Dwarf Galaxies and High-Redshift Irregulars: Similarities and Differences

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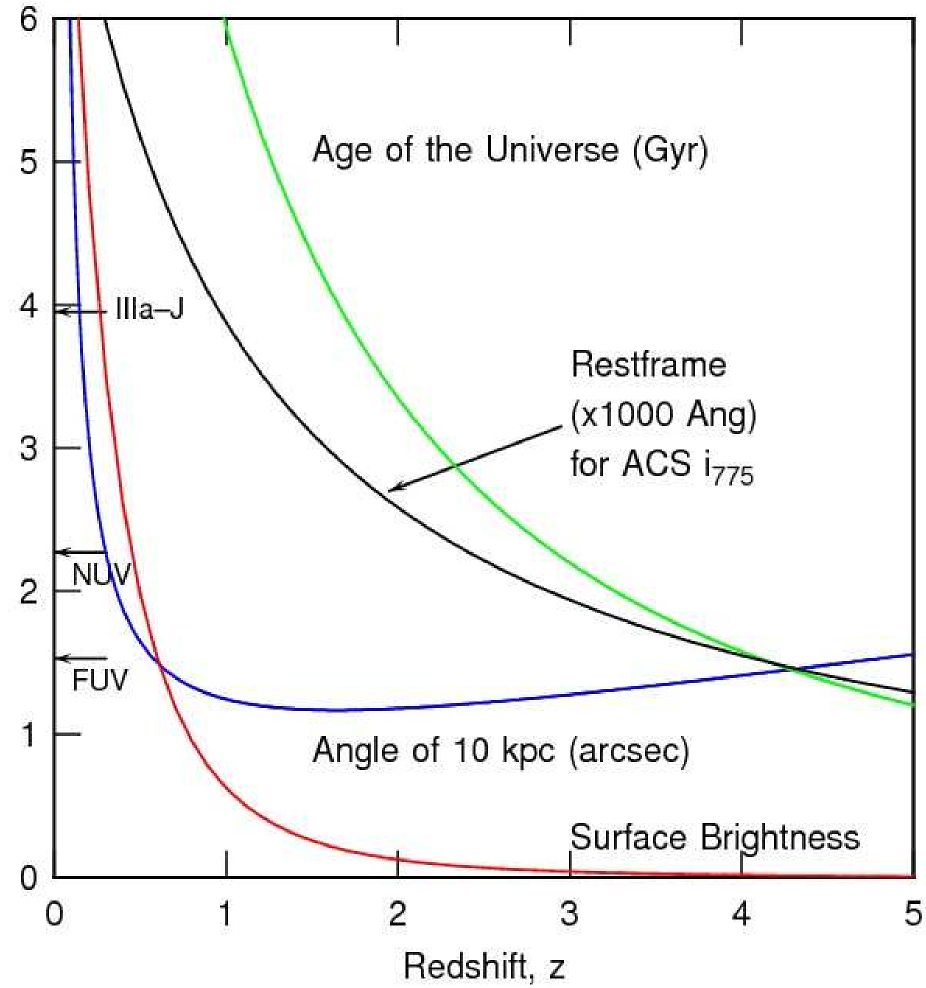
Redshift affects angular size, surface brightness, restframe wavelength, age



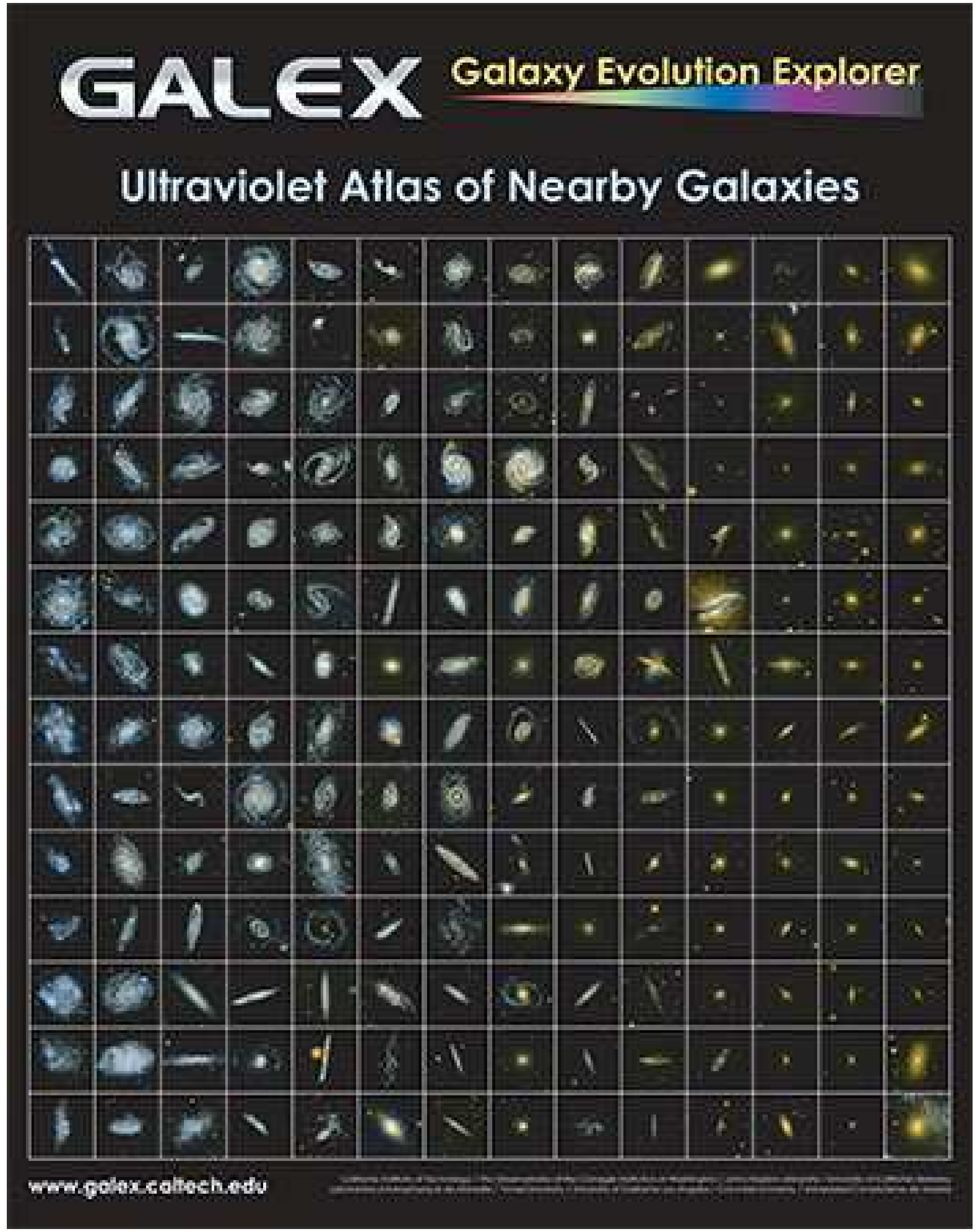
v=0 v=0.6c 0.8c 0.88c 0.925c 0.945c

ΛCDM model

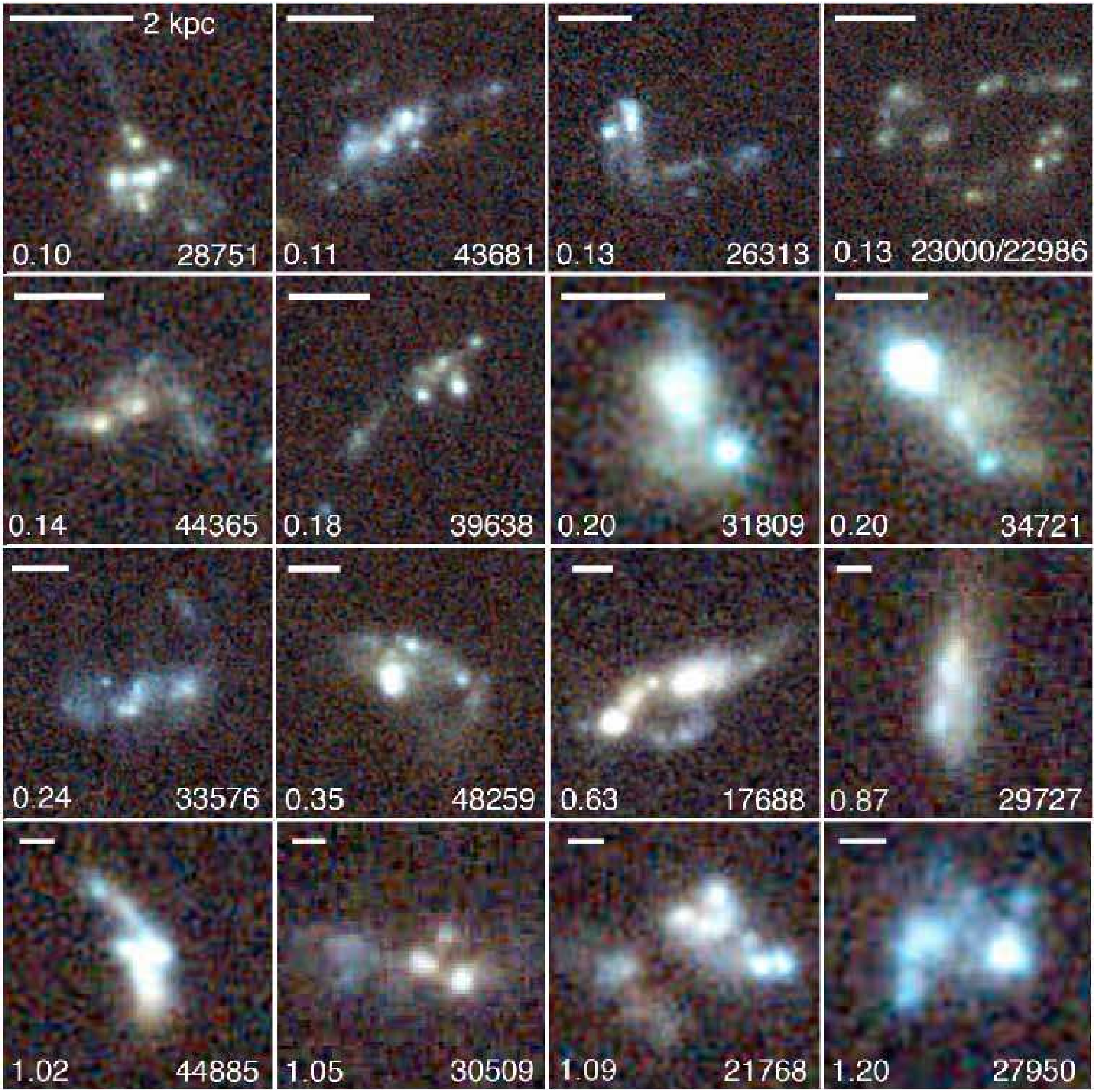
Everyone expected normal galaxies to look like this at high redshift:

UV restframe with

1. exponential disks
2. spiral arms and bars
3. lots of small SF regions
4. disk/spheroid diversity



But they are clumpy.



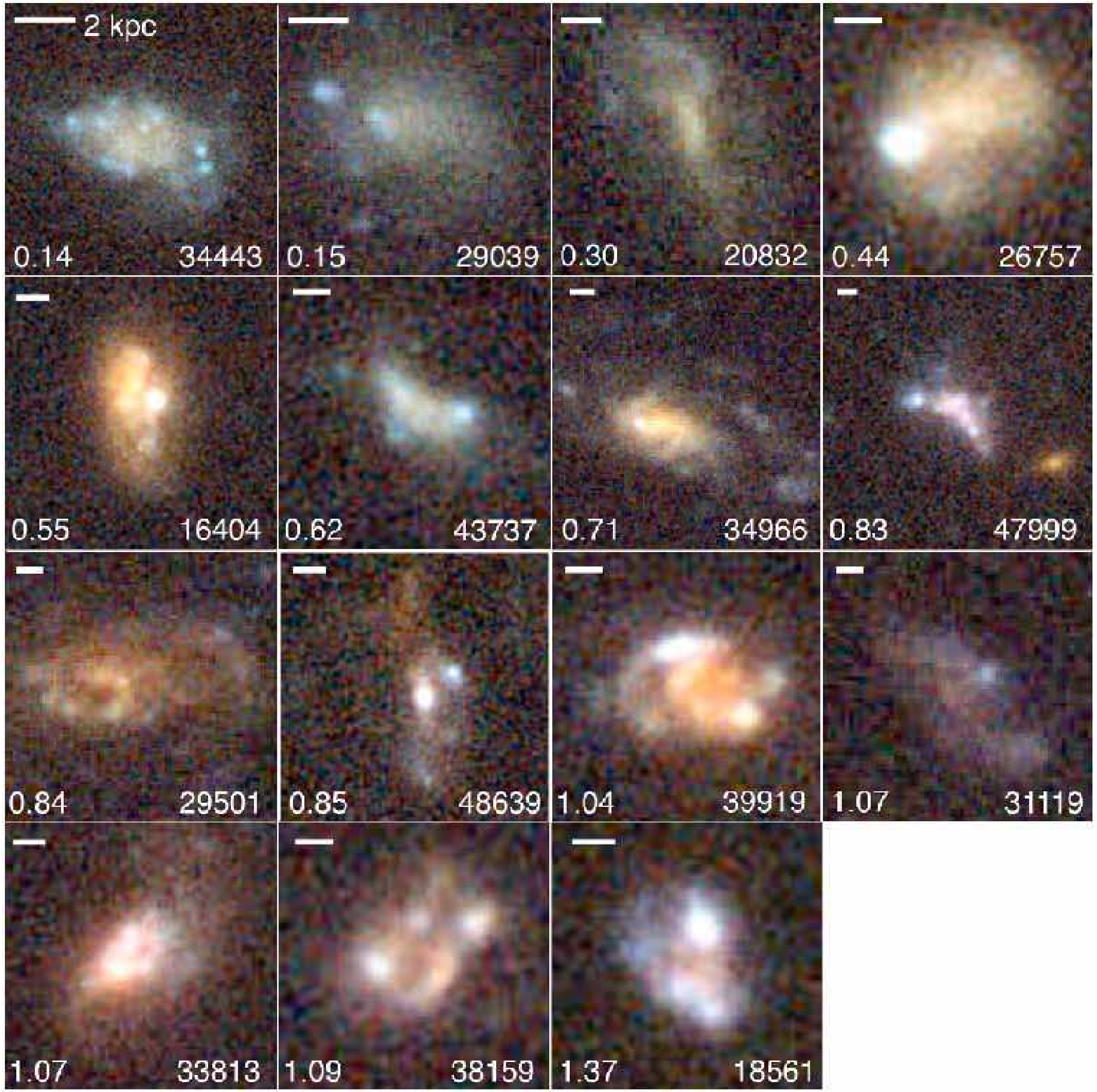
GOODS V-band is Restframe B band for z=0.2

Or clumpy with faint red disks

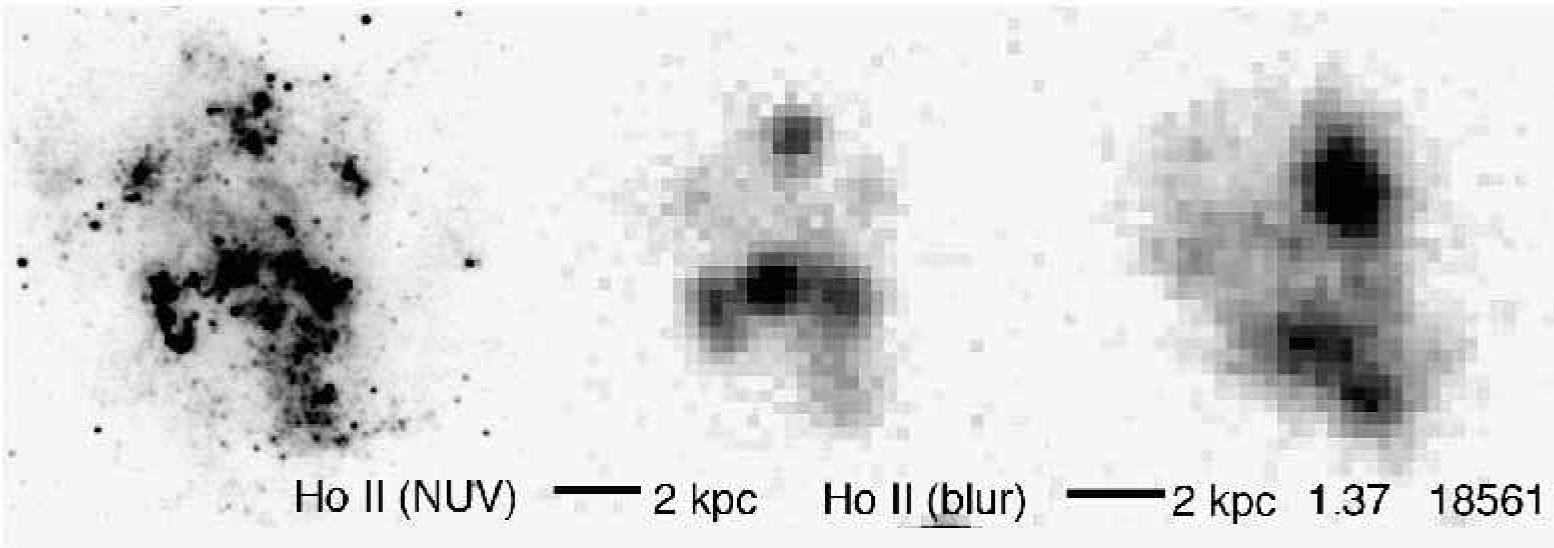
GOODS V-band

Restframe B band for z=0.2

EEMSYP09



Ho II, a dwarf Irregular, viewed in FUV (GALEX) resembles a high-z clumpy galaxy



V_{606} image

<u>Ho II blurred</u> to the same kpc resolution per point source FWHM,
<u>re-pixelated</u> to the same kpc per pixel,
viewed in the <u>same rest wavelength</u>, and
presented with the <u>same scale</u>.

Clumpy high-z galaxies resemble dwarf irregulars

- Both have low Vcirc/σ
  - (Forster-Schreiber +06; Weiner+06; Genzel +06,08; Puech +07)

  → therefore they have big SF complexes relative to the galaxy size, and relatively few of them

  → therefore relatively thick disks
    - L_{Jeans}/Galaxy Size ~ H_{disk}/Galaxy Size ~ $(\sigma/V)^2$
- Both have high gas fractions
  - (e.g., Tacconi + 10, Daddi +10)
  - which, combined with small number of clumps means they are morphologically irregular
- Both are relatively young
  - Downsizing today

This Talk:

- Similarities:
  - low V_{circ}/σ → clumpy, thick disks, irregular

    … plus
  - tadpole/cometary → trace intergalactic medium?
  - clump torques → disk accretion, bulges and BCDs
  - cluster formation → Lyman α emitting galaxies (dwarfs at high z) & metal-poor globular clusters
- Differences:
  - mass, size, V_{circ} → downsizing over cosmic time
  - ISM pressure, metals → H_2 fraction, SF efficiency …?

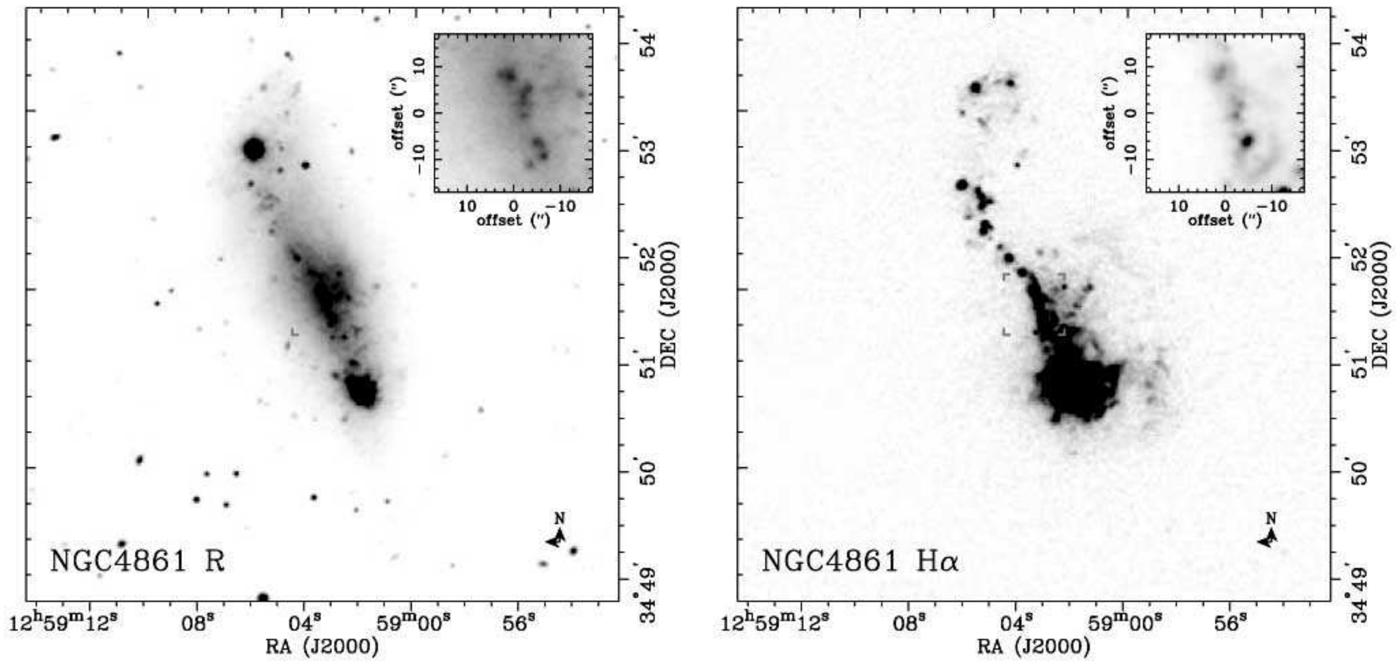
Tadpoles/Comets

Also see talk at noon today by Jorge Sanchez Almeida

Elmegreen & Elmegreen 2010

D.M. Elmegreen, B.G. Elmegreen, Sanchez Almeida, Munoz-Tunon, Putko, Dewberry 2012

NGC 4861



Gil de Paz +03

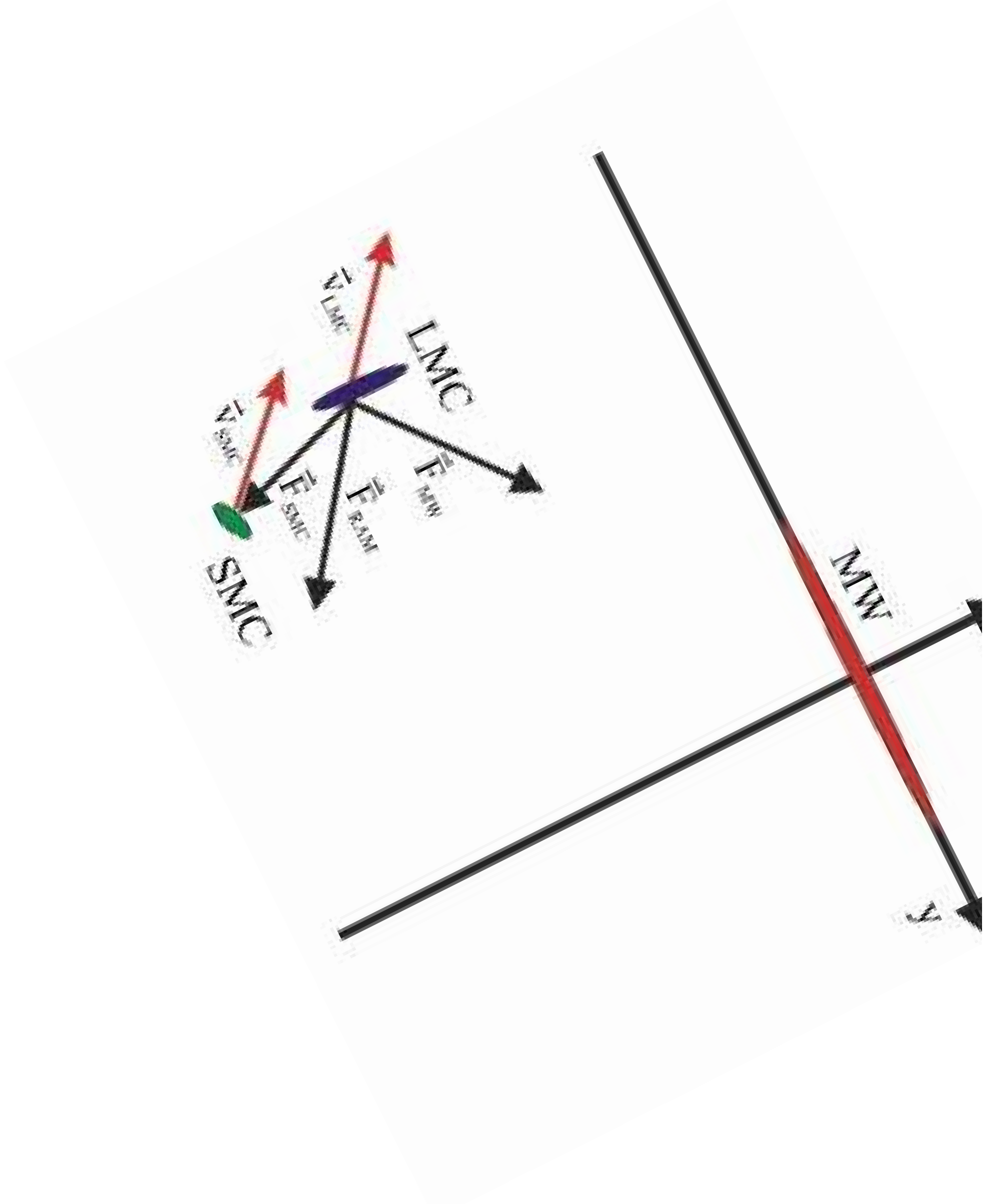
Lop-sided BCDs: “comets,” “tadpoles”

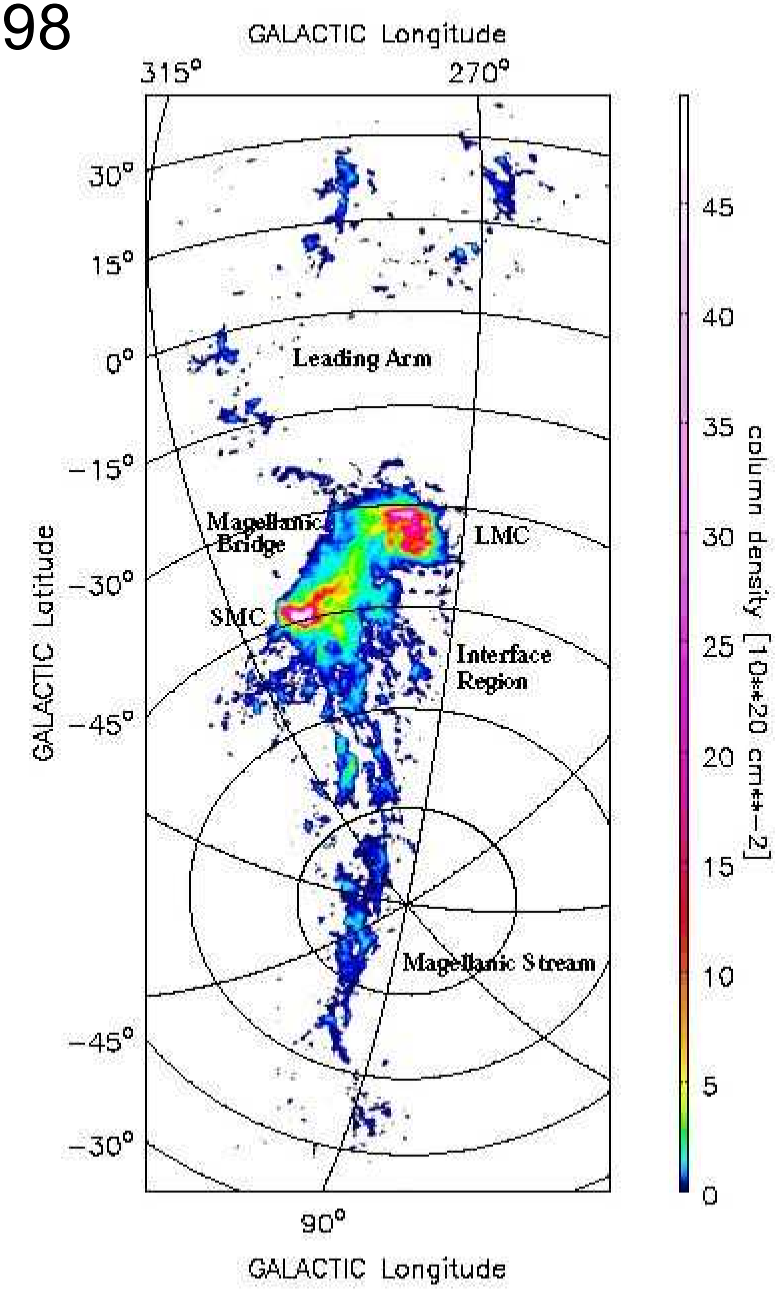
A large fraction of extremely metal-poor BCDs have cometary shapes.

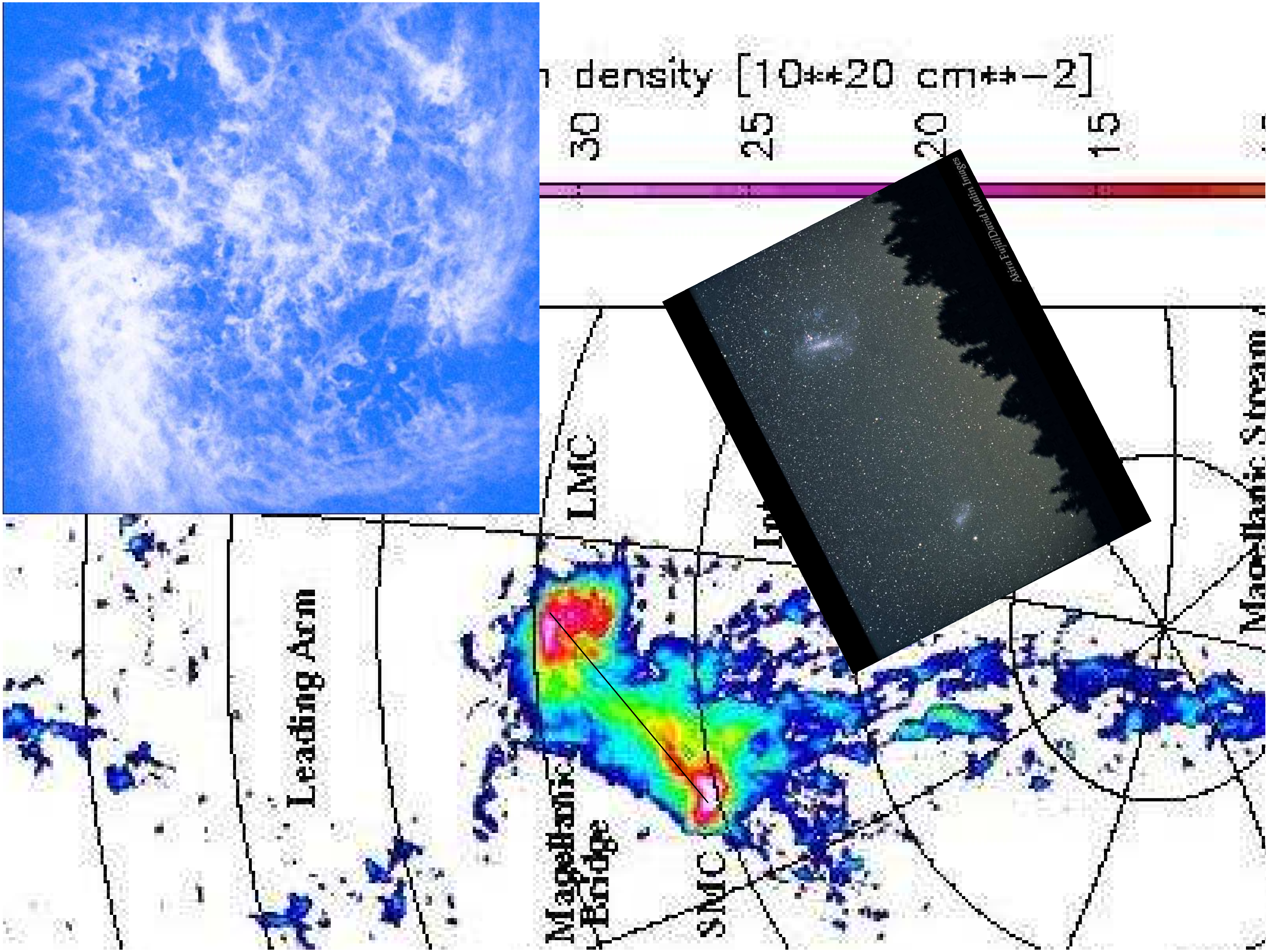
Called sub-class iI,c by Noeske +00

Markarian +69, Loose & Thuan +85, Cairos +01a,b, Kniazev et al. +01, Gil de Paz +03, Papaderos +08, Morales-Luis +11, …

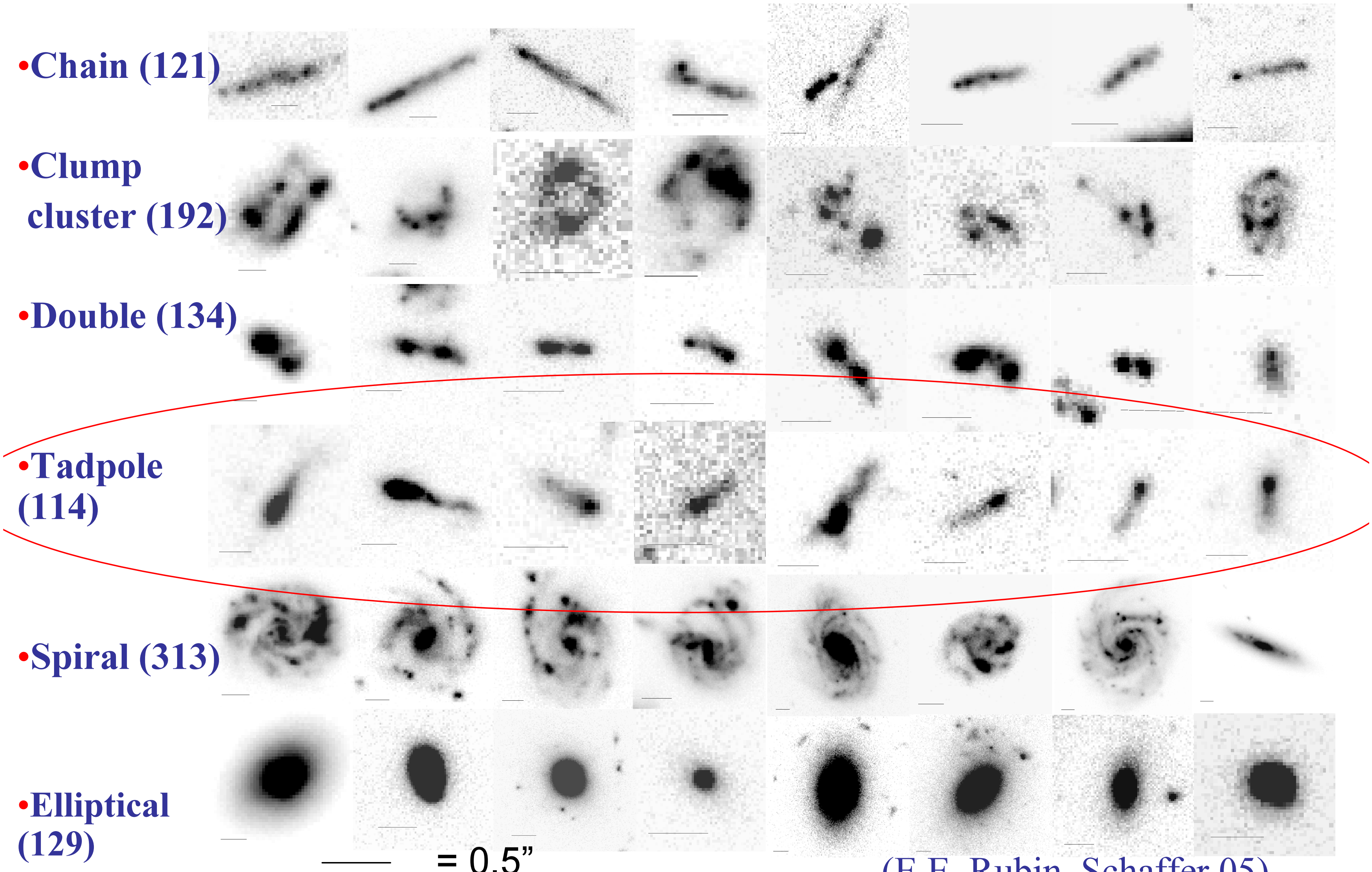
LMC as a tadpole: de Boer et al. 1998






n density [10**20 cm**-2]
30
25
20
15
LMC
Leading Arm
Magellanic Bridge
SMC
Magellanic Stream
Akira Fujii/David Malin Images

In the HUDF, 10% of galaxies > 10px diameter are Tadpoles



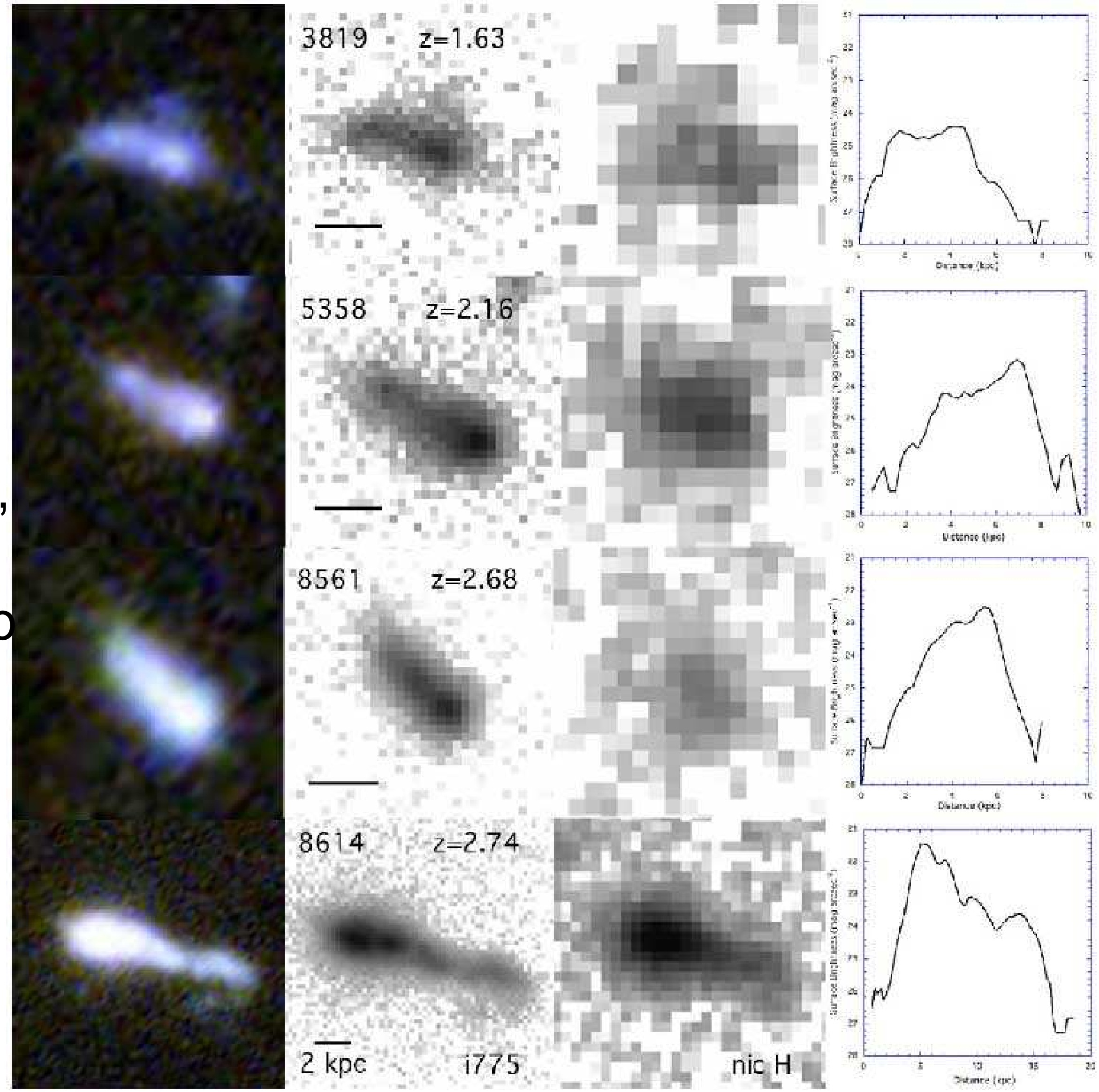
(E,E, Rubin, Schaffer 05)

Called “tadpoles” by van den Bergh +96, Abraham +96 (13% in deep fields)

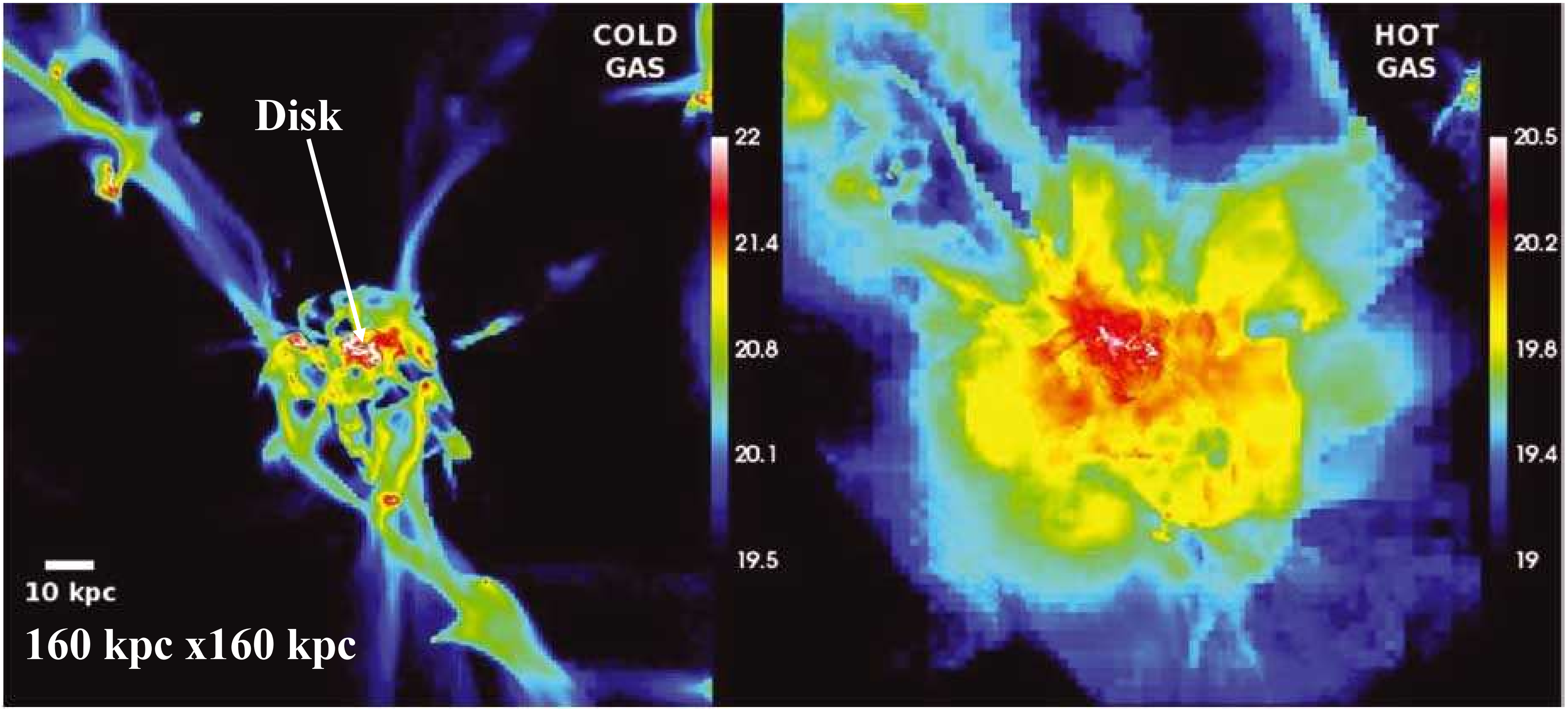
....

Rhoads +05, Straughn +06, Windhorst et al. +06, Rawat +07, De Mello +06ab consider to be <u>mergers</u> but excessive merger rate required (10-30 since z=7)

EE+10: lack companions, suggest they are ram-pressure swept



Sky Walker | ACS i_{775} | NICMOS | Scan through i_{775}



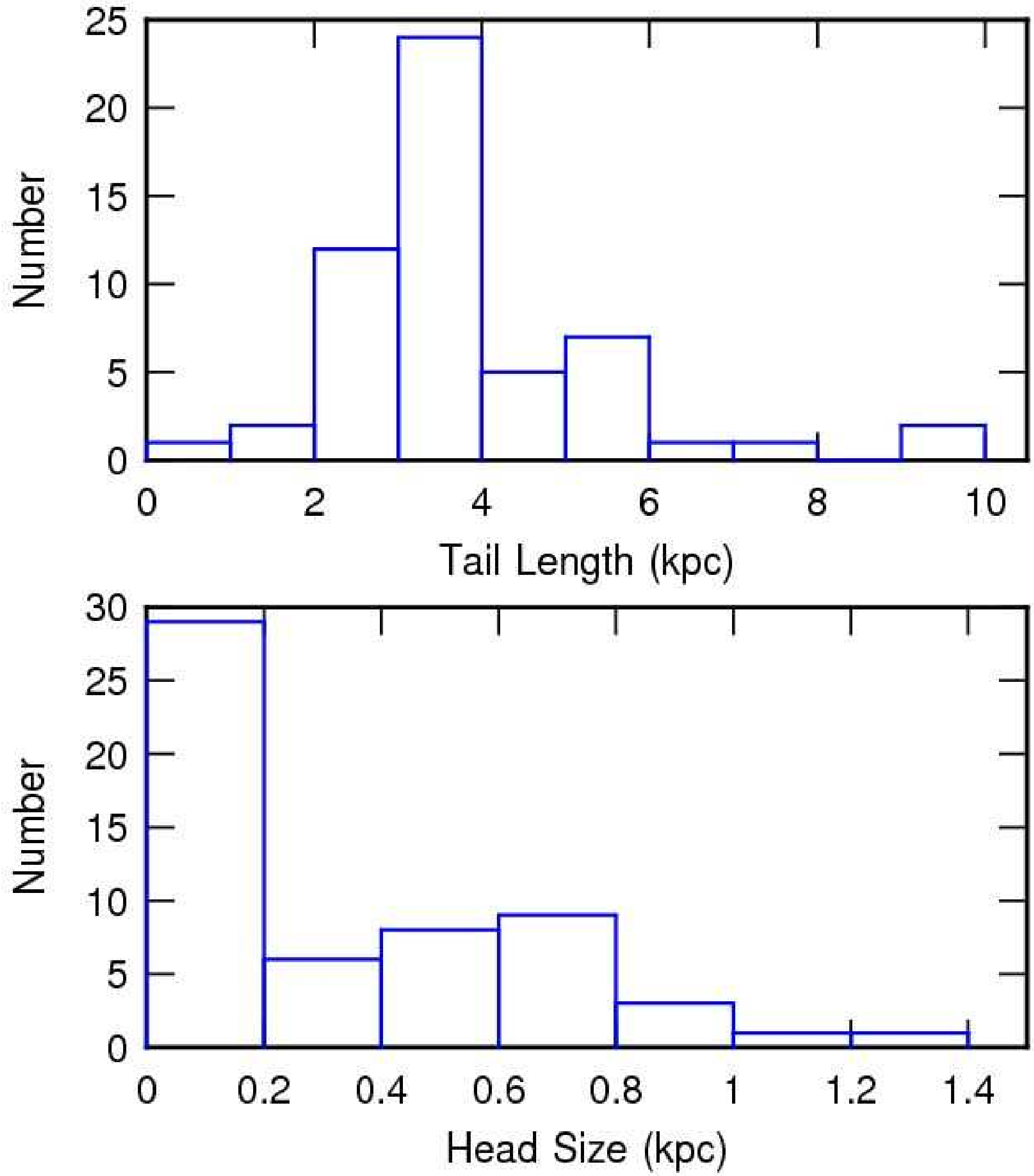
Possible significance of Tadpoles: local flow indicators

Simulation of cold and hot flows with disk galaxy formation

Ceverino, Dekel & Bournaud 2010

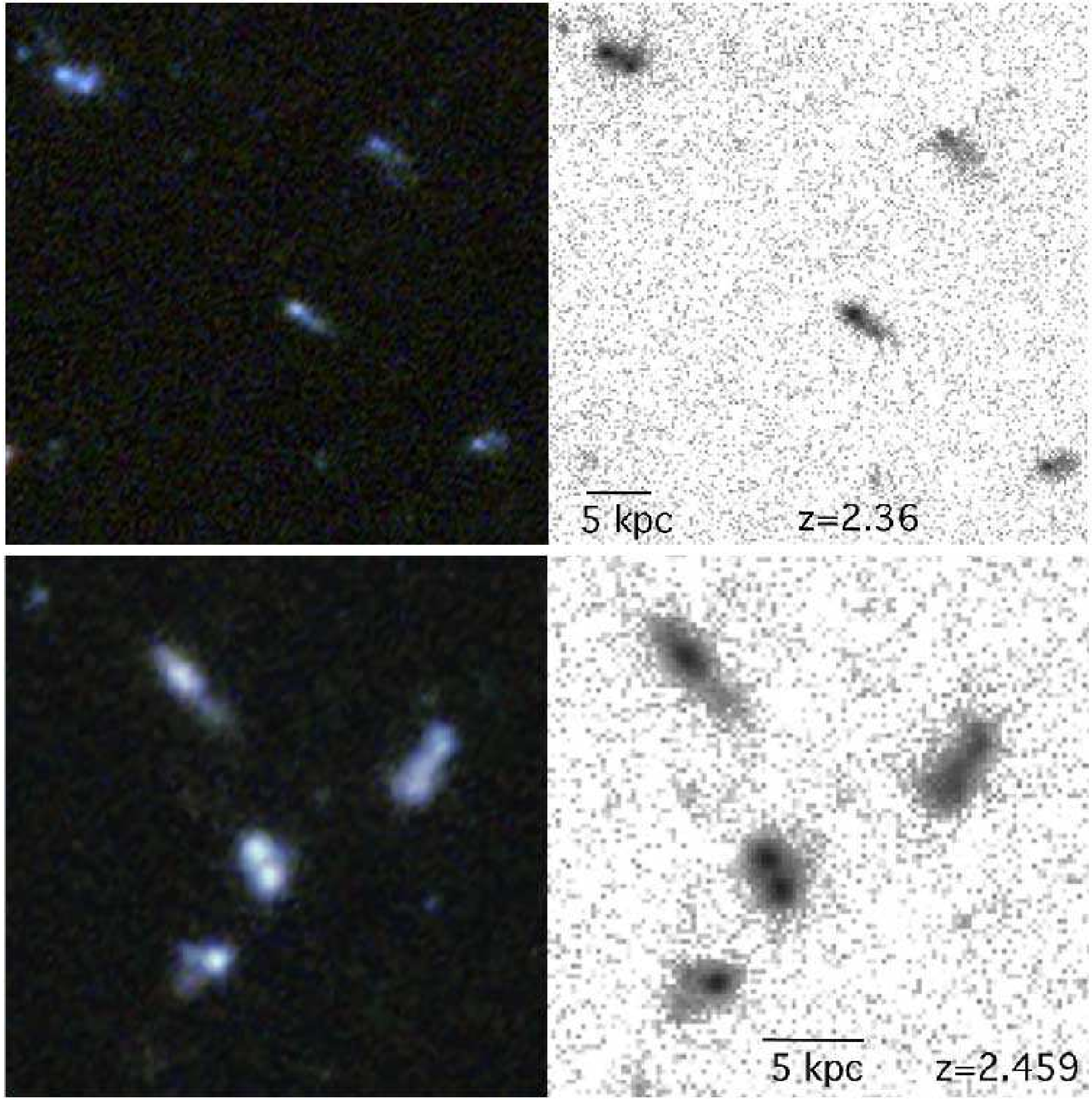
Head and Tail Sizes in Hubble UDF

→Tadpoles are relatively small galaxies



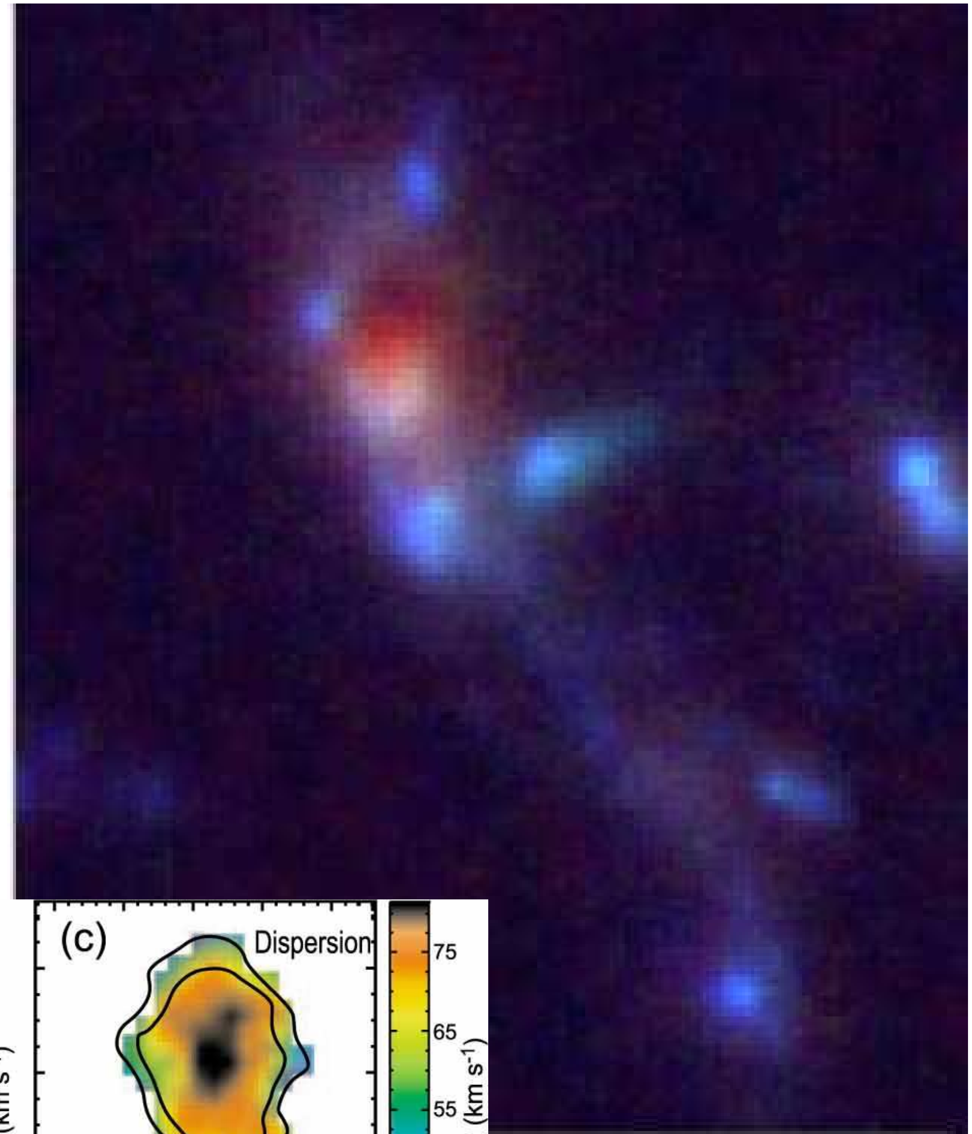
(EE10)

Odd fields with multiple tadpoles ...

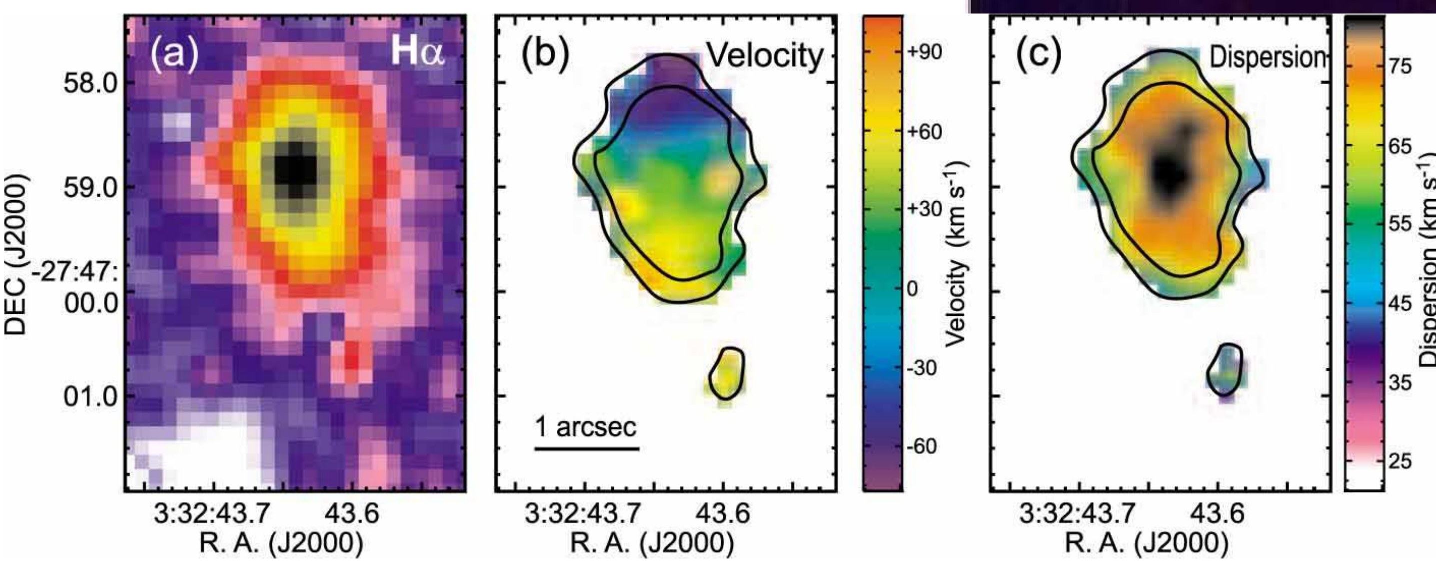


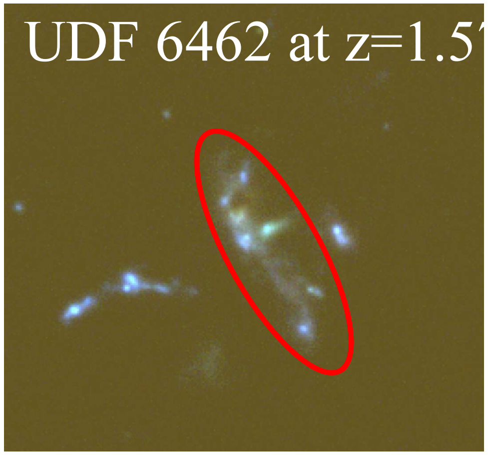
(EE10)

UDF 6462: five tadpoles in a galaxy with “normal” rotation (SINFONI)



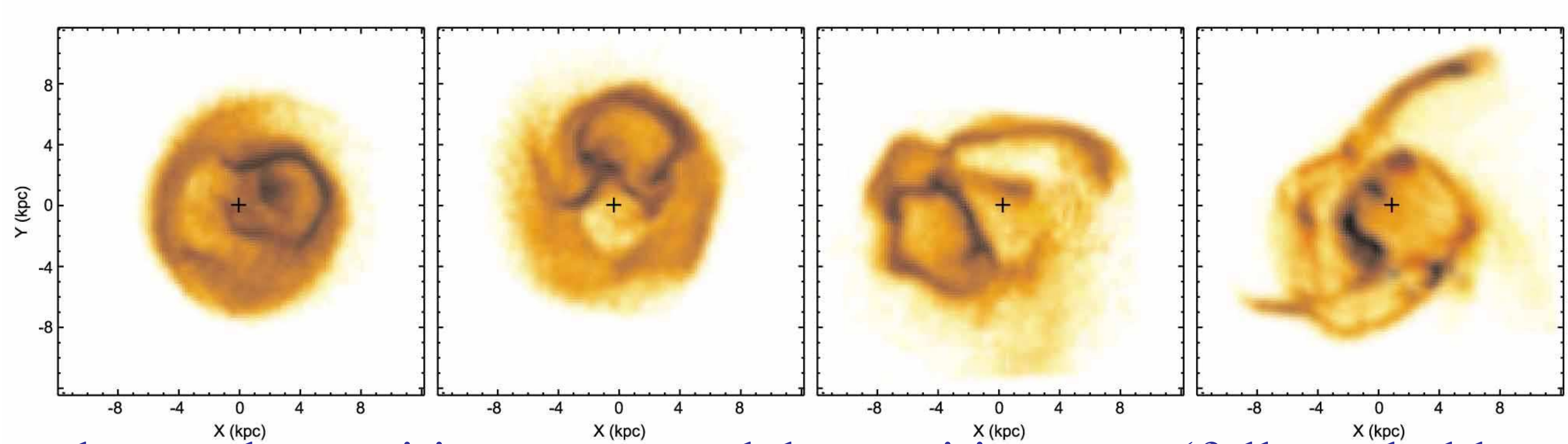
Bournaud +08



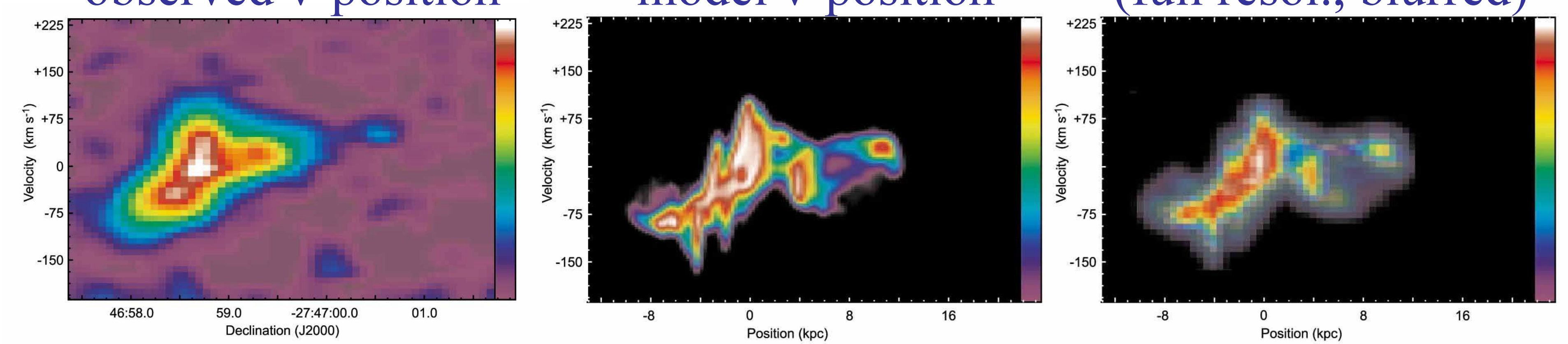


Bournaud et al. 2008:

Modeled with offset initial halo (+), $M=6x10^{10}M_O$, flat profile initially, f_{gas}=0.5, Q_{stars}=1.3, σ_{gas}=11 km/s

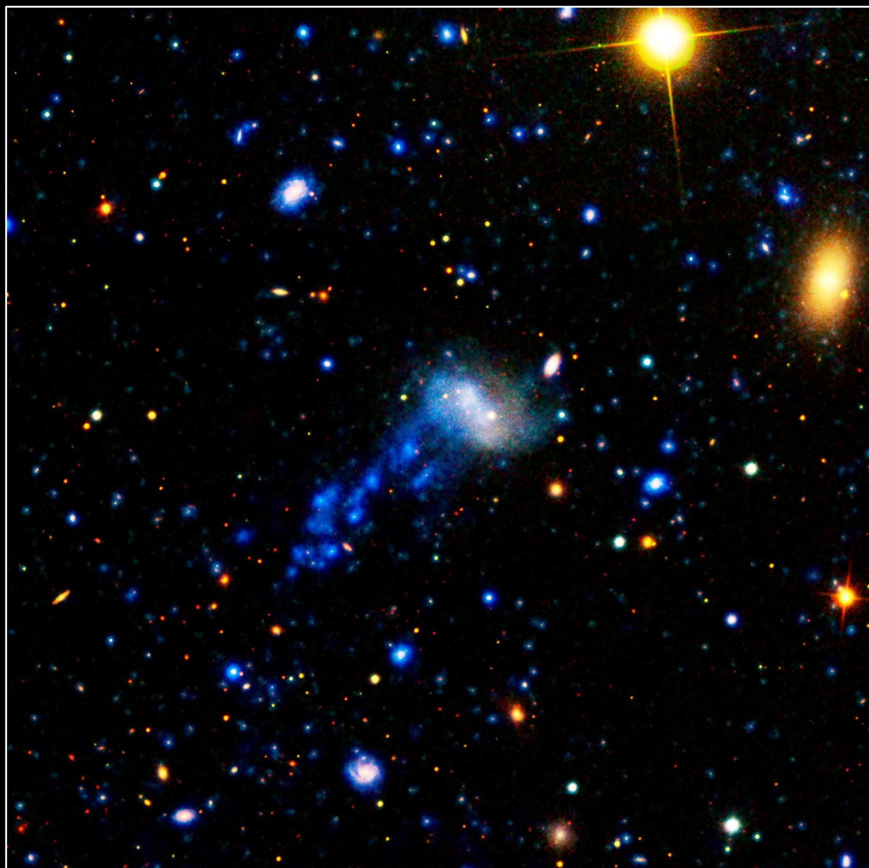


observed v-position   model v-position   (full resol., blurred)



GALEX Galaxy Evolution Explorer

Ultraviolet + Visible/GALEX + SDSS

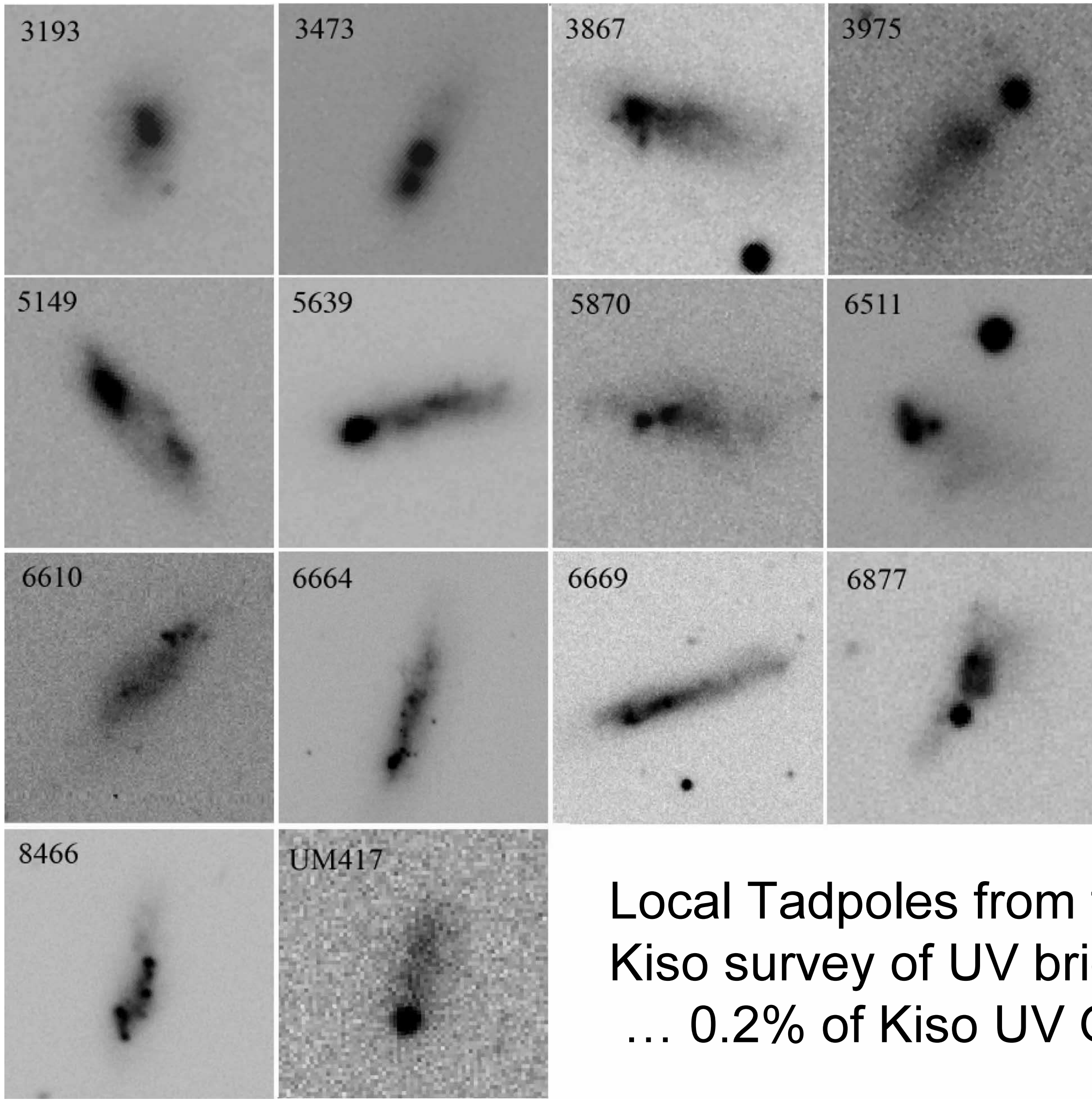


Visible/SDSS

Ultraviolet Tail of Galaxy IC 3418

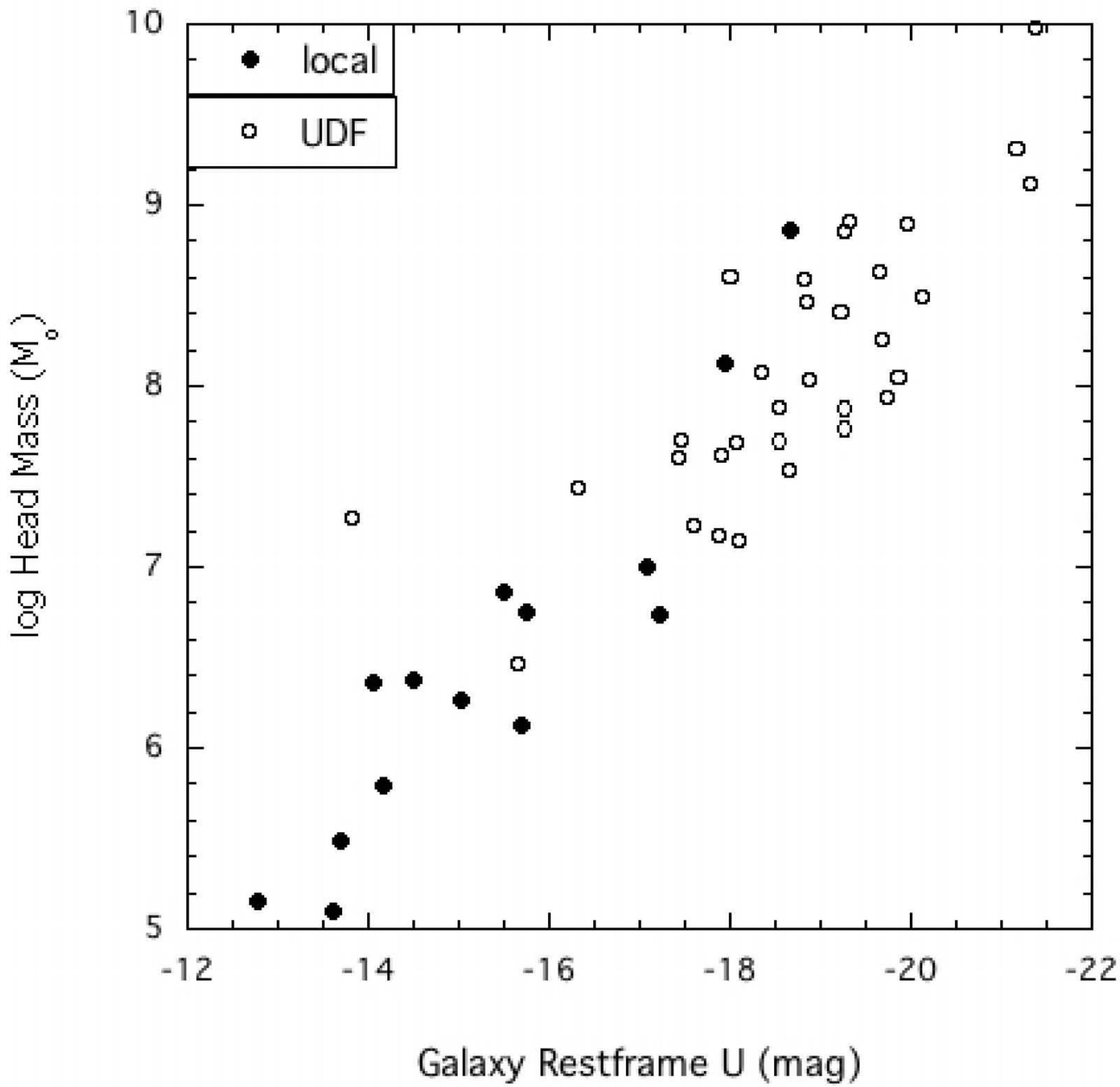
NASA/JPL-Caltech

GALEX • FUV • NUV
Sloan Digital Sky Survey

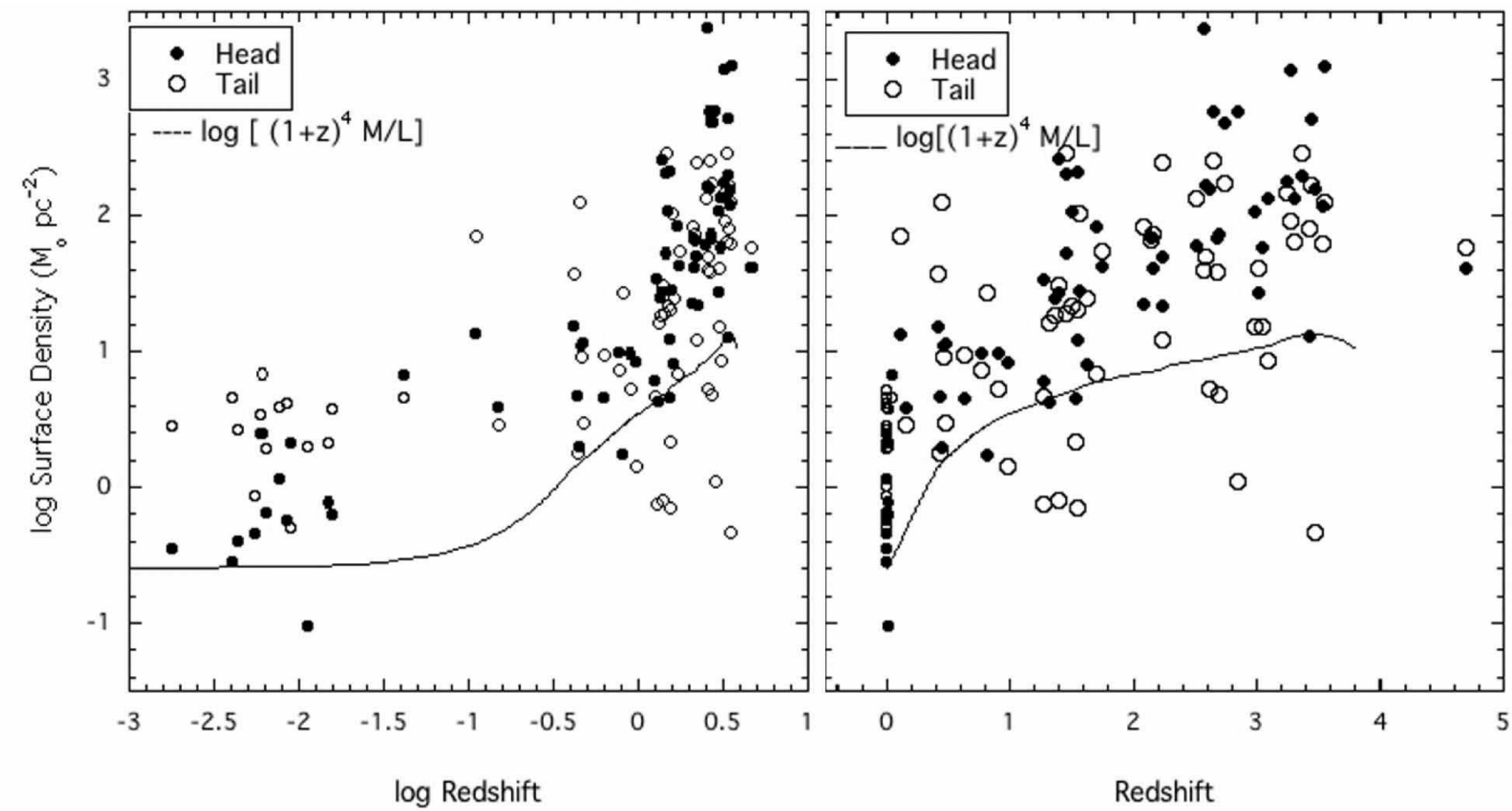


Local Tadpoles from the Kiso survey of UV bright galaxies
… 0.2% of Kiso UV Galaxies

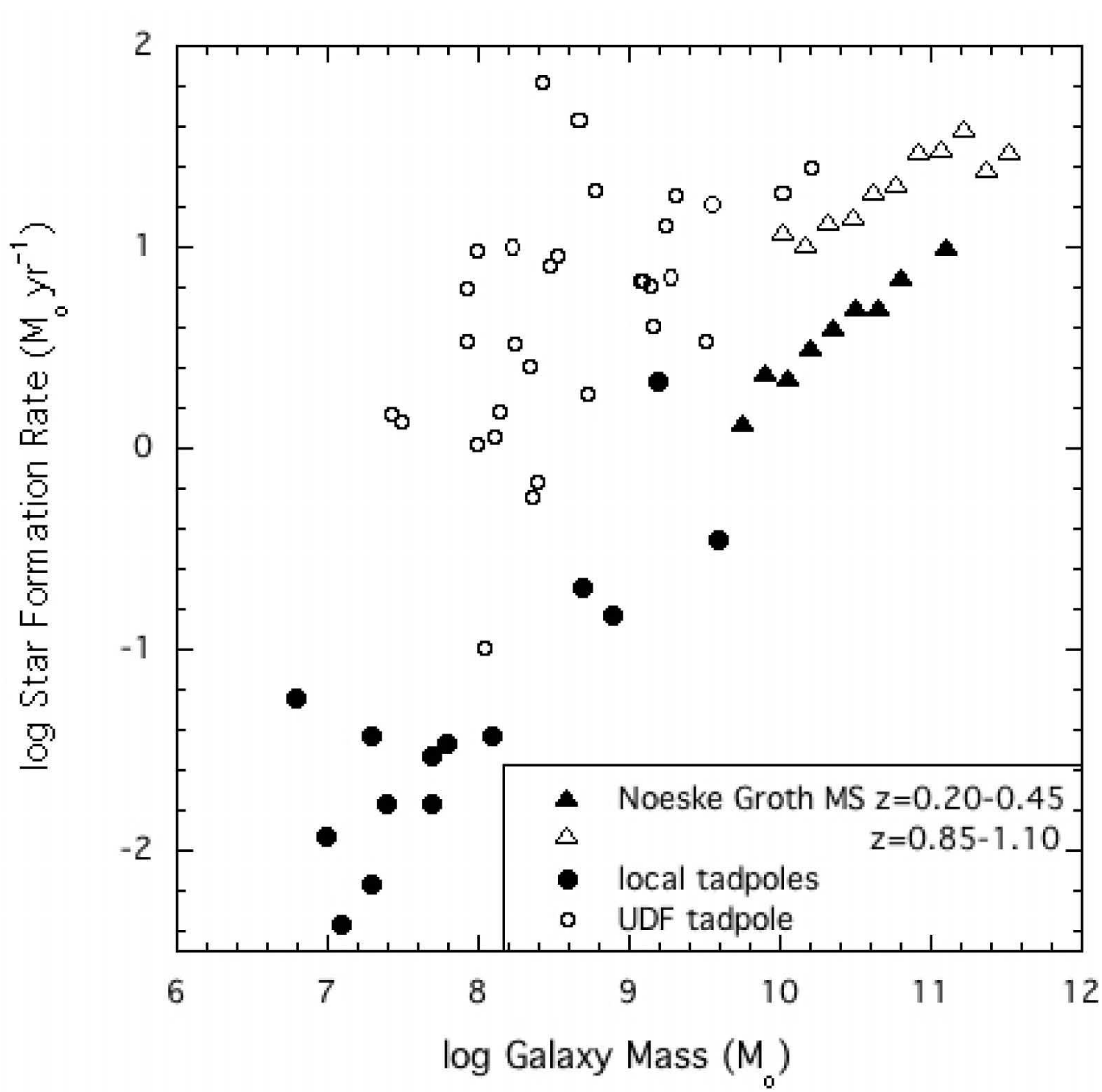
Elmegreen+12



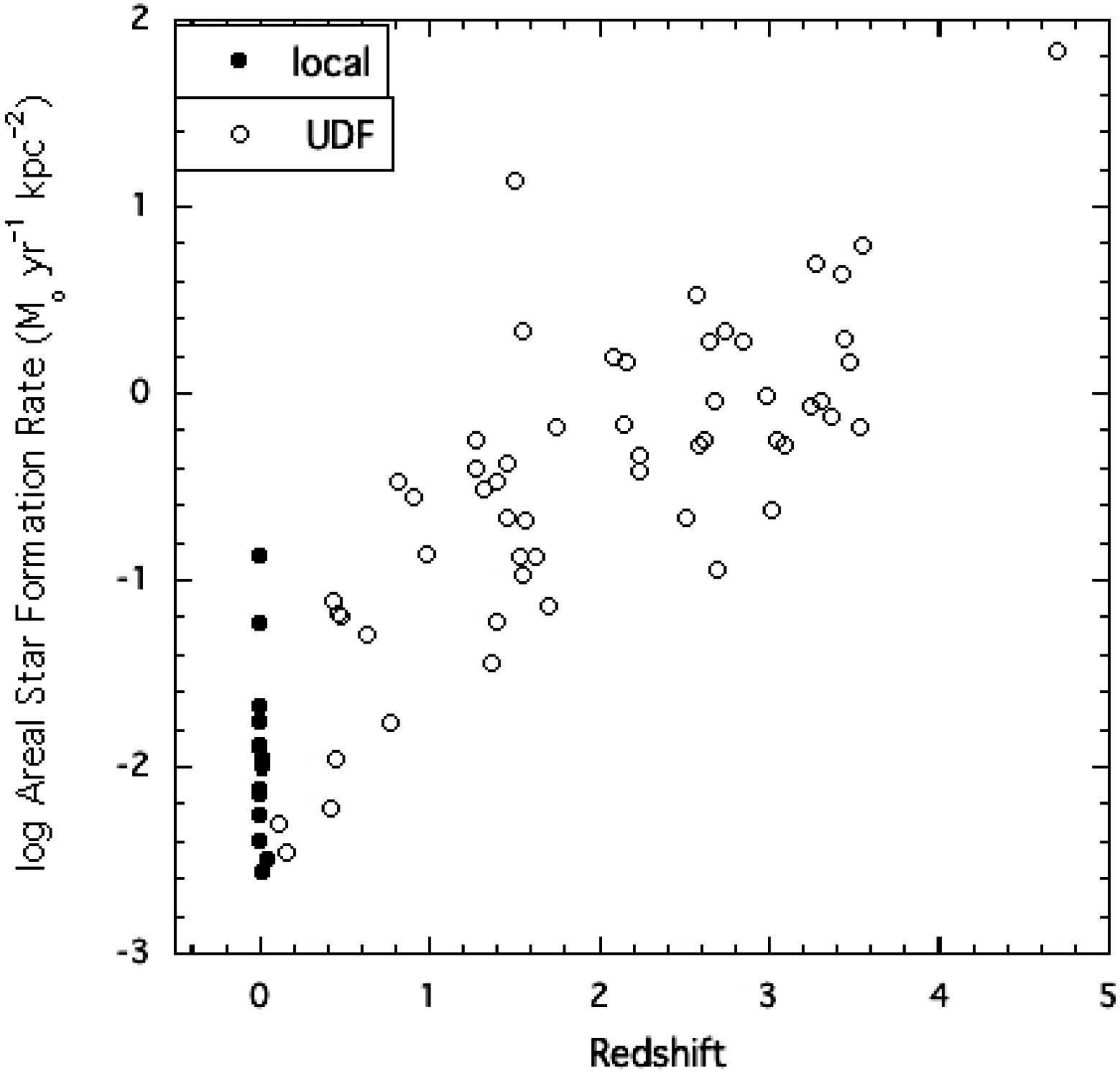
Elmegreen+12



Elmegreen+12



Elmegreen+12

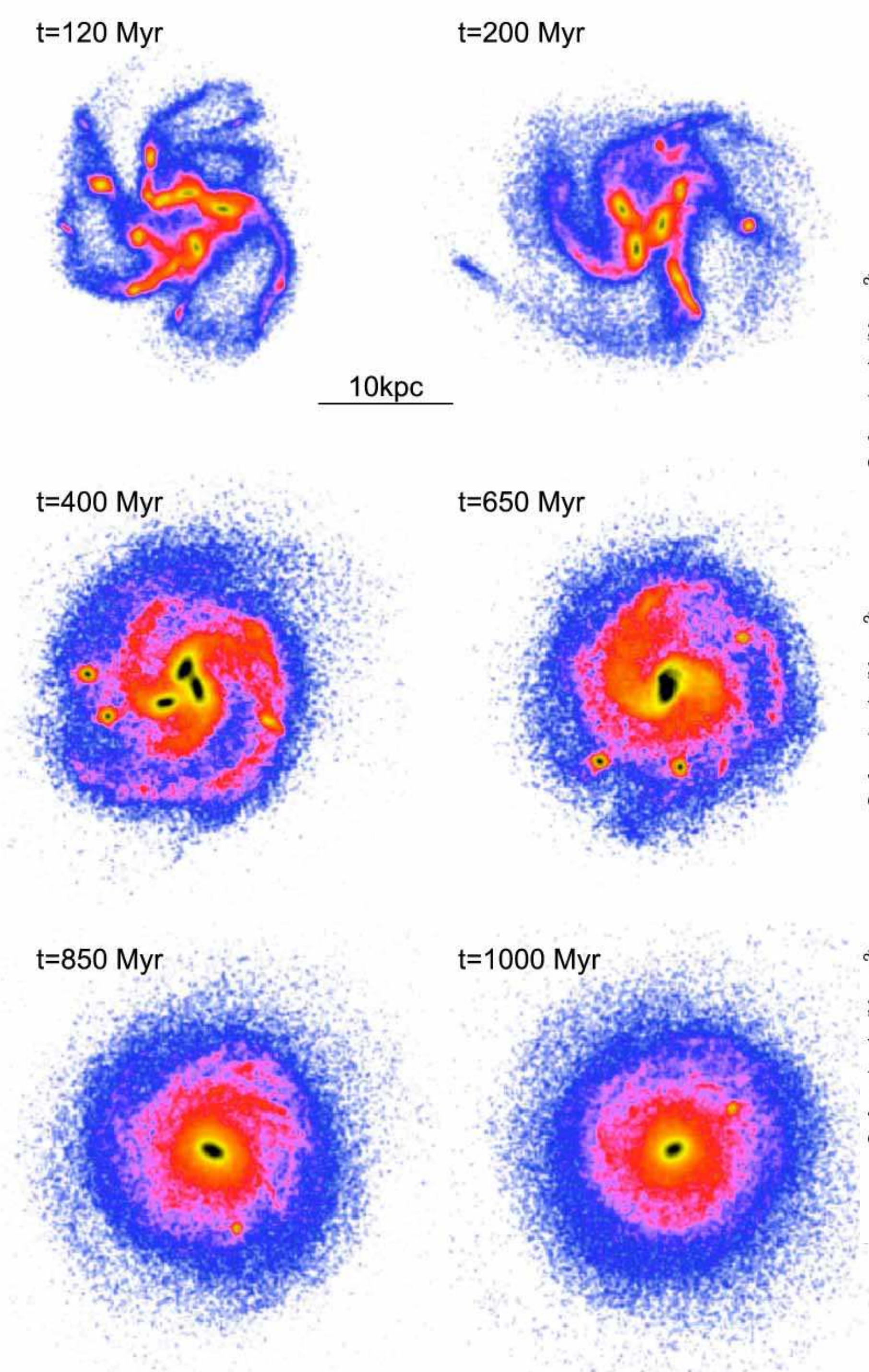


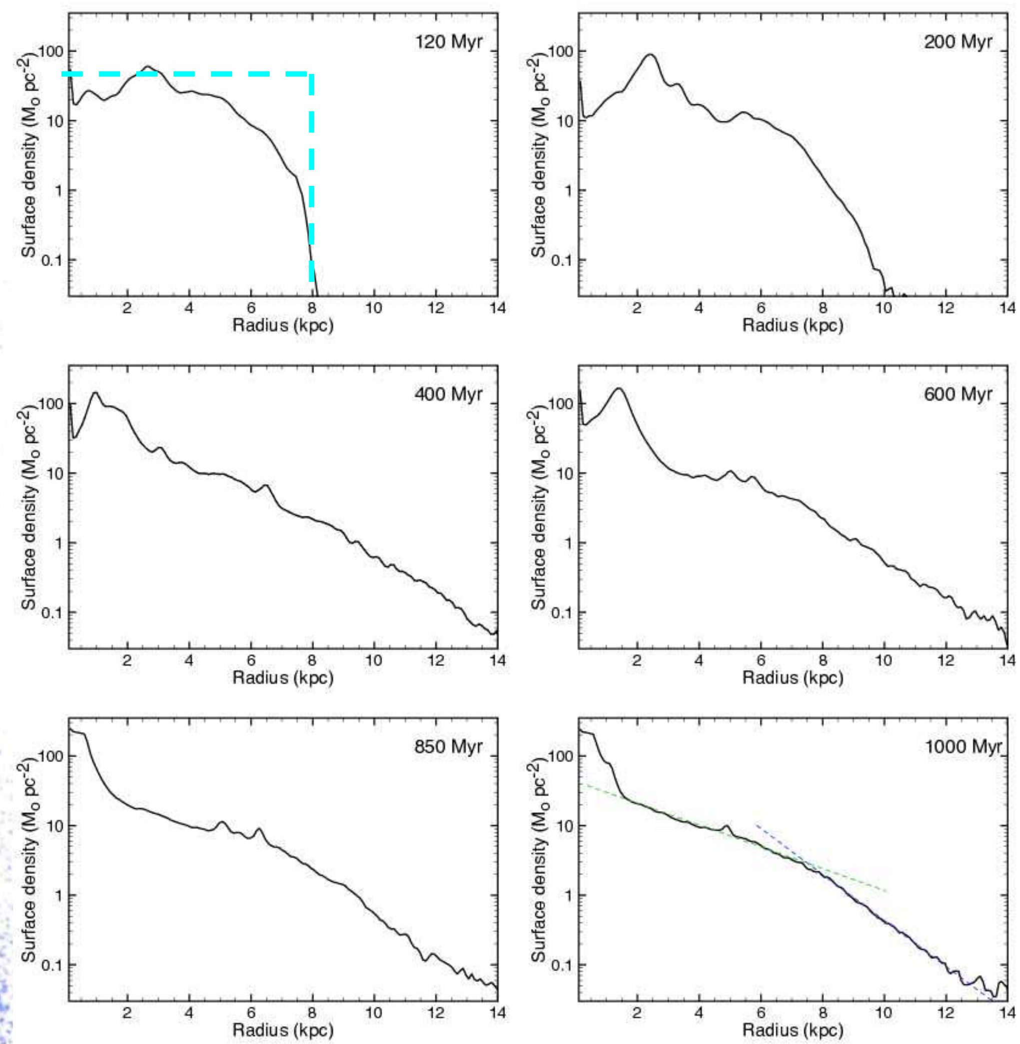
Elmegreen+12

Clump Torques

Elmegreen, Zhang & Hunter 2012

Clumps interact with each other and with disk/halo

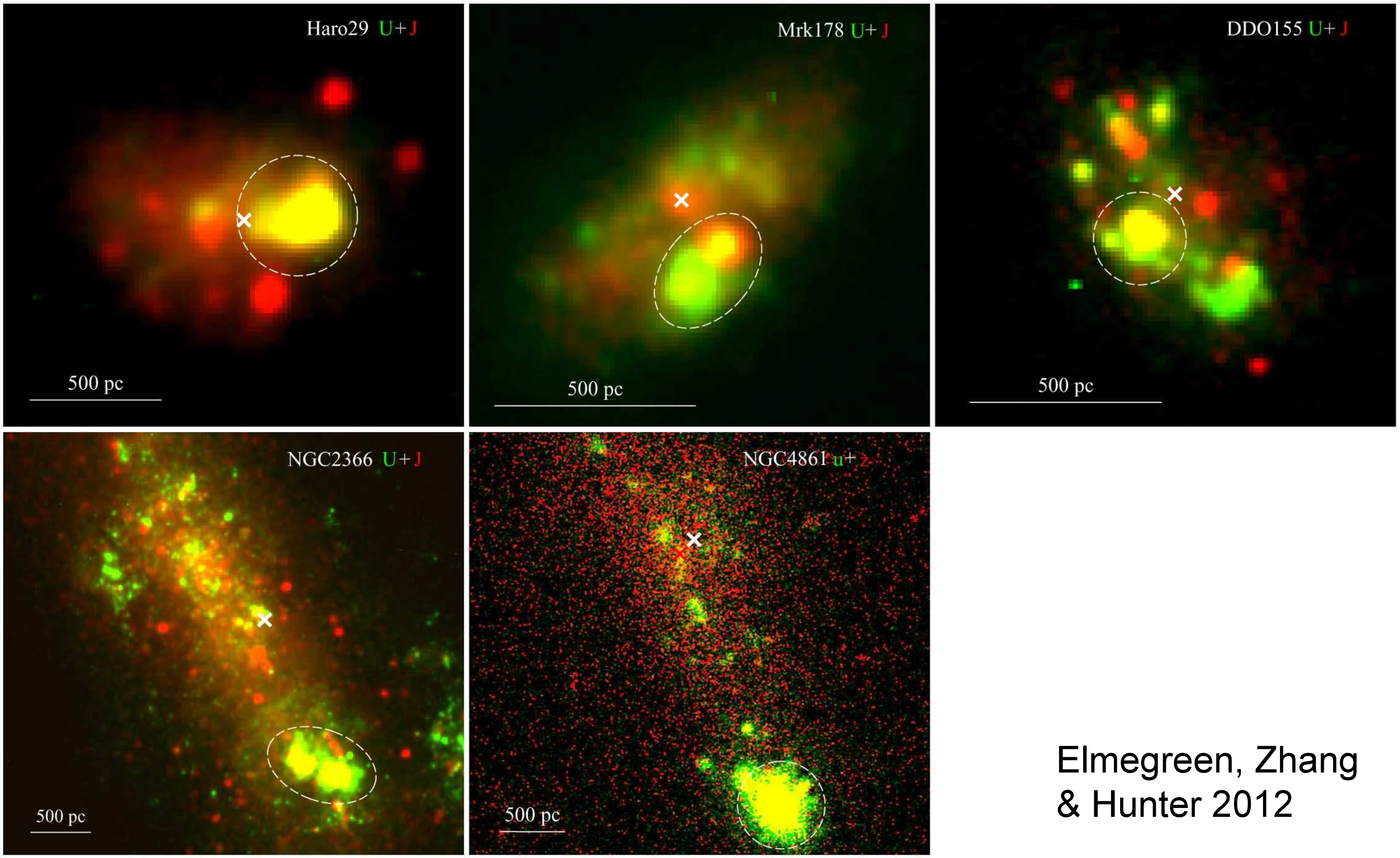




Bournaud, Elmegreen & Elmegreen 07

Will the clumps in today's dwarf galaxies also move to the center?

Consider the most extreme cases, the BCDs.



Elmegreen, Zhang & Hunter 2012

Accretion time from dynamical friction between a clump of mass M_c and a halo of non-rotating particles, in units of the orbit time, r/v:

$$T \equiv \frac{v^2}{r(dv/dt)} = \frac{1}{\ln\Lambda\xi(1+2\beta)} \times \frac{M_{\rm dyn}(r)}{M_{\rm c}} = T_0(r)\frac{M_{\rm dyn}(r)}{M_{\rm c}}$$

ln Λ = Coulomb factor (~3-4)

β= slope of rotation curve at position of clump

M_{dyn}(r) = total mass inside radius of clump

ξ = erf(X)-2Xexp(-X^2)/$\pi^{1/2}$ for X=V/($2^{1/2}\sigma$) with rotation speed V, dispersion σ

Elmegreen, Zhang & Hunter 2012

Table 1. Sample BCD Galaxies and their Clump Properties[a]

Galaxy	D Mpc	log M_s $M_\odot$	log M_b $M_\odot$	log M_c $M_\odot$	r_c kpc	Aperture kpc	log $M_{dyn}(r_c)$ $M_\odot$	$M_c/M_{dyn}(r_c)$	ln Λ	T Gyr
Mrk 178	3.9	7.04	7.39	5.13	0.39	0.32	6.60	0.035	3.4–4.3	0.50–1.4
DDO 155	2.2	6.47	7.22	5.46	0.21	0.24	6.78	0.048	3.2–3.9	0.12–0.37
Haro 29	5.9	7.16	8.06	6.33	0.27	0.74	6.26	1.17	1.3–2.3	0.03–0.06
NGC 2366	3.4	7.84	9.04	6.23	1.31	0.93	8.08	0.014	3.6–4.0	1.3–4.2
NGC 4861	7.6	8.04	8.83	6.89	2.07	0.67	8.48	0.026	1.8–1.8	1.7–6.3

[a] D is the distance, M_s is the galaxy stellar mass, M_b is the galaxy baryonic mass, M_c is the clump stellar mass, r_c is the clump galactocentric radius, *Aperture* is the aperture size used for clump photometry, M_{dyn} is the galaxy dynamical mass inside r_c, Λ is the Coulomb factor, and T is the clump accretion time. For the latter two, we assume $\xi = 0.2$ and a rotation curve slope $\beta = 0.5$ in the first case (NFW core), and $\xi = 0.03$, $\beta = 1$ in the second case (Burkert core), with factors of 0.40 and 0.33 in T, respectively, to account for the decrease in M_{dyn} with radius.

NFW core

Burkert core

Elmegreen, Zhang & Hunter 2012

The BCD "phase"

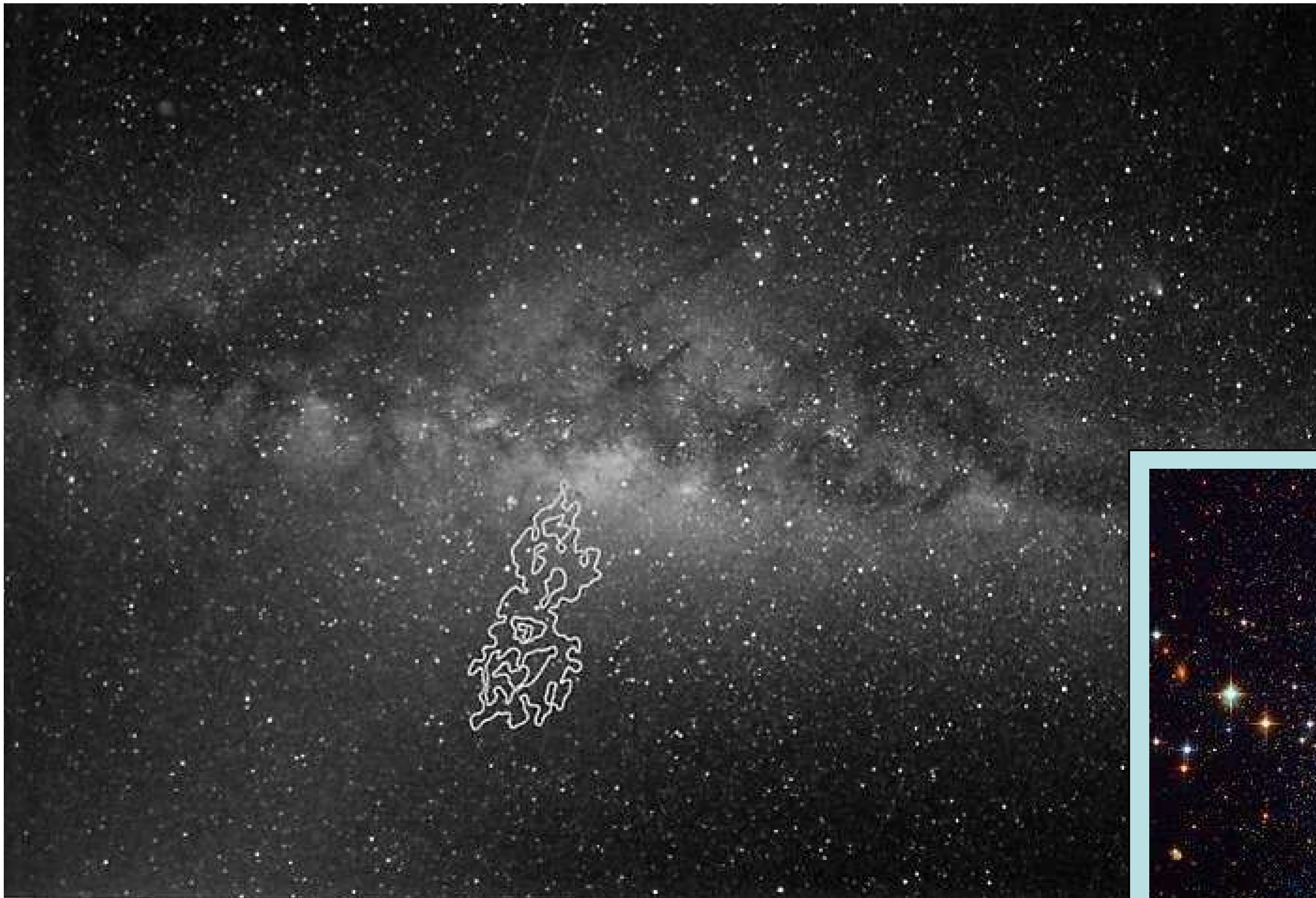
- Merger/Interaction driven, like a starburst in a major merger.
- Internally driven, like bulge-formation in a clumpy galaxy
  - BCD duration: ~Gyr
  - BCD structure: centrally condensed (gas,stars)
  - BCD "bulge": $H/R_d \sim 1$ in center using $H=\sigma^2/\pi G\Sigma$
    - $H = 750\ \mathrm{pc}\ (\sigma/10\ \mathrm{km/s})^2\ /\ (\Sigma/10\ M_O/\mathrm{pc}^2)$
    - $R_d \sim 500\ \mathrm{pc}$

Galaxy	Σ $M_\odot$ pc^{-2}	H kpc	R_d kpc	H/R_d
Mrk 178	4.9	1.8	0.27	6.7
DDO 155	7.4	1.0	0.22	4.5
Haro 29	39	0.19	0.20	0.95
NGC 2366	0.66	1.3	3.7	0.35
NGC 4861	10	0.74	1.0	0.74

Σ is stellar mass/area: comparable amounts in HI are observed and even more in H_2 is expected, lowering H/R_d by 1/2--1/3

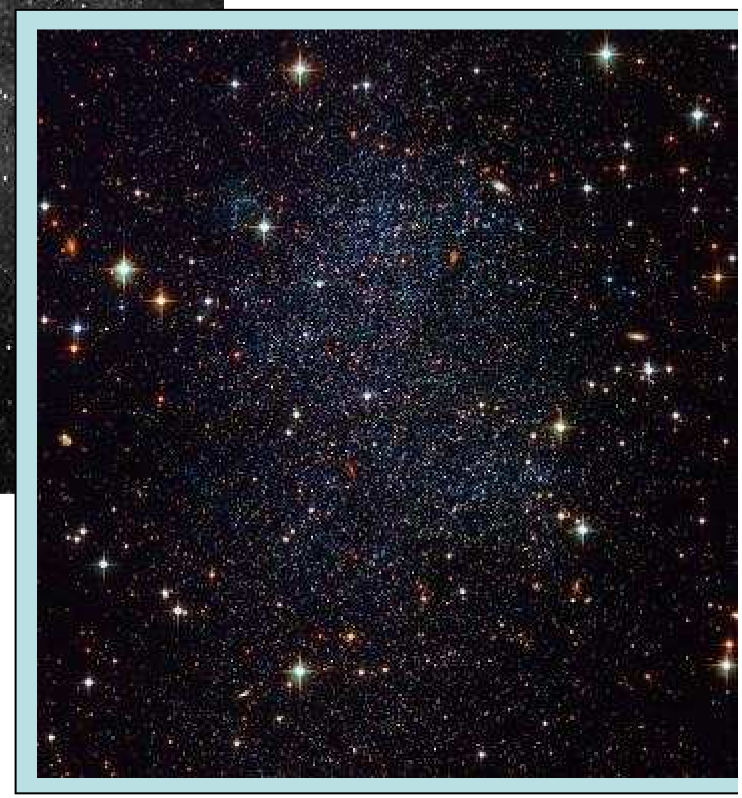
Cluster Formation

Elmegreen, Malhotra, Rhoads 2012 submitted



Associated GCs:
Terzan 7, Terzan 8,
Arp 2, M54,
Whiting 1

Ibata, Gilmore, Irwin 94



NASA, ESA

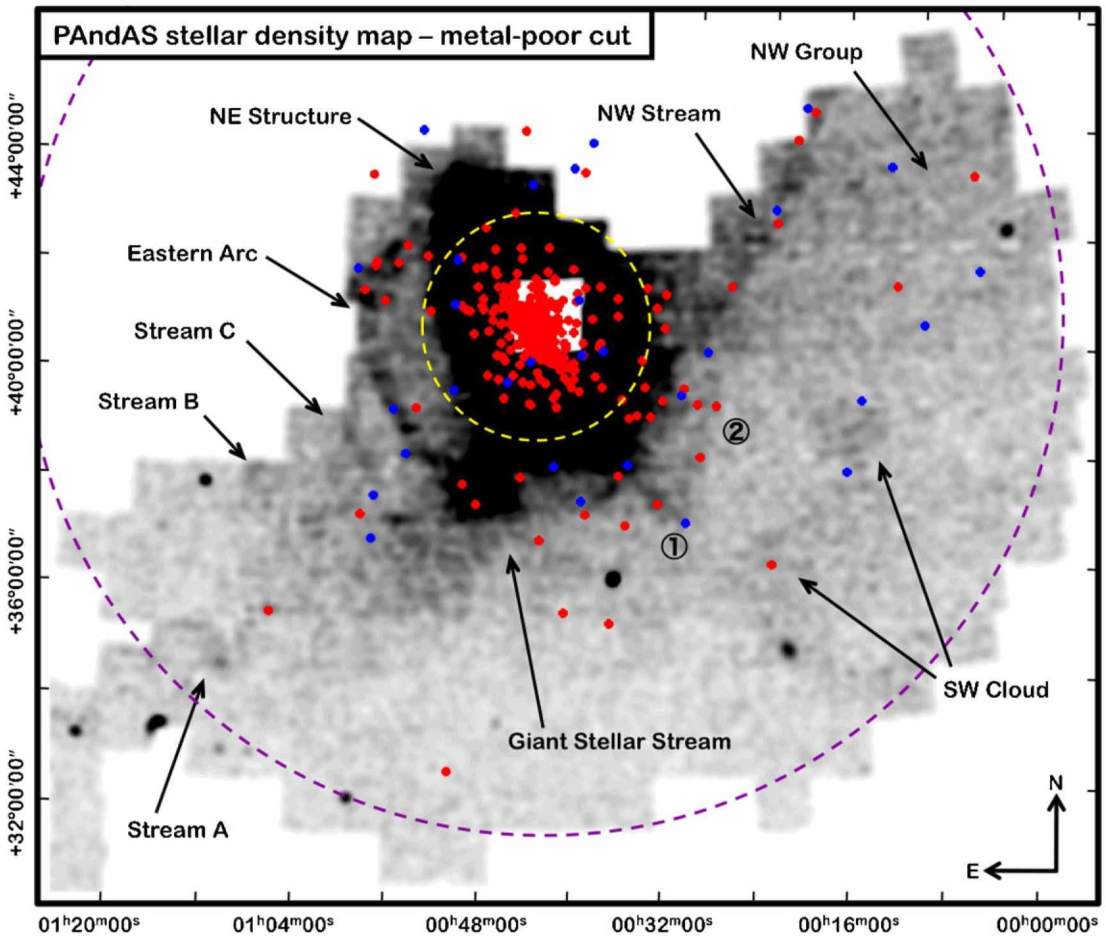
Sagittarius Dwarf Galaxy:

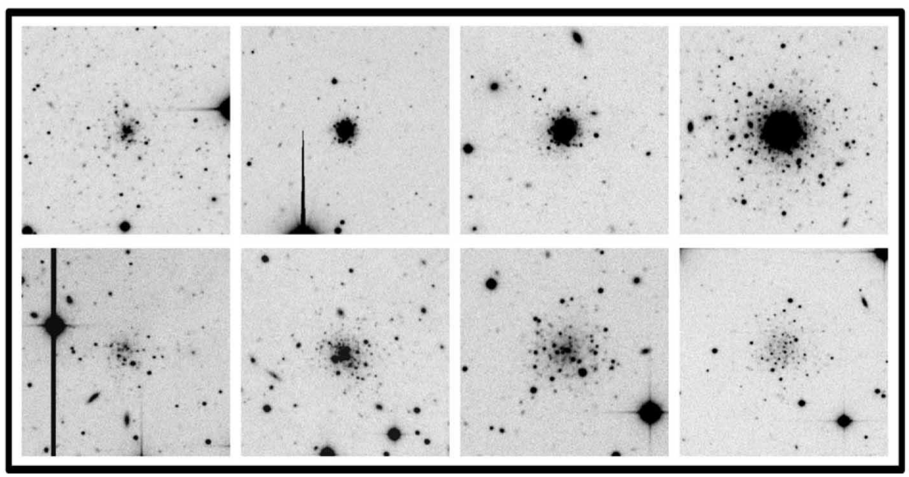
- Halo GCs can enter the MW in dwarf galaxies

Mackey et al. (2010)

M31 star streams with globular clusters

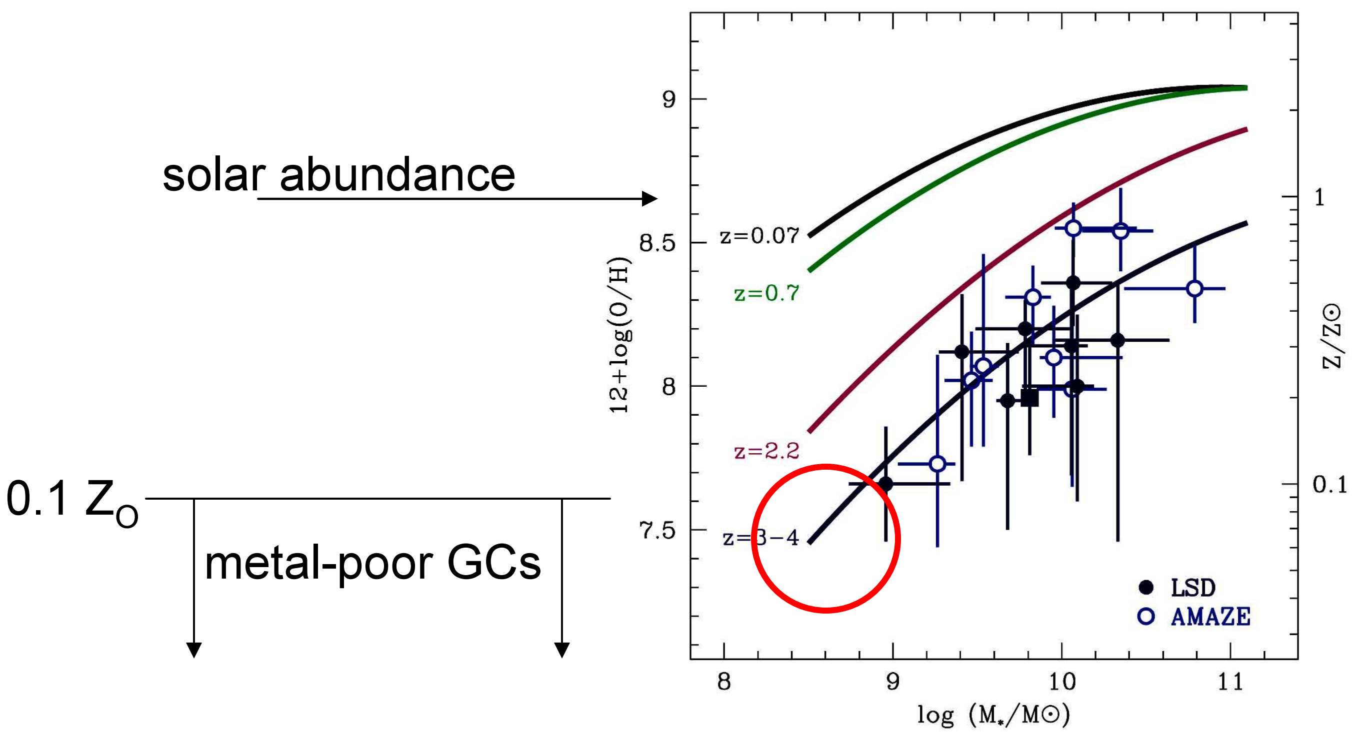
(red = compact,
blue = extended)





Metal Poor GCs form in dwarf galaxies
(Searle & Zinn ’78; Zinnecker ’88)

- Low metallicity of halo GCs comes from the mass-metallicity relation of galaxies at intermediate to high redshift

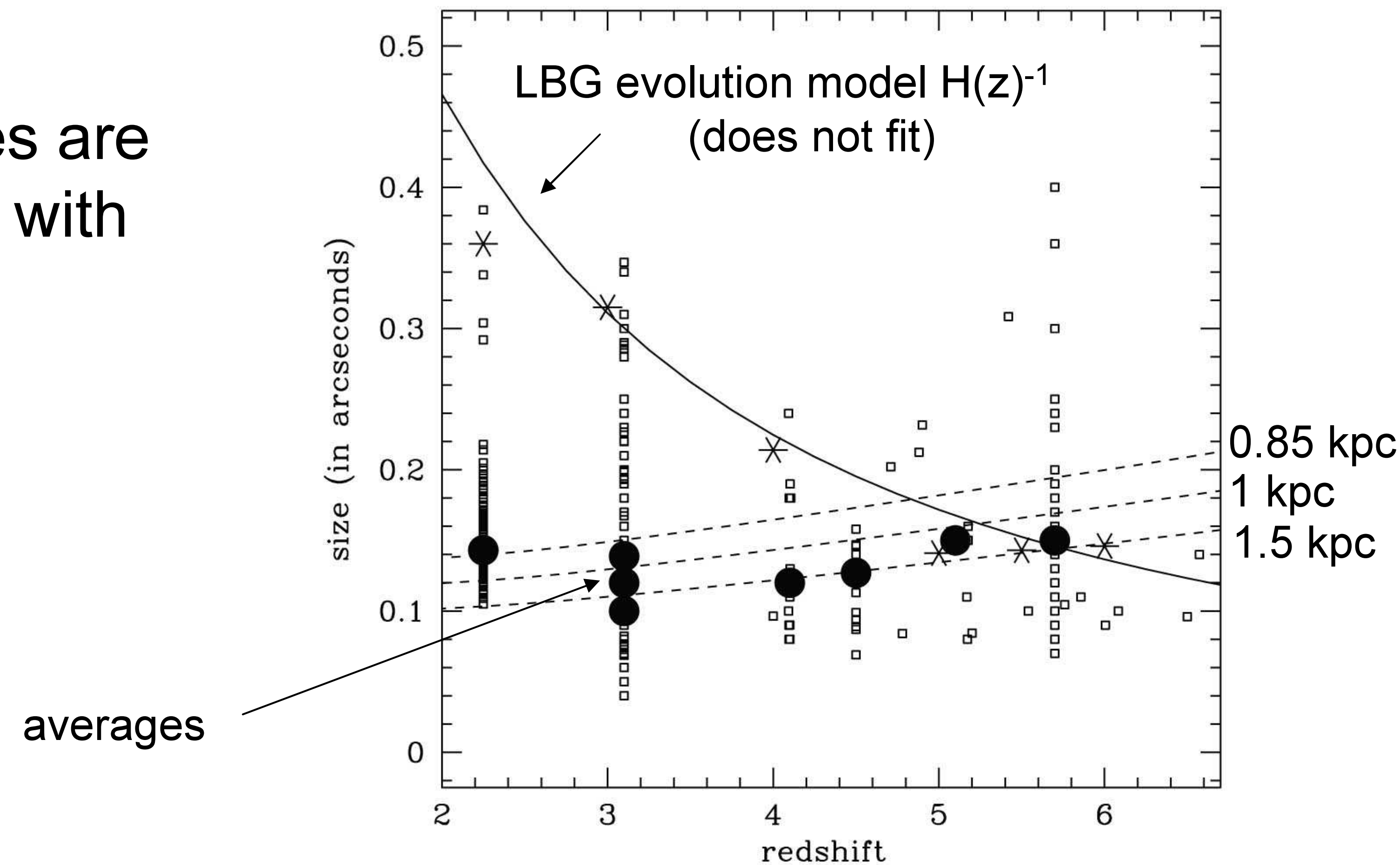


Mannucci +09

LAE galaxies as GC formation sites

- LAE masses ~ 10^7 M_O – 10^8 M_O (Pirzkal +07, Finkelstein +07), some larger (Finkelstein +09)
- Ages ~ 10^7 yrs (Pirzkal +07,Gawiser +07, Finkelstein+07,08,09)
- Metal poor: ~0.1 Z_O (Finkelstein +11, Richardson +12)
- compact: ~1 kpc (Pentericci +09, Bond +09,10)
  – size does not change with redshift (Malhotra +12)

LAE sizes are constant with redshift.



Malhotra et al. 2012

GC space density

- Today's GC density of ~8 Mpc^{-3} (Portegies Zwart & McMillan '00) is about half metal-poor and half metal-rich

  ~4 metal poor GCs Mpc^{-3} today

- GC evaporation mass ~$2.3 \times 10^5\ M_{\odot}$ (McLaughlin & Fall '08)
  - approximation: all of today's GC with $M > 2 \times 10^5\ M_{\odot}$ (the peak in the GCMF) survived evaporation phase
  - $M > 2 \times 10^5\ M_{\odot}$ GCs account for half the total
- Thus the birth density was ~2 Mpc^{-3} for GCs that formed today's metal poor GC with $M > 2 \times 10^5\ M_{\odot}$

How does a $2x10^5$ M_O cluster form?

- Initially more massive (x10) with other clusters and stars, in a $\sim 10^8$ M_O SF region lasting several 10's Myr, maybe 100 Myr.
  - Subsequent SF in the enriched debris of slow stellar winds would have been much dimmer (lasting ~100 Myr).
- The cluster itself, at $2x10^6$ M_O, would have dominated the light during its ~5-10 Myr first-generation formation time.
- With a standard initial cluster mass function $\sim 3x10^7$ M_O of clustered stars might have formed in that ~10 Myr

$3 \times 10^7\ M_O$ of stars in 10 Myr = $3\ M_O$/yr

- With ~1 mag of pre-ionization absorption
- Lyα line luminosity ~ 10^{42} erg s^{-1} with 100% escape fraction, and 2.5×10^{41} erg s^{-1} with more likely 25% escape fraction
  - Blanc +11,Zheng +12,Richardson +12
- Integrating the LAE Luminosity function
  - log(L*) = 42.86+-0.06 and φ*=-3.55+- 0.09, slope=-2

  down to this luminosity gives 0.007 Mpc^{-3} of observable LAE galaxies with SFR to form a GC

Correct for duty cycle of LAEs:

- LAE galaxies observed from z=2 to 7, a period of ~2.5 Gyr, but their duration is only ~10 Myr. Thus probability of observation during GC formation is 0.4%.
- Total formation density of $M>2\times10^5\ M_O$ GC is thus 0.007 Mpc^{-3}/0.4%=1.8 Mpc^{-3}
  - comparable to present day space density of metal-poor GCs with $M>2\times10^5\ M_O$ (~2 Mpc^{-3})

Lower mass GCs:

- An initial GC mass function of $dn(M)/dM \sim M^{-2}$ is the same power-law form as the LAEs luminosity function at low L: $d\varphi/dL \sim L^{-2}$
- If the number of GCs with $M>2 \times 10^5 M_O$ equals the space density of LAE's having the required luminosity, then the number of GCs with $M<2 \times 10^5 M_O$ does also.

→ The metal-poor GCs could have been made in dwarf galaxies during a LAE phase

SUM: Dwarf Irr vs high-z galaxies

- Dwarf galaxies today look like scaled-down versions of high-z massive galaxies
  - $\sigma/V \rightarrow$ morphology (thickness, clumpiness)
  - high gas fraction
- Example: tadpoles at high and low z
- The BCD phase may be analogous to the bulge-formation phase in larger galaxies
- Lyman α emitting galaxies at high-z could be the dwarfs that deliver metal-poor globular clusters to galaxy halos today.

THE END