Getting a Grip on Galactic Girths

Science Review

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February 2, 2015

Outline

1. Fundamental observations of galaxy sizes and evolution
2. Measuring galaxy size growth histories
3. Beyond half-light radii (morphology, multi-component galaxies)
4. Merger rates
5. Galaxy growth in different environments
6. Formation of massive/compact galaxies at z>~3

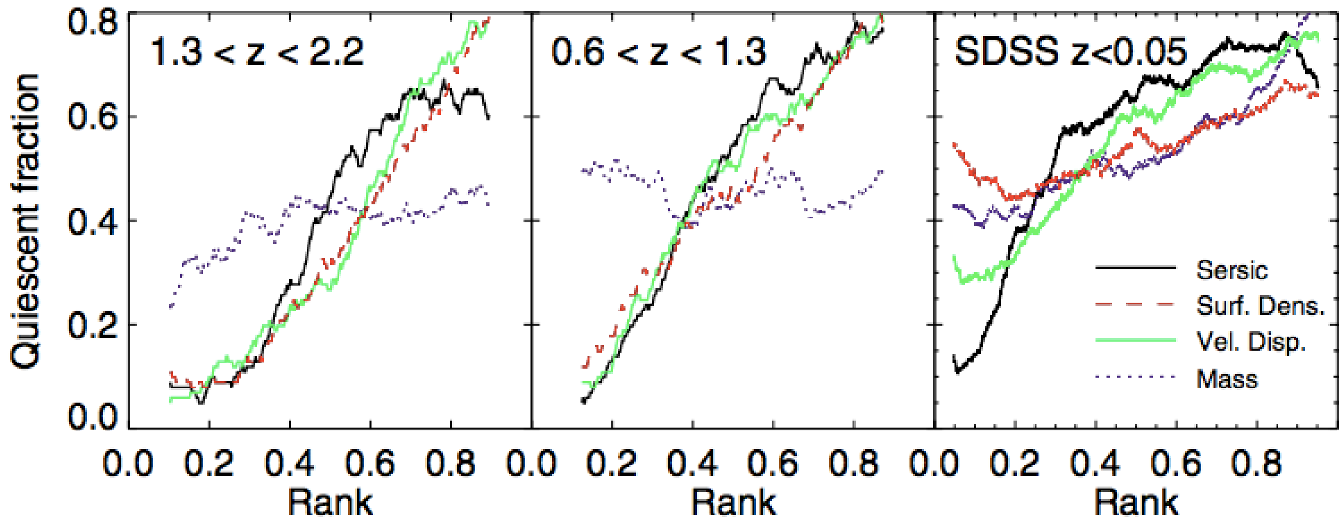
Galaxy Growth Phenomenology

Galaxy structure is closely connected with star formation activity to at least z ~ 2

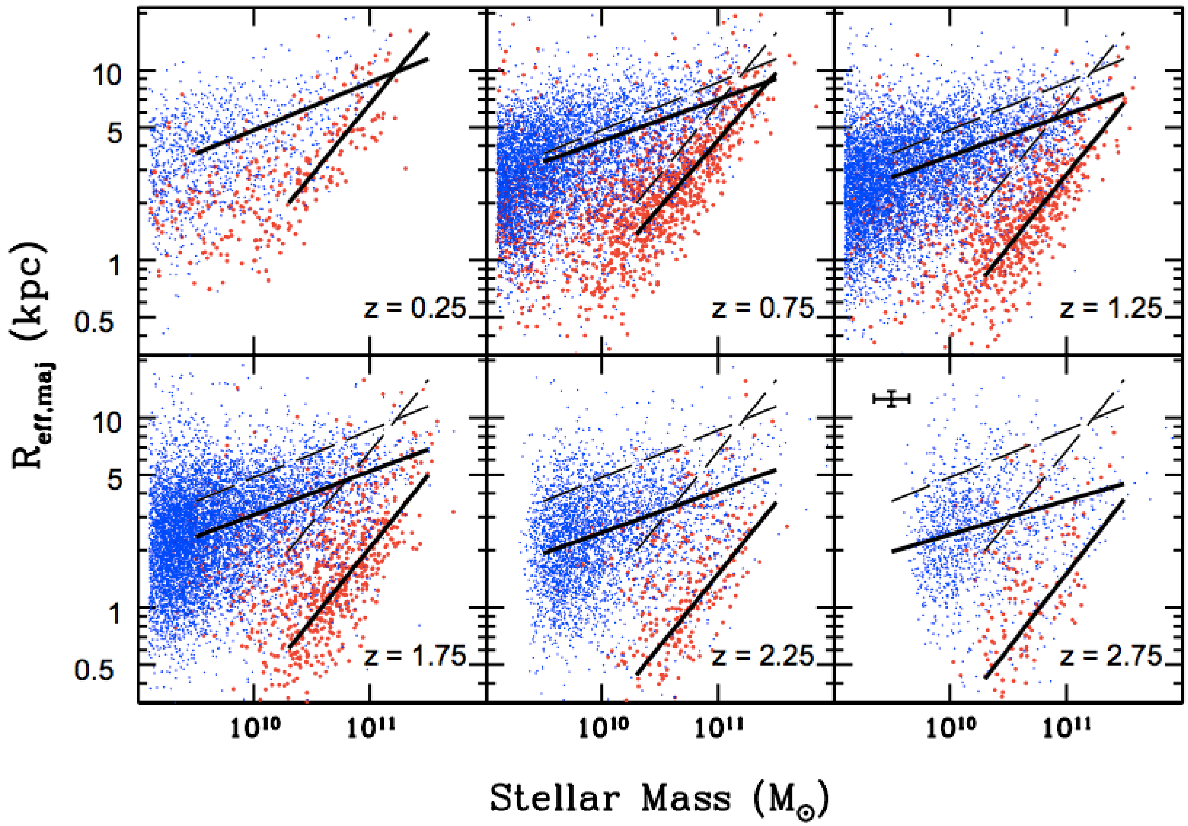
High central density or bulge seems to be a necessary ingredient for quenching

σ: Wake+ 2012
n: Bell+ 2012
Σ: Williams+ 2010
$\Sigma_{1\ kpc}$: Cheung+ 2012, van Dokkum+ 2014

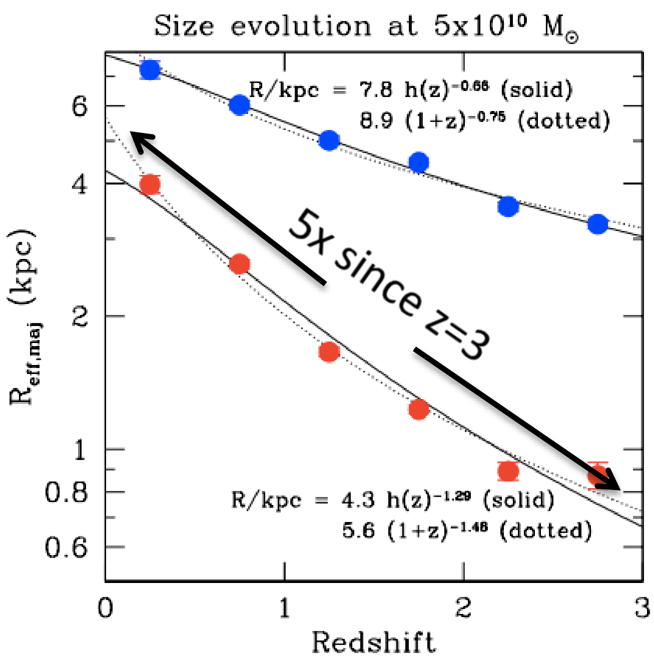
Bell+ 2012



The mass—radius relation evolves strongly

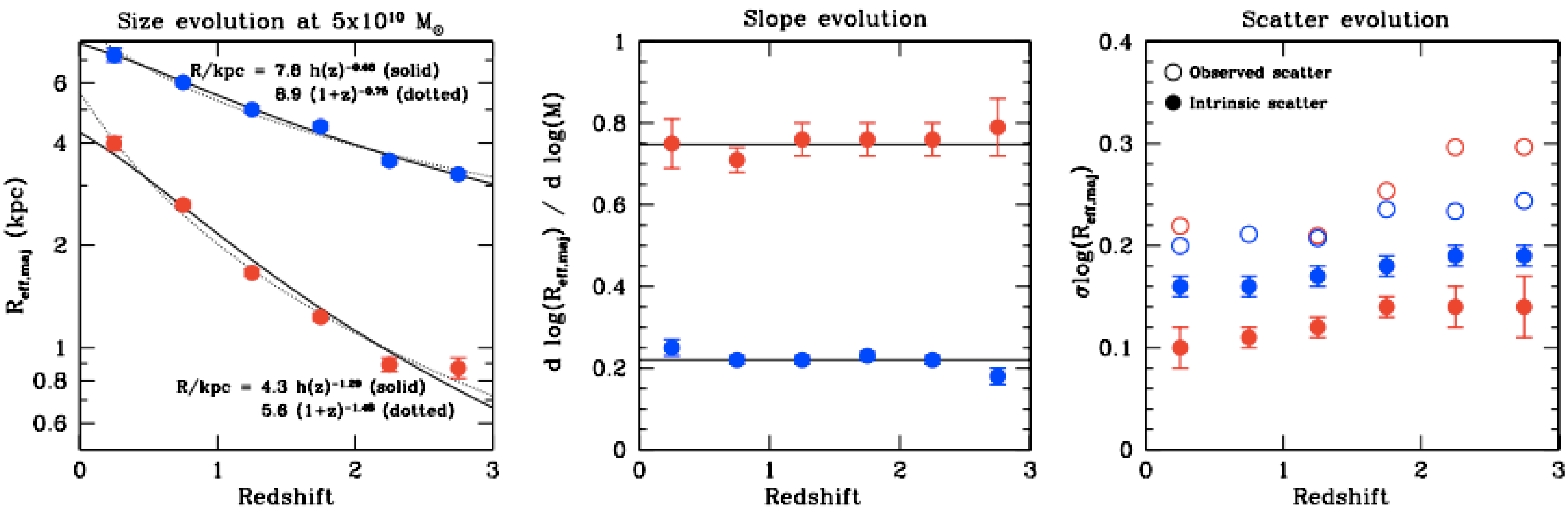


van der Wel+ 2014: 31,000 galaxies in CANDELS



The mass—radius relation evolves for all galaxy types but seemingly *more rapidly* for quiescent galaxies or spheroids.

The mass—radius relation evolves simply

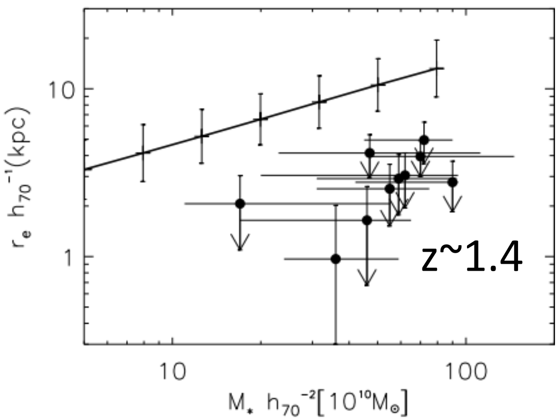


van der Wel+ 2014

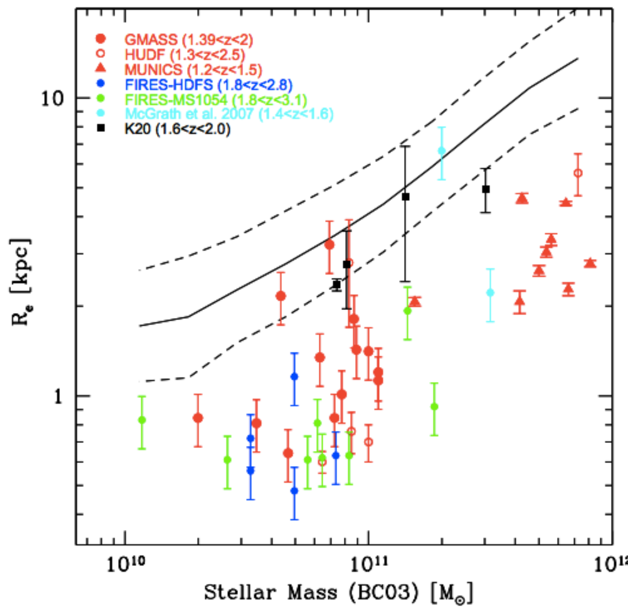
Intercept evolves strongly—slope and scatter, hardly at all

(see also Newman+ 2012)

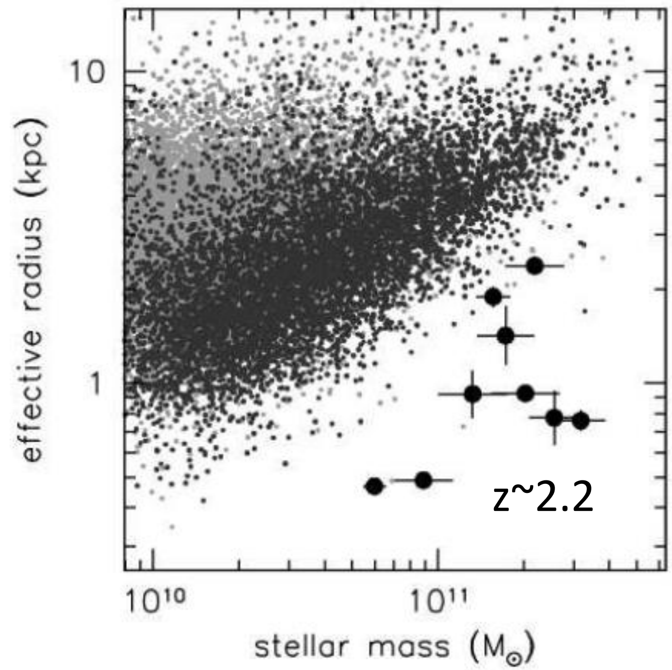
Quiescent galaxies at z~2 are very compact



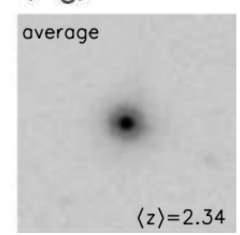
Trujillo+ 2006



Cimatti+ 2008



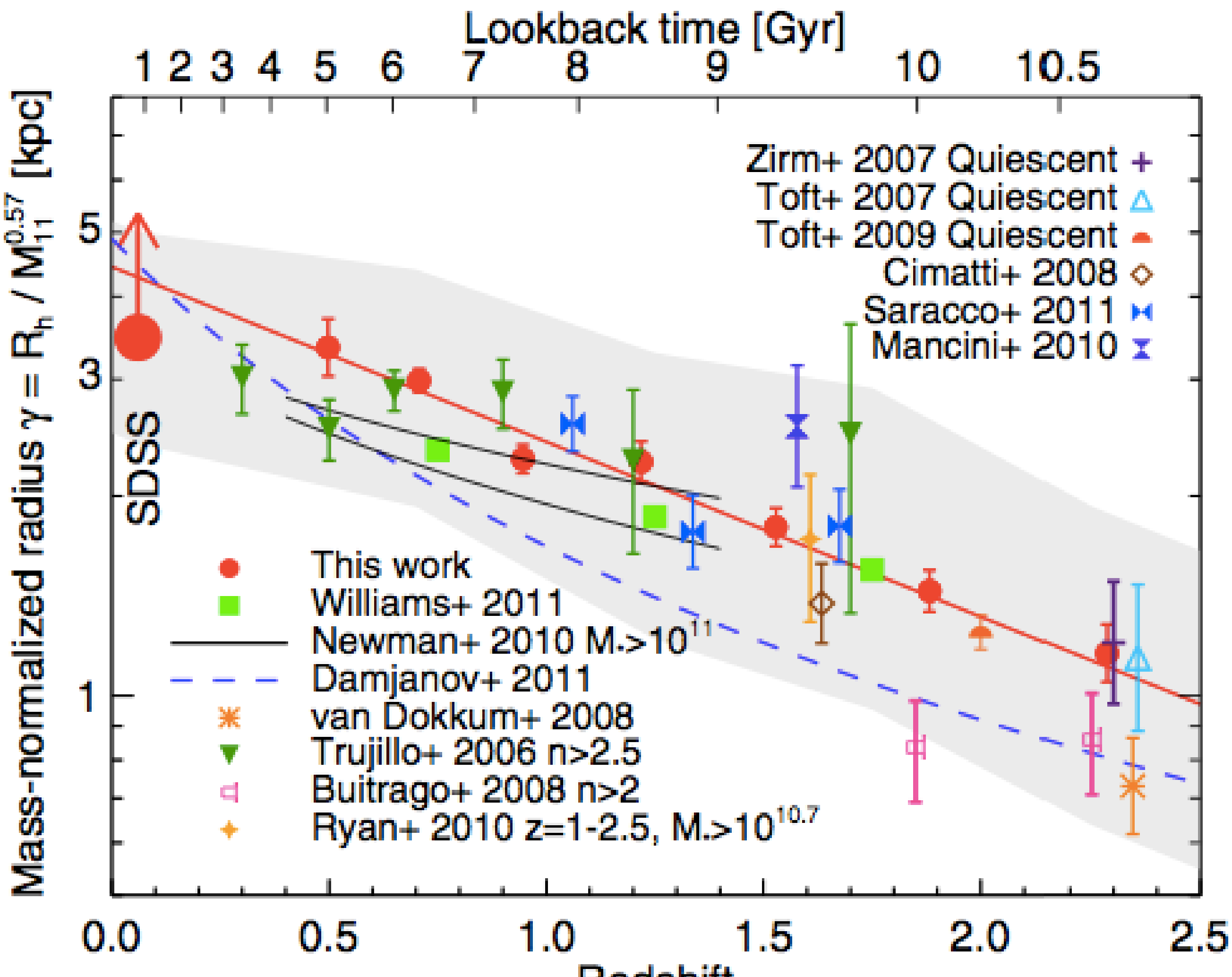
van Dokkum+ 2008



"No evolution" scenario not possible for the ultracompact "nuggets" → "dead" galaxies continue to grow. How and how much?

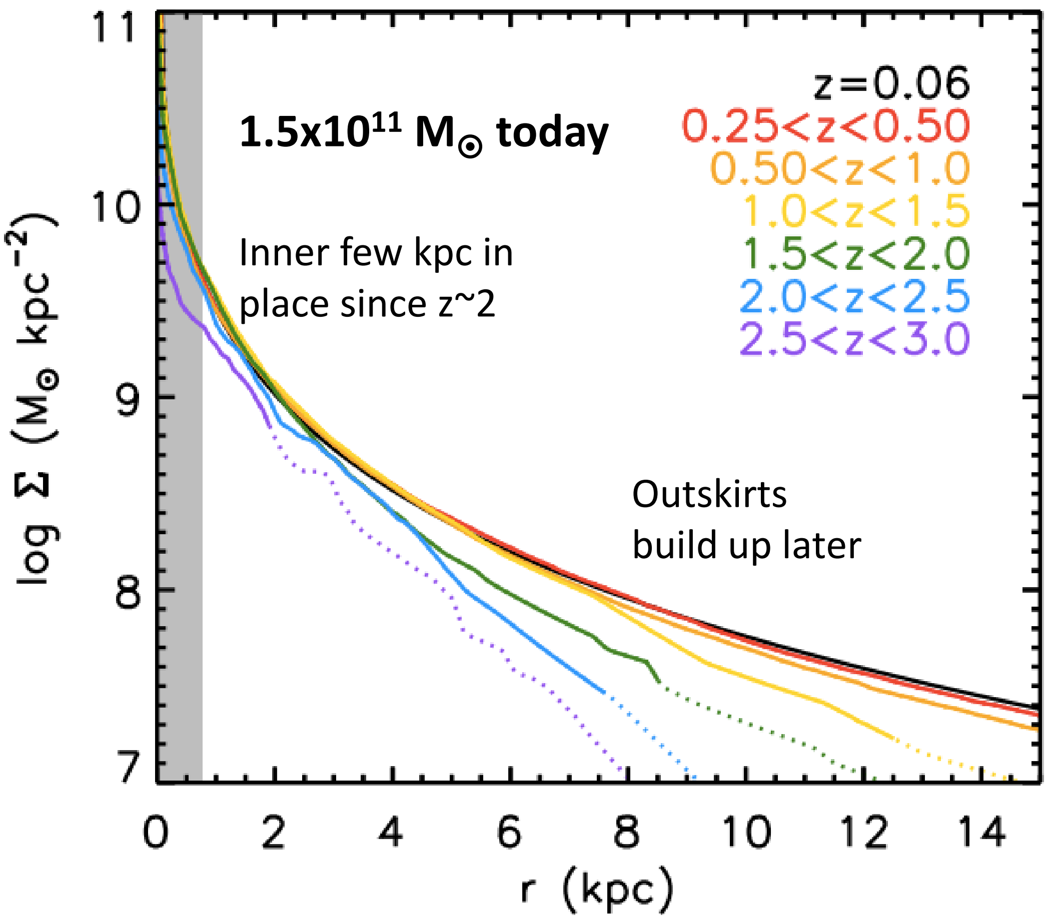
Daddi+ 2005, Trujillo+ 2006, Zirm+ 2007, Toft+ 2007, 2009, Cimatti+ 2008, van Dokkum+ 2008, Buitrago+ 2008, Mancini+ 2010, Ryan+ 2010, Saracco+ 2011, Williams+ 2011, Damjanov+ 2011, Newman+ 2012, Patel+ 2013

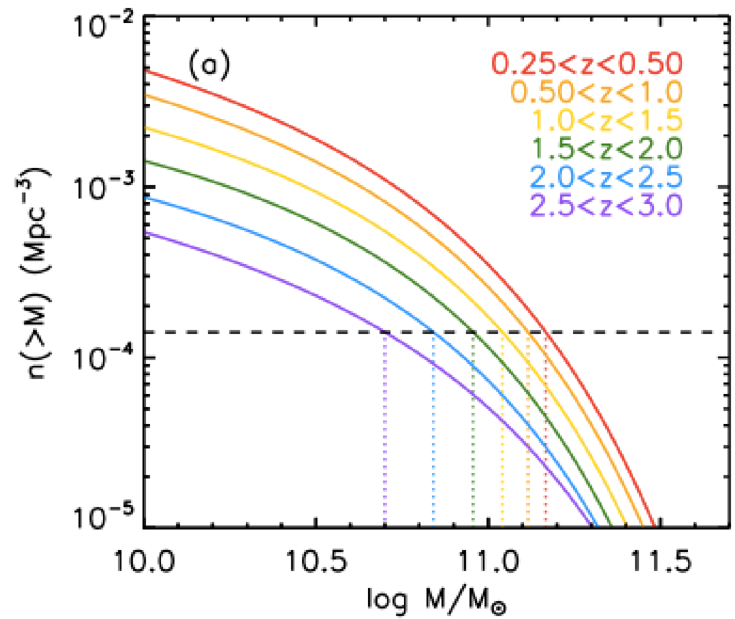
Comparison of z<2.5 size measurements



Newman+ 2012

The growth of massive galaxies is “inside-out”





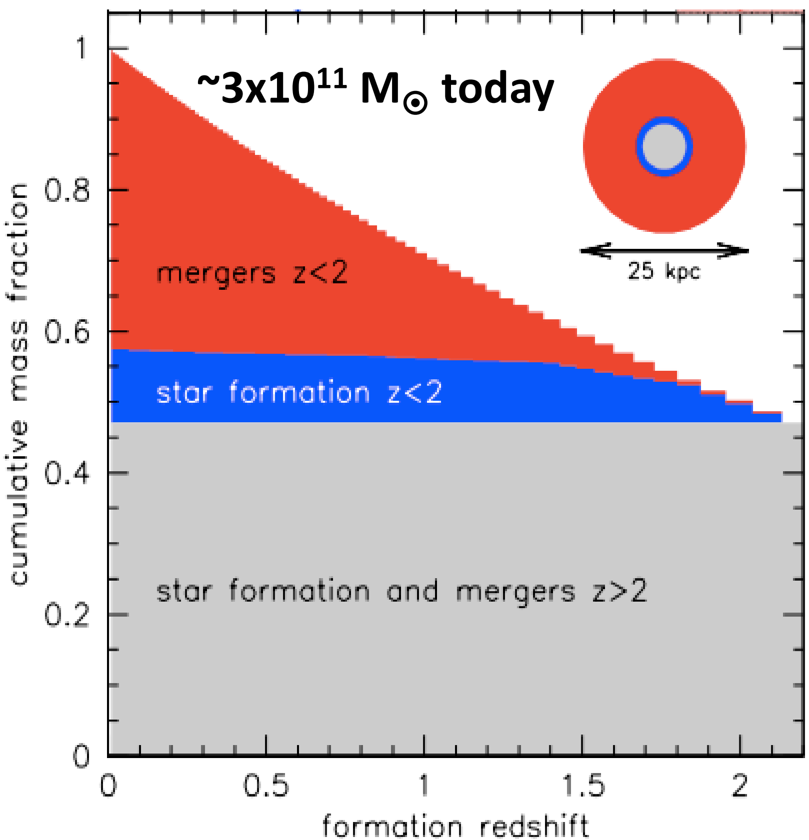
Patel+ 2013

Densities not especially high within a fixed physical aperture

Hopkins, **Bundy**+ 2009, Bezanson+ 2009, Naab+ 2009, Carrasco, Conselice & **Trujillo** 2010, van Dokkum+ 2010, **Patel**+ 2013

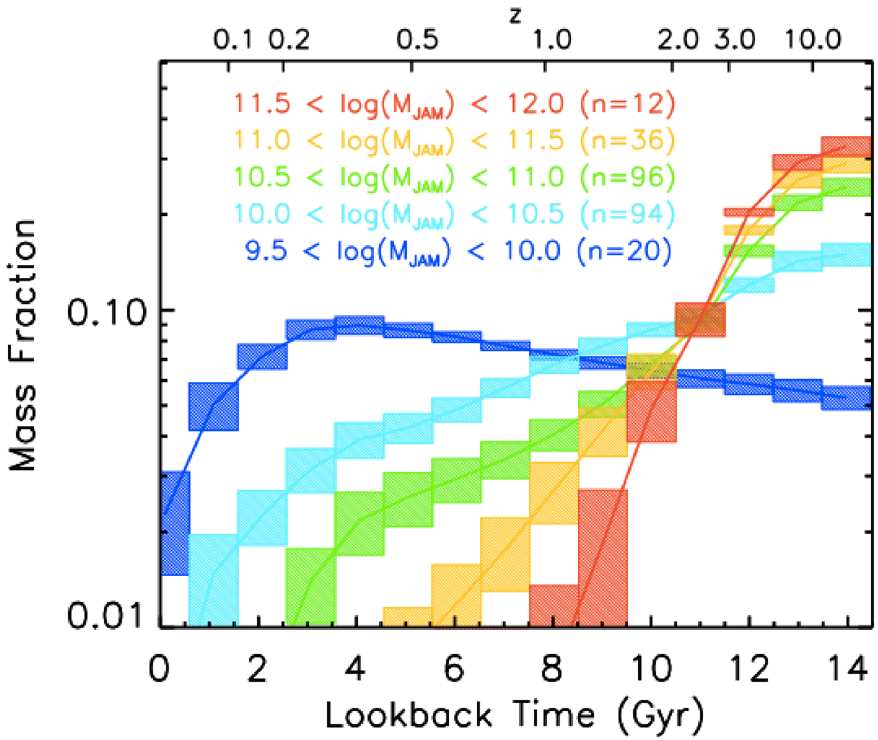
Star formation is not sufficient to fuel mass growth in massive galaxies

Lookback with # density matching



van Dokkum+ 2010

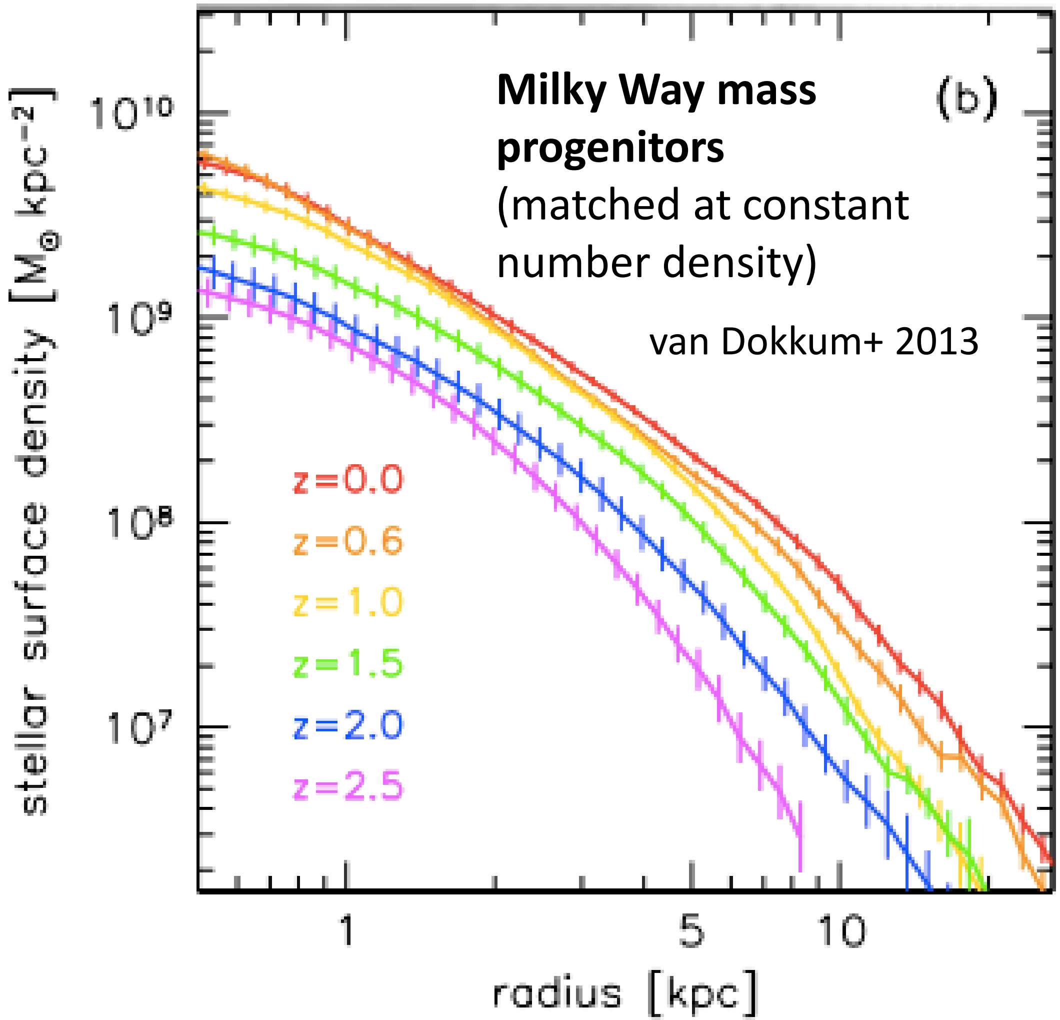
Local archaeology



McDermid+ 2015

Star formation is negligible below z~1.5 → mergers presumably fuel growth.

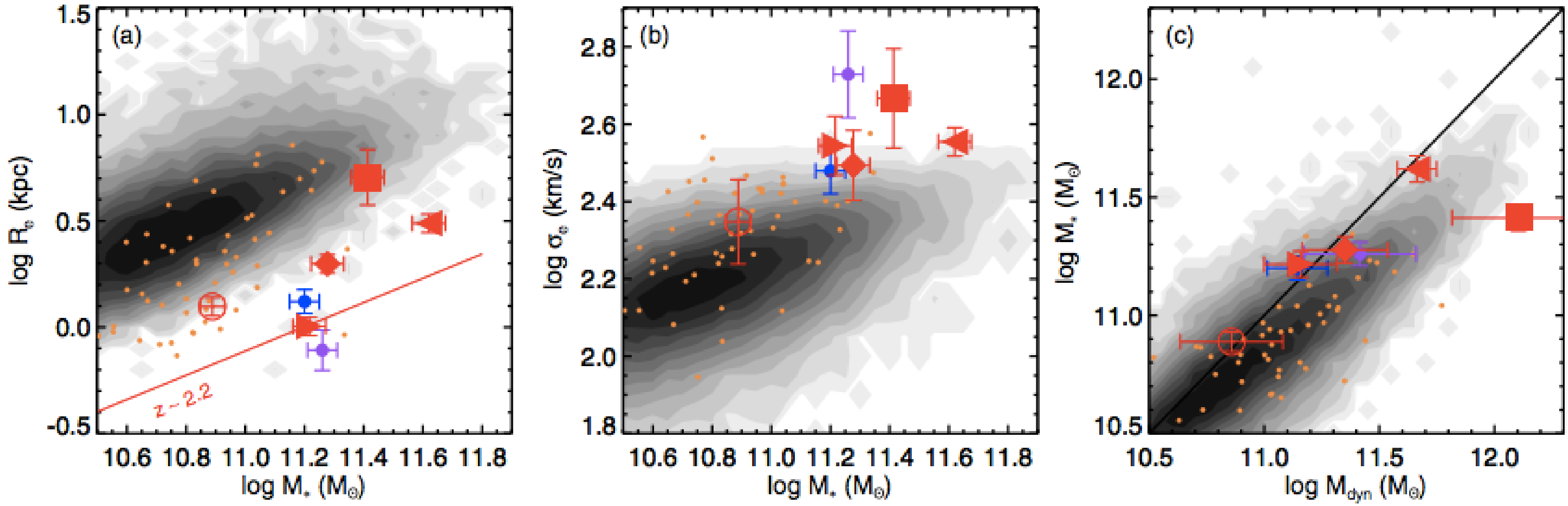
Not all galaxies grow "inside-out" or require mergers



Mass growth is consistent with measured in situ star formation.

Mergers are less significant below 10^{11} $M_{\odot}$ (Bundy+ 2009, Peng+ 2010, Nierenberg+ 2012)

Dynamical masses track stellar masses consistently to at least z~1.5



SDSS red sequence galaxies

z=1-1.6 quiescent galaxies (Keck/LRIS)

z=2-2.5 quiescent galaxies (Keck/MOSFIRE)

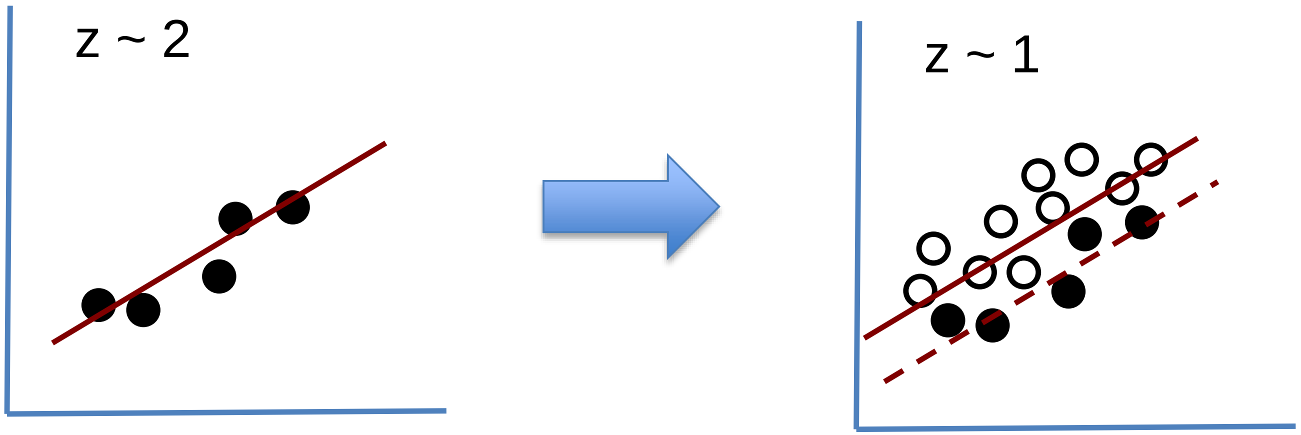
Belli, **Newman**, Ellis & Konidaris (2014)

But see Peralta de Arriba+ 2014

Measuring galaxy size growth histories

a.k.a., Disentangling progenitor bias

Does the evolution in the scaling relation resemble evolutionary paths of galaxies?

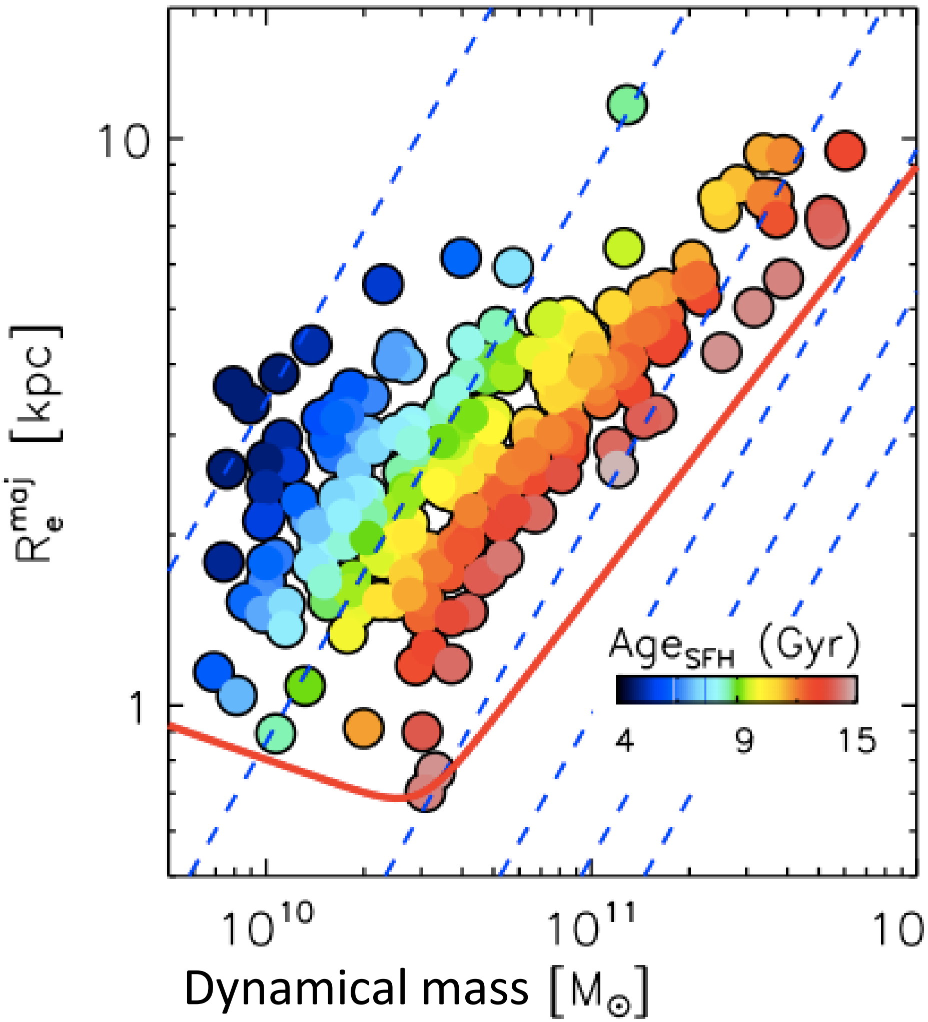


Progenitor bias

How do we connect galaxy populations at different epochs?

Need number densities and age measures

Locally: Older galaxies are smaller at fixed M_*

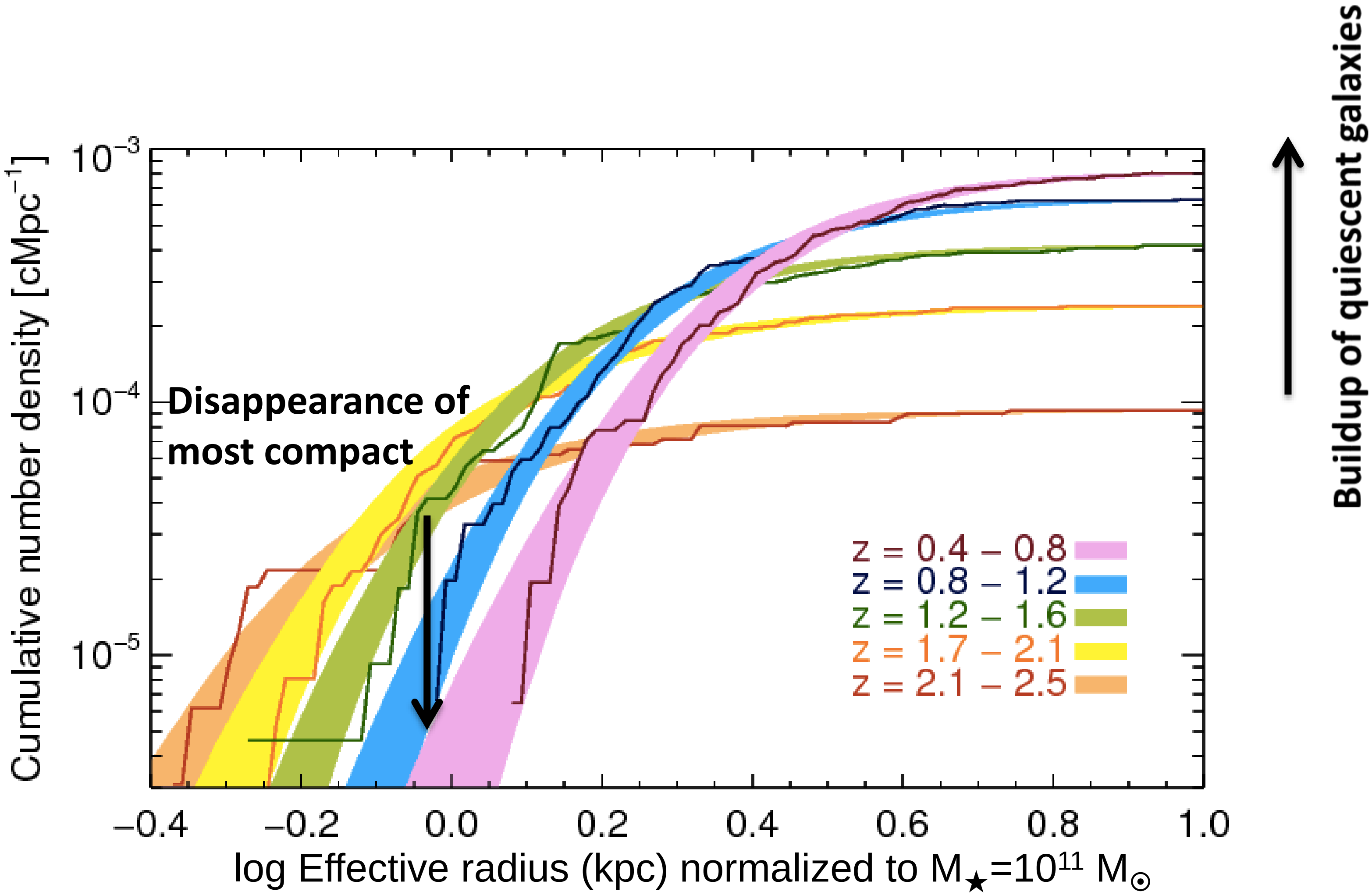


McDermid+ 2015

Stellar population mean age tracks velocity dispersion σ (diagonal lines), not mass.

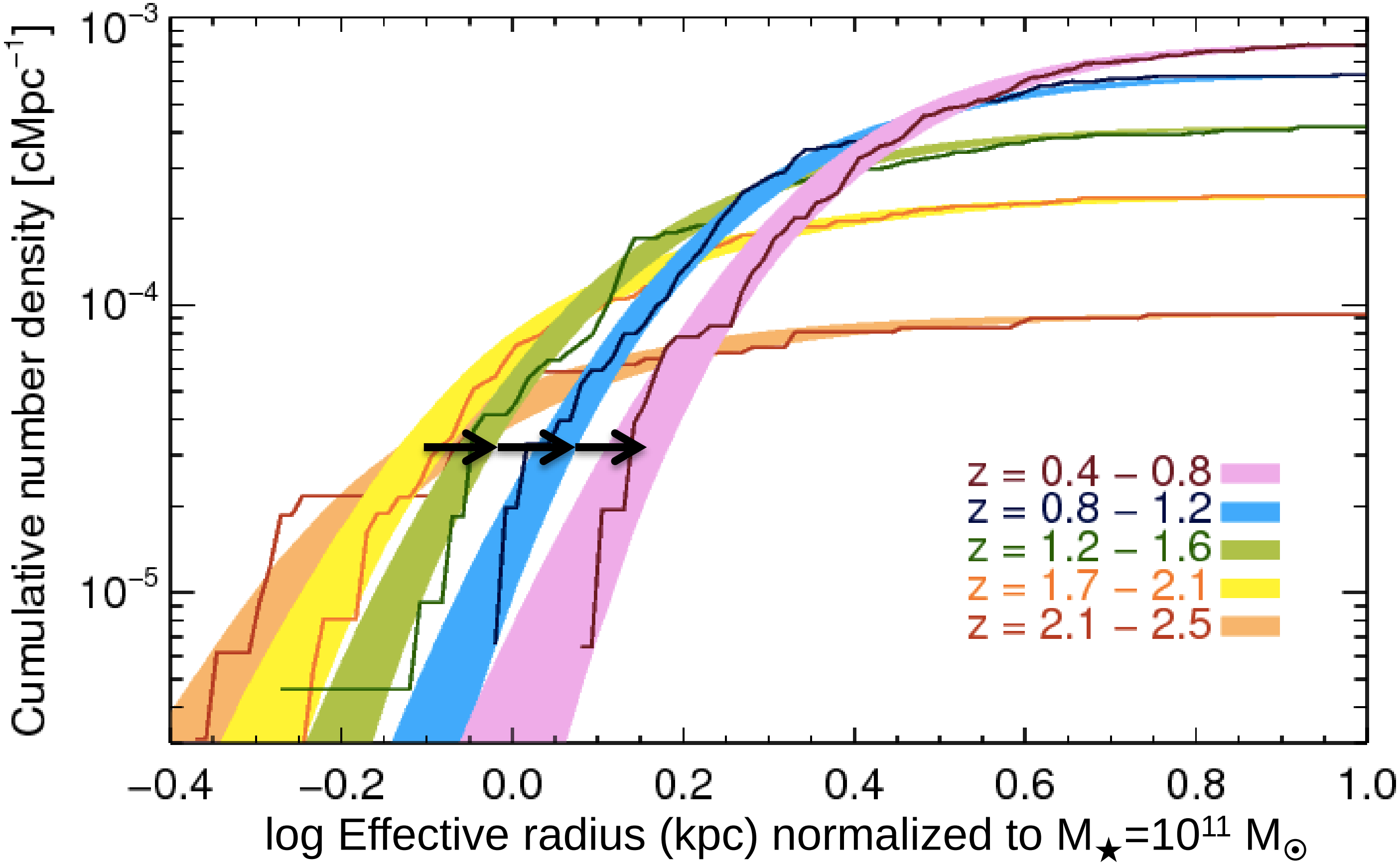
Shankar & Bernardi+ 2009**, van der Wel**+ 2008, 2009, Graves+ 2009, Saracco+ 2009, Valentinuzzi+ 2010, **Poggianti**+ 2013, McDermid+ 2015, *but see **Trujillo**+ 2011*

Method 1: Connecting the most compact galaxies



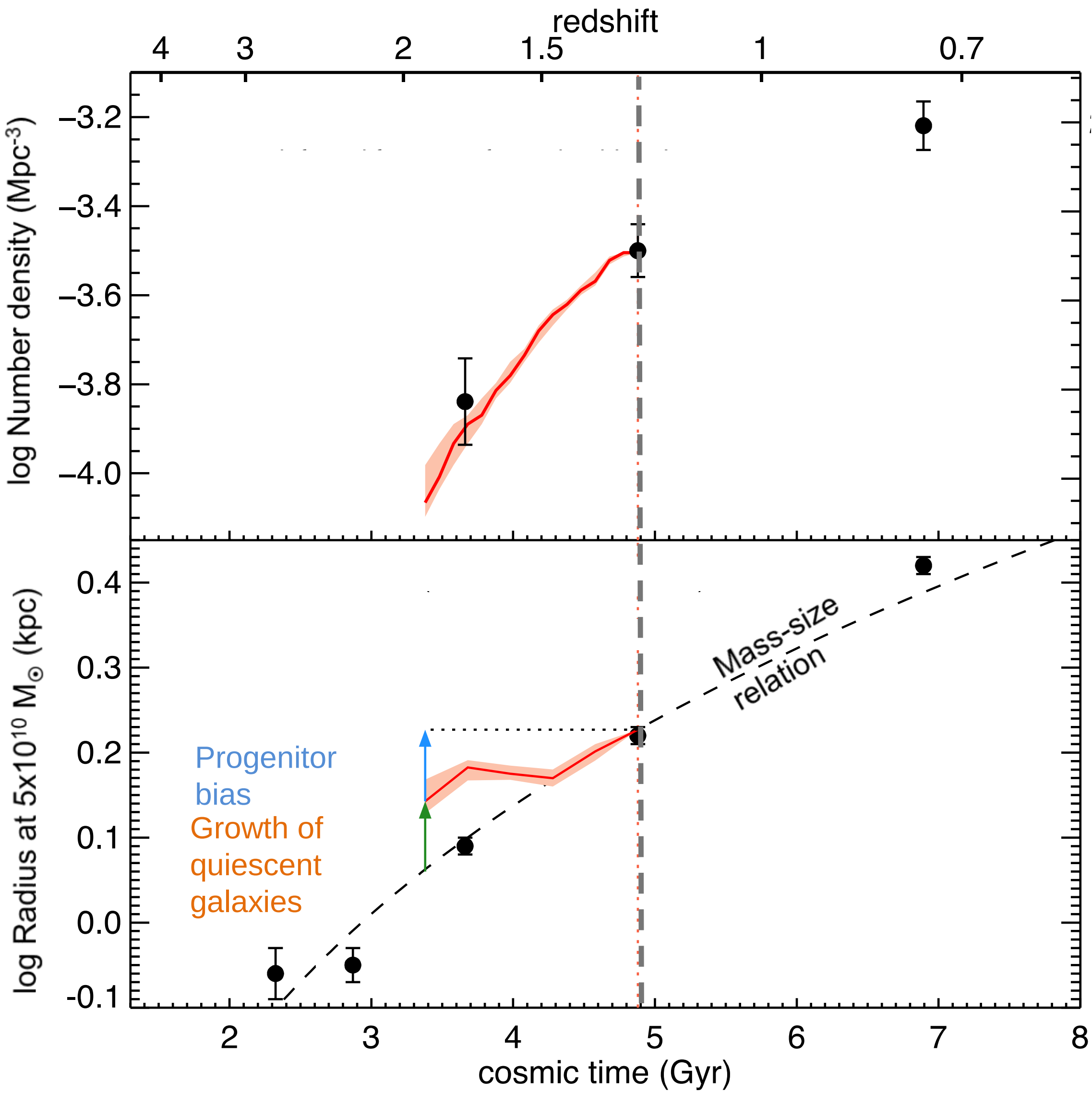
Newman+ 2012

Method 1: Connecting the most compact galaxies



Newman+ 2012

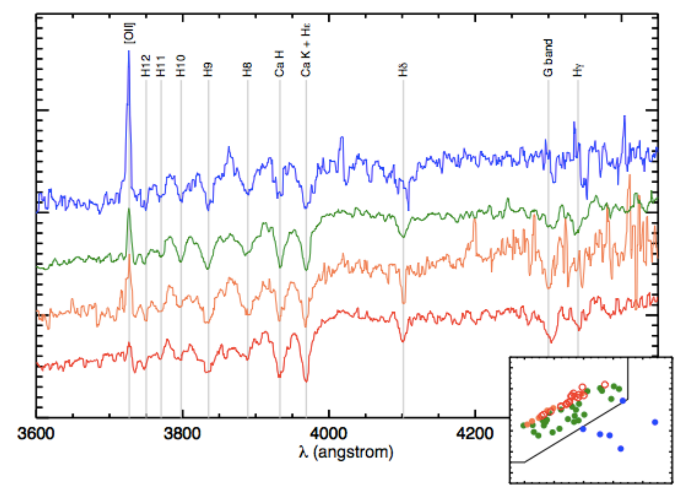
Method 2: Star formation histories



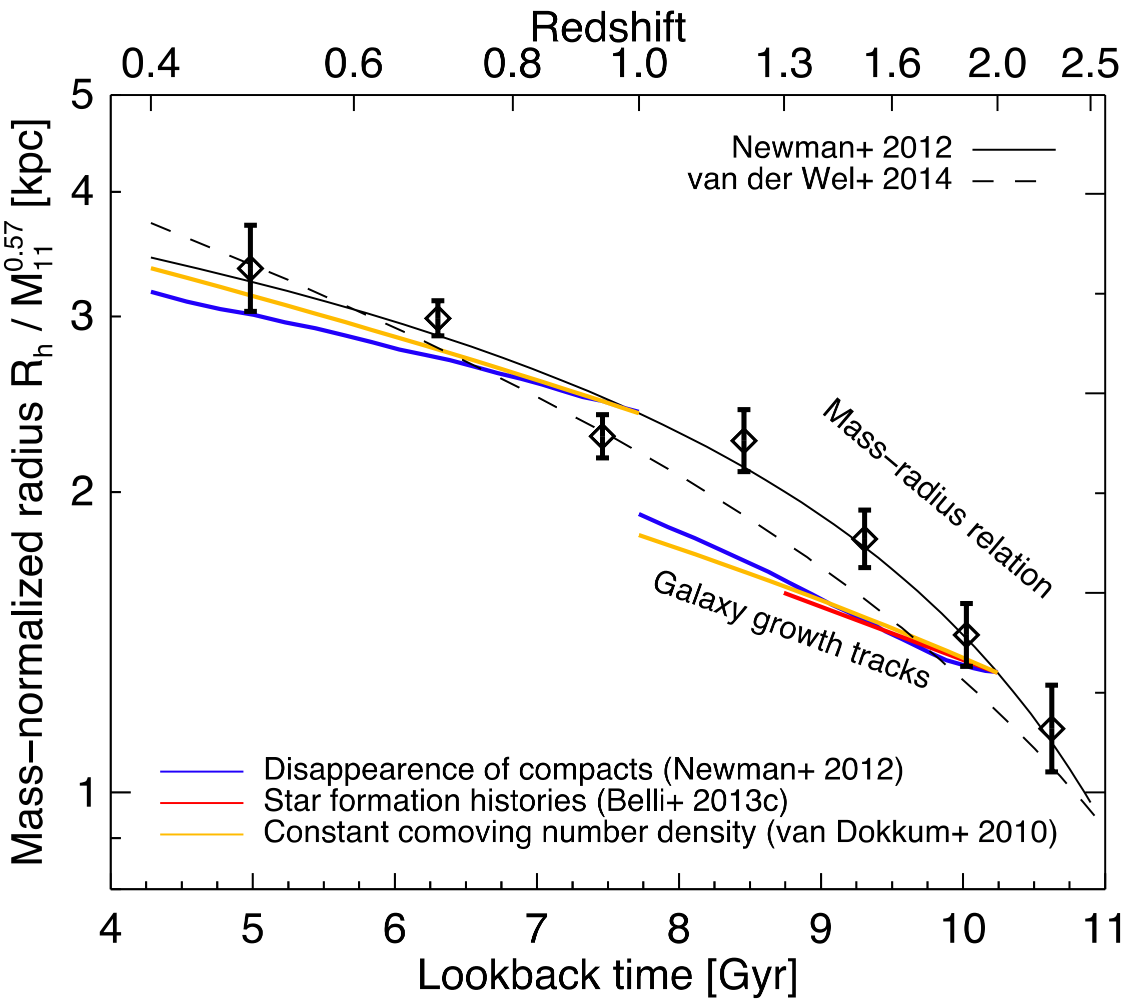
Belli, **Newman** & Ellis 2013c

Star formation histories from **spectra** reproduce the *numbers* of quiescent galaxies over z=1.3-2…

But only ***half*** of the shift in the mass-size relation—remainder is growth of quiescent galaxies



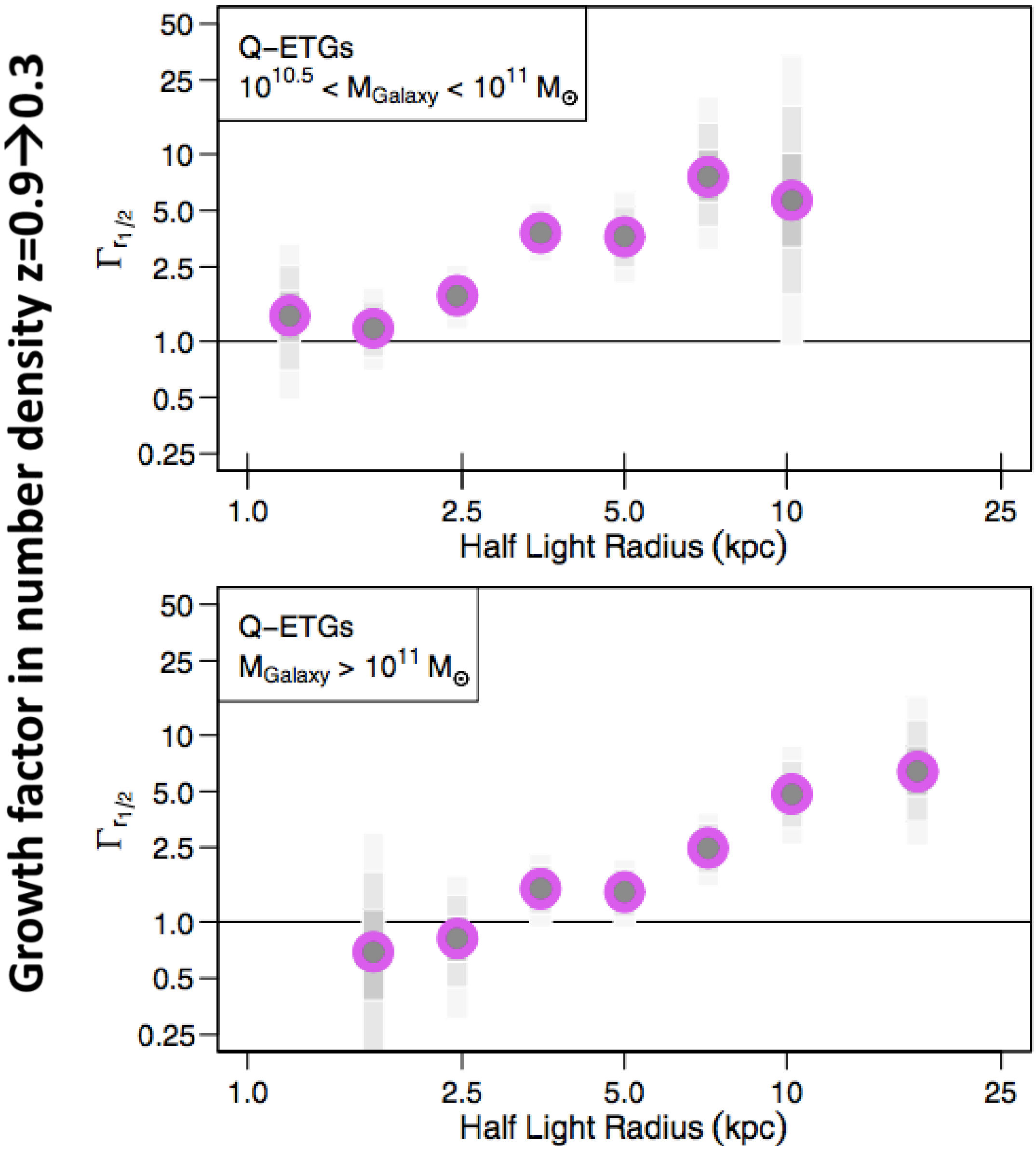
Estimates of the rate of galaxy growth rate (note not mass-size evolution!) agree surprisingly well



Over z=1—2: ~Equal contributions from growth of dead galaxies & progenitor bias

At z < 1: Progenitor bias seems to play a lesser role

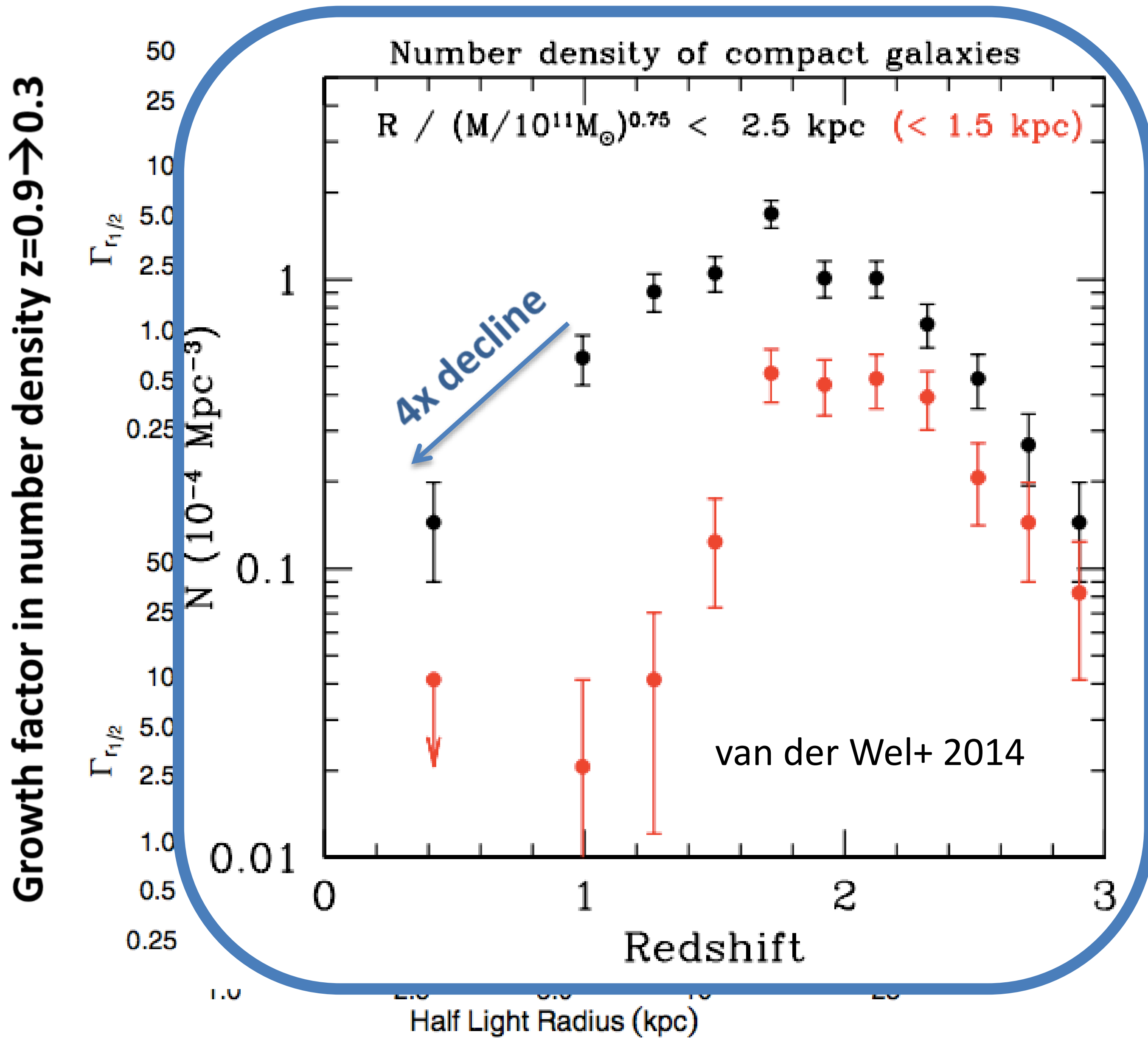
Is ETG size growth significant at z < 1?



Carollo+ 2013

Conclude that quenching of larger galaxies drives almost *all* of the mass—radius evolution since z=1

Is ETG size growth significant at z < 1?



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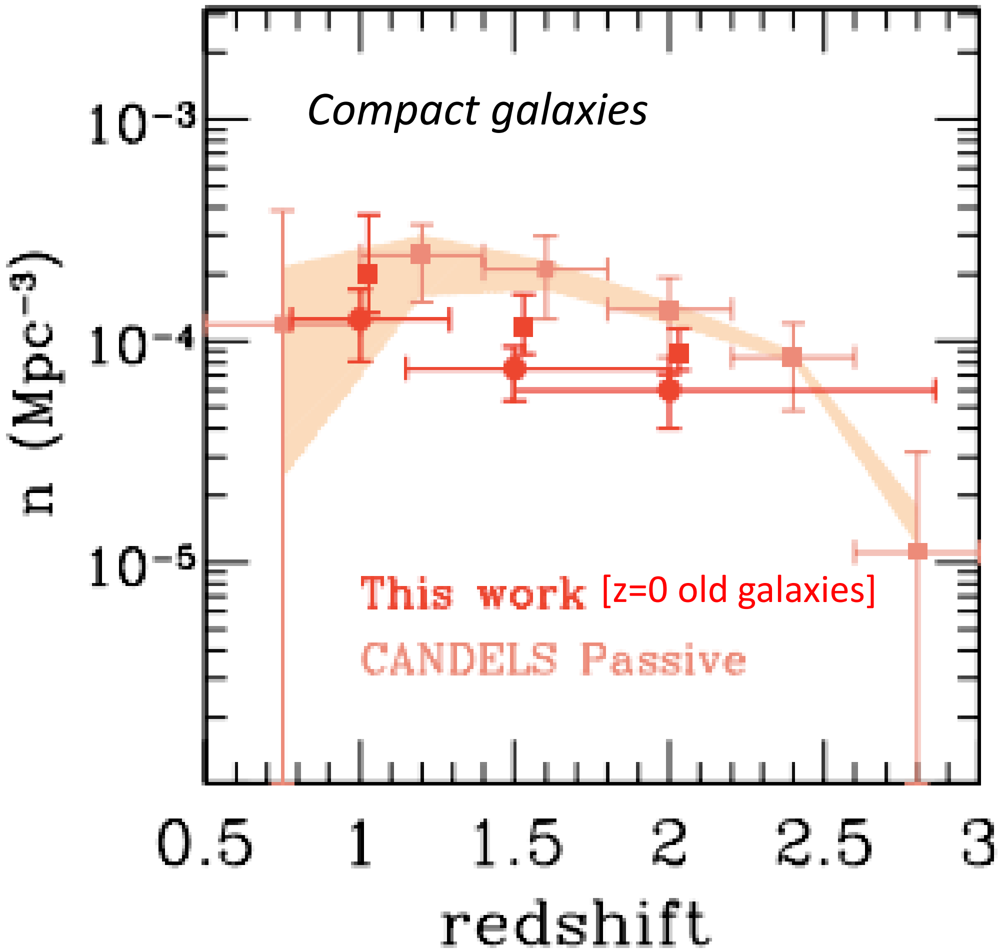
Local archaeology + z > 1 lookback studies

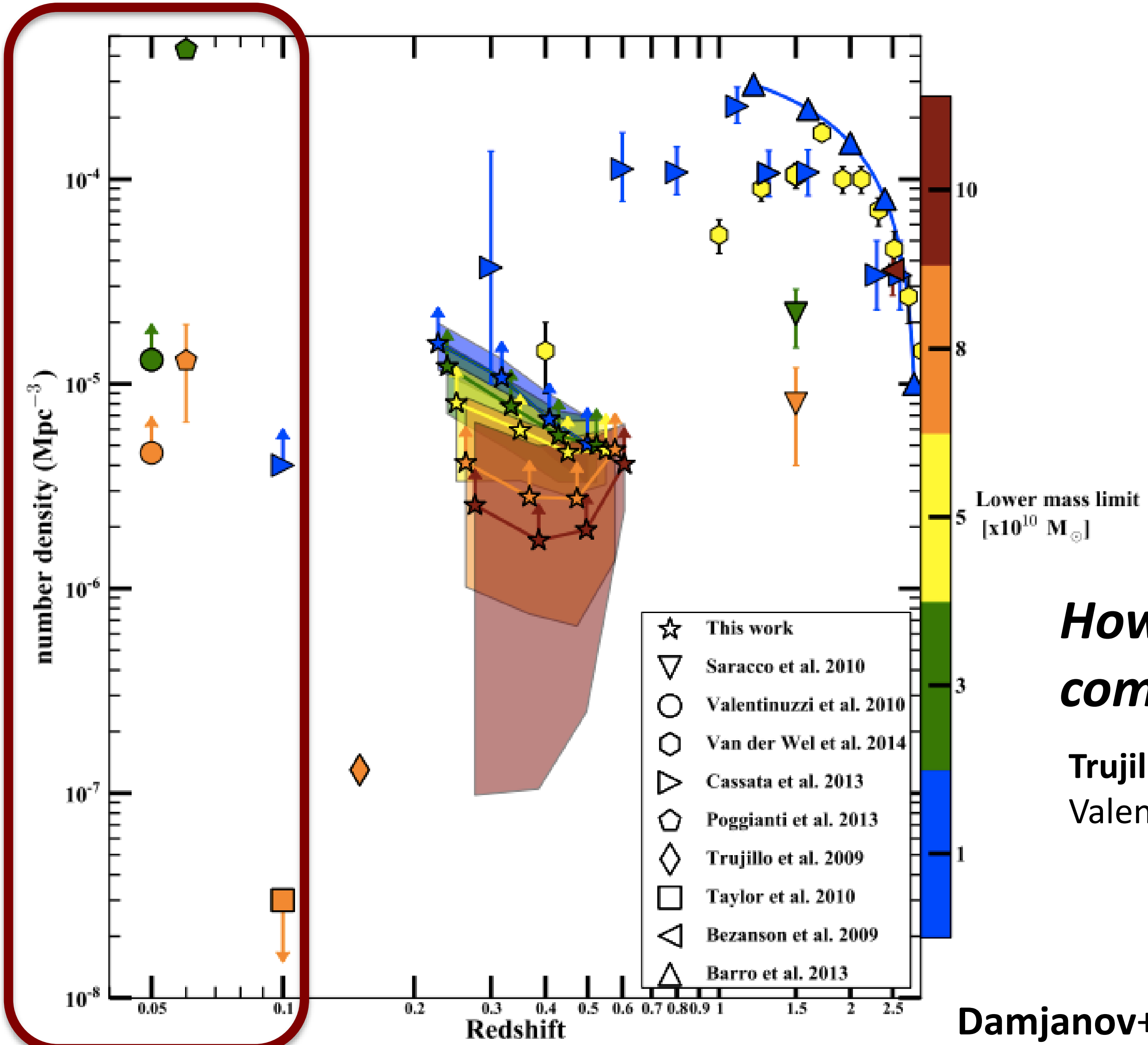


Poggianti+ 2013

Local old compact galaxies are present at ~half the abundance as z ~ 1.5

Infer greater growth for a more restrictive definition of "compact" (the majority at z>2).

How well do number densities agree?



How common are local compact "relics"?

Trujillo+ 2010, Taylor+ 2010, Valentinuzzi+ 2010, **Poggianti**+ 2013

Damjanov+ 2014

Questions

- Have we converged on a size growth rate for quiescent galaxies at $z > 1$ (i.e., separated progenitor bias)?
- What is happening at $z < 1$?
- How many local compact galaxies are there?

No one survey has great statistics at very low ($z=0$) and high ($z=2$) redshift – are our inter-comparisons fraught?

Beyond half-light radii

Morphologies & multi-component light profiles

What processes cause star formation to die or structural changes to occur?

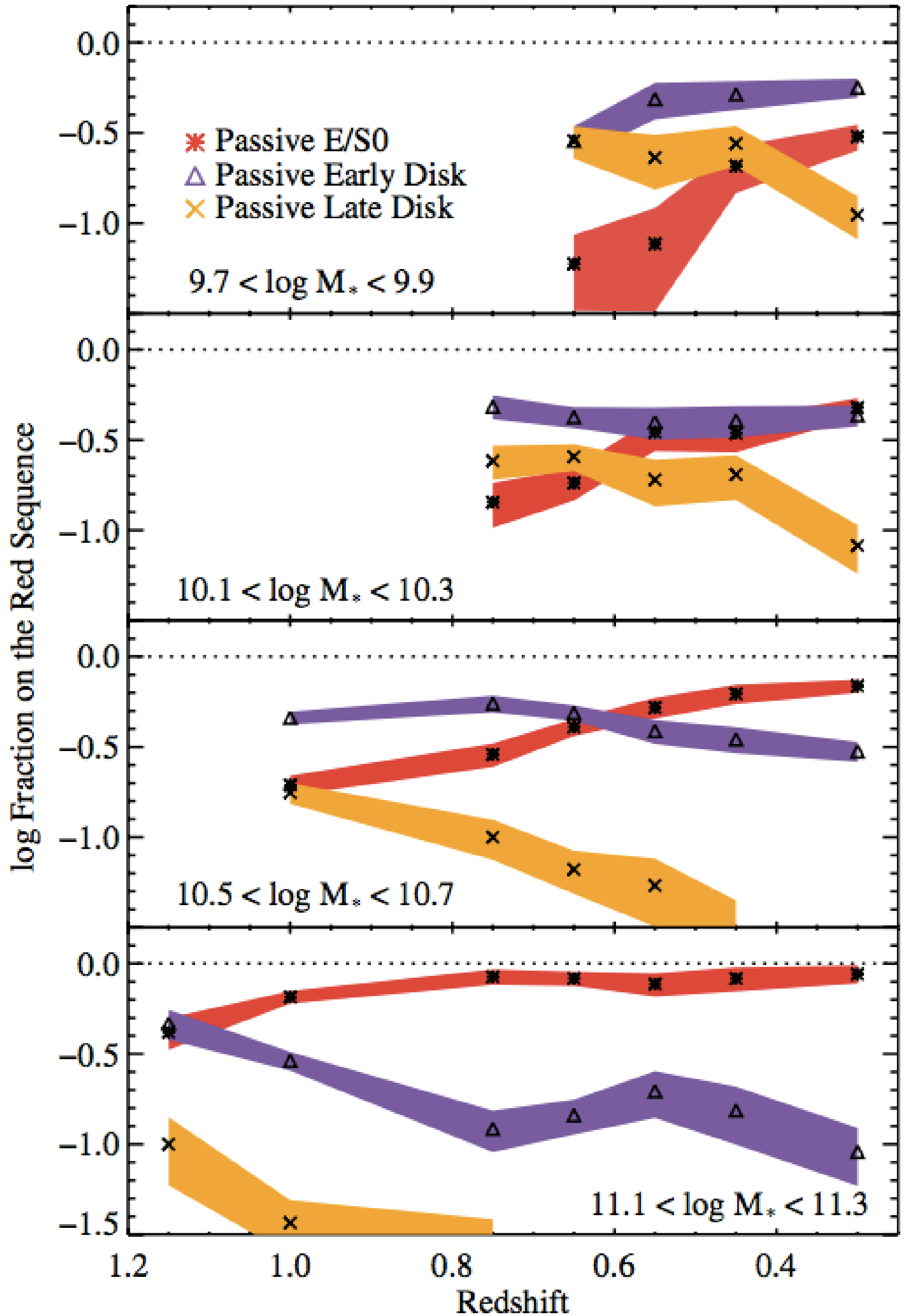
- Harassment
- Starvation / strangulation
- Ram pressure stripping
- Mergers (dry / wet, major / minor)
- Disk instabilities ("violent" or otherwise)
- Secular evolution
- Tidally triggered star formation
- …

Measure:

Connection between star formation and morphology

Timescales via lookback studies

Environmental dependences



Passive disks/spirals

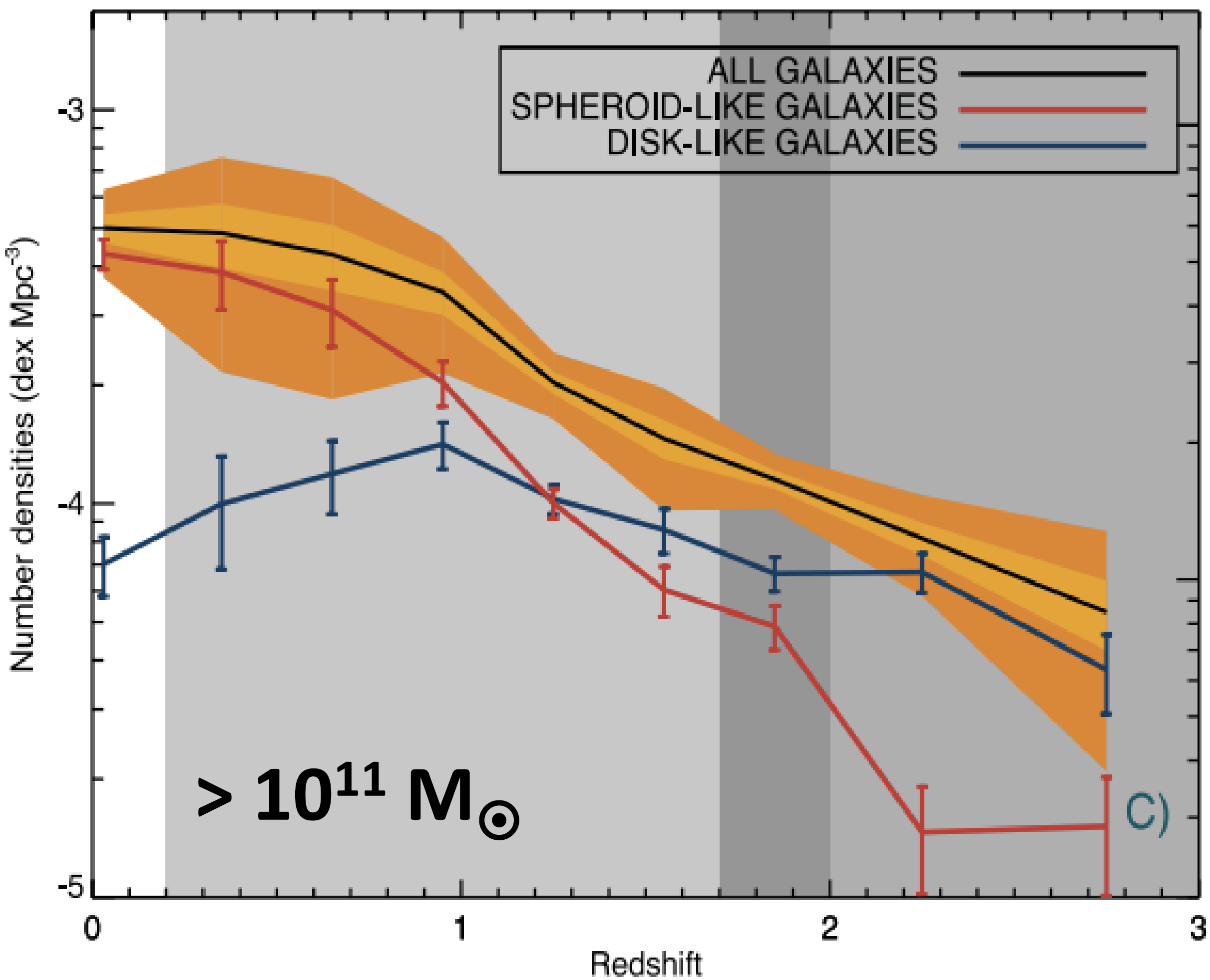
Very common at low masses – quenching processes doesn't always lead to E/S0's

At higher masses passive disks decline since z~1—presumably as they transform to E/S0.

Bundy+ 2010

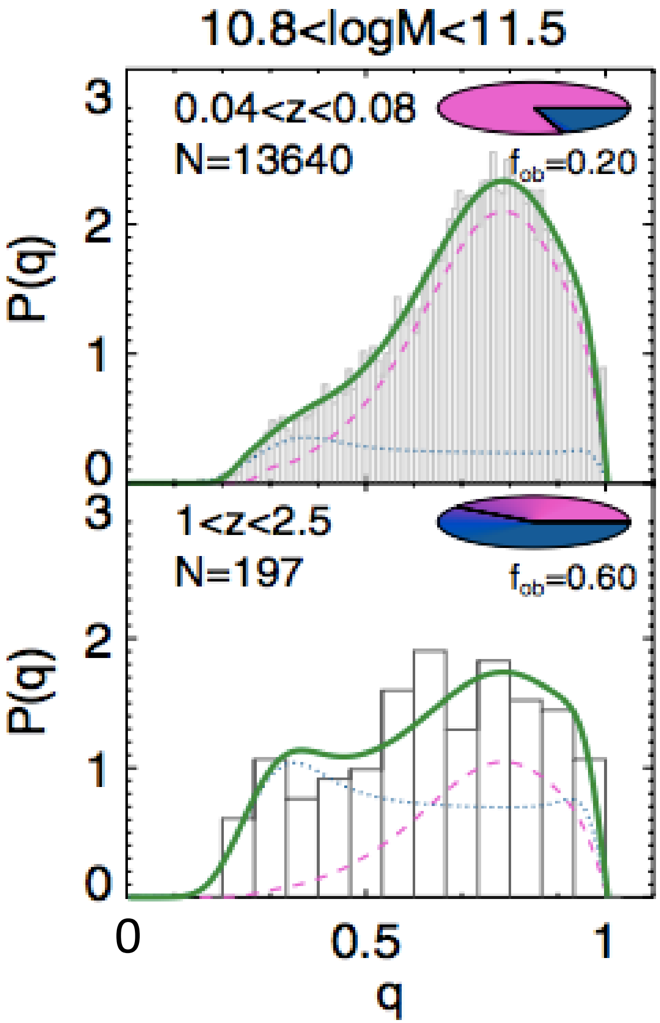
Bamford+ 2009, Masters+ 2010, **Bruce**+ 2012, …

Most massive galaxies at z > 1 are "disky"



Buitrago, **Trujillo**, Conselice & **Häuβler** 2013

The rise of massive spheroids doesn't directly track quenching



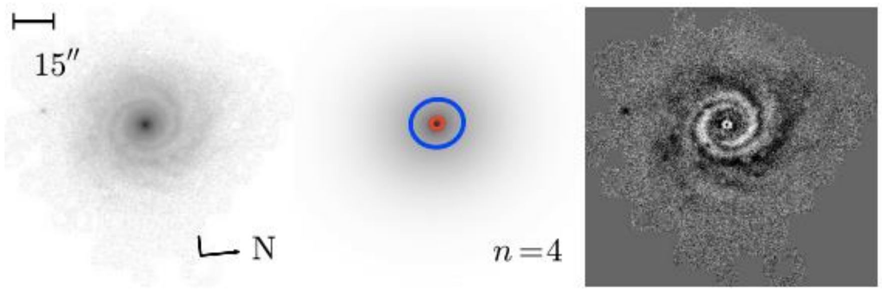
Chang, **van der Wel**+ 2013

Even massive *quiescent* galaxies appear predominantly disky at z=2

Growth in size is accompanied by morphological transformation?

See also van der Wel+ 2011, Bruce+2012, Whitaker+ 2012

Bulge-disk decompositions: Local Universe

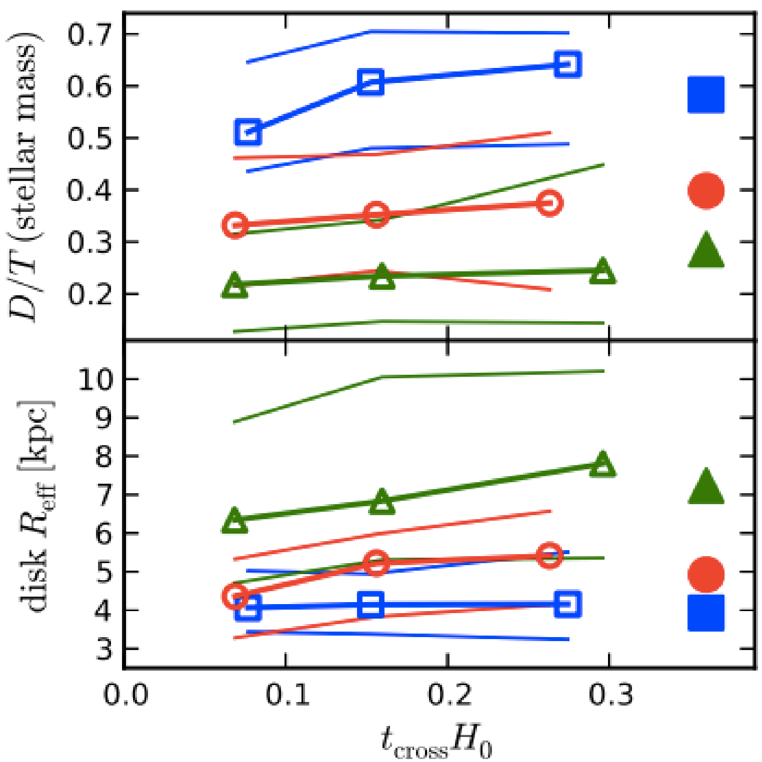


Lackner & Gunn 2012, 2013

71,825 SDSS galaxies

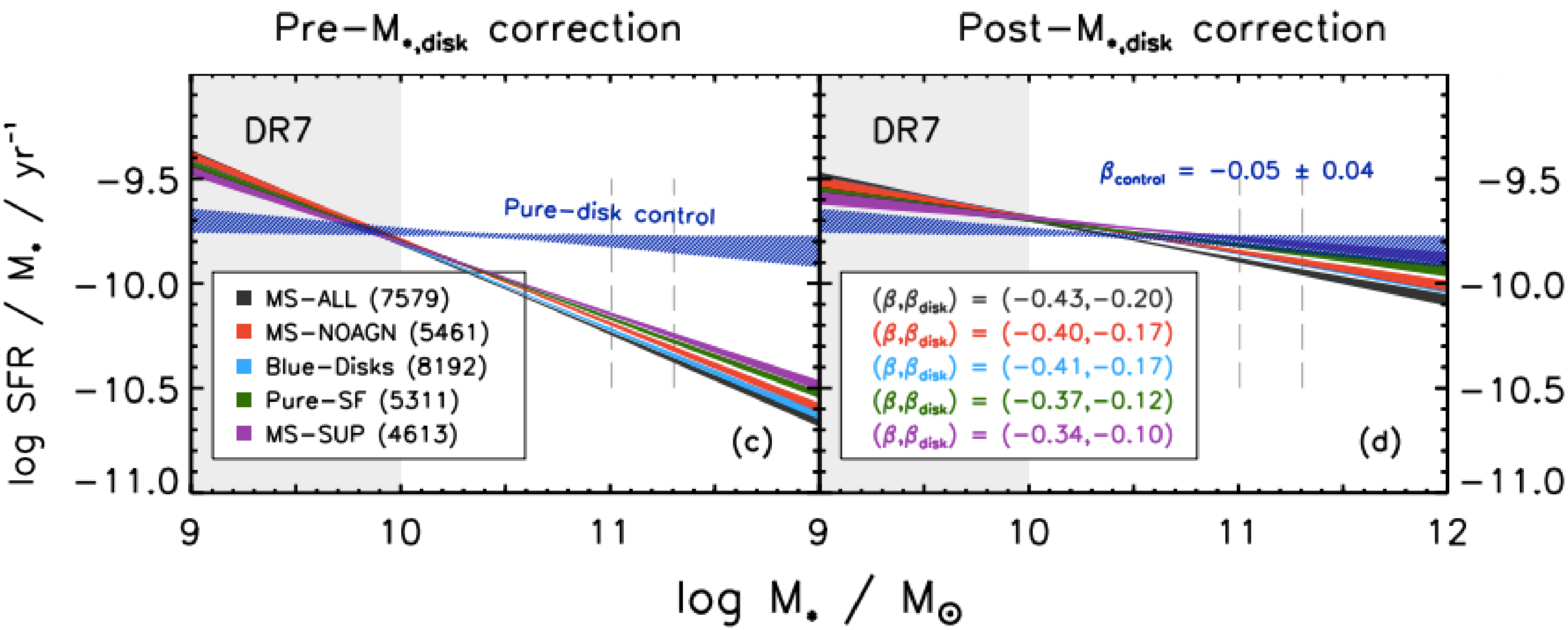
Also Benson+ 2007, Simard+ 2011, …

Colored lines: Fixed bulge mass



Evidence for morphological transformation in galaxy groups associated with number of passages (harassment?)

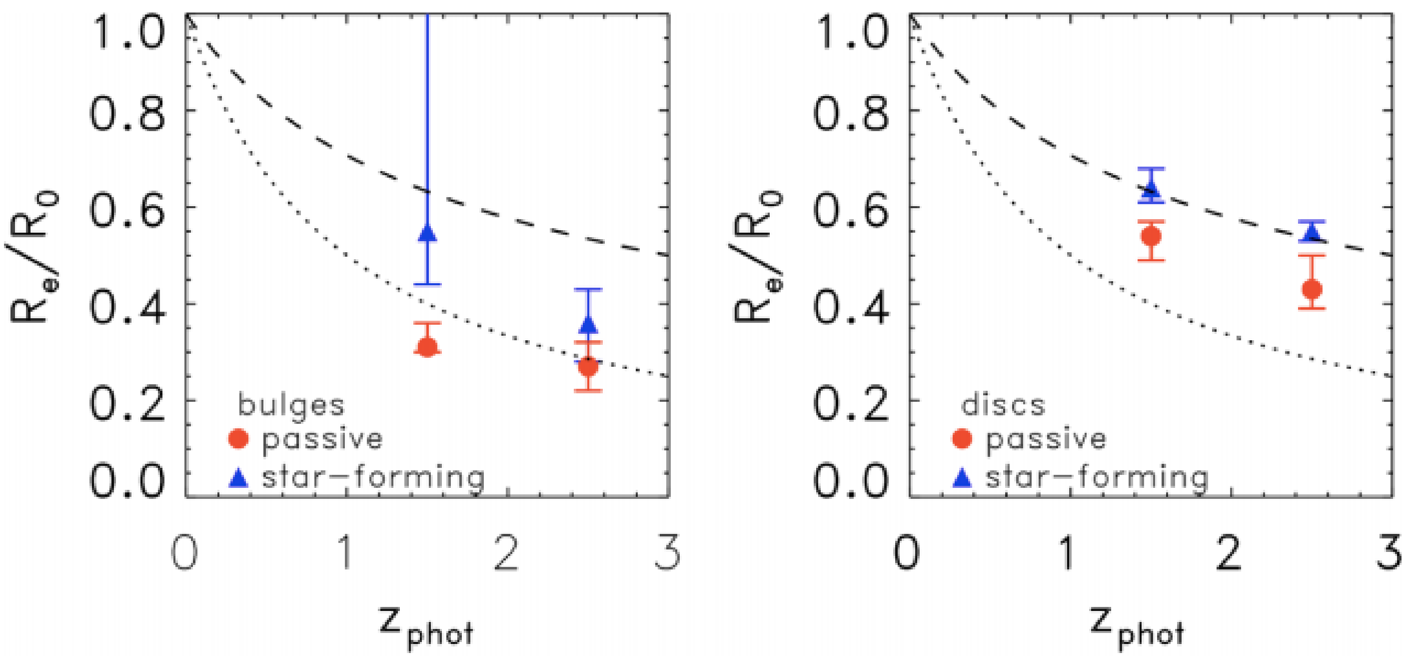
Bulge-disk decomposition & the "Main Sequence"



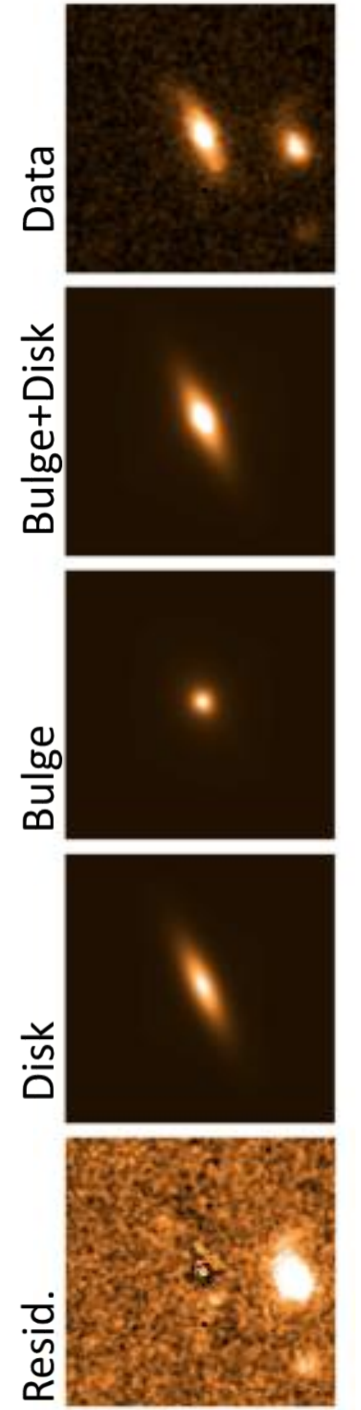
Abramson+ 2014

Slope of "main sequence" greatly reduced when SFR is compared to *disk* stellar mass

Bulge-Disk Decompositions at z=1-3

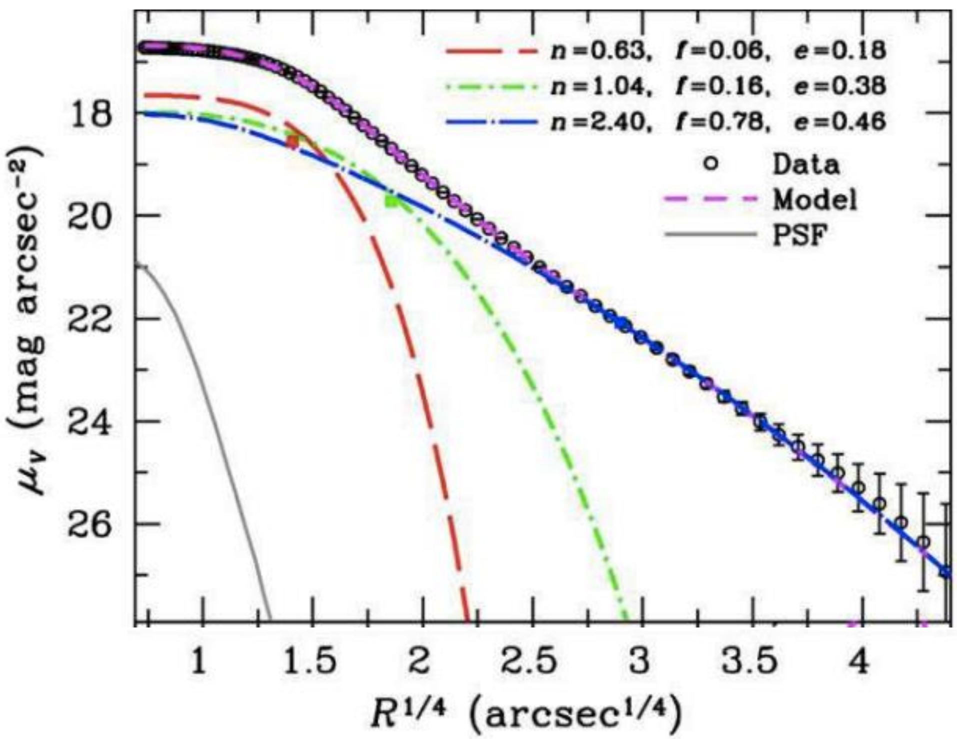


Bruce+ 2014

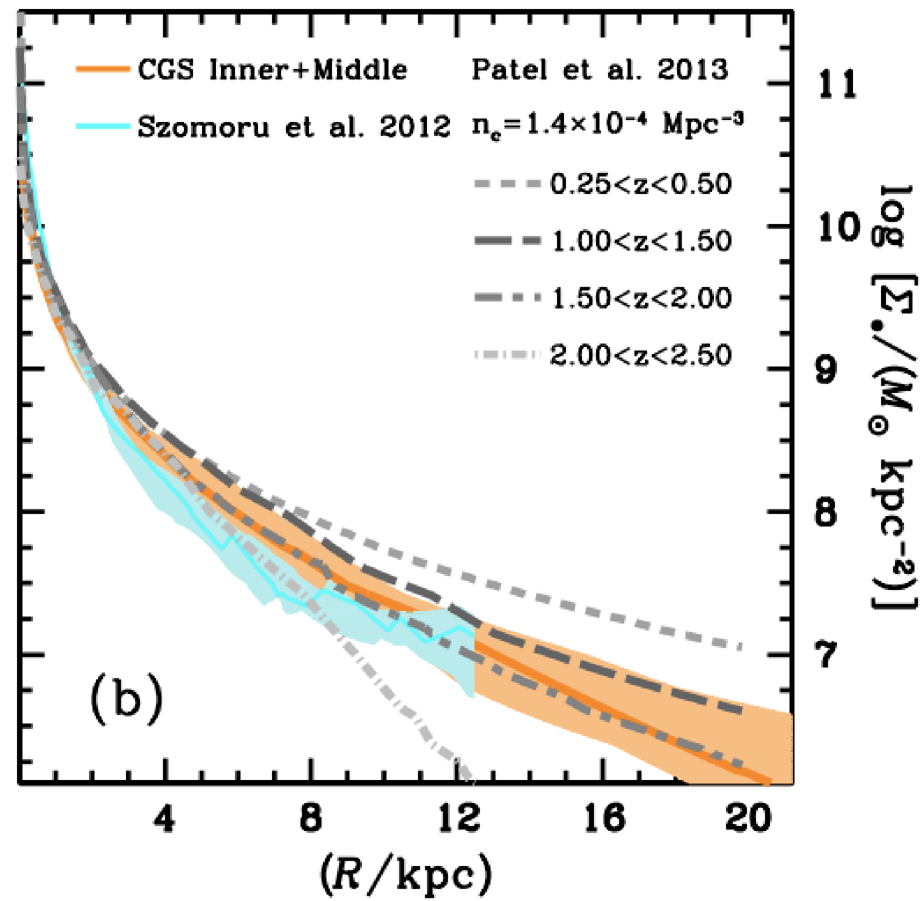


Multi-wavelength bulge+disk fits in CANDELS fields at z=1-3

Can the accreted stellar halo be identified photometrically?



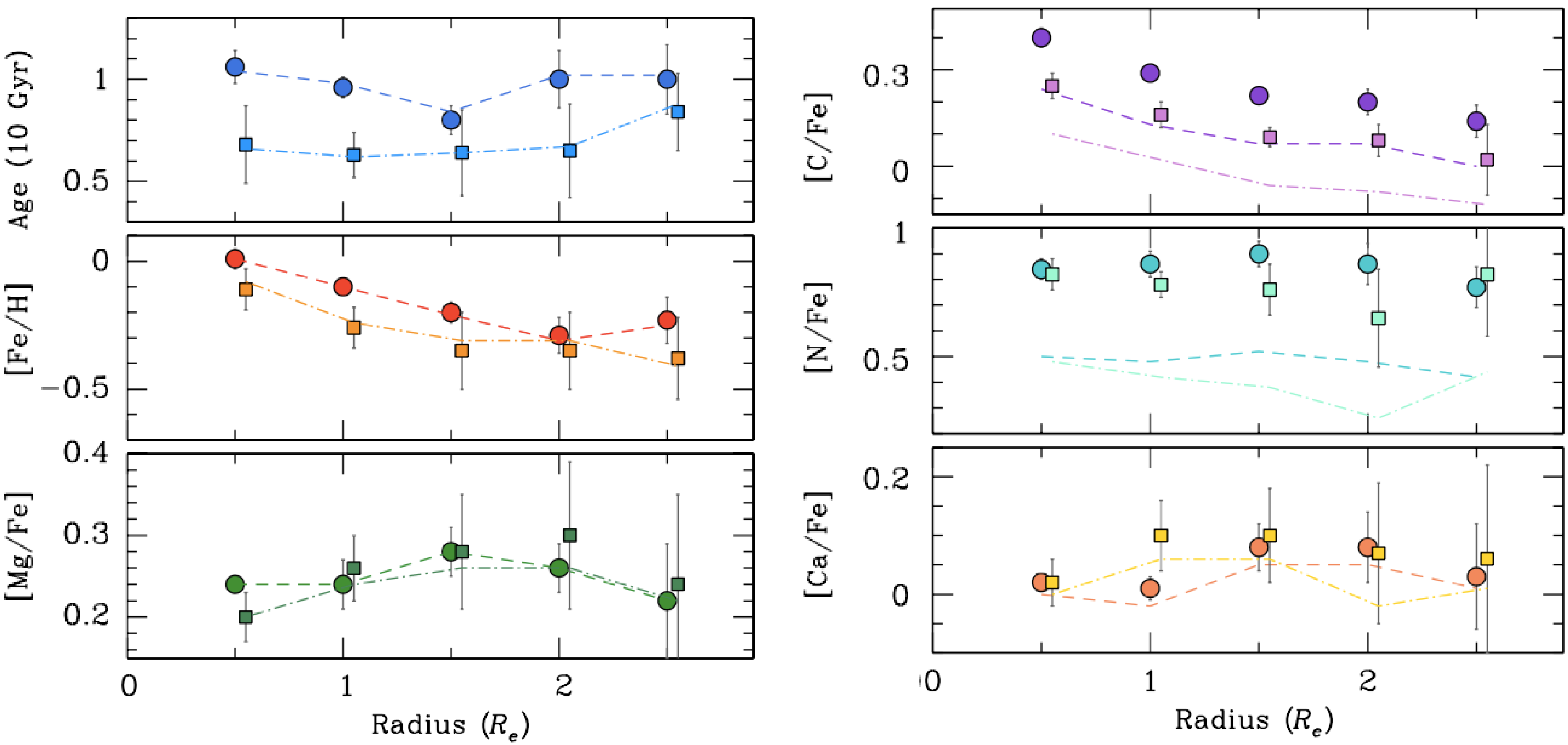
Huang+ 2012, 2013



Inner + middle Sersic components of nearby ellipticals resembles high-z galaxies—but how unique?

Chemical and Kinematic Archaeology

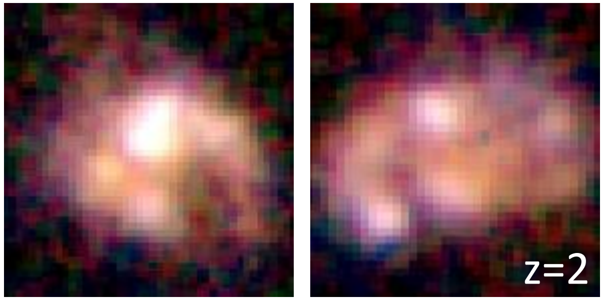
Greene+ 2013



Detailed chemical abundance patterns may allow the accreted stars at large radii to be connected to their formation sites.

Questions

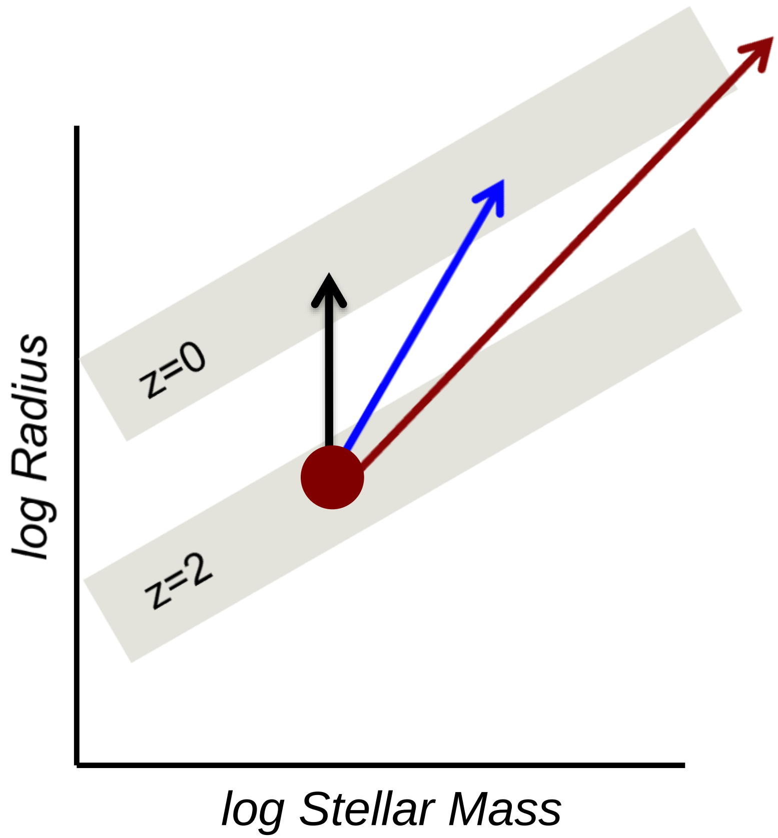
- How do we link the traditional bulge+disk approach, successful at lower redshift, with higher-z progenitors that are often less regular (clumpy, thick, etc.)?



- How to best combine connect ongoing/forthcoming IFU surveys at different redshifts?

Merger rates

Size growth channels



Major (dry) mergers

~1:1 dissipationless mergers grow size proportionally to mass and are rare.

d log R / d log M ~ 1

Minor mergers

Mergers with mass ratio < 1:4 are *more efficient* agents of size growth.

d log R / d log M ~ 1—2

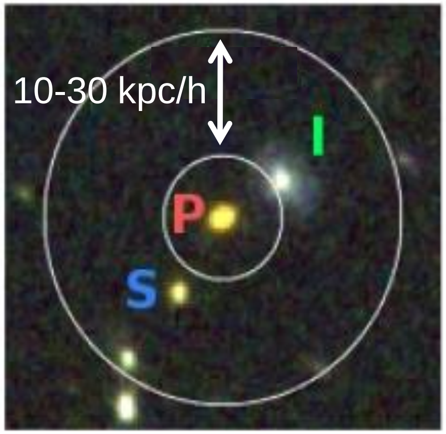
Adiabatic expansion

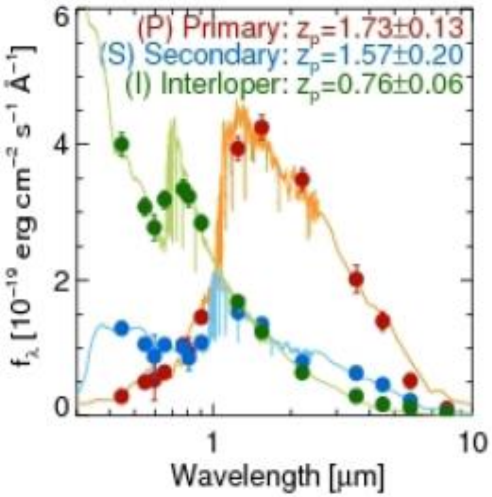
Gas outflows driven by AGN or evolved stars lead to a shallower potential → stars respond by "puffing up"

Fan+ 2008, 2010, **Damjanov**+ 2009, Rangone-Figuera 2011

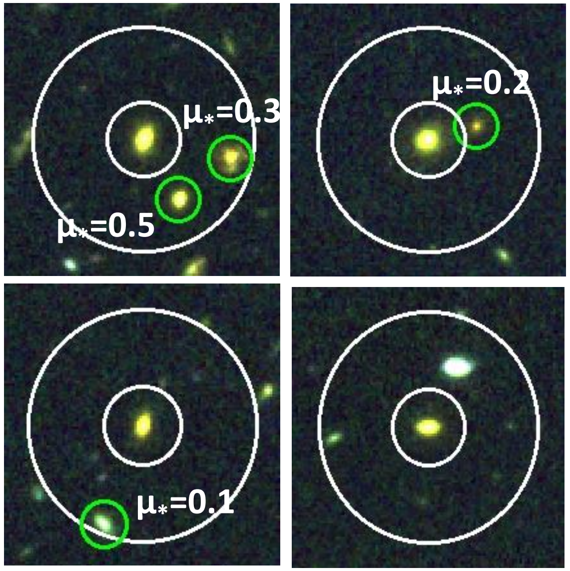
Hopkins, **Bundy**+ 2009, Bezanson+ 2009, **Damjanov**+ 2009, Naab+ 2009, **Nipoti**+ 2012+, **Trujillo**+ 2010, **Newman**+ 2012…

Counting minor mergers to z=2





μ* = stellar mass ratio



Search CANDELS images for excess of nearby galaxies with

- *>1/10 the stellar mass*
- *Consistent redshifts* [$\Delta z_{phot}/(1+z) < 0.2$]

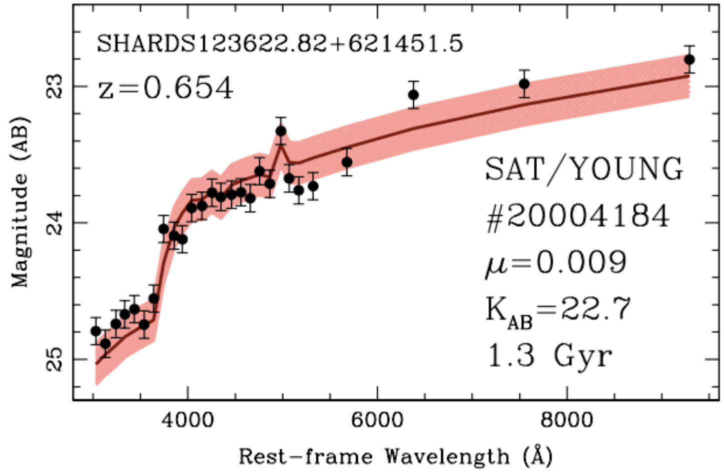
Find **13-18%** of hosts (constant over z=0.5-2) with a likely satellite, leading to 6±2% mass growth per merger timescale

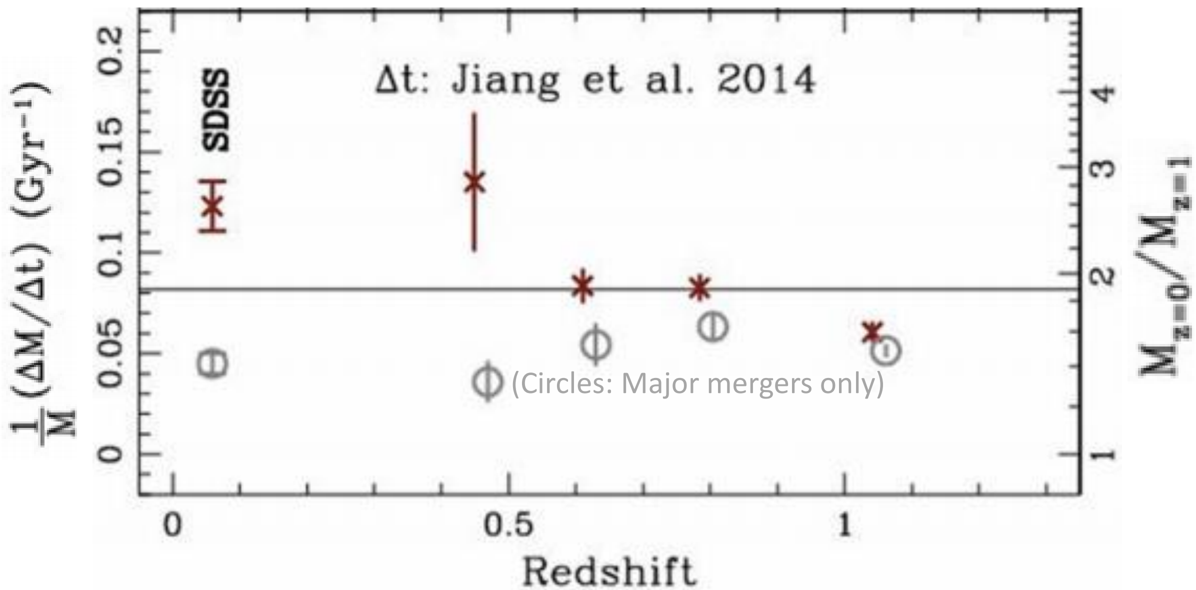
Newman+ 2012

see also Williams+ 2010, Man+ 2014

Counting "milli-mergers" (>1:100) to z=1

SHARDS survey





Flat or declining mass growth rate since z=1

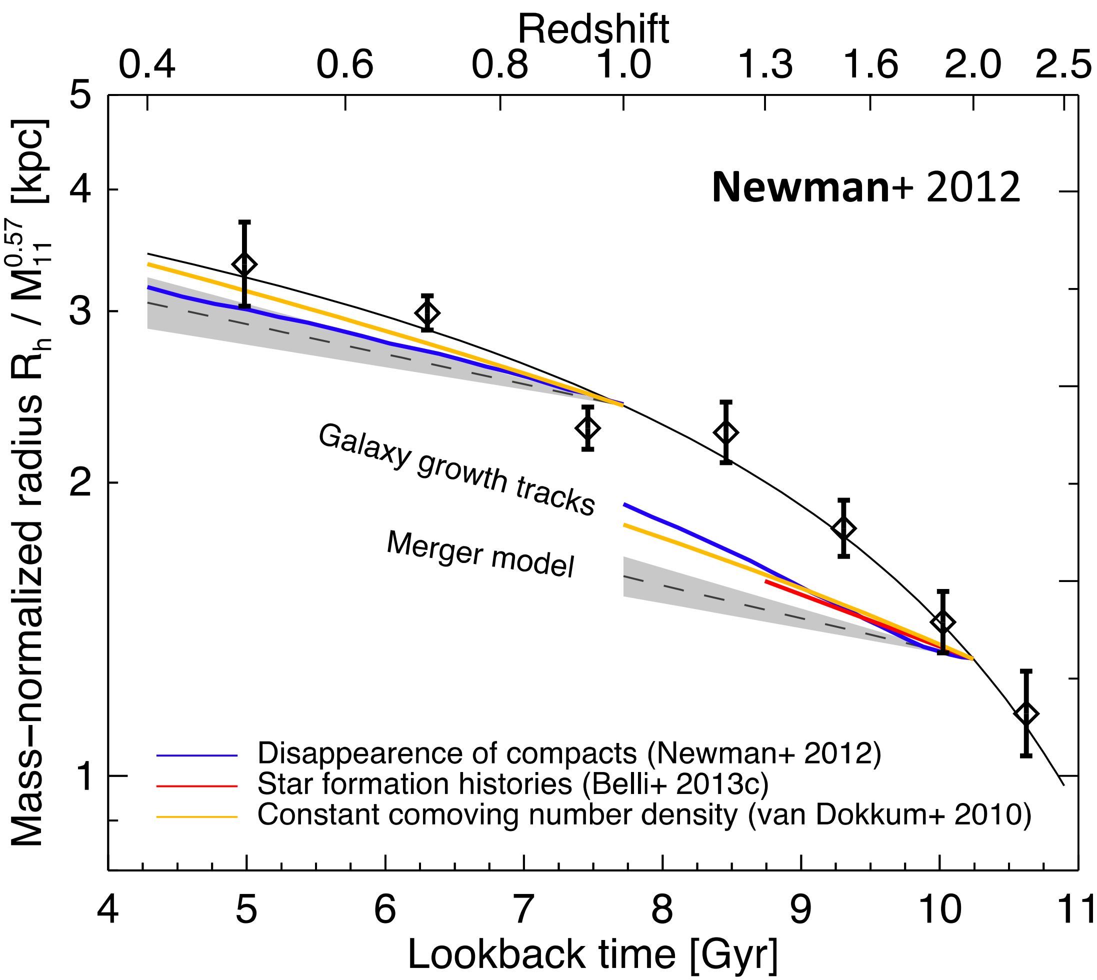
Decreasing importance of very low mass-ratio mergers

Merger history is size-independent
(Díaz-García+ 2013 incl. **Trujillo**)

Ferreras, Trujillo+ 2014

See also Bluck+ 2011, Ruiz+ 2014

Are there enough minor mergers to fuel the observed size evolution?



Ingredients:

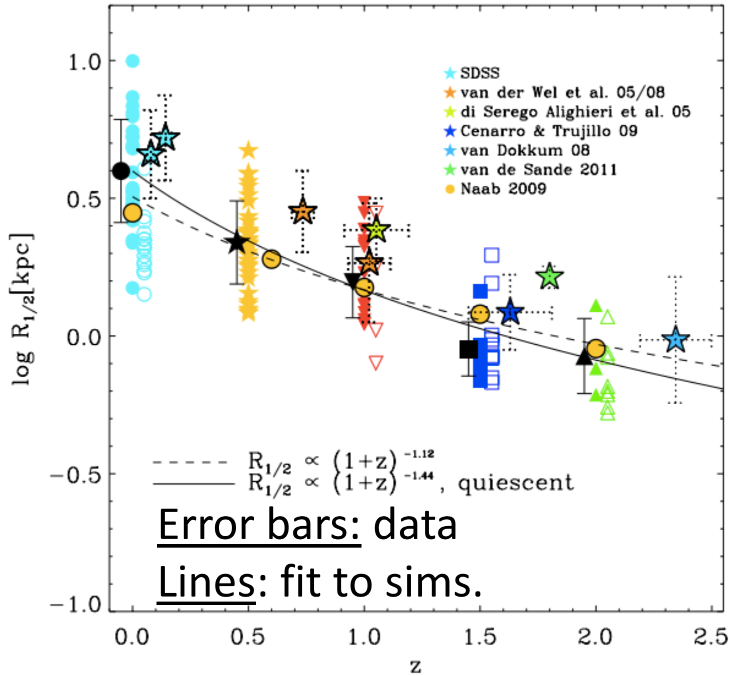
— Observed stellar mass content of satellites

— "Effective" merger timescale: plotted is 1 Gyr *(includes correction for unassociated pairs; short for minor mergers)*

— Size growth efficiency: d logR / d log$M_\star$ = 1.6
Nipoti+ 2012 simulations

Currently seems the answer is no, at least at z > 1

What do models and simulations say?



Error bars: data

Lines: fit to sims.

Oser+ 2012

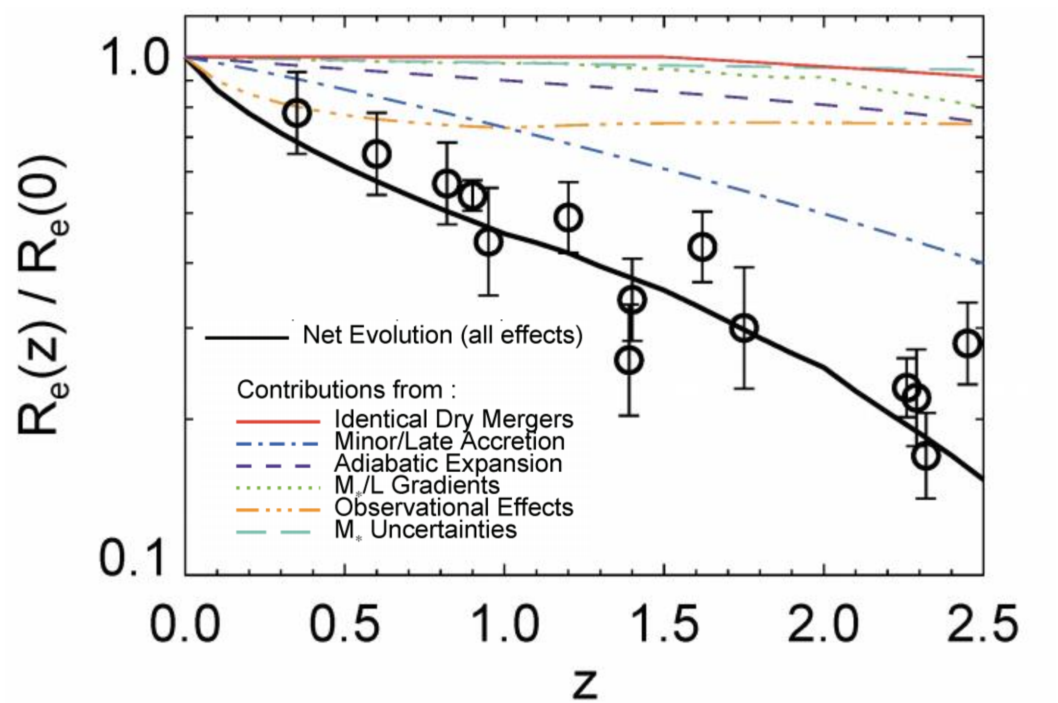
Hydrodynamical "zoom-in" simulations that appears to reproduce the size evolution rate

(Caution: weak feedback, stars over-produced)

Hopkins, **Bundy**+ 2010

Minor mergers generate half of the mass—radius evolution

Significant contributions from *adiabatic expansion* + possible observational biases



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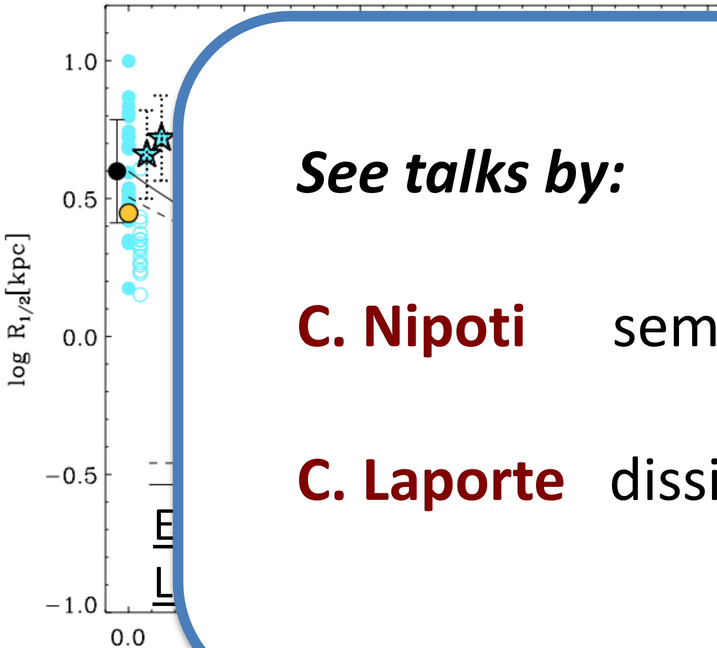

See talks by:

C. Nipoti semi-empirical approach

C. Laporte dissipationless simulations of clusters

Hopkins, **Bundy**+ 2010

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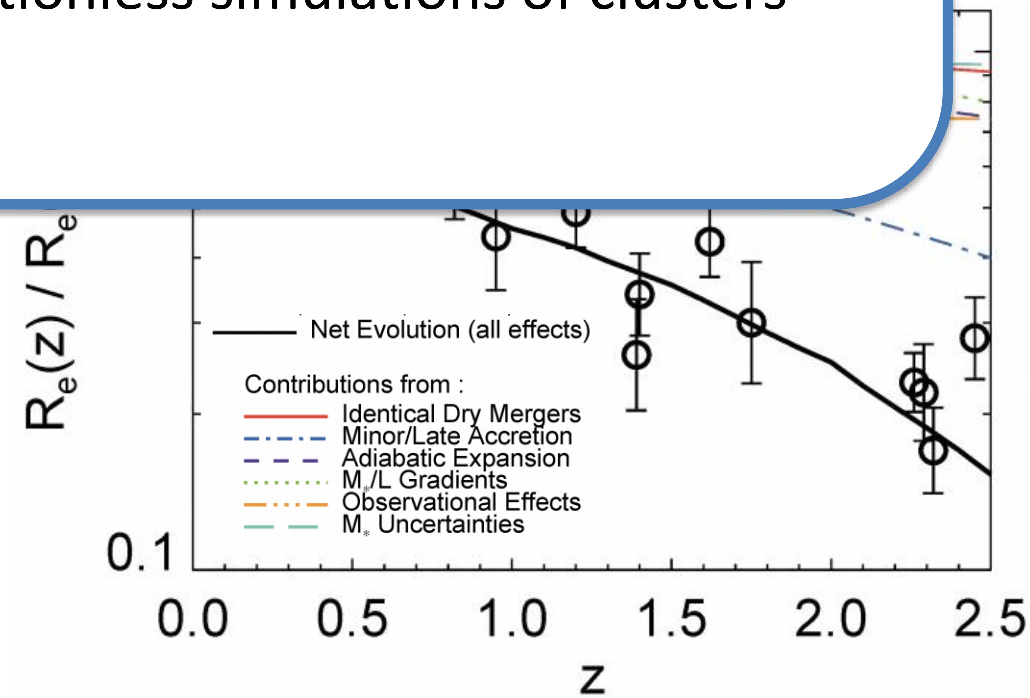
Significant contributions from *adiabatic expansion* + possible observational biases

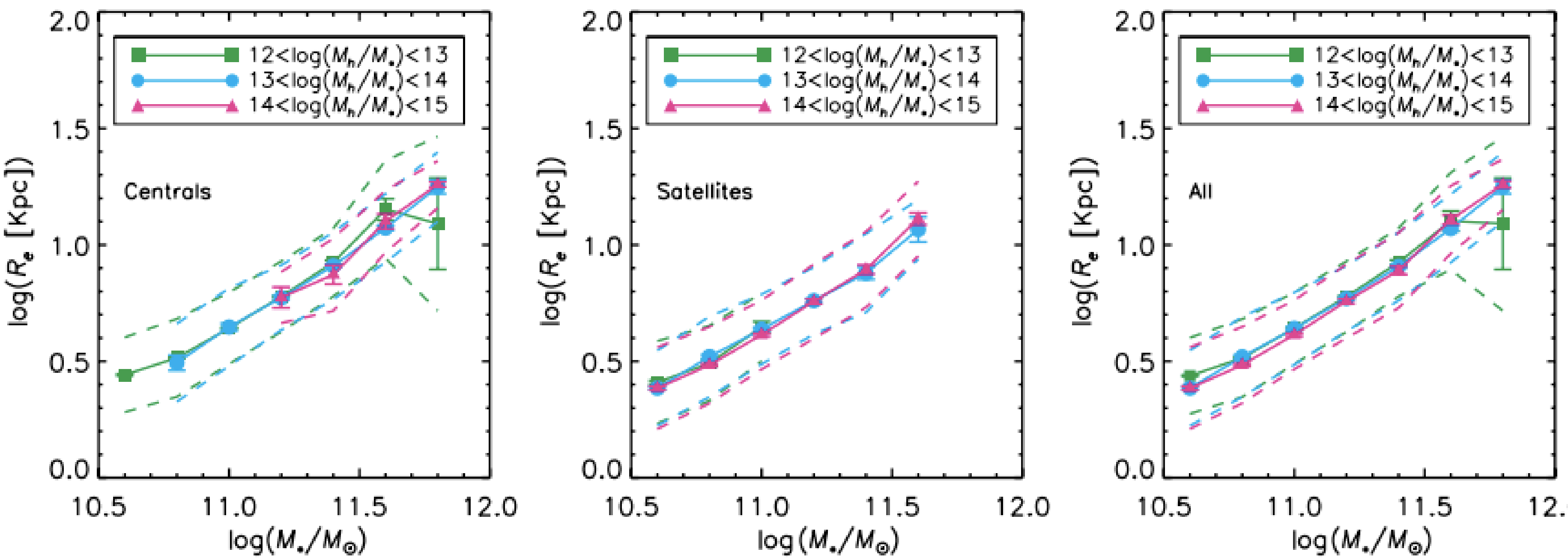


Questions

- Are we missing (important) mergers?
- Are we thinking about the effects of mergers on galaxy sizes too simply, especially at high redshift (e.g., dry, spheroid-spheroid mergers)?
  (A. Sonnenfeld talk)
- Is the low rate of minor mergers consistent with a low number of local compact "relics"?
- Do models/simulations reproduce the tight non-evolution in the slope and *scatter* of the $M_\star$—R_e relation?
  (C. Nipoti talk)

Galaxy Growth in Different Environments

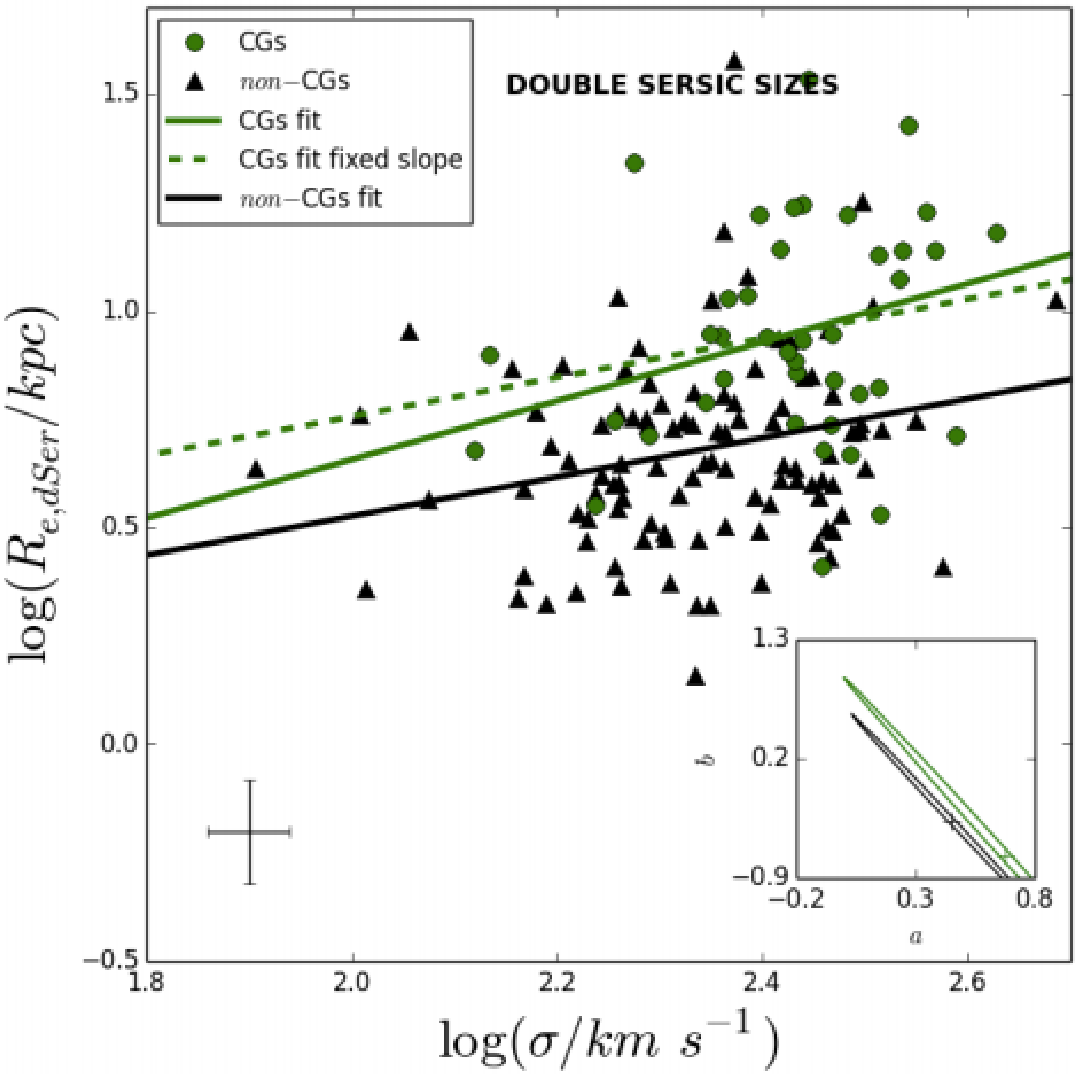
ETG sizes appear remarkably independent of environment at z=0



Huertas-Company+ 2013

Also Weinmann+ 2009, Guo+ 2009, Maltby+ 2010, Nair+ 2010, Cappellari+ 2013, Cebrián & **Trujillo** 2014

Centrals in massive halos

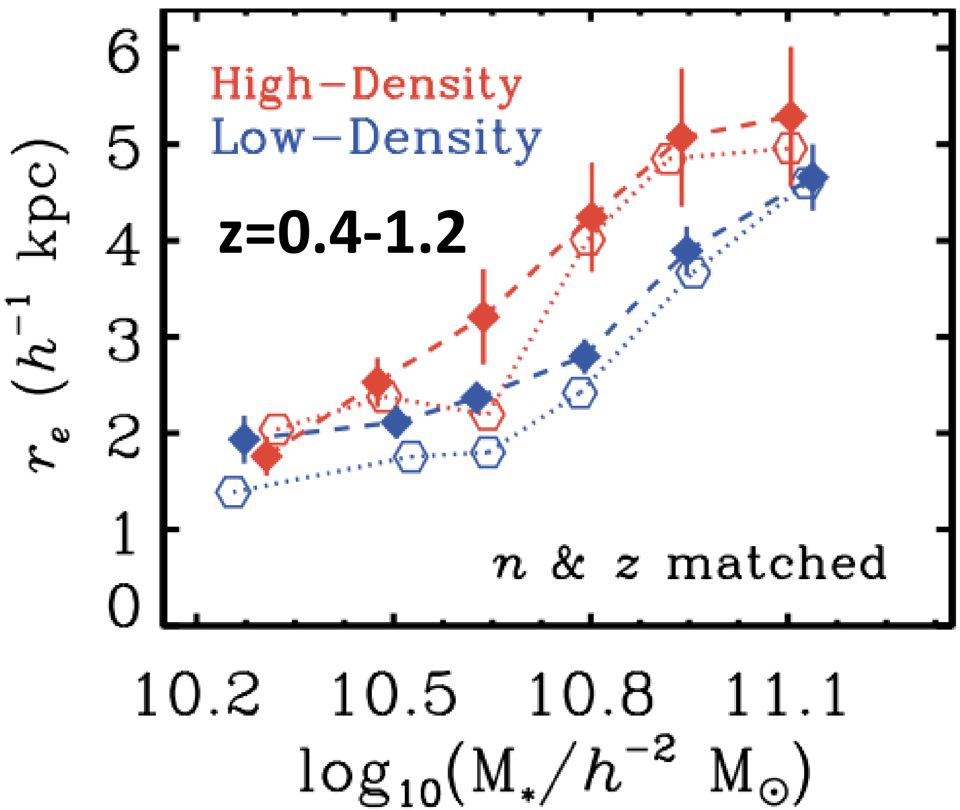


Vulcani, Bundy, Lackner, Leauthaud+ 2014

May be distinguished in other spaces e.g., σ—R_e

See talks in BCG session Friday (Mei, Rettura, Laporte)

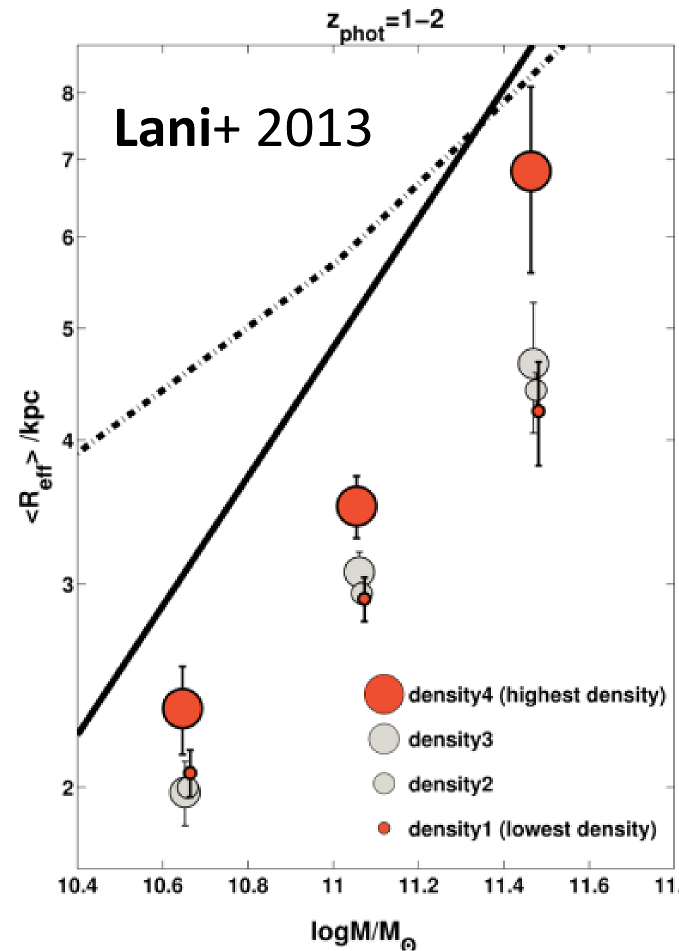
Do ETGs grow faster in groups?



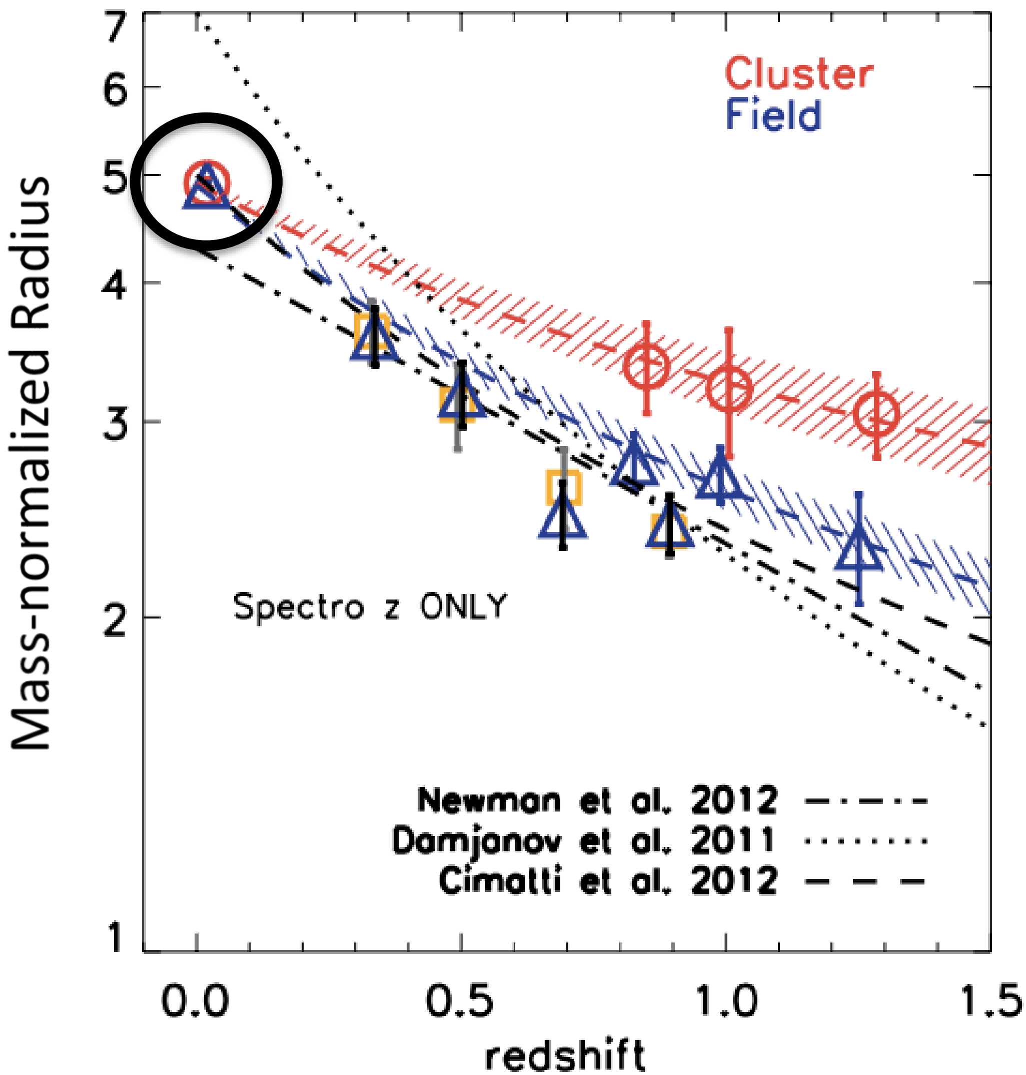
Cooper+ 2013

~30% larger ETGs sizes in denser environments—after matching in Sersic n, z, $M_\star$, color

Growth enhanced more for *massive* galaxies



What about clusters?



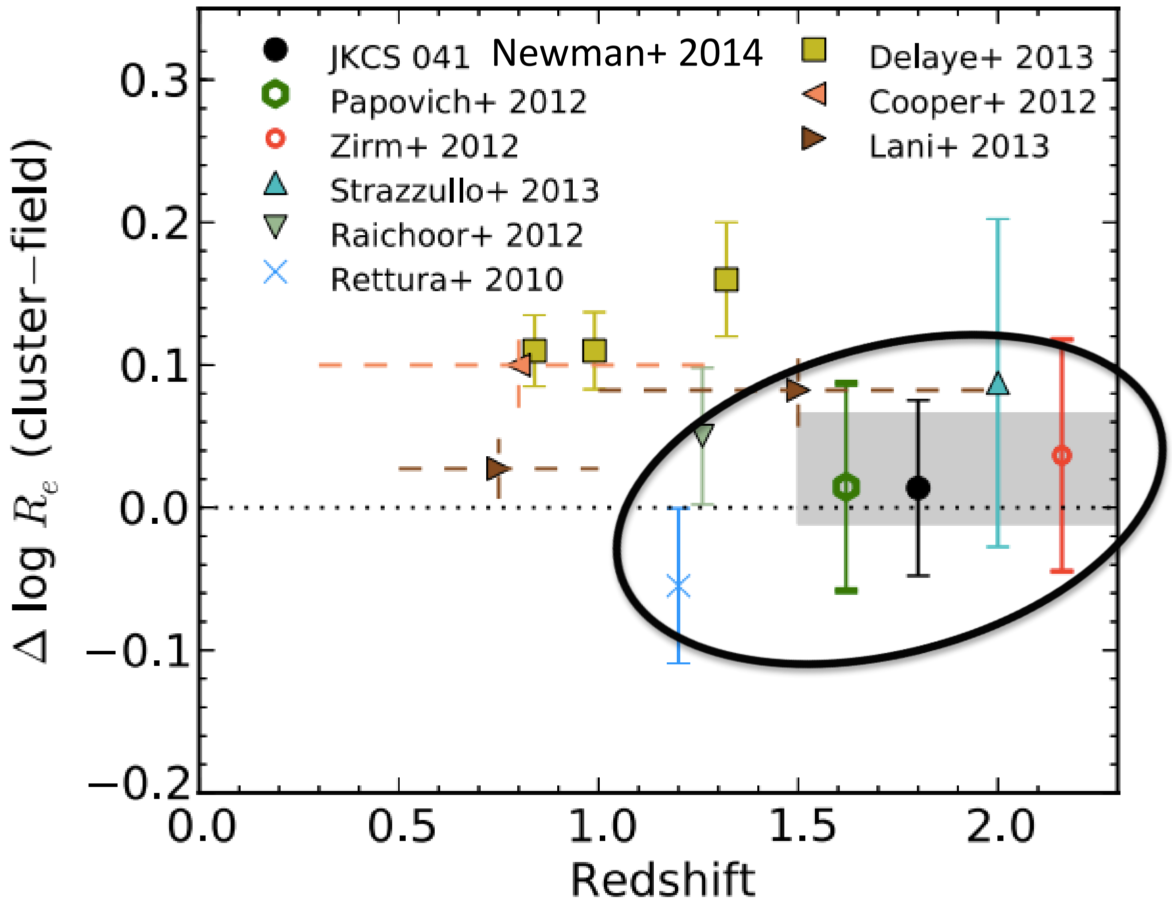
Earlier ETGs growth driven by trends for lower-mass galaxies in cluster cores

Why do clusters galaxies *precisely* catch up with the field at z=0?!?

Delaye, Huertas-Company, Mei+ 2014

Galaxy sizes in early (proto-)clusters

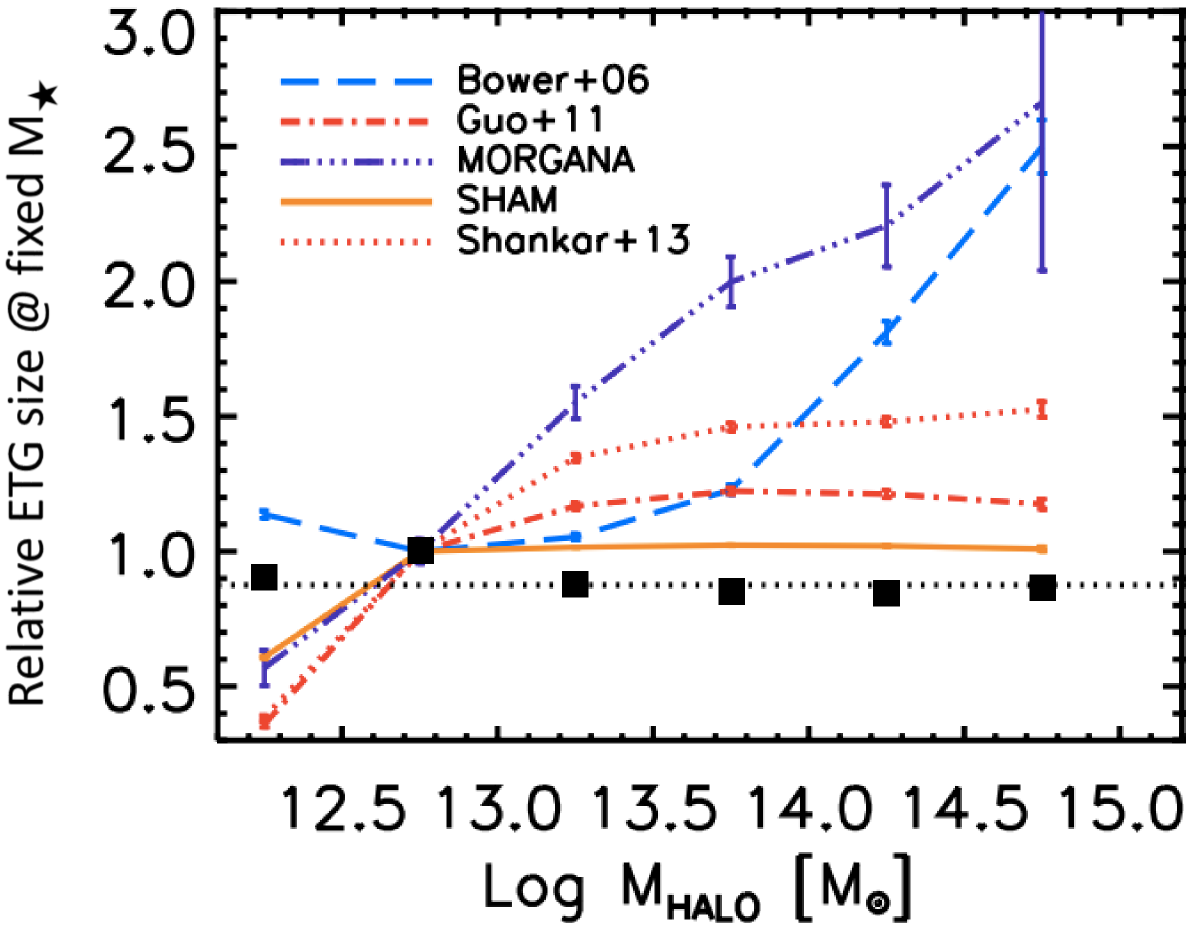
Newman+ 2012 compilation



No clear size difference in early clusters z >~ 1.5

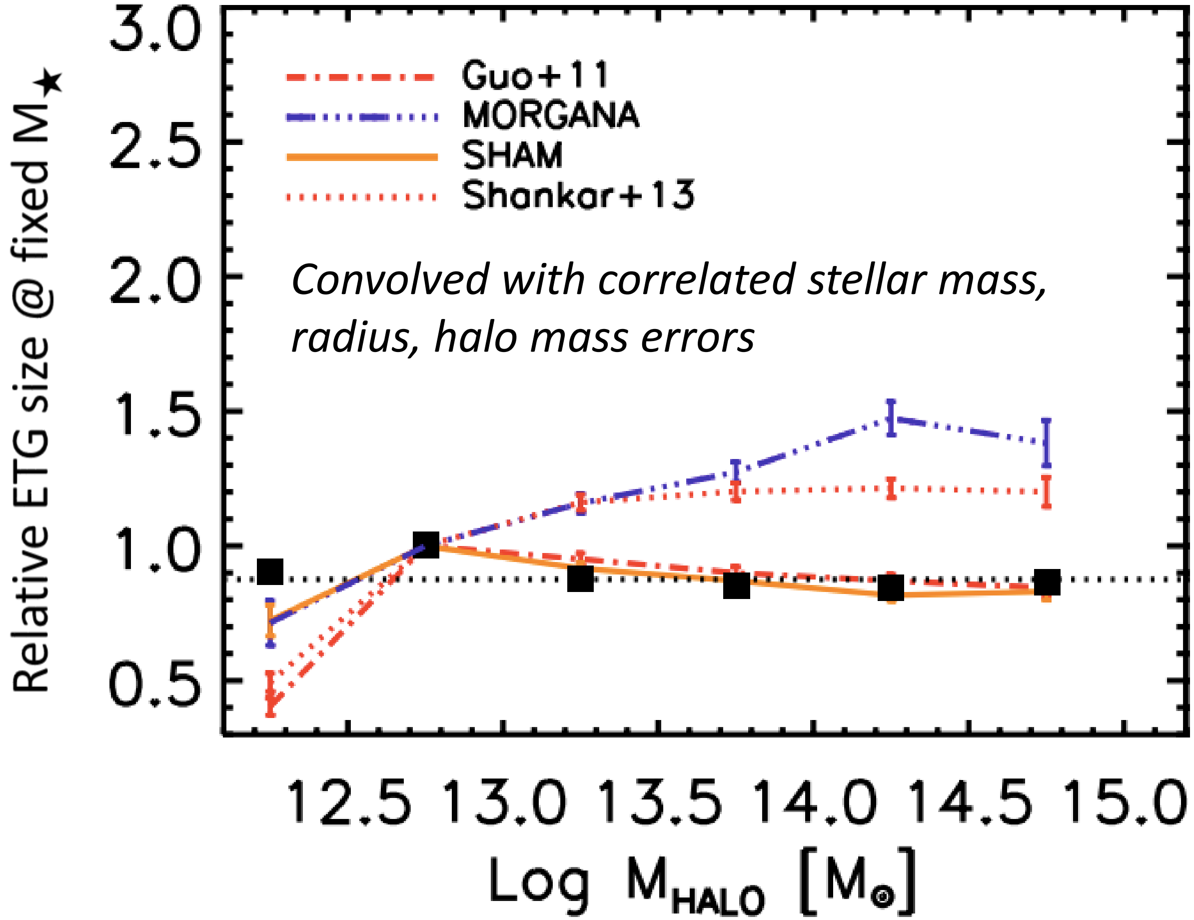
But statistics are limited and comparisons are heterogeneous!

Predictions from semi-analytic models



Shankar**, Mei, Huertas-Company**+ 2014

Even in the SDSS data is not good enough?!



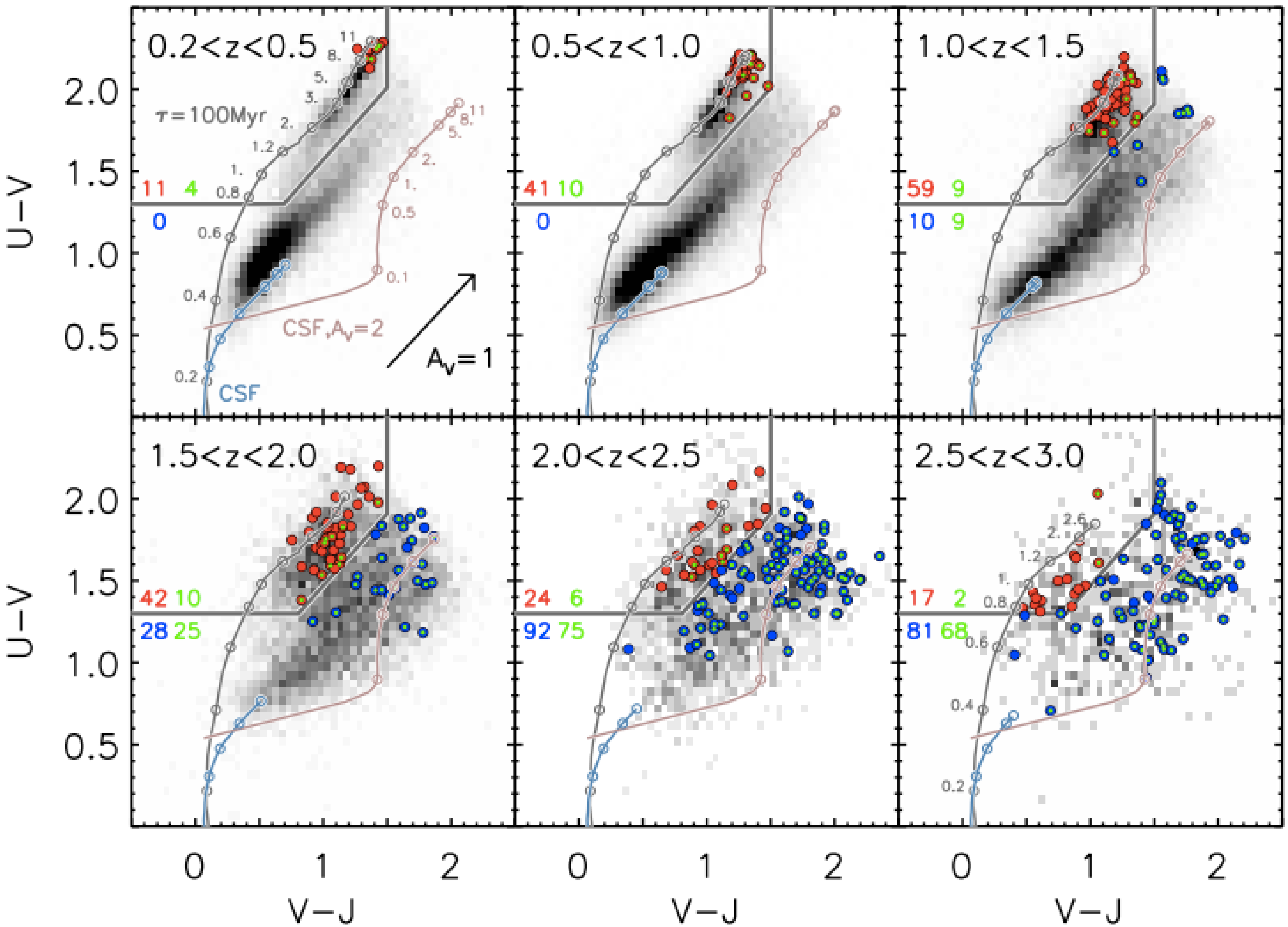
Shankar**, Mei, Huertas-Company**+ 2014

Questions

- How strong the evidence for environmentally-dependent growth at $z > 0$? In what environments/masses/redshifts does it occur?
- Why is its signature seemingly erased by $z=0$ to high precision?
- Must interpret with full models — what do we learn most about from these measurements? (Growth of massive galaxies, quenching of their satellites…)
- What are the best measures of “environment” for future surveys?

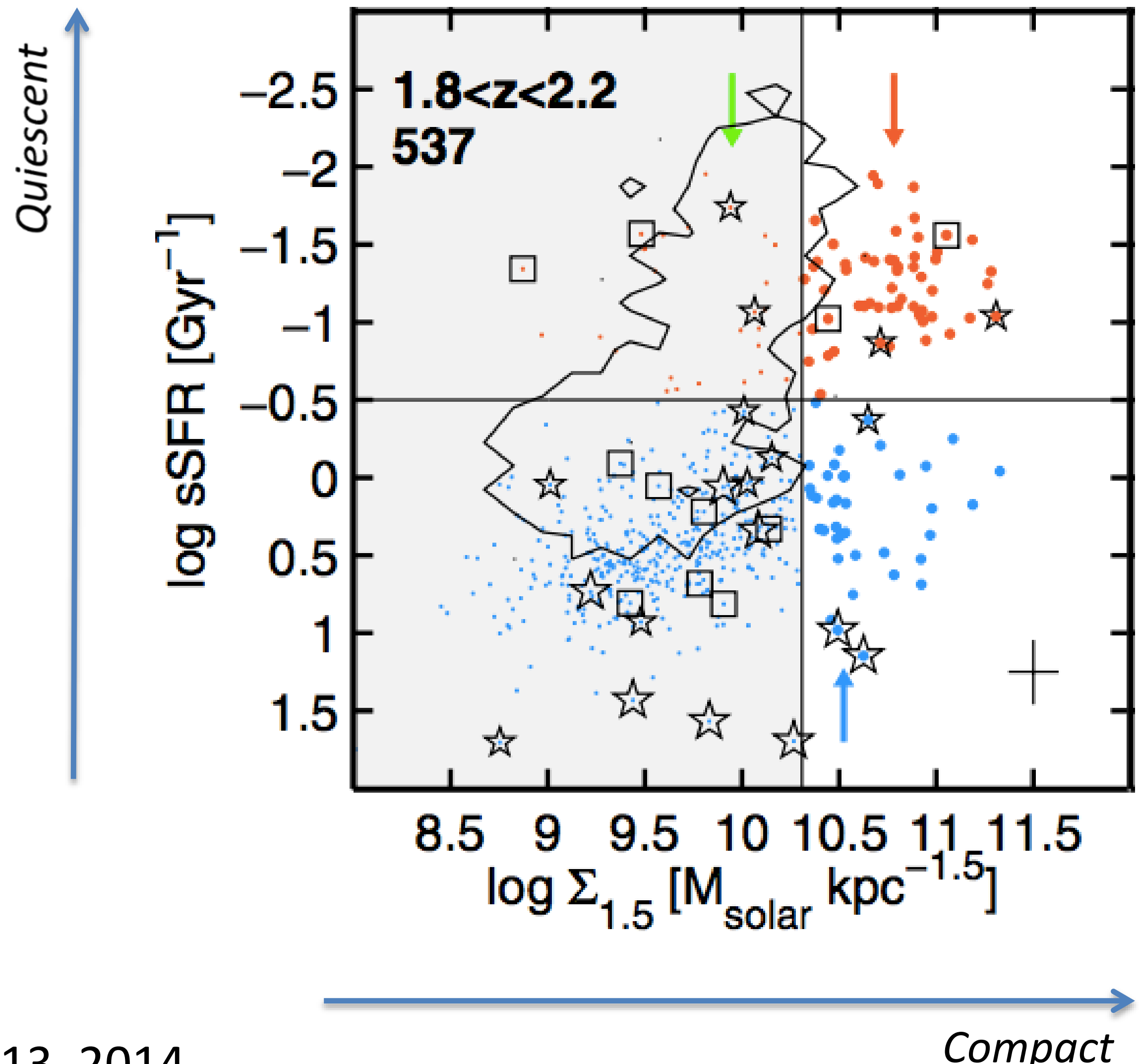
The birth of massive/compact galaxies at z > 3

z~3 progenitors of $10^{11.8}$ $M_\odot$ galaxies are diverse



Marchesini+ 2014 *and see spectrum in talk by **Marsan!!!***

“Blue nuggets”



“Red nuggets”

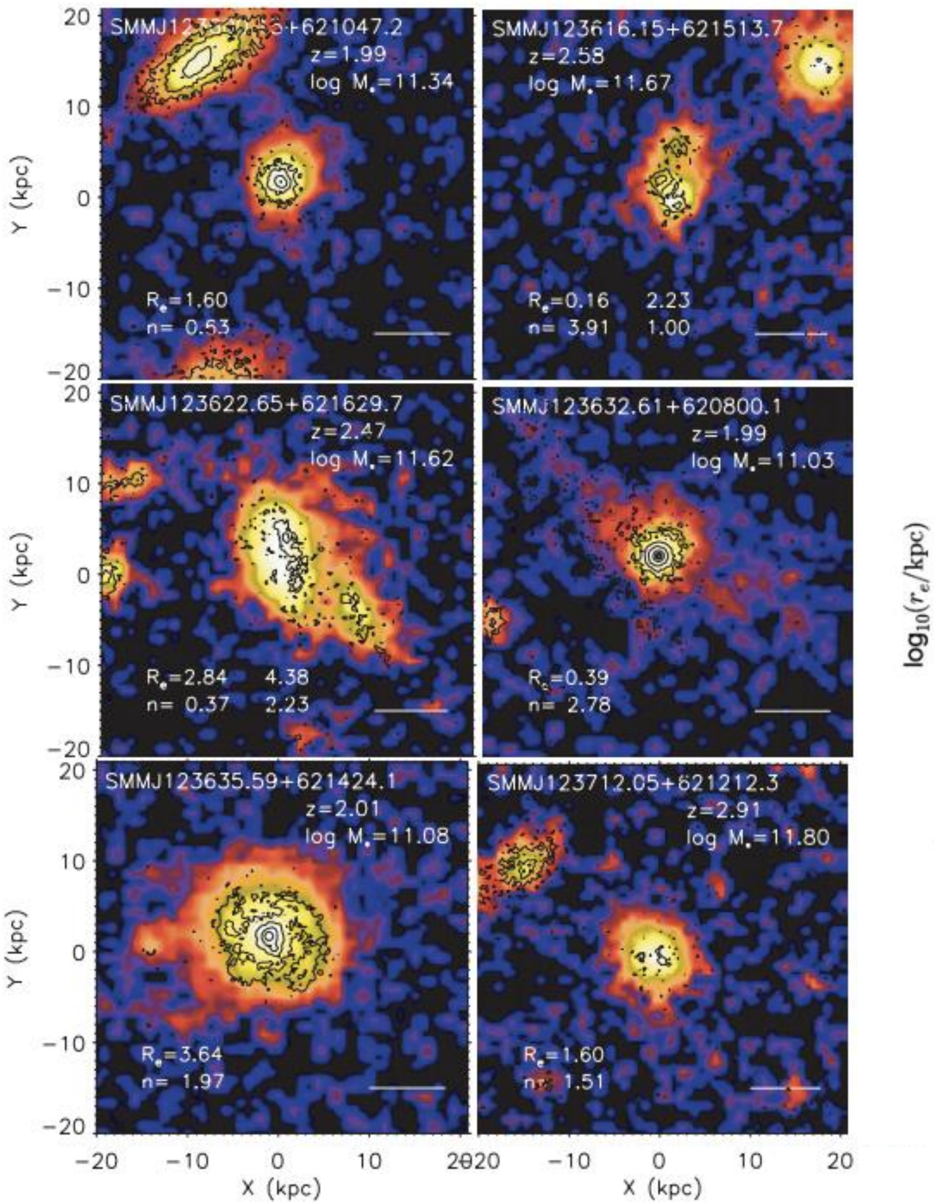
“Blue nuggets”

Incidence of X-ray luminous AGN is 30x the non-compact star-forming galaxies!

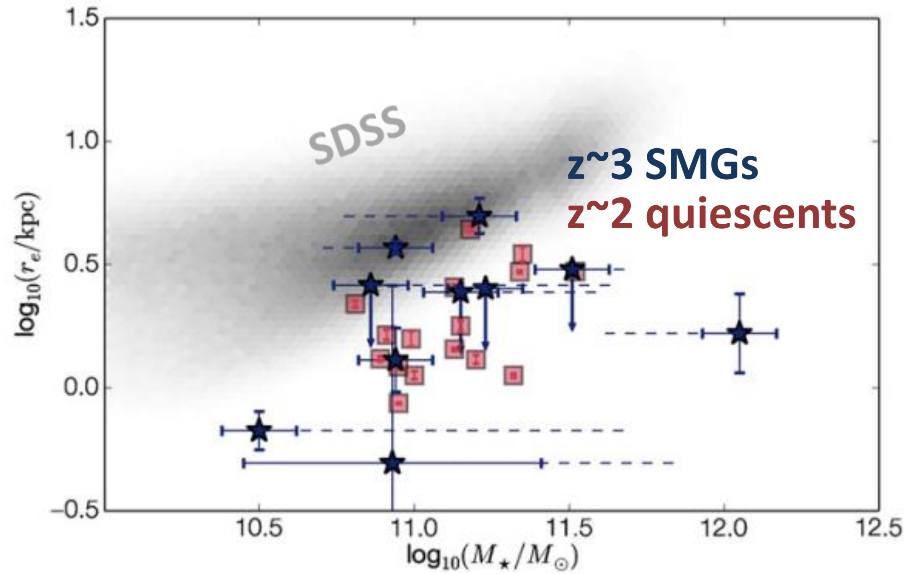
Barro+ 2013, 2014

Sub-mm galaxies

NICMOS images of z~2 SMGs



Ricciardelli, **Trujillo, Buitrago** & Conselice 2010



Toft+ 2014

Questions

- To what extent are we seeing a sequence versus a variety of paths to similar galaxies?

  e.g., SMGs typical for massive galaxies,
  "blue nuggets" typical of lower mass

- Some simulations predict multiple channels to make compact galaxies (Wellons+ 2014). How can we test with future NIR and (sub-)mm data?

Thank you!

Measuring galaxy size growth histories

- Have we converged on a size growth rate for quiescent galaxies at $z > 1$ (i.e., separated progenitor bias)?
- What is happening at $z < 1$?
- How many local compact galaxies are there?

Beyond half-light radii

- How do we link the traditional bulge+disk approach, successful at lower redshift, with higher-z progenitors that are often less regular (clumpy, thick)?
- How to best combine results from ongoing/forthcoming IFU surveys at different z to track kinematic evolution?

Merger rates

- Are we missing (important) mergers?
- Are we thinking about the effects of mergers on galaxy sizes too simply, especially at high redshift?
- Is the low rate of minor mergers consistent with a low number of local compact “relics”?
- Do models/simulations reproduce the tight non-evolution in the slope and *scatter* of the $M_\star$—R_e relation?
- How strong the evidence for environmentally-dependent growth? In what environments/masses/redshifts is it strongest?

Galaxy growth in different environments

- Why is its signature seemingly erased by $z=0$ to high precision?
- Must interpret with full models — what do we learn most about from these measurements? (Growth of massive galaxies, quenching of their satellites…)
- What are the best measures of “environment” for future surveys?

The birth of massive/compact galaxies at $z > 3$

- To what extent are we seeing a sequence versus a variety of paths to similar galaxies?
- Some simulations predict multiple channels to make compact galaxies. How to test with future NIR and (sub-)mm data?