The effects and importance of galaxy merging

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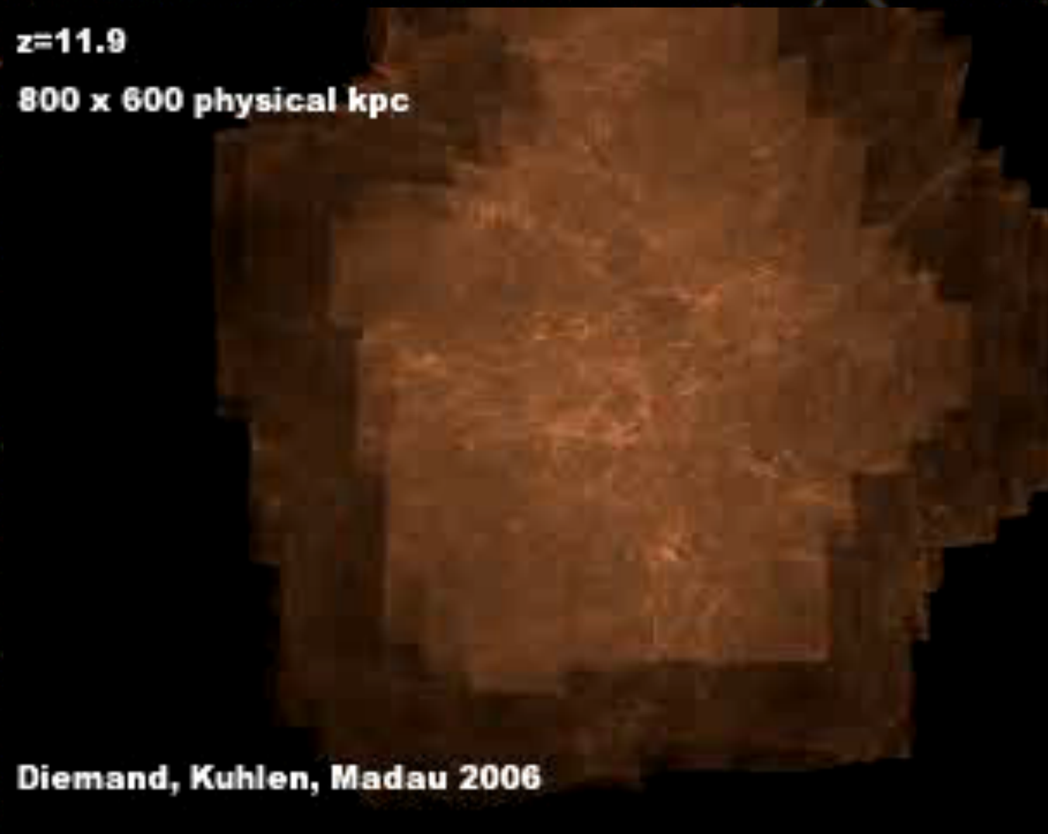
Robaina, Bell et al. 2010, ApJ, 719, 844; Robaina, Bell et al. in prep.; Bell, van der Wel et al. 2012, ApJ, 753, 167; Chang et al. 2013, submitted; van der Wel et al. in prep.; van der Wel et al. 2009, ApJL, 706, 120; Skelton et al. 2009, ApJL, 699, 9; Ruhland et al. 2009, ApJ, 695,1058; Gallazzi, Bell et al. in prep.

Merging with Dark Matter glasses on…

- Quantum fluctuations → overdensities in DM
- Grow through gravity
- Dynamical friction
- Violent relaxation

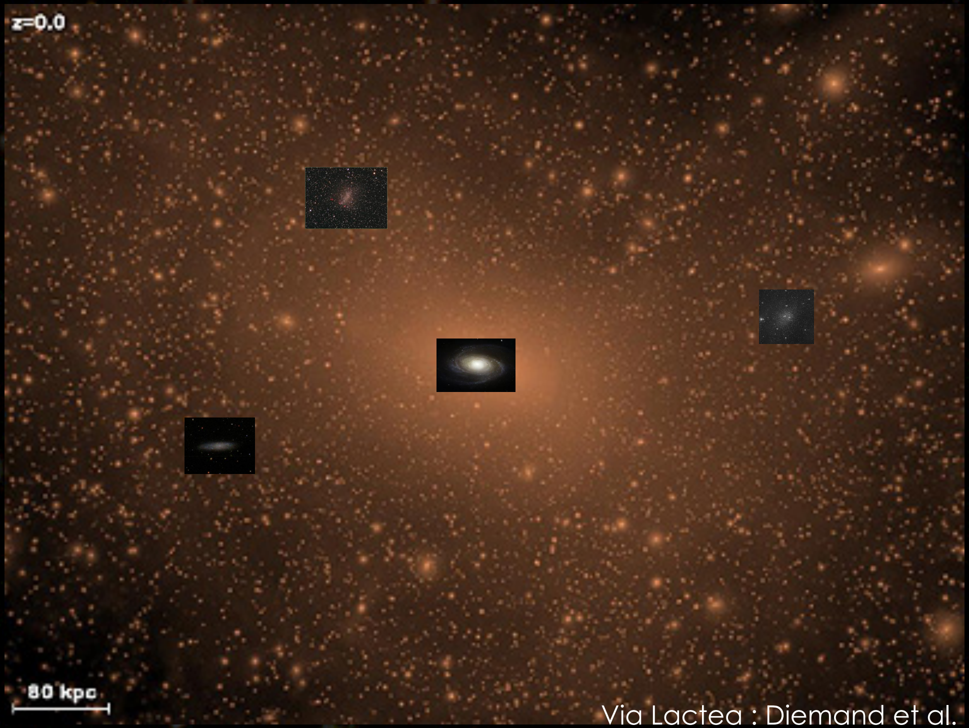


Diemand, Kuhlen, Madau et al. 2006 ; Via Lactea

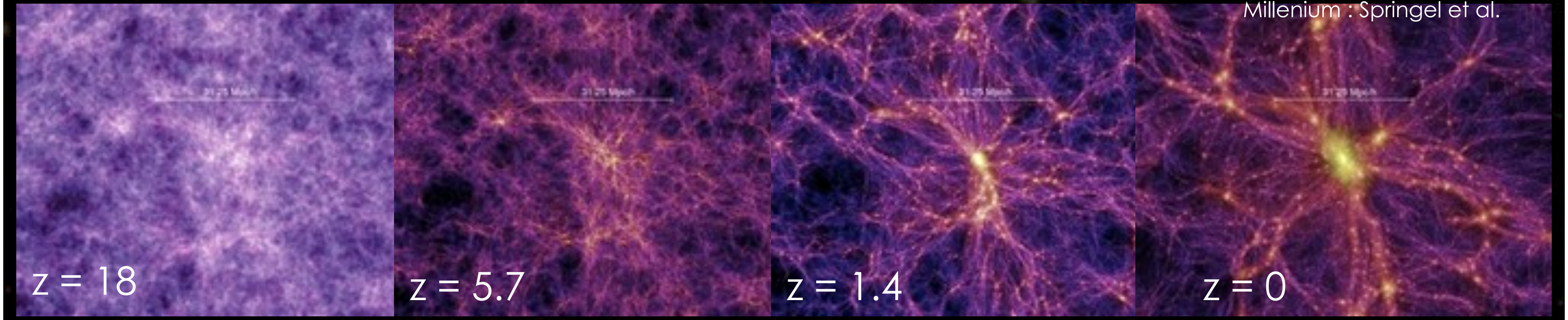
Normal matter

- Halo – largest halo
- Subhalo – smaller halo within virial radius of largest halo

- Central galaxy – sitting in middle of halo
- Satellite galaxies – sitting in subhalos

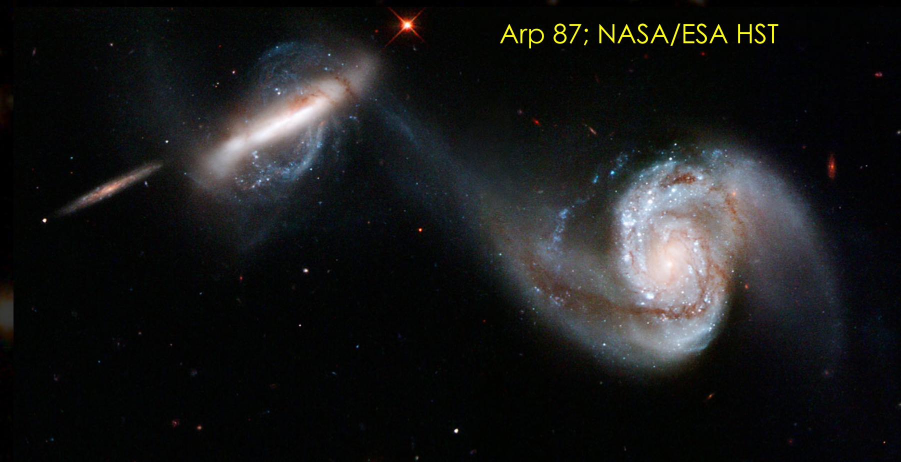


Via Lactea : Diemand et al.
Millenium : Springel et al.



The response of normal matter to merging…

- Whether/how we observe a merger depends entirely on normal matter
- Stars
  - Dyn. cold disks – thin tidal tails, remnant depends on orbit/disk angular momentum
  - Dyn. hot systems – tails broad, diffuse
- Gas
  - Dissipational; can lead to gas inflow, SF & possibly AGN activity.

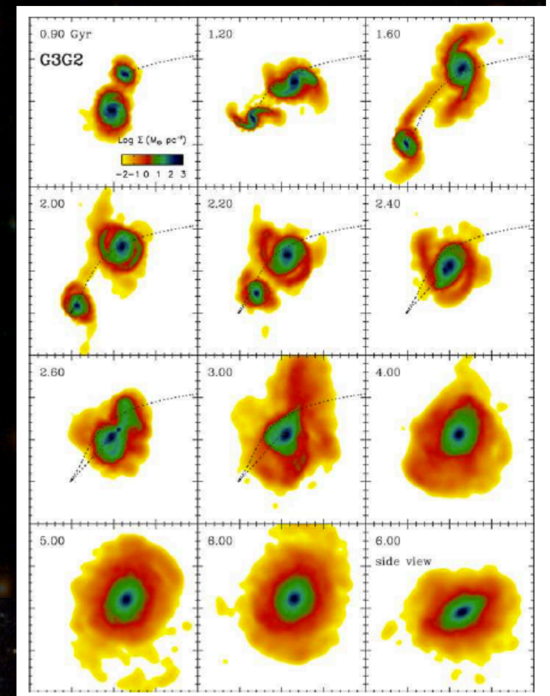


Arp 87; NASA/ESA HST

Duc et al 2011; ATLAS 3-D; CFHT

Consequences of merging?

- Dissipation → steepening of light profiles, enhancement of SF
- Violent relaxation & AM cons.
  - smooth light profiles
  - (considerable) rotation depending on mergers



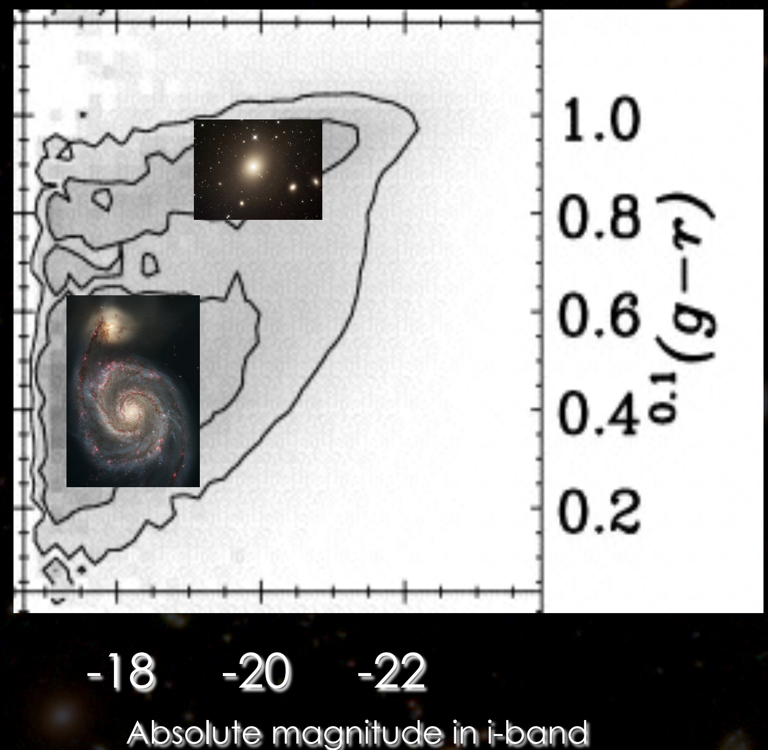
Cox et al. 2008; MNRAS, 384, 386

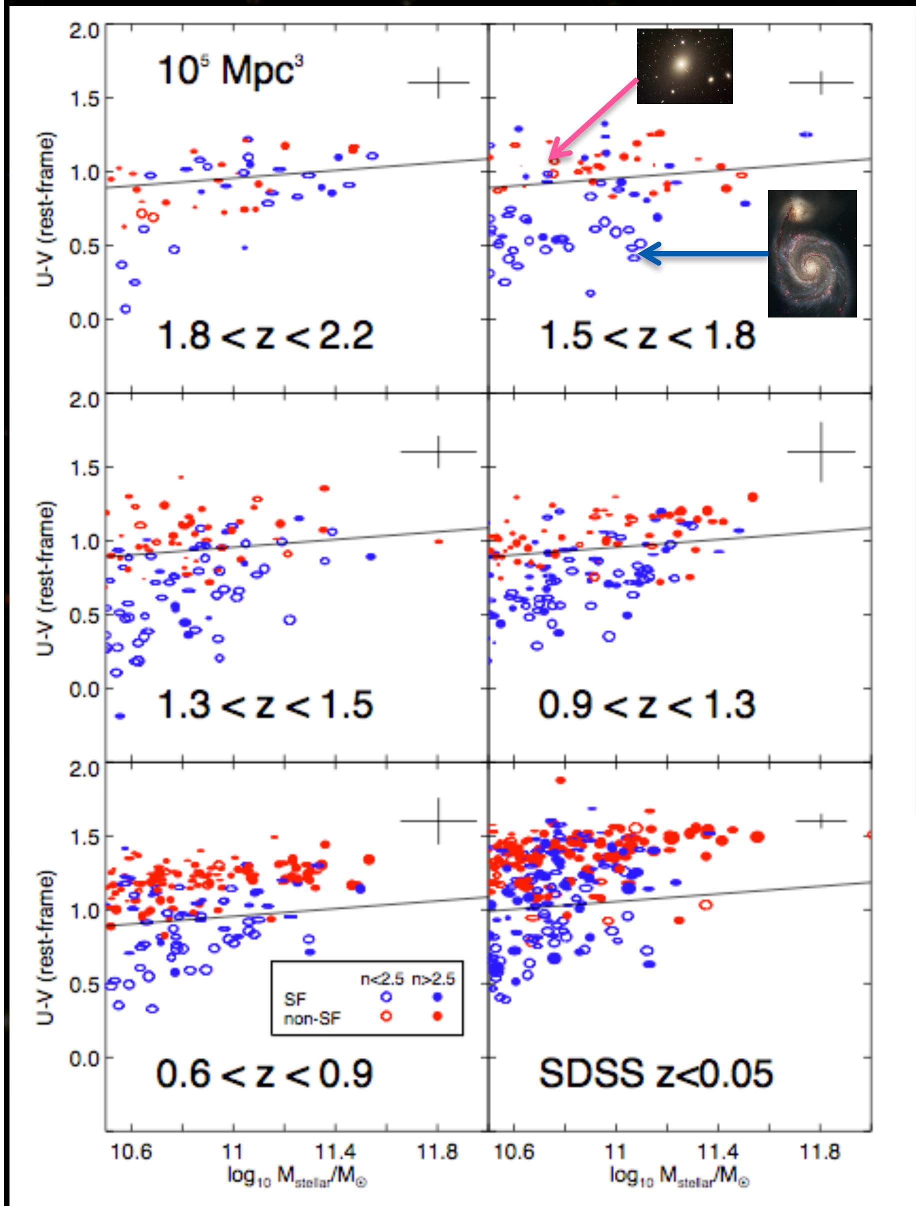
Duc et al 2011; ATLAS 3-D; CFHT

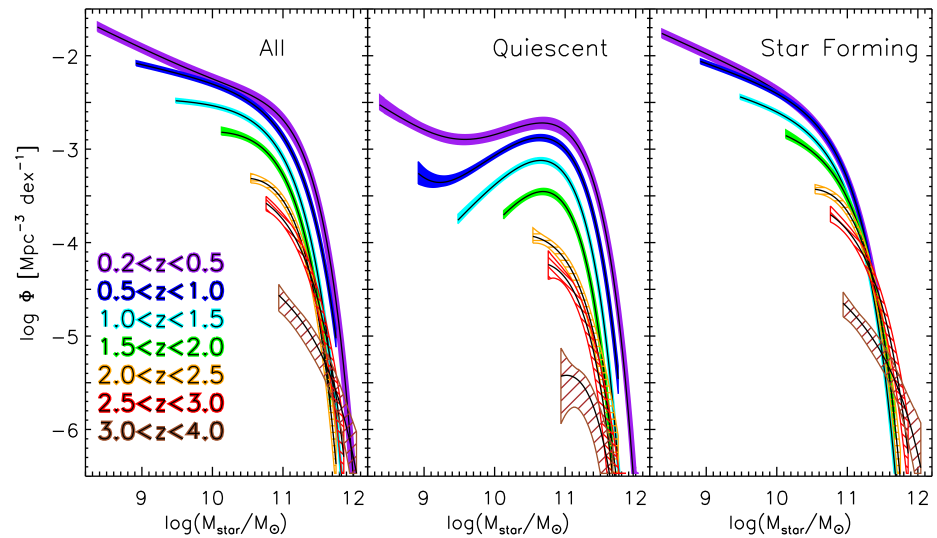
Present-day Census

- Bimodal galaxy population
  - Red sequence
    - Mostly non-star-forming
    - Bulk of galaxies bulge-dominated
    - Most massive galaxies
  - Blue cloud
    - Star-forming
    - Bulk of galaxies disk-dominated
    - Lower mass galaxies
    - Dominates by number
  - half of stars in spheroids, half in disks (Bell et al. 2003; ApJS, 149, 289)

Blanton et al. 2003; ApJ, 594, 186

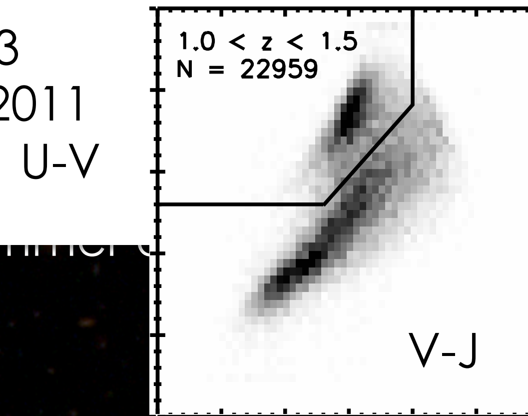






Muzzin et al 2013

Brammer et al. 2011



- Dramatic emergence of massive galaxy population
  - x5-10 increase in number of massive, non star-forming galaxies

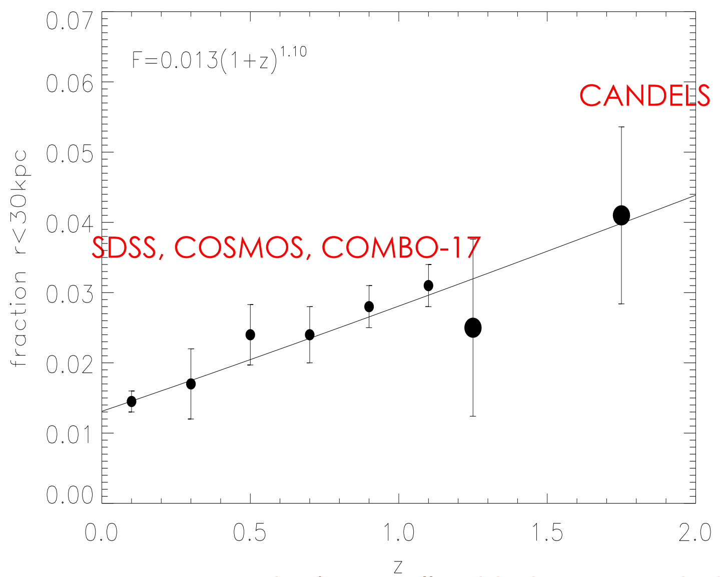
Bell et al. 2012

CANDELS UDS 30'x6'
Williams + photozs
Bell + stellar masses
van der Wel + 2013 Sersic fits (F160W; rest-frame optical)

Merging as a main driver of evolution at $M^*>10^{11}M_\odot$?

- Close pair counts

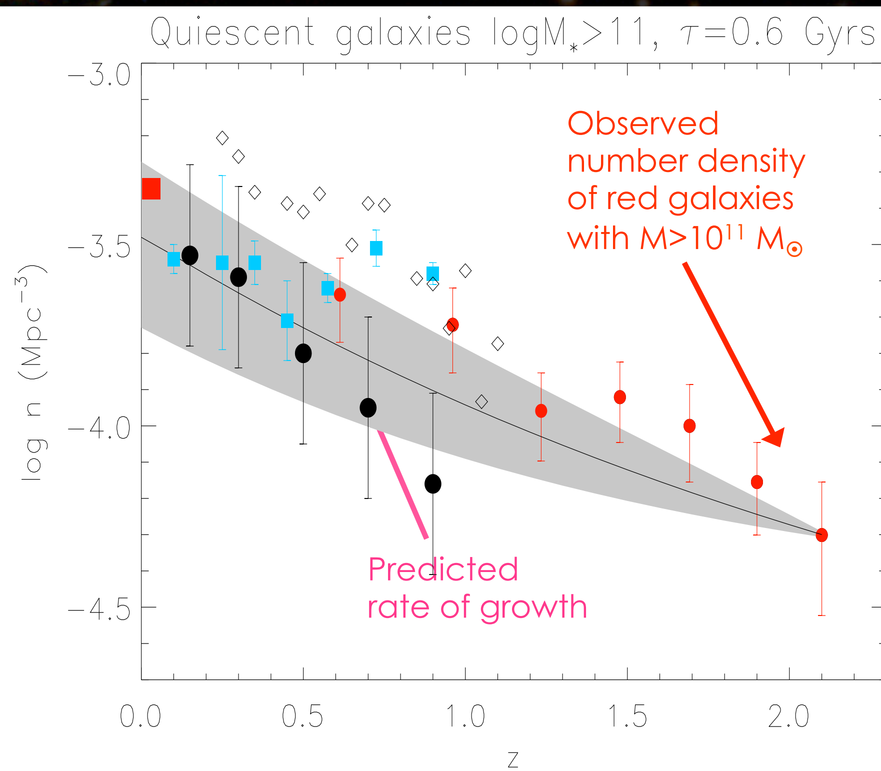
2pt projected correlation function
Inferred <30kpc 3-D separation
Autocorrelation $>5\times10^{10}\ M_\odot$



Robaina, Bell + 2010; ApJ, 719, 844
Robaina, Bell + in prep

- Integrate rate

All pairs merge, result in red $>10^{11}\ M_\odot$
Kitzbichler & White 2008 (corrected)
$t_{merge} \sim t_{orb}, t_{dynfric}, t_{sim}$
@ $>10^{11}\ M_\odot$ mergers can feed quiescent population; z=2 to present!



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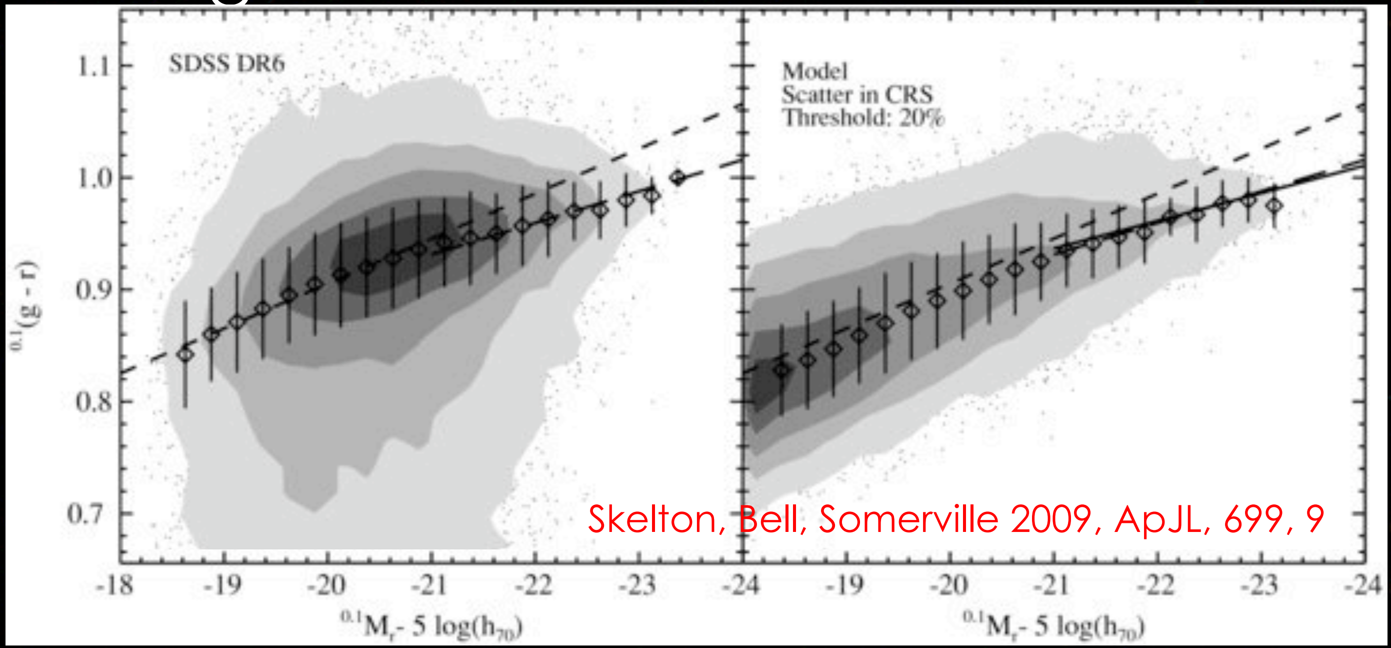
Indirect constraints

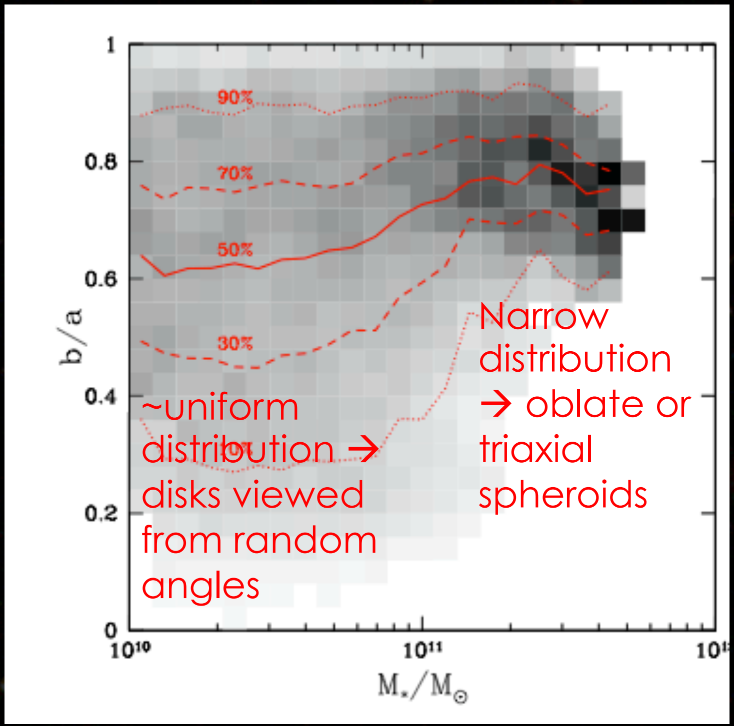
- Color-magnitude relation



- Clustering evolution
  - Shape/amplitude of small scale (<300kpc) correlation function means that satellites must get disrupted, ~1/3 from z=0.9 to z=0.5 (White et al. 2007, Conroy et al. 2007, Brown et al. 2008).

Shapes of quiescent galaxies

- Axis ratio distributions → 3D shapes
- $>10^{11}$ M_{sun} prolate/triaxial
  - mergers between gas-poor galaxies (van der Wel et al. 2009; Naab et al. 2006)
  - Similar out to z~1
  - z>1 slightly diskier
- $10^{10}<M^*/M_{sun}<10^{11}$ disks
  - Kinematics ATLAS3D shows this too; Emsellem+07,11
  - Major mergers can do this – Naab + 2003,2006
  - Minor mergers, secular?



van der Wel et al. 2009
Holden et al. 2010
Chang et al. 2012

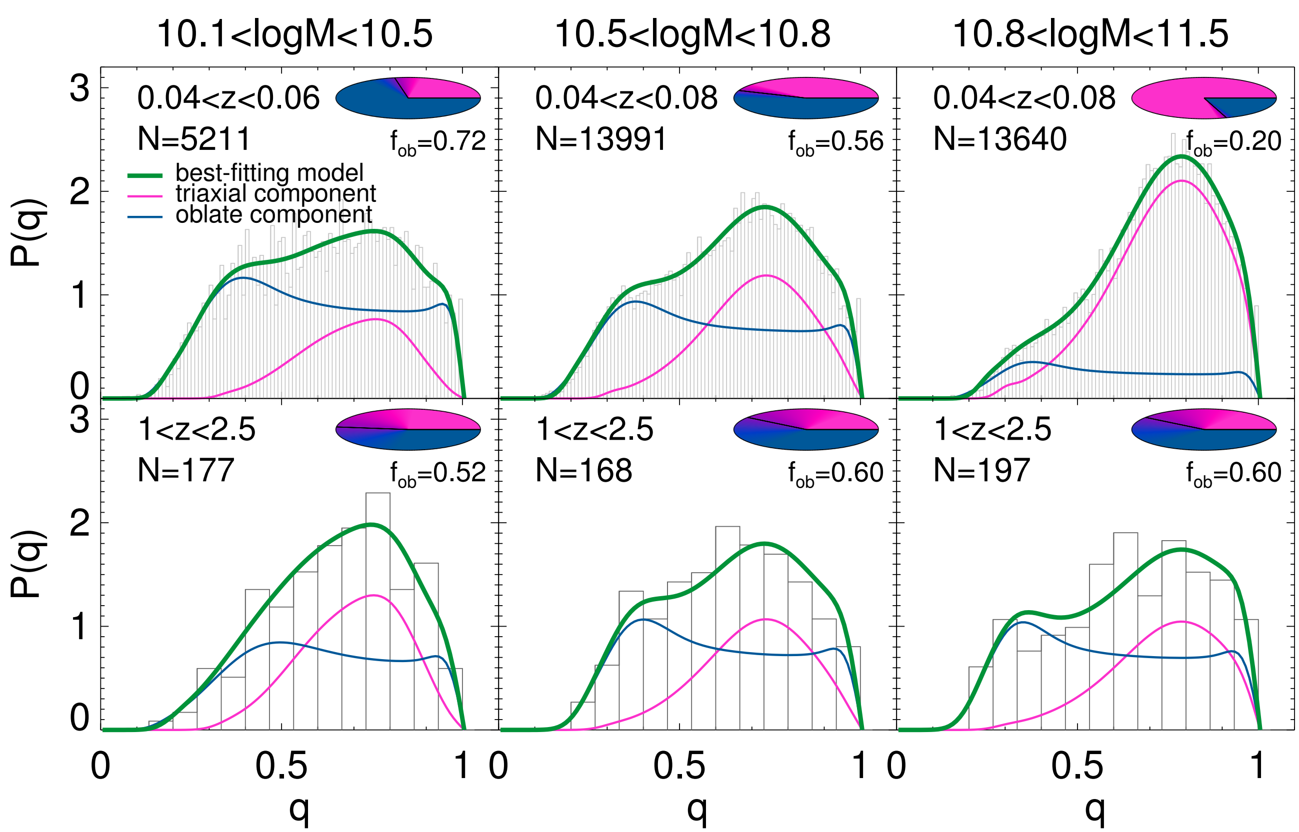
Yu Yen Chang, van der Wel, et al. (2013; submitted)

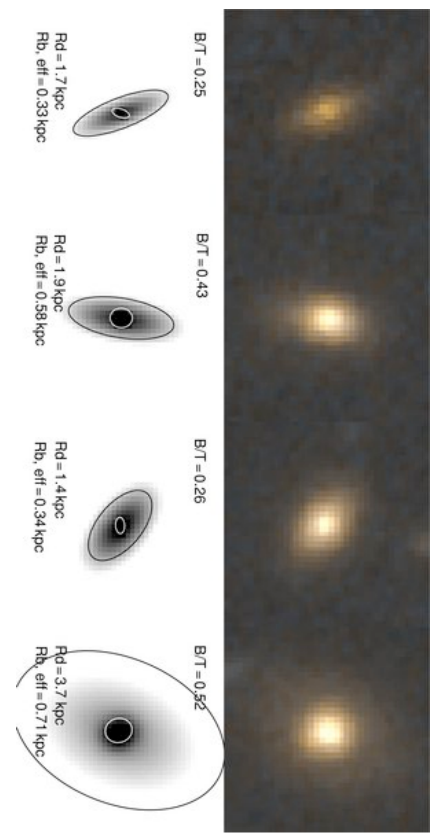
CANDELS Sersic fits + photoz

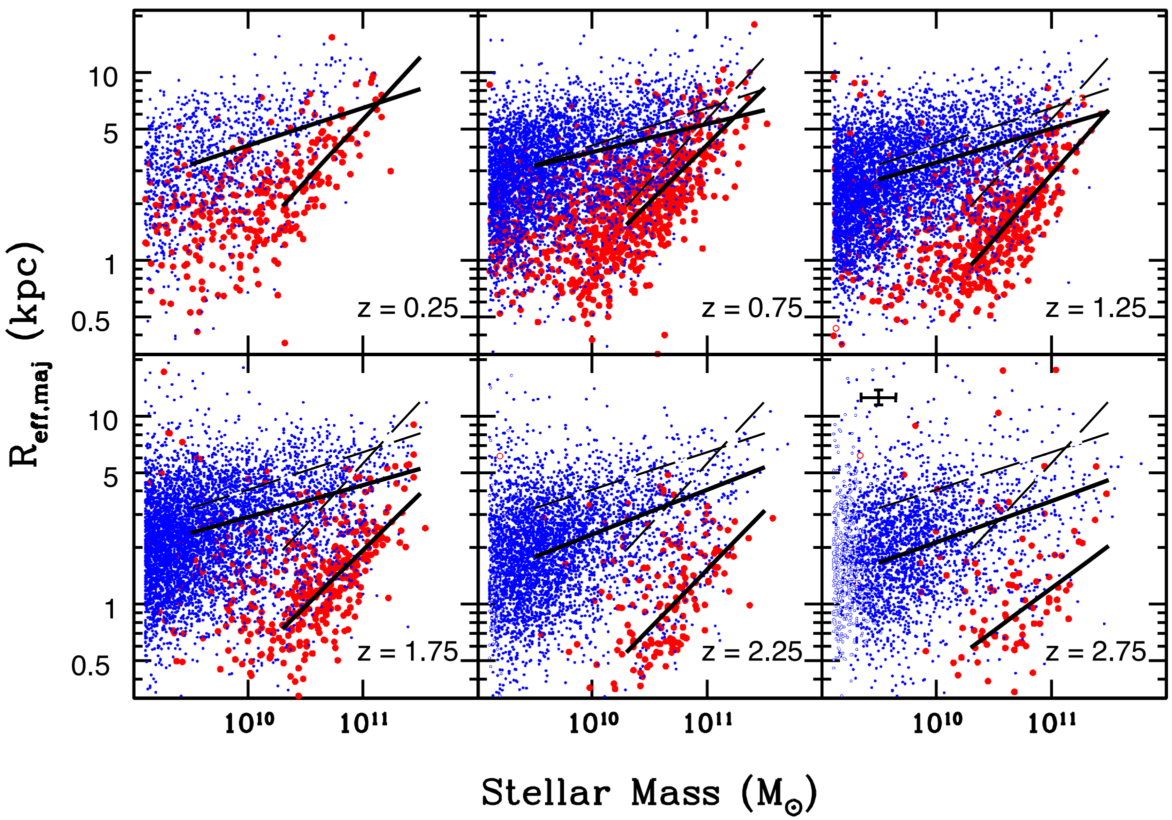
- Disks common z>~1.5 massive galaxies (quiescent)
- Triaxial by z~0 – merging (major/minor)

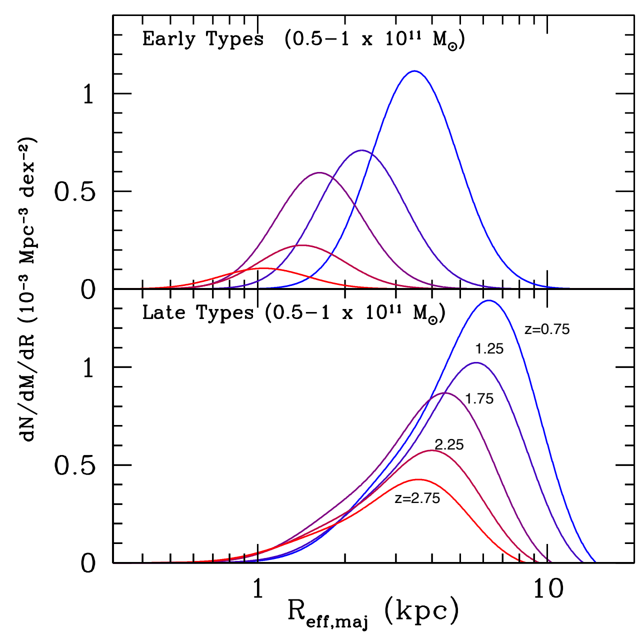
van der Wel (2011)

- Quiescent galaxies oblate at lower masses (all z)









van der Wel (in prep.)

- 3D-HST+CANDELS (photz+grism z)
- Sersic fits of WFC3 IR data; corrected to rest-frame g

Size evolution in SF and quiescent; particularly striking for quiescent

- not obvious that new arrivals are bigger (Whitaker et al. 2012 vs. van der Wel et al. 2008)
- individual early-types must grow, minor mergers? - size evolution without much mass growth

SF much larger than quiescent; dissipation very imp. in setting quiescent sizes

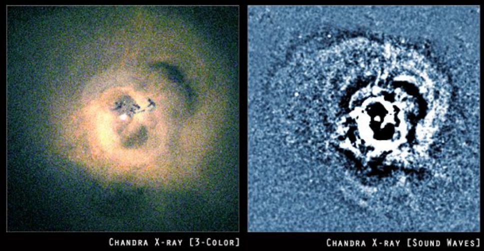
So far…

- Dramatic emergence of massive galaxy population
    - x5-10 increase in number of massive, non star-forming galaxies
    - More quiescent massive galaxies today than there were massive galaxies at z=1.4
- The role of mergers in shaping the massive galaxy population
    - Mergers – set structure?
        - Dominant at $>10^{11}\ M_{\odot}$
        - Likely important at $10^{10-11}\ M_{\odot}$
        - Leaves disks
        - Remnants more compact and concentrated than progenitors
- What is responsible for their lack of star formation?

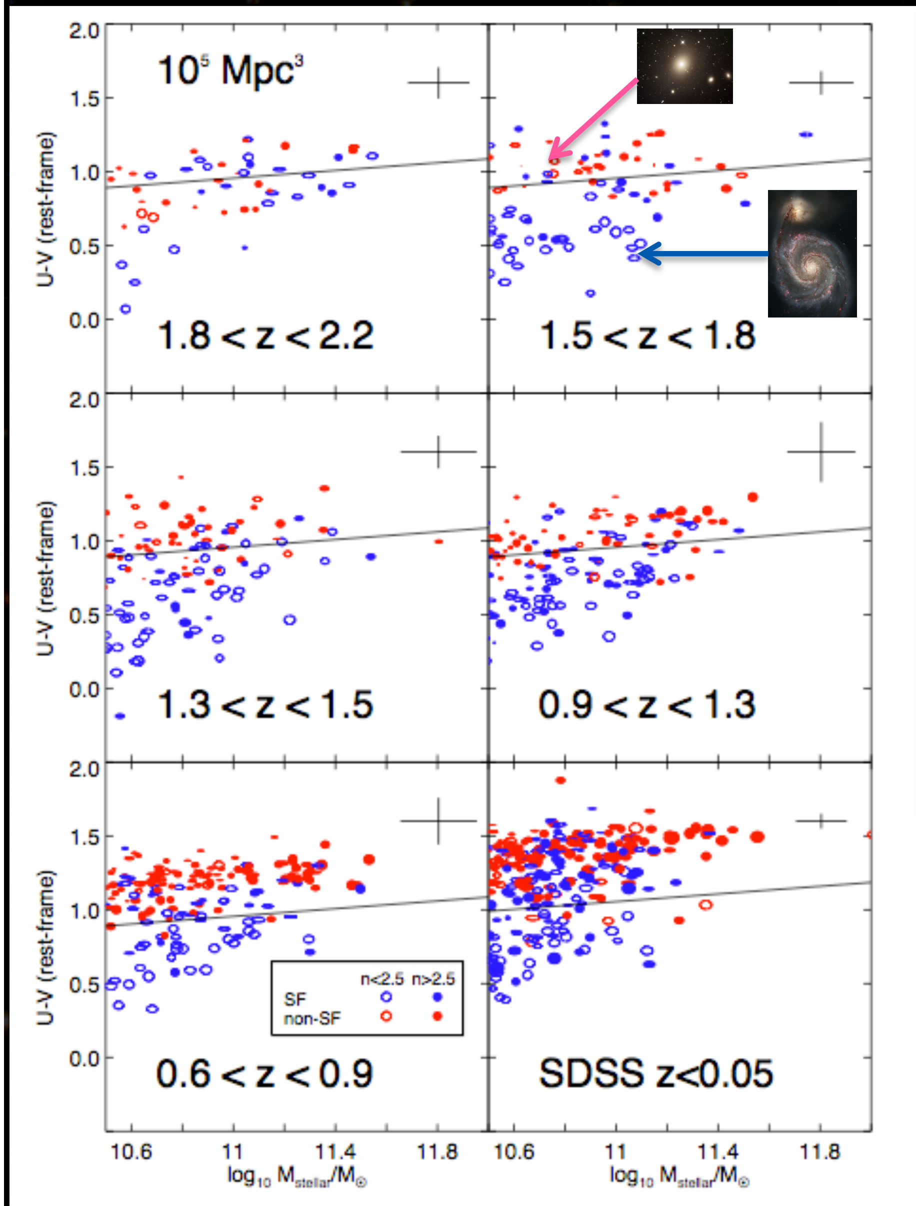
Spheroid-dominated galaxies as plausible remnants

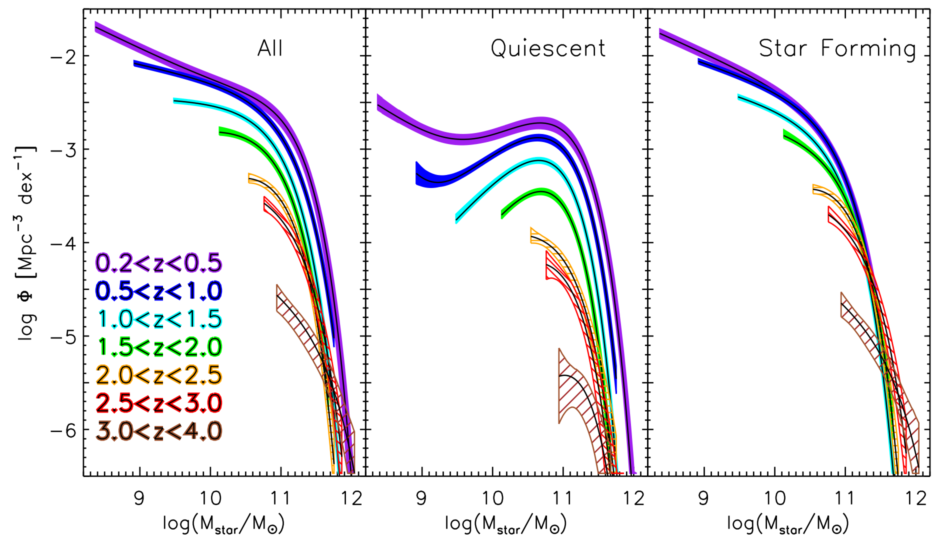
- Gas consumption through star formation insufficient (Barnes 2005?)
  - AGN feedback
    - Supermassive black hole mass correlated with bulge mass (e.g., Gultekin et al. 2009)
    - Ejection of gas in quasar episode; e.g., Kauffmann & Haenehlt 2000 (thought to be associated with merging; Sanders, Hopkins)
    - Heating of gas in hot halo as it tries to cool; e.g., Croton et al. 2006 (big BH required)
    - In either case expect correlation with big bulge
  - Ejection of the gas by star formation-driven winds in some cases? Diamond-Stanic et al. 2012
  - Development of virial shock slows cooling (halo mass $>10^{12}\ M_{\odot}$; Keres et al. 2005; Dekel & Birnboim 2006)

Di Matteo et al. 2005



Fabian et al. 2003
Fabian 2012

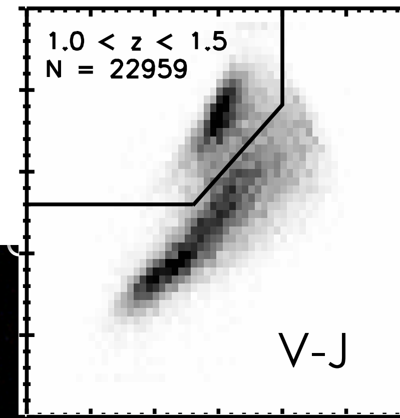




Muzzin et al 2013

Brammer et al. 2011

U-V



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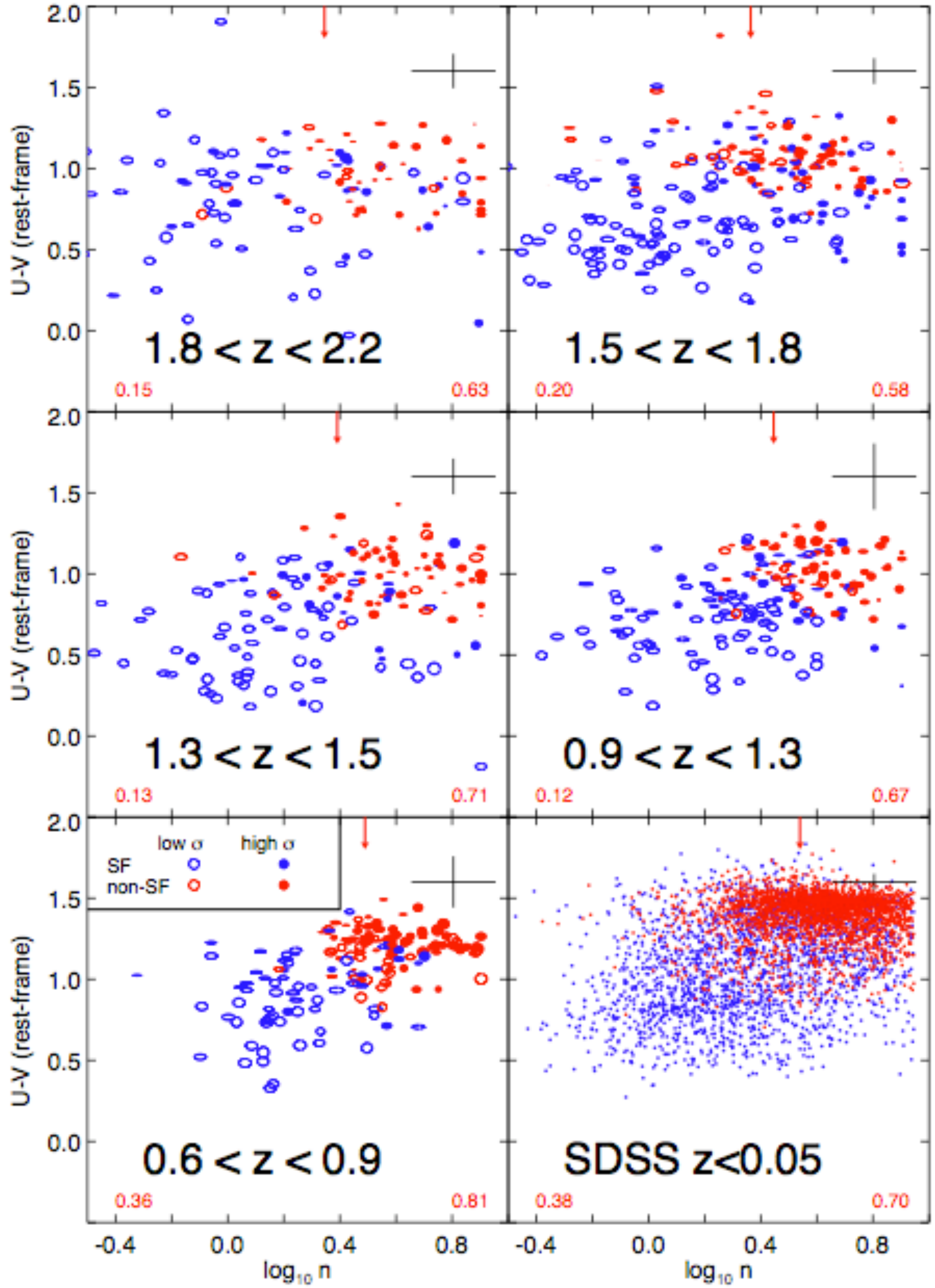
- Most non-star forming galaxies have high n
  - At all redshifts
  - prominent bulge



Ideas for getting rid of cold gas?

- Possible solutions?
  - AGN feedback
    - Ejection of gas in quasar episode; e.g., Kauffmann & Haenehlt 2000 (thought to be associated with merging; Sanders, Hopkins)
    - Heating of gas in hot halo as it tries to cool; e.g., Croton et al. 2006 (big BH required)
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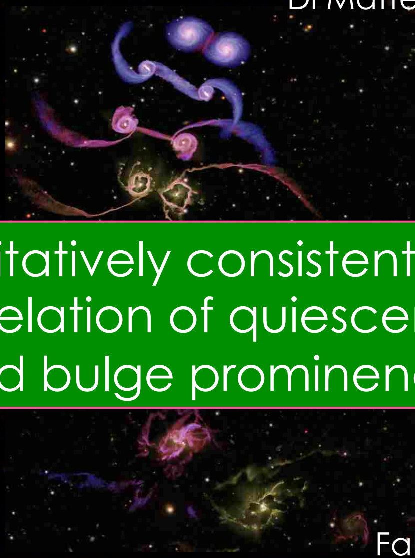
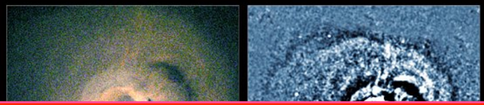


Qualitatively consistent with correlation of quiescence and bulge prominence

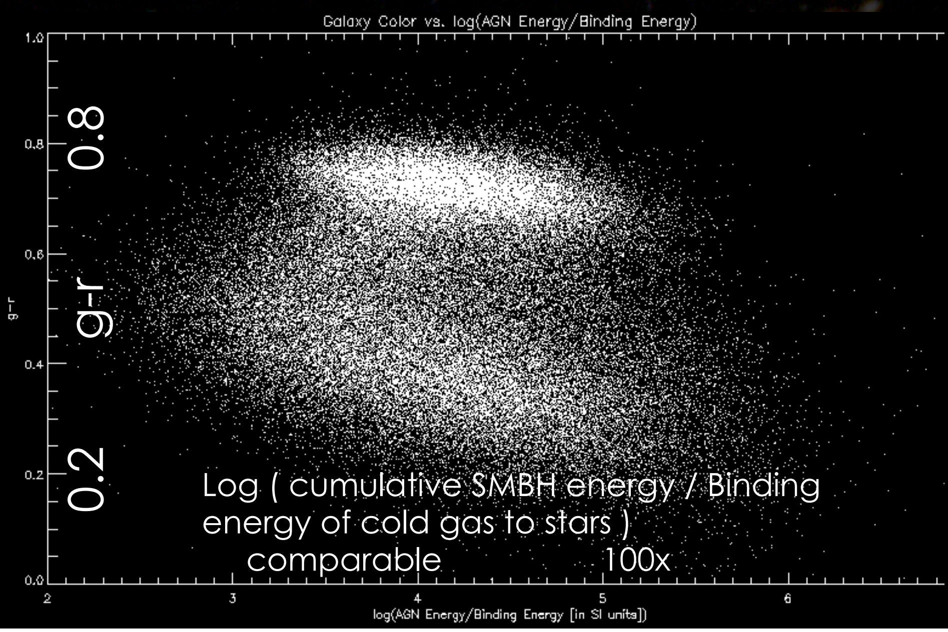
Fabian et al. 2003
Fabian 2012

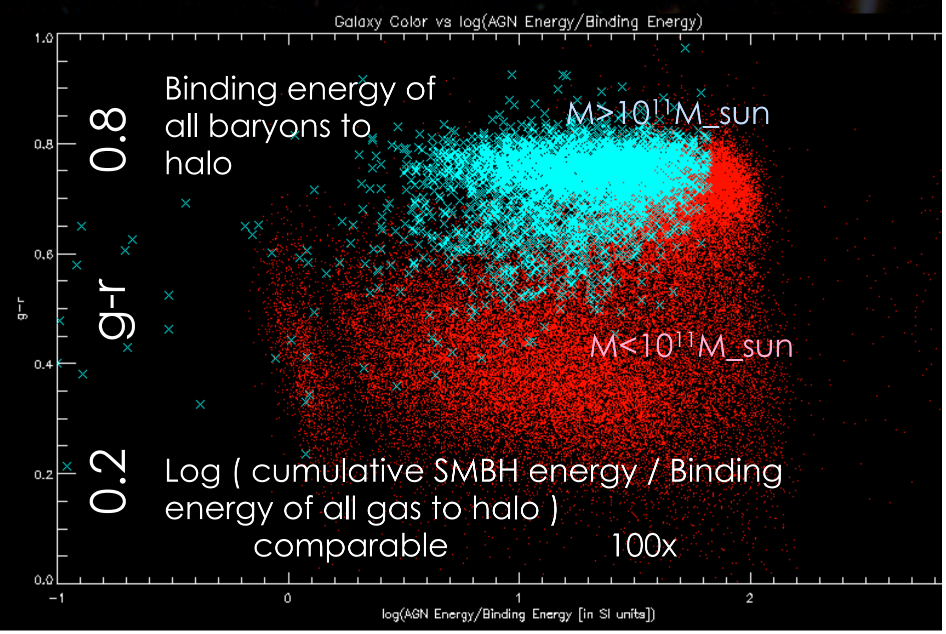


Qualitatively disfavored by lack of stellar mass-quiescence relation (More et al. 2010 argue for reasonably tight M^*-M_{halo} relation)

Testing cartoon AGN feedback

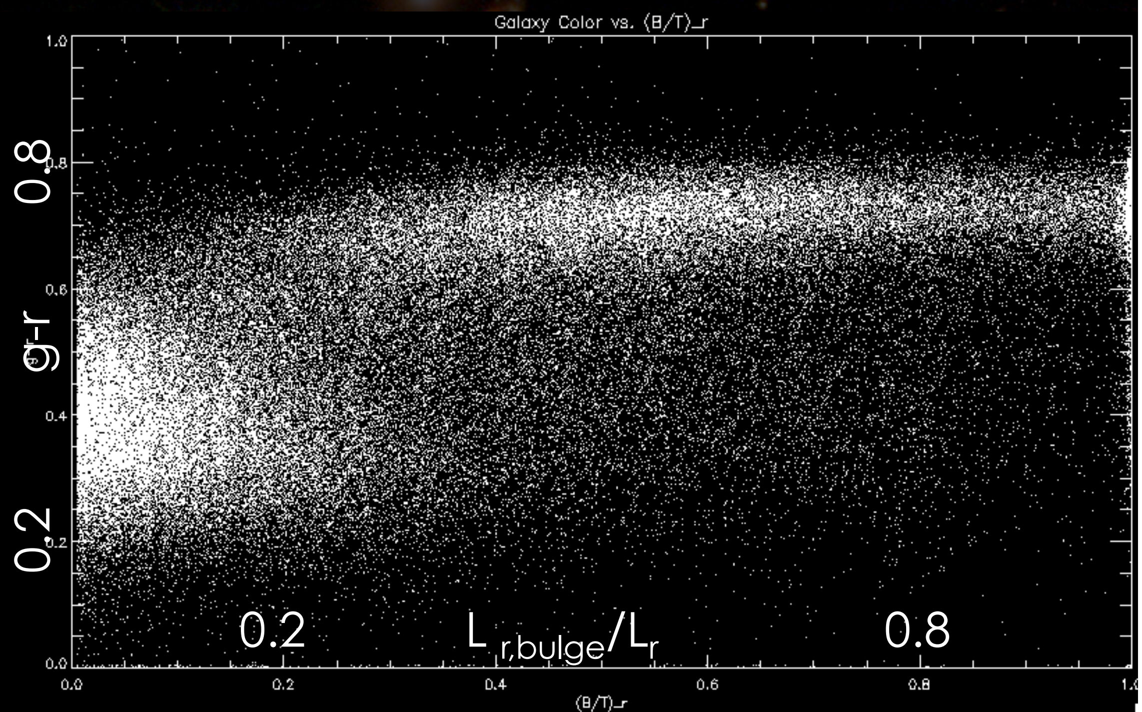
- Feedback strength
  - ~ AGN energy / binding energy
  - ~ $M_{bulge}/(M_*^2/r)$
- Small galaxies suffer most feedback
- Quenched galaxies at ~all AGN/binding energy values





Testing cartoon AGN feedback

- B/T correlates much better with color
  - Quenching does not depend on whether SMBH is 'big enough'
  - Quenching depends on galaxy having developed a bulge
    - Directly?
      - SF wind? Quasar mode?
    - allowing e.g., SMBHs to do their work?



Conclusions

- Dramatic emergence of massive galaxy population
  - x5-10 increase in number of massive, non star-forming galaxies
  - More quiescent massive galaxies today than there were massive galaxies at z=1.4
- Quenching mechanisms
  - Correlates well with galaxy structure (~bulge)
    - Very poor correlation with stellar mass
  - Mergers – set structure?
    - Dominant at $>10^{11}\ M_{\odot}$
    - Likely the driver at $10^{10-11}\ M_{\odot}$
    - Correlate with quenching event
    - Leaves disks
    - Remnants more compact and concentrated than progenitors