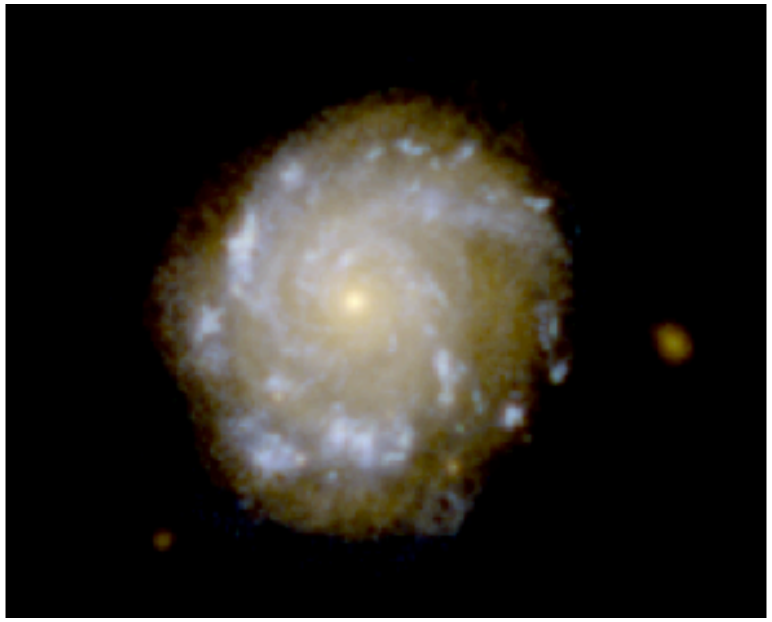
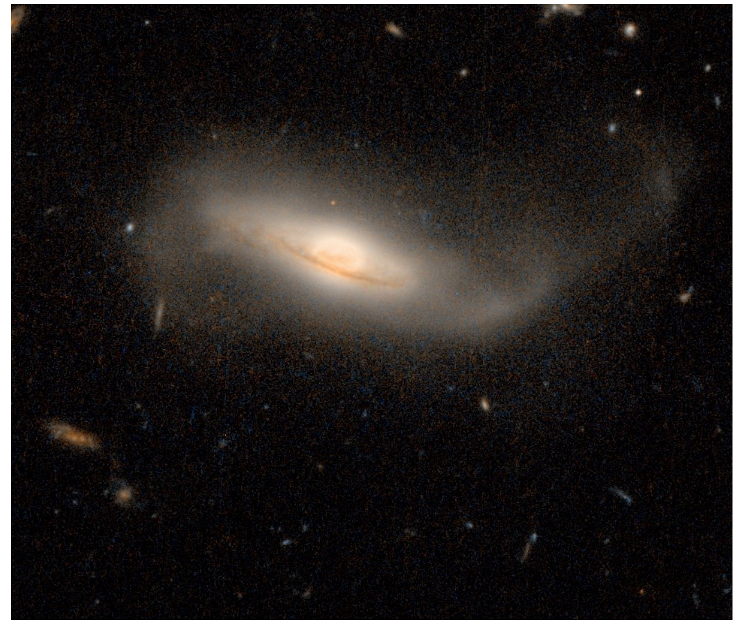
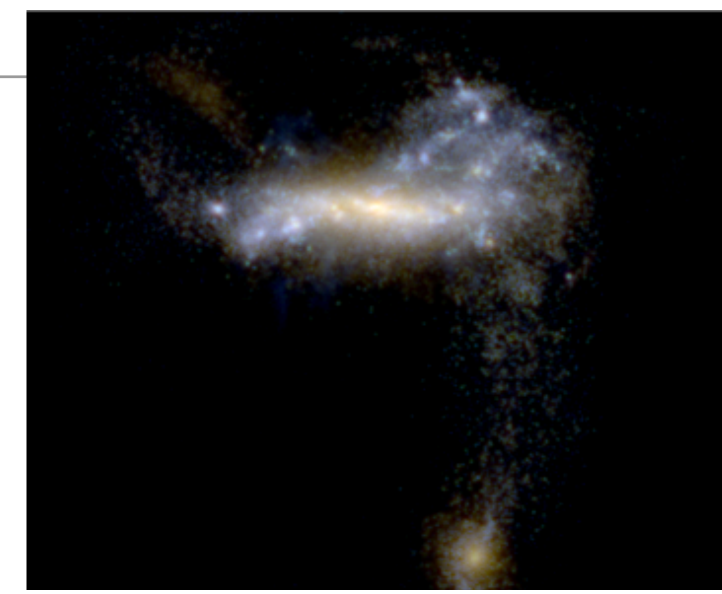
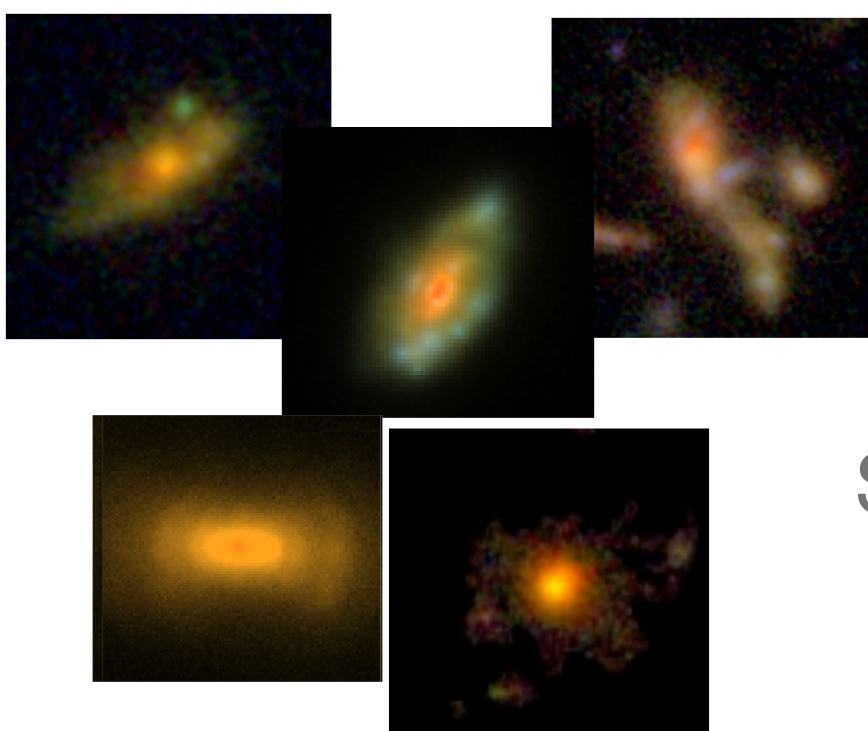




Quantitative Galaxy Morphology (and Simulations)





Jennifer Lotz
Space Telescope Science Institute

Sydney- Galaxy Zoo - Sept 2013

quantitative morphology

statistics that describe shape, size, irregularity of galaxy light profiles

- quantitative numbers, error-bars easy to compute

- can be automated and fast

- can be more easily connected to predictions

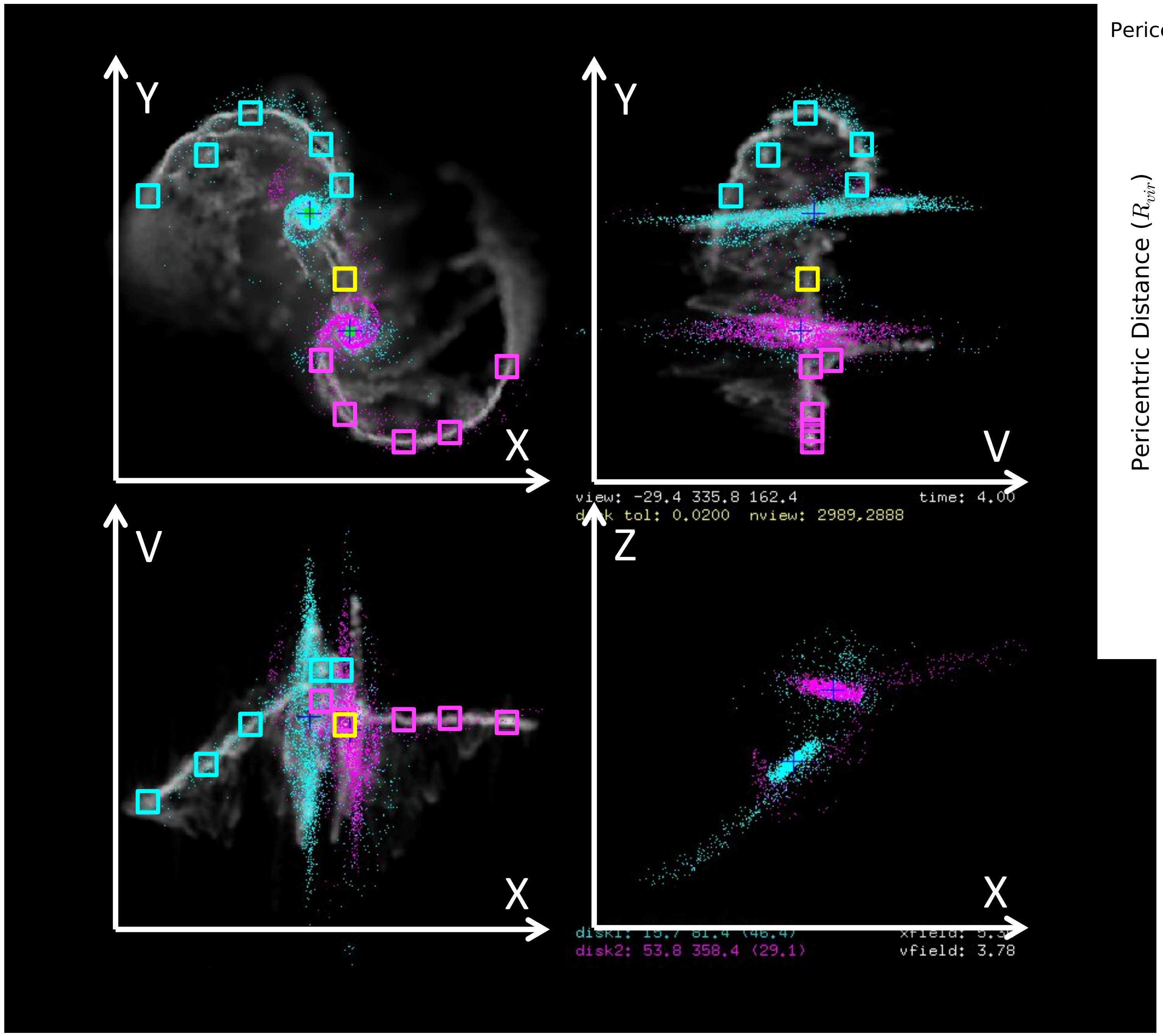
Non-parametric Morphology -- often designed to trace irregular features

Concentration - Asymmetry (Abraham 1994, Conselice 2000),
Gini-M_{20} (Lotz et al. 2004, Abraham et al. 2003),
ψ(multiplicity) (Law et al. 2007)
M-I-D (Freeman et al. 2012)

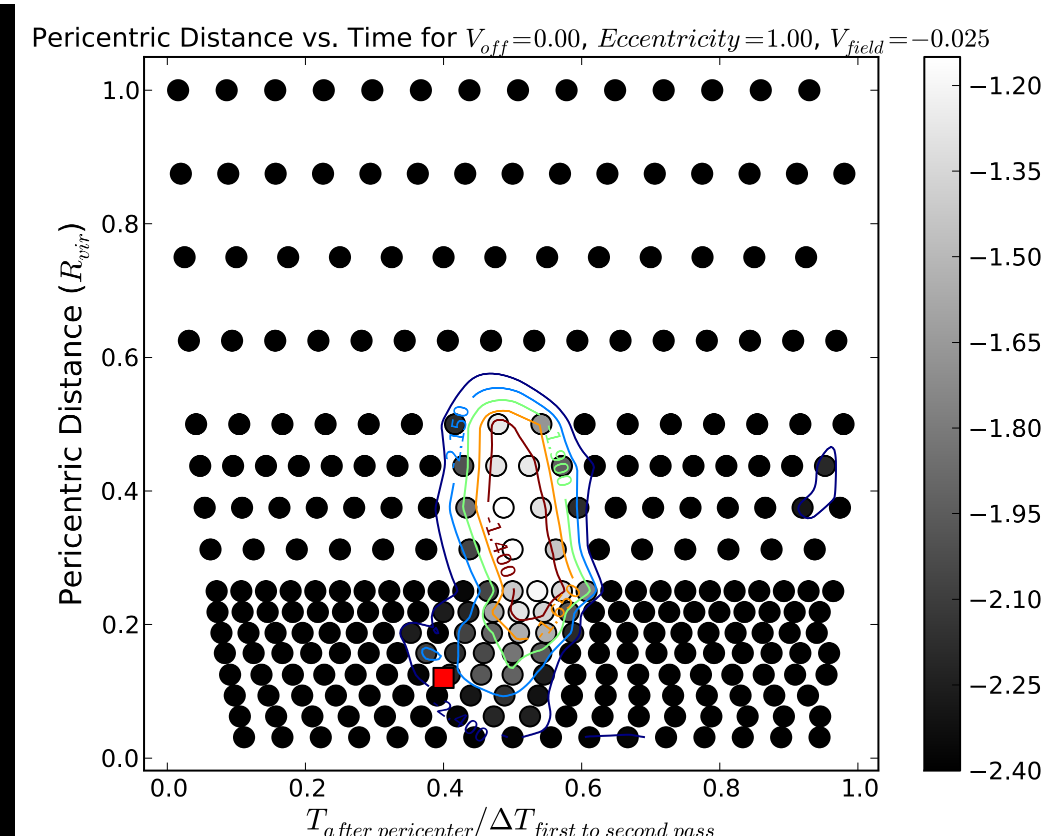
Parametric Morphology/structure -- fits a model to light profile

Sersic n, r_{eff}, b/a,   B/D -- GALFIT, GIM2D (Peng et al. 2002, Simard 1998)
Mergers -- IDENTIKIT (Barnes & Hibbard 2009)

Kinematics + Morphology to probe Mergers



A. Mortazavi & J. Lotz, in prep



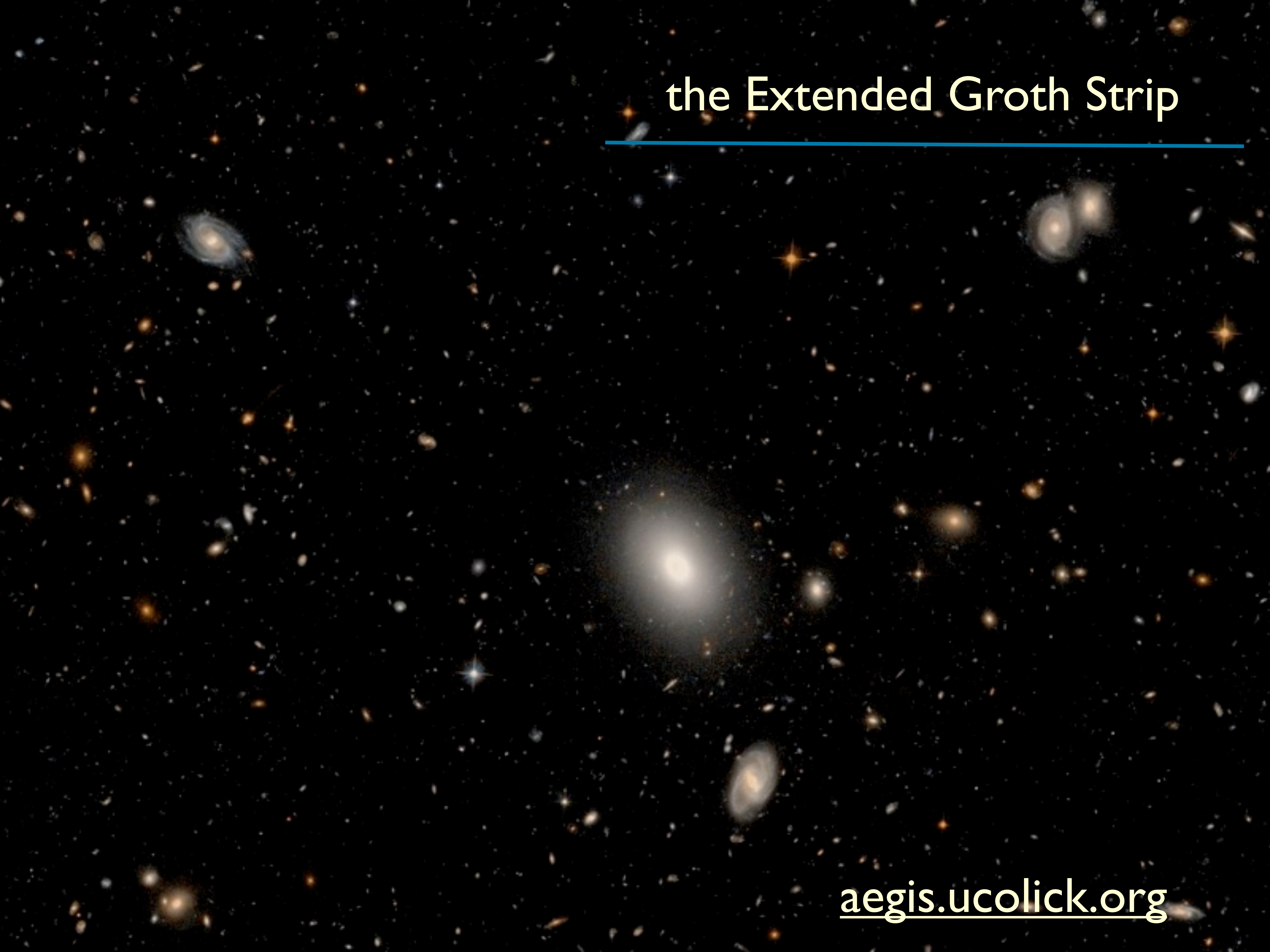
IDENTIKIT (Barnes & Hibbard 2009) fits tidal tail morphology + kinematics

constrain orbital parameters → angular momentum in merger remnants (e.g. Bois et al. 2012)

connecting physics to galaxy morphology

- what is the galaxy merger rate?
- what is the relative importance of mergers (v. gas accretion) in galaxy assembly and star-formation?
- how do galaxy disks settle into thin rotationally-supported spirals?
- how are bulges and spheroids created? how do these quench?
- how are bulge formation and SMBH growth connected?

the Extended Groth Strip



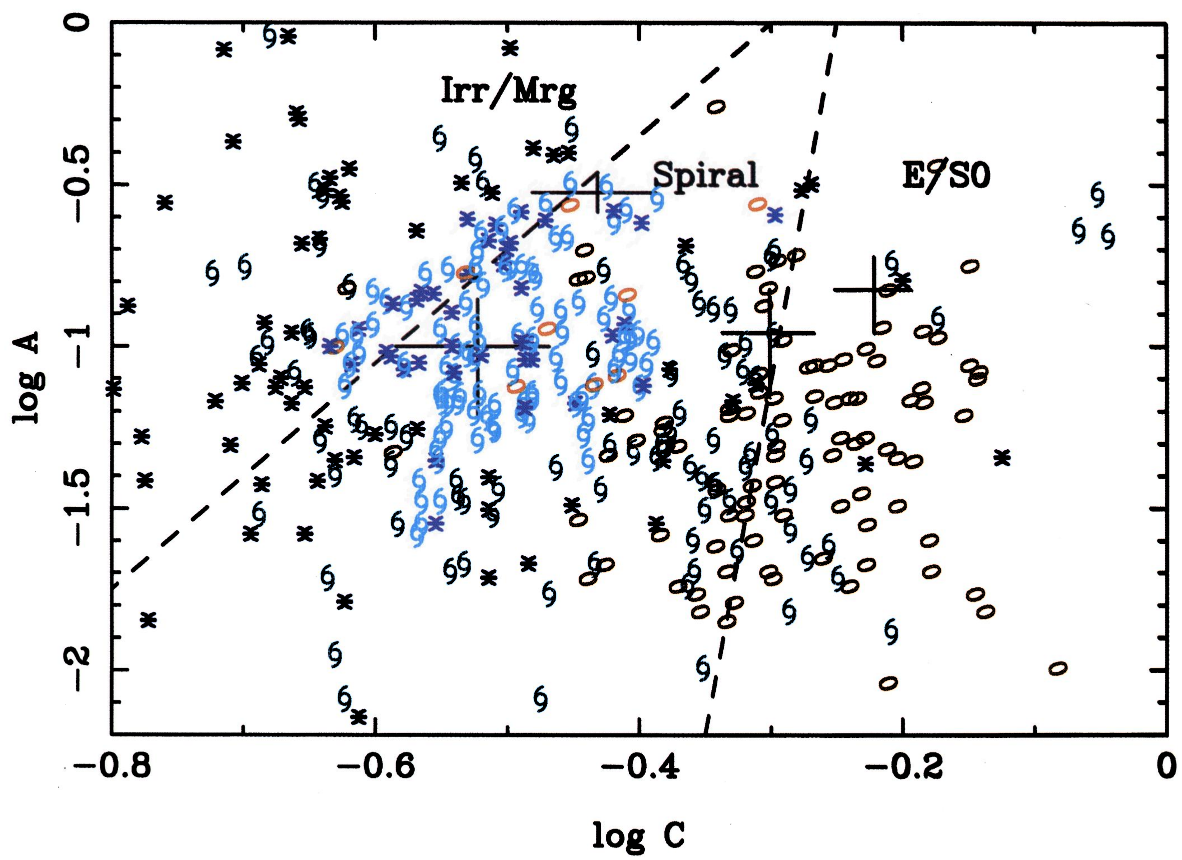
aegis.ucolick.org

the Extended Groth Strip

aegis.ucolick.org

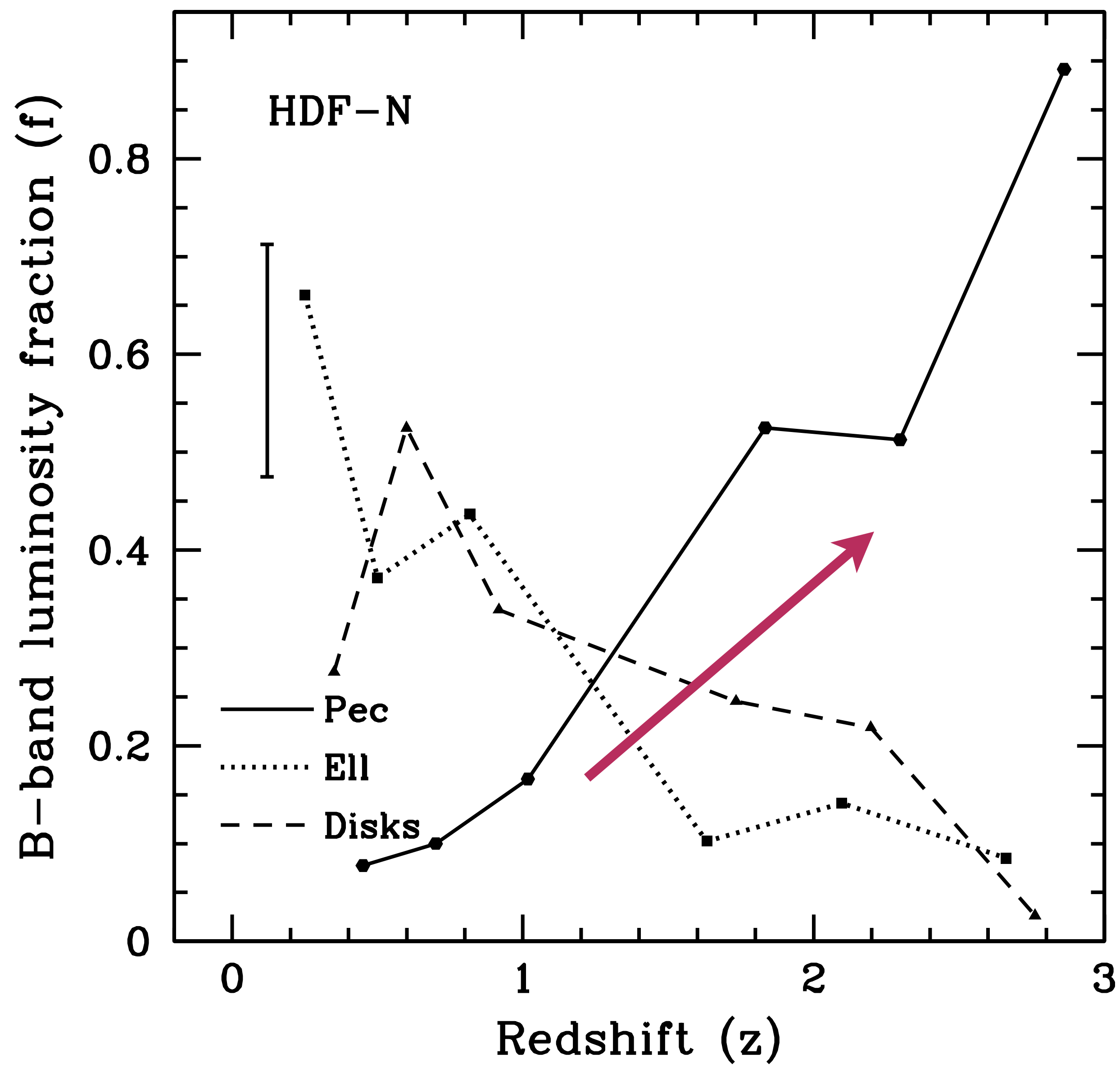

the Extended Groth Strip
aegis.ucolick.org

Concentration-Asymmetry



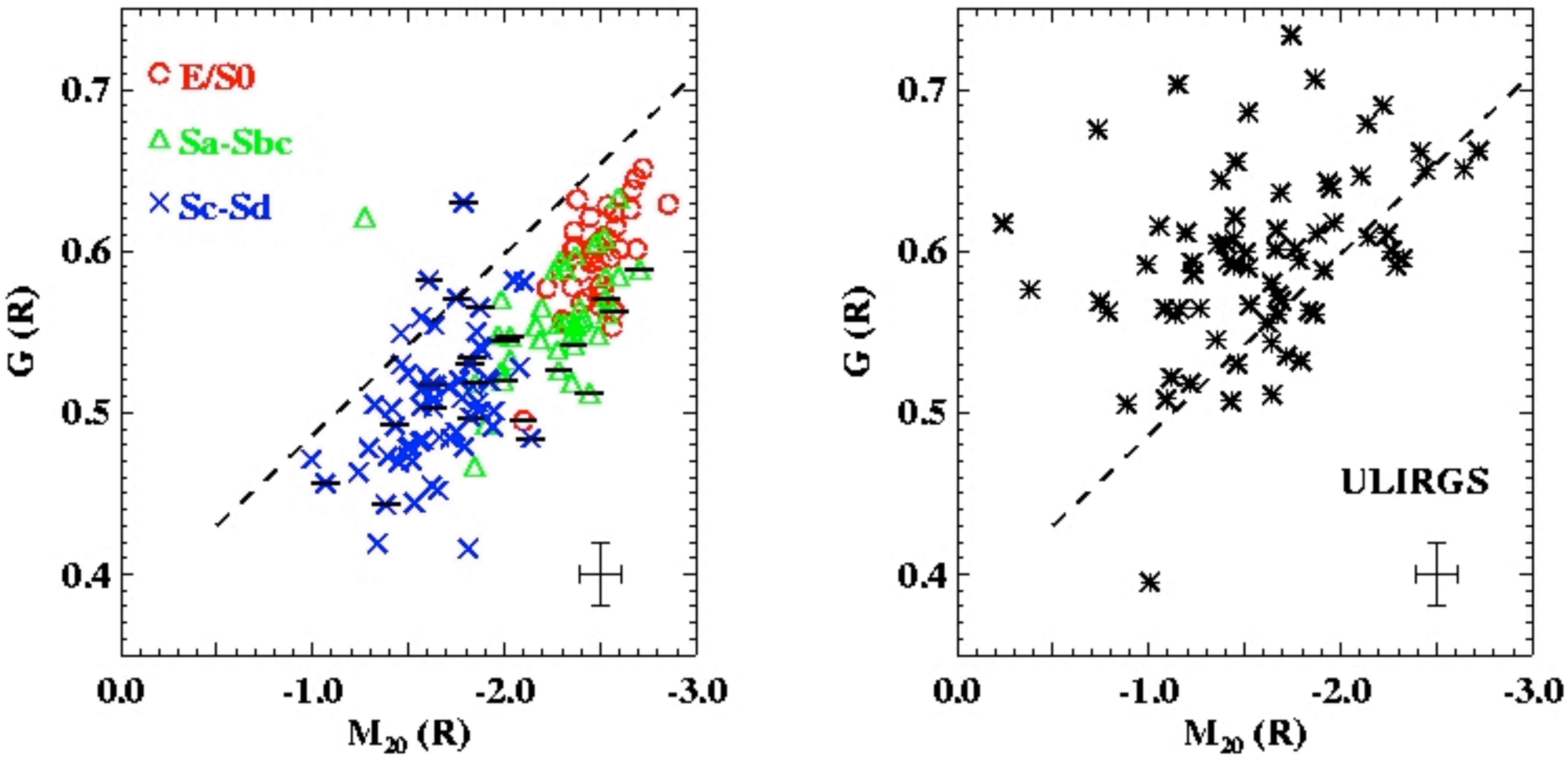
Abraham et al. 1996

early HST studies find strong evolution in asymmetric galaxies



Conselice et al. 2005

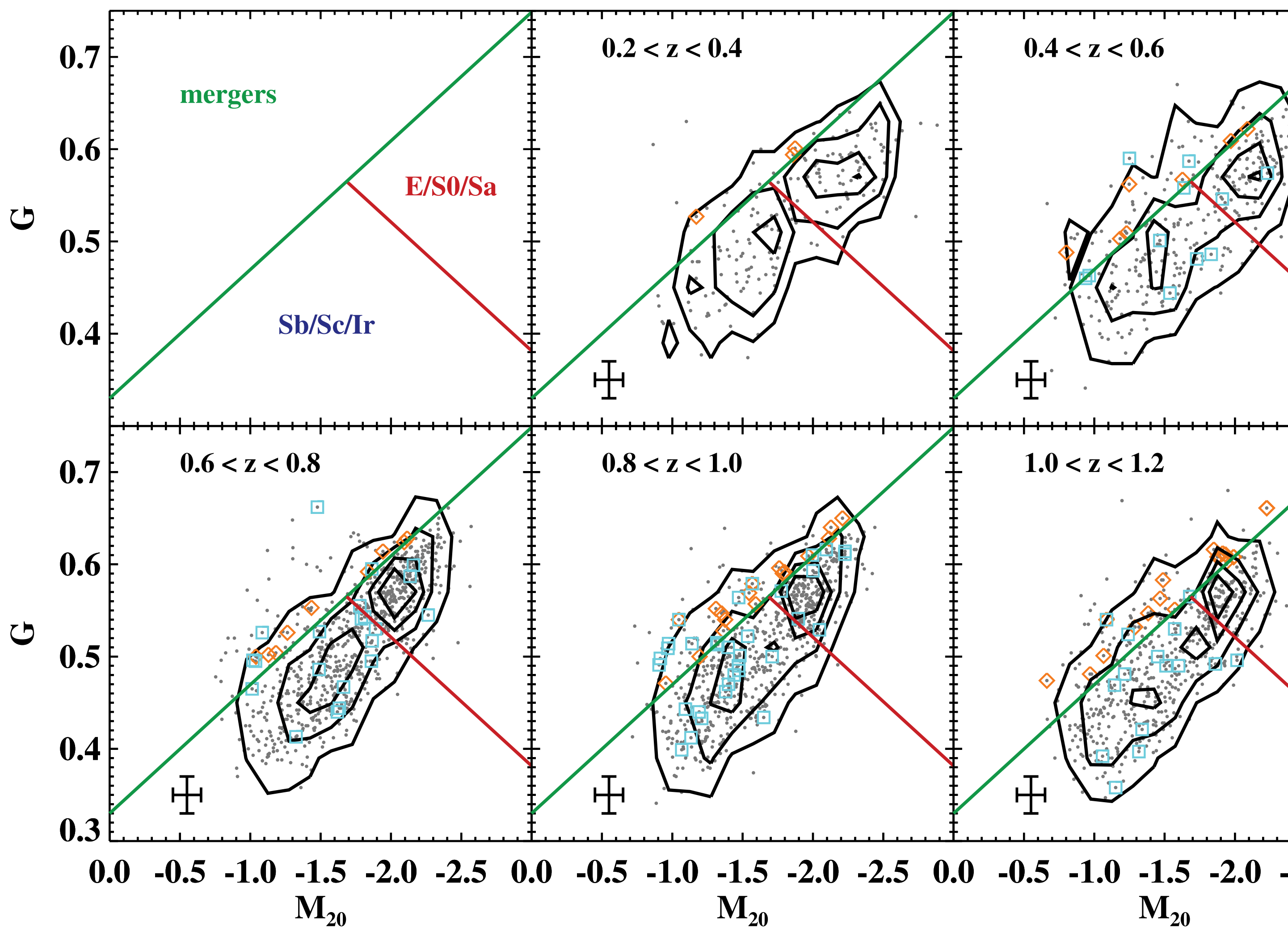
G-M_{20} in the local universe



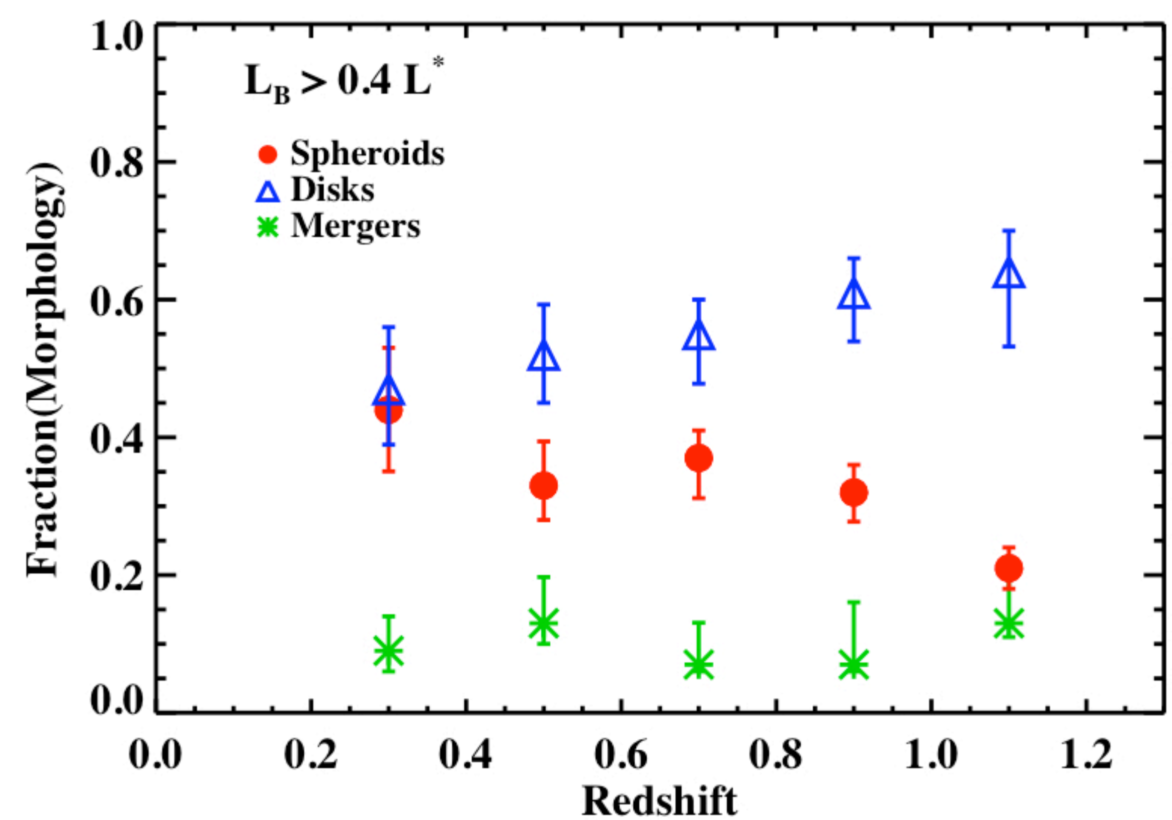
G-M_{20} very effective at selecting multiply-nucleated galaxies

Lotz, Primack & Madau 2004

G-M_{20} finds galaxy mergers out to z~1

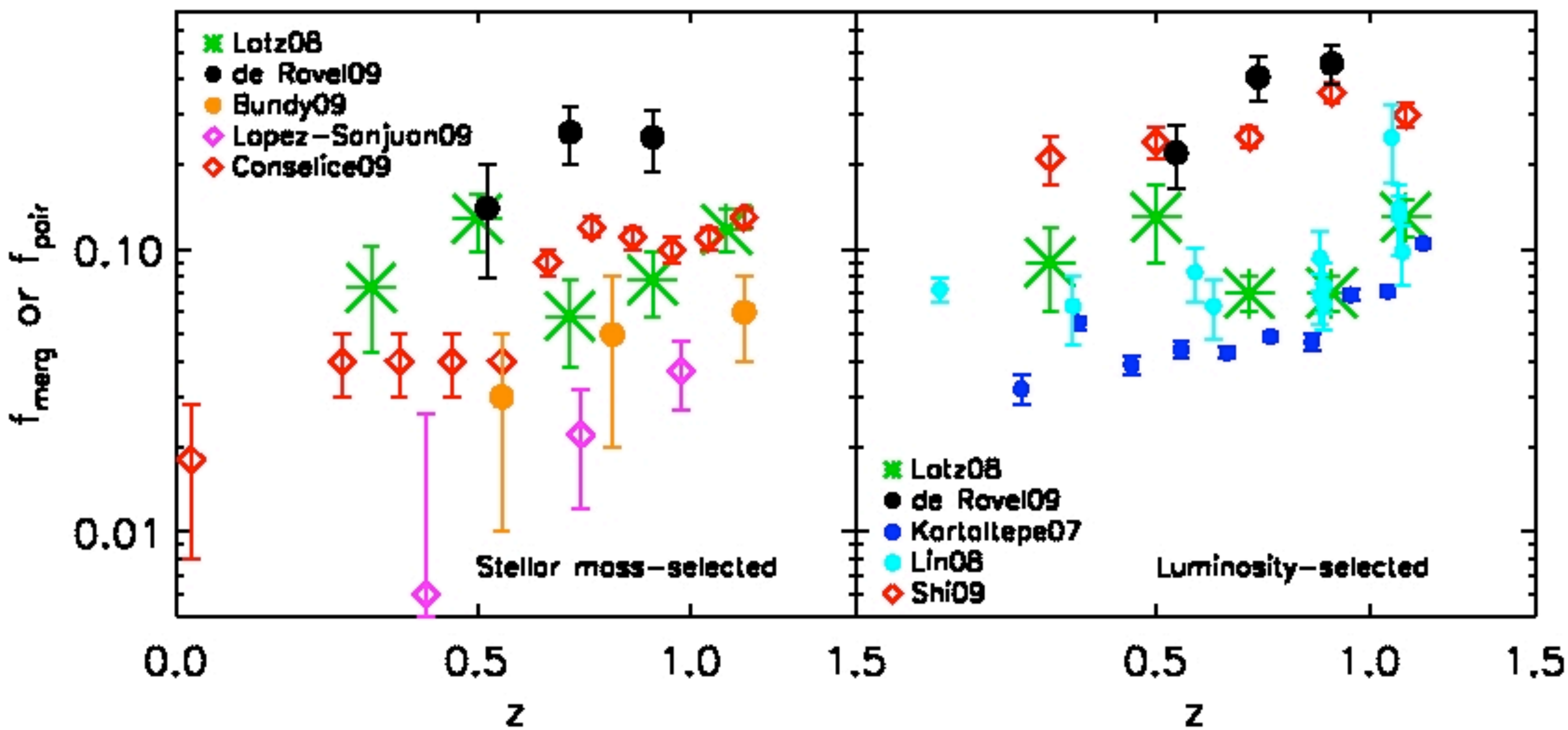


Lotz et al. 2008a, AEGIS team
HST ACS V(z<0.6) and I (0.6 < z < 1.2)



weak evolution in "merger fraction"?

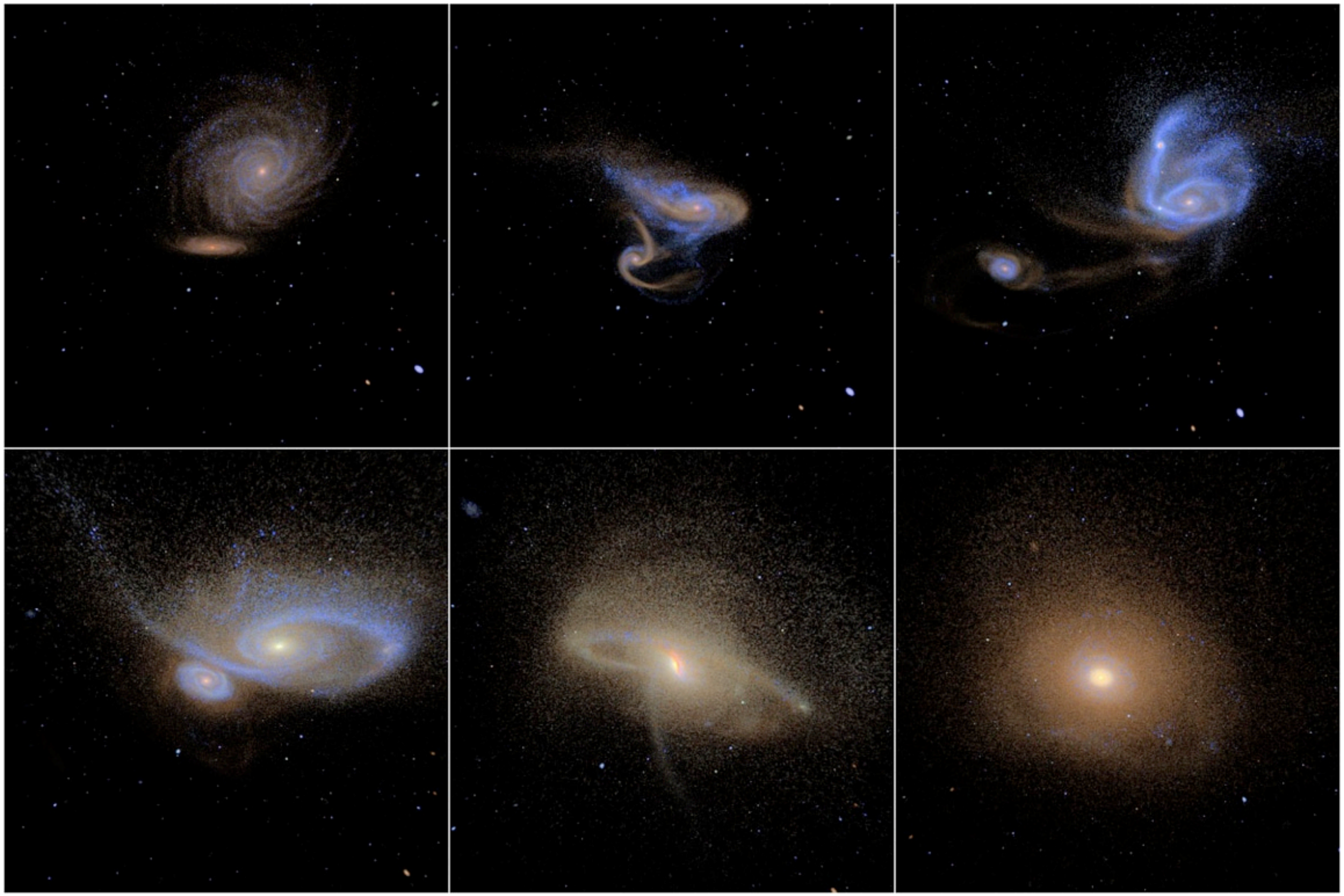
‘merger fractions’ don’t agree...



2009: major disagreement in literature over merger fraction and it’s evolution

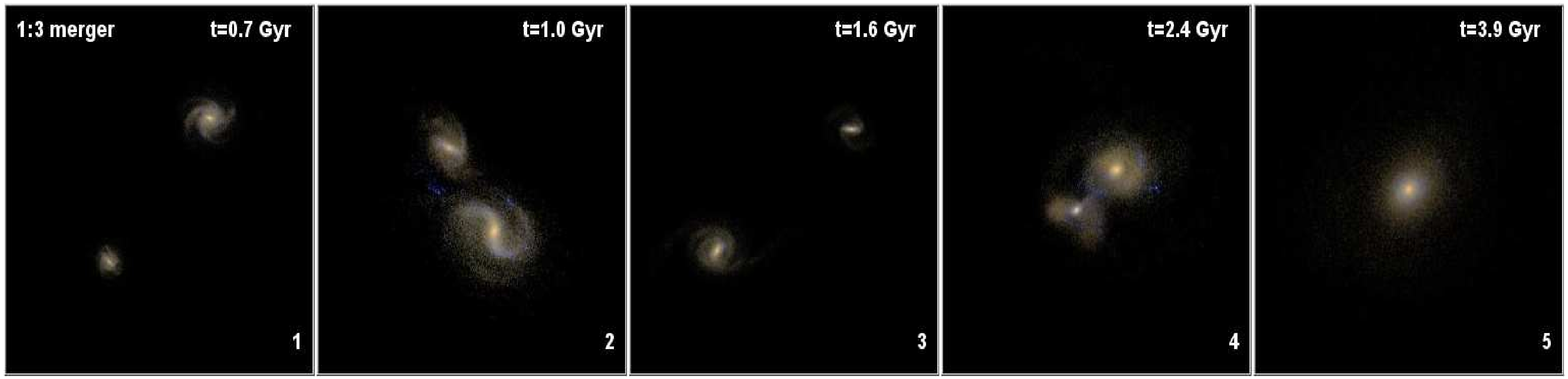
(see also Brinchman et al. 2000, Bundy et al. 2005, Jogee et al. 2008, Bridge et al. 2009, Robaina et al. 2010, Xu et al. 2011...)

Calibrating Morphology with Simulations



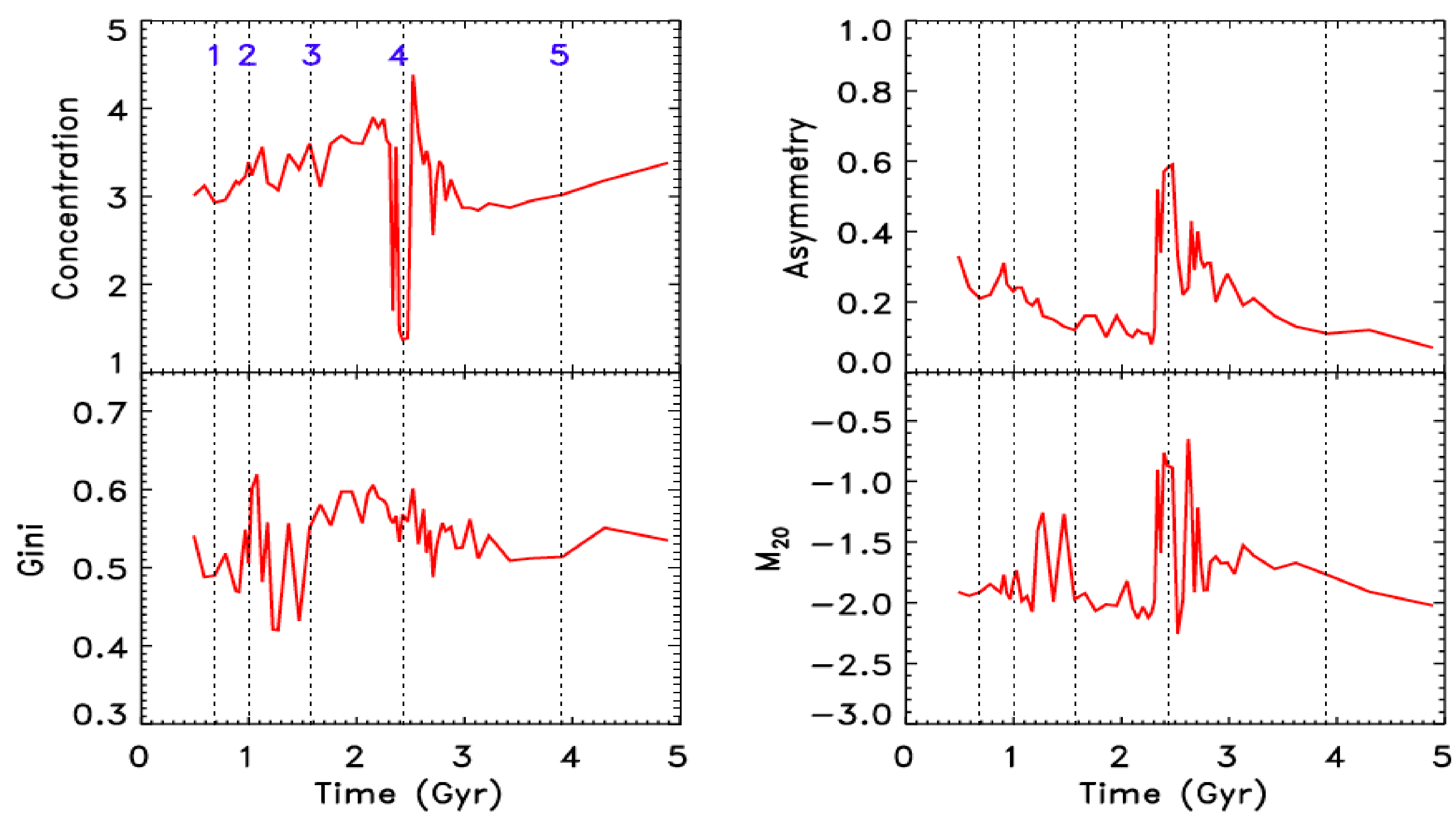
T.J. Cox, P. Jonsson

Timescale for Observing a “Merger”

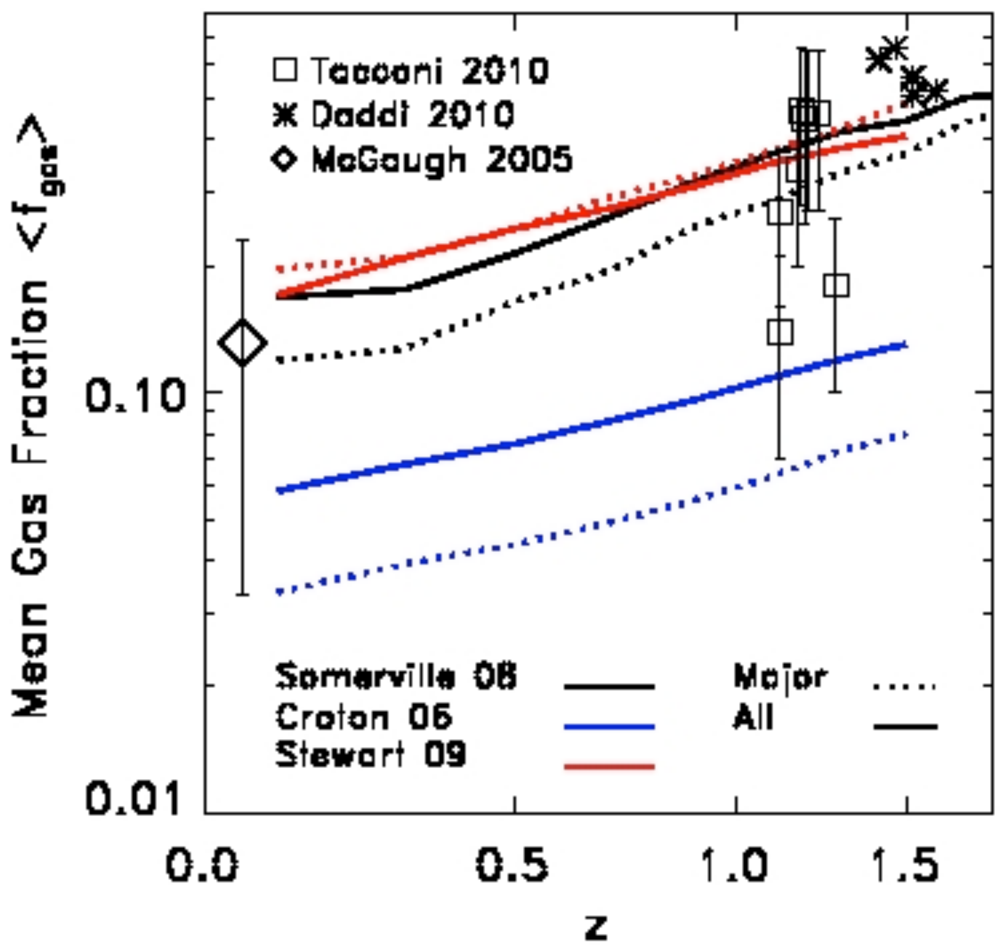


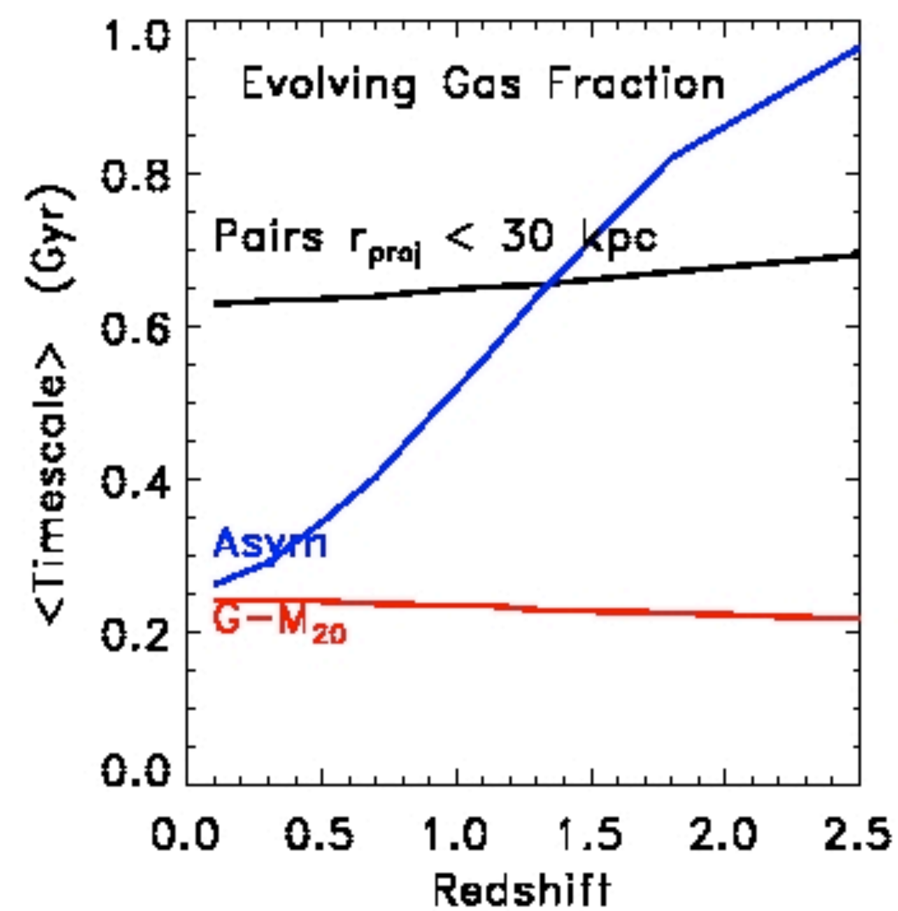
timescales for finding mergers depends on method to find merger and type of merger (major/minor, gas-rich, gas-poor)

Lotz et al. 2008b,
Lotz et al. 2010a, b



Cosmologically-weighted timescales



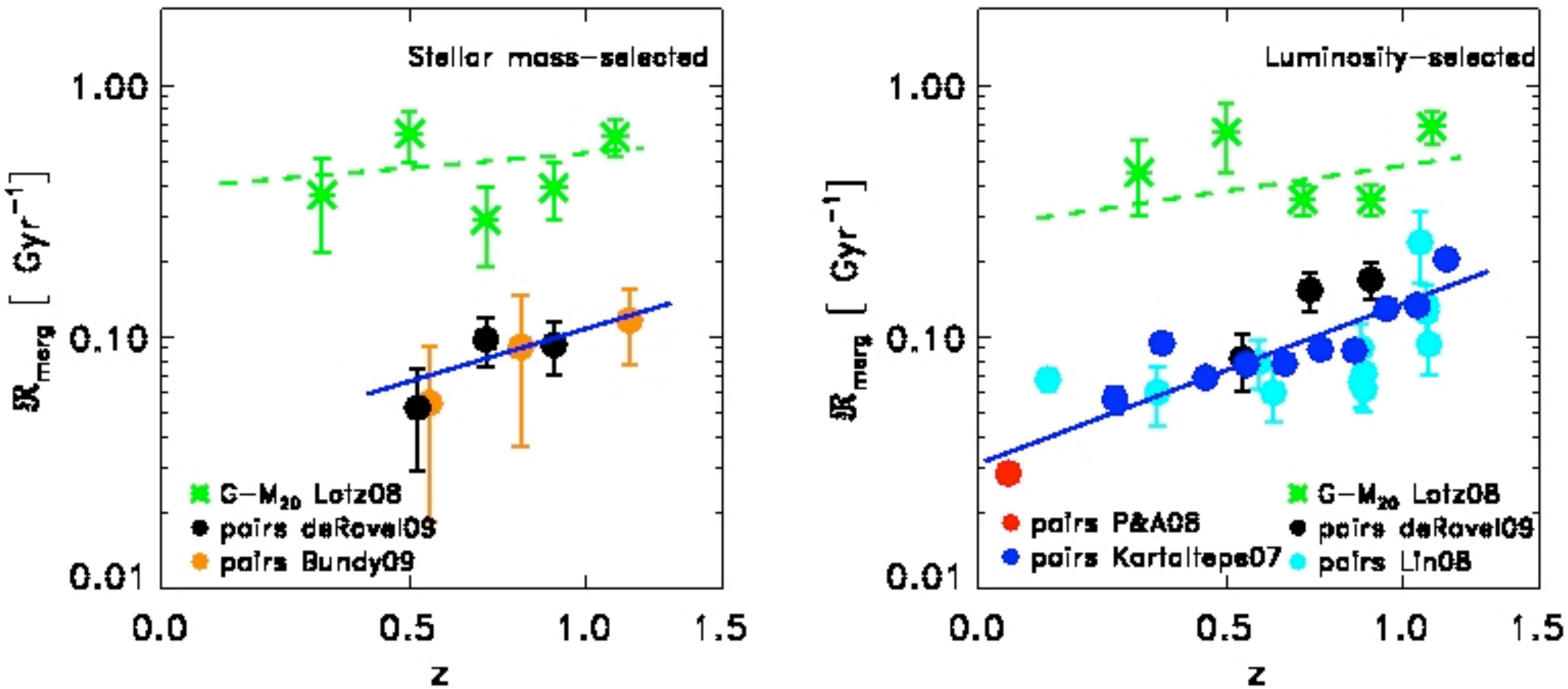


Increasing gas fraction with redshifts

⇒ strongly increasing Asymmetry timescales with redshift

Lotz et al. 2011, ApJ, 742, 103

Merger Rates per 10^{10} M⊙ galaxy at z<1.5



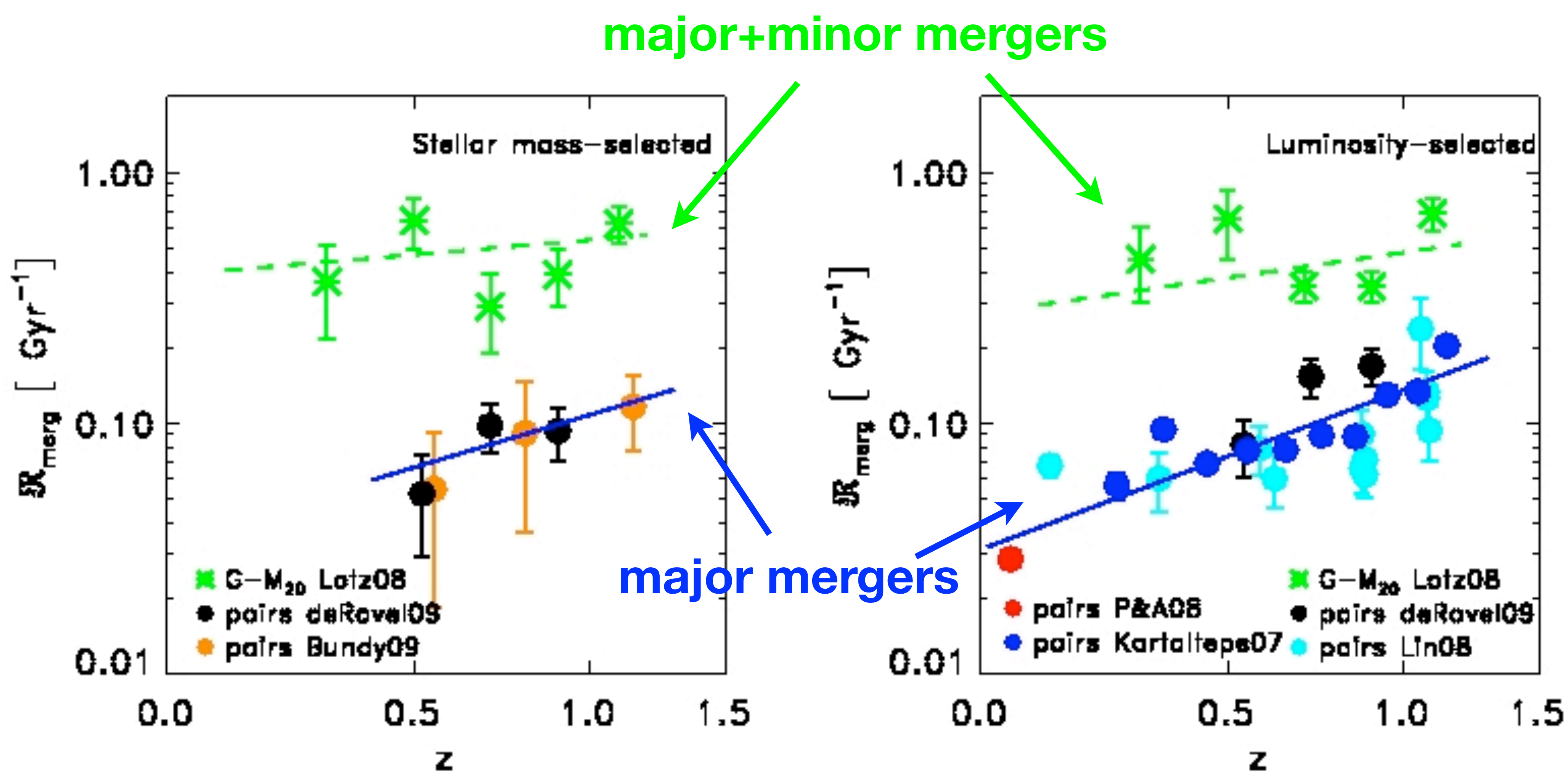
normalize by consistent T(z) and use same parent sample selection:

$\mathfrak{R}_{pairs} \sim (1+z)^{\alpha}$ α = 1.7 ± 3.0 (stellar mass); 2.1± 0.2 (luminosity)

$\mathfrak{R}_{G\text{-}M20\ (major+minor)}$ α = 0.5 ± 1.6 (stellar mass); 0.8 ± 1.4 (luminosity)

Lotz et al. 2011

Merger Rates per $10^{10}\ M_\odot$ galaxy at $z<1.5$



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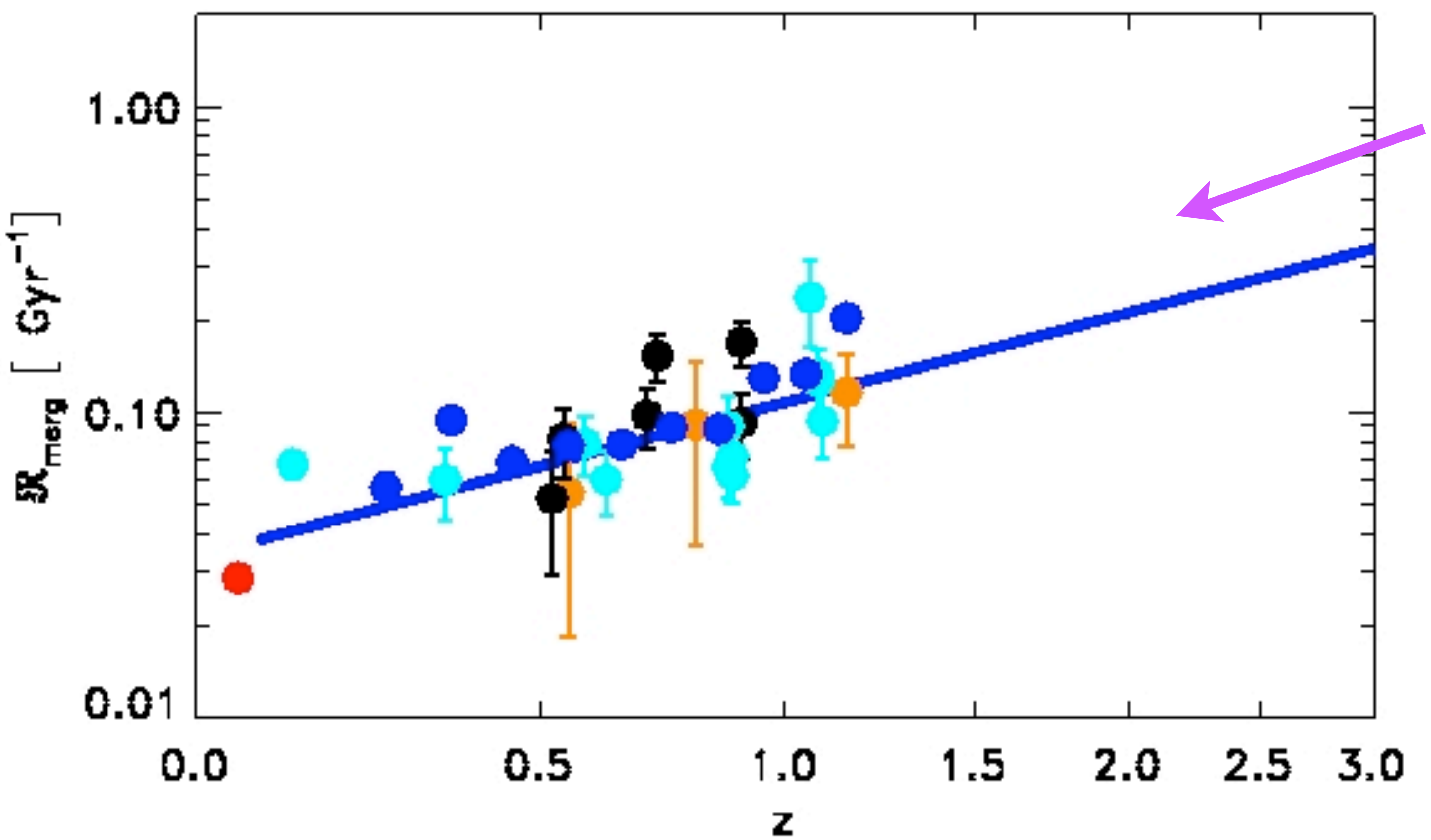
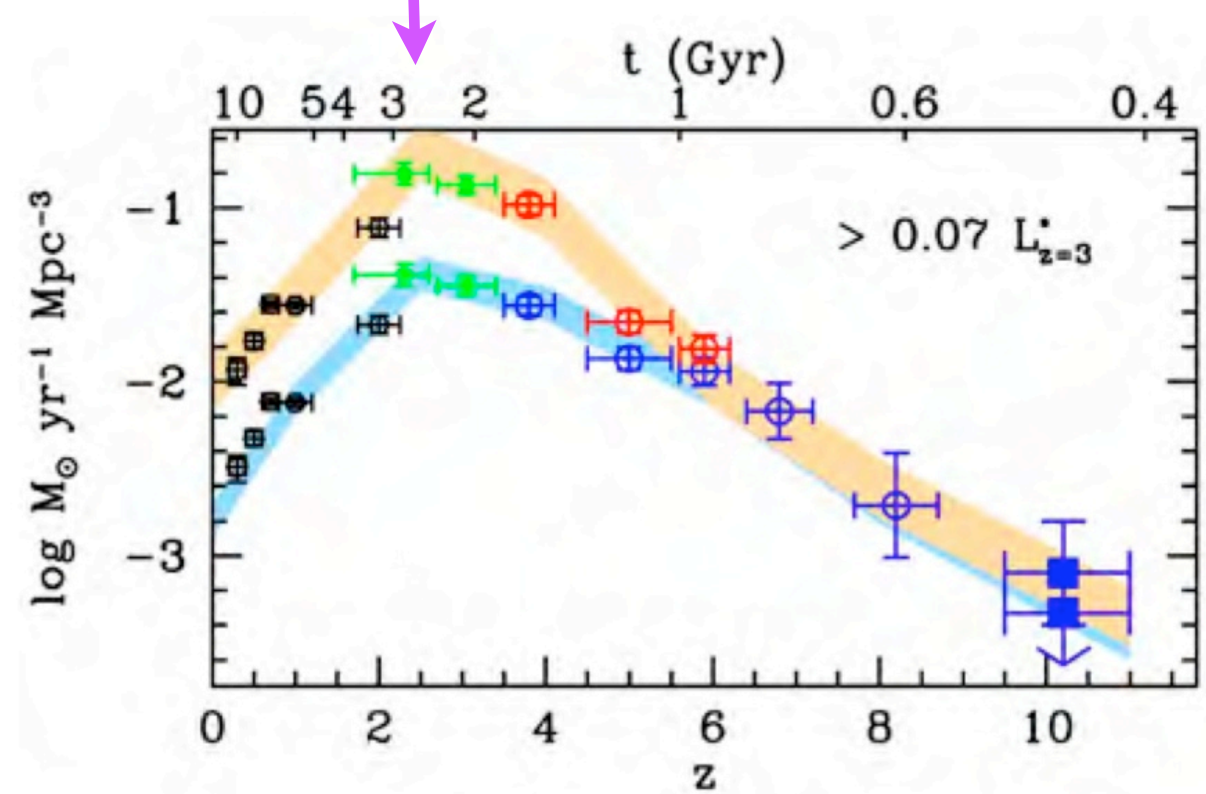
Lotz et al. 2011

Did mergers form bulges, quench galaxies?

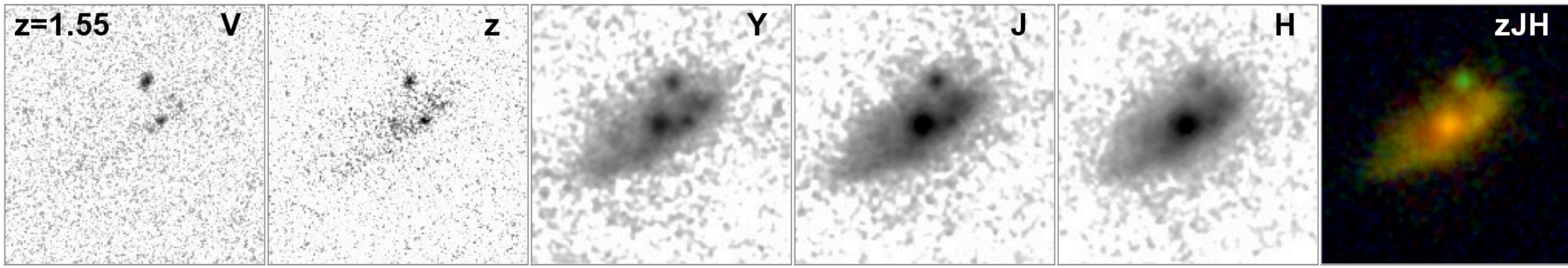


~ 3-4x more major mergers
at 1 < z < 3 ? (Lotz et al. 2011)

peak of SF activity/bulge formation
(e.g. Bouwens et al. 2009)



HST WFC3 needed at z~2



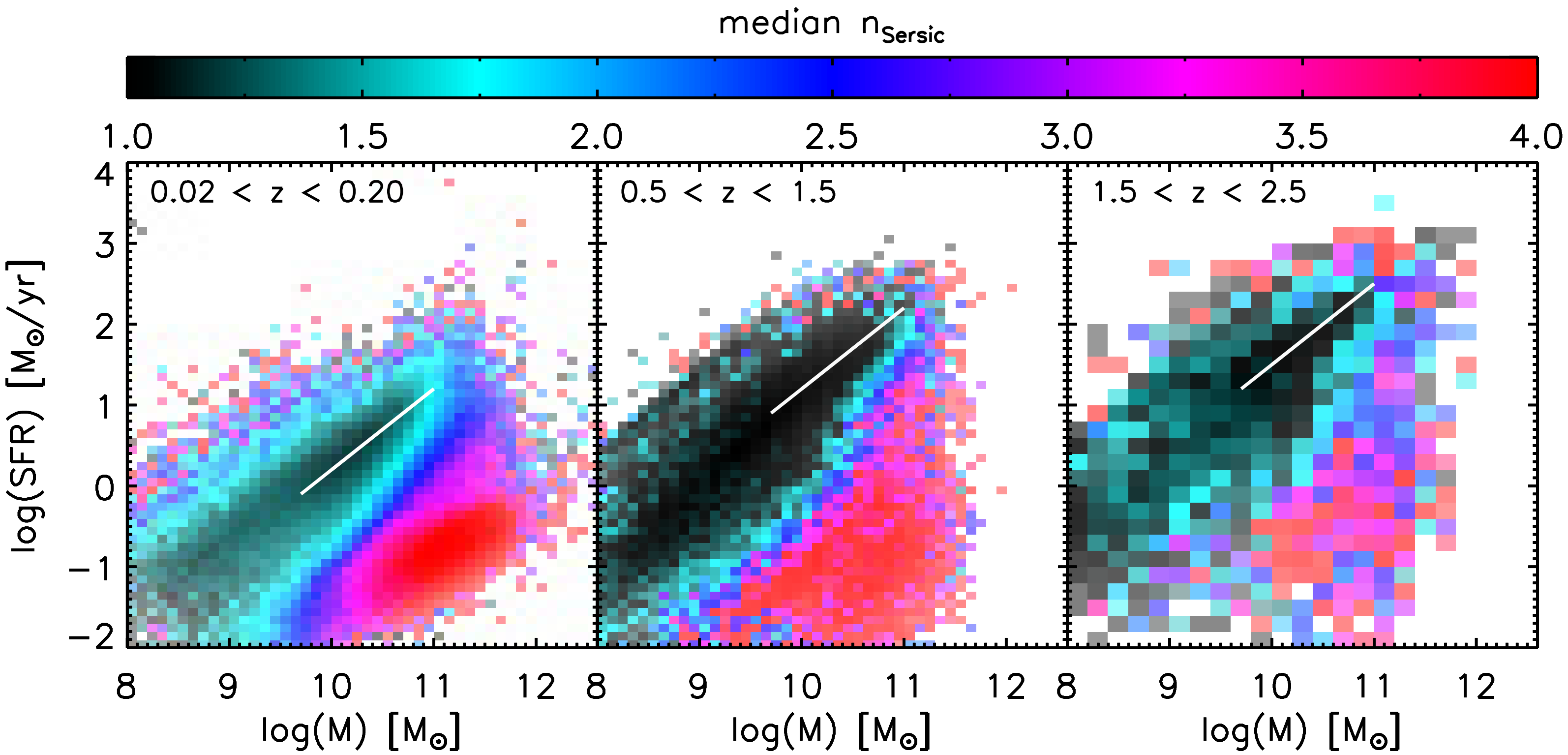
need high-spatial resolution NIR imaging
to probe rest-frame optical structures at z > 1.5

Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
(CANDELS) - PI S. Faber & H. Ferguson

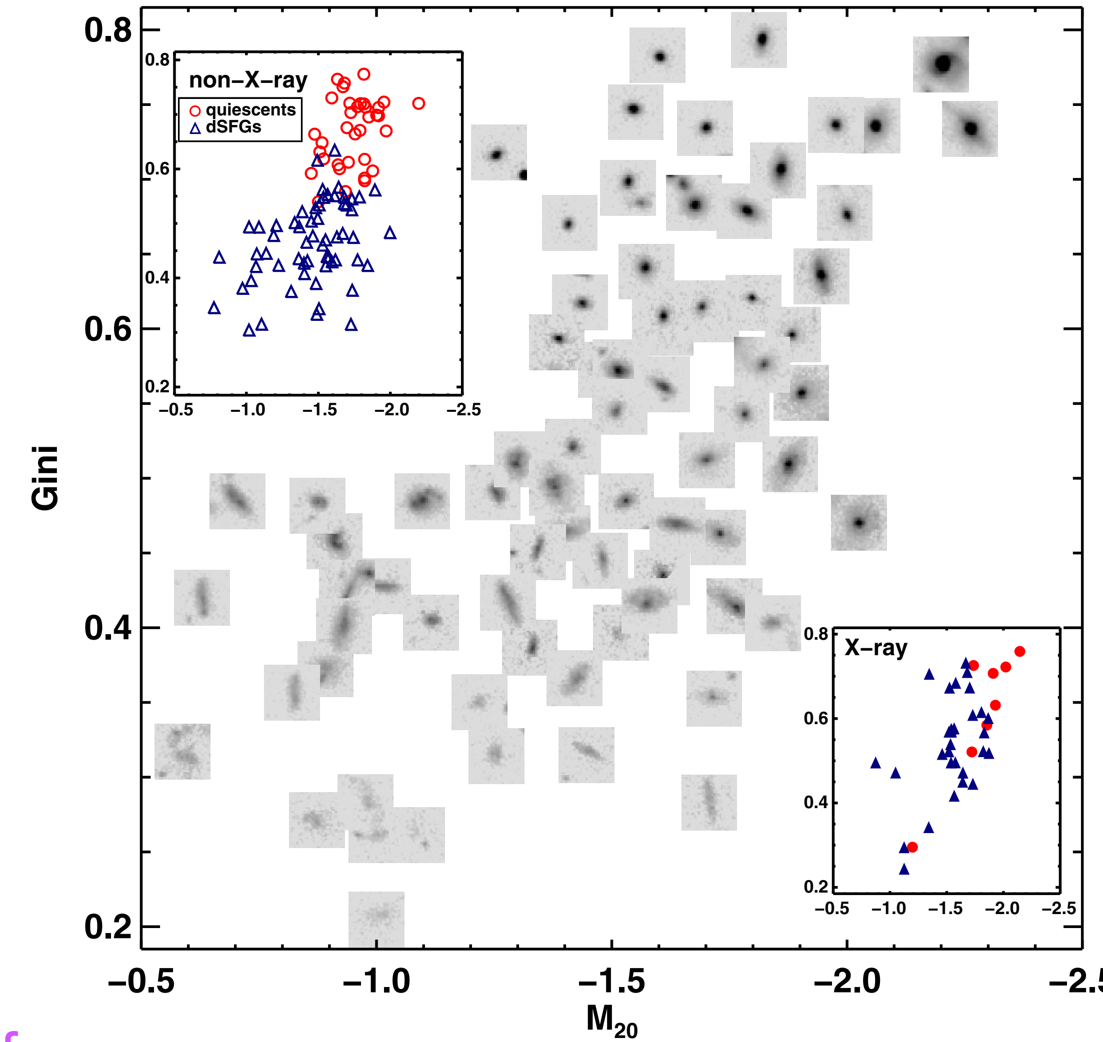
HST WFC3 NIR imaging
wide fields: UDS, EGS, COSMOS, 1-orbit depth J + H, ~0.2 sq. degrees

deep fields: GOODS-N + S, ~4-orbit depth Y, J, H, ~0.04 sq. degrees

z~2 : star-forming disks and quiescent bulges



Wuyts et al. 2012

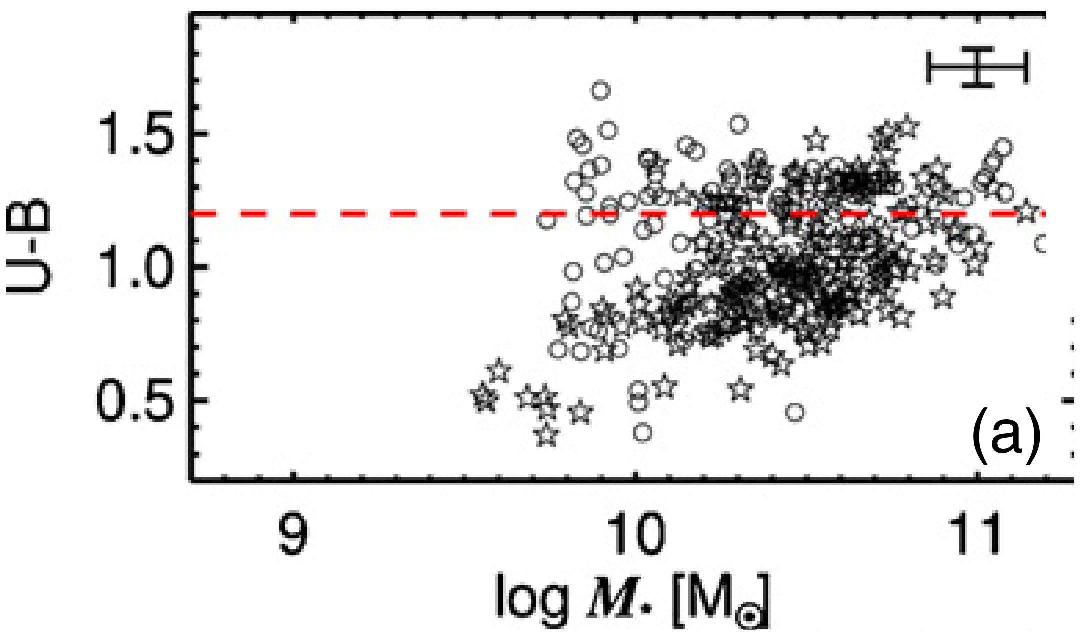


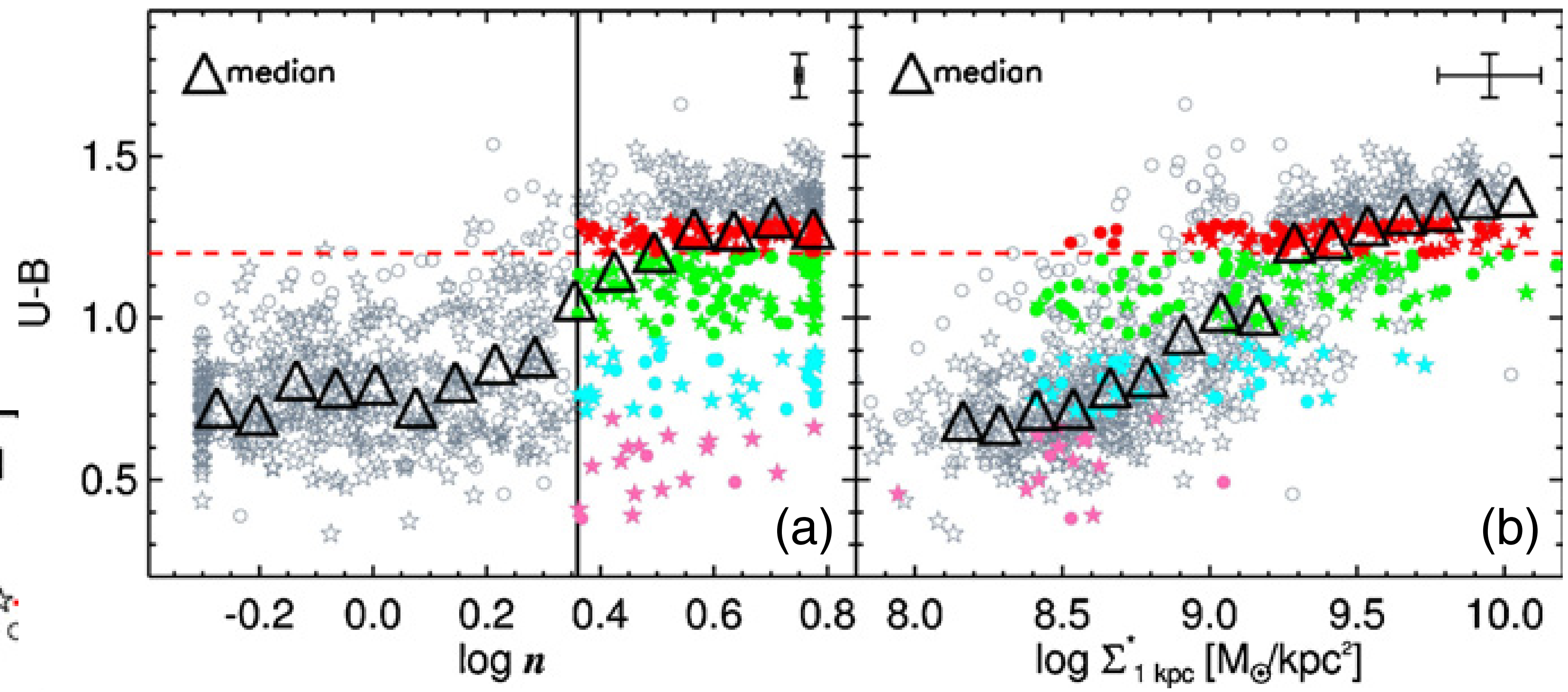
Wang et al. 2012

Color-morphology relationship in place as early as z> 2.5 (Kriek et al. 2010)

Massive quenched galaxies are bulge-dominated from 0 < z < 2.5 (Bell et al. 2012; Wuyts et al. 2012, Wang et al. 2012, Lee et al. 2012)

bulge/central mass concentration = quenching



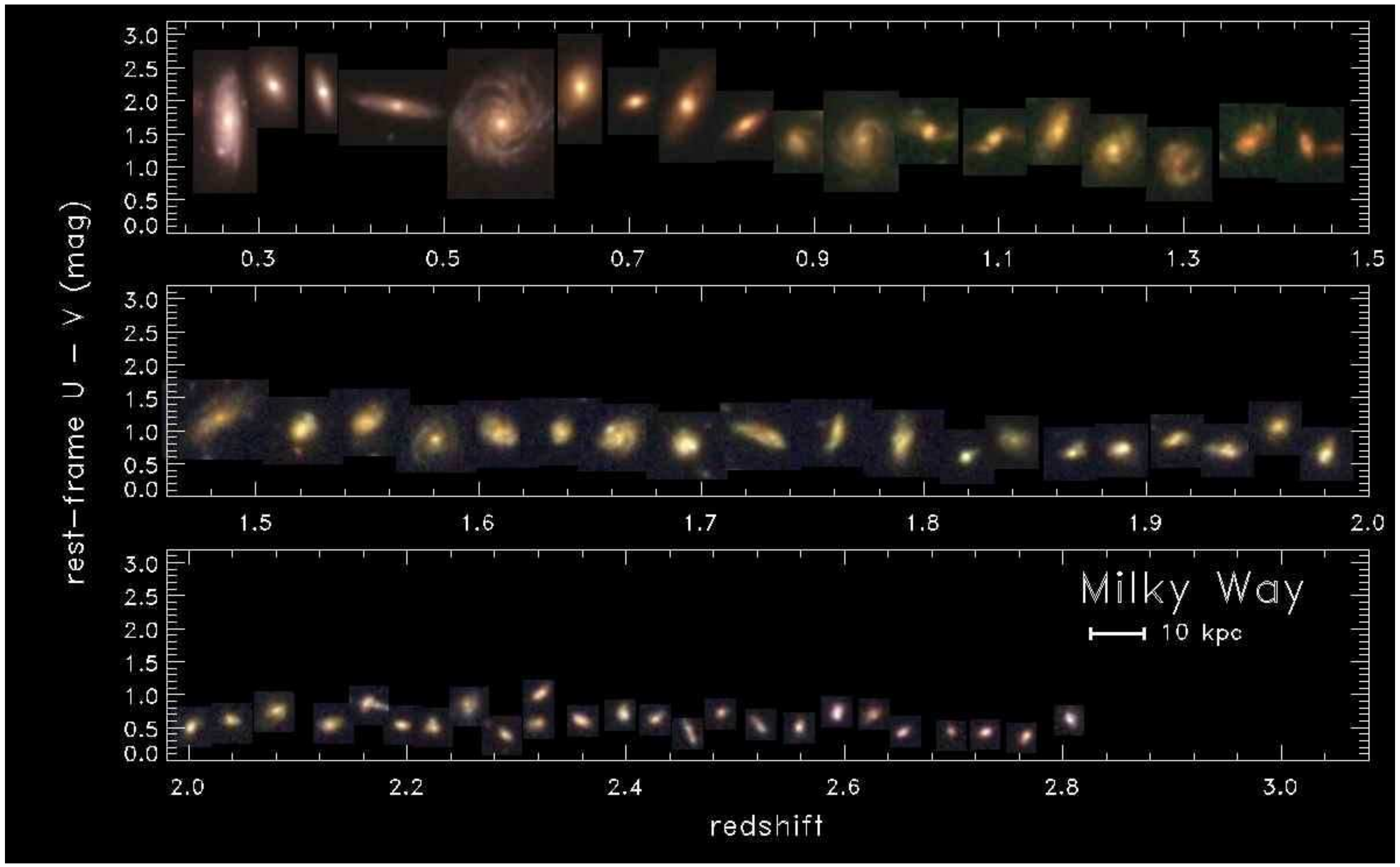


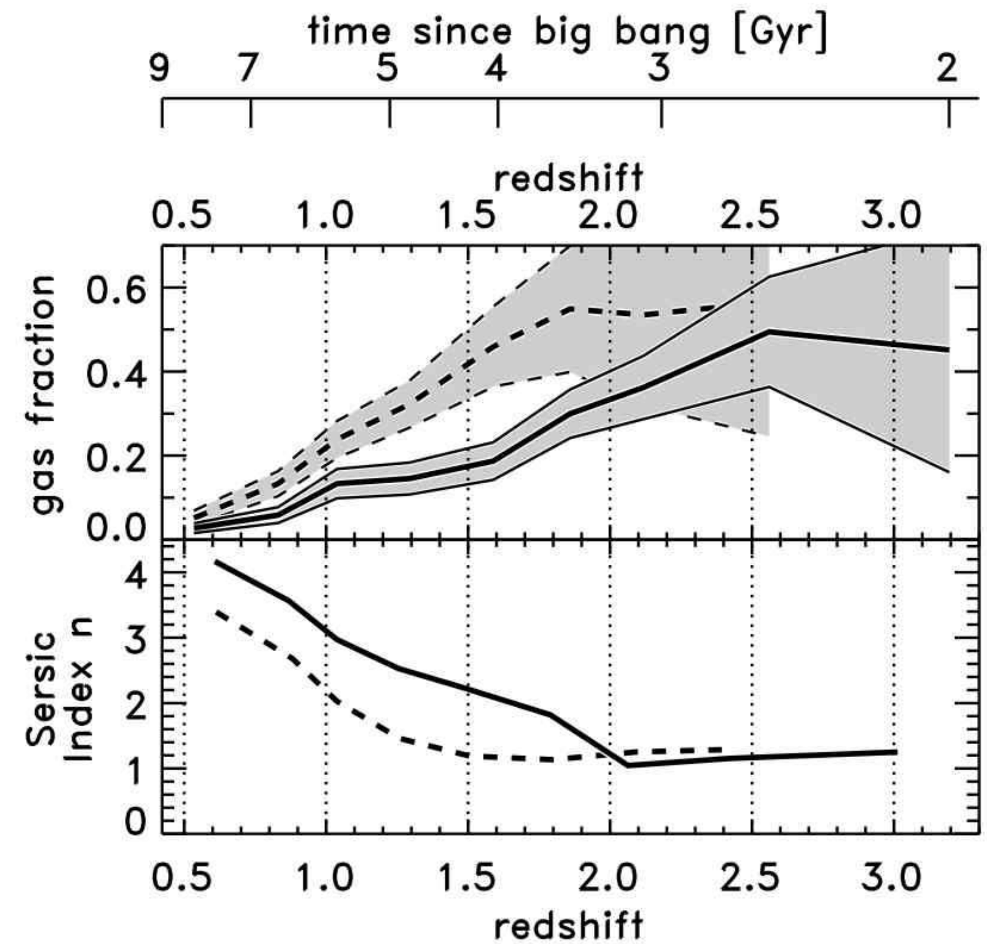
Cheung et al. 2012

Quenching happens when central Σ^* (<1 kpc) > 10^9 $M_\odot/kpc^2$

stronger correlation than with total stellar mass or Sersic n

Milky Way/ Andromeda progenitors



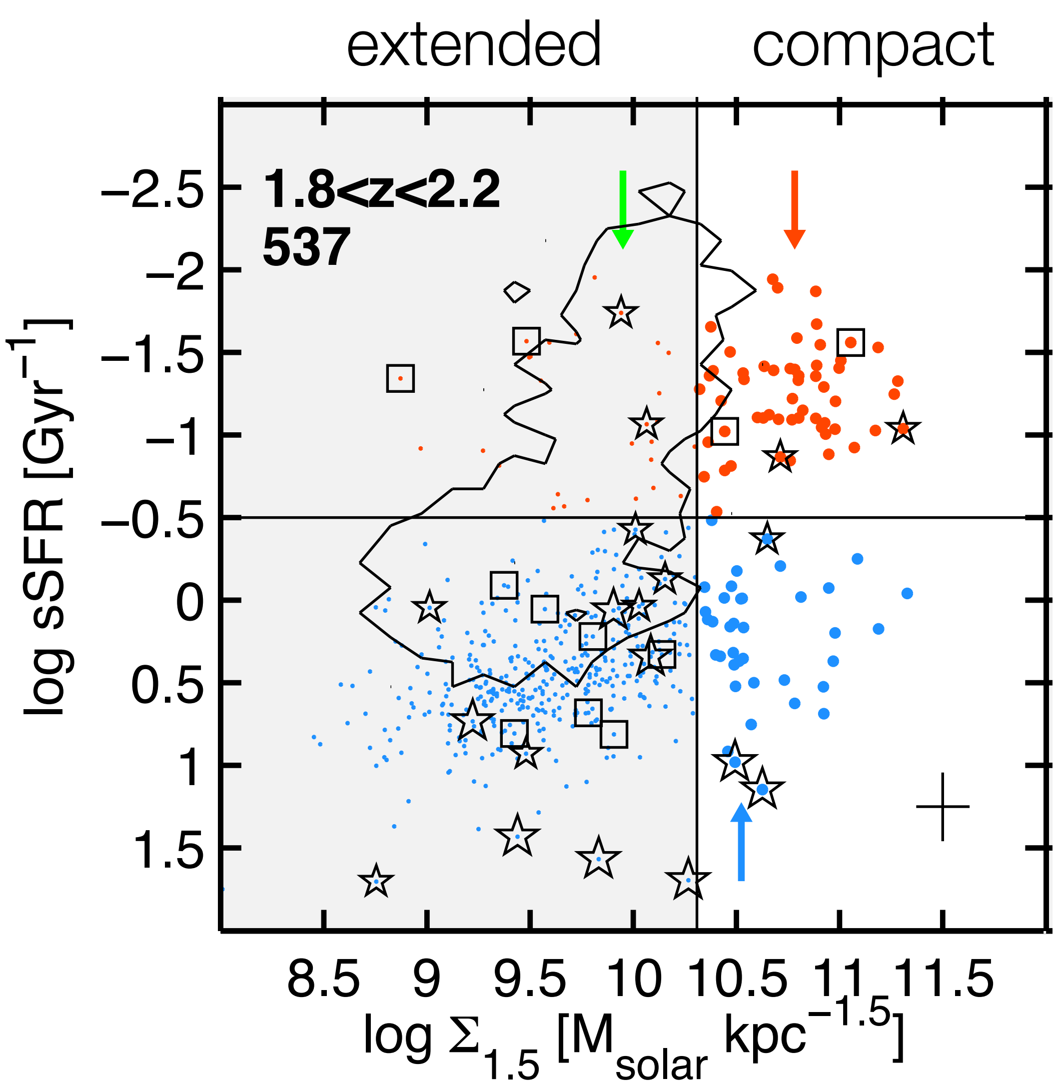


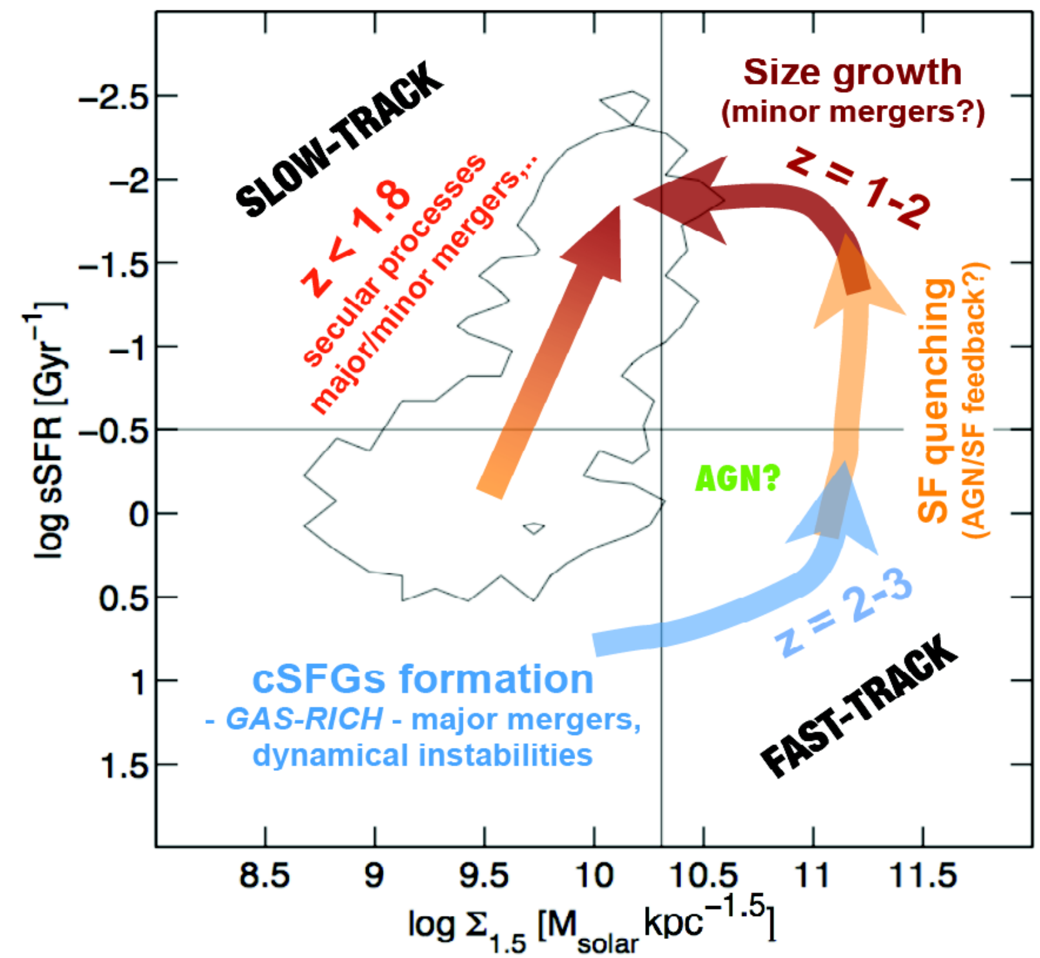
Papovich et al, in prep

Most Milky Way/Andromeda-sized galaxies are quenched today

Transition to bulge-dominated system at z~1- 1.5
correlated with decline in star-formation/inferred gas-fraction
(also Patel 2012, van Dokkum 2012)

Two pathways to create quiescent galaxies?



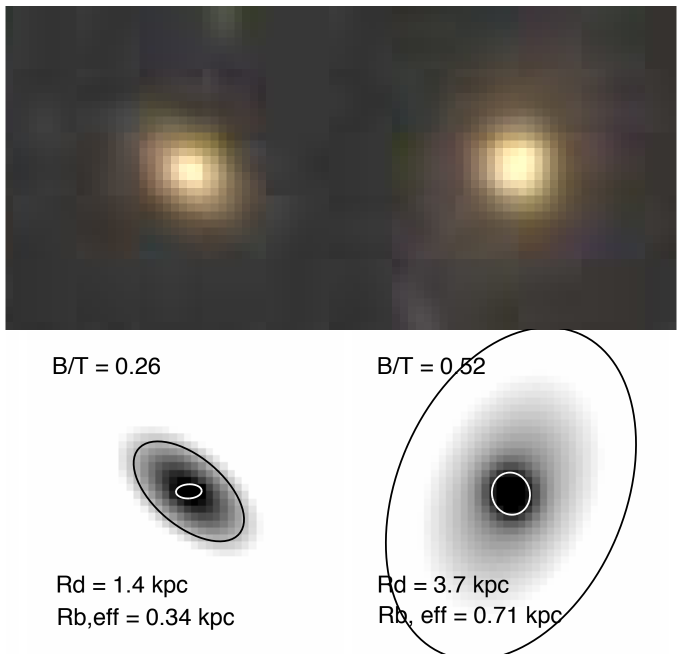


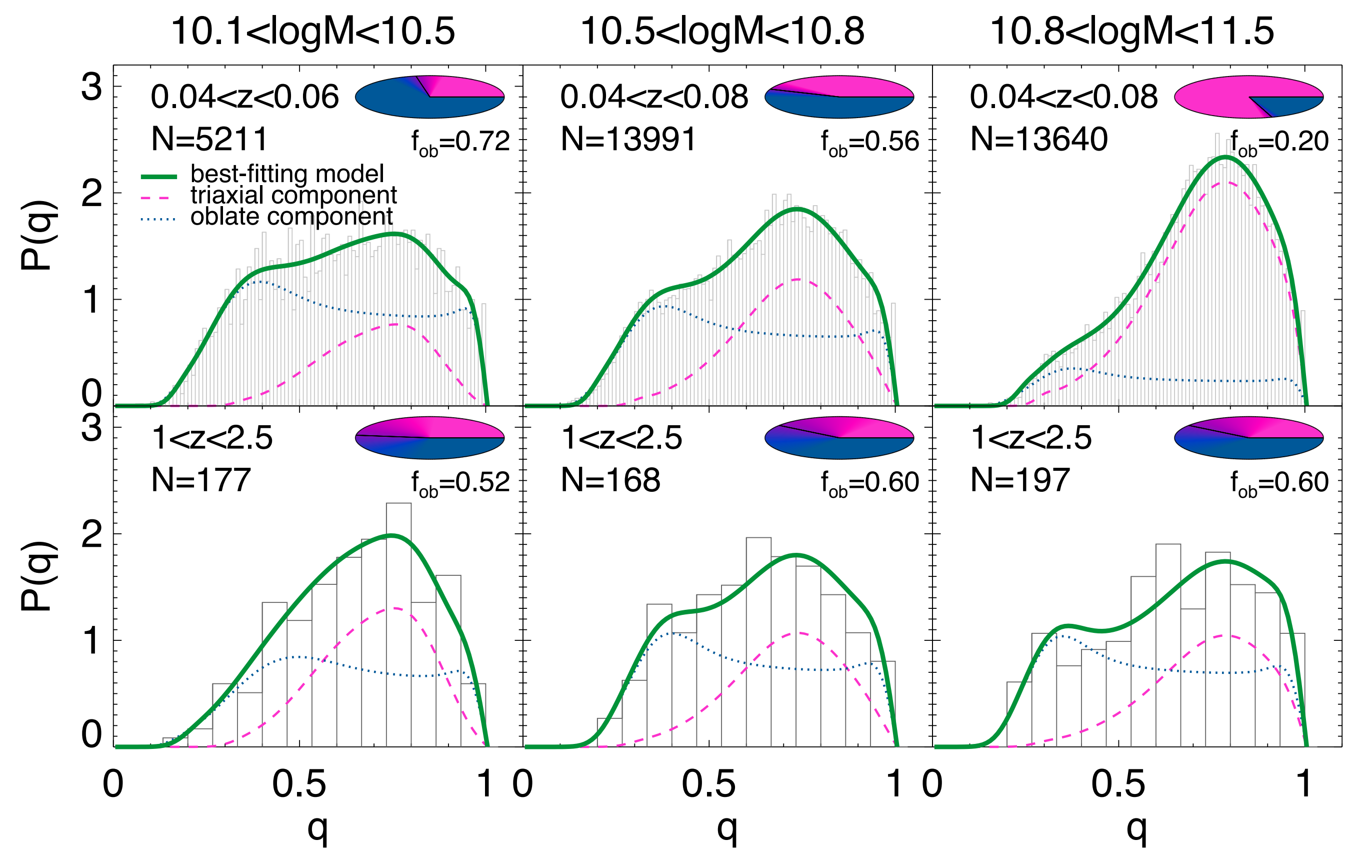
Barro et al. 2012

compact star-forming galaxies more common at z>2,
30x more likely to host luminous X-ray AGN

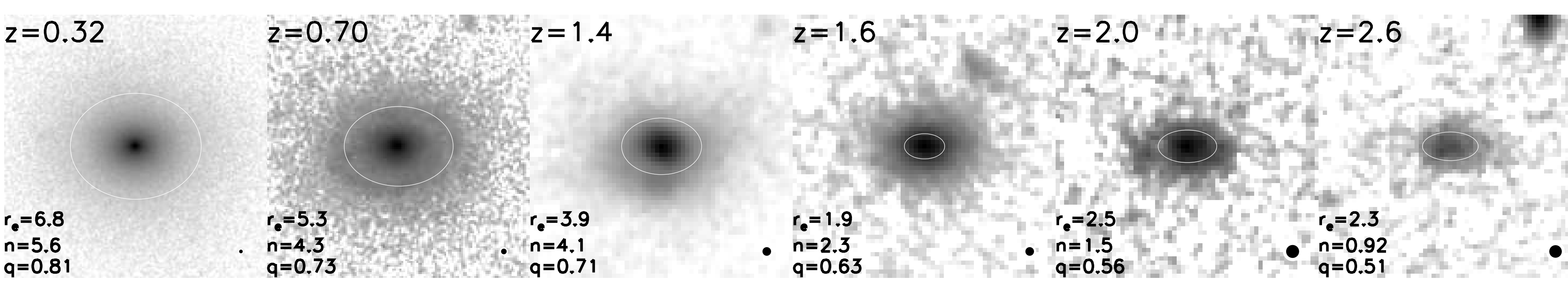
z~2 early-types - disky, not “elliptical”

van der Wel et al. 2011





Chang et al. 2013

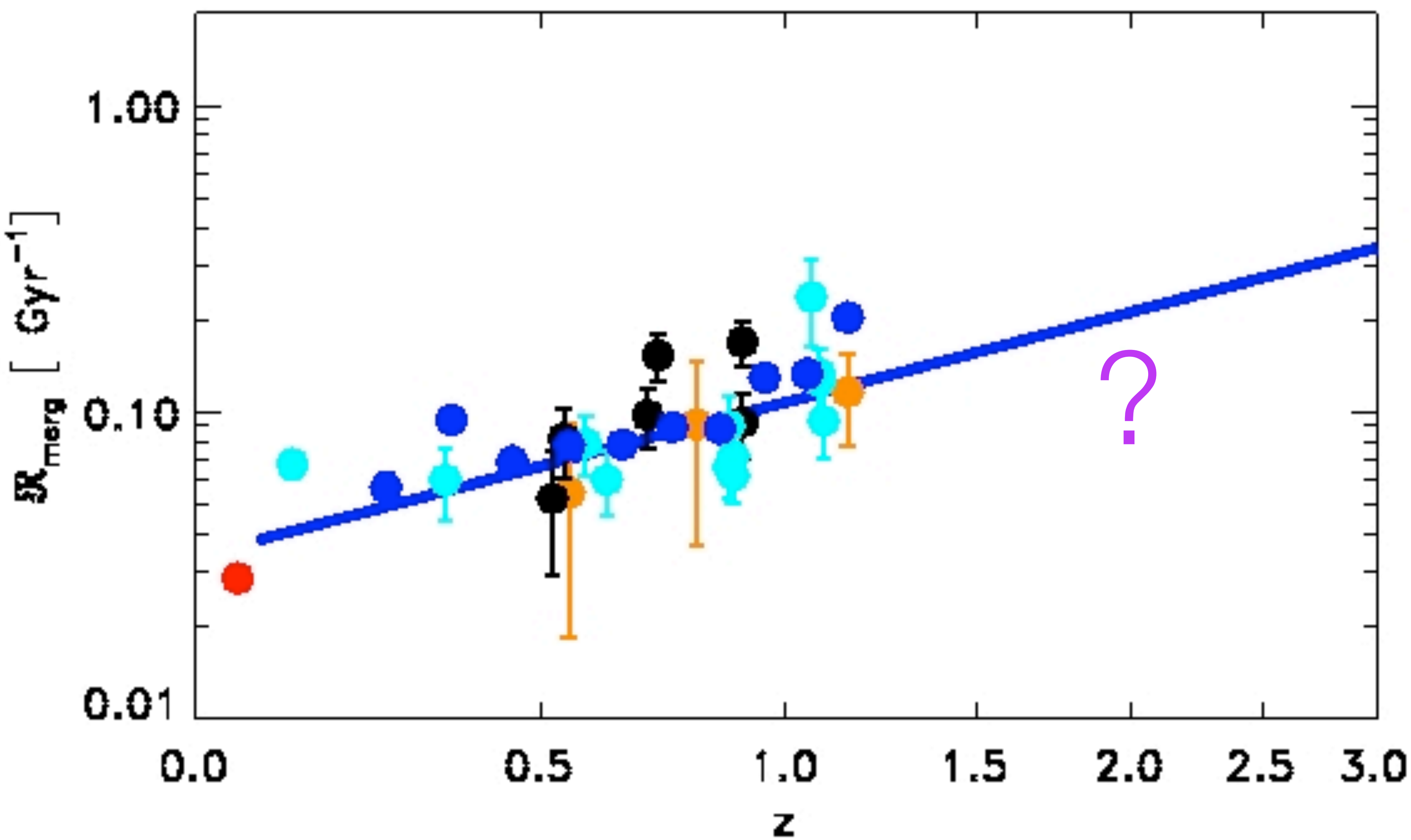


Patel et al. 2013

z~2 massive early-type galaxies appear less round/more disky

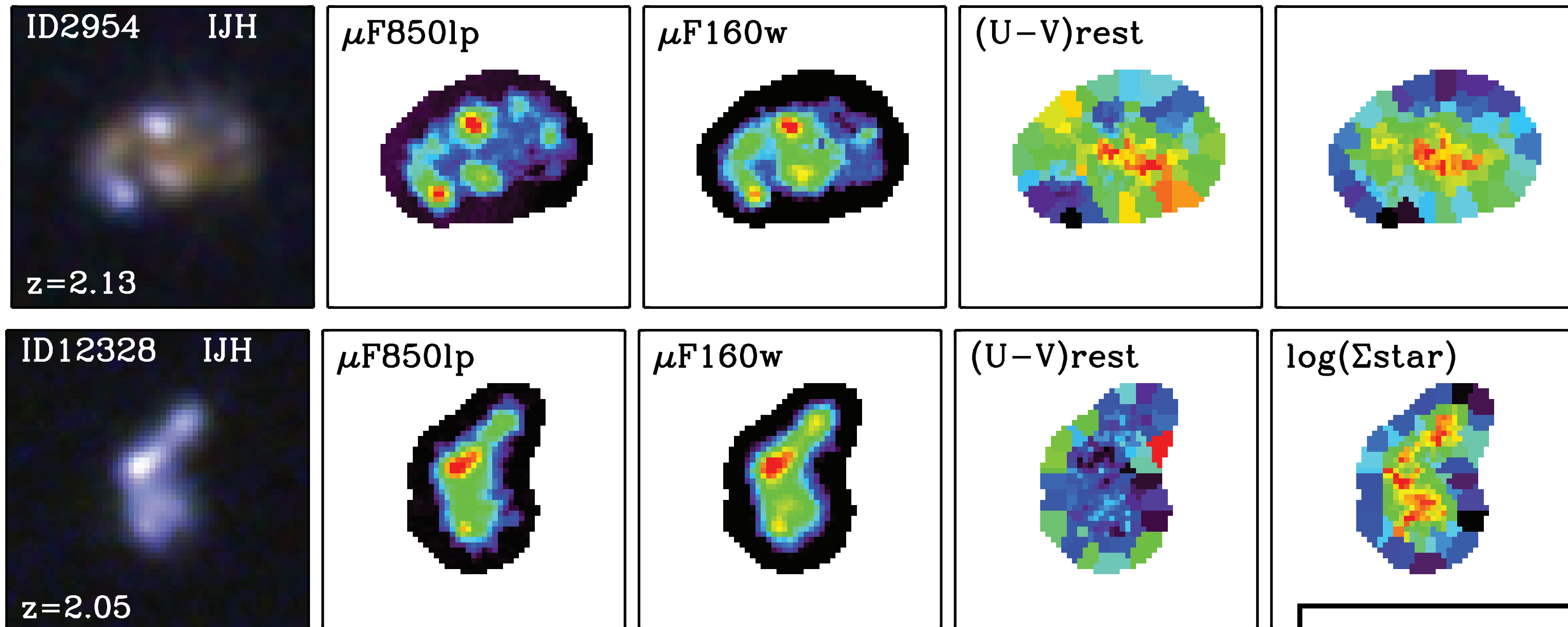
(→ massive fast rotators at high z?   could be mergers:Robertson & Bullock 2008)

Did mergers form bulges, quench galaxies?



Lotz et al. 2011

Clumps v. Mergers

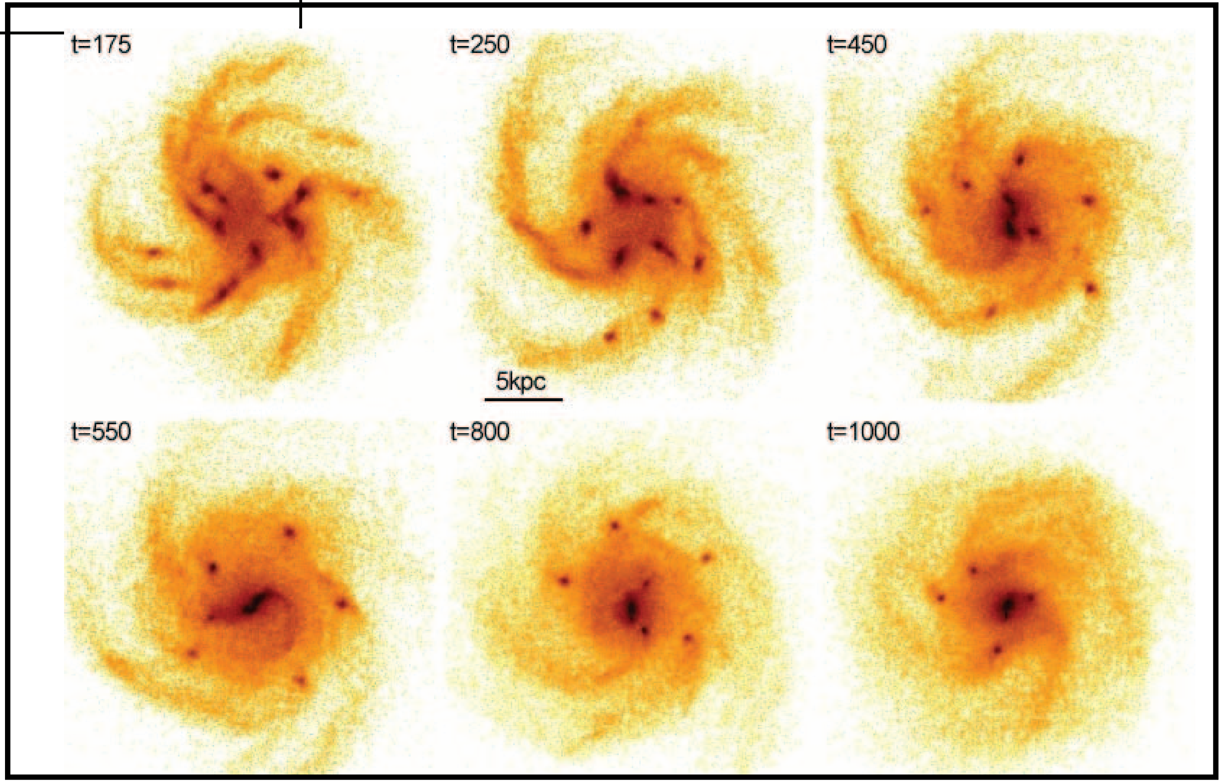


Wuyts et al. 2013

bright-off center “clumps” can look like interactions;

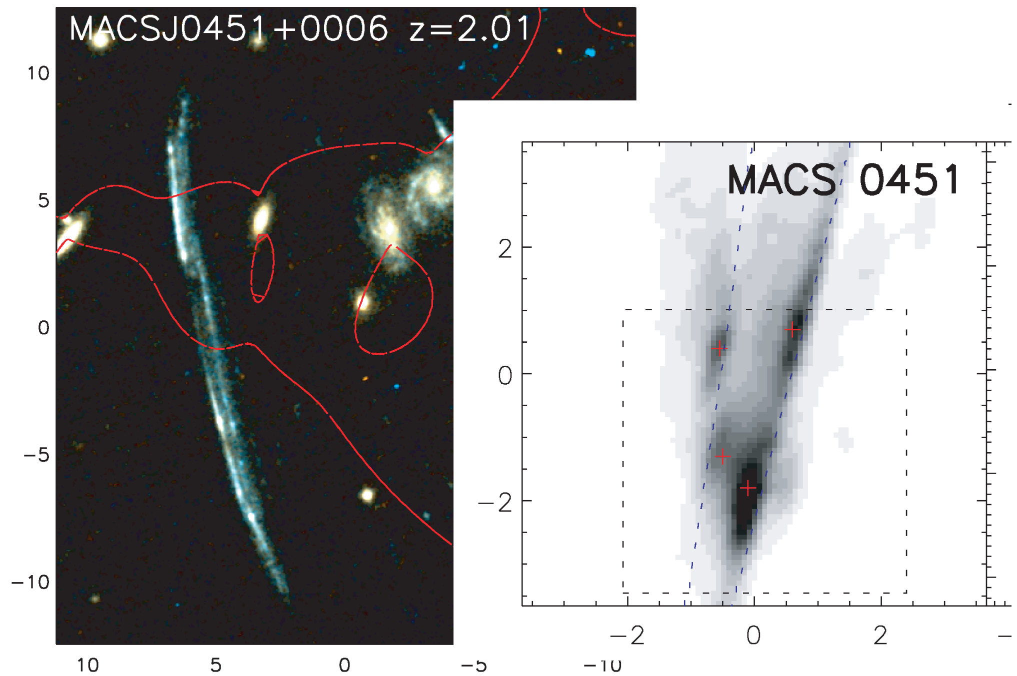
much more common at z>1
(Förster-Schreiber et al. 2006)

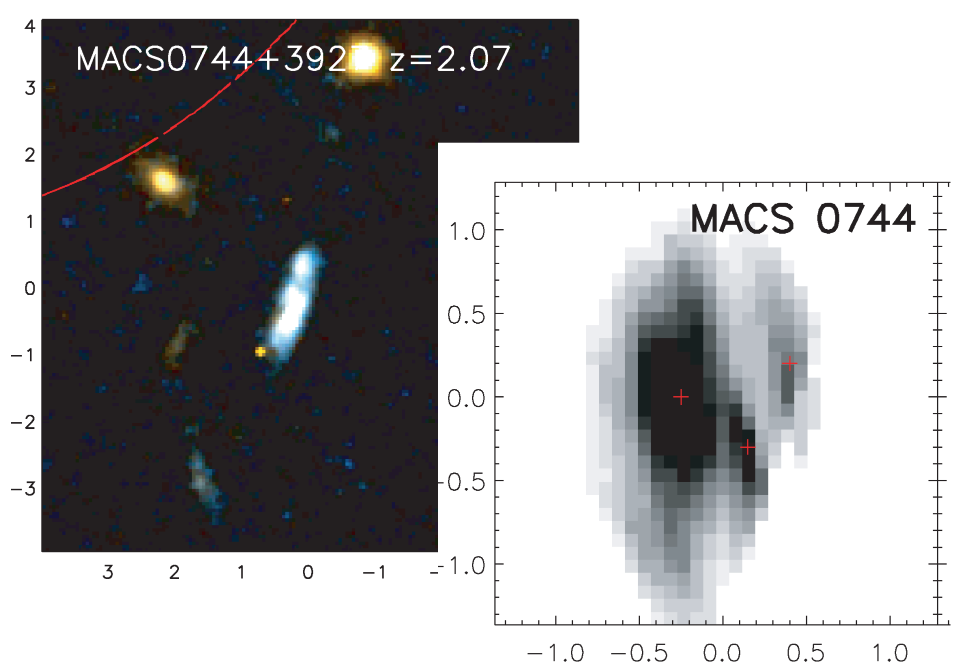
can migrate to center to form a bulge



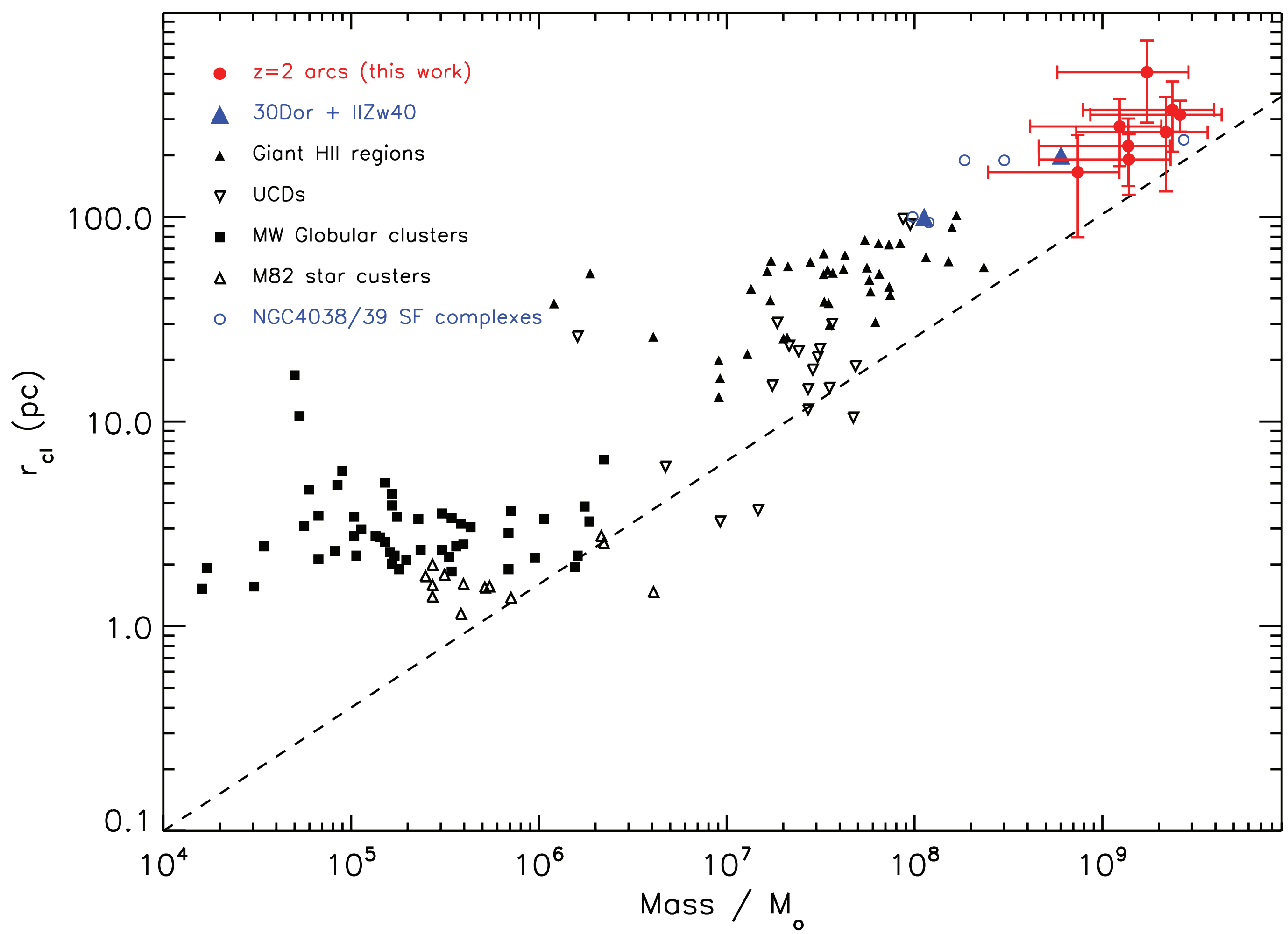
Elmegreen et al. 2009

Clumpy galaxies at high spatial resolution





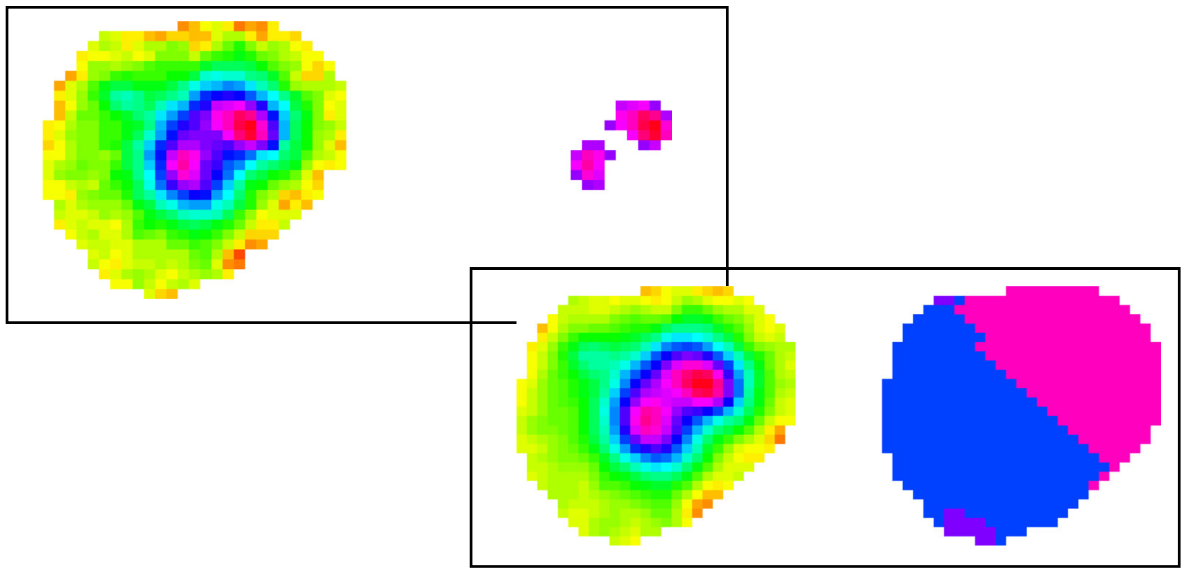
sub-kpc resln



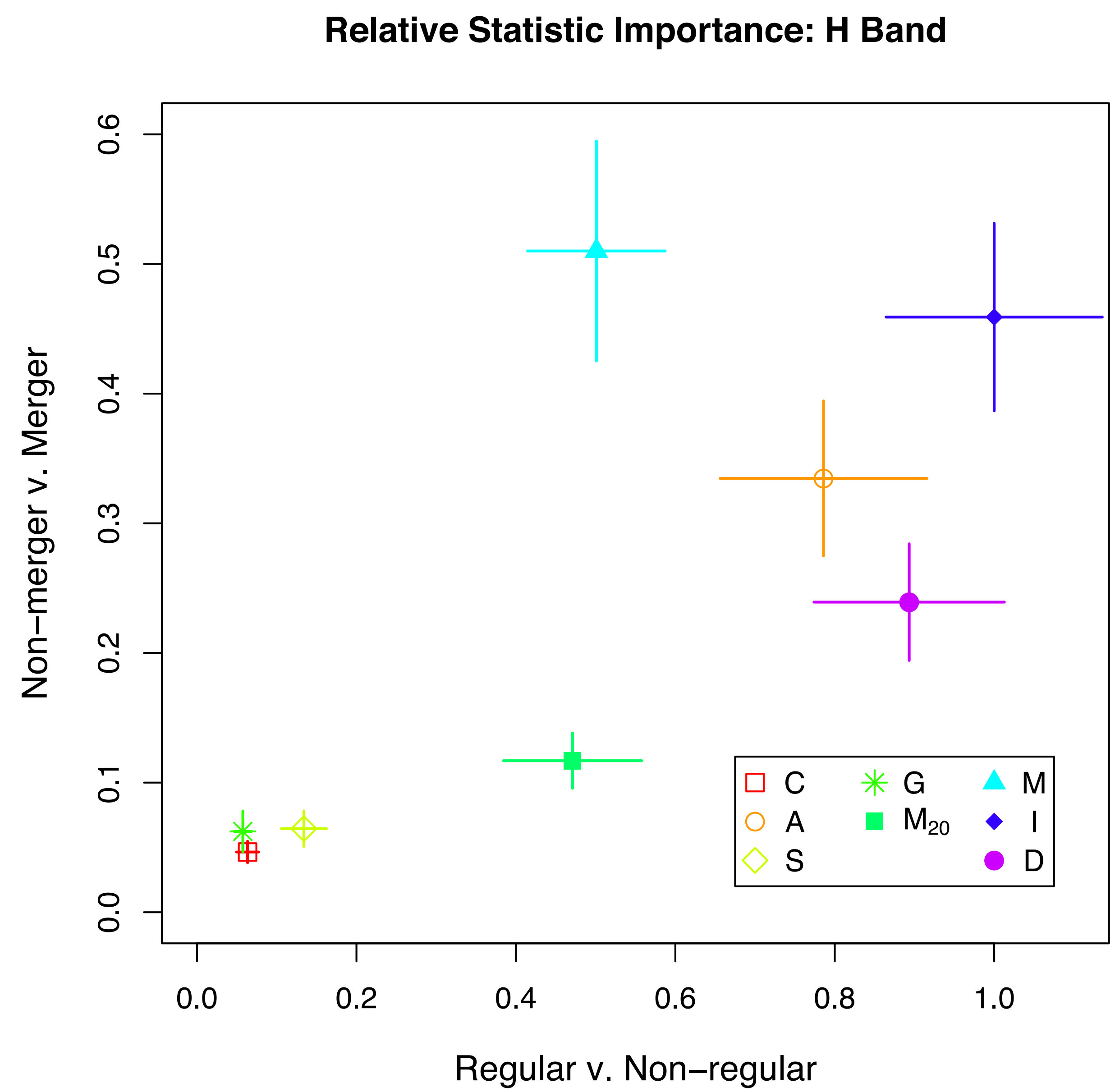
T. Jones et al. 2010 ; Keck AO
lensed z~2 have massive, large star clusters
(consistent with unstable disk picture?)

→expect more from HST Frontier Fields

New (better) way to find z~2 Mergers



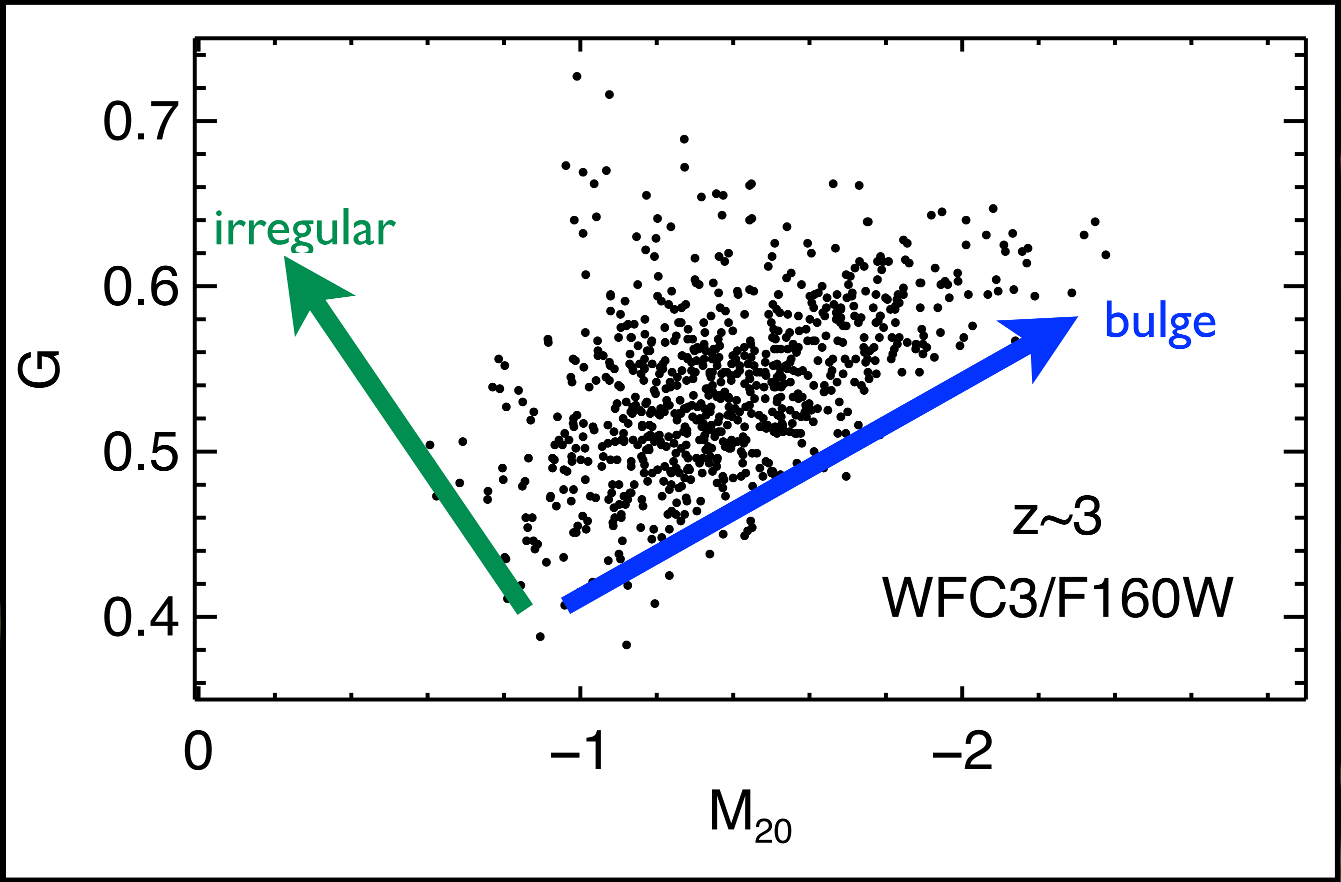
Freeman et al. 2013



new statistics M-I-D examine
the ratios of
area (M), intensity (I) and the distance (D)
between 1st and 2nd brightest clumps

beats G-M_{20}, CAS at finding CANDELS visually classified mergers
for WFC3/H < 24 galaxies

Clumps v. Mergers: how can you tell?



Cosmological hydro-dynamical simulations
now have resolution and baryonic physics to predict morphology
→ tie morphologies to underlying physics

(Greg Snyder, P. Torrey, L. Hernquist, et al. - AREPO
Ceverino, Primack, Dekel, et al. -- hydroART; + SUNRISE)

Summary

- Quantitative morphology is efficient tool for tracking galaxy evolution and connecting to physical models

- Mock images of galaxies from hydrodynamical simulations needed to understand morphological disturbances and TIMESCALES.

- Fraction of 10^{10} $M_\odot$ galaxies undergoing a major-merger increases as $\sim(1+z)^2$ the minor merger rate is several times higher (with weaker evolution)

- Quenching at z~2 is strongly linked to presence of bulge/central mass concentration (more so than total mass)

- Clumpy unstable disks and mergers very hard to distinguish at z~2; need more simulation work   (but both can form bulges?)