S. Jogee (Oral)

Assembly Modes and Star Formation of Galaxies out to z~3

Mergers, smooth accretion, and secular processes are relevant for the assembly and central activity of galaxies in hierarchical models of galaxy evolution, but their relative importance at different epochs remains hotly debated. I will discuss the role of galaxy mergers on star formation and structural assembly based on three of our studies, which target galaxies from the local Universe out to redshifts of 3: (1) In Jogee et al.& the GEMS collaboration (2009), we explore the frequency of galaxy mergers and their impact on star formation over the last 7 Gyr using HST ACS, COMBO-17, and Spitzer data from the GEMS survey. We also compare the empirical merger history for high mass galaxies to theoretical predictions from five different suites LambdaCDM-based models. Among high and intermediate mass systems, we find that the mean SFR of visibly merging systems is only modestly enhanced compared to non-interacting galaxies, and that visibly merging systems only account for less than 30% of the cosmic SFR density over this interval. (2) In Weinzirl, Jogee, Khochfar, Burkert & Kormendy (2009), we set constraints on the merger history of high mass systems out to z∼2 based on the structural property of local bulges. (3) In Weinzirl, Jogee, and the GINS collaboration (2010, in prep.), we discuss the structure, very high star formation rate, and AGN activity of the most massive galaxies (M*=5e10 to few 1e12 Msun) at redshifts of z∼2-3, amd discuss the implications for galaxy evolution models.

Galaxy Mergers and Their Impact on Star Formation over the last 7 Gyr

Shardha Jogee

University of Texas (UT) Austin

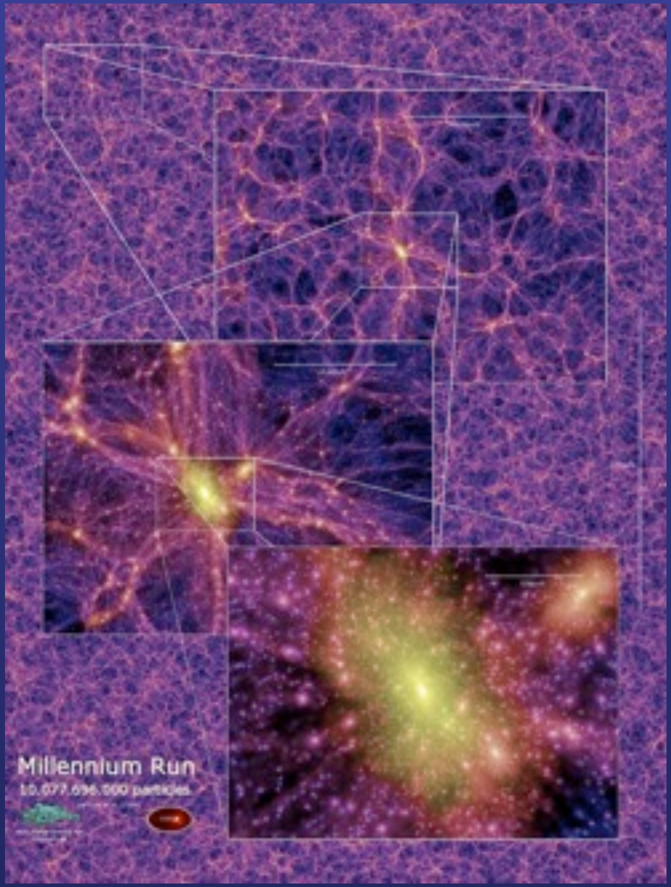
Collaborators
- S. Miller, K. Penner, Tim Weinzirl, Irina Marinova, F. Barraza
- GEMS and GOODS collaboration : H.-W Rix C. Wolf, R. Somerville, E. Bell, C. Papovich, C. Conselice, M. Barden, C. Peng, S. V. W Beckwith

Challenges for Galaxy evolution

LCDM models = good paradigm for how DM evolves on large scales, but predictions for galaxy evolution are not unique, mainly due to uncertainties in modeling the baryonic component

→How to model ISM, SF and feedback

→Translation of DM halo merger history to galaxy merger history non-trivial



Ongoing debate on relative importance of different galaxy assembly modes as f(z):

- major mergers, minor mergers,
- cold flow smooth accretion
- secular modes

Important to set empirical constraints on the history of galaxy mergers and thier impact on structure and activity

Main goals

(Jogee, Miller, Penner et al. & the GEMS collaboration 2009, ApJ, 697, 1971)

1) Provide empirical constraints on major + minor merger history out to z~0.8

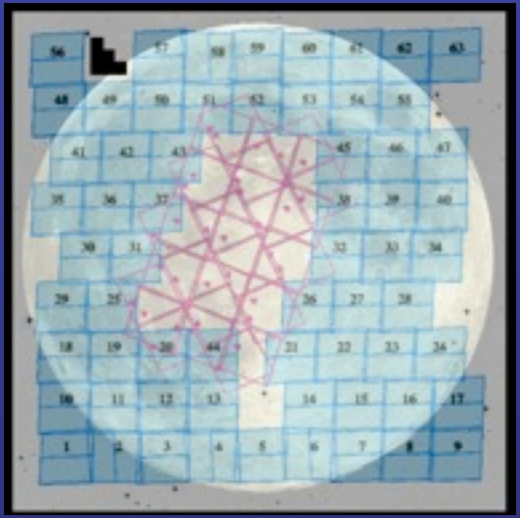
2) Compare merger history with predictions from LCDM-based models

3) By how much is <SFR> enhanced in visible mergers ?

4) What % of the SFR density out to z~0.8 comes from (major) mergers ?

Observational data

1) ACS F606W 0.09" resolution images from GEMS ACS survey (PI: H. W Rix, 2004)



- Large Area : 30'x30' in ECDF-S
  = 120 x HDF = 78 x HUDF = 5 x GOODS-S
- Central mosaic shared with GOODS-S
- 0.09" PSF → 300 pc at z~0.2, 680 pc at z~0.8
- 2 Filters : F606W (V), F850LP (z)
  Depth in V, z = 28.5, 27.3 AB mag (5 σ point source)

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2) Extensive panchromatic data

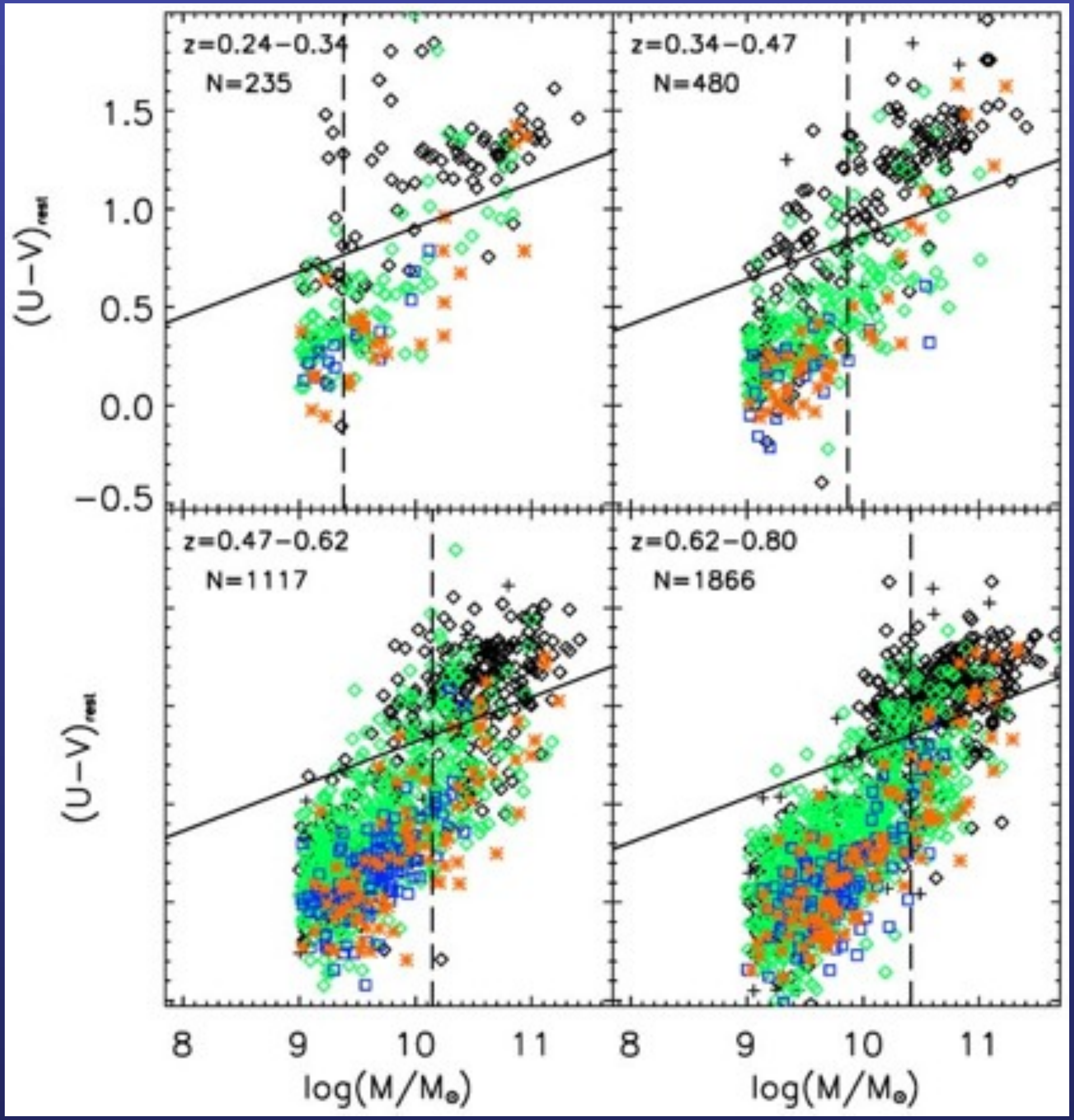
COMBO-17 ground-based data in 17-bands covering UV to optical (Wolf+04)
Deep Spitzer GTO (Rieke+04; Papovich+05)
Chandra CDF-S and ECDF-S data (Giacconi+02; Lehmer+05)

3) Spectro-photo-zs(Wolf+04) with $\delta z/(1+z)$ ~0.02 down to R~24 from COMBO-17

4) Stellar masses (Borch+06) from COMBO-17

5) UV and IR-based SFR (Bell+2007) from COMBO-17 & Deep Spitzer GTO

Two Samples over z=0.2-0.8



1) High mass sample (N~790)

- $M_*/M_0 \sim 2.5 \times 10^{10}$ to 3×10^{11}
- Complete for red sequence and blue cloud

2) Intermediate mass (N~3700)

- $M_s/M_0 \sim 1 \times 10^9$ to 3×10^{11}
- Complete for blue cloud only

(Jogee et al 2009)

Identifying mergers (major or minor)

Definition: Mergers of stellar mass ratio

1/4 < M1/M2<= 1/1 = major mergers

1/10 <M1/M2<= 1/4 = minor mergers

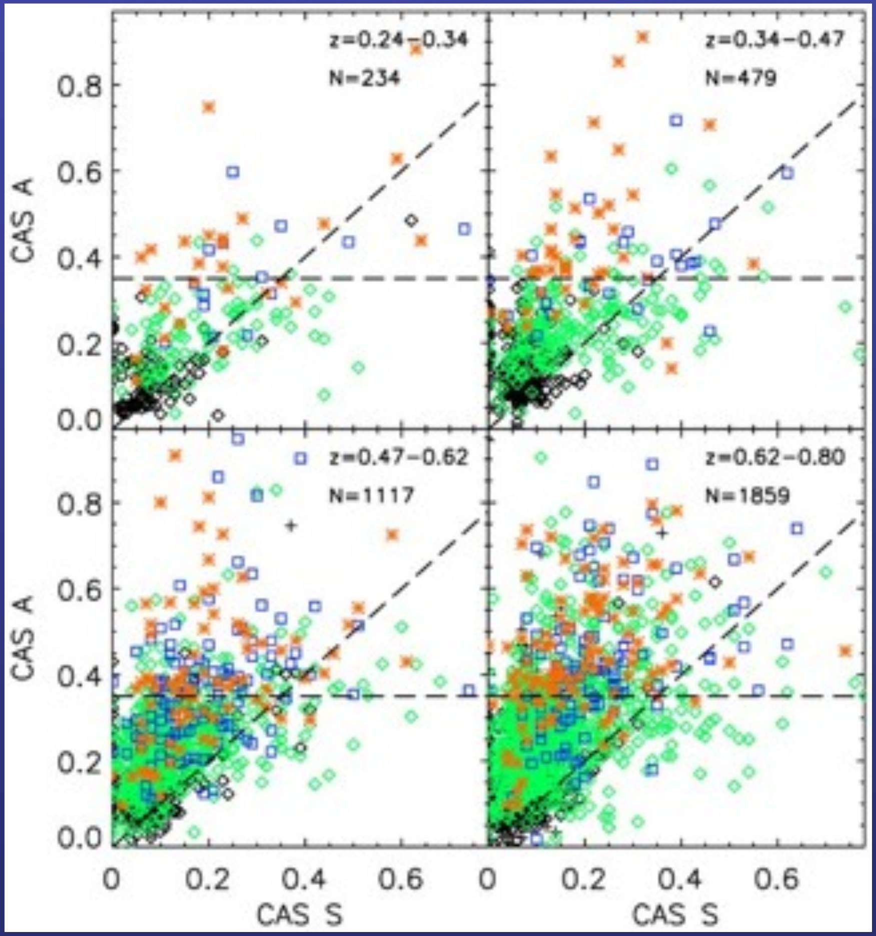
Identification of mergers via 2 methods

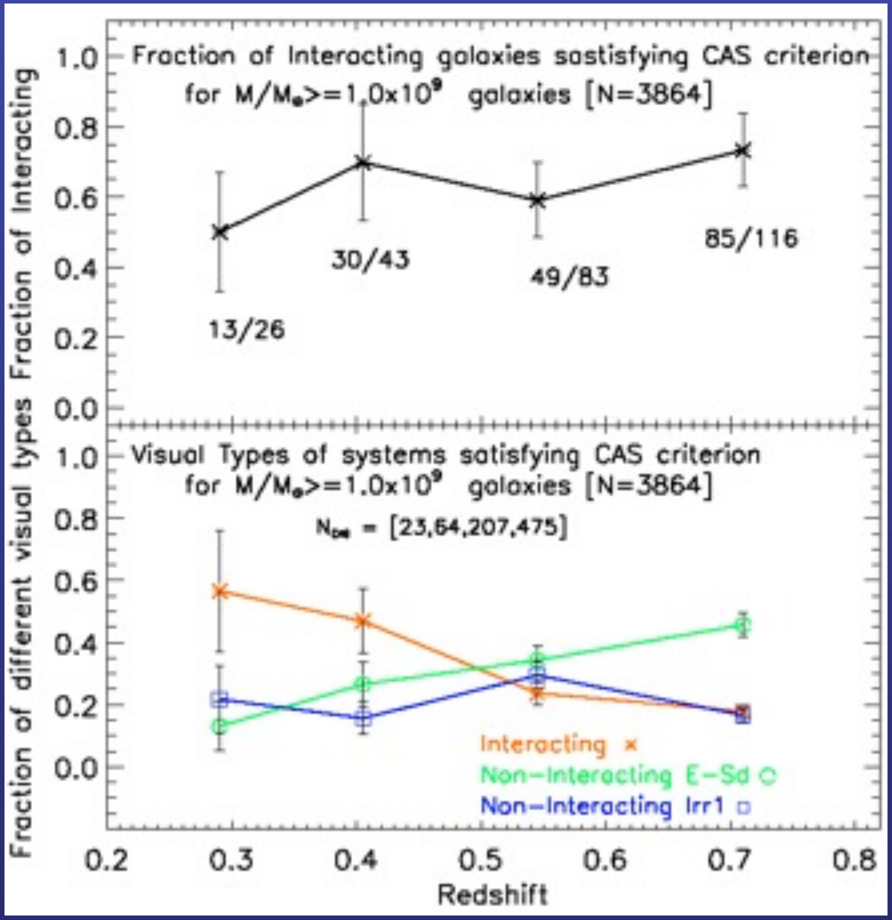
1) Use automated CAS criterion based on asymmetry A and clumpiness S

A> 0.35 and A >S for major mergers (Conselice+03)

2) Use Visual classification (+ info on z, stellar mass ratio for pairs) based on hydro simulations of different merger phases (See Jogee+09 paper for details)

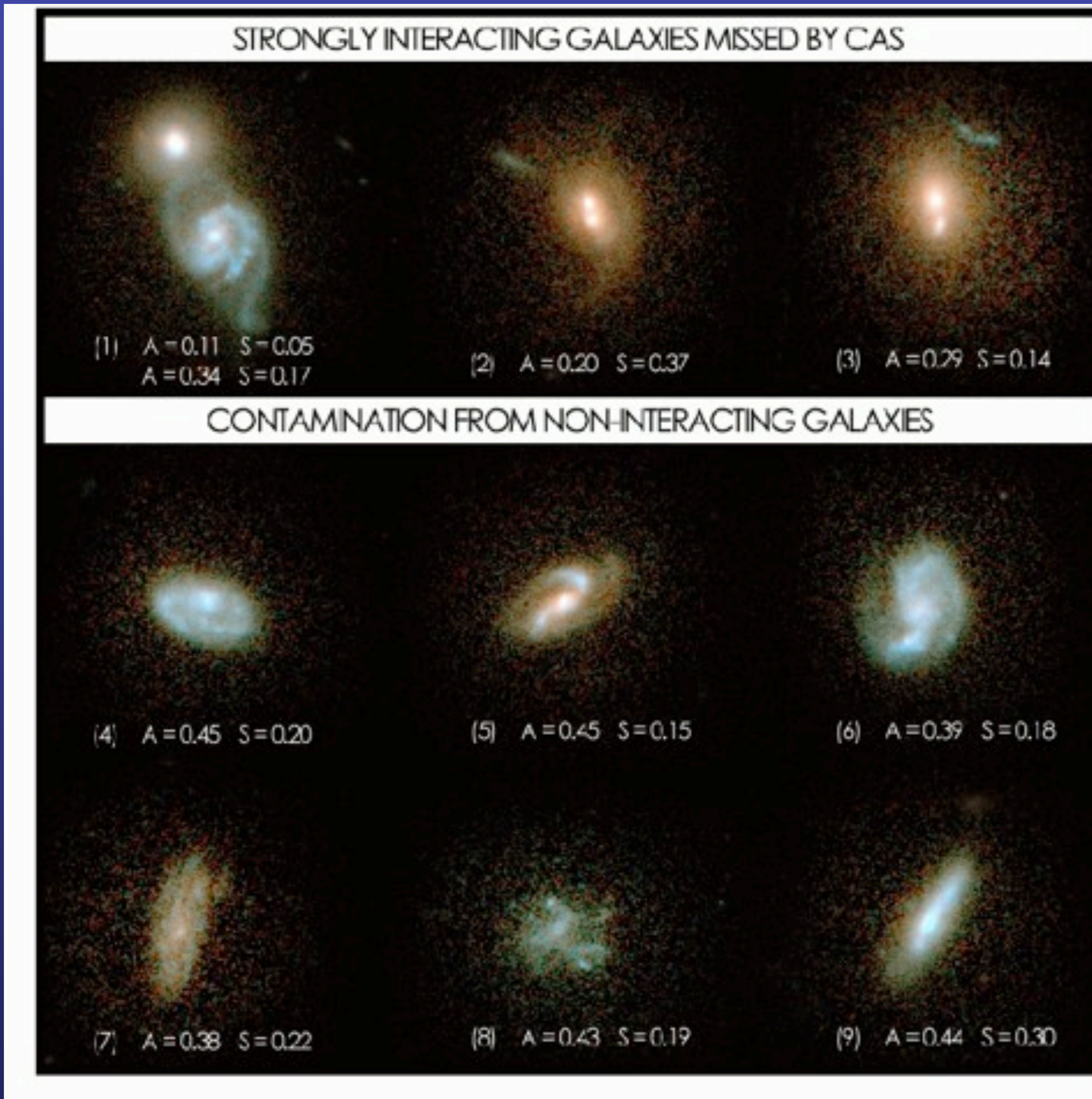
Limitations of using CAS (A>0.35, A>S) to select mergers





Over z=0.2 to 0.8, CAS criterion (A>S, A>0.35),

1) picks 50% to 70% of the visual mergers
2) suffers from contamination: 40%-80% of CAS systems are visual non-interacting (Irr1, E-Sd)
   Contamination severe at z>0.5, where rest-frame λ of ACS V image ~ 3950- 3300 A (NUV)



Interactions/mergers missed by CAS criterion (A>0.35,A>S)

Non-Interacting galaxies picked by CAS criterion (A>0.35,A>S)

- *Dusty star-forming or edge-on galaxies: center unclear → high A*
- *Actively star-forming with small-scale asymmetry in rest-frame blue and NUV light → high A*

Identifying mergers (major or minor)

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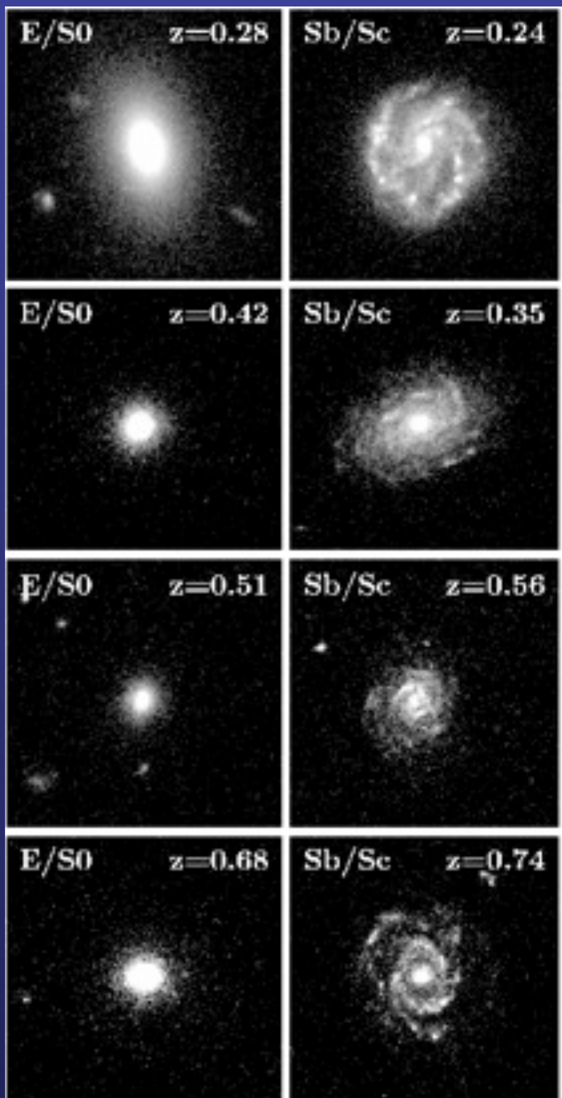
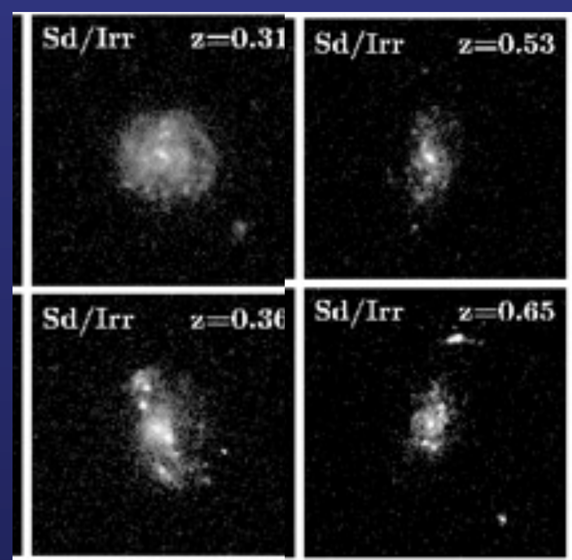
Method 2: Visual Classification of Mergers vs Non-Interacting

Non-interacting E-Sd



Non-Interacting Irr1

Mainly galaxies with small-scale asymmetries that can be internally triggered (e.g., via stochastic SF or low V/σ) without any external galaxy interaction.



Mergers

Systems w/ morphological evidence of a merger of mass ratio >1/10 within the last visibility timescale.

Example of mergers

Type 2 (very close pair)

Very close pair of galaxies that will likely merge in t_{vis} & satisfy 3 criteria

a) One or both systems distorted.

b) z1~z2

c) stellar M1/M2 > 1/10

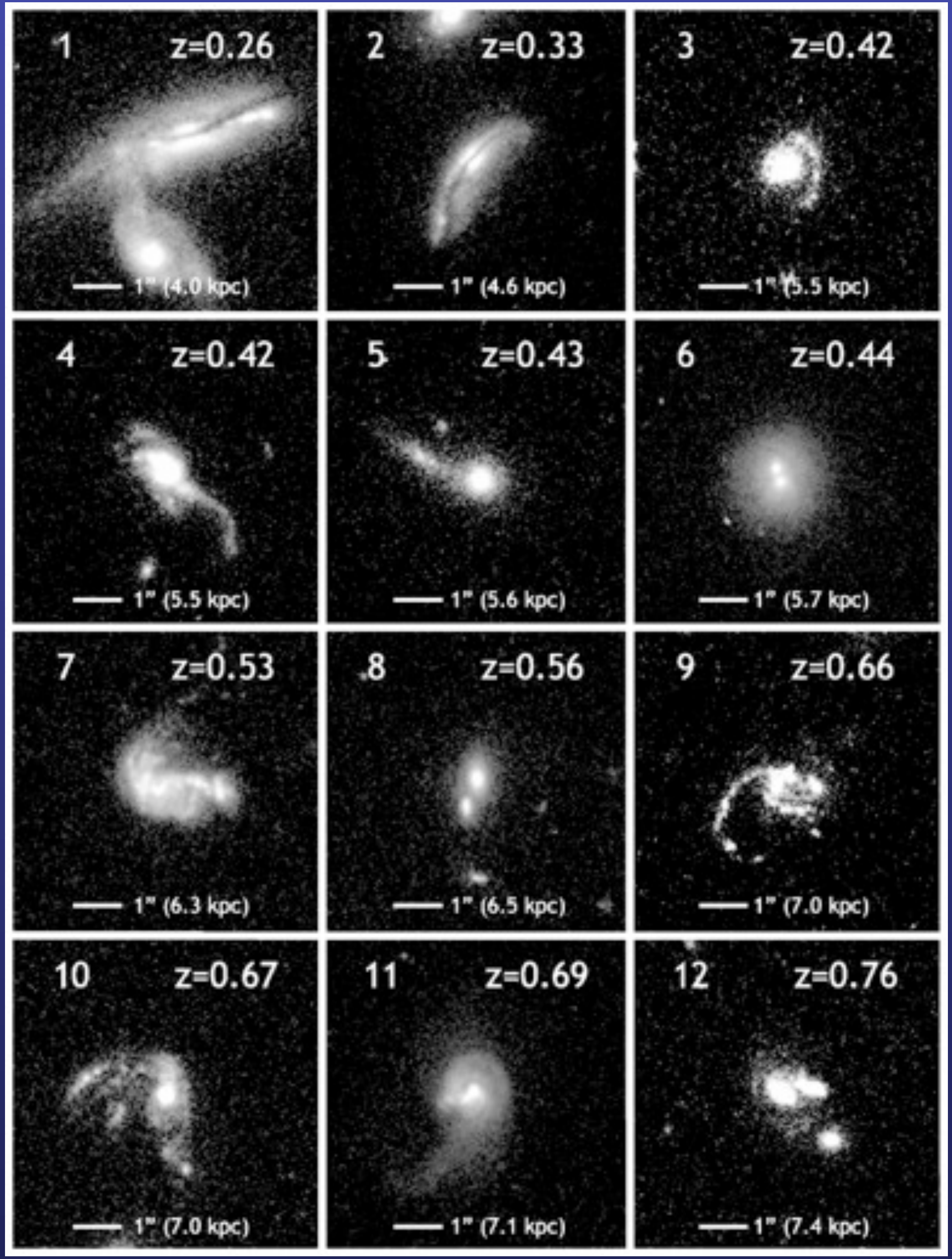
1/4< M1/M2 <=1 : major merger

1/10<M1/M2 <=1/4 : minor merger

Type 1 (advanced merger)

Single coalesced system with distortions similar to those seen in simulations of mass ratio > 1/10 : warps, strongly asymmetric arms, double nuclei, galaxies bounded by a common body or bridge, tails

Includes both major and minor mergers



Separate mergers into major, minor, major/minor

Level of distortion not only f(M1/M2) but also f (orbital geometry and inc, host property)

Mergers

Major (M1/M2>1/4)

- Very close pair with M1/M2>1/4 and z1~z2
- Double nuclei of similar L
- Train wreck

Ambiguous: Major or Minor

Separate mergers into major, minor, major/minor

Level of distortion not only f(M1/M2) but also f (orbital geometry and inc, host property)

Mergers

Major (M1/M2>1/4)

- Very close pair with M1/M2>1/4 and z1~z2
- Double nuclei of similar L
- Train wreck

Minor $(1/10 < M1/M2 < 1/4)$

- Very close pair with M1/M2 ~ to 1/10 and z1~z2
- Single system hosting a surviving disk with a warp or other strong morphological distortions

Ambiguous: Major or Minor

Limit and test effect of bandpass shift

1) Limit bandpass shift by restricting redshfit range from z=0.2 to 0.8

→ Rest frame λ traced by GEMS V image : optical at z<0.6, NUV= 3700-3300 A at z=0.6-0.8

Test bandpass shift in z=0.6-0.8 bin

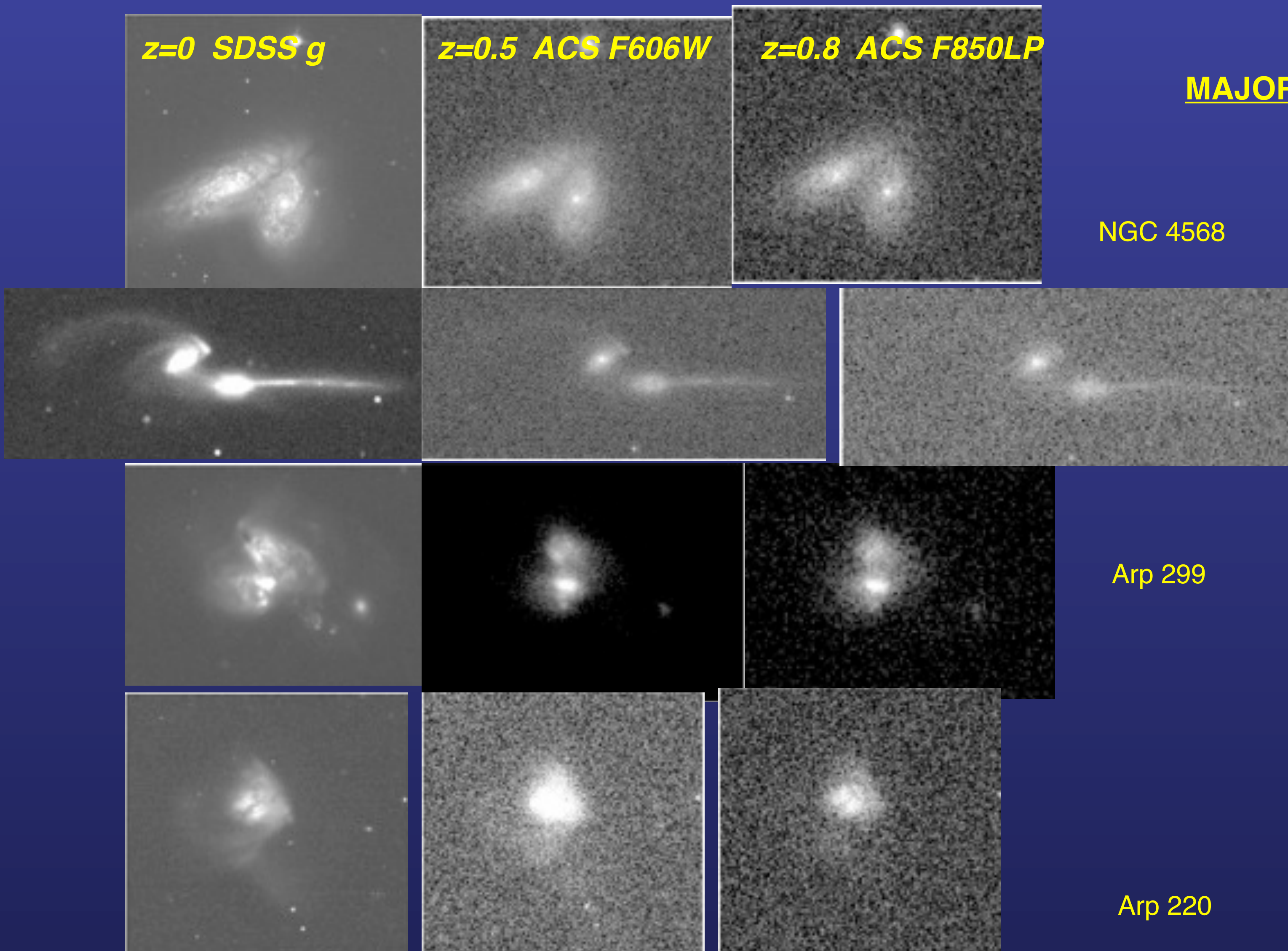
→ Compare merger fraction f
from GOODS z (rest-frame optical)
vs
from GEMS V (rest-frame NUV)

→ Results on f changes by < 1.07

Test effect of cosmological SB dimming, PSF degradation

Artificially redshift local mergers out to z=0.5 and 0.8 and 'observe' with ACS

Use FERENGI (Barden+08) code on SDSS images; assume 1 mag SB evolution out to z=1 (Barden+05)



MAJOR MERGERS

NGC 4568

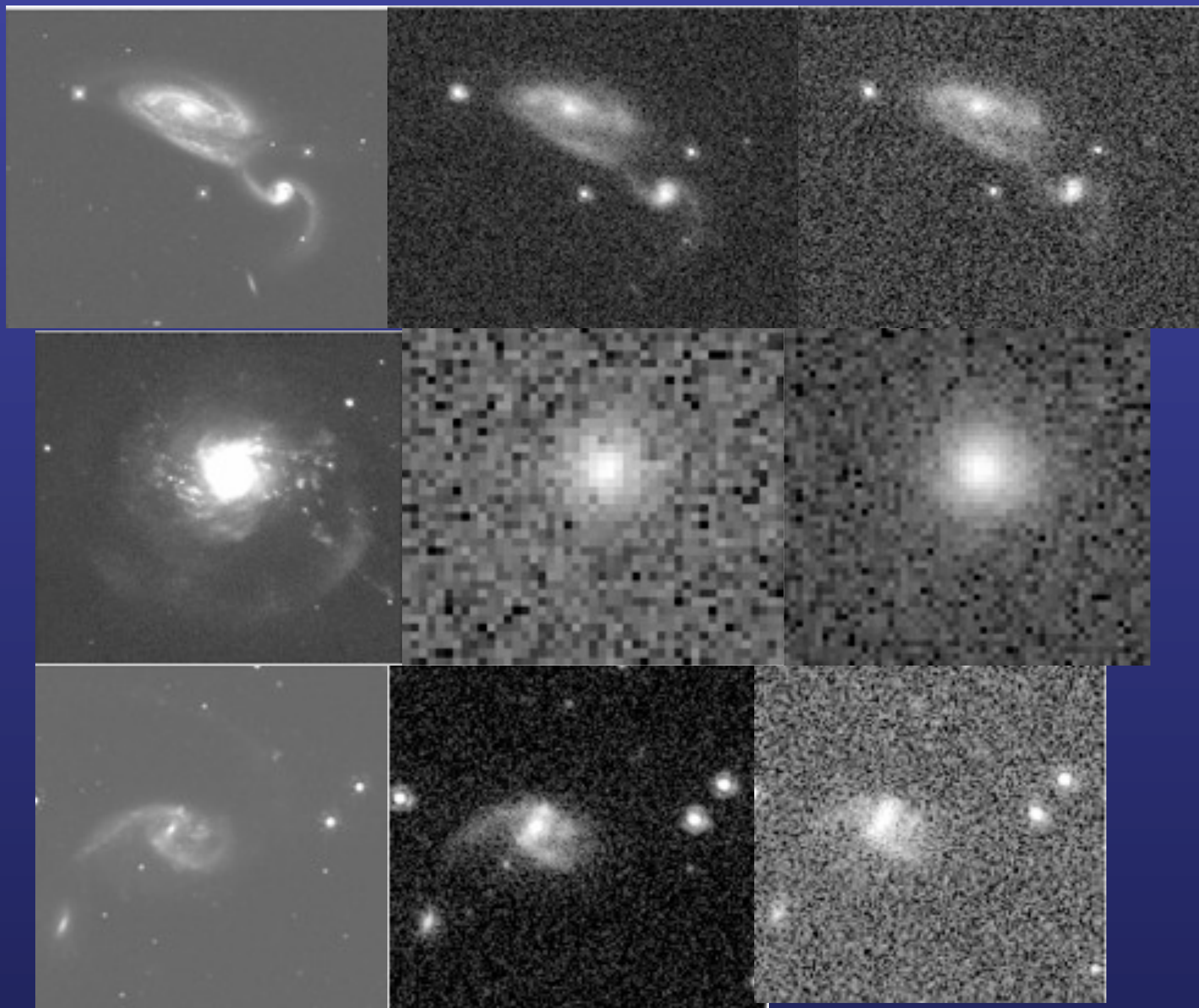
NGC 2623

Arp 299

Arp 220

MINOR MERGERS

z=0 SDSS | *z=0.5 ACS F606W* | *z=0.8 ACS F850LP*

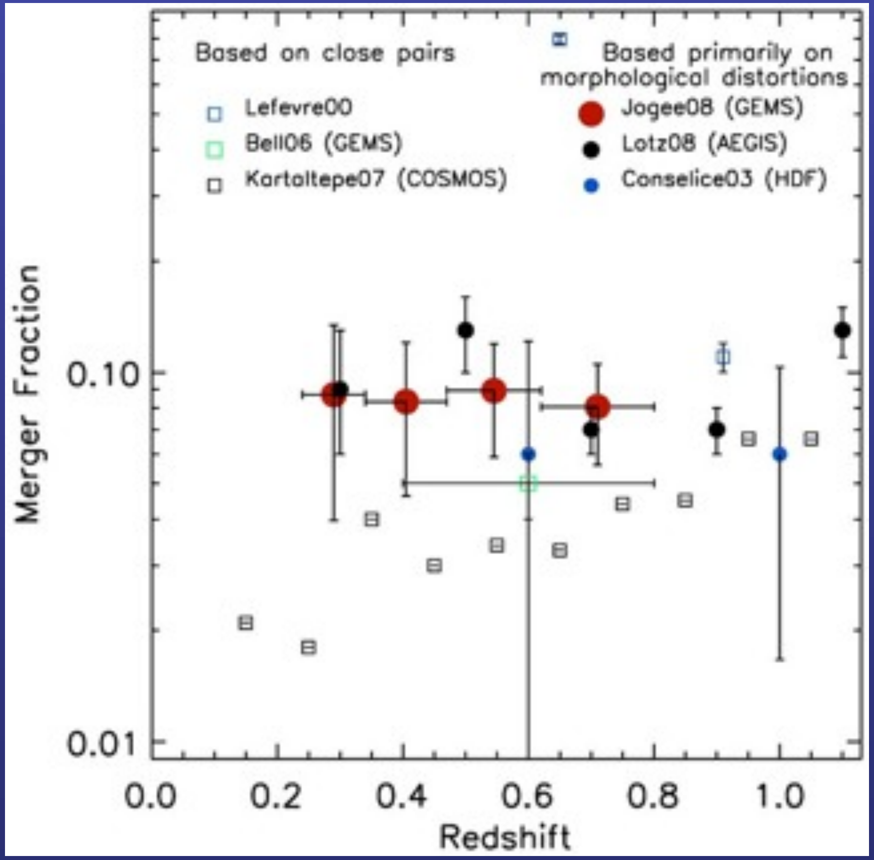


NGC 5395

NGC 3310

NGC 5996

Incidence of major mergers over last 7 Gyr



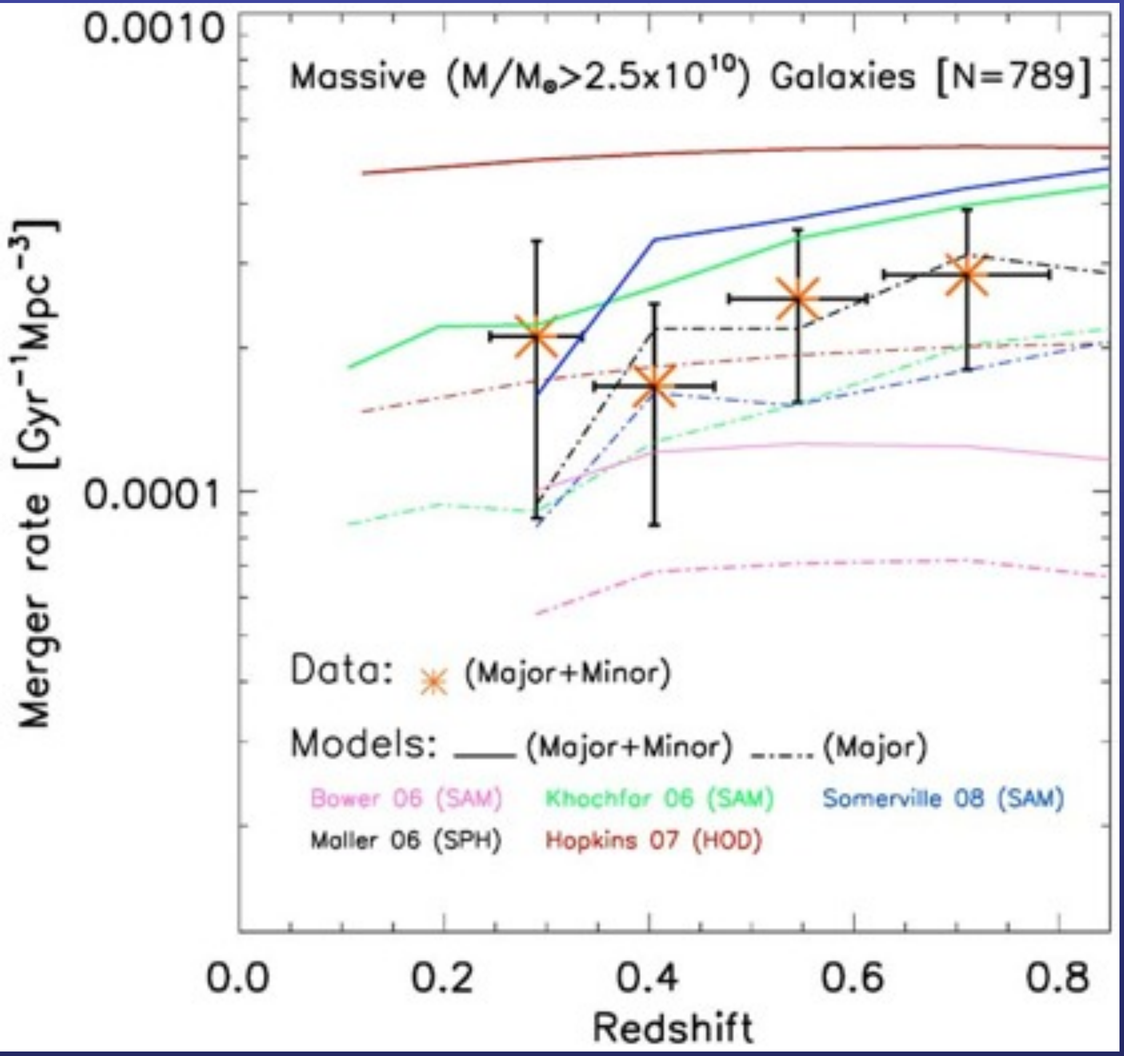
(Jogee et al 2009)

- Morphological methods (visual, CAS, Gini-M20) give higher merger fraction F as they trace (major + minor) mergers while close pairs mostly trace major mergers
- Over z~0.24 to 1.0, both methods give similar low major merger fractions:
  → 1--5% (m) vs 2--7 % (p)
  → mean ~5%
- Major merger rate ($R \sim f\ n / T_{Vis}$)
  < 10^{-4} galaxies Gyr^{-1} Mpc^{-3} ,
  (for visibility time of 0.5 Gyr)

- Observed fraction of visible minor mergers = 5% to 10%

True fraction even higher as minor mergers more impacted than SB dimming

Compare merger rate of galaxies with LCDM models



- Data

  Rate= n f /T_{vis} for (major+minor)

- Models

  solid line = f(major + minor)

  dotted line = f_major

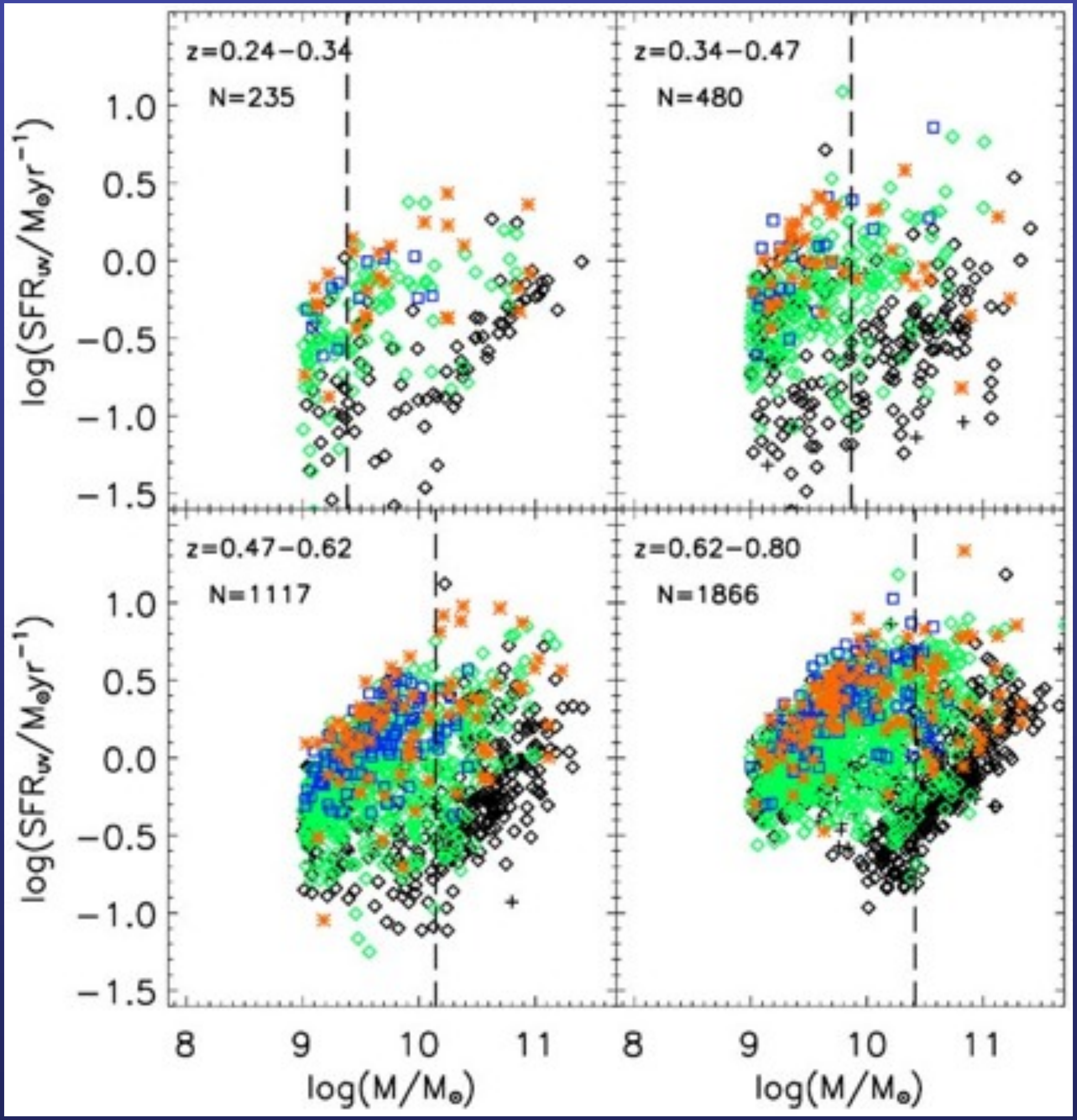
For high mass galaxies, over z~0.2 to 0.8 the (major+minor) merger rate of models

- all show a shallow slope in qualitative agreement w. data

- but show factor of 5 dispersion in their absolute values, such that model values are ~2 times higher or lower than data.

(Jogee et al 2009)

Star Formation Rates



* SFR_{UV} ~ 0.1--25 M_o yr^{-1} (for full sample [N=3698]

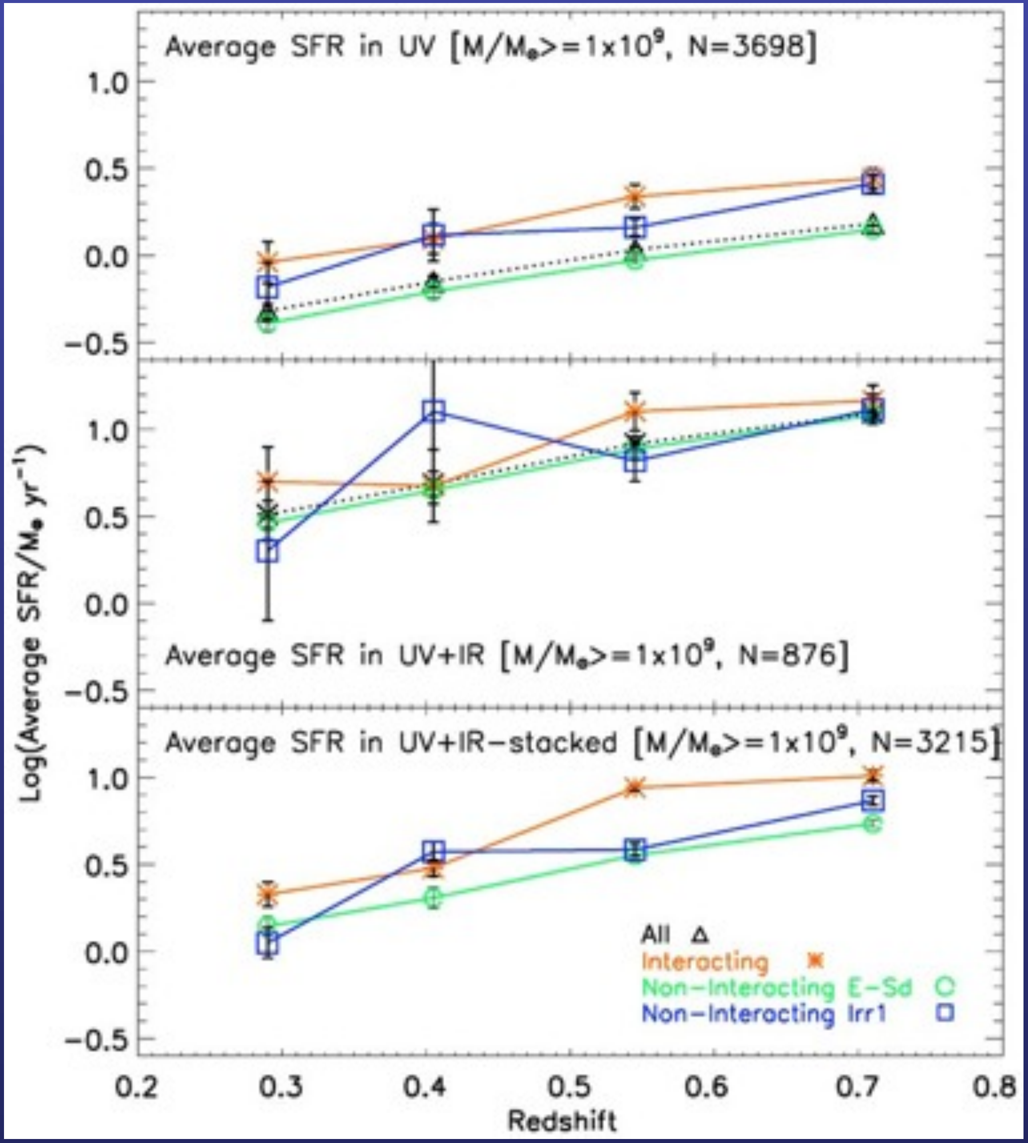
* Spitzer 24mu, detected in 24% of sample [N~876]

→Median (SFR_{IR}/SFR_{UV}) ~ 4

→ significant obscured SF

•At z~0.6-0.8, 24mu data only detects SFR >=5 Mo/yr

<SFR> in Mergers vs Non-Interacting Galaxies over last 7 Gyr



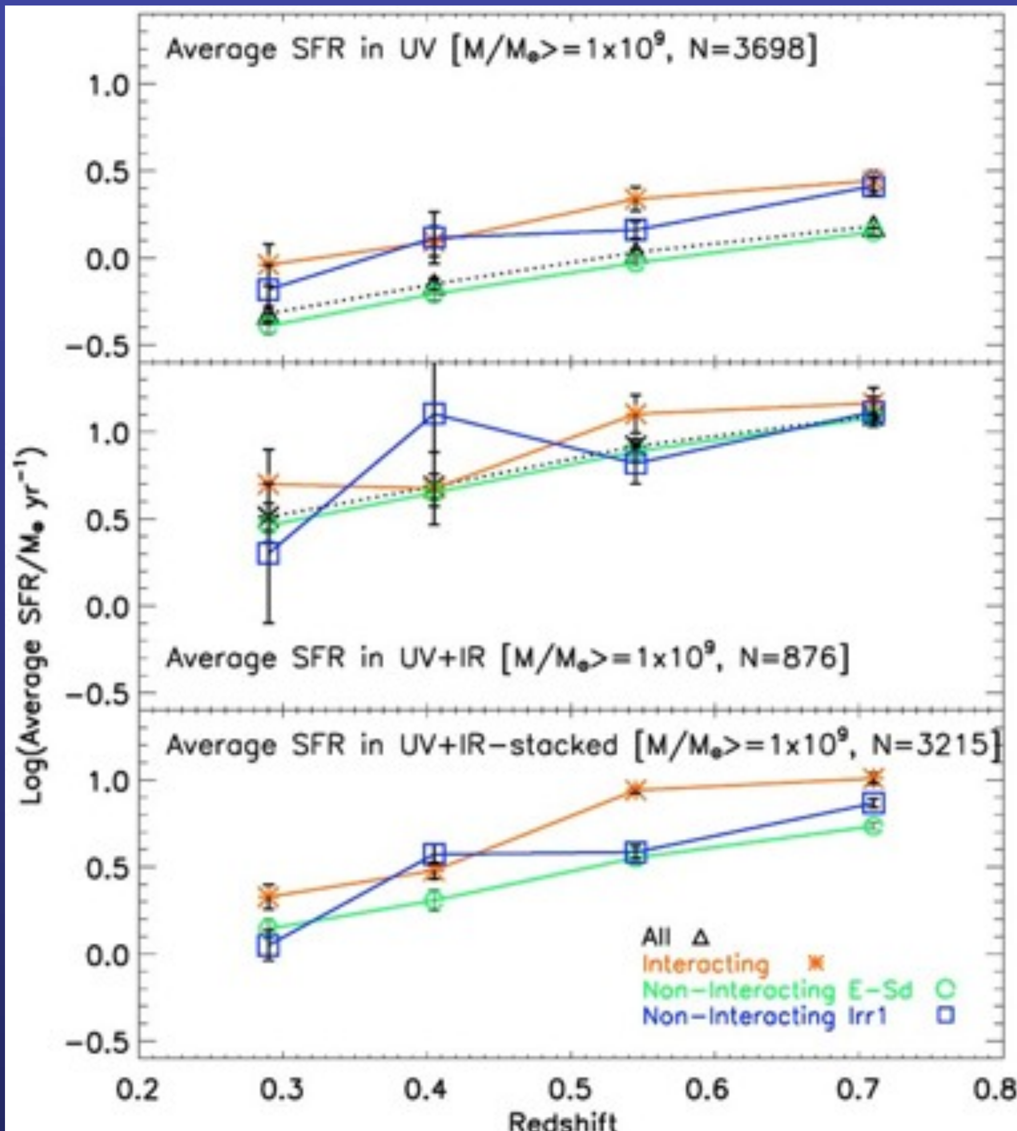
(Jogee et al 2009)

3 measures of SFR

1) SFR_{UV} from L_{UV} of COMBO-17 for full sample [N= 3698]

Mean SFR of visble mergers is enhanced only by a modest factor (~1.6 to 2) w.r.t that of non-interacting galaxies.

<SFR> in Mergers vs Non-Interacting Galaxies over last 7 Gyr



(Jogee et al   2009)

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Similar results by Robaina et al (2009)

Is modest enhancement in SFR consistent with simulations?

SFR enhancement factor Y in major merger compared to non-interacting systems of same mass
= falls for M1/M2<1/1 and longer T_{ave}

T_{ave} [Gyr]	M1/M2	Y
<= 0.1	1:1	5
0.6	1:1	2 to 5
2.5 to	1:1	~1.5
0.6	1:2	~2.5
2.5 to	1:2	~1.5

Y

Cox et al (2008)
Major merger simulations of Milky Way type progenitors (gas fraction ~20%, B/T~0.2)

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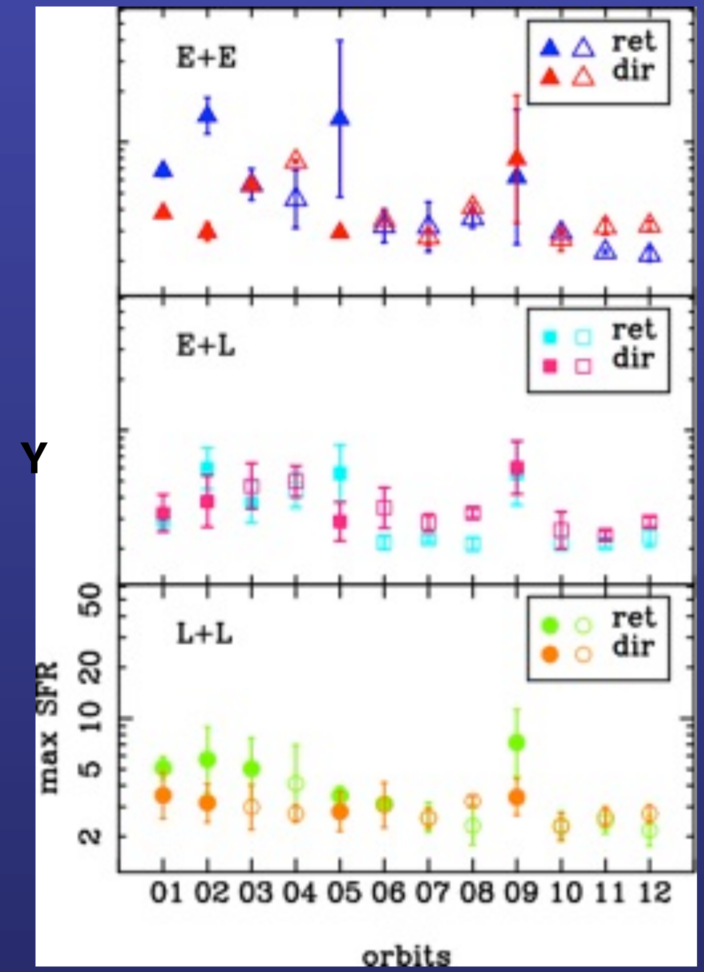

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Cox et al (2008)
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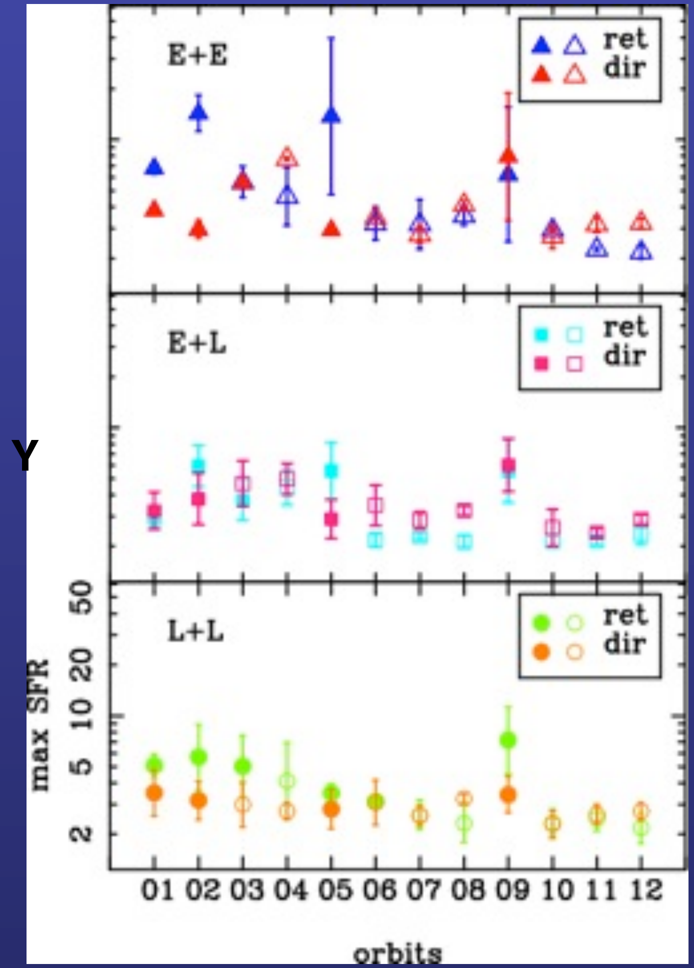
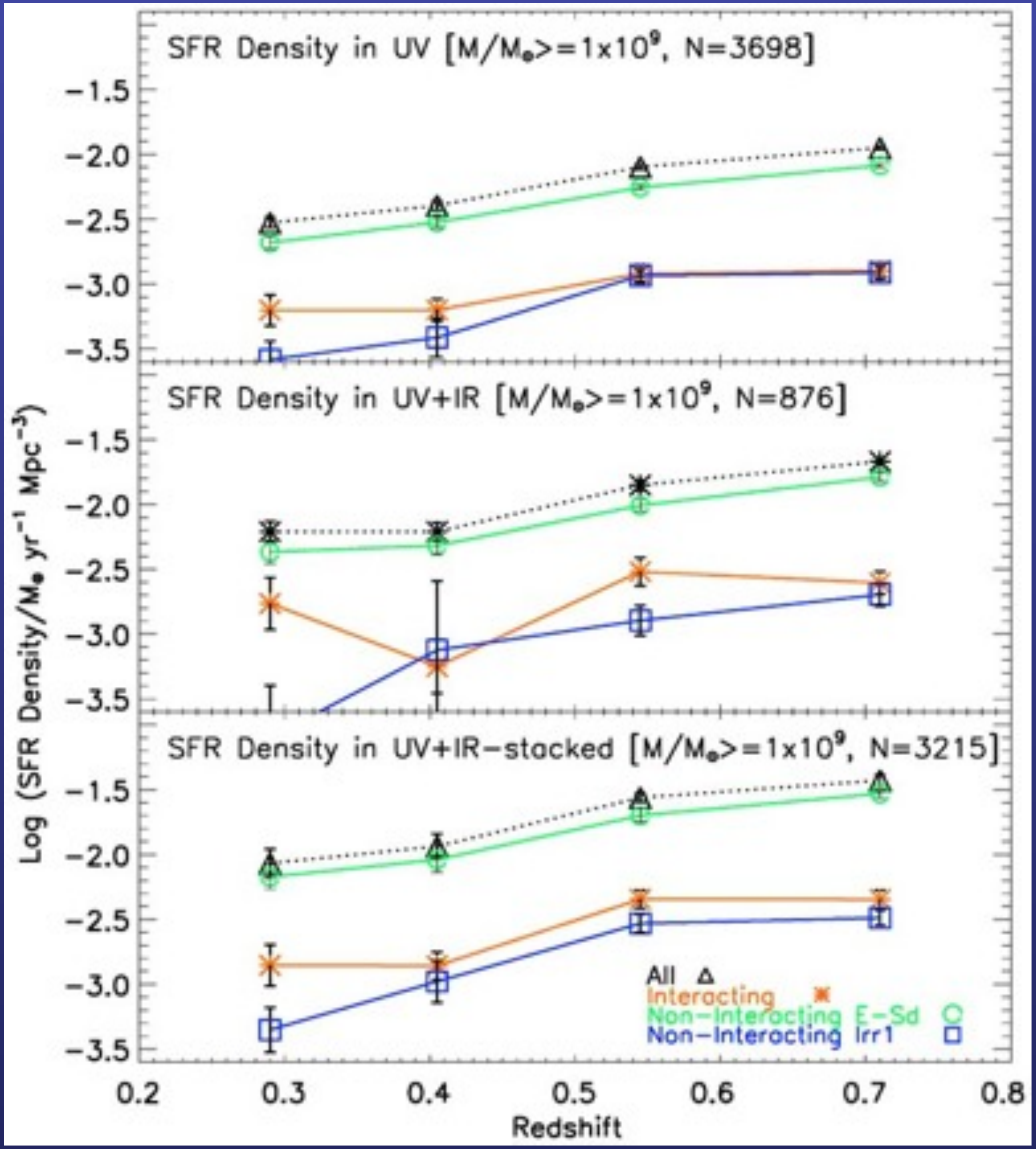


Di Matteo, P. et al. (2007)

Several hundred TREE-SPH simulations of major mergers of different B/D, gas, orbit-parameters
Find max SFR of most mergers is only enhanced by ~2 to 3 compared to isolated case .

SFR density from mergers over last 7 Gyr



(Jogee et al 2009)

- Over z~0.2--0.8, SFR density from visible mergers ~16% (w/ 5% from major mergers)

Even if we assume ALL systems classified as non-interacting Irr1 are undetected mergers: only 23--28% of SFR density due to mergers.

Major mergers account for well below 30% of the SFR density over z~0.2--0.8 (T_b=3 to 7 Gyr) among high to intermediate mass (M/M_0~ $1x10^9$ to $3x10^{11}$) systems

Agrees with theoretical predictions of 15-25% at z~1 (Hopkins+06)

Similar results: Wolf+05; Bell+05 Lotz+08; Sobral+09; Robaina+09 but see Hammer +09

Summary: History of Mergers & Their Impact on SF over 7 Gyr

1. Merger history for high mass ($M^*/M_0 \sim 2.5 \times 10^{10}$ to 3×10^{11}) galaxies

- There is a low incidence of visible major mergers over the last 7 Gyr
  - → Major merger fraction f = 2% to 7%, with mean~5% over z=0.2 to 0.8
  - → Major merger rate ($R \sim f\, n / T_{vis}$) $< 10^{-4}$ galaxies Gyr^{-1} Mpc^{-3} (for T_{vis} 0.5 Gyr)
- Minor mergers at least 2-3 times more frequent

2. Impact of mergers on star formation

For high & intermediate mass ($M^*/M_0 \sim 10^9$ to 3×10^{11}), mostly with $L_{TIR} <= 2 \times 10^{11}$

→ Average SFR enhancement in visible mergers is modest: ~1.5 to 2.0

→ SFR density over z~0.2 to 0.8
- from visible mergers ~16% (5% from major mergers, 11% =minor + ambiguous)
- from visible mergers + all non-interacting Irregular ~28%

→ Major mergers account for well below 30% of SFR density out to z~0.8

The decline in cosmic SFR density from z=1 to 0 is mainly shaped by non-interacting galaxies (and possibly minor mergers), but not by evolution in major merger rate.

Extra slides :

Merger rate from morphological vs close pairs

• Problems in getting merger rates from morphological methods
(visual, CAS,Gini-M20)

→ hard to detect tidal features, especially for minor mergers, due to SB dimming
→ Merger rate ($R = f\ n\ /T_{vis)}$) depends on visibility timescale = a function of F_{gas}
→ Methods based on CAS (A>0.35 and A>5)
- capture only a fraction of visual mergers
- can be dominated by non-interacting systems at rest-frame blue-NUV λ
- trace only 1/3 of the duration of a major merger, where A>0.35
(the eye is sensitive to tidal features over a longer phase)

Problems in getting merger rates from close pair fraction
→ error in phot-z can lead to over-estimate or under-estimate of true pair f
→ chance projection pairs vs 'real' (gravitationally-interacting) pairs
→ even if pairs are real they may not be gravitationally bound
→ gravitationally bound pairs at different separation sample different phases of the interaction and conversion of pair fraction to a merger rate $R = f\ n\ /T_{vis}$ depends on separation, orbital eccentricity, orbital geometry

Model Predictions of Galaxy Merger Rates

ΛCDM models predict DM halo merger rates. In order to predict galaxy merger rate R
→ need to consider galaxy and halo merger timescales, tidal heating and stripping of sub-halos, relation between DM sub-halo mass and galaxy mass, etc
→ model relation between DM & baryonic components via 3 methods

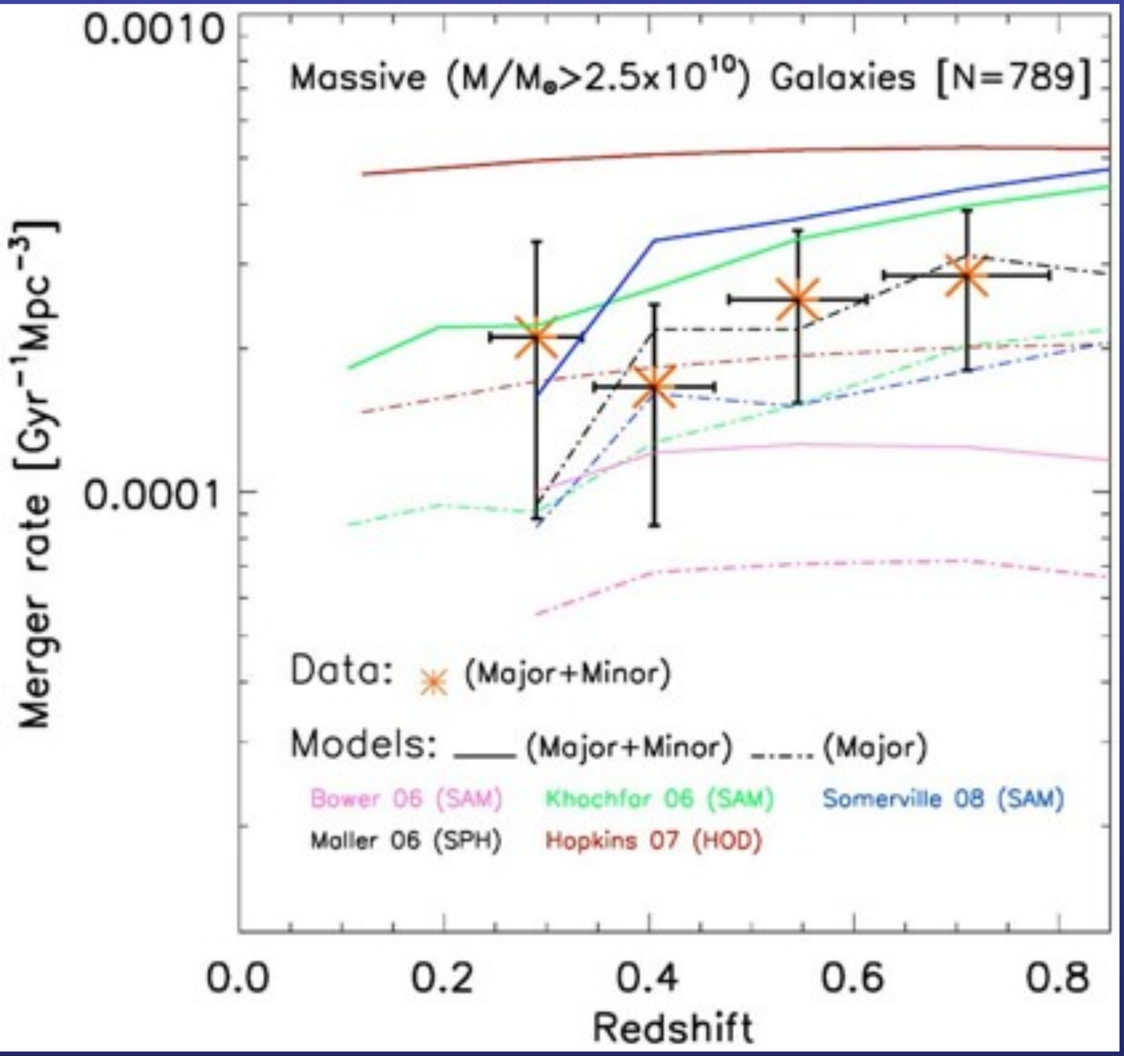
1) Semi-analytical models (SAMs) with AGN feedback
Somerville et al. (2008) ; Bower et al. (2006); Khochfar & Silk (2006)

2) Halo occupation distribution (HOD) model w/ AGN feedback
Hopkins et al. (2008)

3) Hydrodynamic simulations
Maller et al. (2006) : only major merger fraction

Blind comparison, same t_{vis}, same definition of major/minor mergers

Compare merger rate of galaxies with LCDM models



- Data
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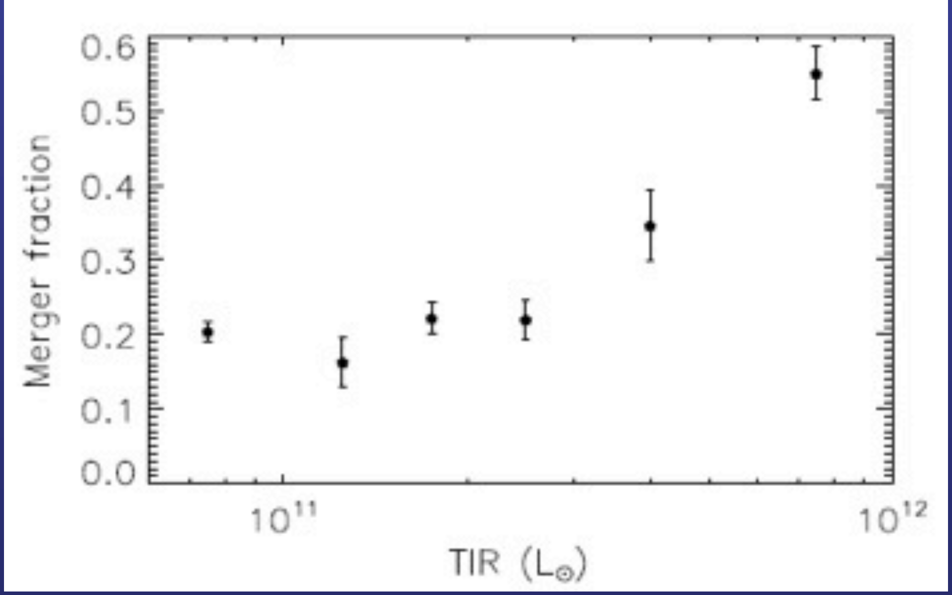
(Jogee et al 2009)

Where do ULIRGs fit in?

Our results (f<=10%, merger contribution of <30% to SFR density) apply to systems, which mosty have $M/M_0 \sim 1 \times 10^9$ to 3×10^{11} and $L_{TIR} <= 3 \times 10^{11} Lo$.

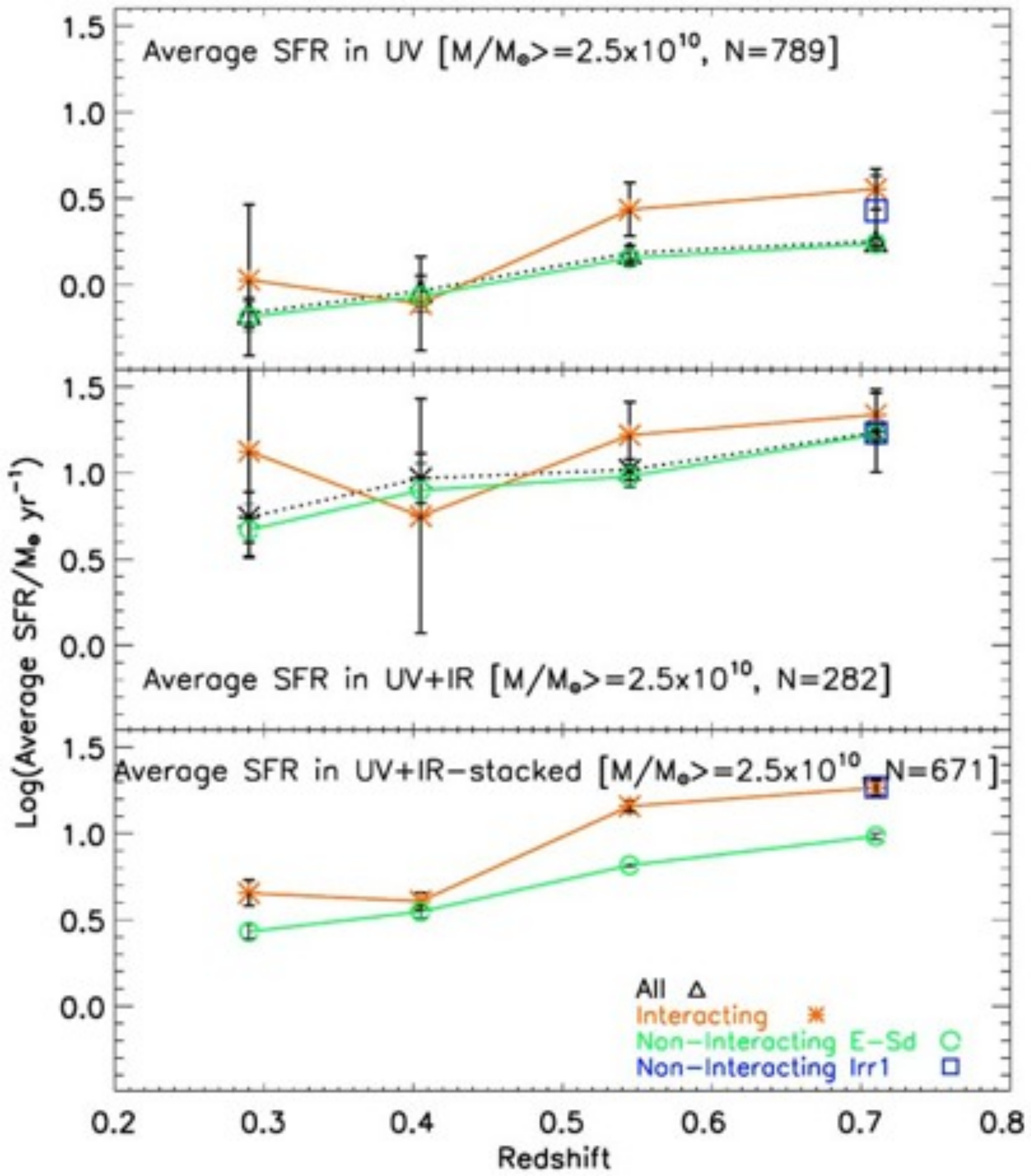
Among extreme systems with $L_{TIR} >> 5 \times 10^{11} Lo$, preselected to host lots of obscured SF, the merger fraction is much higher, e.g., 55% at $L_{TIR} \sim 10^{12} Lo$. → i.e., heavily obscured SF forms preferentially in mergers



(Robaina et al 2009)

At z<1, ULIRGs do not dominate the SFR density (Le Floch 05)

For high mass sample only



Jogee et al 2009

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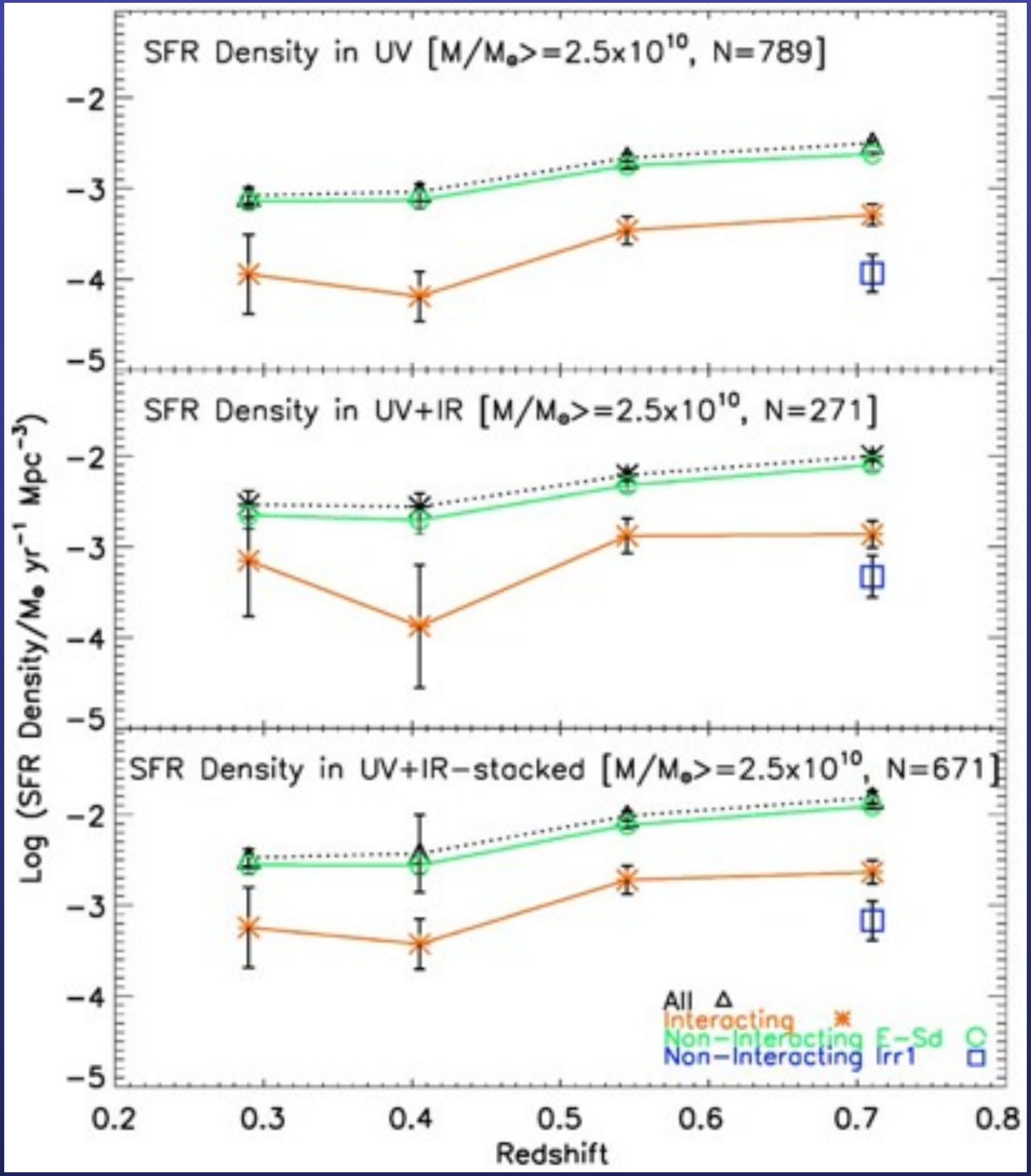
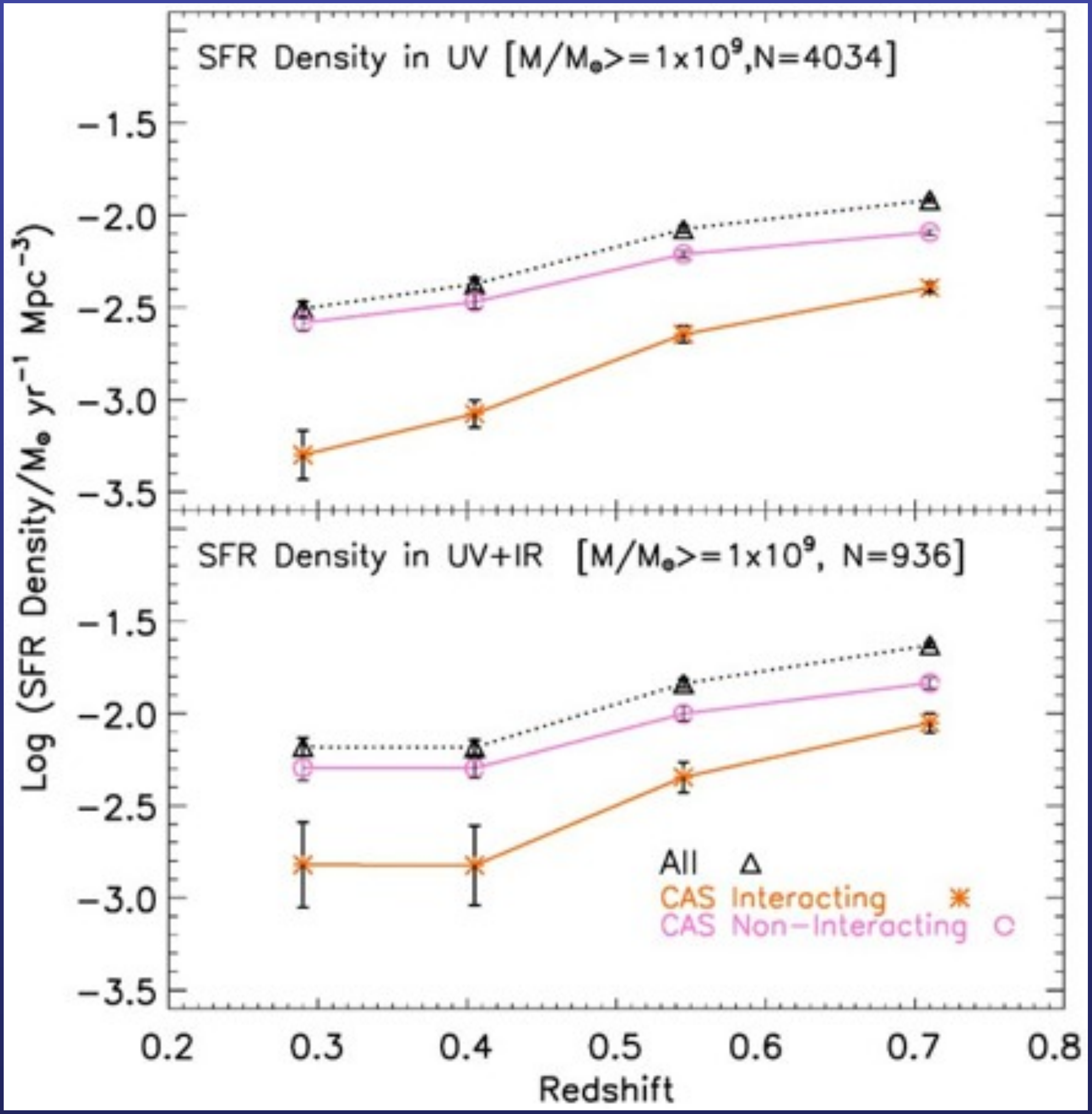


Jogee et al 2009

CAS-based results: intermediate mass sample



Jogee et al 2009

Example of mergers

2 at similar z

2 at similar z