Star Formation in Massive Galaxies at the Cosmic Noon

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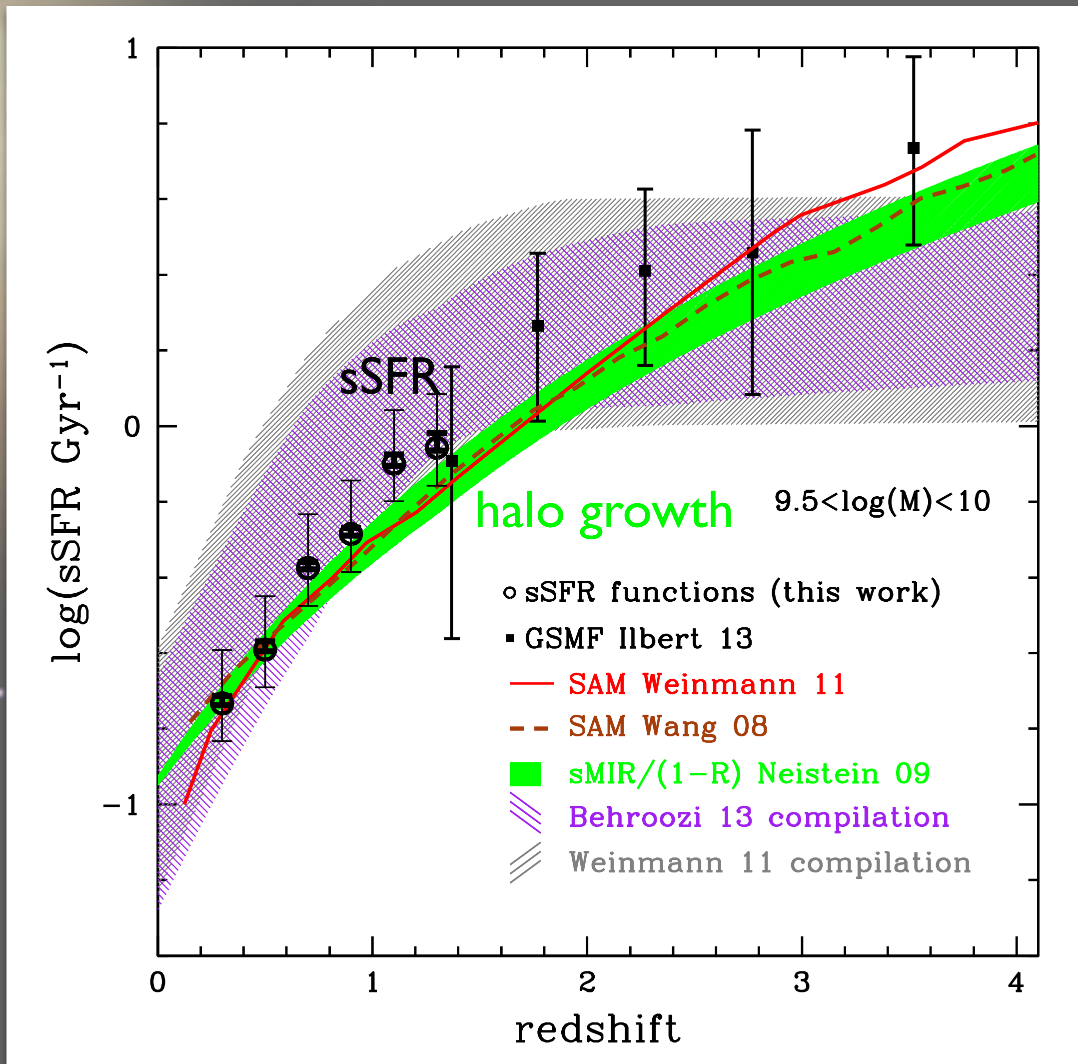
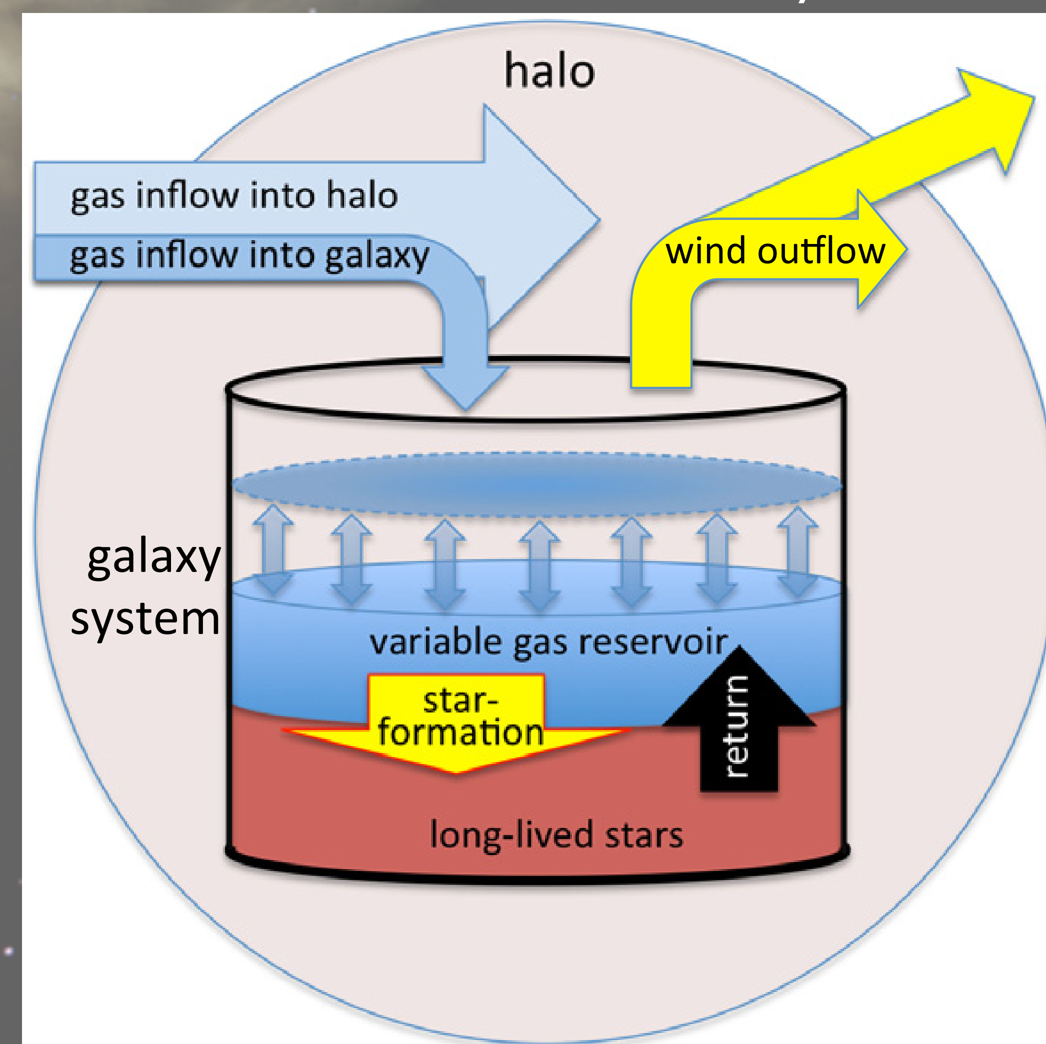
SF connected to halo growth

Ilbert et al. 2015



- SF galaxies: SFR follows halo growth to 0[th] order
- natural prediction in SAMs
- similar results found in cosmo sims:
  - e.g., in Illustris (Sparre+15), EAGLE (Guo+16)
- can explain change of sSFR with time & scatter of M_{star} - sSFR relation (e.g. Lilly et al. 2013, Rodríguez-Puebla et al 2016)

Lilly et al. 2013



- quasi-equilibrium: SFR changes until SFR ~ gas inflow rate (e.g., Bouche et al. 2010, Davé et al. 2012, Lilly et al.13, Feldmann et al. 2013/15, Peng et al. 2014, Dekel et al. 2014, Forbes et al. 2014, Mitra et al. 2015, …)
- gas inflow ~ DM growth (at least for the halo) (e.g., Faucher-Giguere et al. 2011, van de Voort et al. 2011)

Take away

- Halo mass sets the stage:
  - sets stellar masses, average growth rates, average SFR, formation of virial shocks etc.

- but halo growth rate is crucial, too:
  - influences SF / quiescent nature of galaxies at z~2
  - slow halo growth is necessary requirement for quiescence ("cosmological starvation")
  - quickly growing halos always host SF galaxies

- 2 ways to get slowly growing halos:
  - galaxies residing in somewhat under-dense regions
  - galaxies residing near massive neighbors

- stellar feedback can affect the short-time SFR (~dyn. time of a galaxy)
  - even SF galaxies can have SFR suppressed for ~100 Myr but then recover
  - contributes to scatter in M_{star} – SFR
  - likely essential to lower sSFR to very low values in quiescent galaxies (but AGN feedback could also play that role)

Massive FIRE
Feedback In Realistic Environments

- Cosmological, hydrodynamical zoom-in sims (GIZMO/P-SPH)

Massive FIRE

Feedback In Realistic Environments

- Cosmological, hydrodynamical zoom-in sims (GIZMO/P-SPH)
- 40 galaxies in halos ~10^{12} – 3×10^{13} $M_\odot$ at z=2
- High numerical resolution: ~**10 pc**, ~ few **10^4 $M_\odot$**

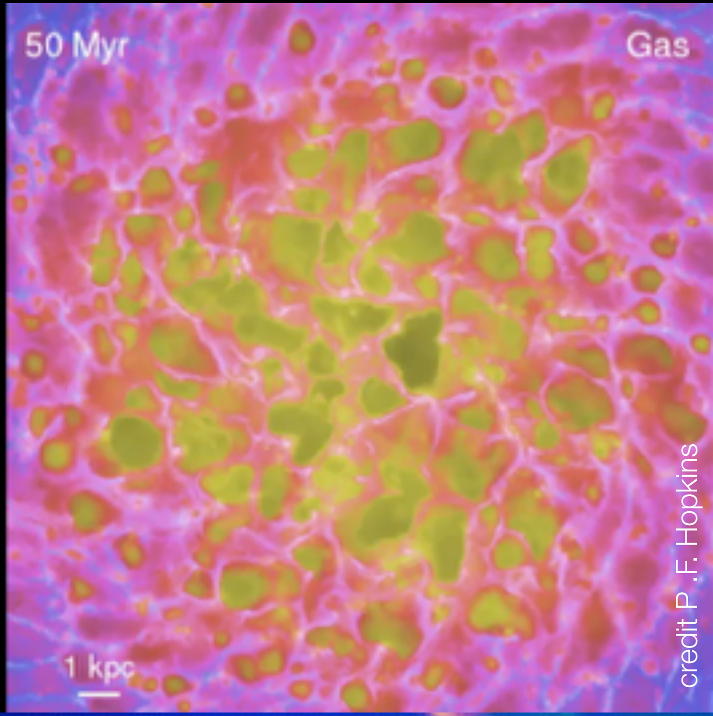
- **Star formation** and **stellar feedback** modeling based on *Feedback in Realistic Environments* (FIRE) approach (Hopkins et al. 2014)
  - star formation:
    in locally bound, dense, molecular gas
  - stellar feedback includes:
    radiation pressure, stellar winds, supernovae

- **no** *energy / momentum injection from* **supermassive black holes**

- same physics as sims presented in Phil's & Andrew's talks

300,000 l.y.

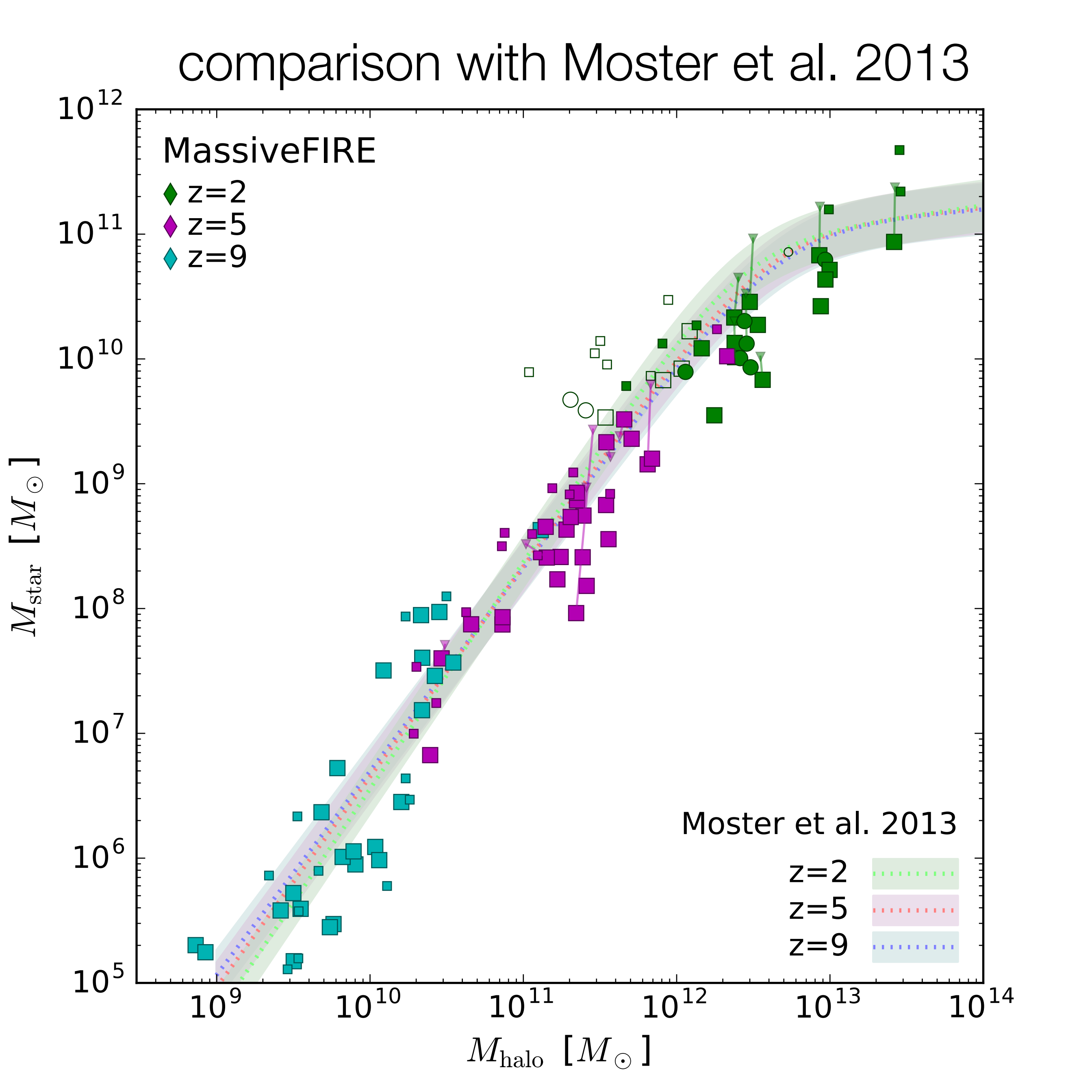
R. Feldmann

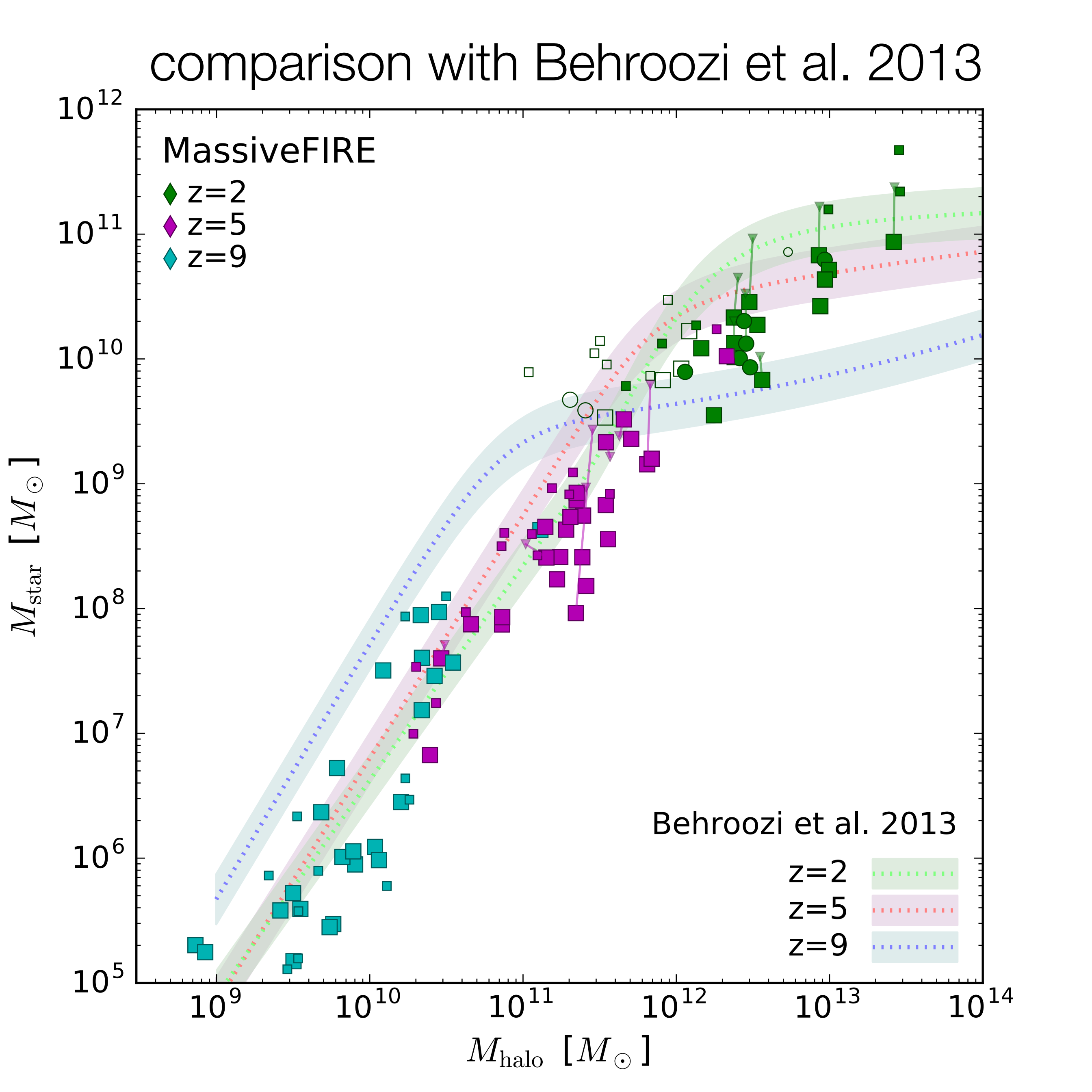


Validation of the physical model

- properties of galaxies in today's Universe, e.g., relations between star formation rate, gas content, mass-metallicity relation
  (e.g. Hopkins et al. 2014, Ma et al. 2016)
- properties of outflows driven by stellar energy/momentum injection
  (Muratov et al. 2015)
- Variability of the star formation rate in galaxies
  (Sparre et al. 2016)
- covering fractions of neutral hydrogen in massive halos
  (Faucher-Giguère et al. 2015, 2016)
- presence of large star forming clumps in massive, young galaxies
  (Oklopčić et al. submitted)
- Soft X-ray emission, Sunyaev-Zel'dovich signal
  (van de Voort et al. submitted)
- Kennicutt-Schmidt relation
  (e.g. Hopkins et al. 2014, Orr et al. in prep)
- ...

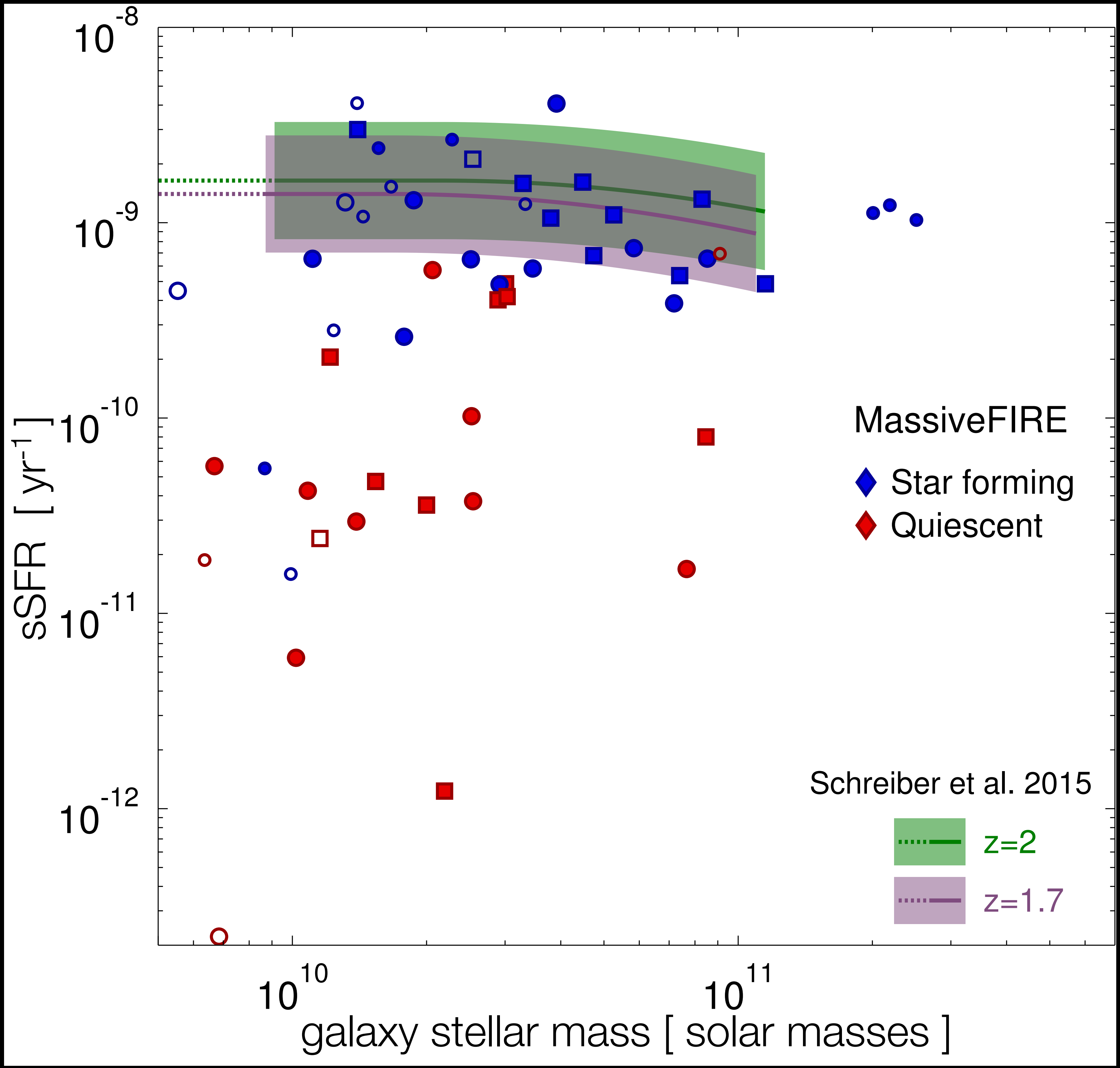
Stellar mass – halo mass relation at z~2-9





- used to be challenge for galaxy formation simulations (“overcooling”)
- reasonably agreement, also scatter (~0.2 dex)
- galaxies evolve more or less along the relation

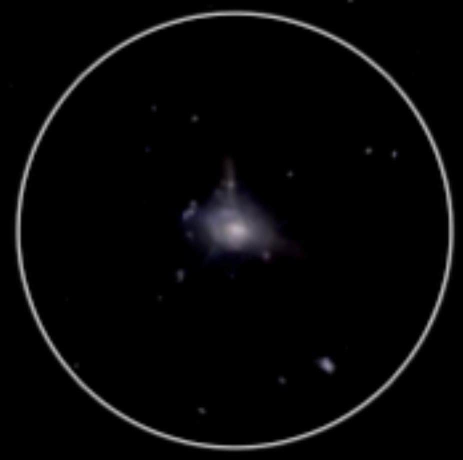
Star forming and quiescent galaxies

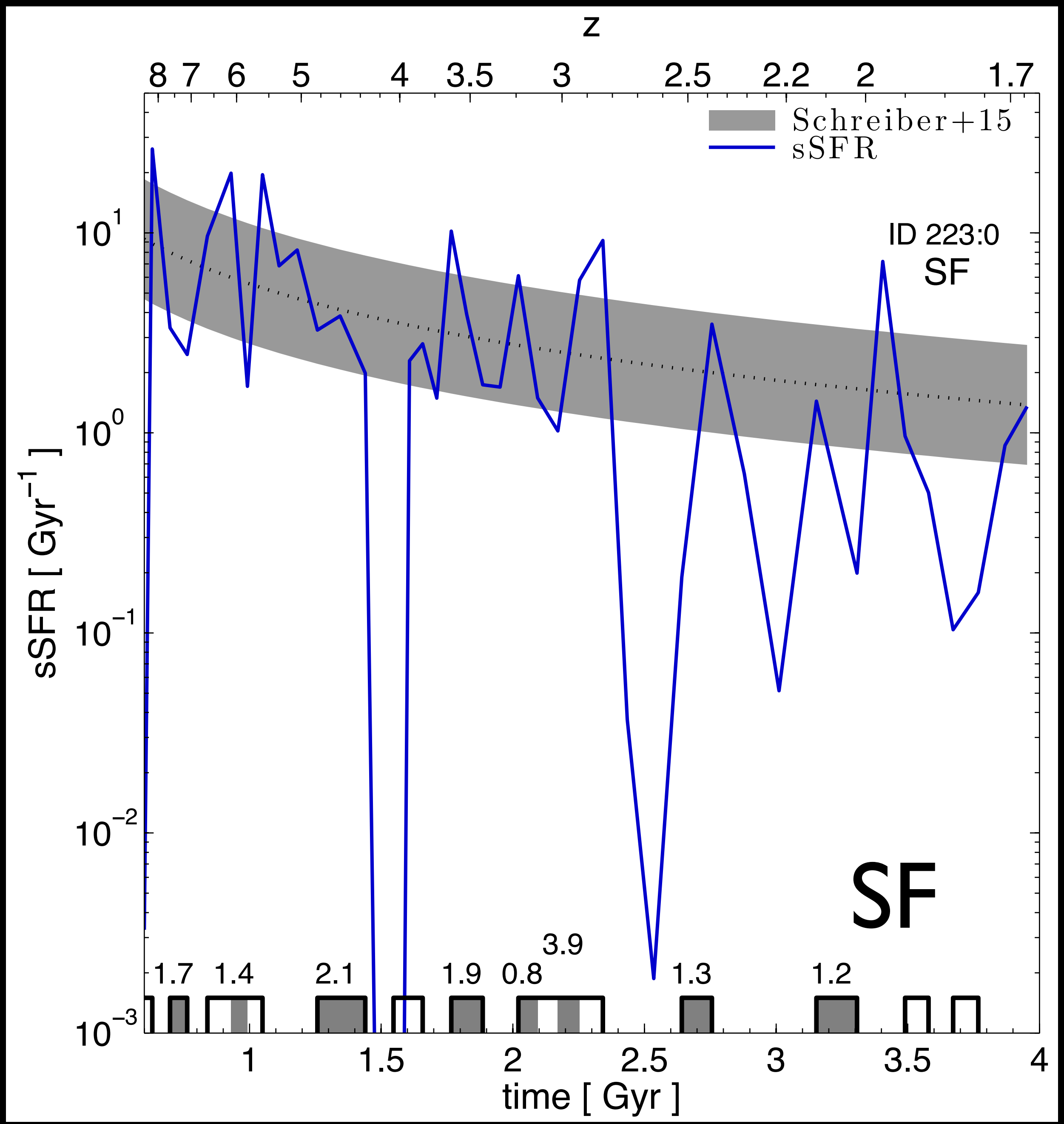


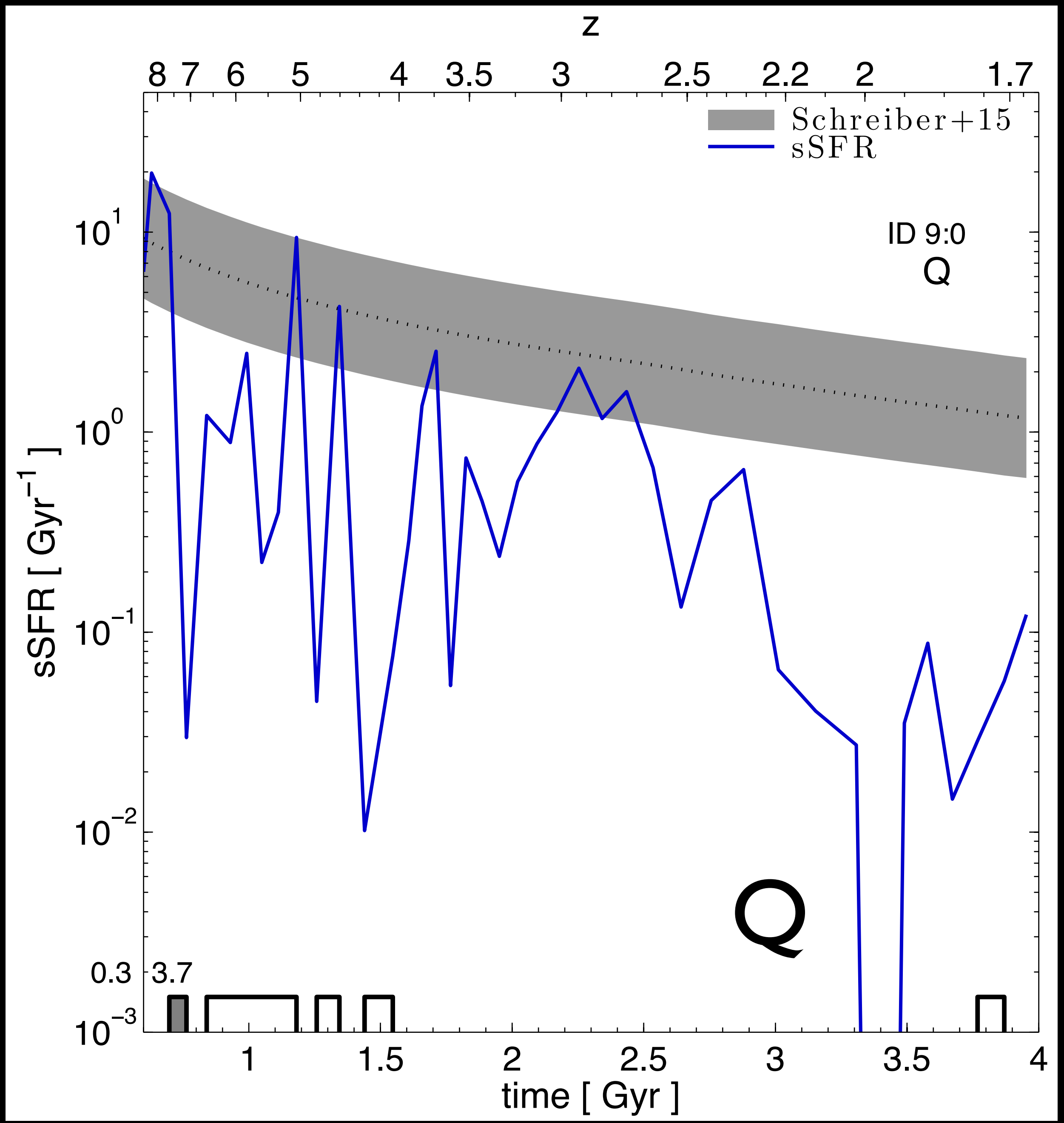
- SF/Quiescent **classification** based on **U-V, V-J** colors (from mock images)
- matches well the split of galaxies into those on and those below the SF sequence

RF et al. 2016 MNRAS

SF histories



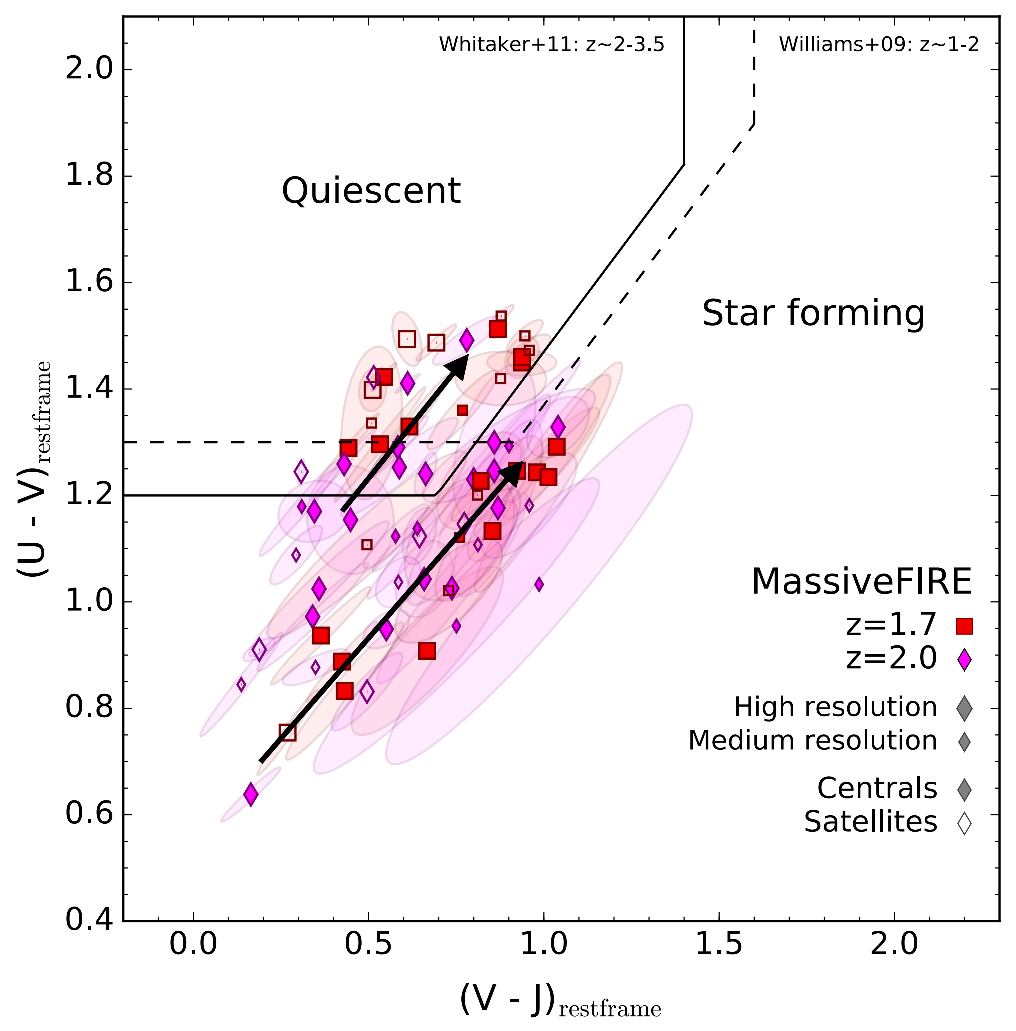




Quiescent galaxies in our simulations vs Nature (Caveats)

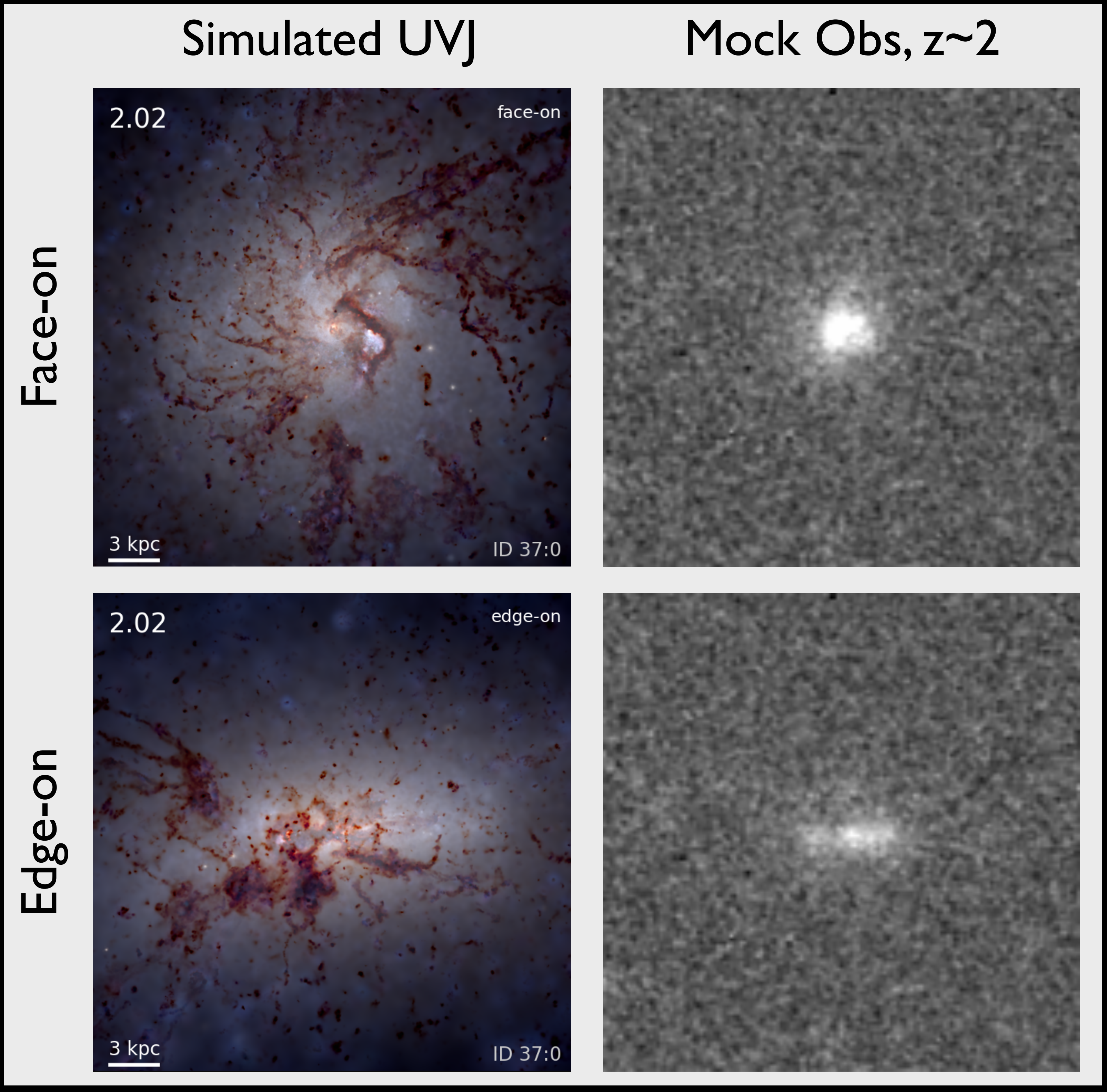
Our simulated quiescent galaxies:

- Are moderately massive (log $M_{star}/M_{\odot}$~10-11)
- Have SFR of a factor ~10 below the SF sequence but are not fully “quenched”
- Are not as red in U-V as some observed massive Q galaxies at z~2 (perhaps because of lower mass, missing physics?)



- Often contain a non-negligible amount of dust (A_V ~ 0.3-0.5), but much less than SF galaxies (A_V ~ 1-1.5)
- Galaxy properties computed without complete forward modeling of observations (PSF, resolution, source extraction etc.)

Measuring galaxy properties with mock observations



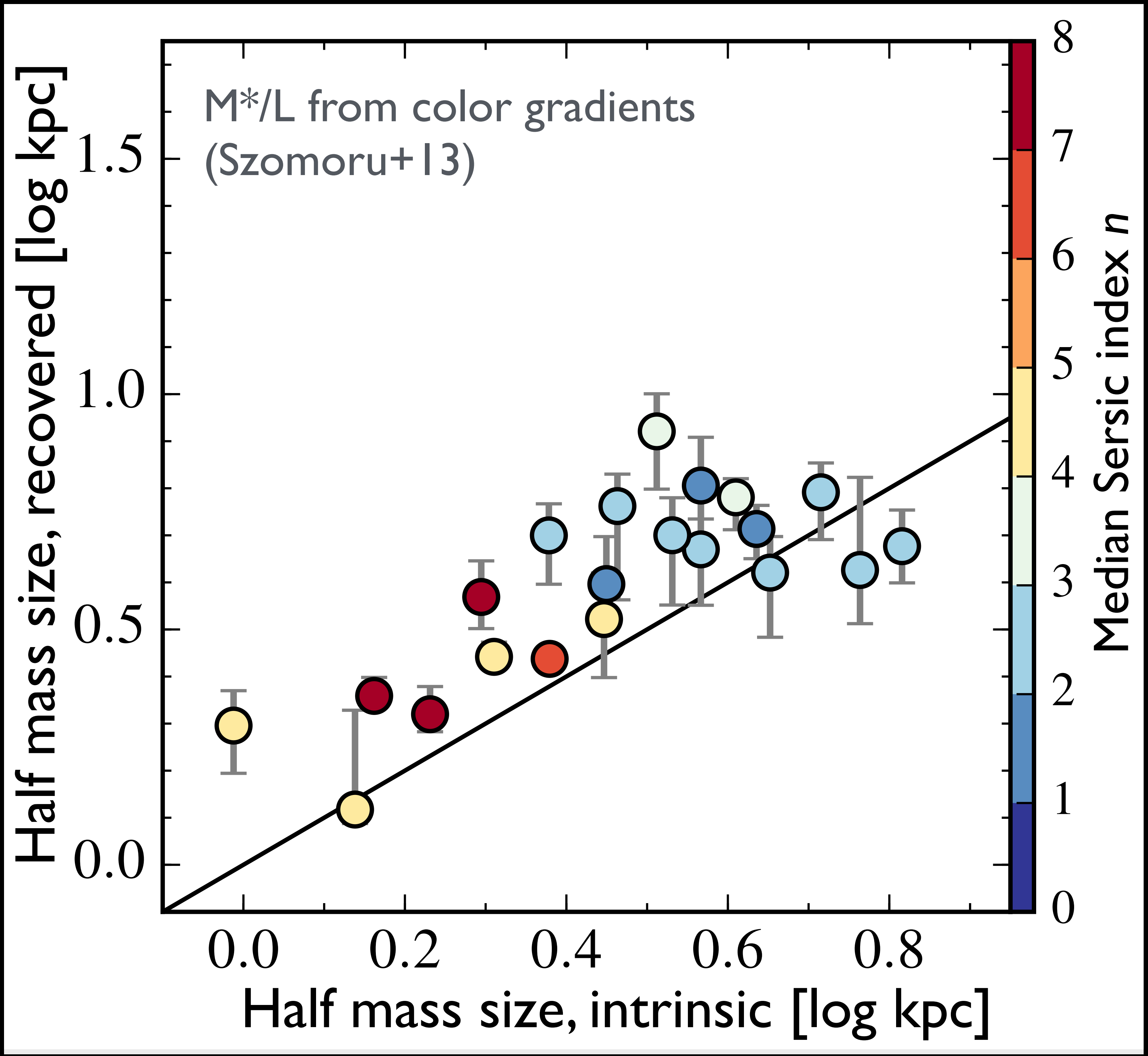
Price et al. in prep

Mock WFC3 images:

- Artificially redshift
- Convolve with CANDELS F160W PSF
- Add average-depth CANDELS noise

Multiple projections for each simulated galaxy,
multiple filters/projection

Measuring galaxy properties with mock observations

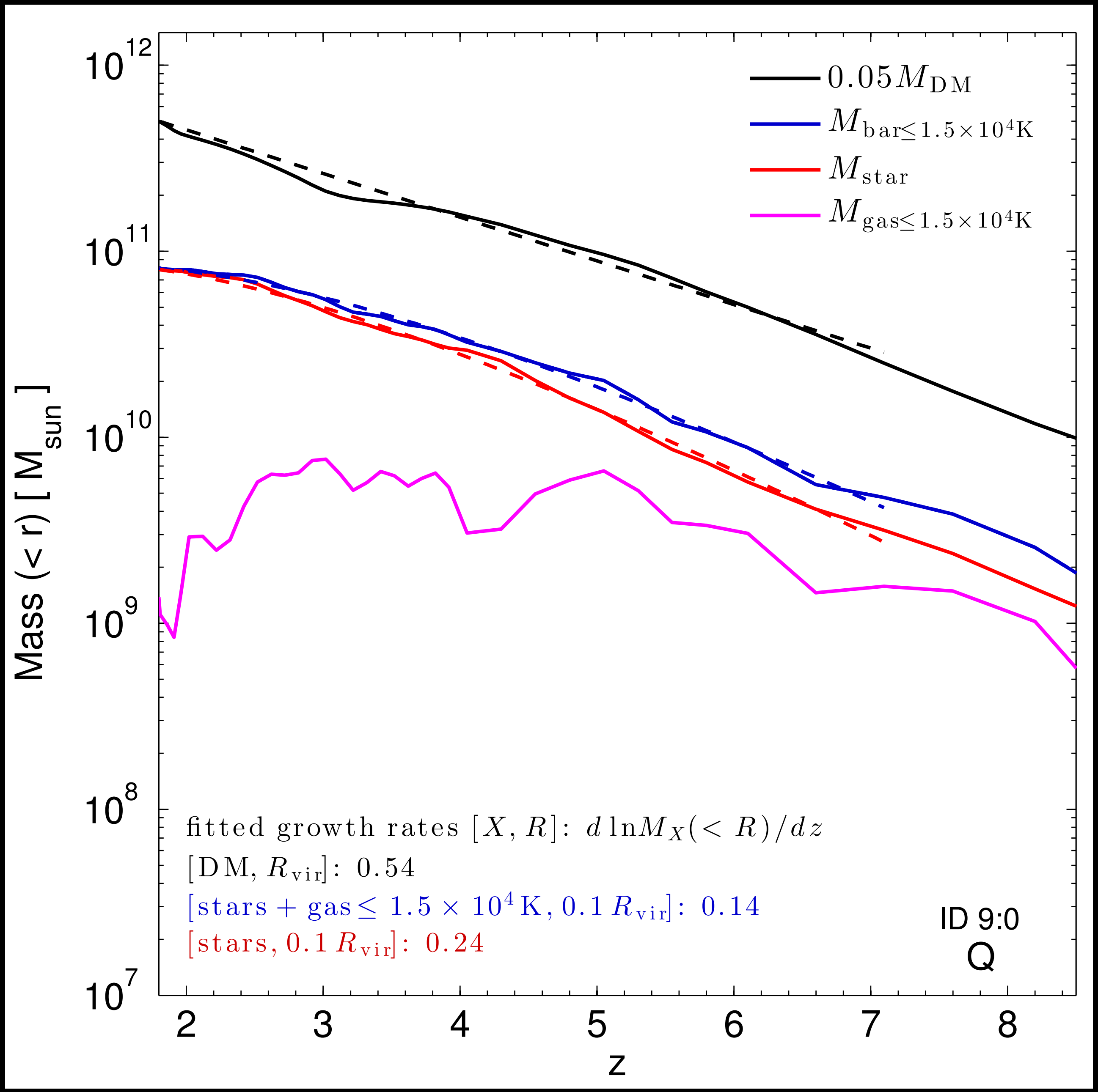


Price et al. in prep

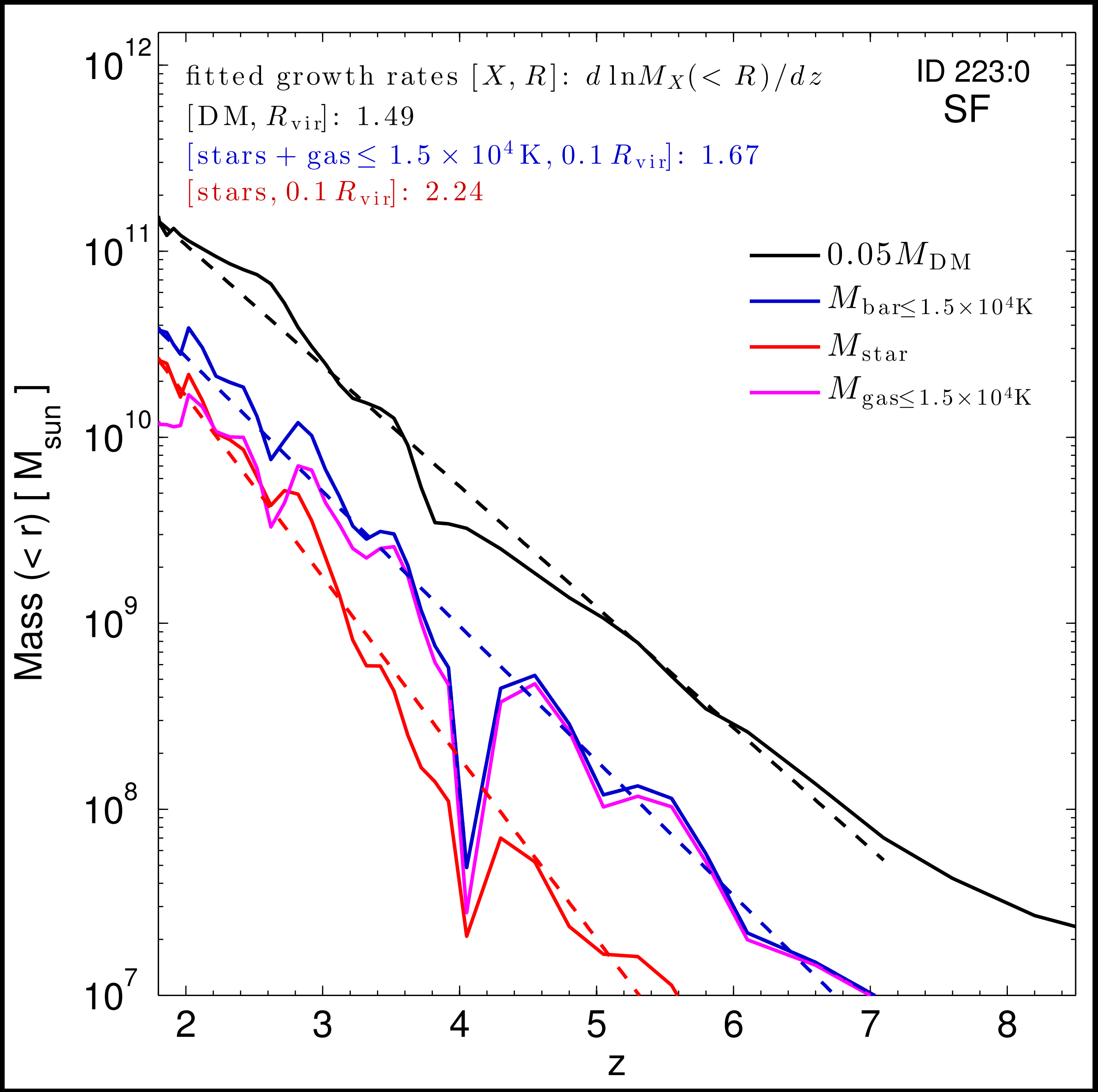
- Half-mass sizes inferred from observations biased relative to true sizes

Growth history of halos and galaxies

Quiescent galaxy



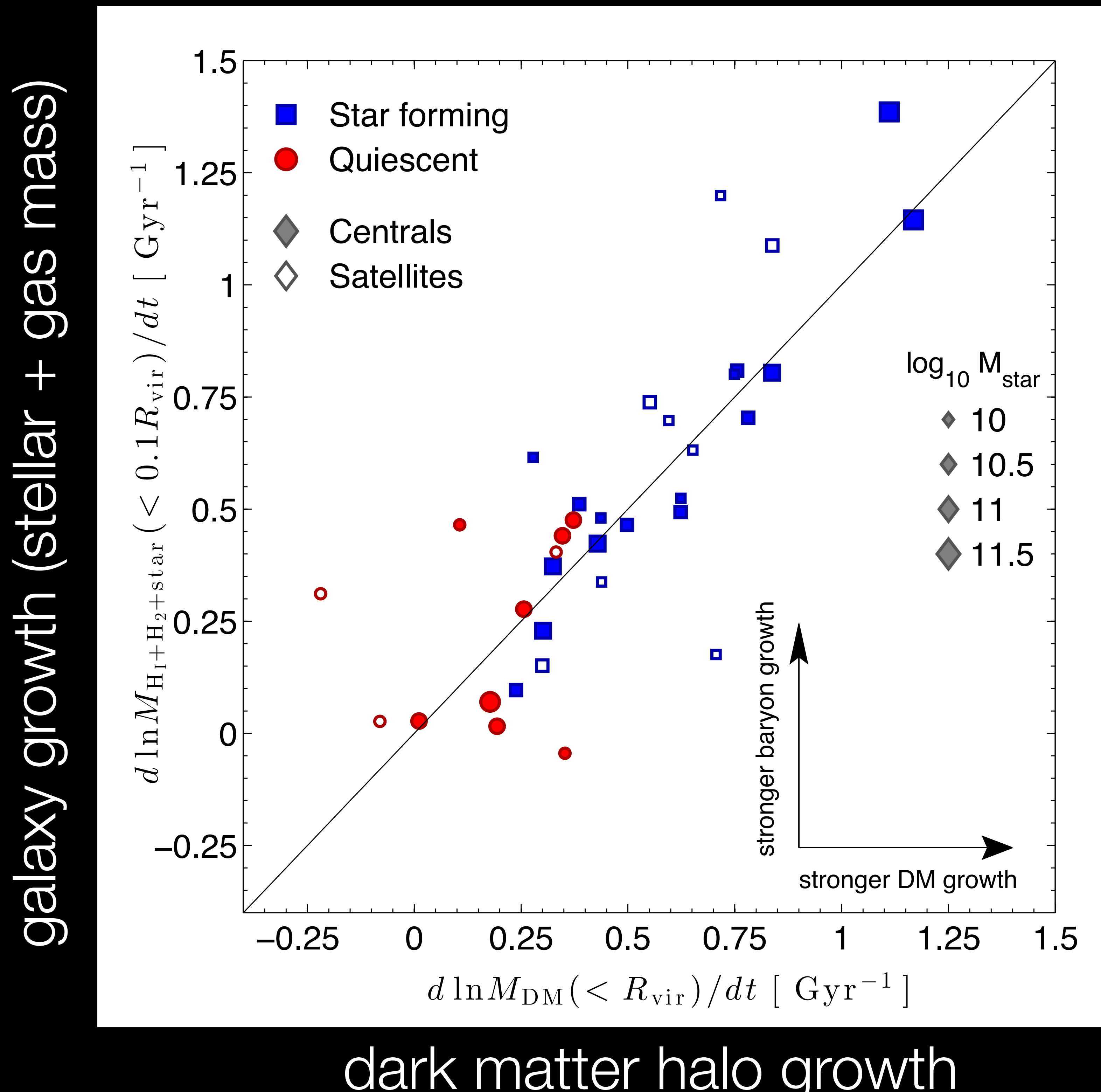
Star forming galaxy



$$M(t) \propto e^{-\gamma z(t)}[1+z(t)]^{\beta}$$

- "smoothes out" individual mergers
- estimate growth rates at z=2

Halo growth vs Galaxy growth



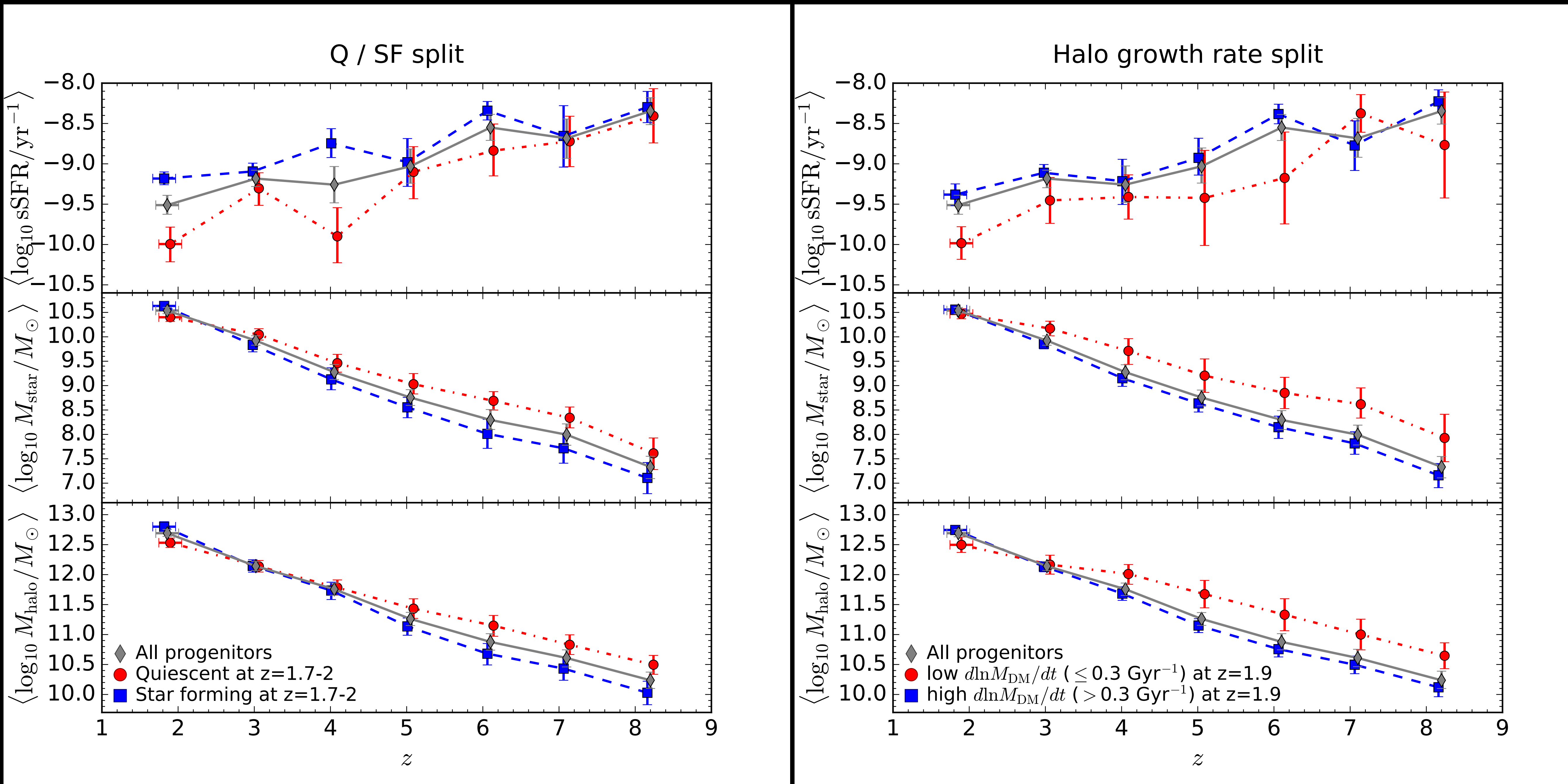
RF et al. 2016 MNRAS,
see also RF & Mayer 2015

- Q galaxies reside preferentially in halos with low specific growth rates
- Physical Interpretation: low growth rate => low gas accretion rate => low sSFR

Cosmological Starvation

- split central galaxies into SF / Q or into those fast / slowly growing halos

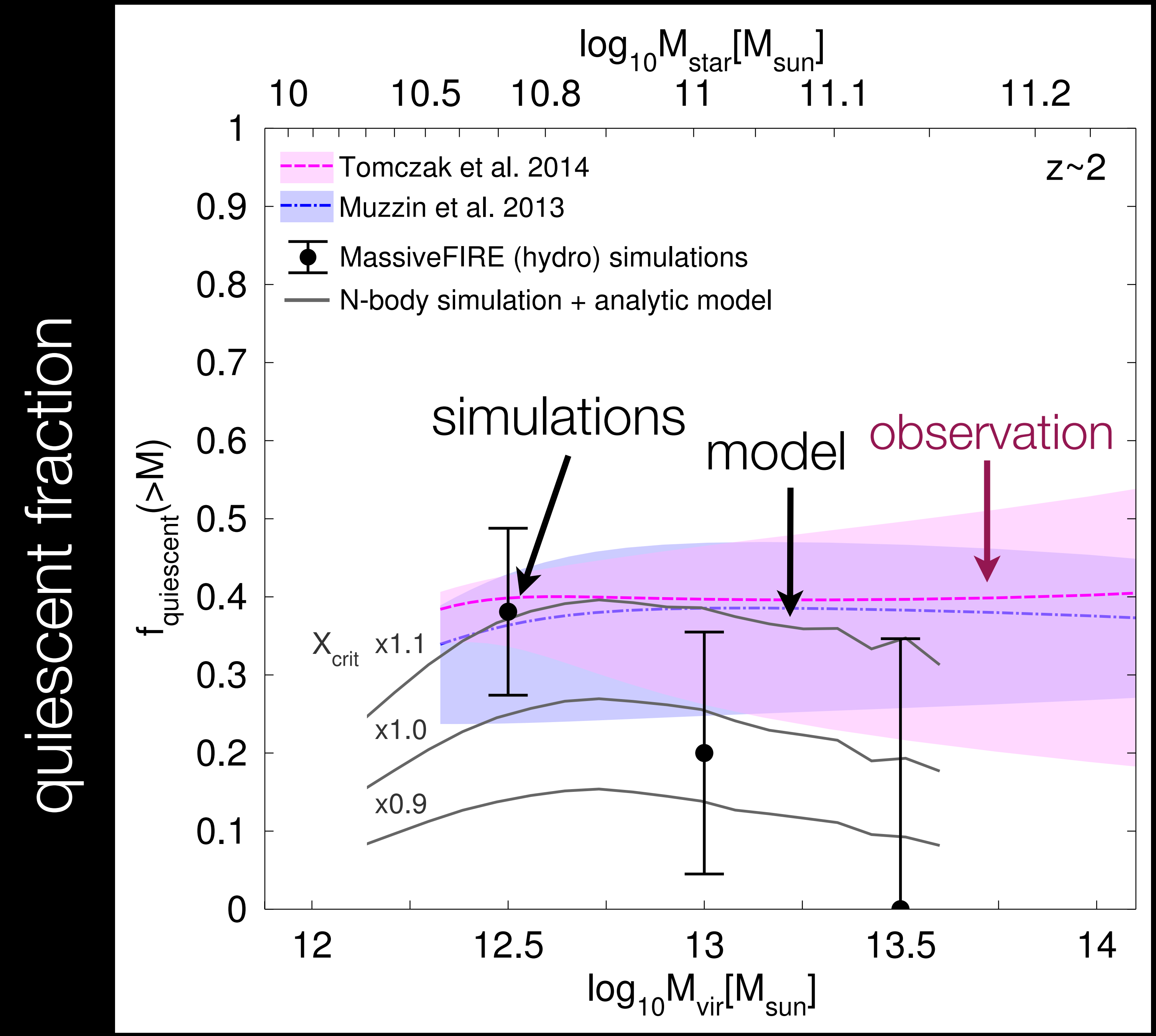
RF et al. in prep



- Progenitors of Q galaxies and those in slowly growing halos at z~2:
  - have lower sSFR, higher M_{star}, higher M_{halo} already much earlier times
- Q/SF-iness of a galaxy is, on average, related to long-term growth processes

Let's do the numbers

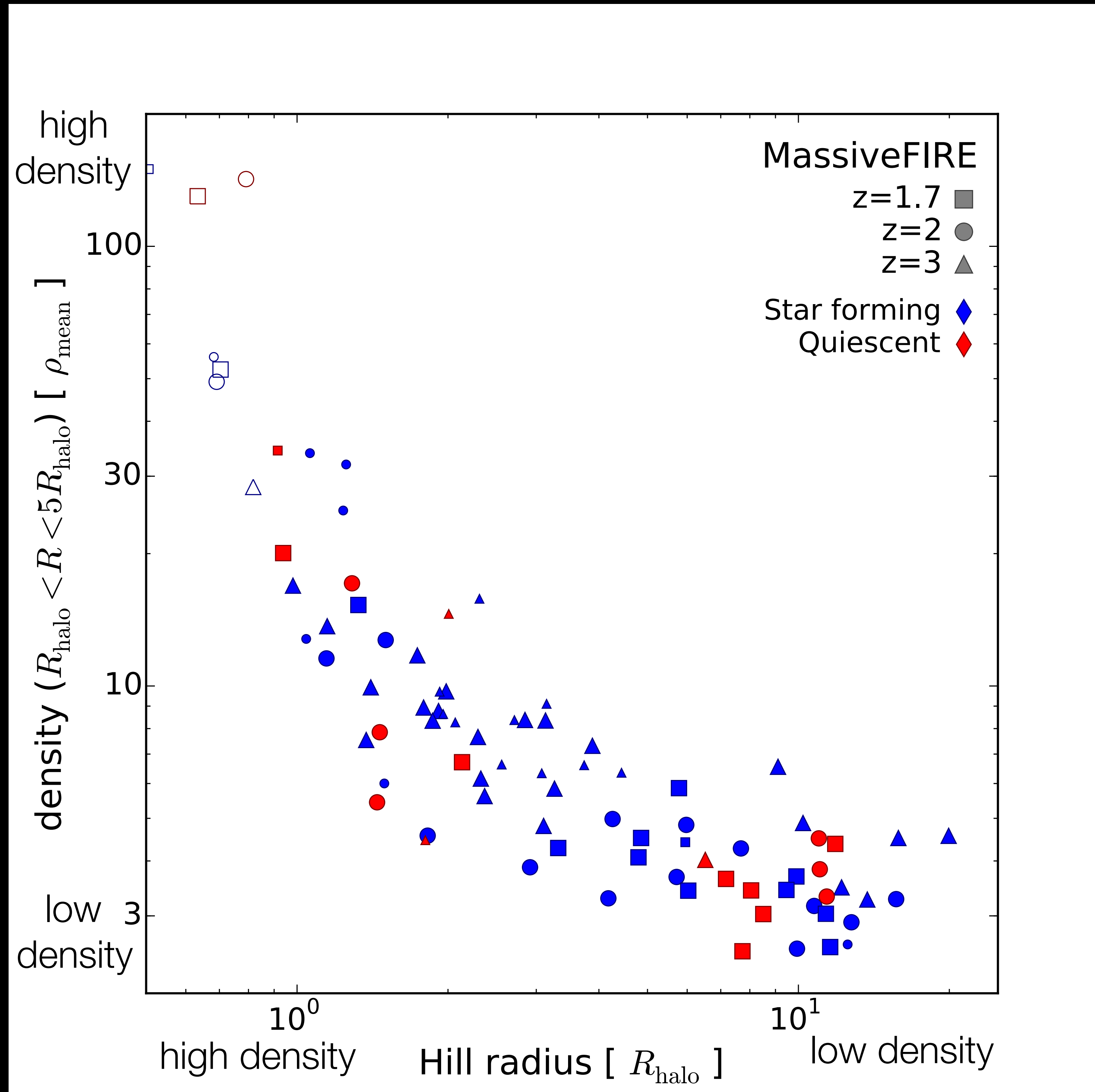
Model: Quiescent galaxies are those with d ln Mhalo / dt $< \chi_{\rm crit}$



RF et al. 2016 MNRAS

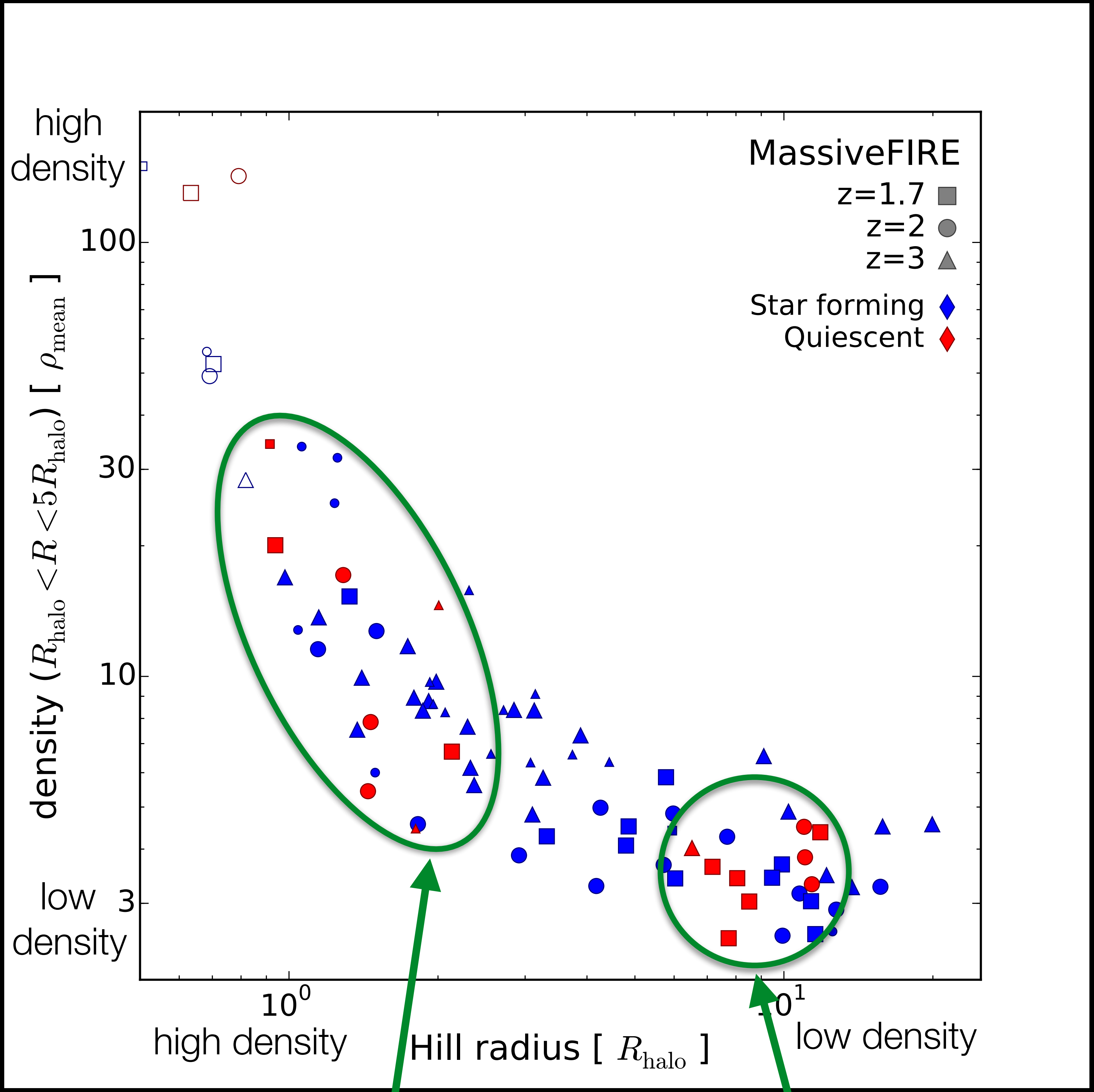
- good agreement for moderately massive galaxies (~few 10^{10} M☉)
- perhaps underpredict quiescent fraction at large masses (> 10^{11} M☉) but not sufficient statistics, AGN feedback needed?

Environments of massive galaxies



Feldmann et al. in prep

Environments of massive galaxies



Feldmann et al. in prep

- Progenitors of Q central galaxies often reside in less dense regions
- But can also become Q near massive neighbor (small Hill radius)

Summary

- latest generation cosmological simulations have overcome many challenges that used to limit predictive power: $M_{star} - M_{halo}$, M_{star} – SFR, …
- sims contain SF and quiescent *central* galaxies (UVJ classification) in massive halos at z~2 **without AGN feedback**
- halo growth rate influences SF / quiescent nature of galaxies:
  - **slow halo growth is necessary requirement for quiescence** (“cosmological starvation”)
  - quickly growing halos always host SF galaxies
- 2 ways to get slowly growing halos:
  - galaxies residing in somewhat under-dense regions
  - galaxies residing near massive neighbors
- stellar feedback can affect the short-time SFR (~dyn. time of a galaxy)
  - even SF galaxies can have SFR suppressed for ~100 Myr but then recover
  - contributes to scatter in M_{star} – SFR
  - probably allows some quiescent galaxies to reach very low sSFR

Thank you