A Deep View on the Early Universe

Extreme Makeovers & Overweight Galaxies

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UC Berkeley
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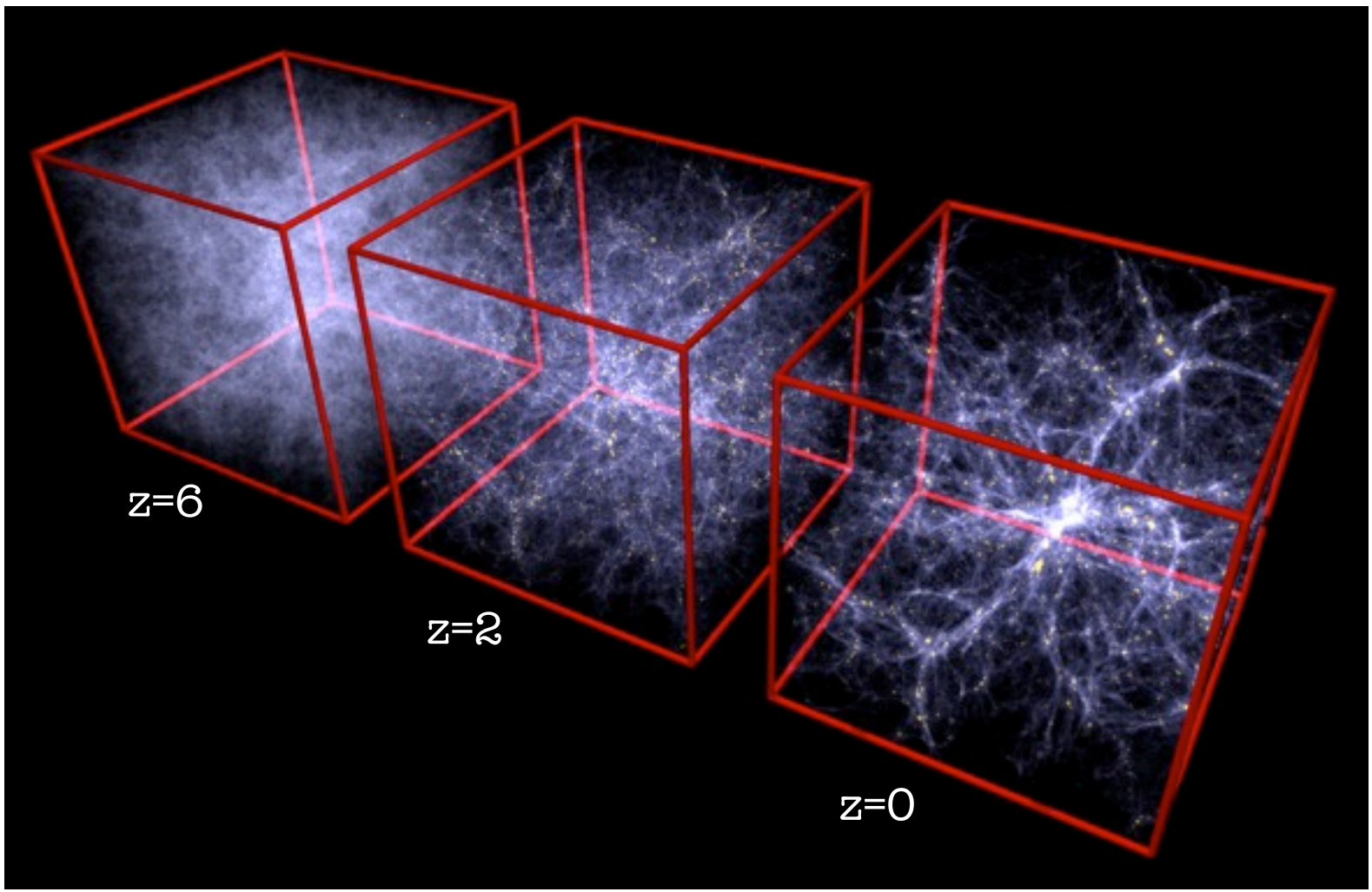
Cosmic Structure

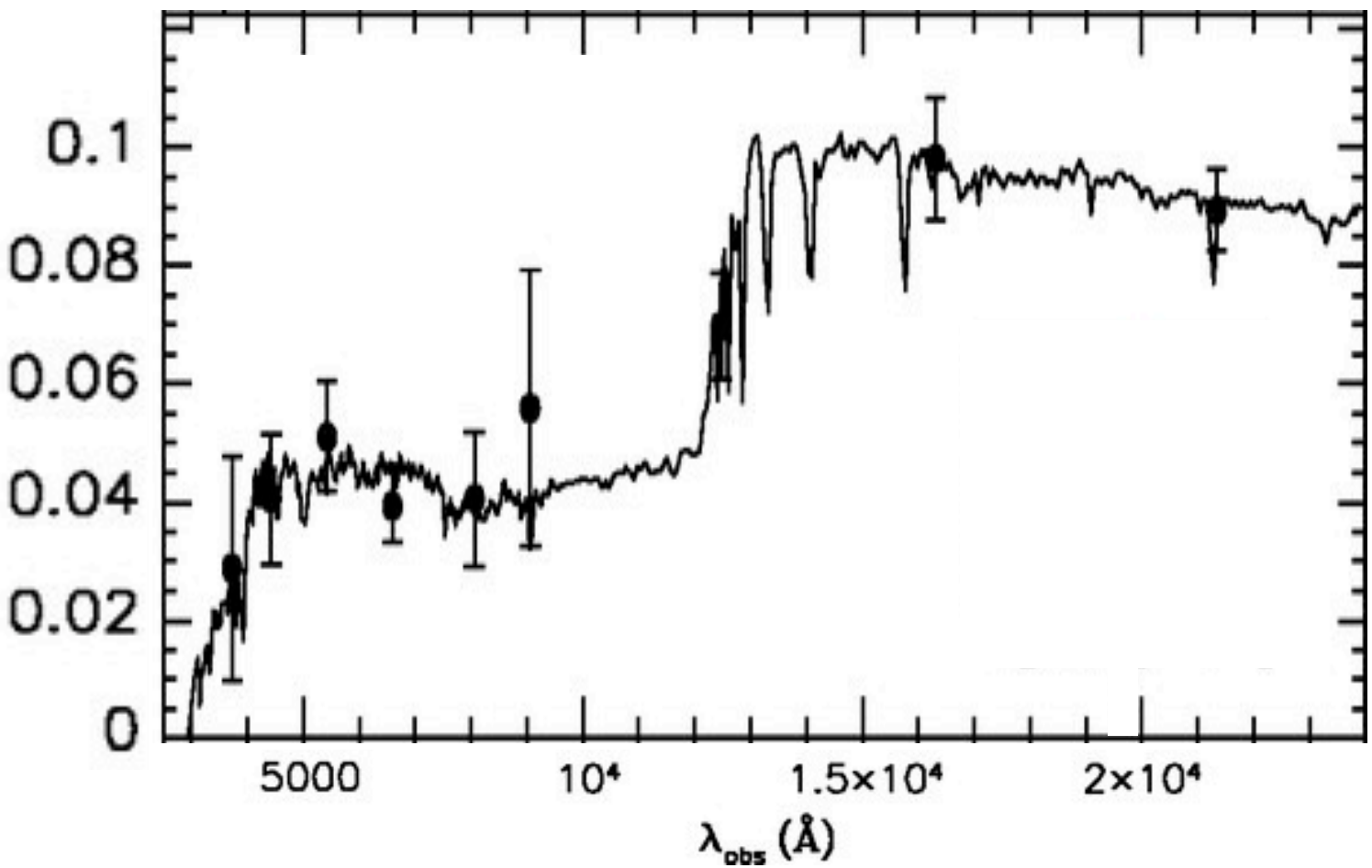


Volker Springel (Millenium simulation)

What we know about local galaxies...

- Massive galaxies are primarily red
- Color - density relation
- Mass - metallicity relation
- Color - size / morphology relation
- Color bimodality and color sequences

A typical massive galaxy at z~2.5



van Dokkum et al. (2006)

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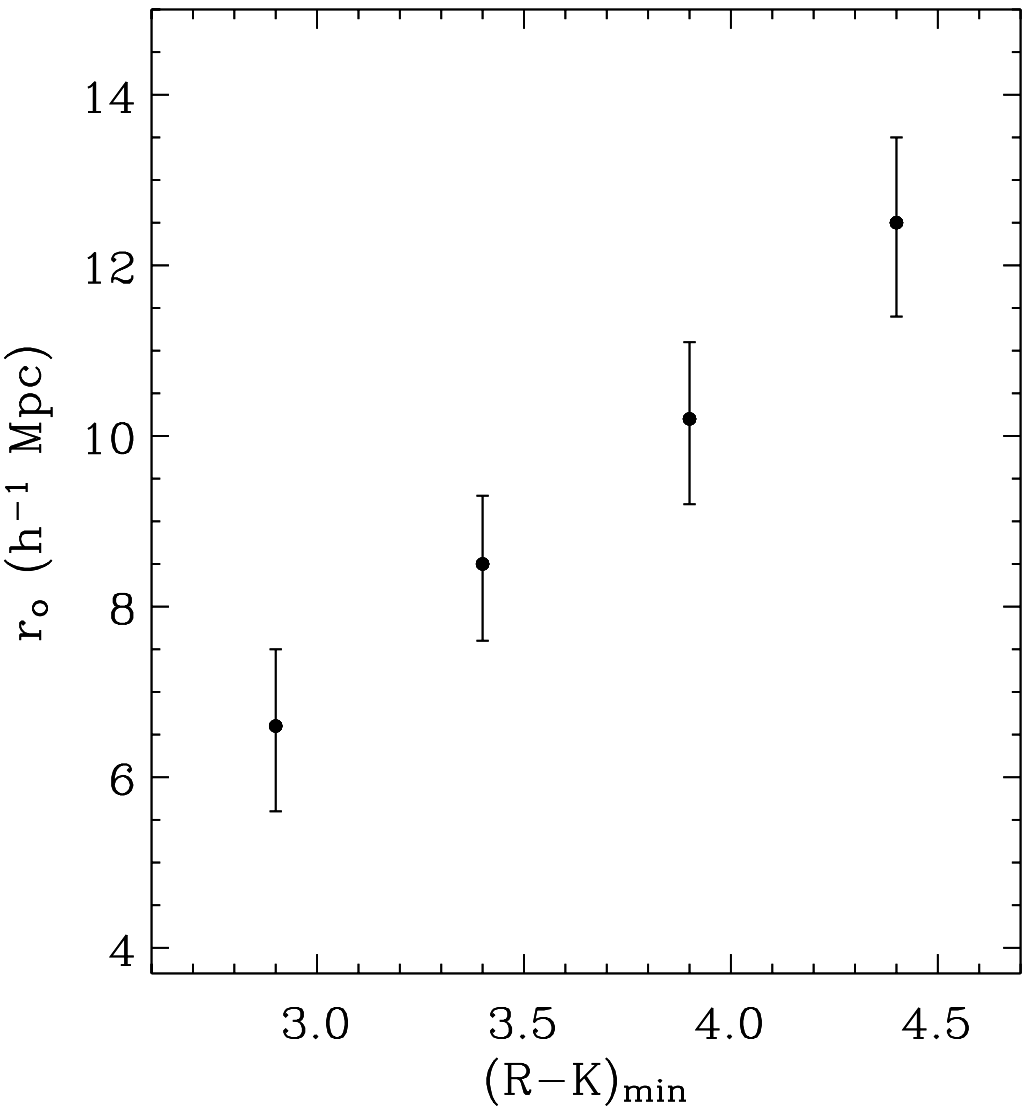
Color - density relation at z~2.5



Quadri et al. (2007, 2008)

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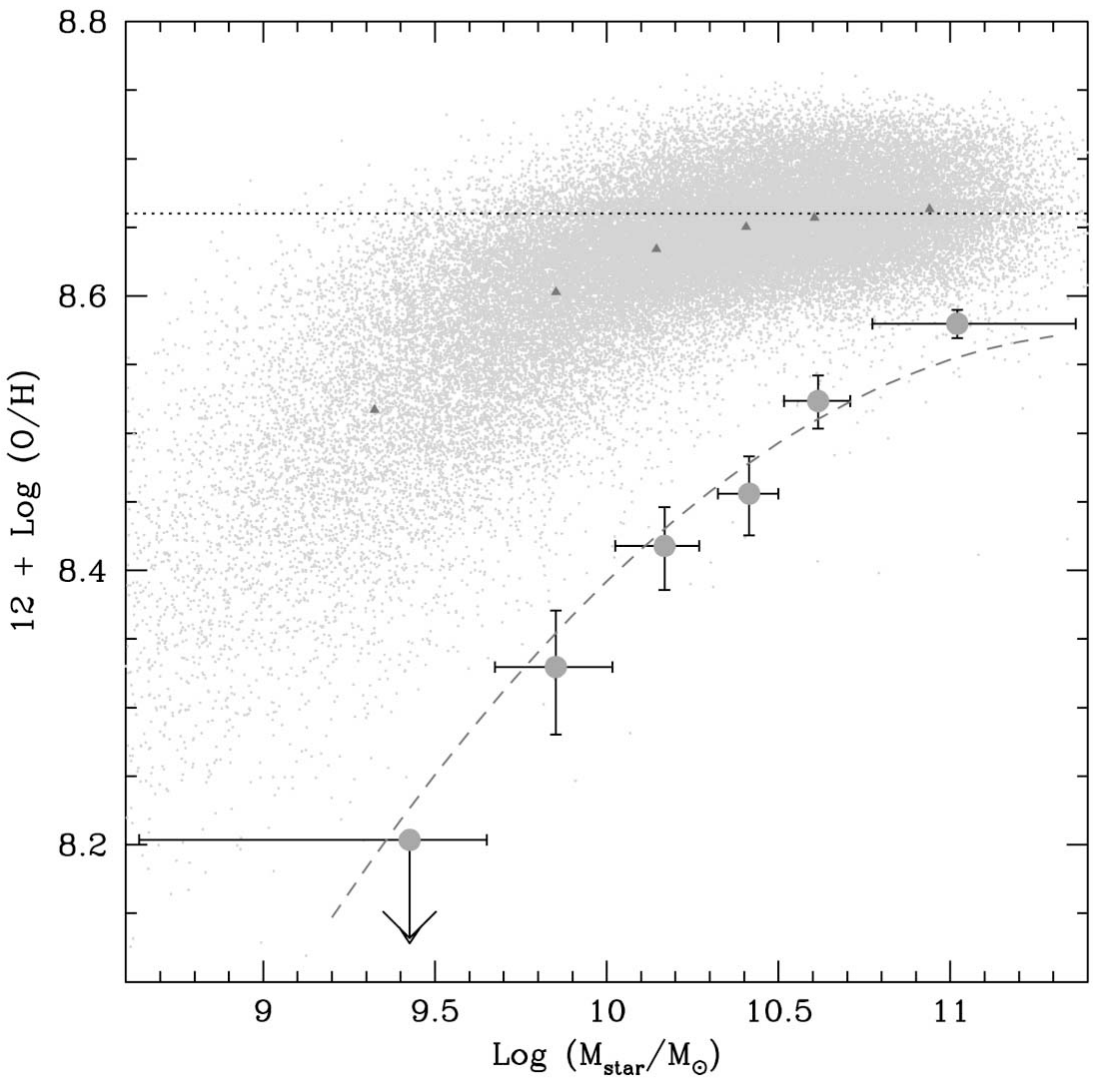
Mass - metallicity relation at z~2.3



Erb et al. (2006)

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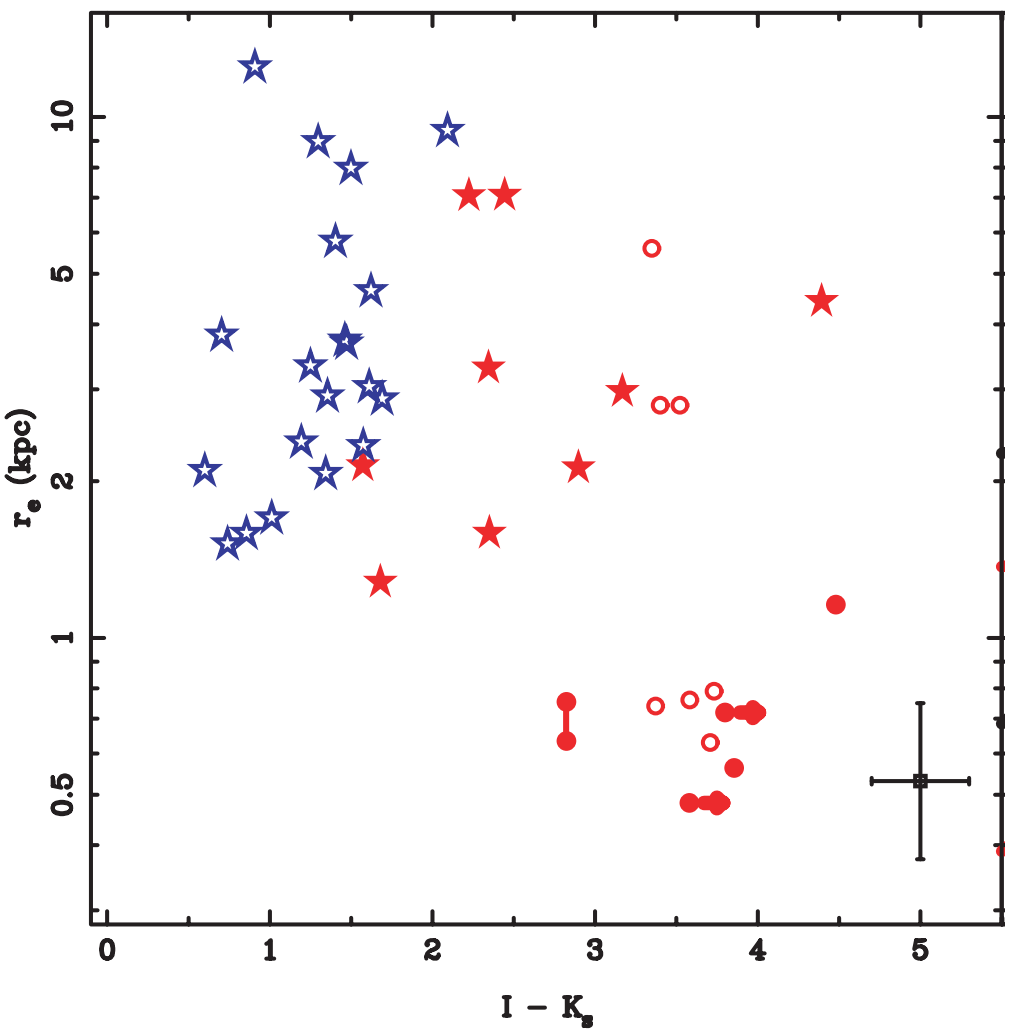
Color - size relation at z ~ 2.5



Zirm et al. 2007 (See also Trujillo et al., Toft et al. 2007)

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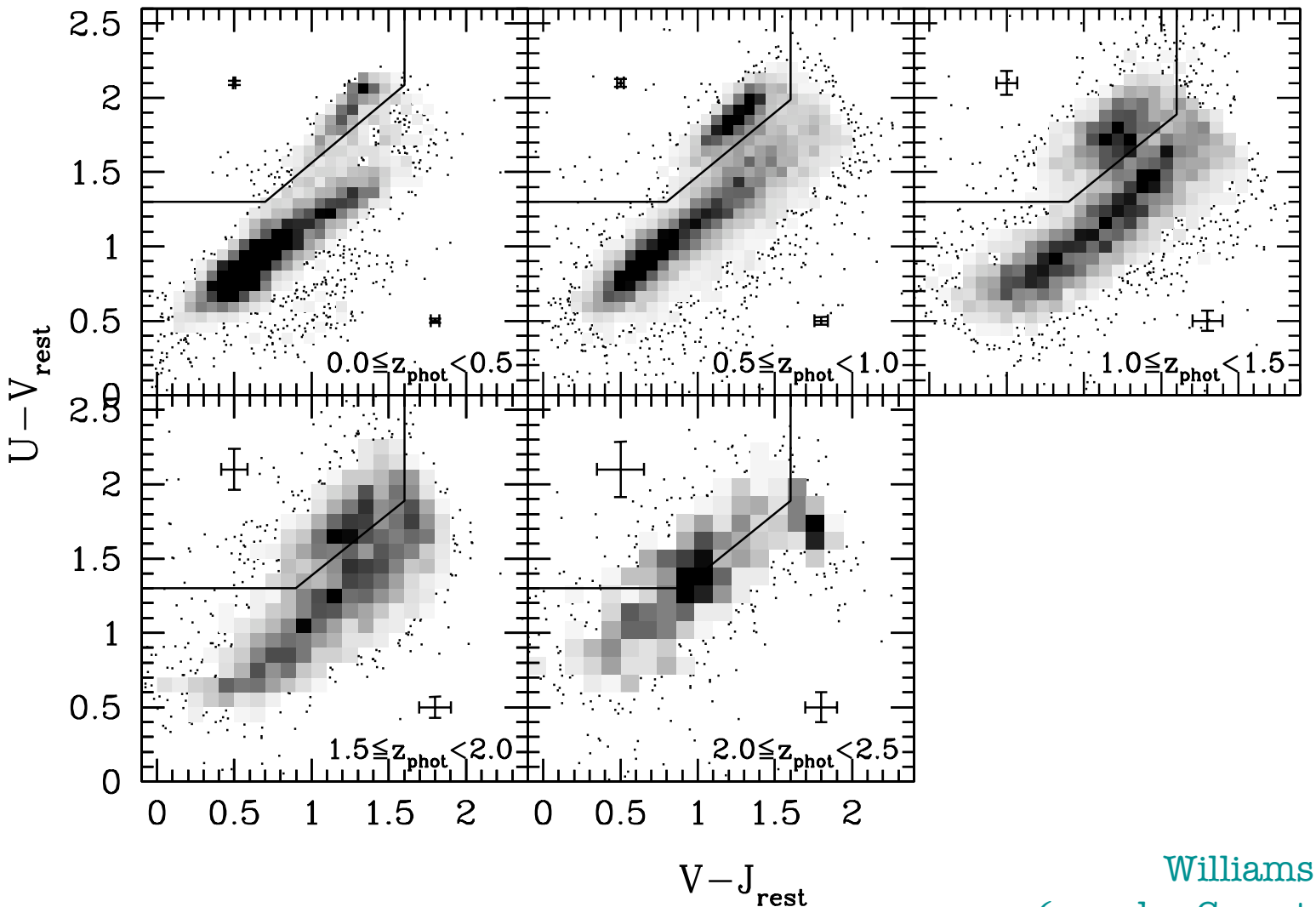
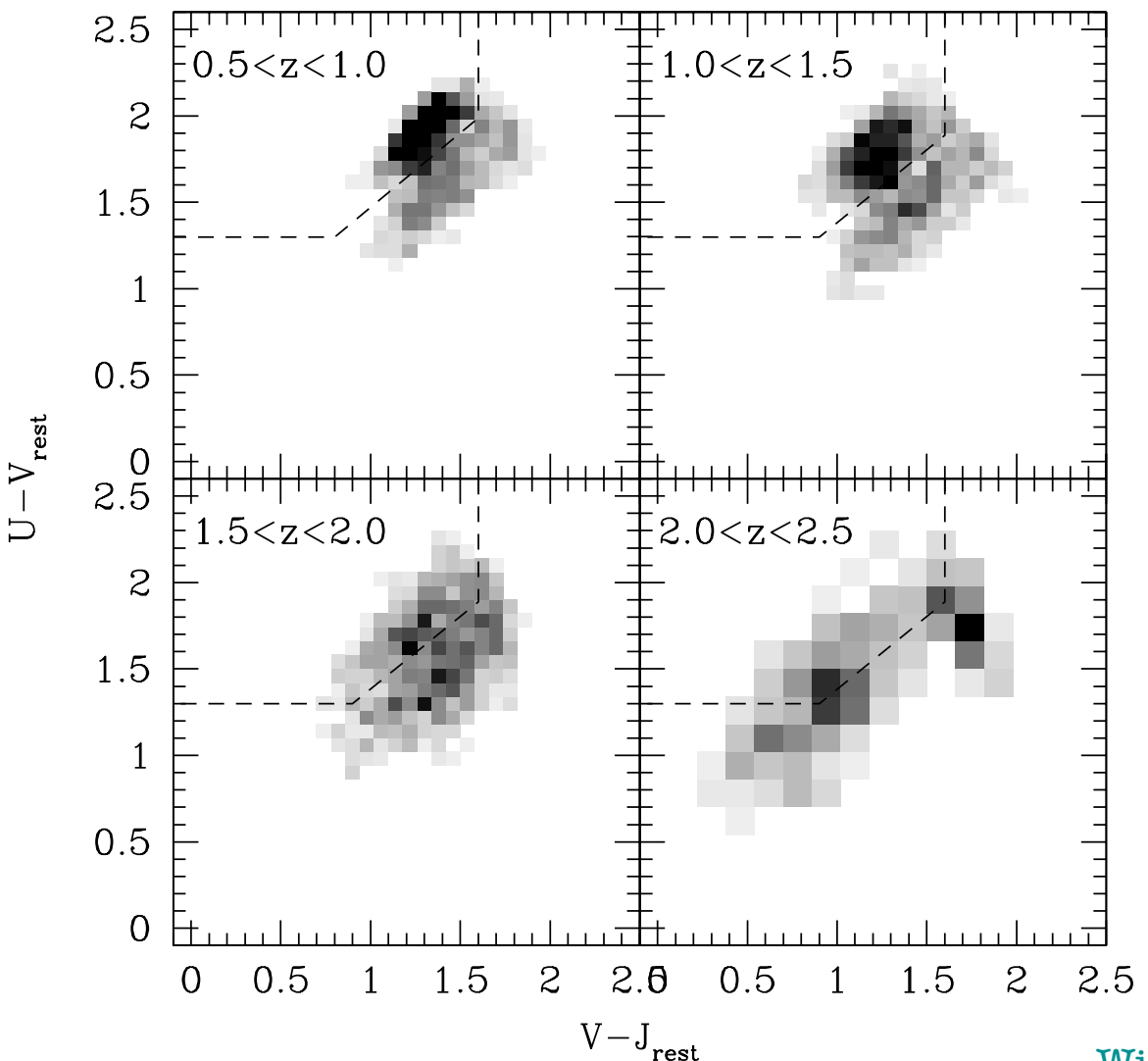
Bimodality in the color distribution up to z ~ 2



Williams et al. (2008)
(see also Cassata et al. 2008)

Bimodality in the color distribution up to z ~ 2



Williams et al., submitted

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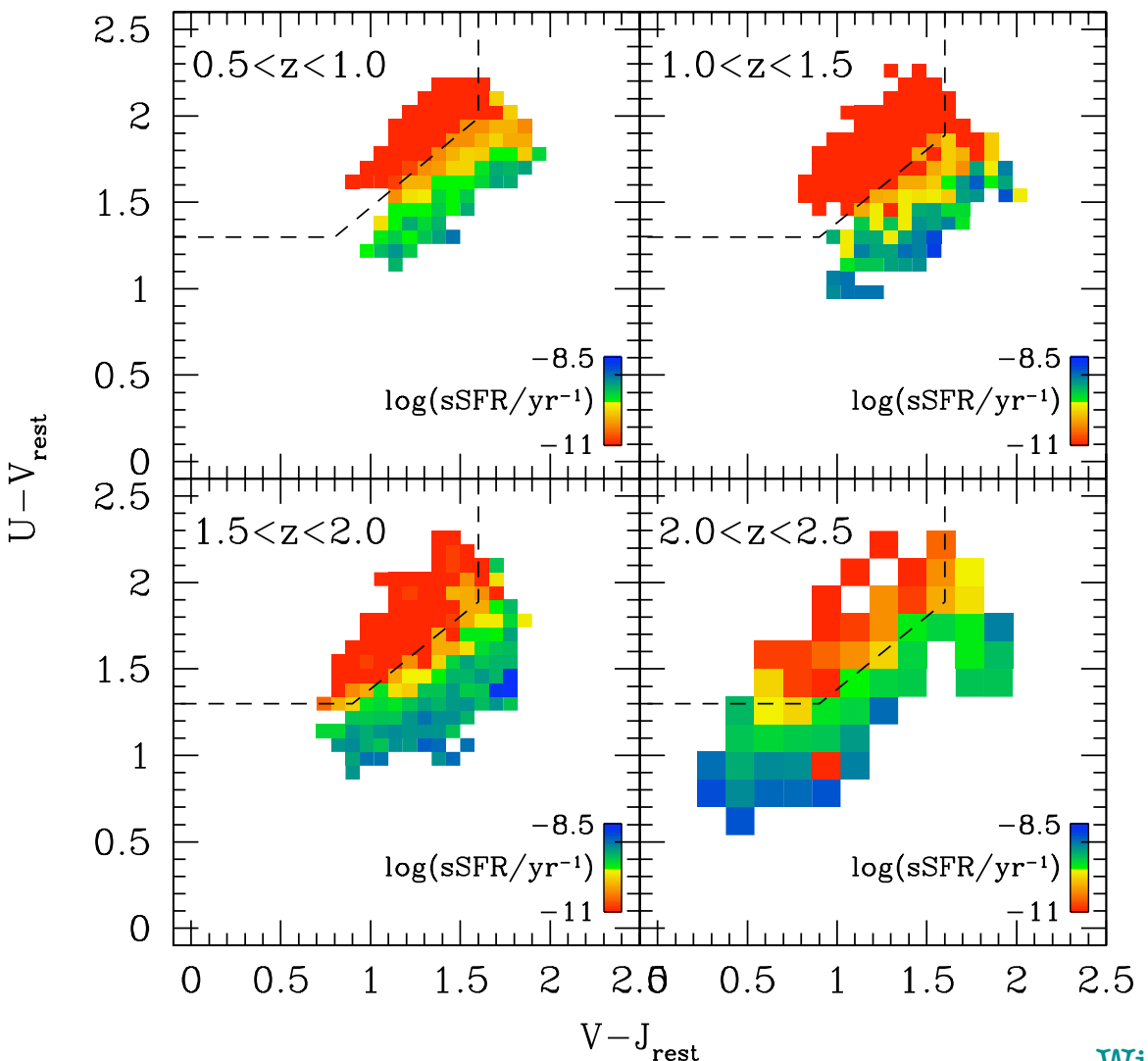
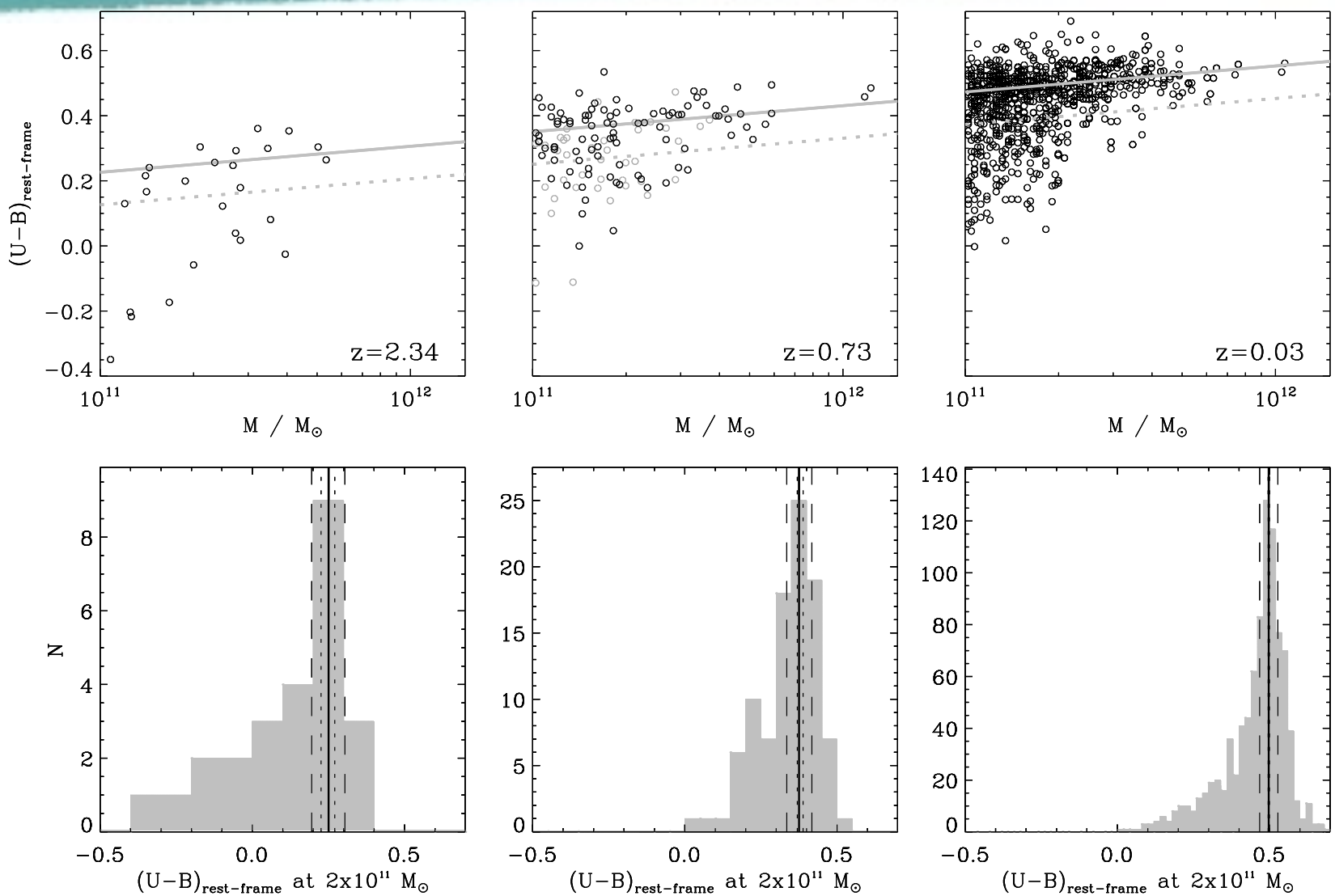


Williams et al., submitted

A red sequence up to z ~ 2.3?



Kriek et al. (2008b)

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The galaxy relations in the z~2 universe look strikingly similar to those in the local universe.

What do these similarities imply?

- Red systems evolve passively from z~2 to z~0?
- There is no structural evolution between z~2 and z~0?
- The metallicity in blue galaxies just gradually increases?
- etc.

Is it really that simple?

No!

- The number of red, quiescent galaxies grows significantly between z~2 and z~0
- The color evolution of the red sequence is not consistent with just passive evolution
- Sizes and morphologies of z~2.3 galaxies are different from low-z galaxies at similar mass

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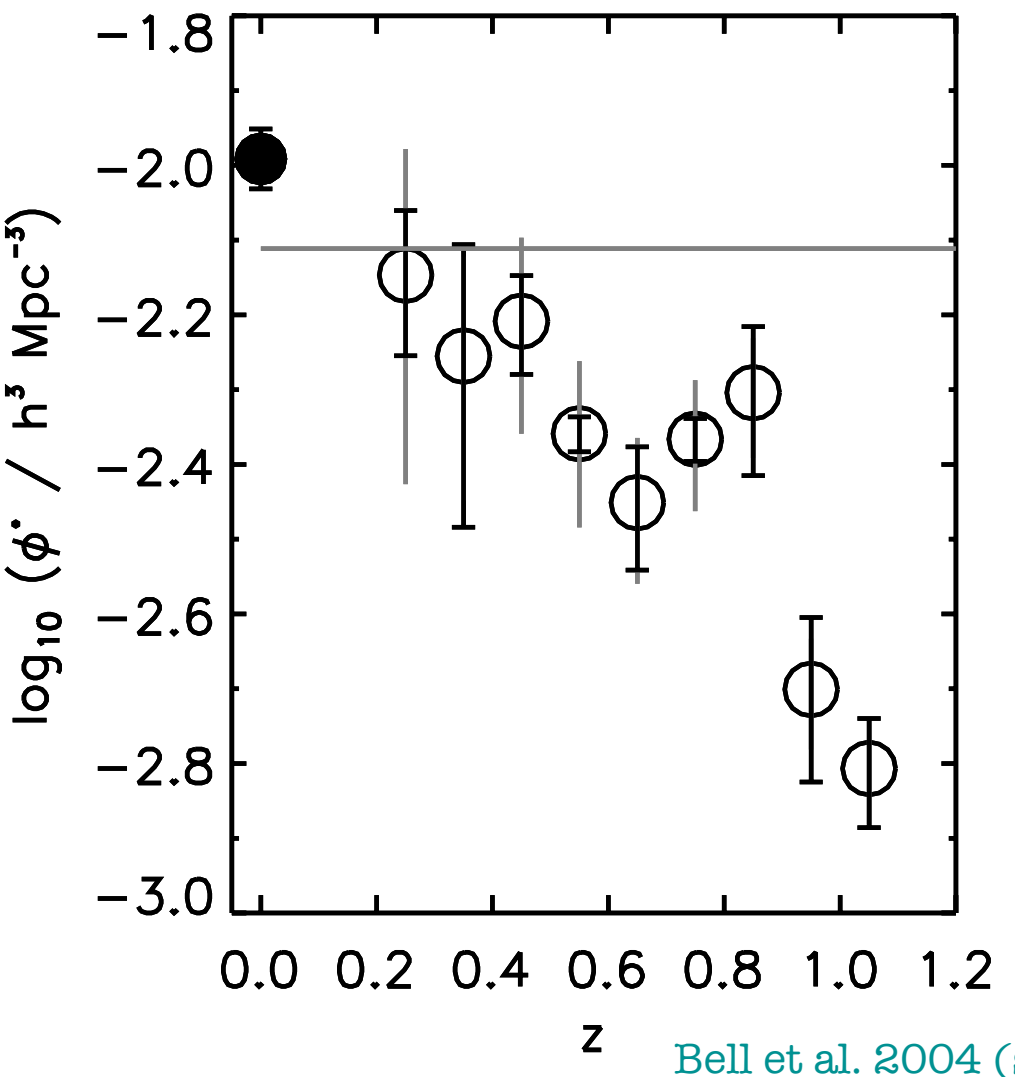
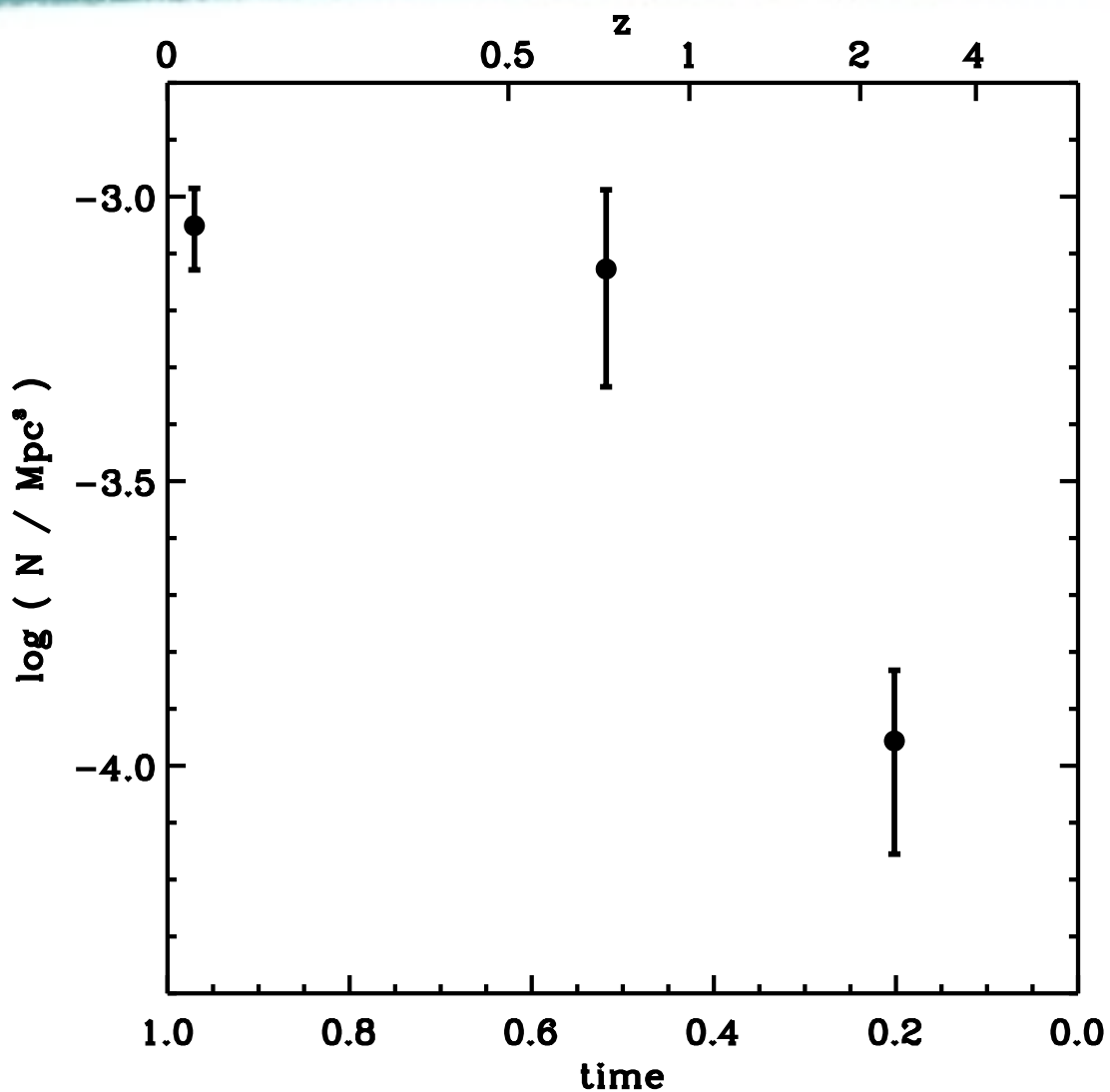
Growth of the red sequence



Bell et al. 2004 (see also Faber et al. 2007)

Growth of the red sequence



Kriek et al. (2008b), see also Taylor et al. (2009)

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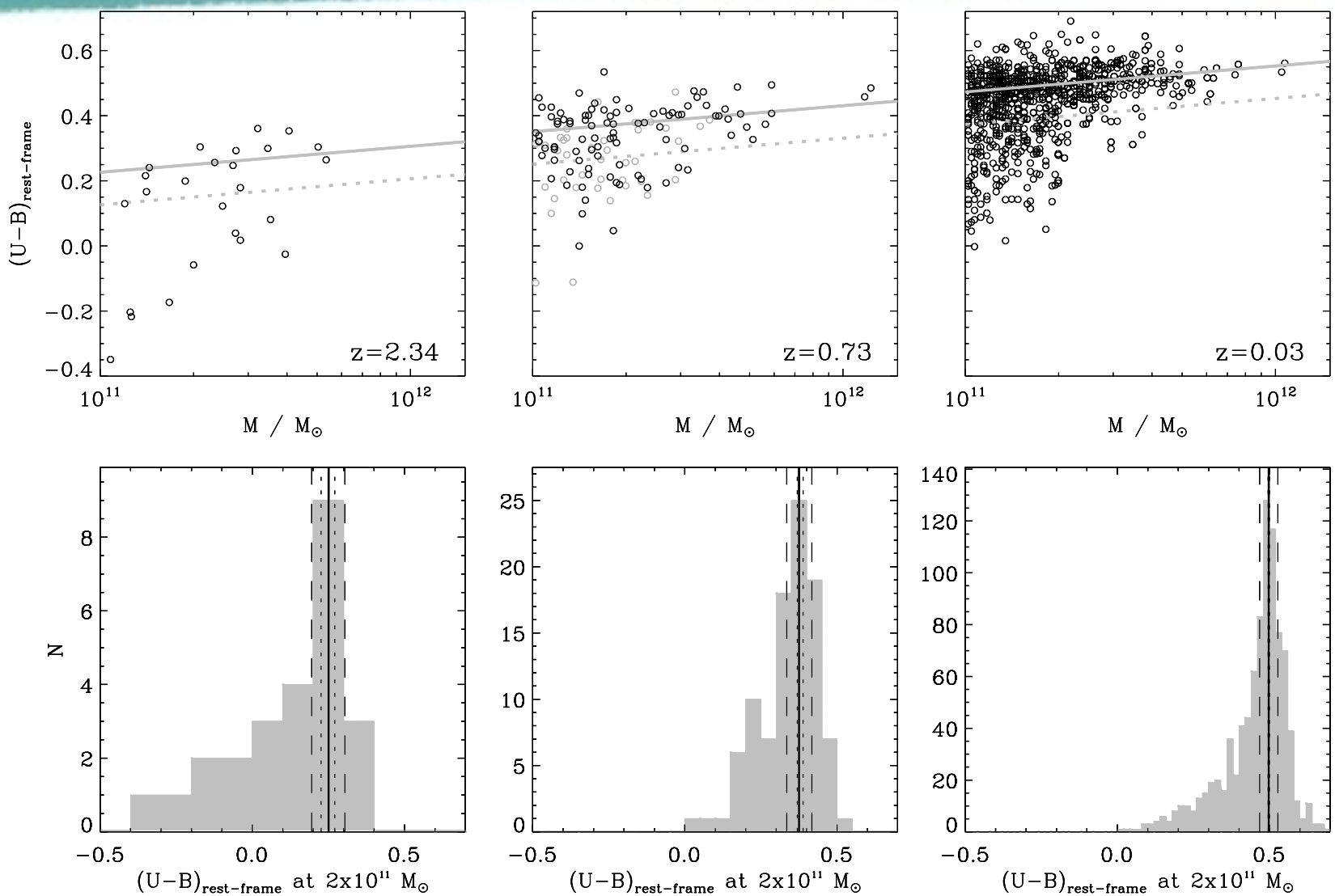
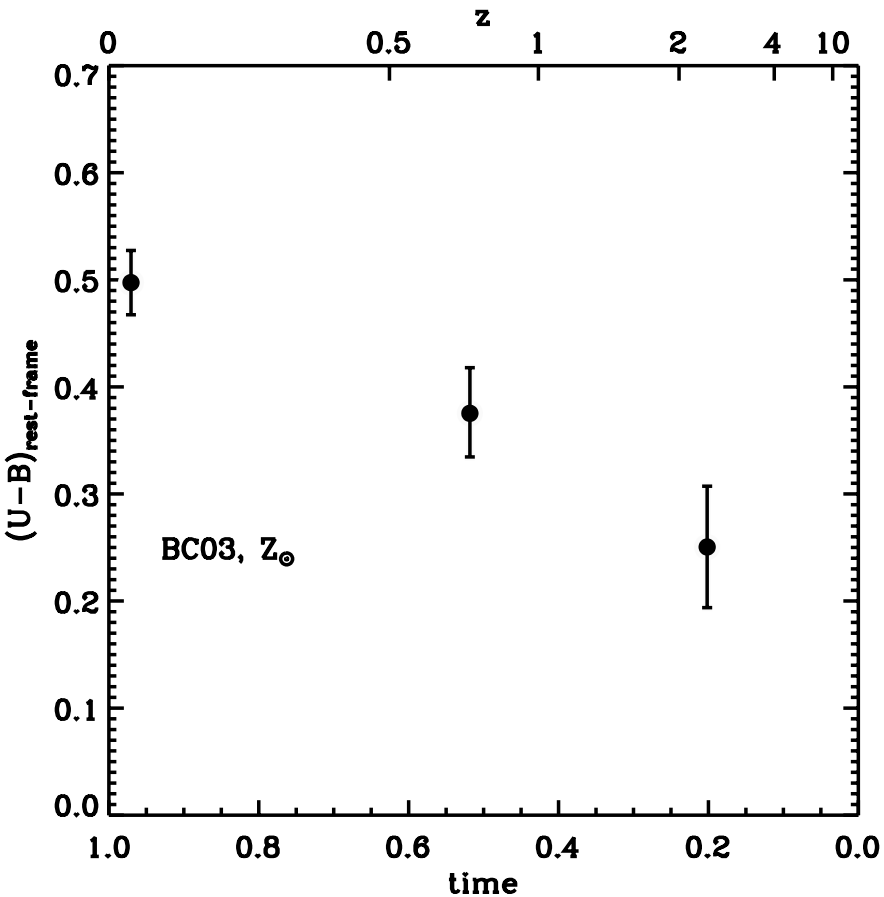
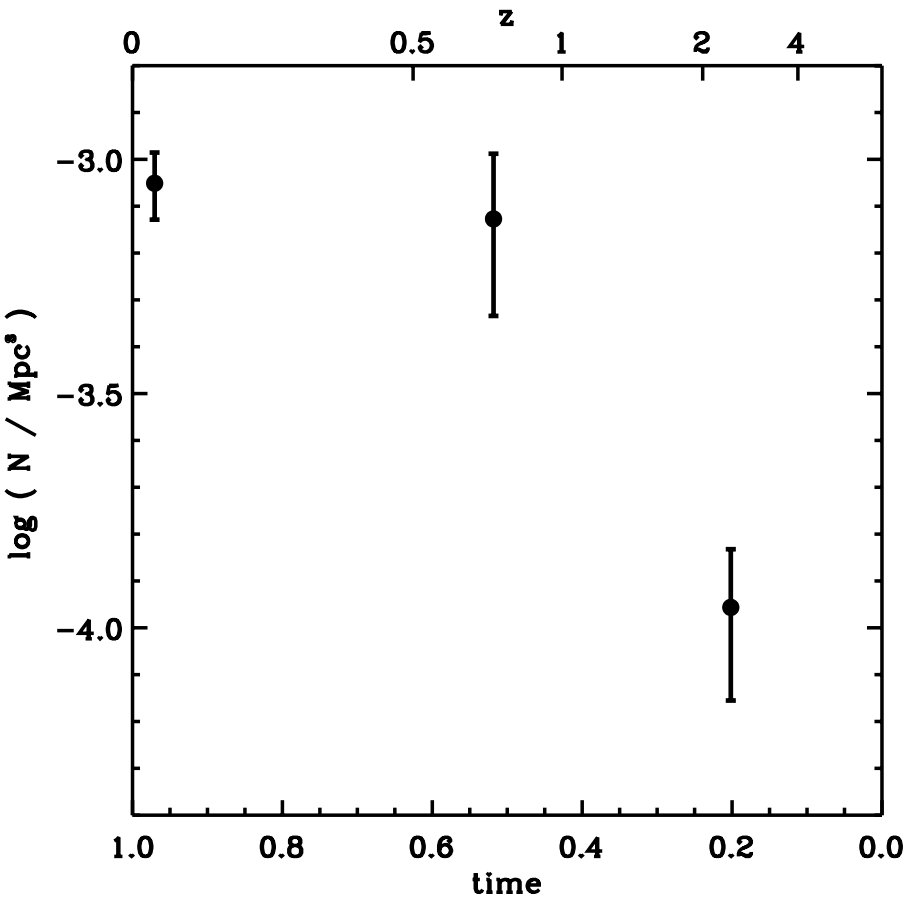
Evolution of the Red Sequence



Kriek et al. (2008b)

Evolution of the Red Sequence





Kriek et al. (2008b)

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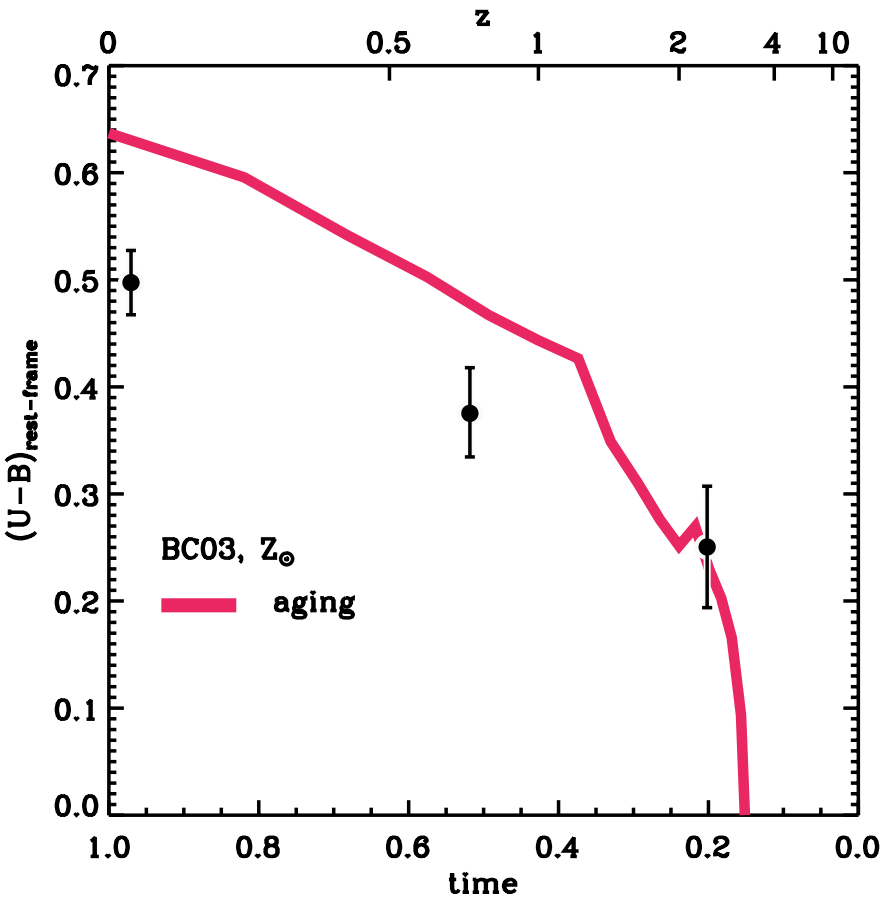

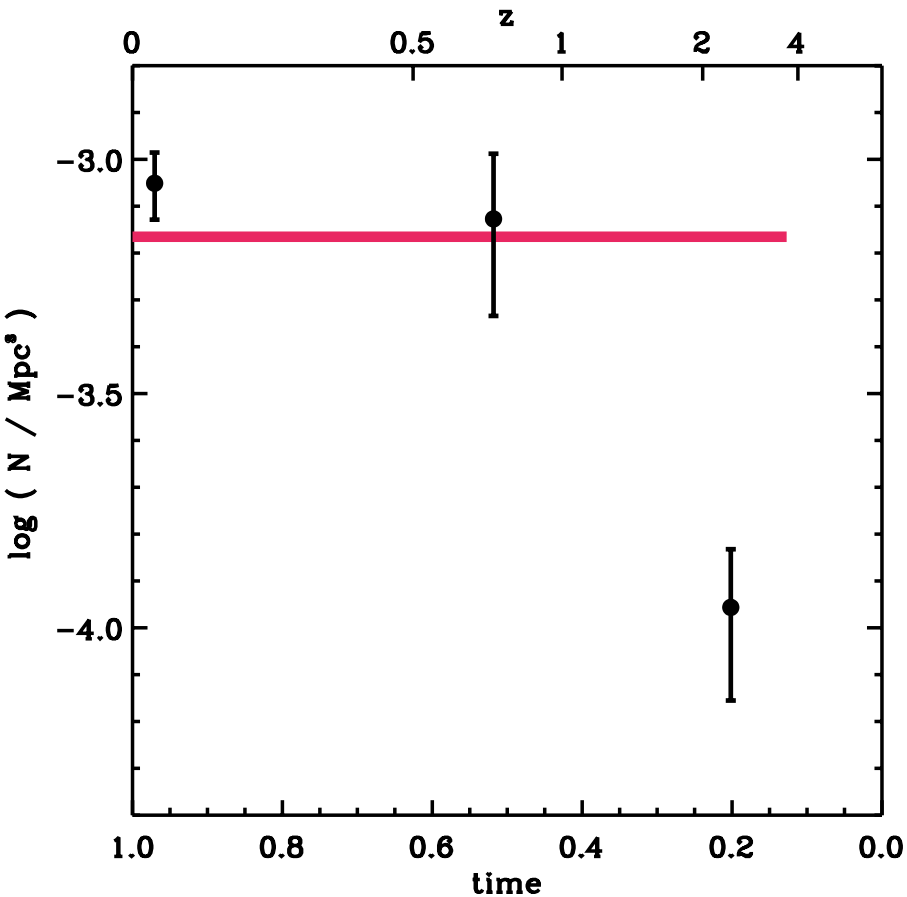

Kriek et al. (2008b)

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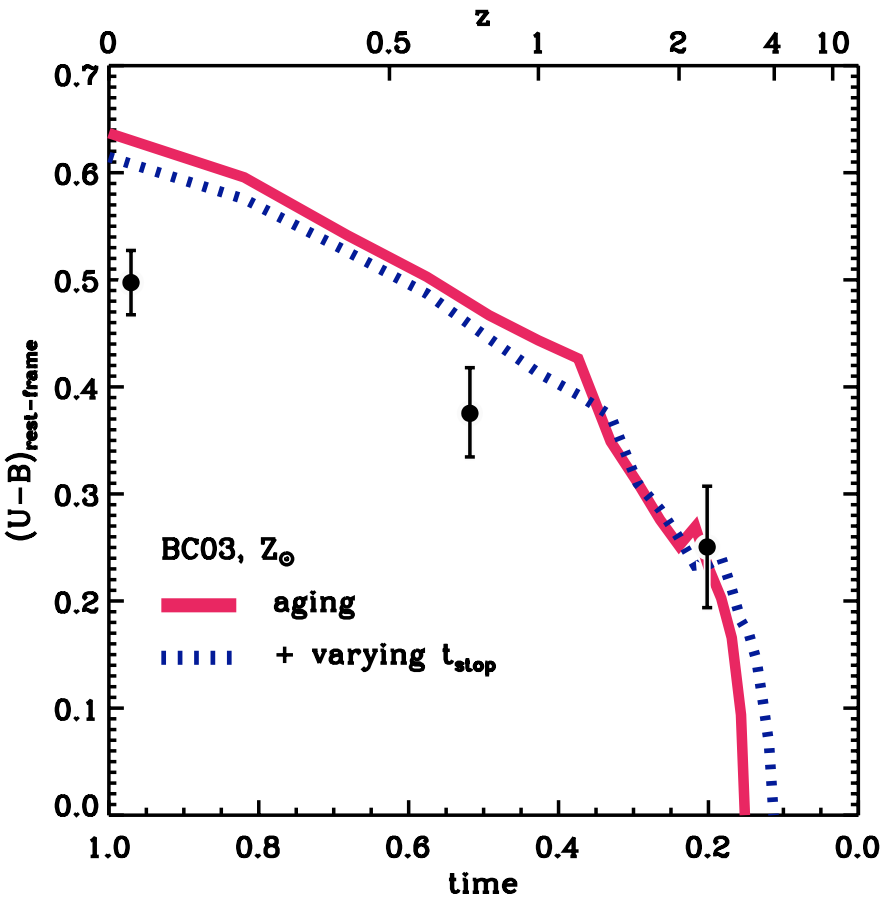

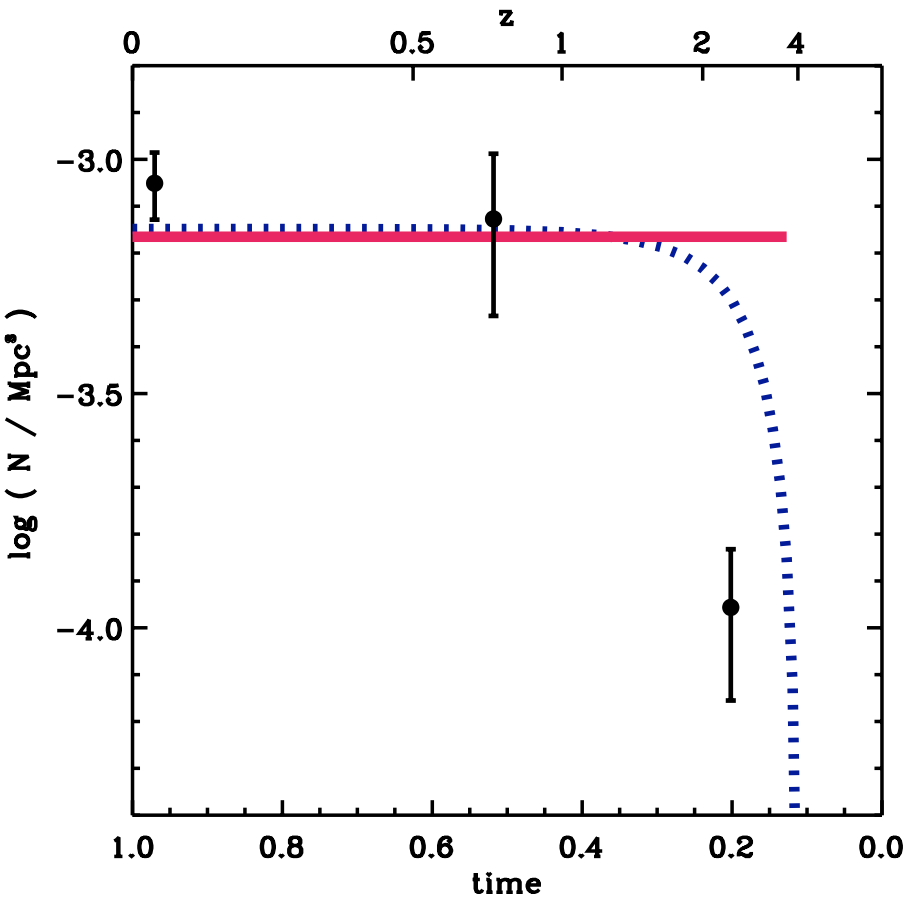

Kriek et al. (2008b)

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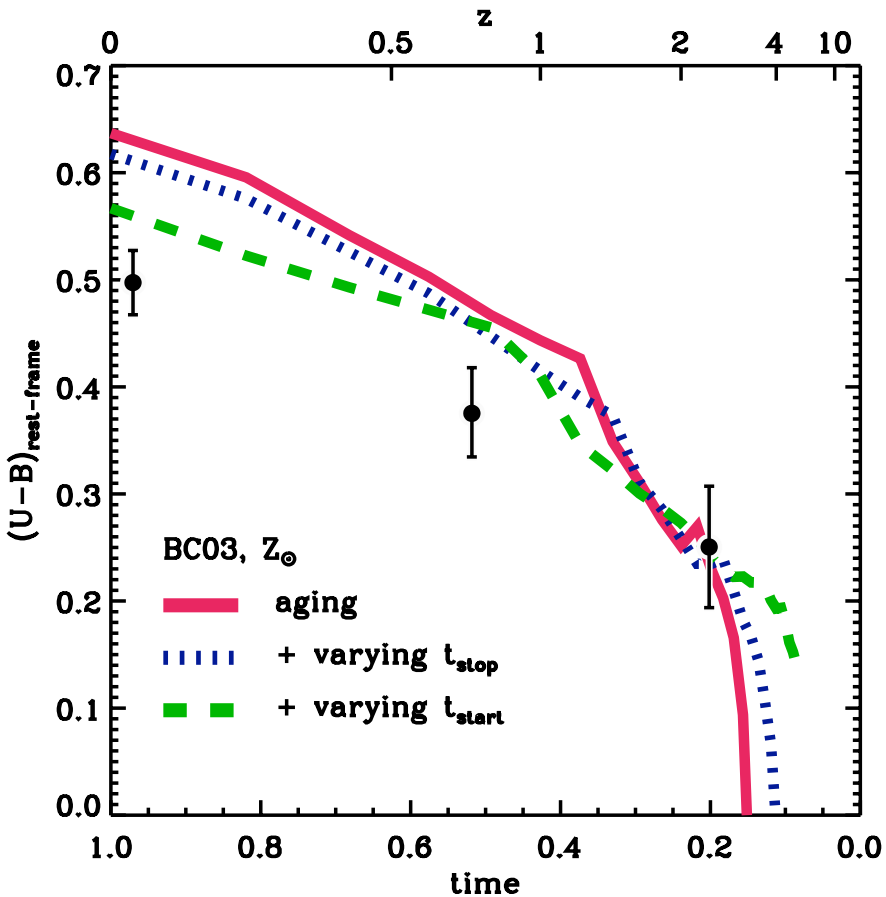
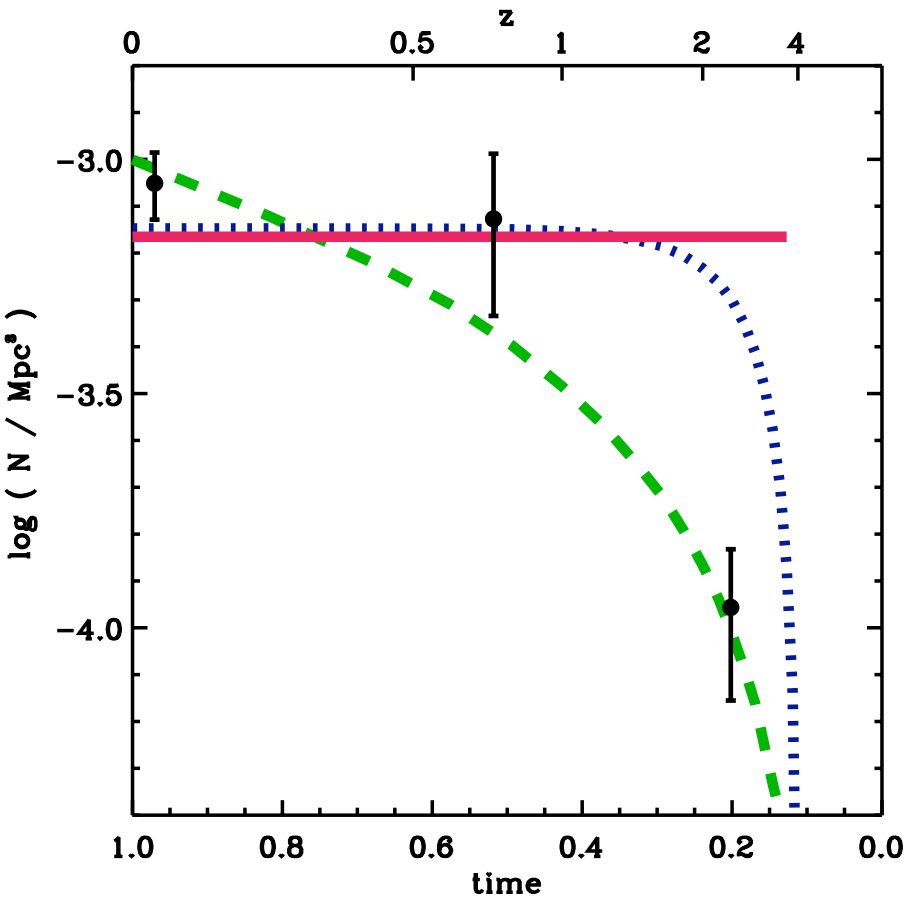
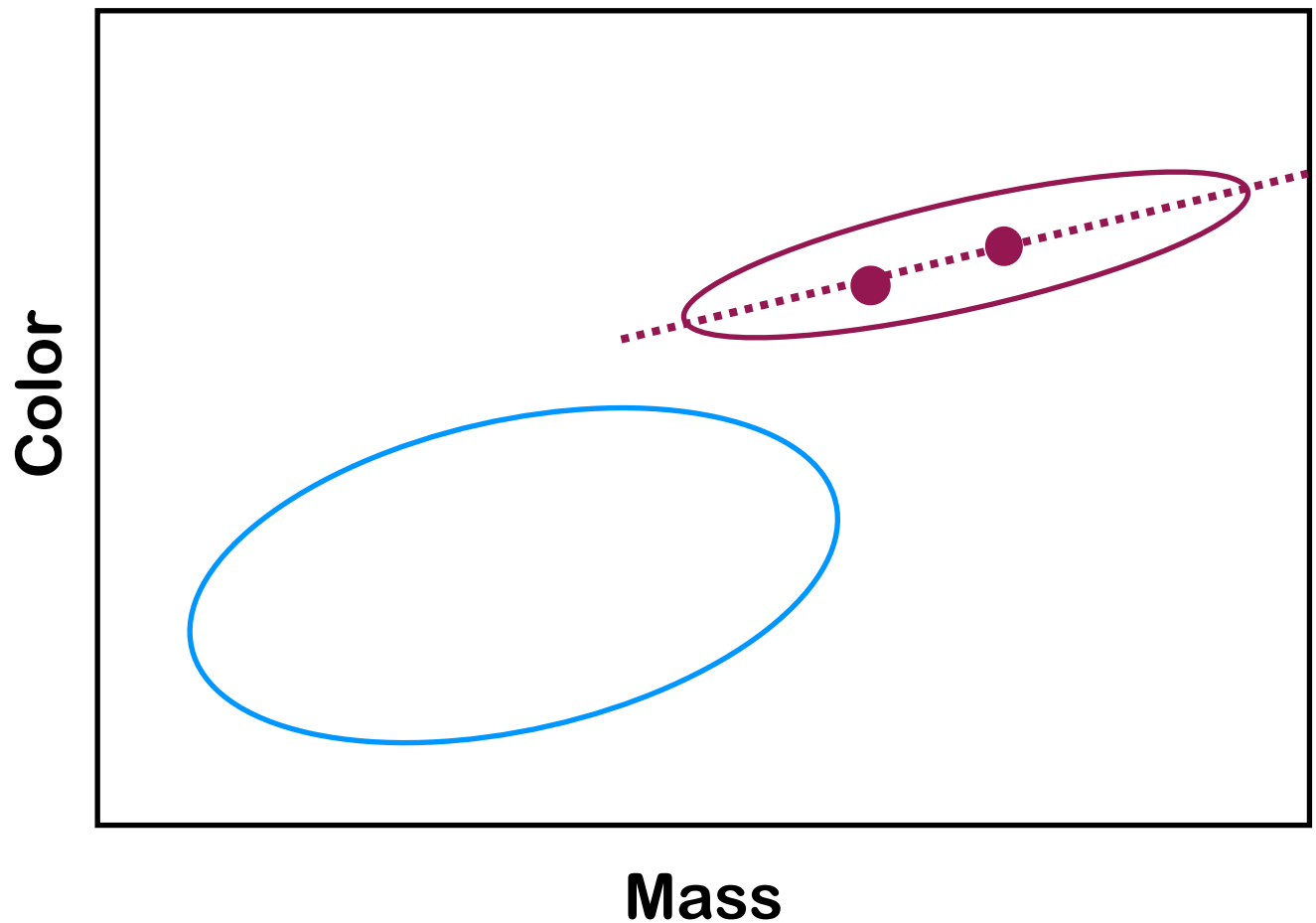


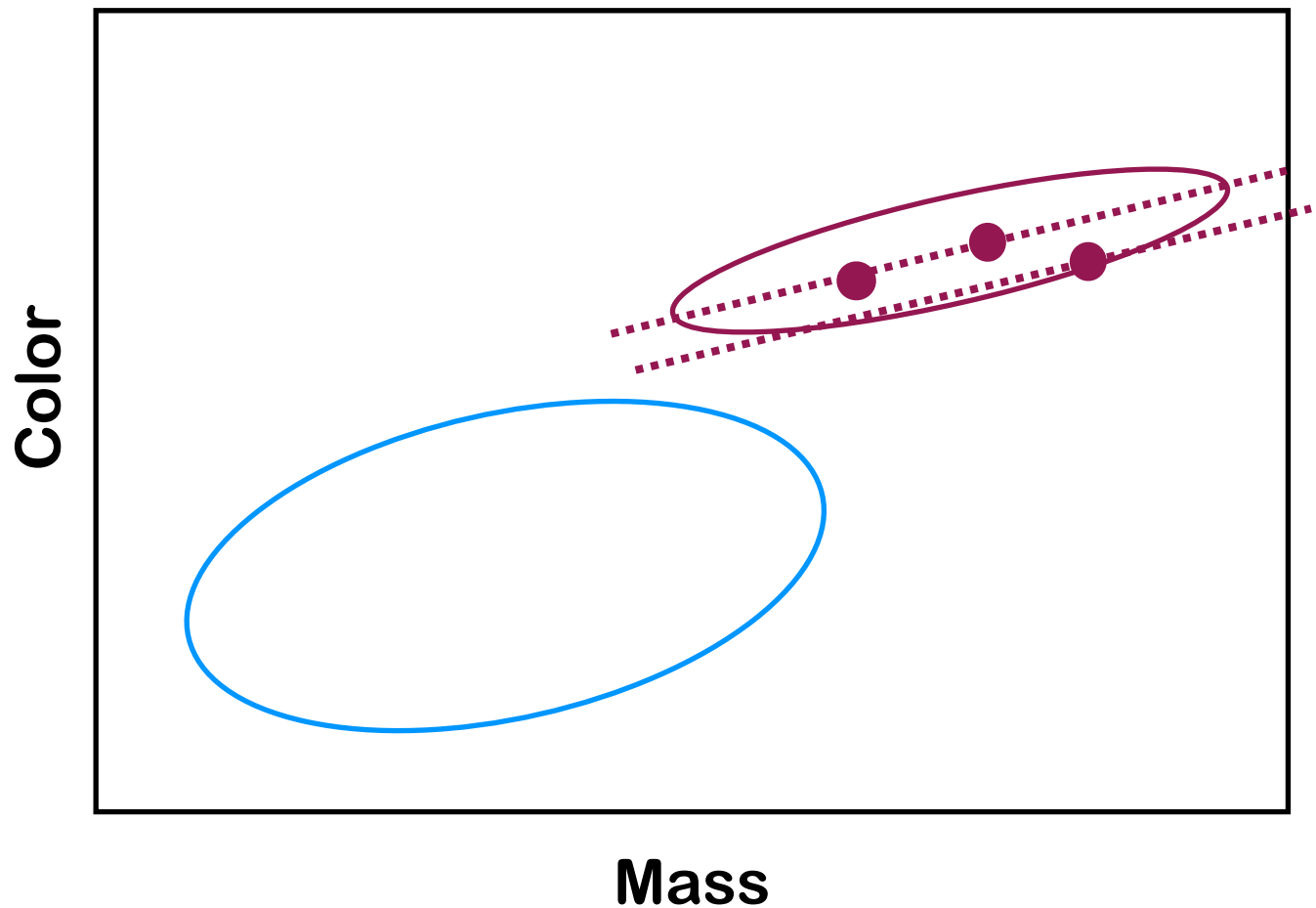


Kriek et al. (2008b)

Red mergers



Red mergers



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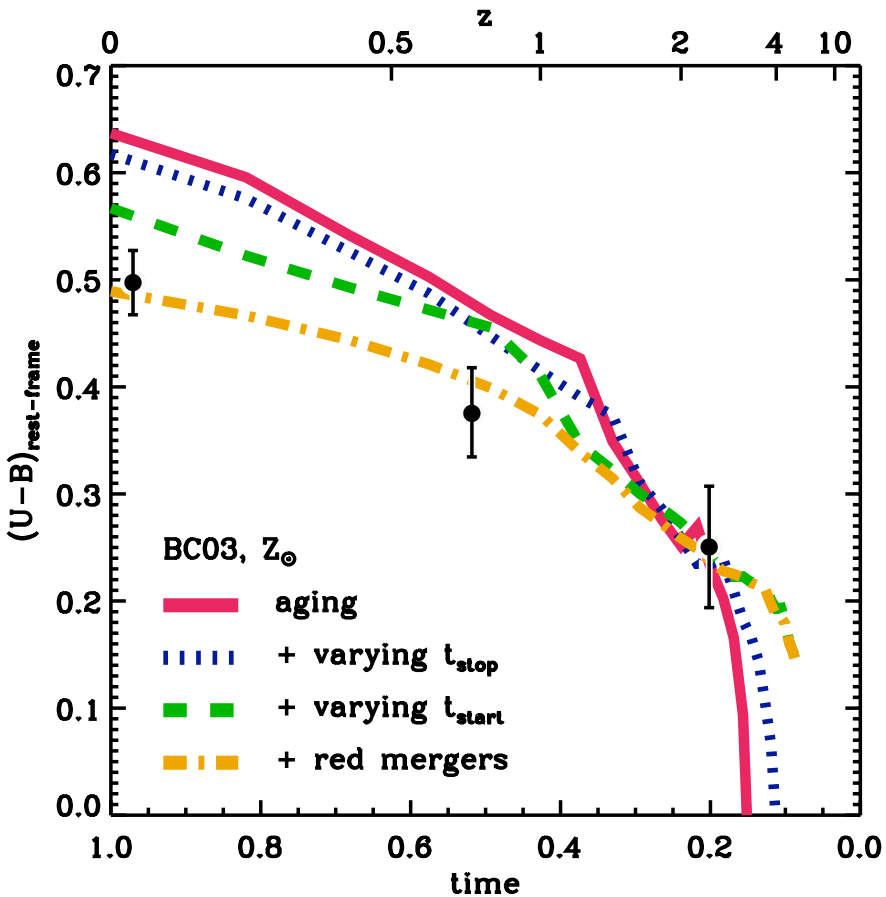

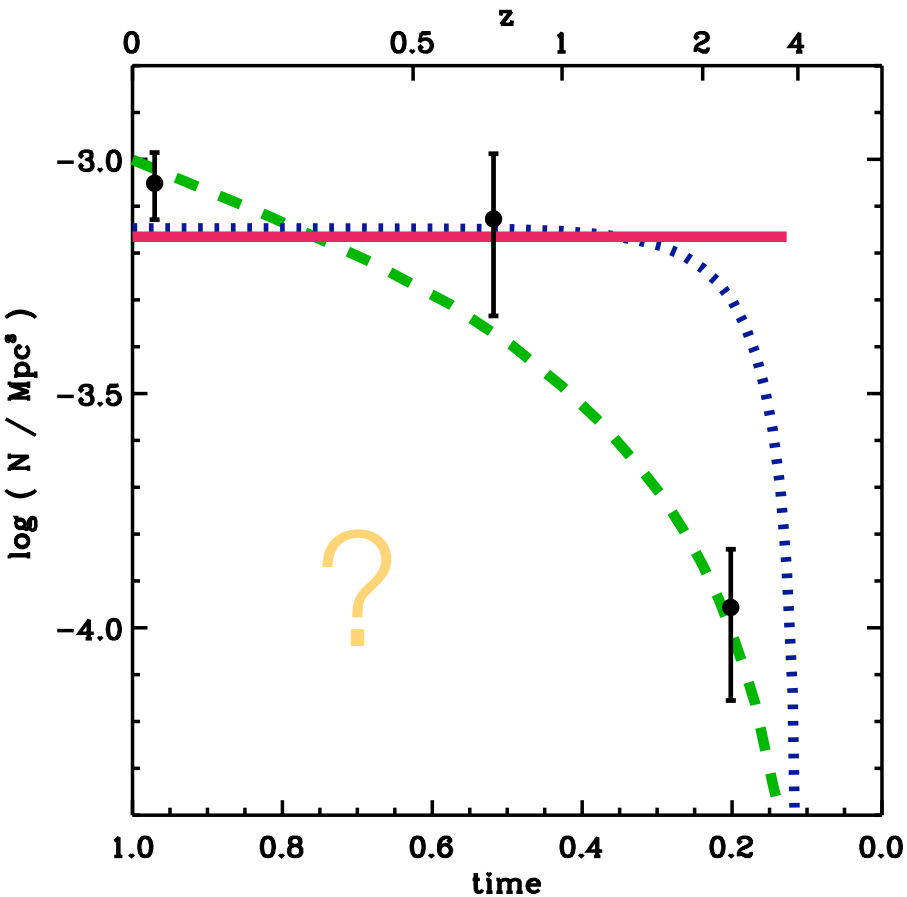

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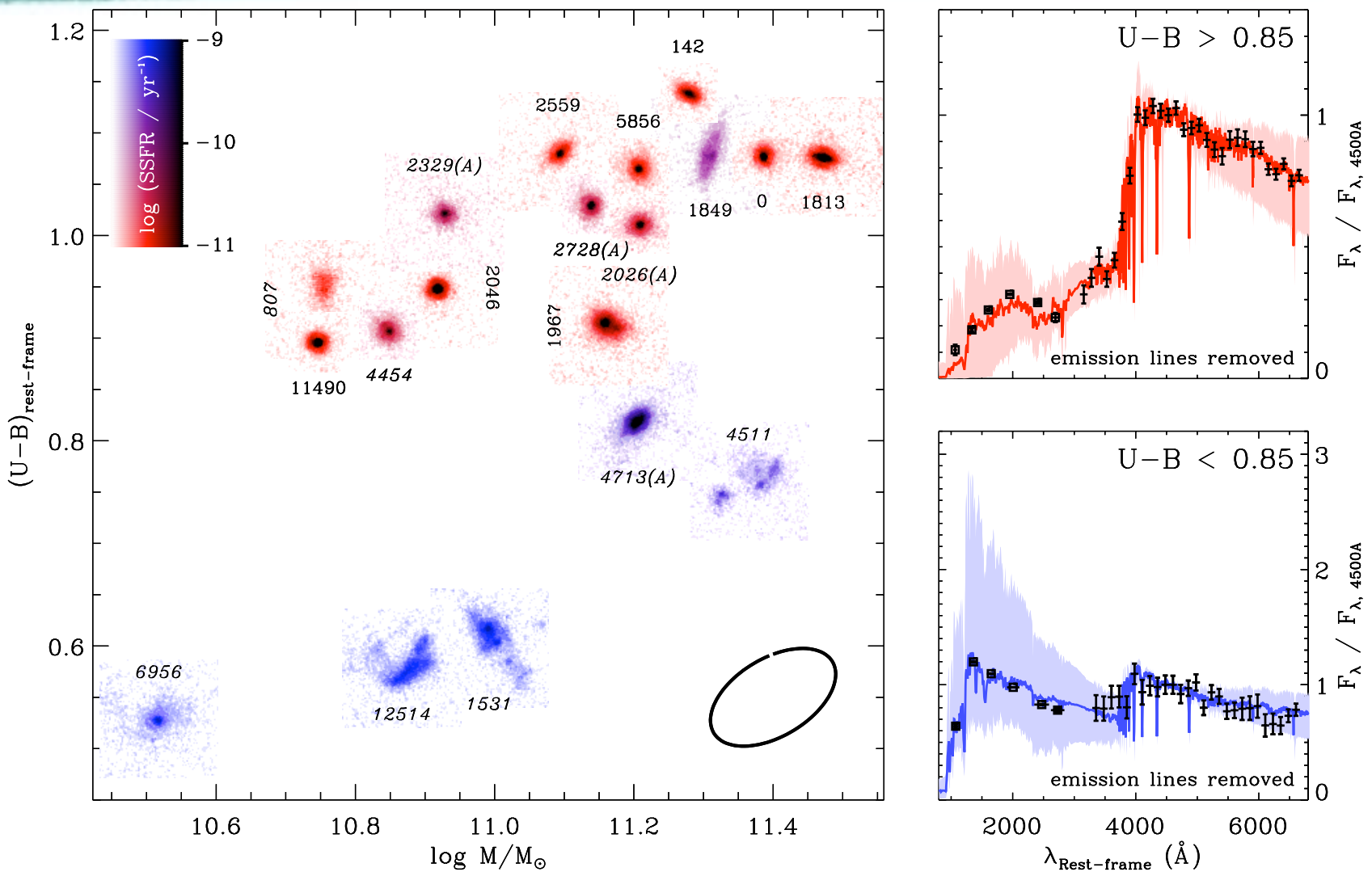
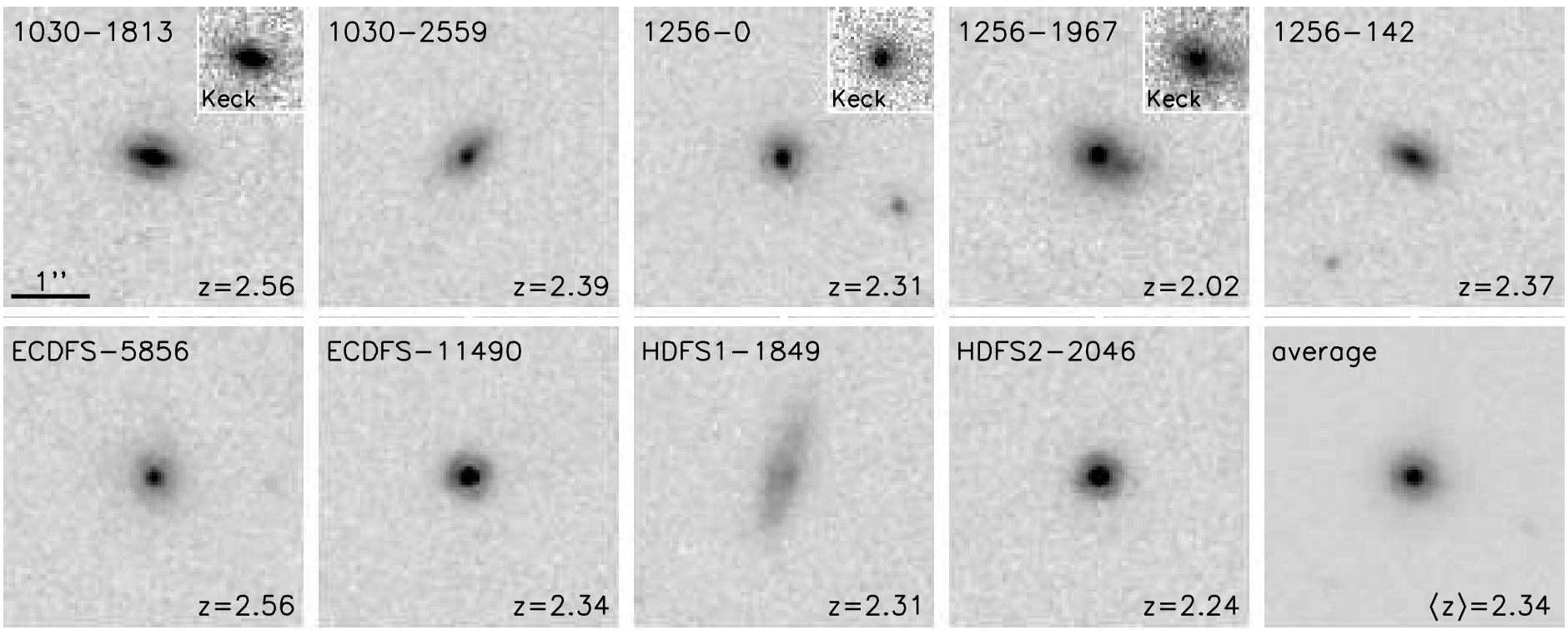
Morphologies of z~2.3 massive galaxies



Kriek et al. (2009b)

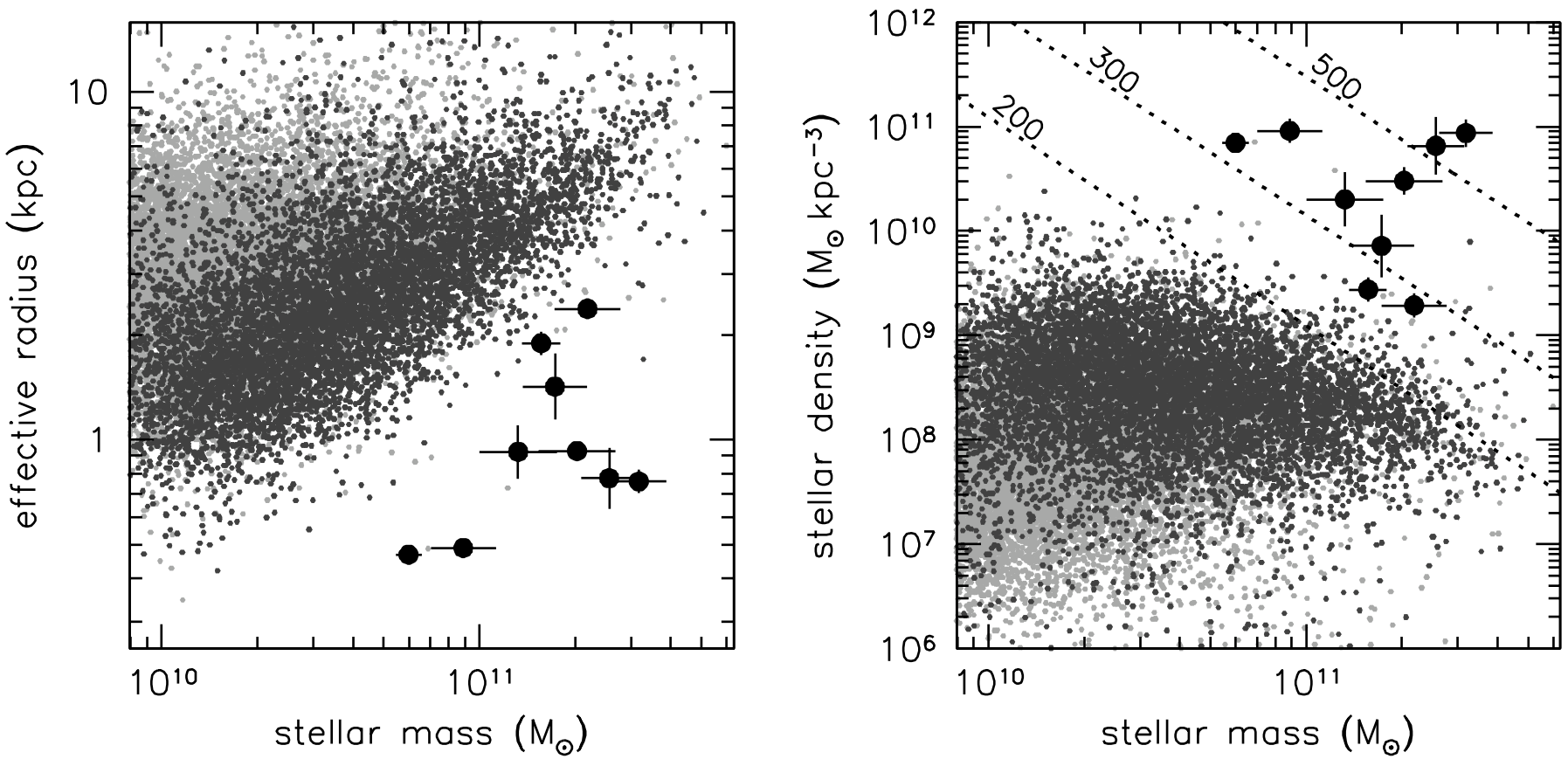
Morphologies of massive, quiescent galaxies at z~2.3



van Dokkum, Franx, Kriek et al. (2008)

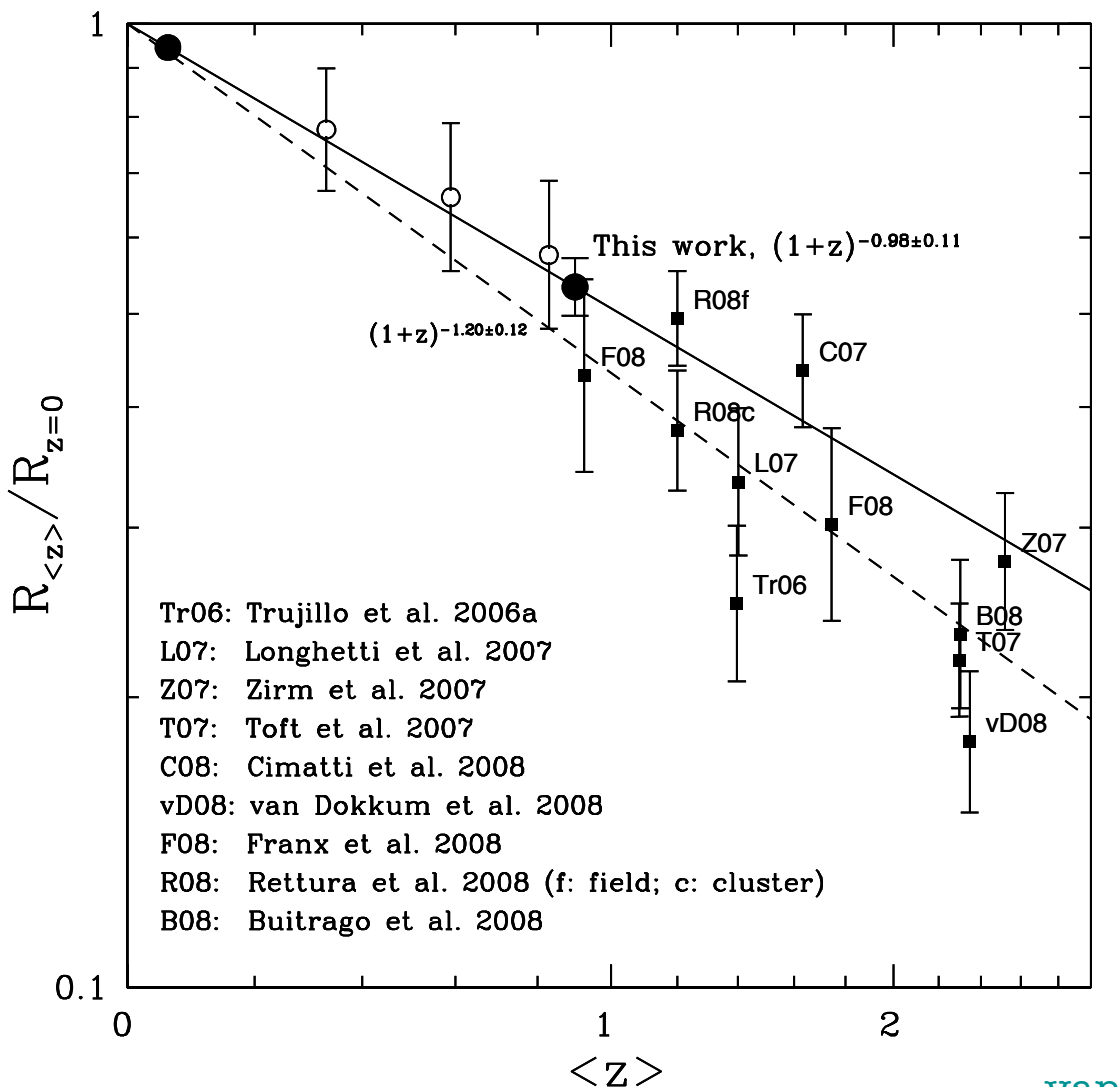
See also Trujillo et al.; Toft et al.; Zirm et al.; Damjanov et al; Daddi et al. etc.

Structural evolution from z~2.3 to z~0.0



van Dokkum, Franx, Kriek et al. (2008)

Structural evolution



van der Wel et al. (2008)

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Implications

In both numbers and structure, the massive galaxy population has evolved significantly from z~2 to the present

Questions

- How do the compact high-z galaxies evolve into local early types?
- How are these compact, quiescent high-z galaxies formed in first place?

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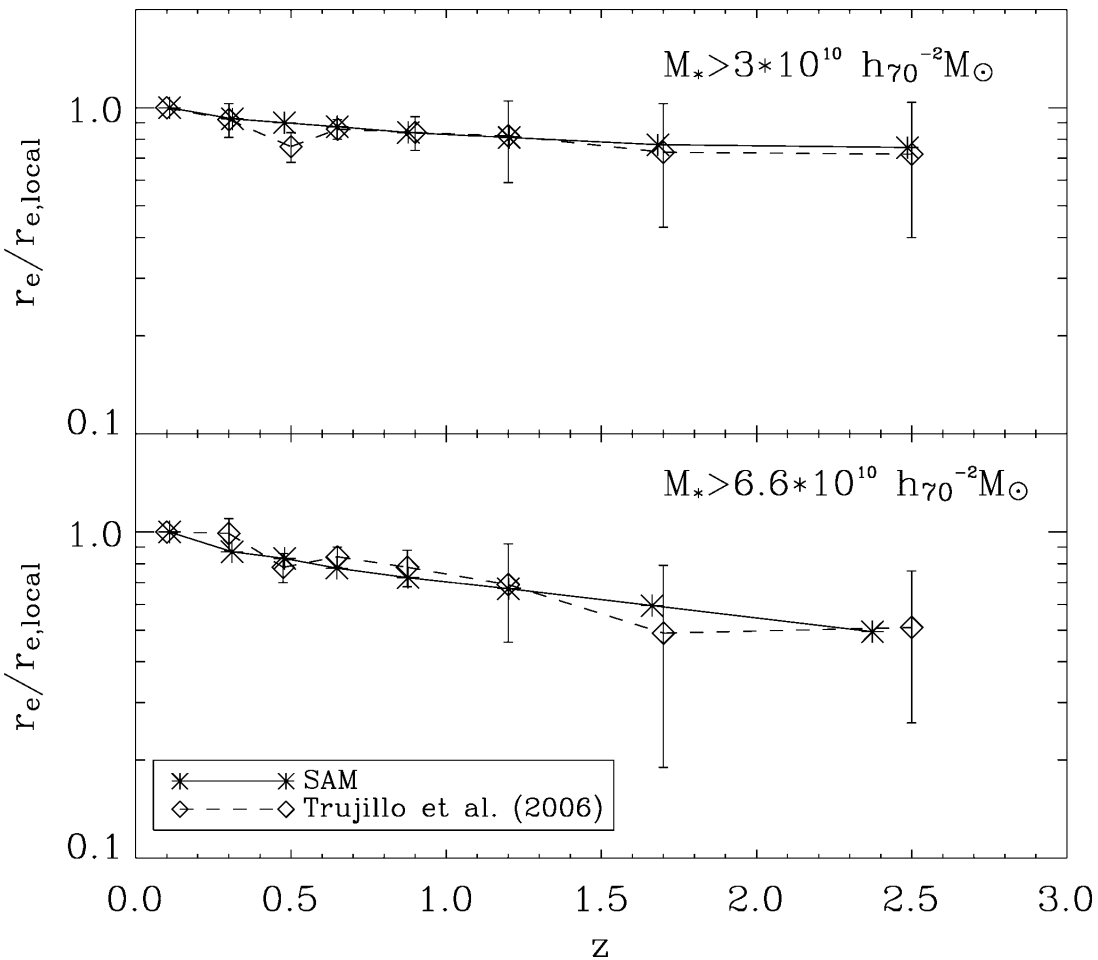
How do compact high-z galaxies evolve into local ETGs?

- Mergers at high redshift are more gas-rich, and thus will result in denser systems
  - e.g., Khochfar & Silk (2006); Hopkins et al. (2007a; 2009d)
- Inside-out growth by minor mergers
- The size evolution may appear more extreme due to systematic effects

Formation at higher redshift results in denser systems



Khochfar & Silk (2006)
(See also Hopkins et al. 2007a; 2009d)

How do compact high-z galaxies evolve into local ETGs?

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- Inside-out growth due to (minor) mergers
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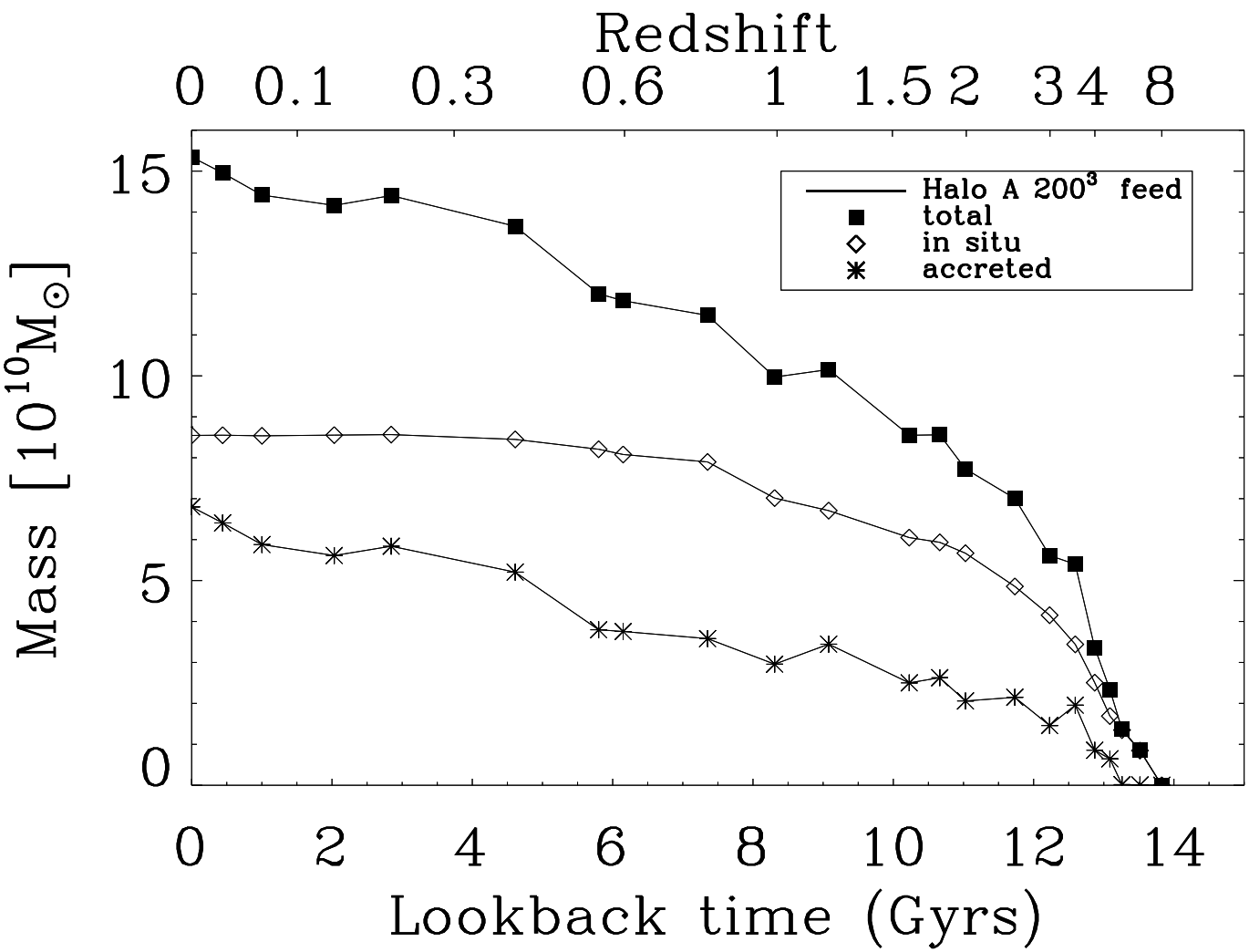
Inside-out growth due to minor mergers



Naab et al. (2009)
(see also Boylan-Kolchin et al. 2006, 2007)

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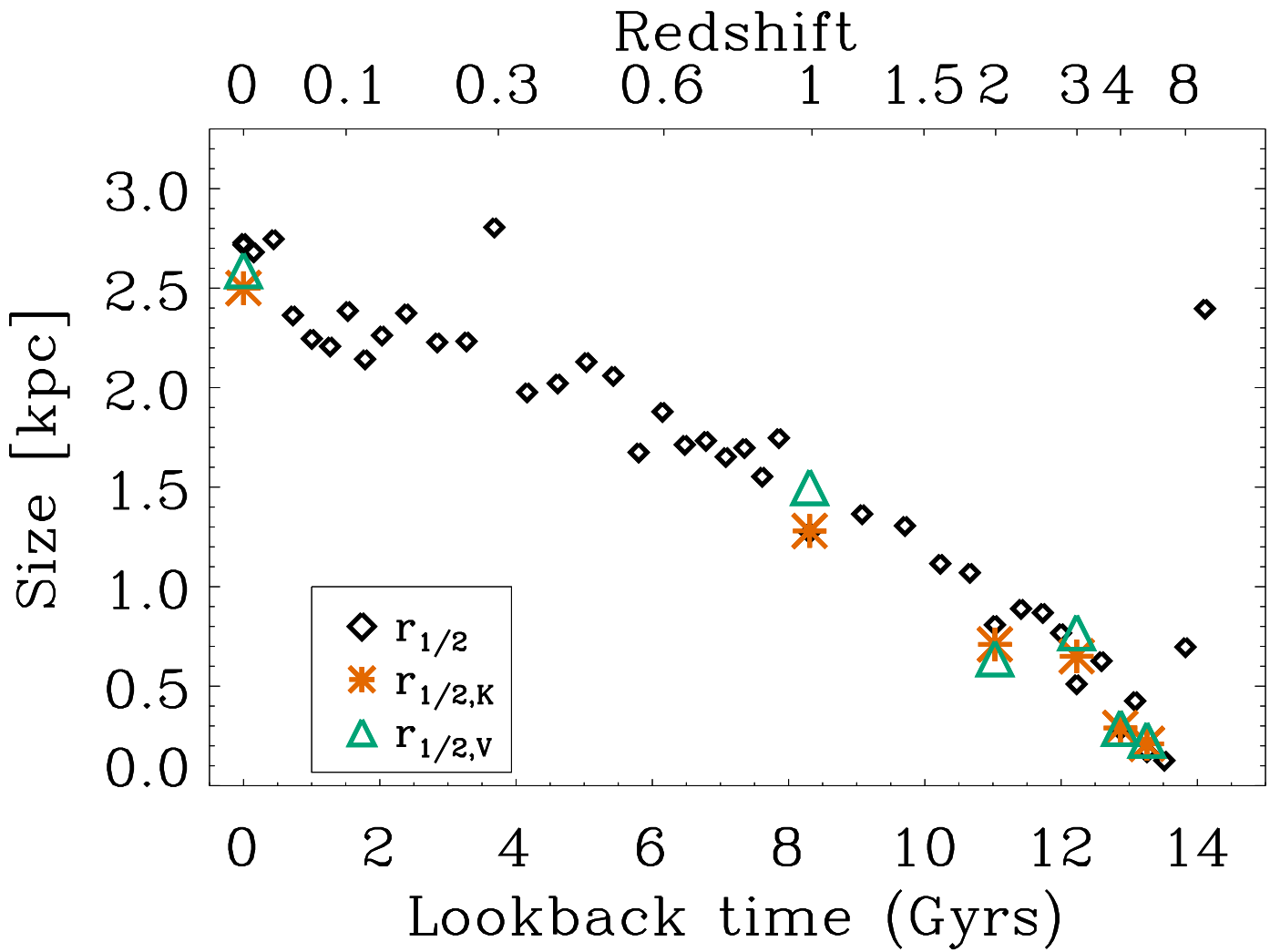

Naab et al. (2009)

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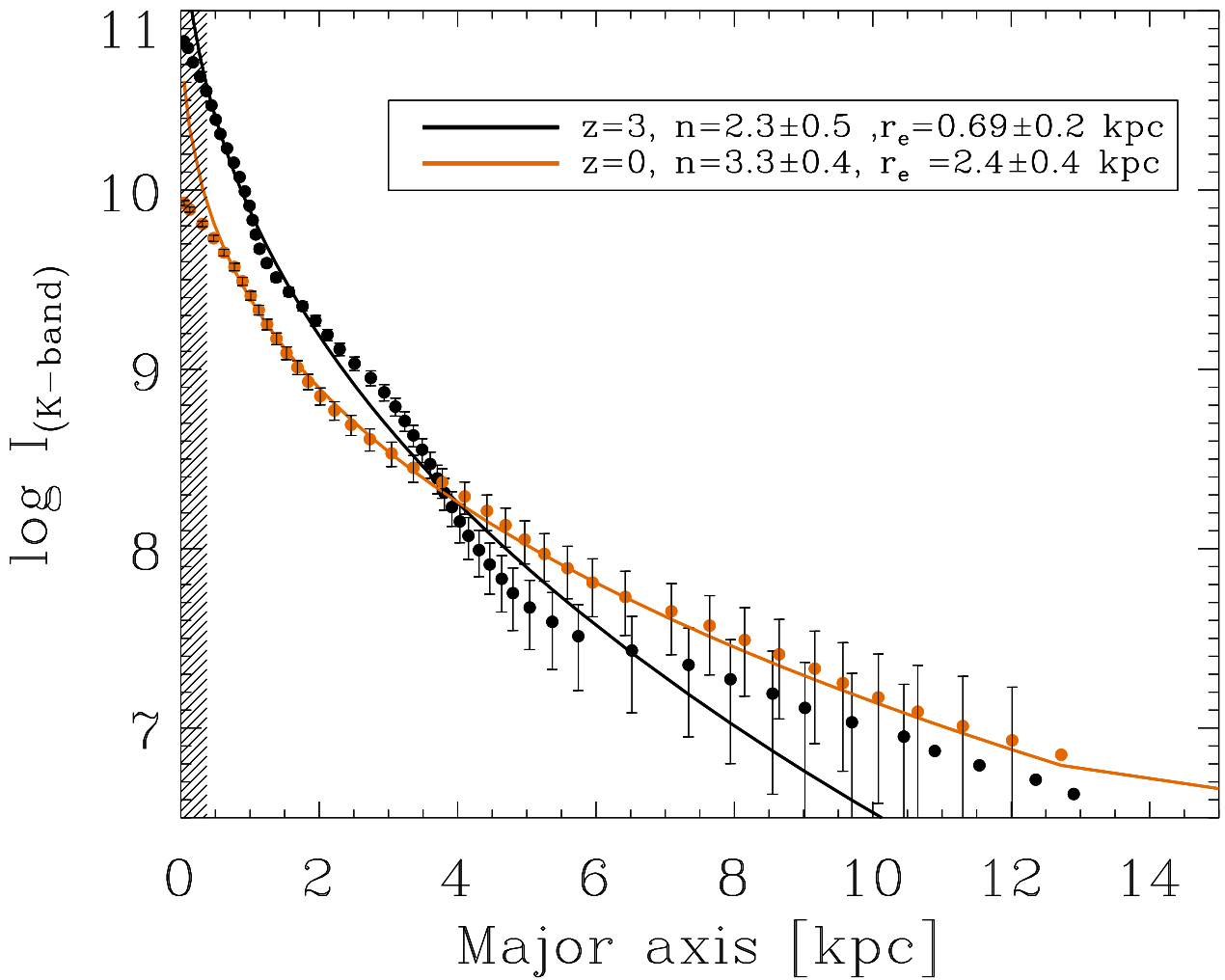
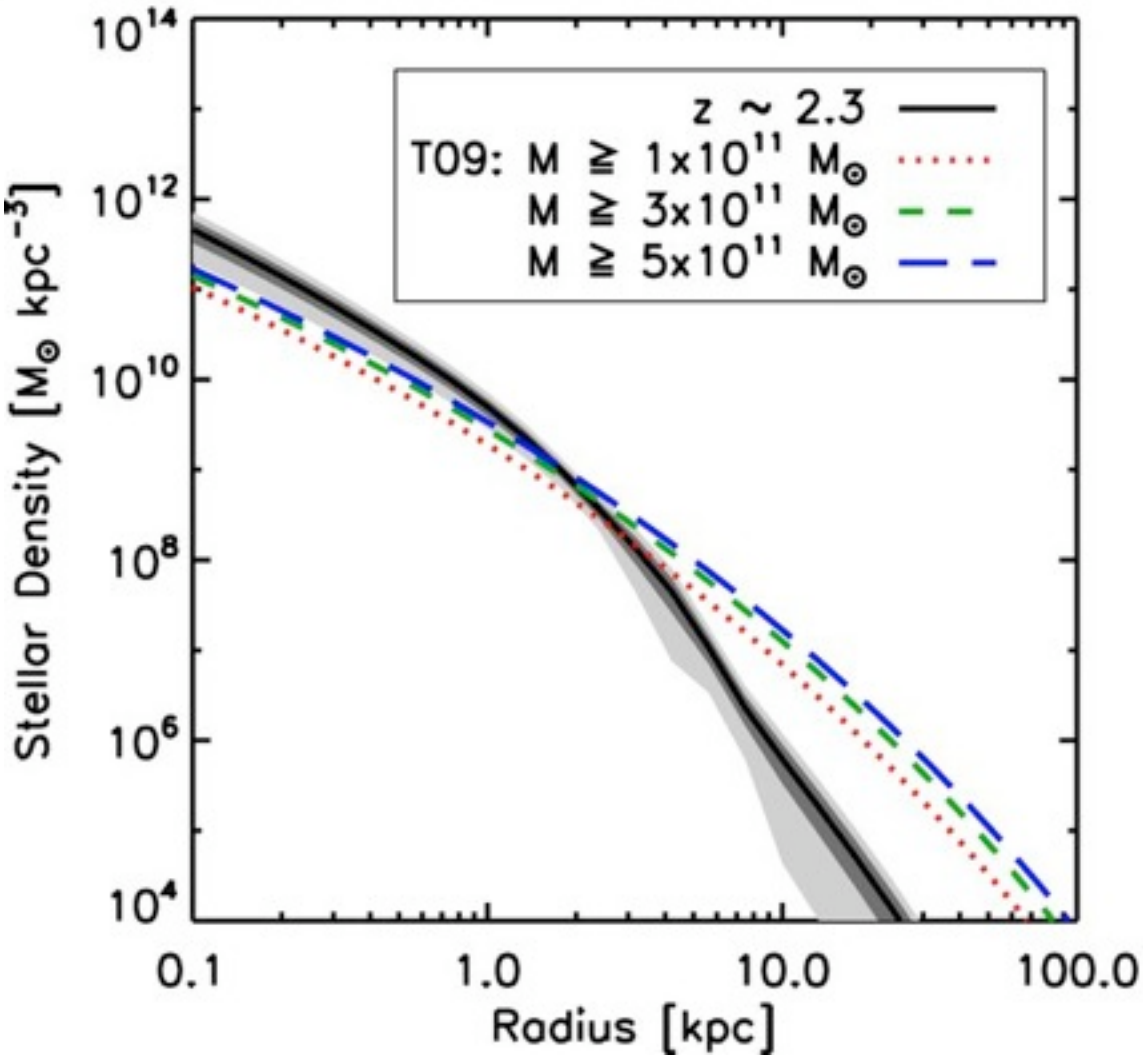


Naab et al. (2009)

Inside-out growth by minor mergers...



Bezanson et al. (2009), see also Hopkins et al. (2009a)

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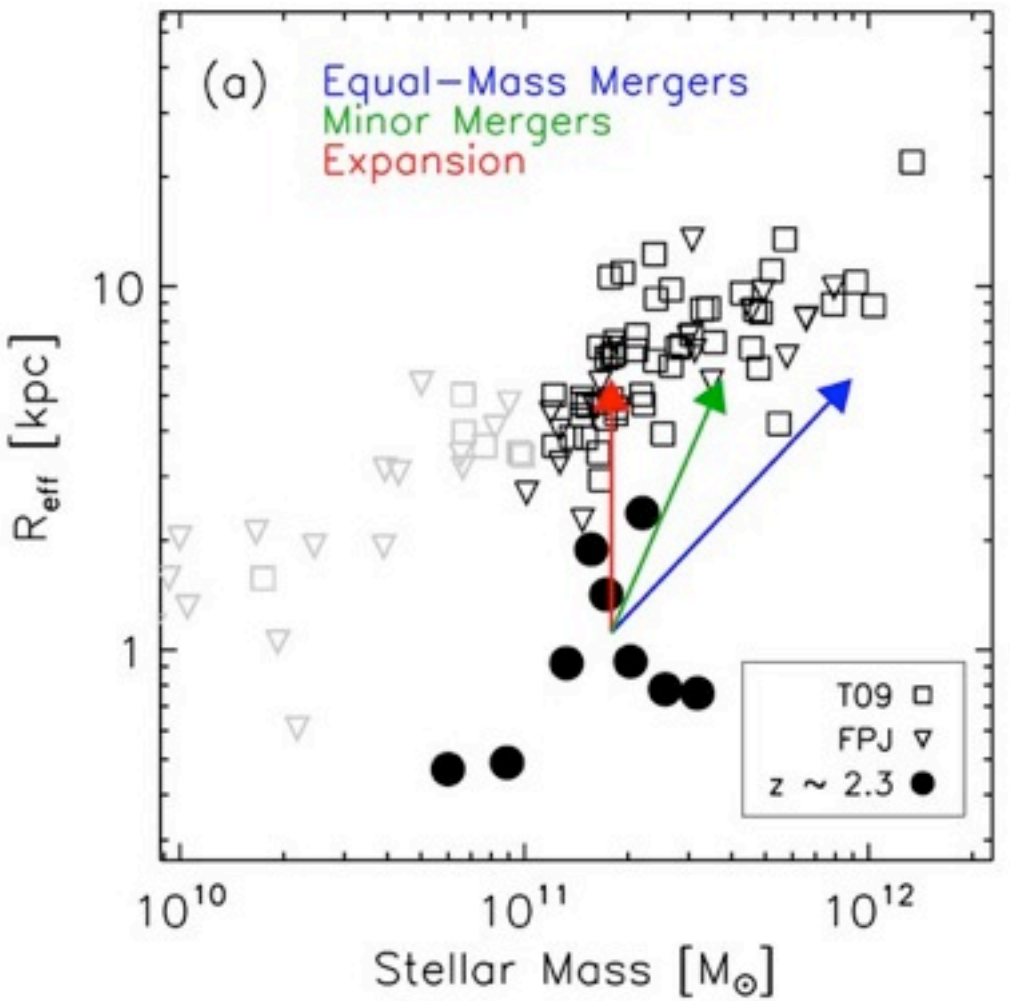

Bezanson et al. (2009)

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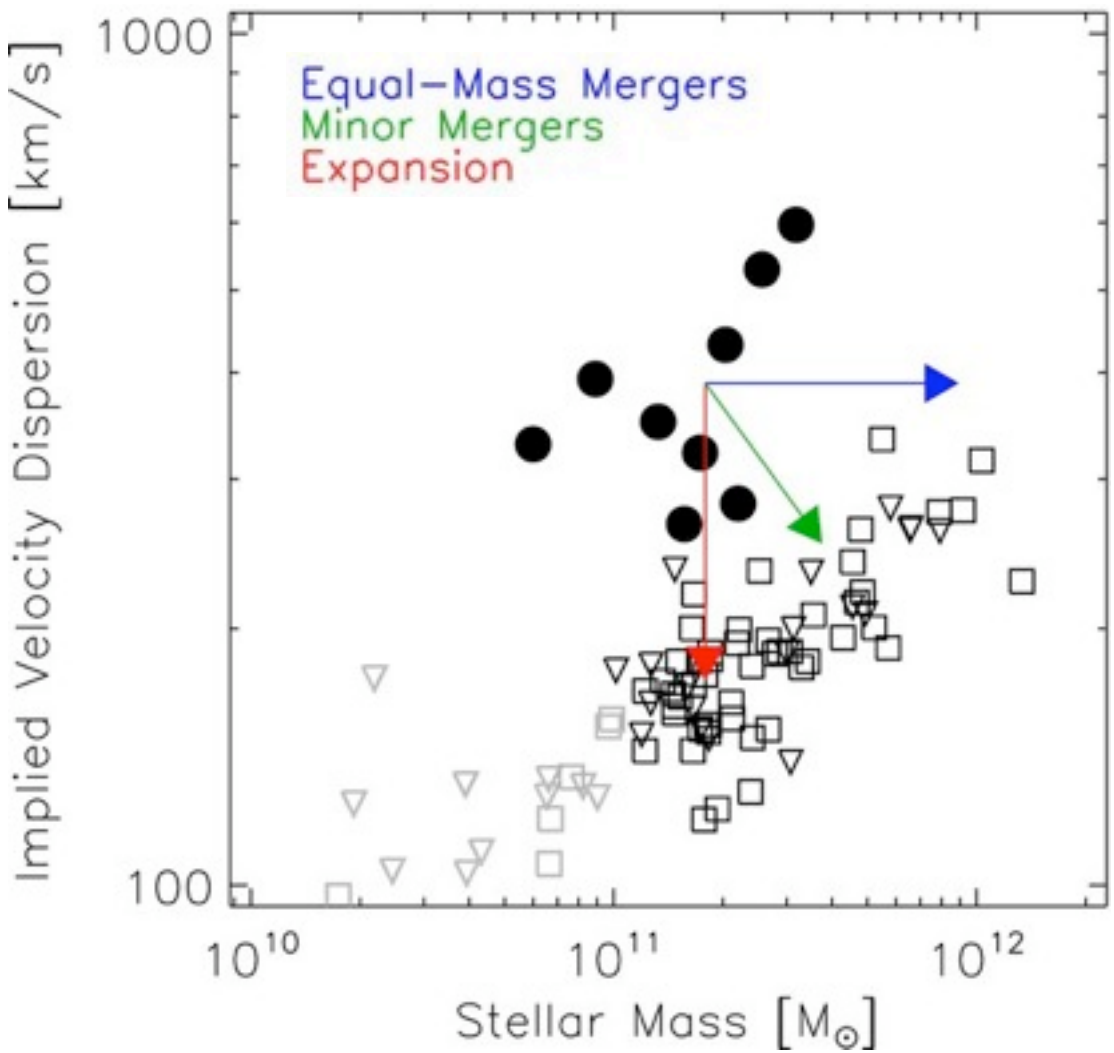

Bezanson et al. (2009)

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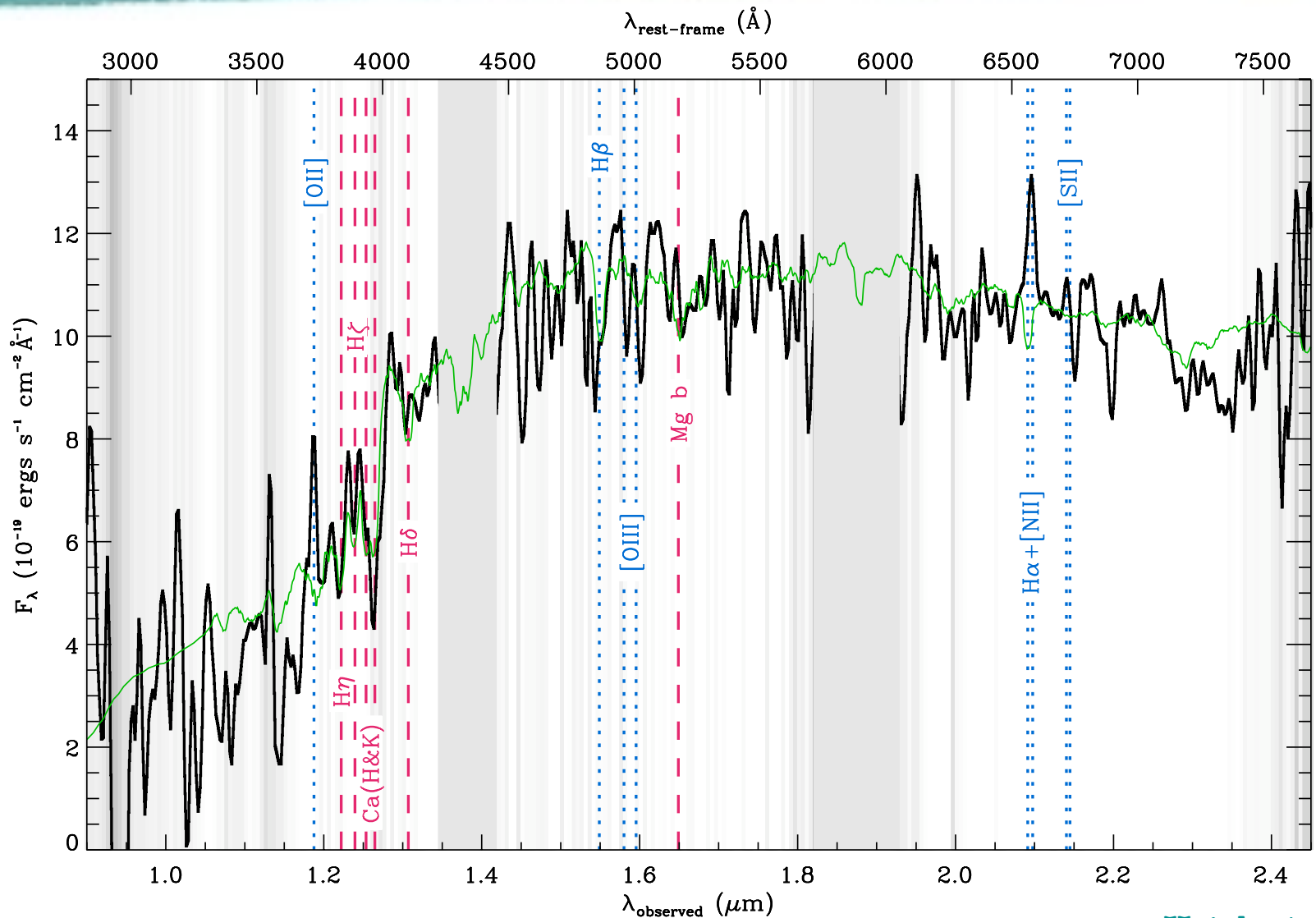
Systematic effects

Mass and structural measurements hampered by many uncertainties

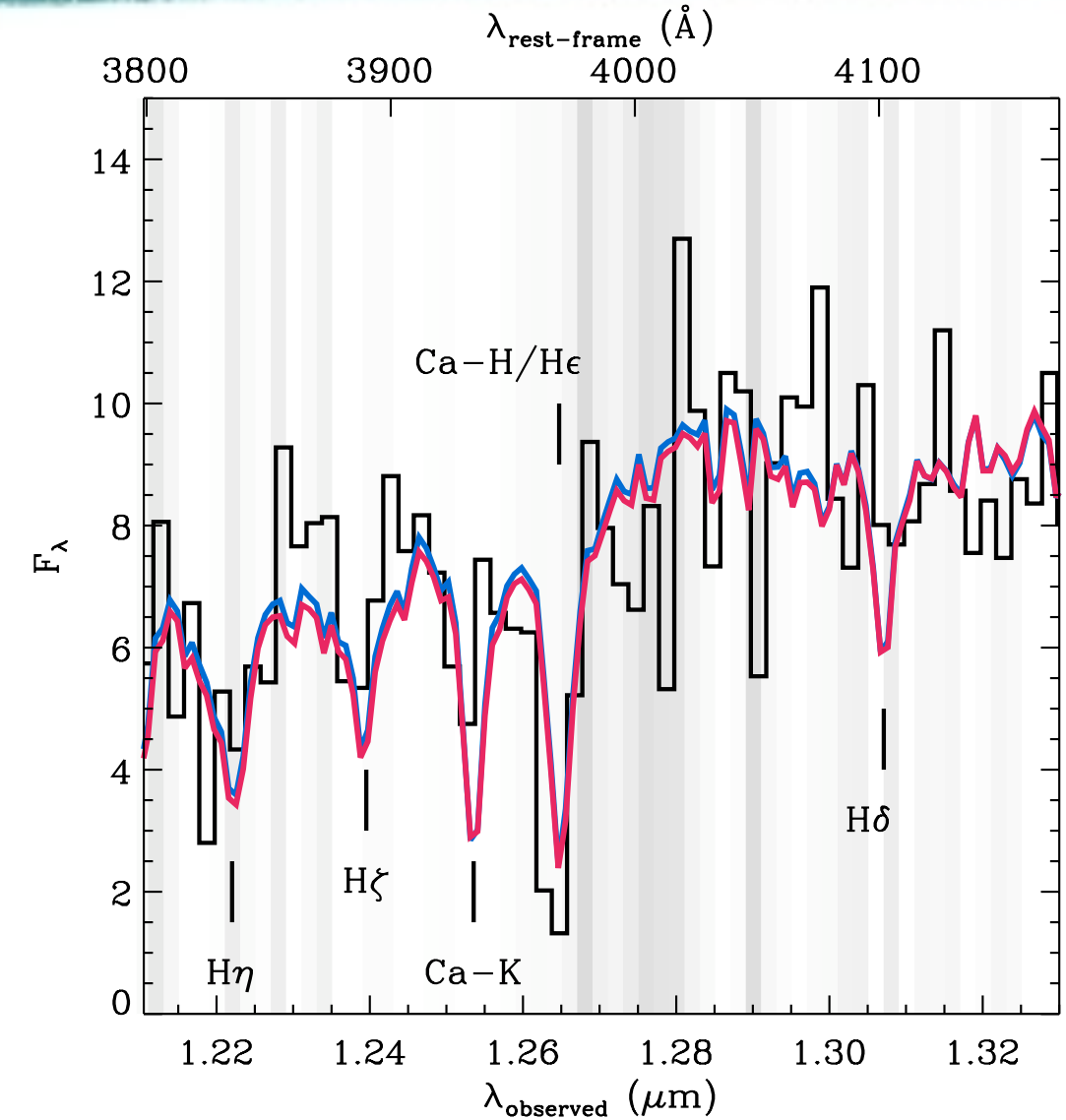
- ✦ in redshifts and stellar populations
- ✦ in the IMF and SPS models
- ✦ did we miss low surface-brightness features?
- ✦ color gradients (recent central starbursts)
- ✦ contribution from an AGN?

29 hrs GNIRS spectrum of a compact quiescent galaxy at z=2.2



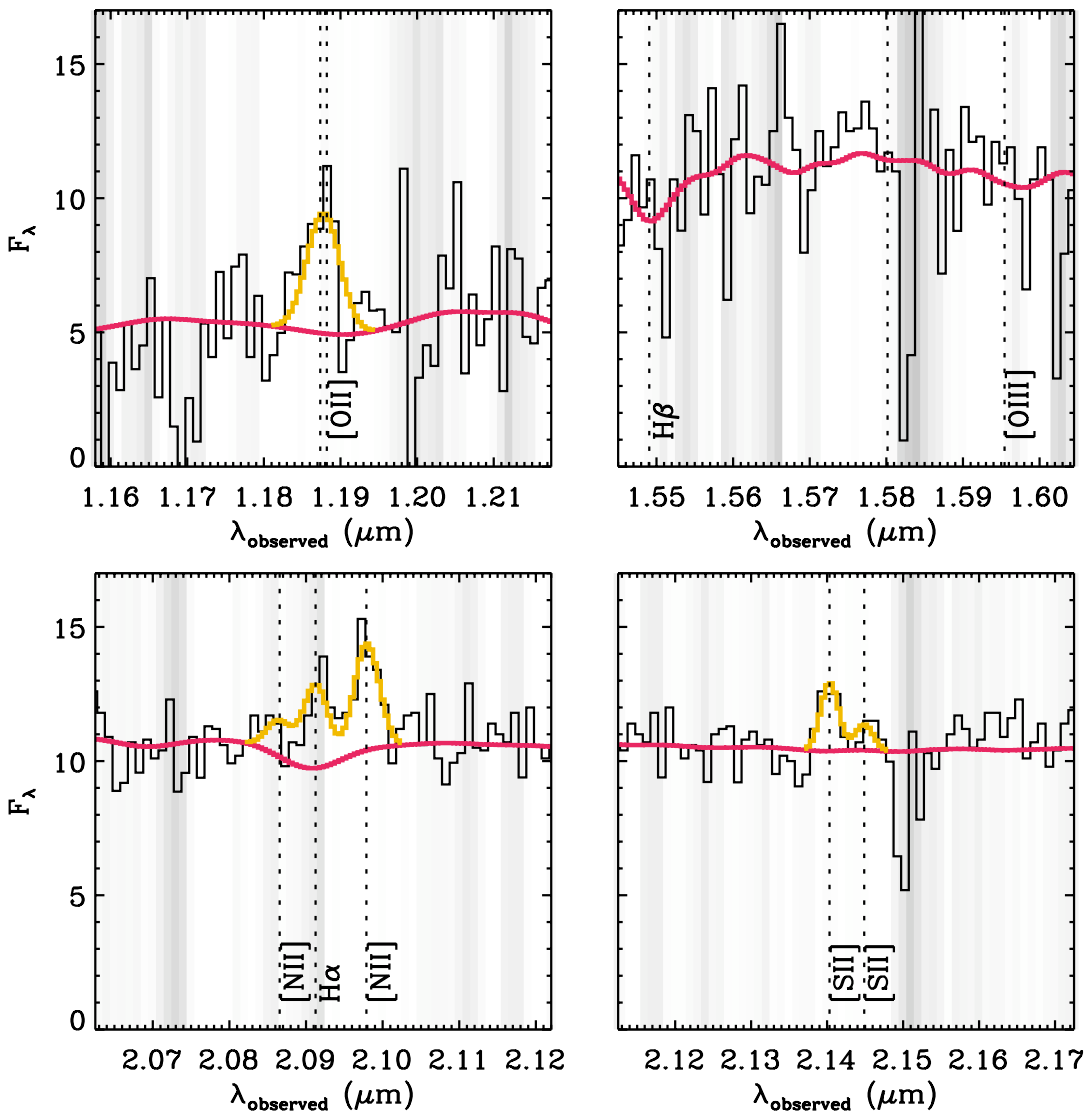
Kriek et al. (2009a)

Absorption features



Kriek et al. (2009a)

Emission lines



Kriek et al. (2009a)

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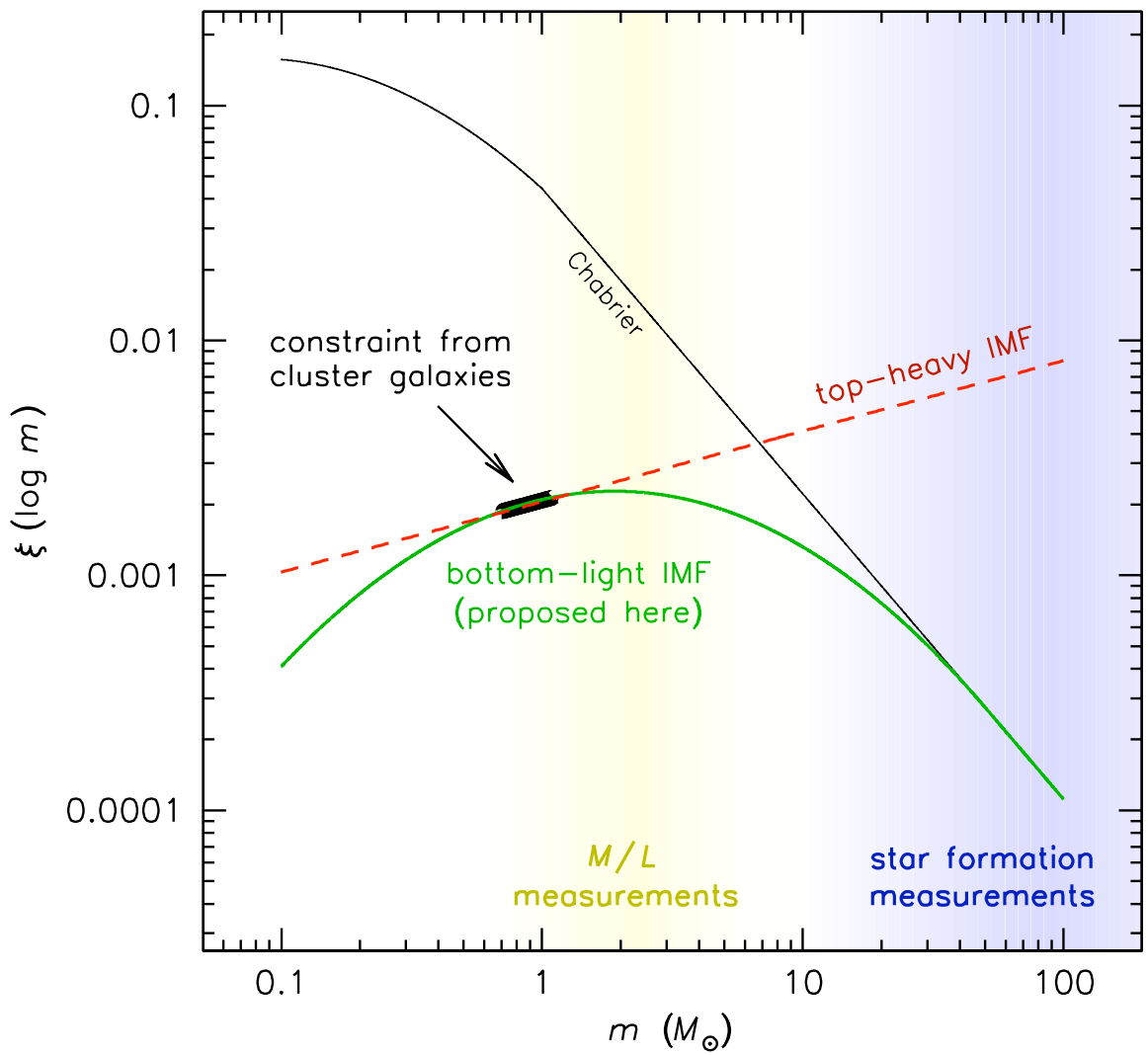
Evolving IMF?



van Dokkum (2007)

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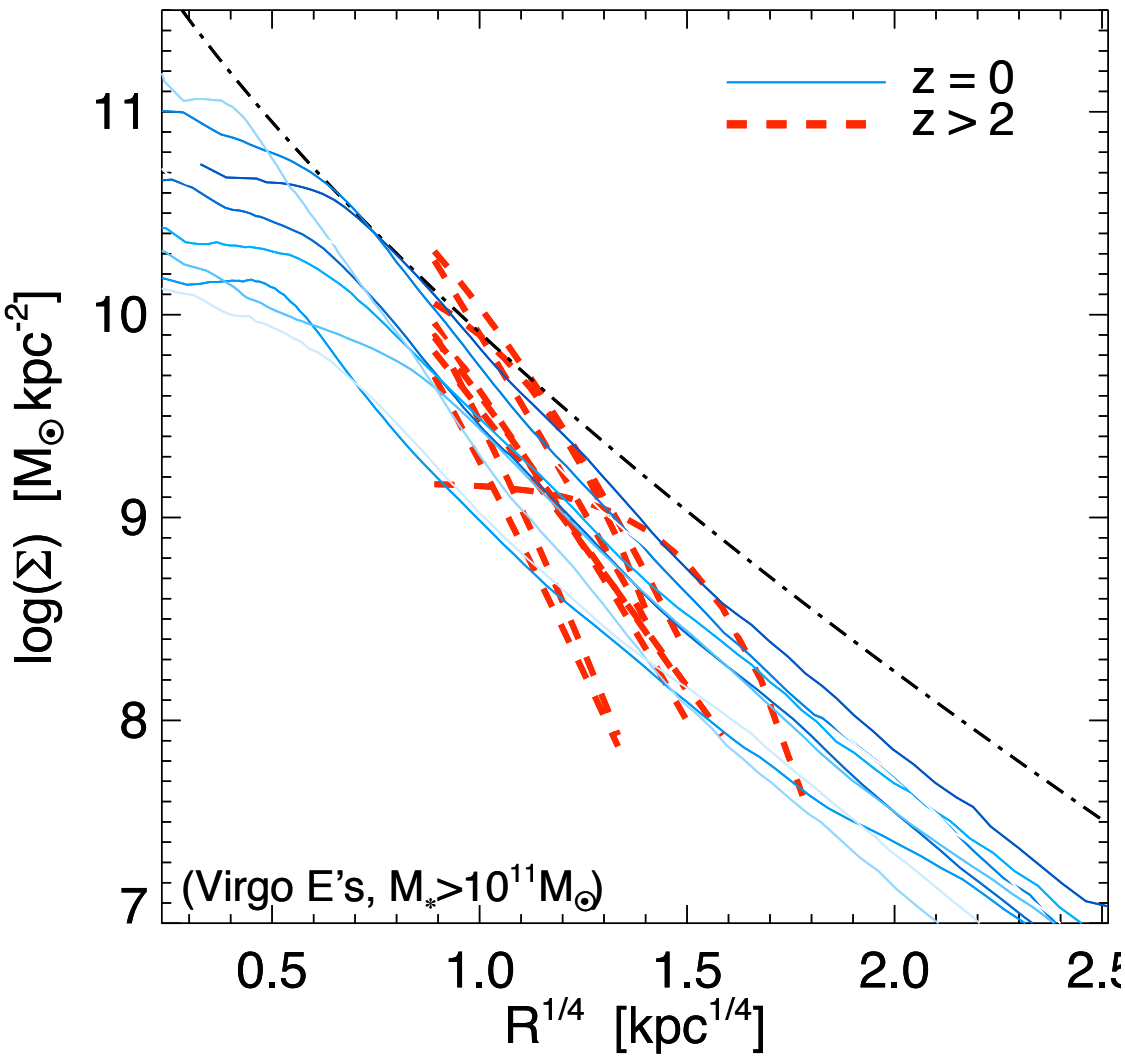
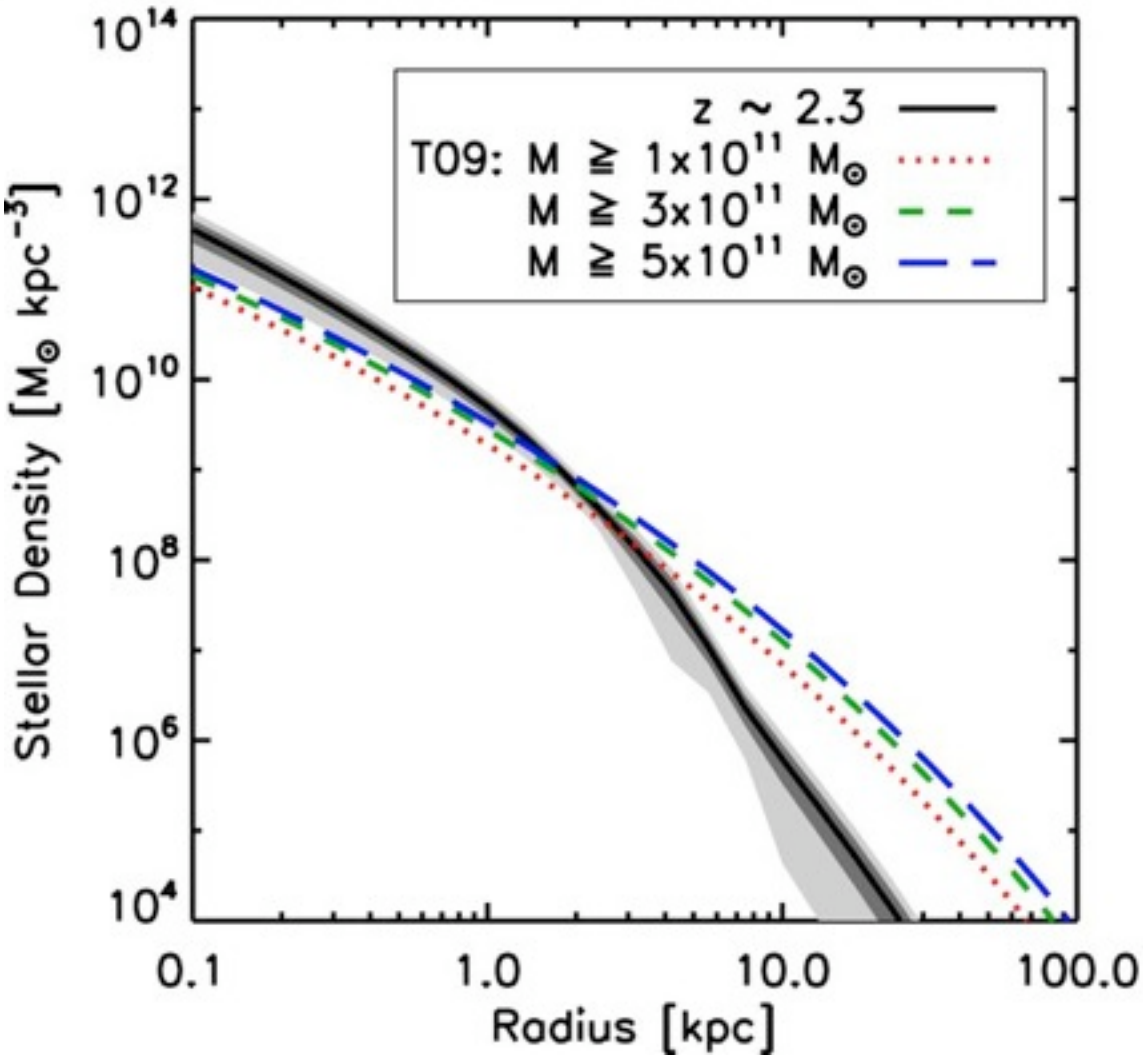
Low surface brightness features



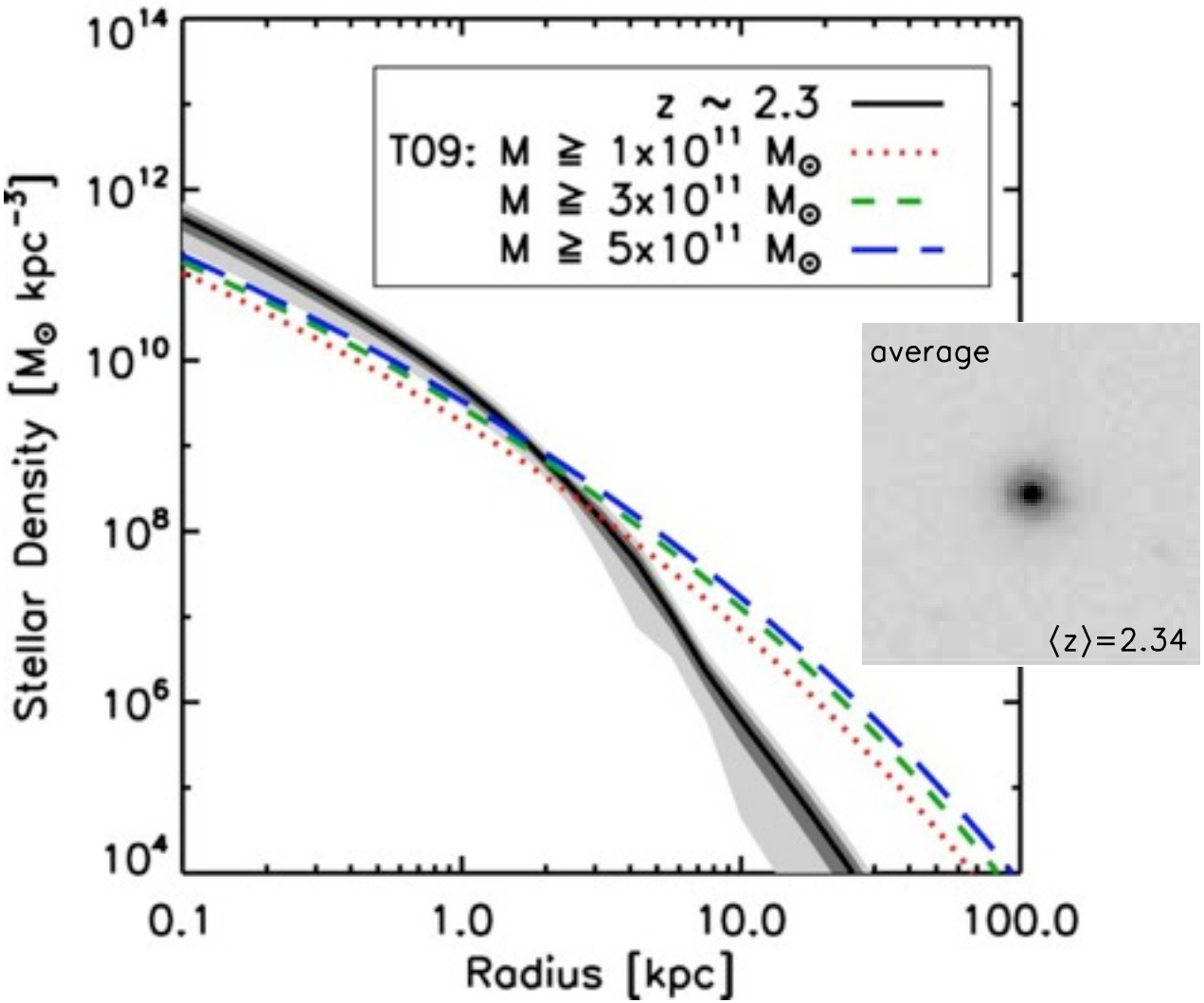
Hopkins et al. (2009a)

Low surface brightness features



Bezanson et al. (2009)

Low surface brightness features



Bezanson et al. (2009)

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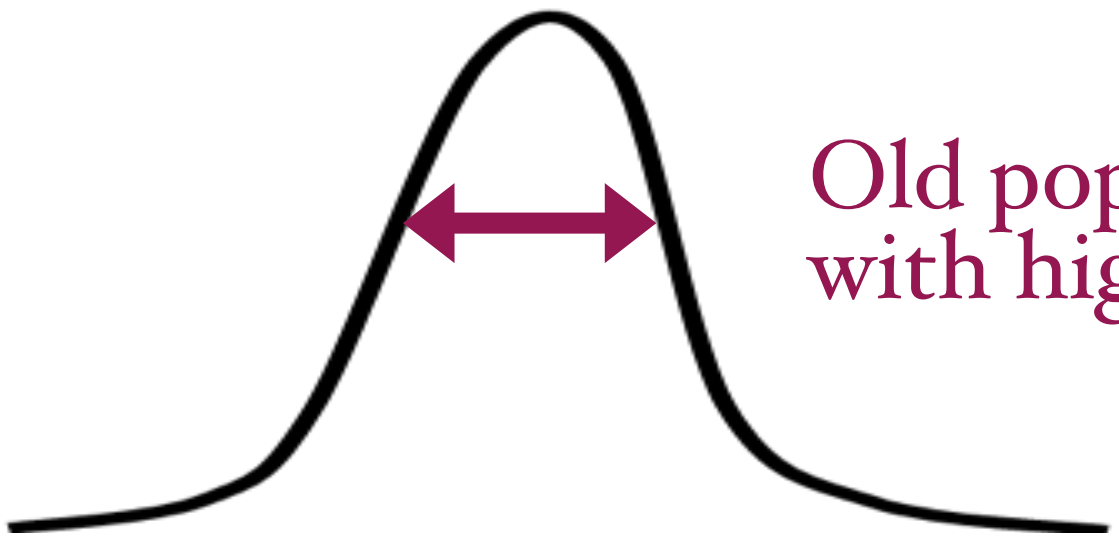
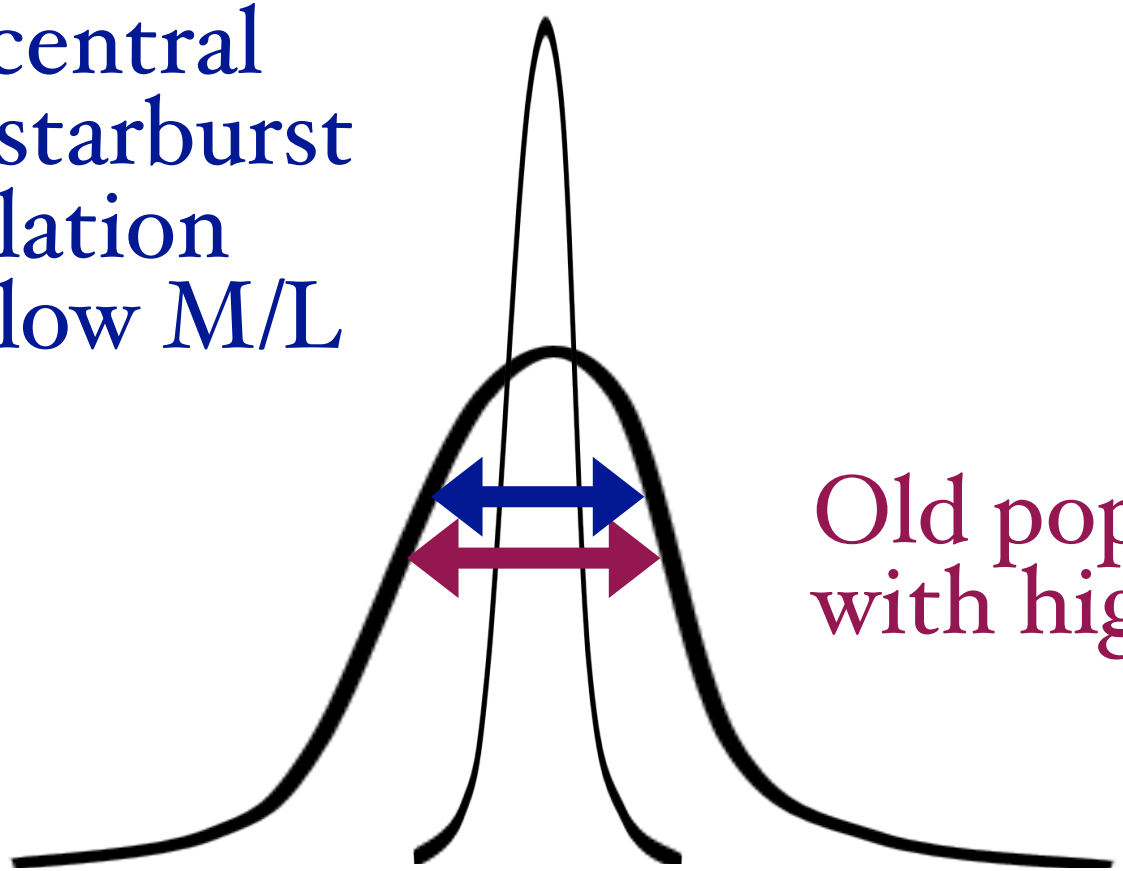
Color gradients?



Old population with high M/L

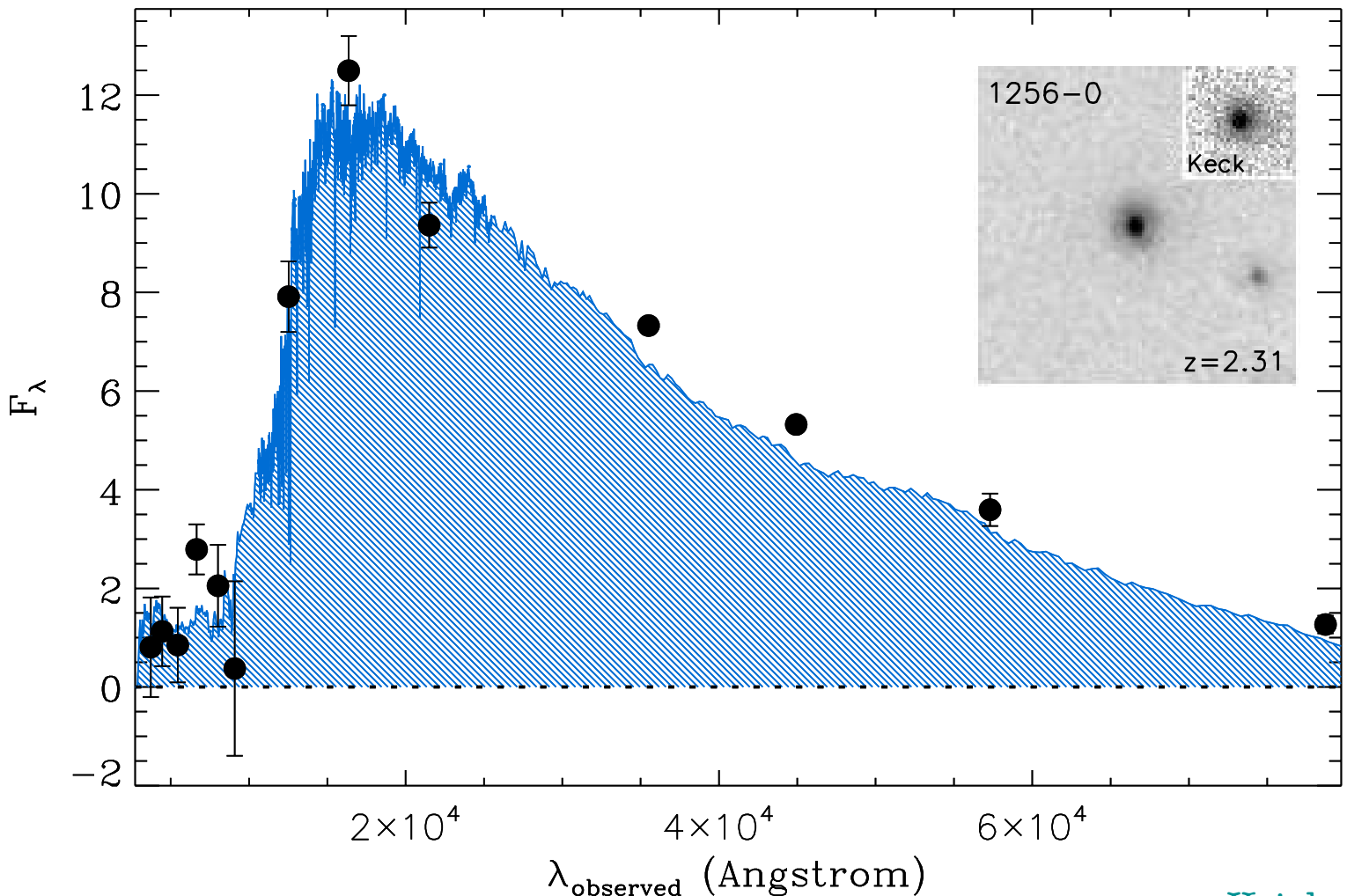
Color gradients?

Add central post-starburst population with low M/L



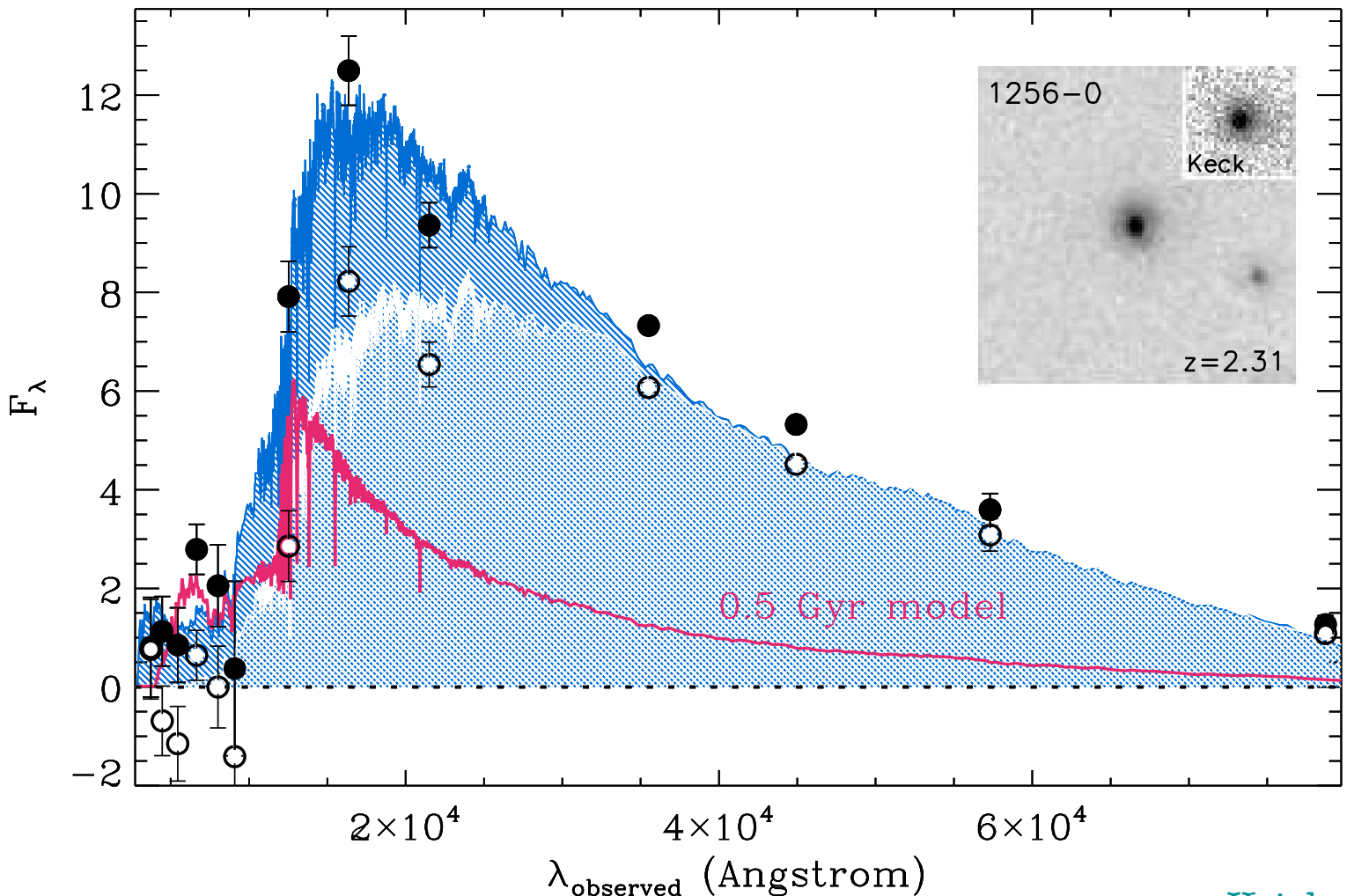
Old population with high M/L

Central post-starburst?



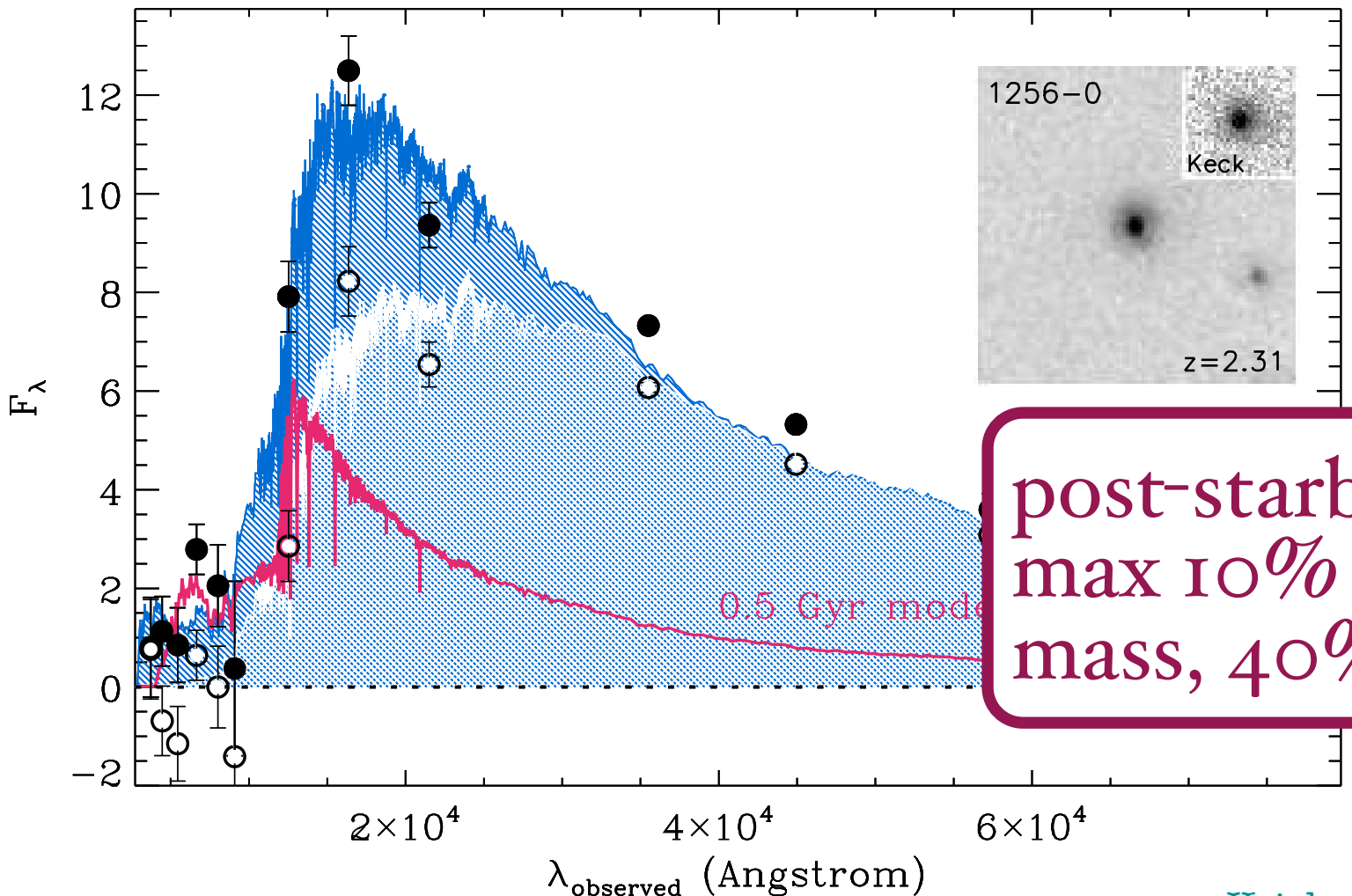
Kriek et al. (2009a)

Central post-starburst?



Kriek et al. (2009a)

Central post-starburst?



post-starburst: max 10% to the mass, 40% to H

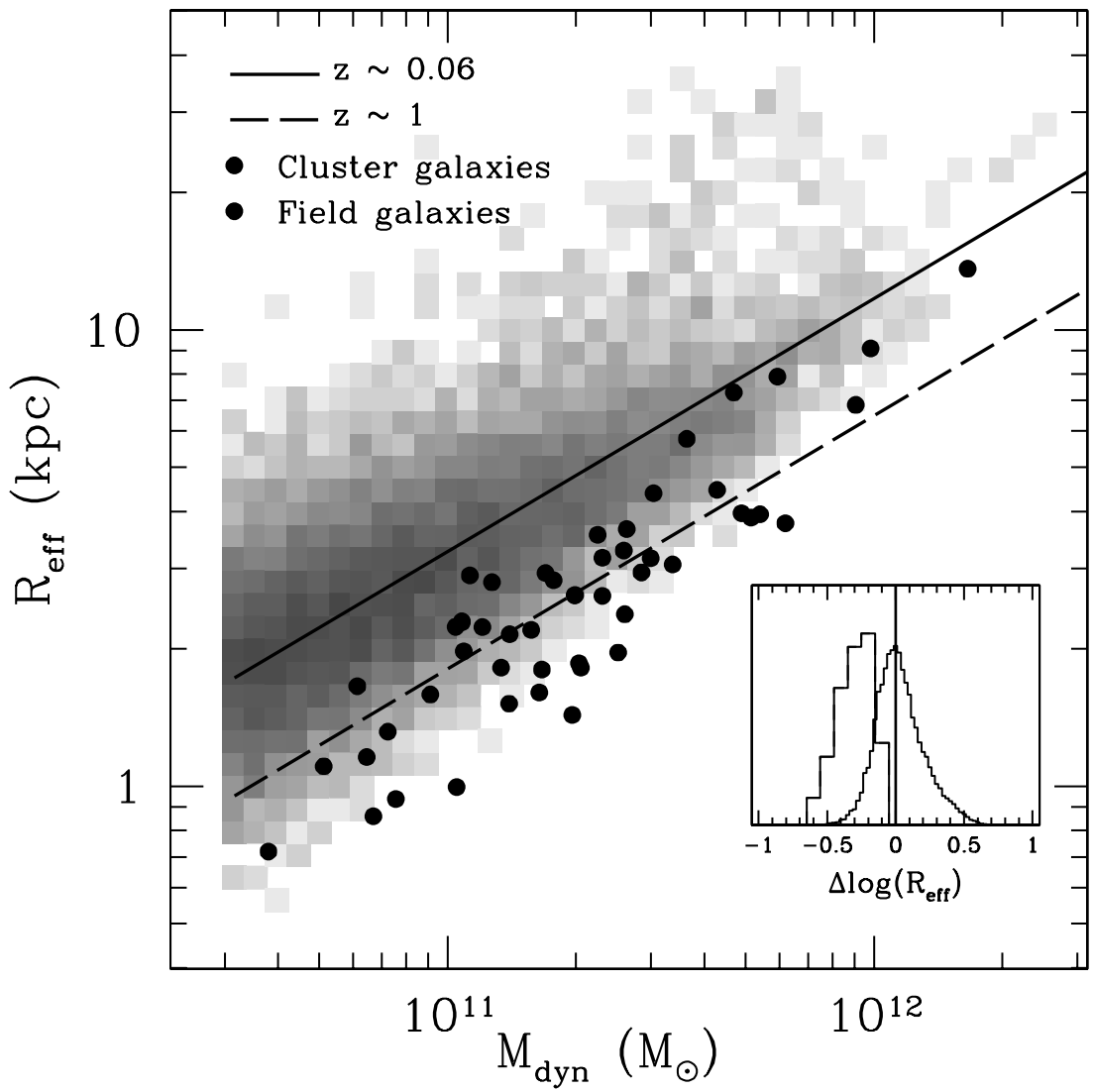
Kriek et al. (2009a)

Systematic effects

Mass and structural measurements hampered by many uncertainties

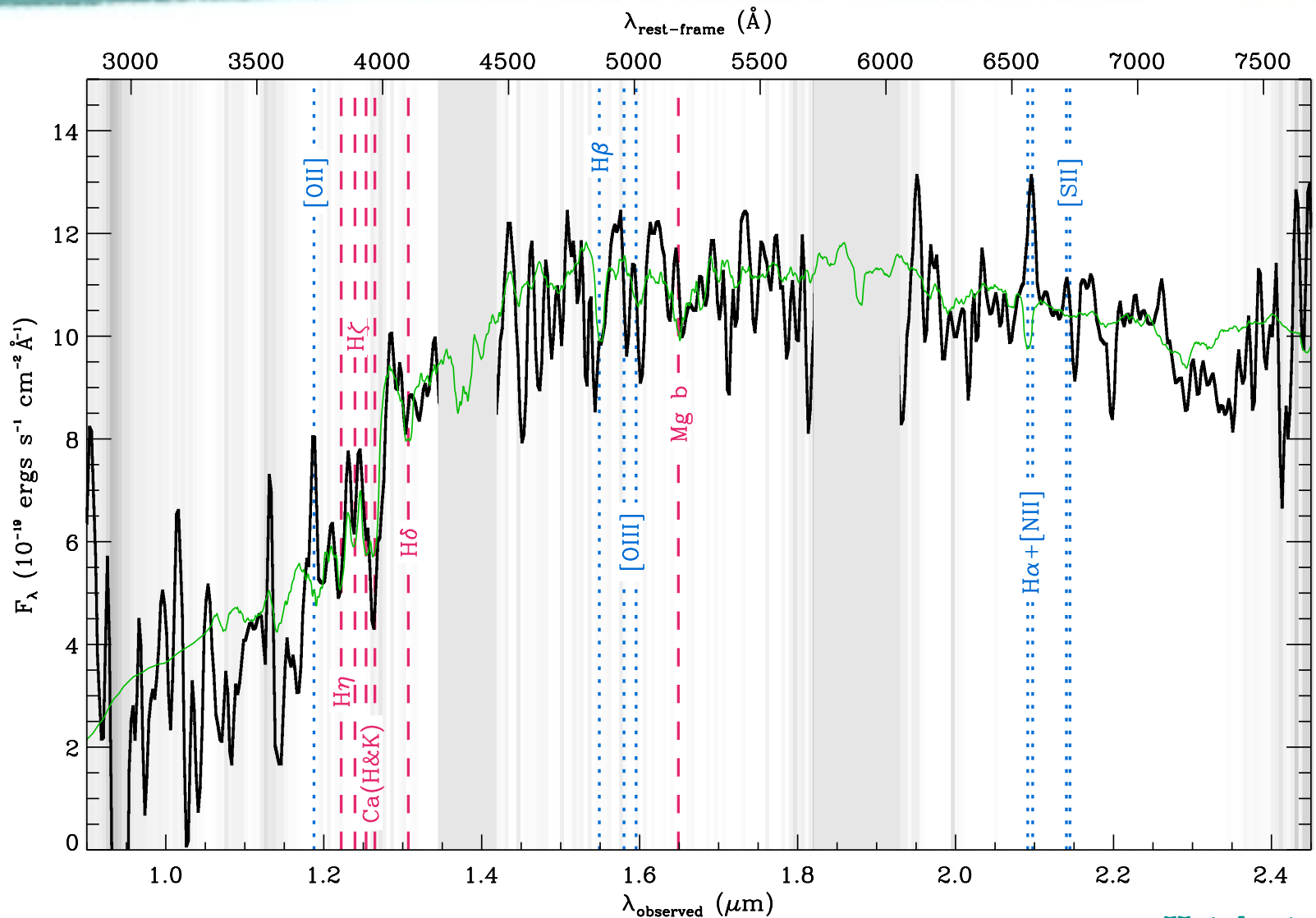
- ✦ in redshifts and stellar populations
- ✦ in the IMF and SPS models
- ✦ did we miss low surface-brightness features?
- ✦ color gradients (recent central starbursts)
- ✦ contribution from an AGN?

Dynamical masses up to z~1



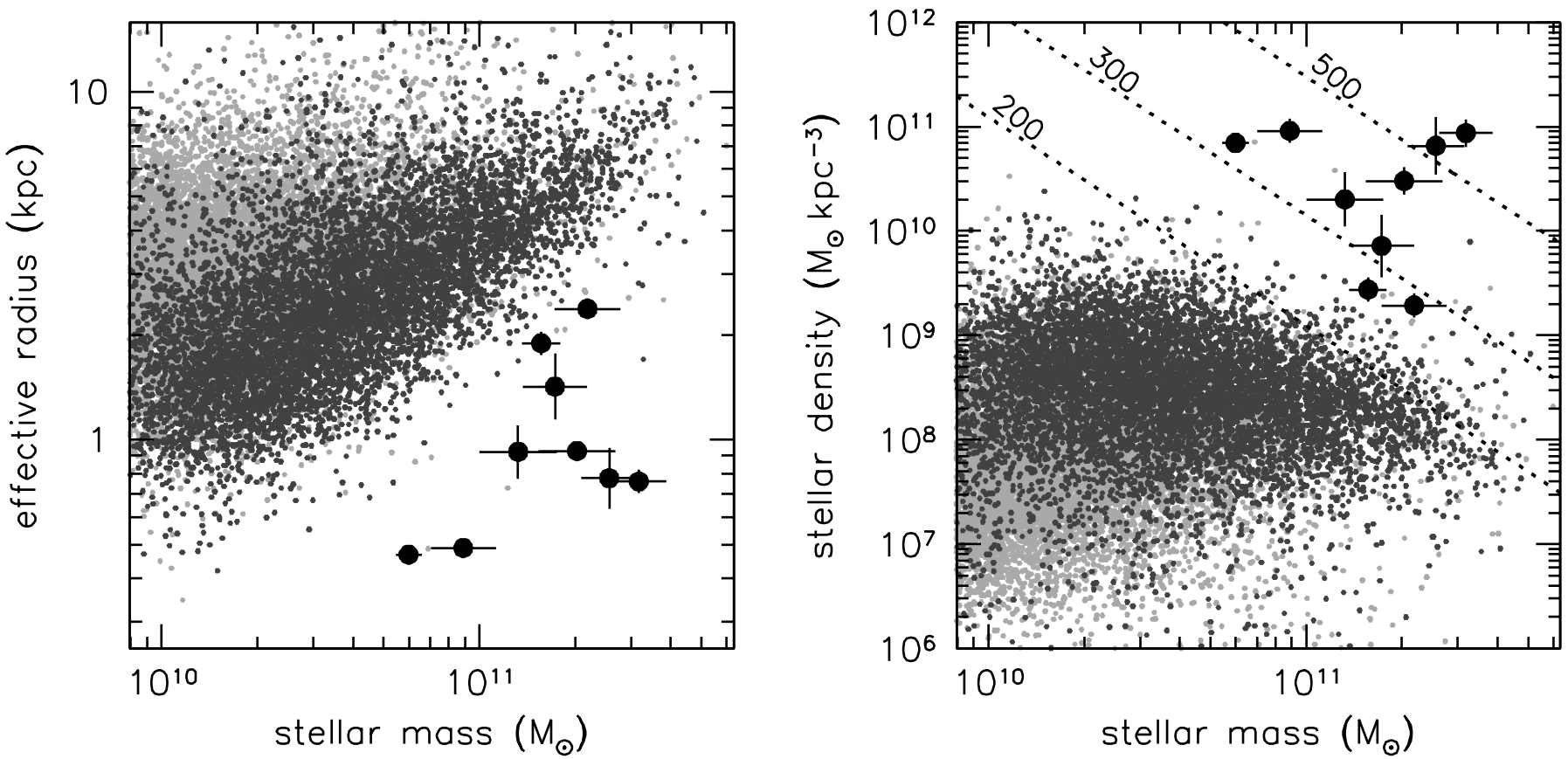
van der Wel et al. (2008)

29 hrs GNIRS spectrum of a compact quiescent galaxy at z=2.2



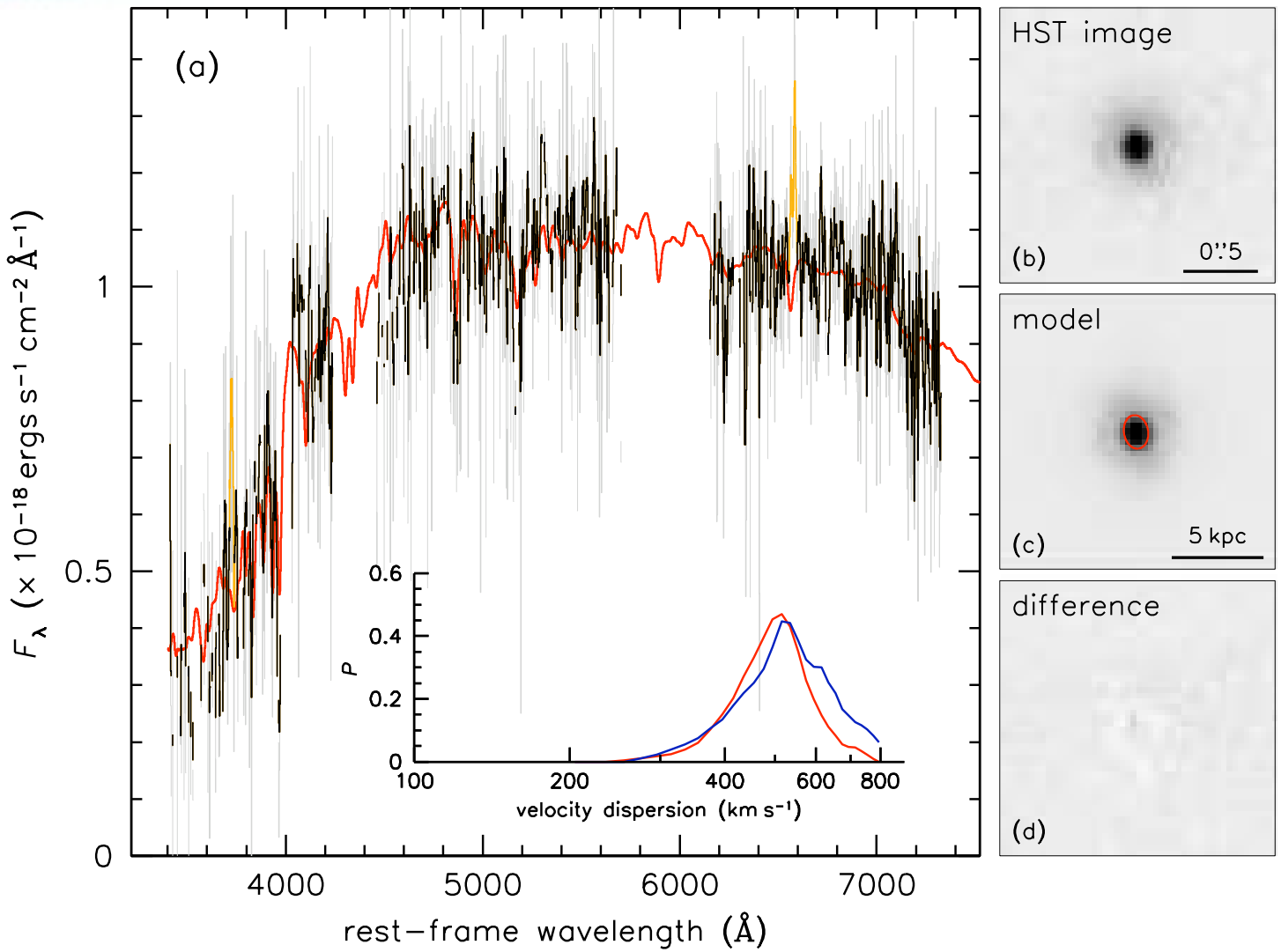
Kriek et al. (2009a)

Structural evolution from z~2.3 to z~0.0



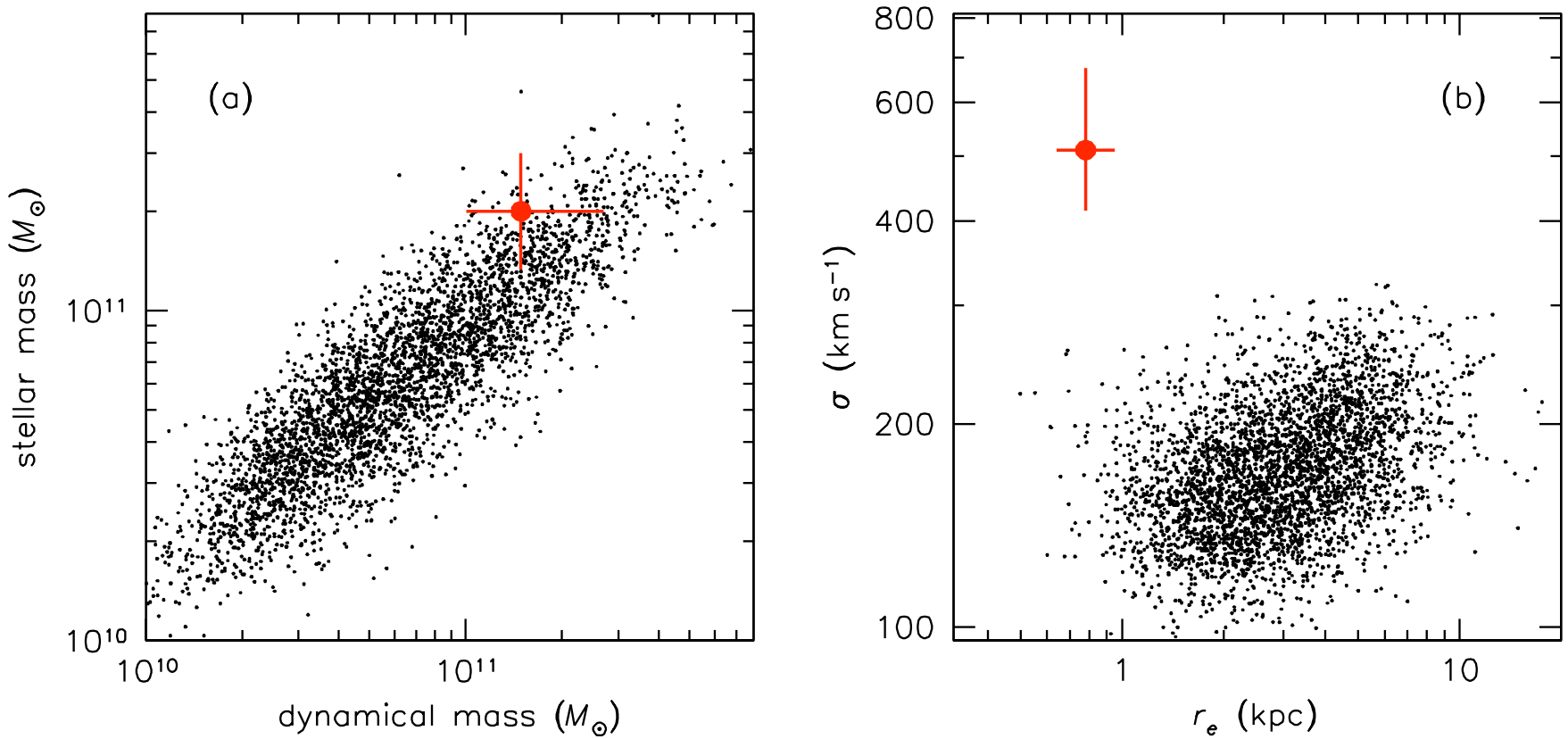
van Dokkum, Franx, Kriek et al. (2008)

Velocity dispersion for a z=2.2 compact quiescent galaxy



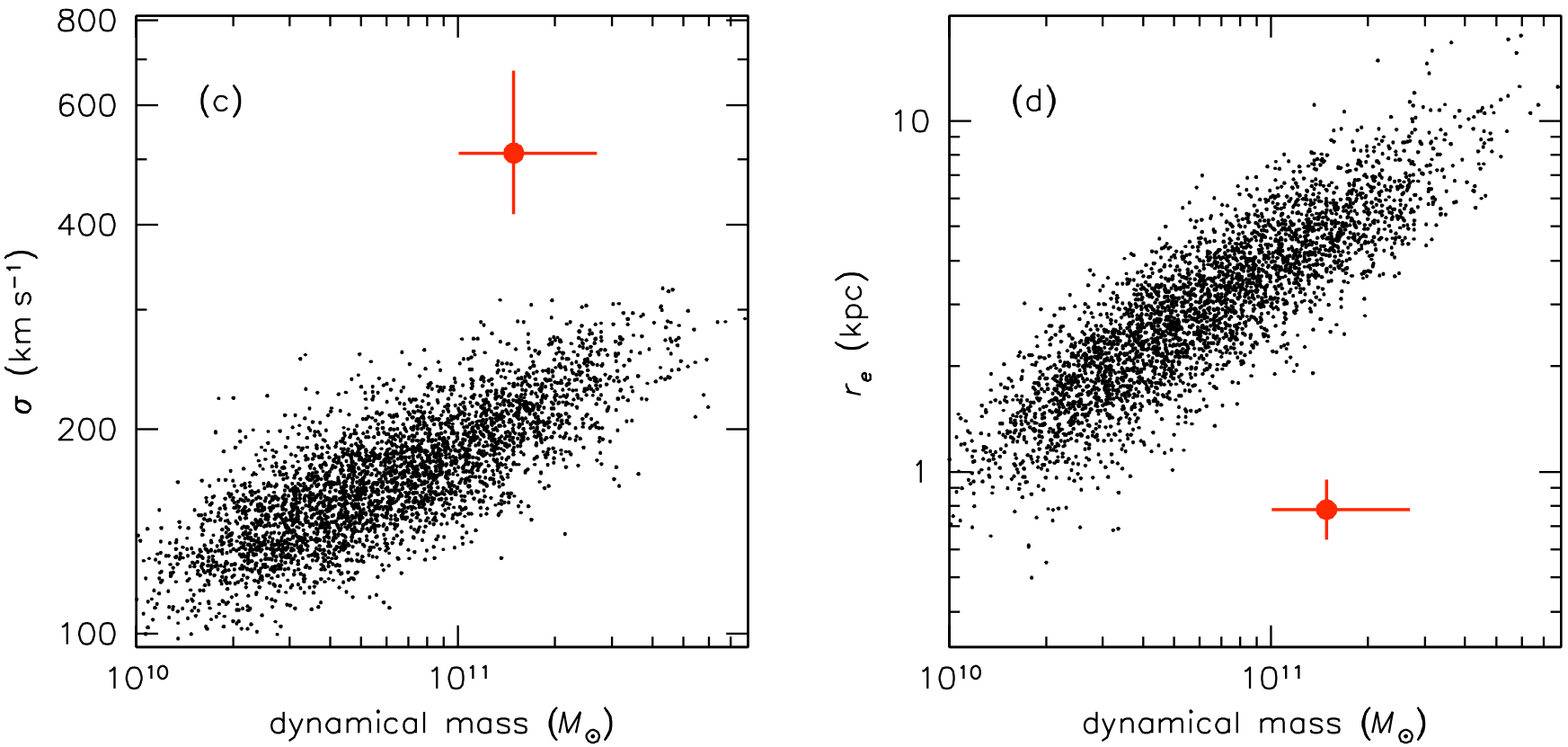
van Dokkum, Kriek, & Franx (2009), see also Cappellari et al. (2009); Cenarro & Trujillo (2009)

Comparison to local galaxies



van Dokkum, Kriek, & Franx (2009)

Comparison to local galaxies



van Dokkum, Kriek, & Franx (2009)

How do compact high-z galaxies evolve into local ETGs?

- ✦ Mergers at high redshift are more gas-rich, and thus will result in denser systems
- ✦ Inside-out growth by minor mergers
- ✦ The size evolution may appear more extreme due to systematic effects

➡ Combination of these different effects?

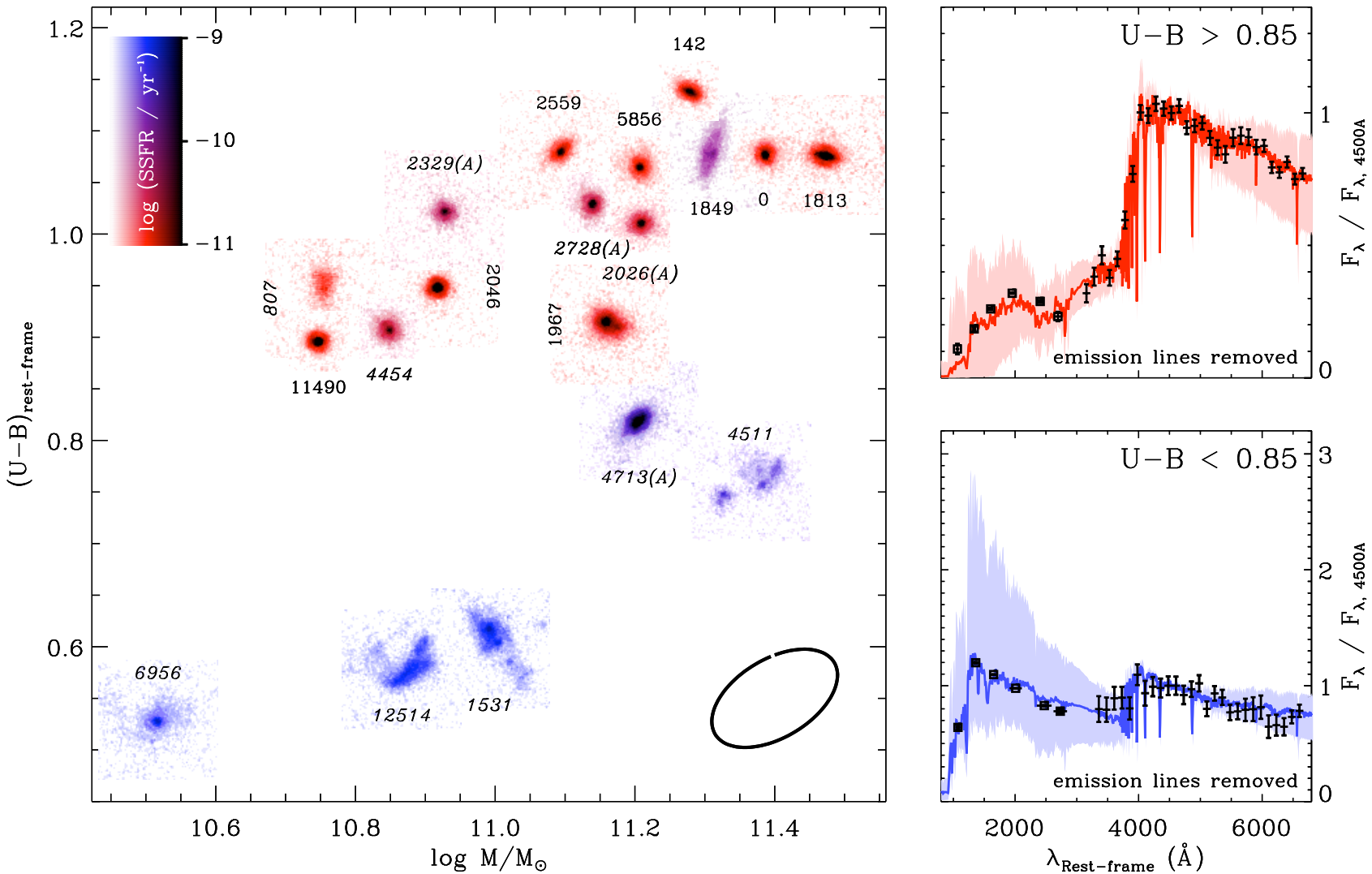
Implications

In both numbers and structure, the massive galaxy population has evolved significantly from z~2 to the present

Questions

- How do the compact high-z galaxies evolve into local early types?
- How are these compact, quiescent high-z galaxies formed in first place?

Progenitors of distant compact galaxies

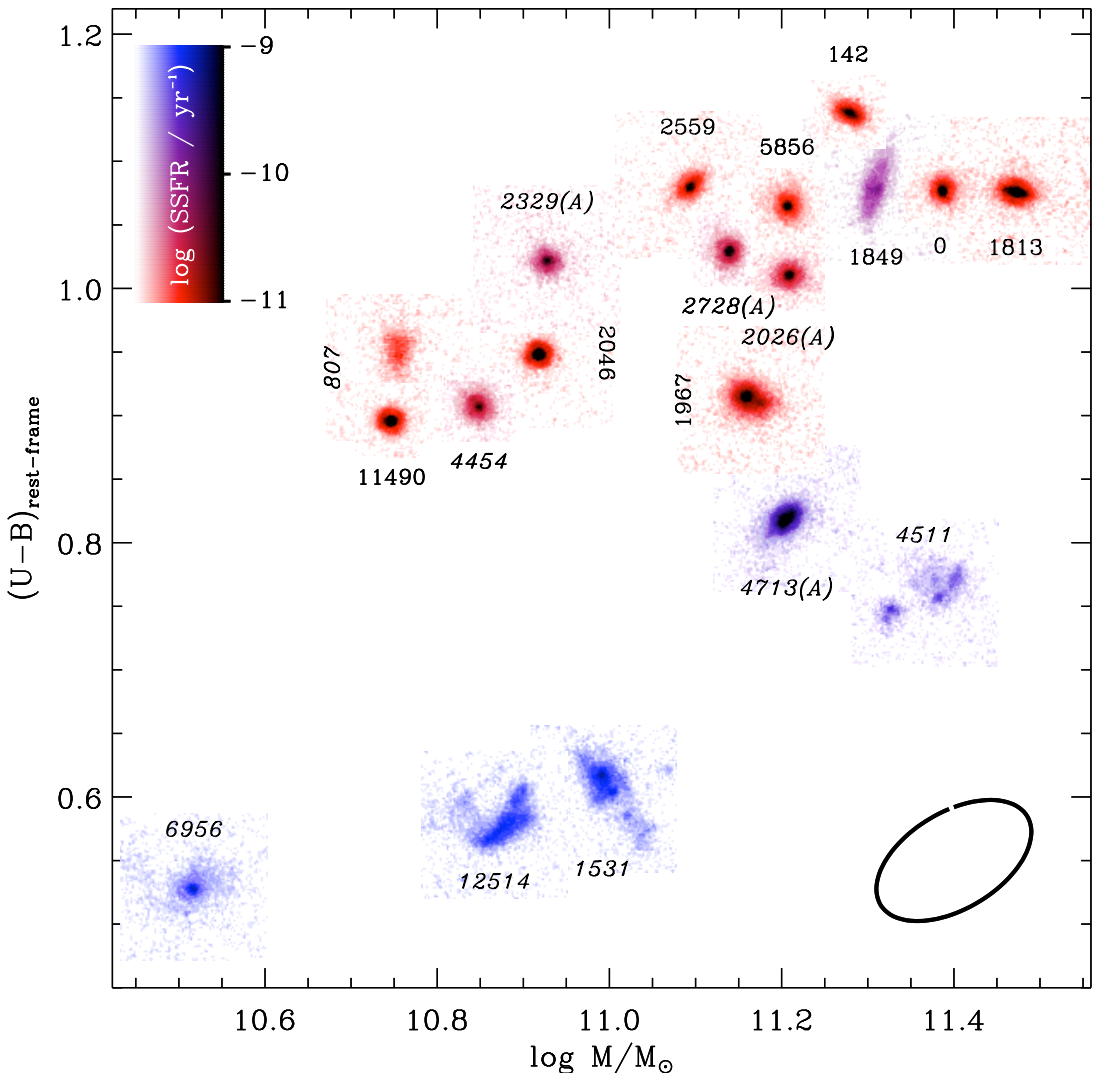


Kriek et al. (2009b)

Connection between large star-forming & compact quiescent galaxies

- Scenario 1: Blue galaxies quench and move to red sequence
  - Fading of outer star-forming regions
  - Build compact core by clump collisions
- Scenario 2: RS galaxies grow at the outskirts by star formation and thus periodically turn blue
- Scenario 3: The two classes are not related at all and follow their own evolution altogether

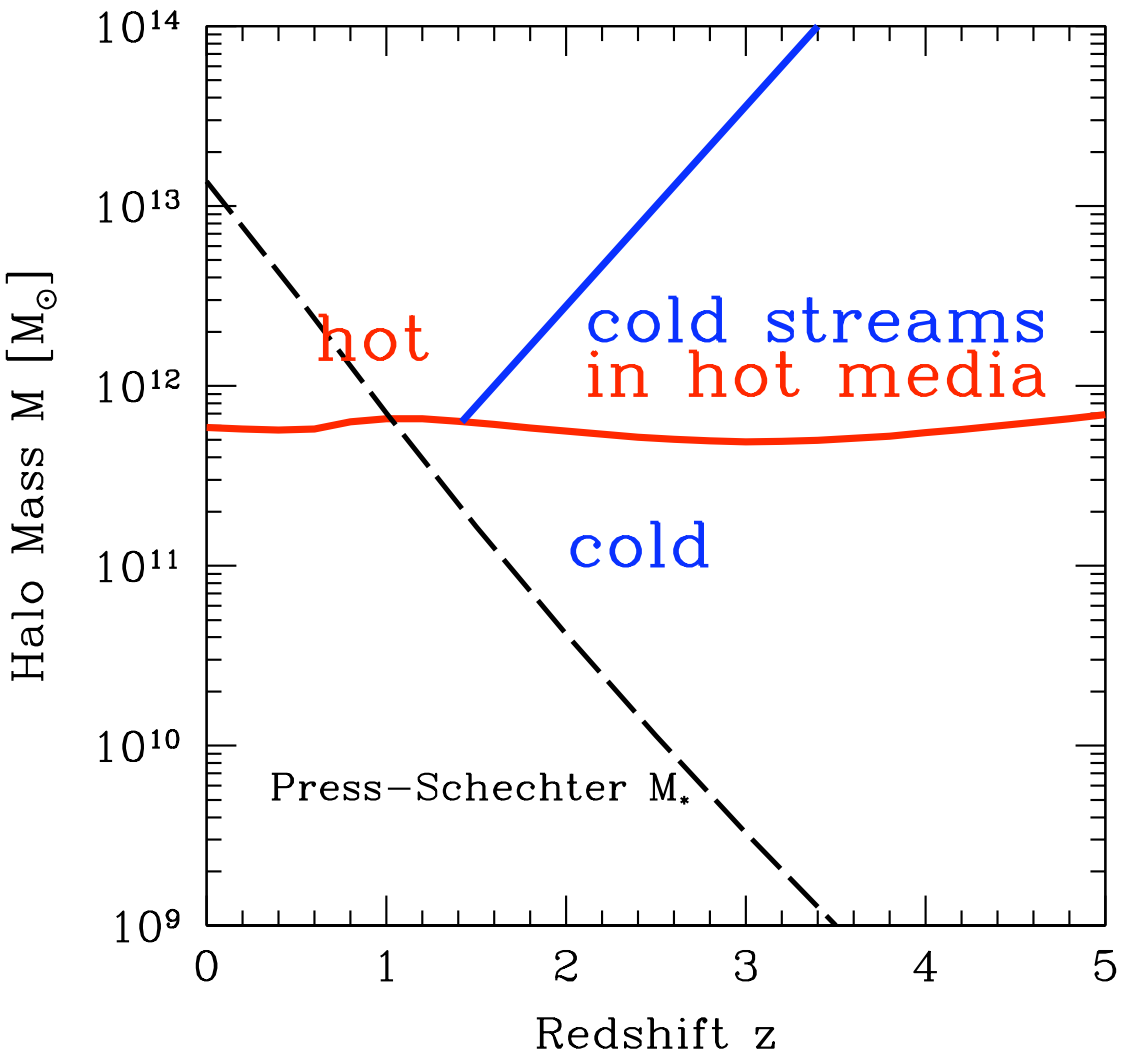
The "Hubble Sequence" beyond z=2



Hot halos

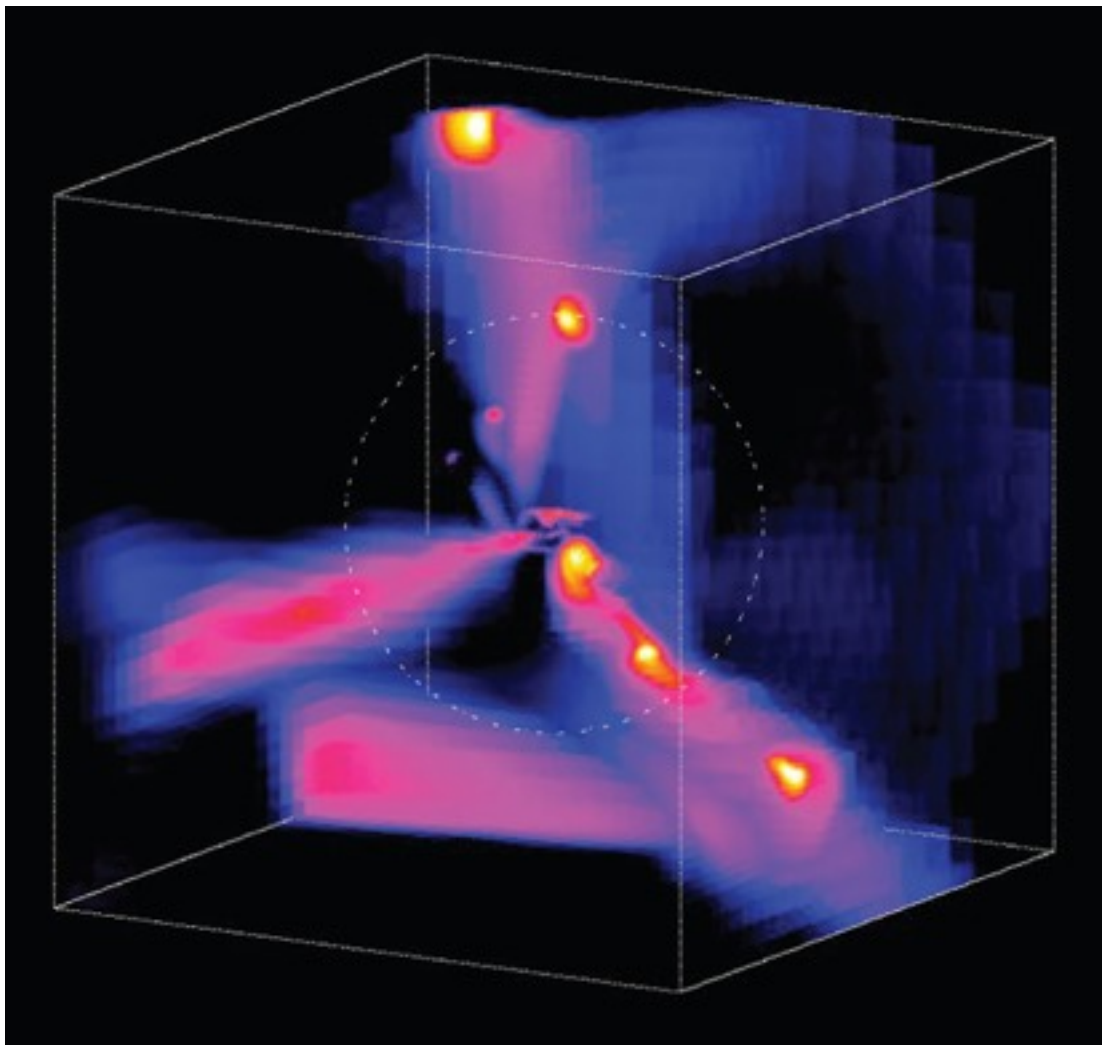
Cold flows

Cold streams in early massive hot halos



Dekel et al. (2009)

Cold streams in early massive hot halos



Dekel et al. (2009)

Connection between large star-forming & compact quiescent galaxies

- Scenario 1: Blue galaxies quench and move to red sequence
  - Build compact core by clump coalescence
  - Fading of outer star-forming regions
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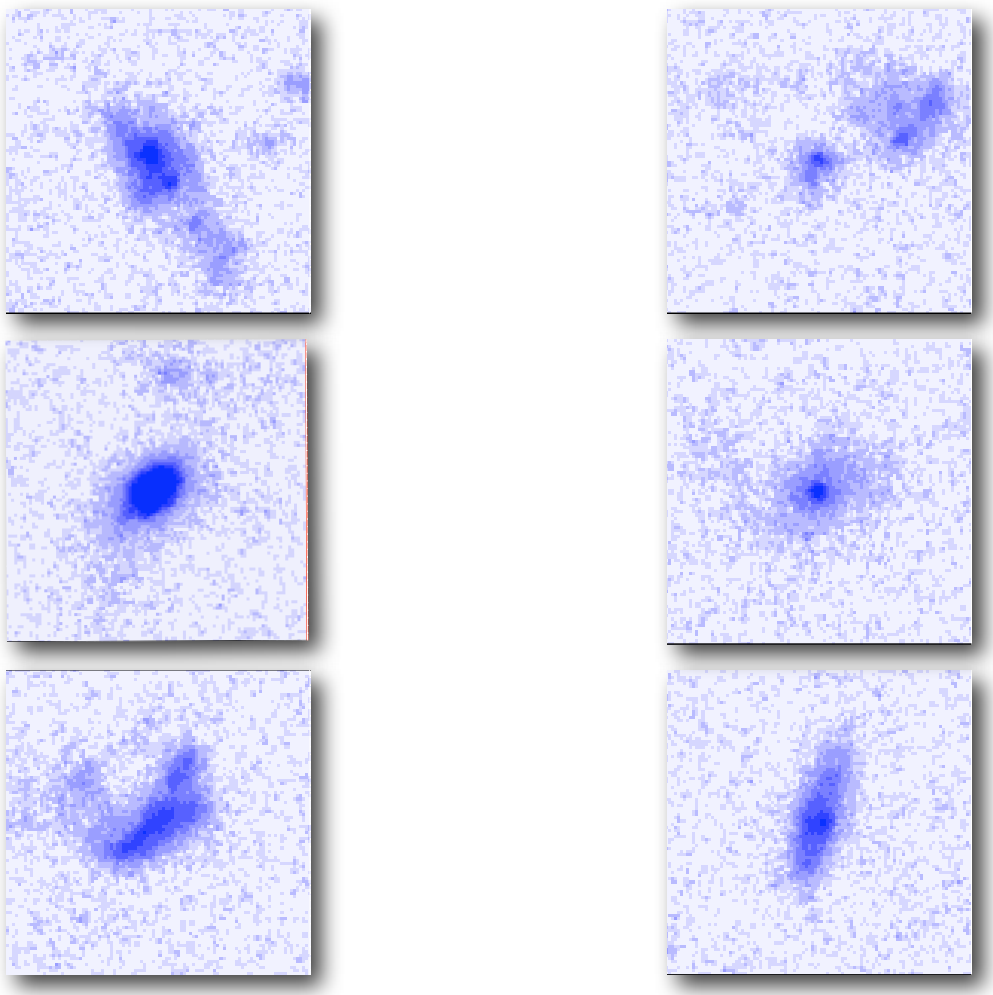
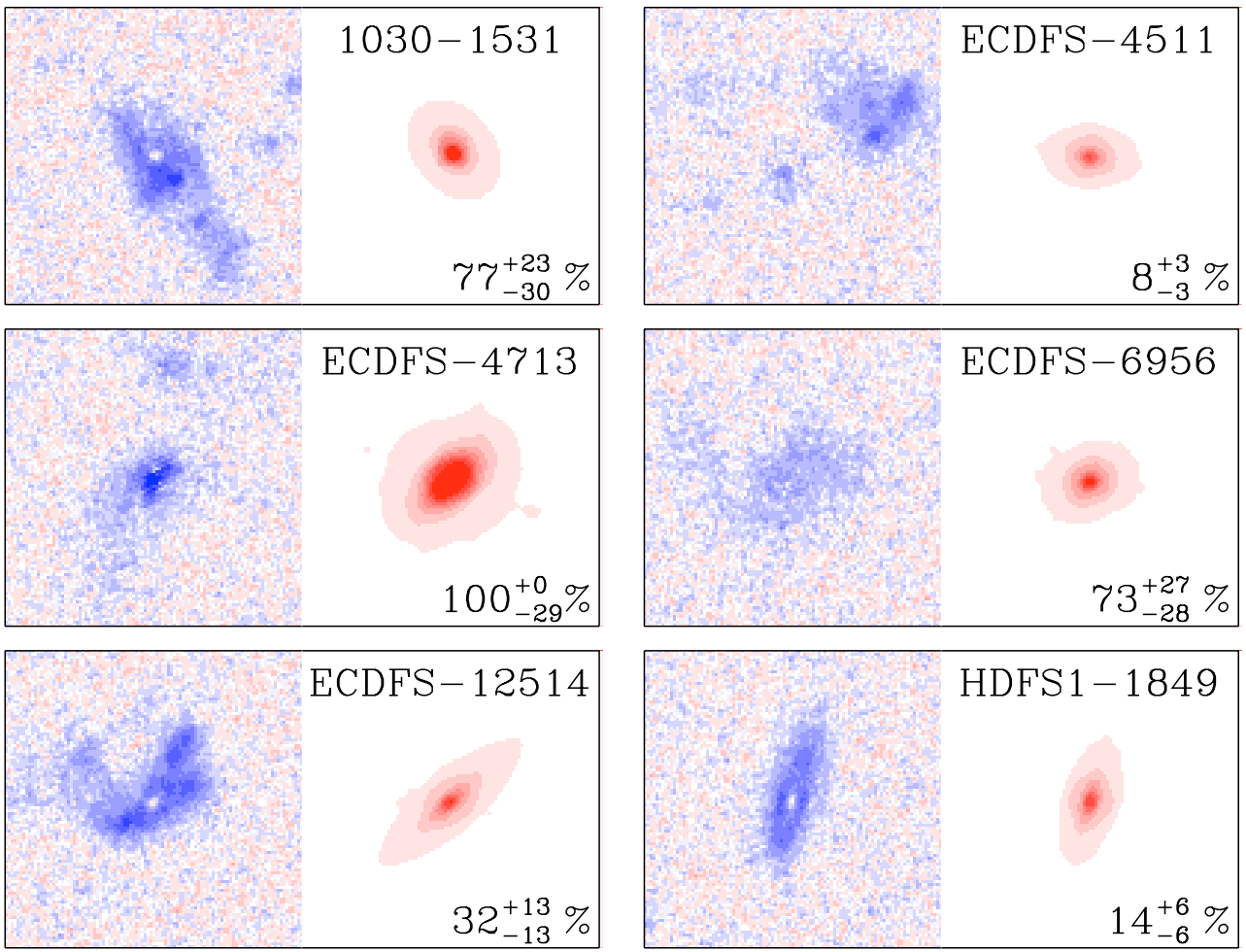
Dense cores in massive star-forming galaxies?



Kriek et al. (2009b)

Dense cores in massive star-forming galaxies?



Kriek et al. (2009b)

Connection between large star-forming & compact quiescent galaxies

- Scenario 1: Blue galaxies quench and move to red sequence
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  - Build compact core by clump collisions
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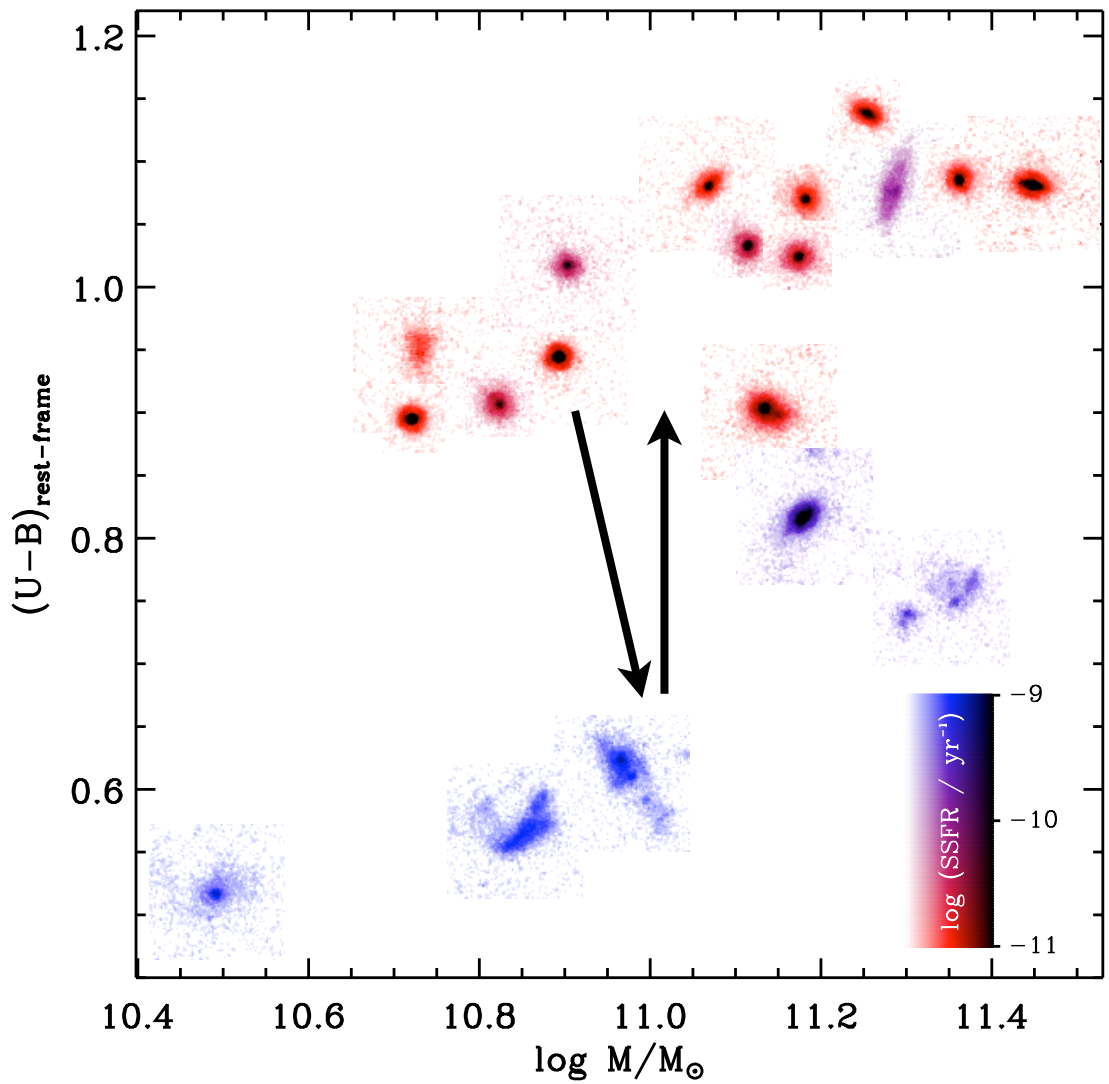
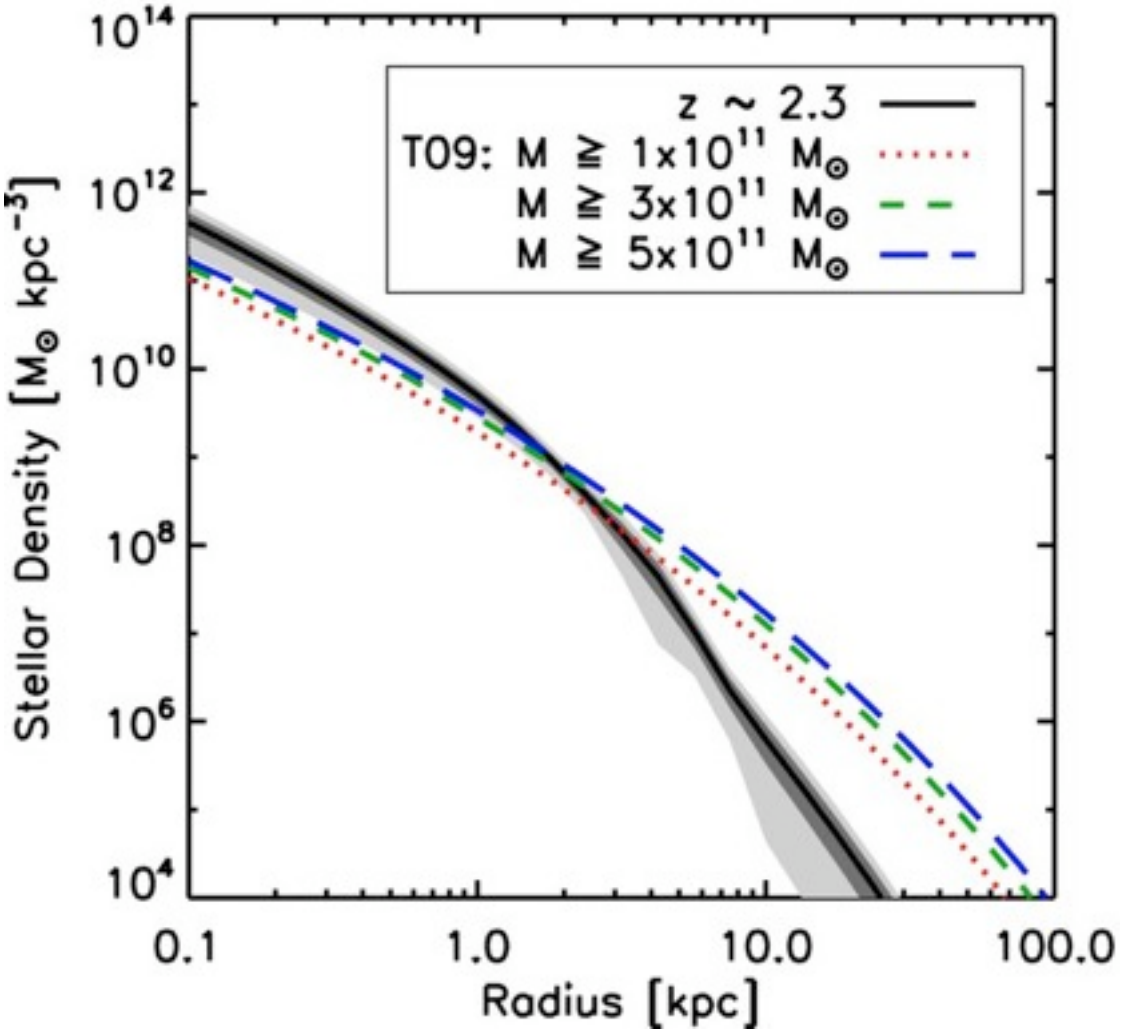
The "Hubble Sequence" beyond z=2

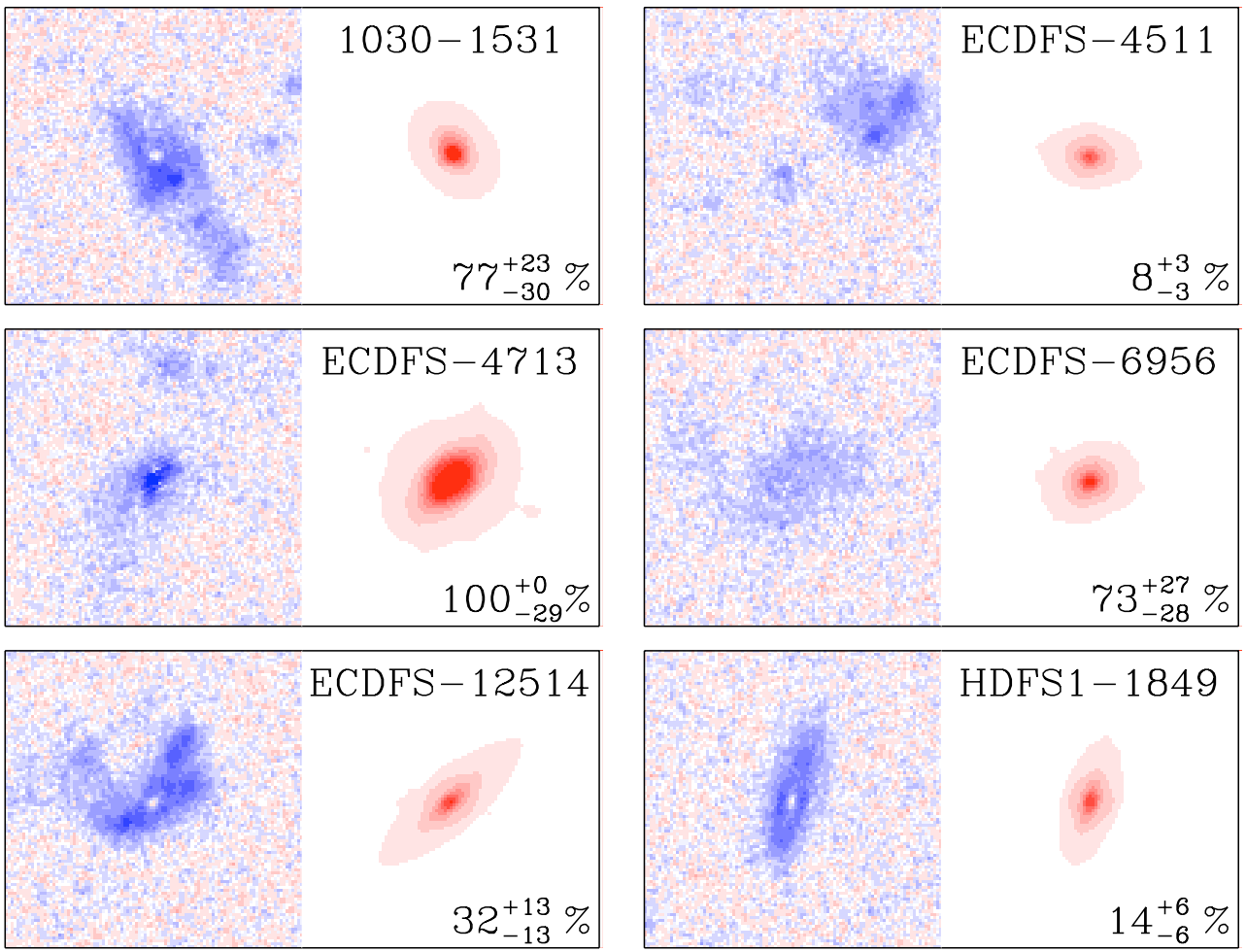


Inside-out growth



Bezanson et al. (2009)

Dense cores in massive star-forming galaxies?



Kriek et al. (2009b)

Connection between large star-forming & compact quiescent galaxies

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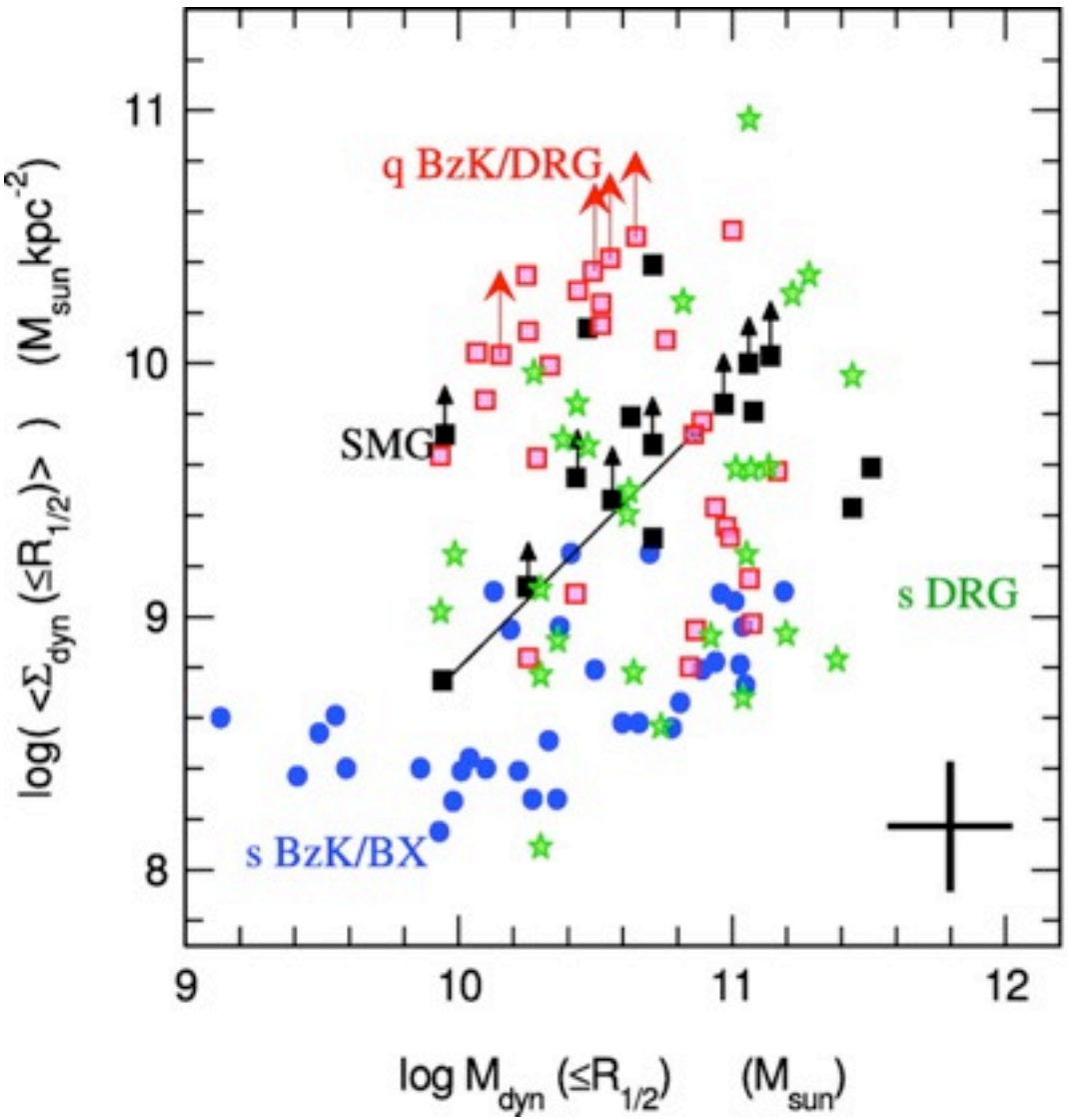
Descendants of sub-mm bright galaxies?

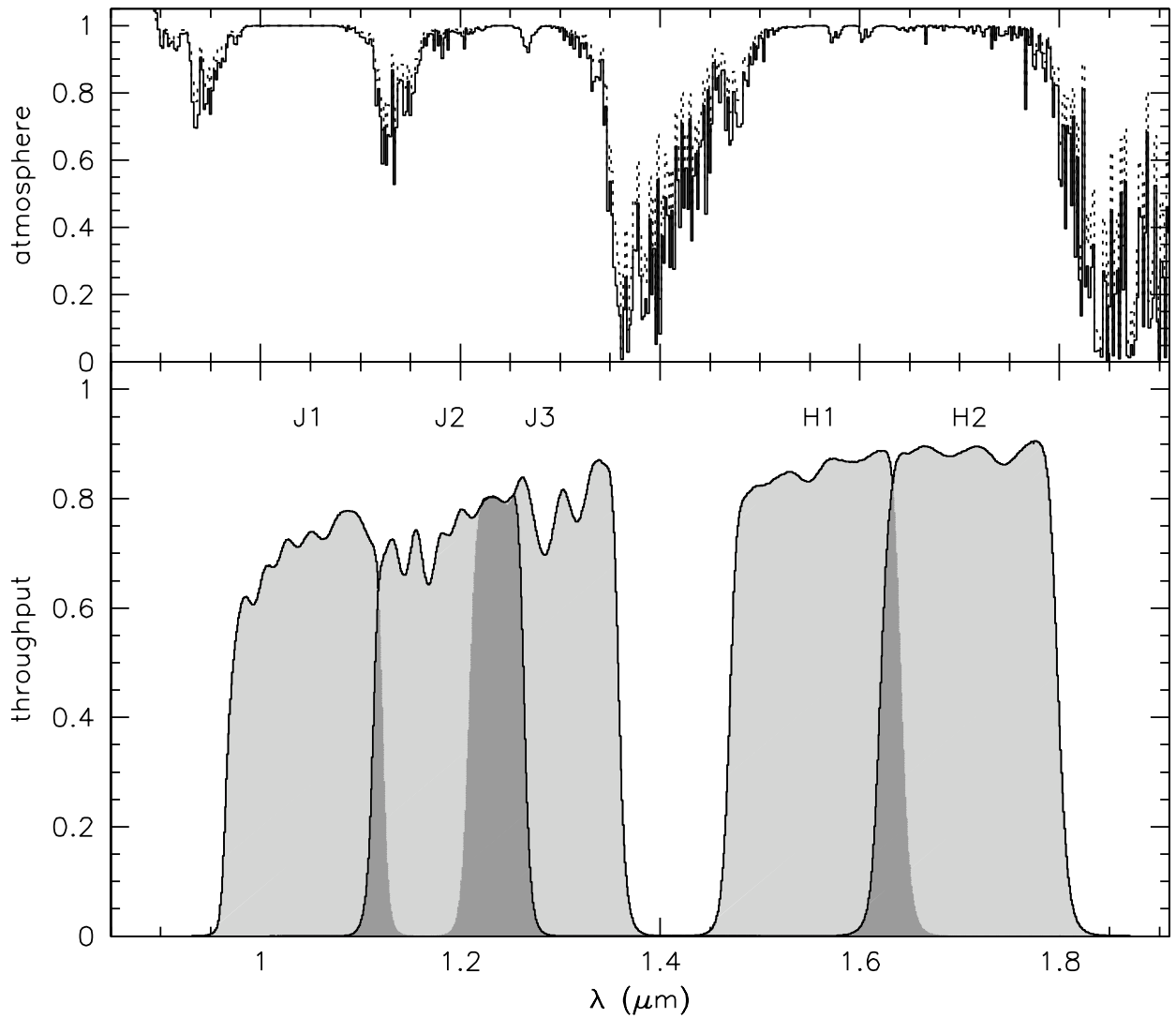


Tacconi et al. (2008)

Conclusions

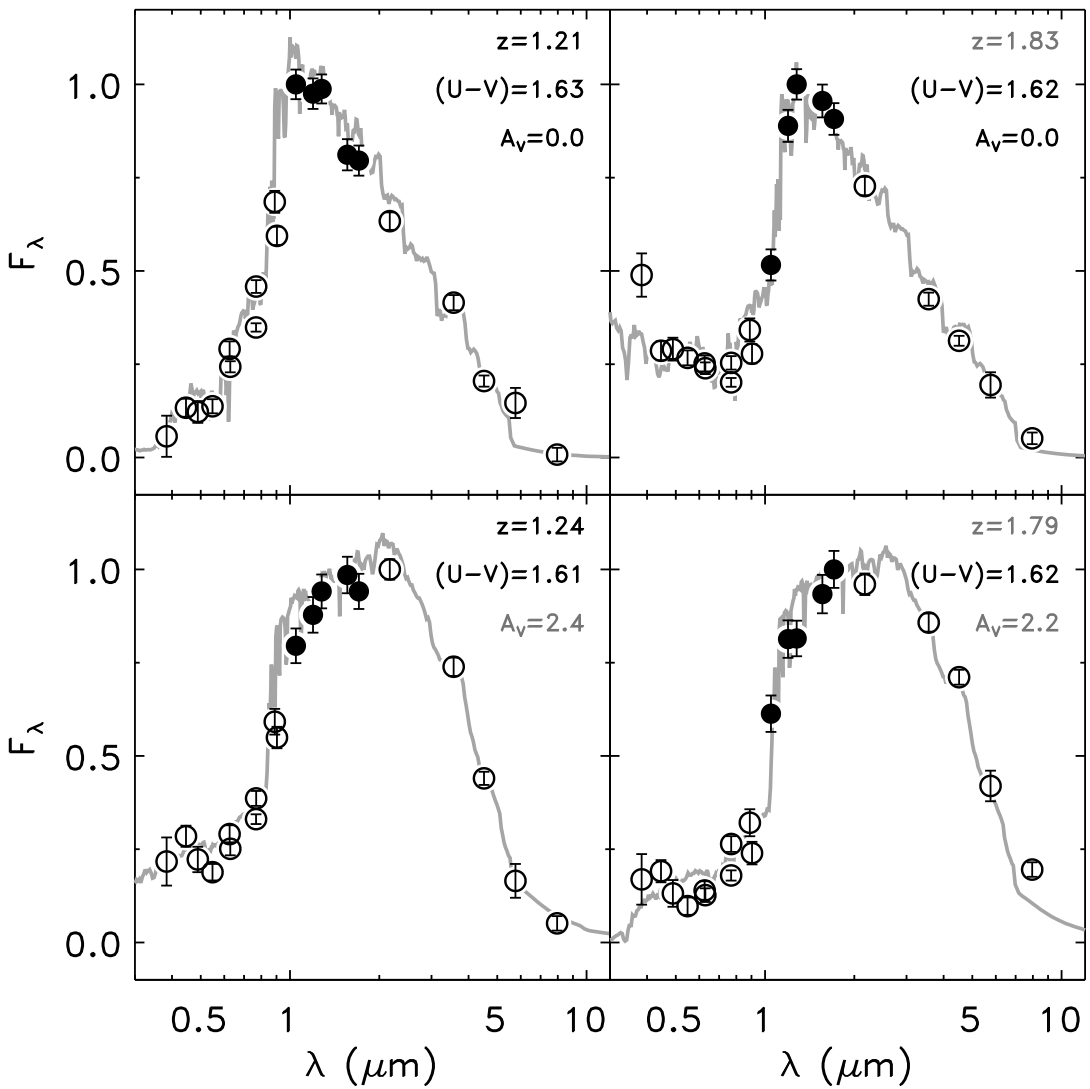
- The imprints of local galaxy correlations are already visible beyond z=2
- Nonetheless, in both numbers and structure the massive galaxy population has evolved significantly from z~2 to the present
- The structural evolution seems to be primarily driven by minor mergers
- Formation of compact galaxies is still not well understood: by mergers of "clumpy" cold streams or by a "sub-mm bright" major merger?

NIR median bands



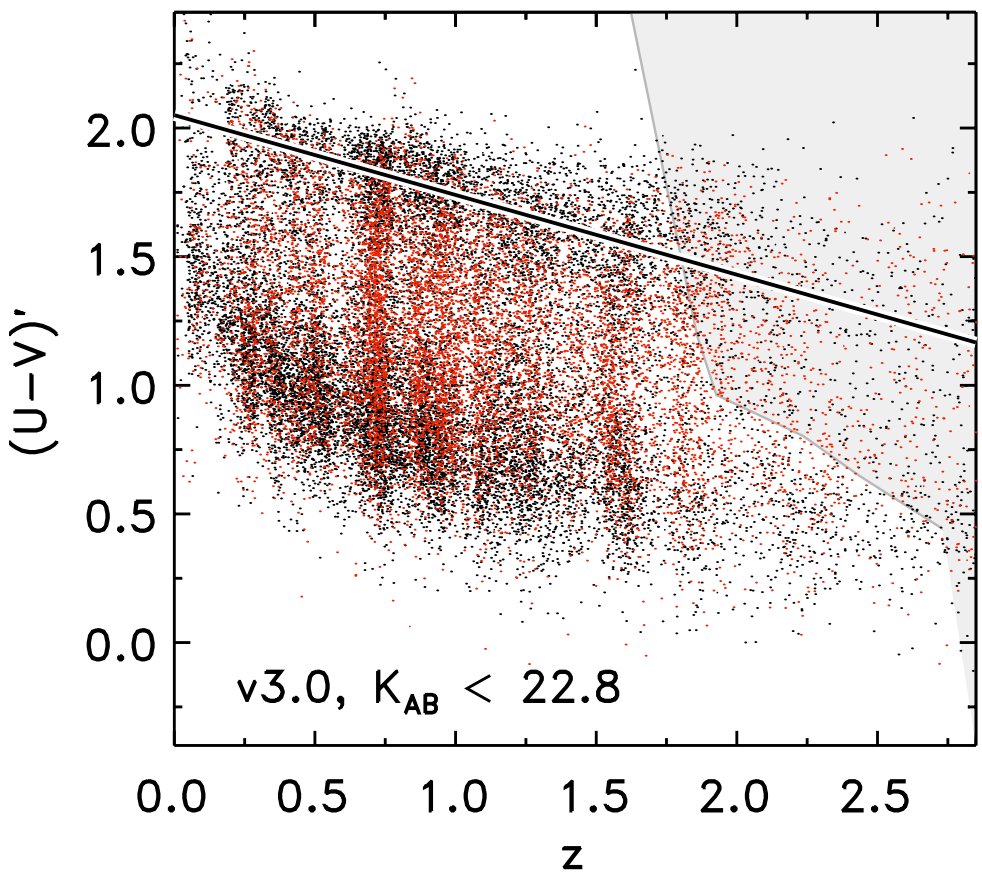
van Dokkum et al. (2009a)

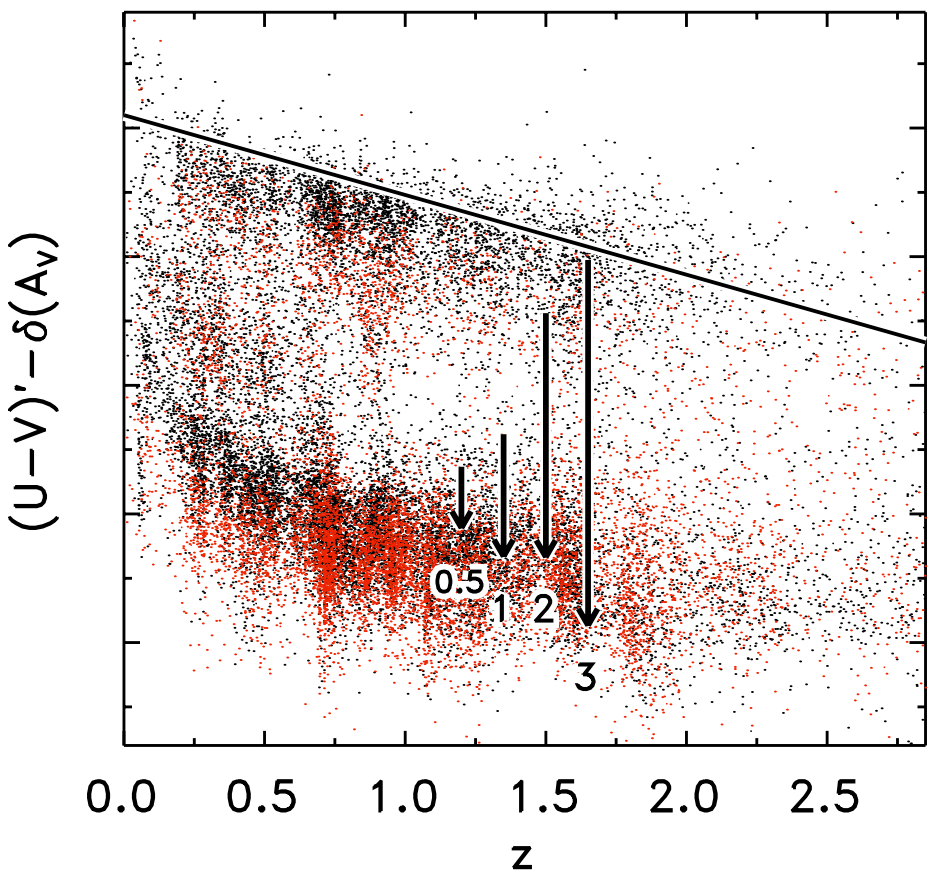
Separating dusty and quiescent red galaxies



Brammer et al. (2009)

Bimodality up to z~2.5





Brammer et al. in prep