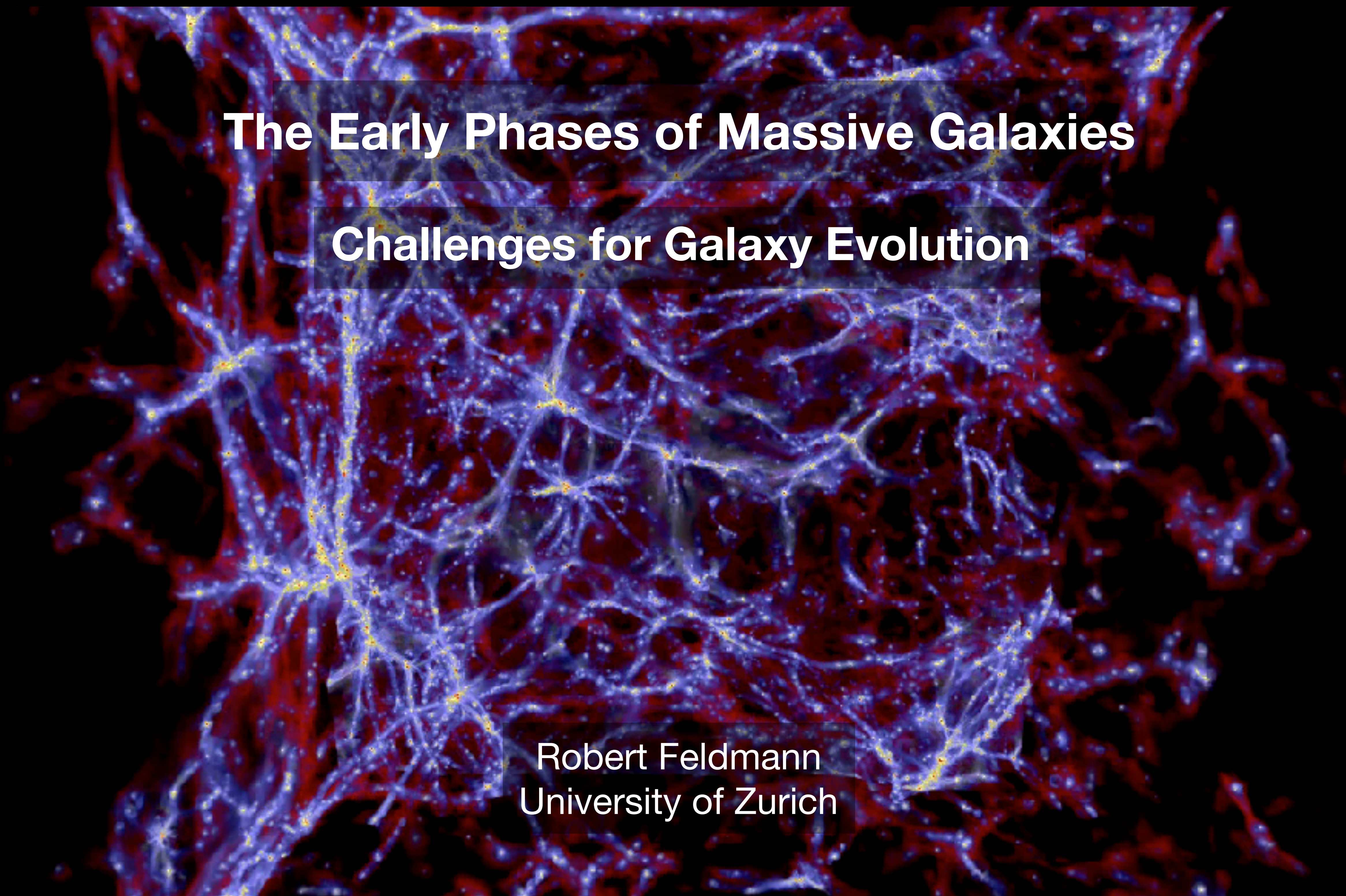


The Early Phases of Massive Galaxies

Challenges for Galaxy Evolution

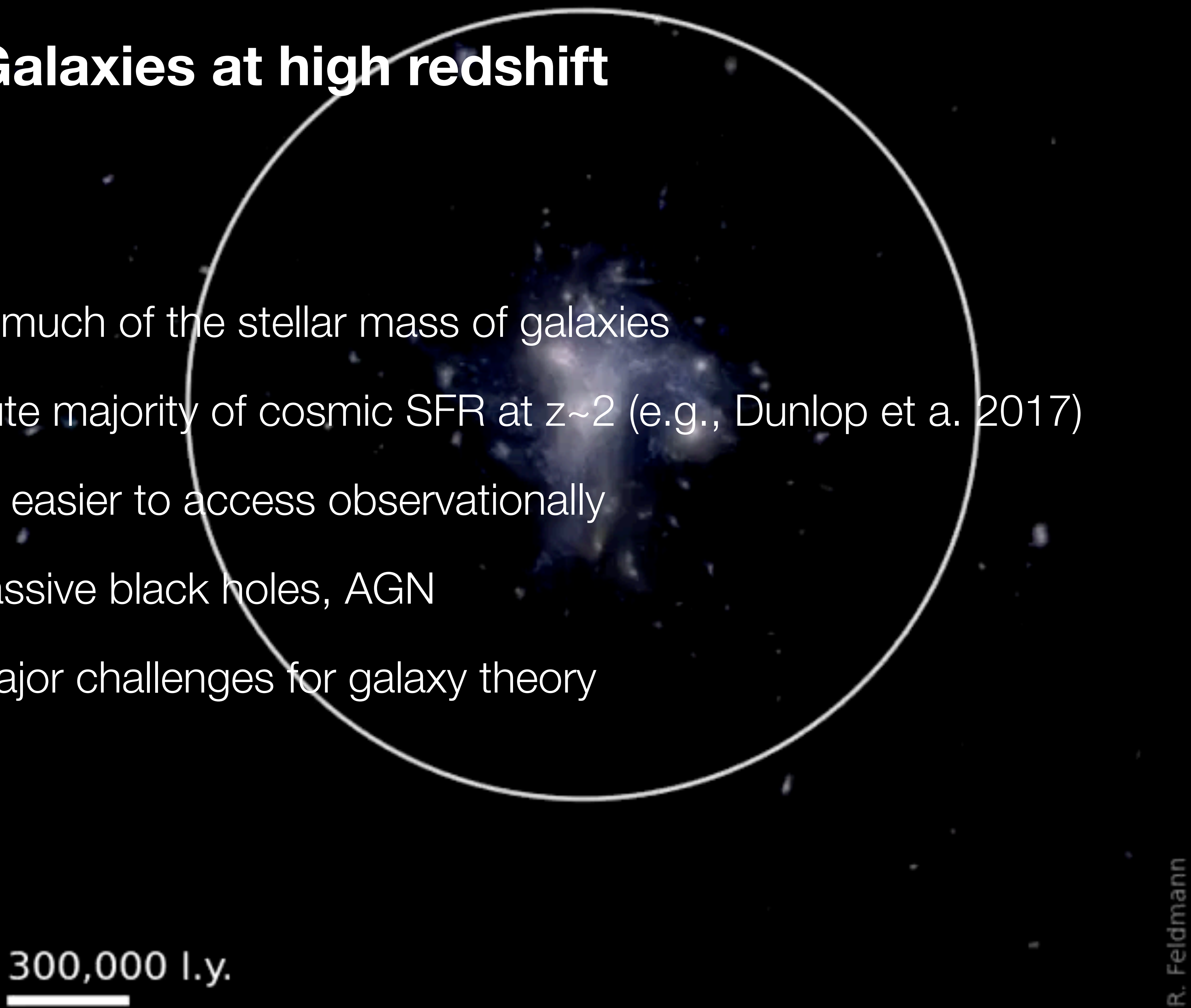
Robert Feldmann
University of Zurich

Massive FIRE
Feedback In Realistic Environments

$z=2$, $M_{halo} = 10^{13.5}\,M_{\odot}$

Massive Galaxies at high redshift

- contain much of the stellar mass of galaxies
- contribute majority of cosmic SFR at z~2 (e.g., Dunlop et a. 2017)
- typically easier to access observationally
- host massive black holes, AGN
- Pose major challenges for galaxy theory

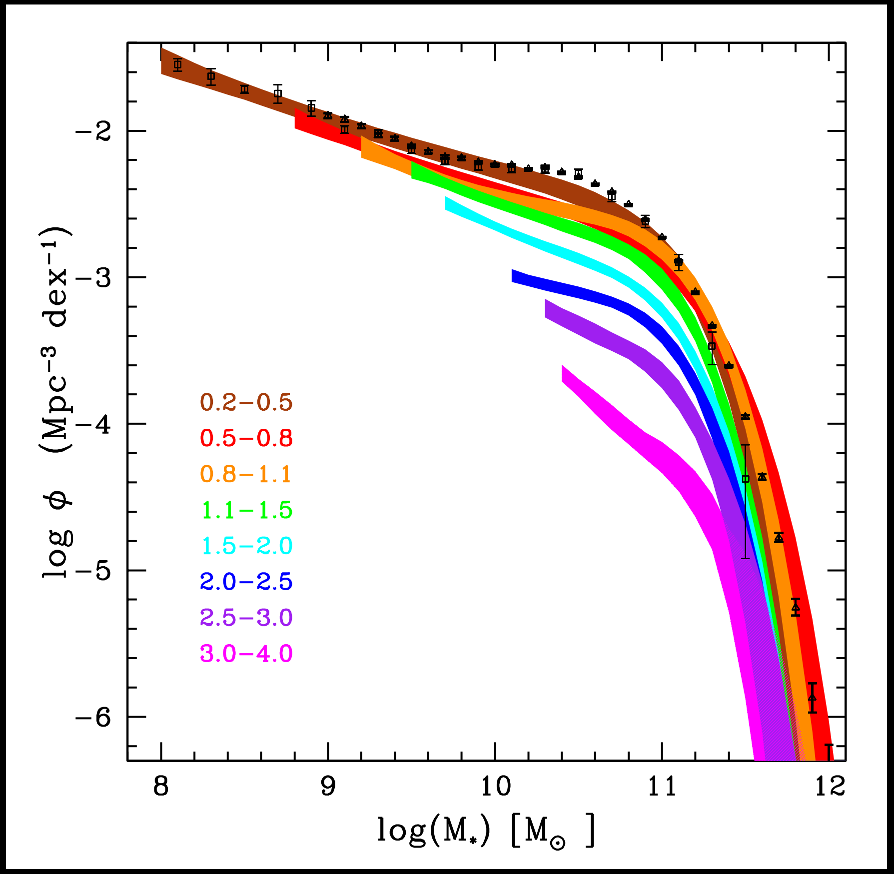


Abundances & Colors

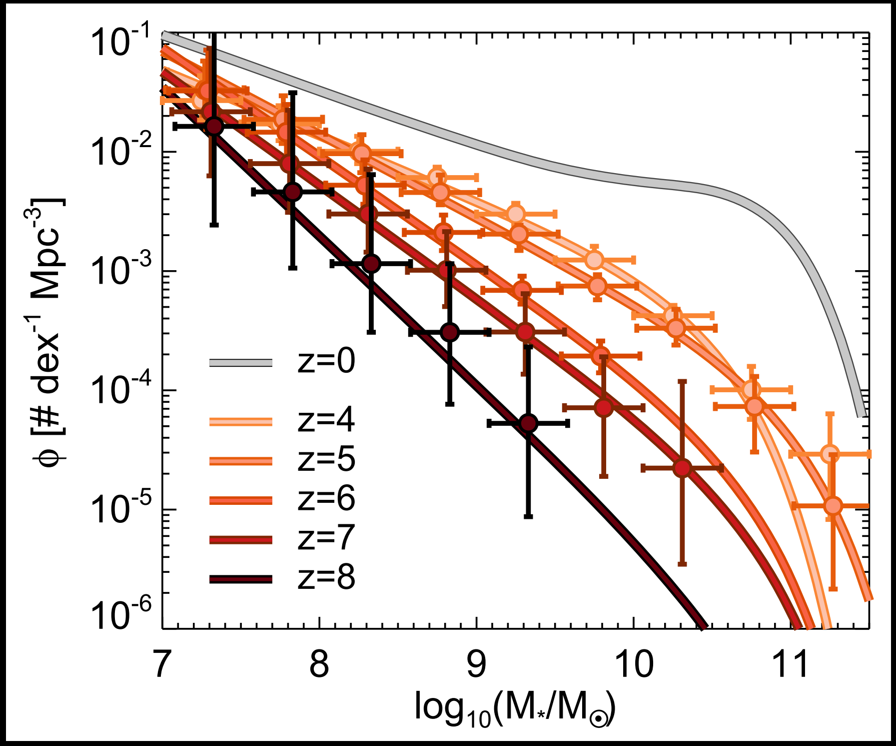
Birth of Massive Galaxies – Observations

- multiband observations (Galex, UltraVISTA, COSMOS, ZFOURGE, CANDELS, …) probe stellar mass function over z=0-8
- z<1: massive galaxies mostly in place, low mass galaxies form (‘downsizing’)
- z~1-3: galaxies of all masses grow
  => Peak epoch of galaxy formation
- z>3: high mass end of mass function evolves quickly
  => Birth-time of massive galaxies
- in agreement with archaeological analysis of stellar populations of local galaxies

see also Perez-Gonzalez+08, Marchesini+09, Pozetti+10, Caputi+11, Santini+12, Muzzin+13, Moustakas+13, Tomczak+14, …

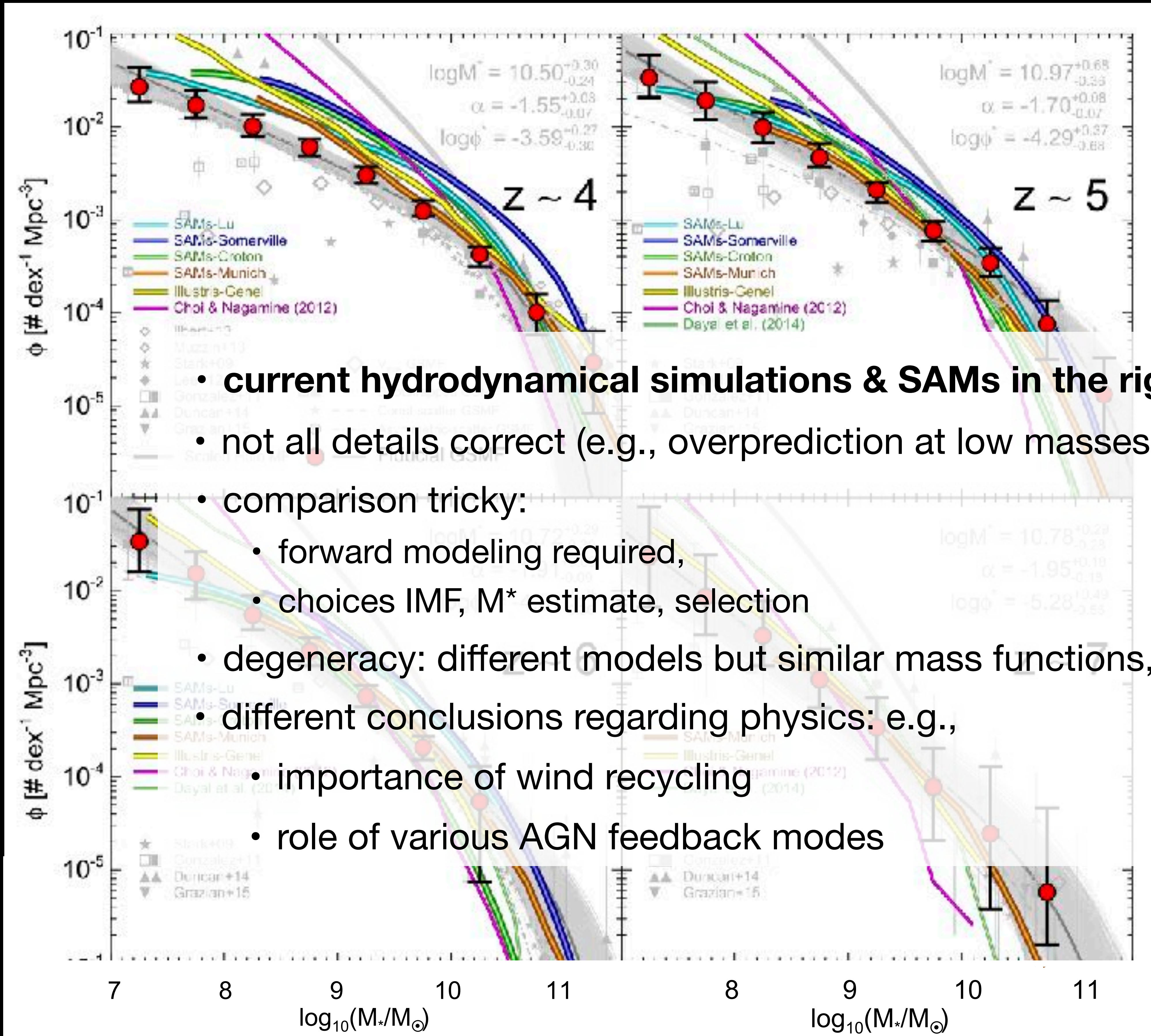


Ilbert et al. 2013



Song et al. 2016

Birth of Massive Galaxies – Simulations



- **current hydrodynamical simulations & SAMs in the right ball-park**
- not all details correct (e.g., overprediction at low masses in Illustris)
- comparison tricky:
  - forward modeling required,
  - choices IMF, M* estimate, selection
- degeneracy: different models but similar mass functions, tuning
- different conclusions regarding physics: e.g.,
  - importance of wind recycling
  - role of various AGN feedback modes

Song et al. 2016

Properties of massive galaxies

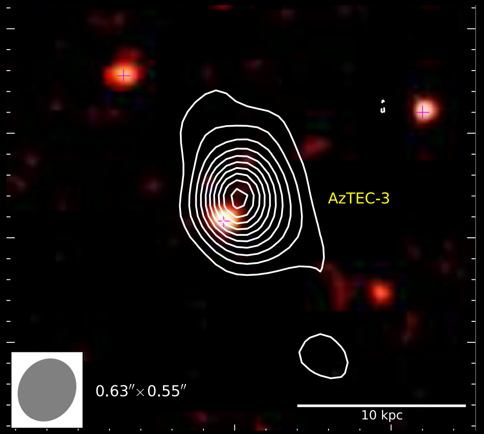
local Universe

Massive galaxies often:

- red,
- gas poor,
- quiescent
- early type

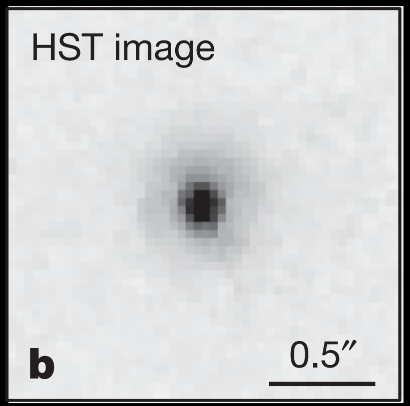
z~2 and above

Riechers et al. 2014

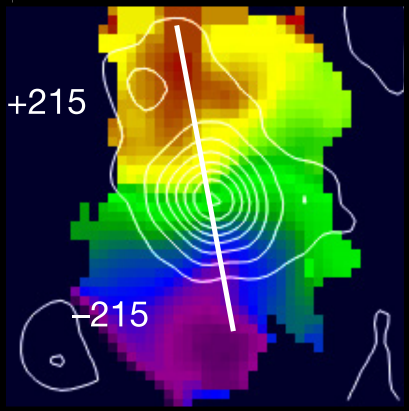


Massive galaxies of many different kinds:

- compact, quiescent galaxies
- baryon dominated disks
- post-starburst
- dusty star-forming galaxies
- sub-millimeter galaxies



van Dokkum et al. 2009



Genzel et al. 2017

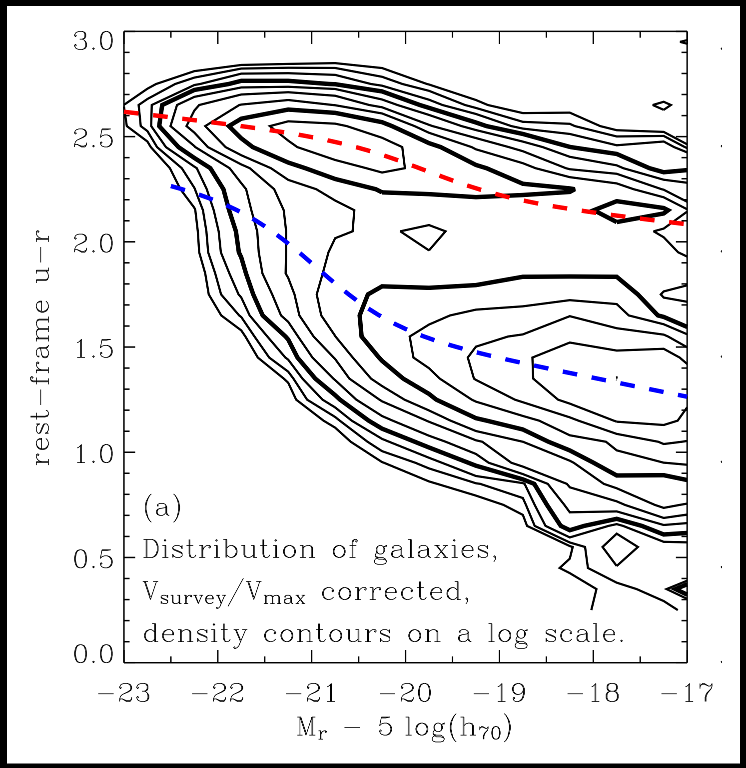
Why large diversity at high z?

Colors of massive galaxies

local Universe

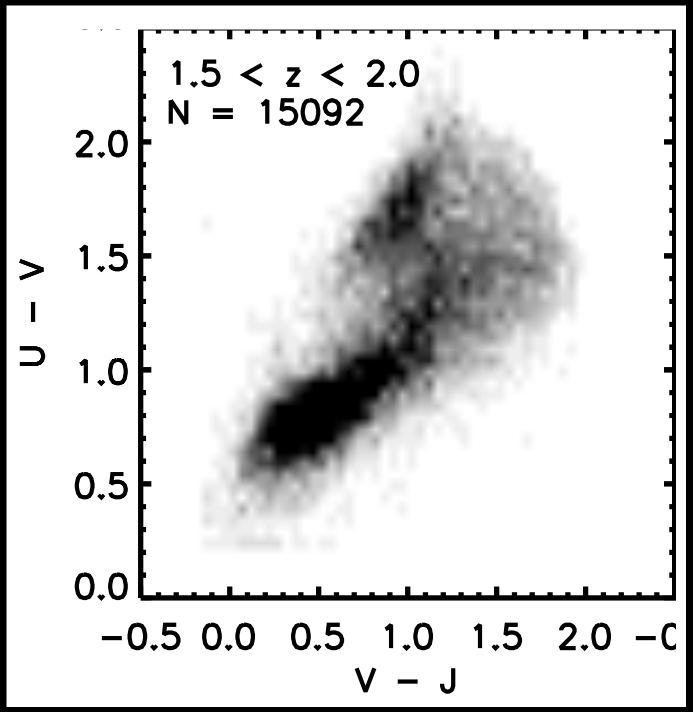
- color bimodality among full population
- almost all massive galaxies are red

SDSS Baldry et al. 2004

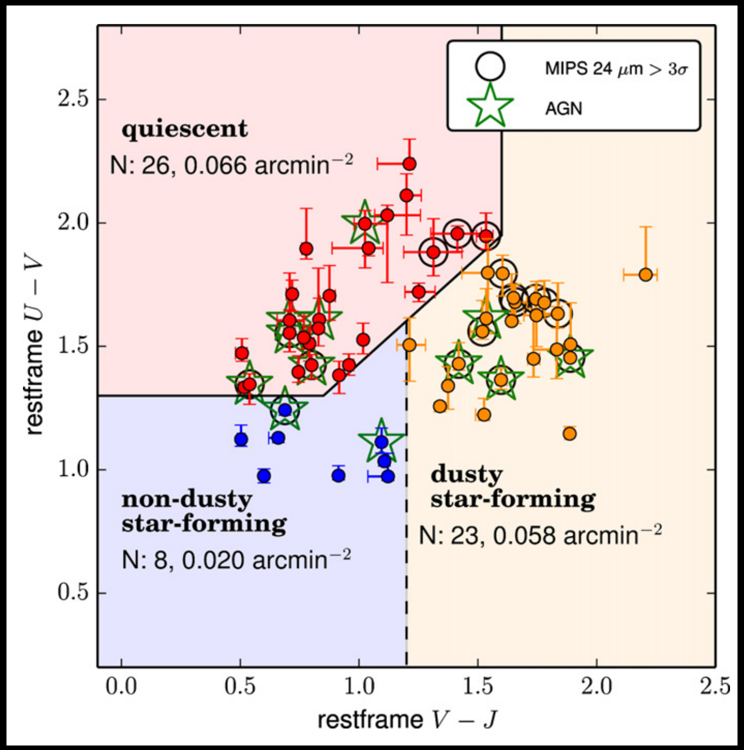


z~2 and above

UltraVISTA Muzzin et al. 2013



- color bimodality out to z~3
- massive galaxies can be:
  - red (because quiescent)
  - red (SF, but dusty)
  - blue (SF, not dusty)



Spitler et al. 2014, see also Marchesini et al. 2010

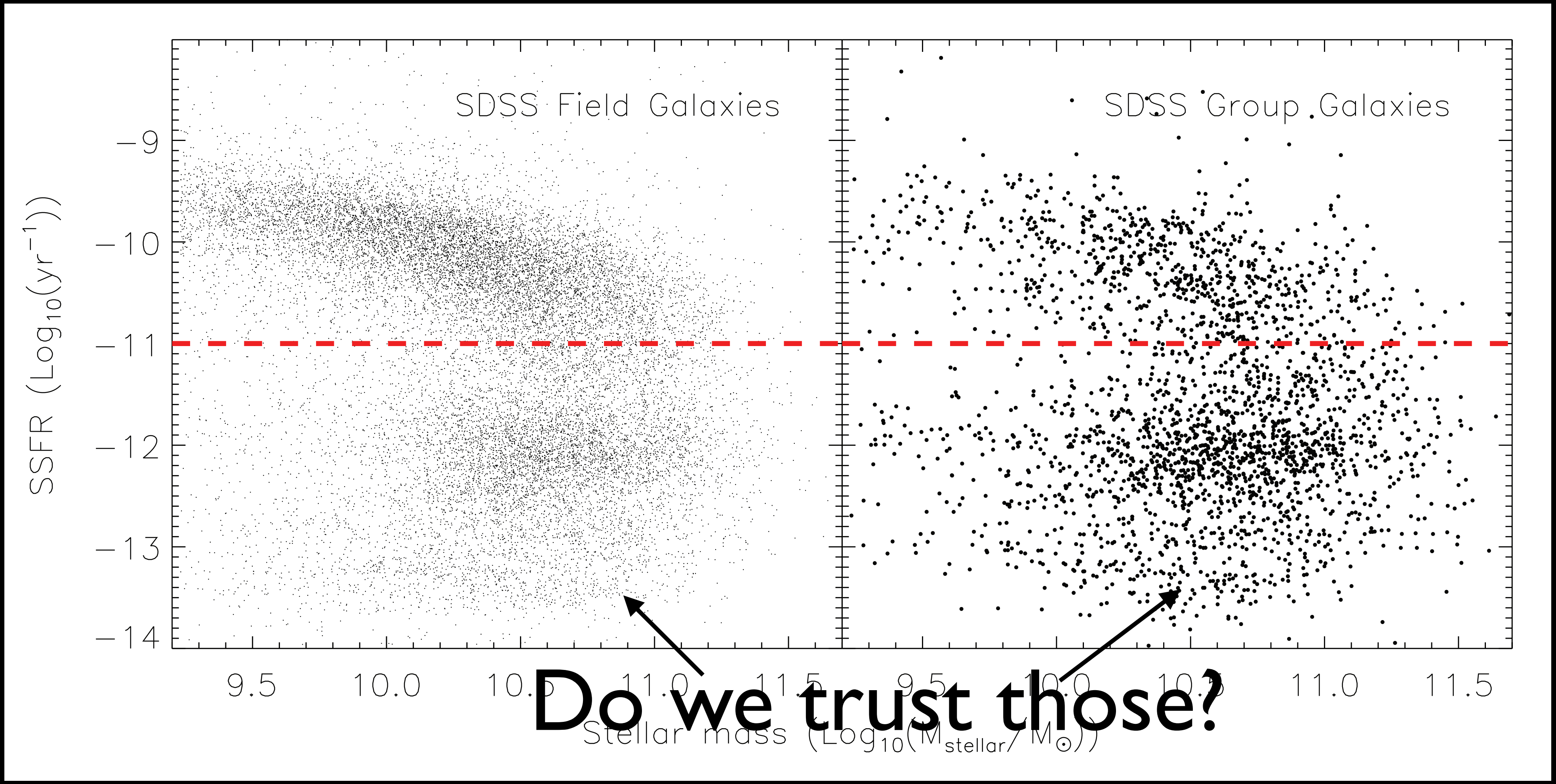
- Q/SF classification: color (UVJ) based or sSFR based

Are quiescent and SF galaxies intrinsically different or do they form a continuum?

SFR bimodality?

SF and Q distinct classes?

- implications for quenching (incl. quenching time)
- SFR distribution uni-,bi-, multi-modal ? In linear or log-space?



McGee et al. 2011

"Examining this figure, it is apparent that galaxies appear bimodal in the SSFR–M⊙ plane. … Thus, similar to the behaviour seen in galaxy colours, the bimodality of galaxy populations seems to be a fundamental property."

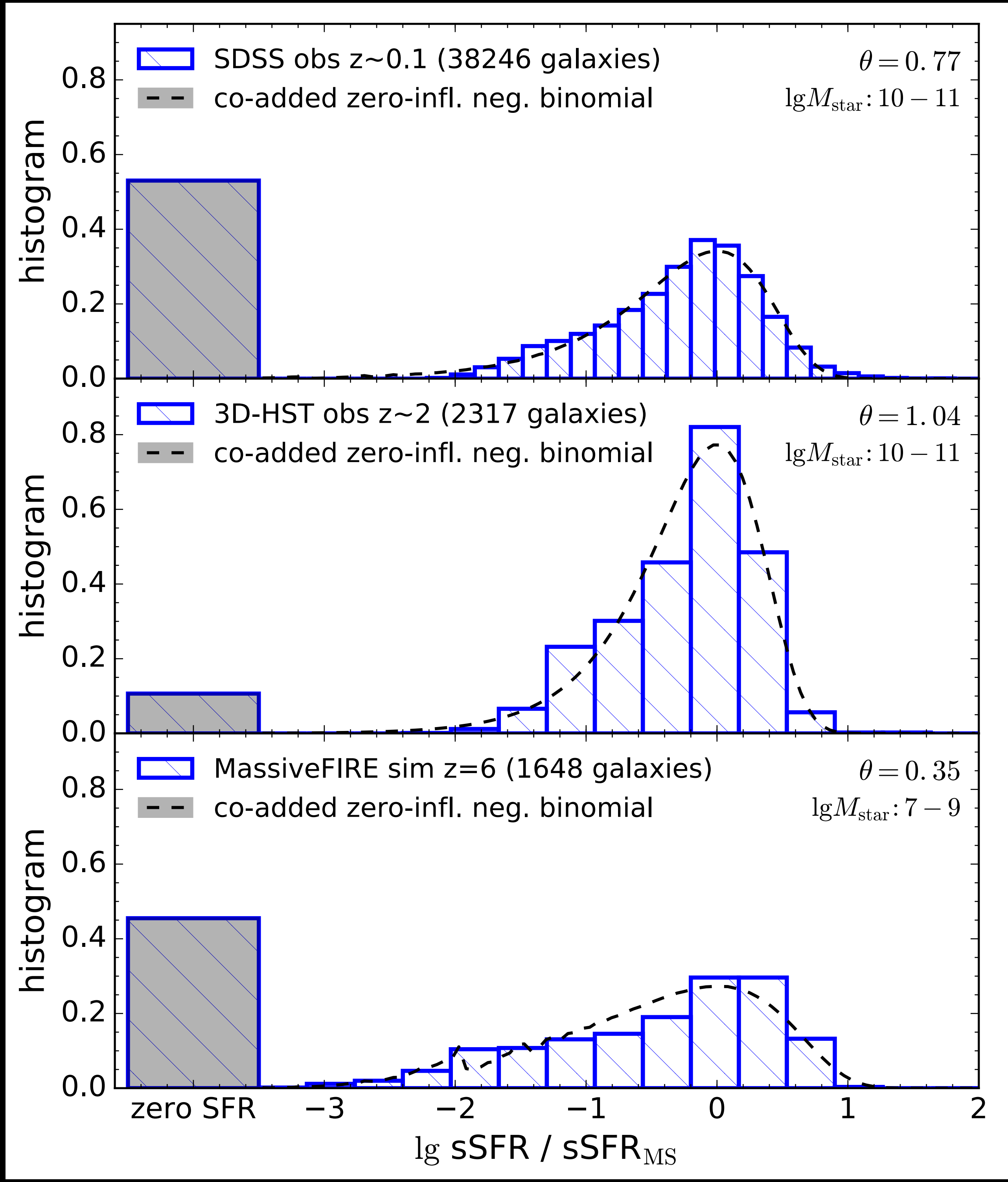
see also e.g. Elbaz et al. 2007, Bisgello et al. 2017

SFR distribution

SFR:

- Chang et al. 2015 (SDSS, z~0)
- Brammer et al. 2012 (3D-HST, z~2)
- RF et al. 2016 (MassiveFIRE simulation, z=6)
- SFR set to zero if non-detected

- distribution for SFR>0 well fit by **negative binomial distribution**
- 'infinite space' near SFR=0 in log-space
- **current data does not constrain whether SFR (in log) is bimodal or not**
- measurement noise and biases can create apparent bimodality and tighten apparent main sequence

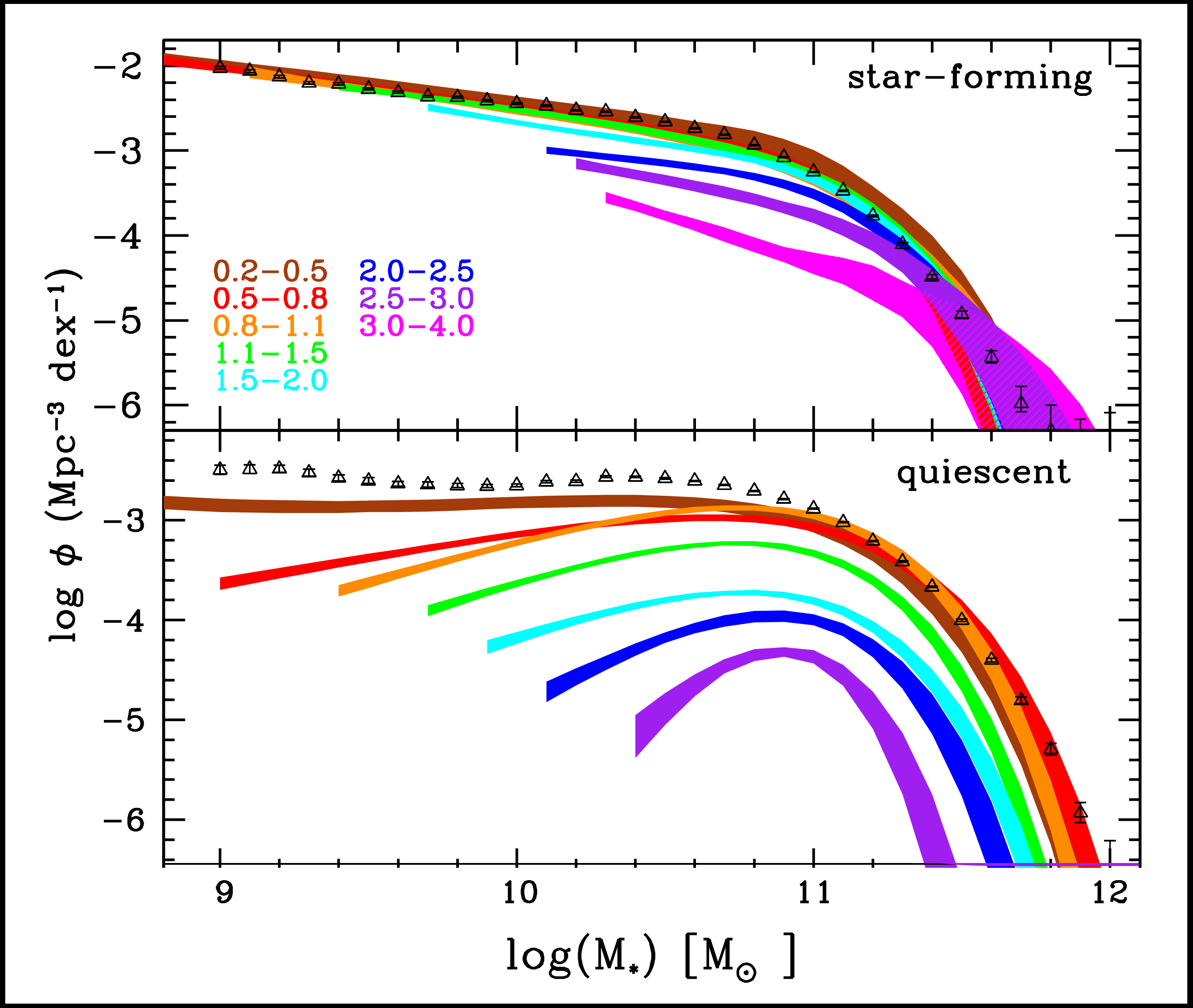


RF 2017

Quenching

Q vs SF galaxies at z ~ 2

Ilbert et al. 2013, see also Muzzin et al. 2013, Moustakas et al. 2013, Straatman et al. 2014, Tomczak+2014



SF

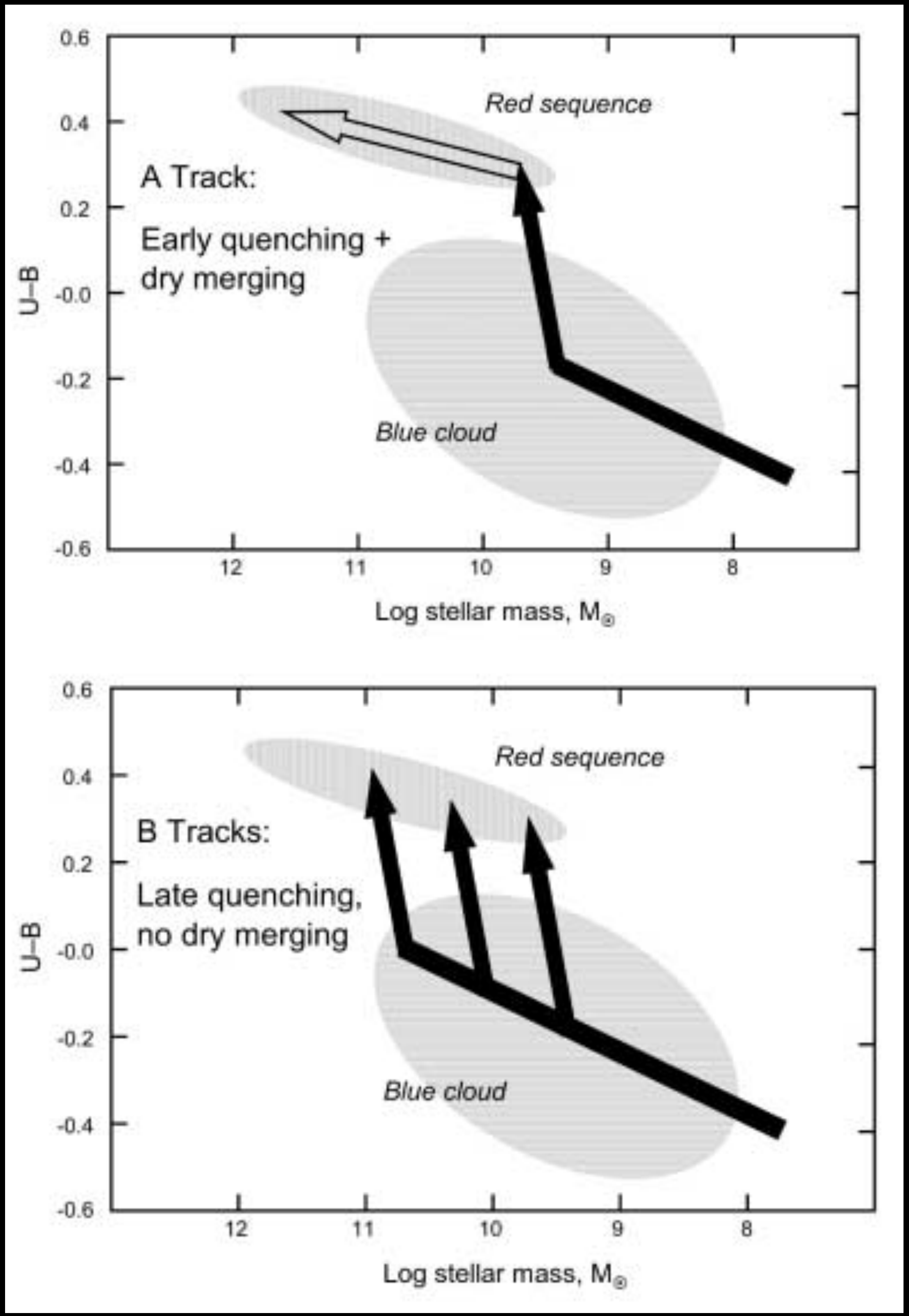
- rare at massive end at low z, but not so at high z
- dusty massive SF galaxies (70-80%) dominate over non-dusty star formers

Q

- Q dominate massive end at z<1, in place by z~1
- Q rare at z>3, SF galaxies dominate at all masses (e.g., Behroozi et al. 18)

z~1-3: Peak epoch of star formation and of quenching!

Quenching



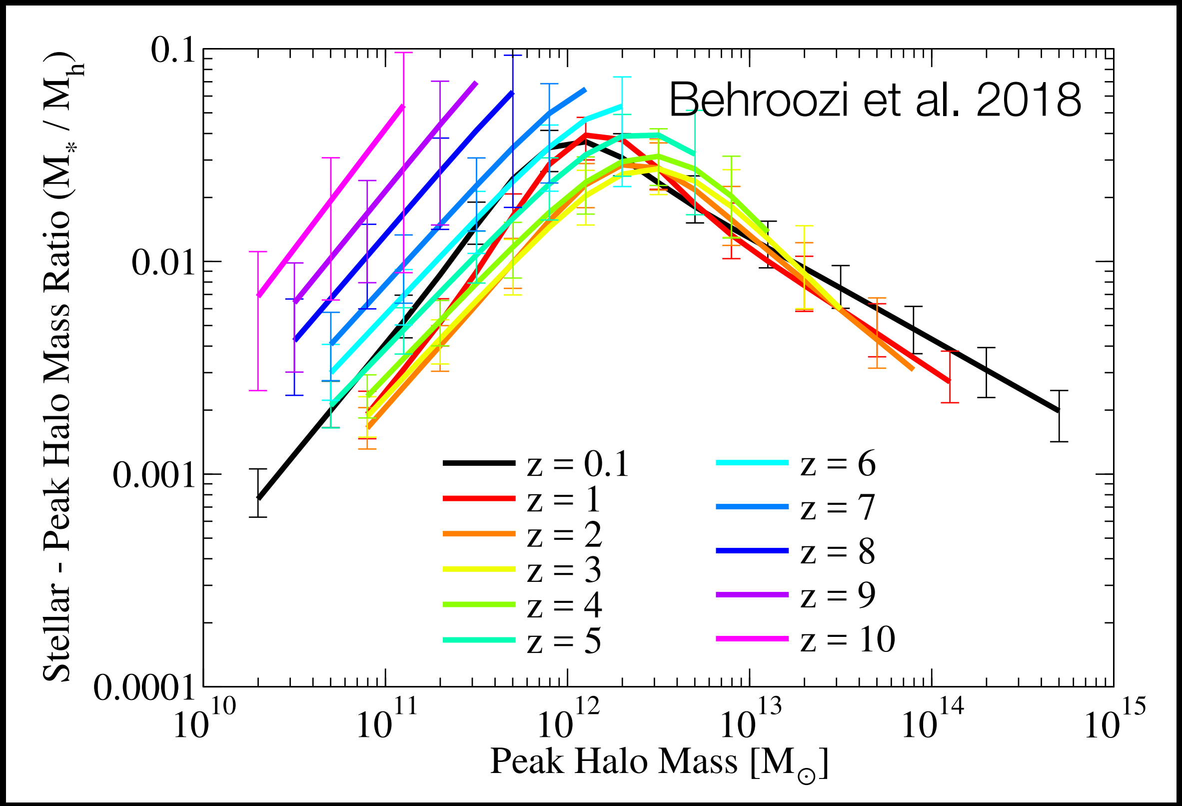
Faber et al. 2007

- What is quenching?
  - Sudden suppression vs maintenance
  - When is a galaxy ‘quenched’?
- When does quenching take place?
- How do galaxies quench?

Emanuele Daddi (Thursday afternoon),
Yingjie Peng (Friday morning)

Two aspects of quenching

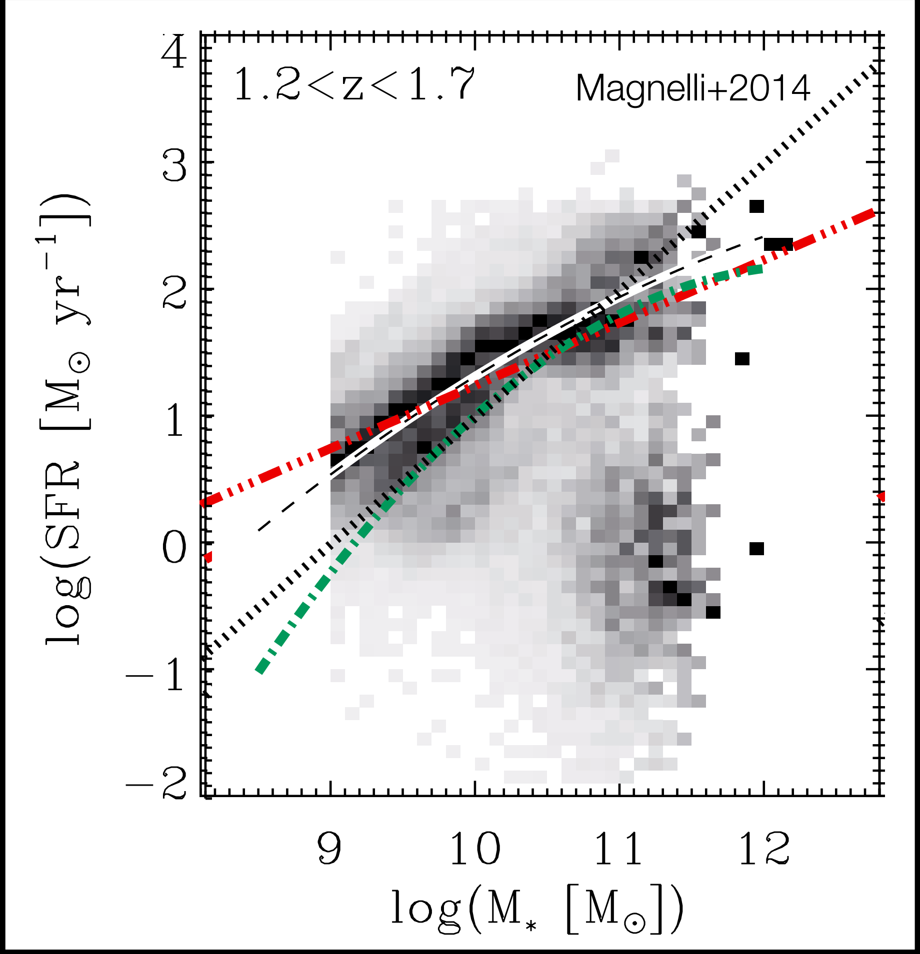
Baryonic efficiency as function of mass



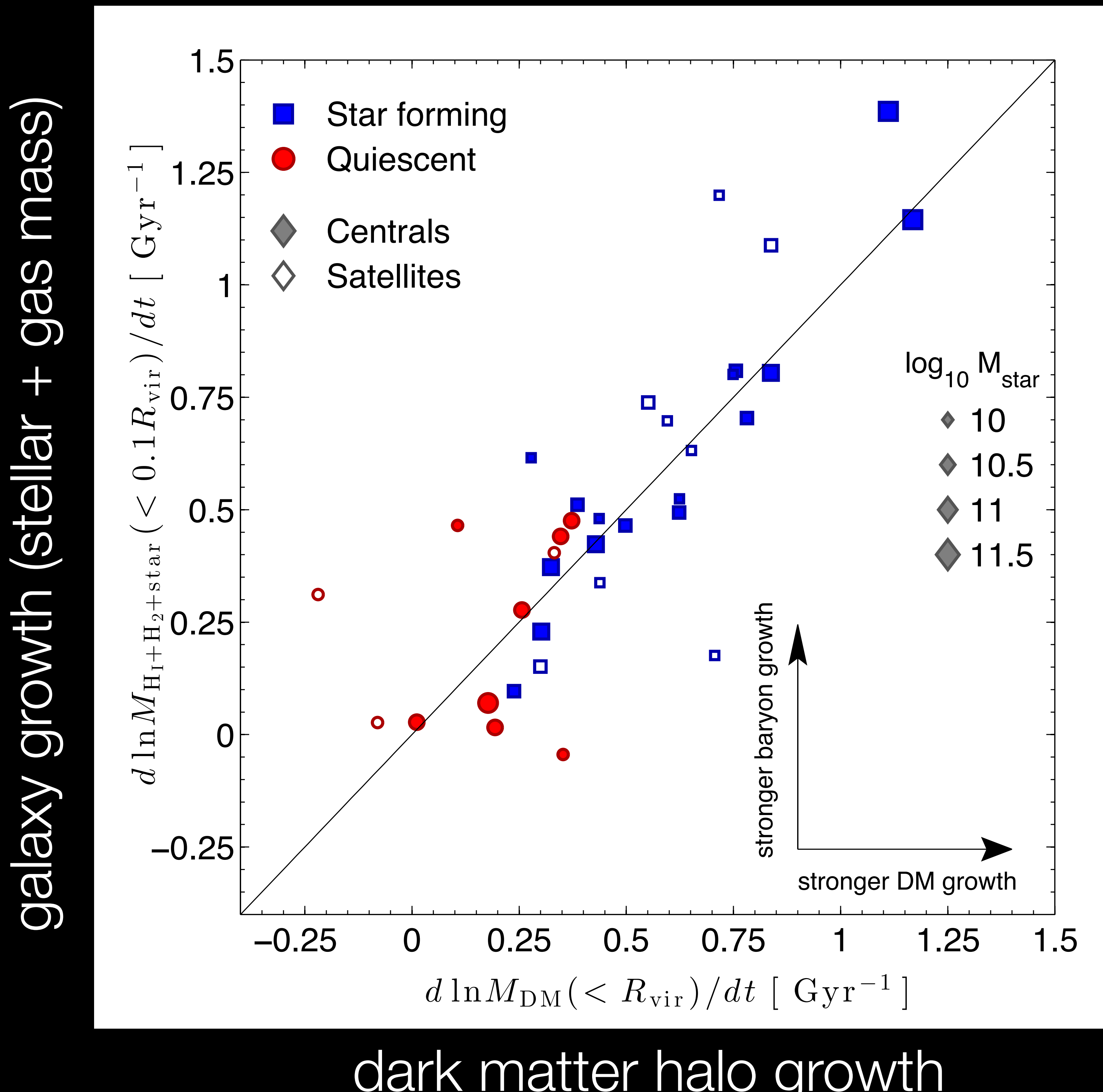
- Quenched fraction increases with mass
- Nature of ‘mass-quenching’?
  - AGN feedback
  - bulge-formation (central stellar density)
  - morphological quenching?
  - mass window of efficient SF?

The spread in SFR at fixed stellar mass

- Why some galaxies SF, others not?
  - environment?
  - mergers?
  - inflow of gas?
  - AGN on/off?
  - difference in halo mass?



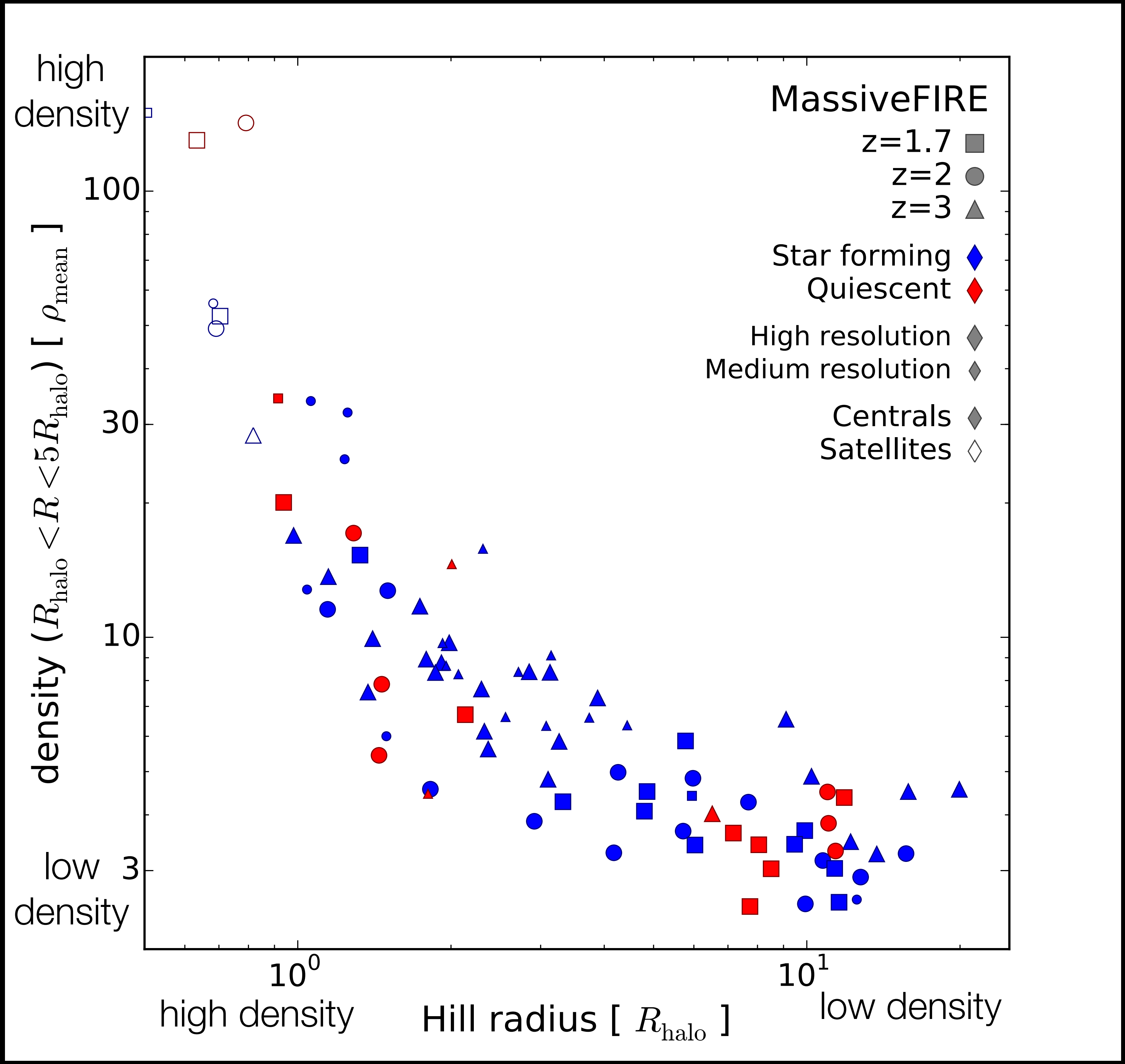
Connection with halo growth



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

Q galaxies reside preferentially in halos with low specific growth rates

Connection with environment



RF et al. 2017

- Progenitors of Q (SF) central galaxies reside in less (more) dense regions
- Can also become Q near overdensity

Gas

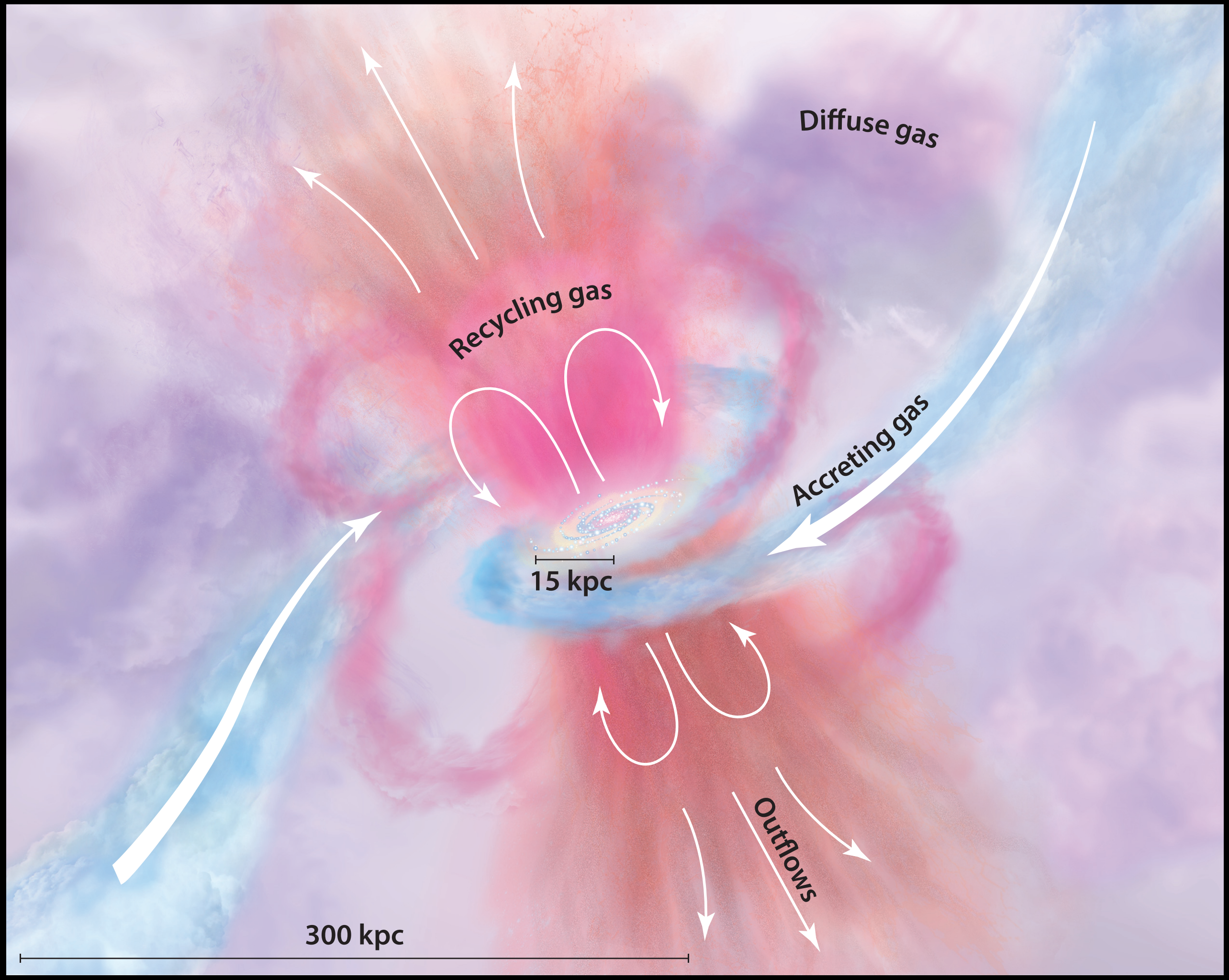
Tumlinson et al. 2017

Gas around massive galaxies

CGM

- X-ray emission; EUV - NUV absorption lines of metal ions; Lyman/Balmer of H
- multiphase ionization structure (both PIE, CIE), complex kinematical structure
- evidence for outflows, wind recycling

How does the gas cycle between IGM, CGM and ISM?

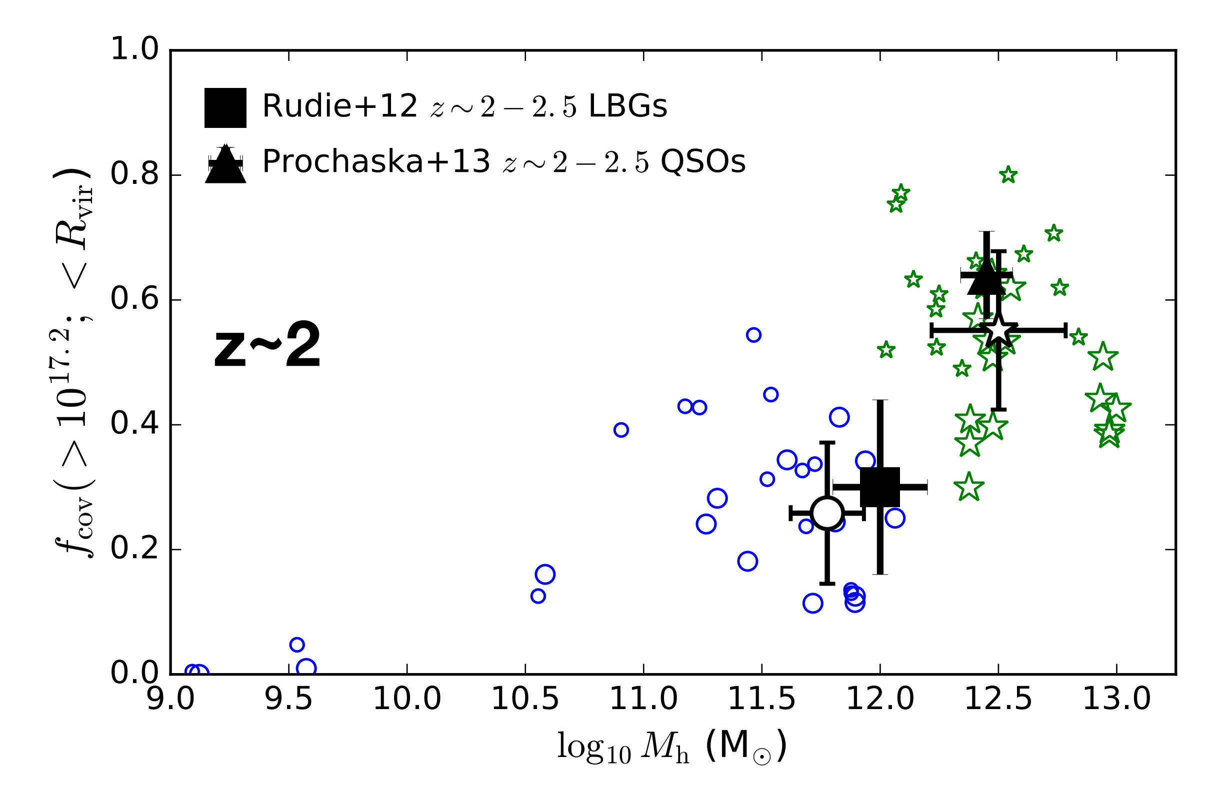


Tumlinson et al. 2017

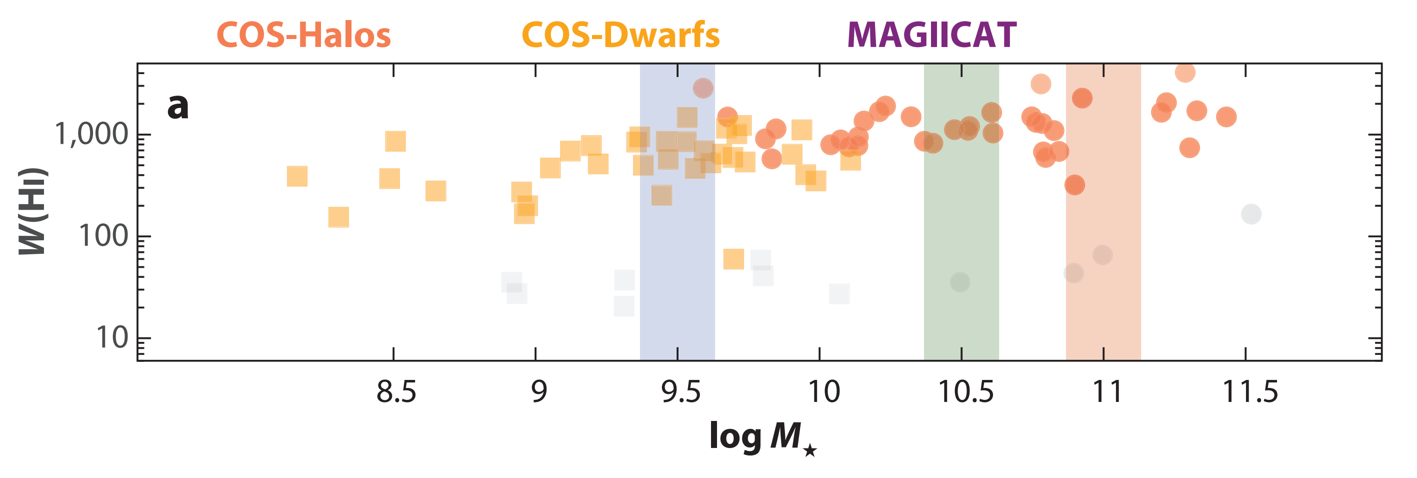
Gas around massive galaxies

CGM

- HI equivalent width and covering fractions do **not** decrease with halo mass
- cool gas in the halos of massive **quiescent** galaxies at high z



Faucher-Giguere, RF, et al. 2016, see also Rudie et al. 2012, Prochaska et al. 2013



Tumlinson et al. 2017, see also Thom et al. 2012, Tumlinson et al. 2013, Bordoloi et al. 2014

How does the cold gas end up there?

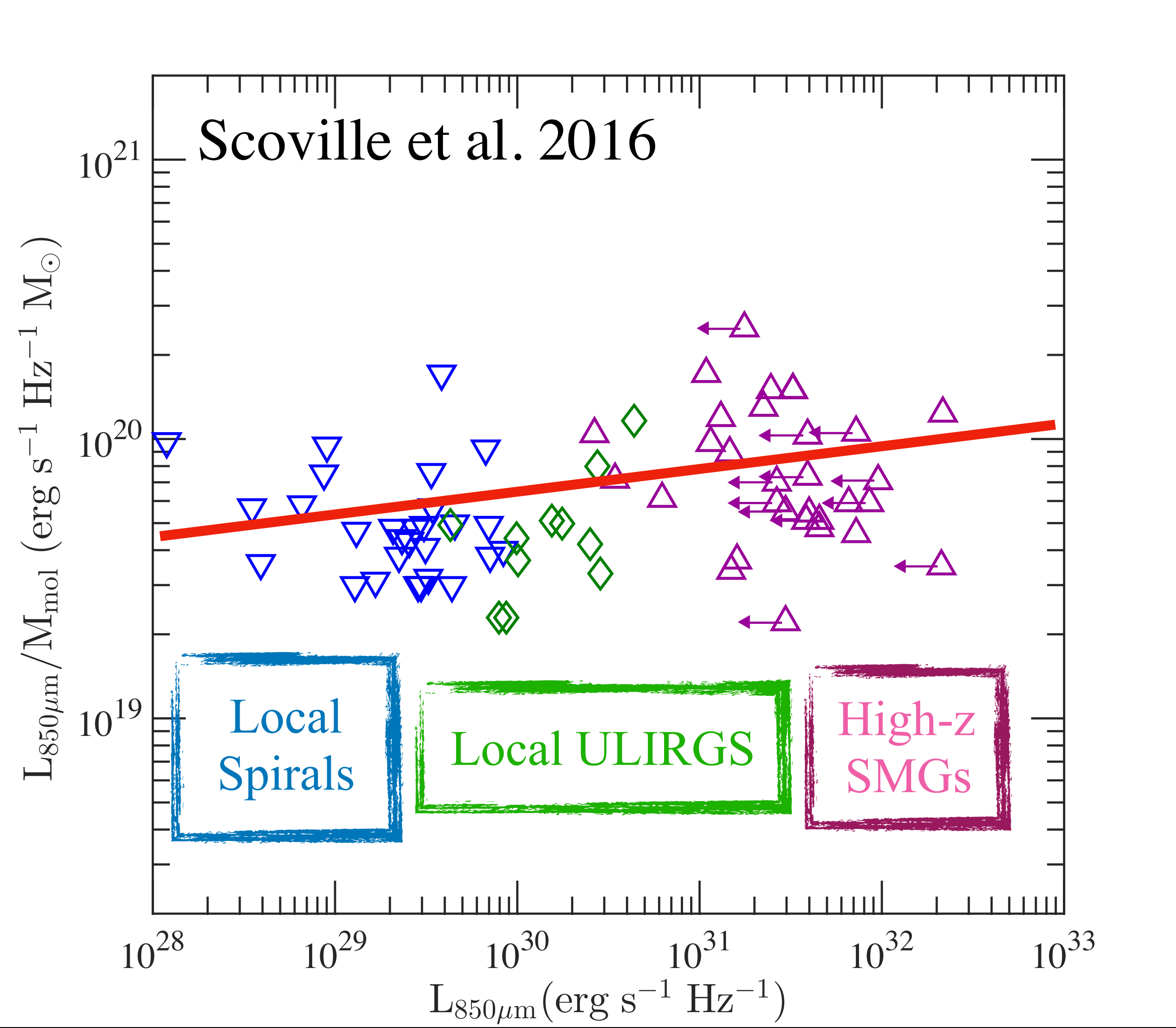
Why do galaxies quench with so much cold CGM?

Gas in massive, z~2 galaxies

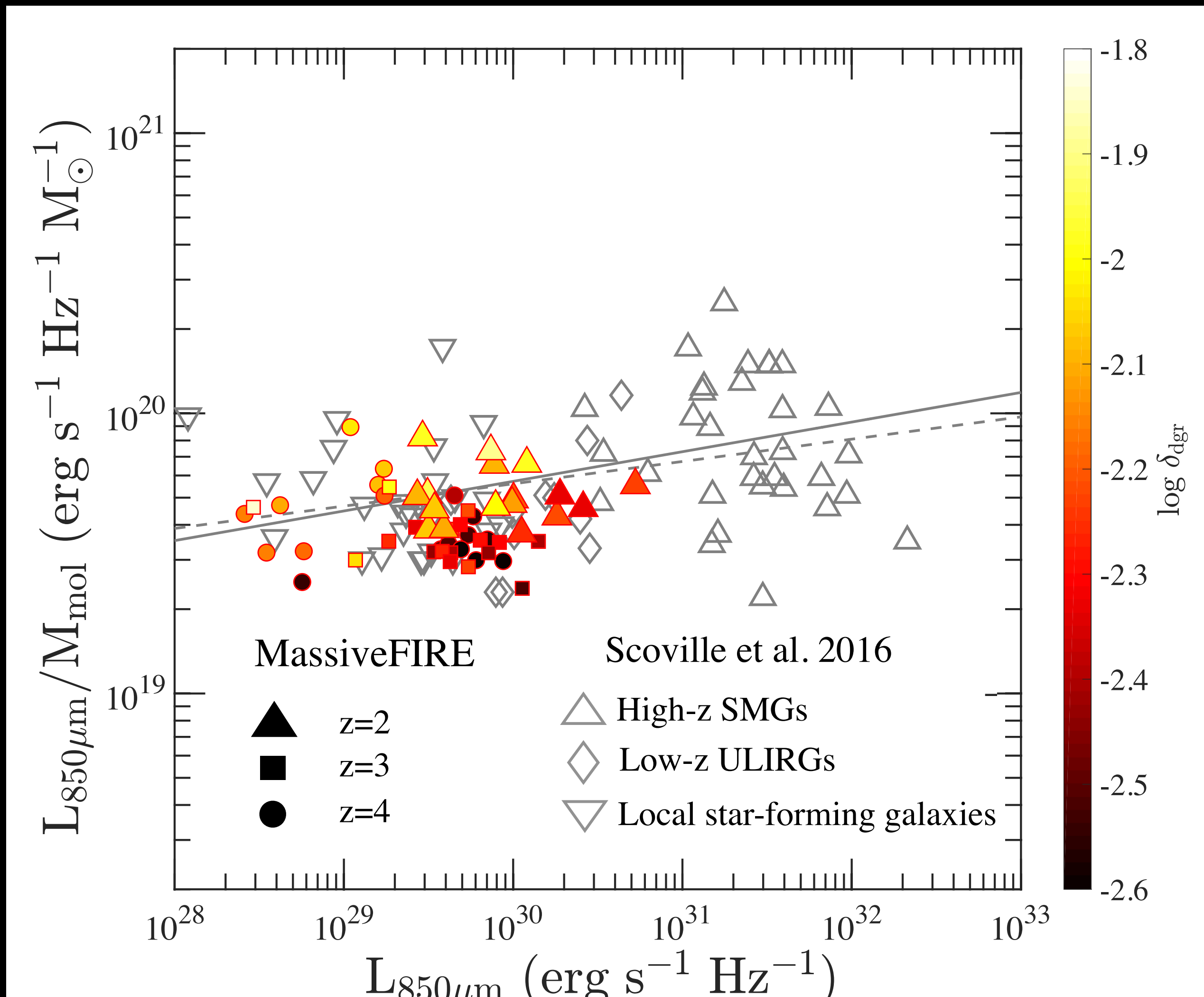
ISM

- <u>CO line emission:</u>
  - molecular gas
  - rotation ladder => physical state of the gas
  - kinematics, redshift
  - ISM mass estimates suffer from X-factor uncertainties
  - long exposure times

- <u>RJ-tail dust continuum emission:</u>
  - fast (~minutes per galaxy with ALMA)
  - possible with a single band (e.g, 850 micron)
  - negative K-correction
    => high z as easy as low z at fixed band (as long as within RJ-tail)
  - perfect for large scale studies

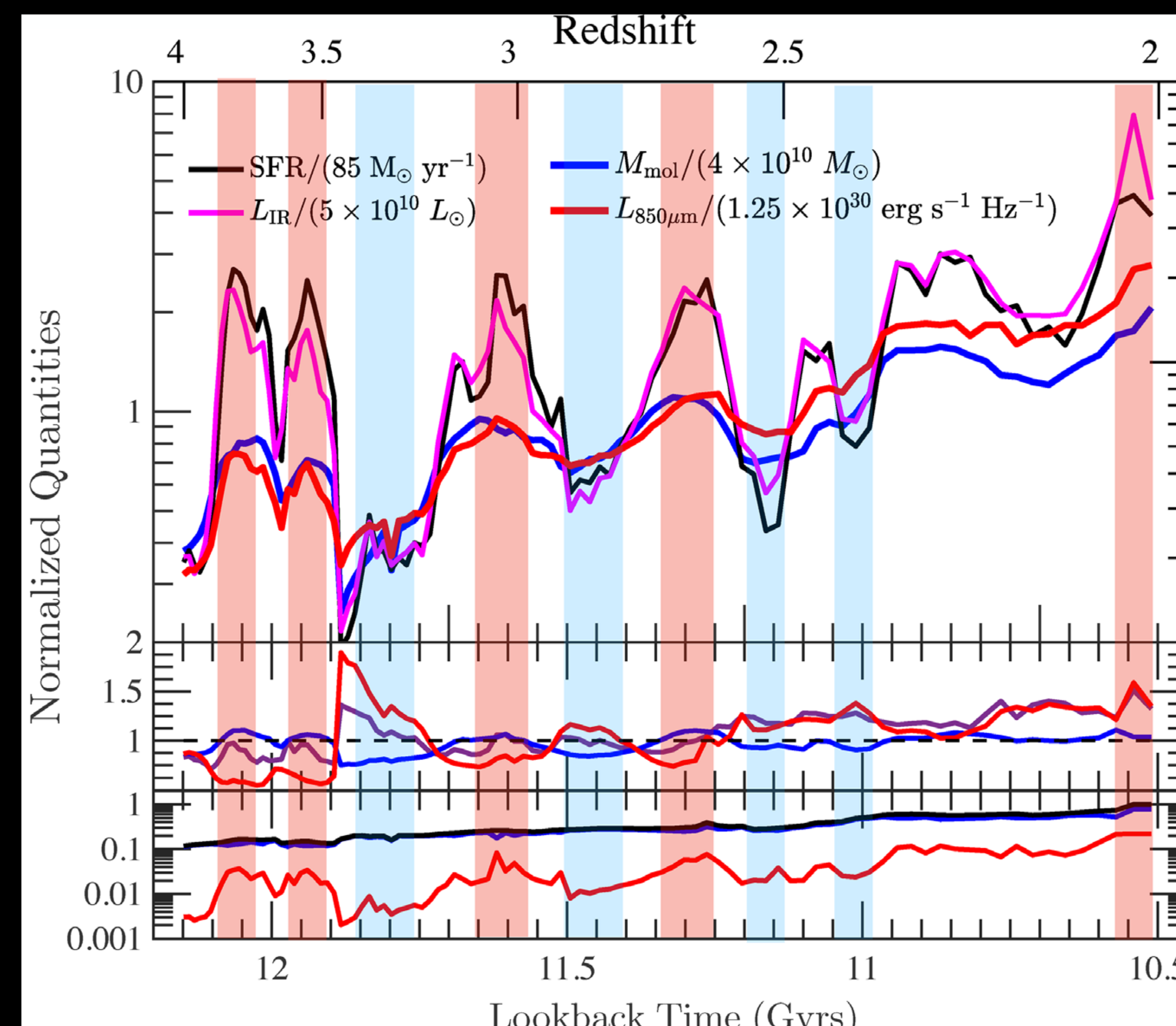


Probing ISM masses with FIR at z~2-4



Liang et al. 2018

- Radiative transfer analysis of cosmological simulations (MassiveFIRE)
- ISM / 850 micron conversion factor reproduced

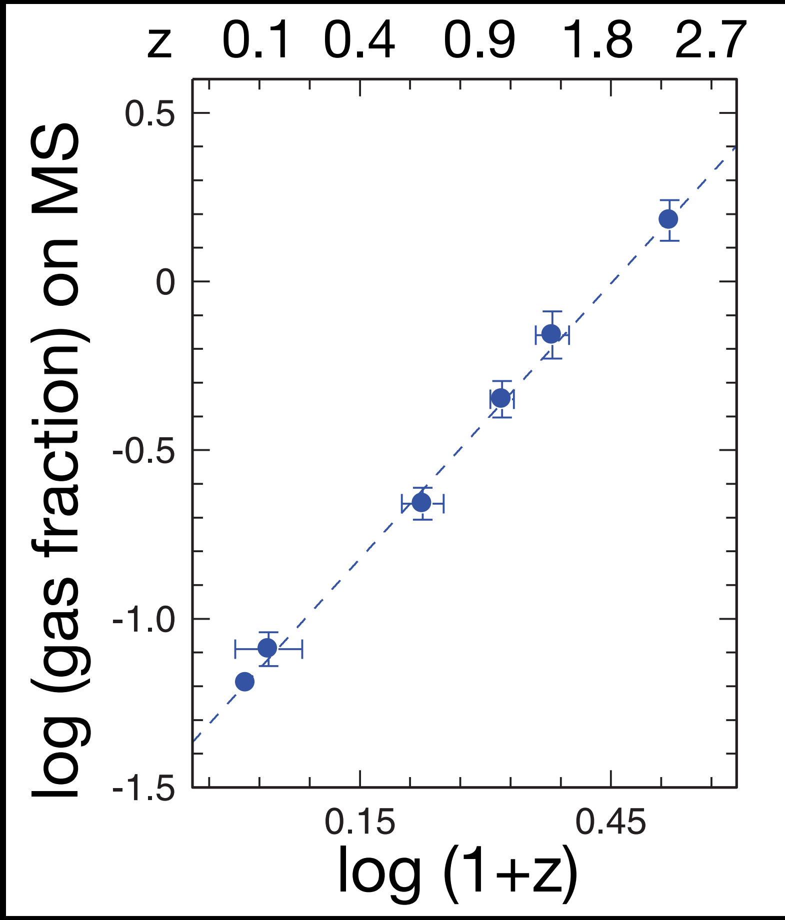


- conversion factor works even during (moderate) starbursts
- trend with 850 micron luminosity
- trend with dust-to-gas ratio

Gas in massive, z~2 galaxies

Gas fractions

- molecular gas fraction increases with redshift
- at fixed z, gas fraction
  - increases with pos. offset from the main sequence
  - **decreases with stellar mass**
- many massive galaxies at high z are gas & dust rich

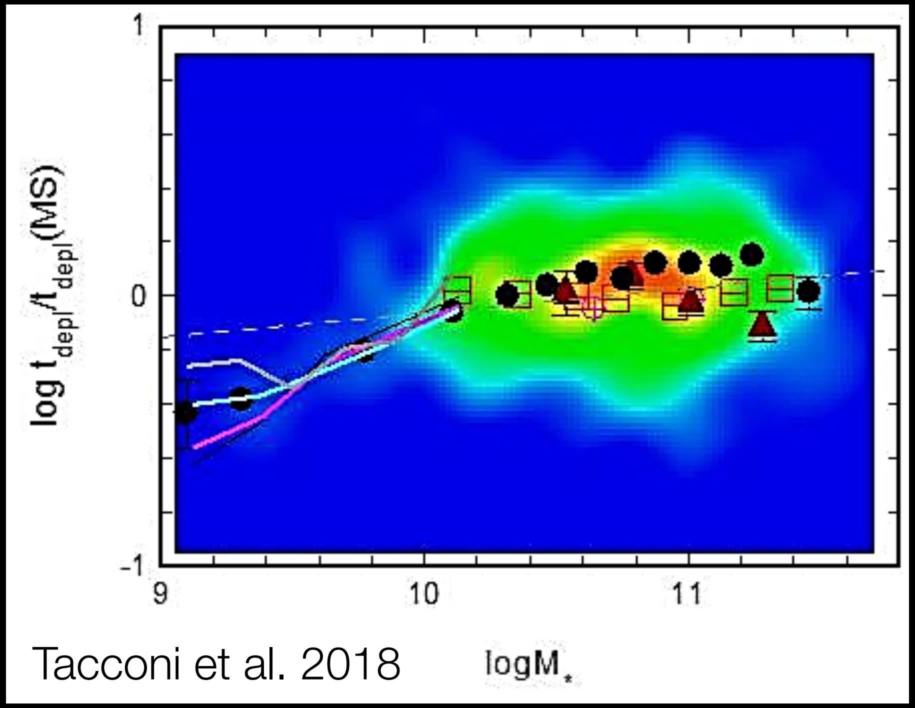


Genzel et al. 2015, see also Saintonge et al. 2013, Tacconi et al. 2013

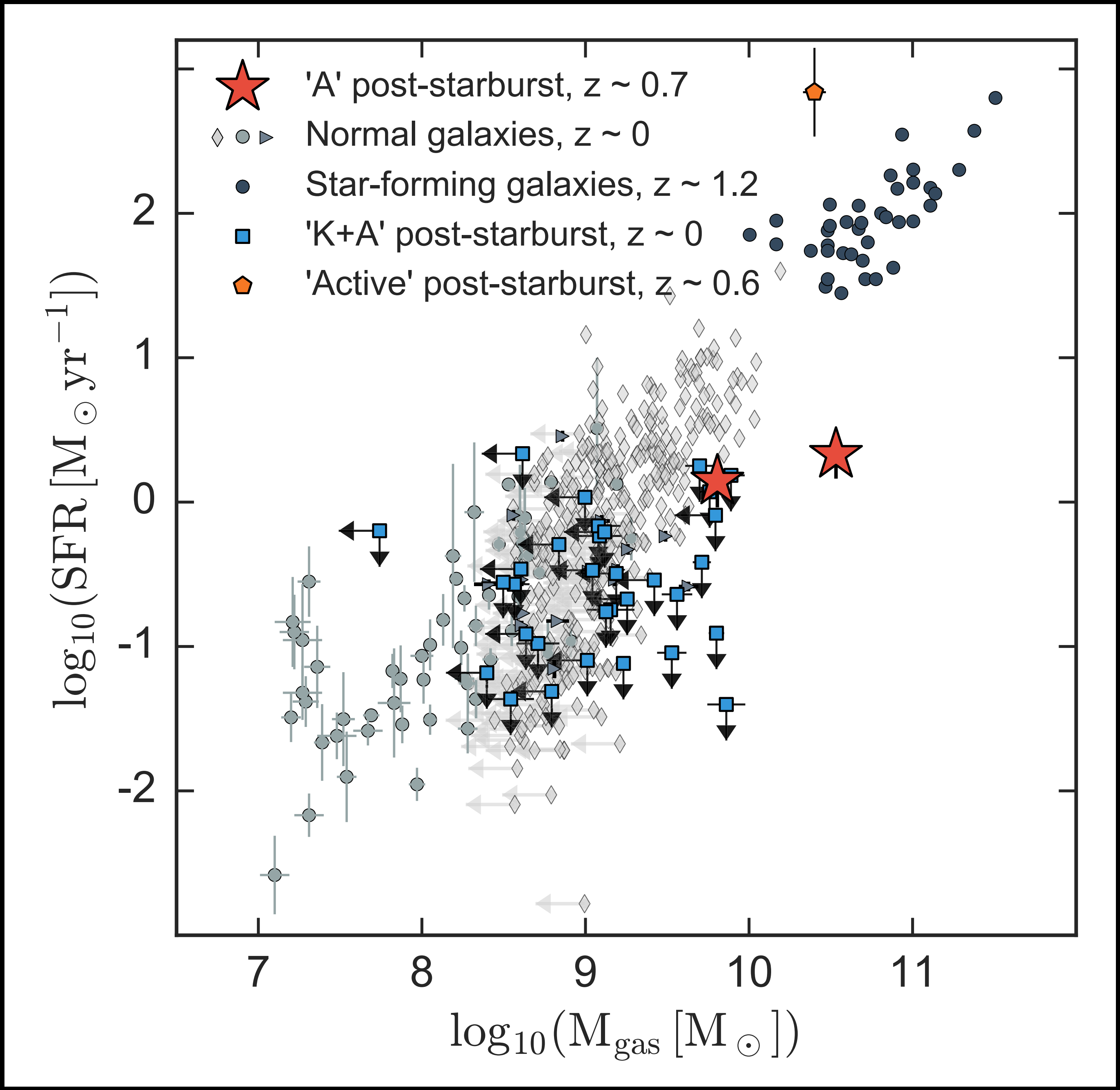
Gas depletion times

- decreases with increasing redshift ($\sim(1+z)^{-0.6}$)
- decreases with increasing sSFR (relative to MS)
- **does not significantly scale with mass**

Suggestive: Quenching related to gas supply



Gas in massive post-starburst galaxies at z~0.7



Suess et al. 2017, see also Hunt et al. 2018

- $M^* \sim 2 \times 10^{11}\ M_\odot$
- M_{gas}: CO(2-1), $\alpha_{CO} = 4$, 1.0 line ratio
- log M_{gas}: 9.8, 10.5
- SFR from [OII]

Quenching with plenty of molecular gas?

Obscured SF?

Summary

- Massive galaxies: formation & growth central to galaxy theory

- Complex physics: gas, star formation, BH growth

- Much of the action happens early on (z~2 and above)

- Major unsolved problems:

  Why large diversity at high z?

  Quiescent and SF galaxies different or a continuum?

  Why is peak epoch of SF also time of quenching?

  Cold CGM around massive, quiescent galaxies

  Cold ISM in massive, post-starburst galaxies