Galaxy Evolution at z > 2: Cosmic Starvation, Mergers, and Morphology

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Feldmann & Mayer, arXiv:1404.3212
Fiacconi, Feldmann, & Mayer, to be submitted

Outline

1. Introducing the Argo Simulation

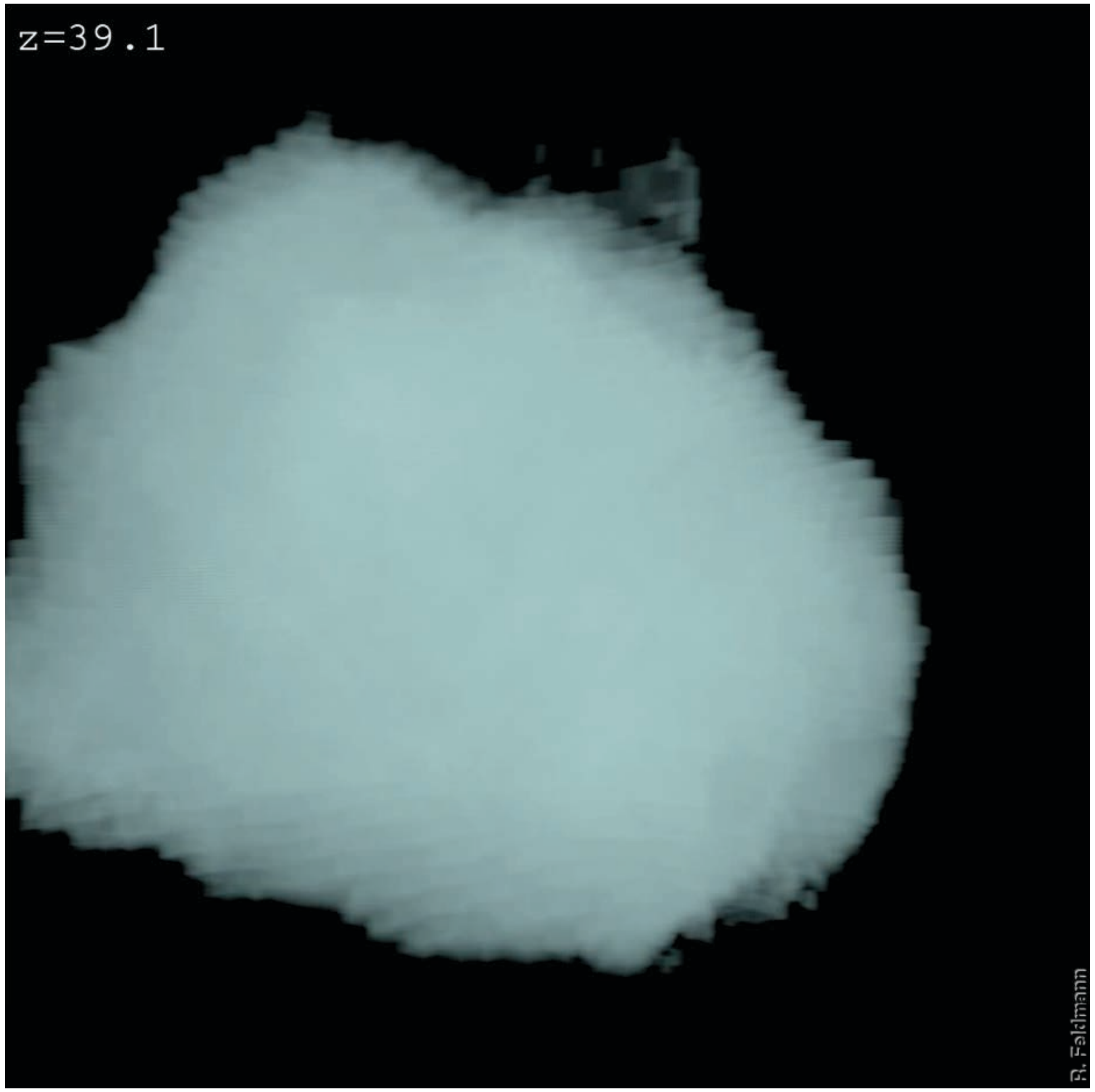
2. Quenching of massive galaxies at z>2

3. Morphological transformations of galaxies at z>2

Argo what?

Goal: study the formation/evolution of z≥2 galaxies with high fidelity

- a cosmological zoom-in simulation of a proto galaxy group (~2×10^{13} $M_\odot$ at z=0)
- 3 comoving Mpc region incl: 1 massive galaxy & tens of lower mass galaxies



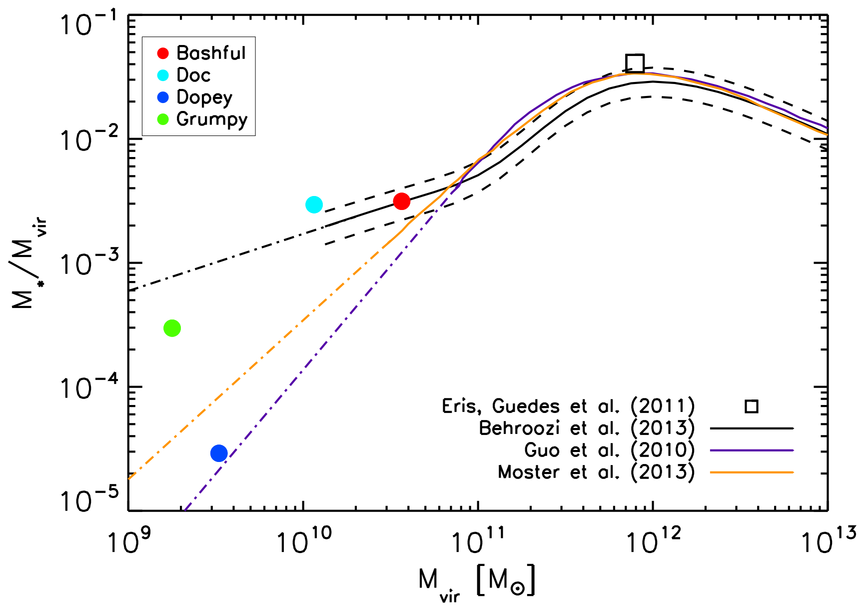
Argo or ARGO?

Acronyms Really Get On my nerves

Argo what?

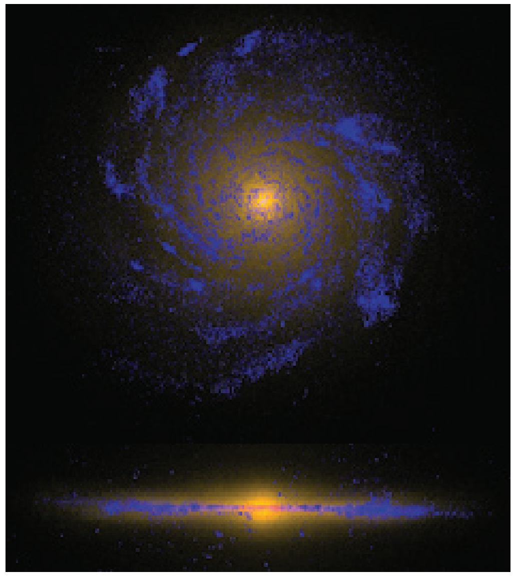
- run with the TreeSPH code Gasoline
- efficient SN feedback ("blastwave"), **no AGN** feedback

dwarfs



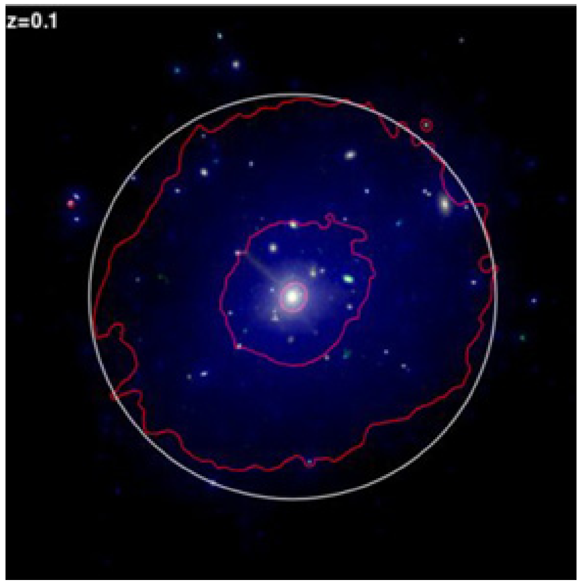
(Shen+13)

MW (Eris)



(Guedes+11)

massive early types

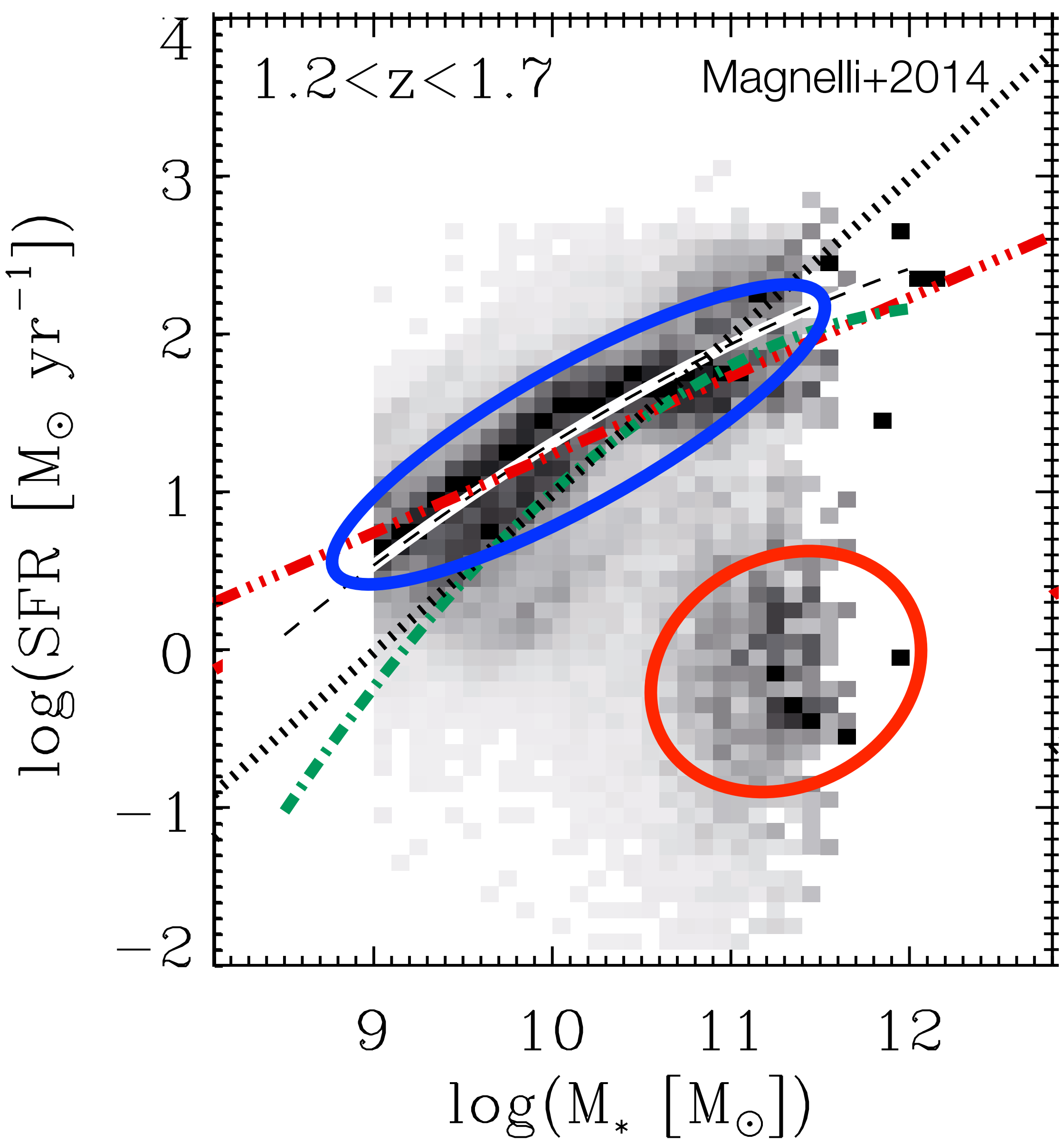


(Feldmann+10)

- the highest resolution run in Argo:

  softening ~100 pc, m_{SPH} ~10^4 $M_\odot$ ➔ same as Eris but more massive

Sequences of SF vs Quiescent Galaxies exist already at z~2



Franx+2003, Cimatti+2004, Saracoo+2004, Förster-Schreiber+2004, Daddi+2005, Labbé+2005, van Dokkum+2006, Kriek+2006, Arnouts +2007, Wuyts+2007, Reddy+2008, Franx+2008, Toft+2009, Williams +2009, McCracken+2010, Ilbert+2010, Newman+2011, Brammer +2011, Cassata+2011, Whitaker+2011, Onodera+2012, van de Sande +2012, Bezanson+2013, Whitaker+2013, Lundgren+2014, ...

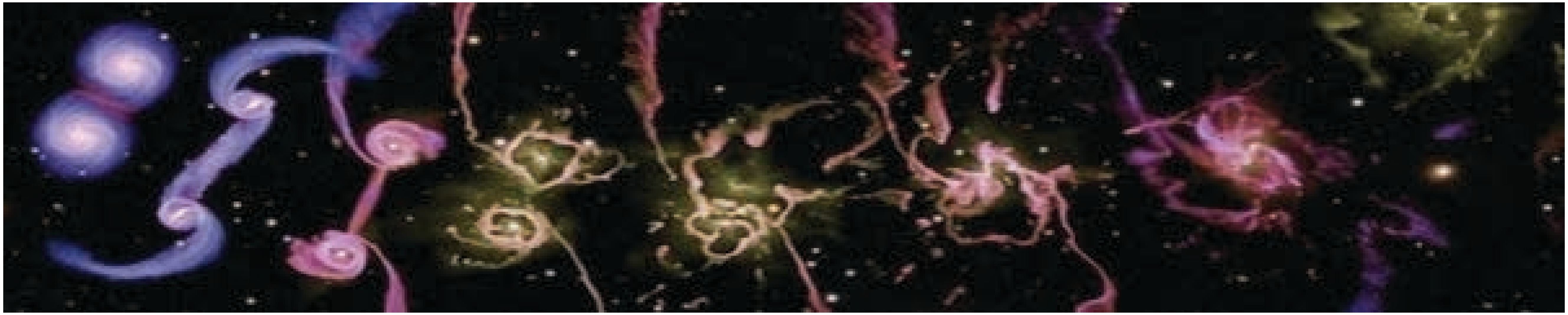
How do massive galaxies quench star formation at such early times?

see talks by e.g., Carollo, Wellons, Tacchella

What is “Quenching”?

	act of suppressing SF	maintaining low SF
low sSFR	this talk	
zero SF		

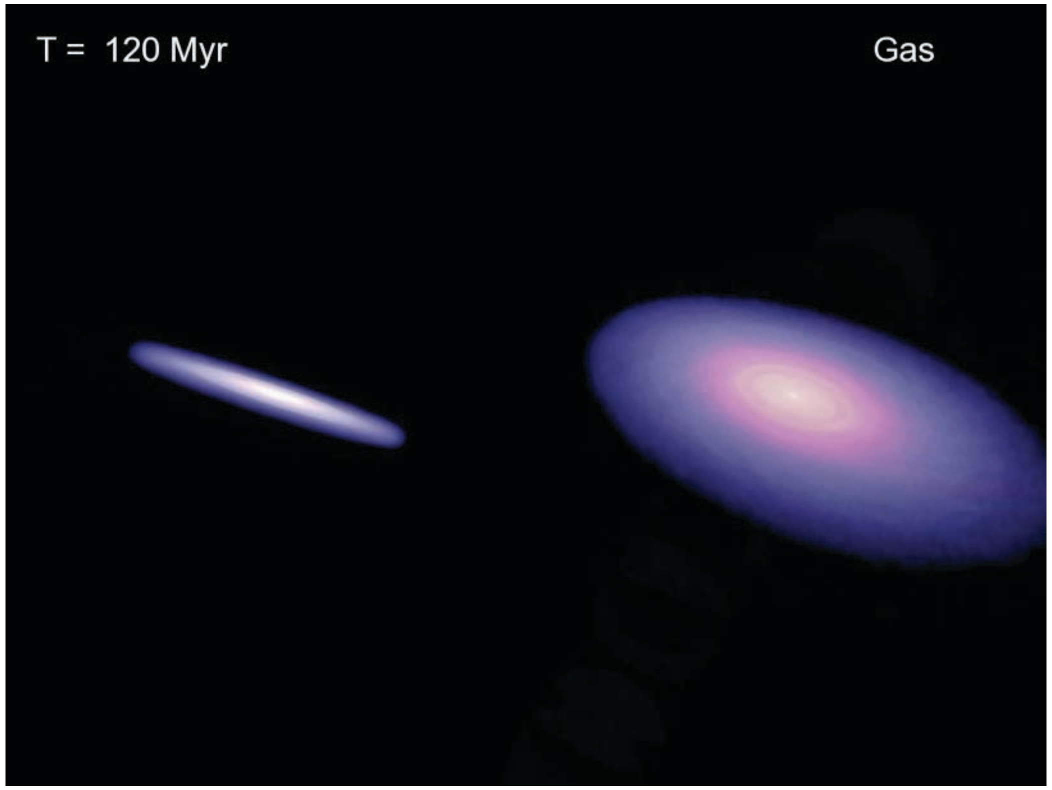
How do massive galaxies stop forming stars?



Springel+05, Hopkins+10, ...

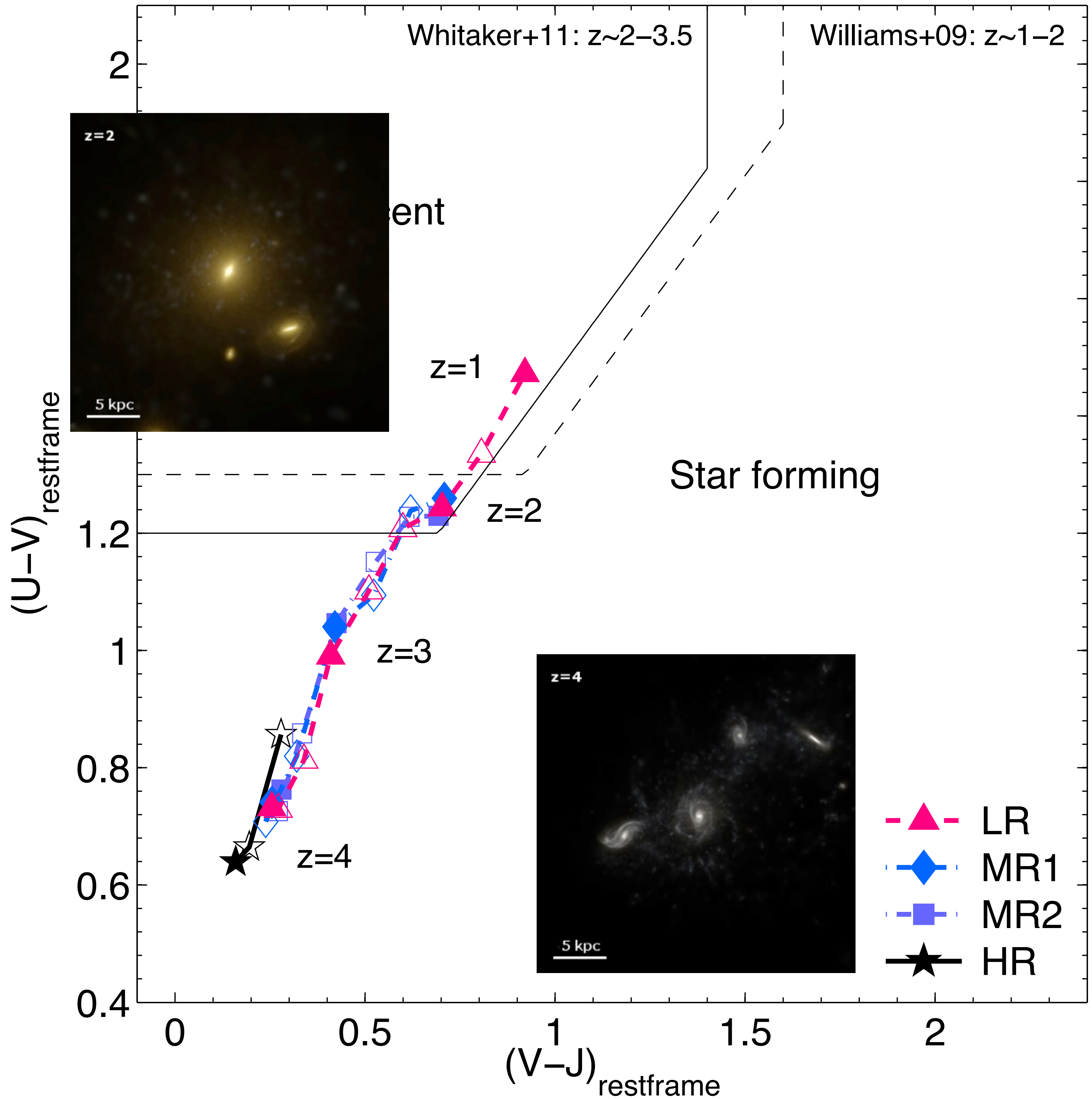
Fiducial Model (Merger + AGN feedback)

1. gas-rich, equal mass merger between disk galaxies with SMBHs
2. tidal torques drive gas to the center of the galaxies / remnant
3. active quasar phase => blow out of gas
4. generated entropy may suppress cooling
5. stellar component forms bulge/elliptical



credit V. Springel, HITS

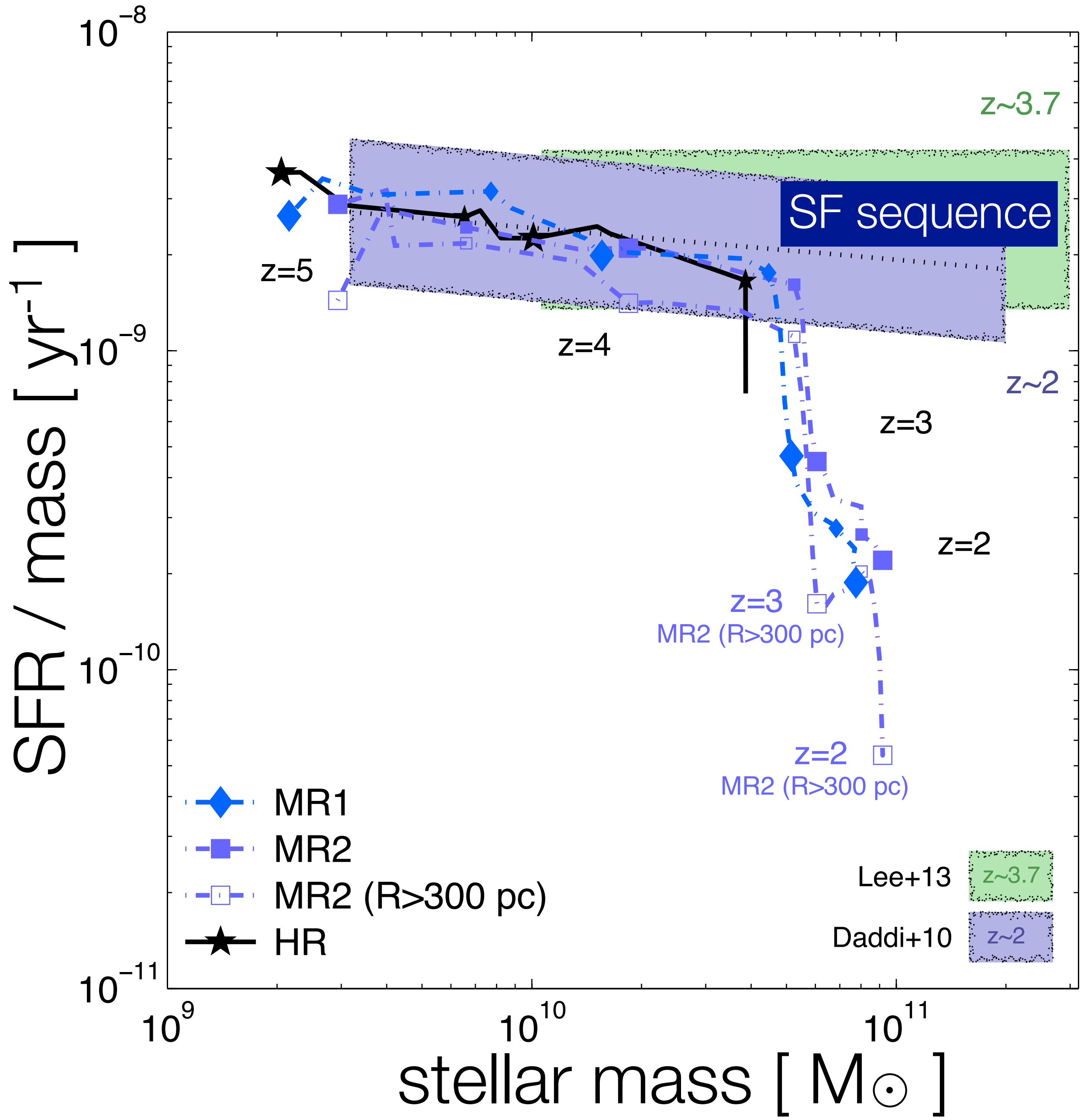
Most Massive Galaxy in Argo

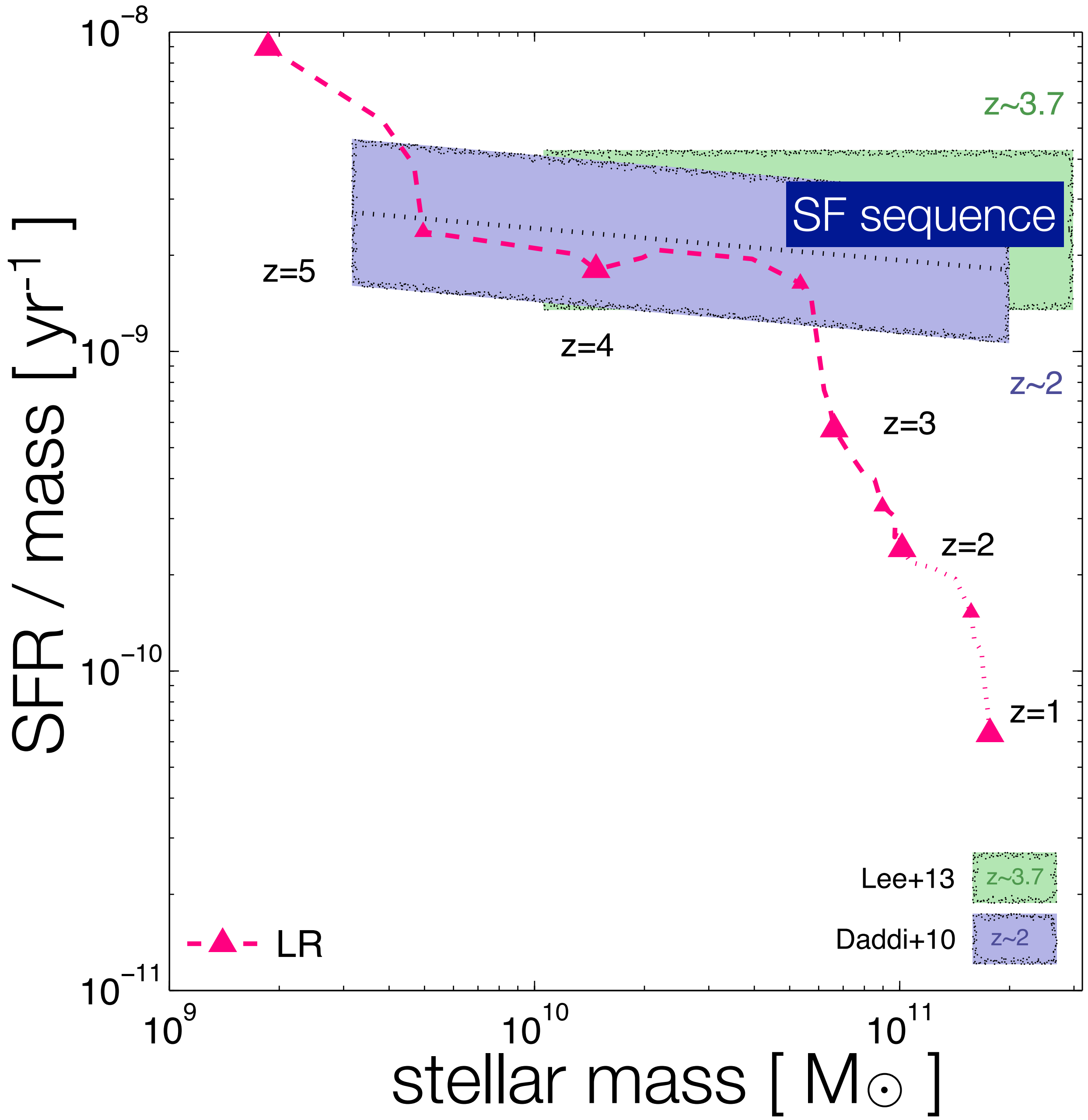


- z~4: star forming
- z~2: boundary SF/quiescent
- z~1: quiescent

Ideal for case study of how SF is suppressed

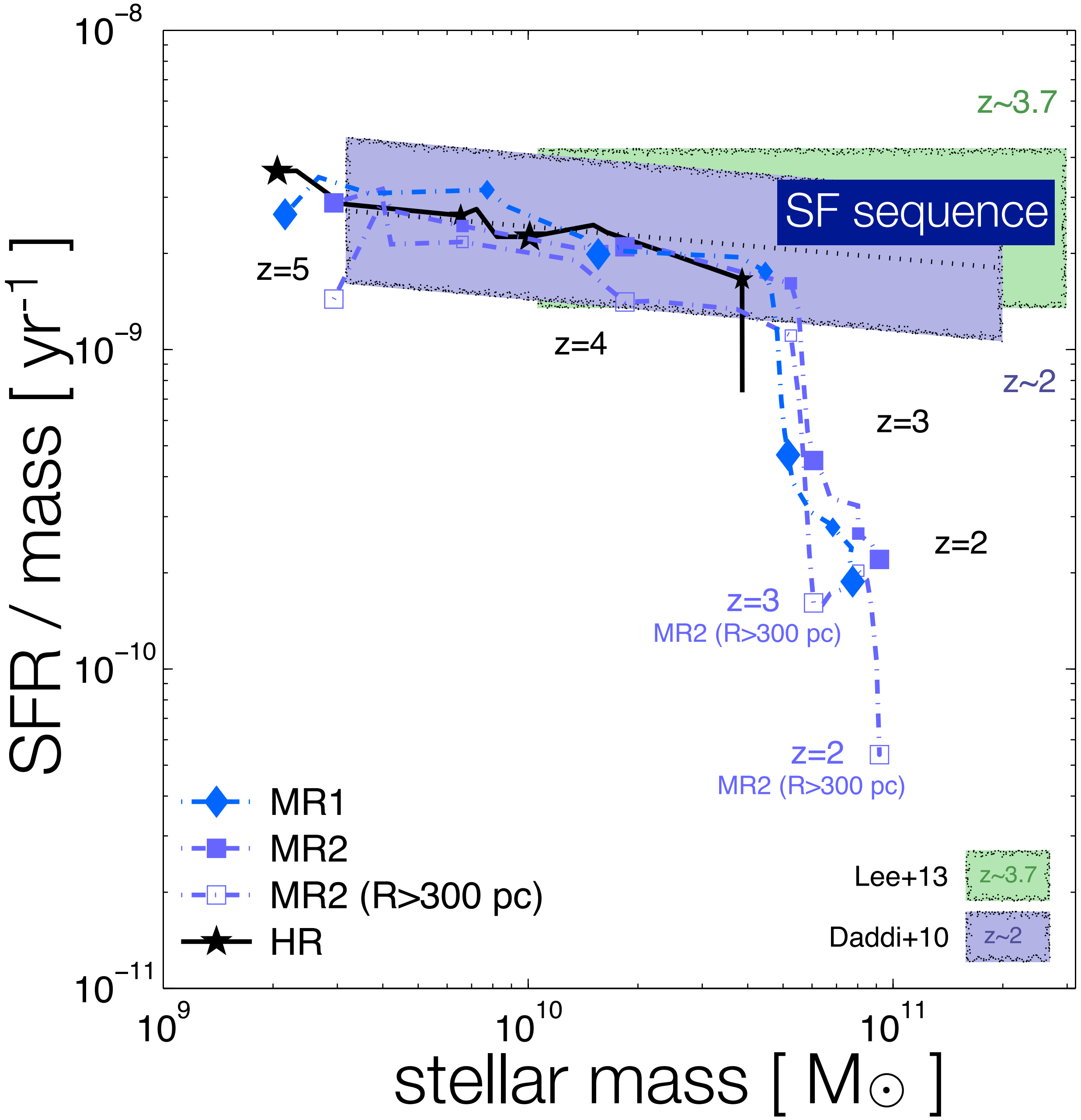
Evolution of the specific SFR

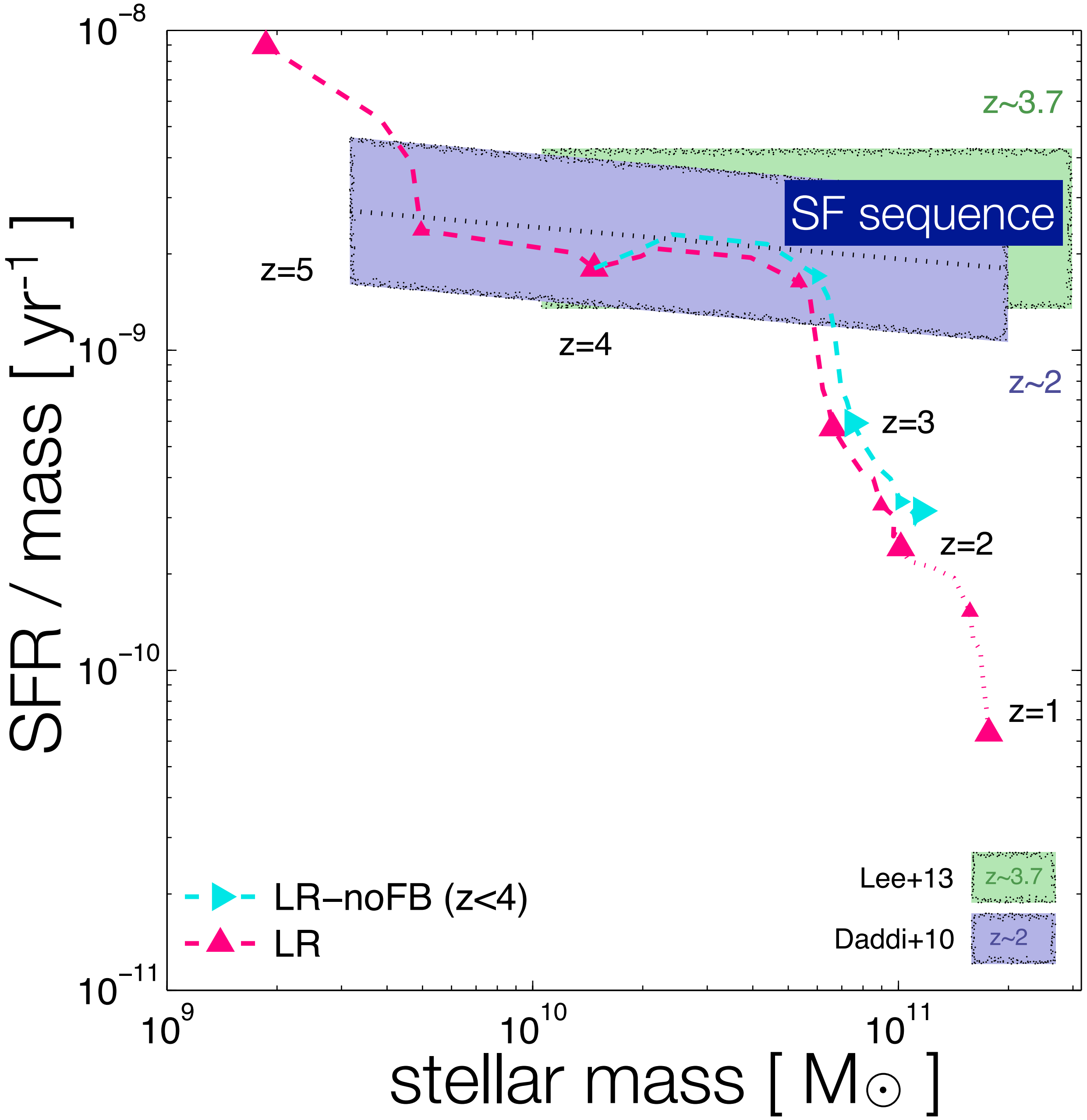




- on star formation sequence at z>3.5
- drops off the SF sequence at z~3.5

Evolution of the specific SFR

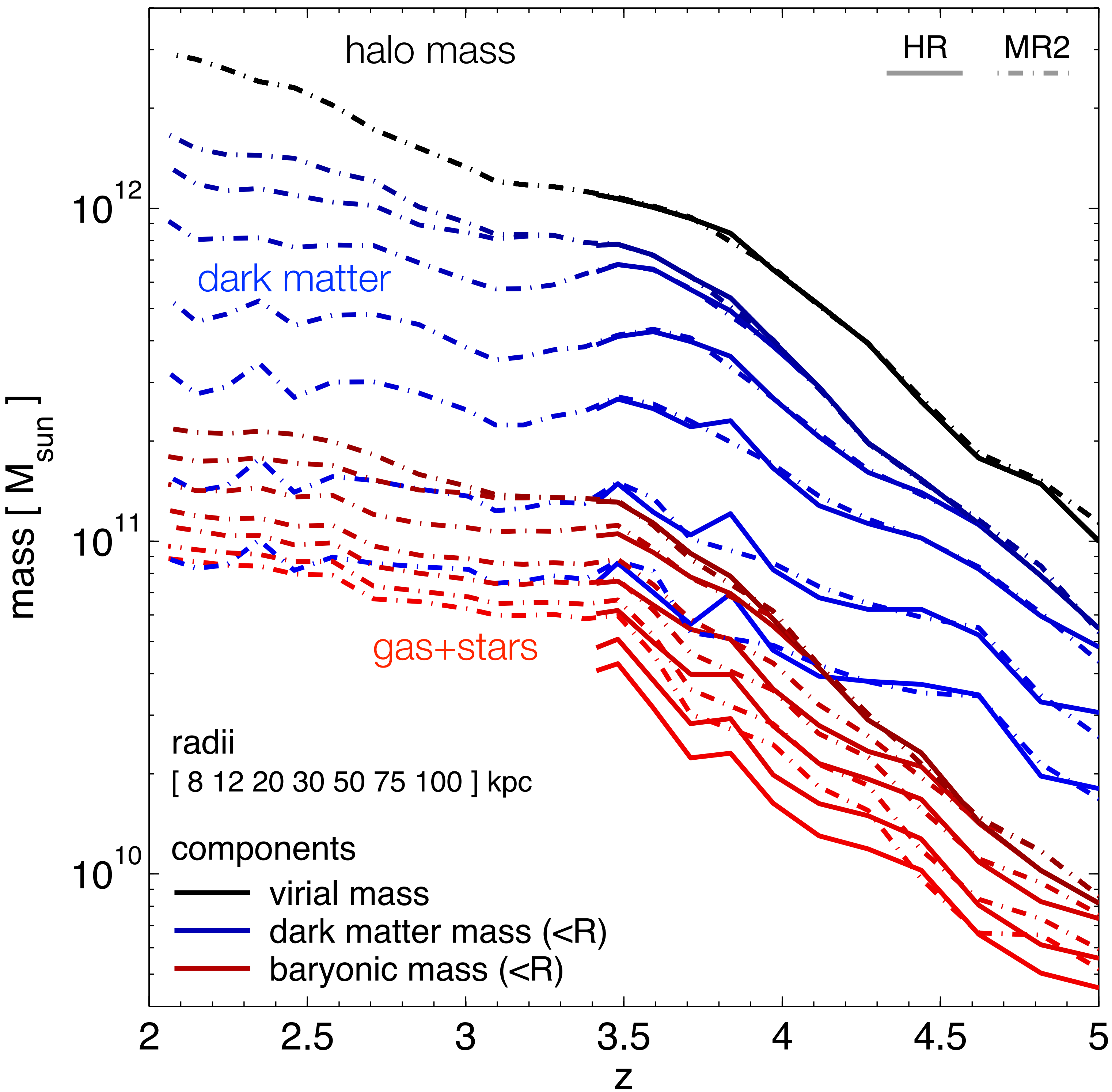




- on star formation sequence at z>3.5
- drops off the SF sequence at z~3.5

- the initial drop not caused by FB
- FB necessary to:
  - reduce SF to less than ~ few M⊙ yr^{-1}
  - suppress SF in central few 100 pc

Feldmann & Mayer 2014, arXiv:1404.3212



- gas & dark matter grow together
- at z~3.5 accretion within fixed physical radii stops

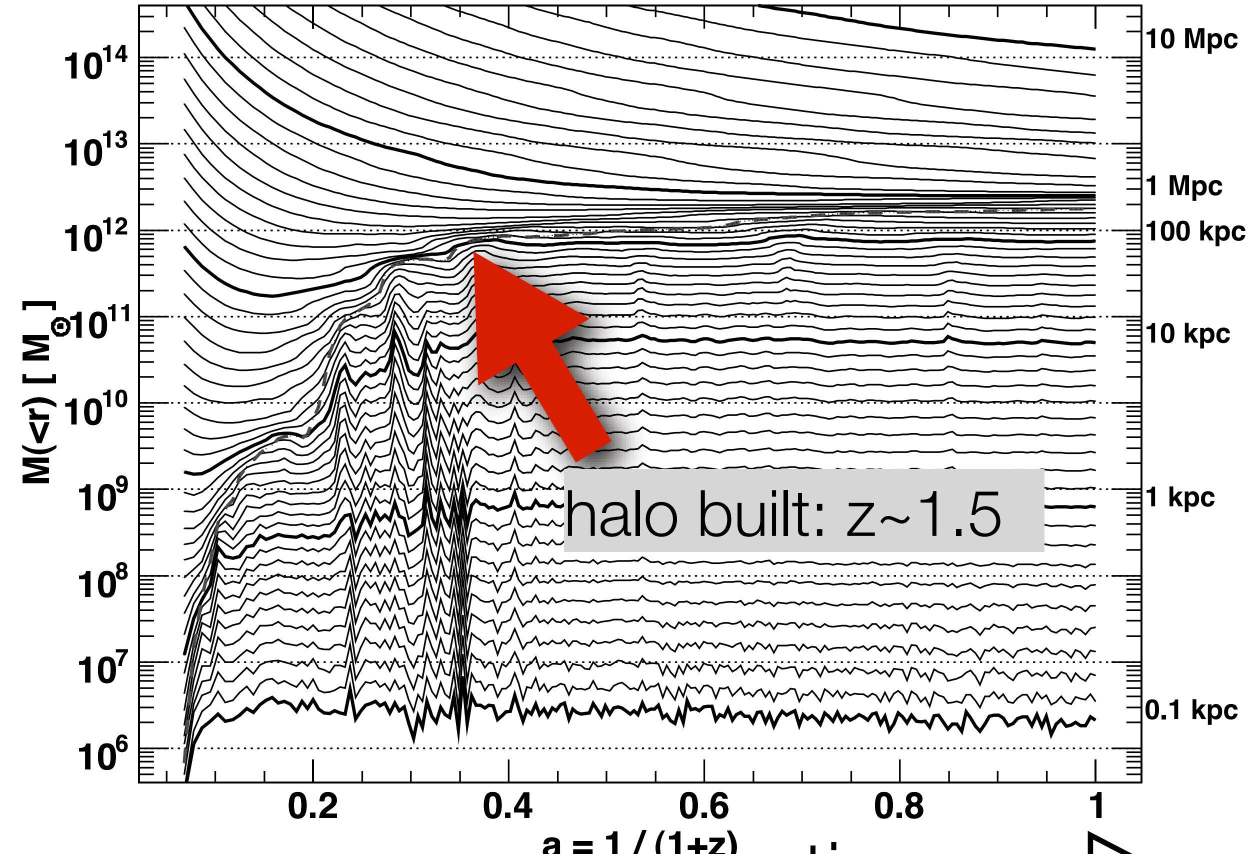
Cosmic Starvation

- accretion only at large radii
- SF runs out of gas => shuts down

N-body simulations (dark matter only)

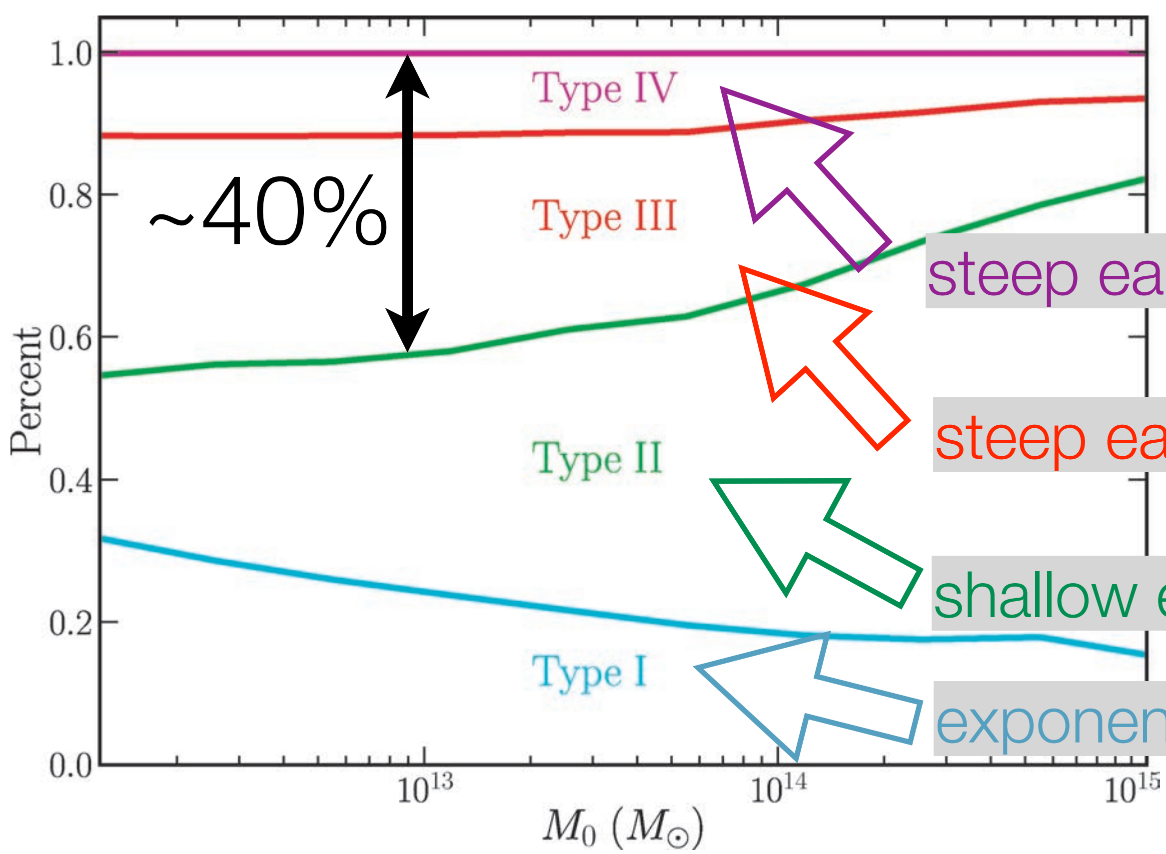
- large fraction of DM halos shows initial growth followed by slow-down
- acknowledged in some contexts (e.g., halo concentration), e.g. Bullock+2001
- yet: somehow role in galaxy formation under-appreciated

Diemand, Kuhlen, Madau 2007



time ⇨

McBride, Fakhouri, Ma 2009



steep early / no late growth

steep early / shallow late growth

shallow early / steep late growth

exponential growth

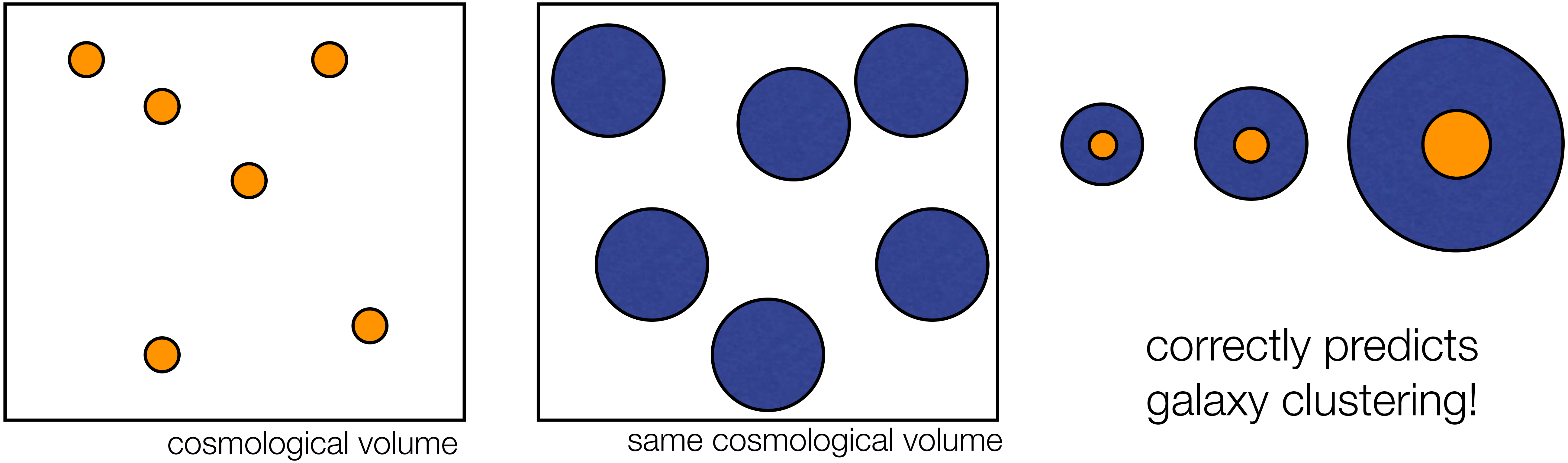
~40% of halos show steep early growth and shallow/no late growth

Abundance matching

galaxies (observation)

dark matter halos (sim)

match number densities

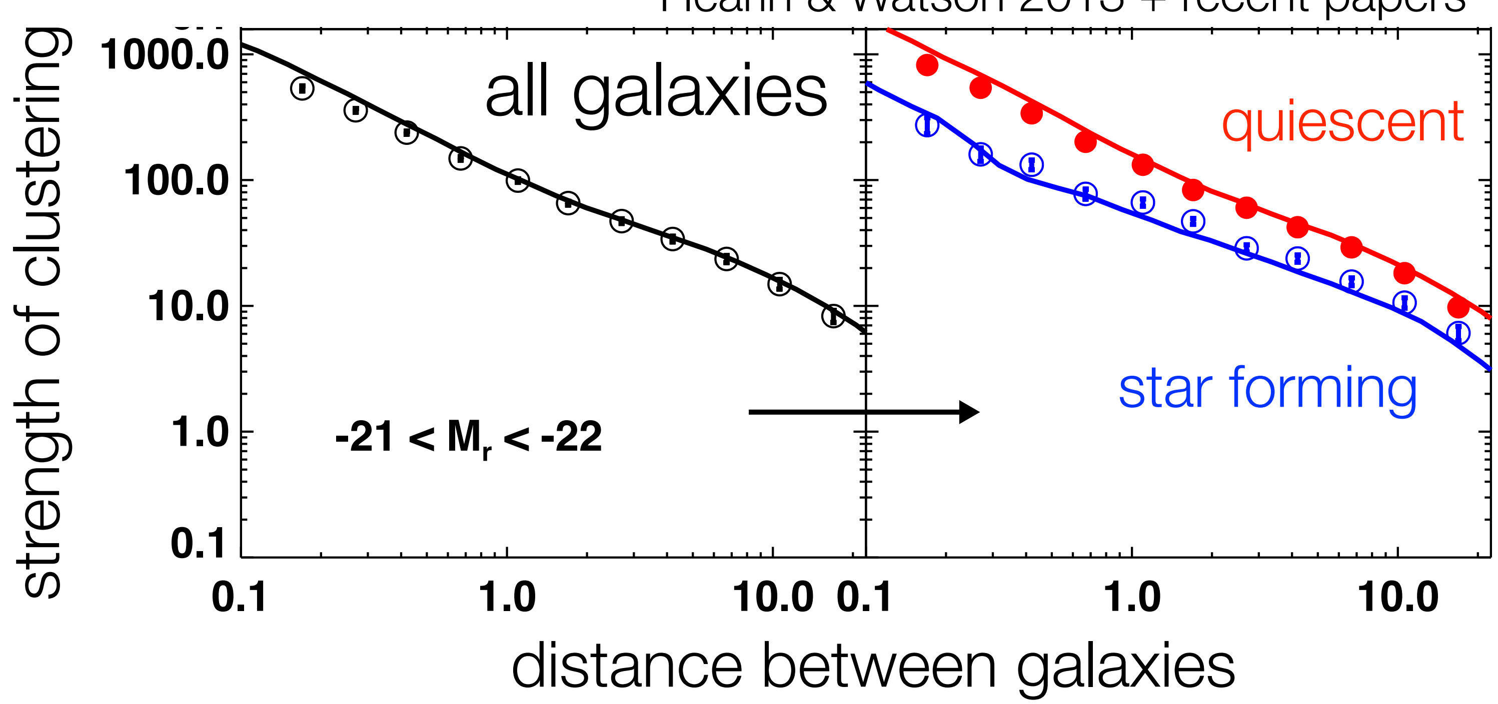


correctly predicts galaxy clustering!

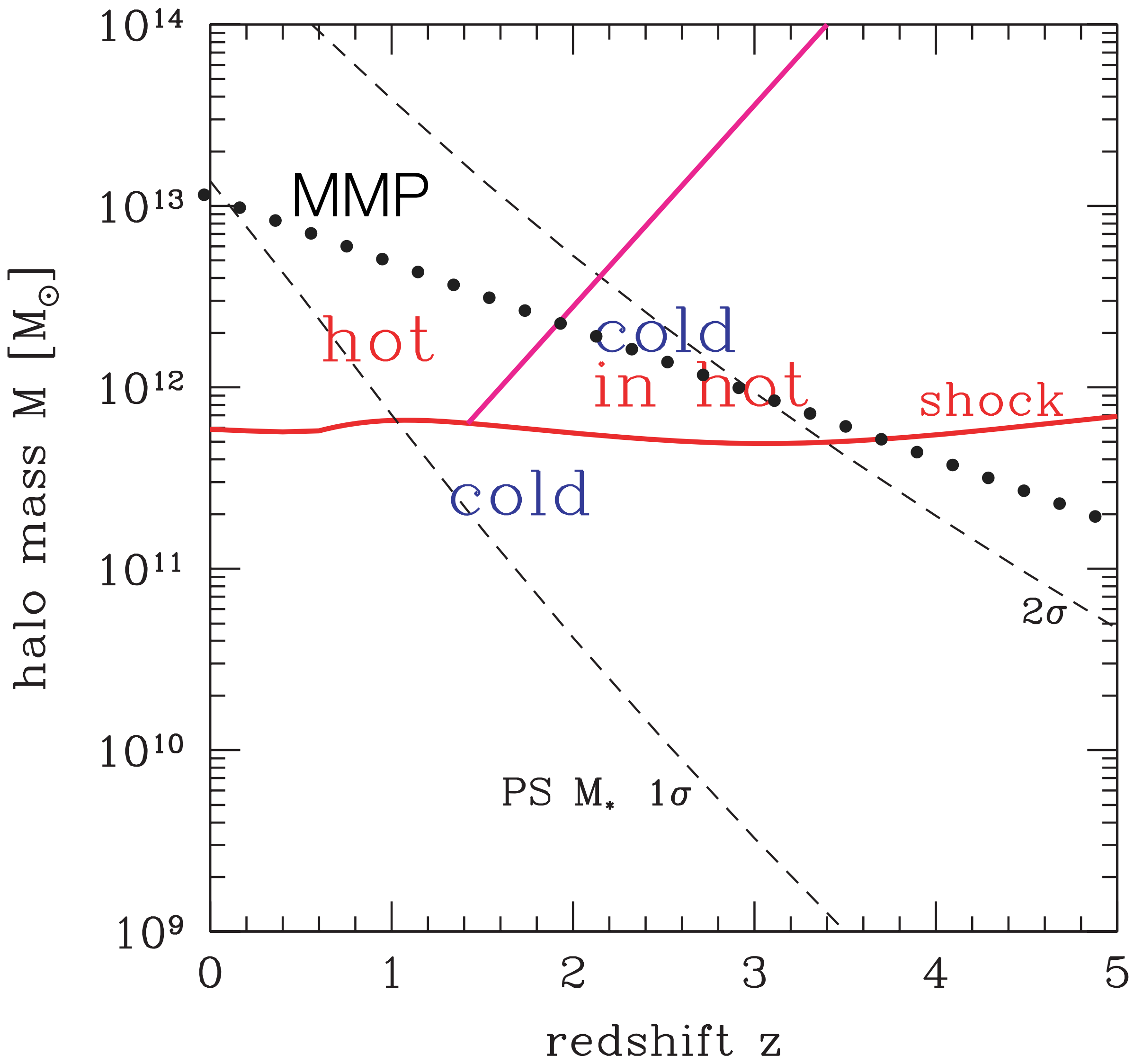
Conditional abundance matching

- **Assumption**: At fixed M* the SF shut-off time set by halo collapse time.
- correctly predicts how star forming (blue) and quiescent (red) galaxies cluster at z=0.
- may explain galactic conformity (see talk by Lilly)

Hearin & Watson 2013 + recent papers



Difference to the halo quenching picture



Birnboim & Dekel 2003, Keres+2005, Dekel & Birnboim 2006, Cattaneo+2006, Ocvirk+2008, ...

Halo Quenching

- Gas accretion onto galaxy stalls once halo above mass threshold
- origin of bimodality at $z<1$?
- working surface for radio mode AGN: suppresses hot gas cooling
- at $z>2$: cold streams

Cosmic Starvation

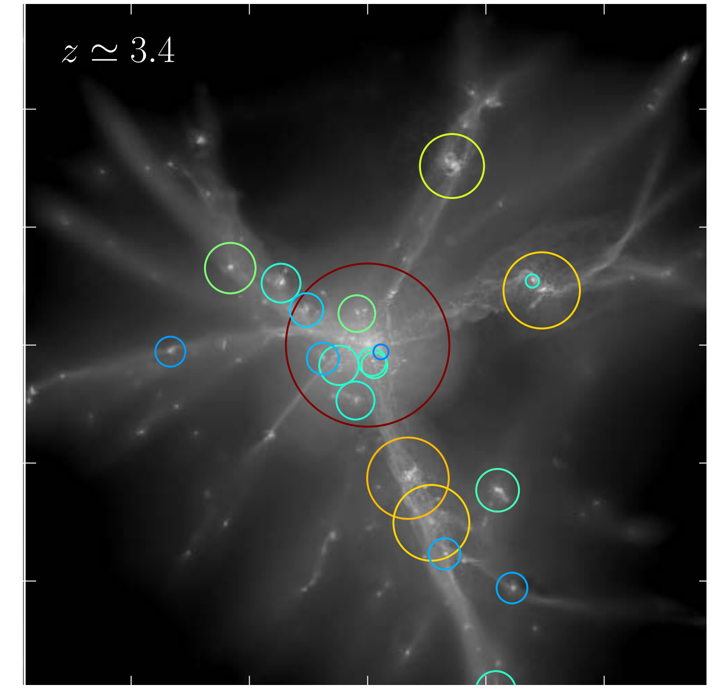
- not a hydrodynamical effect; tied to DM
- gas accretion onto the halo is reduced, not just onto the galaxy
- related to specific accretion rate, not halo mass
- does not shut down SF completely

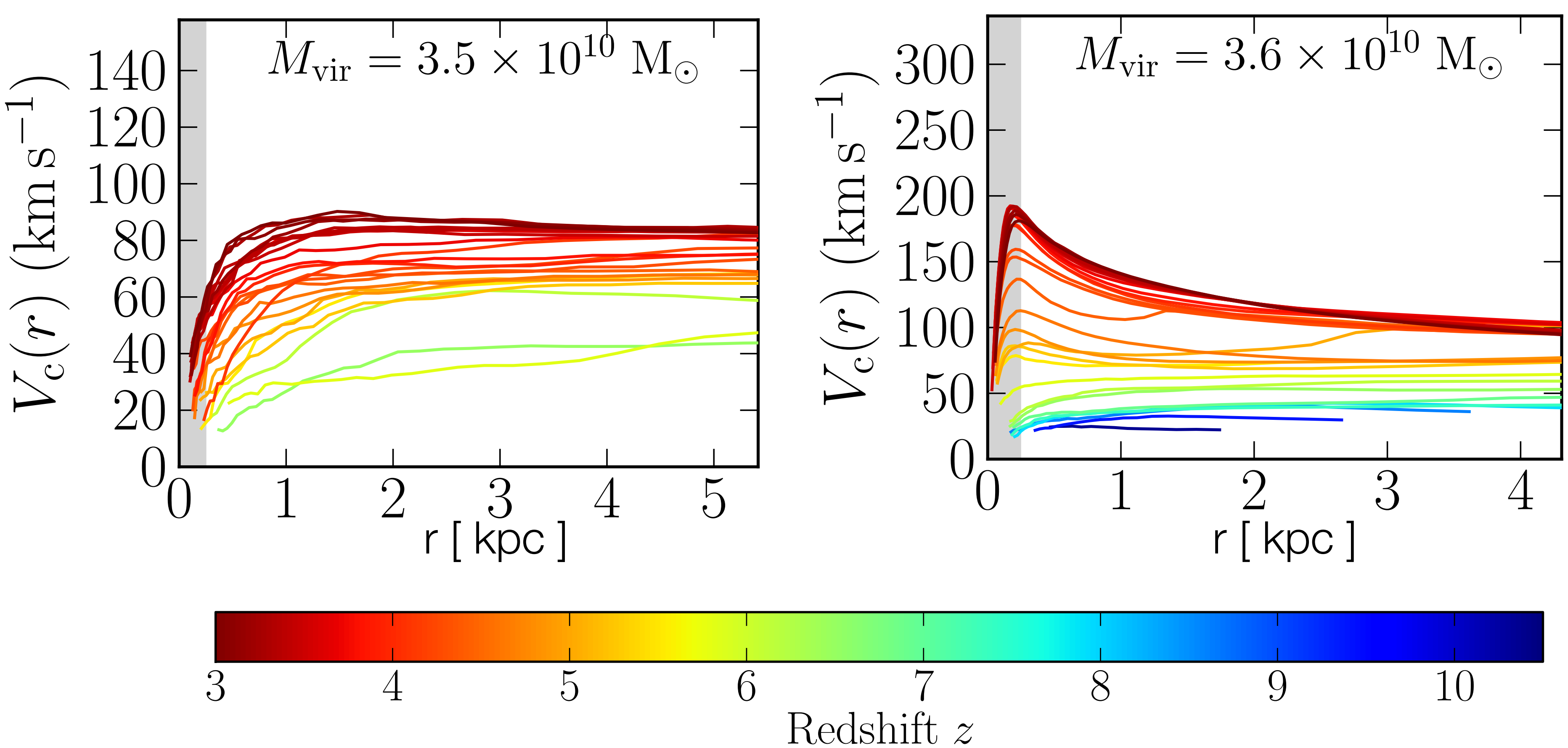
Probably work in combination!

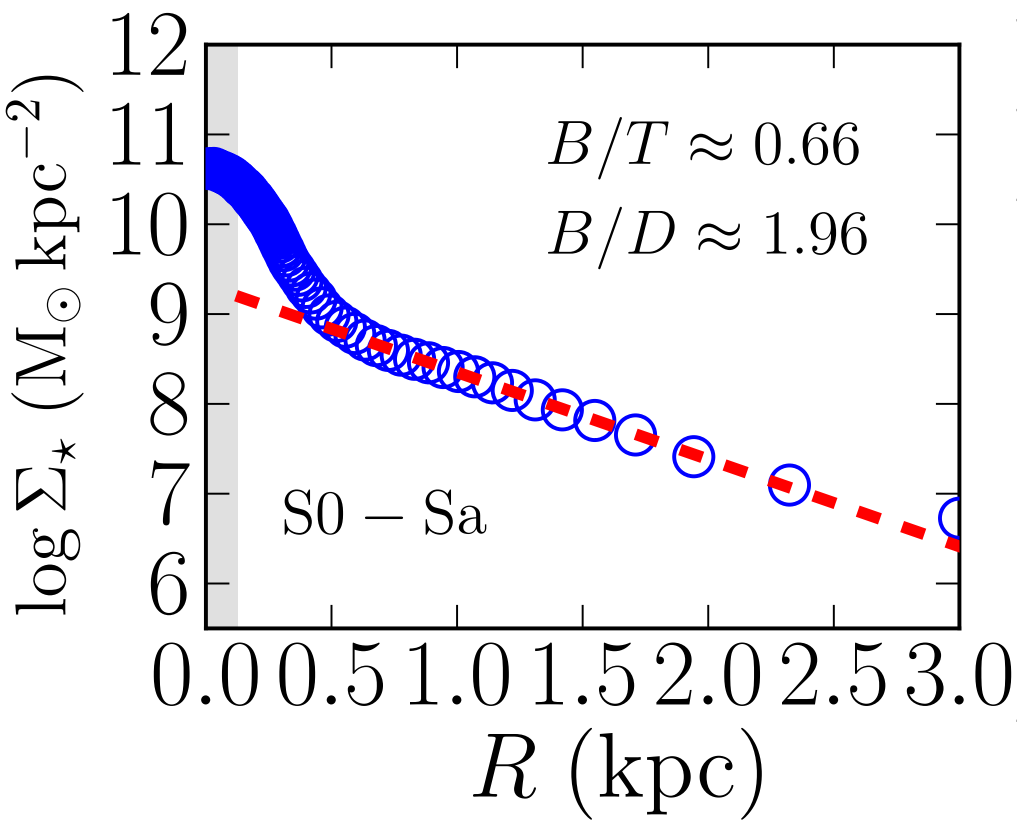
- 22 galaxies at z=3.4 with >10000 star particles

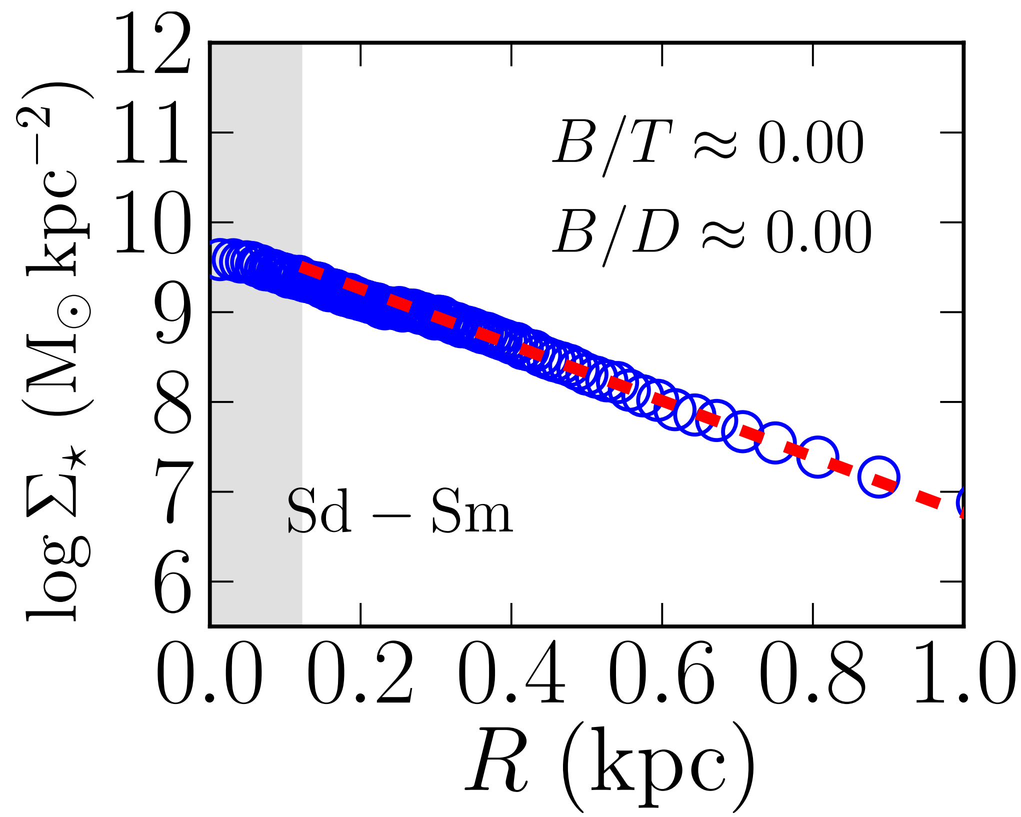
- peaked vs flat circular velocity profiles
  in halos of the same mass(!)

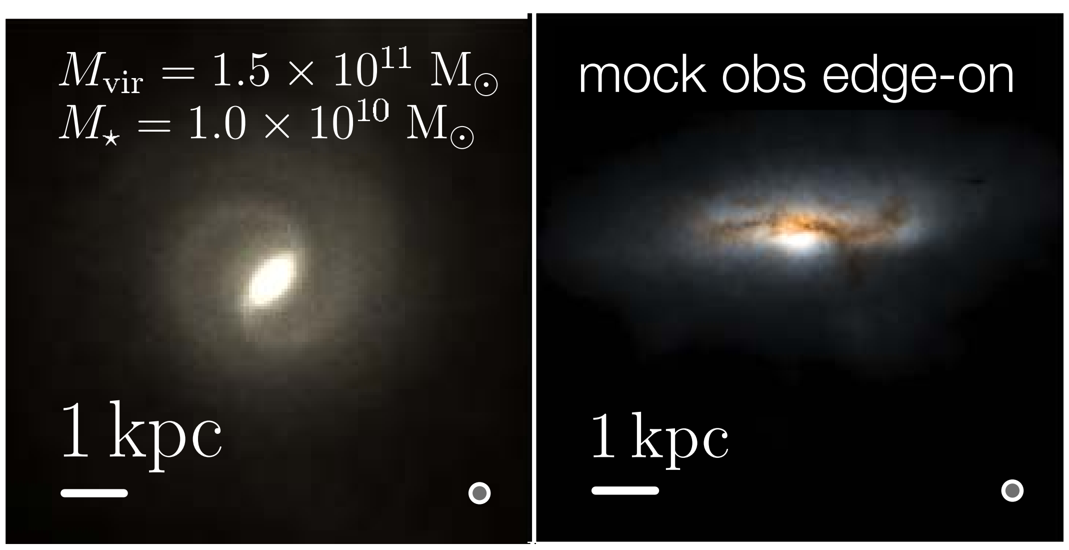
- "Peakedness" = $\frac{v_c(r_{\rm max})}{v_c(r_{\rm h})}$ ← radius where v_c peaks; ← radius containing half of M_{vir}

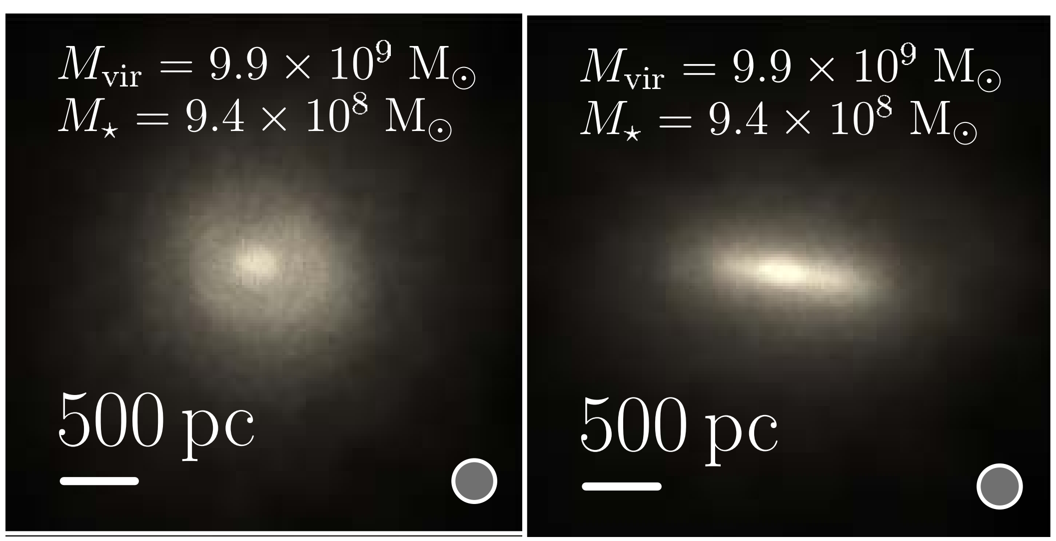






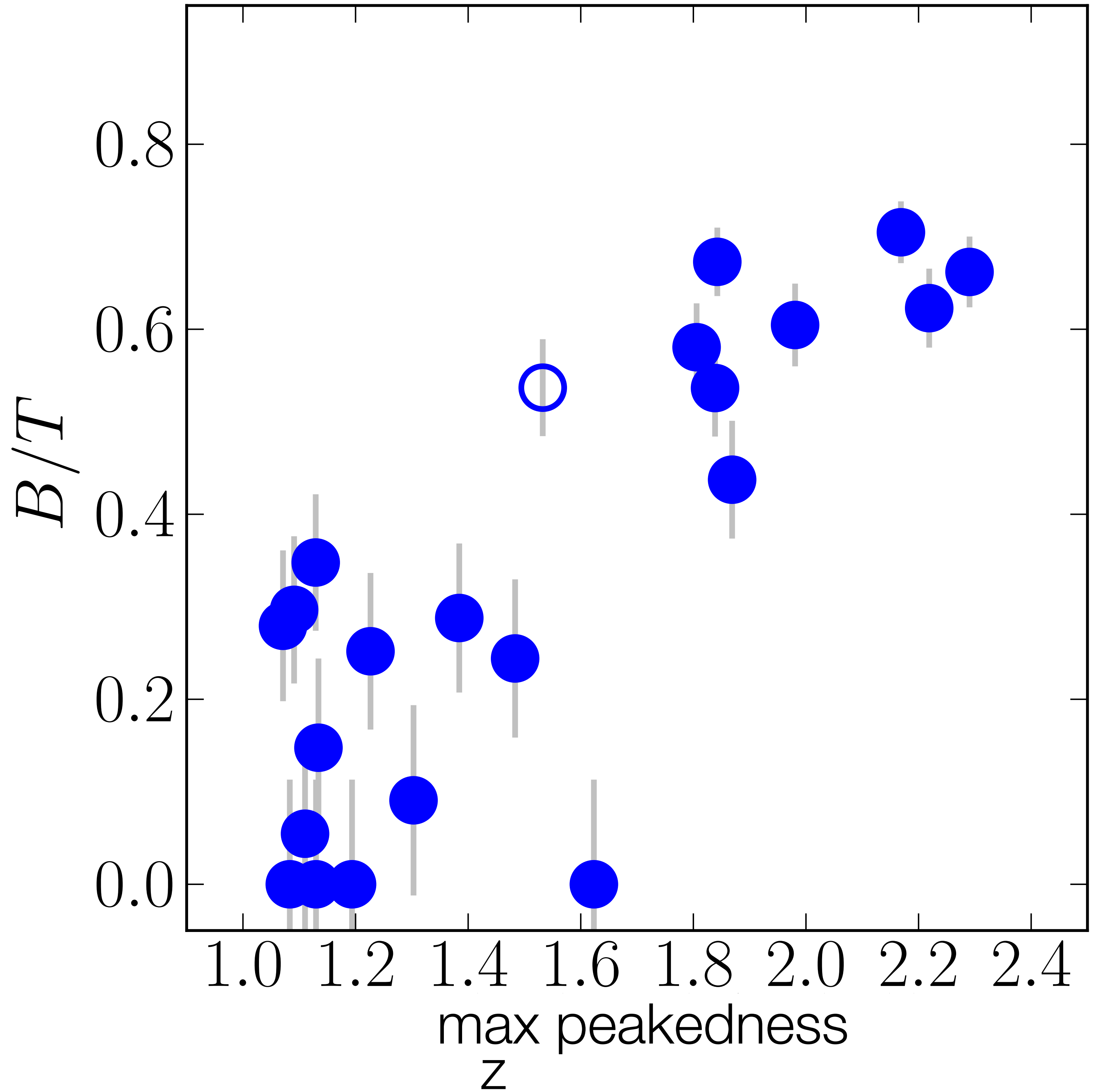






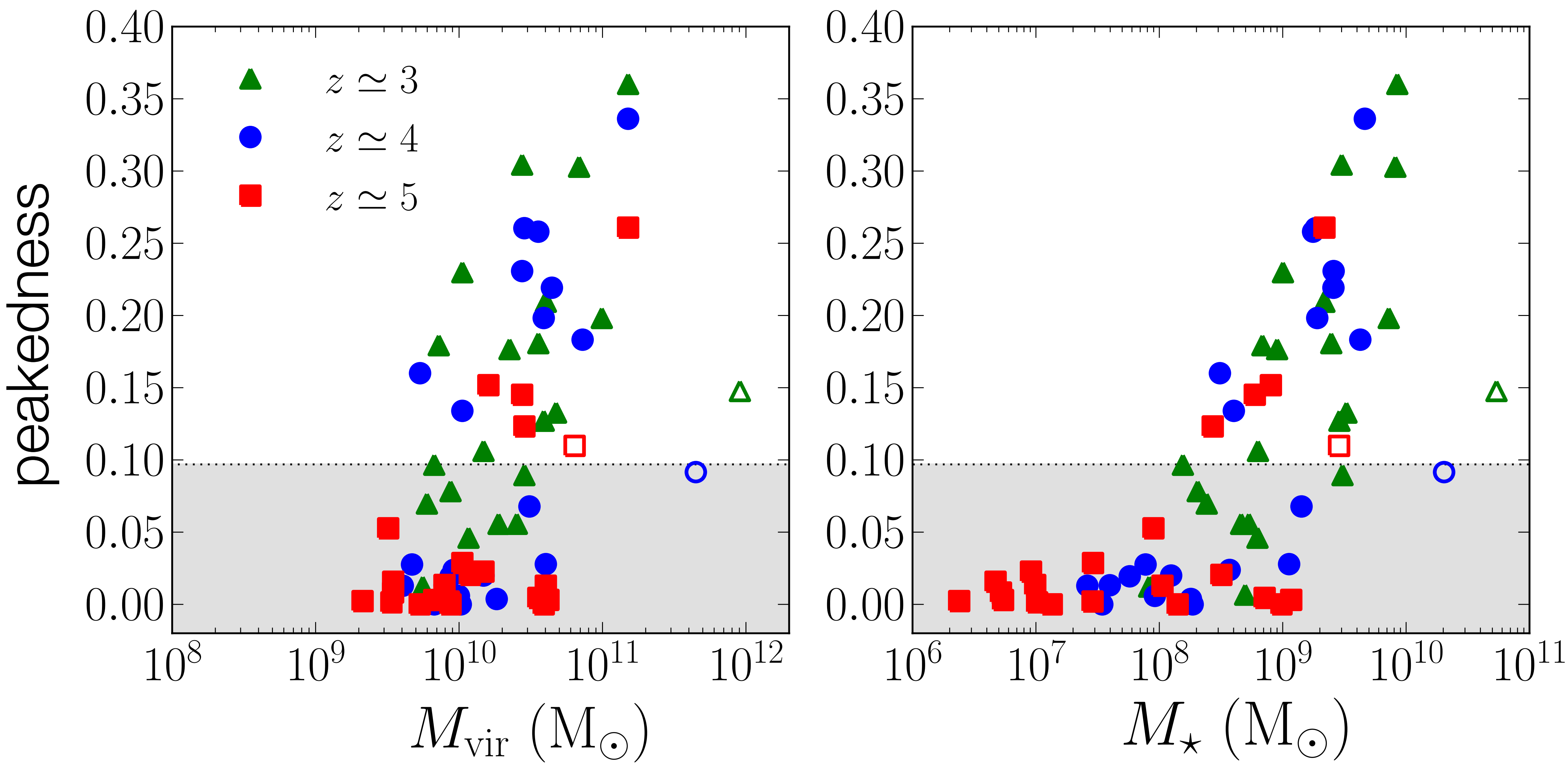
here B/T: includes class. bulge, pseudo-bulge, bar, ...

B/T closely correlates with peakedness of v_c



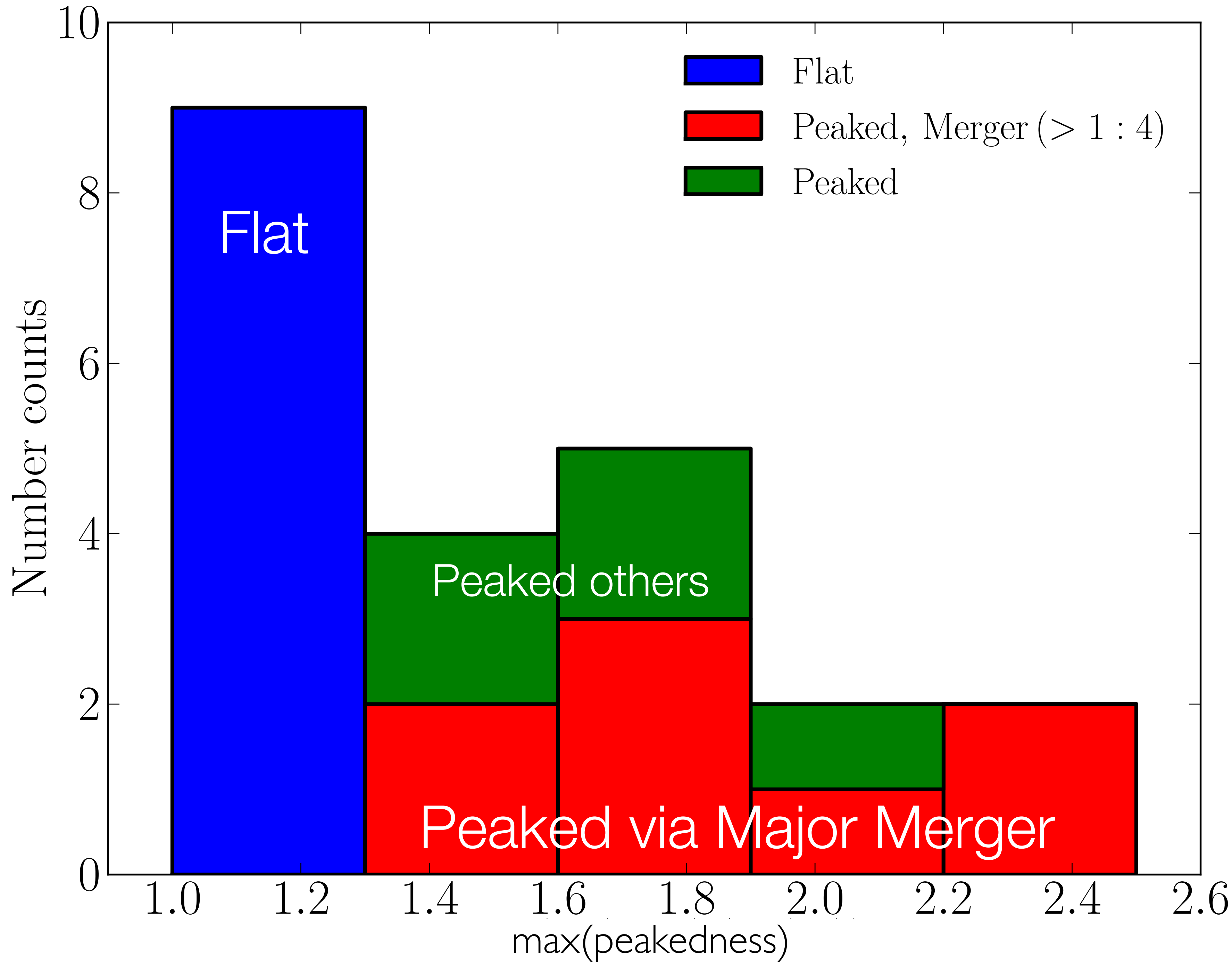
➔ peakedness is proxy for "morphology"

peakedness vs mass



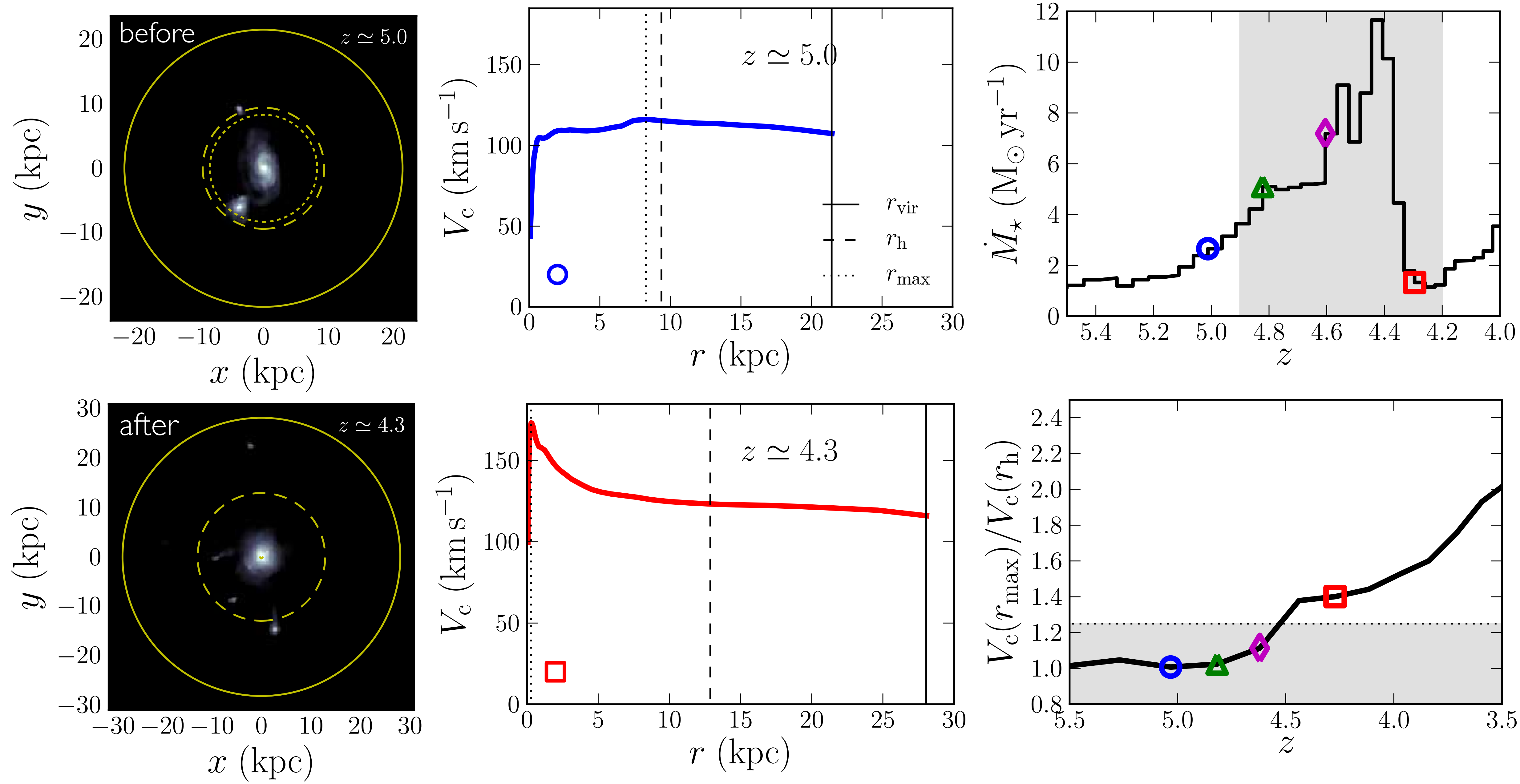
peakedness correlates poorly with M_{vir}, but well with M*

Origin of the peaked velocity curves



- 9 flat (peakedness < 1.25) vs 13 peaked (peakedness ≥ 1.25)
- 8 peaked via >1:4 merger, 5 for other reasons

Origin of the peaked circular velocity curves



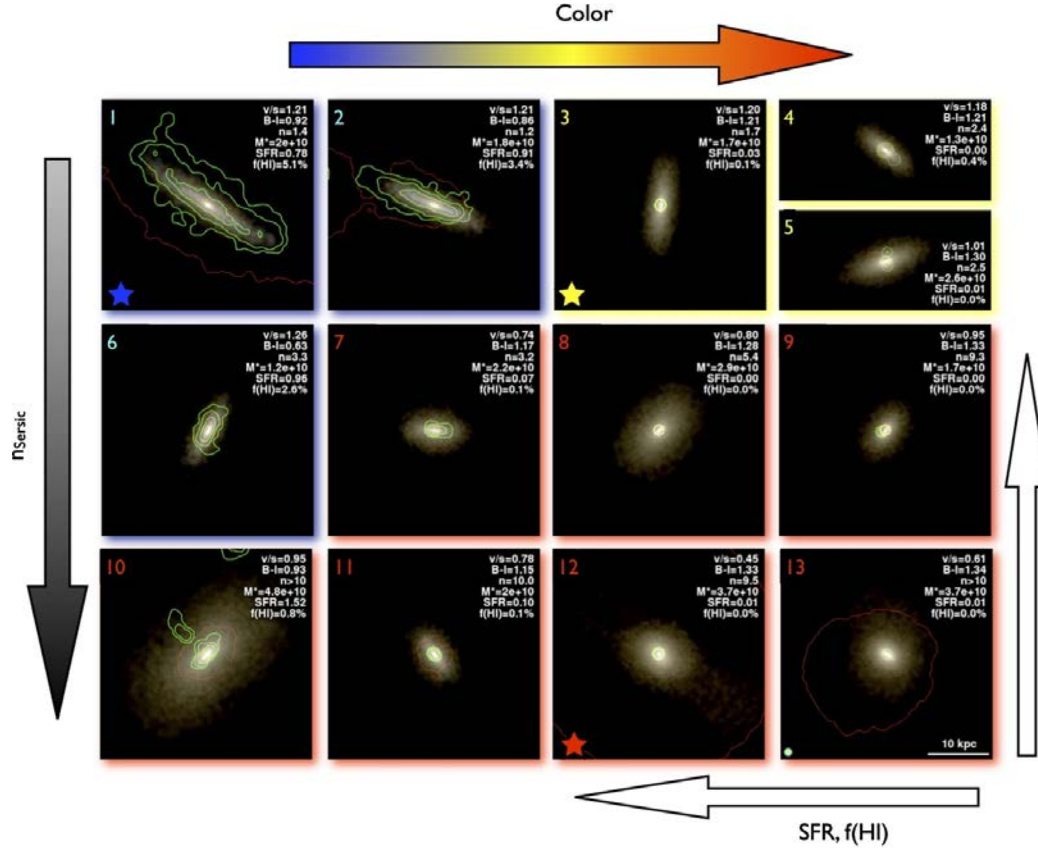
Jump in peakedness during merger & associated starburst

Role of Major Mergers

Major Mergers at z<1

- destroy disks, formation of ellipticals
- size growth
- binary merger simulations
  e.g. Toomre & Toomre 1972, Barnes 1988, Naab & Burkert 2003, Hopkins et al. 2013
- cosmological simulations
  e.g. Naab+09, Feldmann+10, 11, Oser+10, 12, Navarro-Gonzales et al. 2014

Hubble sequence in a cosmological simulation



Feldmann, Carollo, & Mayer 2011

Major Mergers at z>2

- growth of the bulge
- compaction (?), see talks by Barro, Zolotov, Wellons
- difference is the much larger gas fraction (here~10%-80%)
- major mergers of gas-rich galaxies re-build disk (Robertson+06, Hopkins+09)

Summary

Quenching of massive z>2 galaxies:

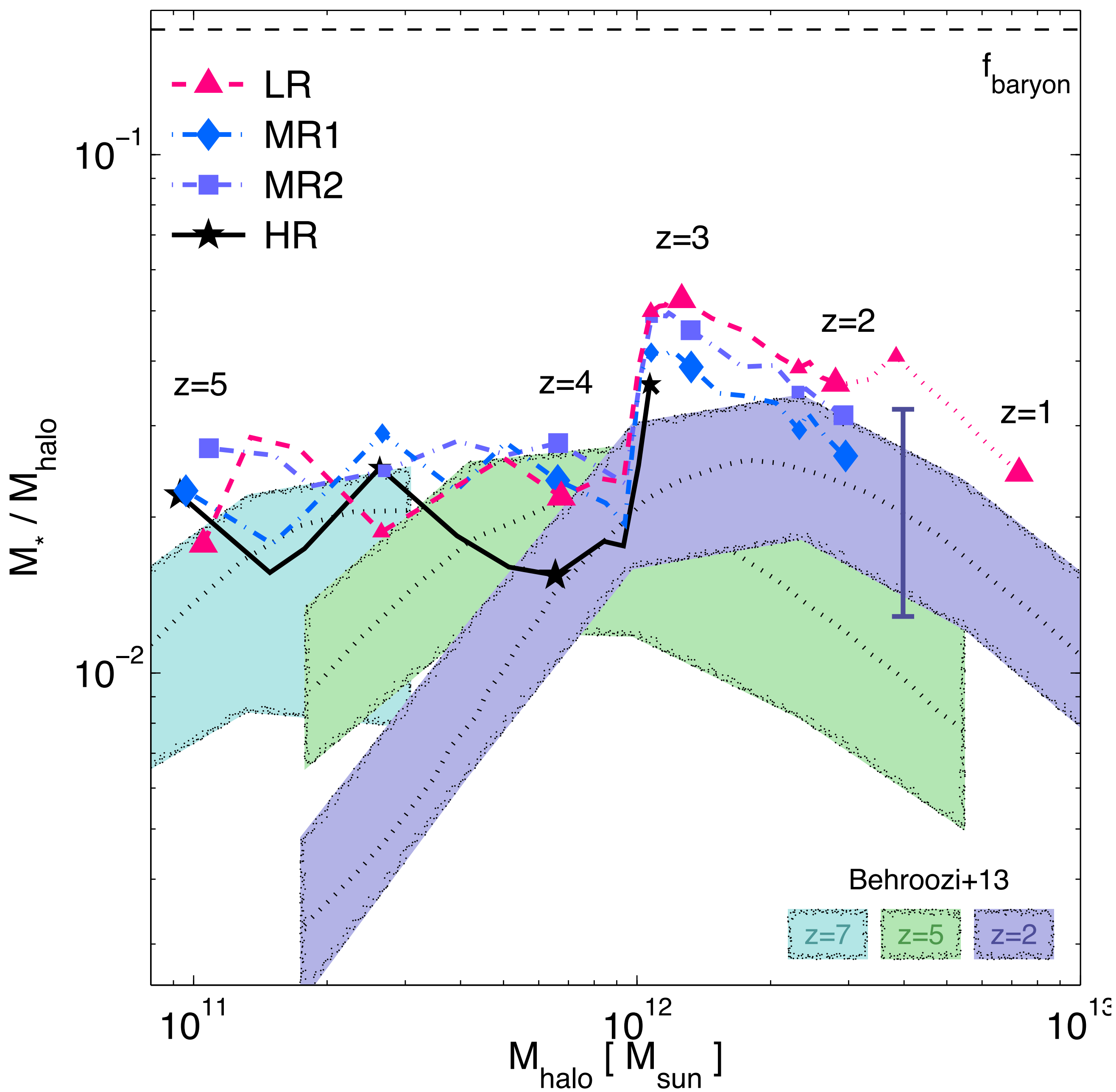
- alternative to the standard (major merger + gas blow out) paradigm
  - cosmic starvation reduces gas accretion, SF reduced to below MS
  - to completely shut down SF require add. physics, e.g., radio mode AGN + hot halo (halo quenching)
  - arises naturally from huge variability in halo accretion histories
  - add. circumstantial evidence: age matching

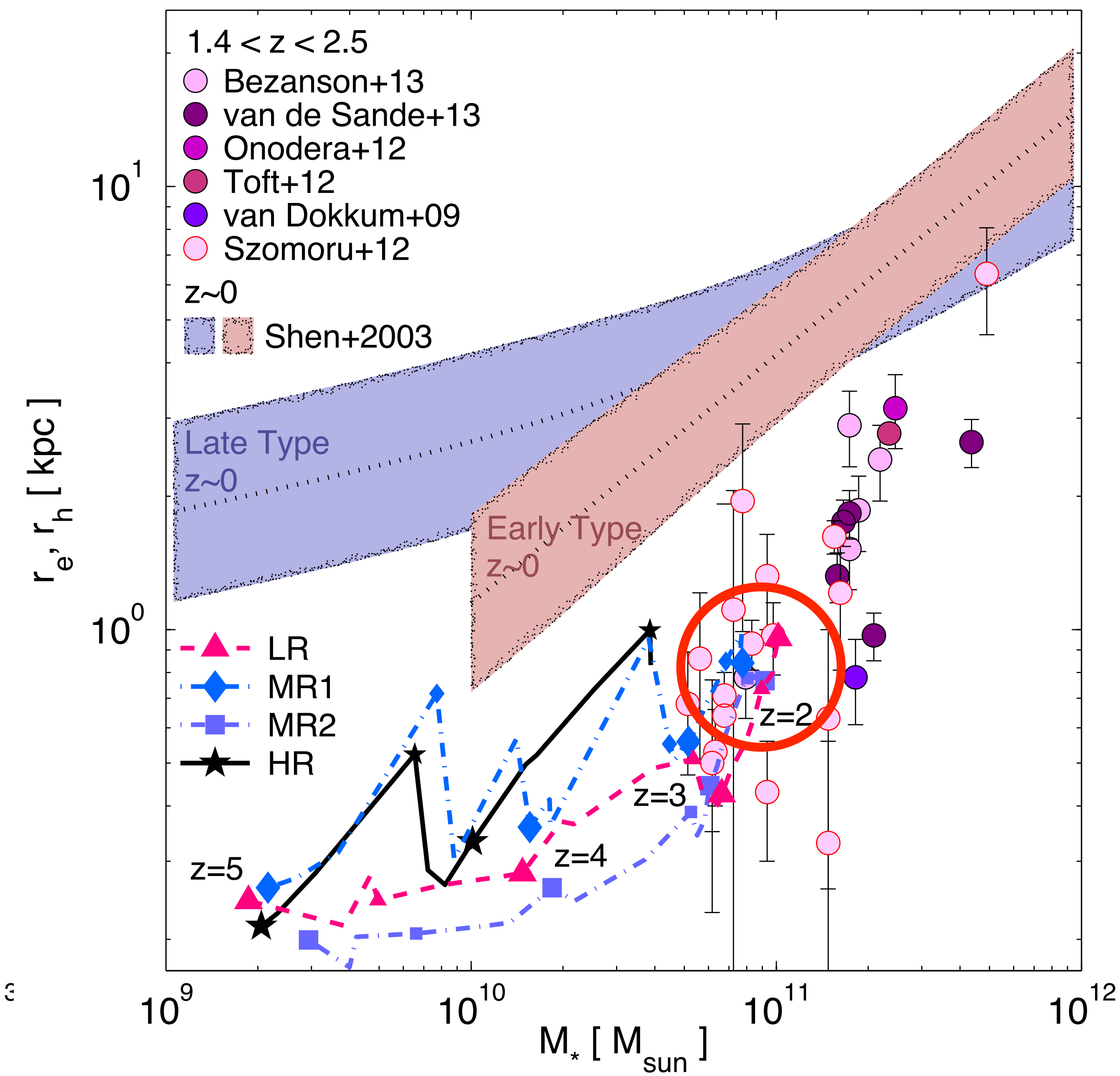
Morphology of low mass z>2 galaxies:

- morphology correlates well with M^*, not M_{vir}
- large B/T ratio primarily acquired in major mergers
- secular processes, minor mergers, flybys secondary importance

Thank you

Add-on: Global galaxy properties agree with observations





- stellar mass to virial mass ratio in agreement with abundance matching at z≤4
- stellar fraction ~ constant, slight increase (x2) during mergers
- size ~ 1 kpc at z~2; consistent with sizes of massive, quiescent galaxies