Galaxy Evolution : Emerging Insights and Future Challenges

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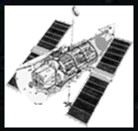


- F. Barazza, I. Marinova, A. Heiderman T. Weinzirl, S. Miller, K. Penner
- GEMS, GOODS, STAGES, COMA collaborations

H.-W Rix, C. Wolf , M. Barden, E. Bell, D. McIntosh, C. Peng, R. Somerville,
S. V. W Beckwith, M. Gray, D. Carter, I. Shlosman, C. Conselice, C. Papovich (SpitzerGTO)

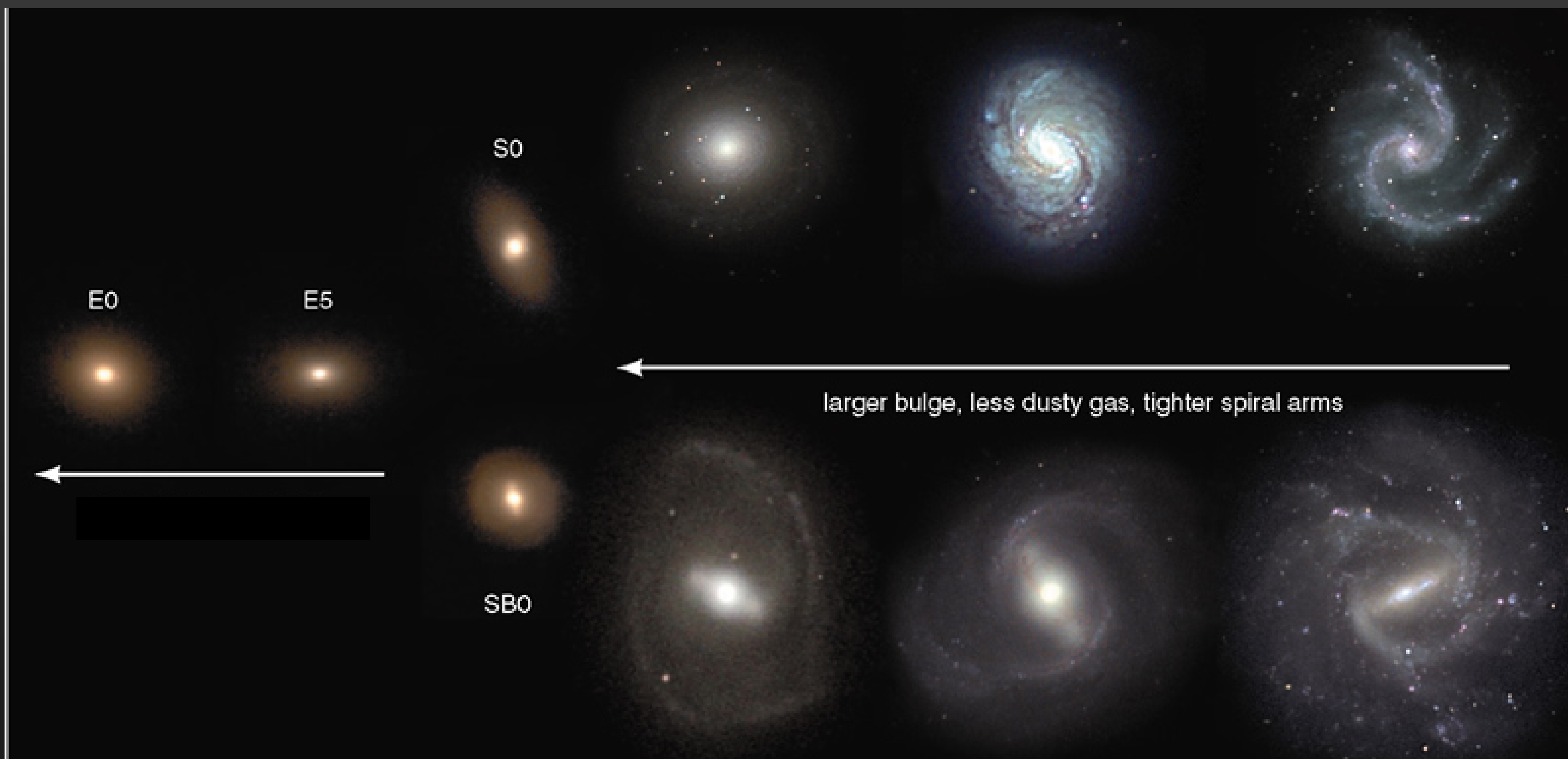
Present –day Hubble sequence

à Ellipticals

à Barred and unbarred disks (e.g., Sa– Sd)

à Irreguliar , Peculiar/Interacting

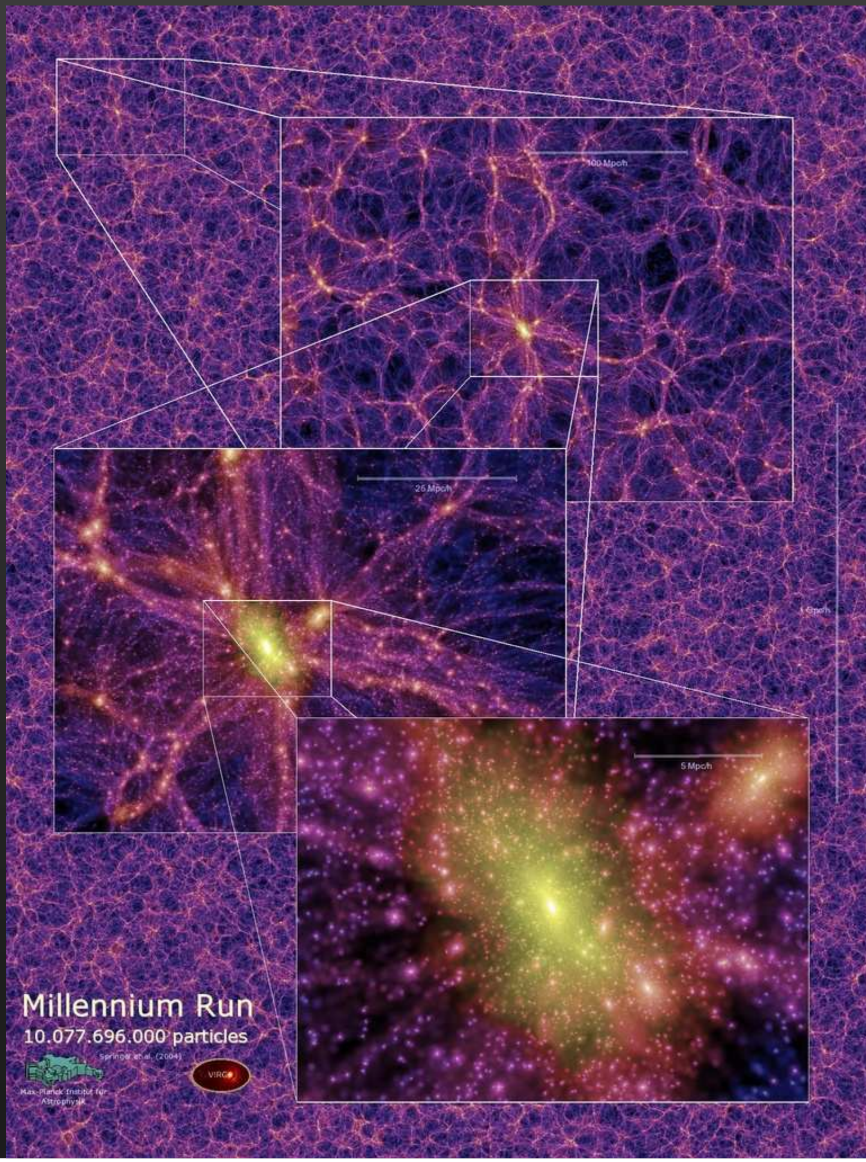
SAa SAb SAc

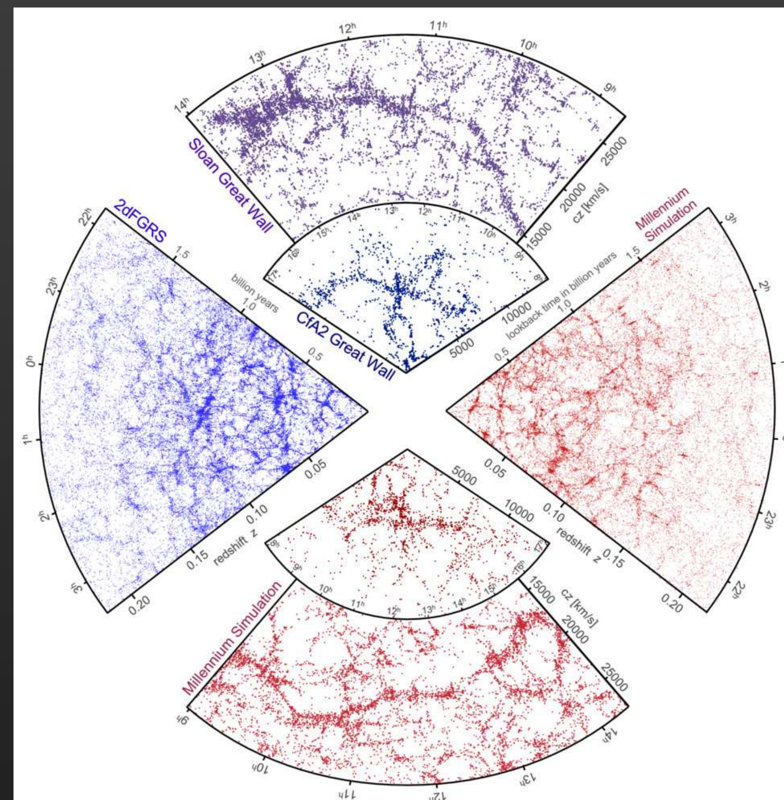


SBa SBb SBc

ΛCDM models

ΛCDM models = good paradigm for how structure and DM evolves on large scales



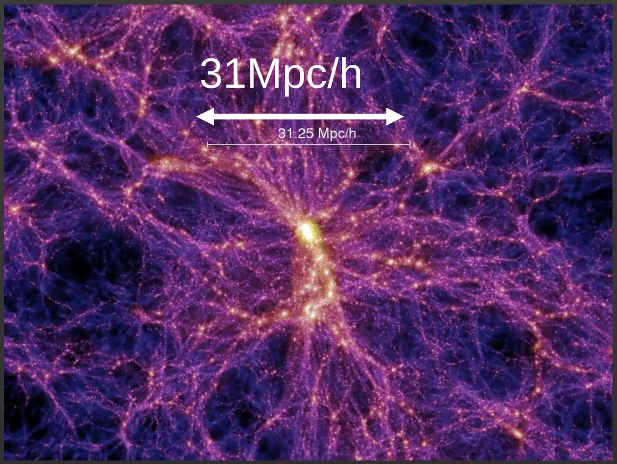


(Springel et al. 2005)

Millenium Run : 10^{10} particles
Follows DM in region D=15 Mpc/h
Resolution = 5 kpc/h

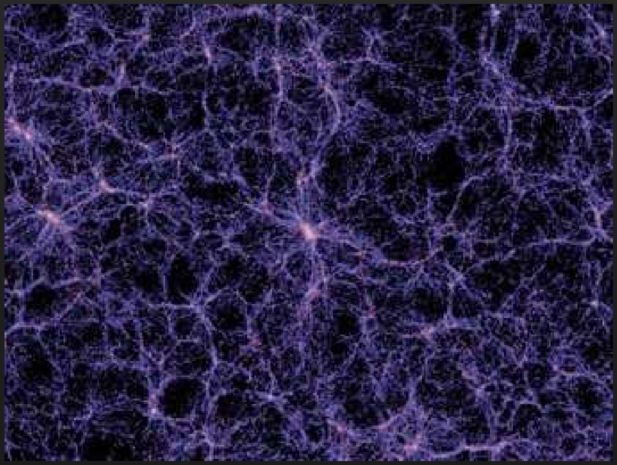
ΛCDM models

Model predictions for the evolution of galaxies depends on



DM

Light



* Dynamic range and spatial resolution

Simulations of large-scale environment cannot resolve galaxy components (bulge, bar, disk)

[$N=10^{10}$, D=500Mpc/h, Resolution~5kpc/h]

* Halo occupation statistics

* Assumed baryonic physics

Phase of ISM, star formation, feedback

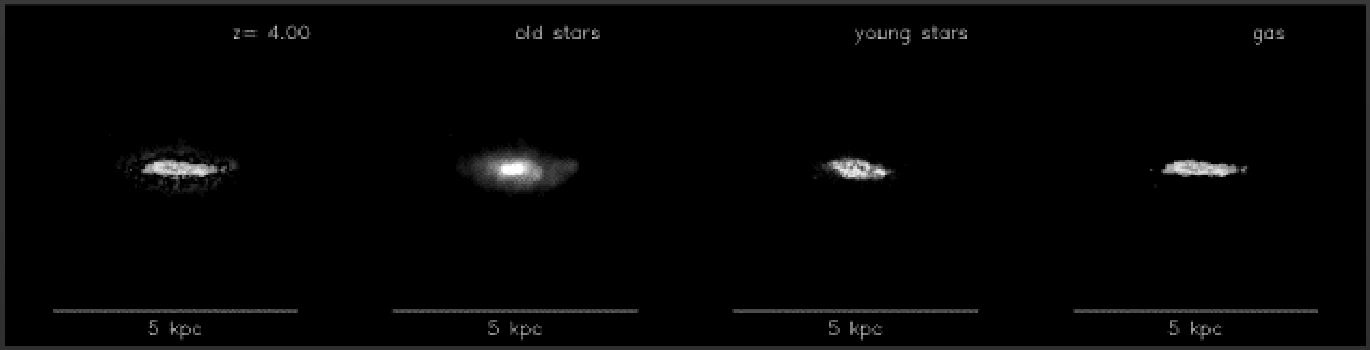
Mechanisms to redistribute ang. momentum (merger, bars, dynamical friction)

Hierarchical origin of galaxy structure

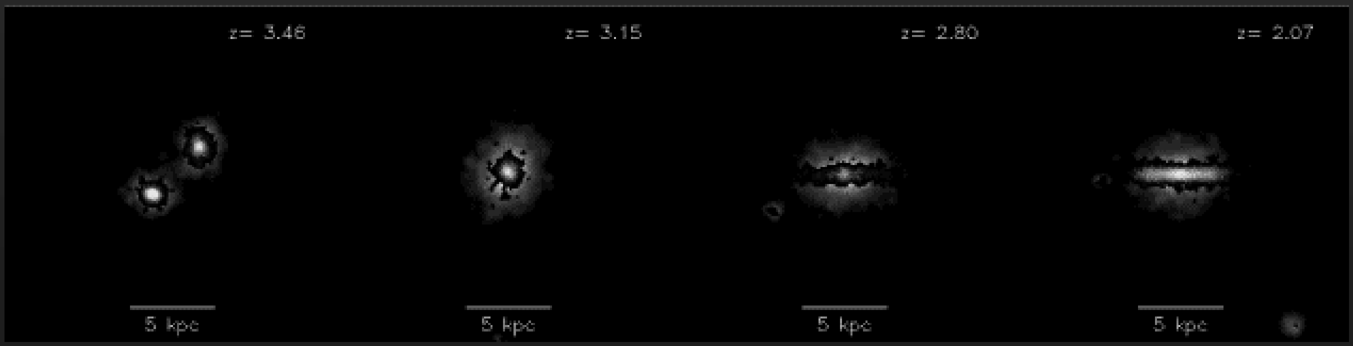
In CDM + baryonic fluid, overdensities on small mass scales collapse first
Baryons radiate and decouple from DM halo

(Steinmetz & Navarro 2002)

Old stars=red   Young stars=blue   Green=gas



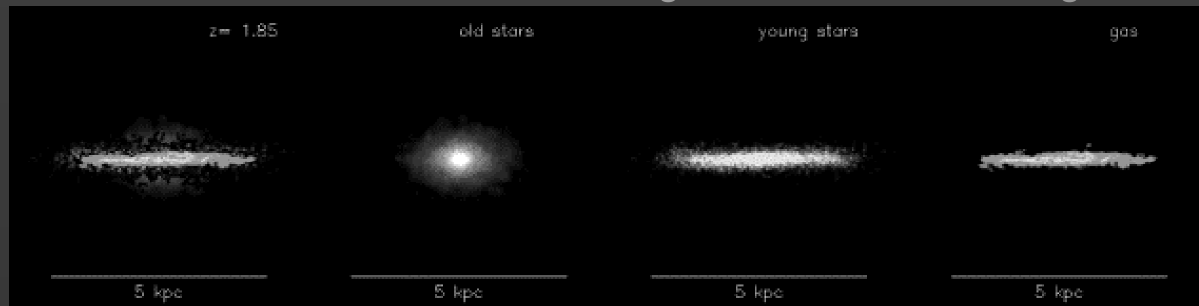
Disks build up from episodes of smooth gas accretion
Disk of gas and stars in place (M ~3e10, D~3 kpc), ongoing star formation



Major merger of two disks + SF à Violent relaxation à $R^{1/4}$ stellar bulge.

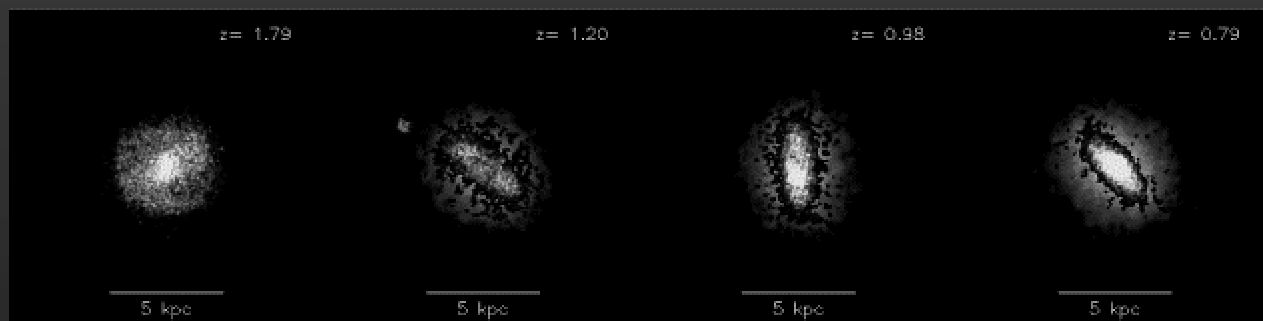
Hierarchical origin of galaxy structure

Old stars=red   Young stars=blue Green=gas

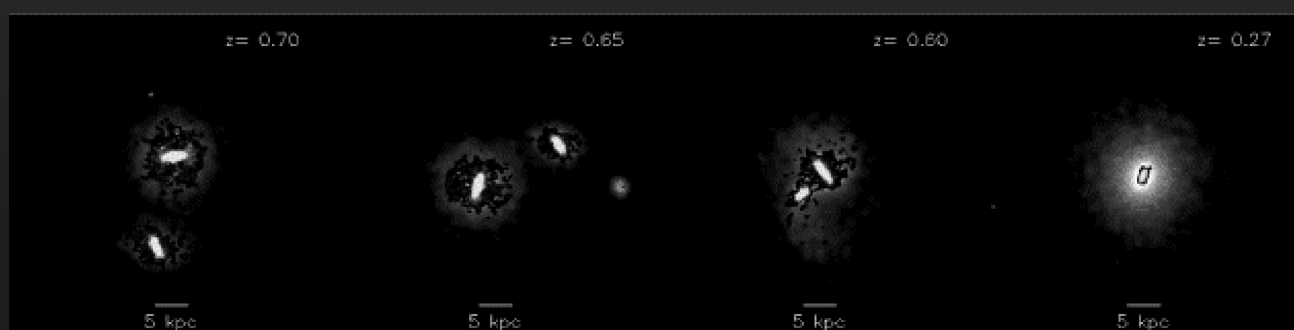


(Steinmetz & Navarro 2002)

Smooth accretion of high ang momentum gas; young disk builds around an old classical bulge.



Accretion of discrete satellites --> tidal triggering of bar. Bar persists till next major merger.



Major merger of 2 spirals à central starburst ; violent relaxation forming triaxial Elliptical

Hierarchical origin of galaxy structure

Left = face on   Right = side on

(Steinmetz & Navarro 2002)

Challenges for ΛCDM models

à No unique predictions for galaxy evolution

f (baryonic physics, resolution)

à Substructure or missing satellite problem

à . Angular momentum problem

à Bulgeless galaxy problem

Empirical Approach

Rely on observations

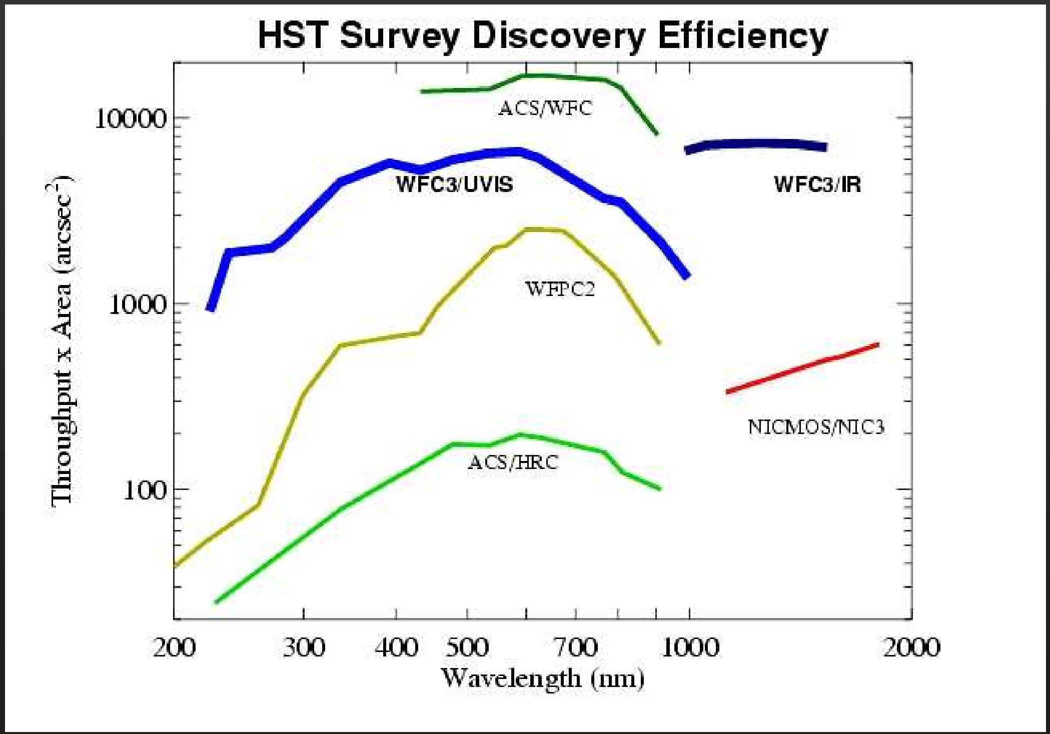
à to map history of mergers, SF, and structural assembly as f(epoch, environment

à constrain baryonic physics input in models

1) Sloan Digitized Sky Survey (SDSS) over z~0.01 to 0.4

2) Large/ deep surveys with
HST/ACS out to z~8
+
(Spitzer, GALEX, Chandra)

Star formation AGN



Empirical Approach

Surveys as function (epoch) + environment= (field,group,cluster)

GEMS (Rix et al 2004) z~0.2 to 1.0

GOODS (Giavalisco et al 2004) z~0.2 to 5.0

AEGIS/DEEP2 (Davis et al 2003/2007, Faber et al 2006) z~0.2 to 1

COSMOS (Scoville et al 2007) out to z~1

Hubble Ultra Deep Field (HUDF; Beckwith et al 2006) z~8

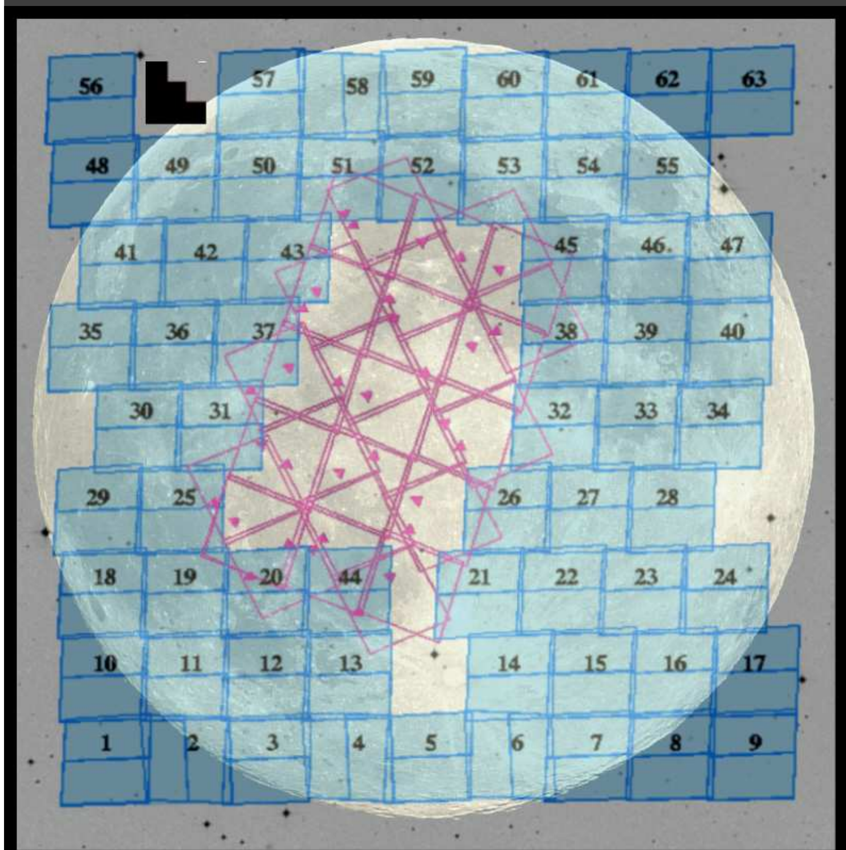
ACS Virgo survey (Cote et al 2004)

ACS Treasury Survey of Coma Cluster (Carter et al 2008) z~0.025

STAGES A901/902 Supercluster (Gray et al 2008) z~0.17

NICMOS imaging of GOODS (Conselice/Bouwens et al ; ongoing)

GEMS (Galaxy Evolution from Morphology and SEDS)



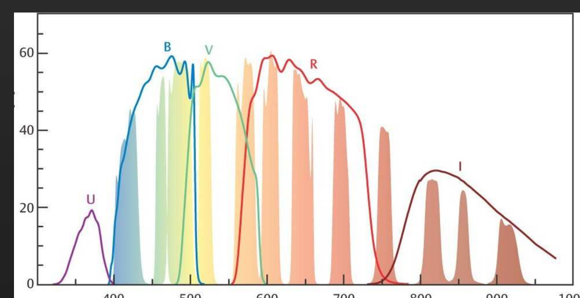
30’

Large area 2-filter imaging survey w/ HST
(Rix et al 2004)

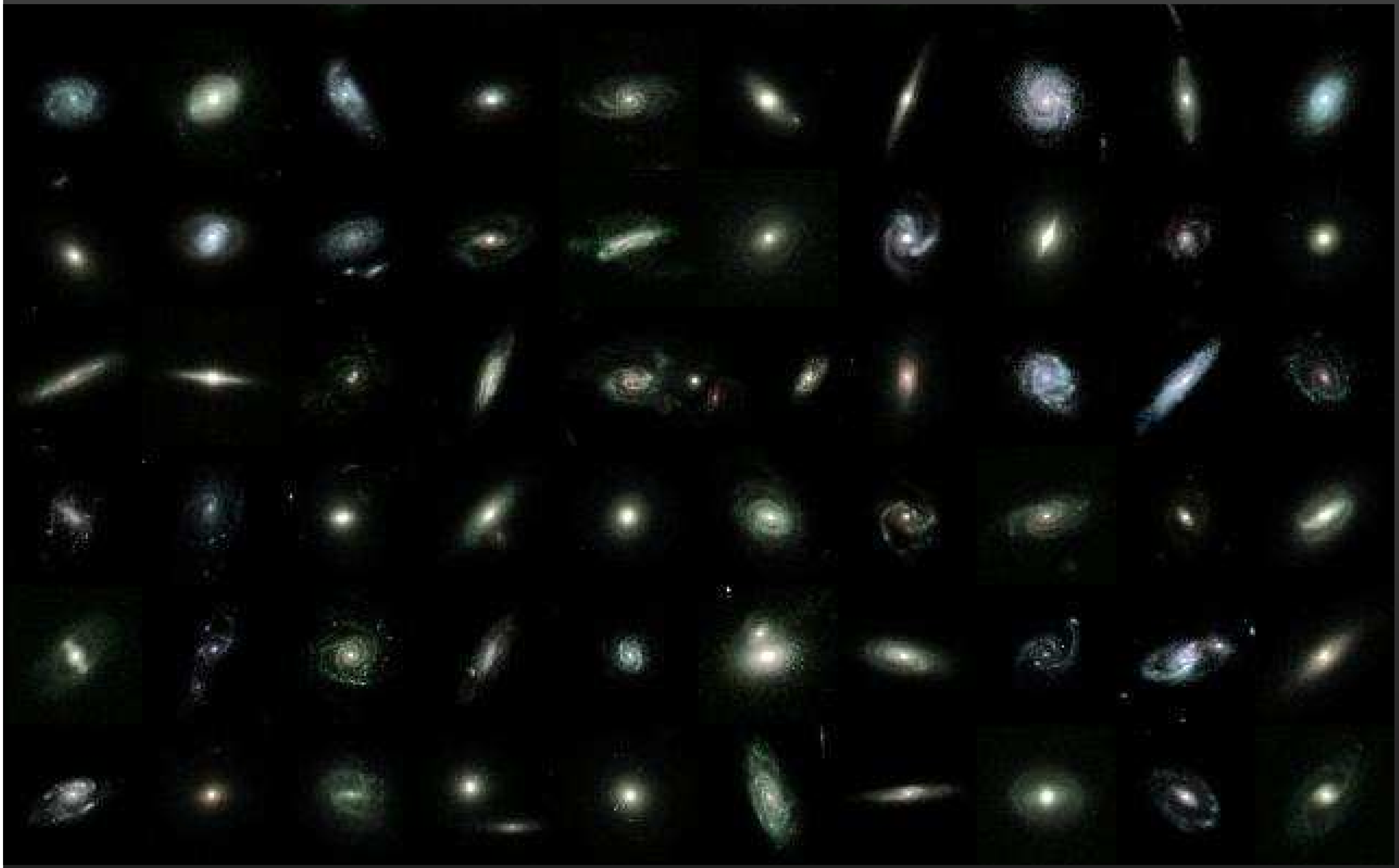
Area : 30’x30’ = 120 x HDF
= 78 x HUDF = 5 x GOODS-S
Filters : F606W (V) , F850LP (z)
(26.8, 25.7 AB mag)

Central mosaic (1 orbit) shared with GOODS
(Giavalisco et al 2004)

Accurate z from COMBO-17 (Wolf et al. 2004)
[δz/(1+z)] ~ 0.02 (R<24 Vega z=0.2-1.0)



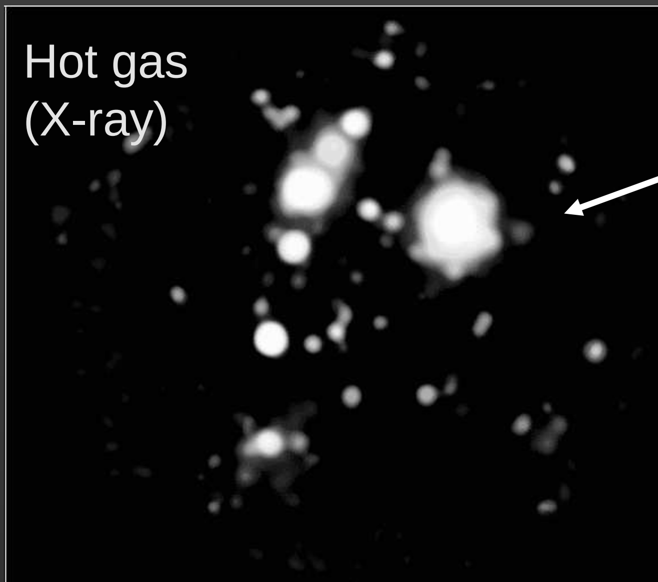
à ACS: Trace rest-frame optical structure of 8200 galaxies out to z~1 (T_b~8 Gyr)
à Spitzer, Chandra, GALEX, Ground-based spectroscopy



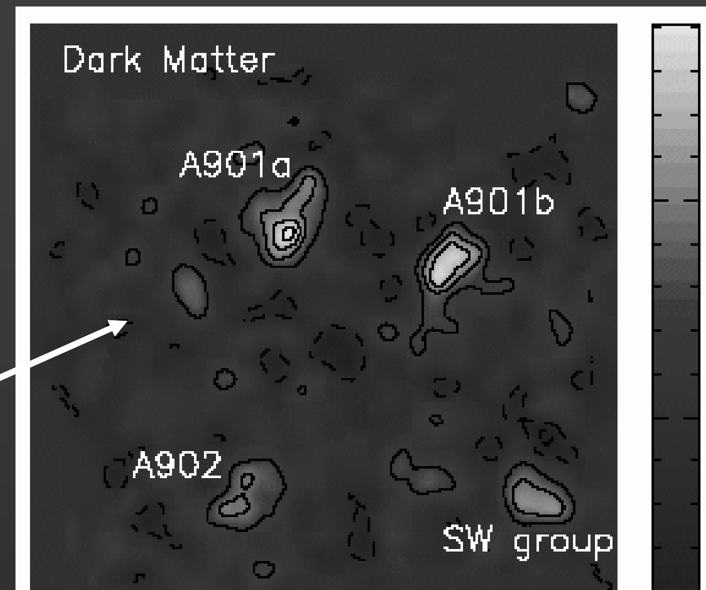
Example of galaxies over z=0.7-1.0 (T_{back}~ 6-8 Gyr)

ACS data + catalogs are publicly available on MAST archive

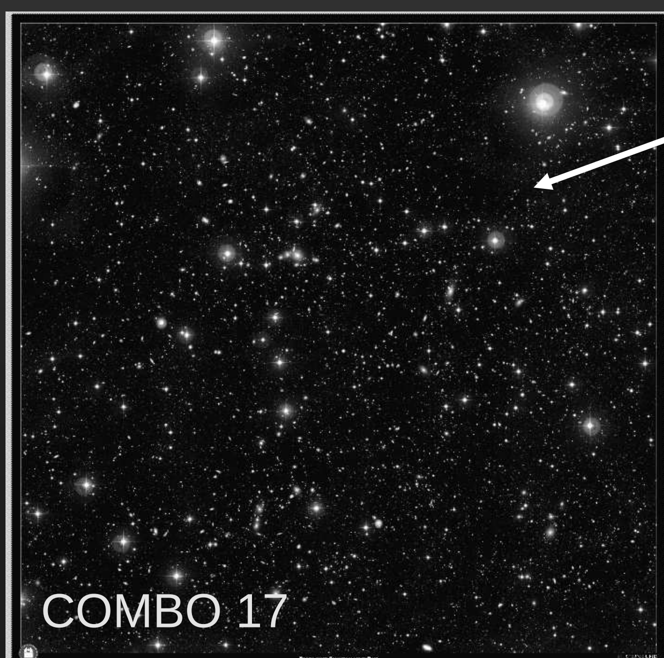
STAGES: Space Telescope survey of A901/902 supercluster



Hot ICM (XMM)

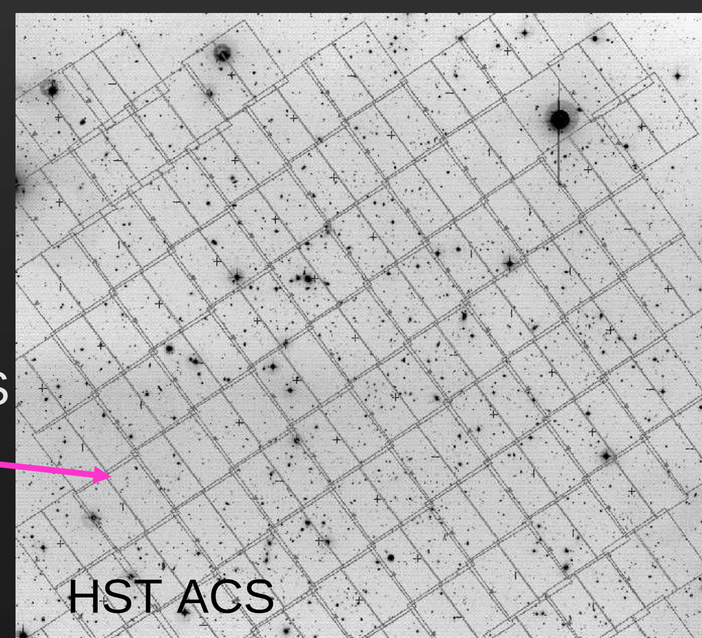


Dark matter map
(Heymans et al 2008)



17-band SEDs and
z from COMBO-17
(Wolf et al. 2004)

Morphology from ACS
(Gray et al 2008; PI)
30’x30’, m_R=24
(80 orbs; S/N=10, 0.8”)



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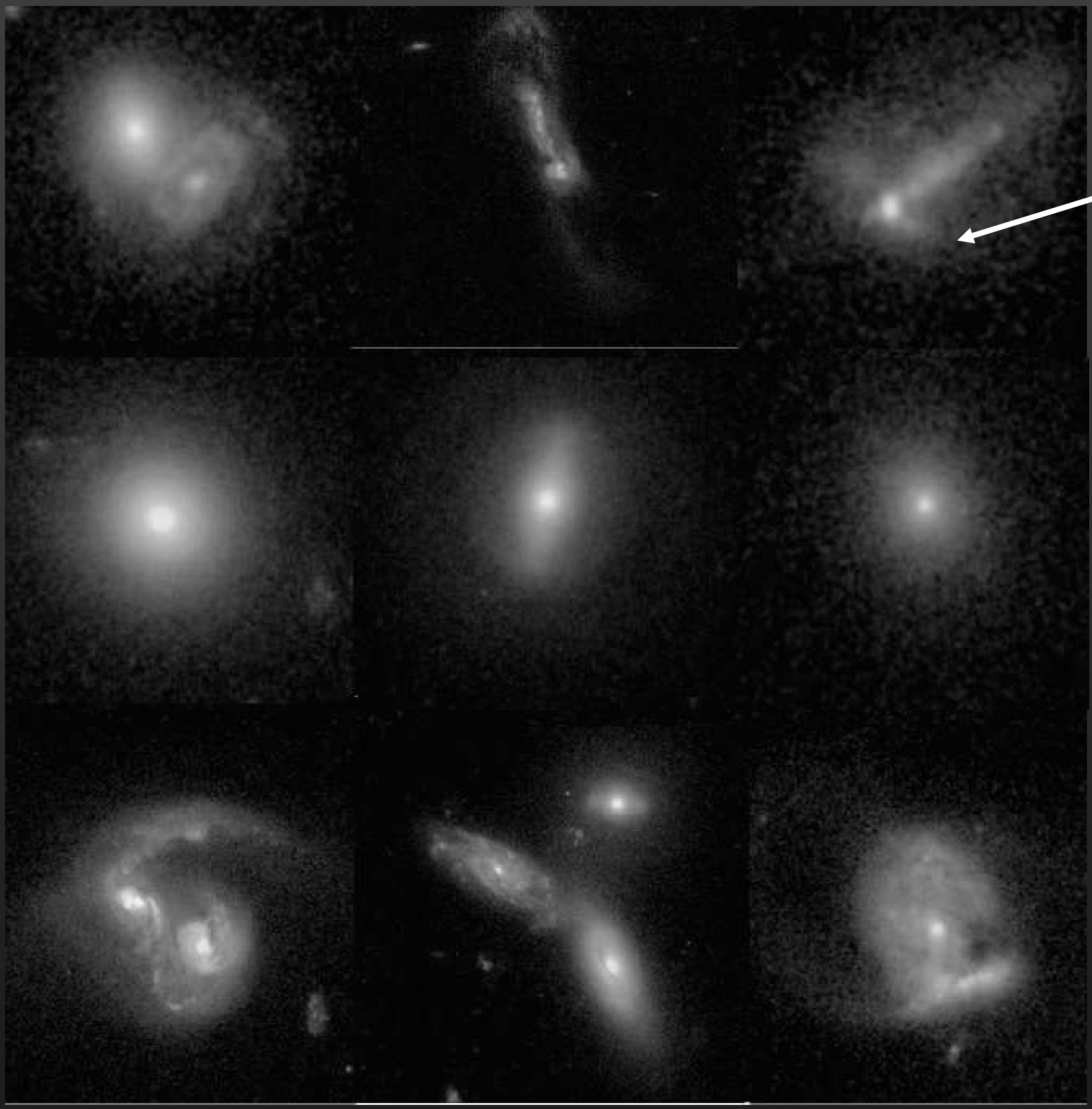
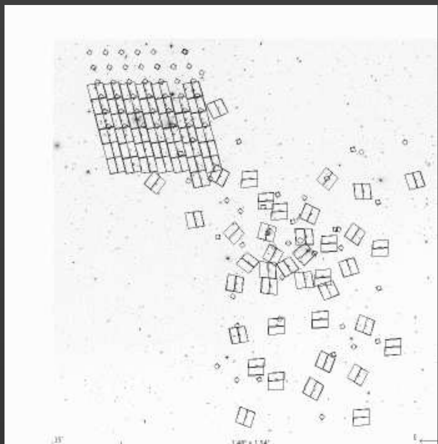
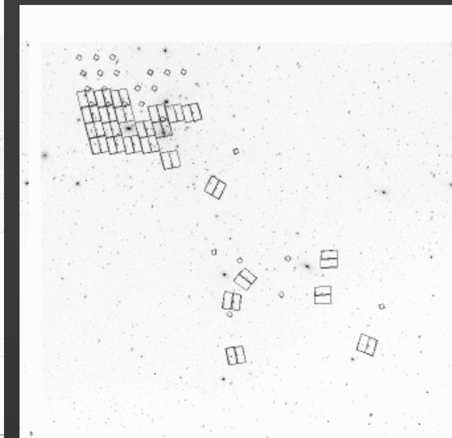


(From Heiderman, Jogee & STAGES 2008, in prep)

Data release planned for end of Feb 2008 (Gray et al 08) .

ACS Treasury Survey of the Coma cluster





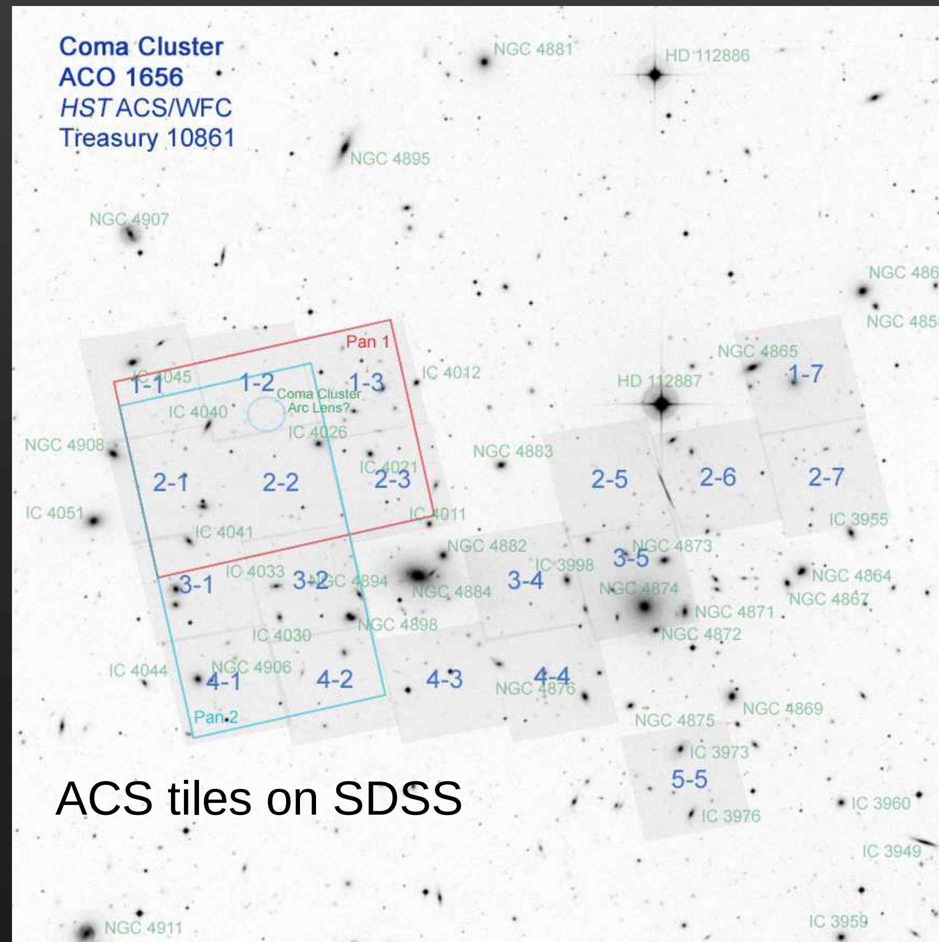
ACS survey (Carter et al 2008)

164 orbits; 1/3 done at ACS failure

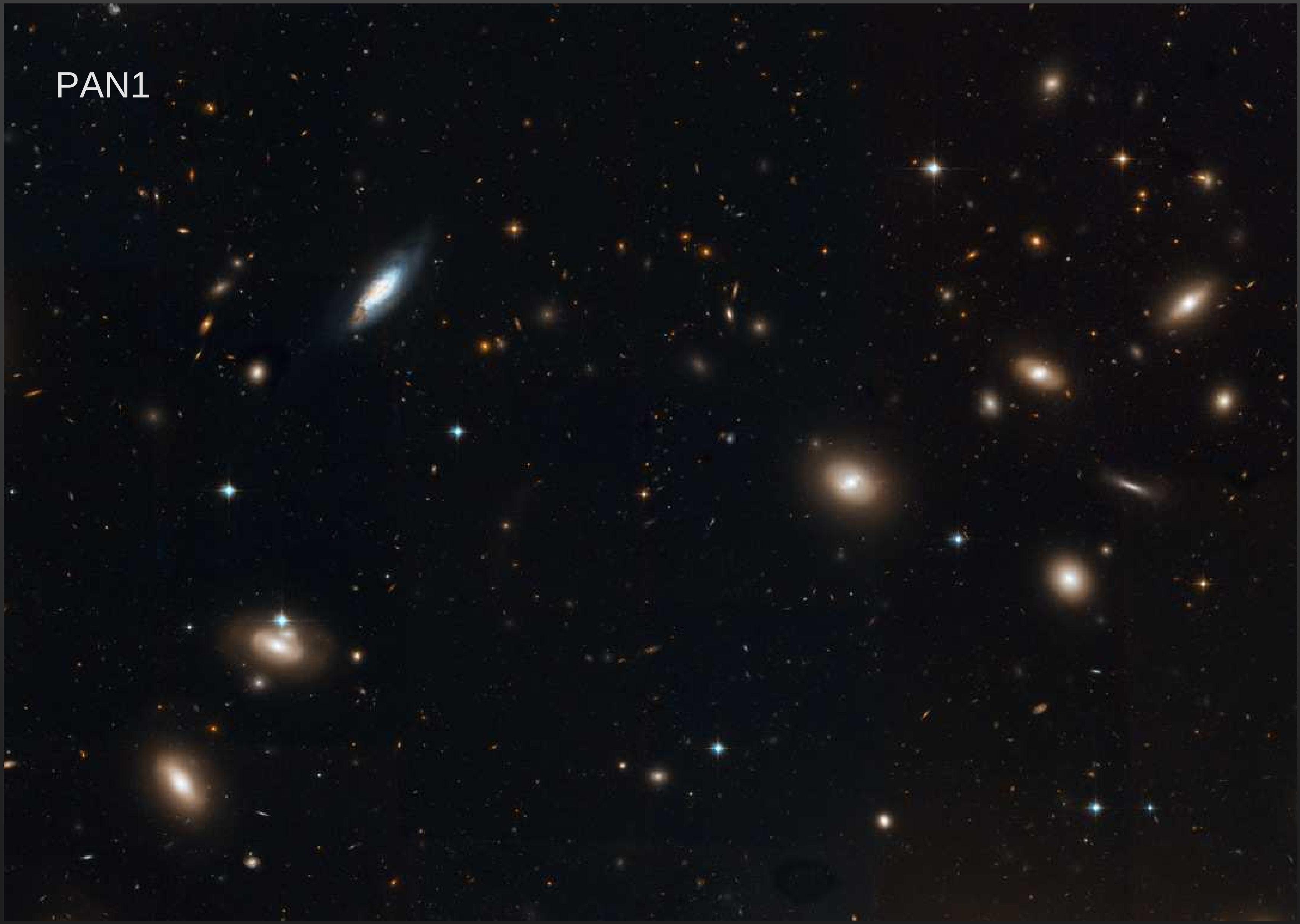
F814W (I=251); F475W (B=27.3)

Complementary: GALEX, Spitzer,
XMM Chandra, Radio

ACS data release planned
for summer 2008

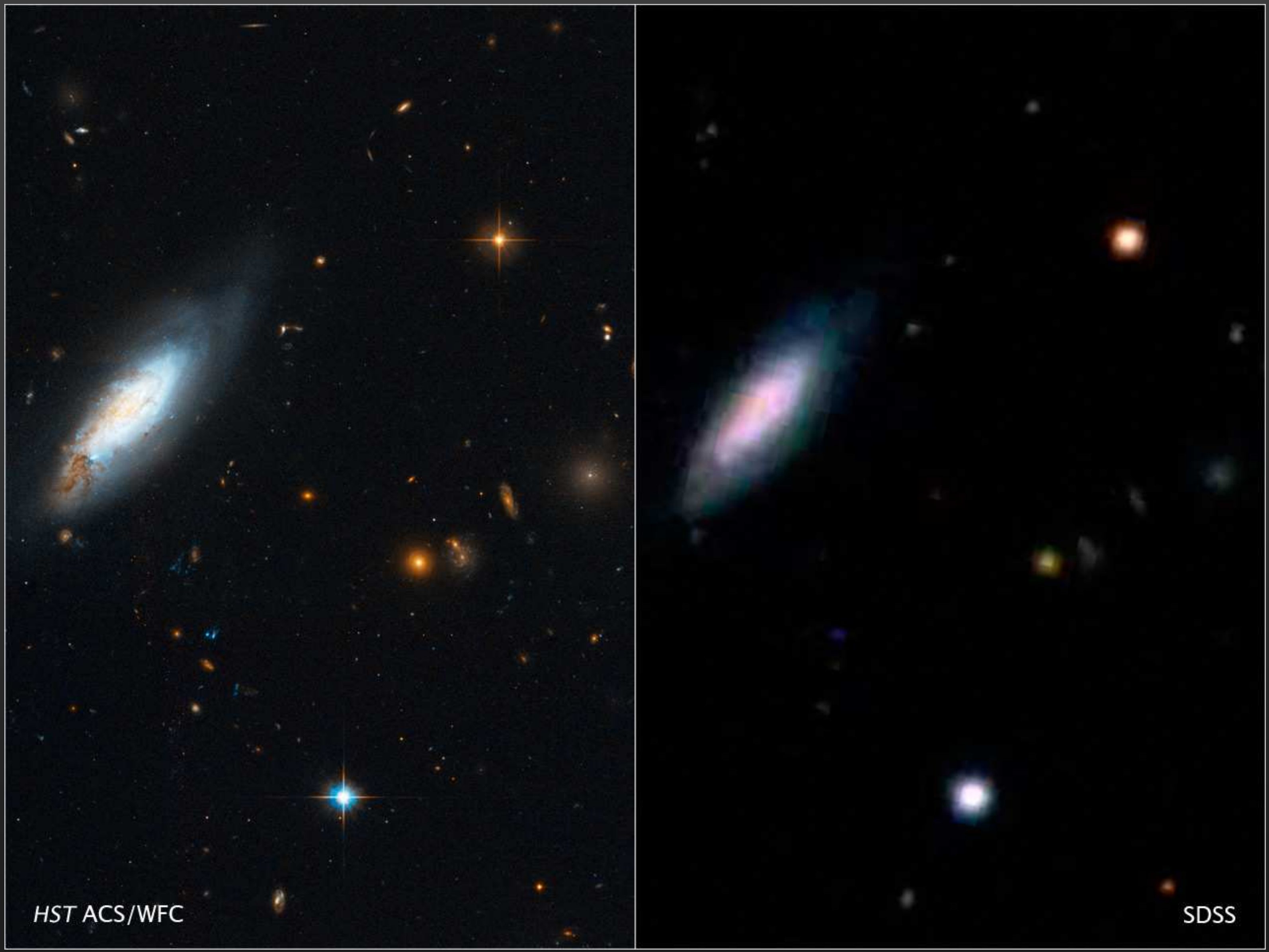


ACS Treasury Survey of the Coma cluster



Courtesy: Z. Levay (STScI) NASA, ESA, Coma ACS Treasury Team

ACS Treasury Survey of the Coma cluster



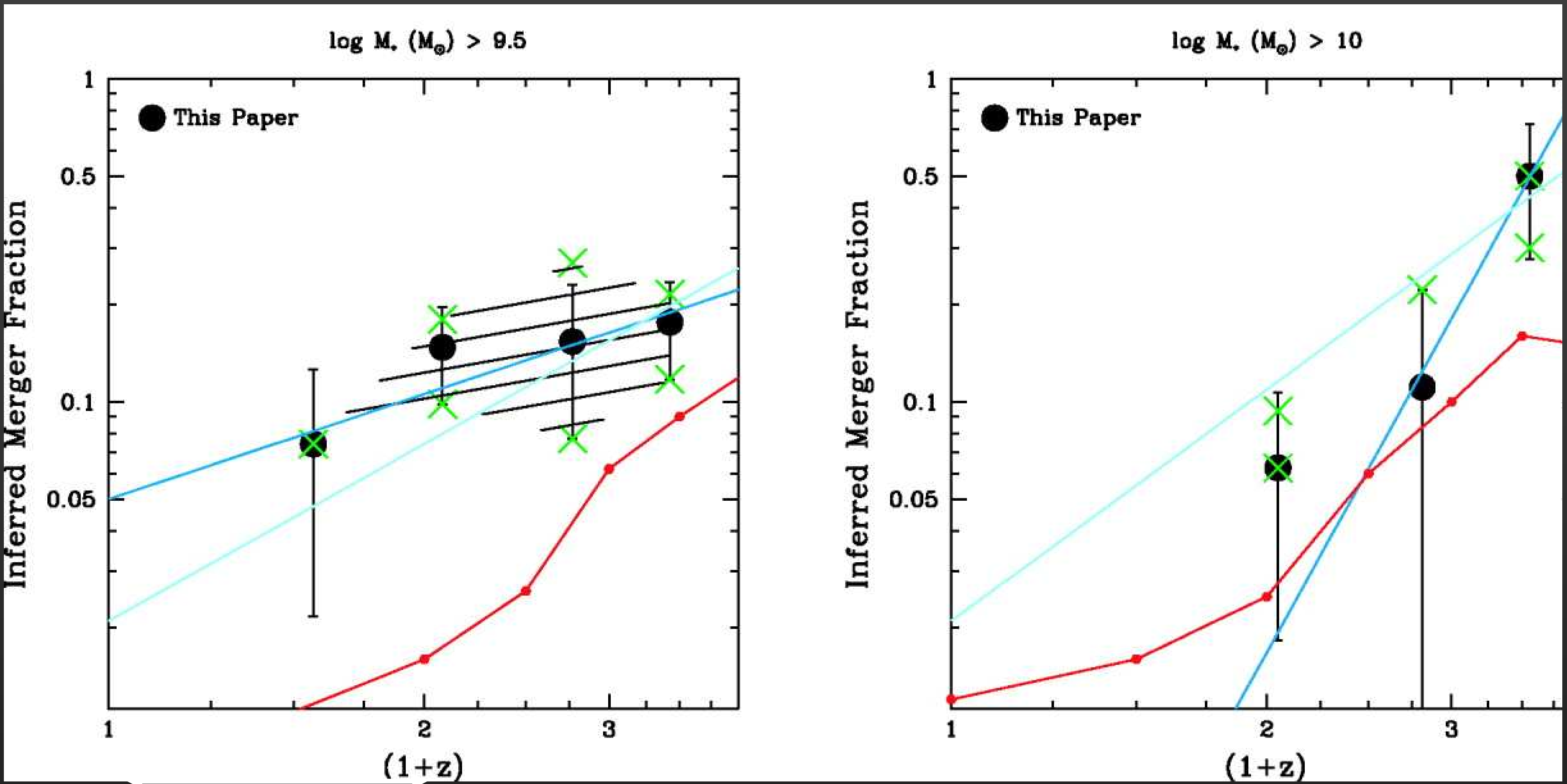
Courtesy: Z. Levay (STScI) NASA, ESA, Coma ACS Treasury Team

Some Science Themes

- Merger history
- Star Formation History
- Structural Assembly and the Problem of Bulgeless Galaxies
- [Galaxy evolution as a function of environment (field, group clusters)]

Merger history

Merger fraction at high z

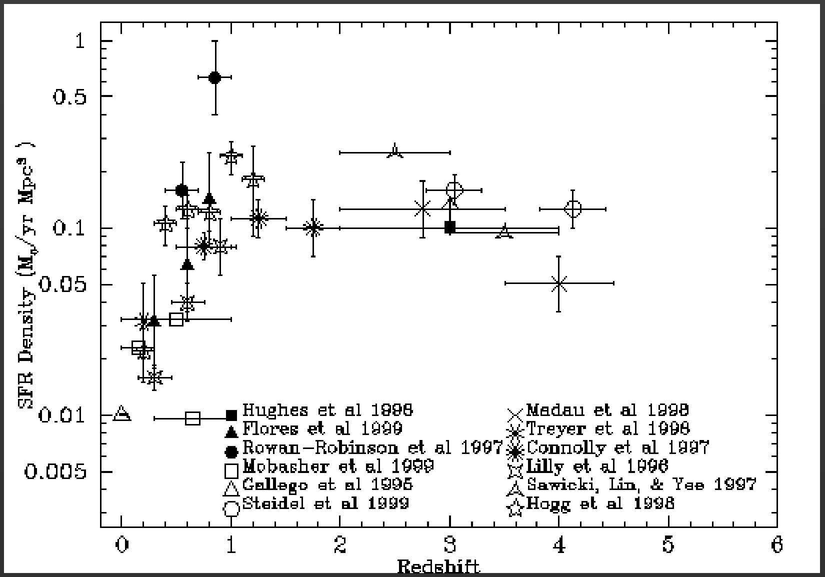


Conselice et al 2003

z~0 to 1
(last 8 Gyr)
58% of age of Universe
Few constraints

Merger fraction ~50% at z~2.5 for high mass (M/Mo>1e10) galaxies

What drives decline in cosmic SFR density over z =1 to 0



(Harsma et al. 2000)

Decline in merger rate

Decline in cold gas content due to gas consumption/removal by SF/AGN

Decline in accretion rate from filaments

Mergers and SF history out to z~0.8 (last 7 Gyr)

(Jogee et al 2007, 2008)

Ingredients

- 4500 galaxies (R<24) over z=0.24 to 0.80 (T_{back}~3 to 7 Gyr)
- ACS F606W high resolution images from GEMS survey (Rix et al 2004)
- Stellar masses from Combo-17 (Borch et al 2006)
- UV and IR-based SFR from Combo-17 & Spitzer (Bell et al 2007)

Classification of galaxies (visual and quantitative CAS code)

Relatively symmetric galaxies = normal = (E+S0+Sa, Sb-Sc, Sd)

Irregular-1 galaxies

Strongly Distorted Interacting/Merging galaxies

Separate internally vs externally triggered asymmetries

Strongly Distorted

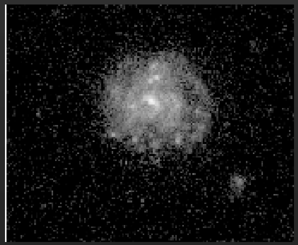
Galaxies with asymmetries which cannot be spontaneously induced in an isolated galaxies and require a strong external trigger, typically an interaction of mass ratio 1:1 to 1:10

e.g., tidal tails, warps, shells, strongly asymmetric arms,double nuclei, galaxies bounded by a common body or bridge

Irregular-1

Galaxies with asymmetries that can be internally triggered without any galaxy-galaxy interactions.

e.g., asymmetries due to stochastic SF or low V/σ in low mass galaxies



Rel. Symmetric

(E+S0+Sa, Sb-Sc, Sd)

EXPLORATORY STEP
Use stellar masses and photz, and morphologies to set a lower limit on the major merger fraction

Major merger/interaction (M1/M2<1:4)

Minor merger/interaction (1:4 to 1:10)

Either

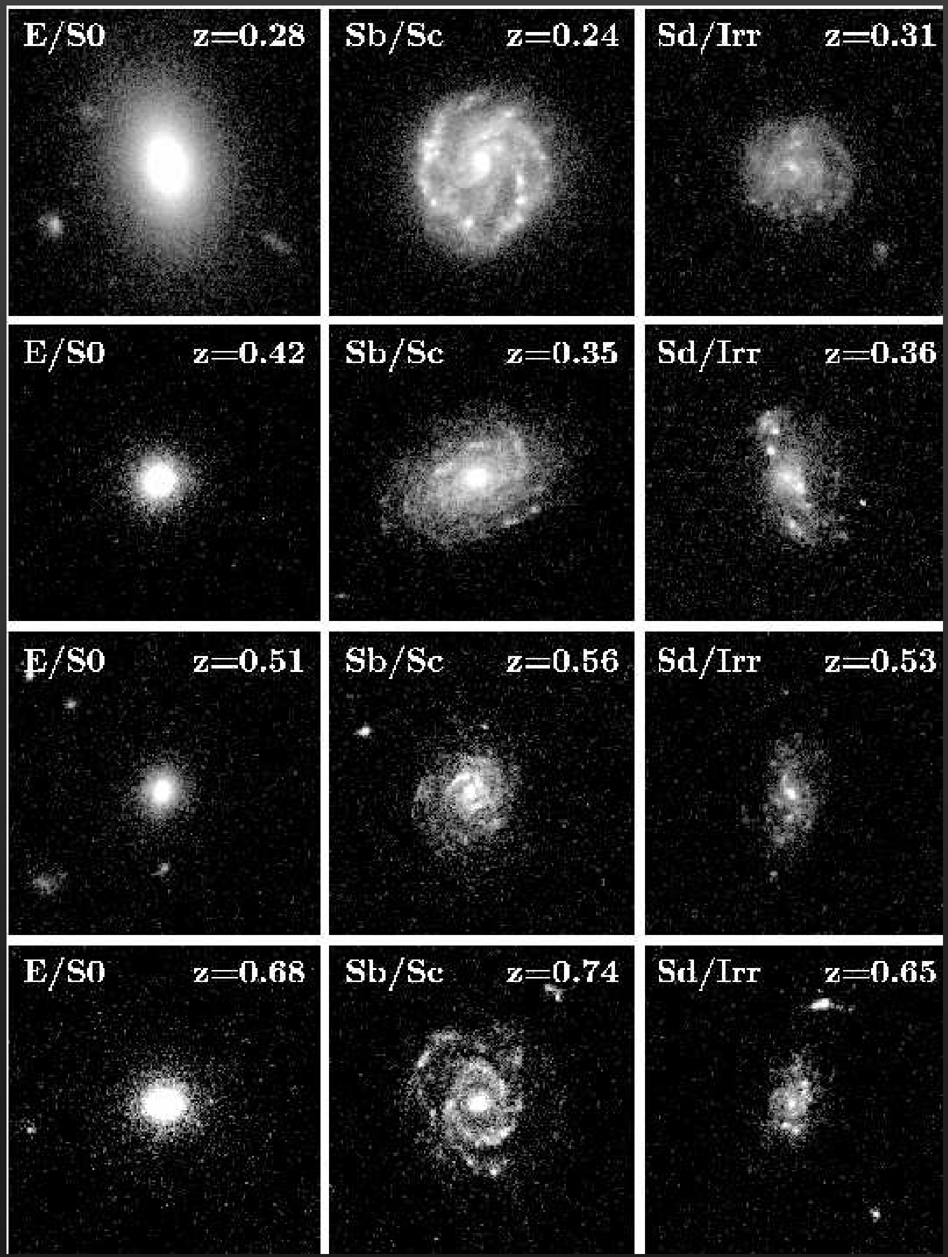
Example of normal undisturbed (E+S0+Sa, Sb-Sc, Sd–Irr1)

Bin 1
z =0.24-0.34
T=3-4 Gyr

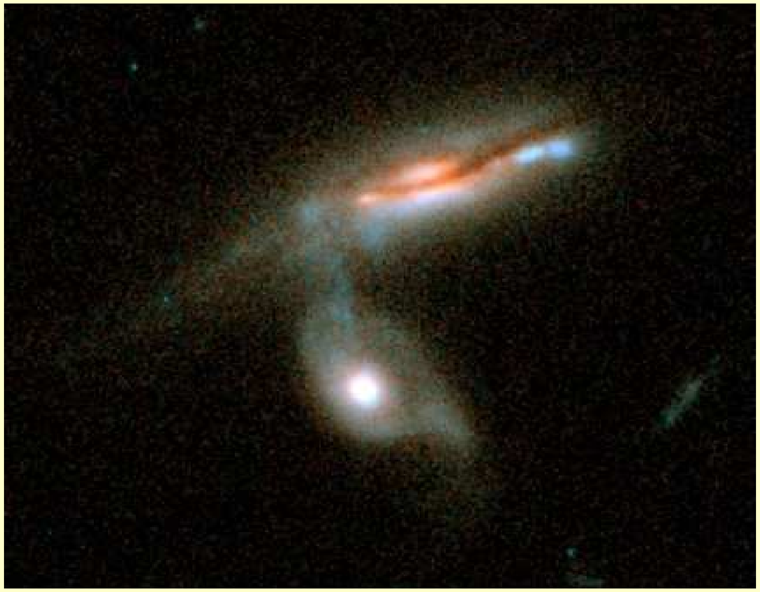
Bin 2
z =0.34-0.47
T=4-5 Gyr

Bin 3
z =0.47-0.60
T=5-6 Gyr

Bin 4
z =0.60-0.80
T=6-7 Gyr

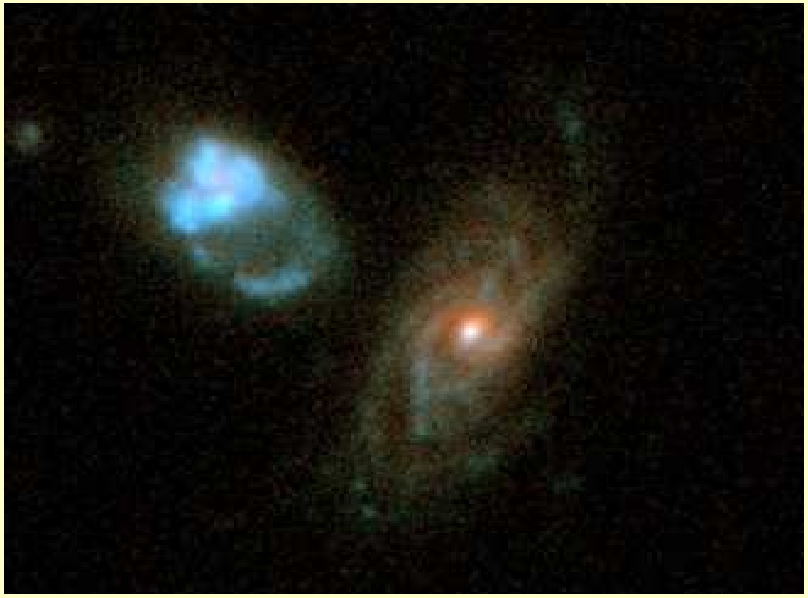


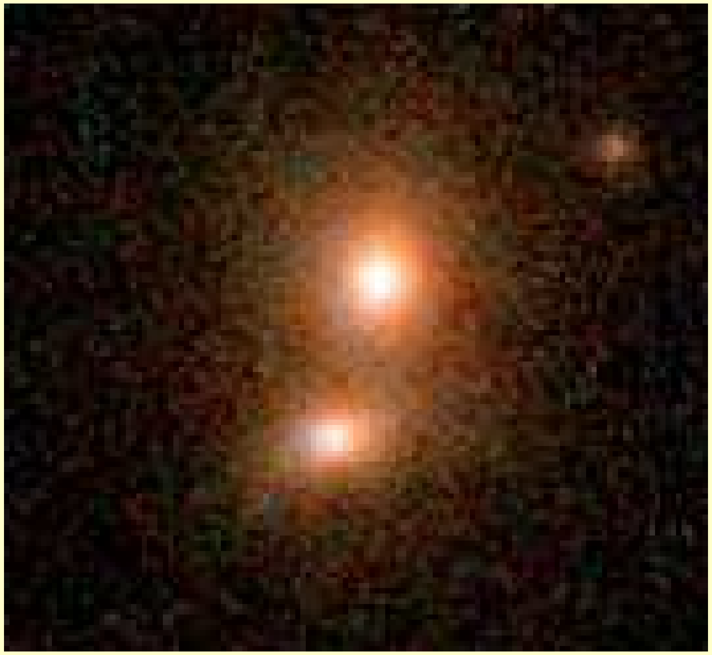
Example of strongly disturbed/interacting (Dist/Int)



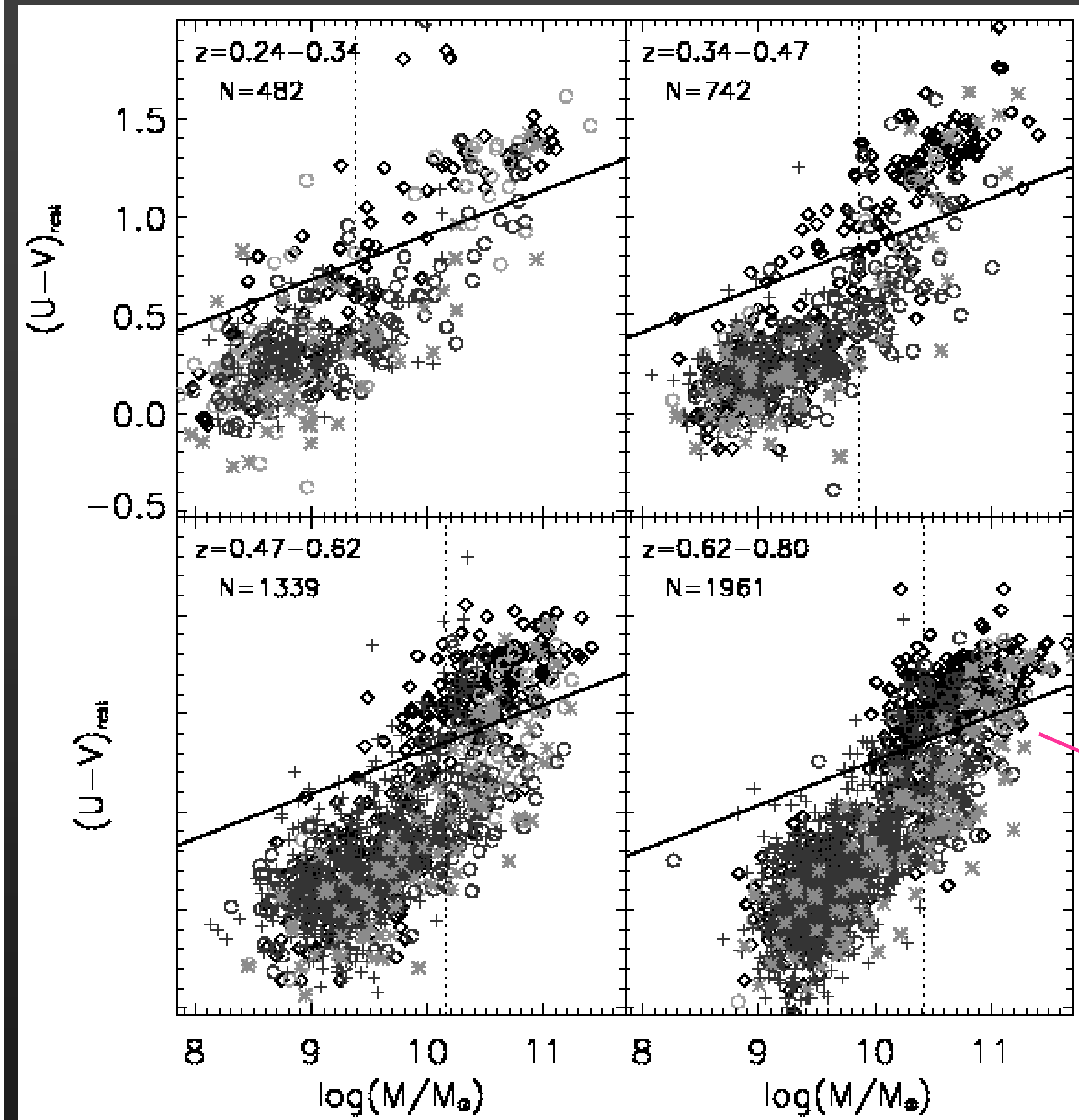
2 at similar z

Example of strongly disturbed/interacting (Dist/Int)





Color–Mass



Total No of galaxies = 4524
Each bin =1 Gyr

Hubble types coded

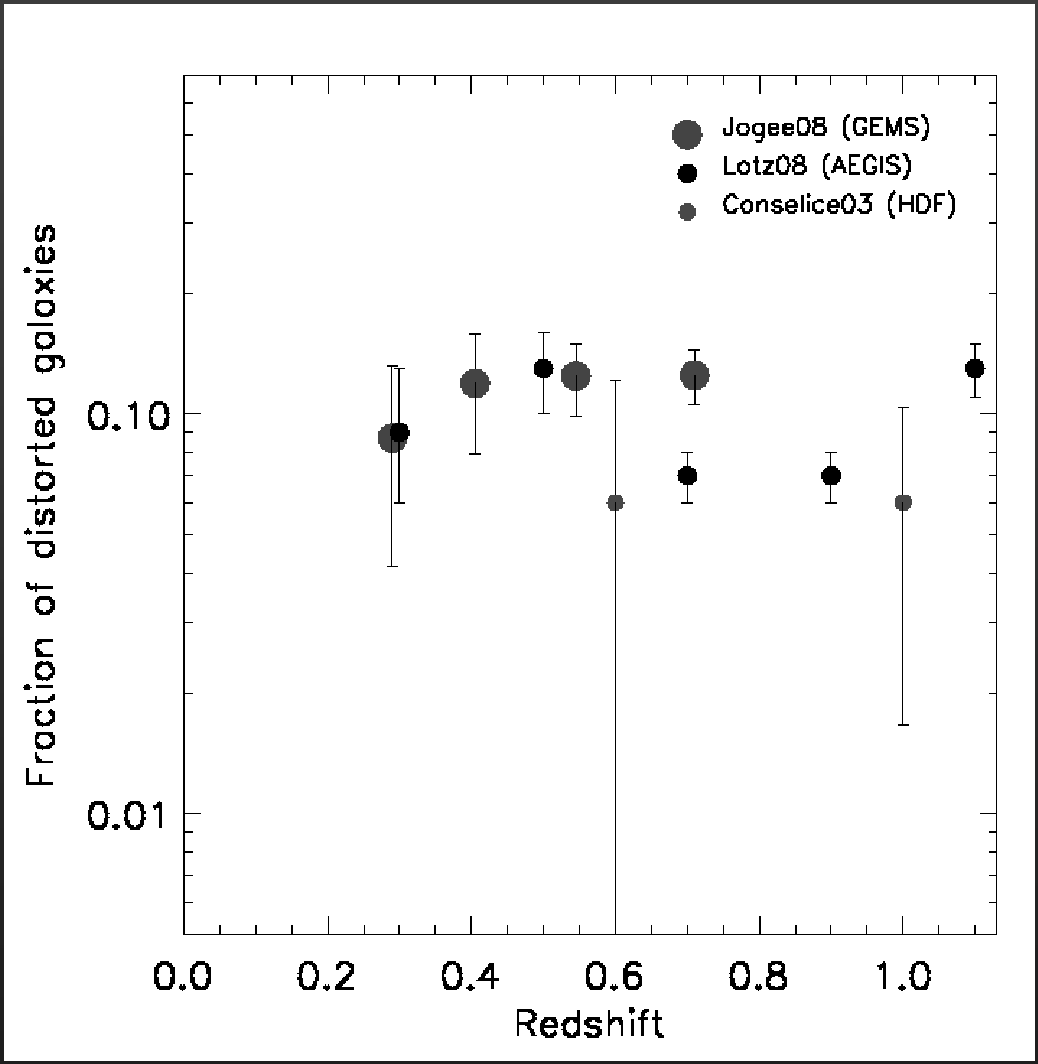
- Strongly disturbed=orange
- Normal = Sb-Sc (blue circle), Sd-Irr (blue cross) Sa (green), E+S0 (black)

Red sequence complete at high (M/M_0 >= $2.5x10^{10}$)

Blue cloud complete at M/M_0> 1.0×10^9

Jogee et al 2008a,b

Merger fraction



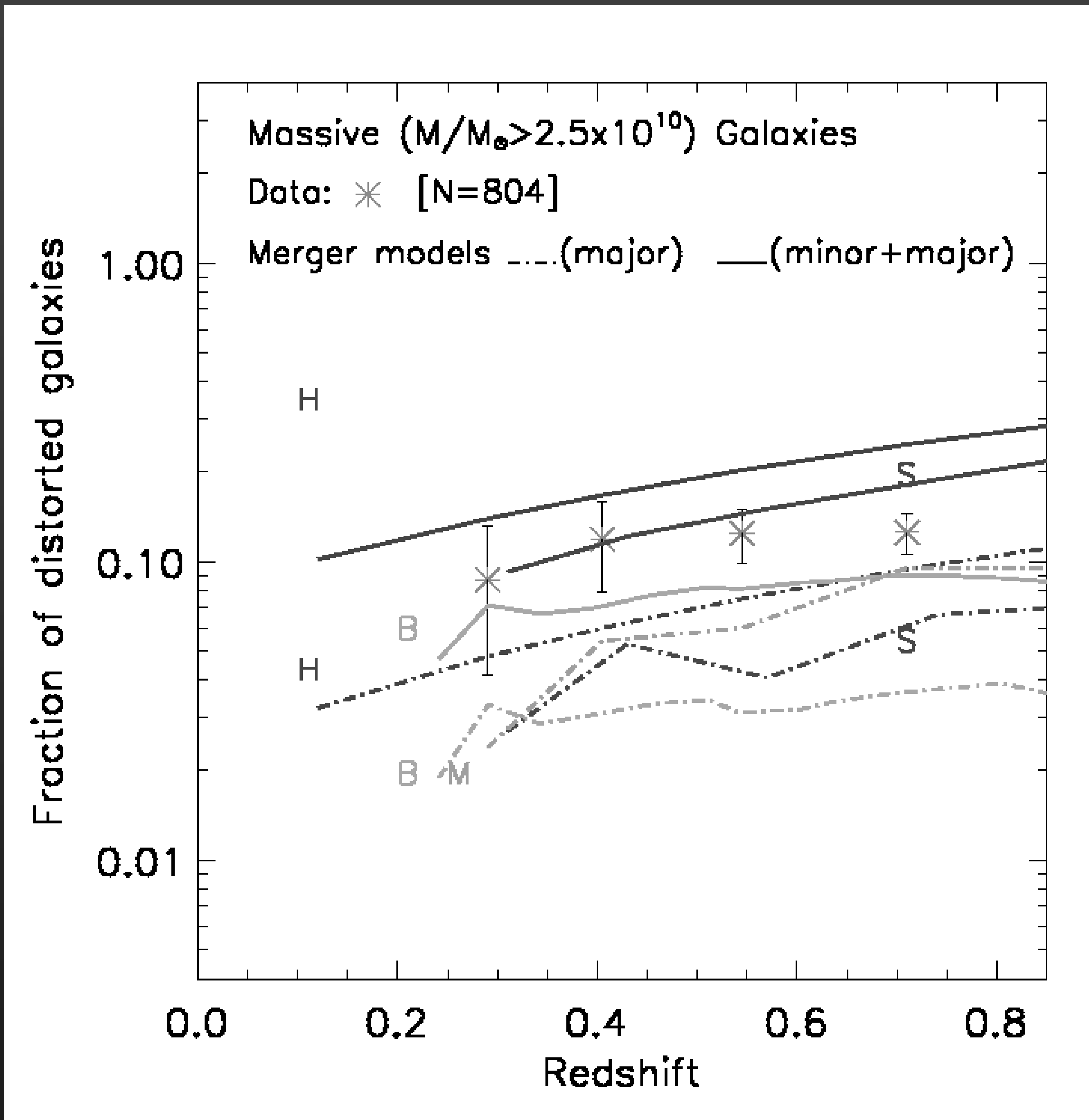
Jogee et al 2008a

Observed fraction F strongly distorted merging /interacting galaxies ~9% -12% over
z~0.2 to 0.8

Merger rate = F n /Tvis
~ few x 10^{-4} Mpc-3 Gyr-1

Agree within a factor less than 2 w/ Lotz et al (2008; AEGIS)

Compare fraction of strongly disturbed systems with models



Jogee et al 2008a

Merger fraction predicted by models

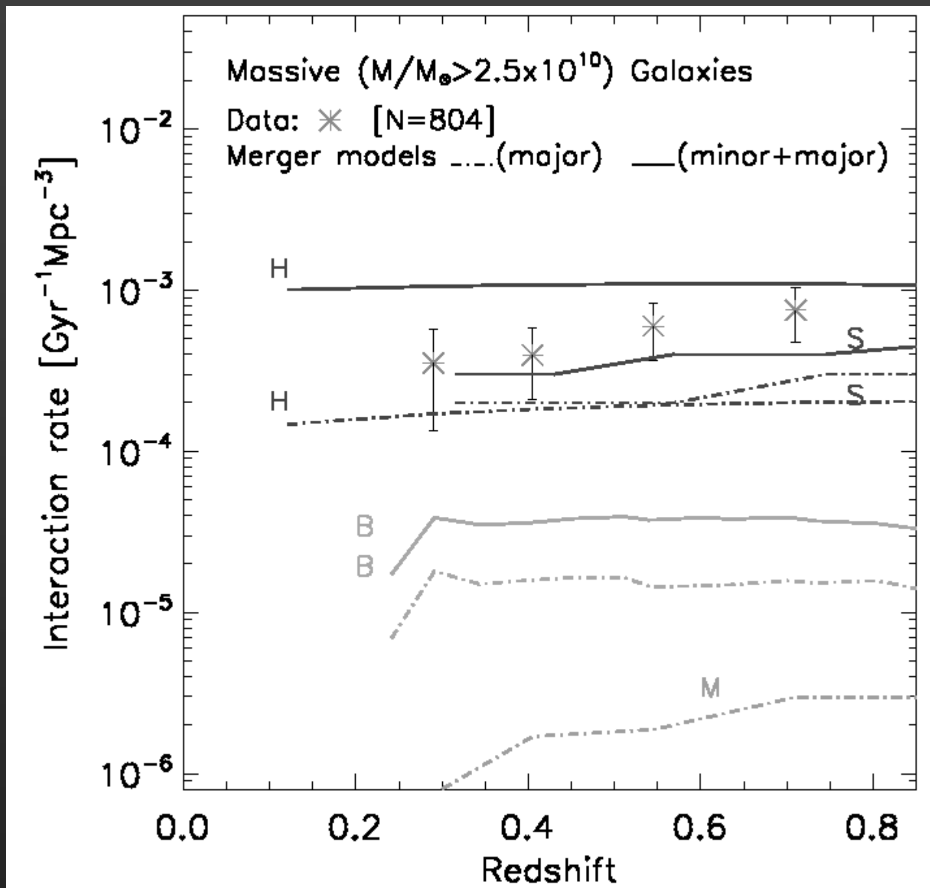
Major (<1:4)
Minor (1:4 to 1:10)

LCDM SAM:
H H = Hopkins et al 2007 ;
S S = Somerville et al in prep;
B B = Benson et al 2005

LCDM Hydro :
M = Maller et al 2006
TBA = Millenium simulations

à Model (major + minor) fraction consistent w/ data within a factor of 2

Comparison of merger rates in data vs models



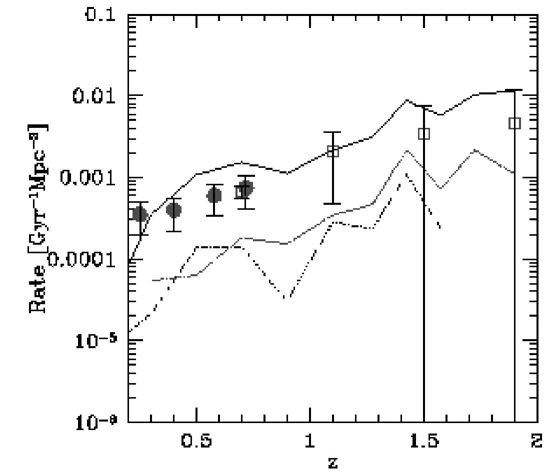


Figure 2. Total merger rate (major+minor) (solid line) and major merger rate only (dotted line) of dark matter haloes, per unit volume (comoving), as a function of redshift, derived from cosmological simulations. The merger rate derived from GEMS data is also displayed (filled circles, Jogee, private communication) and from *HDF* of Conselice (2003, open squares). The rate per unit volume of the flybies of dark halos is plotted for comparison (dashed line).

(D'onghea et al. 2008)
1e13 particles

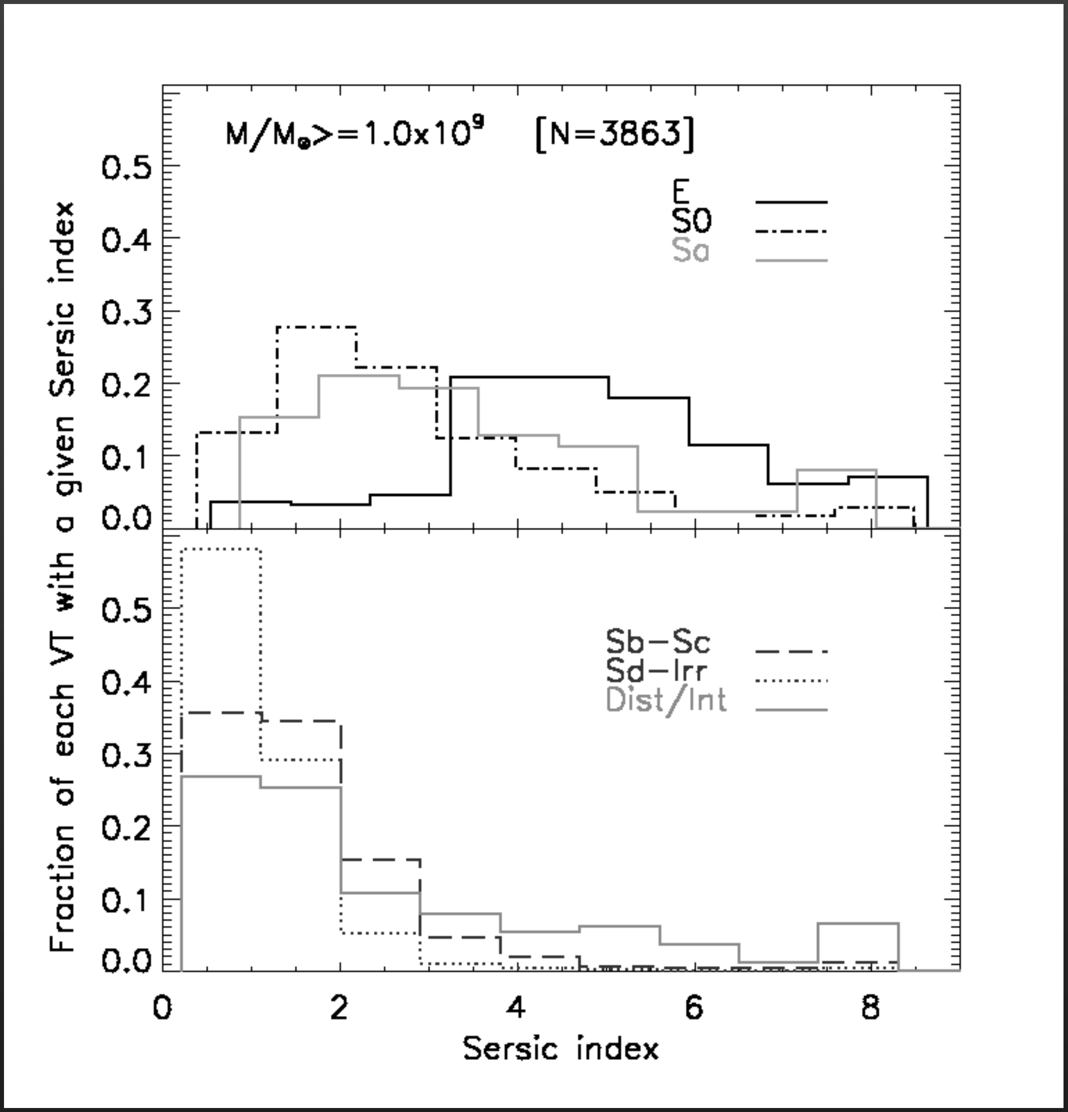
$R = n F / T_{vis}$

(Jogee et al 2008a)

Different number density as f(M) in models.
Different mass function for models w/ and w/o AGN feedback?

Tests on systematic effects

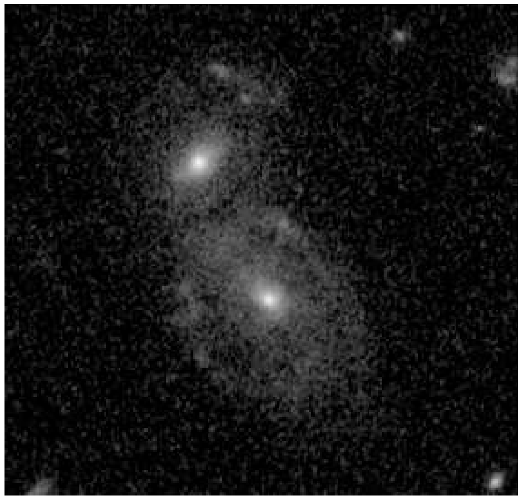
Tests on visual classes of normal galaxies

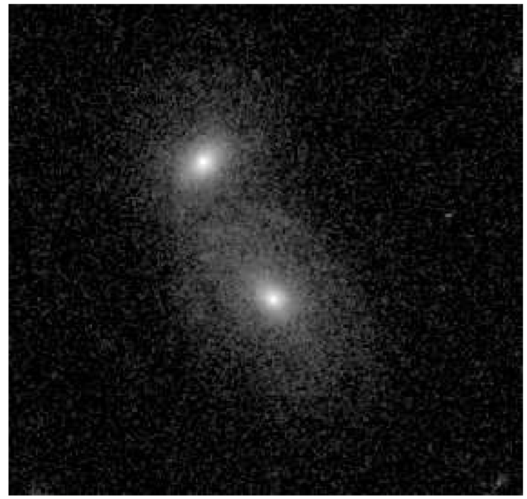


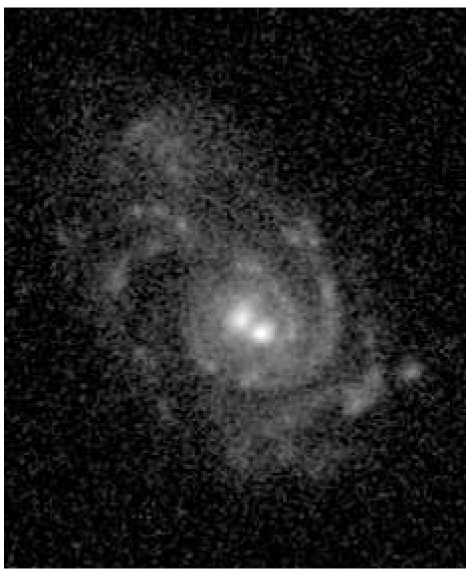
Distribution of Sersic n

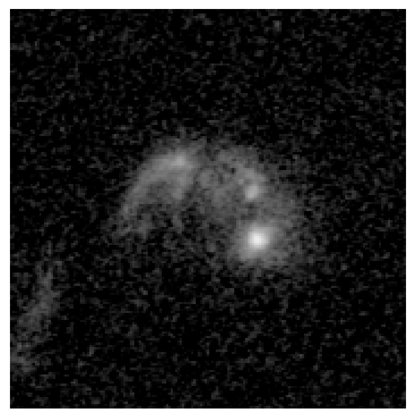
Testing effect of bandpass shift (3480 A to 5300 A) in z=0.6 to0.8

F606W (3480 A) **F850LP (5300 A)**



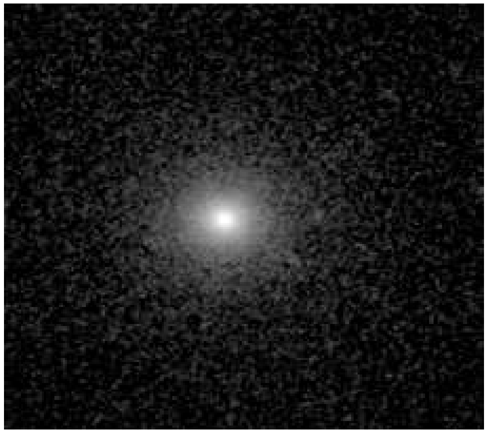




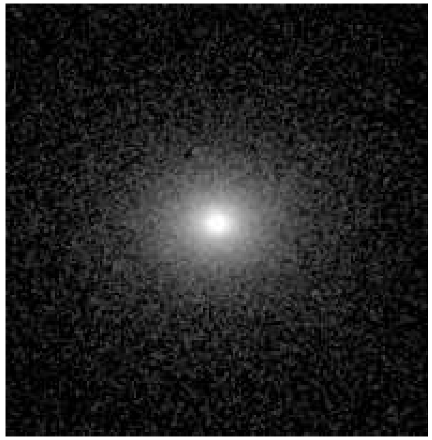


F606W **F850LP** **F606W** **F850LP**

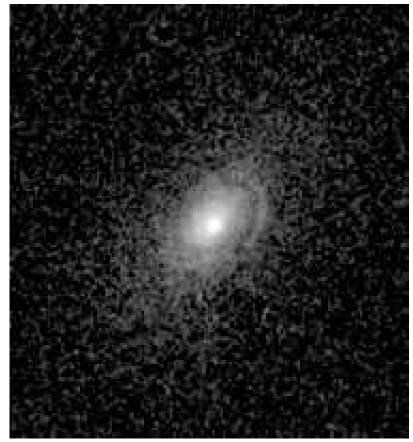
Test impact of bandpass shift (3480 A to 5300 A) in z=0.6 to0.8



F606W (3480 A)

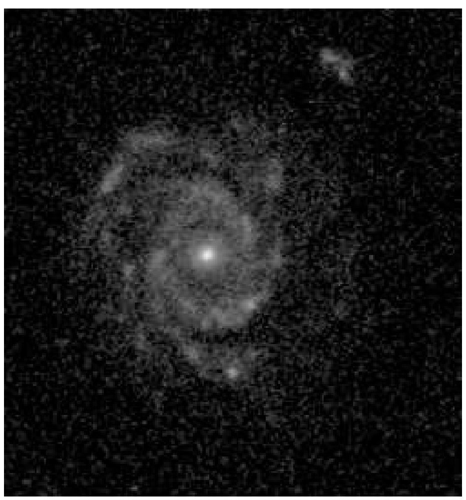


F850LP   (5300 A)

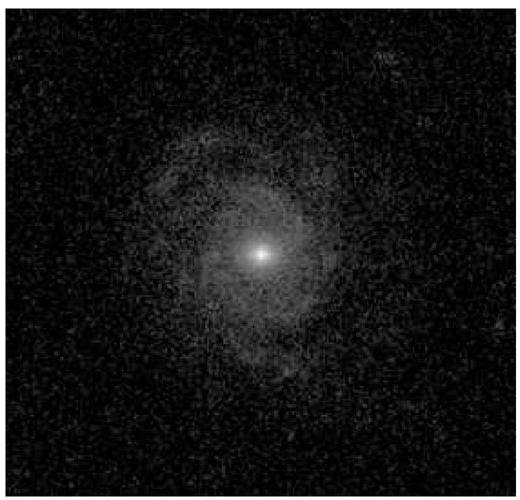


F606W

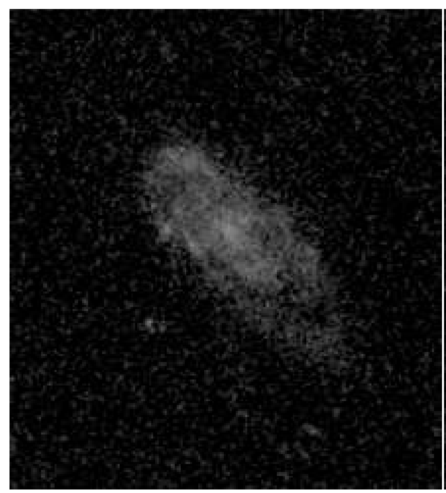
F850LP



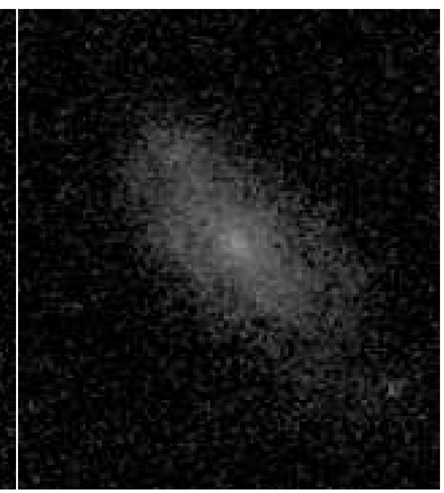
F606W



F850LP



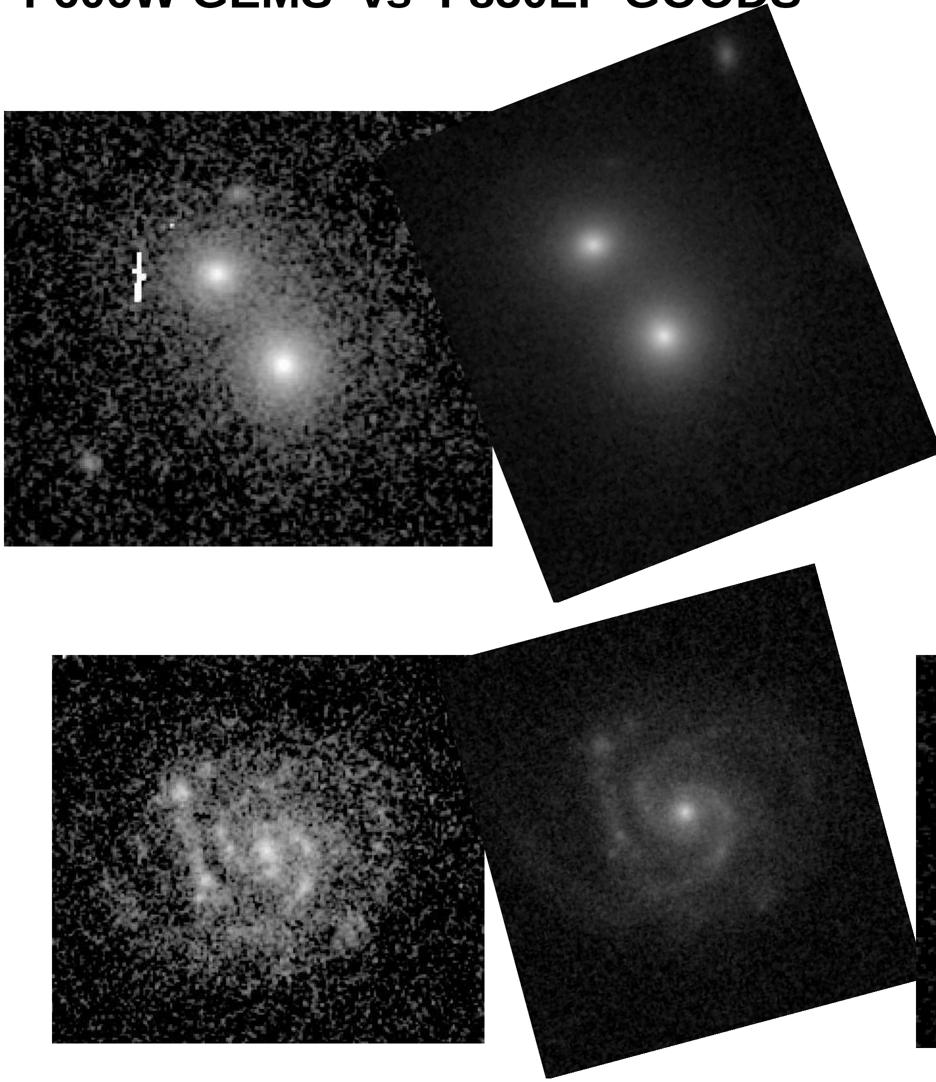
F606W



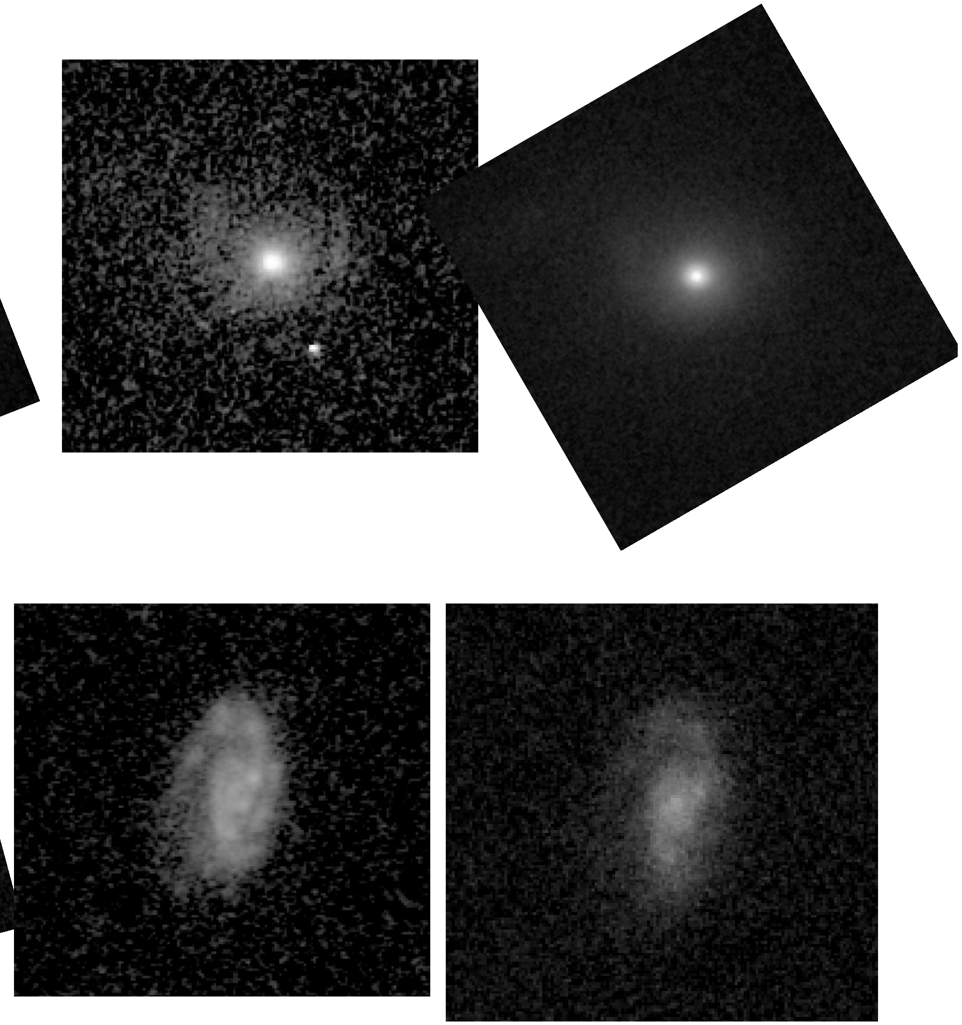
F850LP

Test impact of SB dimming: Shallow vs Deep Image

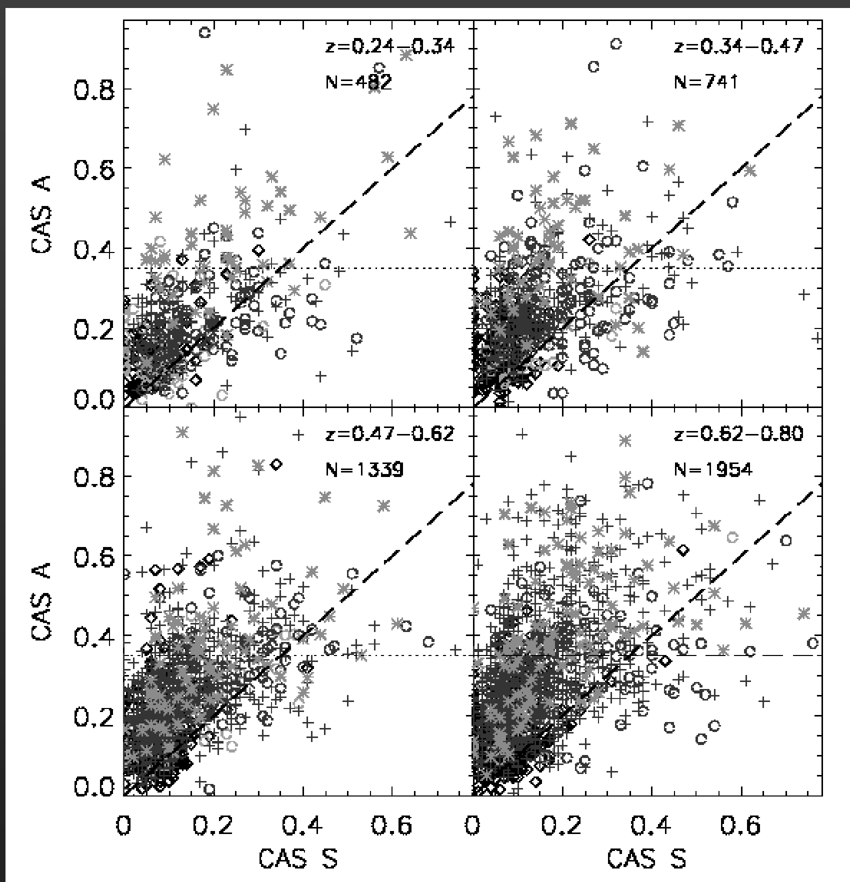
F606W GEMS vs F850LP GOODS

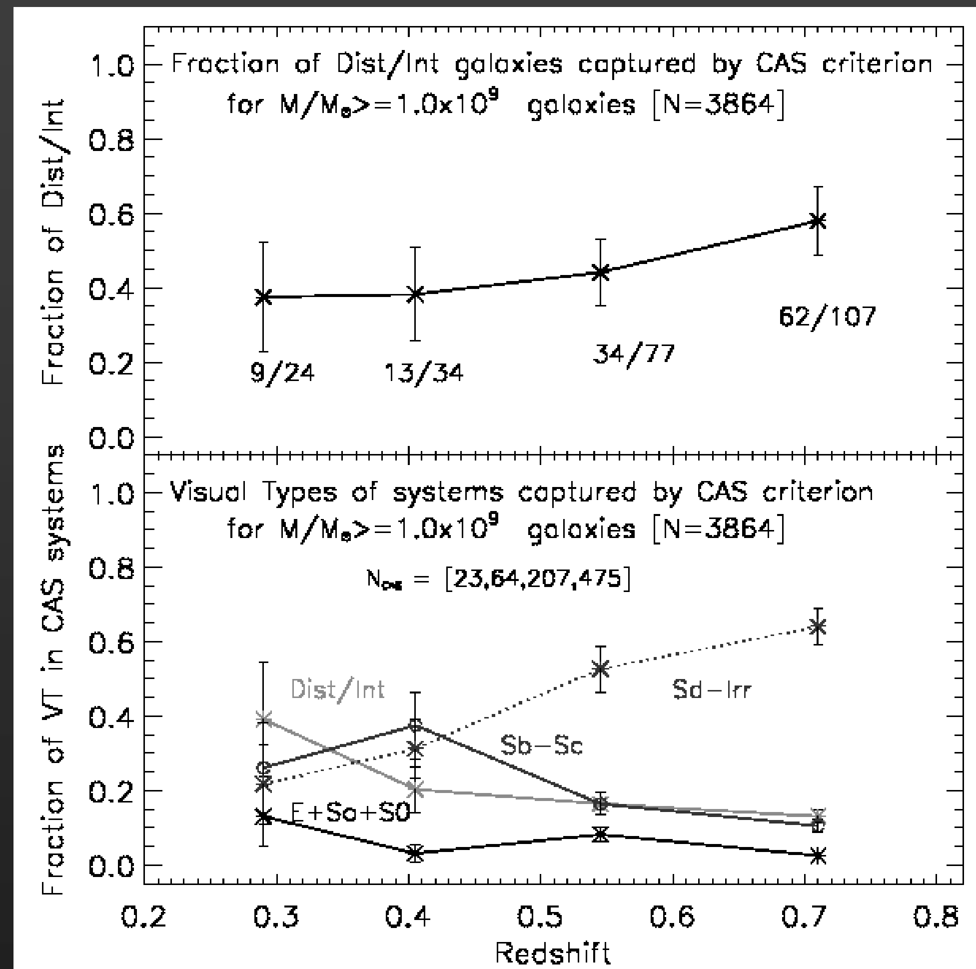


F606W GEMS vs F850LP GOODS



Tests using quantitative CAS merger criterion (A>S and A>0.35)





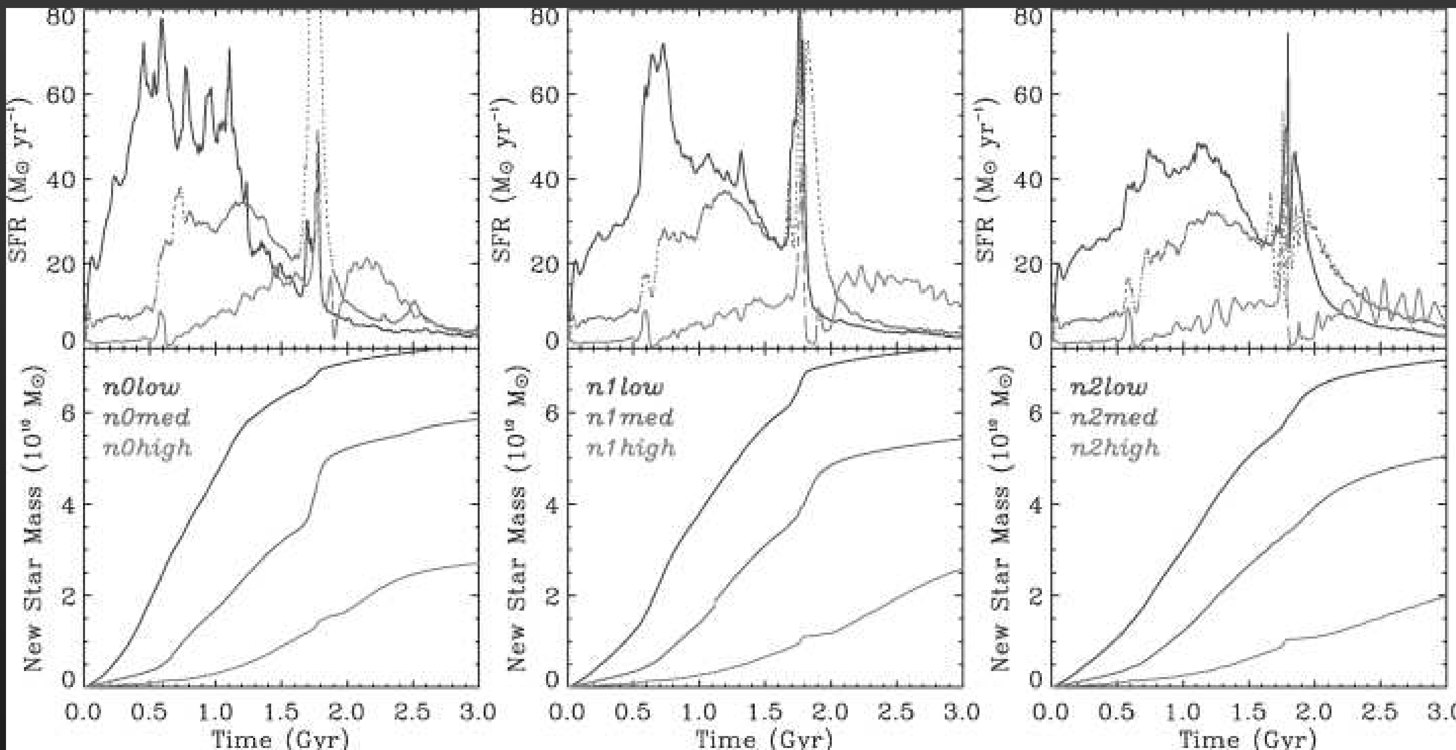
CAS Recovery Rate =50%
CAS contamination by normal

Impact of Mergers/interactions on Star Formation

Enhancement of SFE during mergers

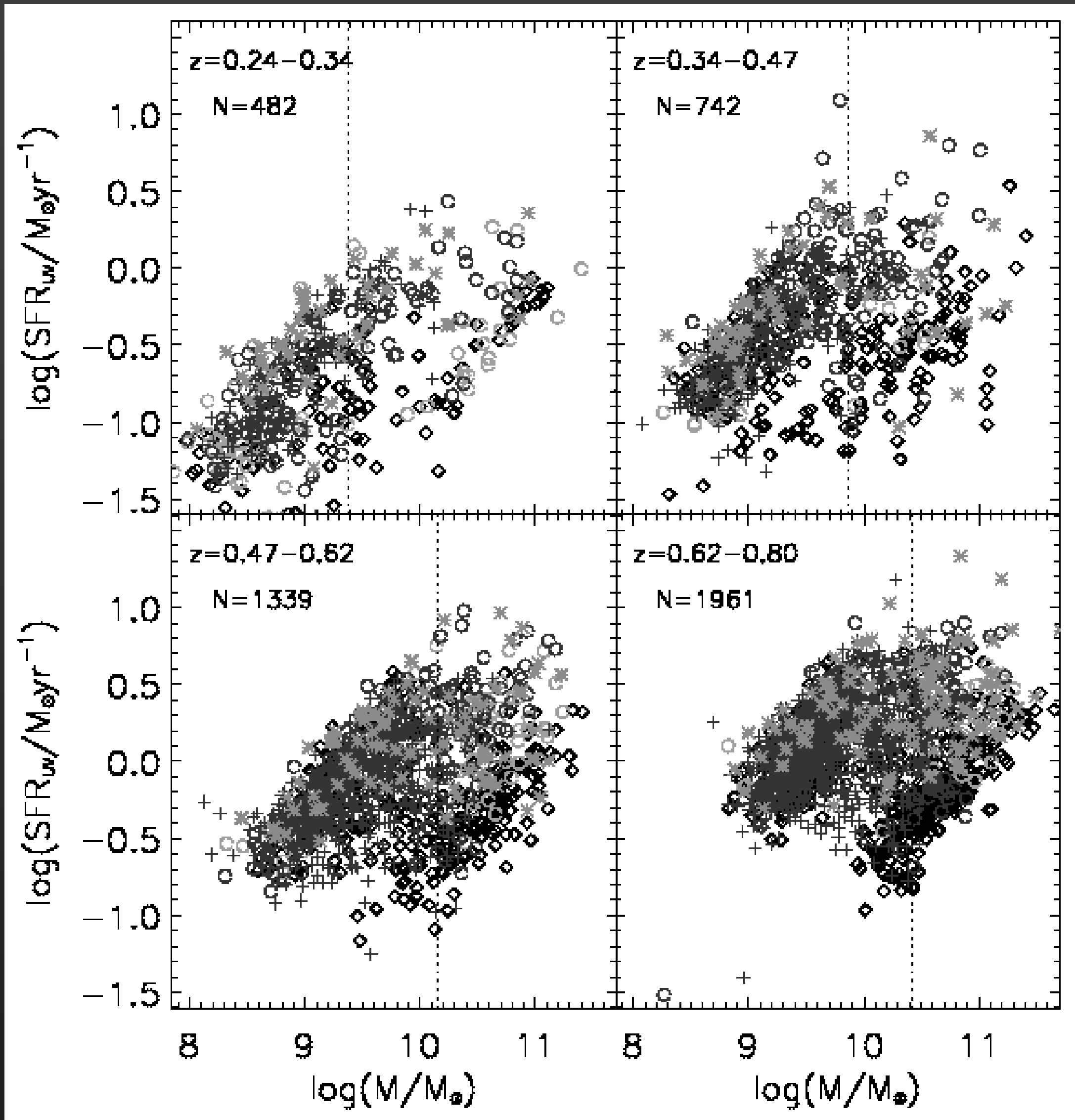
Star formation efficiency during simulations of major merger depends on

Physical properties : Orbital parameters Gas fraction, B/D
Assumptions: Model of star formation Treatment of the ISM
- Model for stellar feedback or [AGN feedback]



Higher SFR during major megers with lower feedback (n~0) model (Cox et al 2006)

SFR in Interacting vs Normal galaxies



Total No of galaxies = 4524

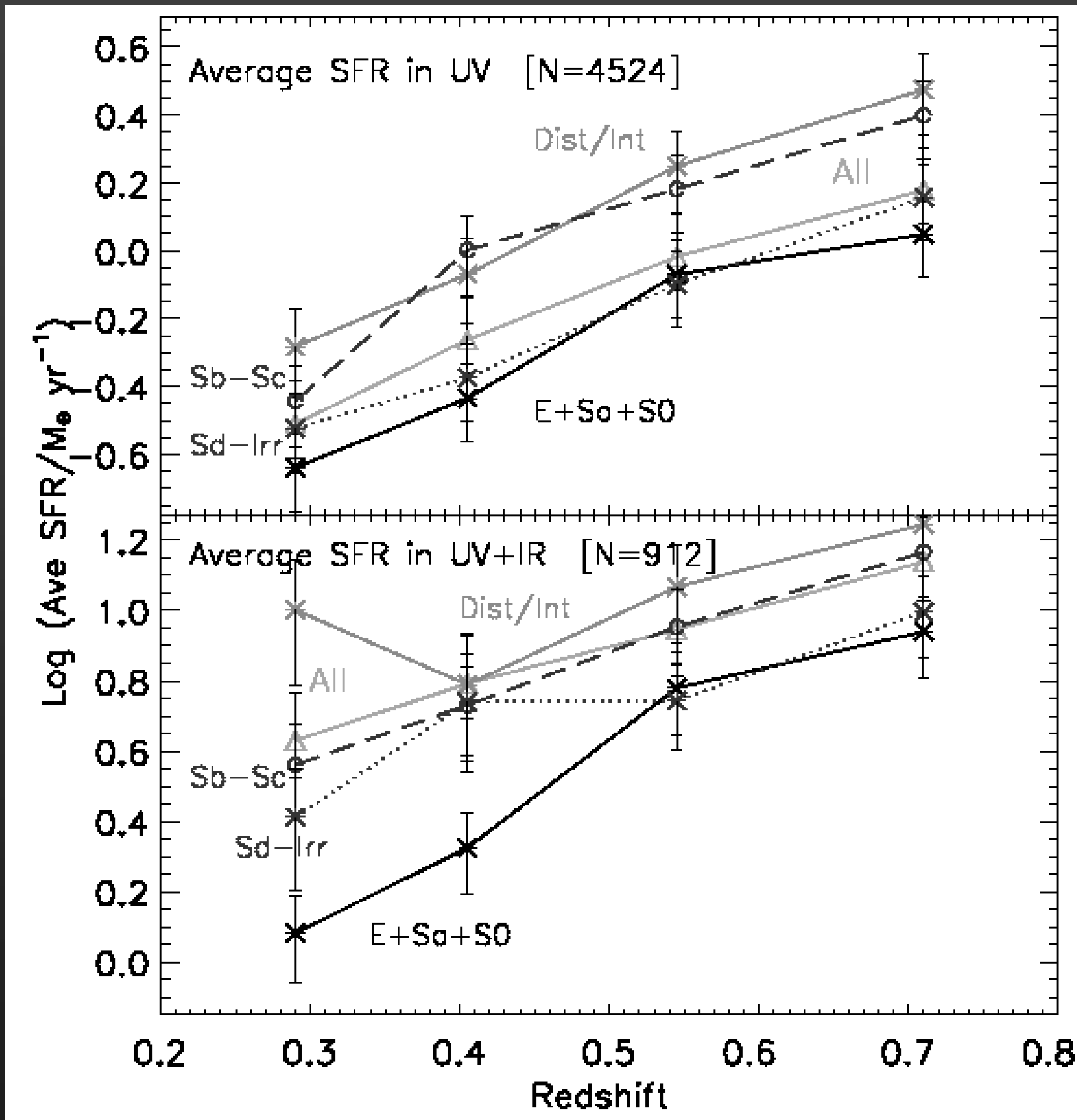
SFR_{UV} ~mainly 0.1--5 M_o yr^{-1}

SFR_{UV+IR} ~mainly 0.5- 20 M_o yr^{-1} for 900 galaxies with both Spitzer and UV data

Extinction correction factor ~3-4

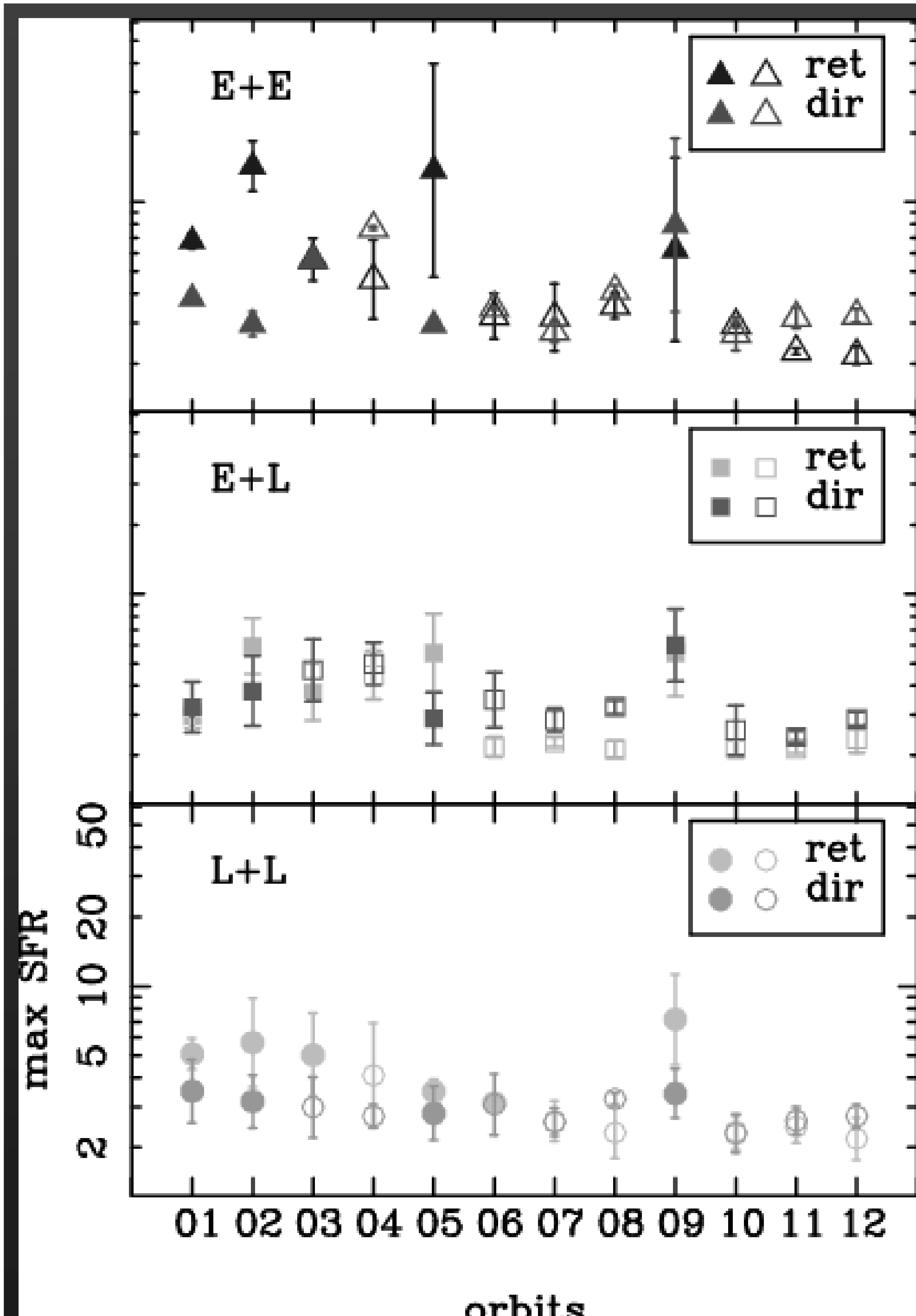
Jogee et al   2008b

Average SFR in Interacting vs Normal galaxies



Average SFR of strong/y disturbed galaxies is enhanced only by a factor of a few w.r.t that of normal undisturbed galaxies

Jogee et al   2008a,b

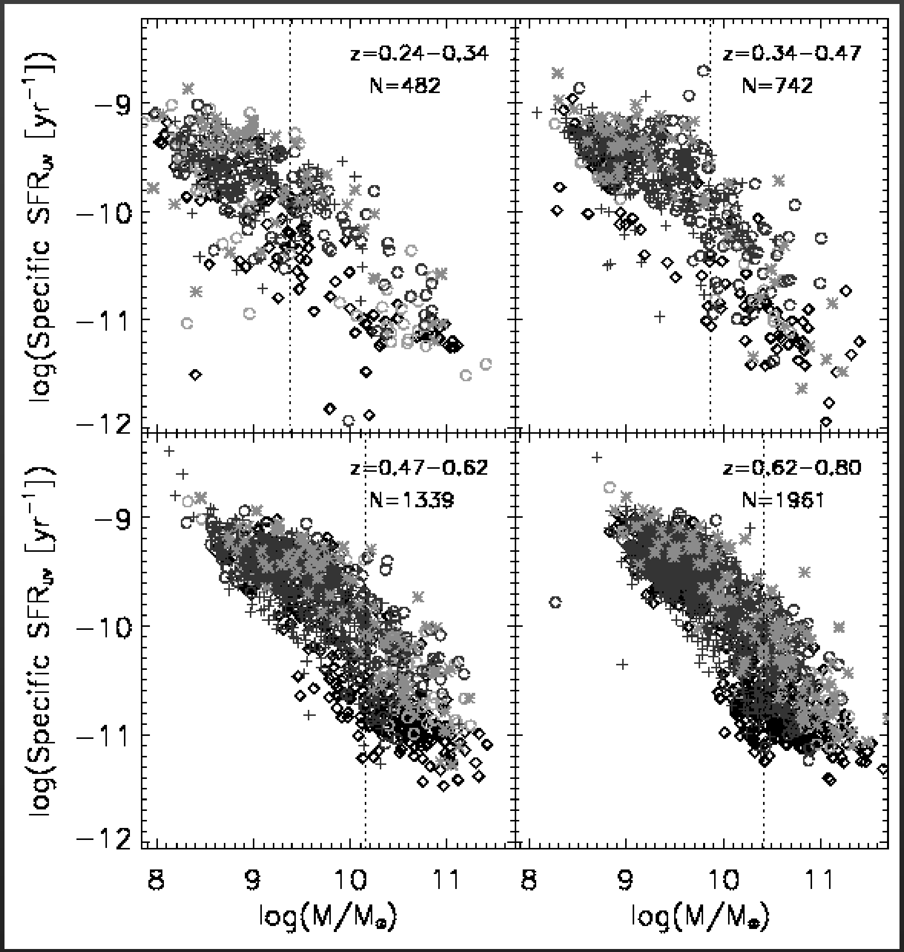


Di Matteo, P. et al. 2007

Statistical study of several hundred TREE-SPH simulations of major mergers of different B/D, gas, orbital parameters, etc

Max SFR of most mergers compared to isolated case is only enhanced by ~2 to 3, not factor of 10-20

Specific SFR vs Mass : the fractional growth of galaxies

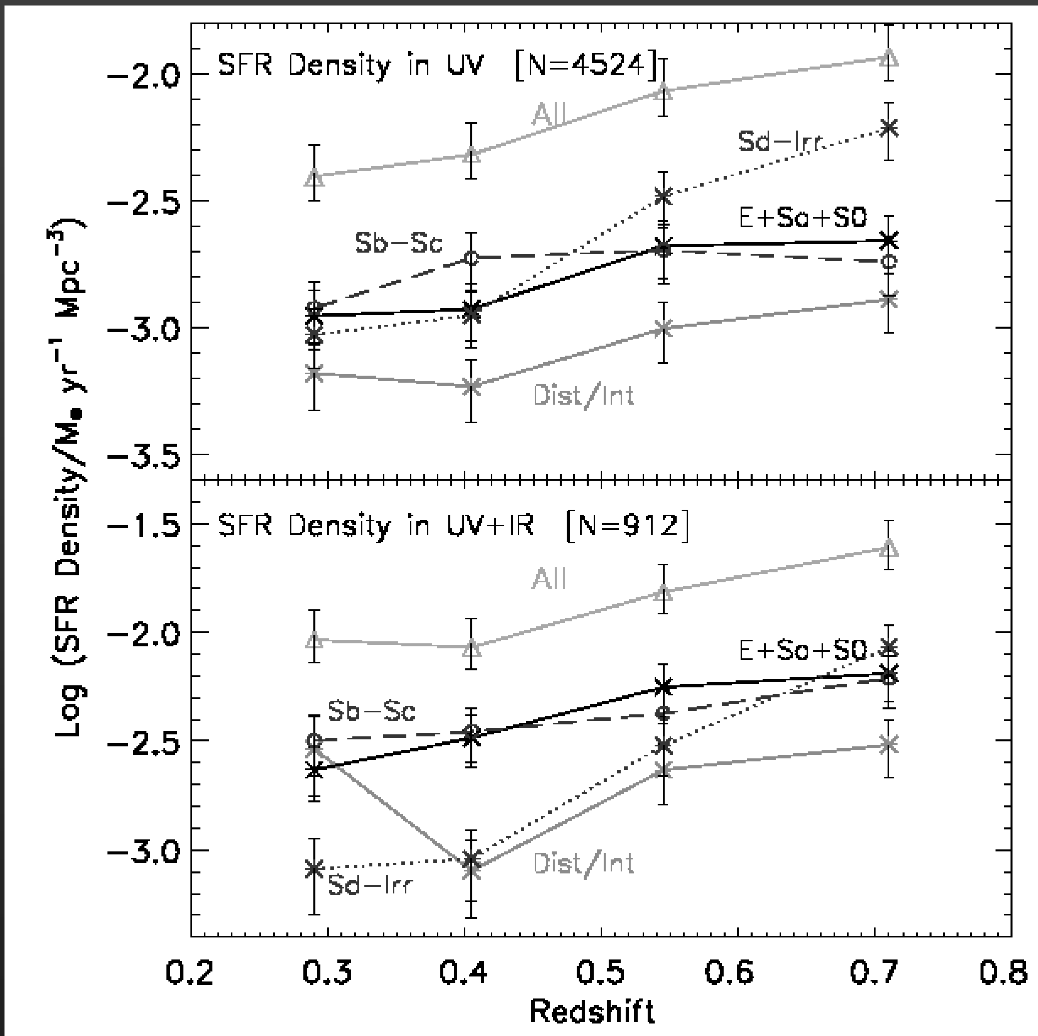


Only modest enhancement in SSFR of Dist/Int vs normal galaxies

Larger fractional growth in low mass than high mass galaxies at z<1 (“downsizing”)

à See Noeske et al al (2007) : SFR as f(M) and proposal of staged SF model

Madau plot : SFR density in normal vs interacting galaxies



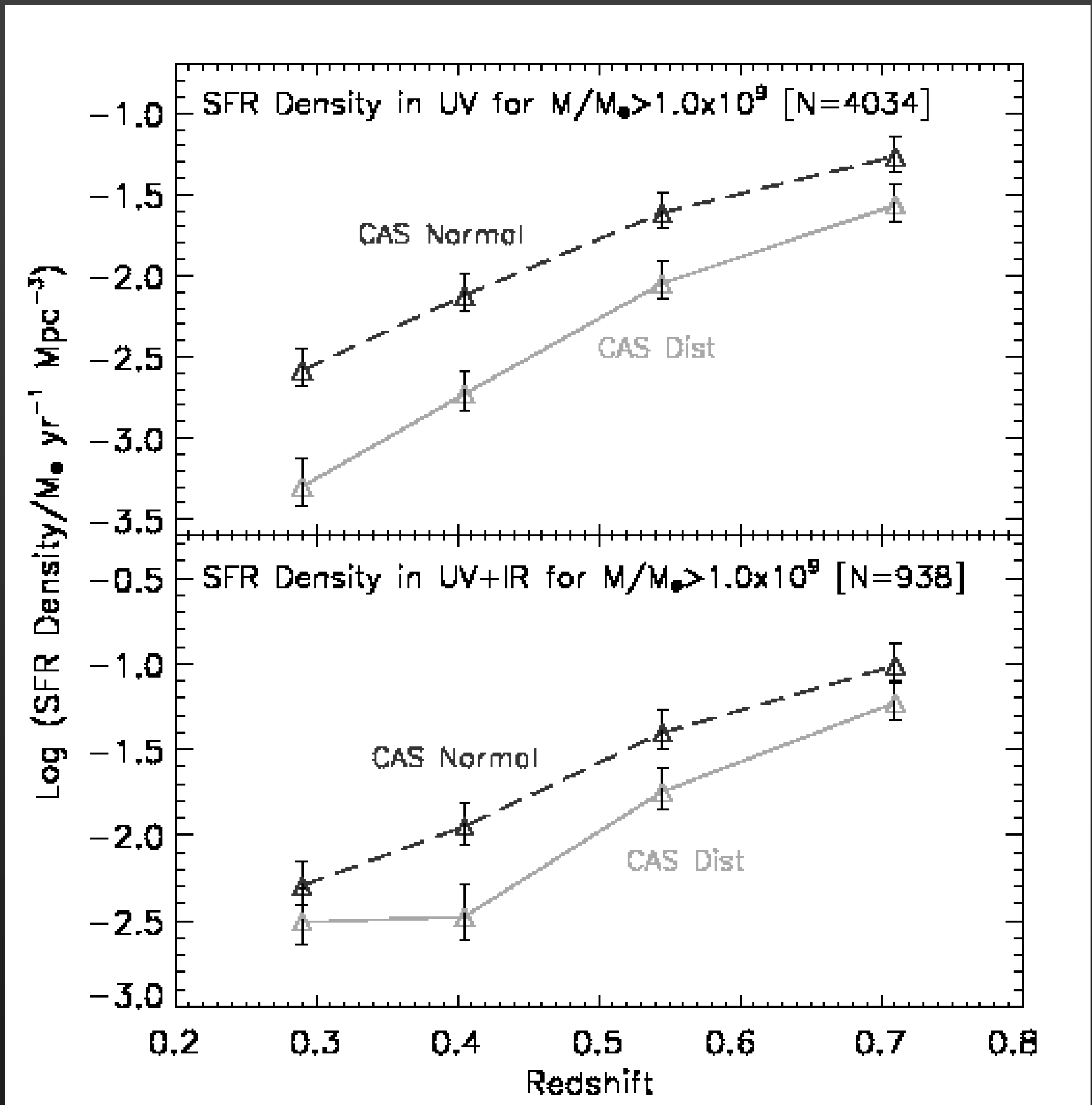
Cosmic SFR density over z=0.2 to 0.8 is dominated by undisturbed galaxies (Sb-Sc, E+S0+Sa) , while strongly disturbed/interacting galaxies contribute only 20 to 35%

Similar results at z~0.7: Wolf et al (2005), Bell et al (2005); Noeske et al (2007)

Models predict ~20% out to z<2 (Hopkins et al 2005)

Results hold even if Sd-Irr are contaminated since (Sb+Sc+E+S0+Sa) > (Sd-Irr) + (Dist/Int)

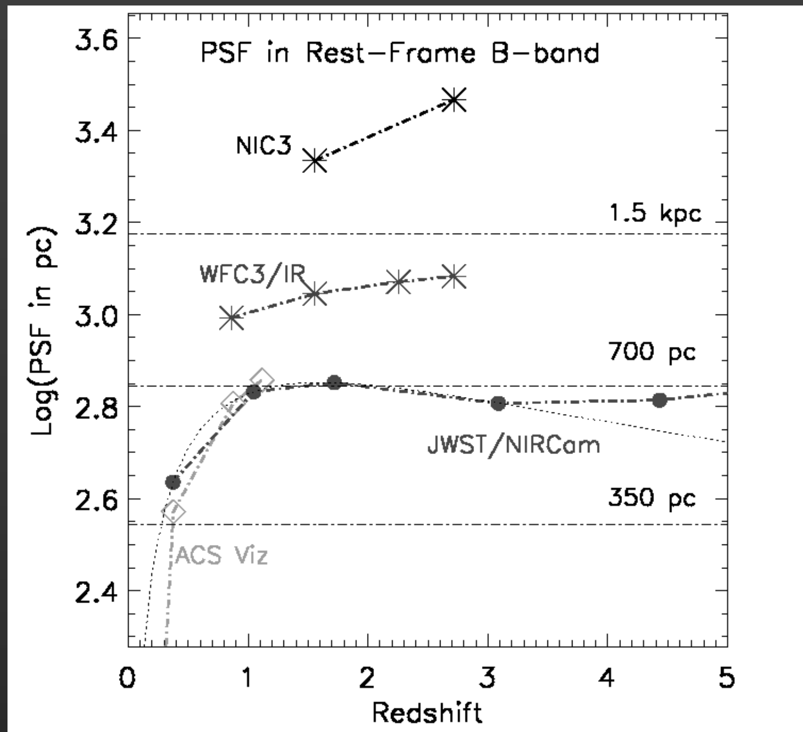
Similar qualitative results using CAS method



Future steps

Next: push studies in rest frame B or NIR (1 mu) to z>1

WFC3 and JWST



2) Ground-based 30-m class telescope with AO : PSF and spectroscopy

PSF of WFC3/IR = 128 to 160 mas over λ= 0.8 to 1.7 micron

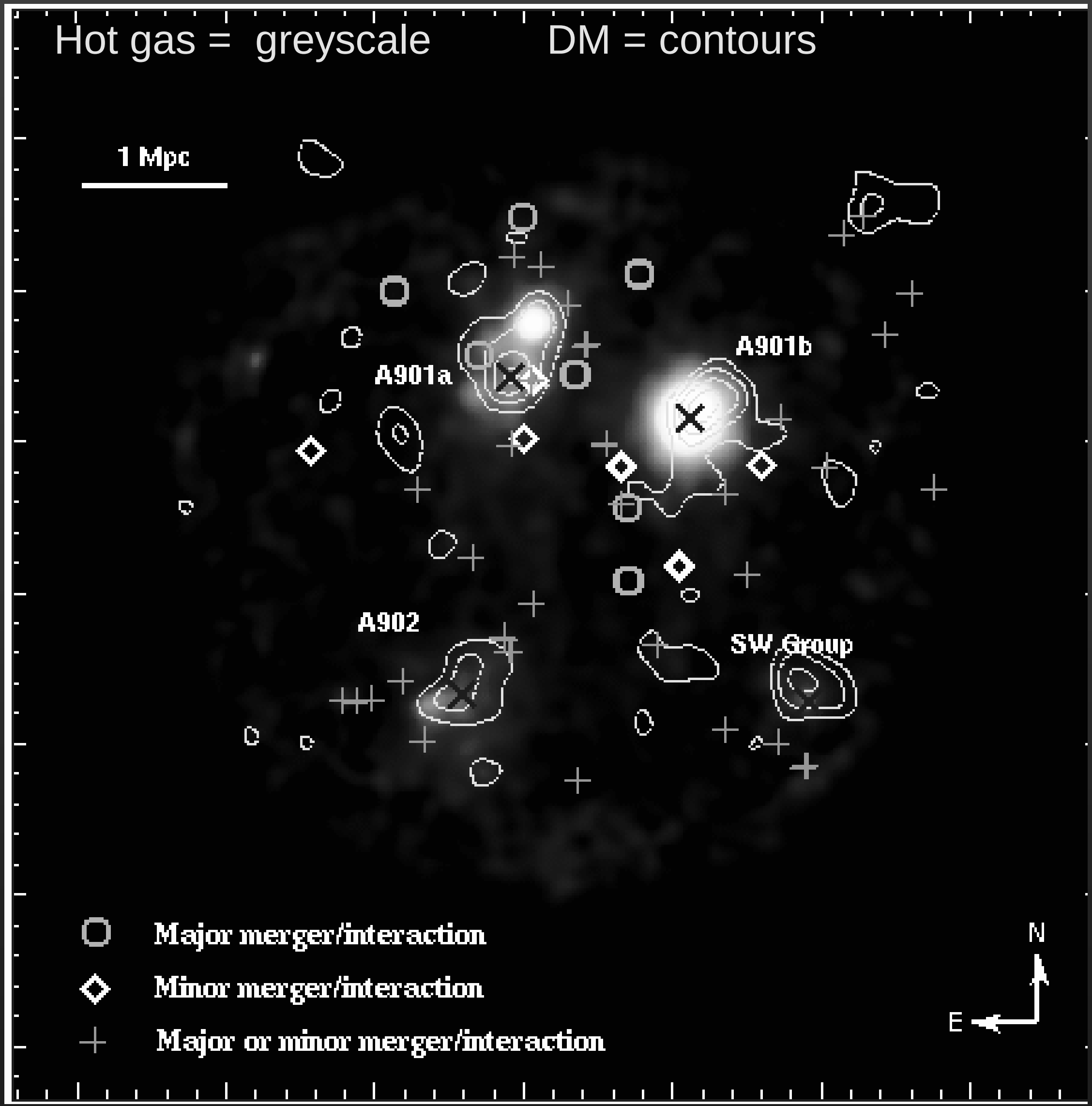
PSF of JWST/NIRCam = 84 to 197 mas over λ = 0.6 to 4.7 micron

30 m TMT or GMT with AO (diffraction limited) = tens of mas

R > 5,000 : Gas kinematics (disk signature, inflow, outflow). Metallicity

Stellar mass density at M<1e10

Merger/Interaction in different enviroments



(Heiderman, Jogee & STAGES, 2008 in prep)

Major mergers in A901/902 are offset from center of cluster, and peaks of DM

Does F rise from cluster to field at given M, z?

~ 1% in A901/902 at z~0.16

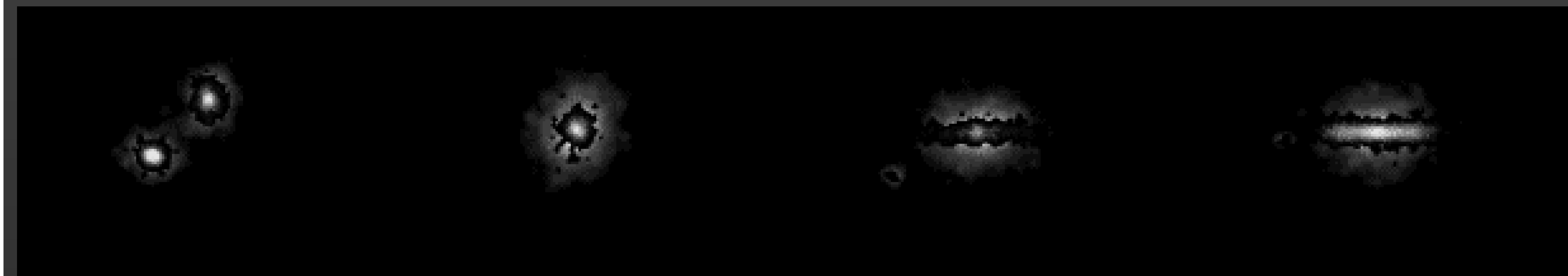
~ 1.5% in groups z~0.12 (McIntosh et al 2007)

~ 7% to 9% in field (Jogee al 2008)

The problem of bulgeless galaxies

Formation of classical bulges

1) Classical bulge: $R^{1/4}$ de Vaucouleurs profile , low v/σ



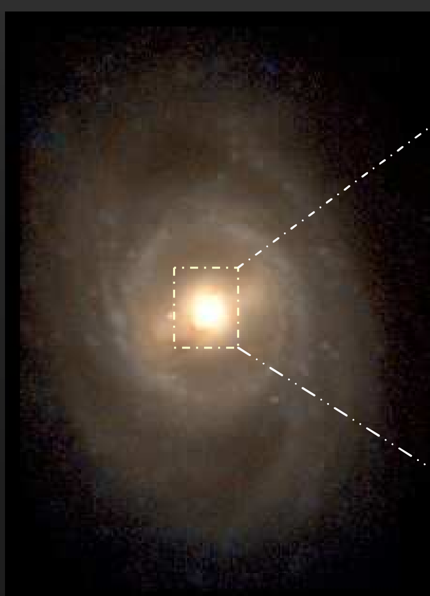
Major merger of two disks of stars+gas à   Violent relaxation à $R^{1/4}$ bulge.

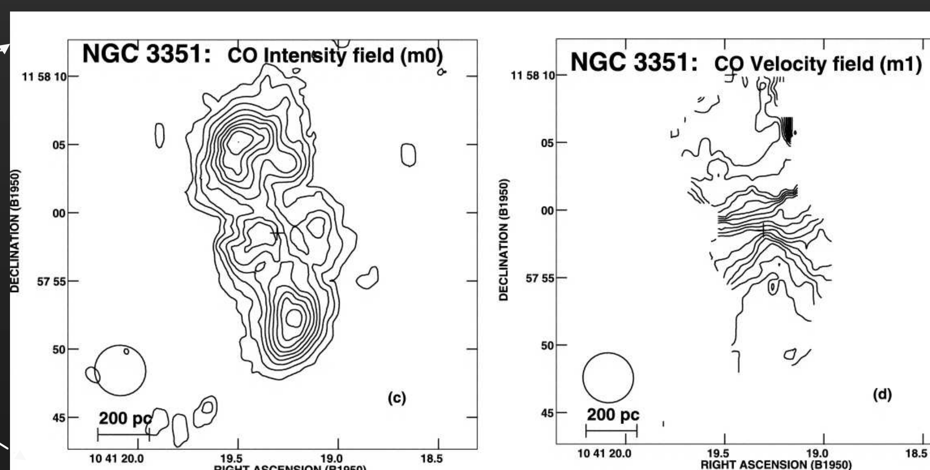
Formation of disky bulges from bars/minor mergers

Disky bugles = high v/σ, often exponential, stellar component in the inner kpc,

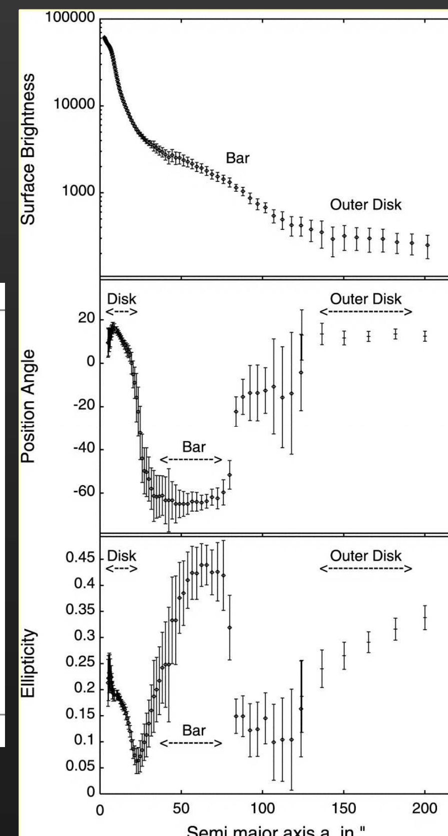
bars/minor mergers drive gas inflows, fuel central starburst à build CN disks

(Kormendy 93; Kormendy & Kennicutt 2004; Athanassoula 2005; Jogee, Scoville, & Kenney 2005; Debattista et al 2006)





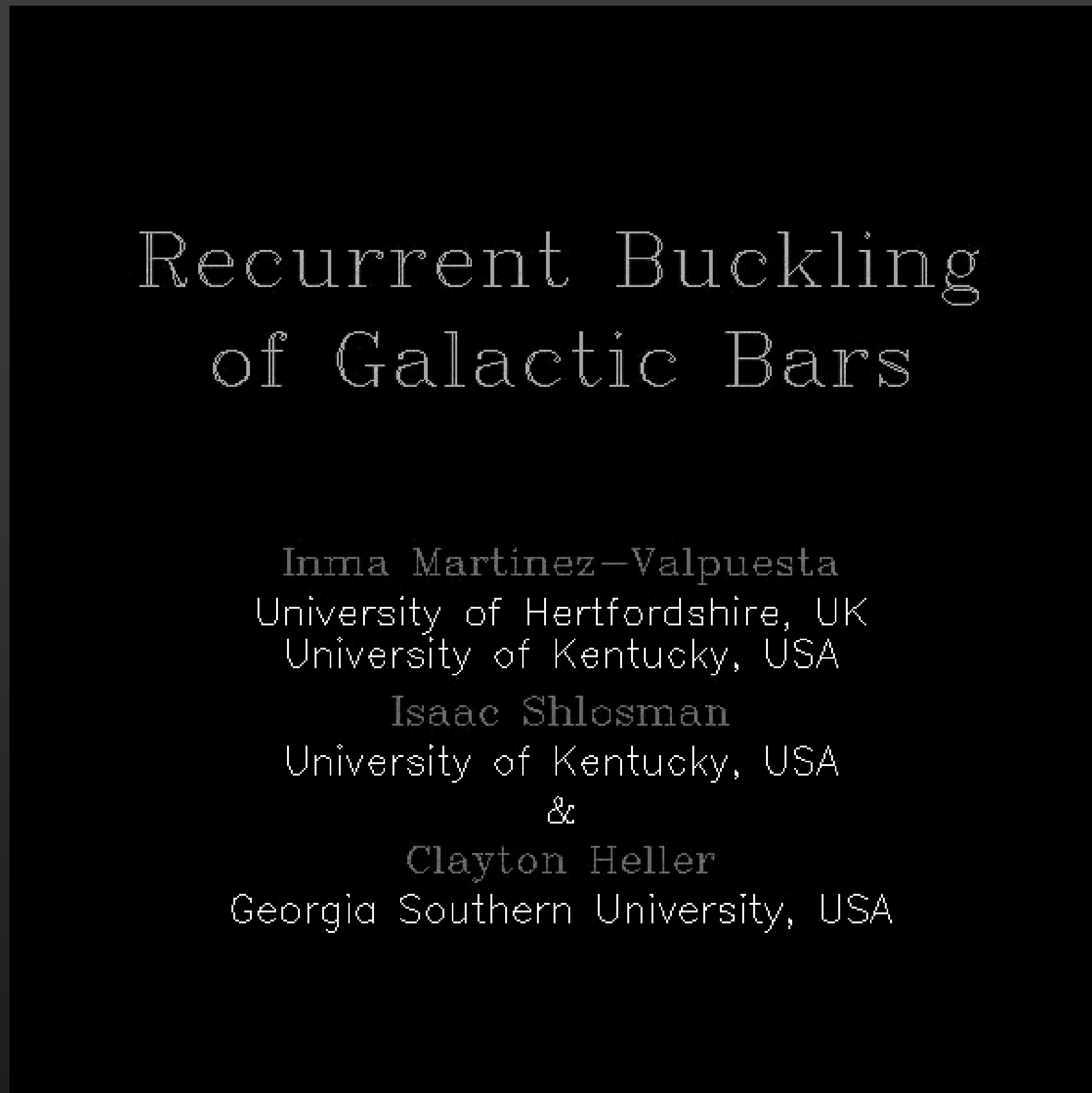
NGC 3351 (Jogee, Scoville, & Kenney 2005)



Formation of boxy/peanut bulges from bars

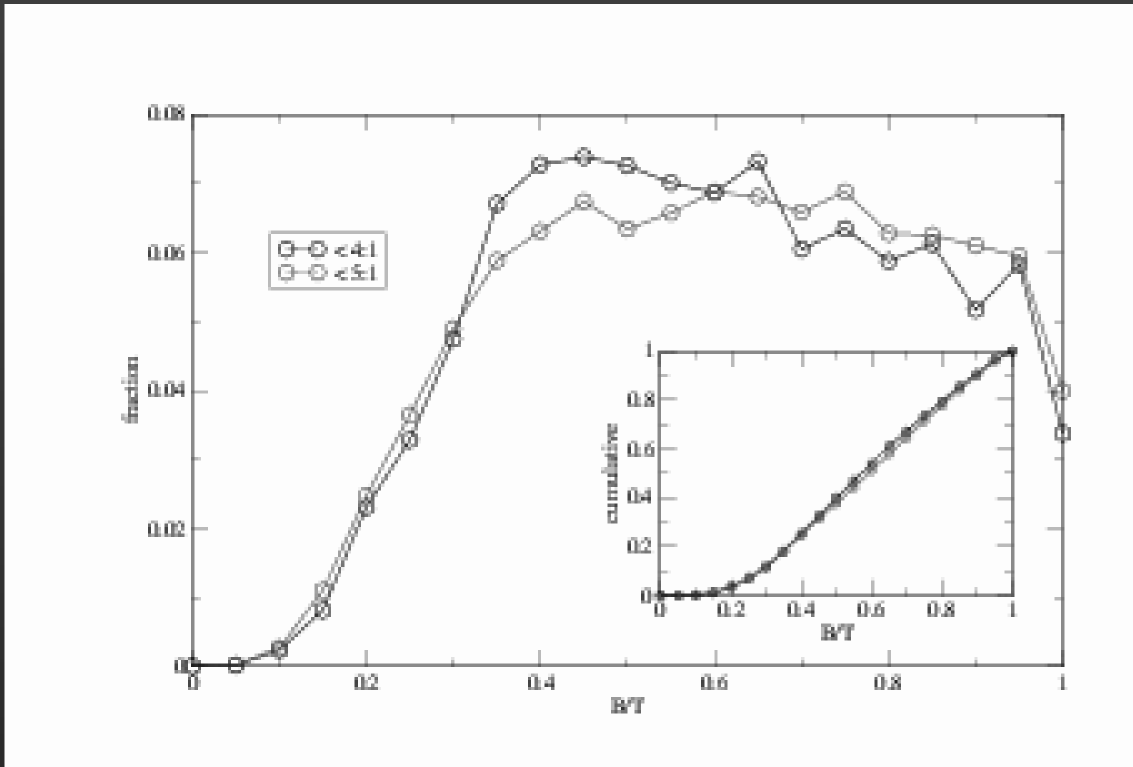
Buckling instability and vertical ILRs make edge-on bars look peanut/boxy

Bulge of Milky Way



Martinez-Valpuesta, Shlosman, & Heller 2005

Bulgeless galaxy problem



Cosmological simulations predict very few bulgeless or low B/T galaxies

(Burkert, Kochfar & D'onghea 2008)

Yet bulgeless and very low B/T galaxies common in local Universe

- Scd/Sd galaxies

- 15% to 20% of inclined disk galaxies at z~0.01-0.03 are bulgeless
  (Kautch et al 2006; Barazza, Jogee & Marinova 2007)

Bulgeless Galaxies

z=0.24 to 0.34   (T_b=3 to 4 Gyr)

z=0.34 to 0.47   (T_b = 4 to 5 Gyr)

z=0.47 to 0.80   (T_b = 5 to 7 Gyr)

Future work needed for bulgeless galaxy problem

Theoretically

Is the bulgeless galaxy problem

- due to merger history?
- due to lack of spatial resolution (central condensations = bulge) ?
- due to excessive loss of angular momentum ?
- due to inadequate feedback ?

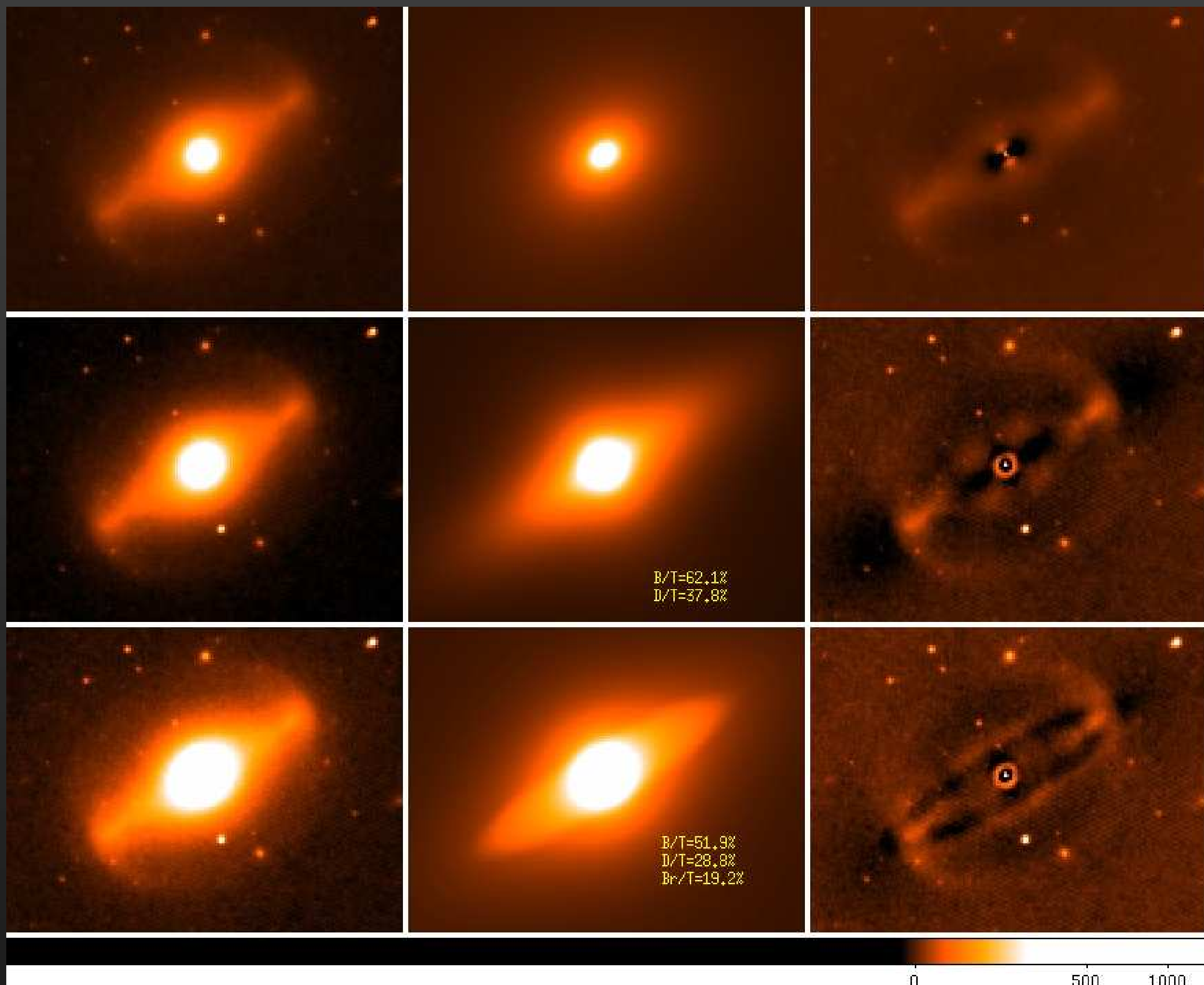
Observationally

Better characterize frequency and properties (M, SSFR, L) of bulgeless galaxies

Map B/T as function of (z, merger history, environment).

3-component Bulge + Disk + Bar decomposition to derive B/T

Data Model Residuals



(Weinzirl & Jogee, in prep.)

1 cpt = Single Sersic fit

2 cpt = Bulge + Disk fit
B/T ~ 62% D/T~ 38%

3 cpt = Bulge+Disk+Bar

Bar/T ~19%
B/T ~ 52% D/T~ 29%

(Laurikainen et al 2004; Reese et al 2007; Peng et al 2002)

Bars and Secular Evolution

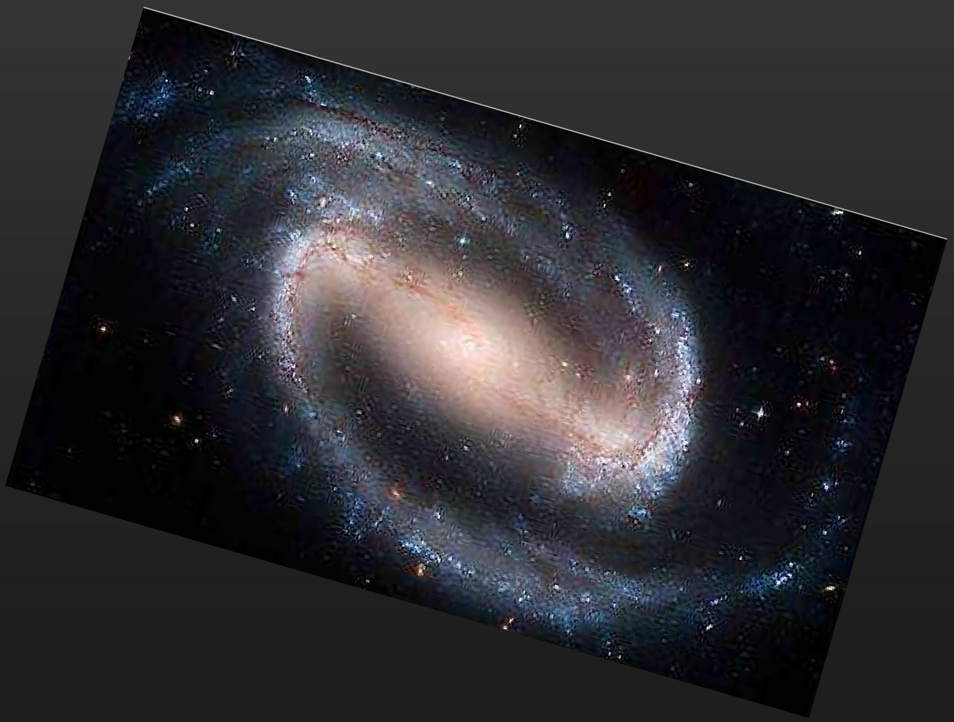
Importance of Bars

Bars redistribute angular momentum in baryonic and DM component of disk galaxies driving their evolution

Bars resonantly exchange L with disk + DM halo.

Bars drive gas inflows into inner kpc via g-torques and shocks

à fuel central starbursts
à indirectly help BH to grow
à bulild disky bulges



Frequency of bars at z~0

For intermediate Hubble type (Sb-Sc)

Optical bar fraction

B-band ~ 44% (Marinova & Jogee 2007); ellipse fit

R-band ~ 43% for B+D systems (Barazza et al 2007) e-fit

I-band ~ 47% (Reese, Sellwood et al 2007), B+D+Bar decom

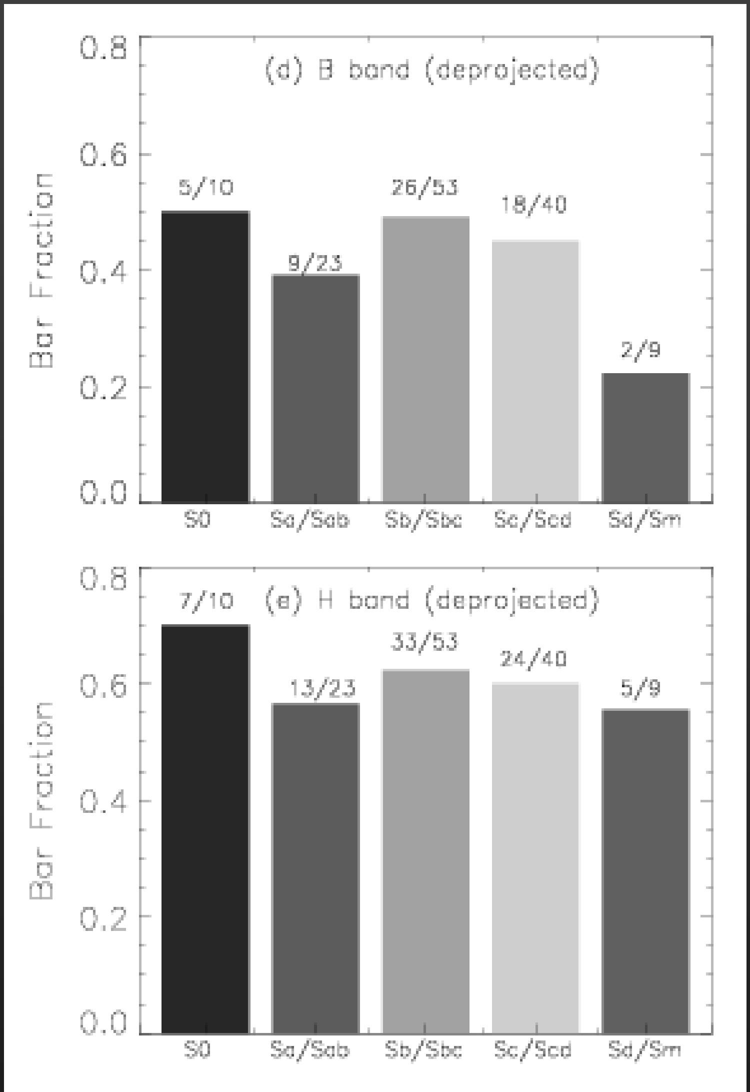
NIR bar fraction

H-band ~ 60 % (Marinova & Jogee 2007), e-fit

H-band ~ 60 % (Laurikainen et al 2004)

K-band ~ 58% (Menendez-Delmestre et al. 2007) e-fit

à **Correction for obscuration = 1.3 for e-fit at z=0**



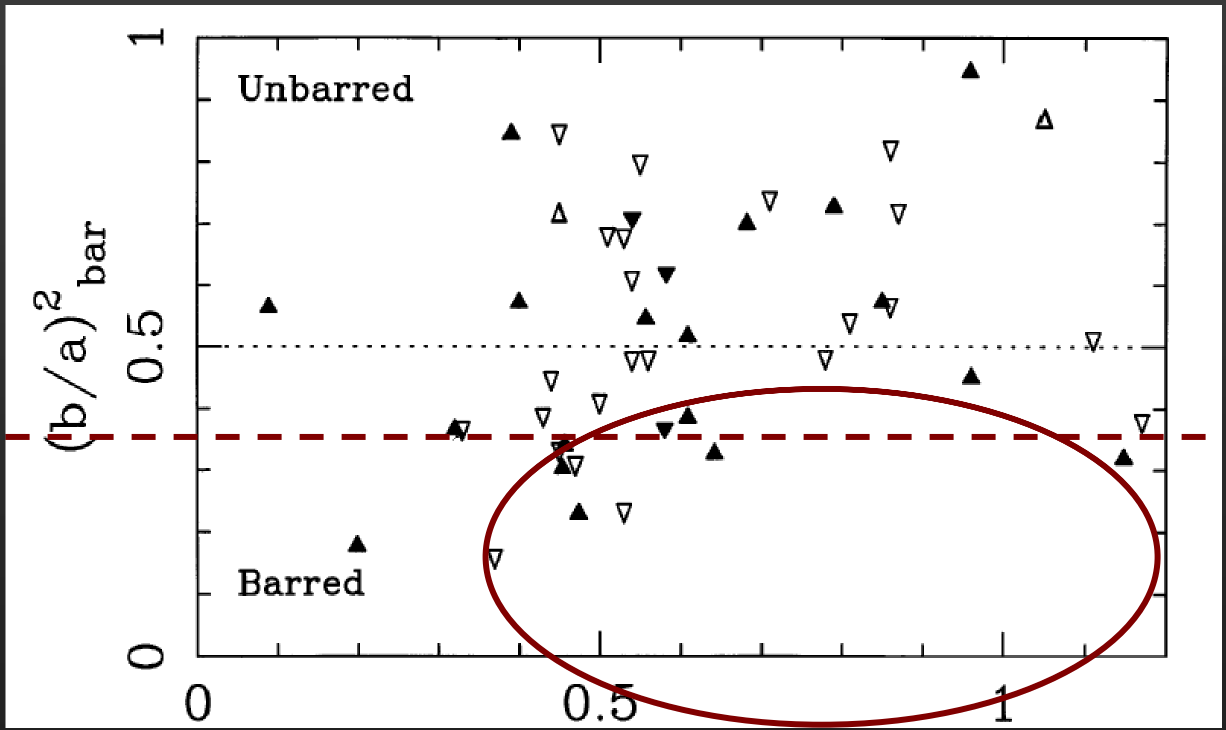
(Marinova & Jogee 2007)

How frequent are bars out to z~1

Order of magnitude decline in bar fraction from z~0 to 1
  “from 21% to 34%” to   “below 1%”   (van den Bergh et al 00)

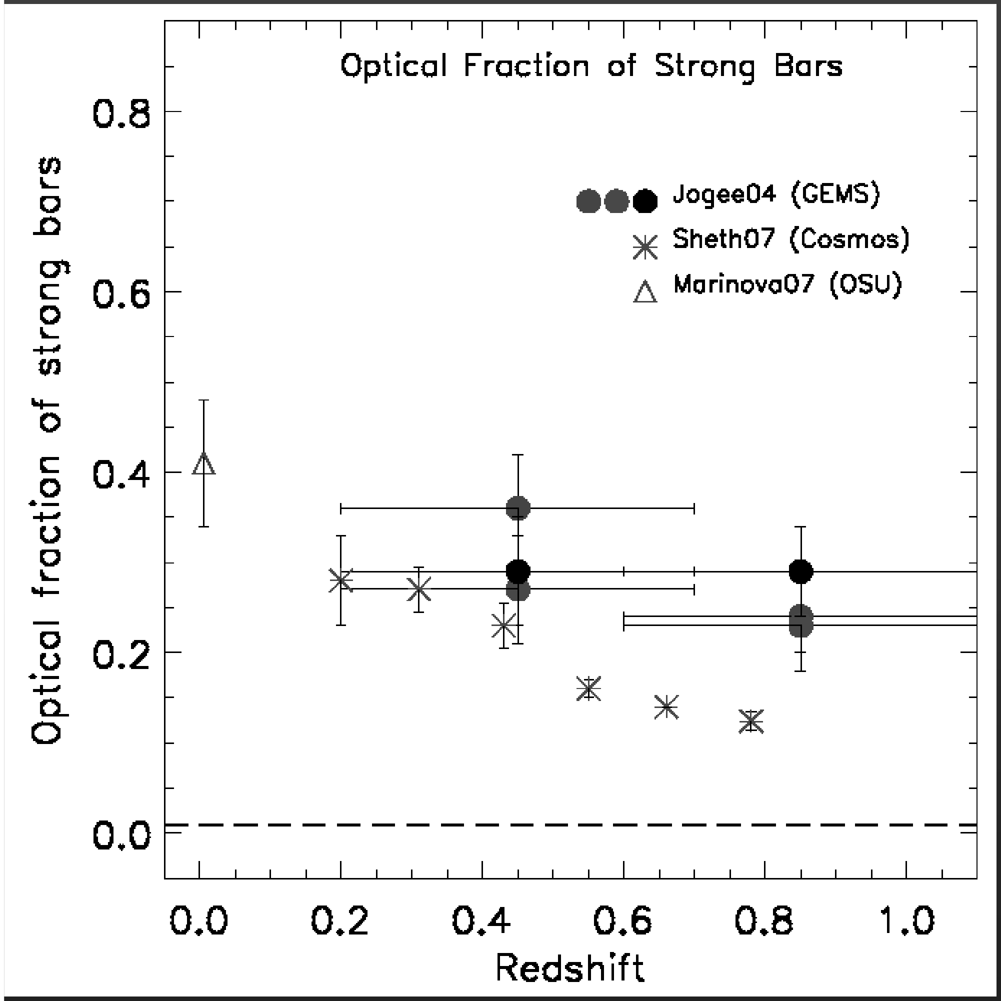
“A striking decline in bar fraction at z>0.5

(Abraham et al 1999)



At z>0.5, there are no strong bars [e>0.4 corresponding to (b/a)^2 <0.36] on Fig

The optical frequency of strong (e>0.4) bars out to z~1



The optical fraction (F_{sb}) of strong (e>0.4) bars does not decline by an order of magnitude, to below 1%.

Raw data allows for a constant bar fraction or a decline of ~2.

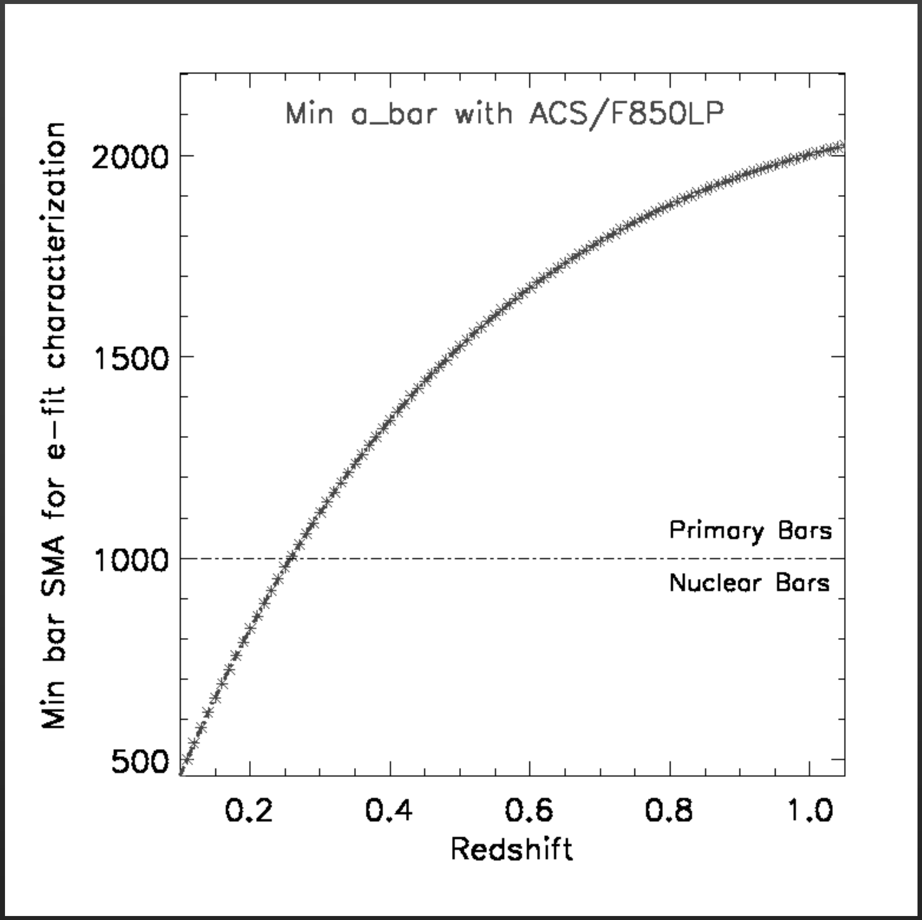
But a large part of this decline can be due to artificial loss of bars due to systematic effects at higher z

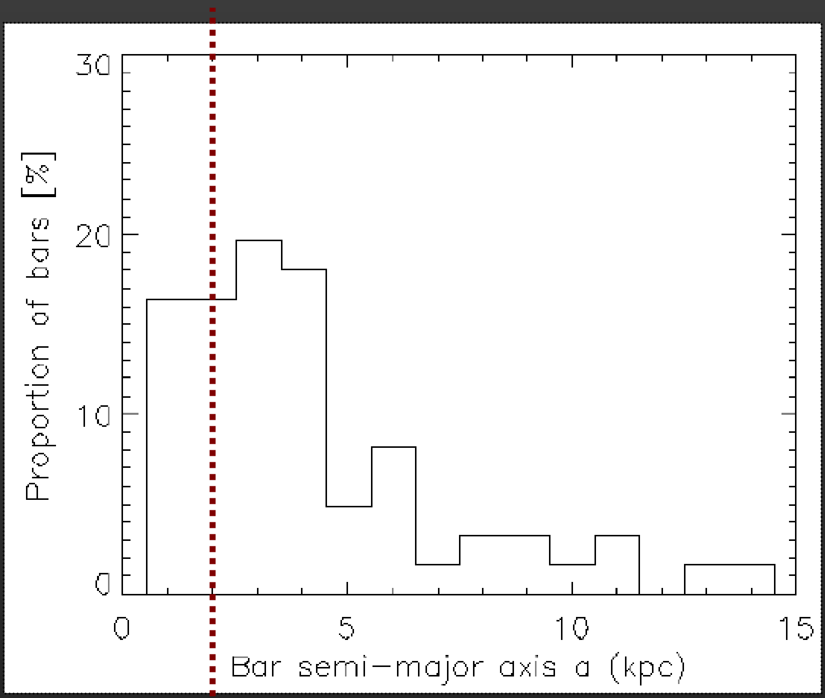
- lower resolution
- rising obscuration by gas/dust
- SB dimming

After correcting for these effects, data allow for several possibilities

- moderate decline (<1.3)
- constant bar fraction
- a rising bar fraction with z

Artificial loss of bars as over z=0.2-0.8 due to spatial resolution



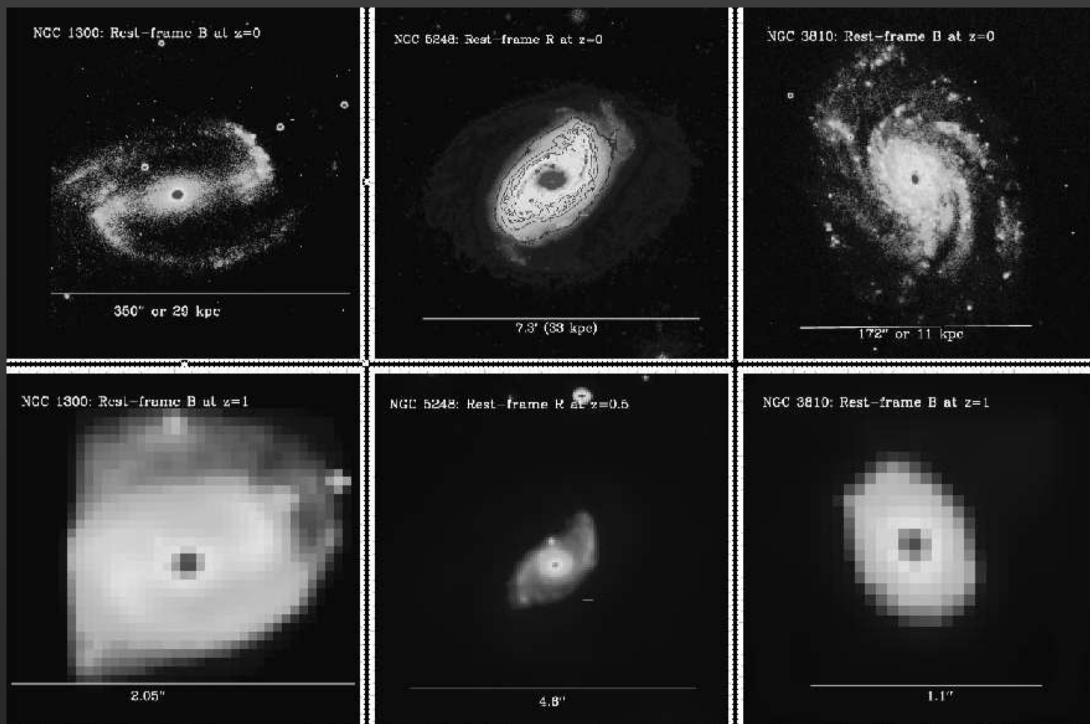


(Marinova & Jogee 2007)

For ellipse fit to reliably detect bars need a>2.5 PSF and a >= 5 pixels.
Start to lose primary bars over z~0.3 to 0.8.

à Loss factor X1= 1.4

Artificial loss of bars as over z=0.2-0.8 due to spatial resolution



From z=0

To z=0.6 (R) z=1 (B)

à Small primary bars (d<4 kpc or a<2 kpc) not reliably traced in ACS images

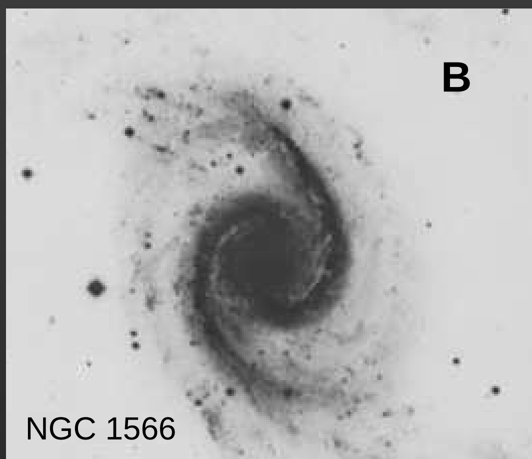
à Weak bars with SF in very faint disks may be mistaken for disks with spirals

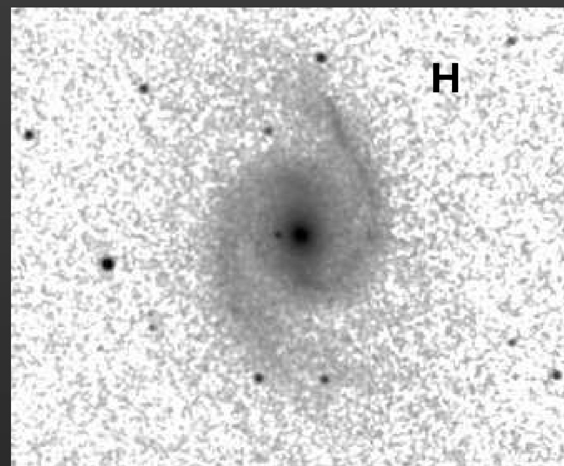
Artificial loss of bars as over z=0.2-0.8 due to rising obscuration

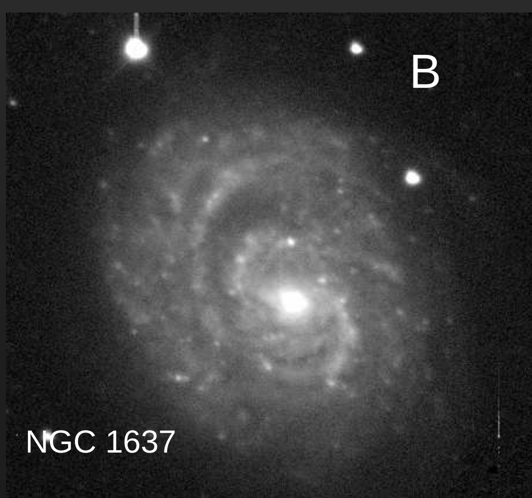
- **At z =0 ,** correction X_{obs} for obscuration of bars in the optical by SF and dust = 1.3

  Optical bar fraction ~ 44% to 47% (Marinova & Jogee 07; Reese et al 07; Barazza et al 07)

  NIR bar fraction I ~ 58% to 60% (Laurikainen et al 04; Menendez-Delmestre et al 07; MJ07)







Artificial loss of bars as over z=0.2-0.8 due to rising obscuration

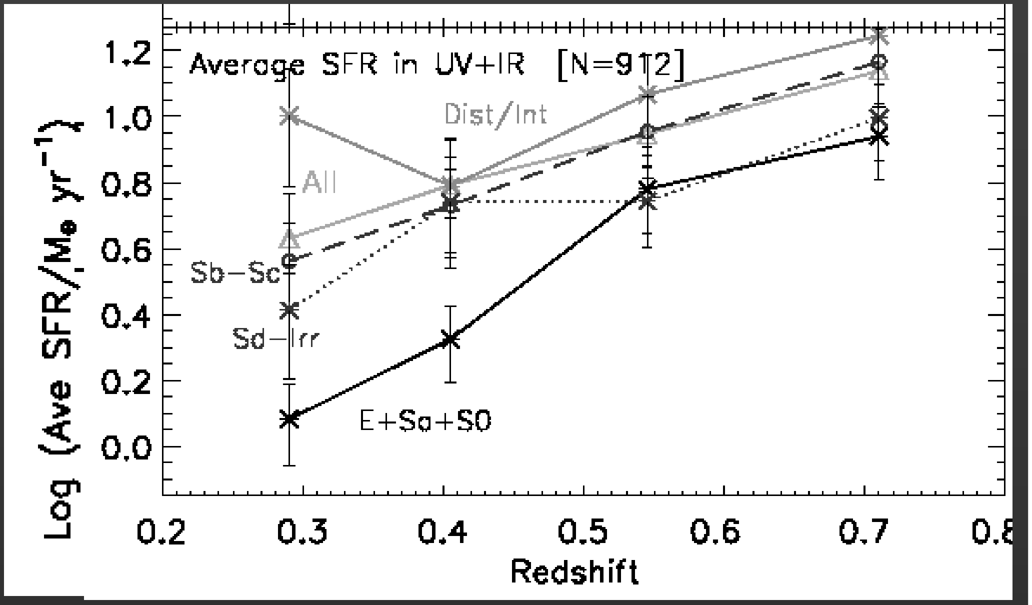
- **Over z =0.2 to 0.8**

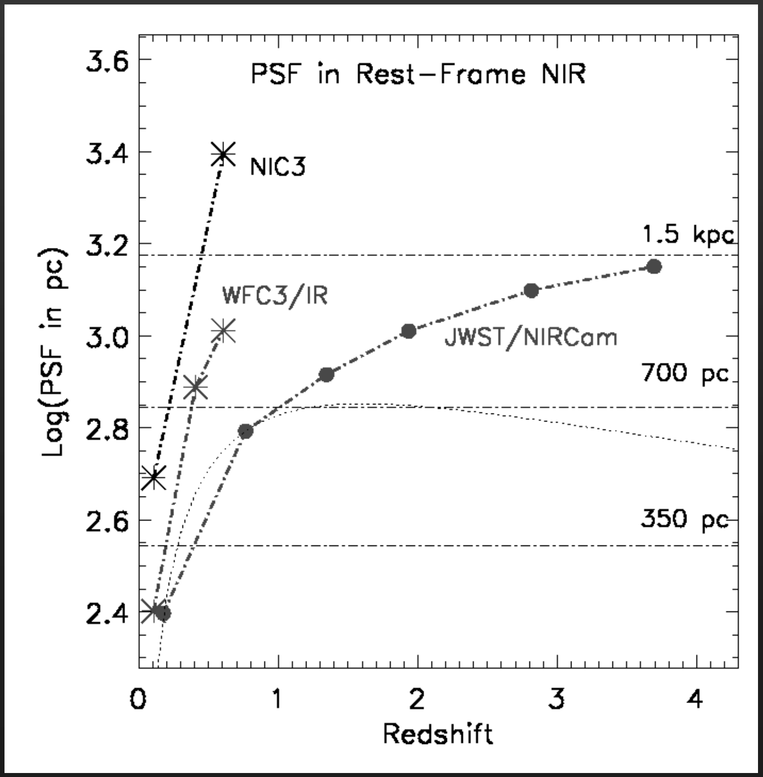
- average SFR increase by ~4 with z

à gas dust/content likely rises with z

à Obscuration of bars in optical lrises

Artificial loss by factor X2> 1.3





How to estimate X2 ?

Need high resolution rest-frame NIR (>=1mu) to detect obscured bars of intermediate size

* WFC3/F160W over z=0.2 to 0.6

* JWST/NIRCam 1.76mu to 5mu over z=0.2 to 3

* TMT or GMT with A0

Summary

HLCDM models provide a good paradigm for how DM evolves on large scales.
Complementary insights from large/deep surveys ACS (+ Spitzer, Chandra,GALEX)

Merger history since z<2

- the frequency of strongly disturbed merging/interacting galaxies drops significantly from z>2 (>40%) to z< 1 (< 10%)

- Merger rate is ~ few 10^{-4} galaxies Mpc-3 Gyr-1.
  At least 1/3 are candidates for minor mergers

- Merger fraction at z~0.2 to 1 are in good agreement with HLCDM models

- Secular and internal processes (bars/minor mergers, smooth accretion, bars)? become increasingly important at z<1 vs z>2

Summary

Star formation since z<1

- Average SFR of strongly disturbed galaxies is enhanced only by a factor of 2-3 w.r.t that of normal undisturbed galaxies. While huge bursts of star formation may happen in galaxy interactions/mergers, they are not the norm at z<1

- Cosmic SFR density over z=0.2 to 0.8 is contributed mostly by normal undisturbed galaxies (80%) vs strongly distorted galaxies (20%)
  à its decline may be caused by drop in gas content
  à consistent w/ theoretical models of merger-driven BH growth (H05)

Summary

Structural assembly

Bars are frequent at z~0.2 to 1 and do not decline by an order of magnitude. Current data, after correcting for systematics (PSF, obscuration, SB dimming) allow for a bar fraction that is

à moderately declining (~1.5) , constant or even rising with redshift
Need WFC3 or large ground telescope/AO

Bulgeless galaxy problem: LCDM cosmogonies predict few galaxies of low B/T while observations suggest such systems are common (f~15% to 20% at z<0.3)

à need B/T as function of (z, merger history, environment).

Future

WFC3, JWST, GMT/TMT, ALMA