of  $z$

# Cold Dark Matter model

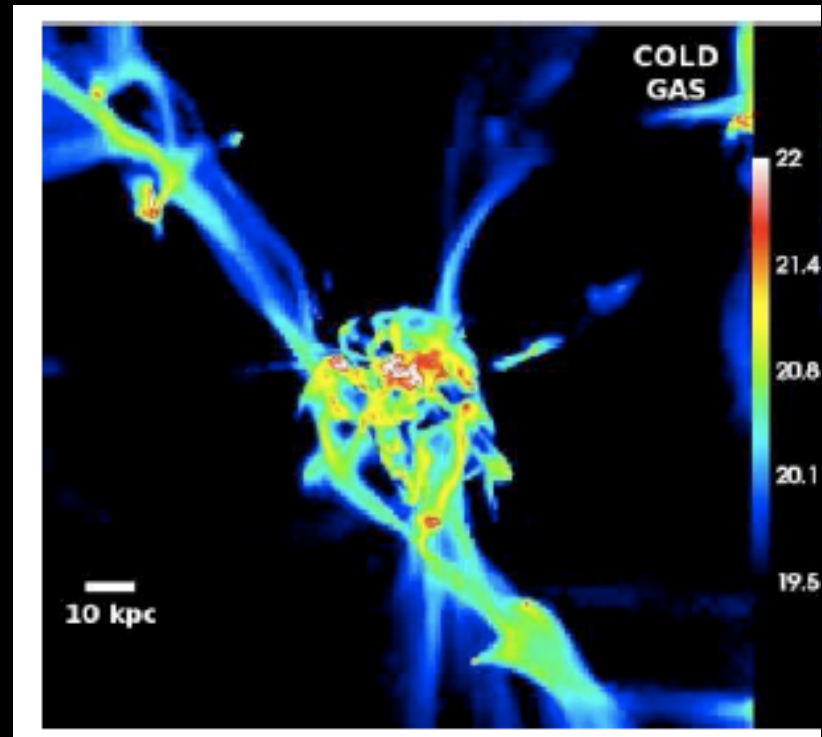


17 million  
particles; Los  
Alamos NL  
group site, 1995

**Cosmological simulations show that** cold gas may stream along cosmic web filaments onto young galaxies



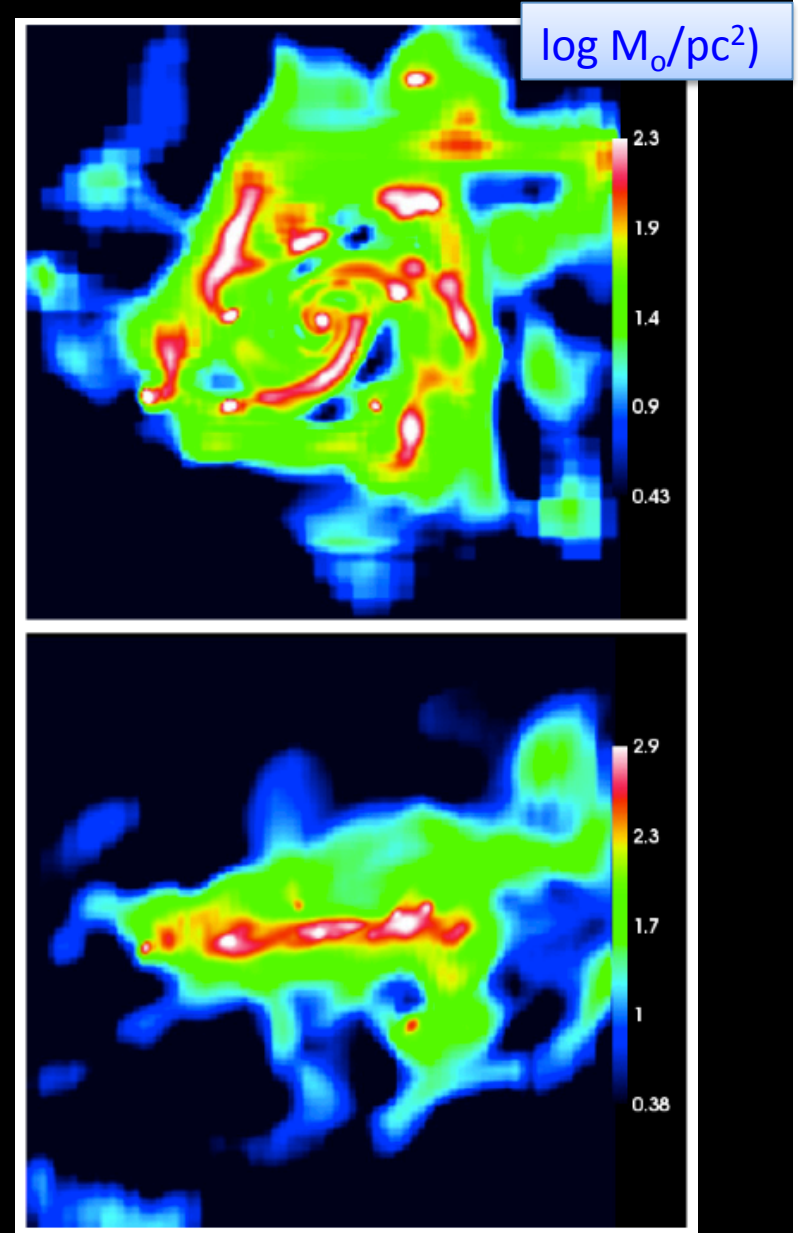
320 kpc box  
Dekel et al. 2008



Ceverino, Dekel, Bournaud 09

Top and side view of  
gas surface density for  
 $z=2.3$  galaxy from  
cosmological gas  
streams forming giant  
clumps in disks

Dekel et al. 2009

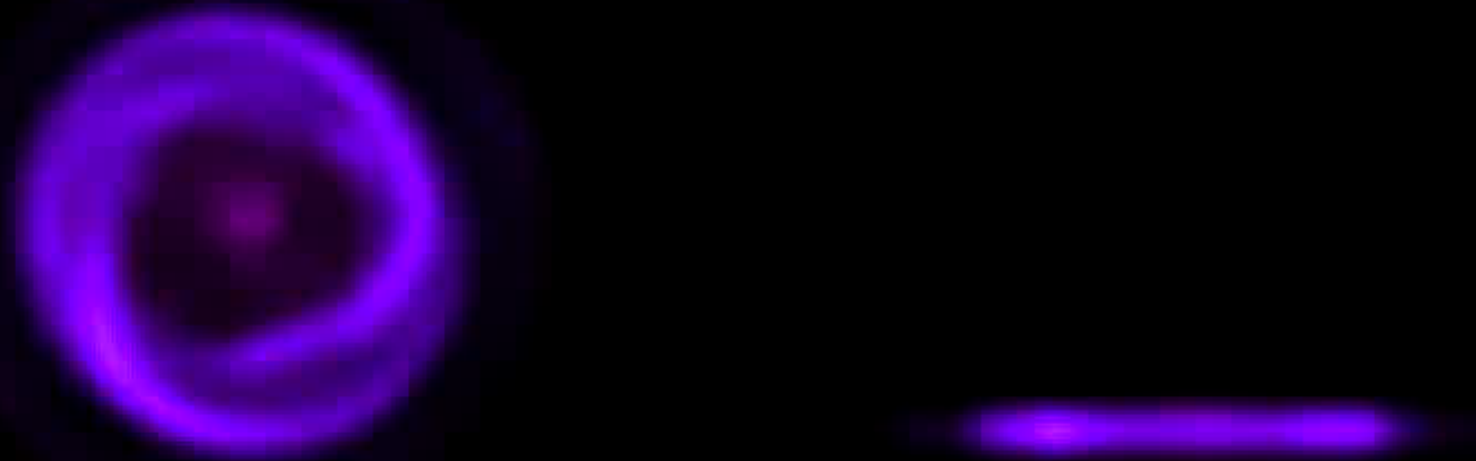


# Simulations of clump cluster evolution

- **Particle-mesh, sticky particle gas**
  - Grid resolution 110 pc
  - $10^6$  particles each for halo, stars, gas (halo scale length 15 kpc)
- **Schmidt star formation law**
  - probability per unit time that particle converts to star  $\propto \rho^{1.4}$
- **Initial disk profile flat, bulgeless**
  - 6 kpc radius,  $7 \times 10^{10} M_{\odot}$  disk
- **50% gas fraction initially in this model**

(Bournaud, Elmegreen & Elmegreen 2007,8)

Simulation of clump evolution: clumps merge to center to build bulge or disperse to develop disk

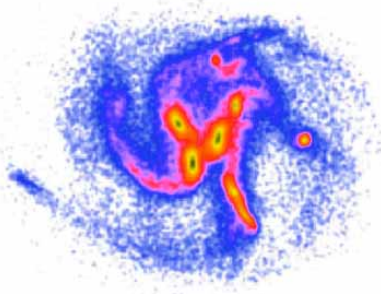
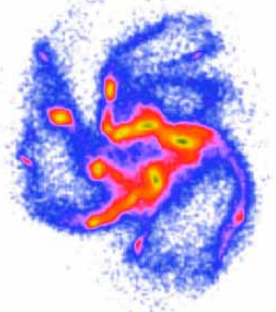


Bournaud, Elmegreen & Elmegreen 2007

# Evolution of disk and mass profile

t=120 Myr

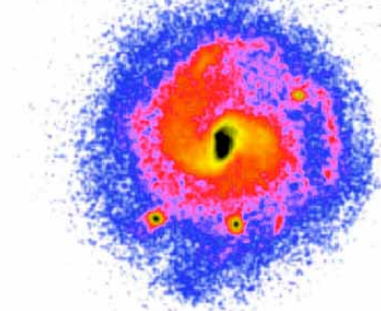
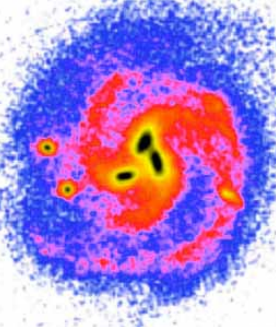
t=200 Myr



10kpc

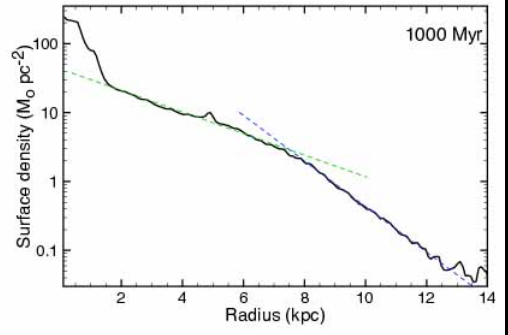
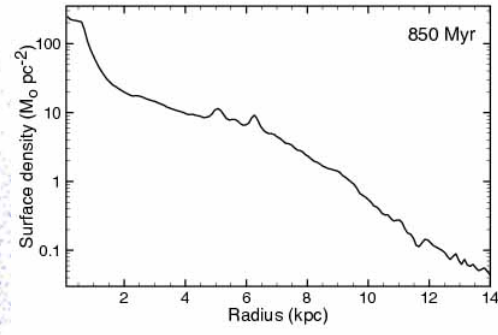
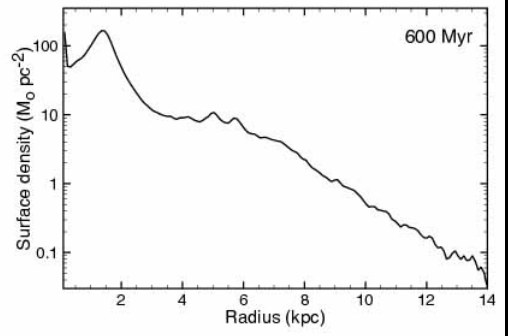
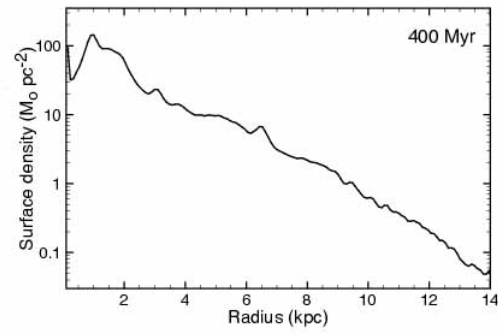
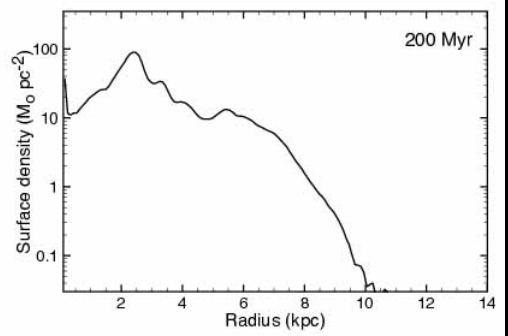
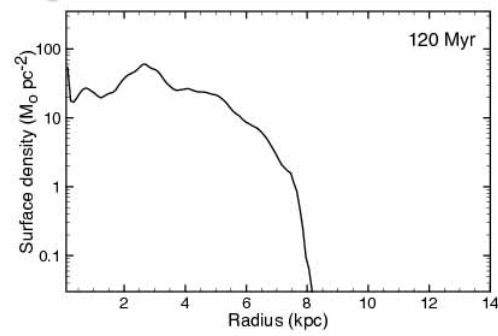
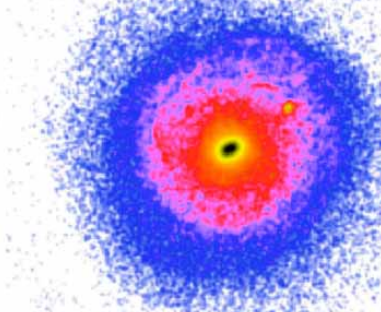
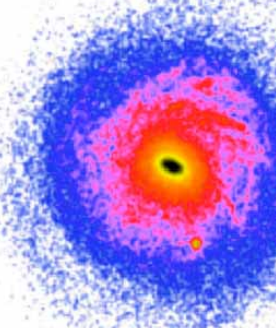
t=400 Myr

t=650 Myr



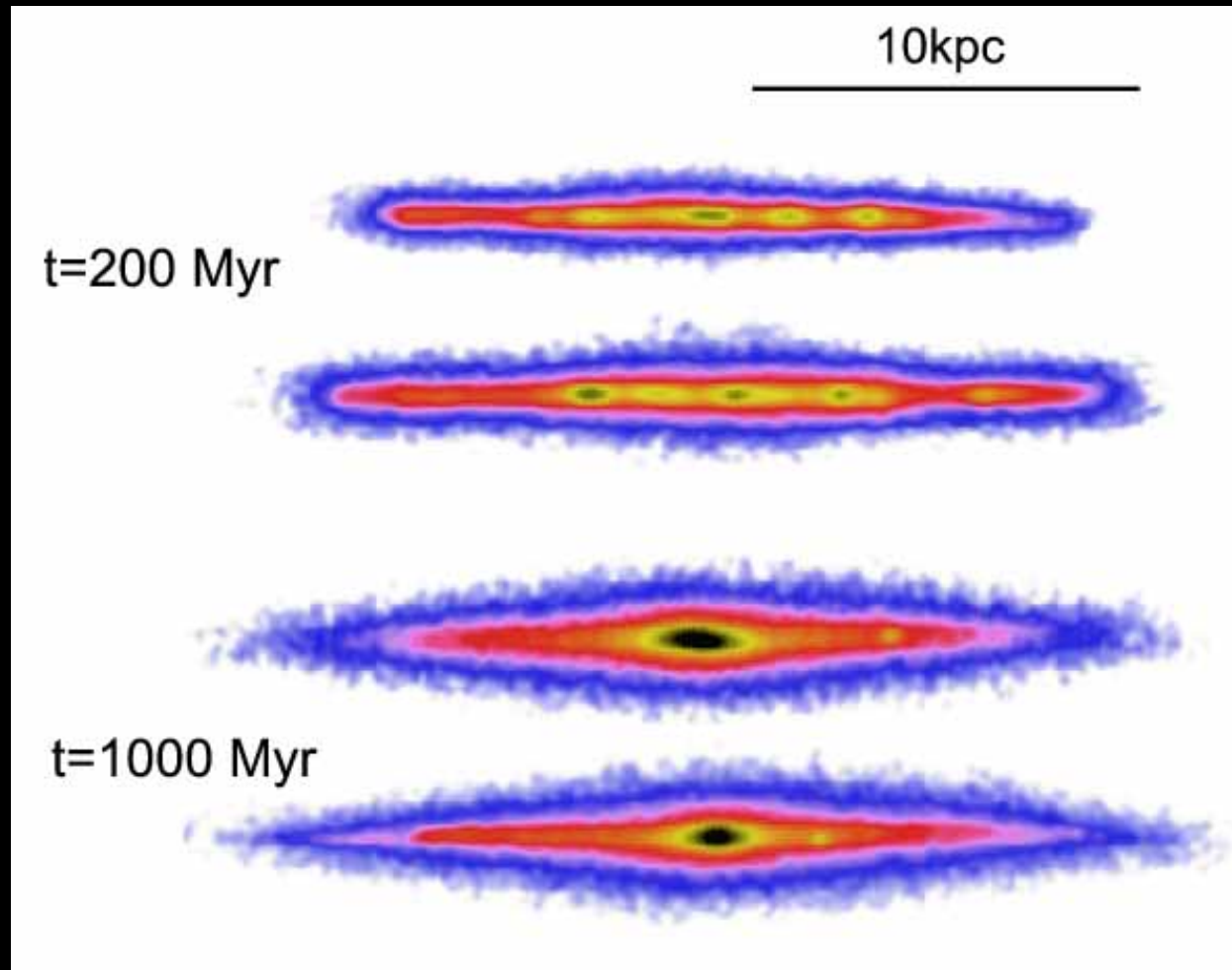
t=850 Myr

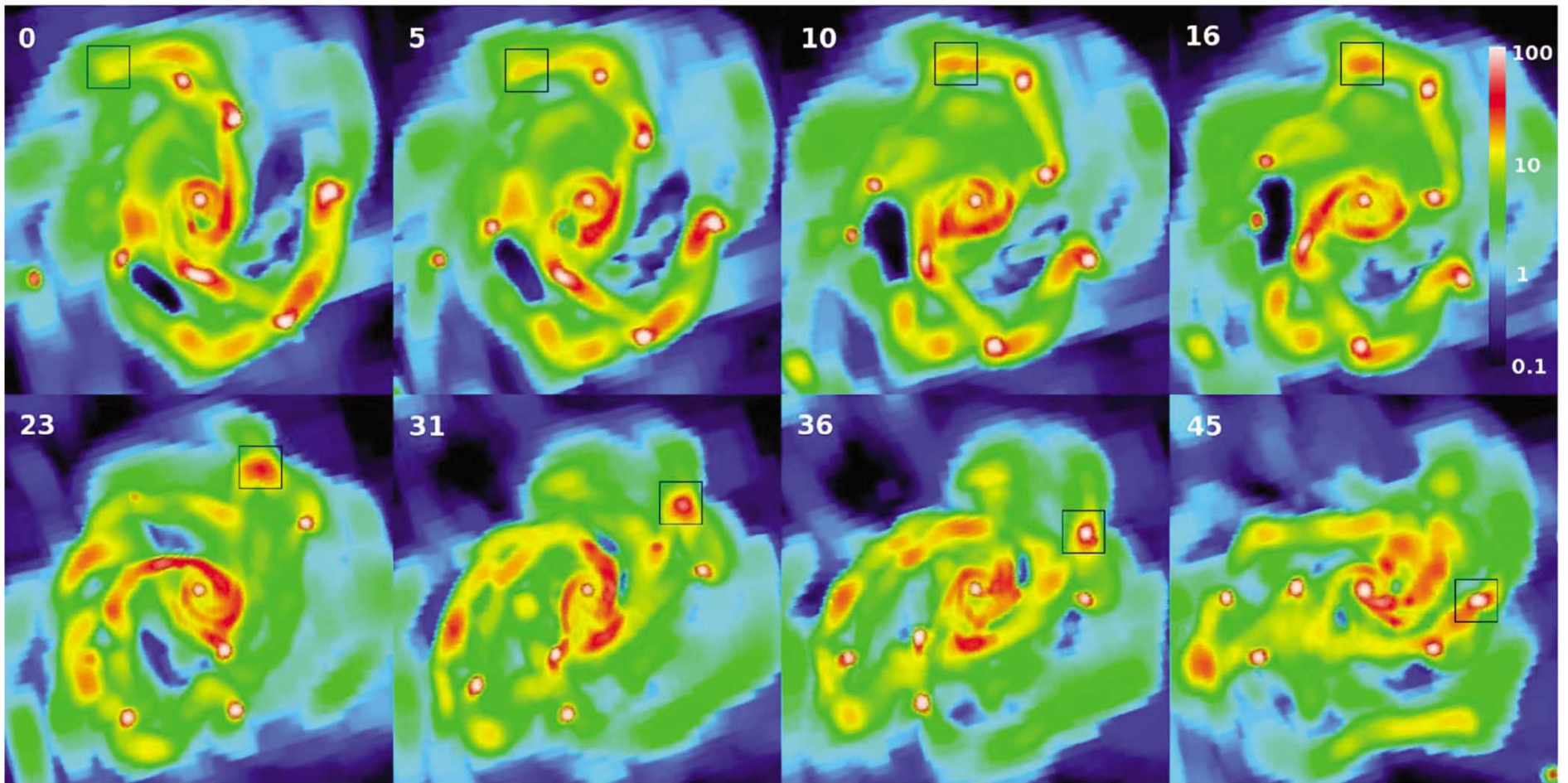
t=1000 Myr



Bournaud, Elmegreen & Elmegreen 07

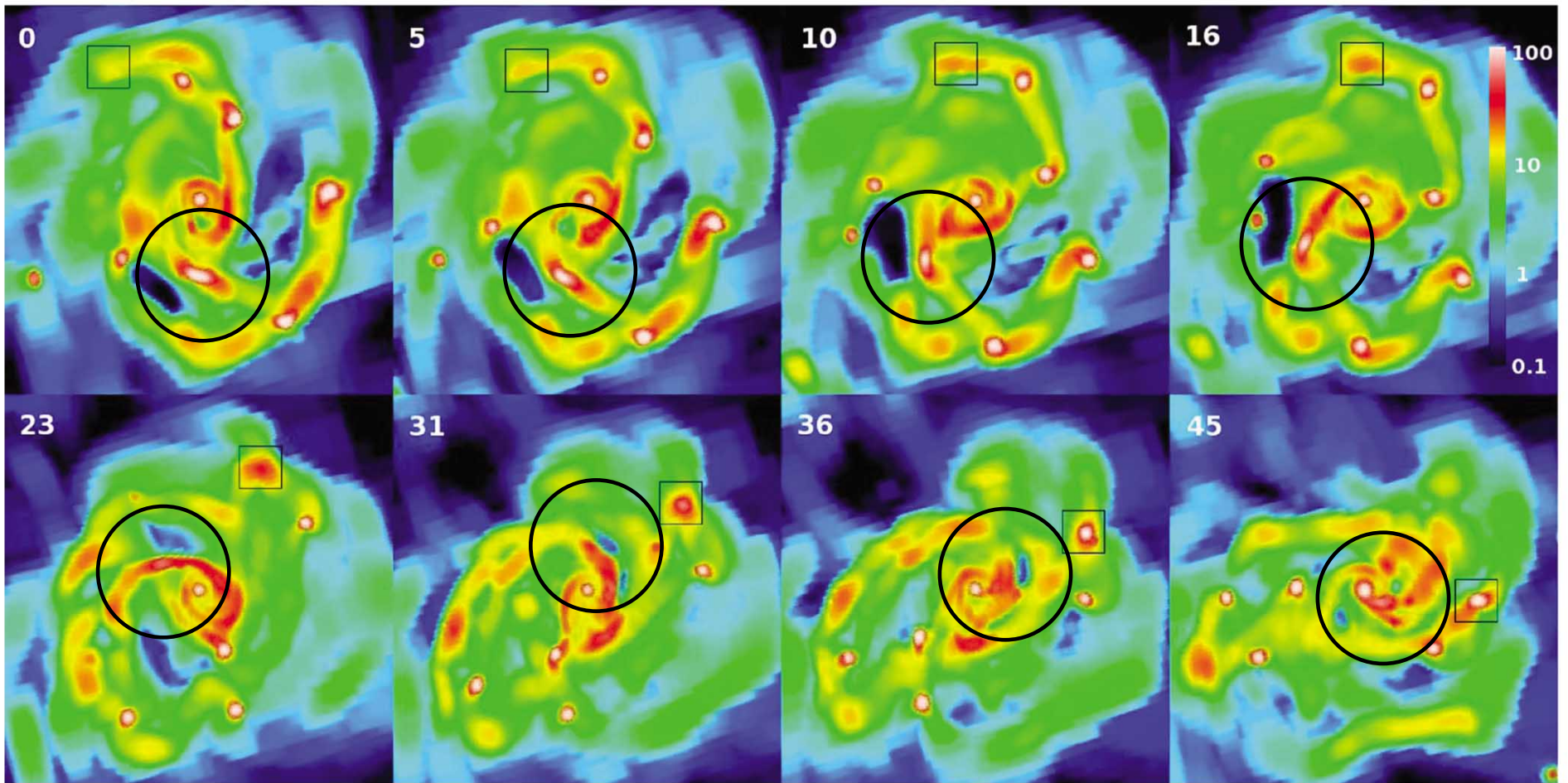
# Edge-on disks evolve from chain galaxies to normal bulge-centered, exponential-disk spirals





Ceverino et al. 2010

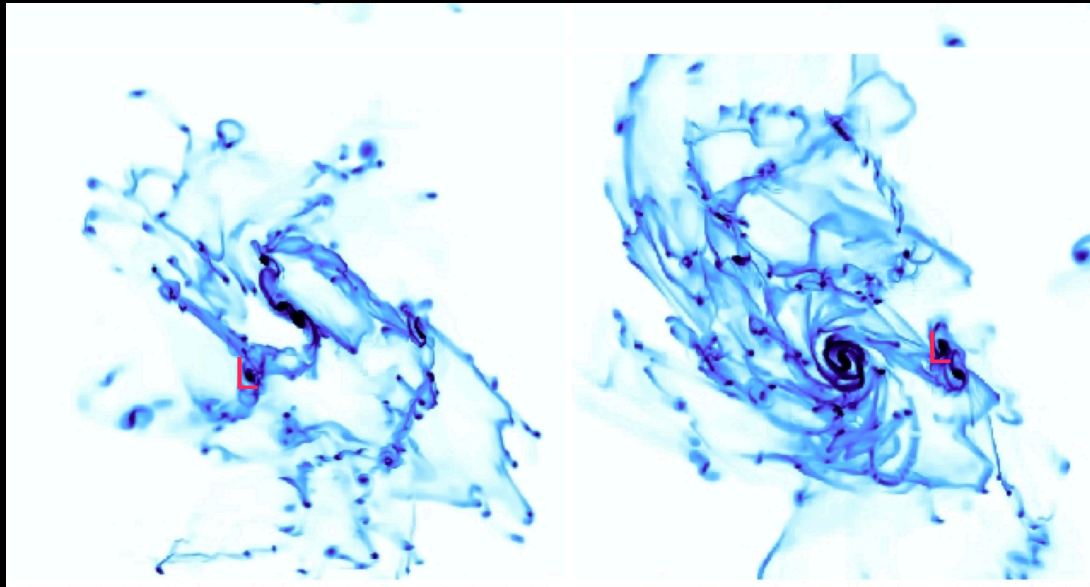
Formation of a clump followed by star formation in it



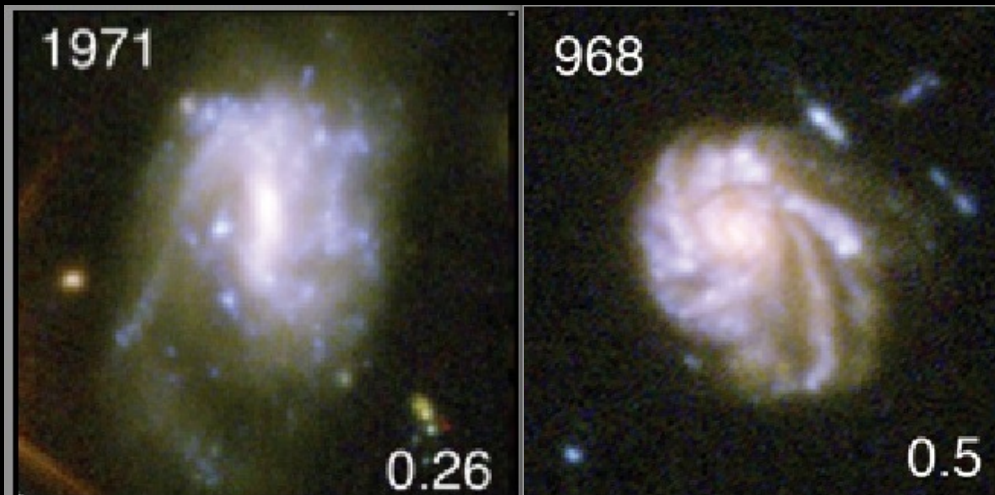
Ceverino et al. 2010

Migration of a clump to the center in 1 rotation

## More evolved, 700 and 800 Myr after simulation

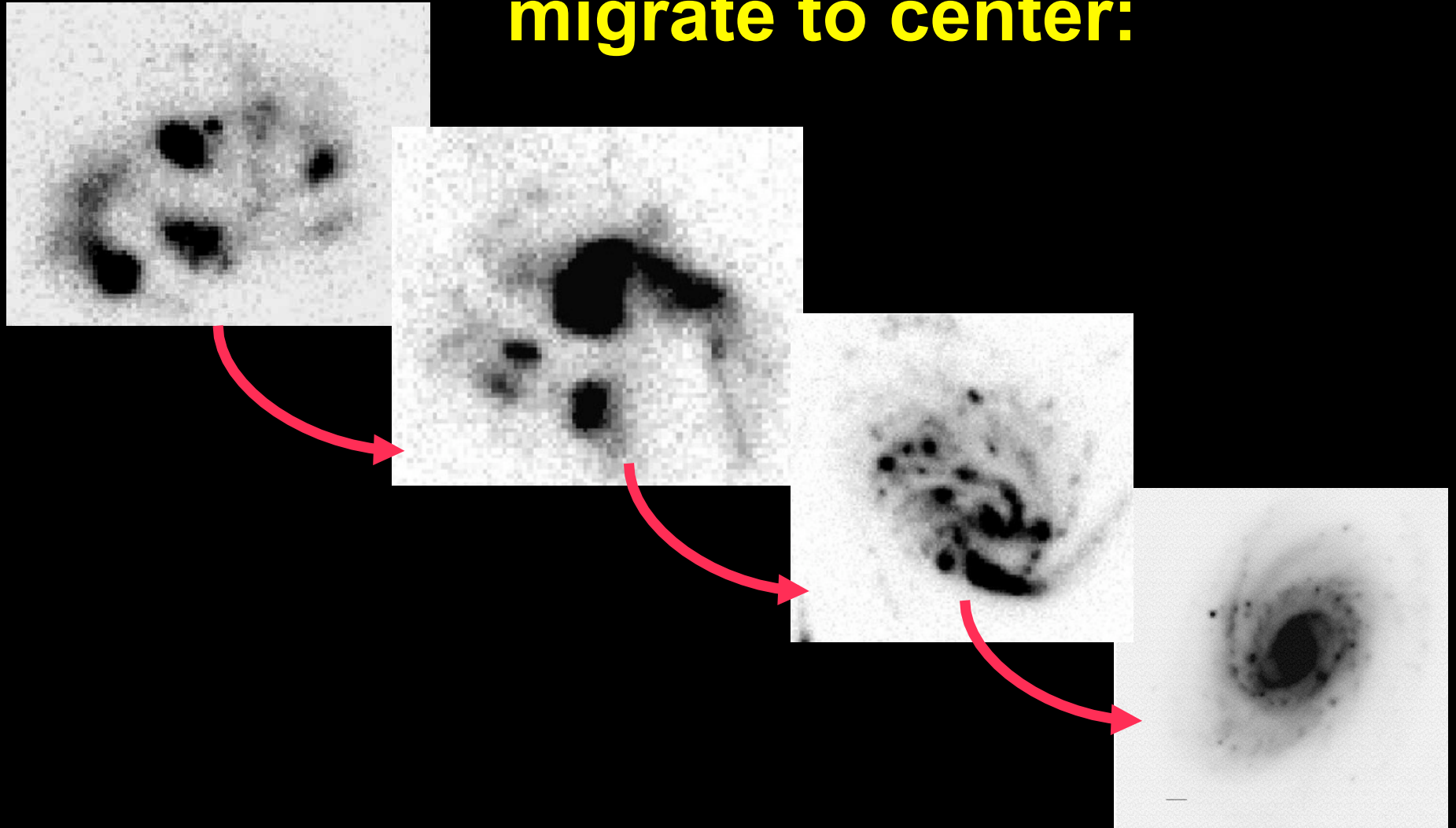


Bournaud et al.  
'13 in prep



Initially 60% gas; 40% left at this stage, so still some big clumps, although disk starts to be more stable, with smaller clumps

# Proposed evolutionary sequence as clumps dissolve or migrate to center:



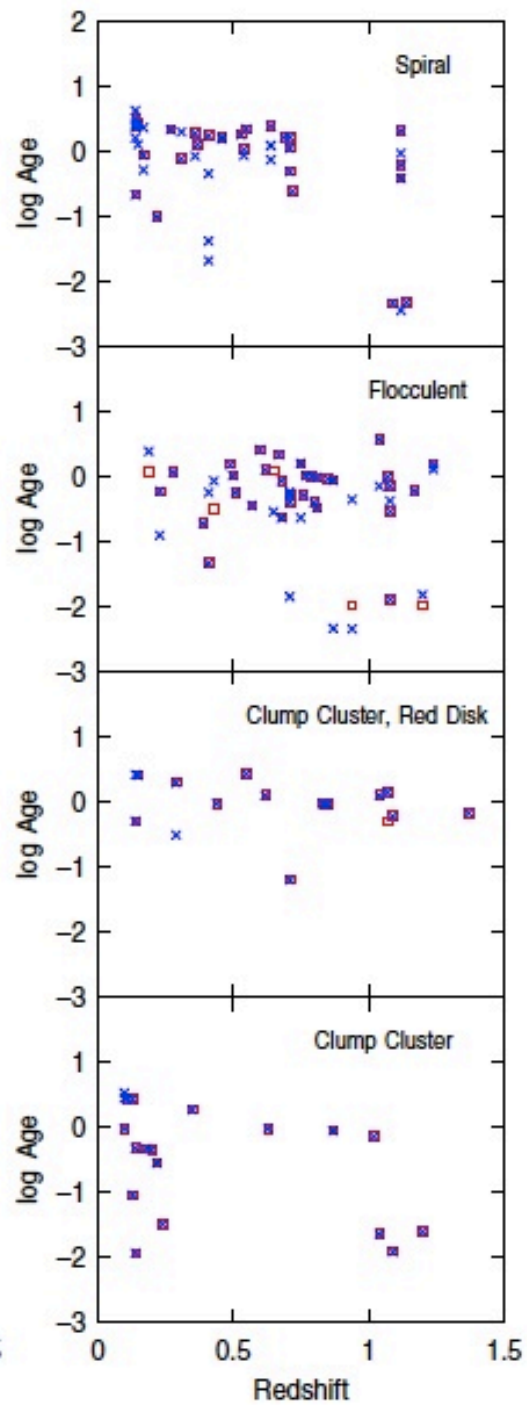
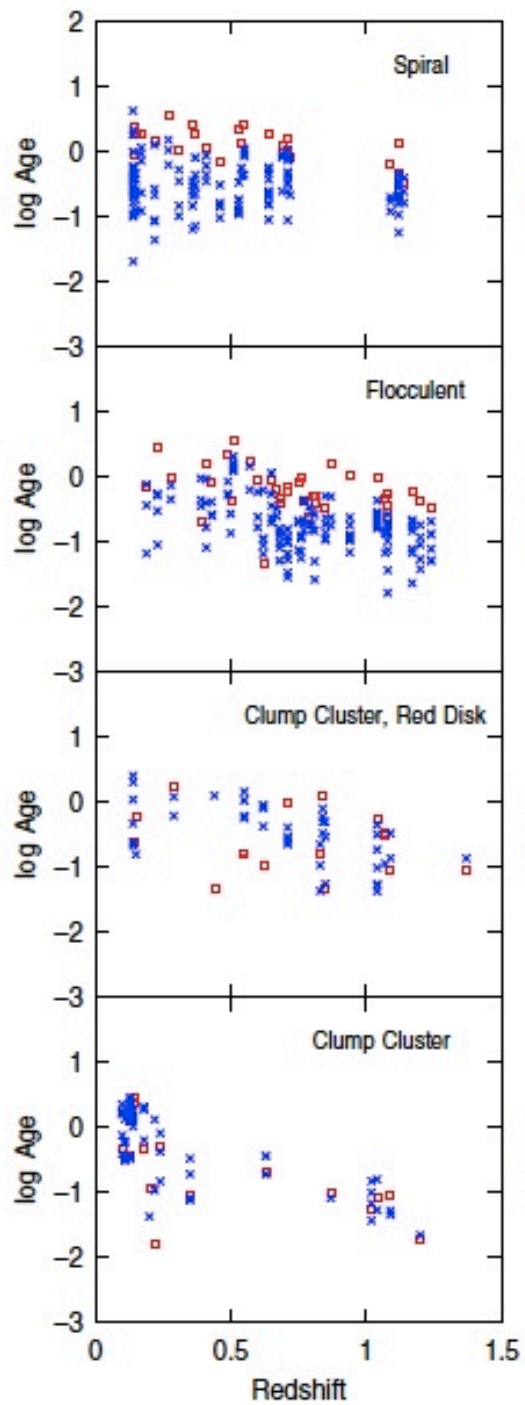
# Conclusions

- Disk galaxies dominate over spheroidal at  $z > 1$
- Clumpy galaxies dominate over spiral galaxies at  $z > 1$
- Grand design galaxies appear as early as  $z \sim 2$   
(universe 4 Gyr)
- Bar fraction decreases with increasing redshift, but most strongly for small galaxies/bars
- Clumpy and spiral galaxies co-exist over  $z=0.1$  to 2
- Spirals evolve from clumpy galaxies once disks are not so hot

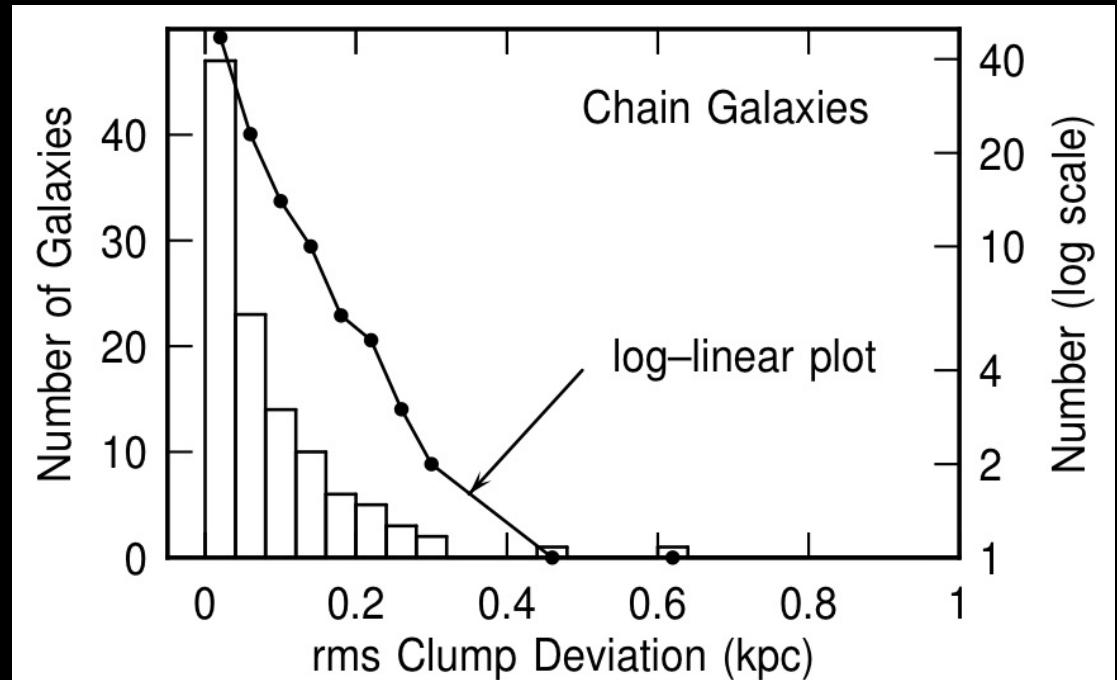
*Thank you!*

谢谢

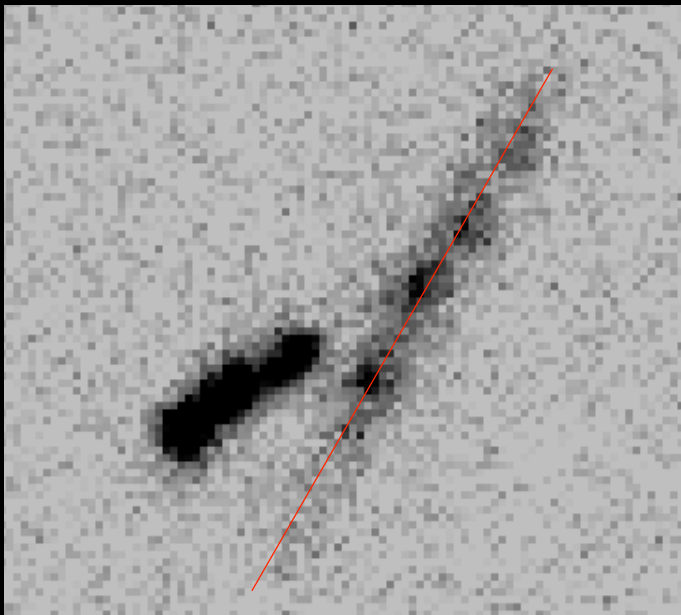
**EXTRAS**



Also, clumps in chains are highly confined to midplanes (~ 100 pc)



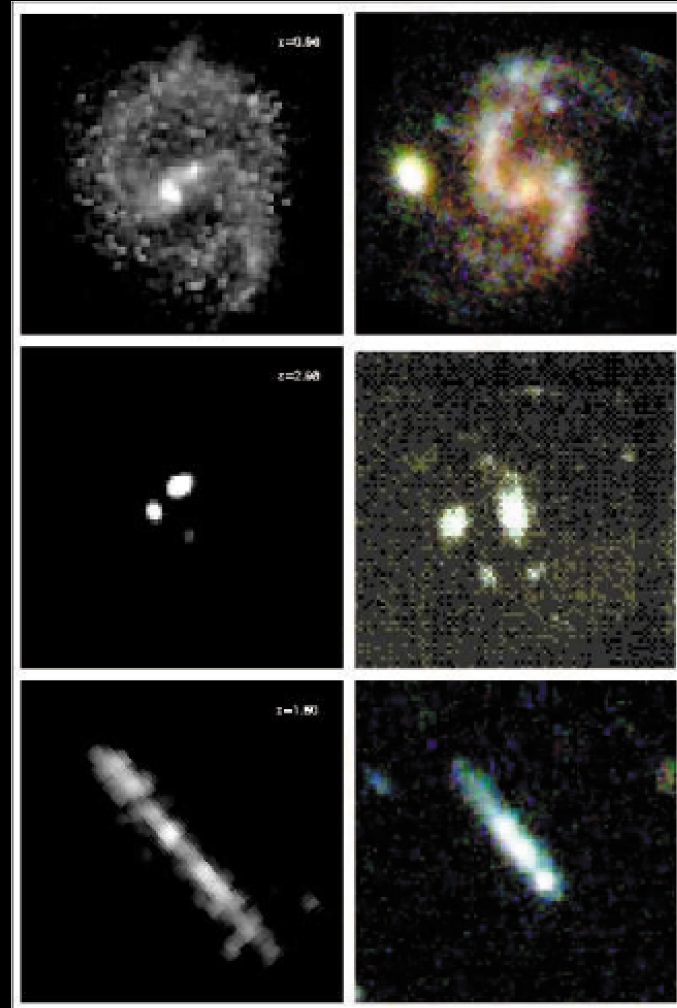
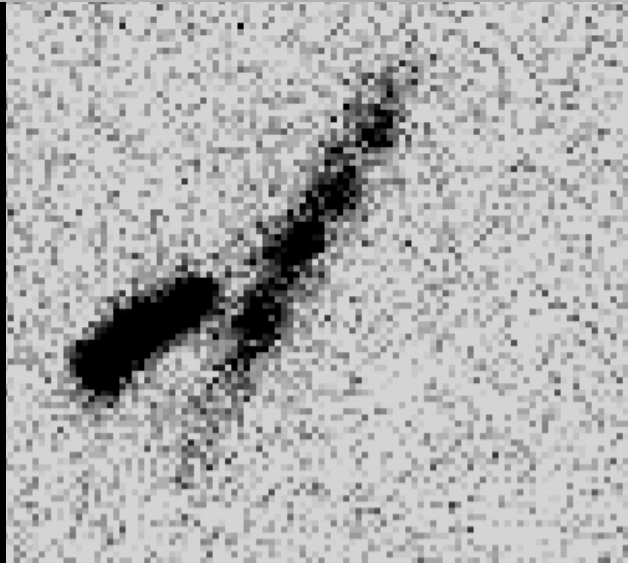
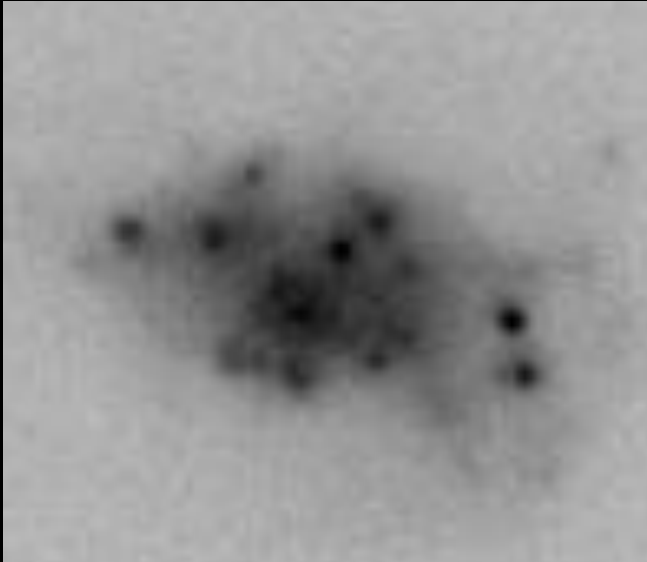
EE '06



→ requires *in situ* formation of clumps rather than clump accretion

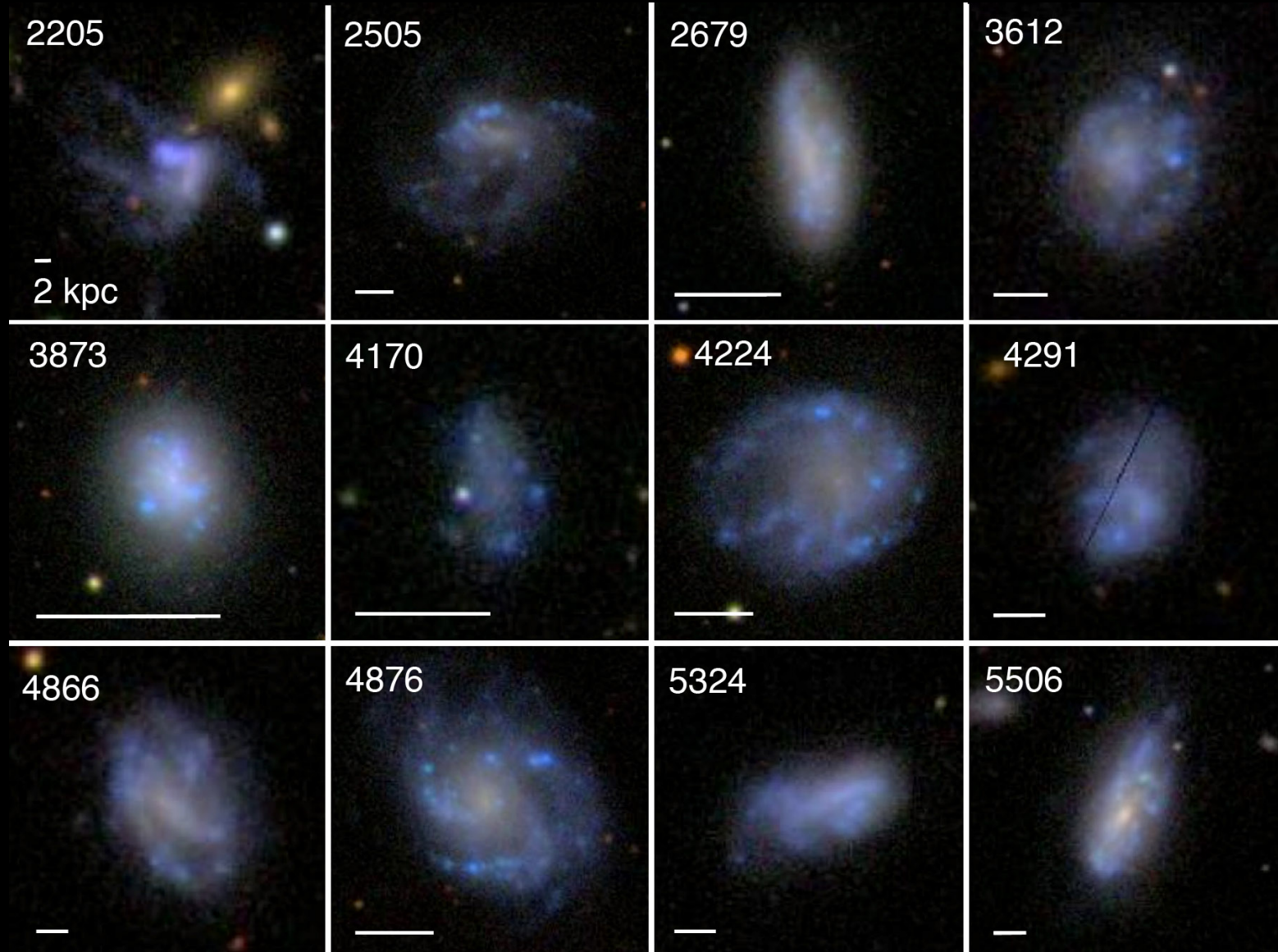
(also, clumps have similar ages and masses, and normal rotating disks are observed)

# Chain and clump cluster galaxies - different viewing aspects of a disk

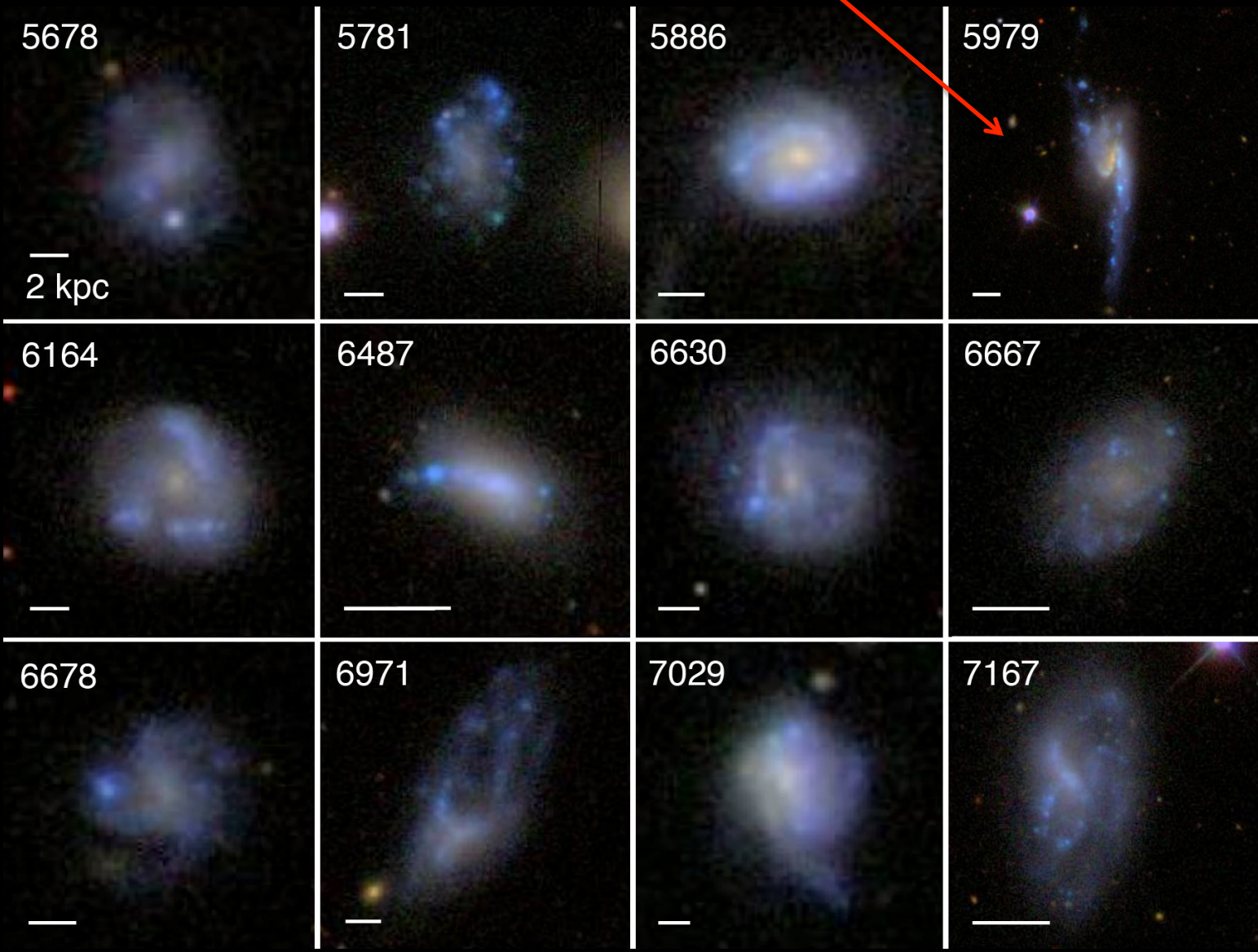


models - Immeli 2004; observations - EE

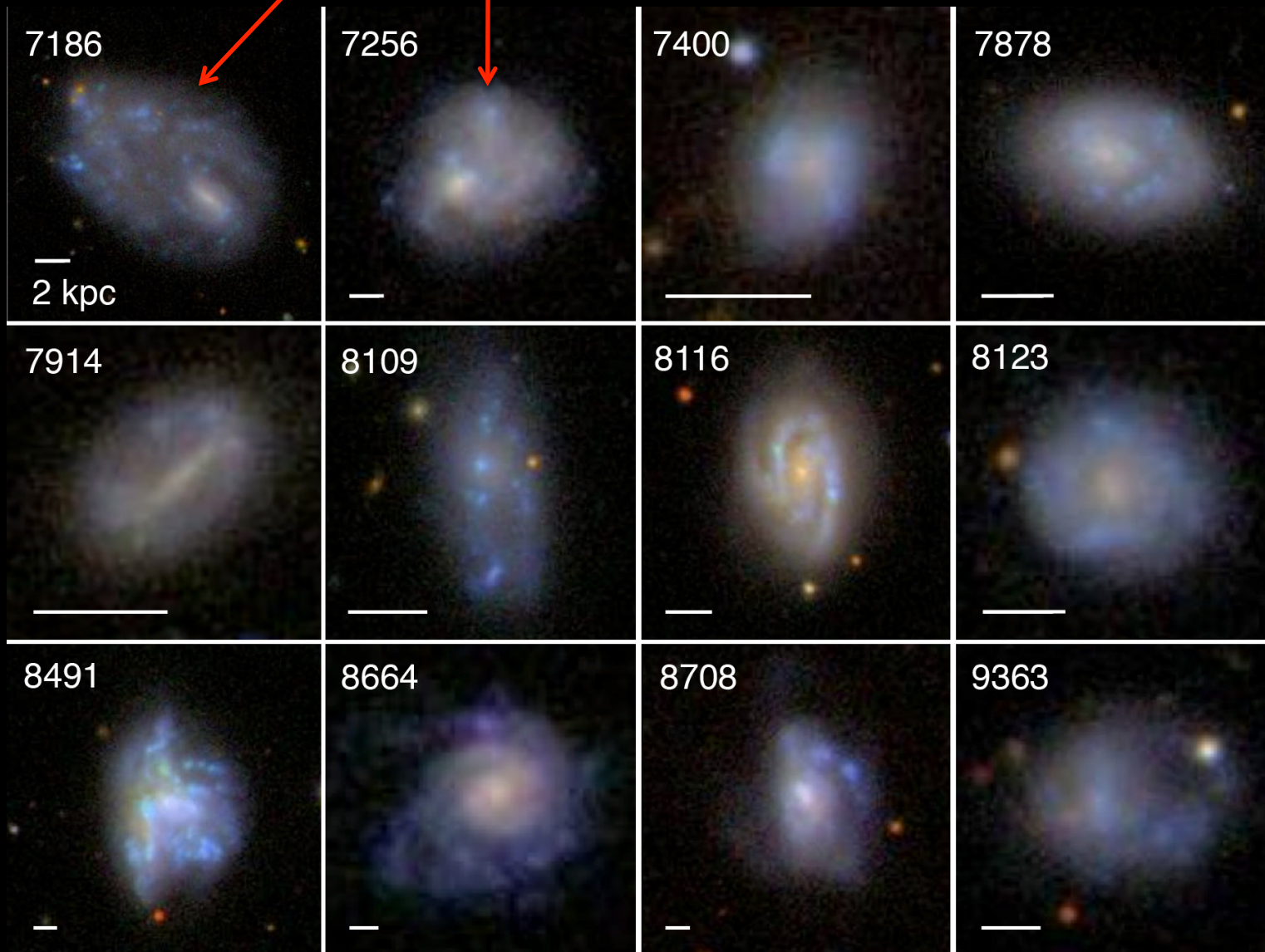
# Local ultraviolet-bright galaxies range from irregular to spiral



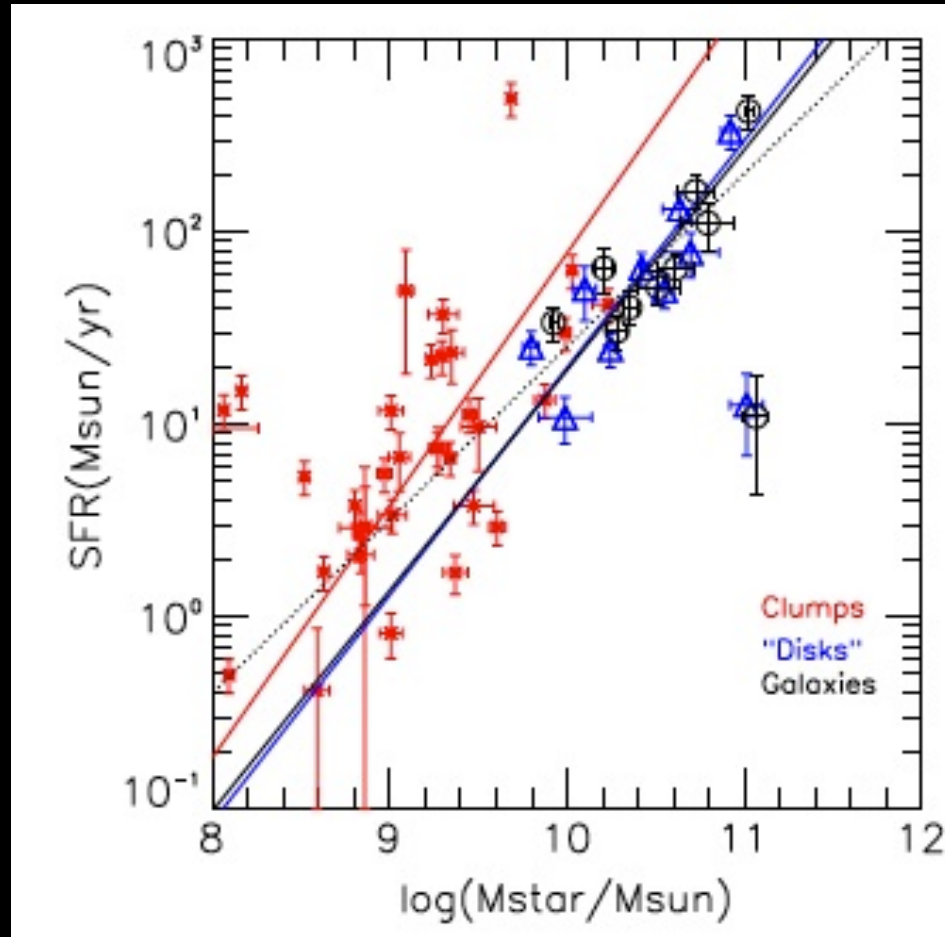
# Some have tidal arms



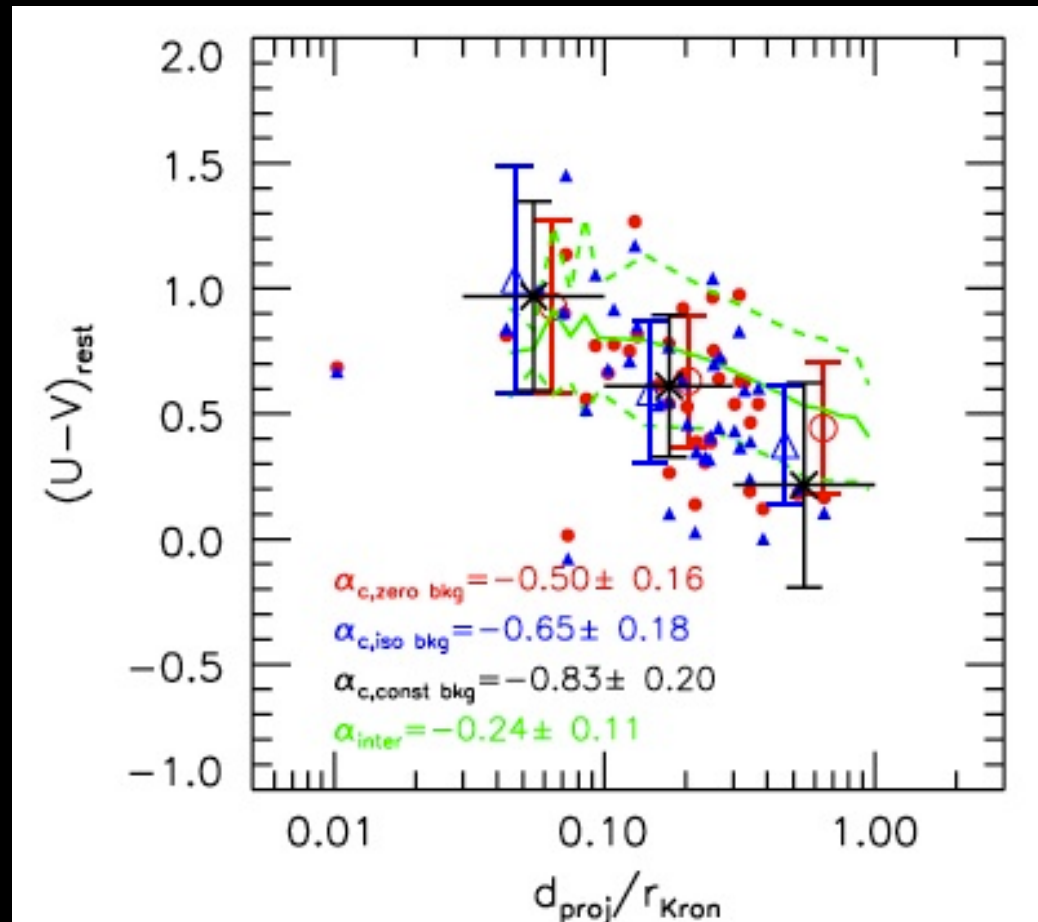
# Some have off-center bulges



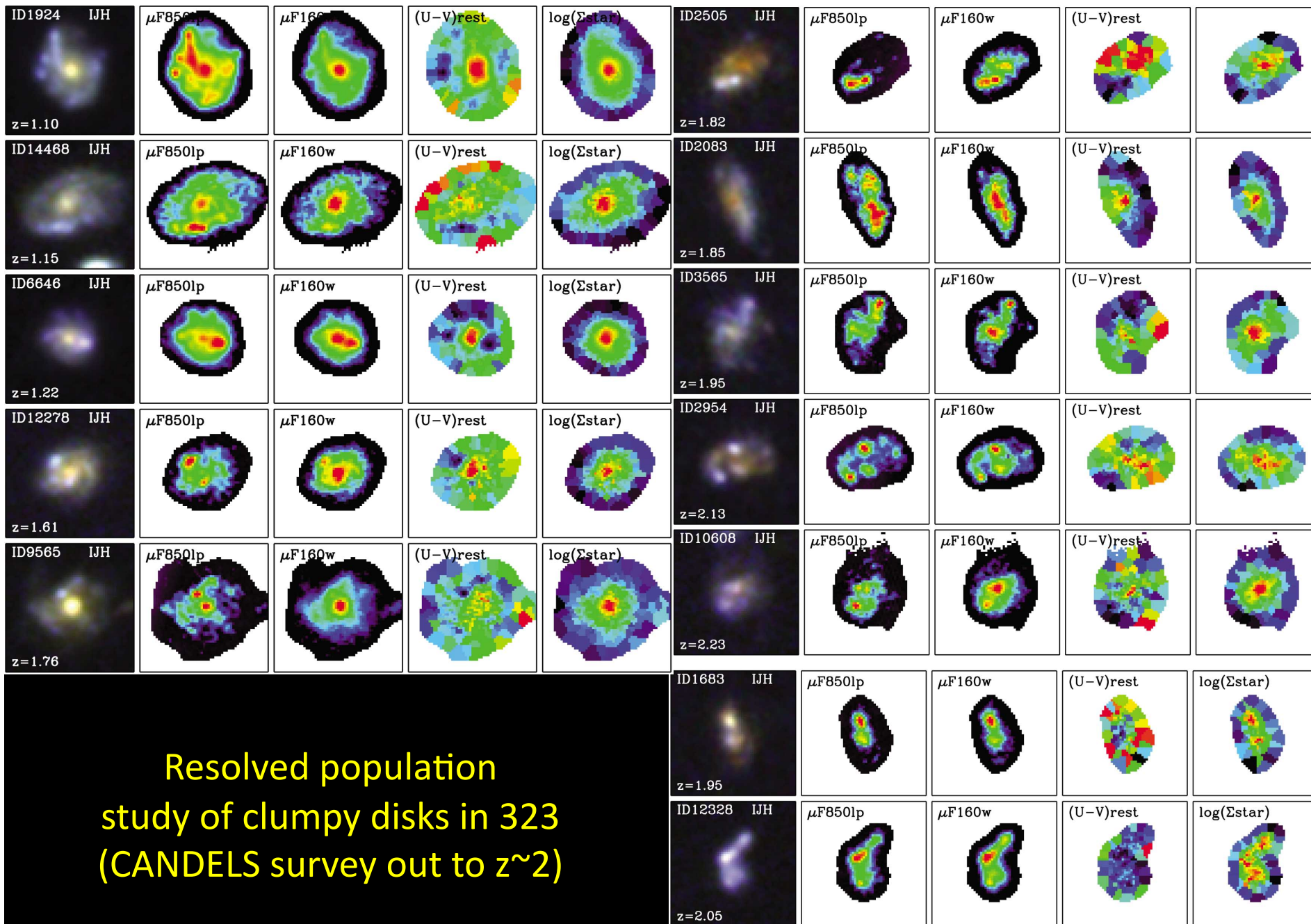
# Enhanced SF in clumps



# Radial variation in clump colors

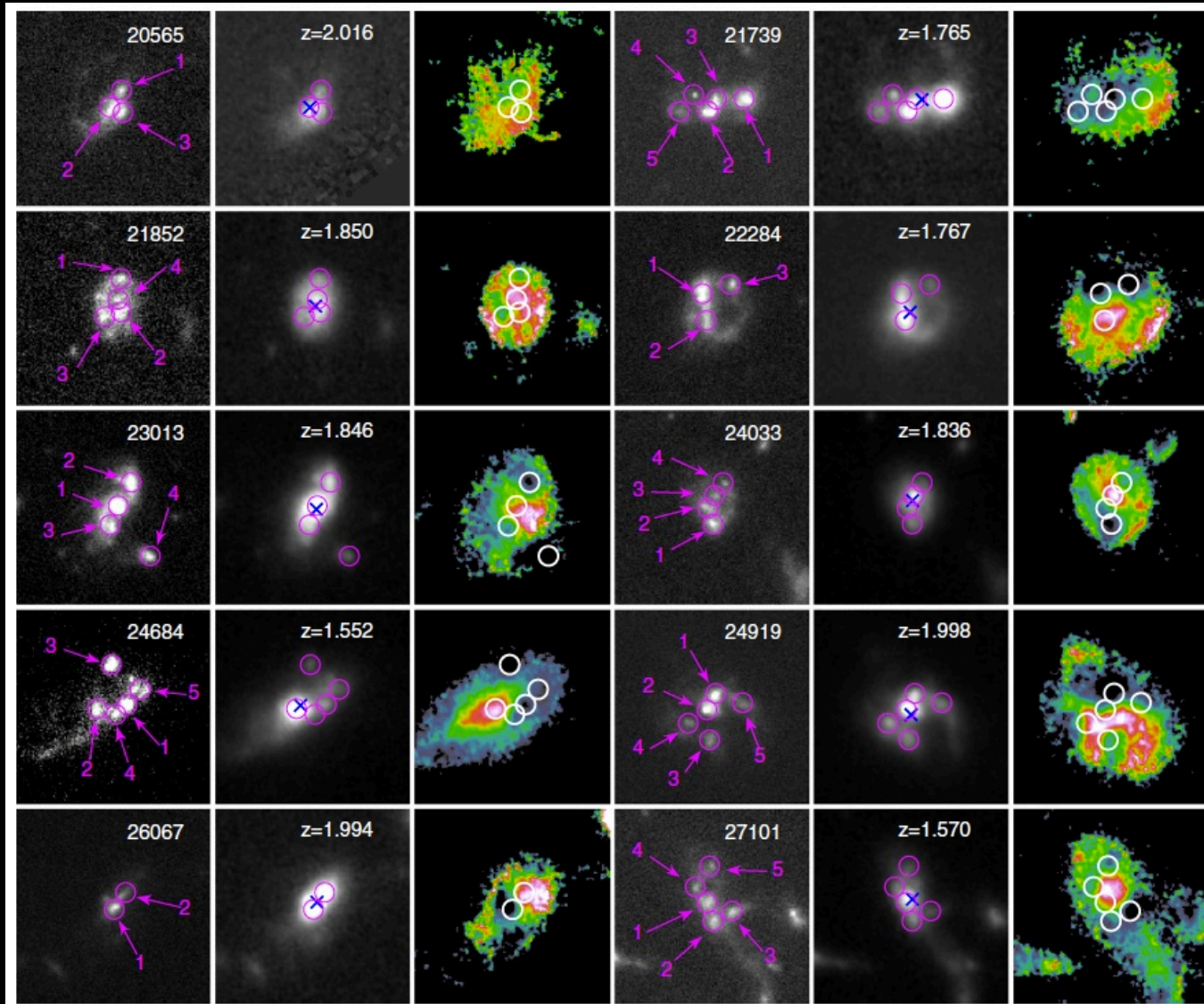


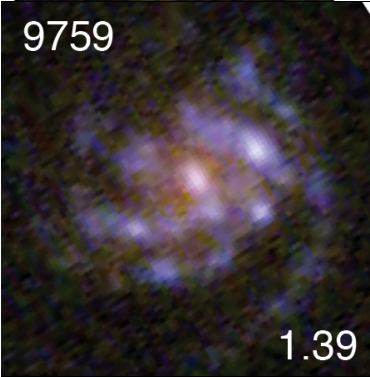
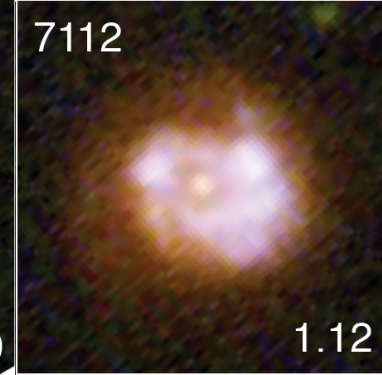
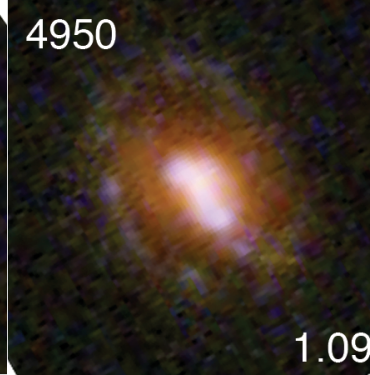
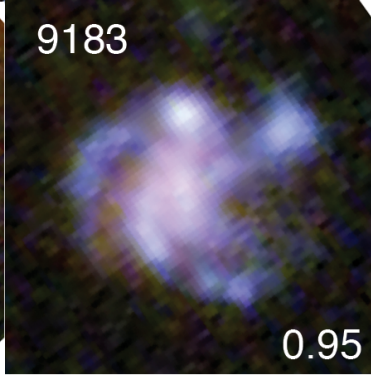
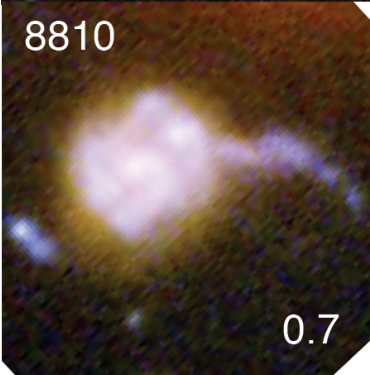
→ Inner region has older clumps, maybe from in-spiral



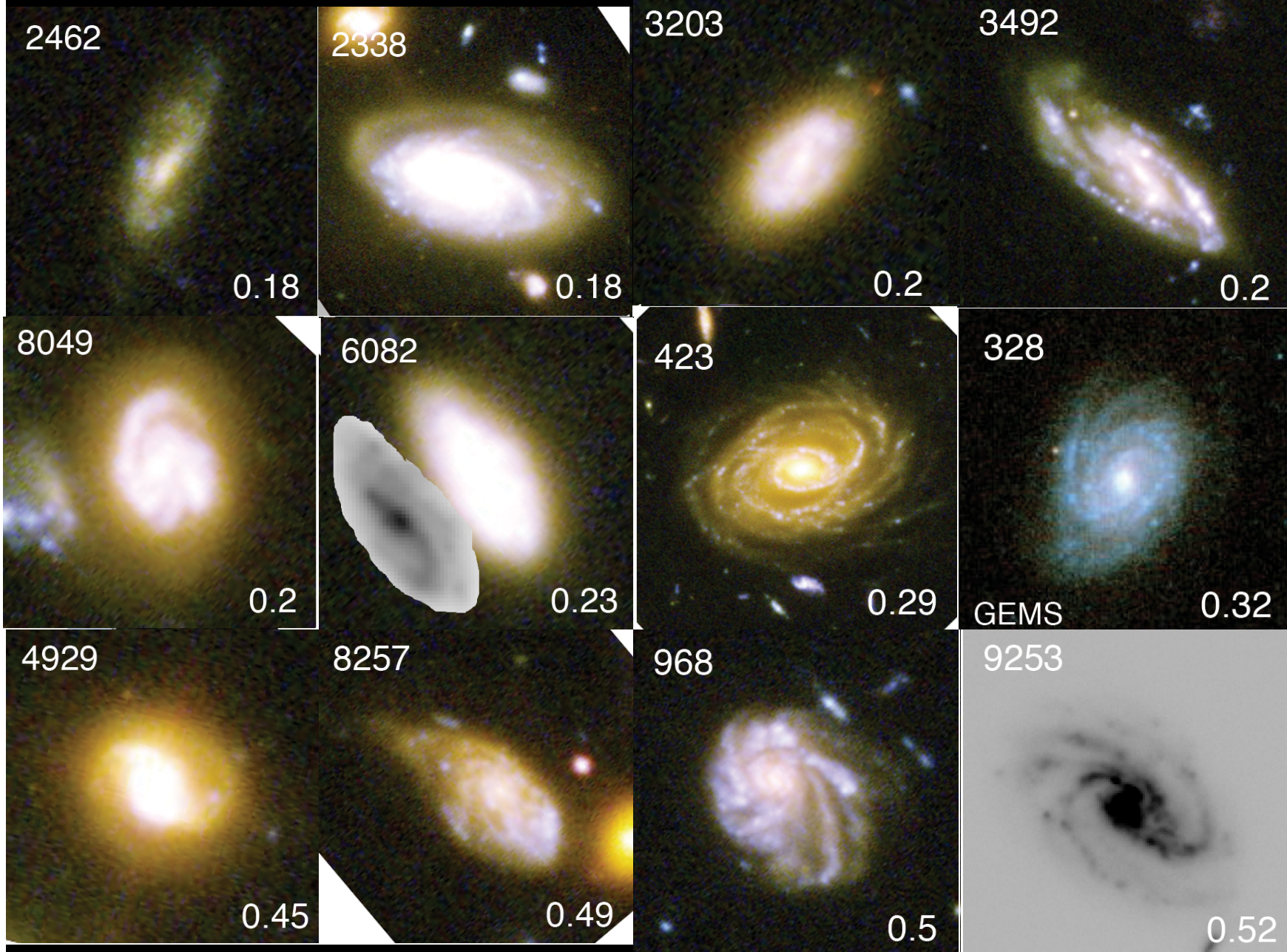
Resolved population  
 study of clumpy disks in 323  
 (CANDELS survey out to  $z \sim 2$ )

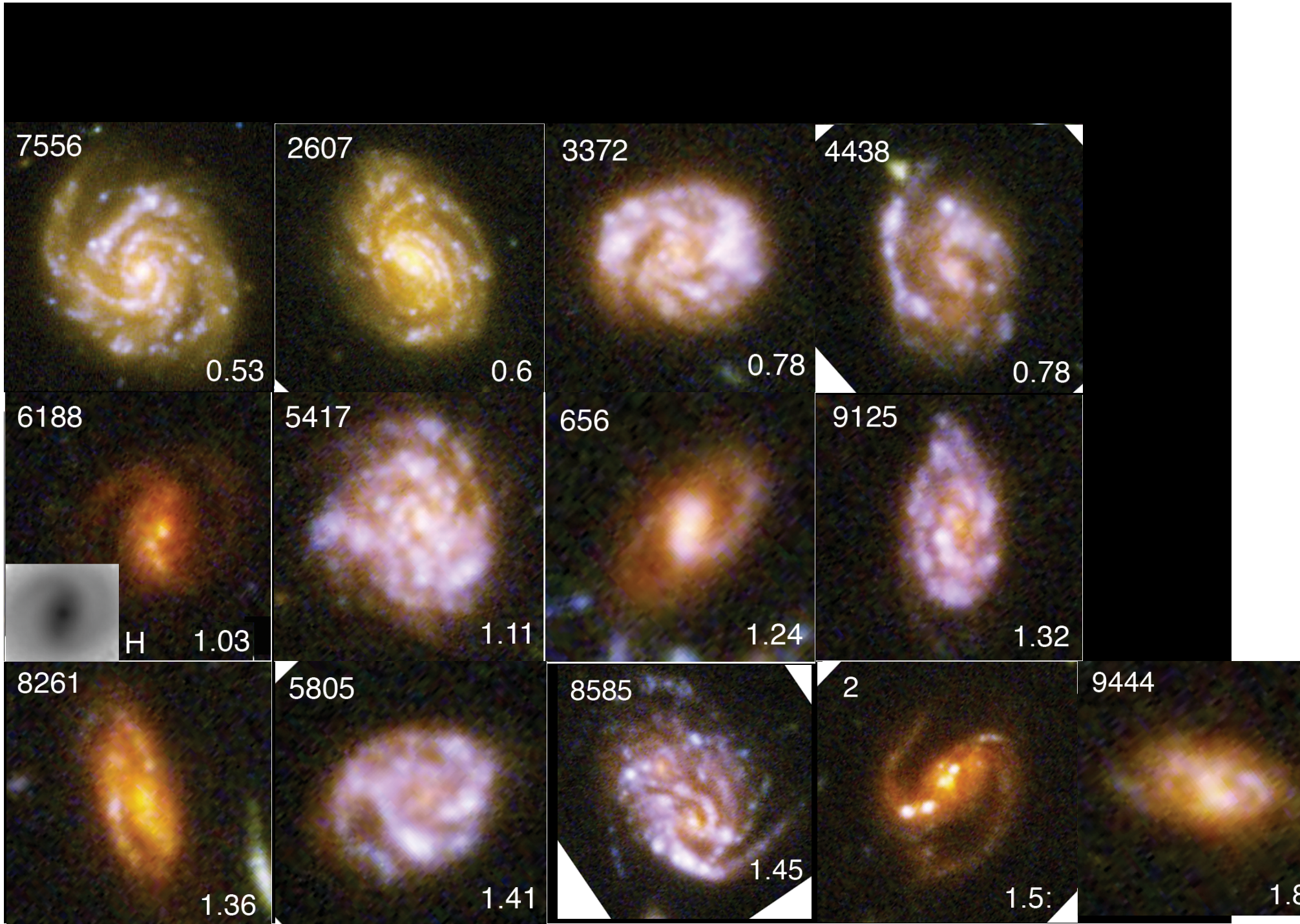
# Recent results: CANDELS $z \sim 2$ multi- $\lambda$

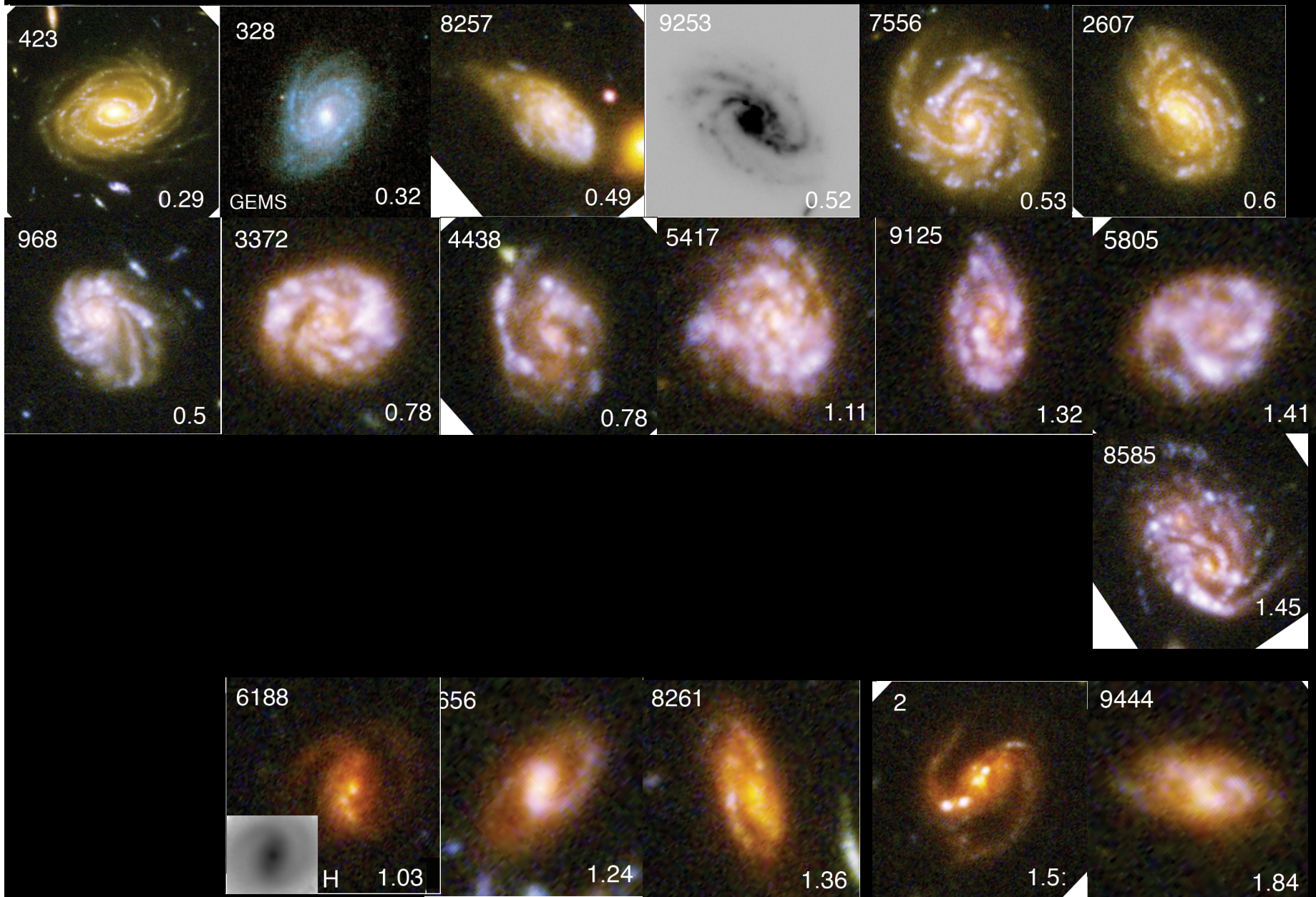




# Multiple arm and grand design galaxies in the UDF





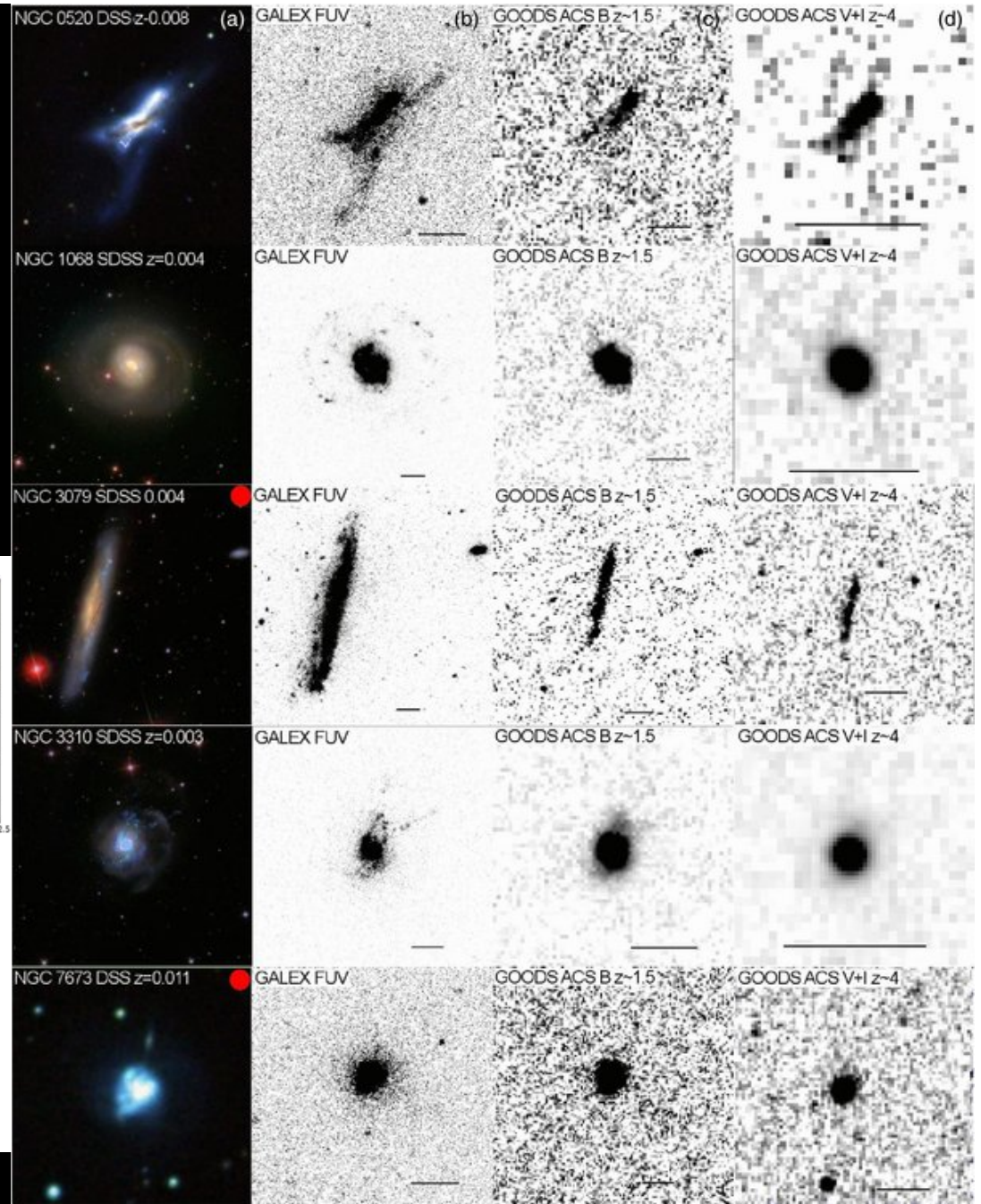
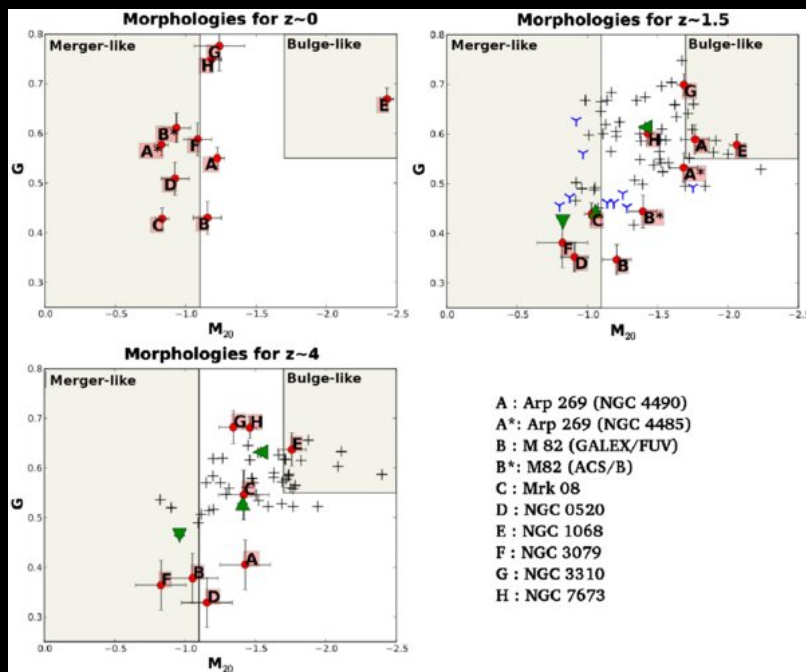


Petty et al. 2009:

Gini coef,  $M_{20}$ , Sersic n  
for redshifted local galaxies

→ smoother (lower Gini)

→ more centrally concentrated (lower  $M_{20}$ )



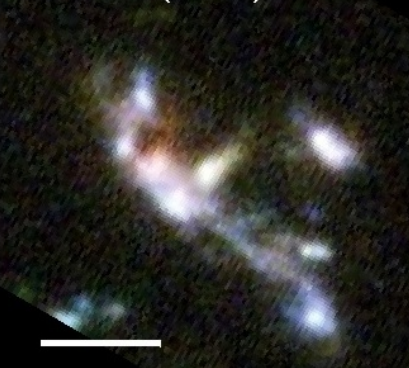
# Would a local spiral galaxy look like a clump cluster if viewed at high redshift? No.

(a) clumpy galaxies at high redshift

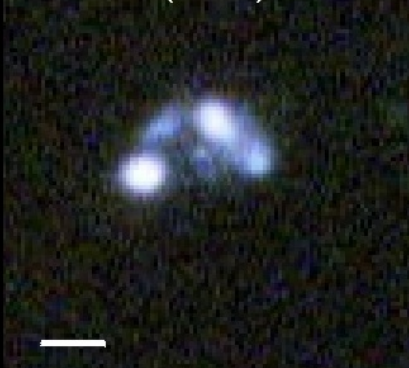
UDF1801 ( $z=1.6$ )



UDF6462 ( $z=1.6$ )



UDF4006 ( $z=2.3$ )

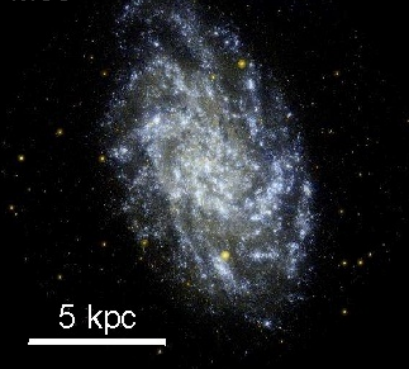


UDF4006 ( $z=2.1$ )

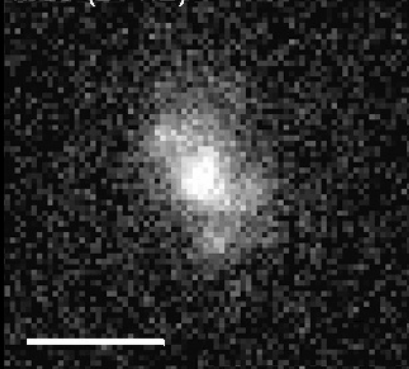


(b) modern spiral galaxies

M33



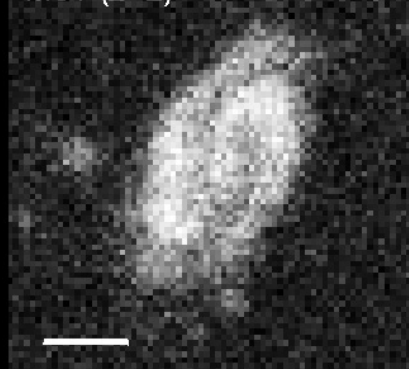
M33 ( $z=1.2$ )



M81

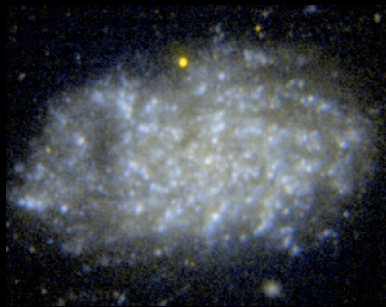


M81 ( $z=2$ )



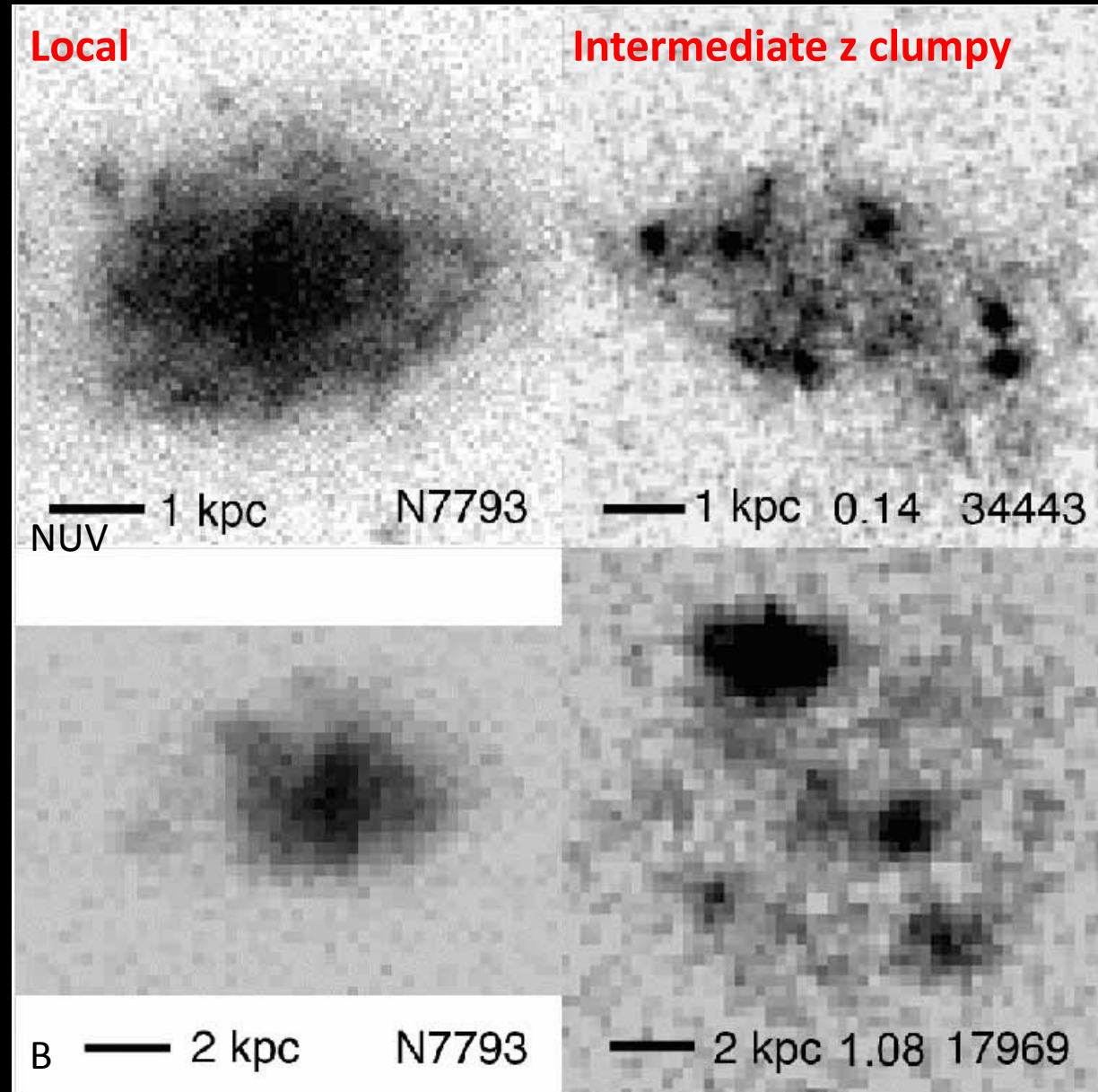
GALEX FUV, NUV re-pixelated to high  $z$  scale

# What about a flocculent spiral? No.



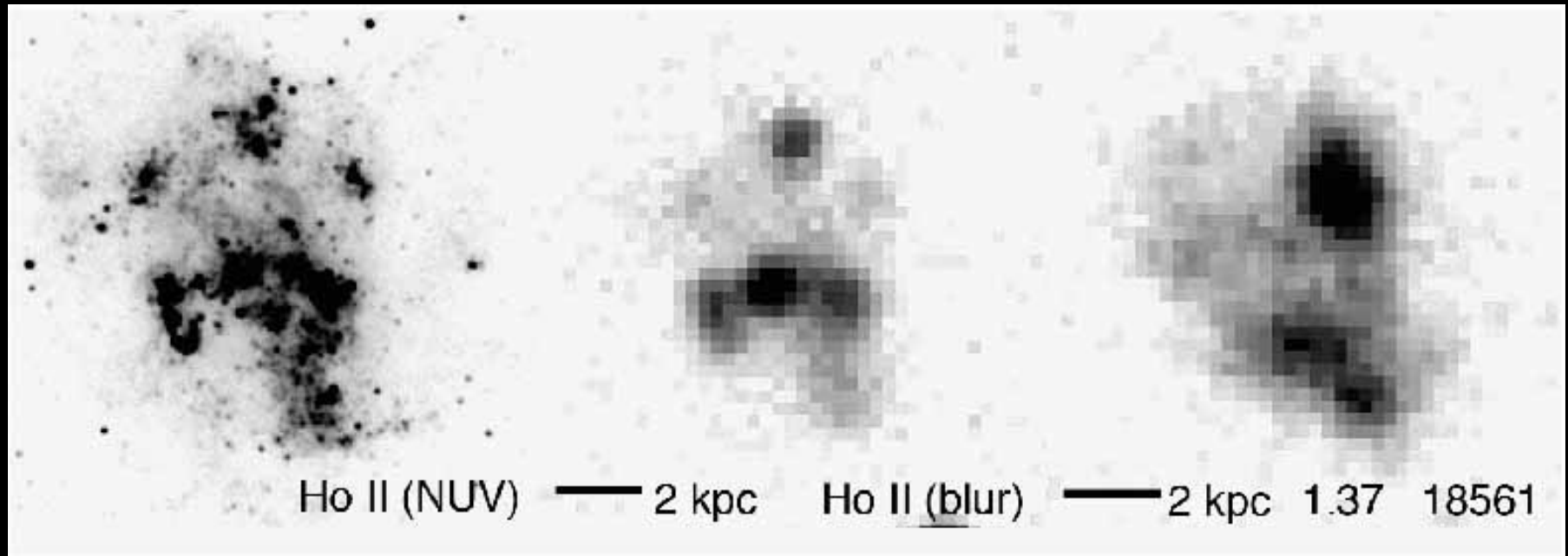
- Local galaxy blurred to the same kpc resolution per point source FWHM,
- re-pixelated to the same kpc per pixel,
- having same rest wavelength,
- and presented with the same scale.

Local galaxy still shows bright central region



## What about a local dwarf Irregular? Yes.

Clump clusters resemble local irregulars, but CCs are more massive (30x) with more massive clumps (and local irregulars have underlying old **exponential disks**)

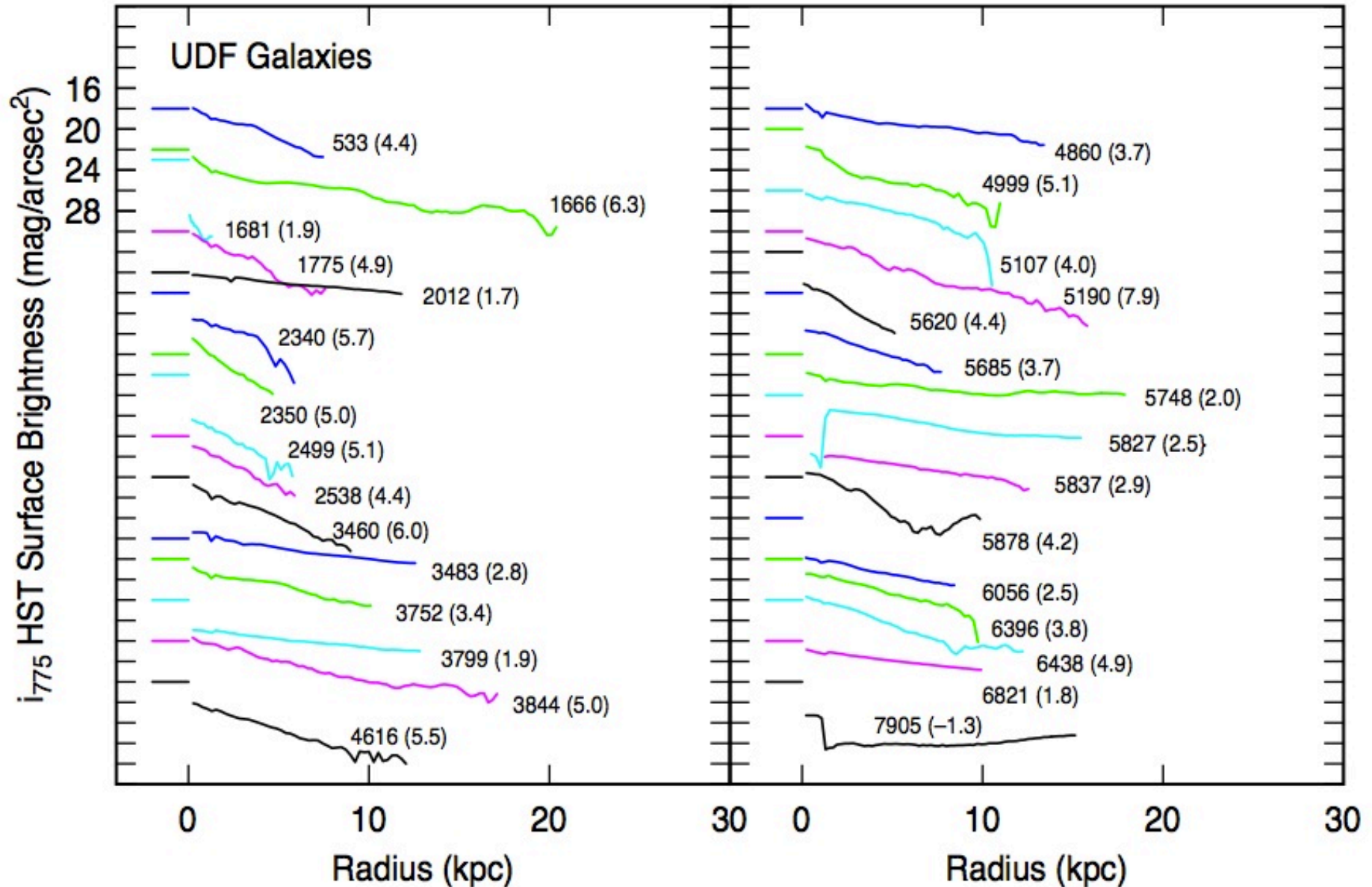


Local Irr

Local Irr shifted to  $z=1.4$

Clump cluster at  $z=1.4$

# UDF ellipse-fit profiles are very flat



# Recent observations by SINFONI group

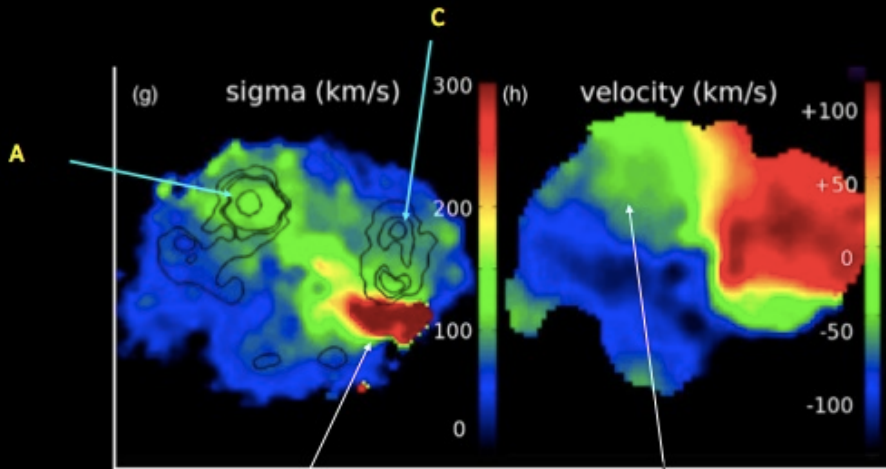
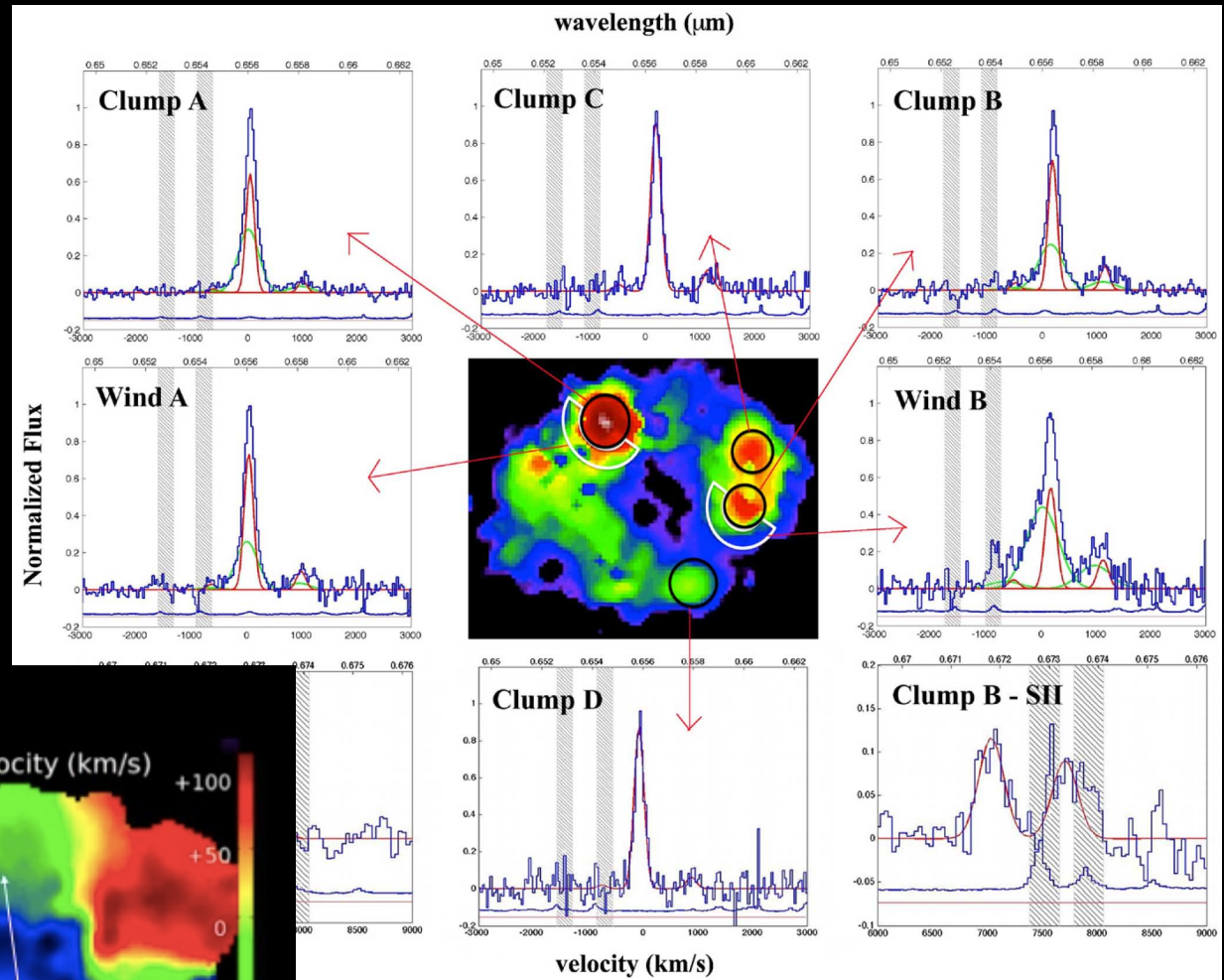
## Kinematic properties of clumps in a $z \sim 2$ galaxy

Blue-shifted line wings suggest massive winds

$\sigma \sim 85\text{-}290$  km/s

$V_{\text{wind}} \sim 400\text{-}800$  km/s

SFR  $\sim 40$  (A) - 11 (B)  $M_{\odot}/\text{yr}$



B is "windy" region

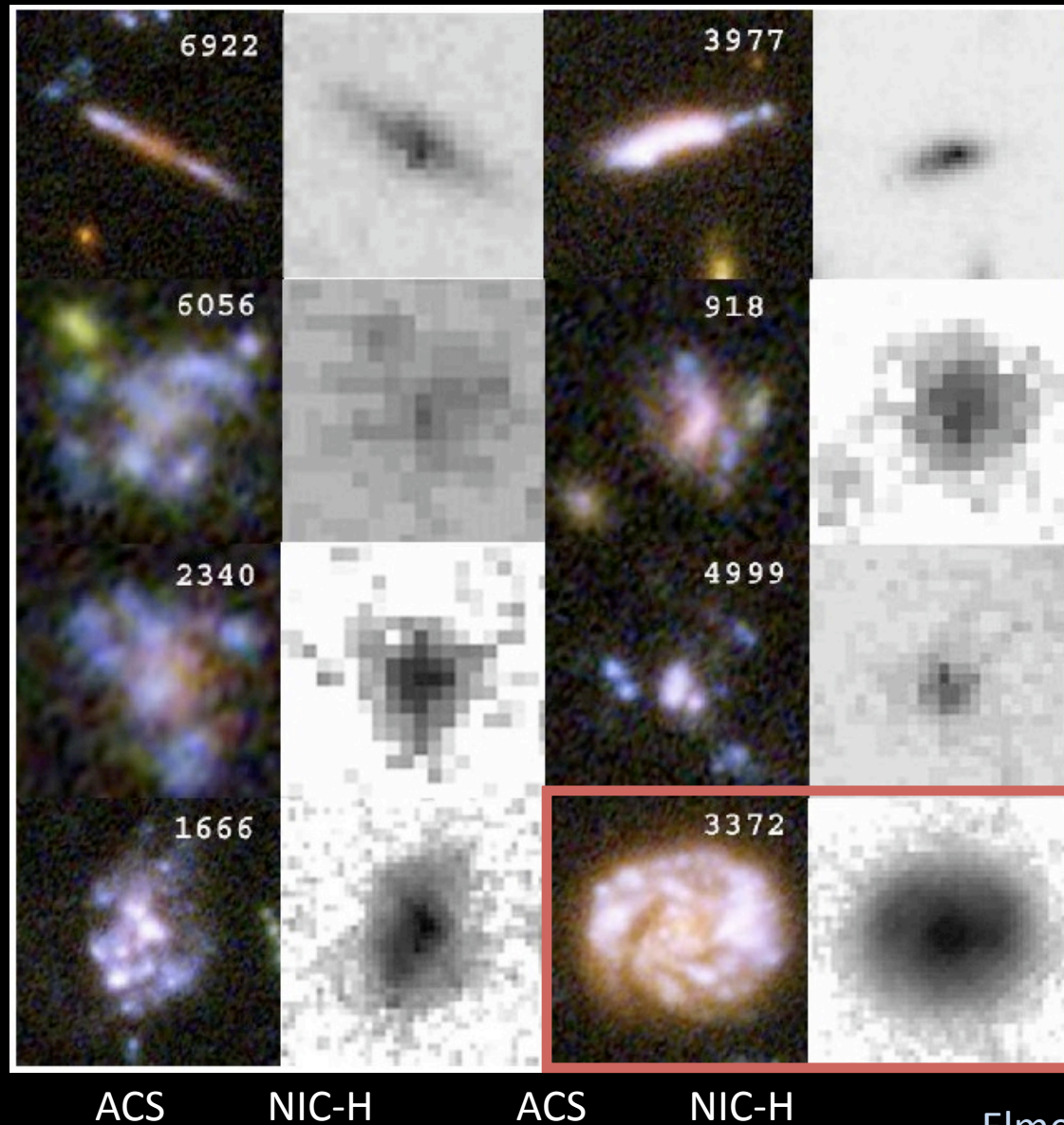
A: Self-gravity distorted rotation curve?

Newman et al. 2012

# What about bulges? Centralized bulge-like clumps show in infrared images

30% of chains and 50% of UDF clumpy galaxies have "bulges"

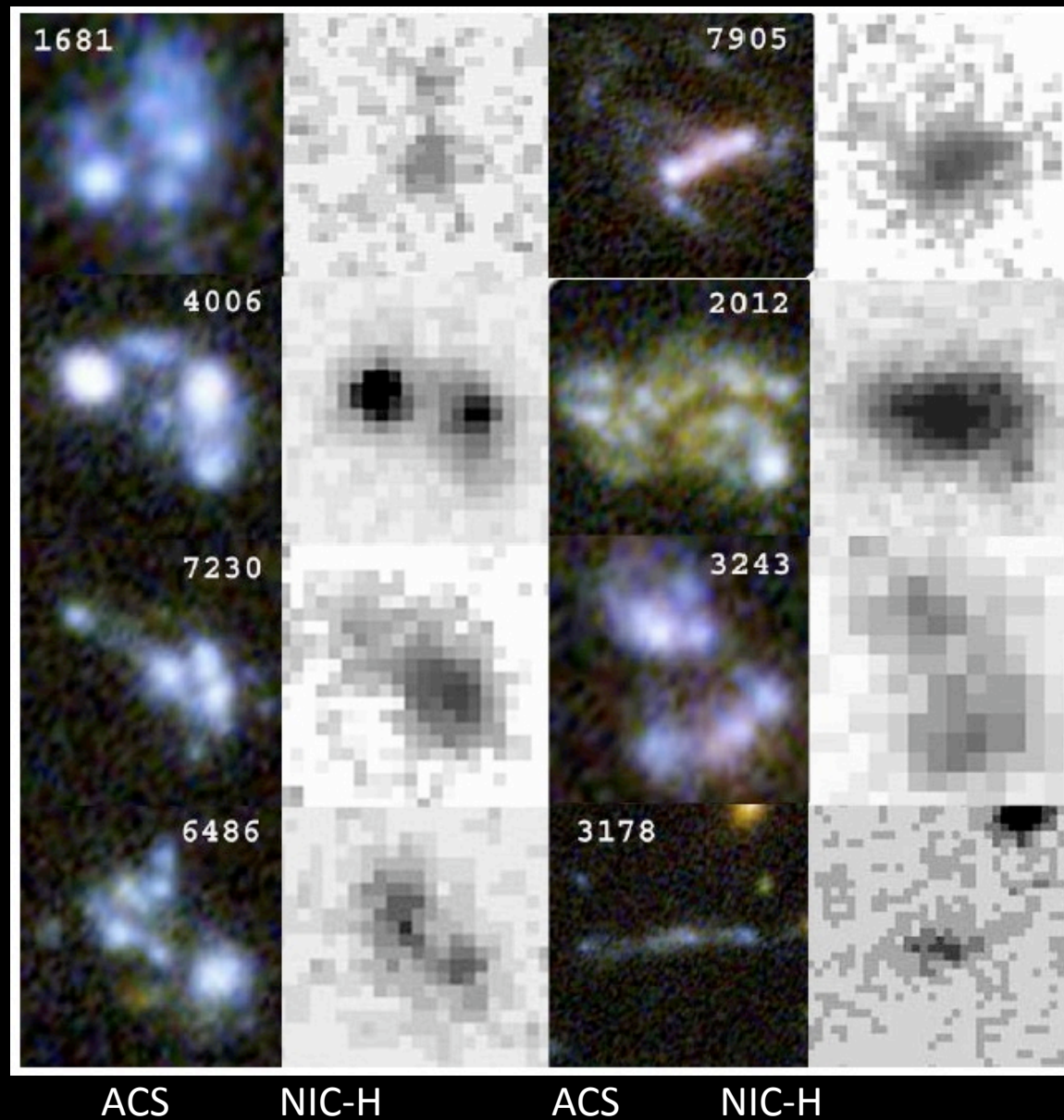
$z \sim 2$



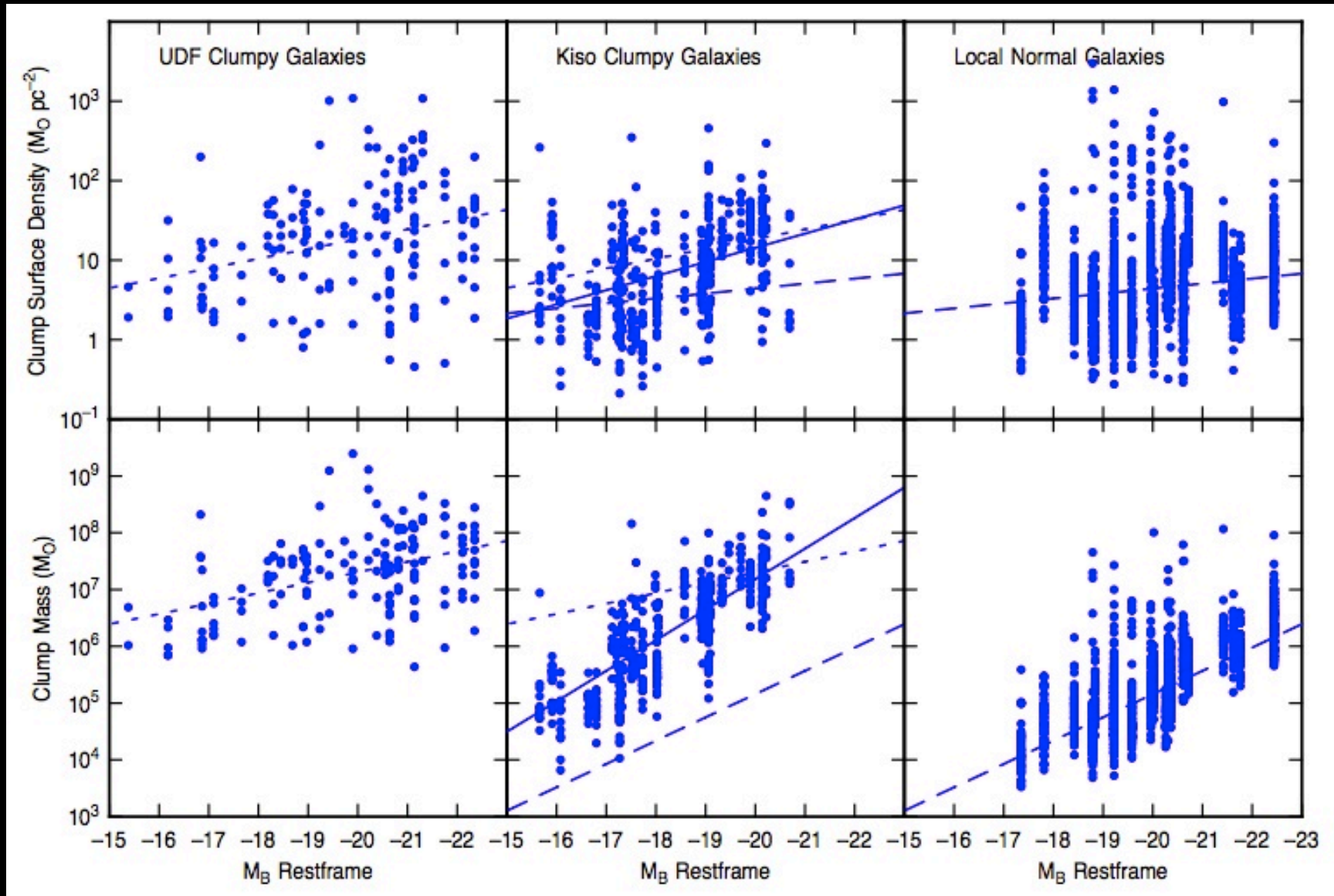
For comparison: spiral with bulge

Elmegreen et al 2009

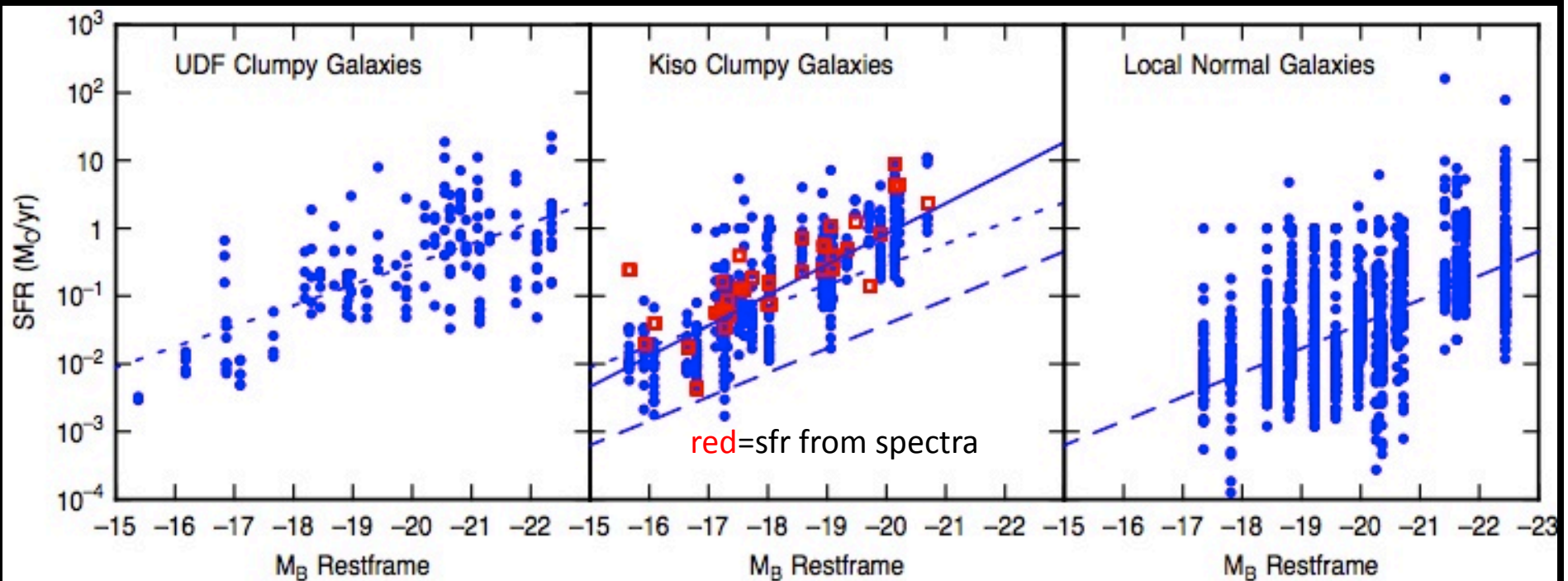
# Galaxies without obvious NICMOS-H central bulges



# Comparison of high z clumps, local Kiso clumpies, and normal galaxies

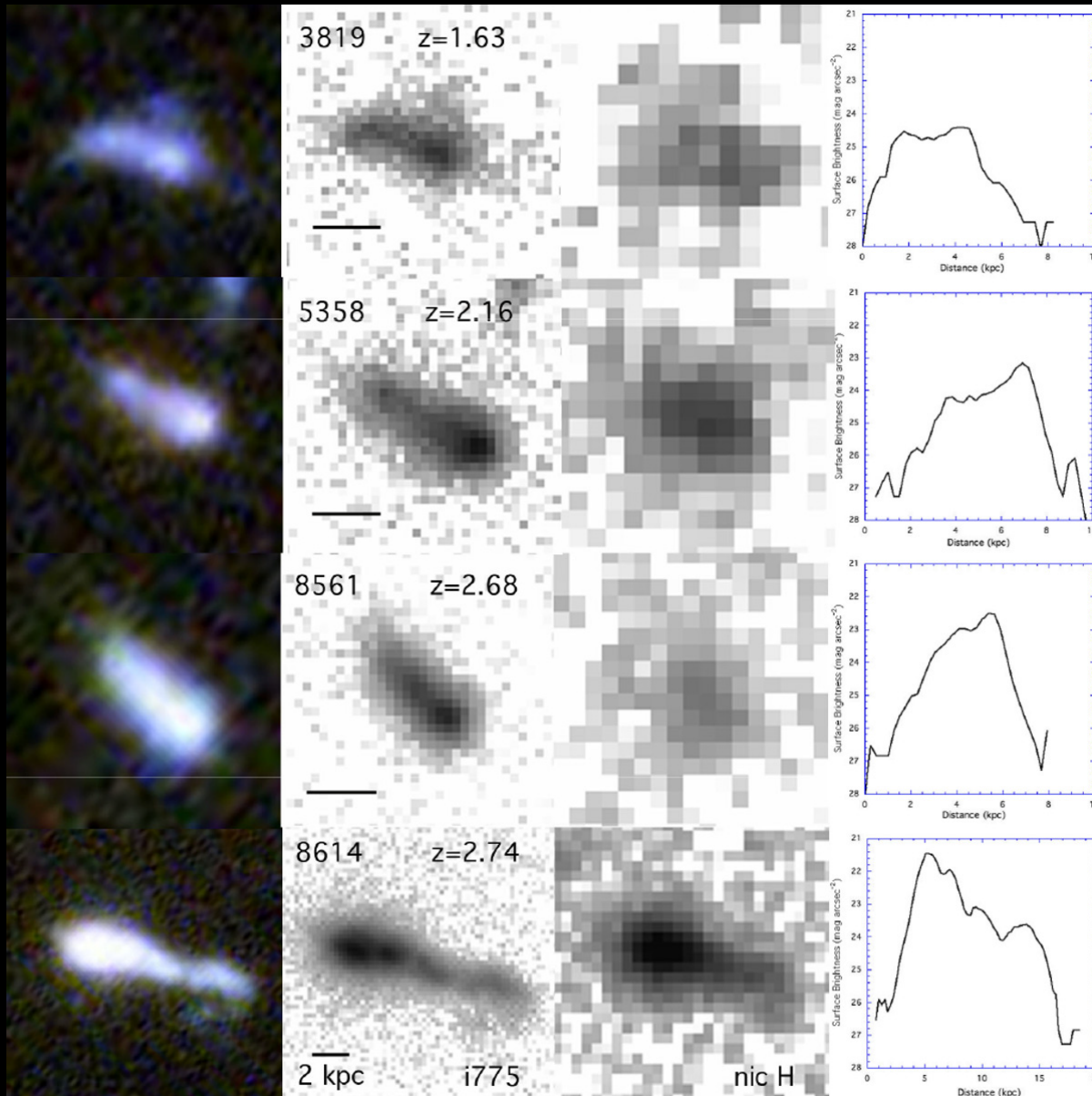


# Comparison of Star Formation Rates

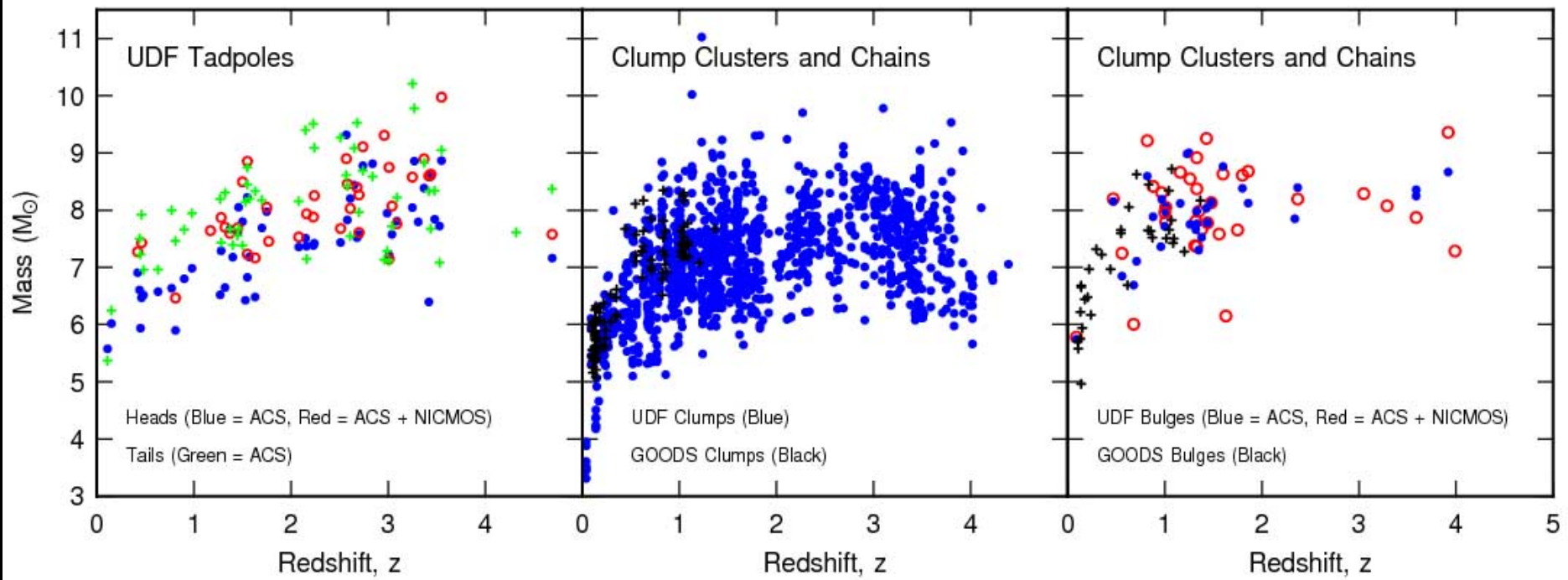


Kiso clumpy galaxies have similar SFRs as UDF clumpy galaxies, higher than local normal galaxies

# UDF tadpole galaxies



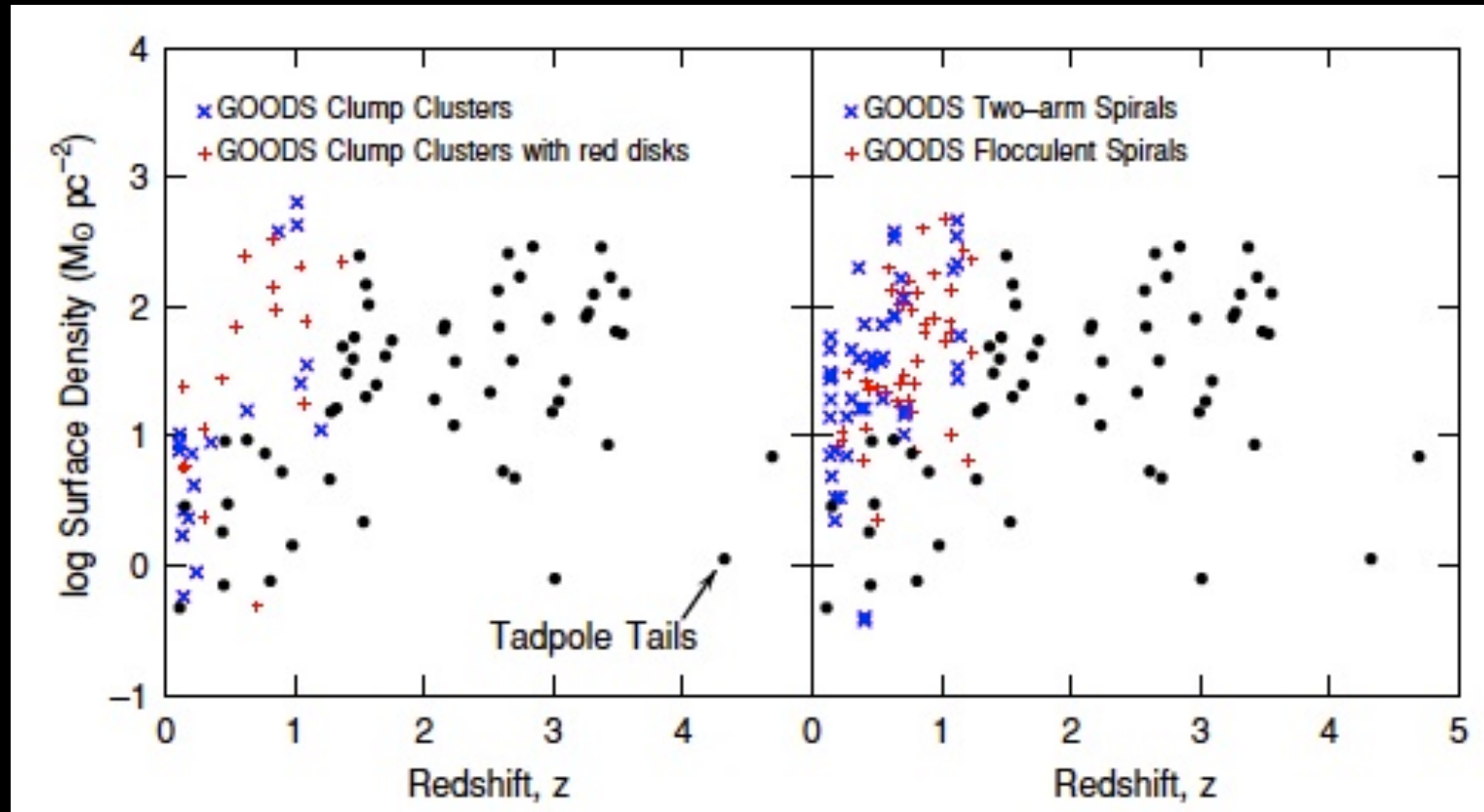
Account for  
10% of UDF  
galaxies in  
our sample  
(97 out of  
1003)



High redshift tadpole head masses are comparable to clump cluster and chain bulge-like masses and to the largest clump cluster and chain clump masses

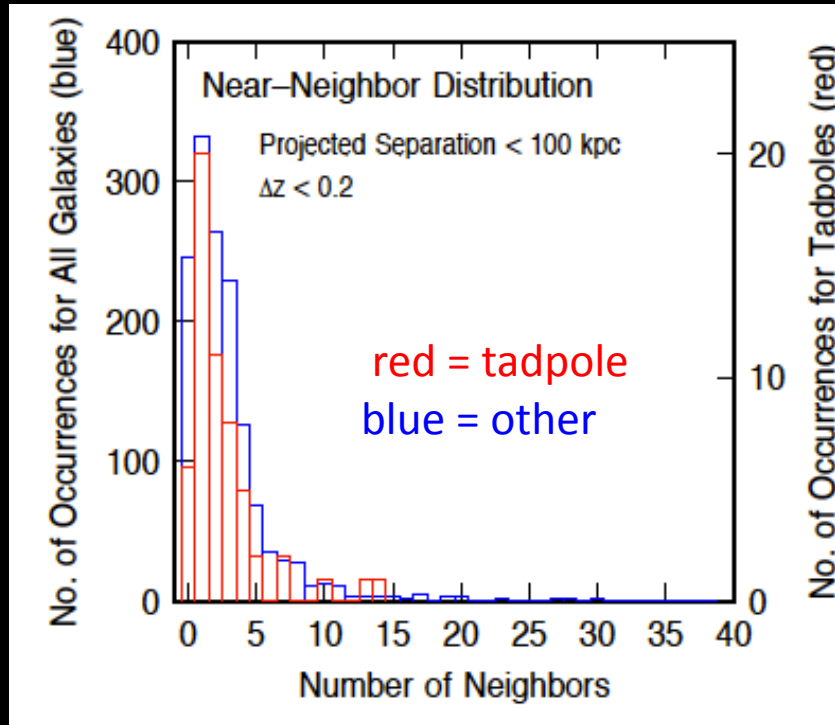
Tadpole tail masses are  $\sim 5x$  the head masses; lengths 1-10 kpc

# Mass surface densities of tadpole tails compared with disks of GOODS galaxies



→ tadpole tails are not as evolved (less dense)  
(surface brightness dimming means only the densest are seen at high z)

## UDF Tadpoles: mergers?



No excess of neighbors compared with other galaxies  
→ they are clumpy disks, not mergers

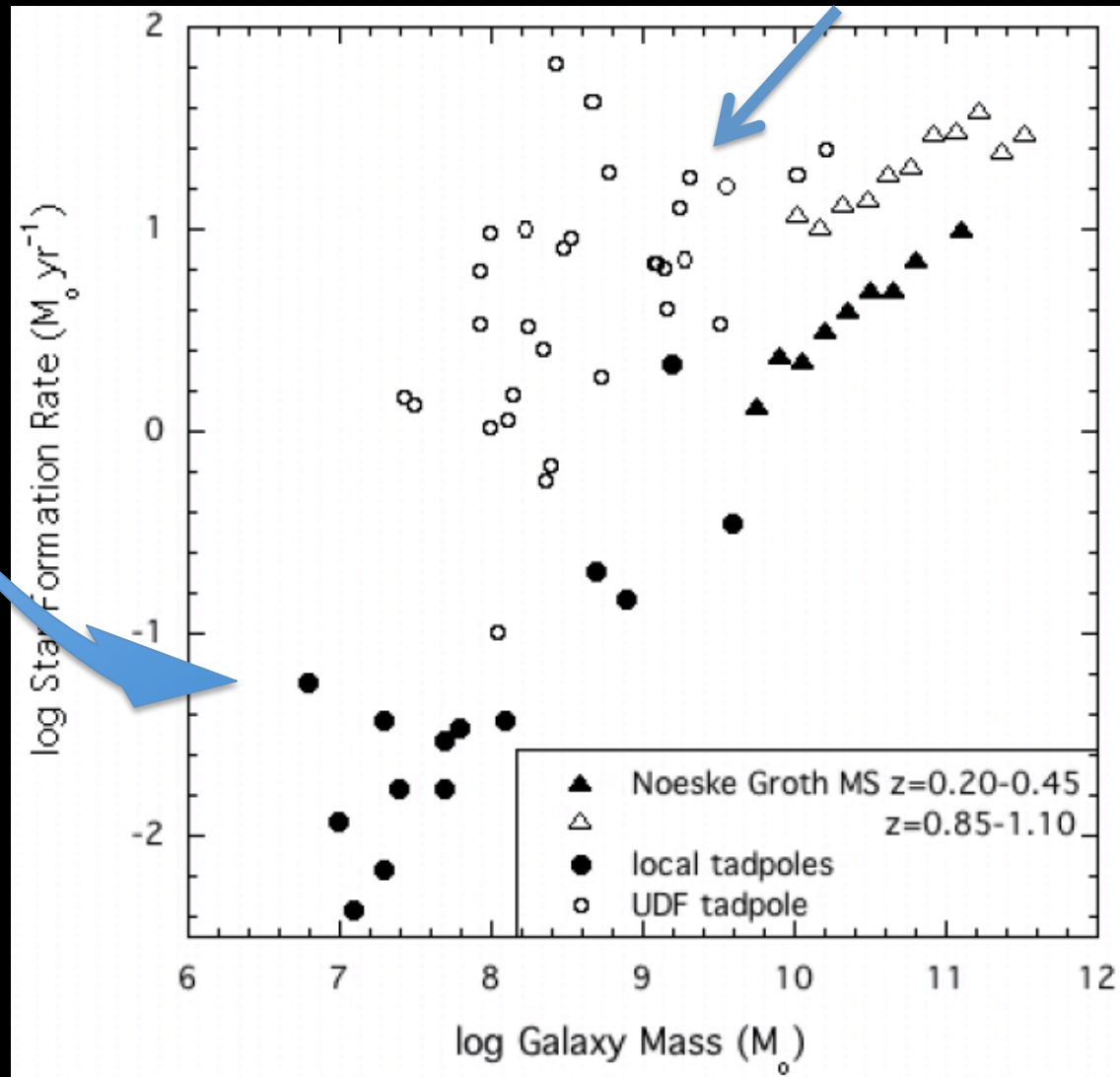
K-S test: 74% probability of same population

Possibly a wind-swept origin for some, moving through intergalactic medium



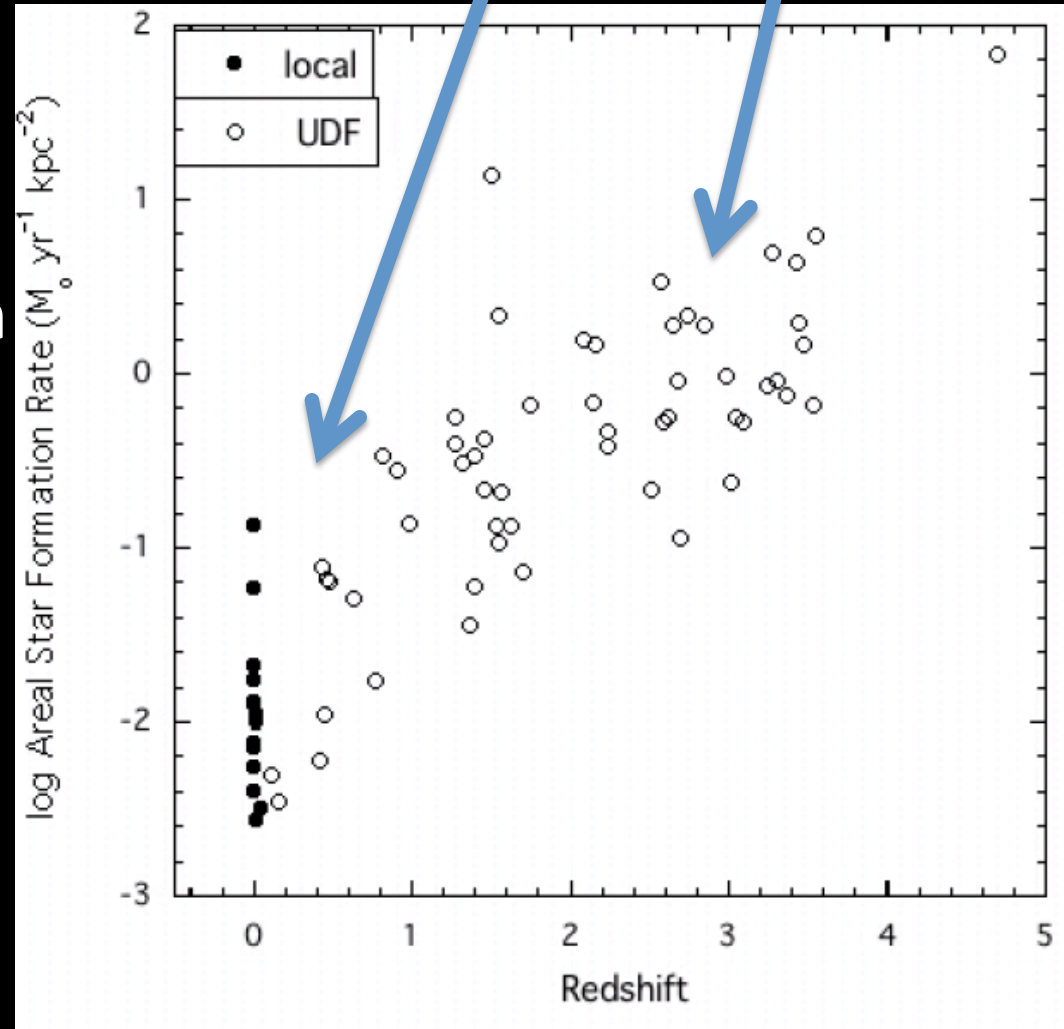
Elmegreen & Elmegreen 2010

Local tadpoles continue the low z Groth strip “main sequence” of SFR vs mass, whereas high redshift tadpoles continue the high z “main sequence”



# SFR per unit area is much greater in high redshift tadpoles than in locals

- consistent with observed higher general star formation rates in the early universe



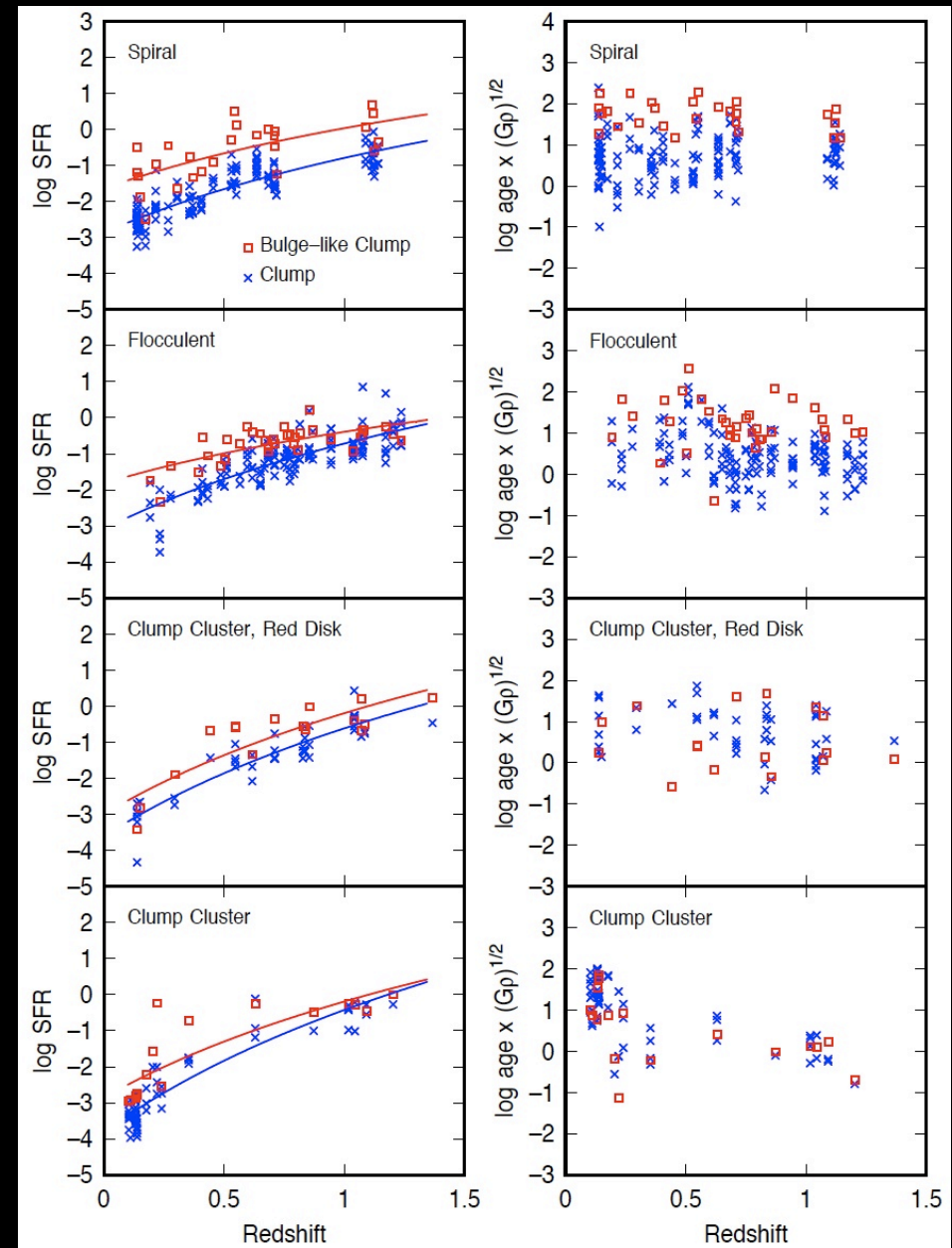
**SFR** increases with  $z$  due to selection effect

- Size limit increases with  $z$
- Surface brightness limit increases with  $z$
- Age may decrease with  $z$

## Dynamical rate

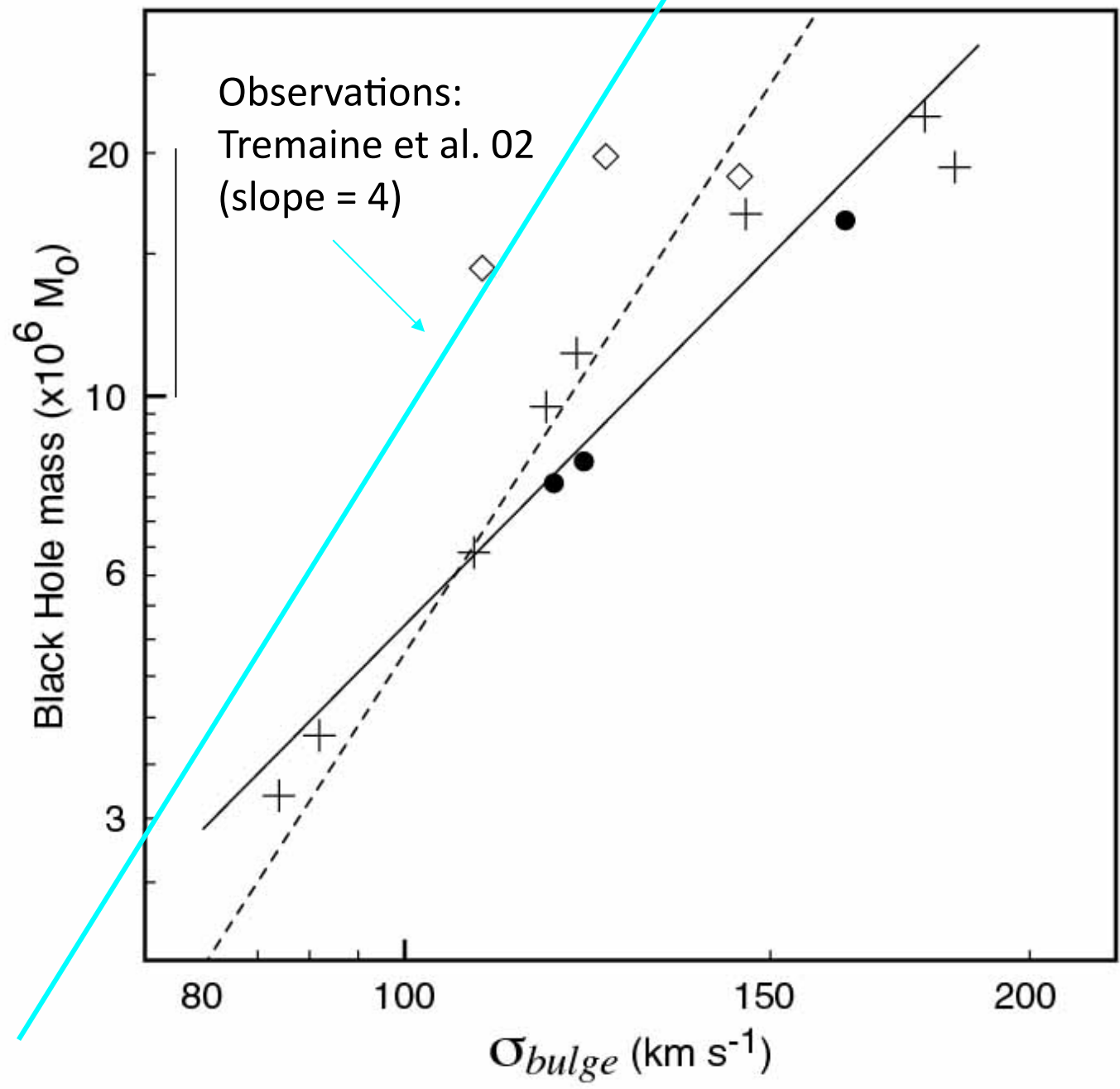
- Ratio of clump age to dynamical time
- $\sim 1$  for clumps,  $\sim 1$  for BLCs in clump clusters, and  $\sim 10$  for bulges in spirals
- Bulges have stopped star formation, but clumps have not

SFR  $\log M_{\odot} \text{ yr}^{-1}$  dynamical rate

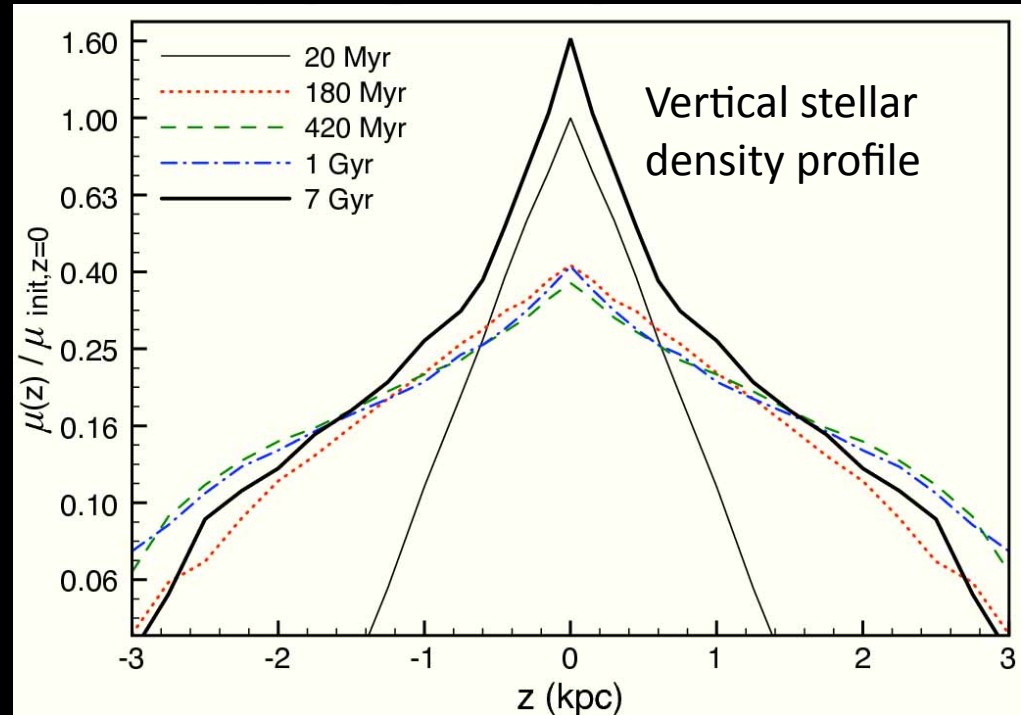
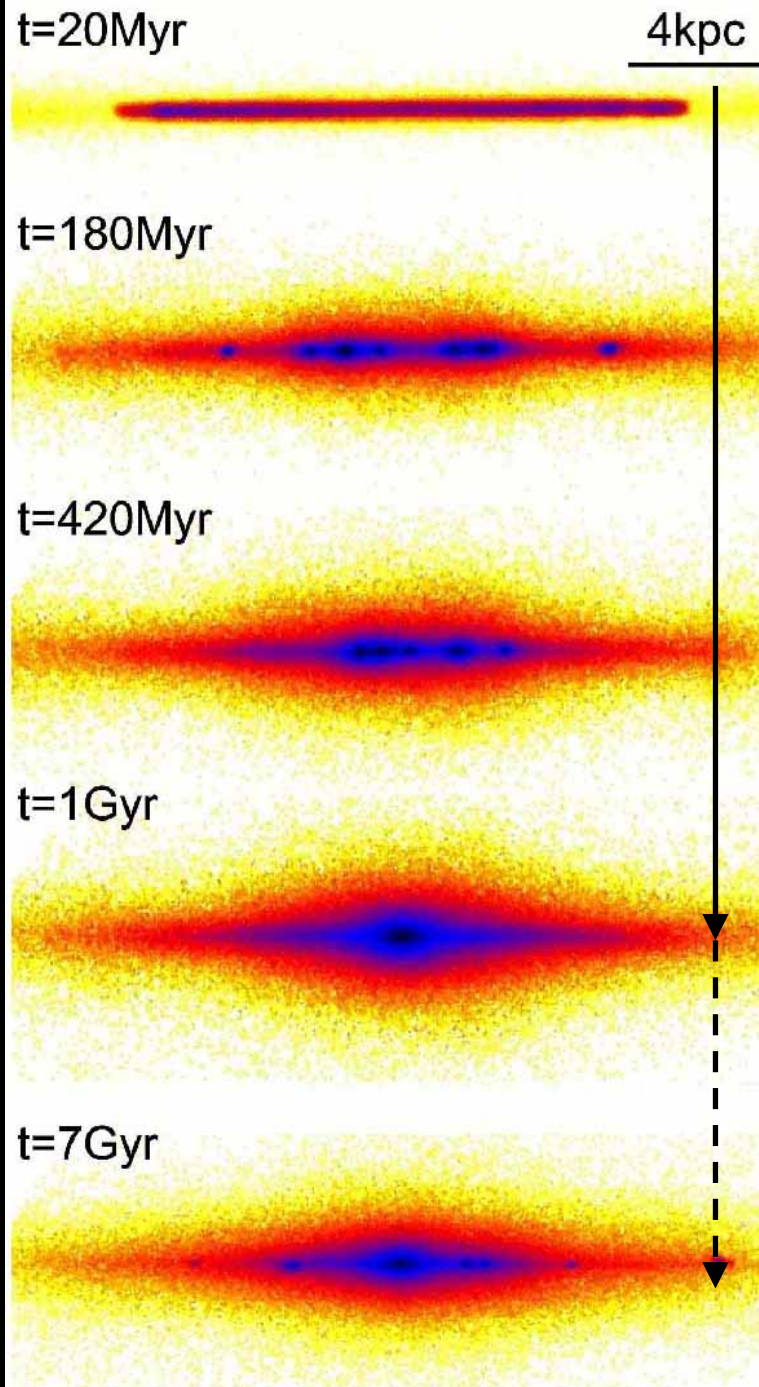


# How do bulges form?

- **Growing evidence for secular bulge evolution (internal processes, rather than mergers), even for classical bulges:**
  - classical bulge fraction (high Sersic  $n$ ) decreases out to  $z \sim 1$  (Sargent +07)
  - bulge and disk colors correlate, suggesting classical bulges and disks co-evolve (Balcells & Dominguez-Palmero 07)
  - The MW old thick disk and bulge have similar metallicities: co-evolution (Melendez +08)
  - The central disk mass concentration ( $\sim$ bulge/disk) increases over time at  $z \sim 2$  (Genzel +08)
  - $\Lambda$ CDM cosmological simulations do not reproduce the observed small value of  $M_{\text{bulge}}/M_{\text{disk}}$  (e.g., Graham & Worley 08), suggesting few major mergers during disk formation (Weinzirl +08)
  - Young disks have clumpy structure and young bulges are similar to disk clumps (Elmegreen +08, 09)
- **Simulations suggest disks with high gas fractions and high turbulent speeds form massive clumps**
  - Clumps move to the center to make a “classical” bulge (Noguchi 99, Immeli +04, Bournaud, Elmegreen, Elmegreen 07,08ab)



# Clumpy galaxy evolution



In first Gyr, constant galaxy mass

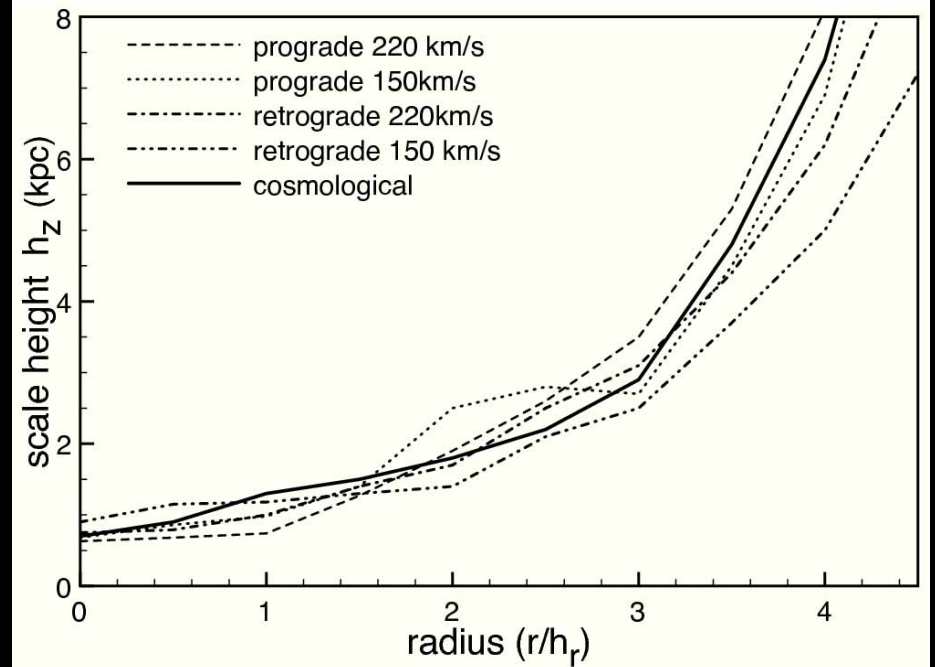
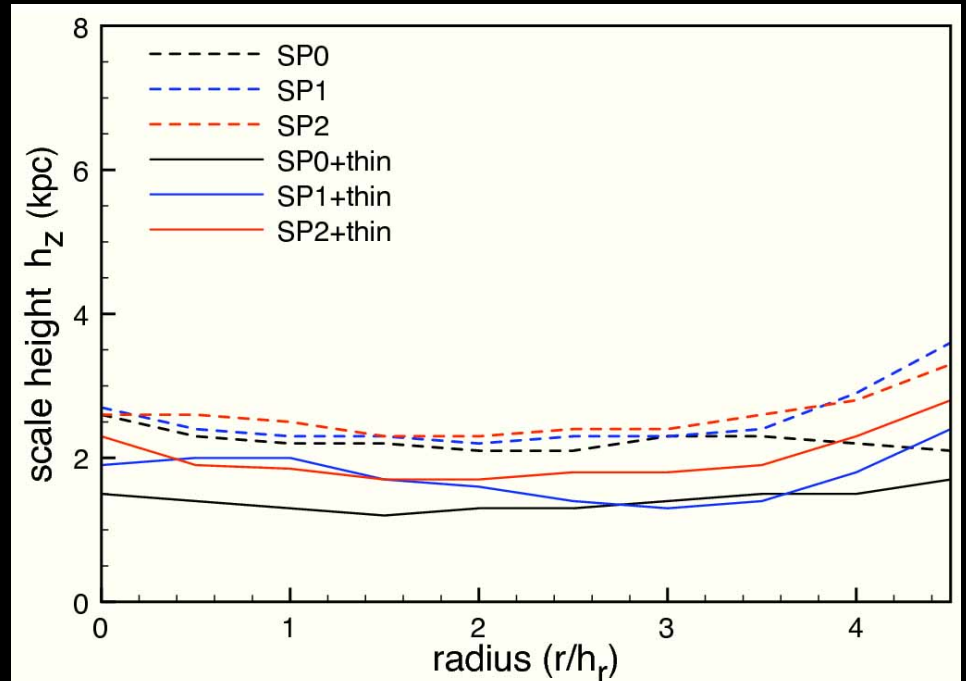
– builds thick disk

In next 6 Gyr, gas added at rate of  $10 M_{\odot}/\text{yr}$  to outer disk (15 kpc radius, 1.5 kpc thick), with angular momentum equal to average in inner disk

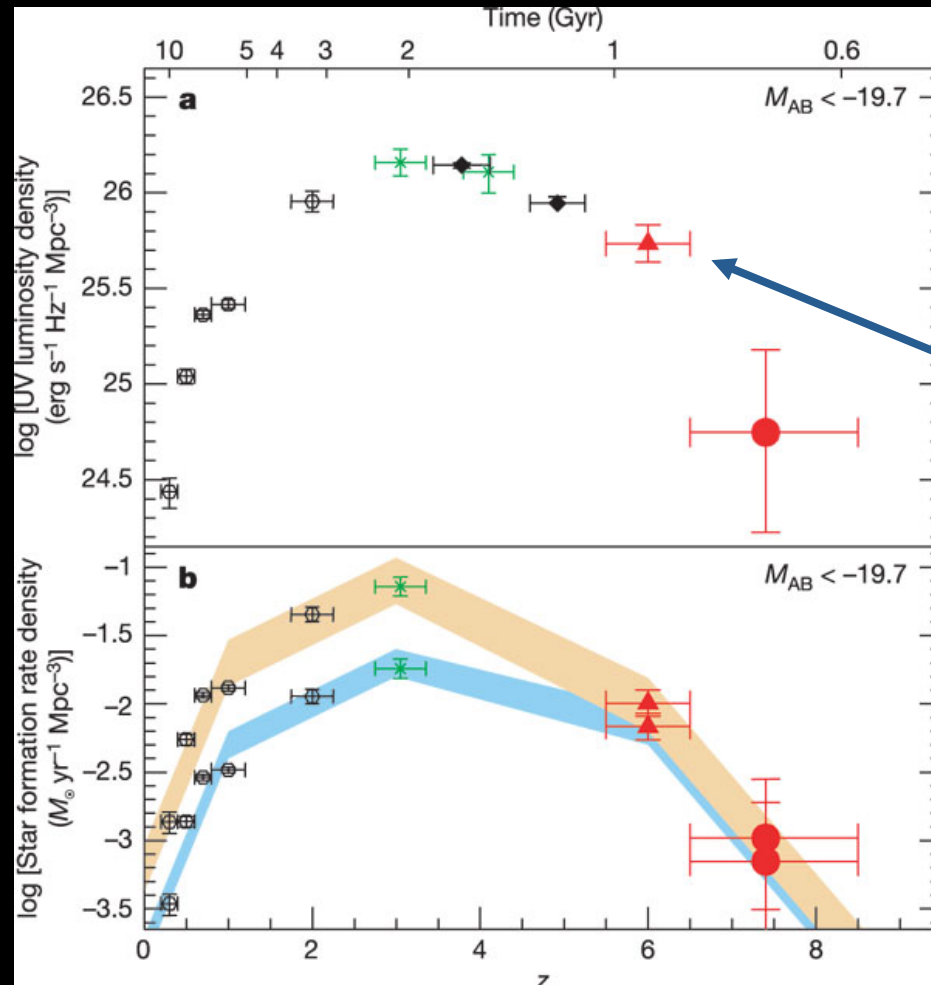
– builds thin disk

**Internal evolution in 3 cases**  
(different disk masses and gas fractions) show thick disk scale heights that are **constant** with radius

**Four minor merger (10:1) cases and a cosmological merger case** all have thick disk scale heights that **increase (flare)** with radius.



# Overall, star formation peaks at $z=2-4$ (based on measuring uv redshifted light)



Build-up of  
luminous  
galaxies

Bouwens &  
Illingworth 06

(Only  $\sim 1$  star/yr in spirals today; 100's/yr at high z)

# Comparison of UDF clump and bulge masses from model fits

## Bulges:

- $10^8$ - $10^9 M_{\odot}$   
(up to  $10^{10} M_{\odot}$  in spirals)

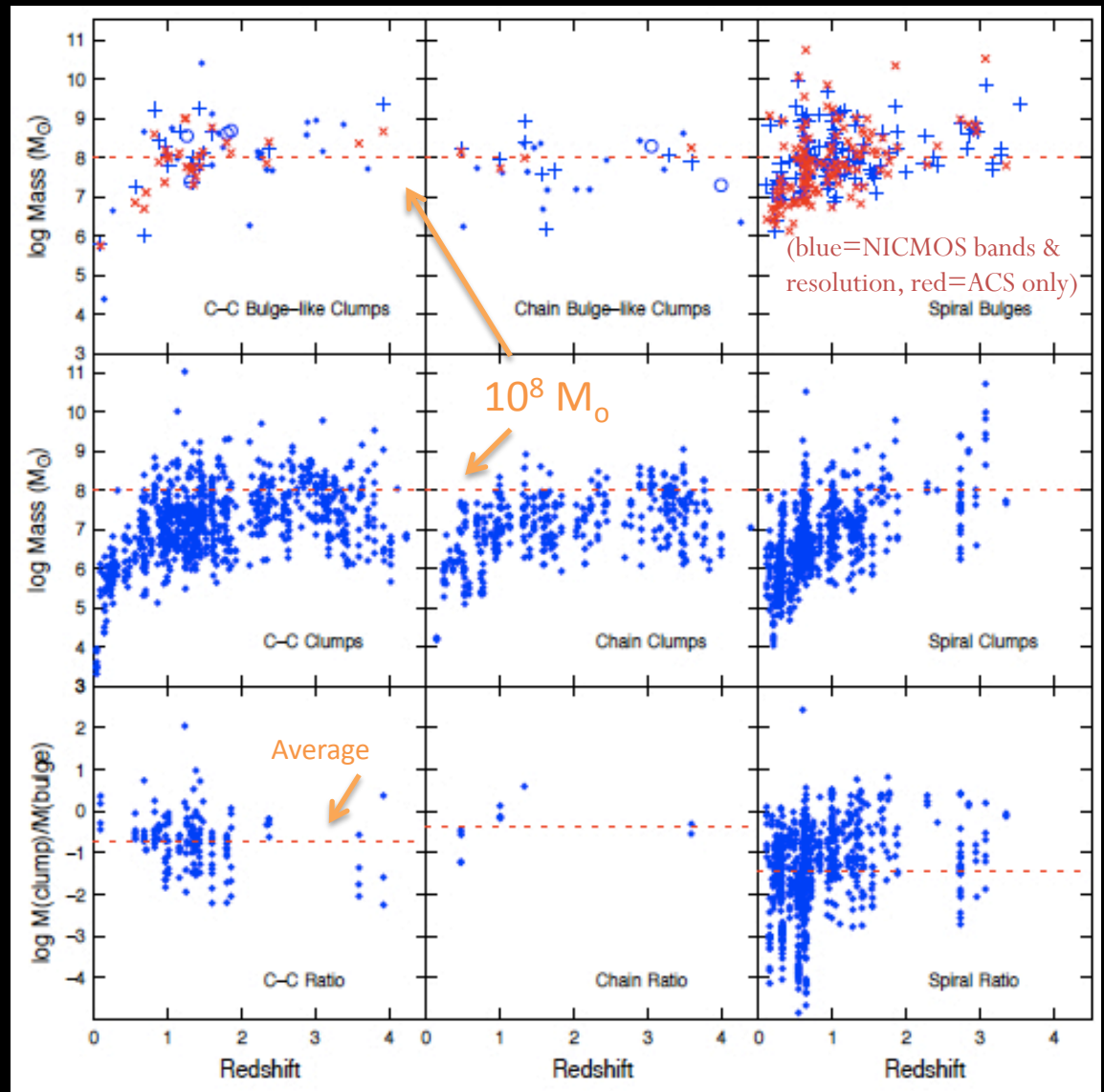
## SF clumps:

- $10^7$ - $10^8 M_{\odot}$

## Ratio, clump/bulge

- $\sim 1/26$  for spirals
- $\sim 1/3$  for cc's & chains
- $\sim$  constant with  $z$

→ BLCs are more similar to star-forming clumps in clumpy galaxies than bulges are to SF clumps in spirals



# GEMS & GOODS: Clump mass

Left:

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

Right:

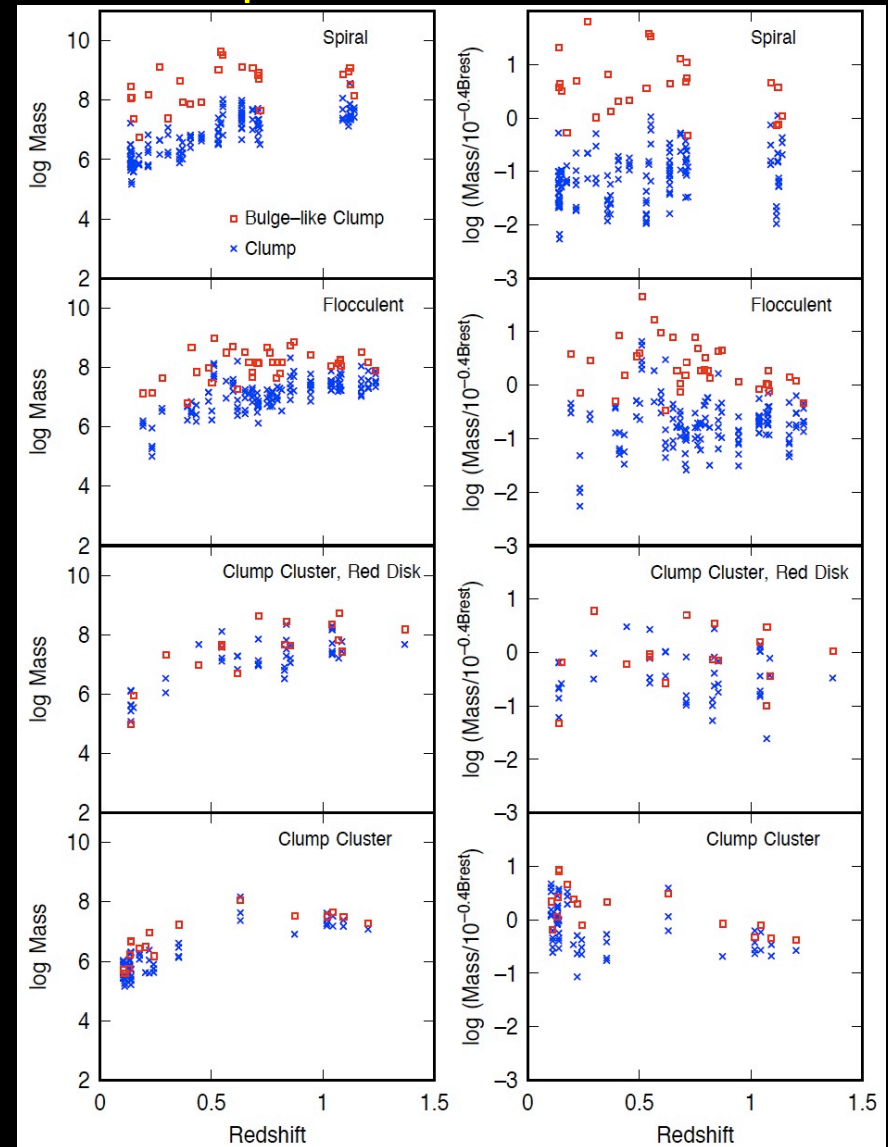
Clump mass per unit galaxy light  $\sim$  independent of redshift;  $\sim$  **100x** local galaxies

Red=bulges or BLCs

Blue=non-bulge clumps

Clump Mass

Clump Mass/  
Galaxy Light



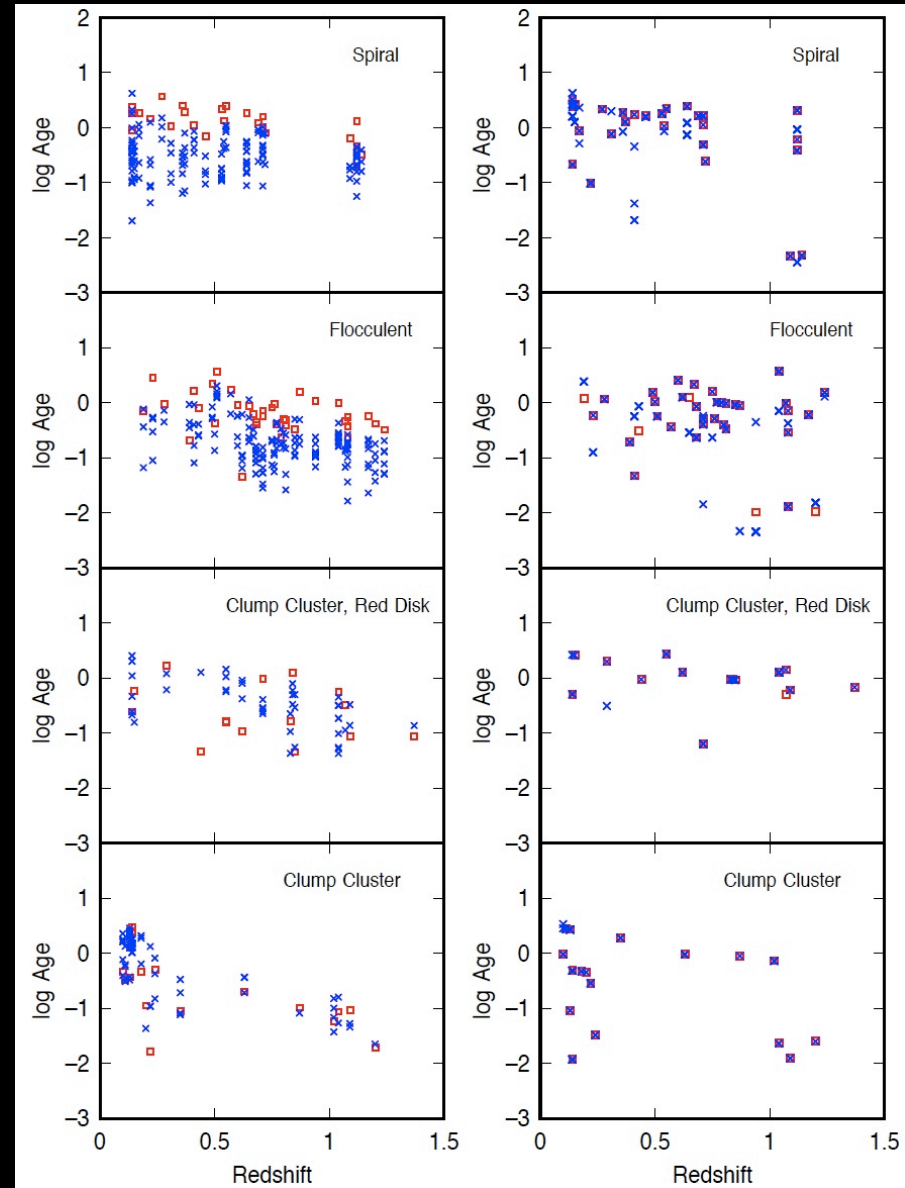
# Age

(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 in CC's without red underlying disks

(More evidence for evolution)

Clump, bulge or BLC    Interclump



Ages in Gyr

# Surface density

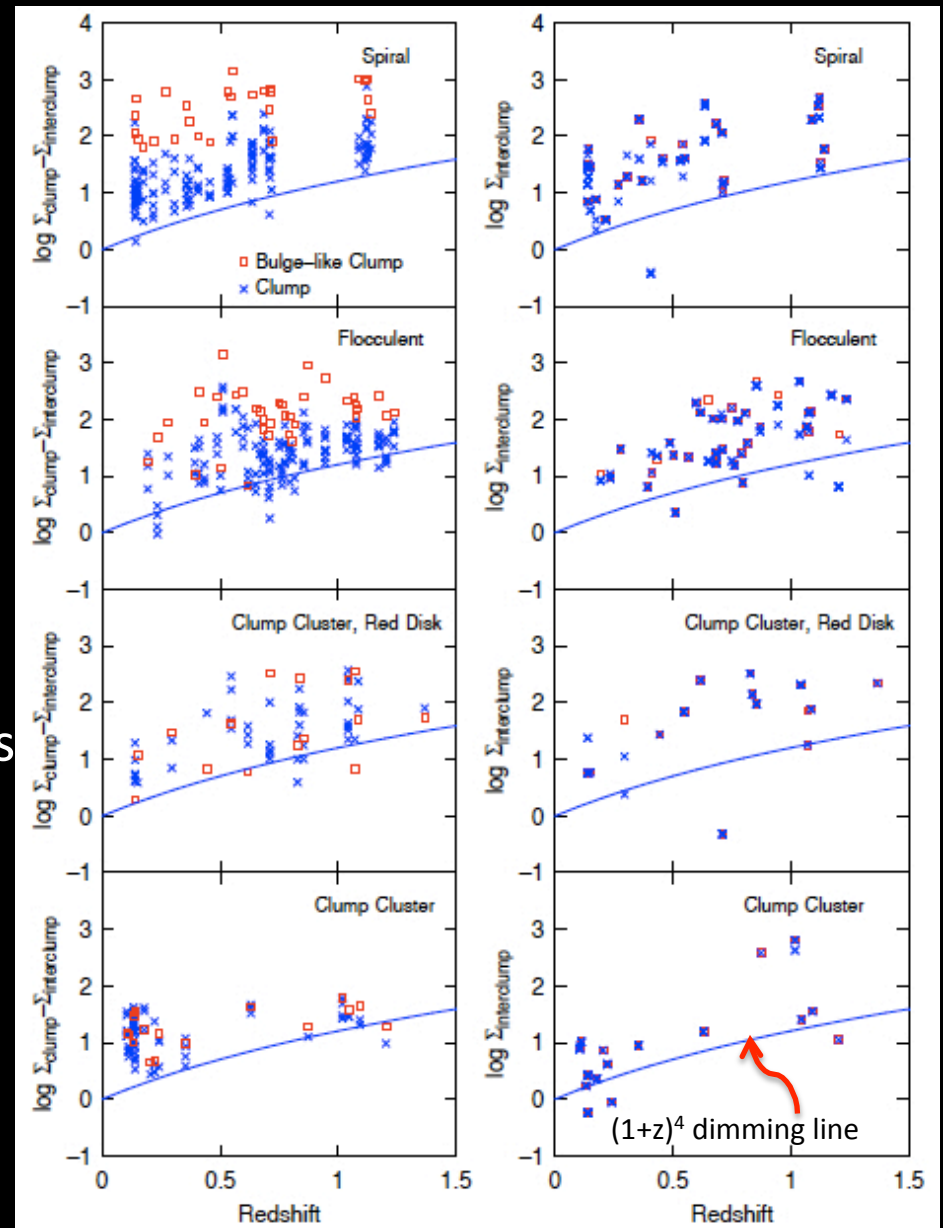
Left:  
Clump excess  
Right:  
Interclump

Bulge/clump surface density:  
7.5x in spirals,  
but 1 in clump clusters

Interclump density 2x higher in spirals  
than clump clusters

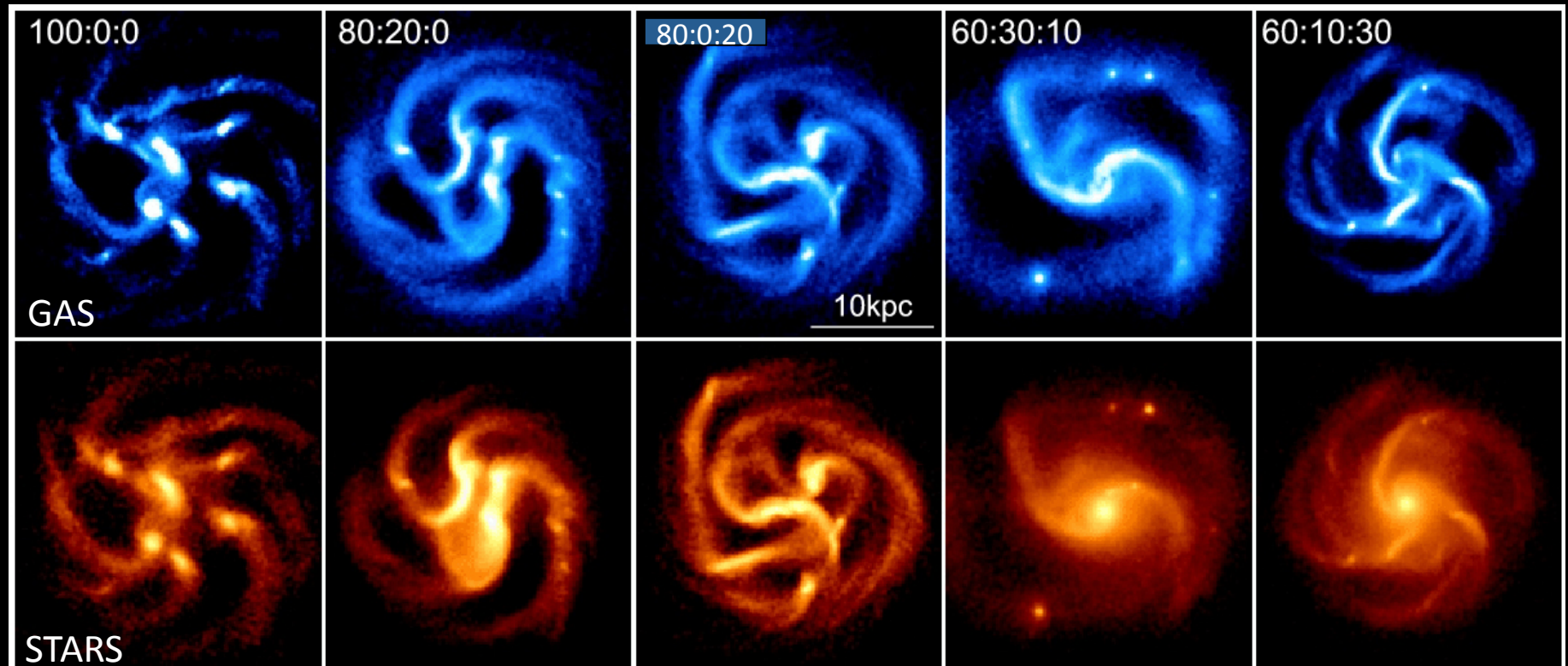
**Implication:** Evolution of bulges  
and interclump medium towards  
higher surface densities as clump  
clusters convert into spirals

Surface density distribution,  $M_{\odot} \text{ pc}^{-2}$



Red=bulges or BLCs

Blue=non-bulge clumps



stellar mass fraction in **disk:bulge:halo** indicated (all gas is in disk)

**Conclude: giant clump formation requires >80% of the stars (and all of the gas) in a ~ bulgeless disk.**

→ Makes even minor mergers (10:1) unlikely during galaxy build-up;  
*Requires smooth gas accretion.*