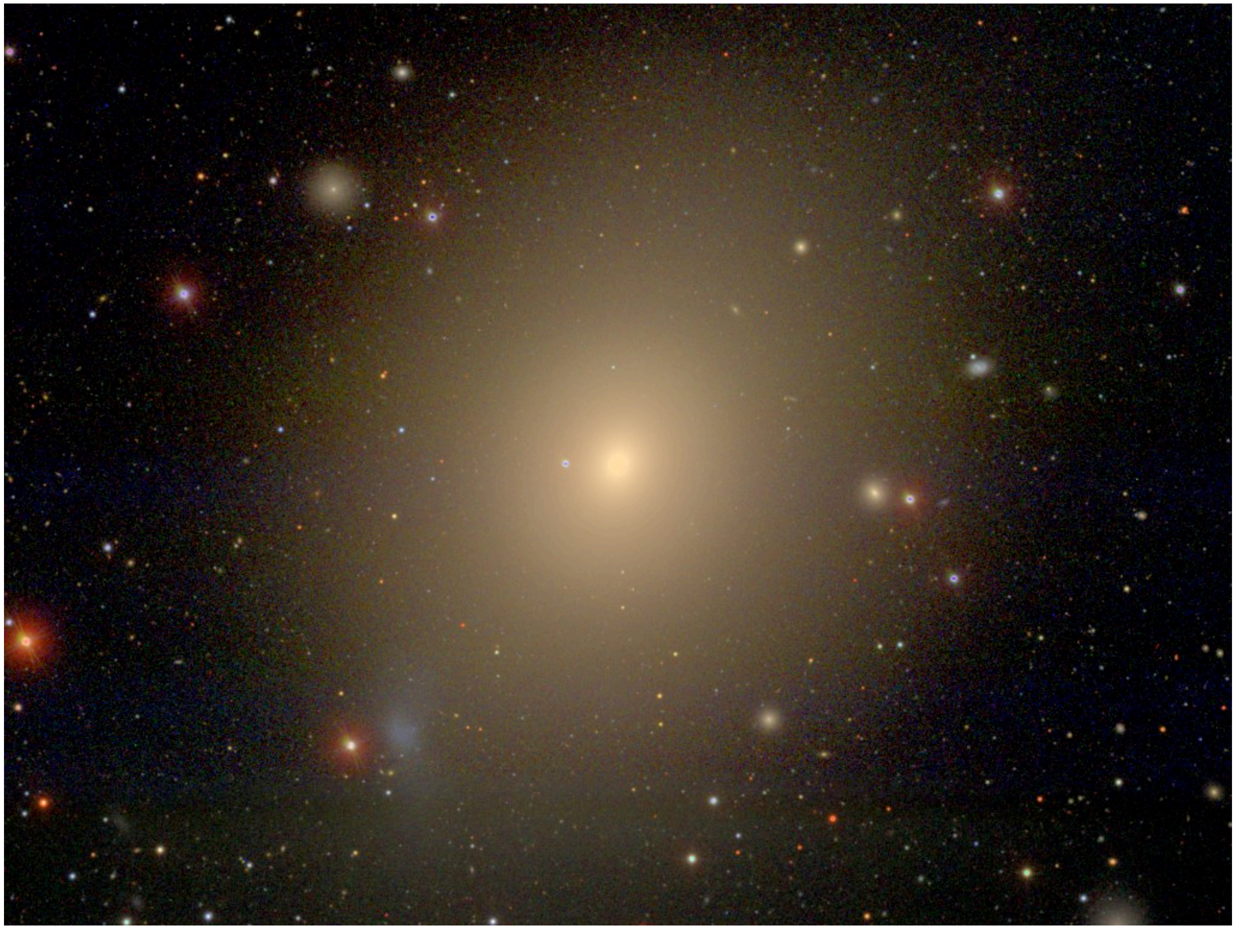
Obesity in the Universe: How Fast Can Early Type Galaxies Grow?

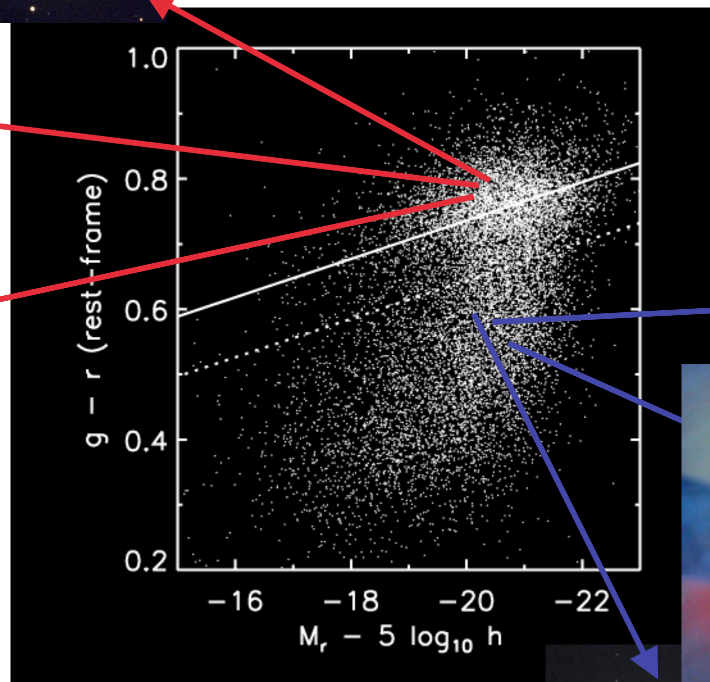
Richard Ellis (Caltech)



NEXSI/UCSC

October 14th 2011

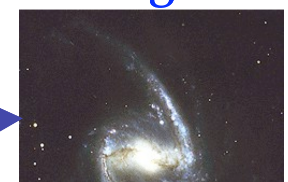
Bimodal Galaxy Distribution



Bell et al. 2003

Passive
Red
Early type
Old

Star forming
Blue
Late type
Young



Hubble Sequence - morphology shows dynamically distinct populations

Gas content/integrated colors - different ages and star formation histories

Changing Views of Early Type Galaxies

- **Old, red and dead – monolithic collapse/single burst at high redshift**
  Eggen, Lynden-Bell & Sandage (1962) – rapid collapse
  Struck-Marcell & Tinsley (1978) – red colors and SF history
  Bower, Lucey & Ellis (1992) – tight scatter on color-luminosity relation

- **Hierarchical assembly – product of disk mergers and late formation**
  Toomre (1977); White (1978) – numerical simulations
  Kauffmann, Charlot & White (1996) – CFRS redshift survey statistics

- **Mass-dependent assembly – `downsizing', `selective merging' and `feedback'**
  Treu et al (2005); van der Wel et al (2005) – evolving Fundamental Plane
  Bundy et al (2005, 2007), Borch et al (2006); Ilbert et al (2010) – type dependent evolving stellar mass functions

NO LONGER SUCH A SIMPLE PICTURE!

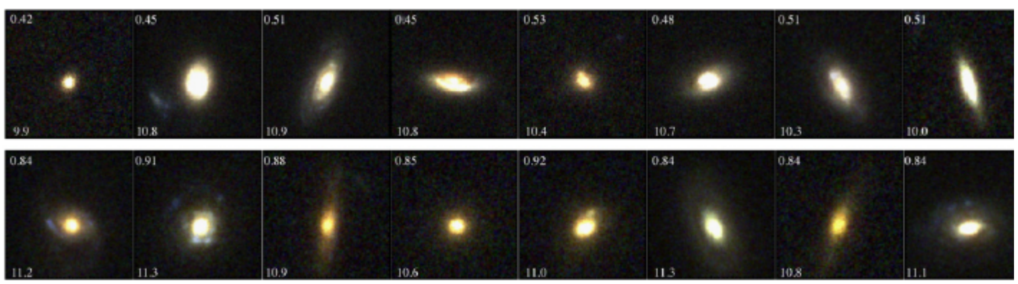
Part review – part collaborative work with
Drew Newman (CIT), Kevin Bundy (IPMU), Tommaso Treu (UCSB)

Note on Nomenclature

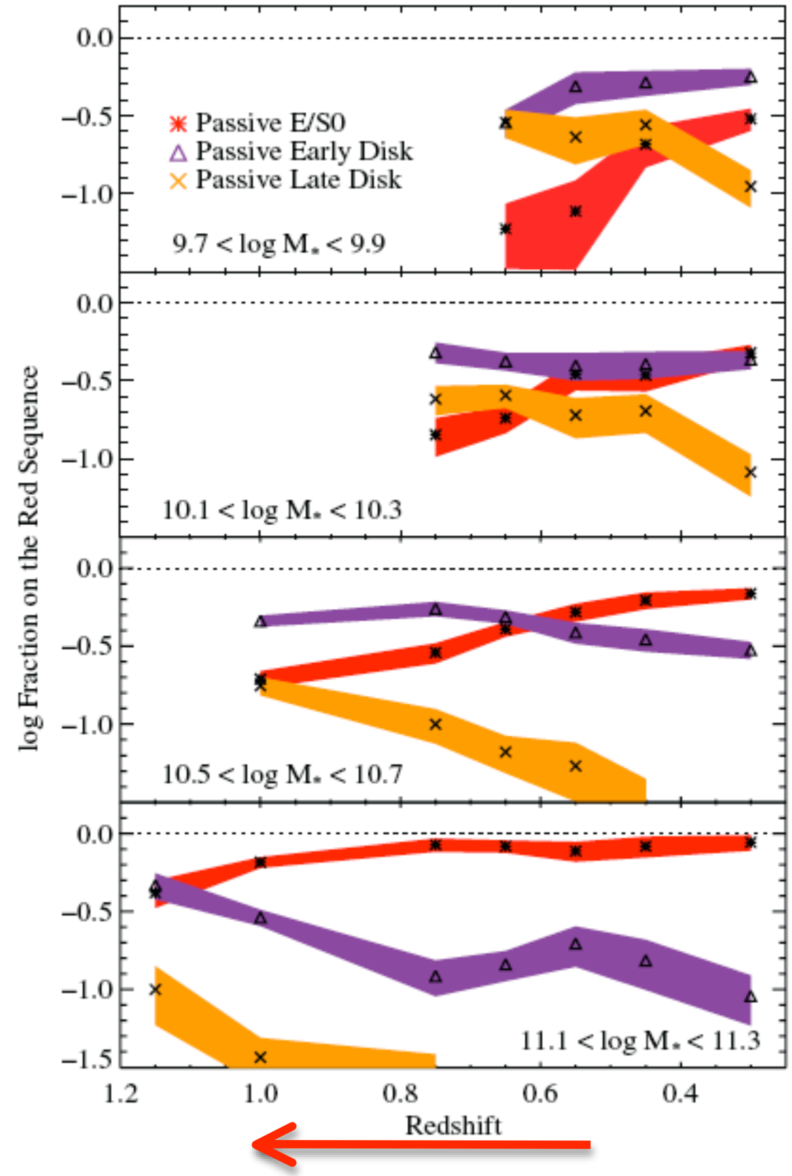
Should "early-type" or "passively-evolving" galaxies be selected by color or morphology?

Correspondance between traditional color cuts and spheroidal morphology is not perfect, especially at low stellar masses

More than 50% of red-sequence galaxies in COSMOS with M <10^{10} $M_{\odot}$ have disk-like morphologies!

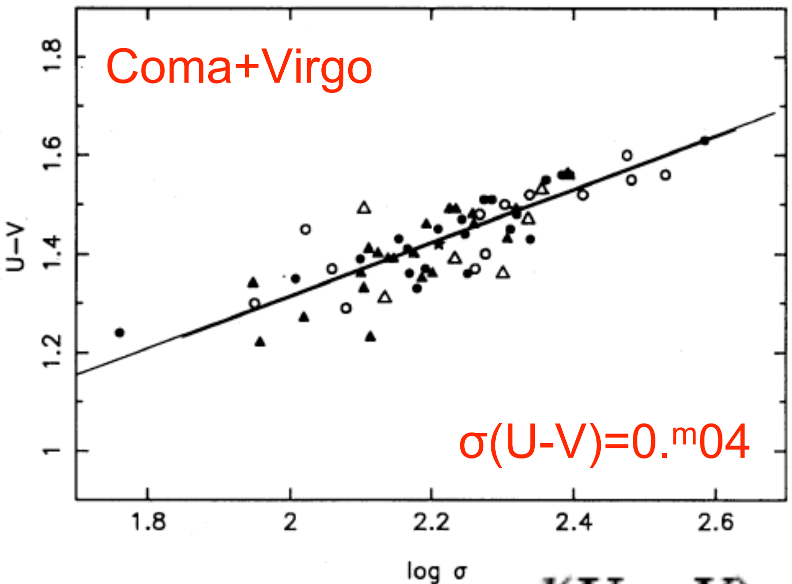


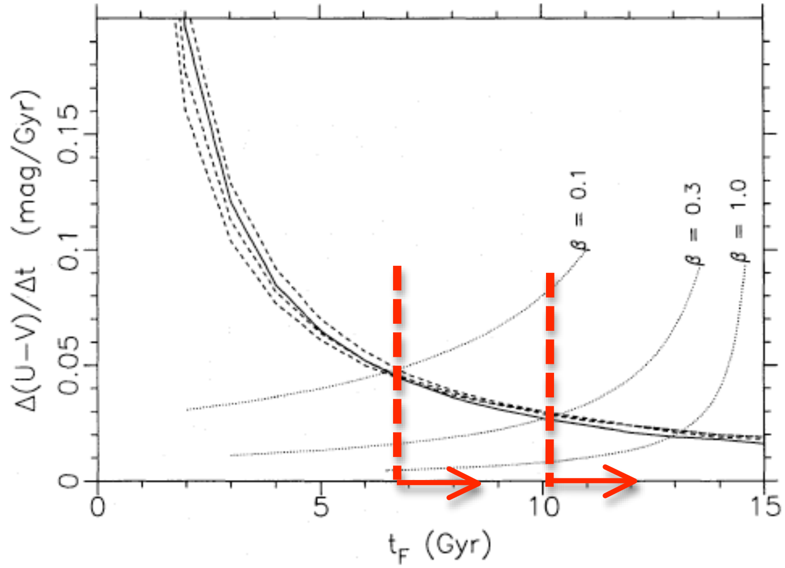
`Passive disks' in GOODS-N



Bundy, RSE et al (2010) Ap J 719, 1969

Old Stellar Populations: I – Color Magnitude Relations





$$\frac{d(U-V)}{dt}\beta(t_H - t_F) \leq \sigma$$

Bower Lucey & Ellis (1992), see also Sandage & Visvanathan (1978)

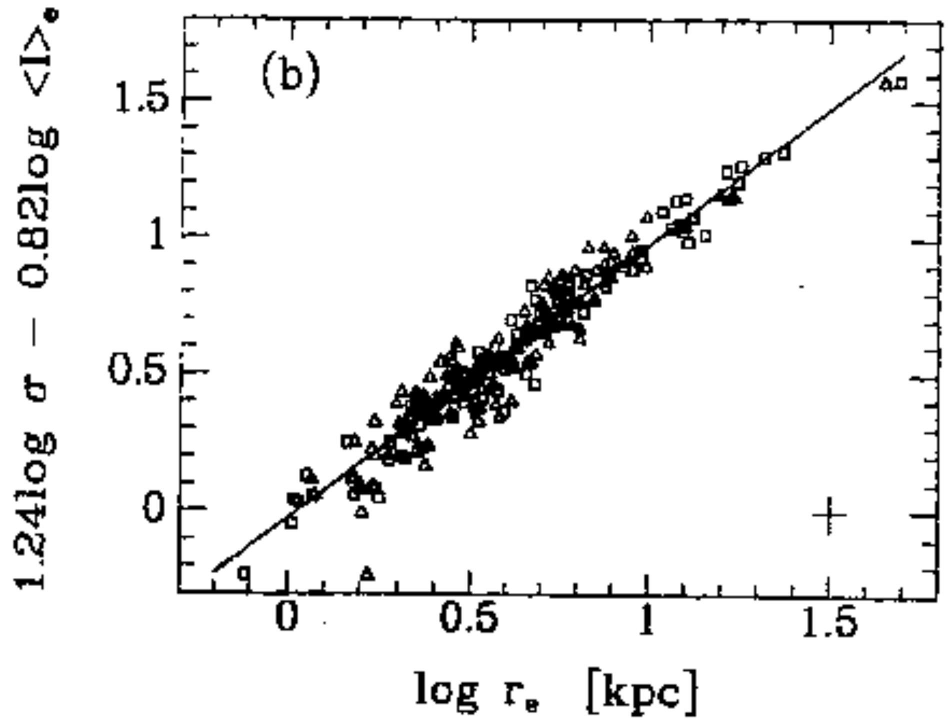
Scatter in U-V color **σ** constrains uniformity of contribution from MS stars

σ places joint constraint on age of last burst $\mathbf{t_F}$ and synchronicity parameter **β** which governs distribution of ages within interval $\mathbf{(t_H - t_F)}$

Extended to cluster samples at z~0.5 by Ellis et al (1997)

Old Stellar Populations: II - Fundamental Plane

Empirical relation between size (r_e), velocity dispersion (σ) and luminosity L



Dynamical mass: $M \propto \sigma^2 r_e$

- no IMF dependence

- Close proxy for halo mass

- Provides robust M/L ratio

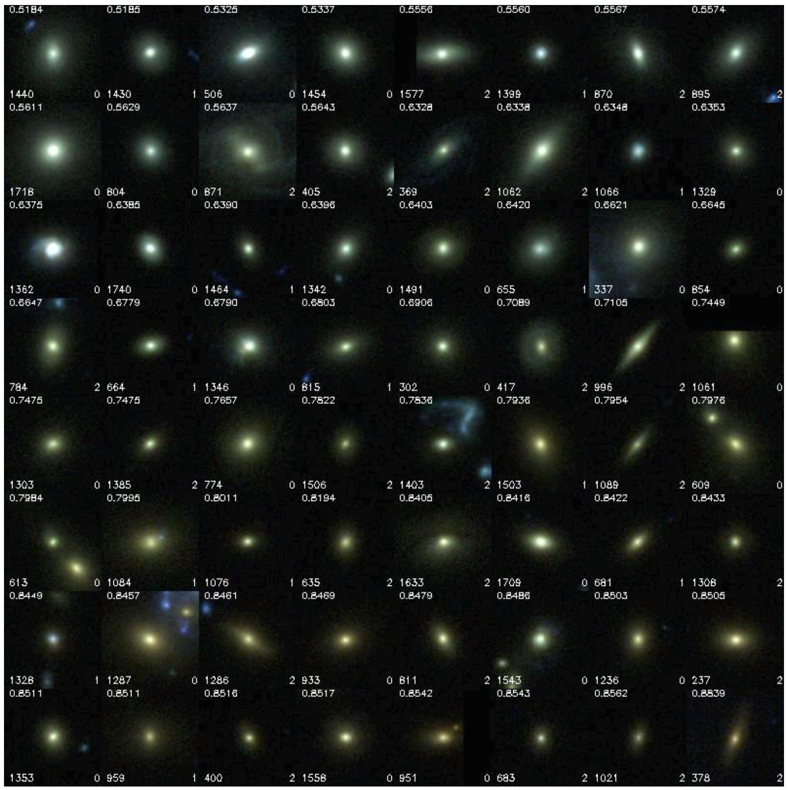
Tough to measure at high z:

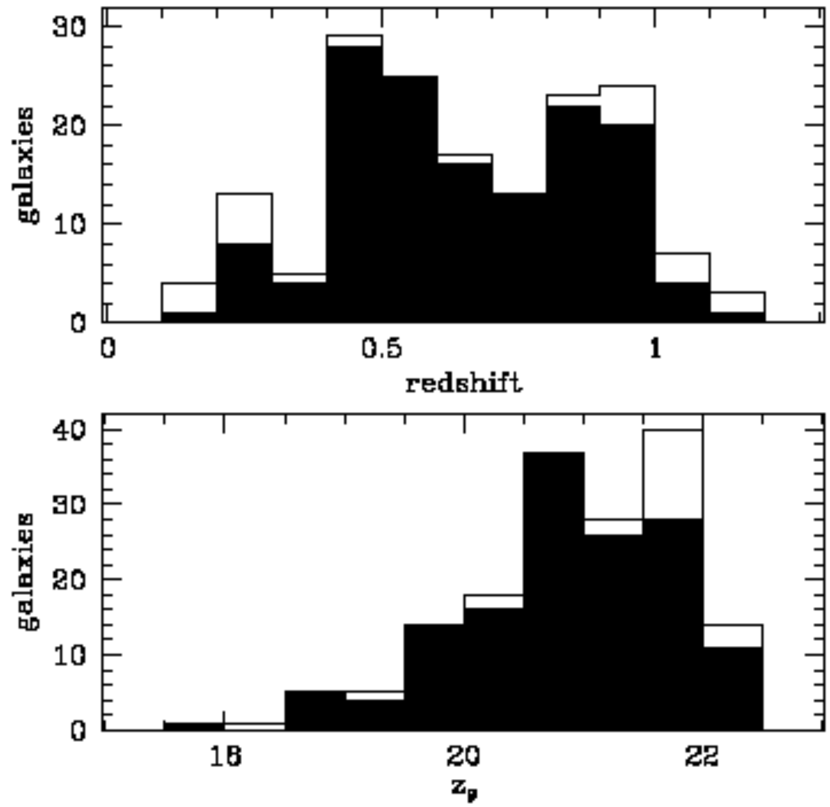
- σ demands high s/n spectra

Dressler et al. 1987; Djorgovski & Davis 1987;
Bender Burstein & Faber 1992; Jorgensen et al. 1996

Keck study of 163 field spheroidals 0.2<z<1.1

HST-GOODS: morphological selection, effective radii: z_{AB}<22.5
DEIMOS: stellar dispersions: 6-12 hrs/mask 1200 line 0.33Å px^{-1}

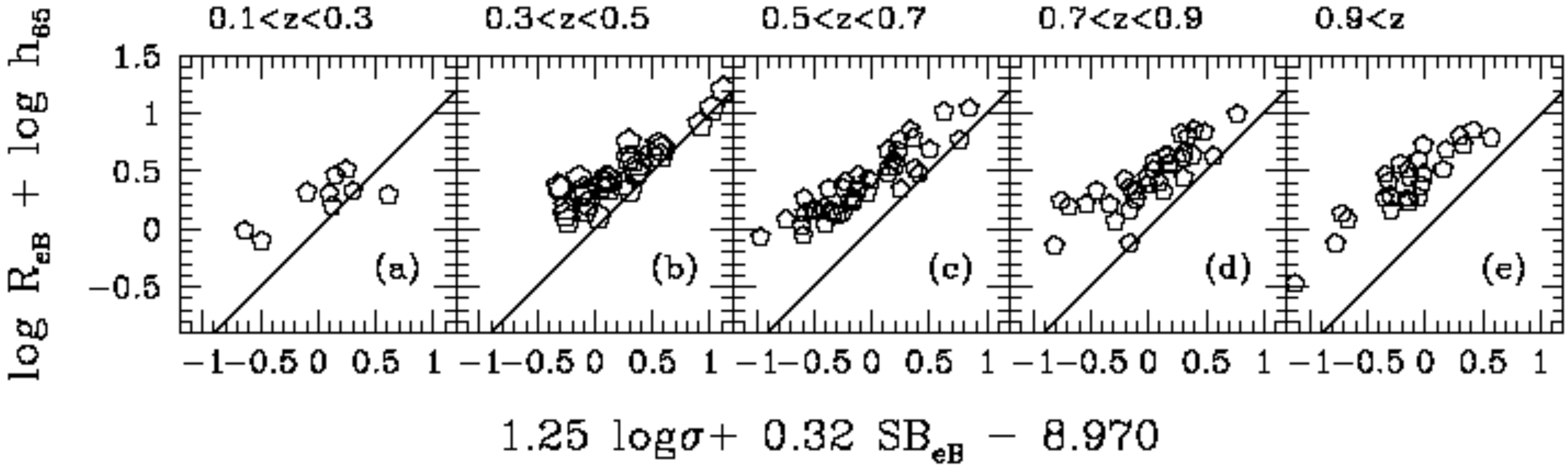




Treu, RSE et al Ap J 633, 174 (2005)

(See also van der Wel Ap J 631, 145, 2005)

Evolution of the Fundamental Plane



142 spheroidals: HST-derived scale lengths, Keck dispersions

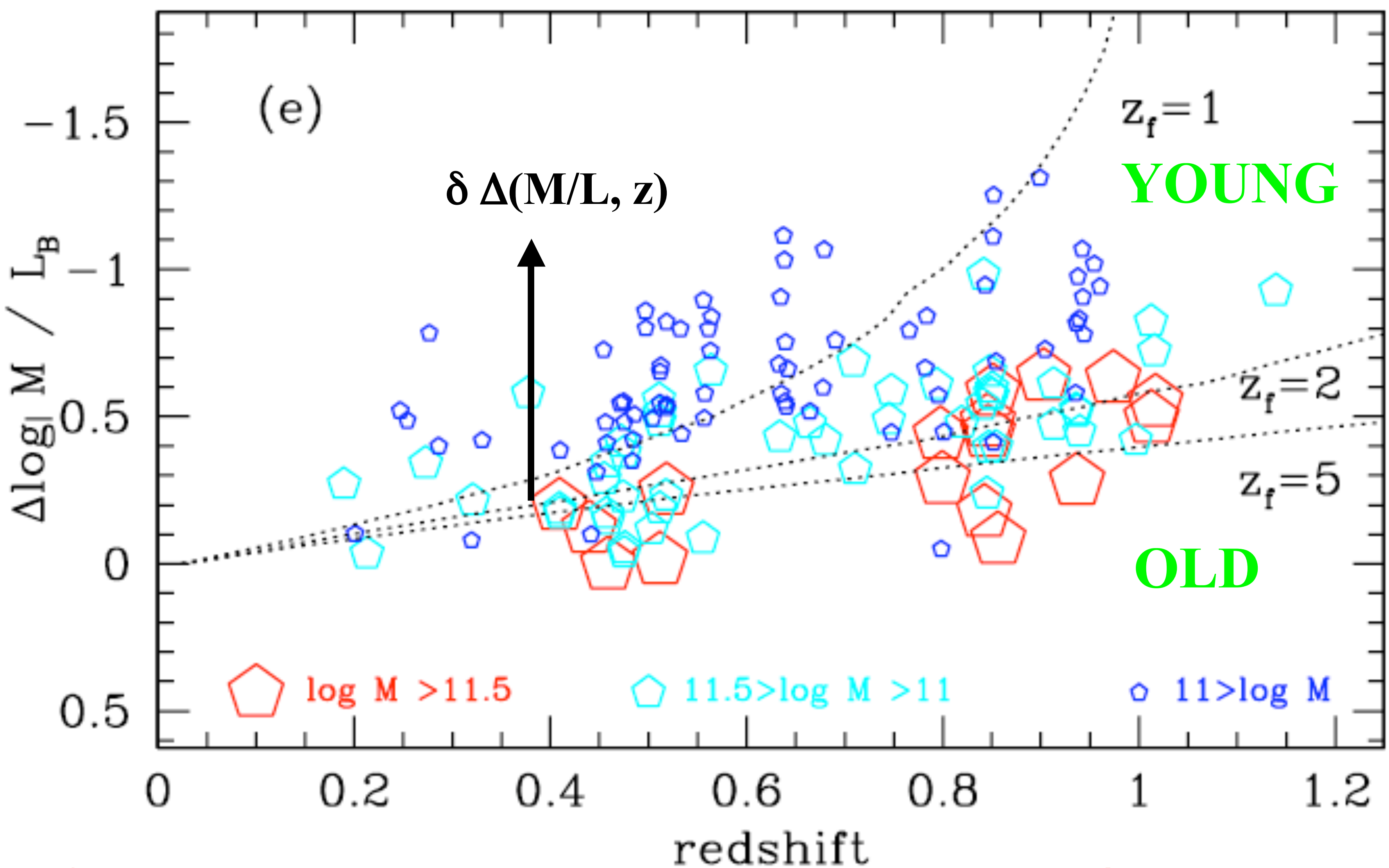
Increased scatter/deviant trends for lower mass systems:

If $$\log R_E = \alpha \log \sigma + \beta\, SB_E + \gamma$$

Effective mass $M_E \propto \sigma^2 R_E / G$

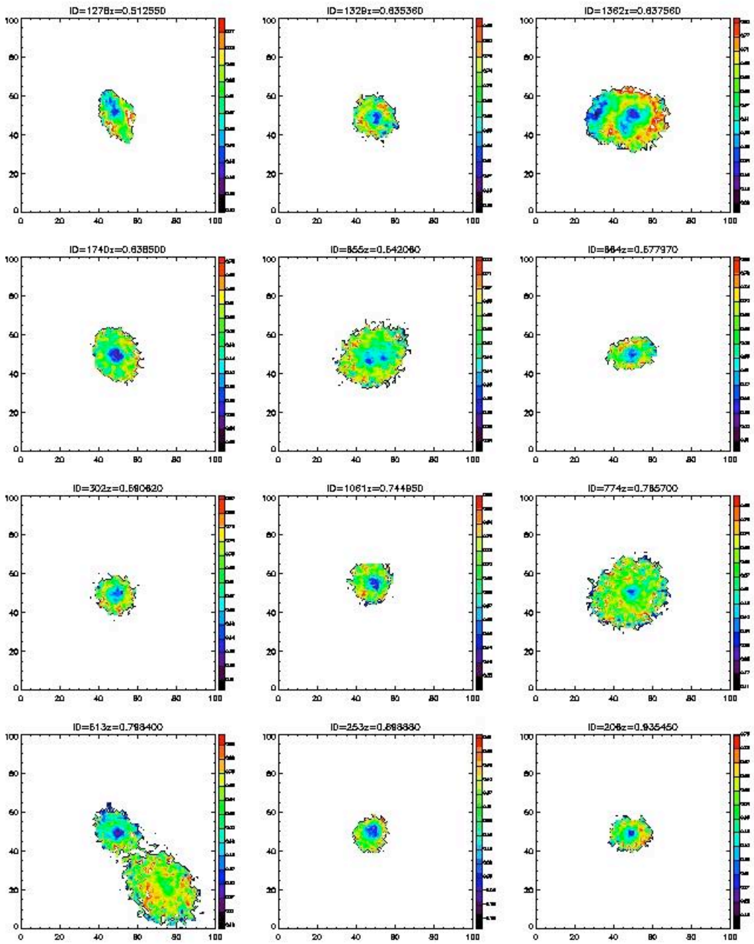
So for fixed slope, change in FP intercept $\Delta\gamma^i \propto \Delta \log (M/L)^i$

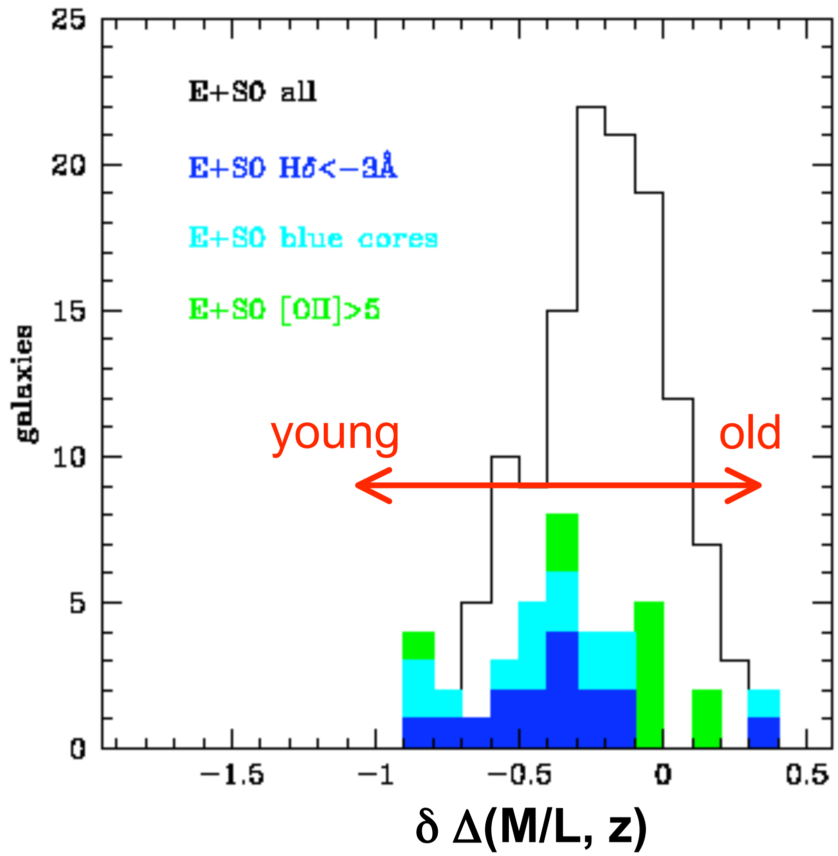
Evolution in the Intercept γ of the FP (~ΔM/L)



Strong trend: lower mass systems more scatter/recent assembly

Mass-dependent trends due to recent growth





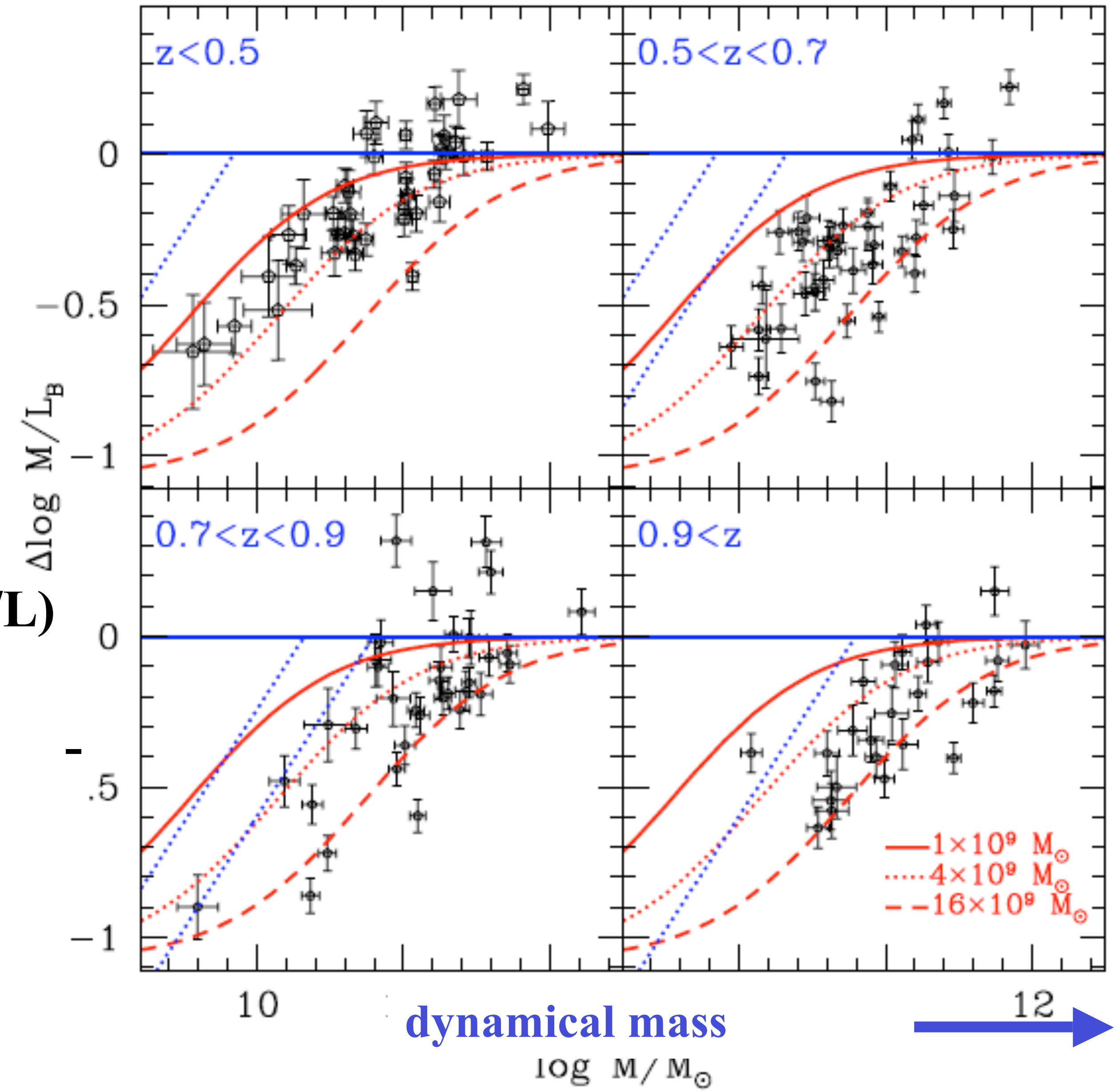
FP deviation δ correlates with diagnostics of recent growth: blue cores in ACS images and strong Balmer absorption in Keck spectra

See also Menanteau, Abraham, Ellis (2001) MN 322, 1

How Much Recent Growth in Spheroidals?

"age"

δΔ(M/L)



High mass spheroidals ($>10^{11.5}$ M$_\odot$) have < few % growth since z~1.2

Lower mass systems ($< 10^{11}$ M$_\odot$) show 20-40% growth

"DOWNSIZING"

Caveat: Dry Mergers

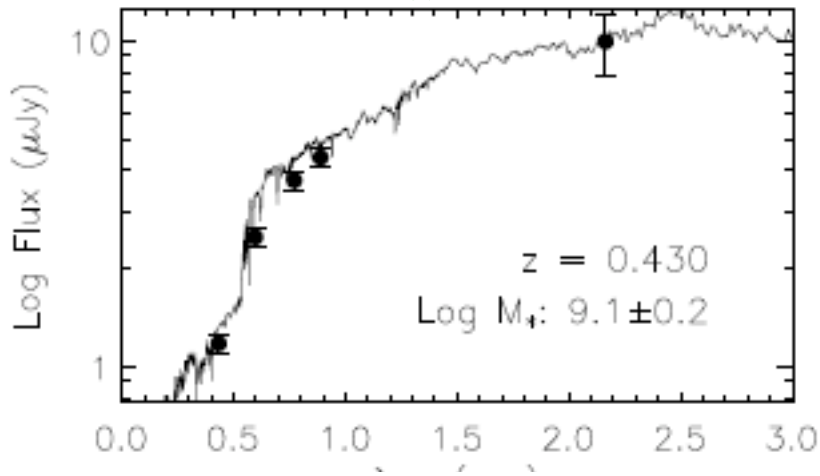
Fundamental Plane measures *ages of stars* in galaxies of different masses. Young ages are seen for *stars* in low mass galaxies and old ages for *stars* in massive galaxies.. in contrast to the idea of hierarchical assembly.

van Dokkum (2006) notes red tidal features & red mergers in local samples which, coupled with a postulated increase in merger rate $(1+z)^m$ could imply significant mass evolution is still possible in large galaxies.

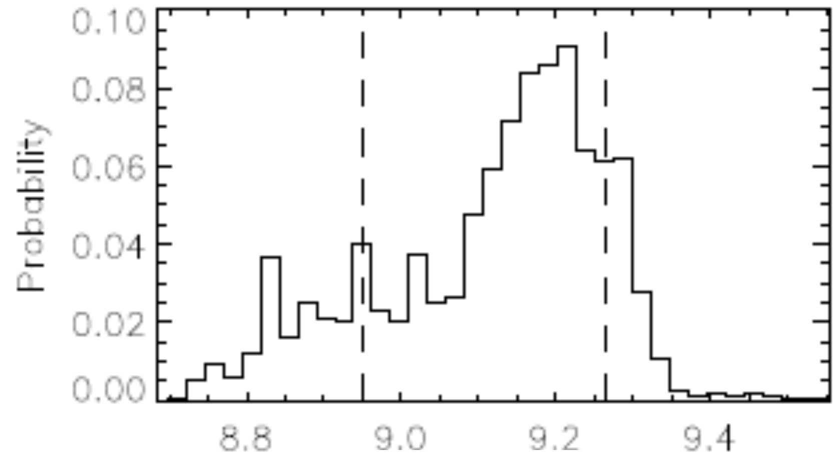
Stars could be old but *assembled mass could be younger* via self-similar merging of red sub-units (so-called `dry mergers')

Stellar Masses: Poor Substitute for Dynamical Masses

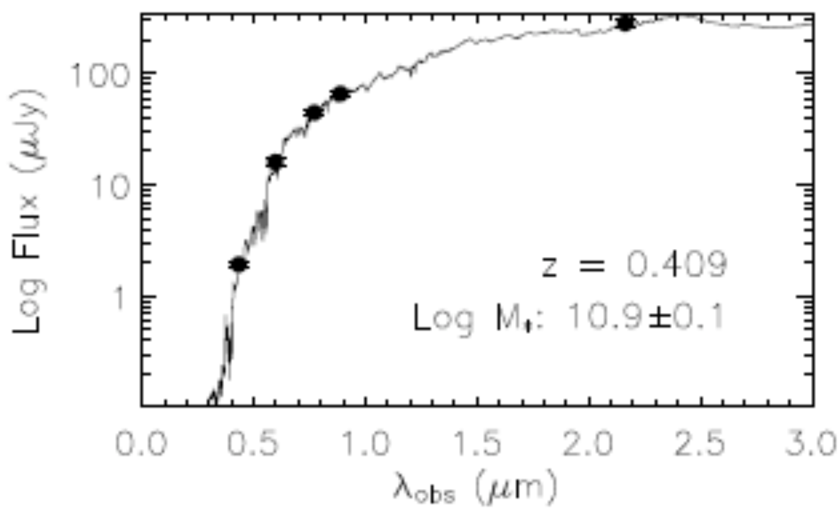
spectral energy distribution

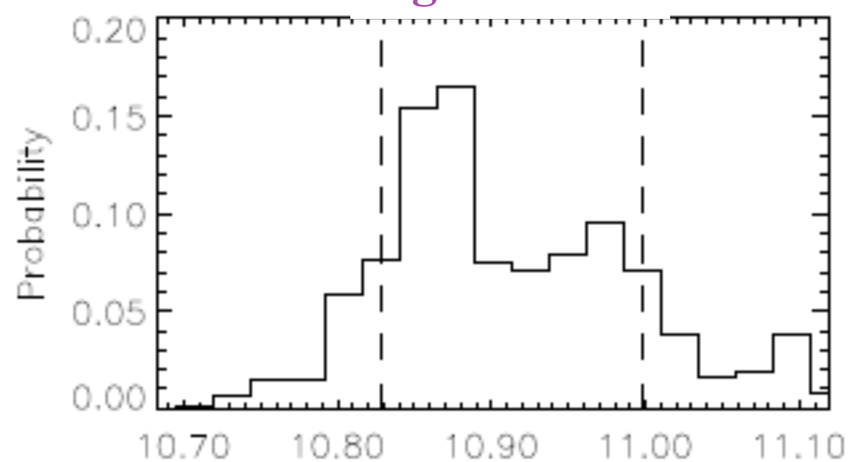


Mass likelihood function



log mass





log mass

Spectral energy distribution → stellar M^*/L_K Redshift → L_K hence stellar mass M^*

Constraints on Recent Formation of Early Types

Type-dependent stellar mass functions over $0 < z < 1$ can, in principle, determine:

- how much has the spheroidal/early type population grown in number?
- is this growth in abundance mass-dependent?
- is it at the expense of a declining population of blue star-forming galaxies?
- if so, what is the physical mechanism: mergers, truncation/gas depletion...?

Recent surveys:

Bundy et al (2006): DEEP2/P200:	N~8000, R_{AB}<25.1, K_{AB}<22.5	1.5 deg^2
Borch et al (2006): COMBO-17	N~25,000, R_{AB}<25.5, no IR	0.8 deg^2
Ilbert et al (2010): COSMOS	N~196,000, F(3.6μm)< 1μJy	2.0 deg^2

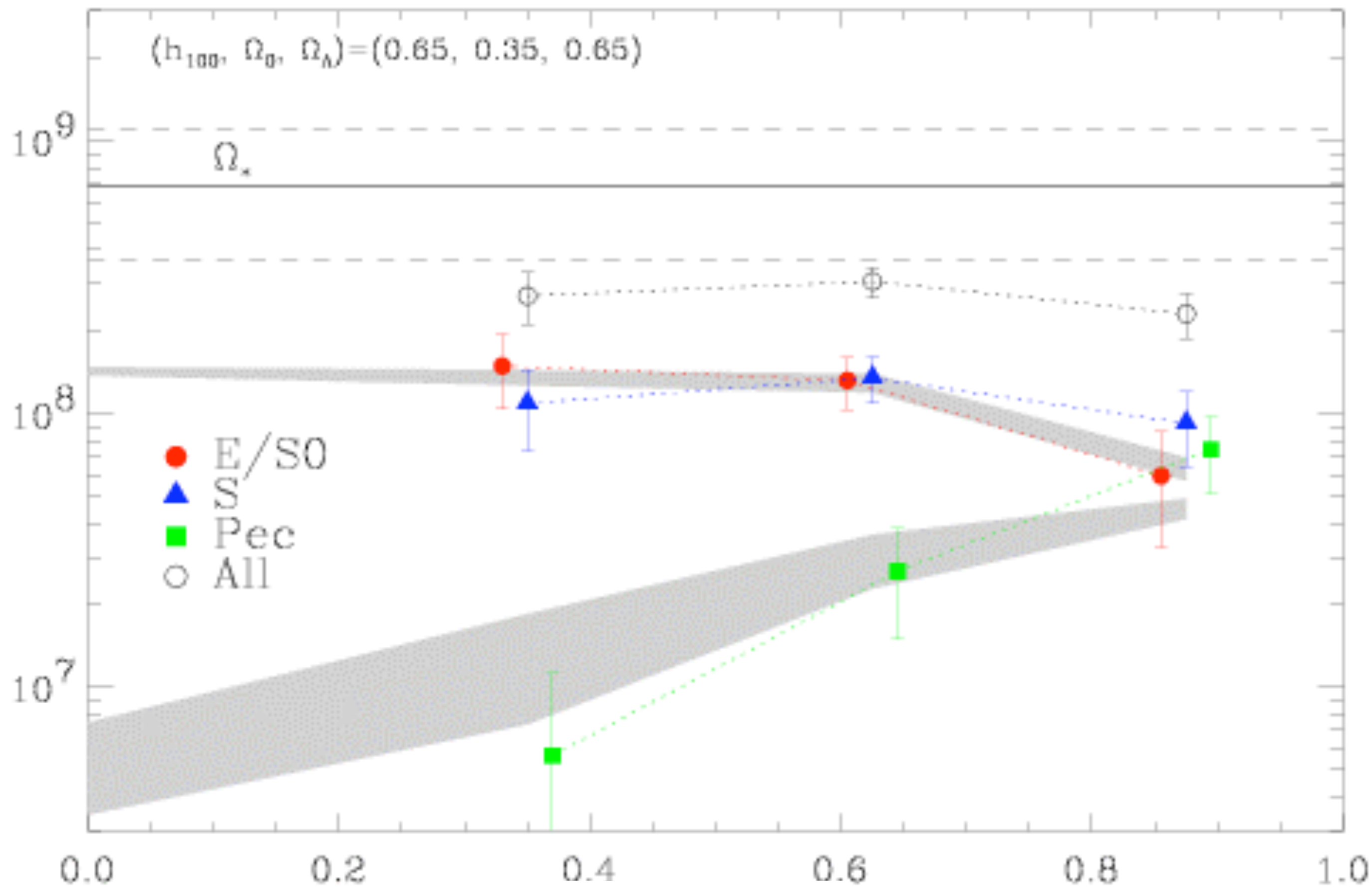
These surveys give somewhat conflicting results

Cosmic variance remains a concern even with such large samples

Integrated Stellar Mass by Morphology

CFHT/LDSS redshift surveys & HST WFPC2 imaging

Comoving mass density $M_{\odot}$ Mpc^{-3}

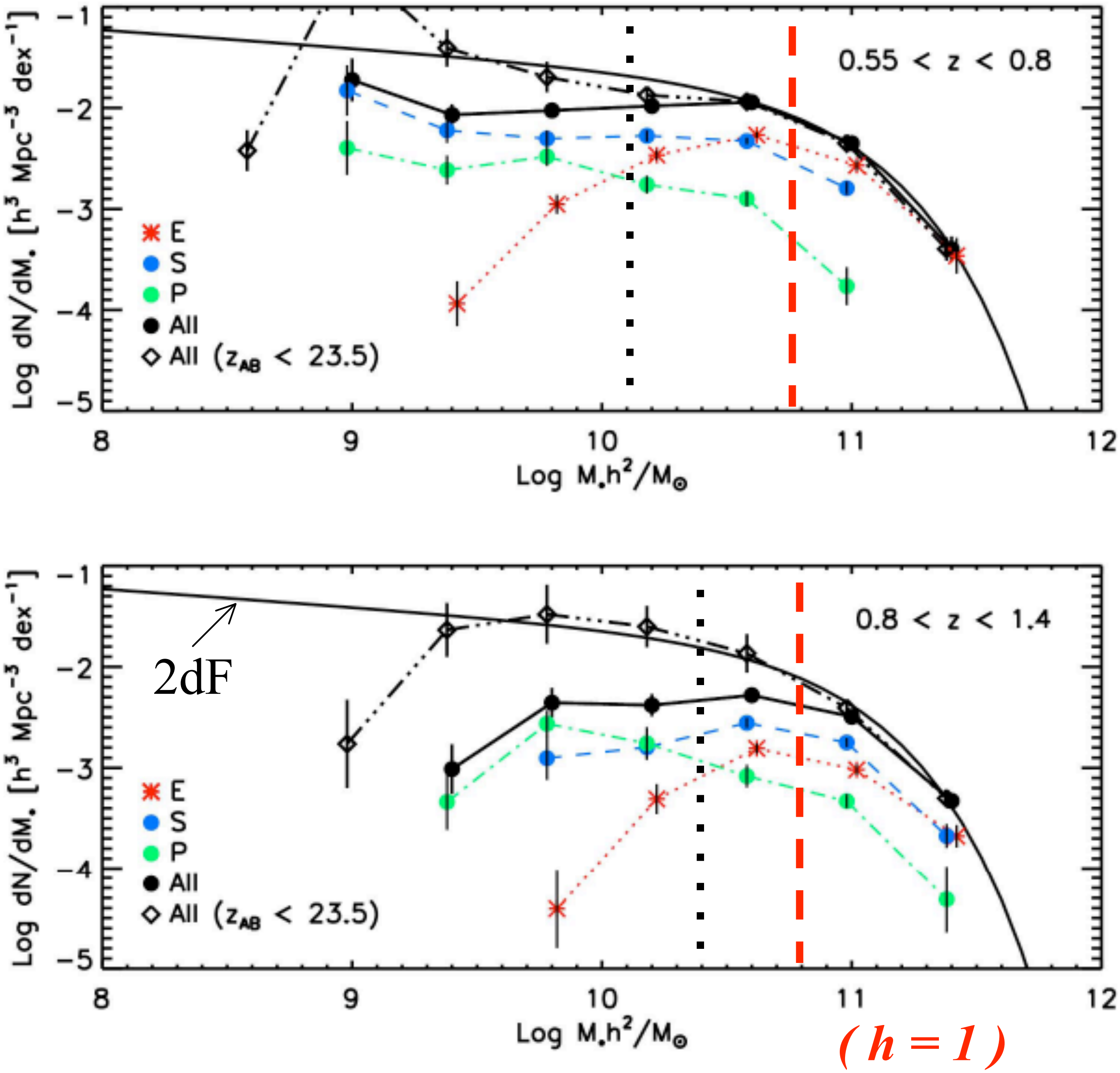


Redshift

Early result: the decline in stellar mass in late-types occurs at the expense of a modest growth in that of regular spirals & ellipticals, i.e. tranformation (Brinchmann & Ellis 2000 Ap J 536, L77)

Stellar Mass Assembly by Type in GOODS

- No significant evolution in massive galaxies since z~1
- Modest growth in massive spheroidals, most change at lower mass
- Bulk of associated evolution is in massive Irrs

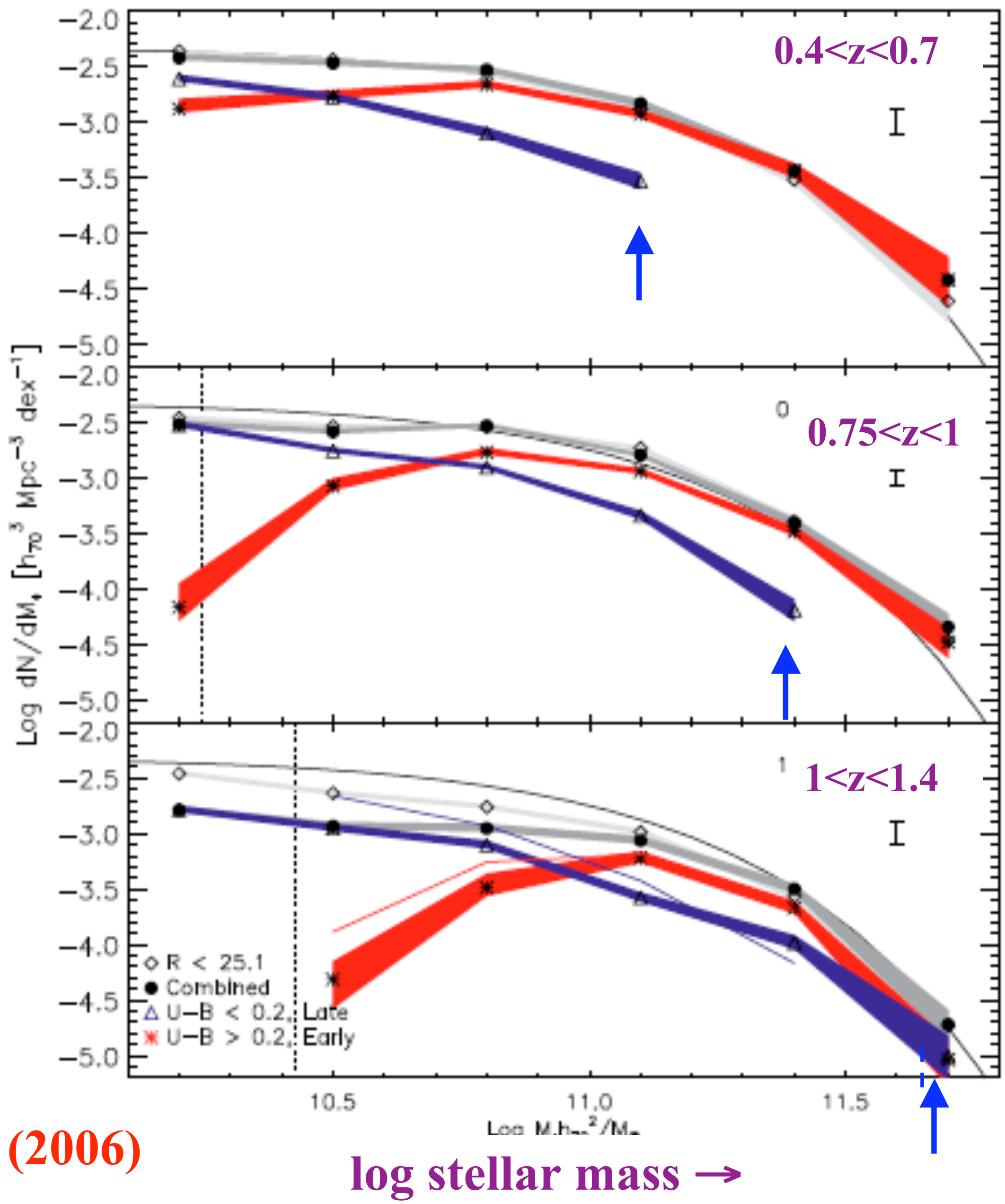


Bundy, RSE et al (2005)

Ap J 634,977

Color-Selected Mass Functions in DEEP2 survey

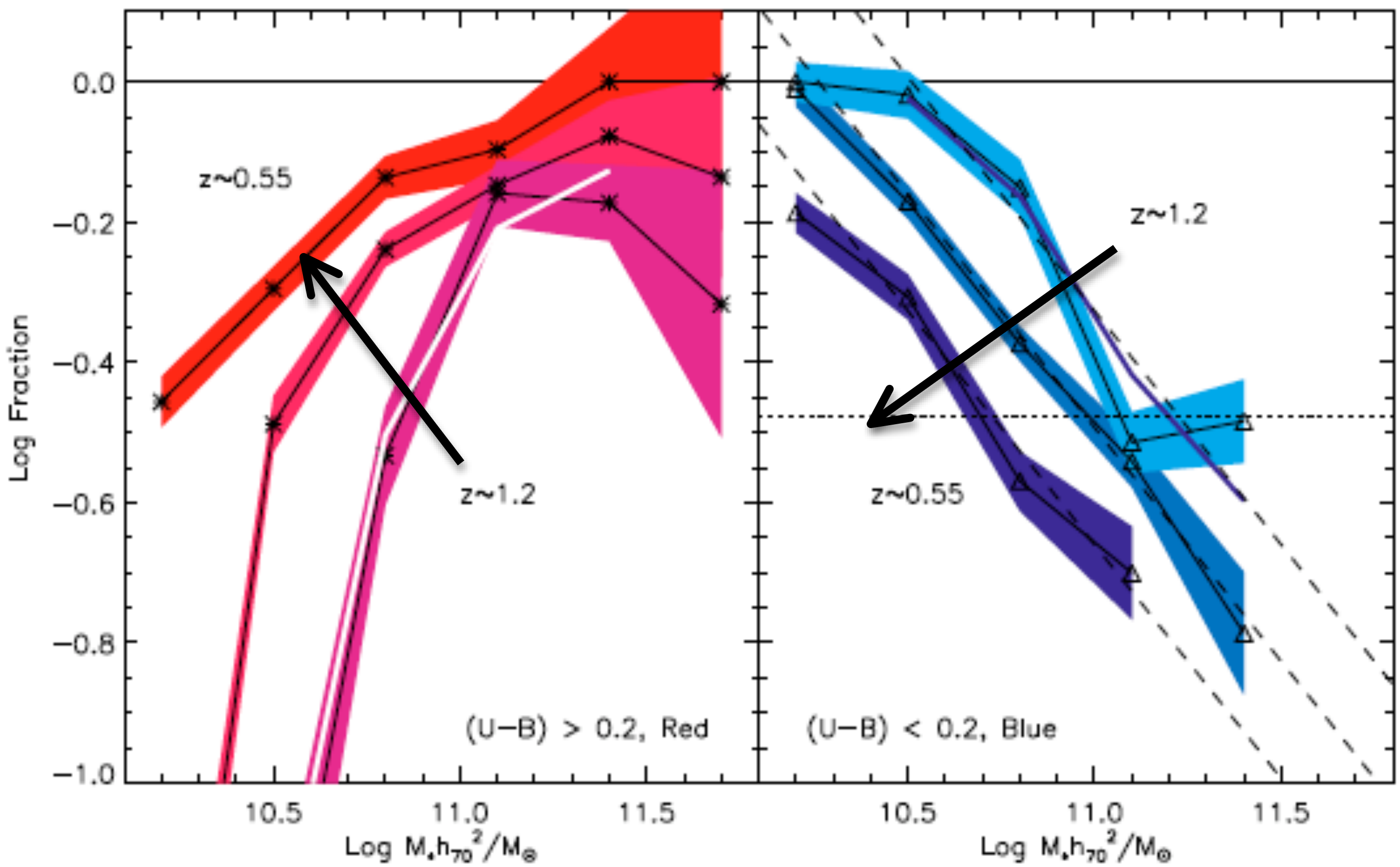
- Color selection via rest-frame U-B for 8000 galaxies
- Cut at U-B=0.2 analyzed in terms of DEEP2 spectra (SFR~0.1-0.2 M¤ yr^{-1})
- Very little growth in passive objects for M > 10^{11} M¤
- Star formation shifts from including high-mass galaxies at early epochs (z~1-2) to only lower-mass galaxies at later epochs.
- Stellar mass functions reveal a <u>threshold stellar mass</u> above which SF is somehow quenched



Bundy, RSE et al Ap J 651, 120 (2006)

Declining Blues Match the Rising Reds

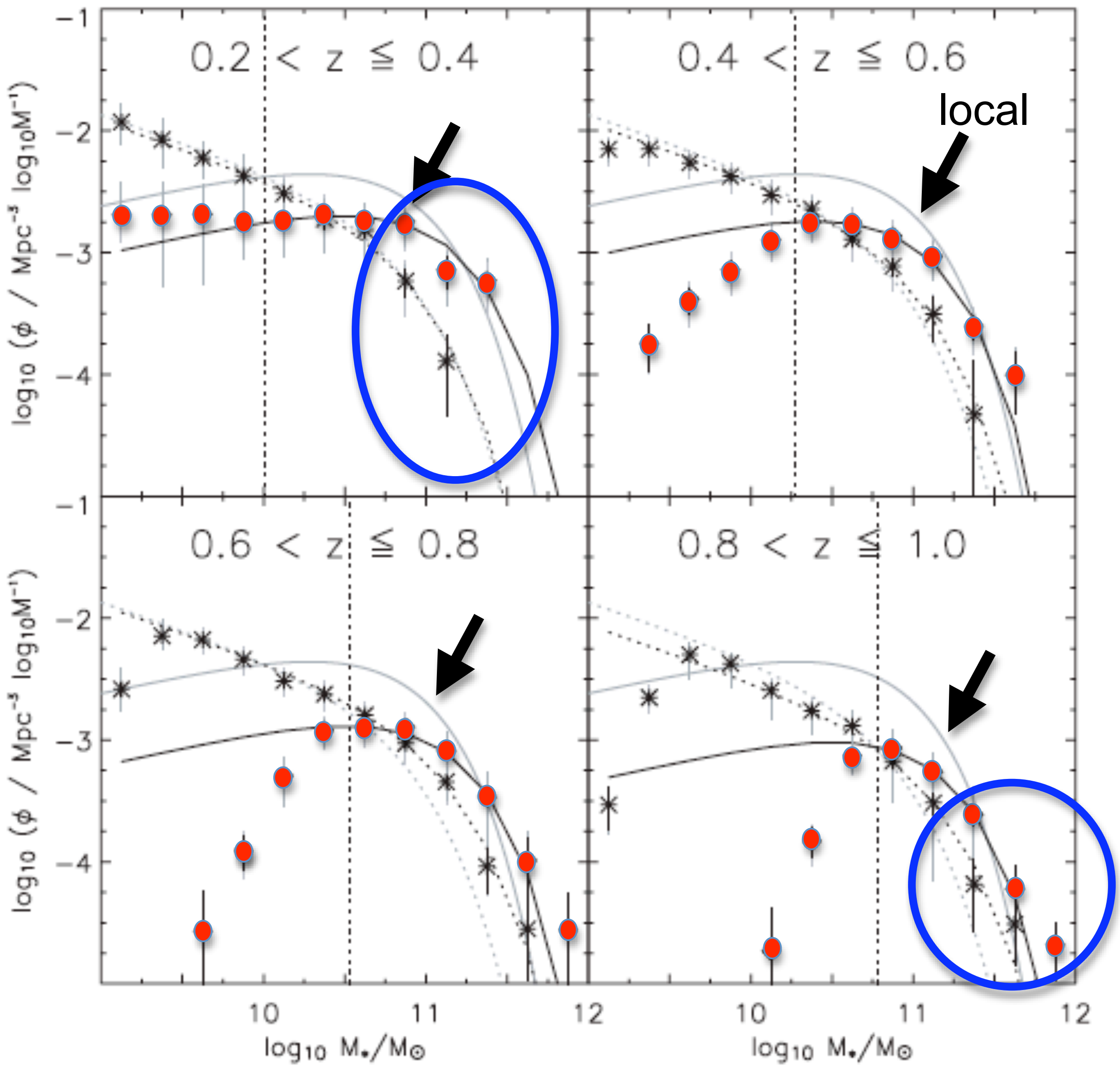
Log Fractional Contribution to Total Stellar Mass 0.4<z<1.4



~40% increase in $M>10^{11}M_{\odot}$ early types over 5 Gyr

Mass Functions from COMBO-17 Survey

- More galaxies than DEEP2 extending to lower z (but fewer fields)
- More filters but no infrared data or spectra
- Color split in terms of rest-frame U-V
- **Similar result on mass growth in red ● galaxies**
- **Less clearly, a decline in number of massive blue (*) galaxies**
- But this is not what Borch et al conclude by focusing on global Schechter function fits



Borch et al 2006 A&A 453, 869

Constant Mass Density of Blue Galaxies?

A constant mass density over 0<z<1 in blue galaxies is a surprising claim given well-documented evolution in blue galaxy counts, LFs, and SF density (×10 higher at z~1; Madau et al 1995)

Implies little or no connection between declining blue light and growth of red galaxies

In practice claim is based on integrating Schechter functions to unobserved limits

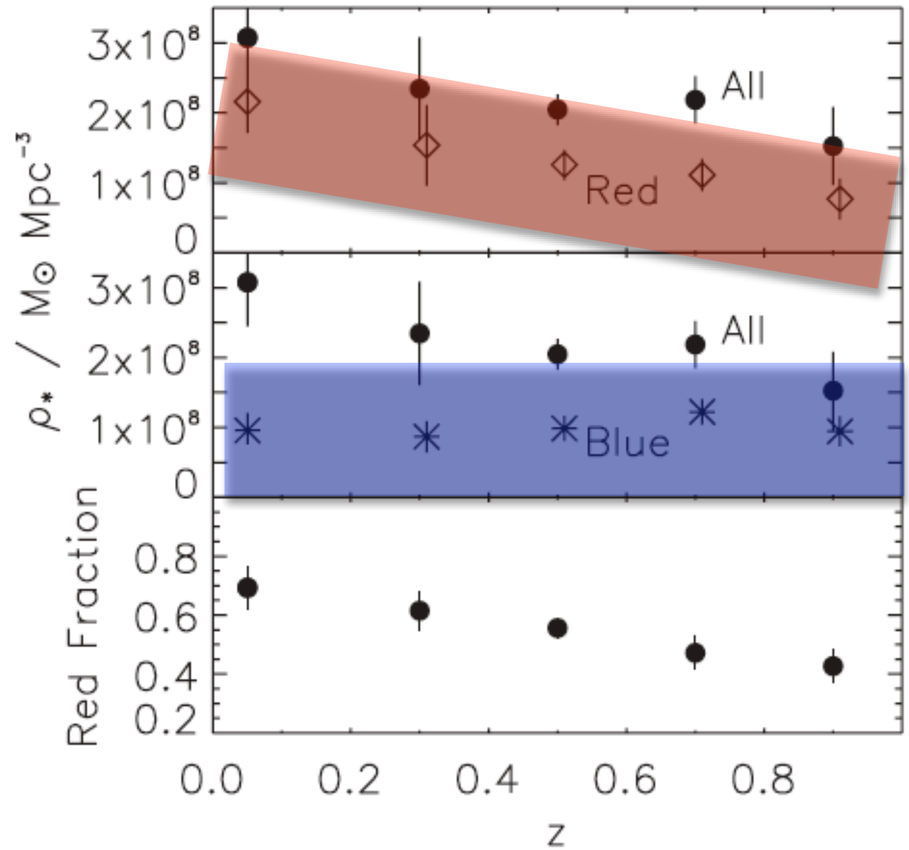
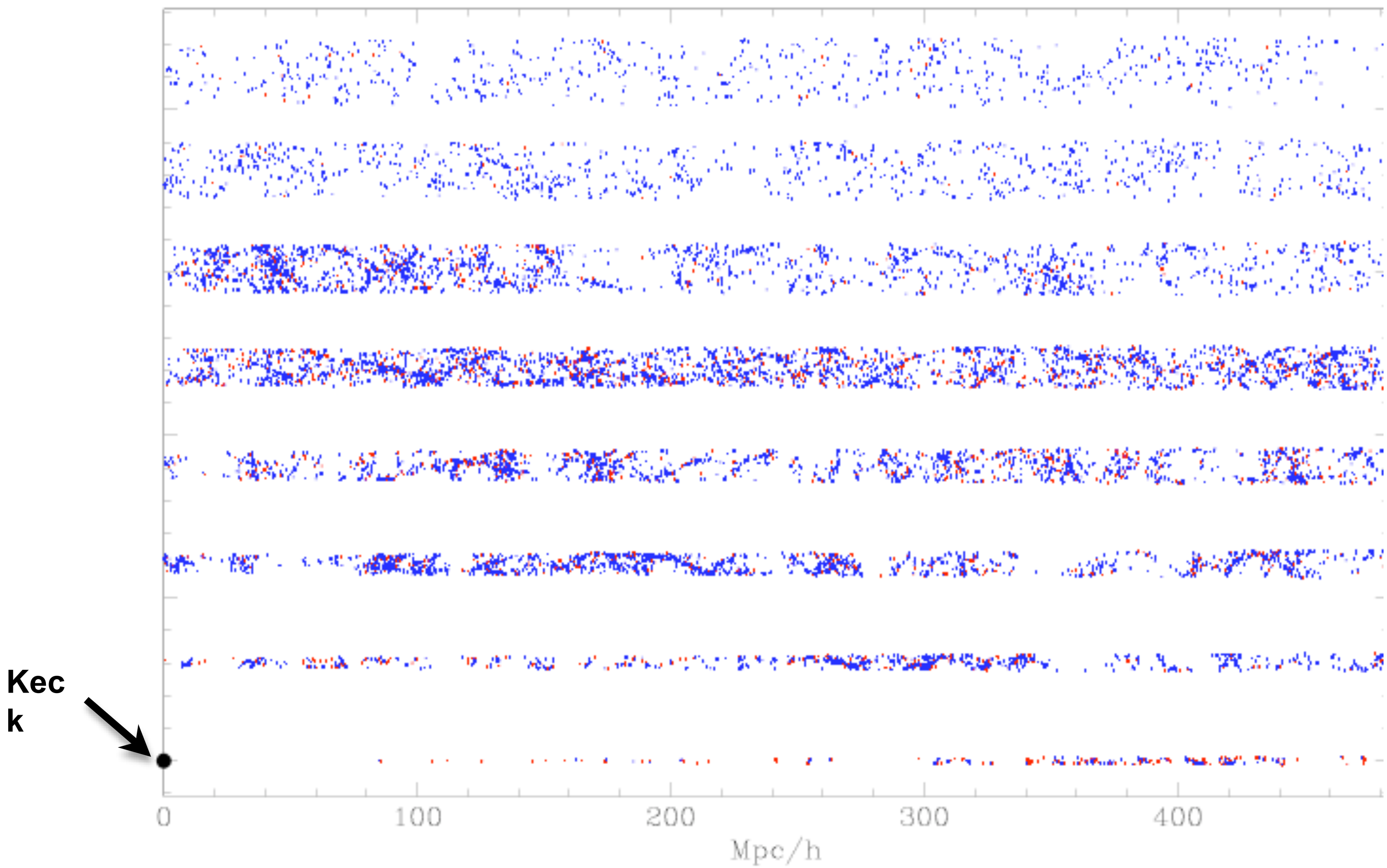


Fig. 10. The integrated stellar mass density as a function of redshift. In the *upper two panels* the total mass density for all galaxies (filled circles) is compared with those for red-sequence galaxies (diamonds), and for blue cloud galaxies (asterisks) seperately. The *lower panel* shows the fraction of mass in red sequence galaxies as a function of redshift. In all cases, mass functions are integrated down to zero mass and error bars come from field-to-field variation divided by $\sqrt{2}$. The $z = 0$ datapoint is taken from Bell et al. (2003).

Cosmic Variance: I



One of 20 lightcones from the Millenium Simulation mimicing DEEP2 survey
Galaxies generated using GALFORM code and Bower radio-mode feedback

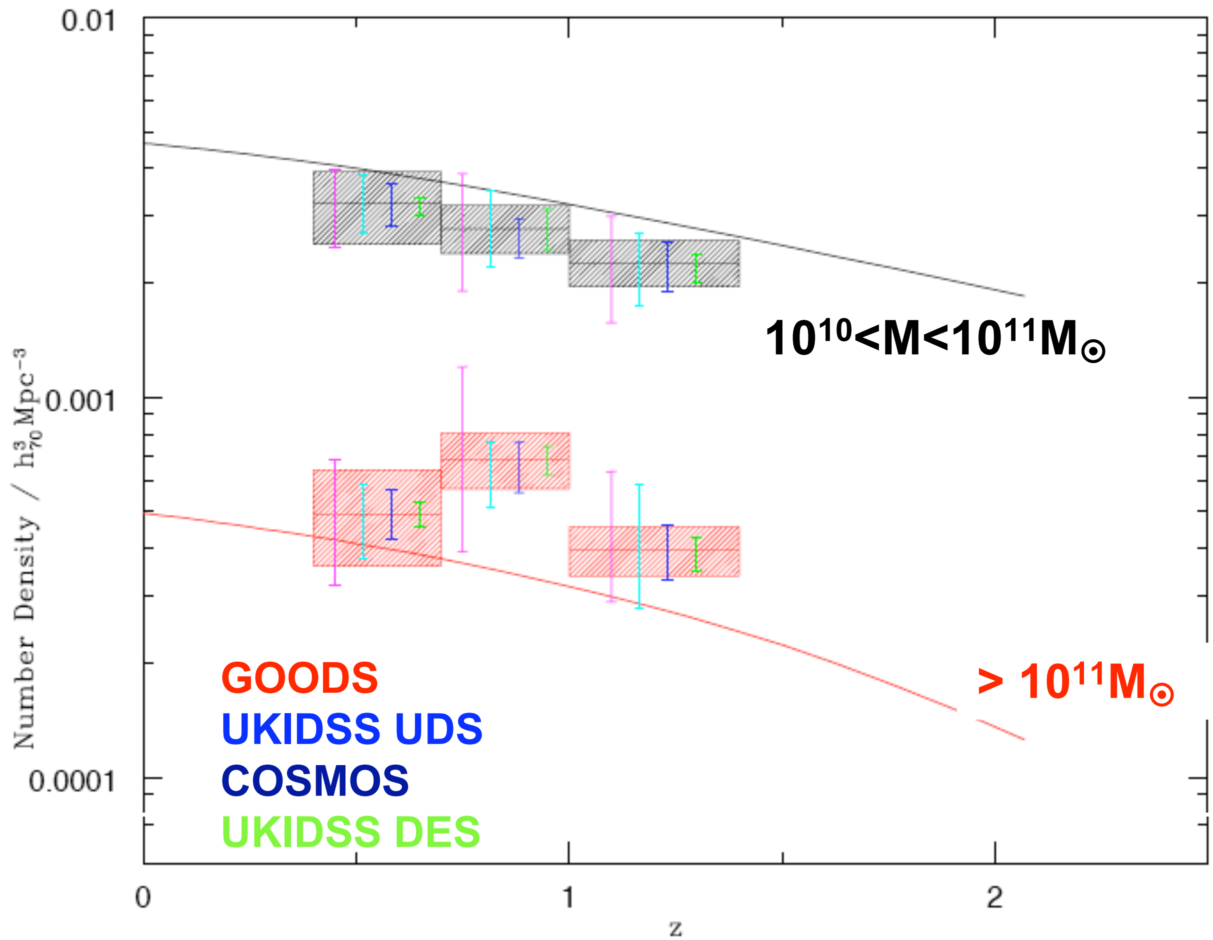
Stringer, RSE et al (2010) MN 393, 1127

Cosmic Variance: II

Consider the growth of the stellar mass function deduced from the entire Millenium Simulation

How accurately is *differential growth* of the mass function realized from current and future surveys?

For current HST-based surveys, effect of cosmic variance remains a limitation - comparable to uncertainties introduced by poorly-estimated stellar masses



Definitive studies will require surveys of 100's deg^2
e.g. HyperSuprimeCam, VISTA-VIKING, LSST

Stringer, RSE et al (2010) MN 393, 1127

Can Mergers Account for Recent Growth of Early Types?

See modest growth in massive early types over 0<z<1 but significant growth in lower mass examples: can this be explained by major mergers?

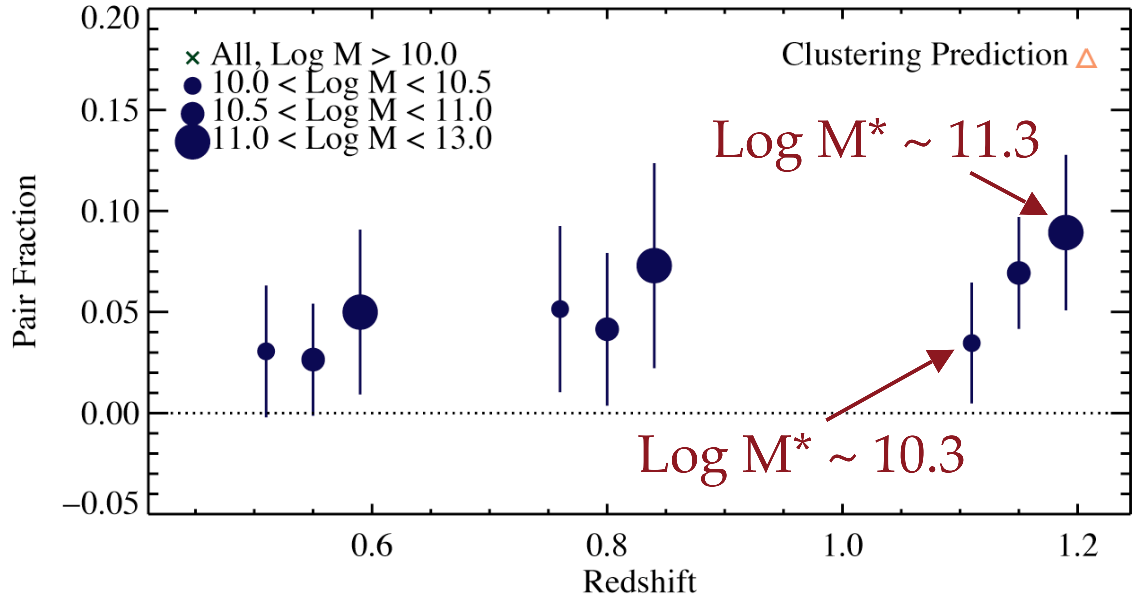
• Observational constraints from deep imaging in redshift survey fields, typically counting close pair fraction (5 < r < 20 kpc) to fixed luminosity limit

- optical imaging (e.g. LeFevre et al 2000) – poor tracer of mass
- K-band imaging (Bundy et al 2004, 2009) – more robust tracer

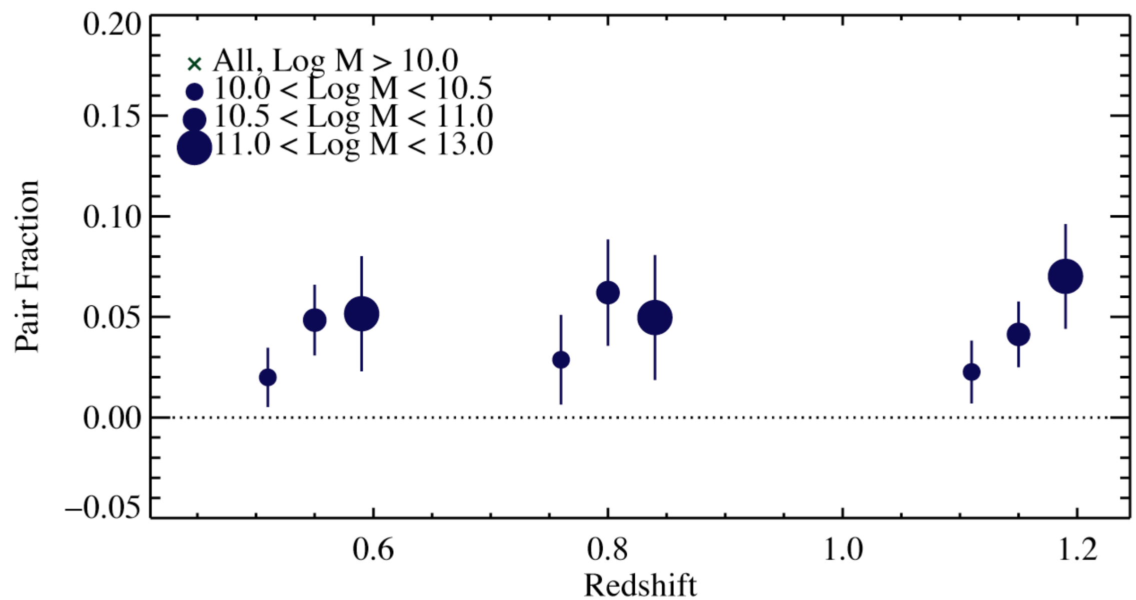
• Identifying kinematically-associated pairs in redshift surveys (e.g. Patton et al 2002, Lin et al 2008, 2010)

Conclusion: pair fraction is low (~4%) and largely independent of redshift;
somewhat larger for higher mass galaxies
dry mergers are more common in dense environments

Pair Fraction from Subaru/VLT K_{AB}~24 Imaging in GOODS



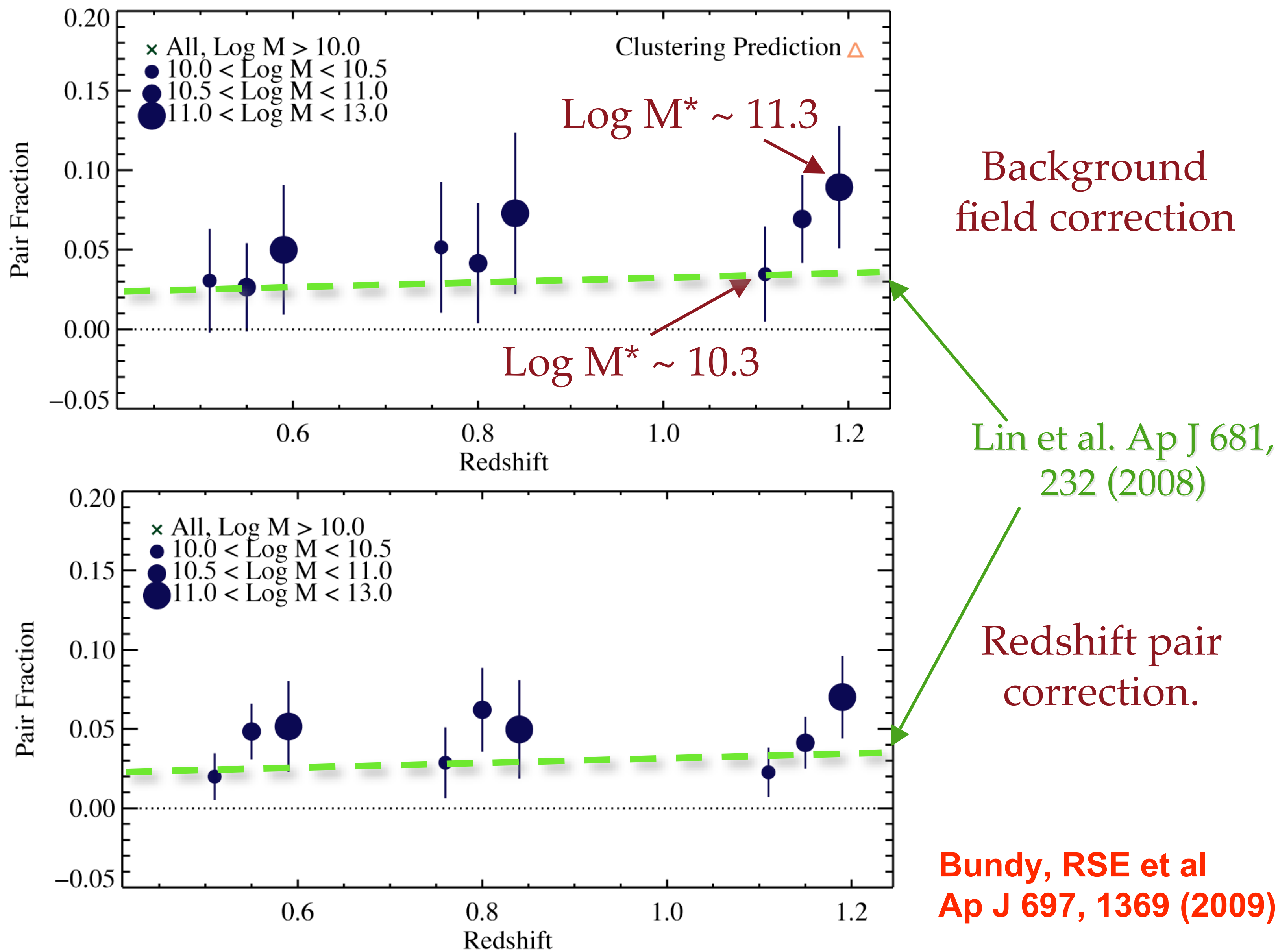
Background field correction



Redshift pair correction.

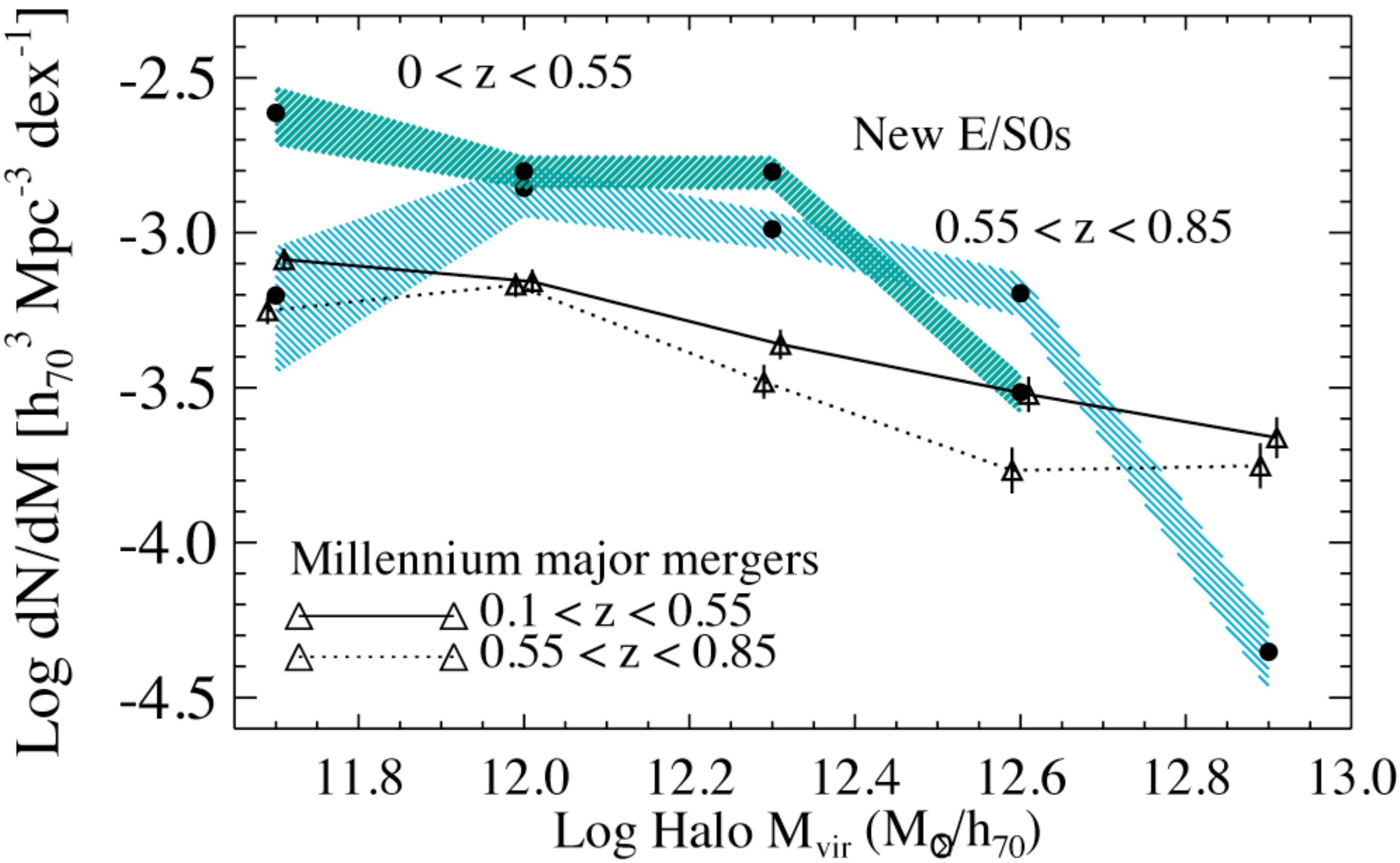
Bundy, RSE et al
Ap J 697, 1369 (2009)

Pair Fraction from Subaru/VLT K_{AB}~24 Imaging in GOODS



Bundy, RSE et al
Ap J 697, 1369 (2009)

Major Mergers Predicted in Millenium Simulation



Growth rate of halos seen in MS also fails to match production rate of halos hosting new spheroidals in DEEP2/GOODS surveys

Bundy, RSE et al. Ap J 665, L5 (2007)

Assembly History of Early Type Galaxies 0<z<1.2 Summary

• Detailed studies of stellar populations (colors, FP) indicate the bulk of massive early types (>10^{11} $M_\odot$) contain old stars which formed at z_F > 2 and suffered very little recent growth

• In contrast, lower mass early types (< 3. 10^{10} $M_\odot$) have seen more recent and diverse activity with significant contributions from young stars since z~1.2

• Statistical surveys based on stellar mass functions confirm this mass-dependent growth but accurate differential trends are hampered by significant cosmic variance

• Modest growth in number of massive early types (40%) over 0.5 < z < 1.2 could arise from major mergers if largely `dry'.

• Significant growth in lower mass early types cannot be attributed to major mergers and probably arises in part via gas-depletion in blue disk population

• Further evidence for transformation of blue disks to red early types arises from preponderance of `passive disk galaxies' in low mass red sequence

Was It Surprising to Find Early Type Galaxies at z~2?

letters to nature

A high abundance of massive galaxies 3–6 billion years after the Big Bang

Karl Glazebrook[1], Roberto G. Abraham[2], Patrick J. McCarthy[3], Sandra Savaglio[1], Hsiao-Wen Chen[4], David Crampton[5], Rick Murowinski[5], Inger Jørgensen[6], Kathy Roth[6], Isobel Hook[7], Ronald O. Marzke[8] & R. G. Carlberg[2]

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Old galaxies in the young Universe

A. Cimatti[1], E. Daddi[2], A. Renzini[2], P. Cassata[3], E. Vanzella[3], L. Pozzetti[4], S. Cristiani[5], A. Fontana[6], G. Rodighiero[3], M. Mignoli[4] & G. Zamorani[4]

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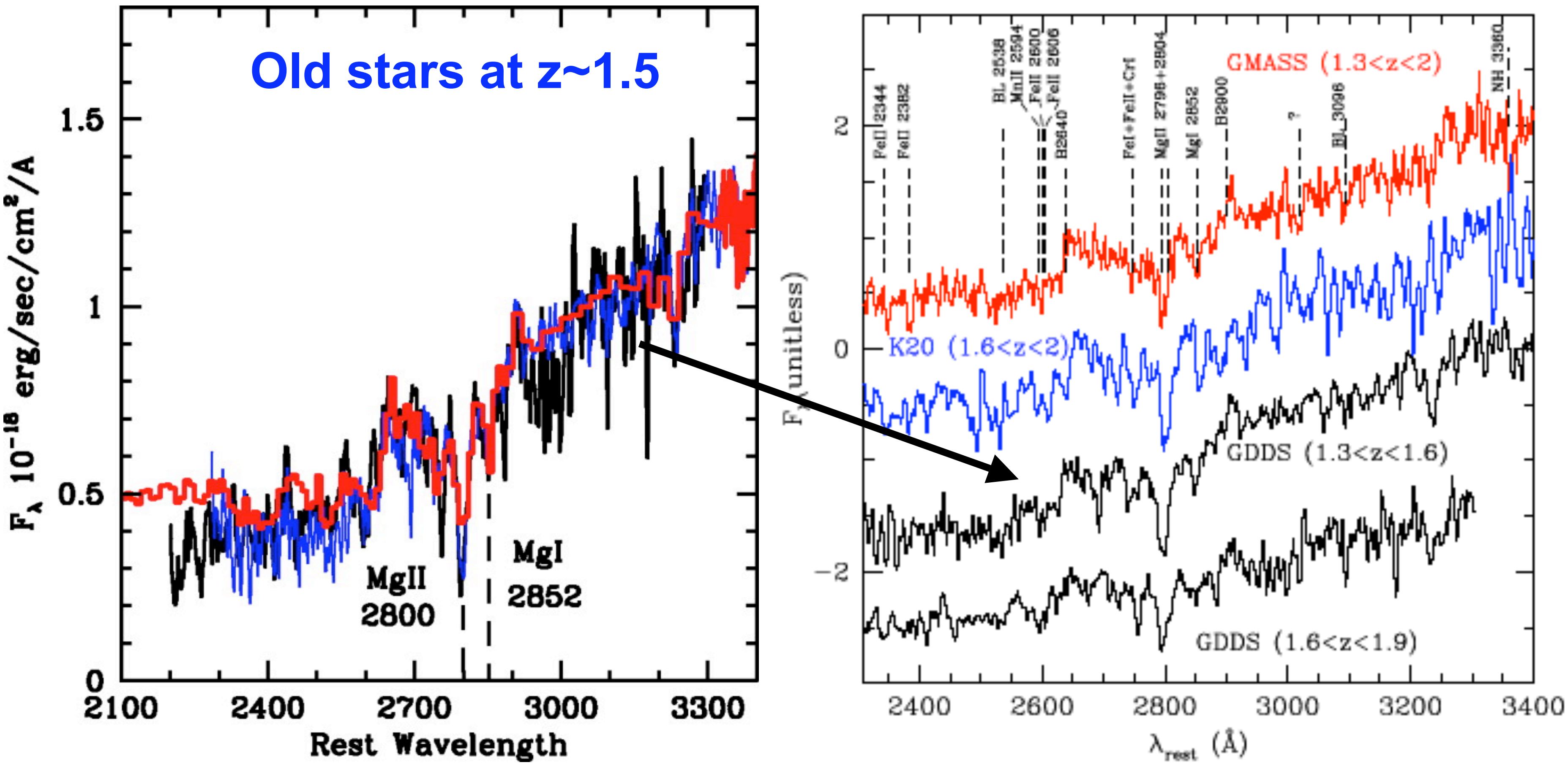
Glazebrook et al 2004 Nature 430, 181

Cimatti et al 2004 Nature 430, 184

Distant Red Galaxies: Spectroscopic Evidence



- 20 red galaxies z~1.5, age 1.2 - 2.3 Gyr, z_F=2.4 - 3.3
- Implies progenitor SFRs ~ 300-500 $M_\odot$ yr^{-1} (<u>submm gals</u>)

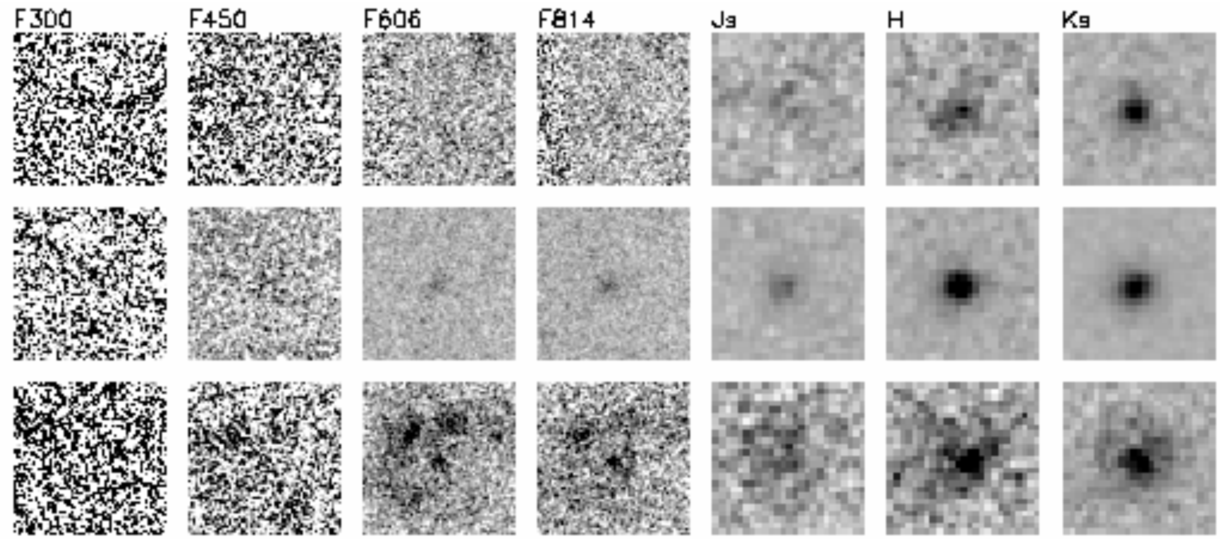
McCarthy et al (2004); Cimatti et al (2008)

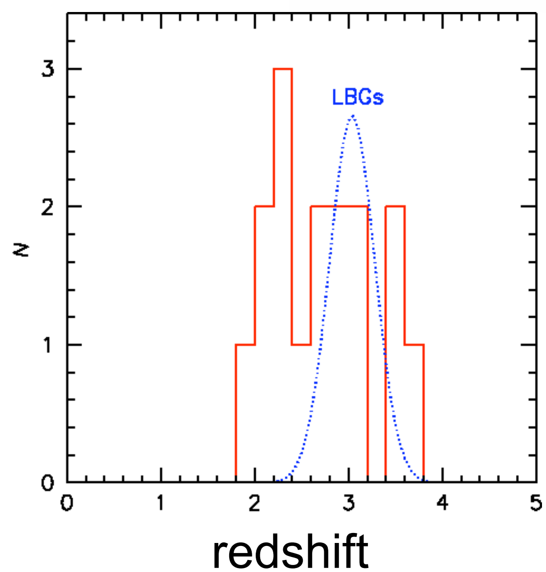
Quiescent `Distant Red Galaxies'

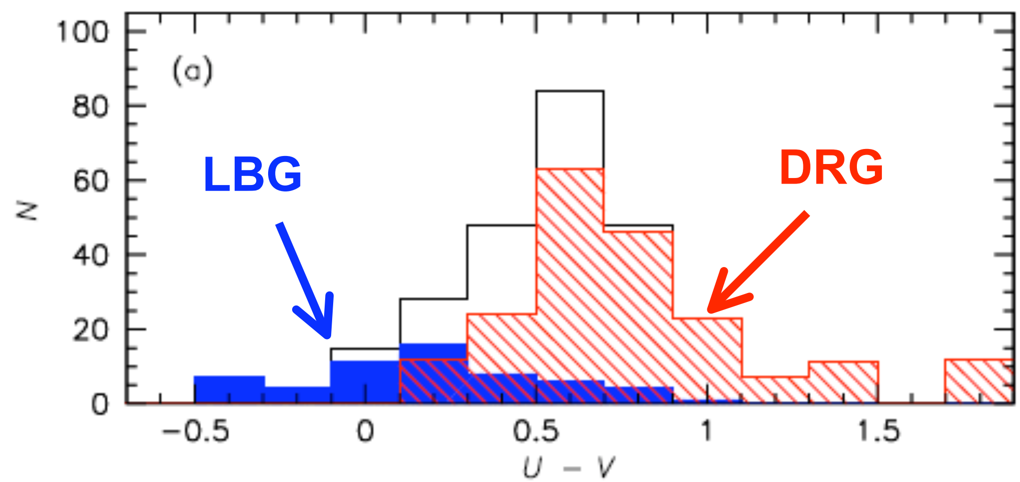
Franx et al 2003 (FIRES VLT survey)

J-K > 2.3

$2 < z_{photo} < 3$







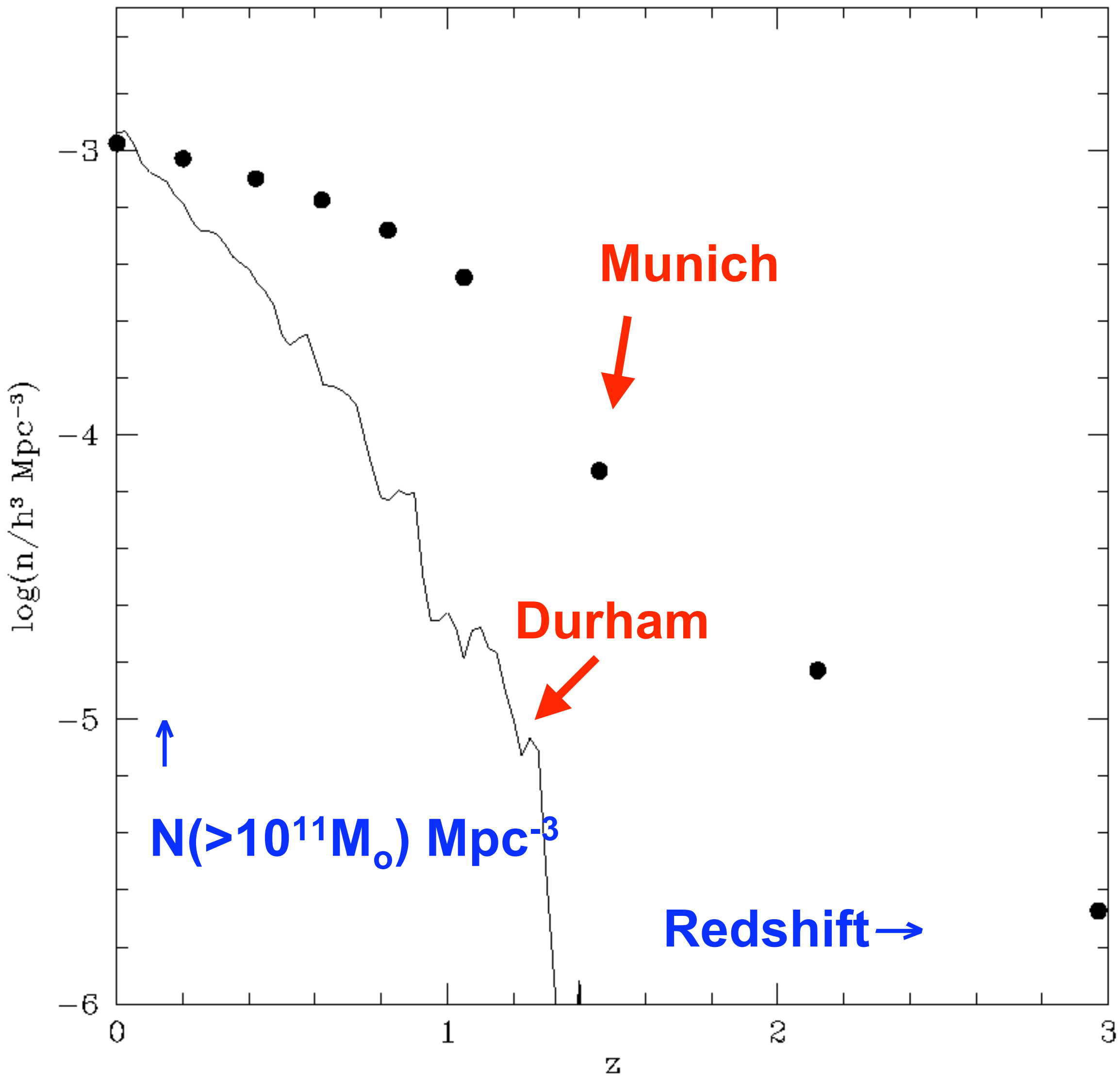
van Dokkum et al Ap J 638, L59 (2006)

Census of N~300 with $M > 10^{11} M_{\odot}$ in 400 $arcmin^2$
Most massive galaxies are DRGs(77%); LBGs constitute only 17%

Semi-Analytic Predictions (epoch 2002)

Hierarchical models confidently predicted decline in abundance of massive galaxies with redshift!

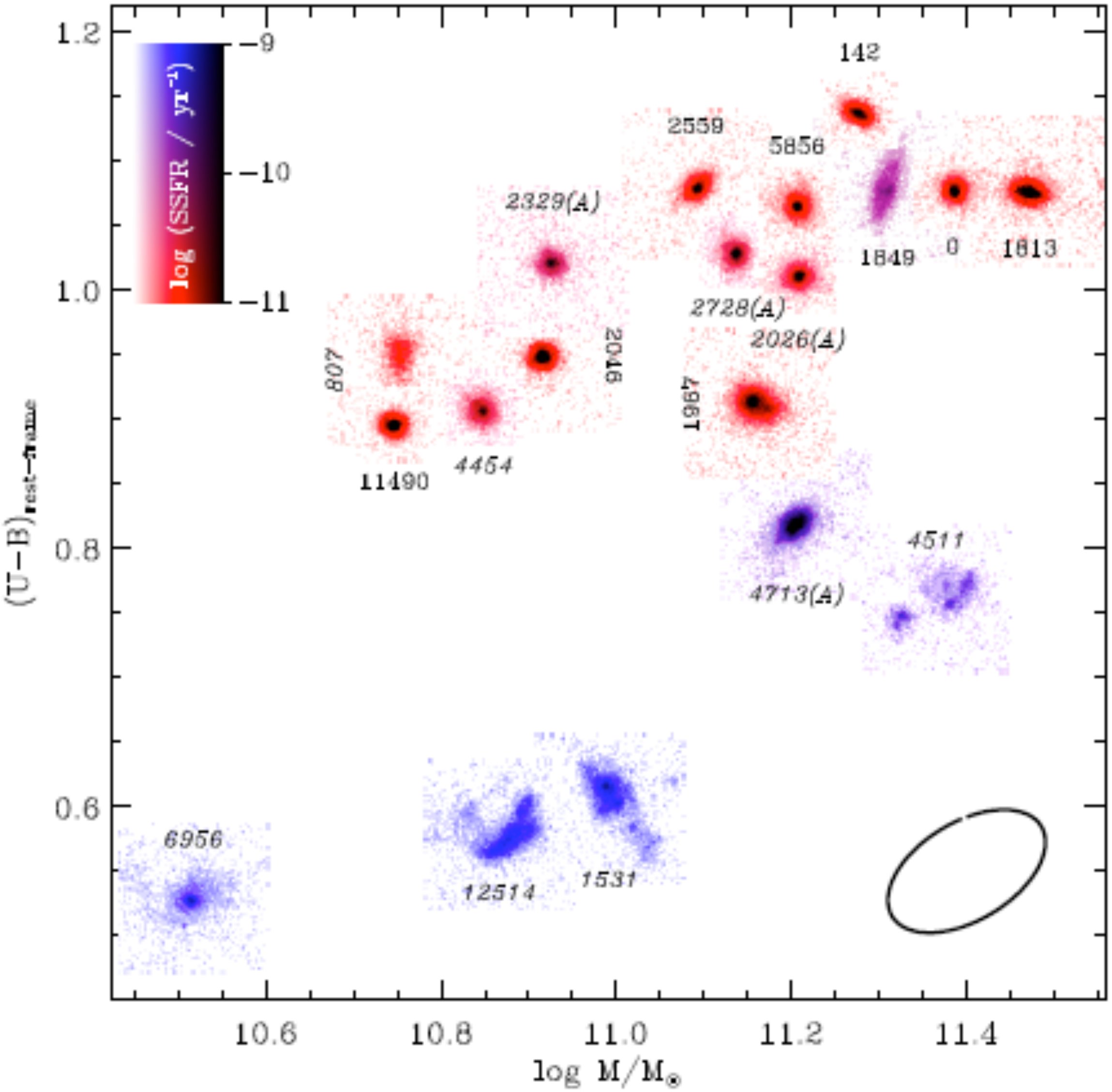
[In detail, predictions are very sensitive to assumed assembly particularly for high masses where mass function is steep]



As discussed by Benson, Ellis & Menanteau MNRAS, 336, 564 (2002)

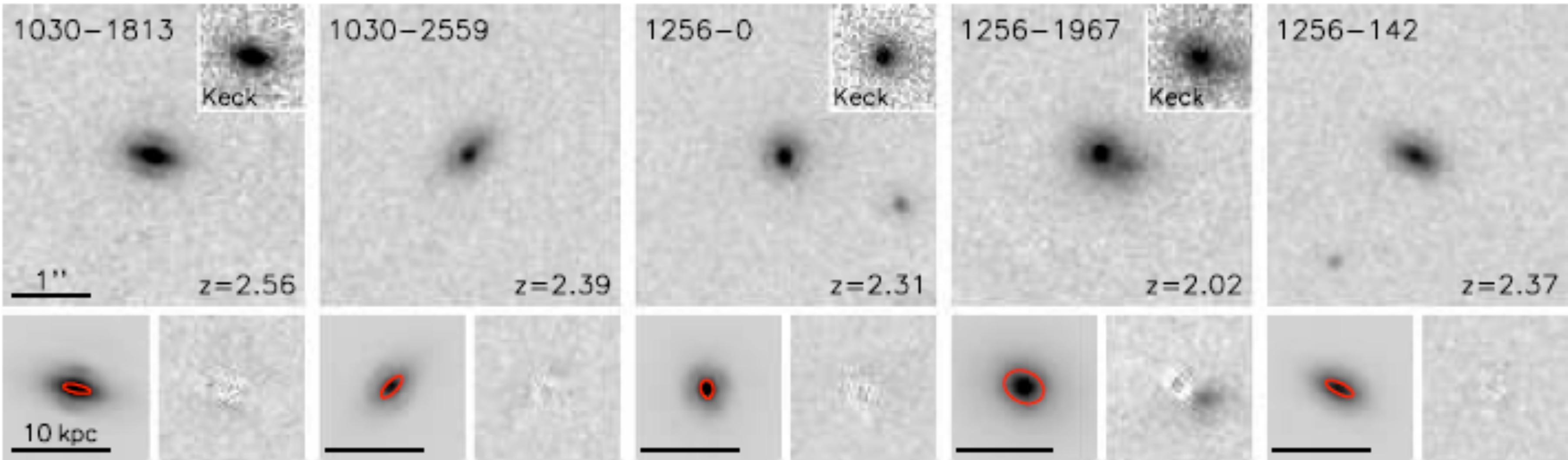
Courtesy: Bob Abraham

NIC2 Morphologies of z~2.3 Massive Galaxies



Kriek et al 2009 Ap J 705, L71

What is a Surprise: DRGs @ z=2 are Small!



HST NIC2 sizes of a representative sample of z~2-3 red galaxies with $M > 10^{11}\ M_{\odot}$: $r_e \sim 0.9$ kpc

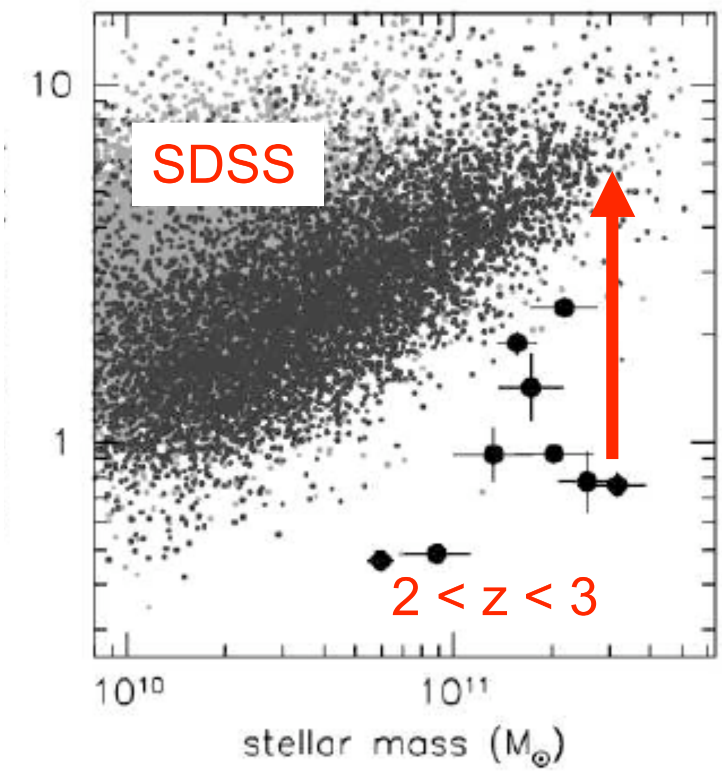
2-5 times smaller than comparably massive z~0 ellipticals!

Growth in size but not mass?

van Dokkum et al (2008)

Earlier claims by:

Daddi et al (2005), Trujillo et al (2006)



The `Red Nuggets' Problem: Observational Uncertainties

- Some skepticism at observational claims
- Perhaps mass overestimated e.g. “bottom light” IMF, or size underestimated (e.g. M/L gradients)
- Perhaps size underestimated due to surface brightness effects: some evidence for diversity in sizes at $1<z<2$ (Saracco)
- Dynamical data would confirm masses but early work (van Dokkum, Kriek, Capellari) presented conflicting evidence - very difficult observations
- Can we observe self-consistent size evolution of ETGs over $0<z<2$?
- How much growth occurred?
- What does it all mean?!

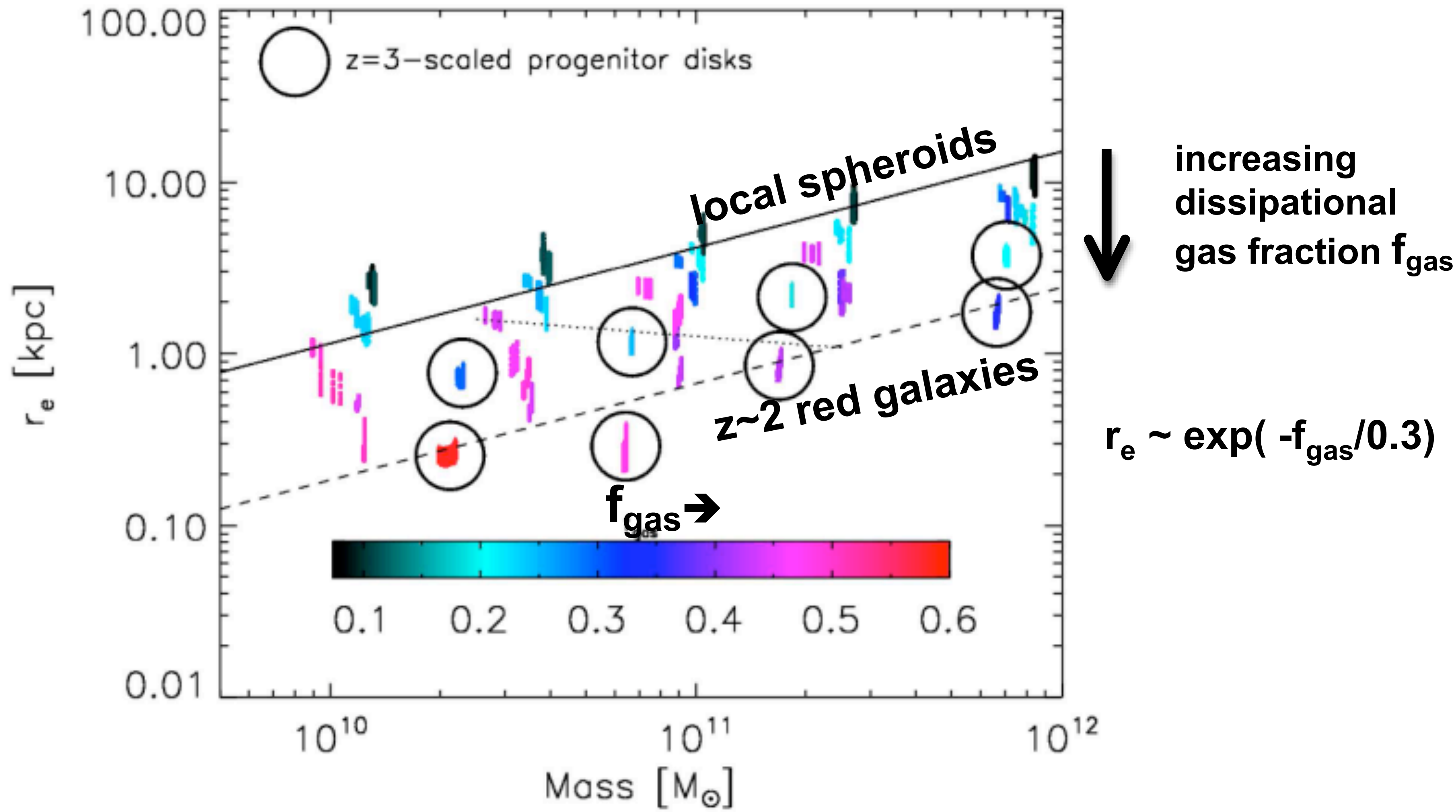
How Big Should a Massive Galaxy Be? Ask a Theorist

Observations probe the projected distribution of light, sampling it by a discrete number of pixels after it was smeared by a point spread function (PSF). In addition, the signal is superposed by noise. The translation to a physically more meaningful mass profile involves the assumption of a mass-to-light ratio M/L. Although often for simplicity assumed to be a constant, spatial variations in M/L may occur due to age, metallicity and/or dust gradients. Furthermore, since the total size of a galaxy is ill-defined, one refers to (circularized) size as the radius r_e containing half the mass. Given the finite image resolution, this quantity is generally obtained by fitting a template profile, taking pixelization and PSF smearing into account. In most of the literature, a one-component Sersic (1968) profile has been adopted, providing satisfyingly flat residual images given the noise level of the observations.

Numerical simulations provide an excellent tool for the interpretation of galaxy structure. The simulated data offers a three-dimensional view of the mass, age, and metallicity profile at high resolution, free of sky noise[1].

Wuyts et al 2010 Ap J 722, 1666

Size Depends: I – On Gas Fraction of Initial Merger

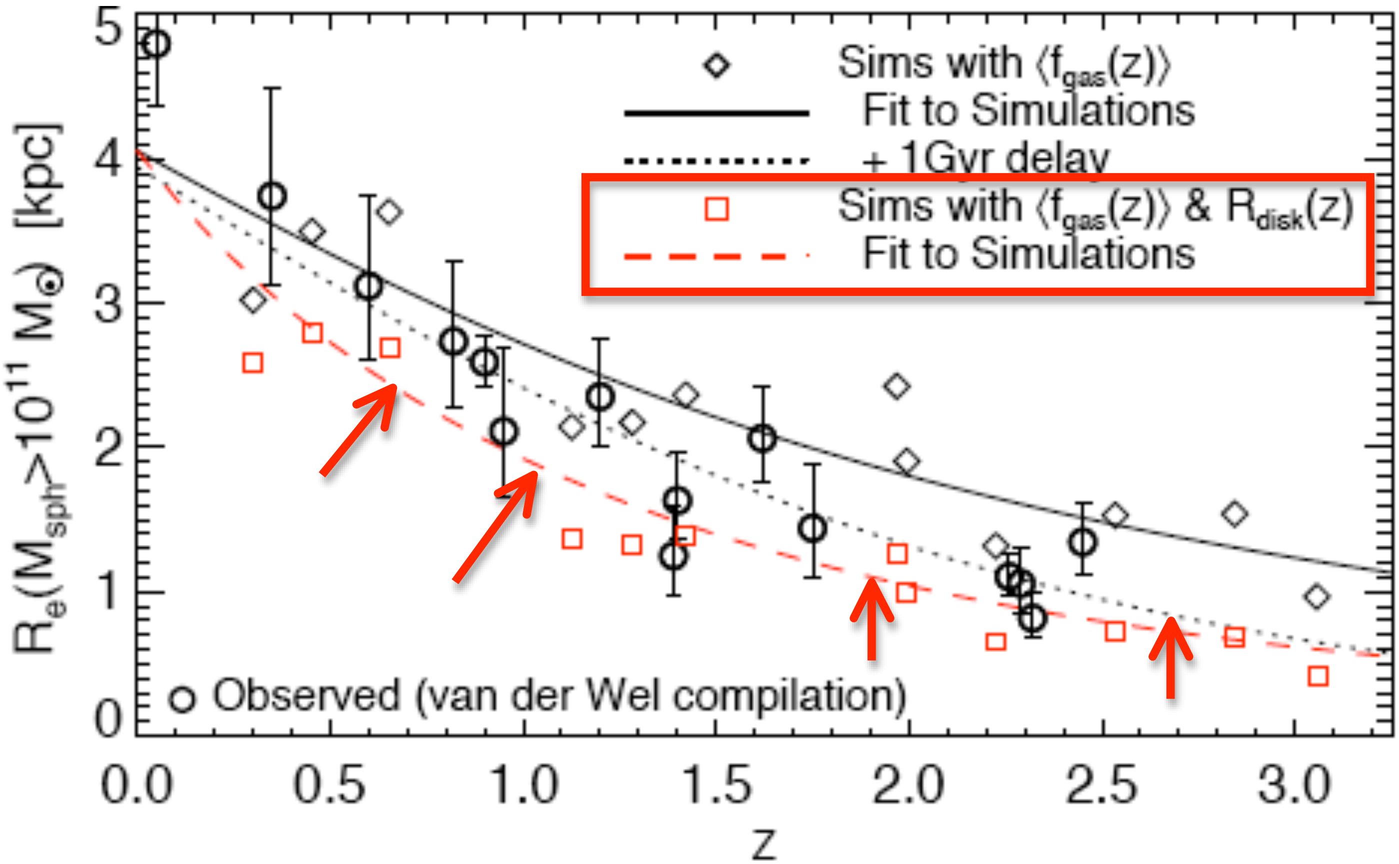


Equal mass merger SPH simulations using GADGET-2 with gas cooling, multi-phase ISM and SN/AGN feedback (Springel, Hernquist et al)

Remnant is smaller for suitably-scaled z~3 disks with high gas fractions

Wuyts et al 2010 Ap J 722, 1666

Size Depends: II – On Epoch of Merger



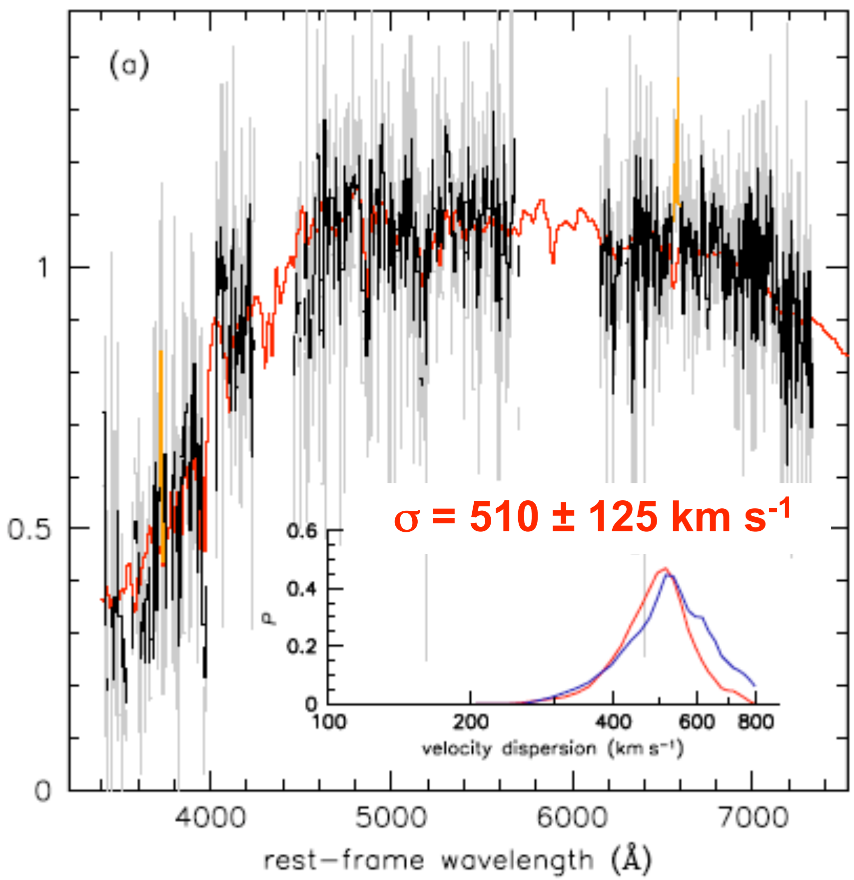
Since gas fraction f_{gas} declines with time, later merger products are larger

NB: In principle this could account for expansion in size from z~2 to 0 but such a simple explanation is ruled out by low rate of major merging <u>and</u> absence of significant decline in abundance of fixed mass spheroids for z<1

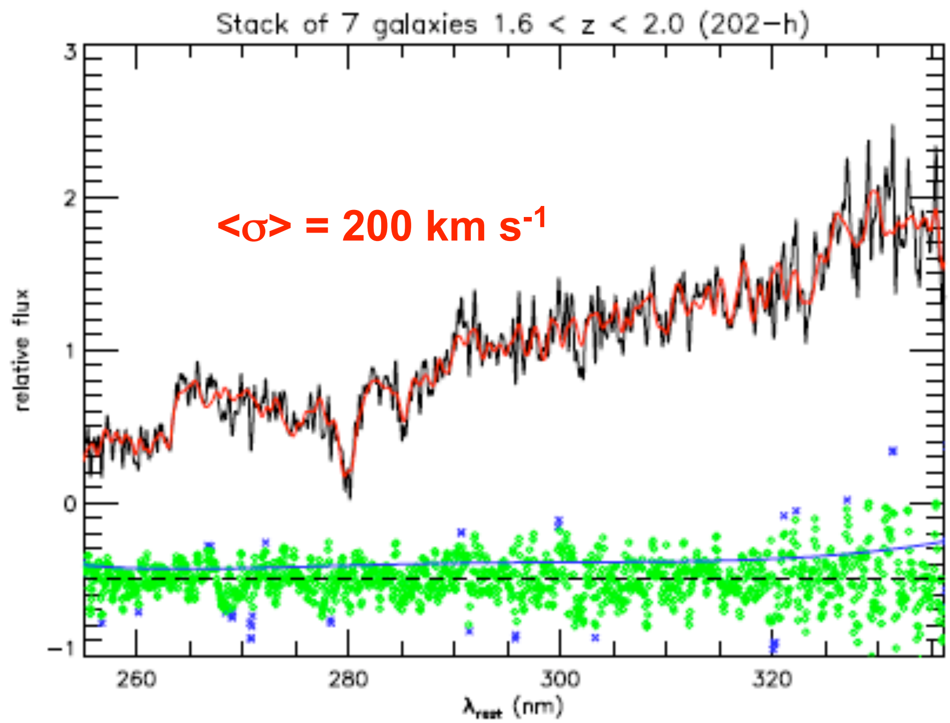
Hopkins et al 2010 MN 401, 1099

Dynamical Masses: Stellar Velocity Dispersions

Conceivably, stellar masses of z~2 DRGs have been over-estimated
If massive & compact, expect high central densities & stellar velocity dispersions
Requires high S/N absorption line spectroscopy of very faint objects



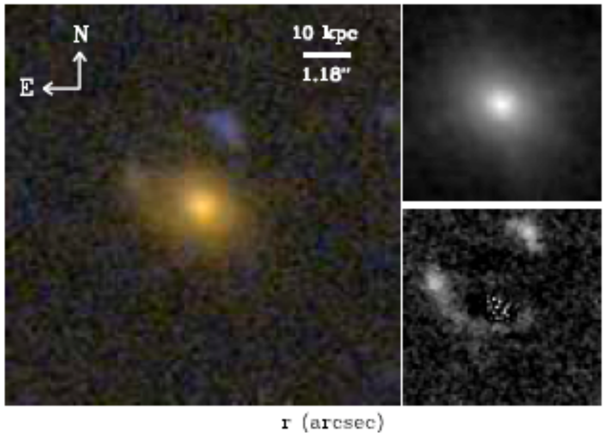
GNIRS z=2.186; 22hrs
van Dokkum et al (2009)

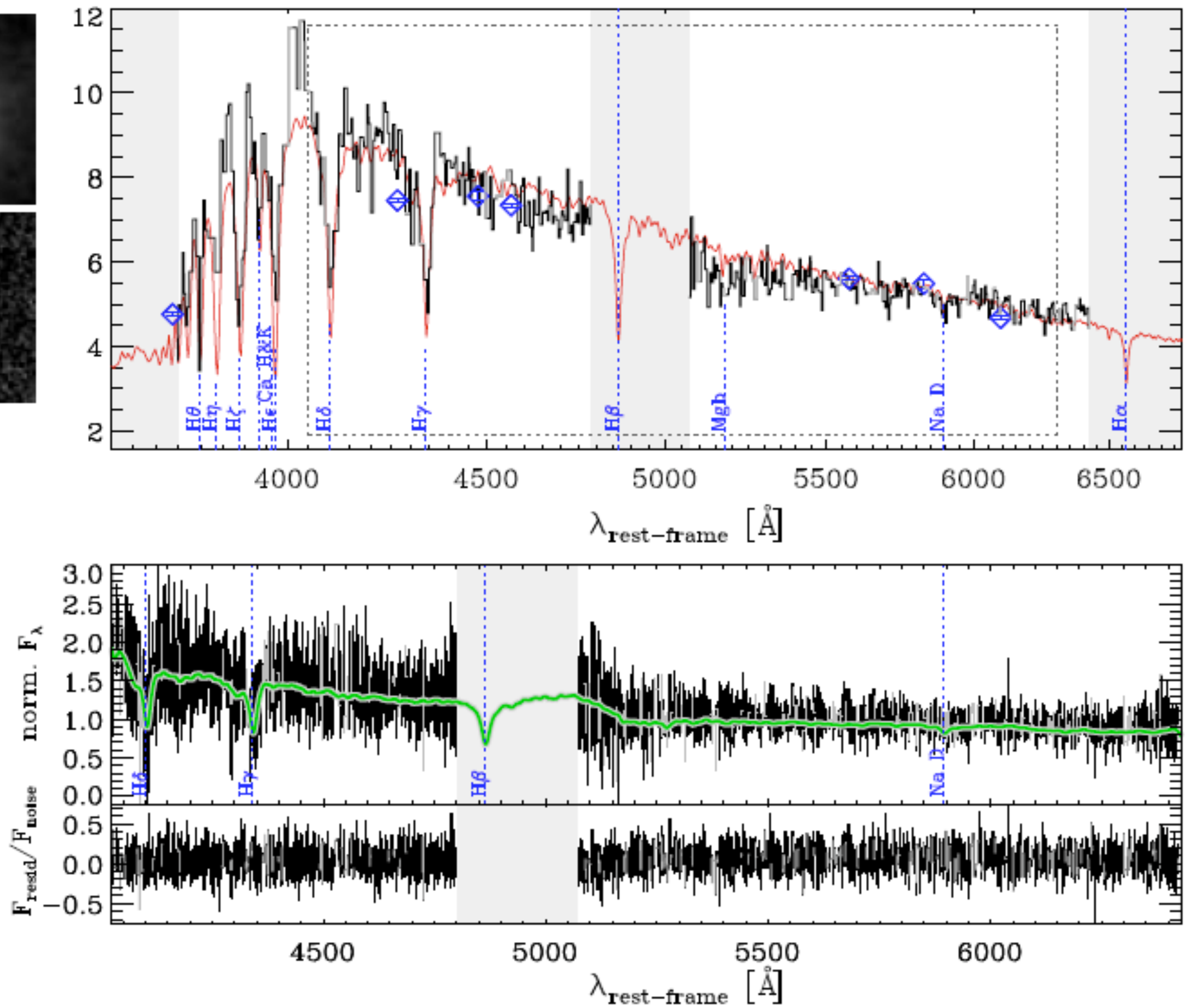


FORS <z> ~ 1.8; 7 x ~29hrs
Capellari et al (2009)

X-shooter Spectrum of NMBS-C7296

z = 1.80 K = 19.6 luminous nugget





$M^*=1.5\ 10^{11}\ M_\odot$

$\sigma = 294 \pm 51$ km s^{-1}

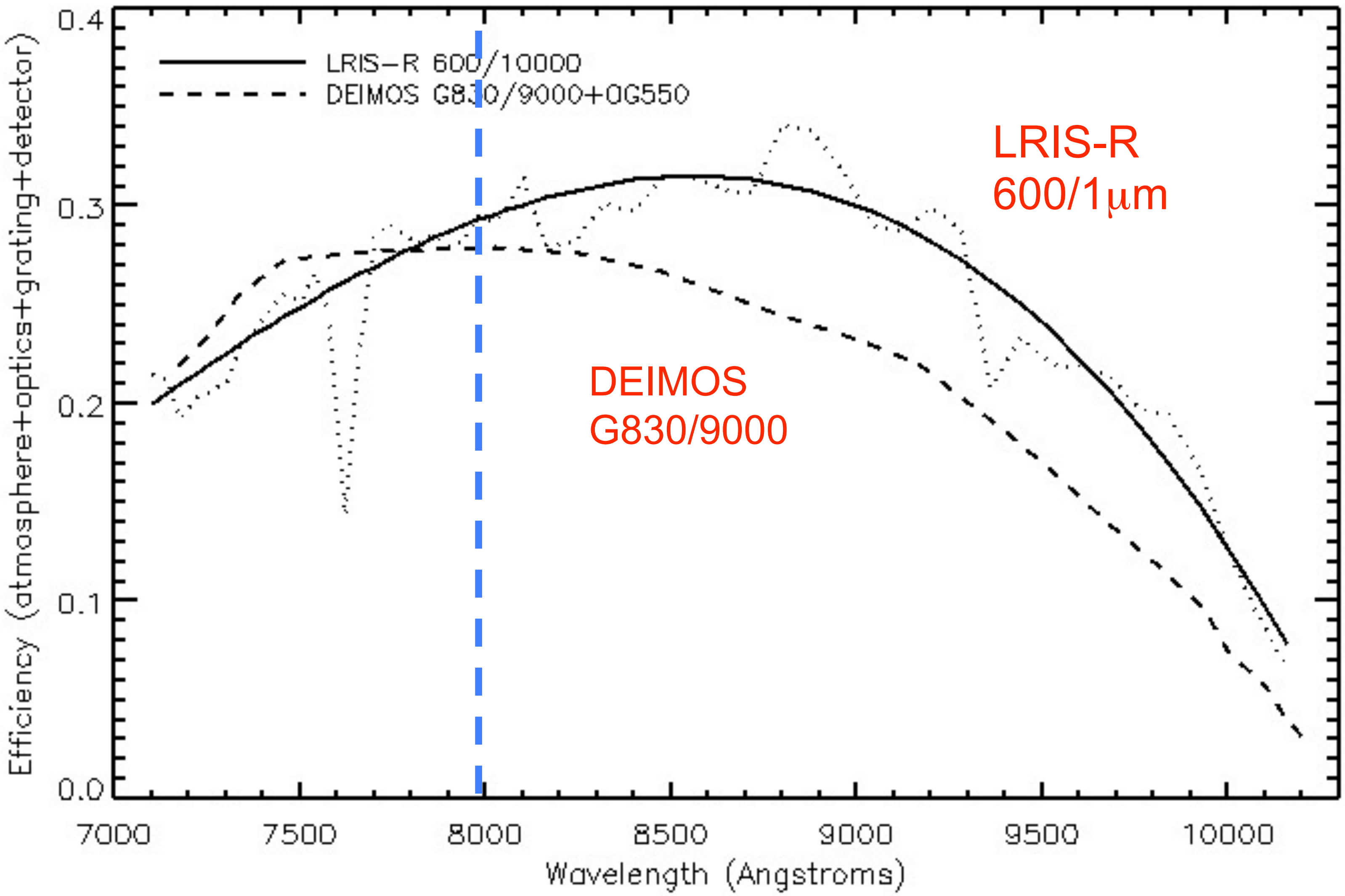
$r_e = 1.6$ kpc

$M_{dyn} = 1.7\ 10^{11}\ M_\odot$

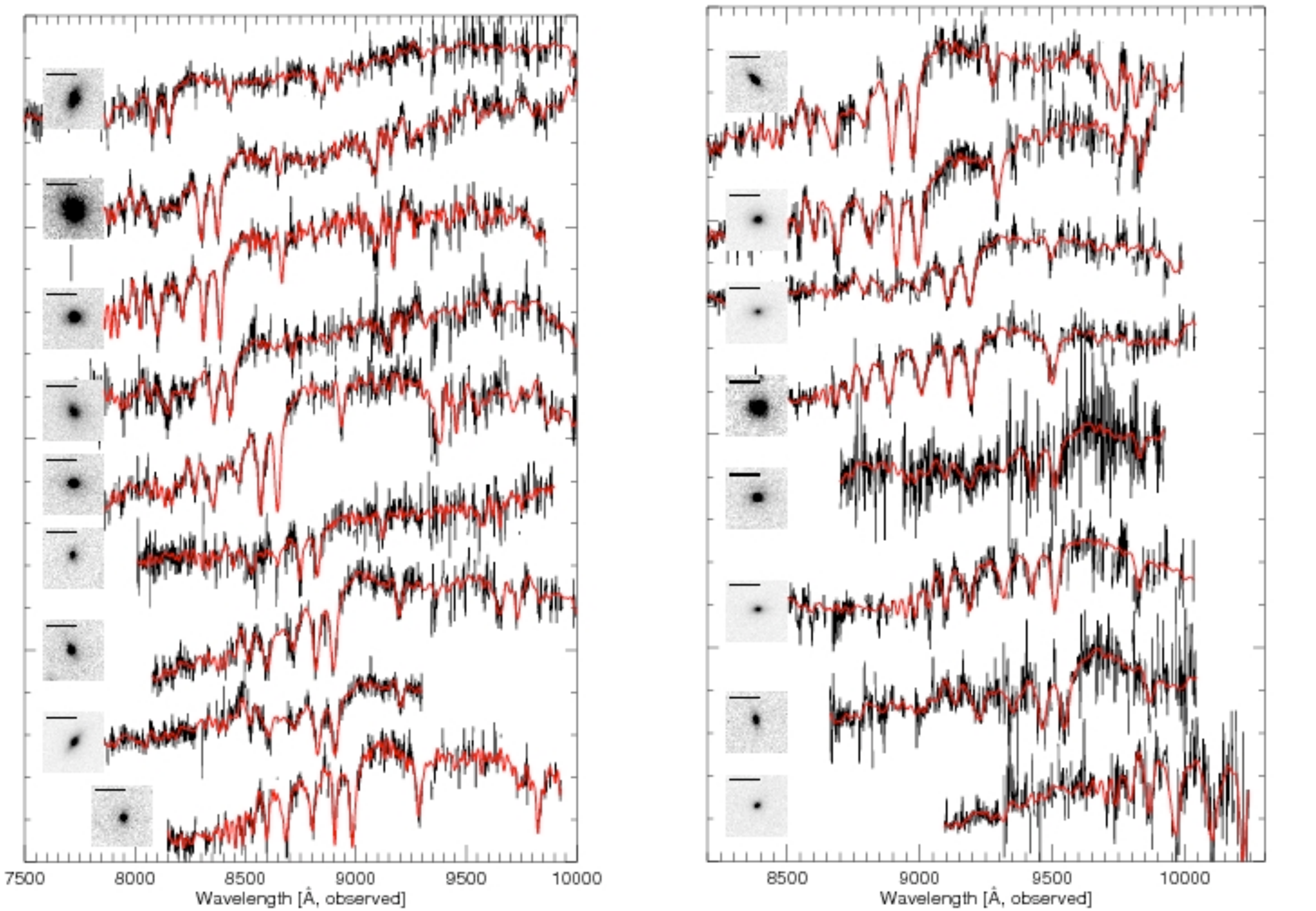
van de Sande et al astro-ph/1104.3860

Keck 1 LRIS red CCD upgrade

Efficiencies of Keck workhorse spectrographs



Keck LRIS-R: I_{AB}<23.5; 12-16 hr exposures, 1.1 < z < 1.60



Newman, RSE et al 2010 Ap J 707, L103

Size evolution at fixed dynamical mass

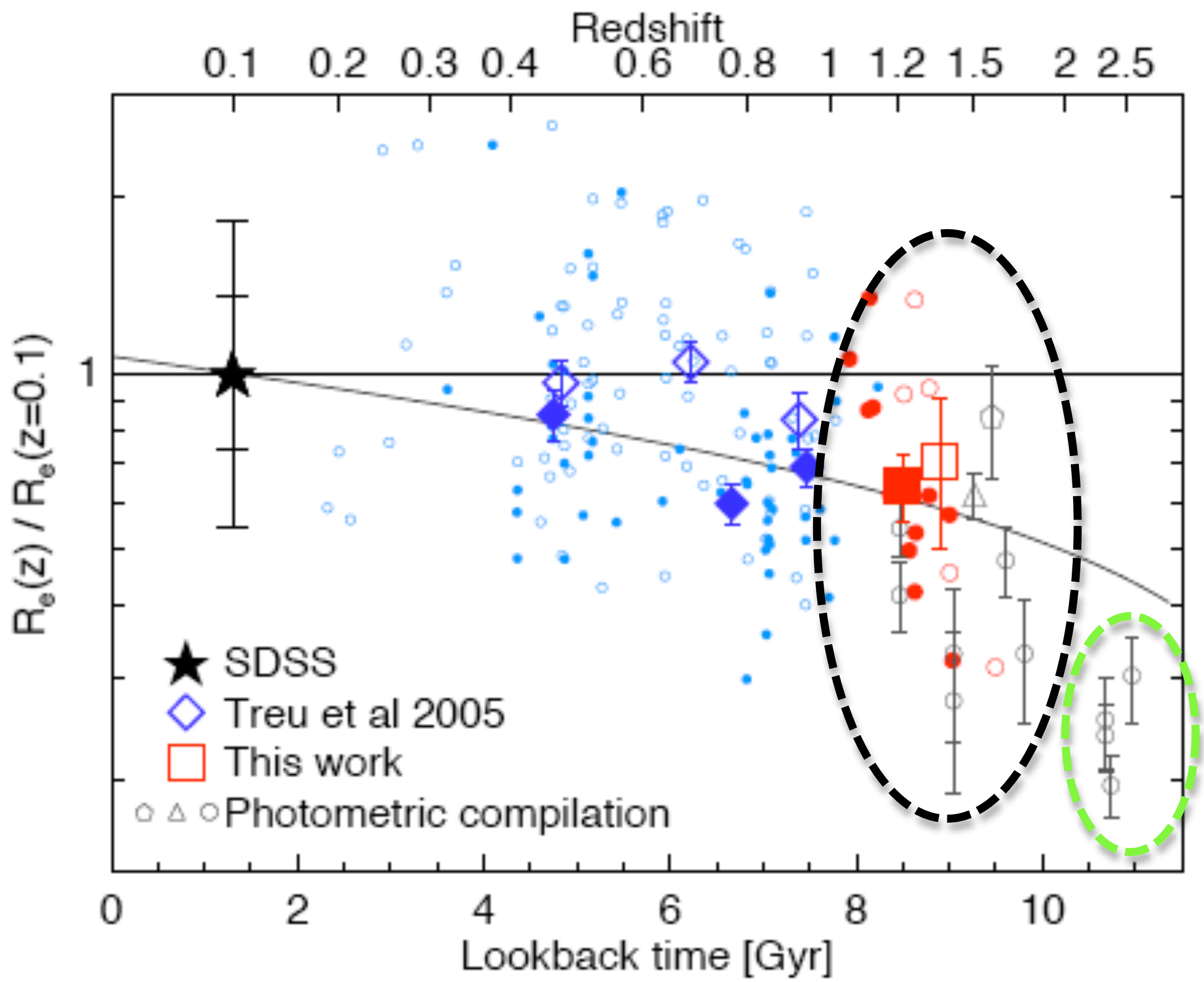
Standard test conducted in literature:

size ~ $(1+z)^{-x}$

Unlikely evolutionary path

For $M>10^{11} M_{\odot}$
$x = 0.70 \pm 0.11$
(40% by z=1)

For $M<10^{11} M_{\odot}$
$x = 0.16 \pm 0.16$



- **Only massive early-types are significantly growing in size**
- **There is considerable diversity in measures within 1 < z < 1.6**
- **z > 2 objects appear ultra-compact implying very fast growth??**

Size evolution at fixed velocity dispersion

More physically meaningful

Mergers should increase size but not velocity dispersion

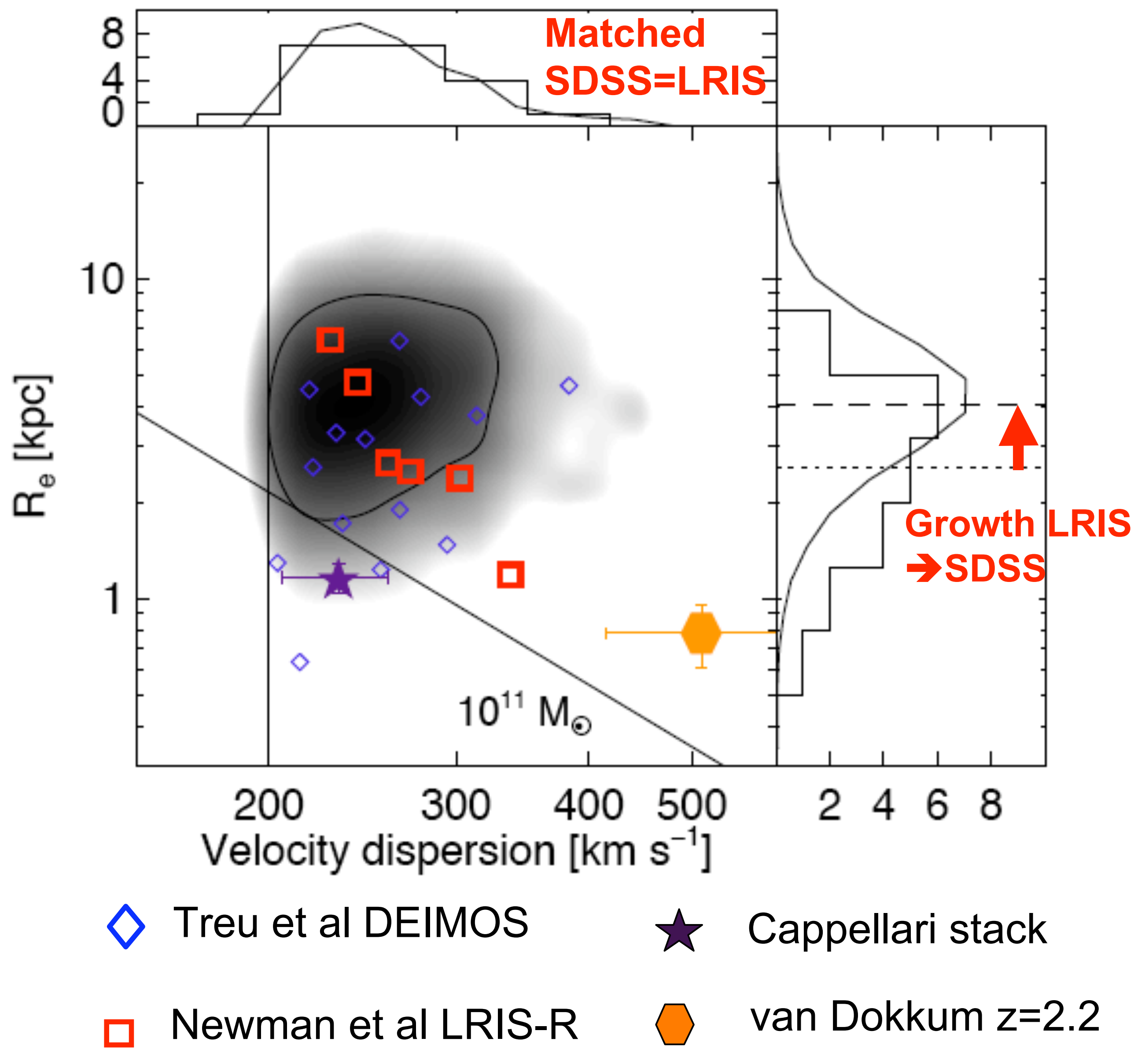
Exploits unique dynamical data

Tests “progenitor bias” (cut in M_{dyn} restricts in σ, R so could give false evolutionary trend)

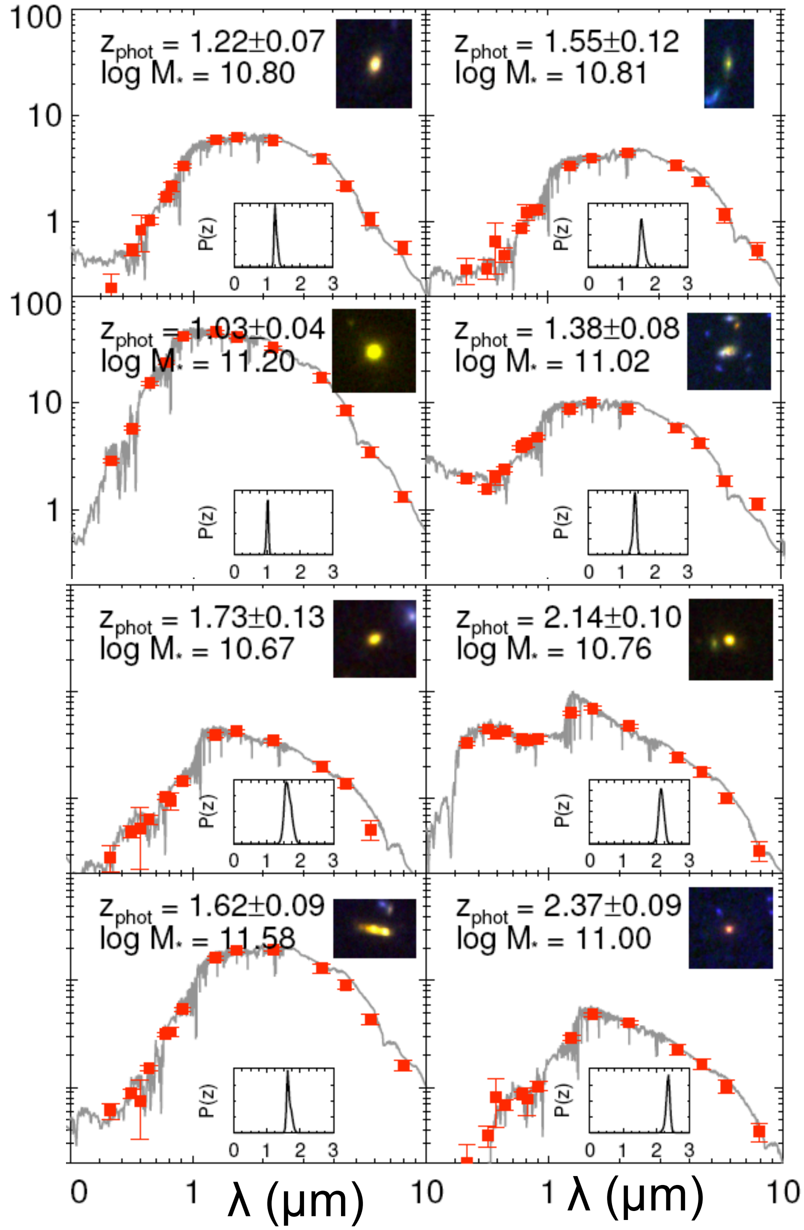
For σ > 225 km s^{-1}

x = 0.69 ± 0.21

Growth ×1.7-2.7 since z~2

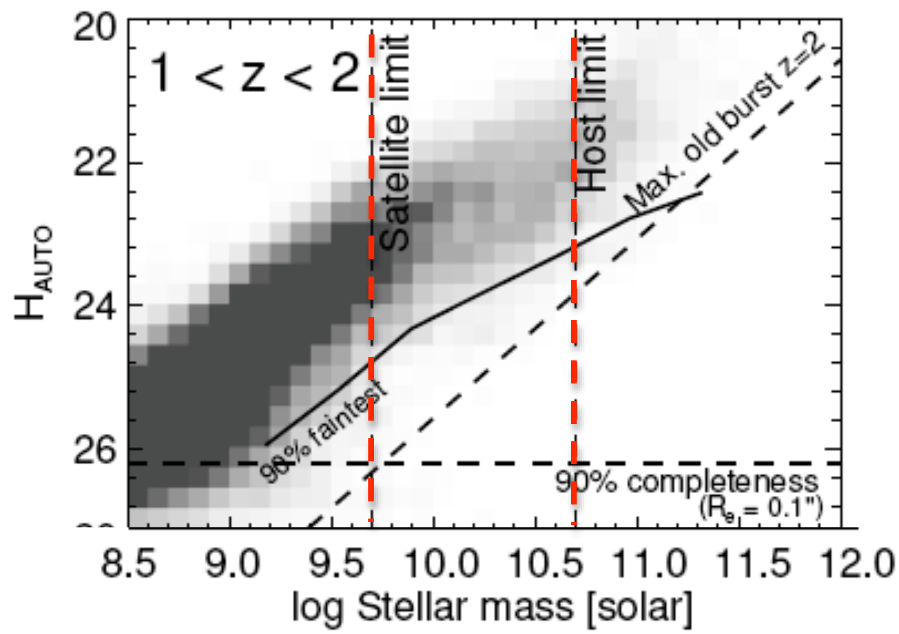


Growth Rate in CANDELS data



Newman et al (astro-ph/1110.1637)

Using excellent photometry in UDS and GOODS-S (HST, Subaru, VLT, UKIRT, Spitzer), made a mass-selected sample of 935 massive (>$10^{10.7}$ $M_\odot$) sources over 311 arcmin^2 with 0.4<z<2.5 to gauge growth rate.

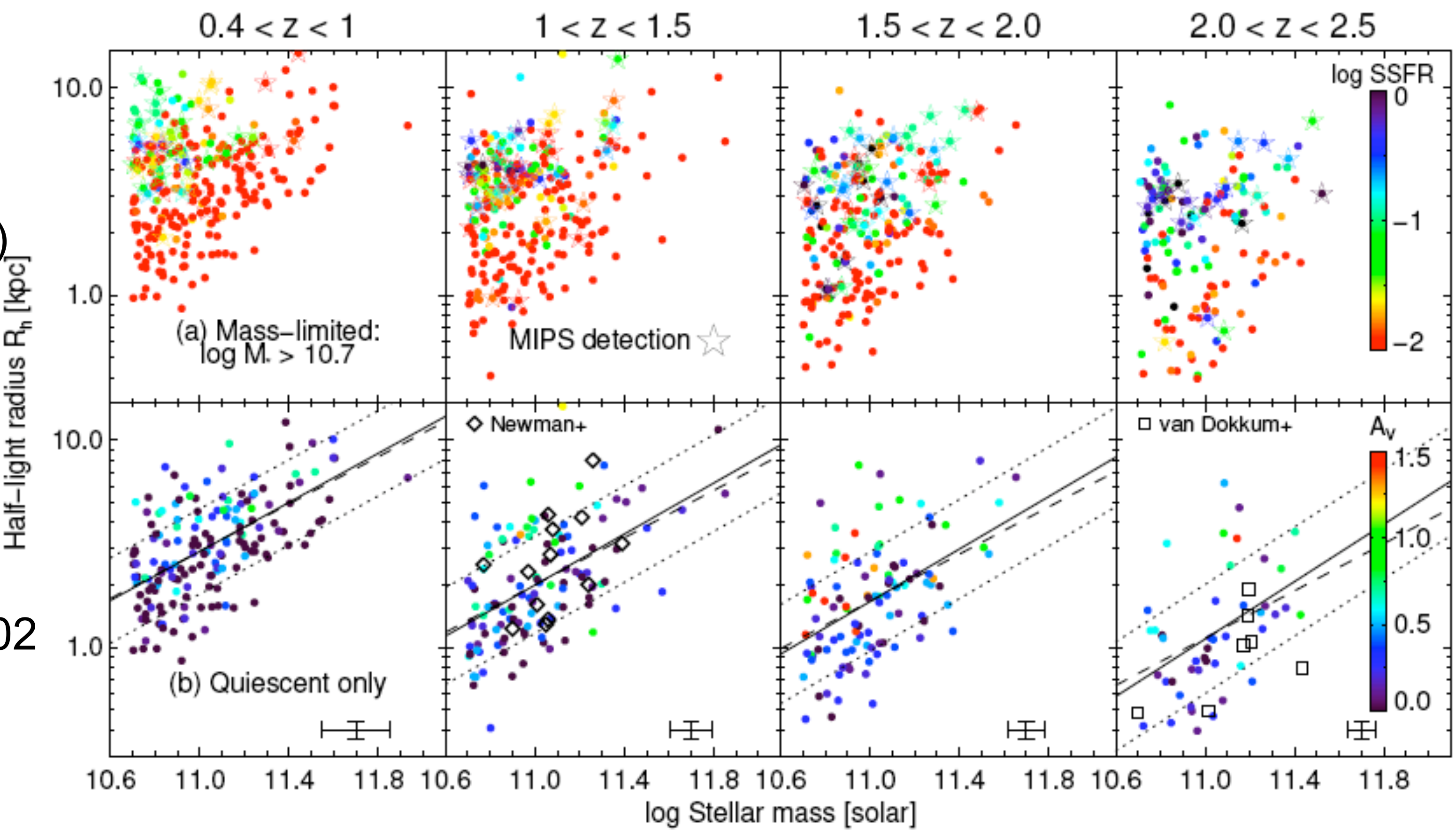


Completeness simulations indicate 90% complete to log $M/M_\odot$ = 9.7 to z=2 so can also search for minor mergers with 10:1 mass ratio around hosts with log $M/M_\odot$ > 10.7

Size-Mass Relationship in CANDELS Data

All with $M>10^7\ M_\odot$)

Quiescent subset ($SSFR<0.02\ Gyr^{-1}$)

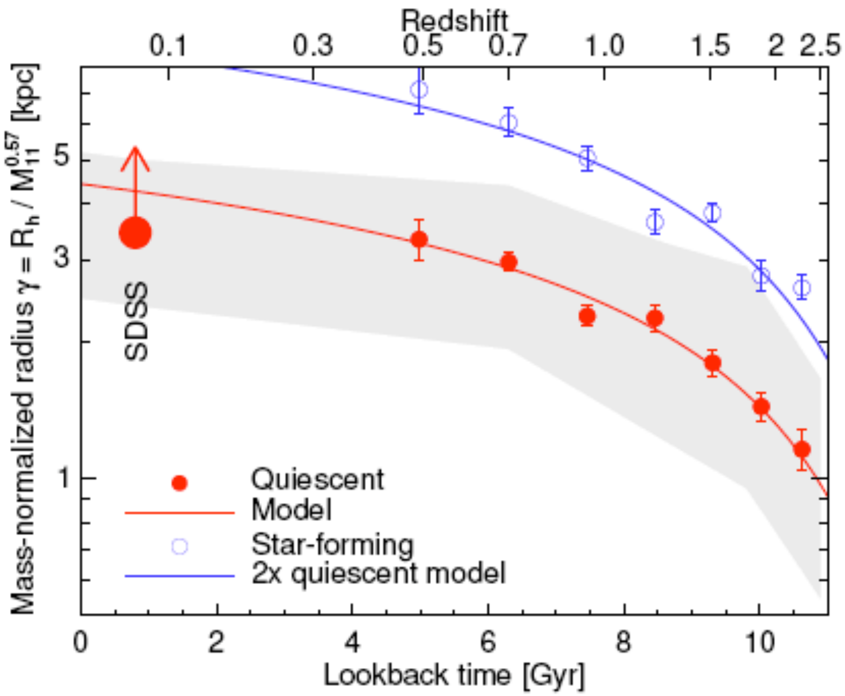


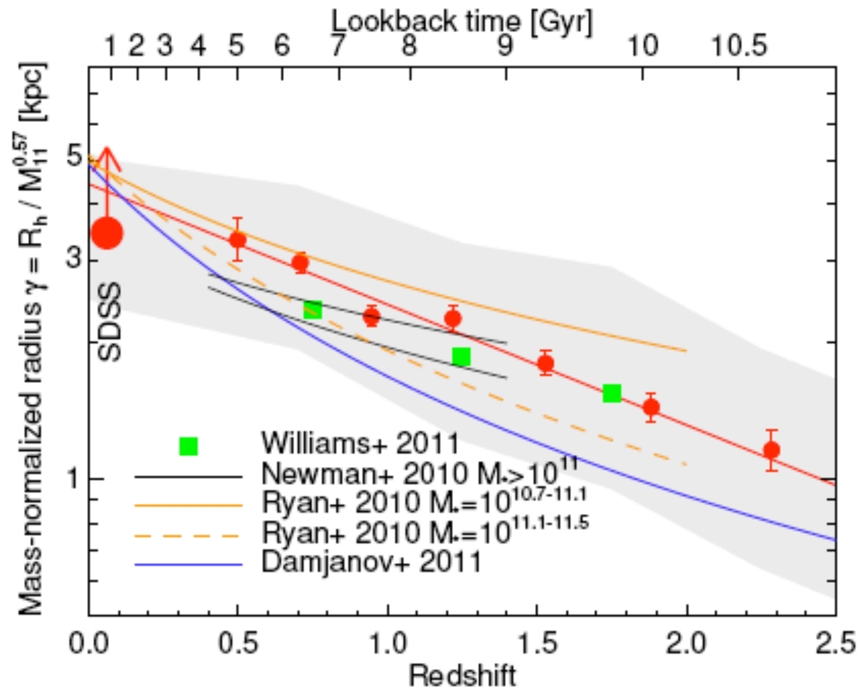
Unique sample probing small sizes for $M<10^{11}\ M_\odot$ at z~2 (<0.1-0.2 arcsec)
The most compact systems at each redshift are quiescent
For quiescent subset with SSFR < 0.02 Gyr^{-1} no evolution in size-mass relation

$$R_h = \gamma \left(\frac{M_*}{10^{11} M_\odot} \right)^\beta$$

β = 0.61± 0.05 c.f. 0.57 (SDSS)

Size Growth Rate in CANDELS data





Noting uniformity of size-mass relation, normalize all sizes to those at $M=10^{11}\ M_\odot$
Overall see size growth for $10^{11}\ M_\odot$ galaxy of × 3.5 ± 0.3 over $0.4 < z < 2.5$
But scatter (1σ region) is significant (and valuable information)
Growth rate consistent with that found in limited dynamical data and particularly rapid in 2 Gyr period from $1.5<z<2.5$

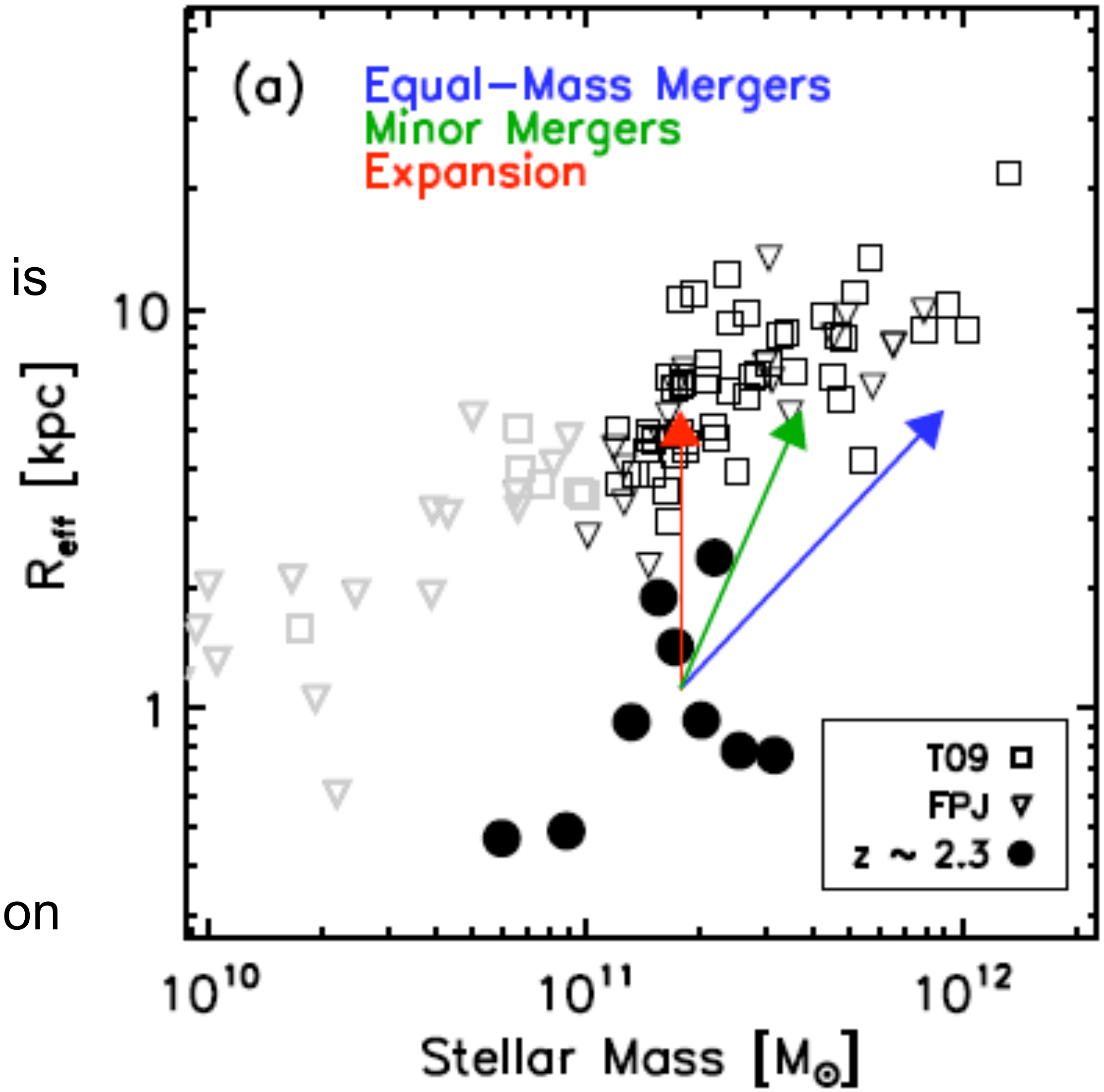
Newman et al (astro-ph/1110.1637)

How Did Early Galaxies Enlarge?

Improved observational data (dynamical masses, HST images) confirms size growth is real!

What, physically, could lead to this growth in size?

- Major mergers
- Minor mergers
- Mass loss/adiabatic expansion



Size Growth During Dissipationless Merging

From virial theorem, total energy $E_i = -\frac{1}{2}M_i\langle v_i^2\rangle = -\frac{1}{2}\frac{GM_i^2}{r_{g,i}}.$

Consider merger such that $M_f = M_i + M_a = (1+\eta)M_i$

and define $\epsilon = \langle v_a^2\rangle/\langle v_i^2\rangle$

Assuming conservation of energy (e.g. parabolic orbits, Binney & Tremaine 2008) $\frac{\langle v_f^2\rangle}{\langle v_i^2\rangle} = \frac{(1+\eta\epsilon)}{1+\eta}.$ $\frac{r_{g,f}}{r_{g,i}} = \frac{(1+\eta)^2}{(1+\eta\epsilon)}$

Major merger $\eta = 1$: no change in v, M and R double, **d log R / d log M = 1**

Lots of minor mergers $\epsilon << 1$ find **d log R / d log M = 2**

SPH simulations of minor mergers indicate **d log R / d log M ~ 1.3 – 1.6**

Naab et al 2009 Ap J 699, L108

(see also Khochfar & Silk 2006 Ap J 648, L21; Khochfar & Silk 2009 MNRAS 397, 506)

Adiabatic Expansion Through Mass Loss?

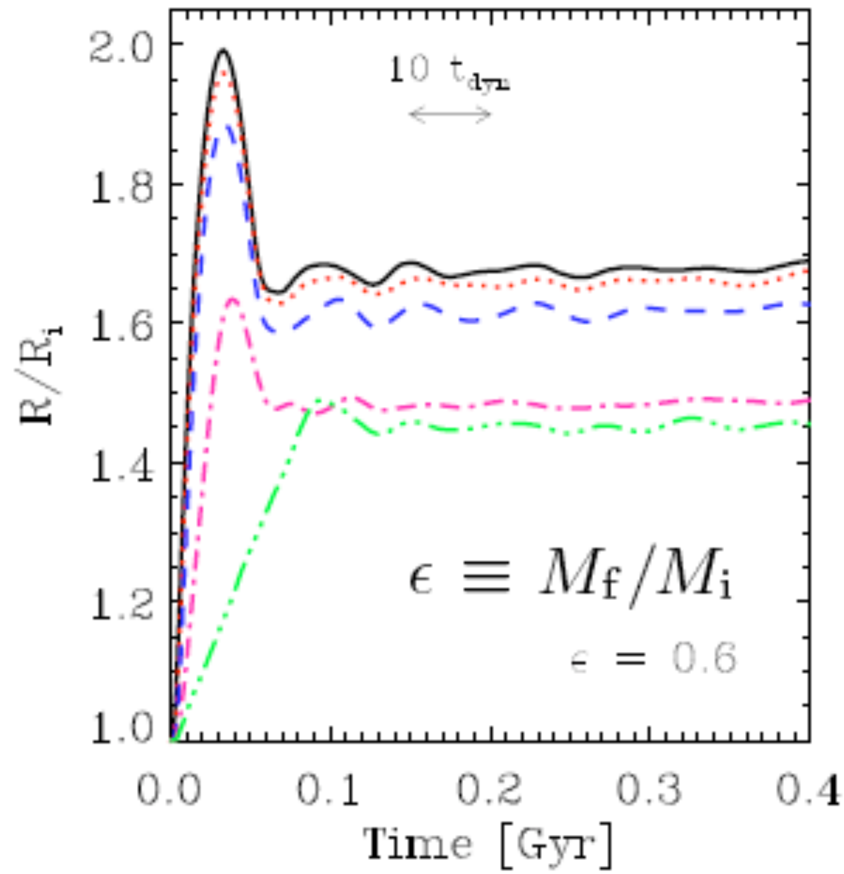
- Consider a galaxy that expels a significant fraction of its gas e.g. via AGN or SN driven galactic winds

- Stars and DM will expand in response to shallower central potential

- Simple homology criterion in spherical symmetric case:

$$M(r)\,r = \text{constant} \quad (R_e \propto M^{-1})$$

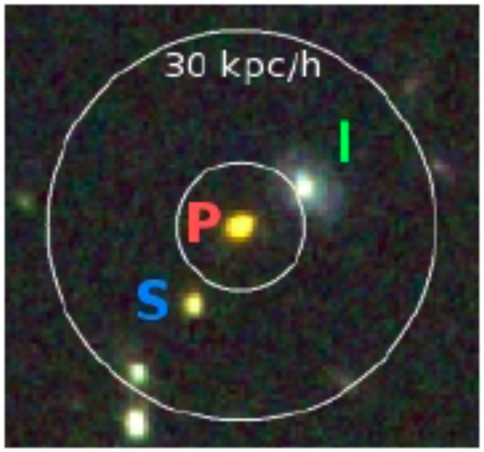
- Differences from classical work on star clusters (e.g. Tutukov 1978) include role of DM halo and timescales

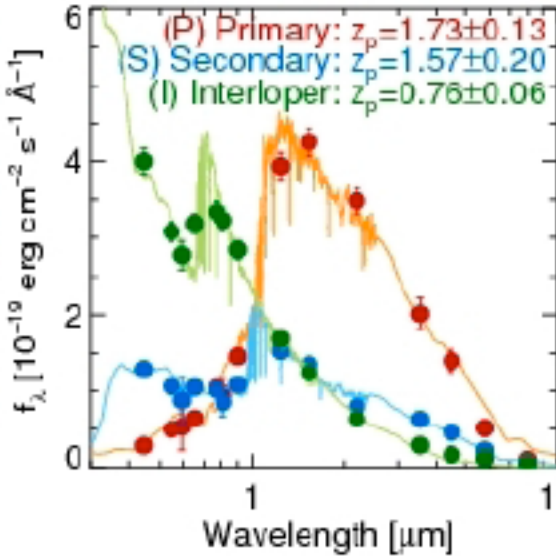


Loss of significant baryonic mass can induce size increase but simulations show this \`puffing up' occurs only when the stellar population are much younger (<0.5 Gyr) than for any of the early type galaxies under consideration.

Ragone-Figueroa & Granato astro-ph/1101.4947

Measuring the Minor Merger Rate in CANDELS Data



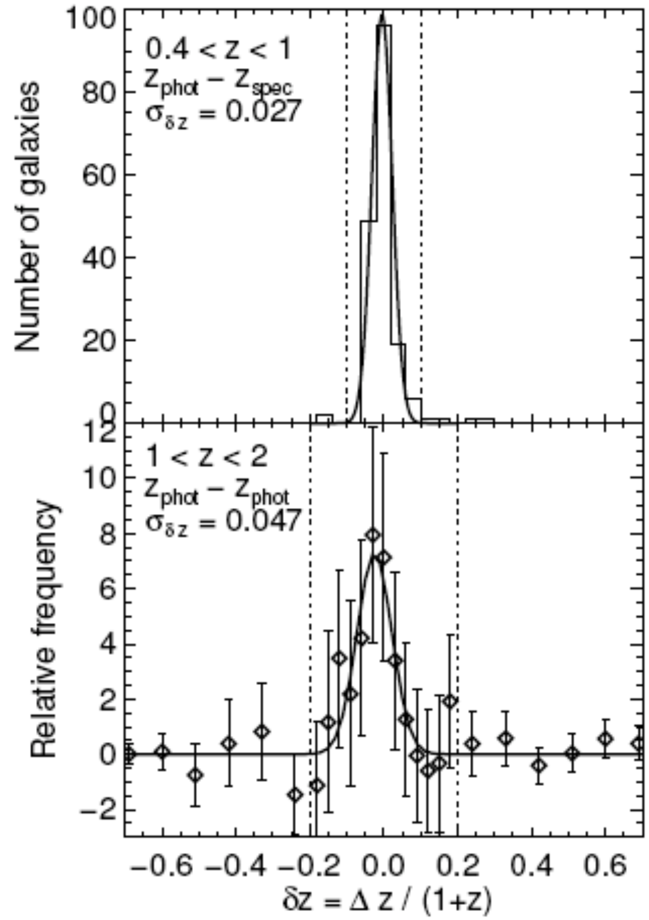


WFC3/IR data is sufficiently deep (H<26.5) that we can secure photometric redshifts for secondaries 1/10th as massive for 404 quiescent primaries with log $M_P/M_\odot$ < 10.7 over 0.4 < z < 2

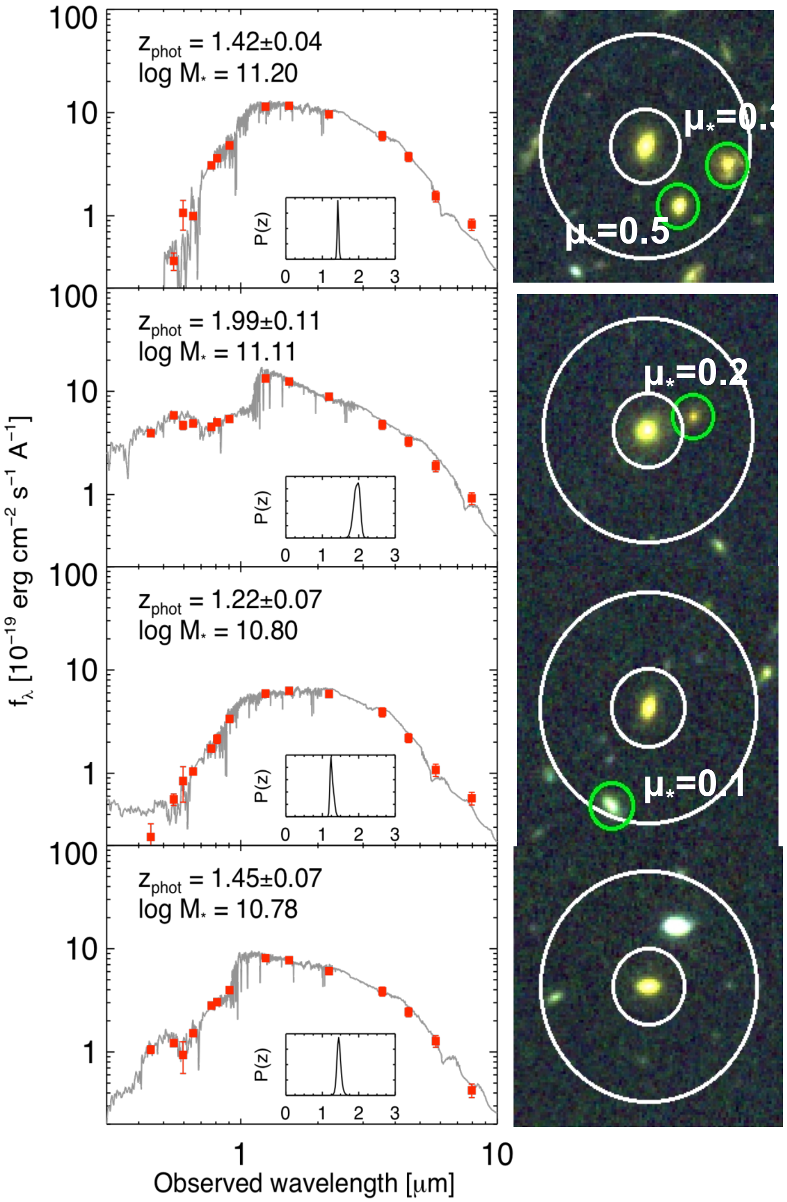
Search area 10 < R < 30 h^{-1} kpc
$\delta z < 0.1$ (for z < 1) and $\delta z < 0.2$ (for 1 < z < 2)
Mass ratio $\mu = M_S/M_P > 0.1$

Caution: such photo-z associations could still lead to an over-estimate of pairs that will ultimately merge given environs in which red galaxies lie (see later)

Satellite photo z precision



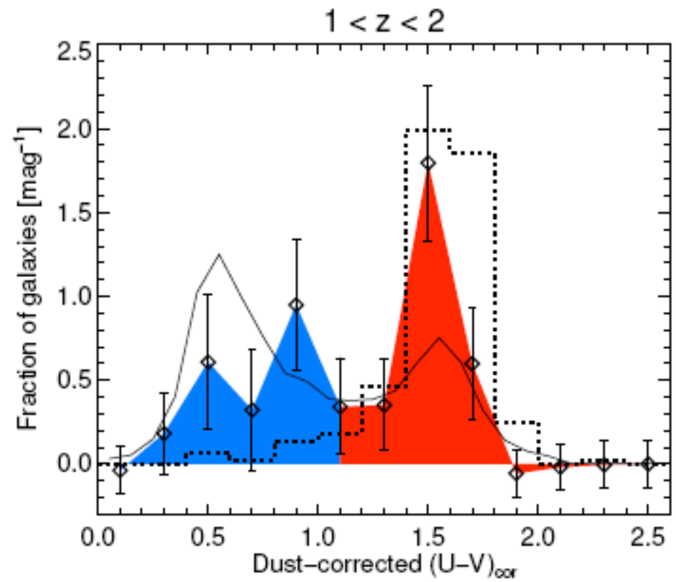
Measuring the Minor Merger Rate in CANDELS Data



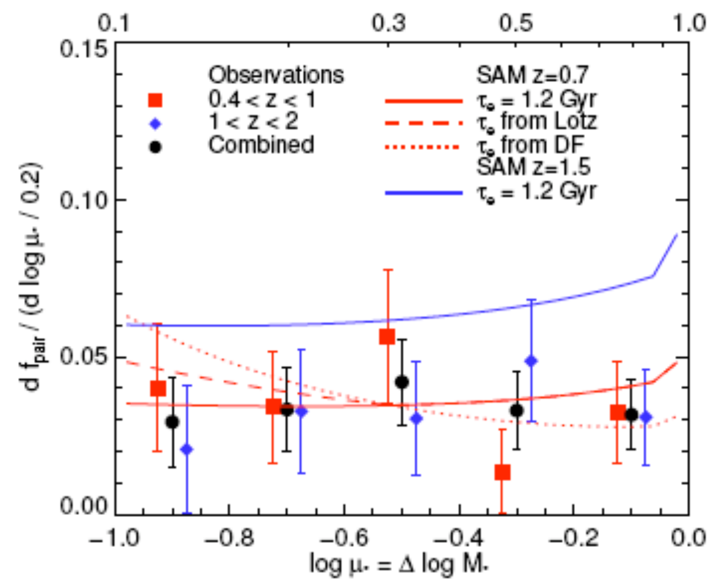
Newman et al (astro-ph/1110.1637)

Find f_{pair} = 0.16 ± 0.03 over full z range

Majority of secondaries are also red



μ (mass ratio) distribution quite flat as expected from SAMs



Can Minor Merging Explain Growth: I ?

Assuming:

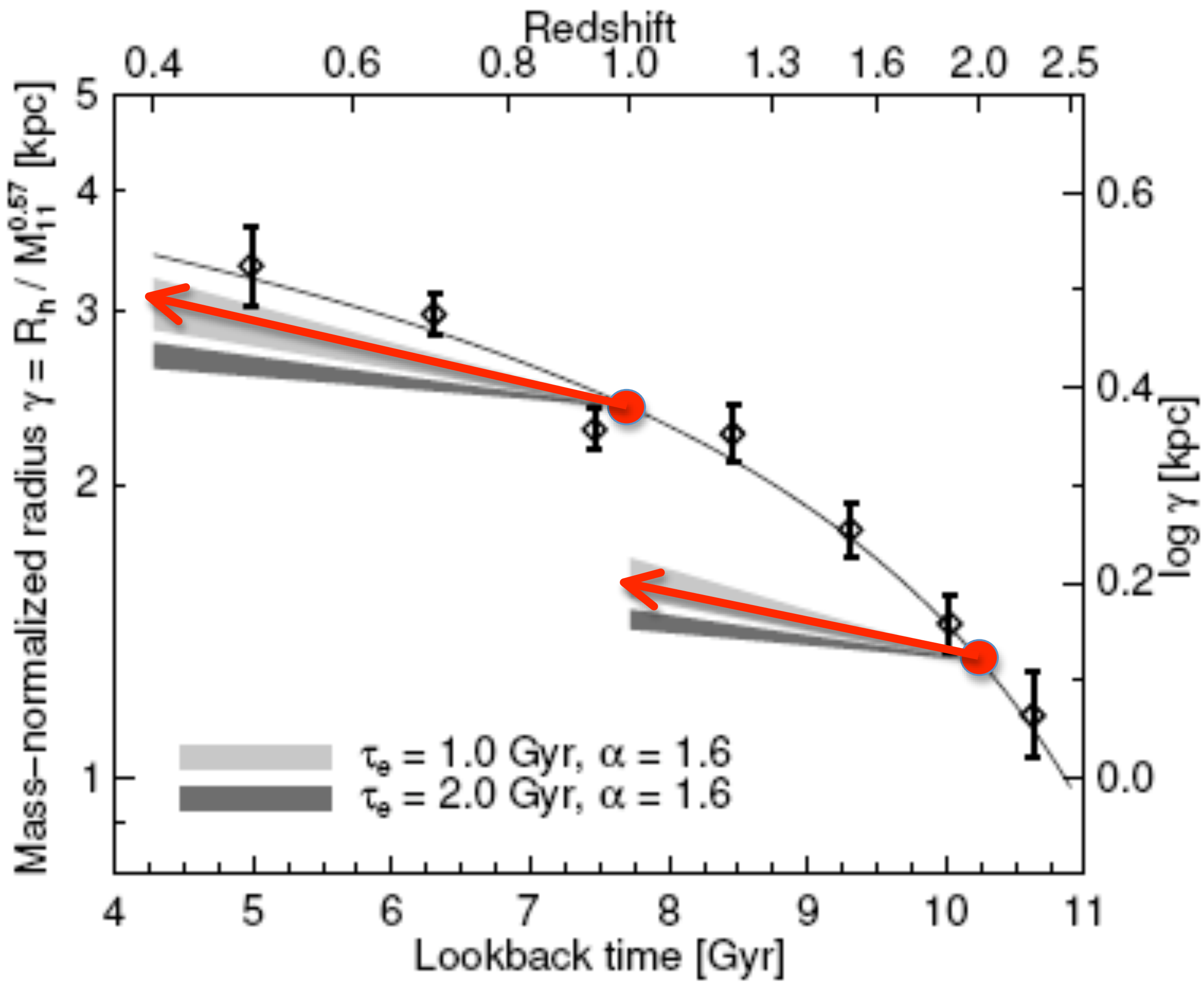
1.Merger timescale

T_e ~ 1-2 Gyr
(Patton+, Lotz+,
Kitzbichler+)

2. Bound fraction of
projected pairs
C_{mg} (=f_{3D})~0.5

3. Size growth per
mass increase

dlogR / dlogM ~1.6
(Nipoti+)



Size growth over 0.4<z<1 is broadly consistent with that expected from observer minor merger fraction IF merger timescale is fast
Size growth over 1<z<2 is inconsistent with observed minor merger fraction for any reasonable choice of parameters

Evolution in Number: Two-Phase Model

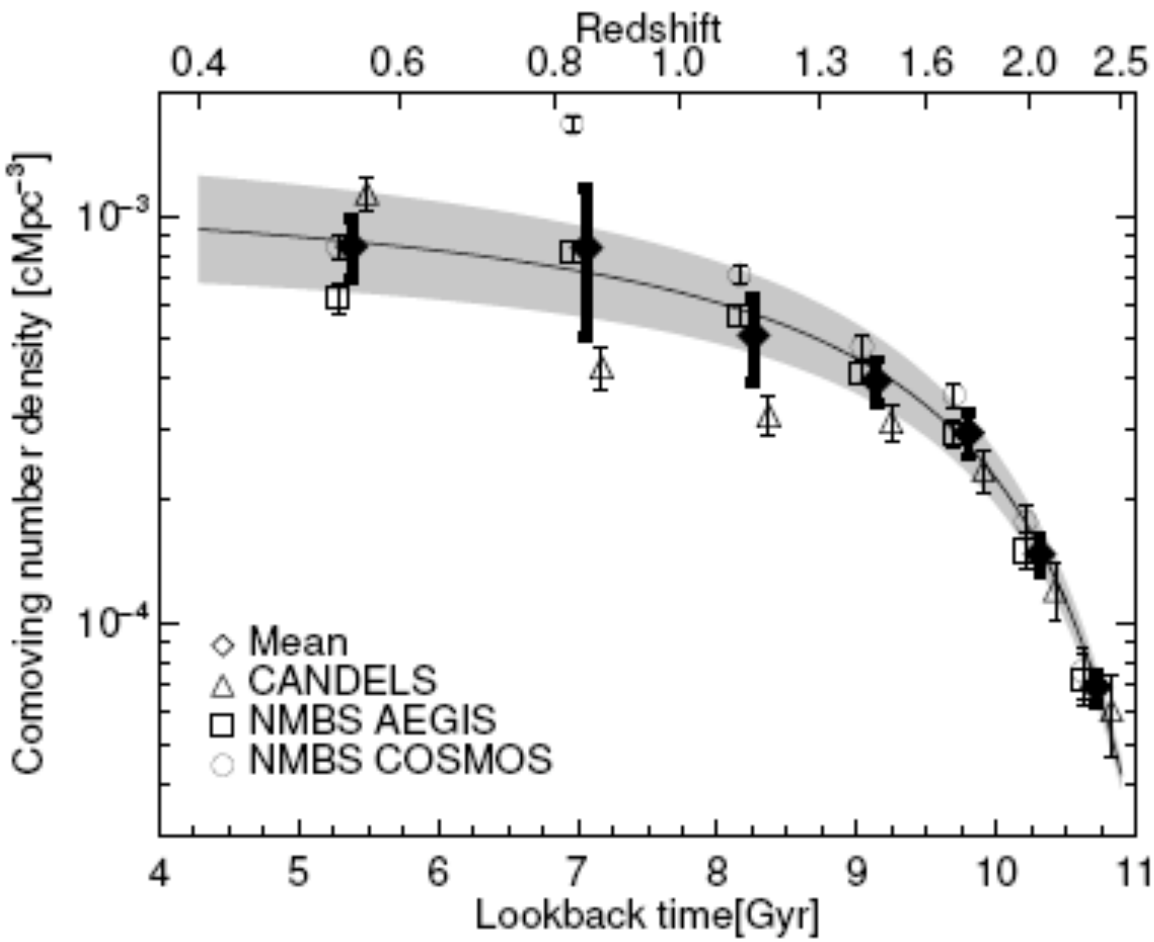
Simple model is naïve as it assumes all sources enlarge *in lockstep* from z~2 progenitors.

In reality population comprises old galaxies which formed at z~2 and perhaps expand via mergers

AND

Newly arrived quiescent systems whose size reflects their epoch of formation

Comoving no. density of log M>10.7 quiescents



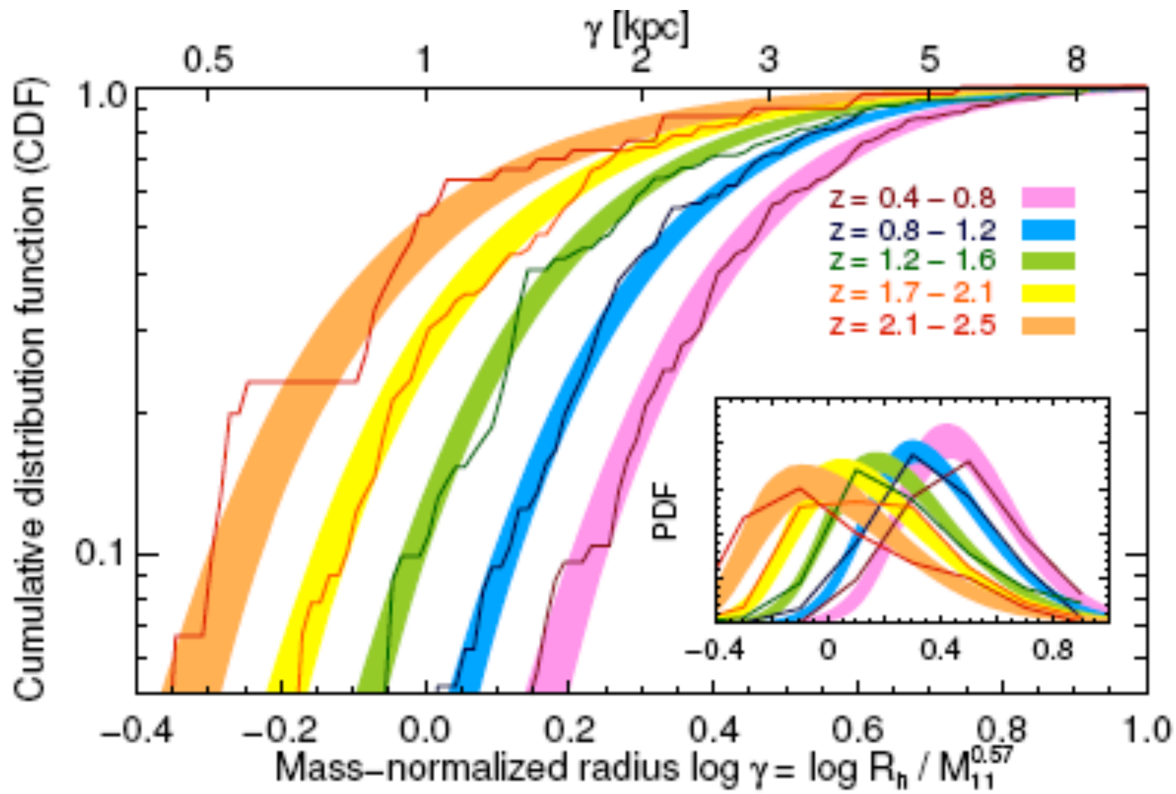
Rapid size growth at high z may be associated with remarkable increase in no. density over 1.5<z<2.5

Evolution in Size Distribution Function

$$R_h = \gamma \left(\frac{M_*}{10^{11} M_\odot} \right)^\beta$$

Key to distinguishing growth of pre-existing sources and the arrival of new sources is the **cumulative distribution of mass-normalized radius γ**

Cumulative Distribution Function (CDF) is fit by a skew-normal distribution at various redshifts



In addition to matching the evolution in **mean size growth** and **number density** of quiescent galaxies, a satisfactory model must also account for the **rate of depletion of the most compact systems** from high redshift to low redshift.

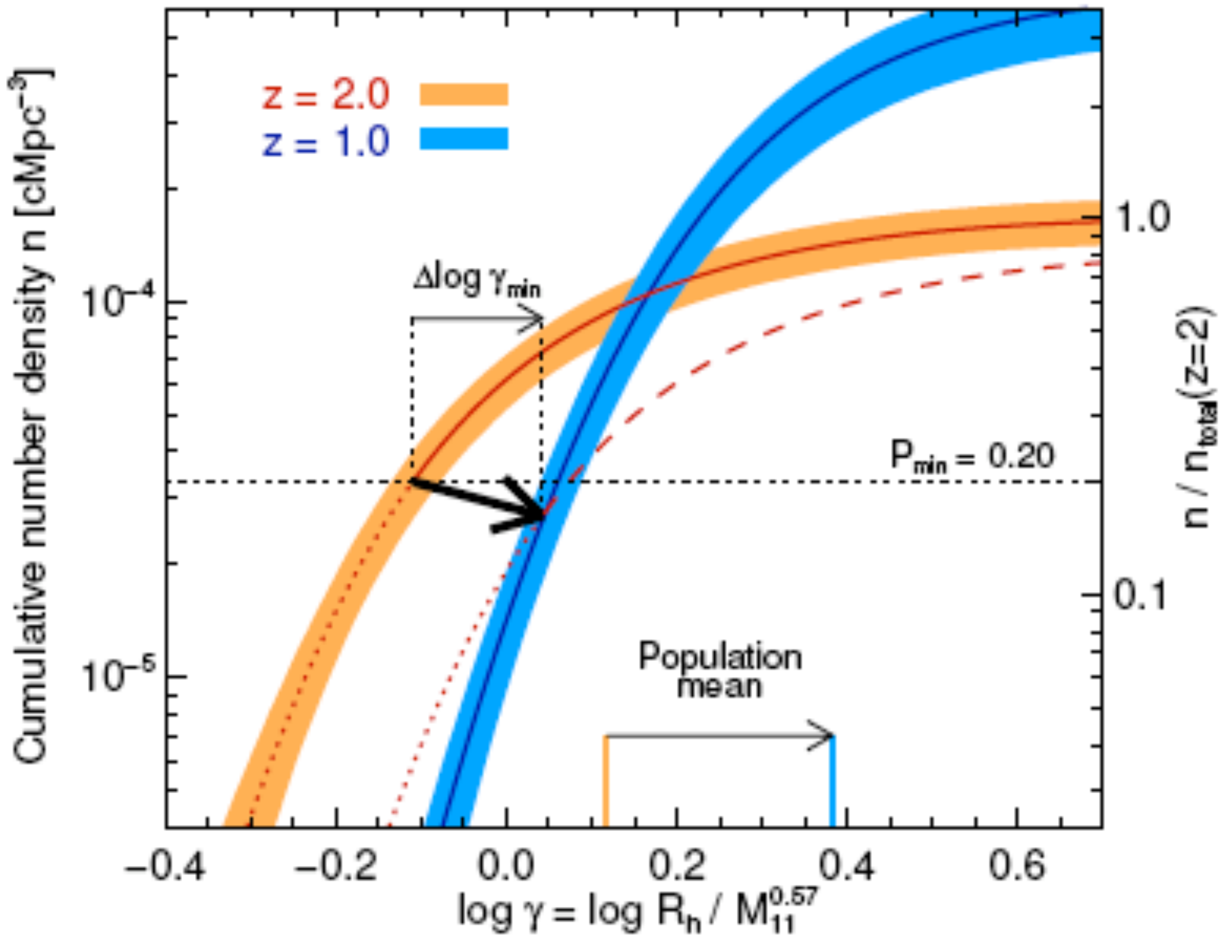
A Two Phase Growth Model

Consider CDF at z~2 and z~1:

Mergers add mass and lead to enlargement.

For “intra sample mergers”, the number also declines.

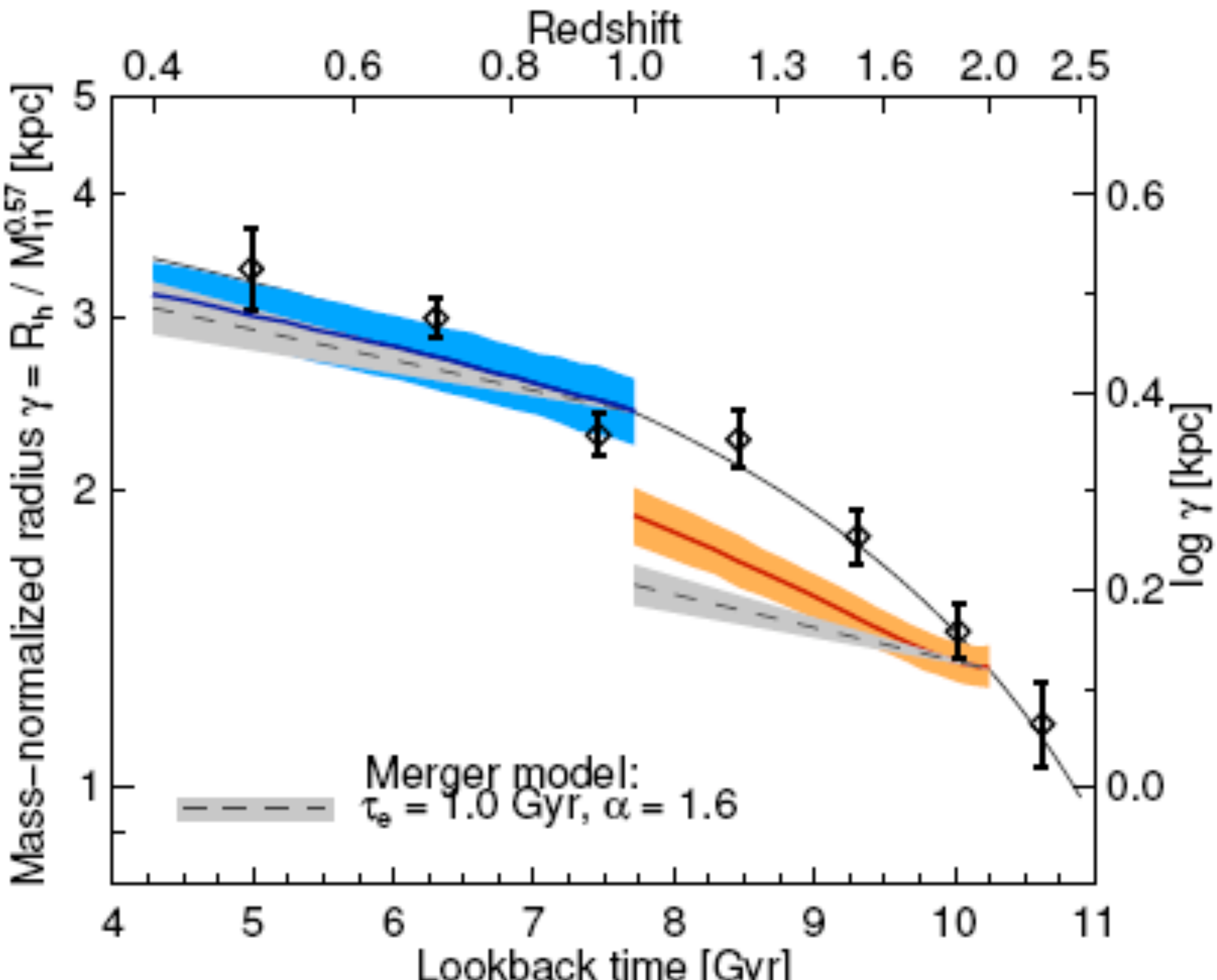
Plausible model will shift some fraction P of the most compact z~2 sources to lie within the z~1 CDF with the remainder (1-P) as `new arrivals’



Defines $\Delta \log \gamma_{min}$

The test is thus whether the observed rate of minor mergers can deplete this fraction of <u>the most compact sources</u> in the observed CDFs

Can Minor Merging Explain Growth: II ?



Conclusion unchanged: 0.4<z<1 size evolution is readily explained by observed rate of minor mergers, but rapid growth over 1<z<2.5 is harder to understand

Newman et al (astro-ph/1110.1637)

Summary

• Present-day massive early type galaxies formed most of their stars by z~2

• Evolving stellar mass functions place some limits on the continued appearance of massive early types: most are not genuine `new arrivals' but represent some combination of dry mergers and truncated star formation in massive blue galaxies

• At lower mass, significant transformations occurred since z~1 as evidenced by the discovery of passive disks in the red sequence at low and intermediate redshift

• The compact nature of early types at z~2.5 is confirmed by CANDELS data; we observe a × 3.5 growth in mean size over 0.4<z<2.5 for quiescent systems with masses > $10^{10.7}$ $M_{\odot}$.

• Dynamical data has been key in verifying the relevant masses, at least to z~1.6; the `red nugget puzzle' is unlikely to be due to observational errors/mis-interpretations

• Minor mergers are so far the only plausible mechanism for the size growth. A study of 404 0.4<z<2 quiescent hosts in the CANDELS data gives a pair fraction of 13-18% for mass ratios > 0.1.

• Modeling suggests the observed merger rate can explain the growth observed since z~1 but explaining the rapid growth observed over 1.5<z<2.5 remains a challenge