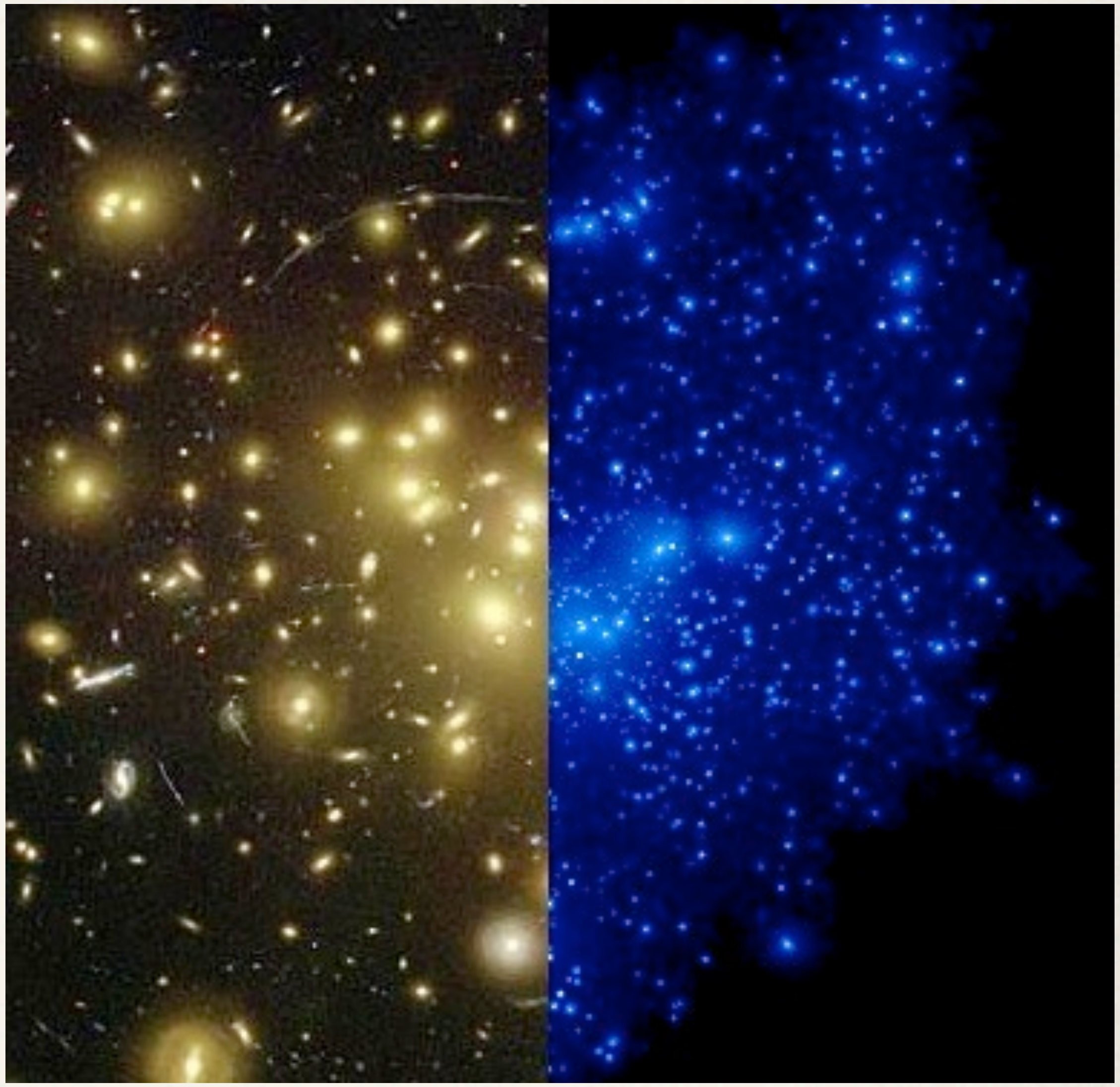
Galaxy Evolution in Groups & Clusters in a Hierarchical Universe



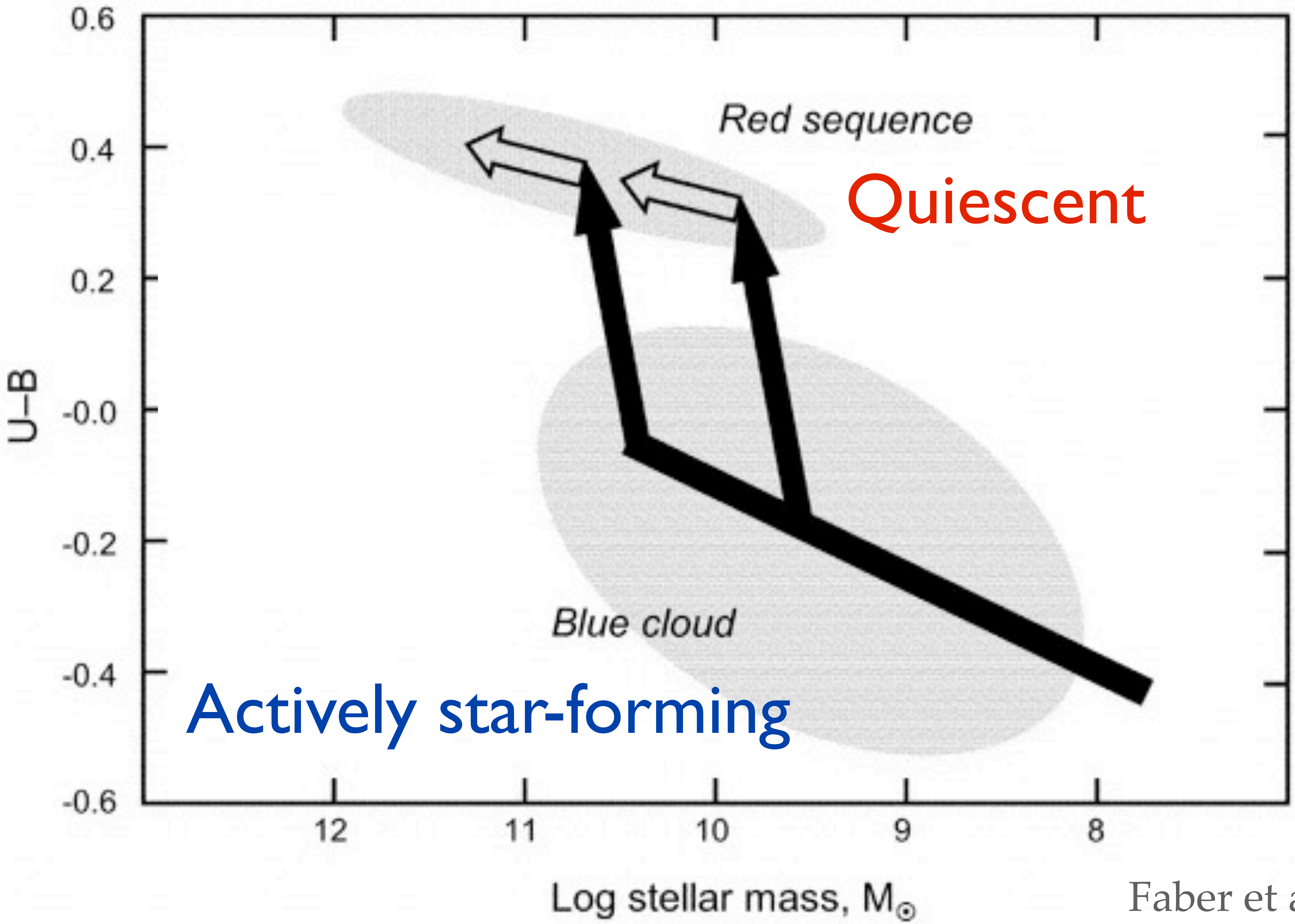
Andrew Wetzel

Yale University

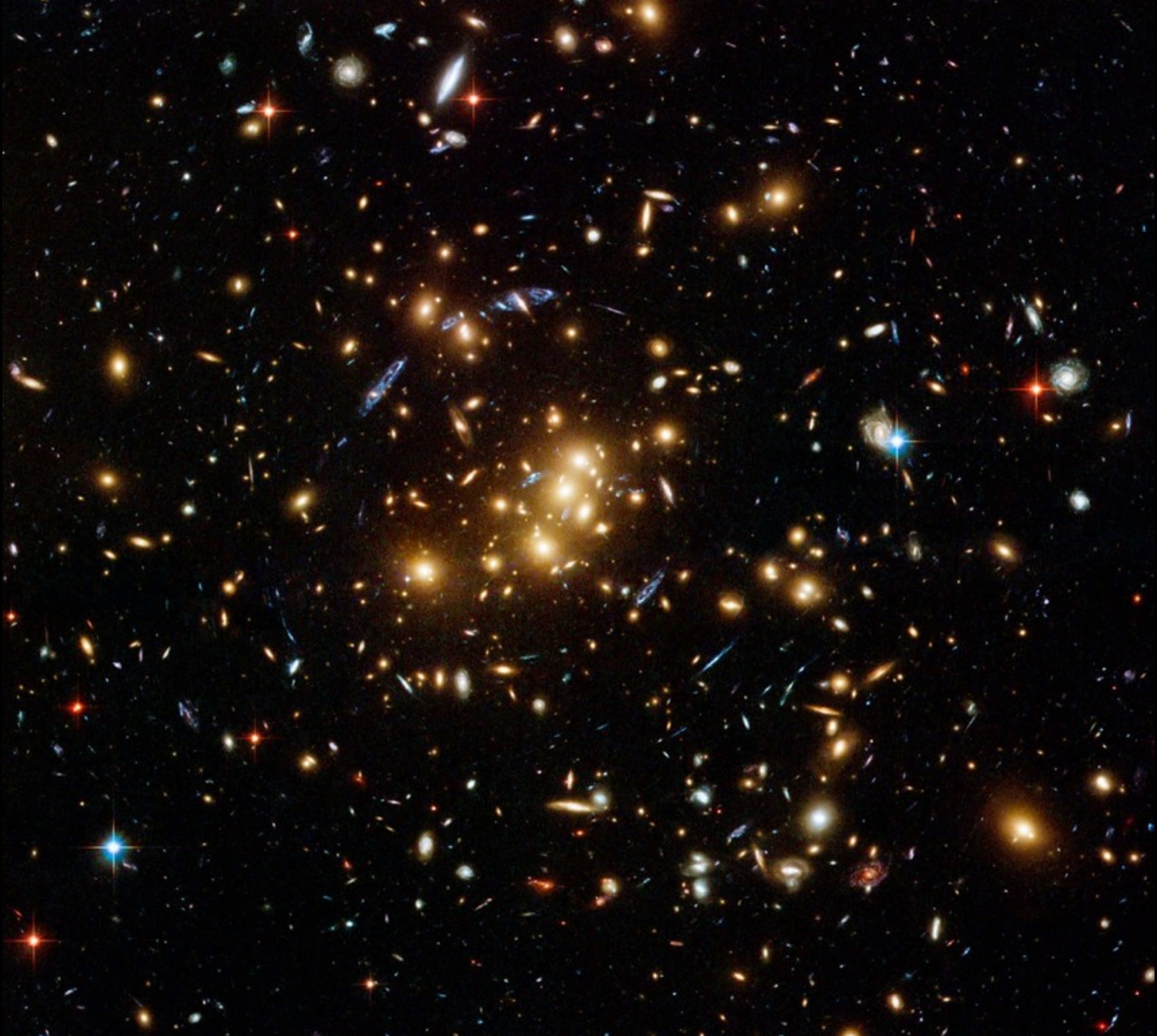
Kavli IPMU

February 6, 2013

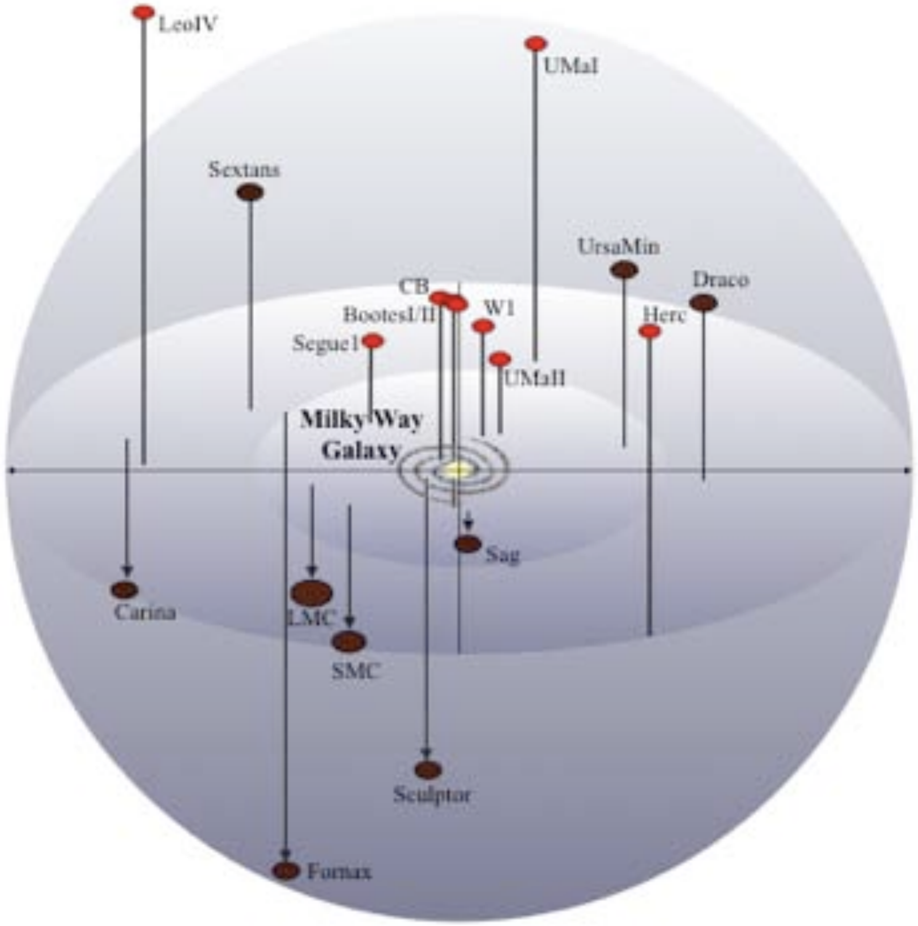
Star Formation in Galaxies

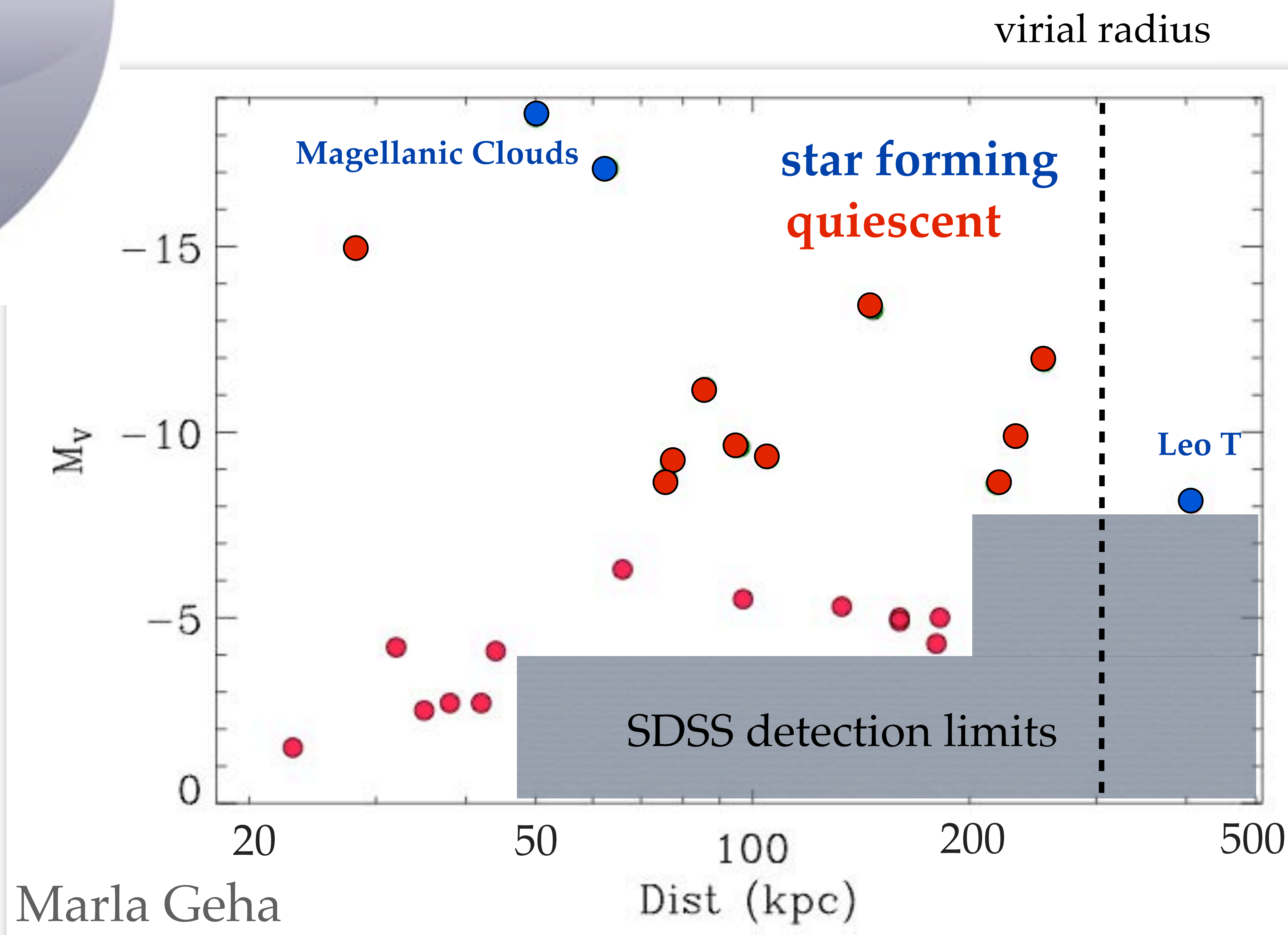


Faber et al 2007



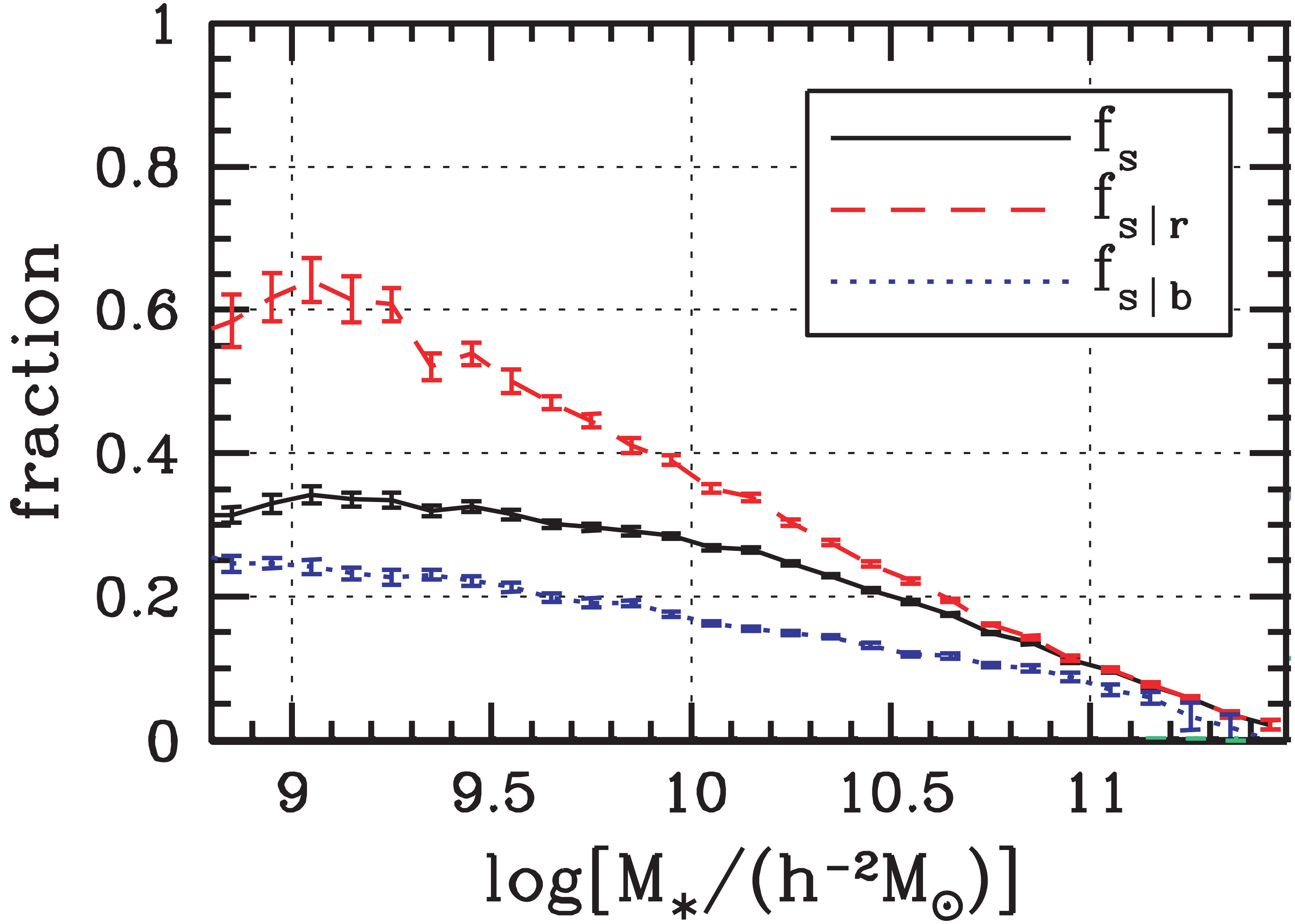
Satellites of the Milky Way Halo





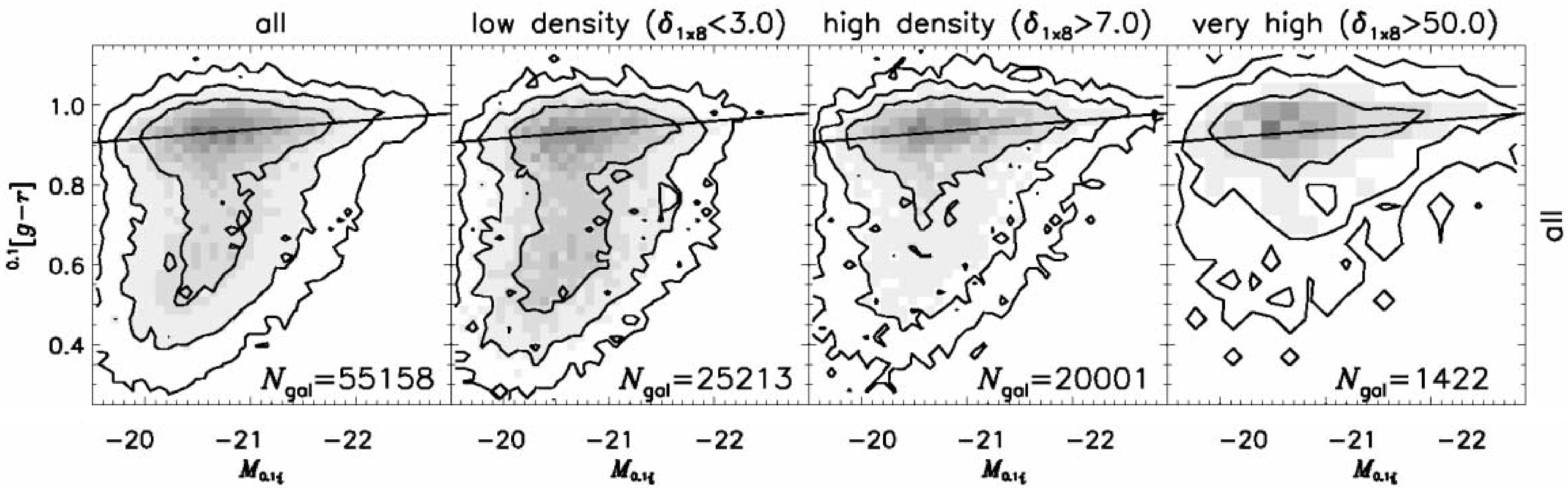
Importance of satellite galaxies in groups/clusters

van den Bosch et al 2008

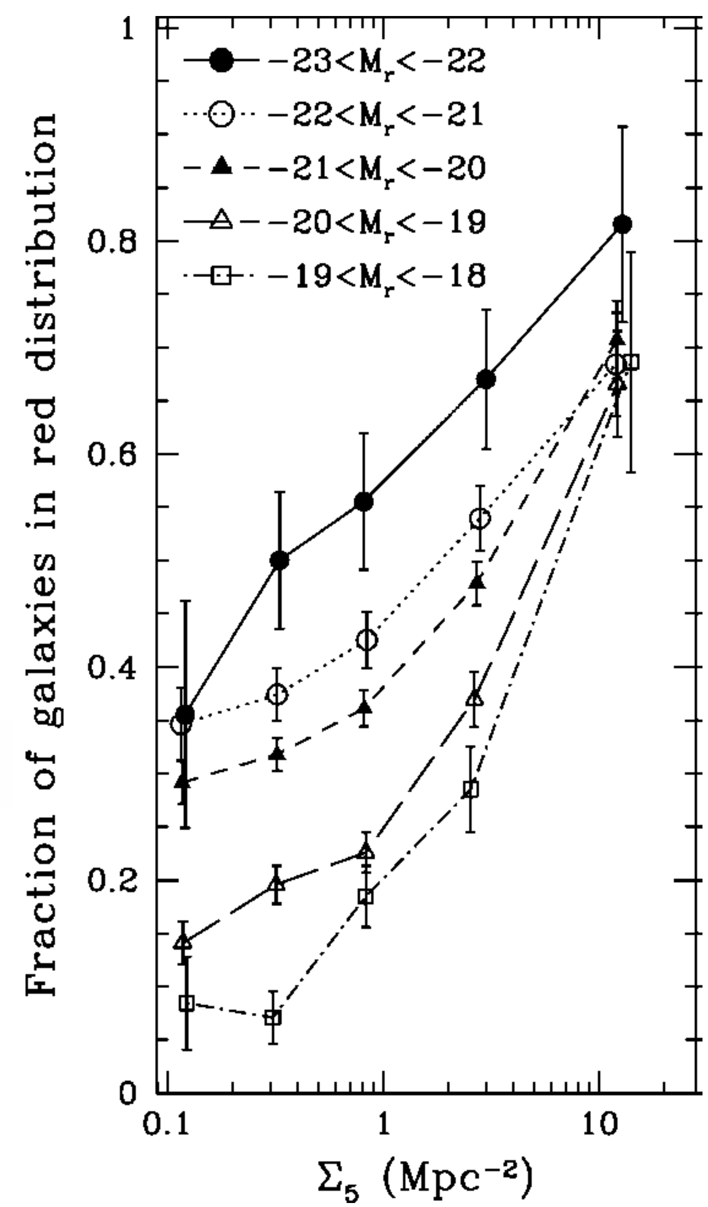


Galaxy properties depend on environmental density

Oemler 1974
Dressler 1980
Postman & Geller 1984



Hogg et al 2004



Balogh et al 2004

Outstanding questions about environmental quenching

What is the physical extent of environmental dependence?

How long does it take satellites to quench after infall?
How does SFR evolve in detail?

What is the physical mechanism for quenching satellites?

Collaborators

Jeremy Tinker

New York University

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UC Santa Cruz

Frank van den Bosch

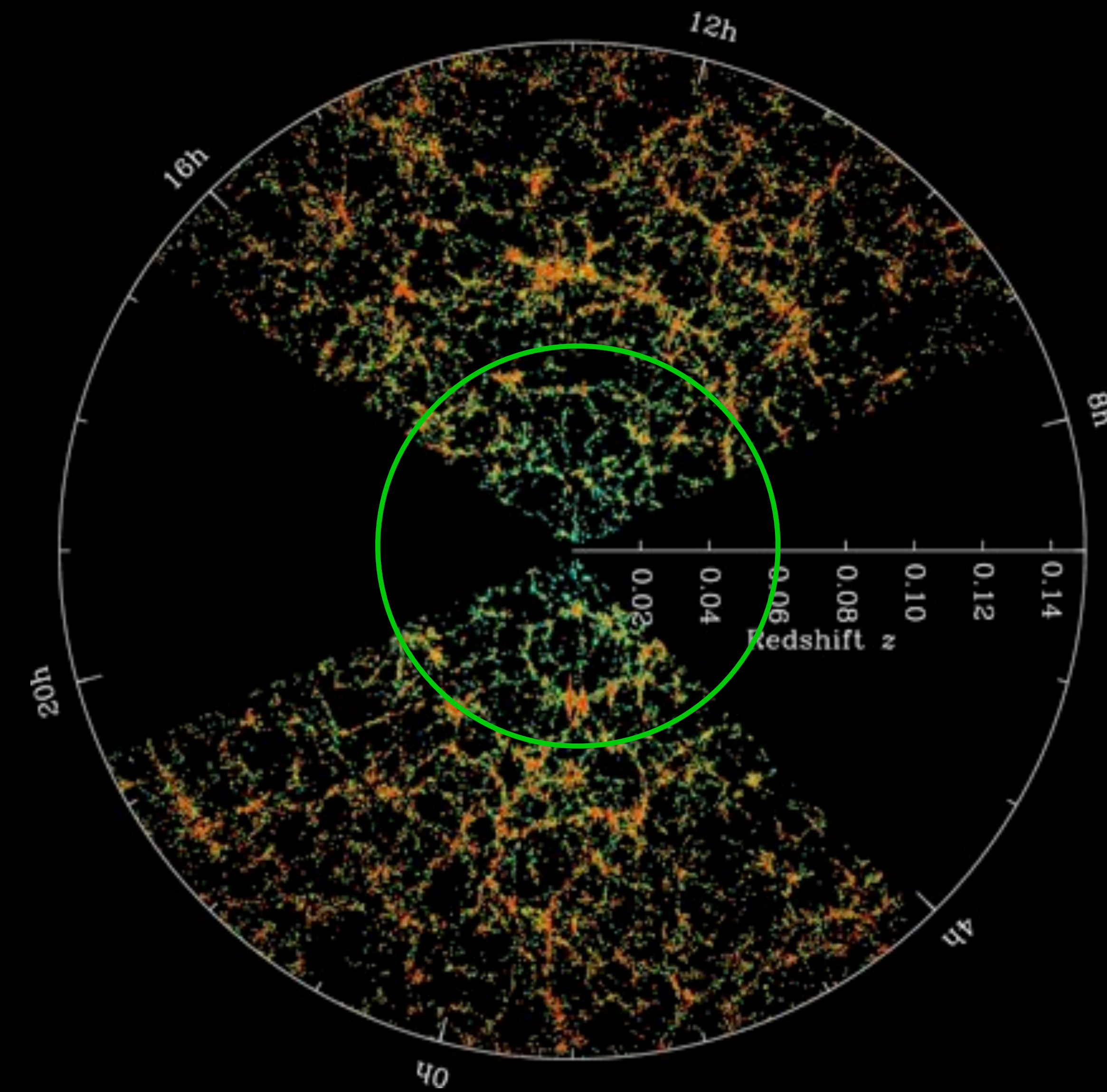
Yale University

Galaxy Catalog

SDSS Data Release 7: $z < 0.06$

NYU value-added spectroscopic catalog   Blanton et al 2004

Spectroscopically (Hα) derived star formation rates   Brinchmann et al 2004

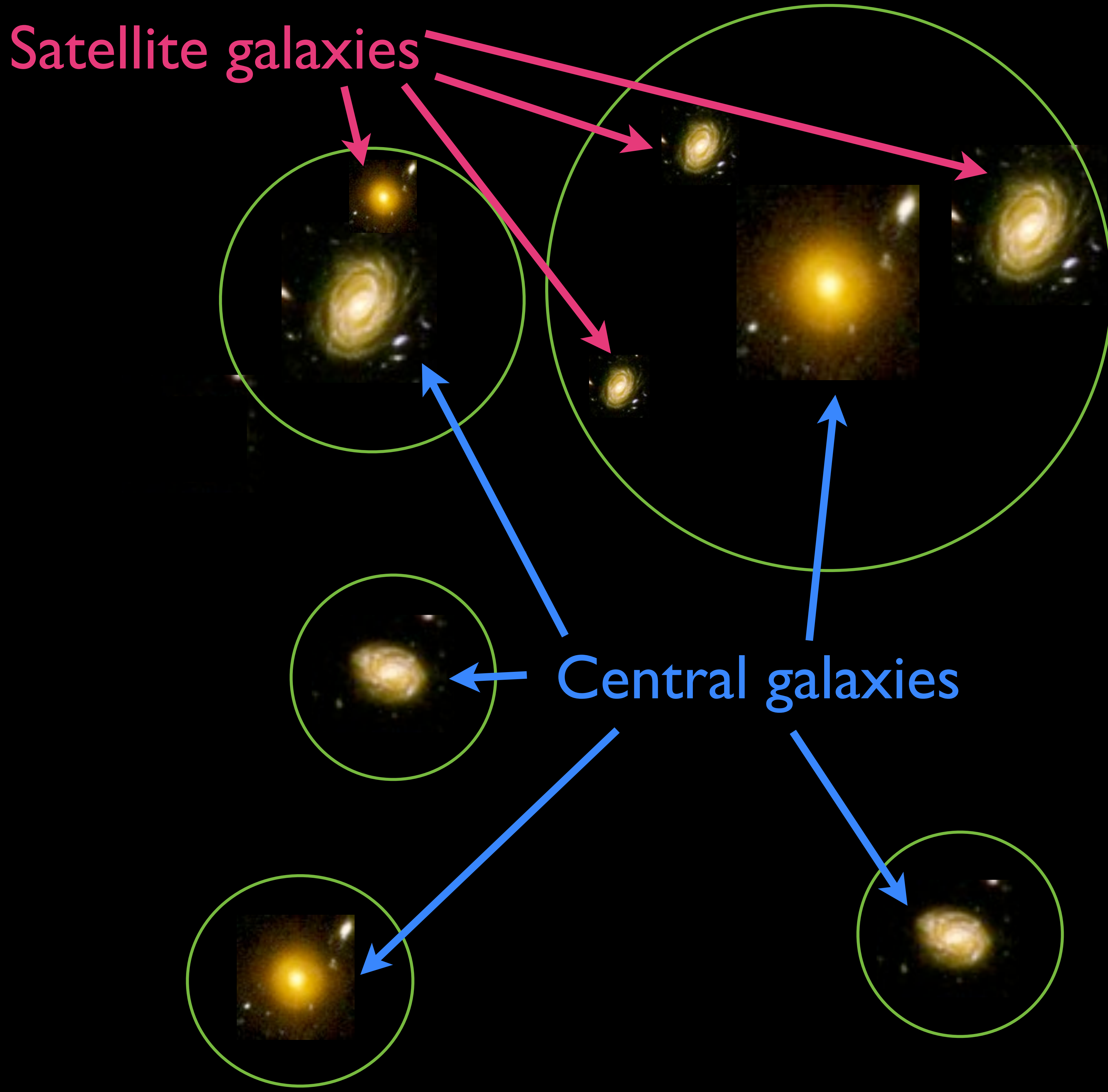


Galaxy Group Catalog   method of Yang et al 2007

Method of placing all galaxies in a ‘group’ (‘halo’)

Each group has one ‘central’ (most massive) & possibly several ‘satellite’ galaxies

High purity & low contamination (~15%) as calibrated against mock catalogs


Satellite galaxies
Central galaxies

Outstanding questions about environmental quenching

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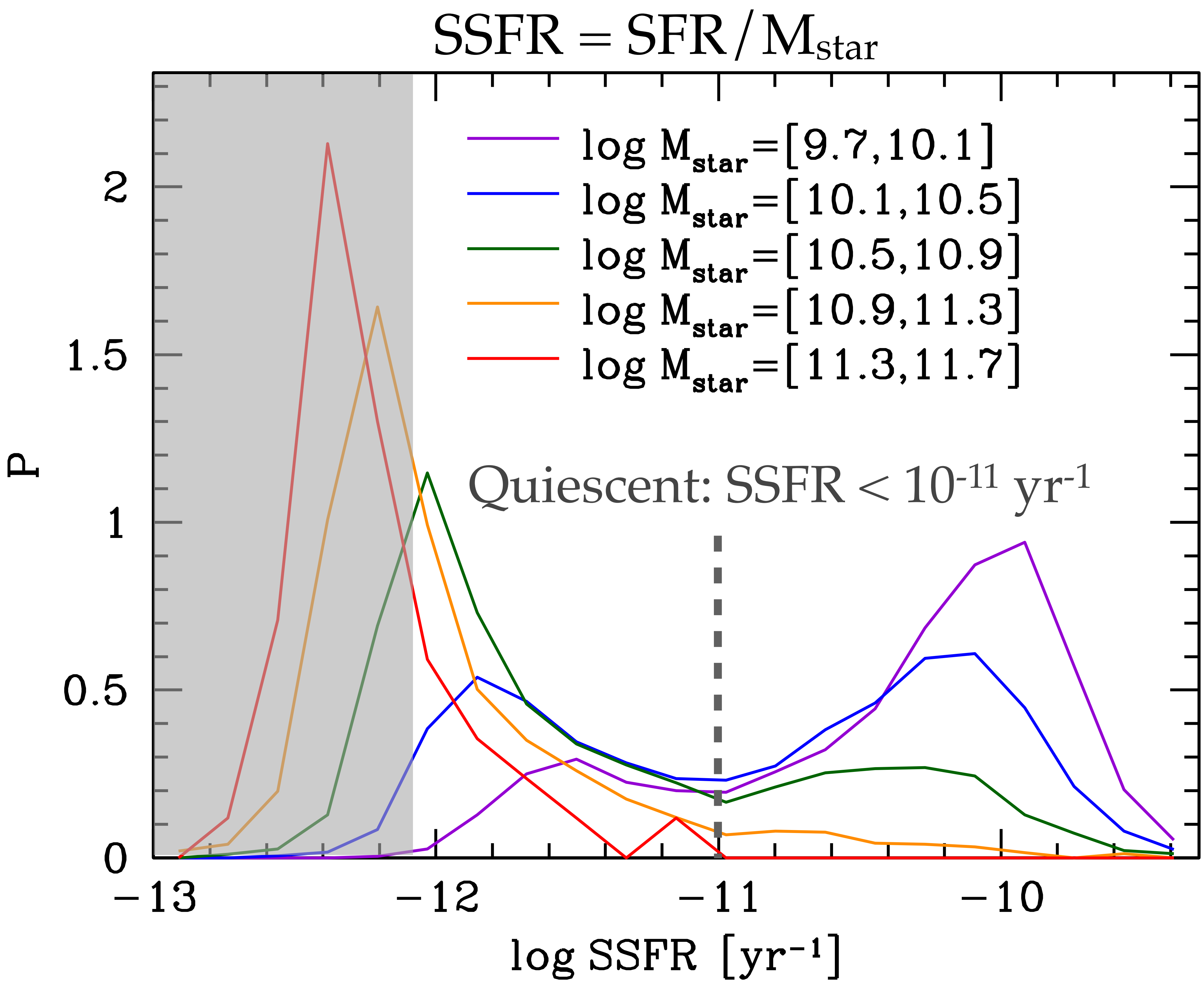
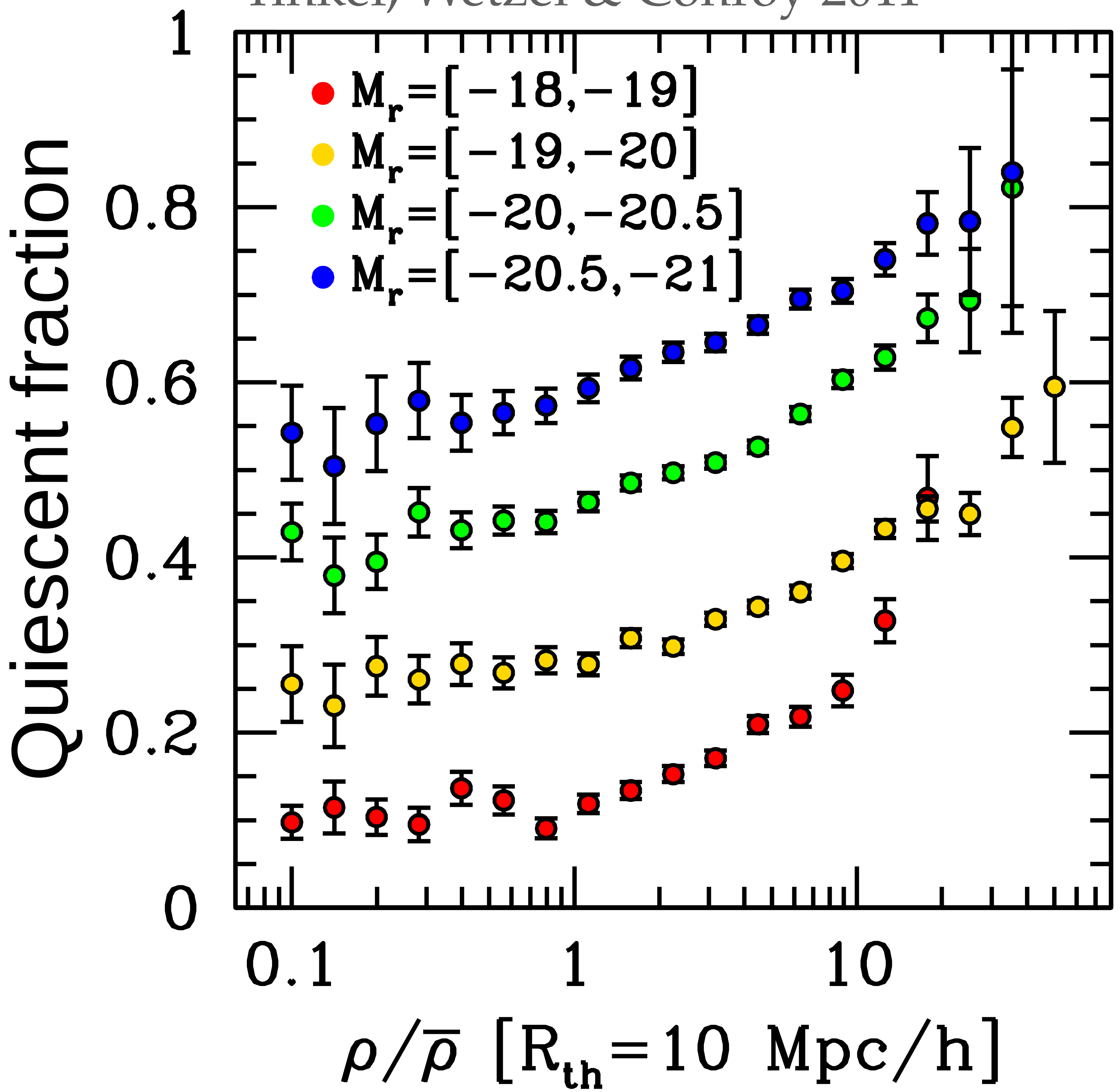
Star formation rate distribution of galaxies



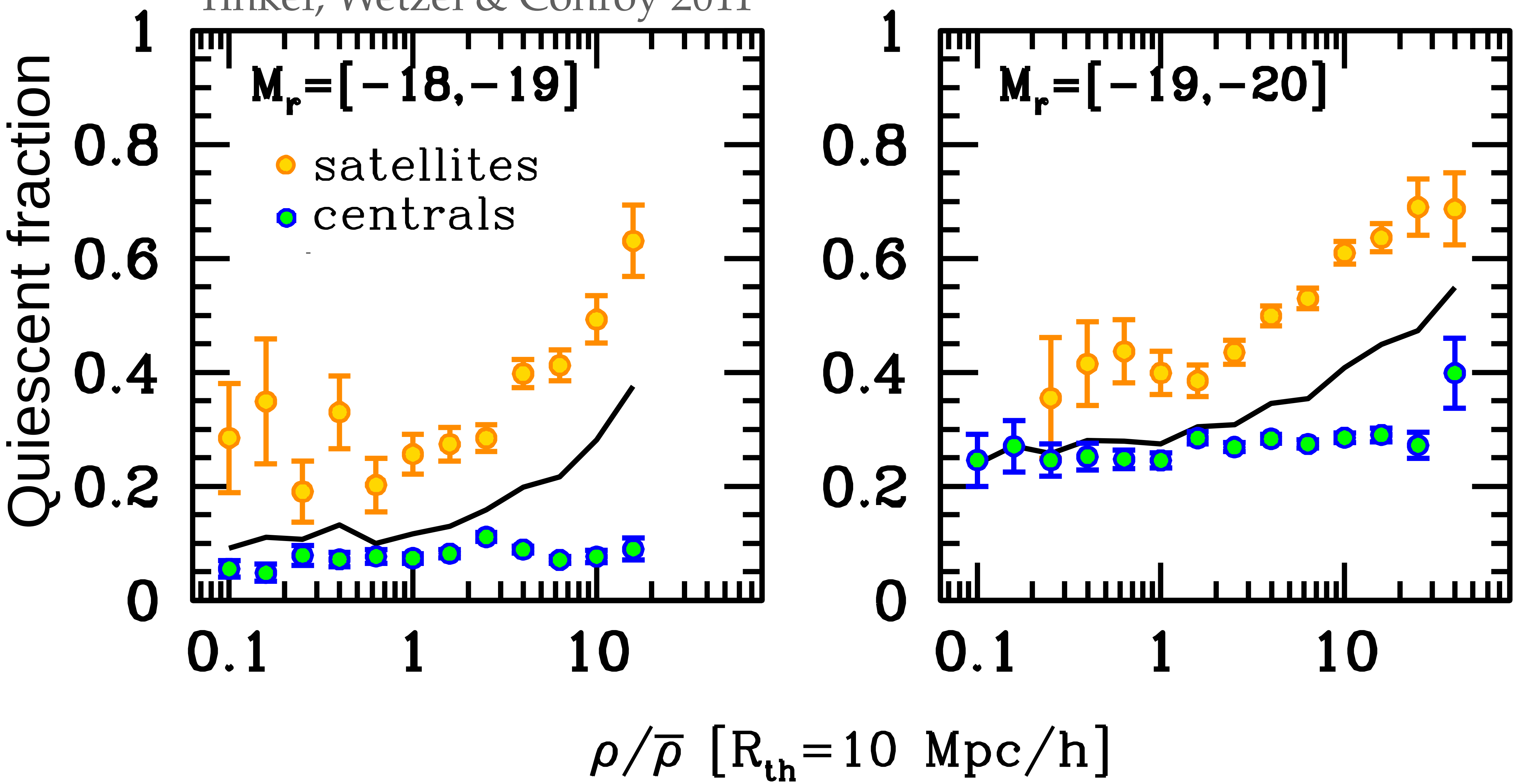
Environmental dependence of galaxy star formation

Tinker, Wetzel & Conroy 2011



Environmental dependence of galaxy star formation

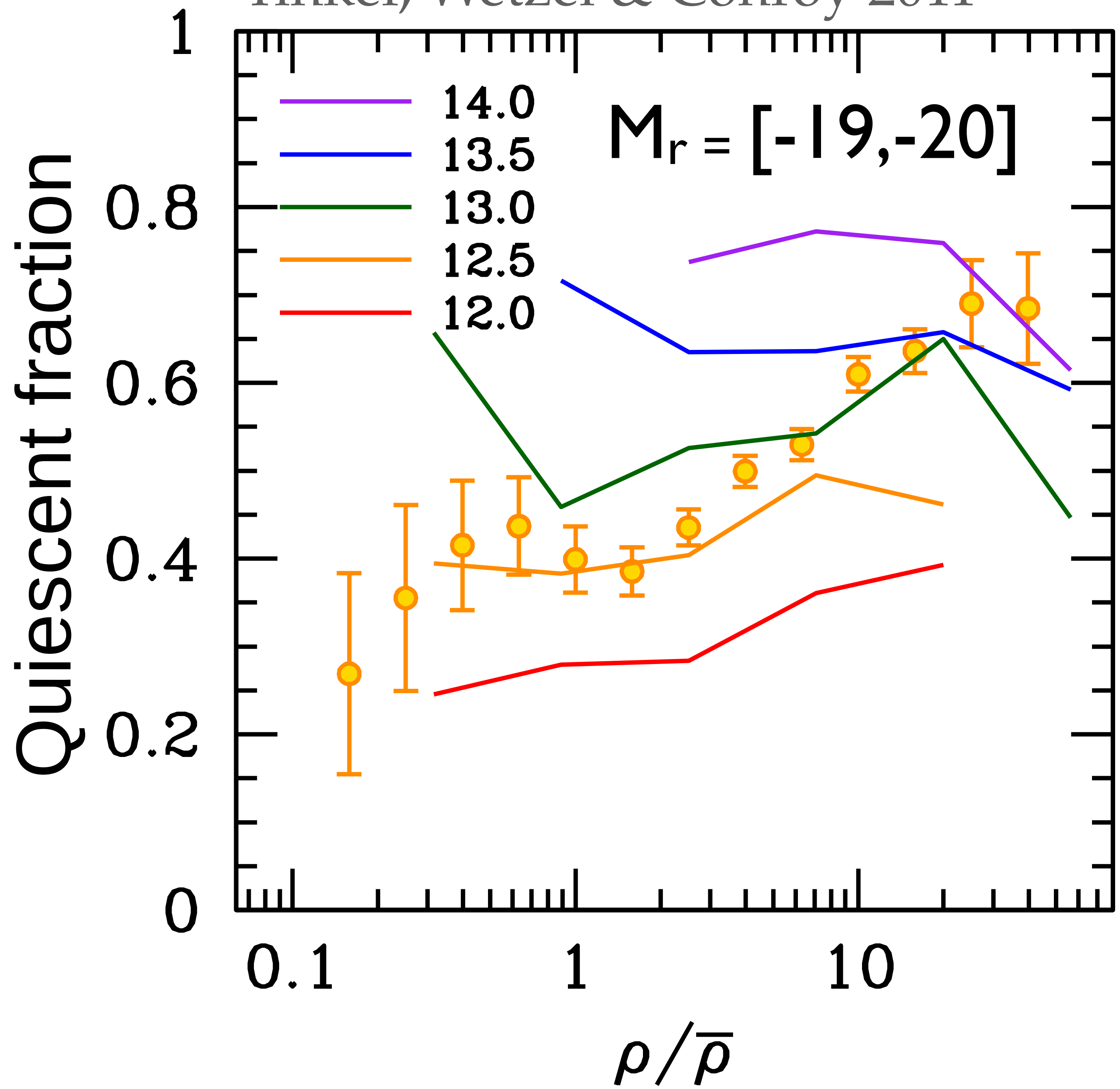
Tinker, Wetzel & Conroy 2011



- Environmental dependence = satellite galaxies

Environmental dependence of galaxy star formation

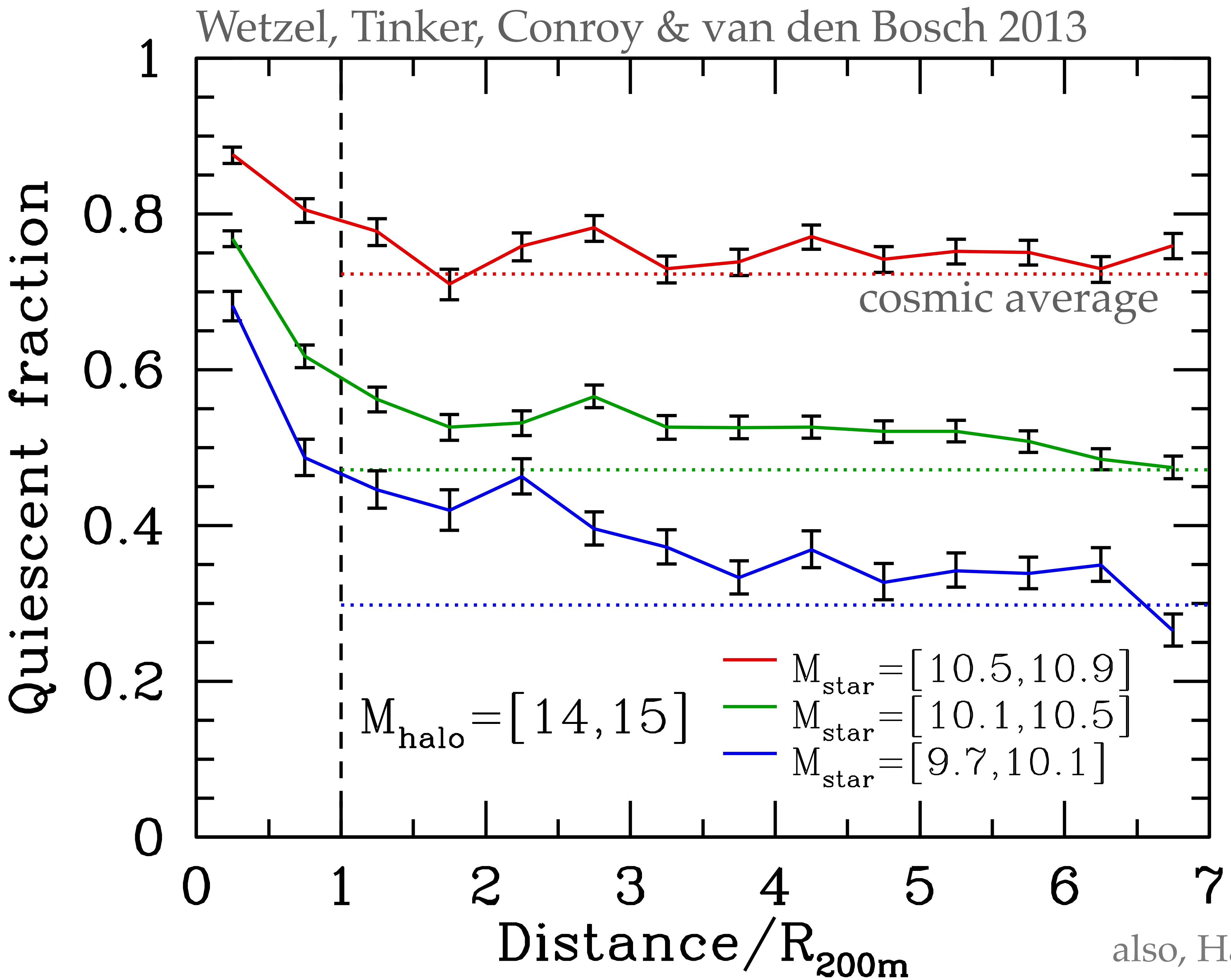
Tinker, Wetzel & Conroy 2011



also, Hogg et al 2004
Kauffmann et al 2004
Blanton et al 2005
Blanton & Berlind 2007
Wilman et al 2010
Peng et al 2010, 2011

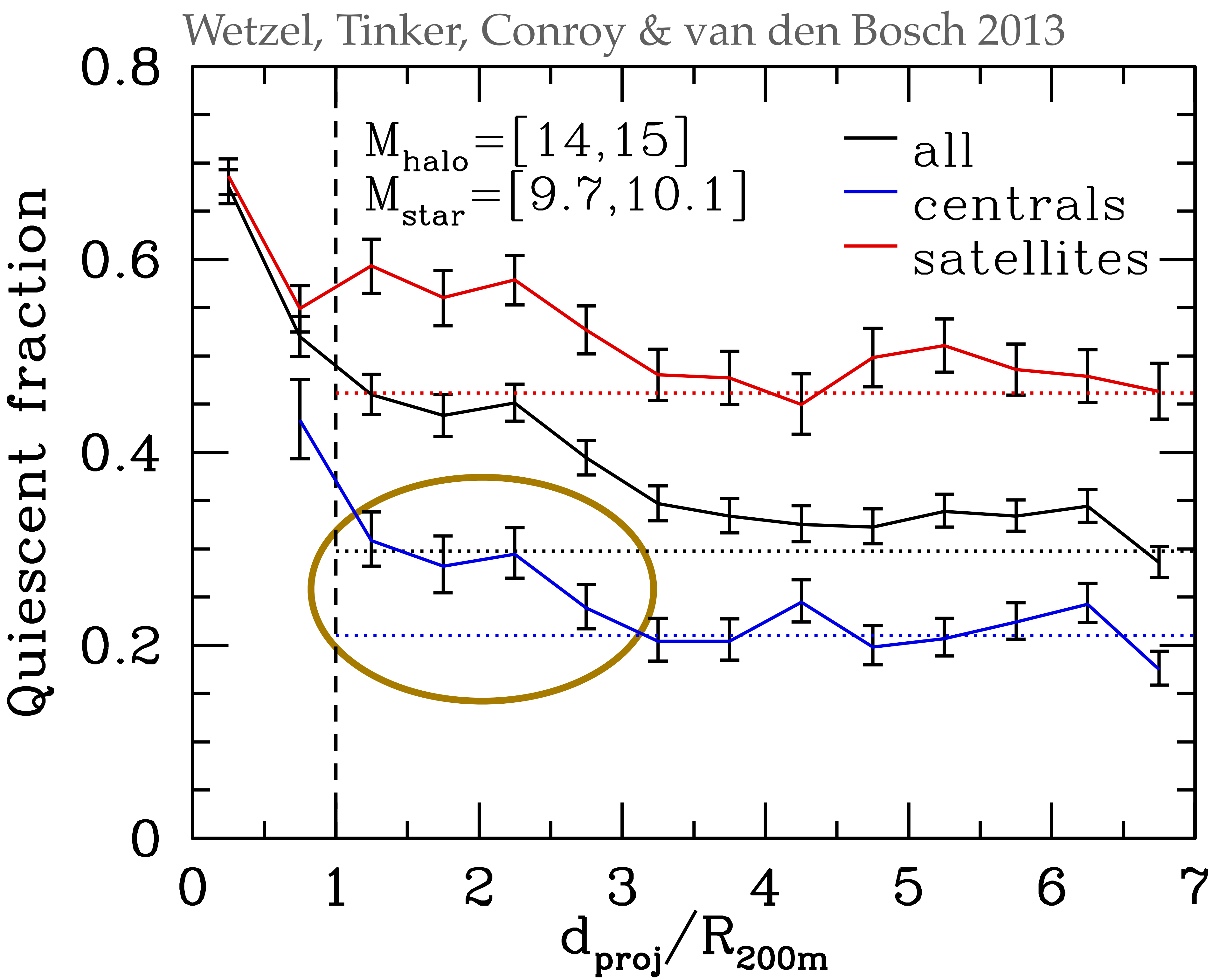
- Environmental dependence = satellites in different mass halos

Is SFR affected beyond the virial radius?



also, Hansen et al 2009
von der Linden et al 2010

Is SFR affected beyond the virial radius?



Outstanding questions about environmental quenching

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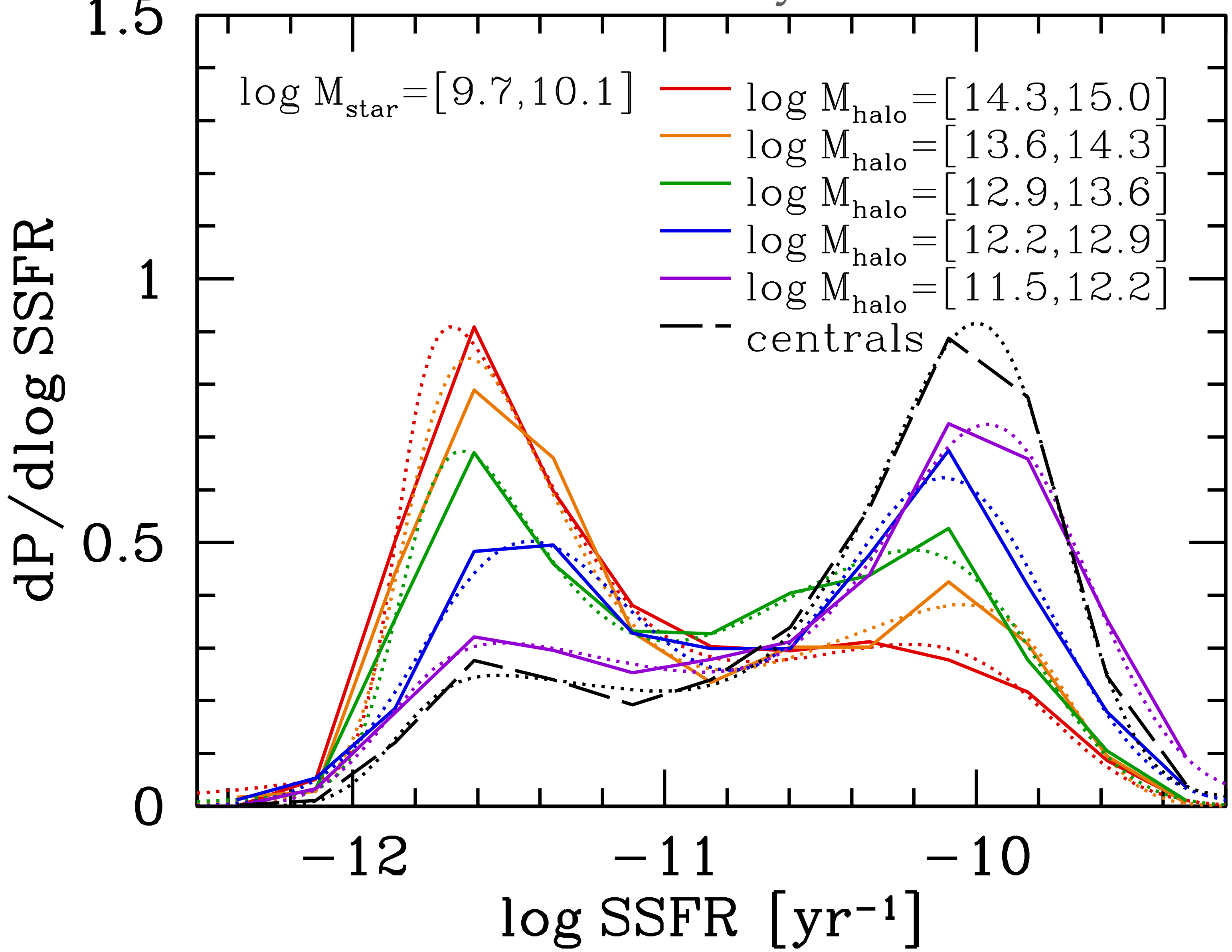
Specific Star Formation Rate Distribution

Wetzel, Tinker & Conroy 2011



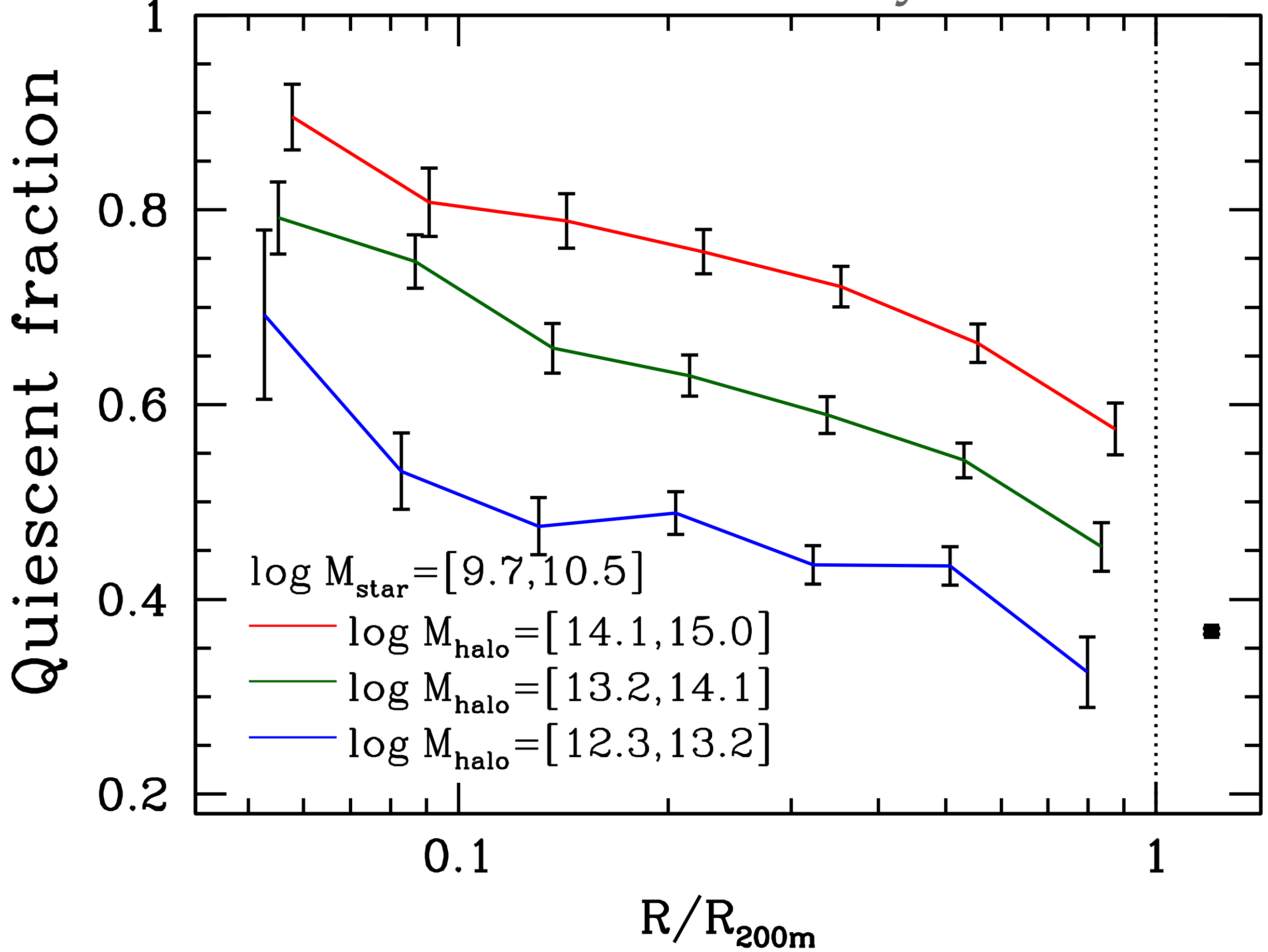
Satellite SFR depends on mass of its host halo...

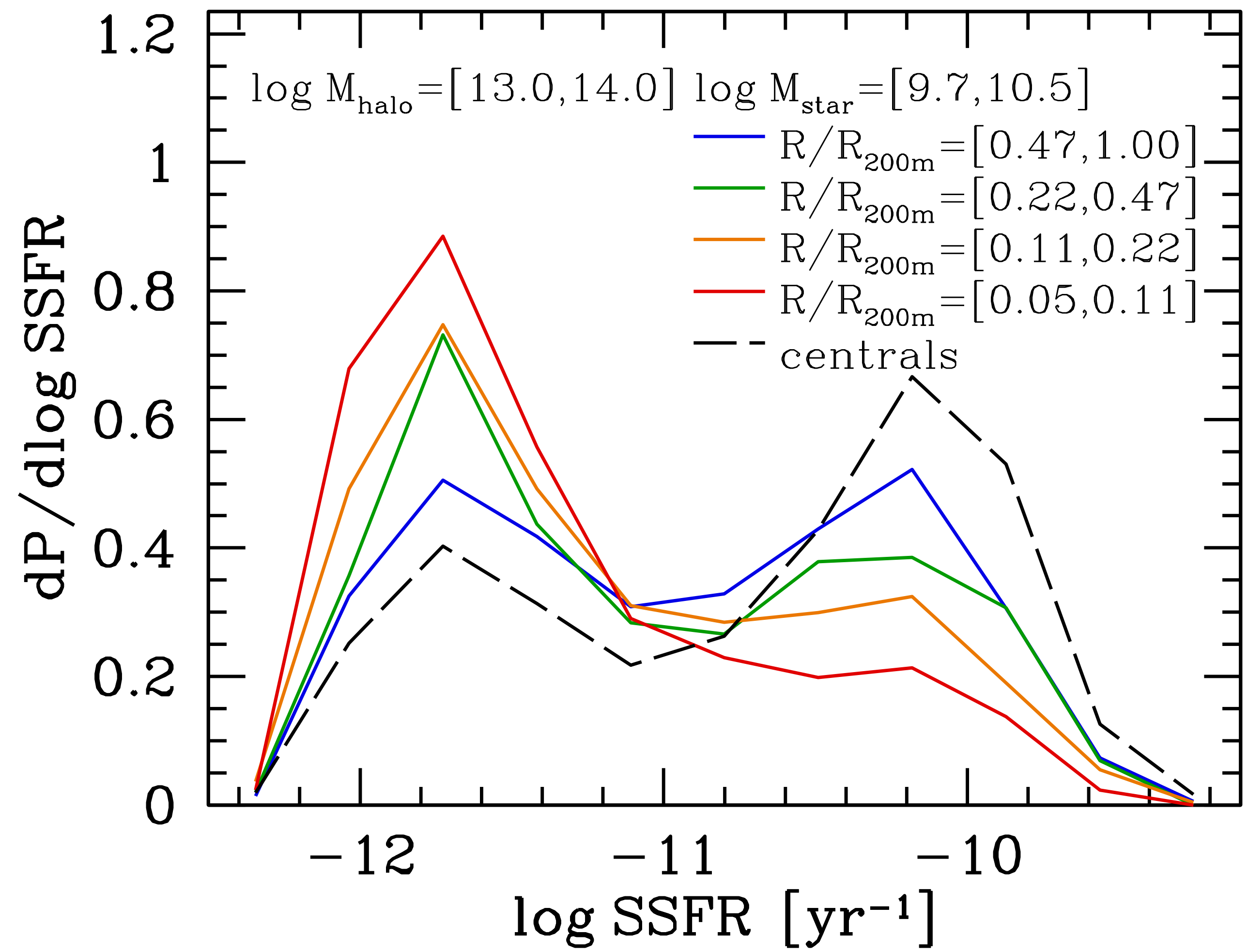
...but SFR bimodality persists across **all** host halo masses

also, Brinchmann et al 2004, Kauffmann et al 2004, Weinmann et al 2006, Kimm et al 2009, Pasquali et al 2010, Peng et al 2011

Satellite SFR depends on halo-centric distance

Wetzel, Tinker & Conroy 2011





- but SFR bimodality persists at **all** halo-centric distances

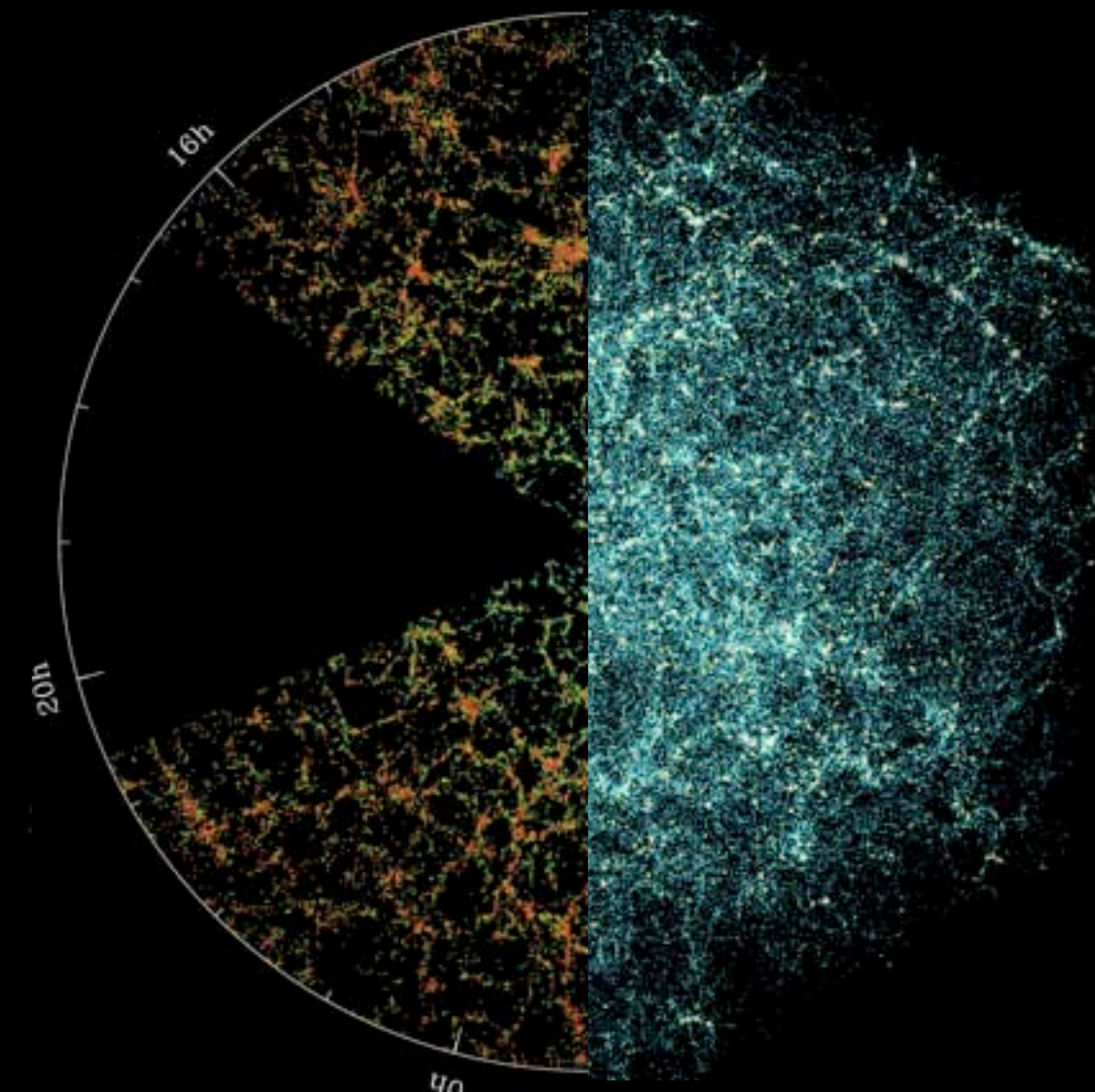
also, Balogh et al 2000, Ellingson et al 2001, De Propris et al 2004, Weinmann et al 2006, Blanton & Berlind 2007, van den Bosch et al 2008, Hansen et al 2009, Pasquali et al 2009, von der Linden et al 2010 z=11.9

800 x 600 physical kpc

Diemand, Kuhlen, Madau 2006

High-Resolution, Cosmological *N*-body Simulation

Box size	250 h^{-1}Mpc
Force resolution	2.5 h^{-1}kpc
Particle mass	10^8 $h^{-1}M_\odot$
Particle count	8.6 billion



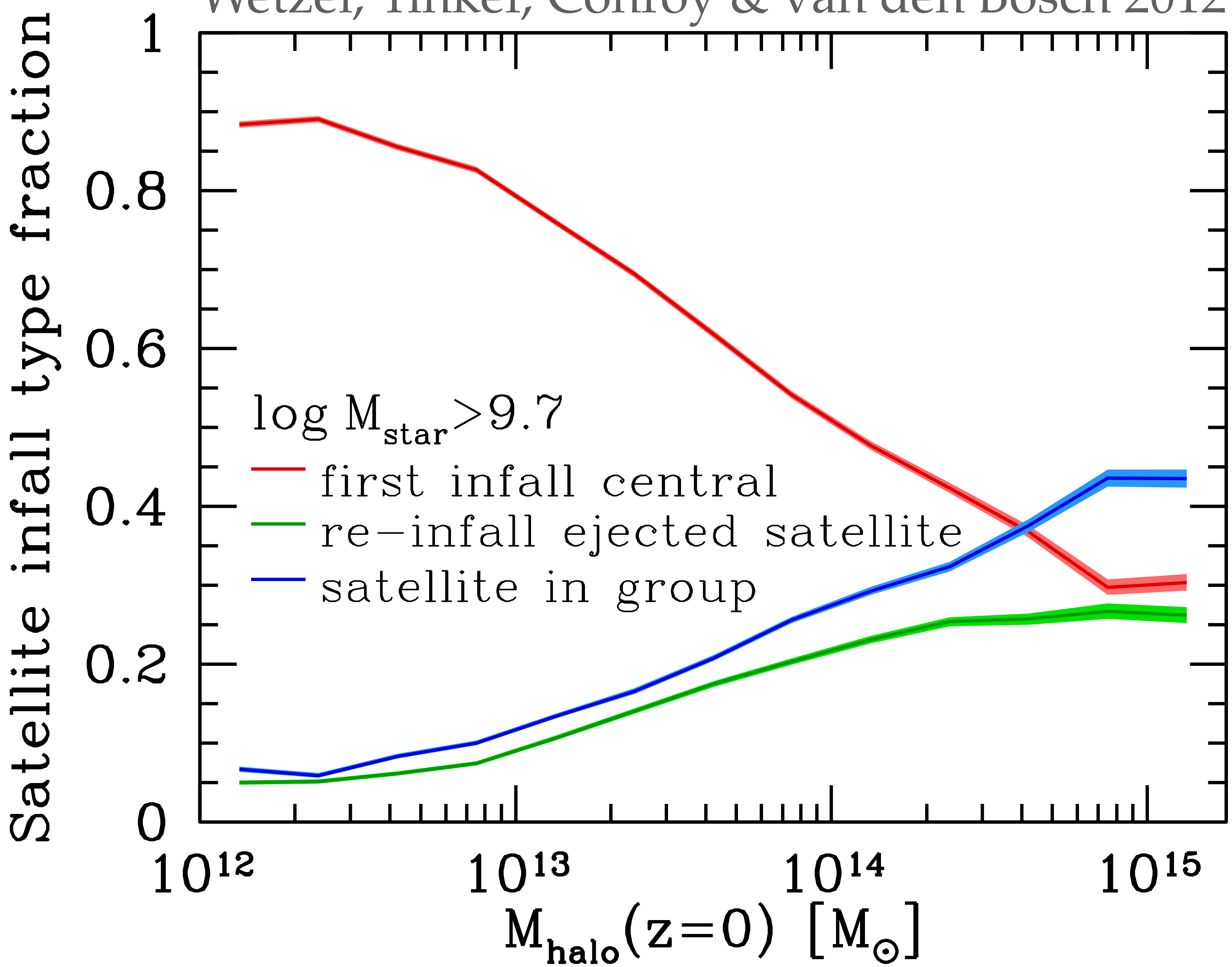
Use abundance matching to assign stellar mass to subhalos

$n_{(sub)halo}(>M_{inf}) = n_{galaxy}(>M_{star})$

Vale & Ostriker 2006
Conroy, Wechsler & Kravtsov 2007

Apply group finder to simulation to create 'mock' simulation group catalog

How do satellites fall into halos?

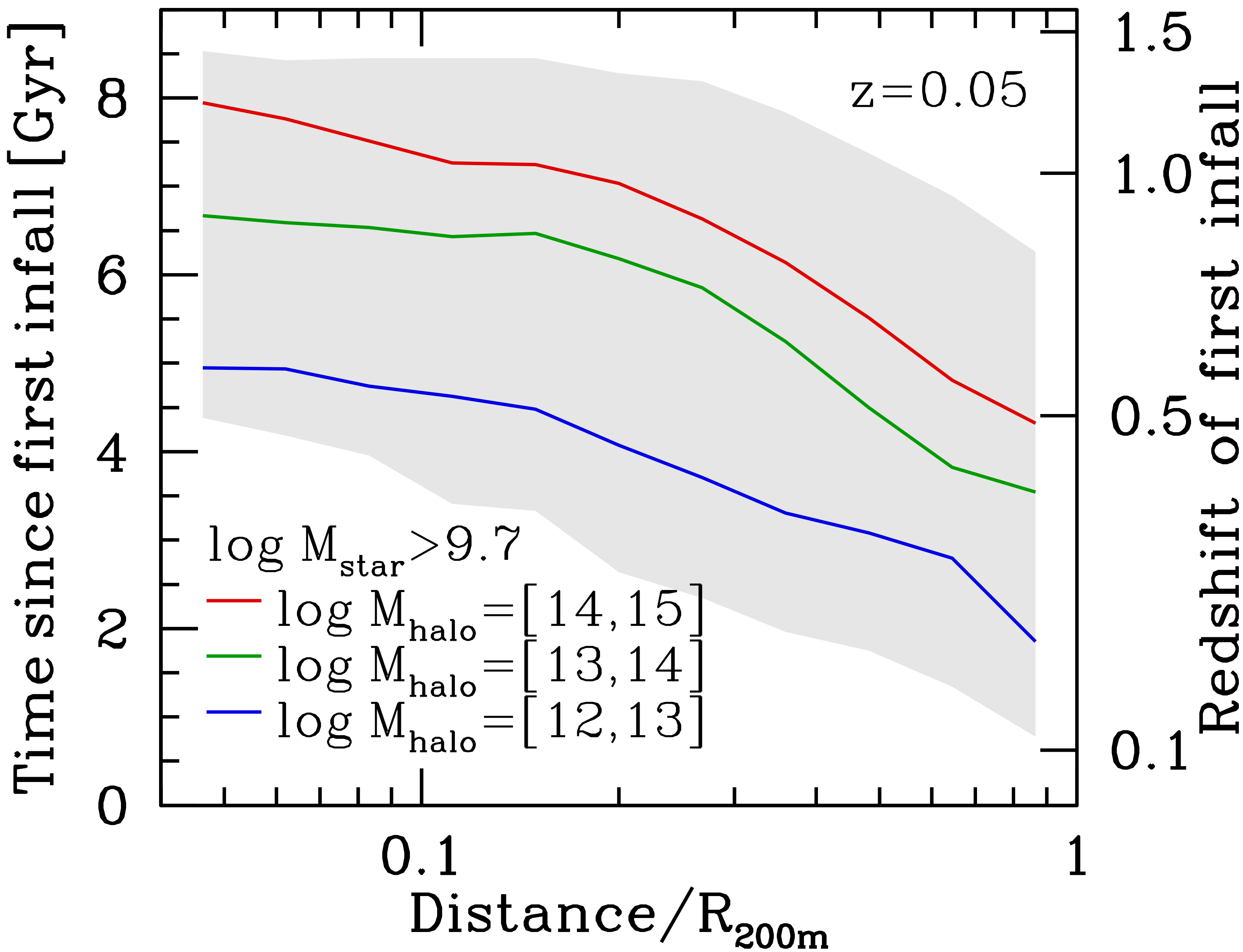


also,
Berrier et al 2009
McGee et al 2009

- In halos > 10^{14} $M_\odot$, most satellites do **not** fall in directly from the field

Satellite infall times

Wetzel, Tinker, Conroy & van den Bosch, in prep



- Earlier infall time in more massive halos & at smaller halo-centric distance
- Median redshift of first infall was z ~ 0.5

Satellite SFR initial conditions at the time of infall

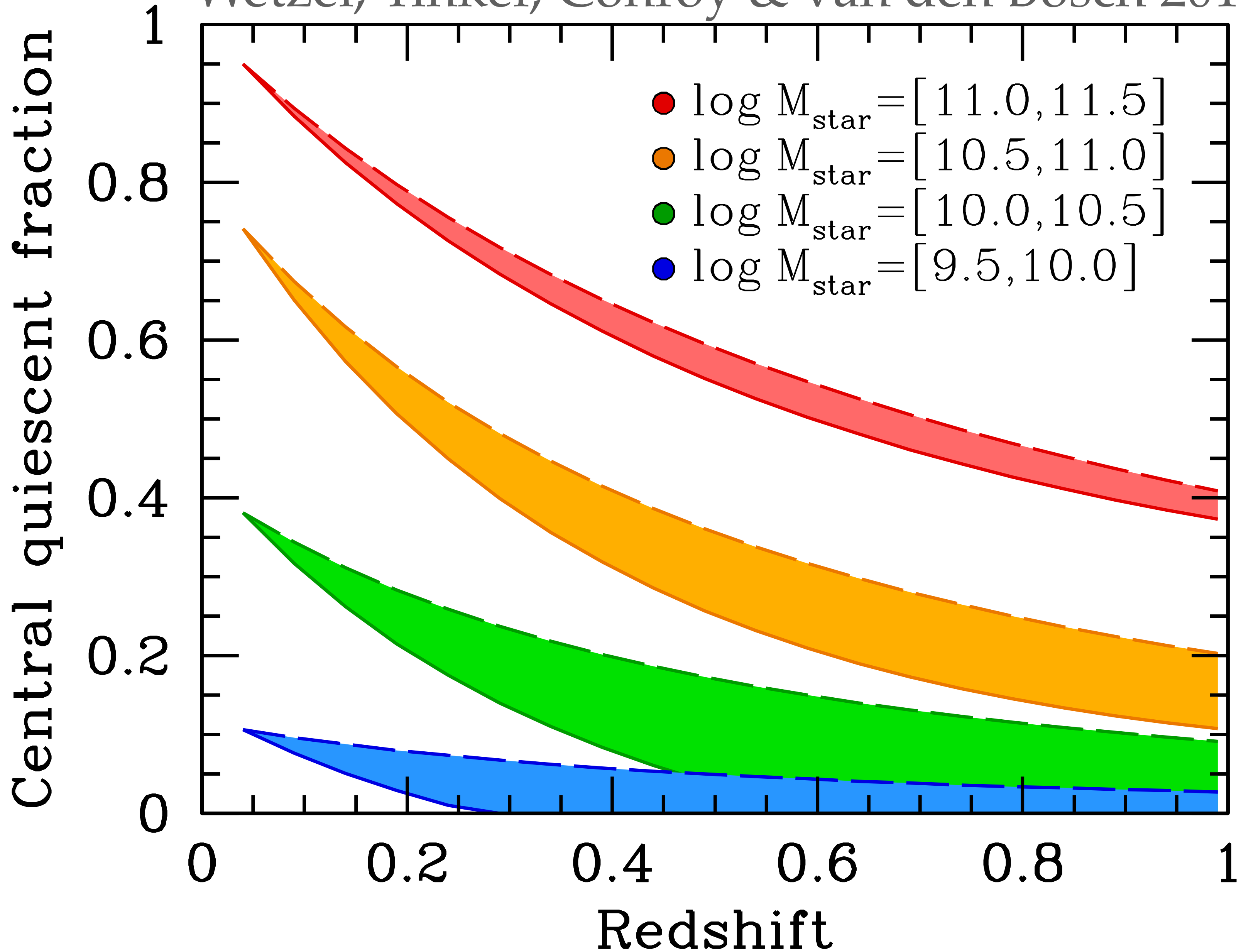
To understand satellite SFR evolution after infall, need accurate SFR initial conditions at the time of first infall

Satellites at $z = 0$ typically fell in at $z \sim 0.5$

Use **empirical** method to assign satellite initial SFRs, based on the evolution of central galaxy SFRs

Evolution of SFR for central galaxies

Wetzel, Tinker, Conroy & van den Bosch 2012



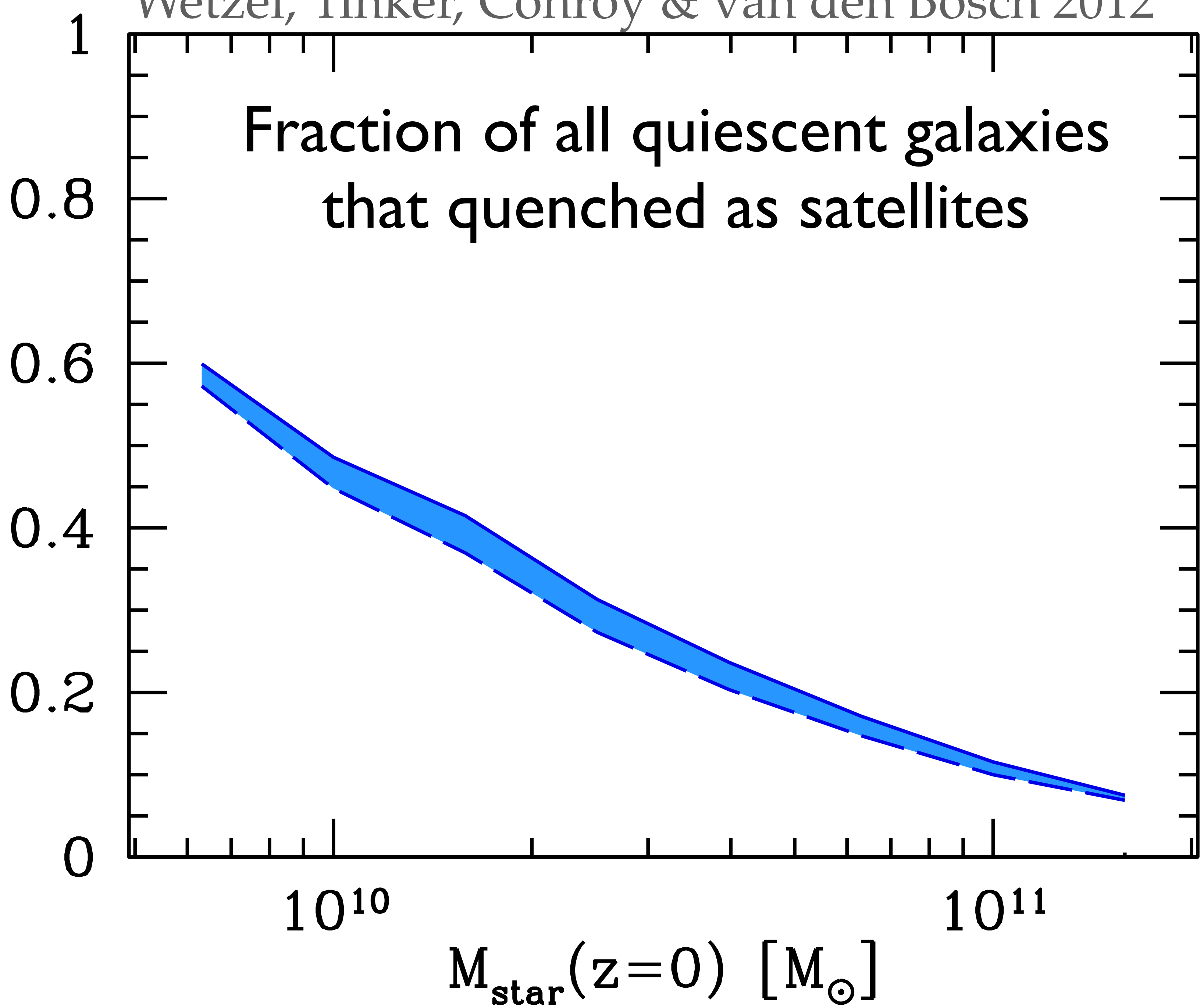
Obtain quiescent fractions for all galaxies from SDSS & COSMOS Drory et al 2009

Use spatial clustering to disentangle central & satellite galaxies Tinker & Wetzel 2010

Evolve normalization of SFRs for actively star-forming galaxies Noeske et al 2007

Importance of satellite quenching in building up the red-sequence population at z = 0

Wetzel, Tinker, Conroy & van den Bosch 2012



- At $M_{star} < 10^{10}\,M_\odot$, **most** quiescent galaxies quenched as satellites

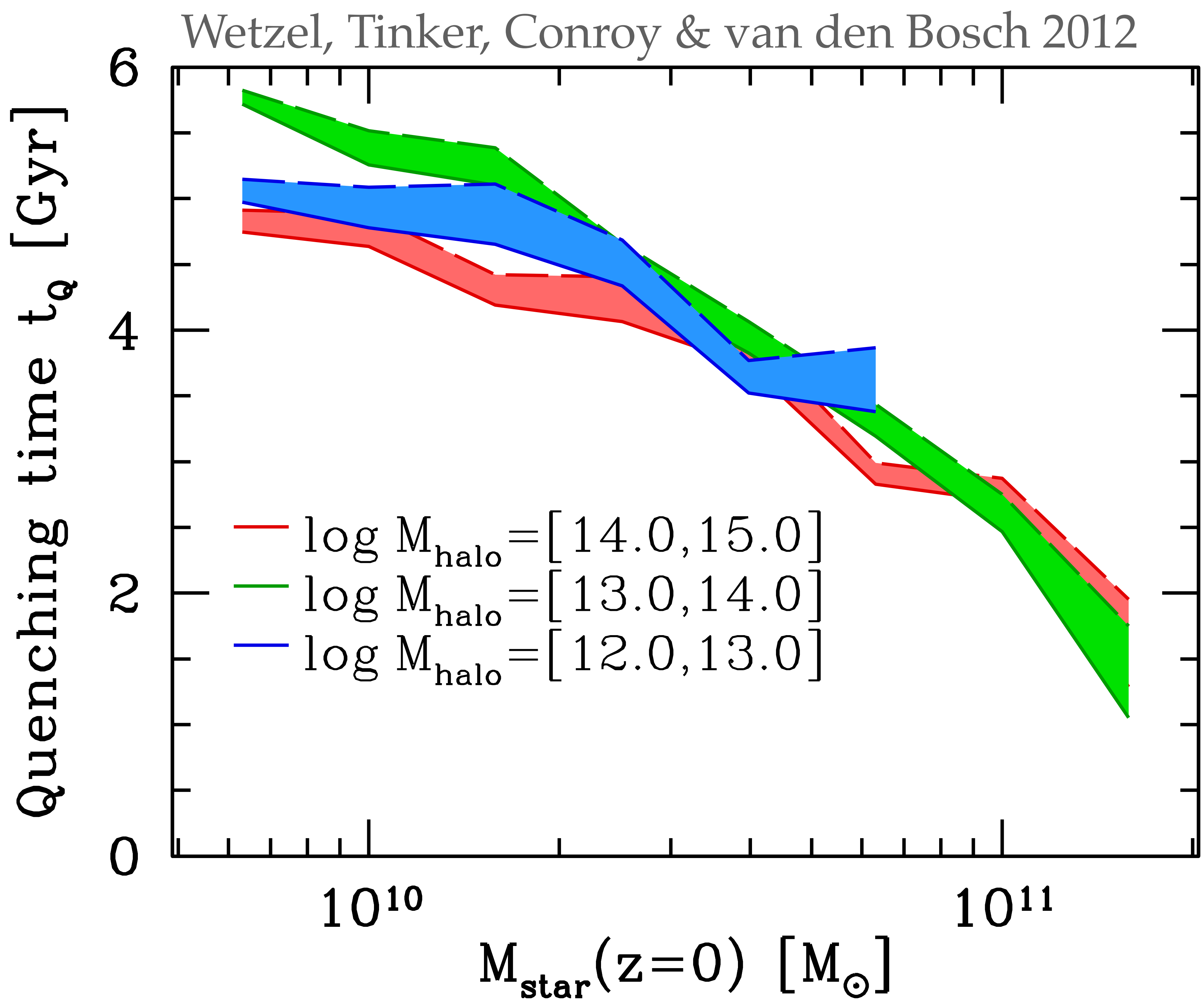
Modeling satellite SFR histories

Ansatz: a satellite's quenching likelihood is given by its time since first infall

(1) Identify satellites in simulation that were star-forming at time of first infall

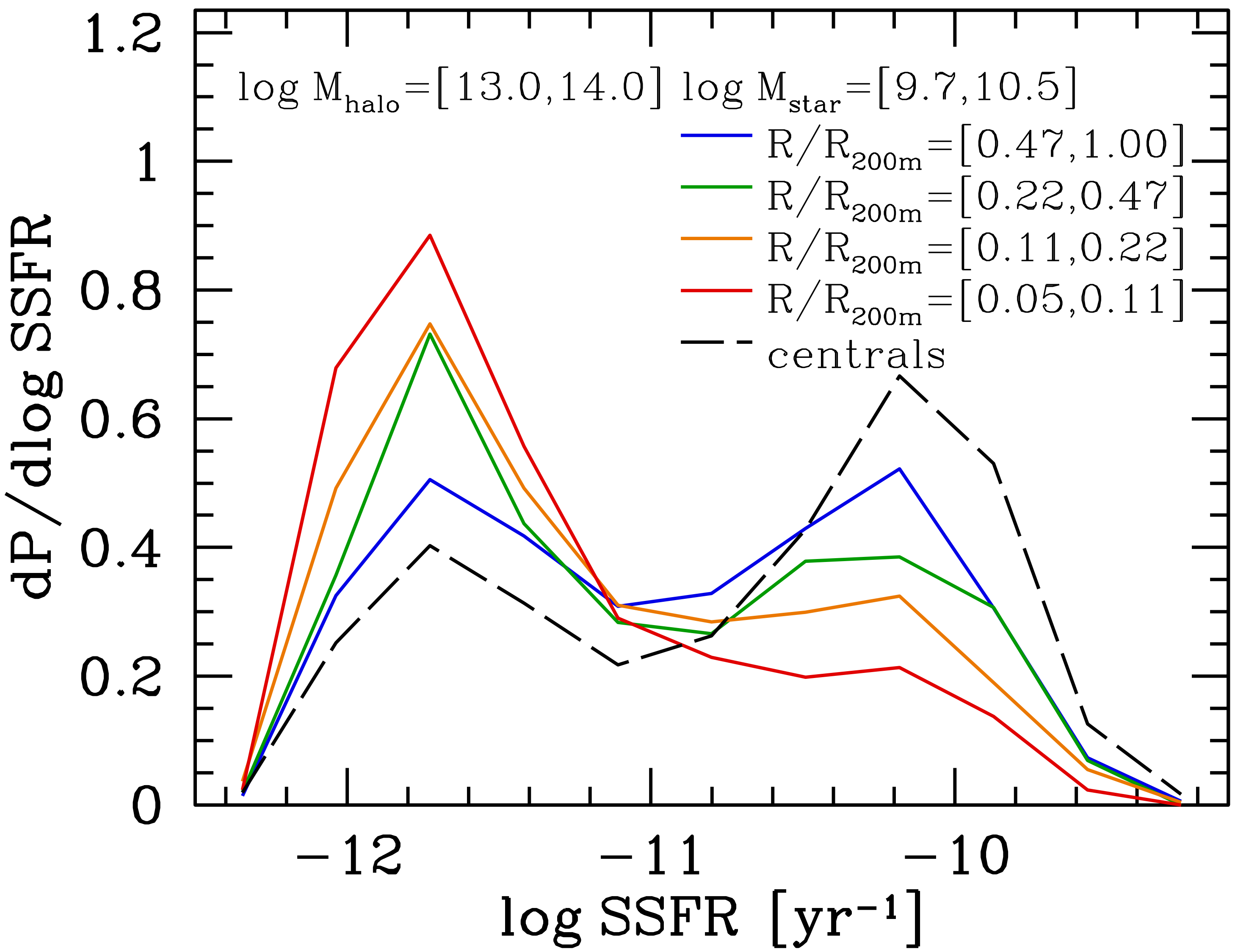
(2) Star formation is quenched if satellite has been in a host halo long enough (threshold in time since infall)

(3) Adjust threshold to match observed satellite quiescent fraction in bins of satellite & host halo mass



- Satellite quenching time depends on stellar mass, but not on host halo mass

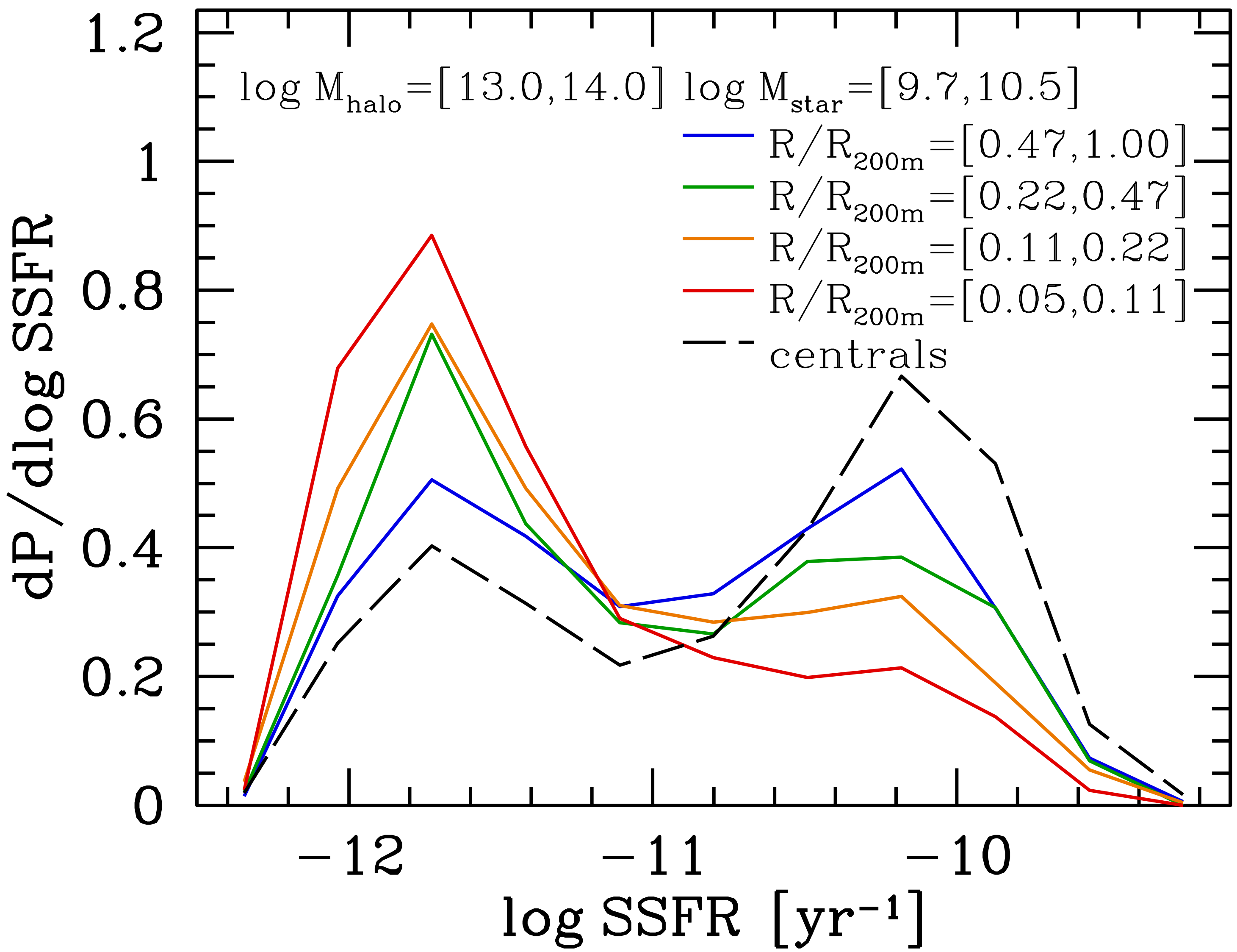
Satellite SFR evolution in detail



(1) Satellite SFR evolves unaffected for roughly a halo crossing time (several Gyrs)

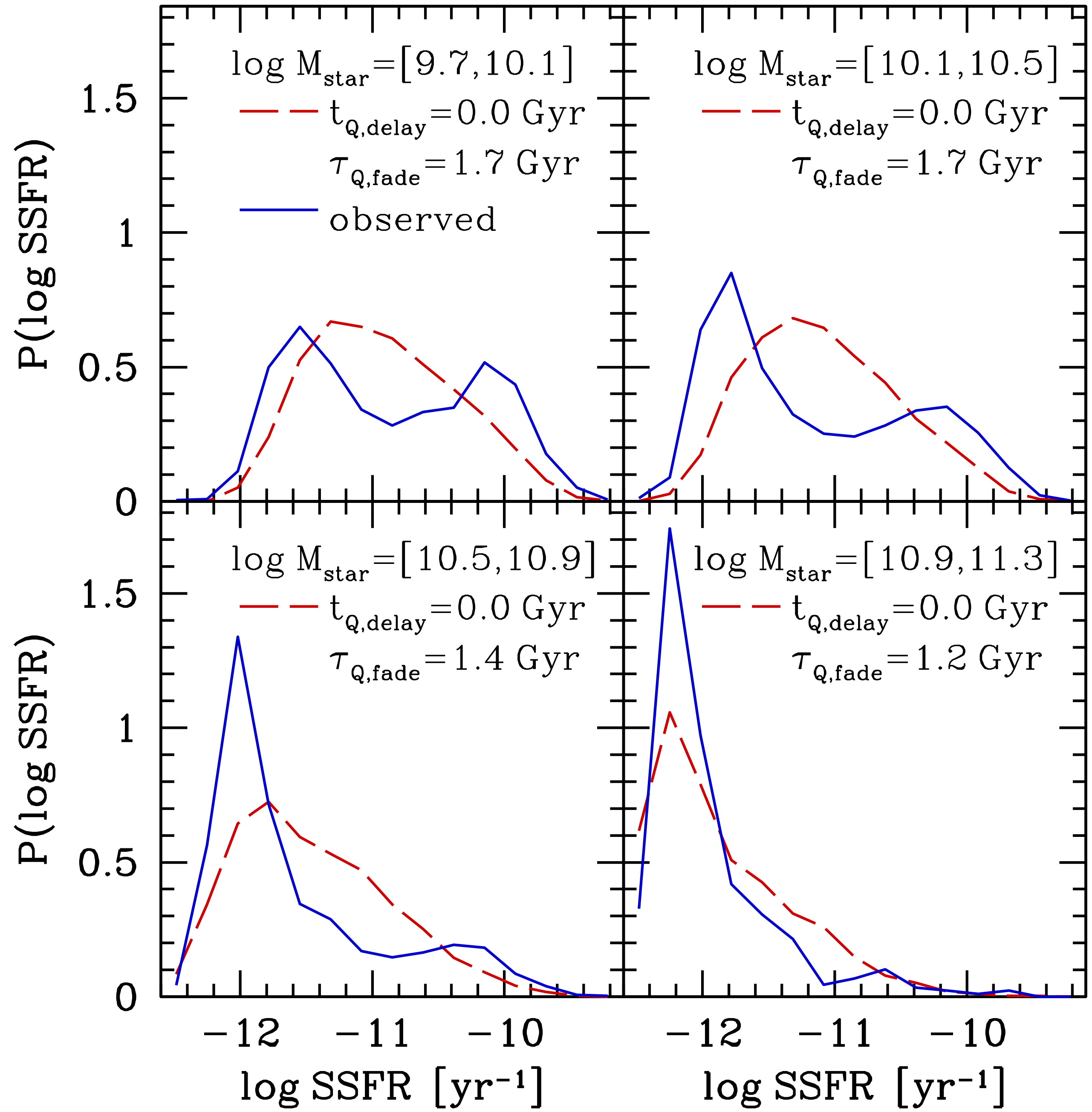
(2) Once begun, satellite SFR quenching is rapid

Satellite SFR evolution in detail



$$\mathrm{SFR_{sat}}(t) = \begin{cases} \mathrm{SFR_{cen}}(t) & t < t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \\ \mathrm{SFR_{cen}}(t_{Q,\,\mathrm{start}})\, e^{\left\{-\frac{(t - t_{Q,\,\mathrm{start}})}{\tau_{Q,\,\mathrm{fade}}}\right\}} & t > t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \end{cases}$$

Slowly fading SFR - no bimodality



Wetzel, Tinker, Conroy & van den Bosch 2012

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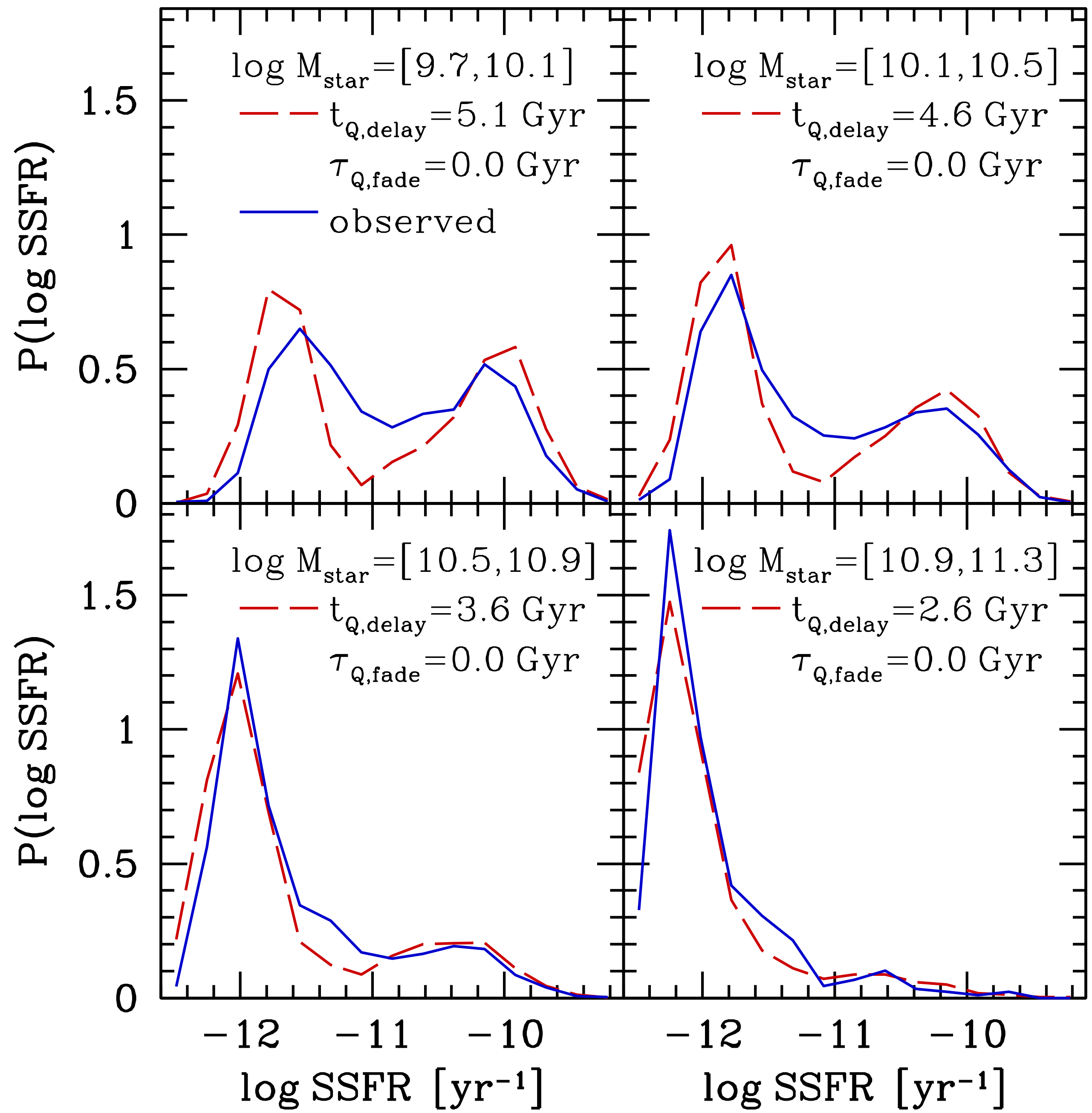
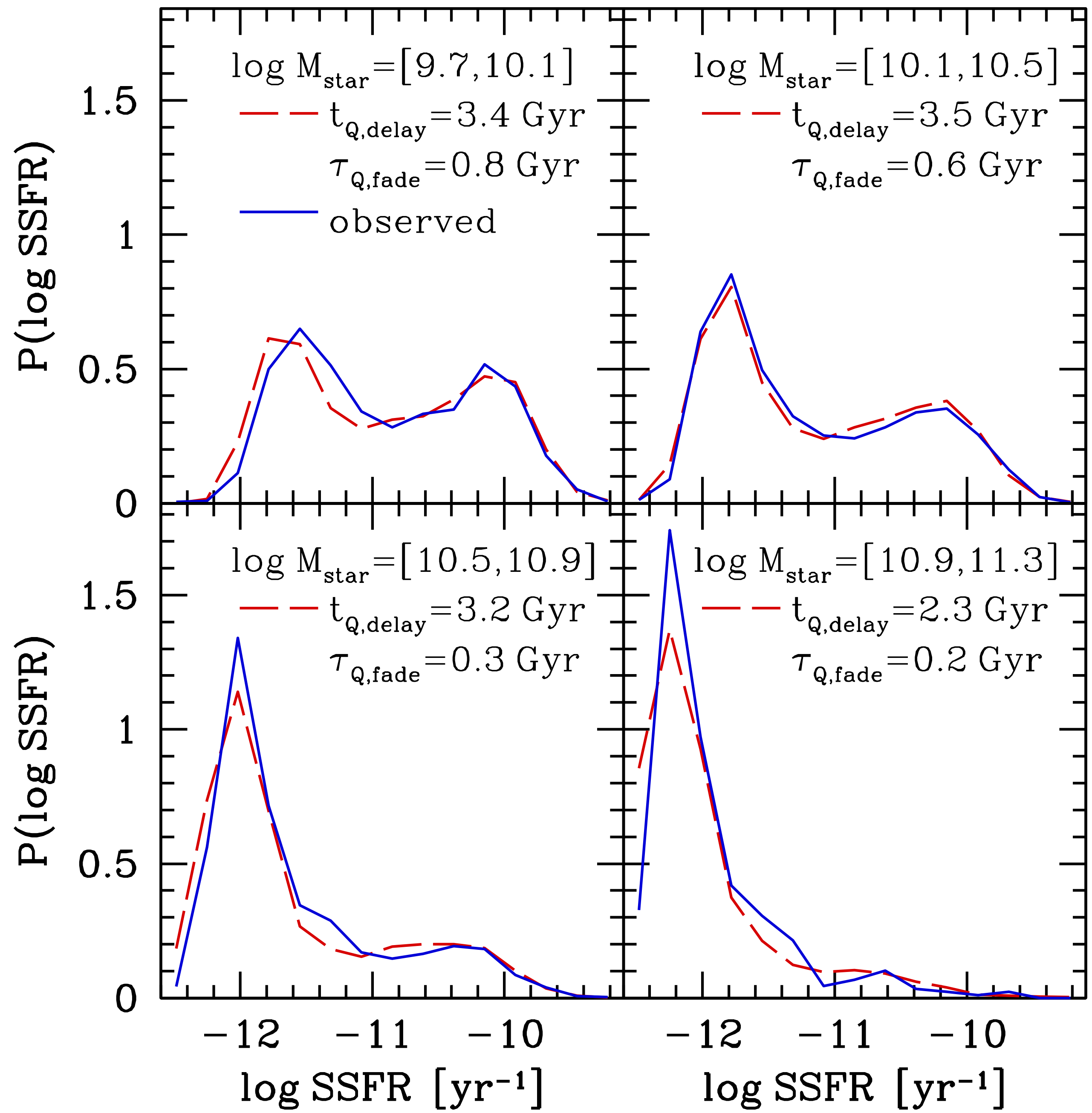
Delayed-then-instant quenching - bimodality too strong



Wetzel, Tinker, Conroy & van den Bosch 2012

$$\mathrm{SFR}_{\mathrm{sat}}(t) = \begin{cases} \mathrm{SFR}_{\mathrm{cen}}(t) & t < t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \\ \mathrm{SFR}_{\mathrm{cen}}(t_{Q,\,\mathrm{start}})\, e^{\left\{-\frac{(t - t_{Q,\,\mathrm{start}})}{\tau_{Q,\,\mathrm{fade}}}\right\}} & t > t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \end{cases}$$

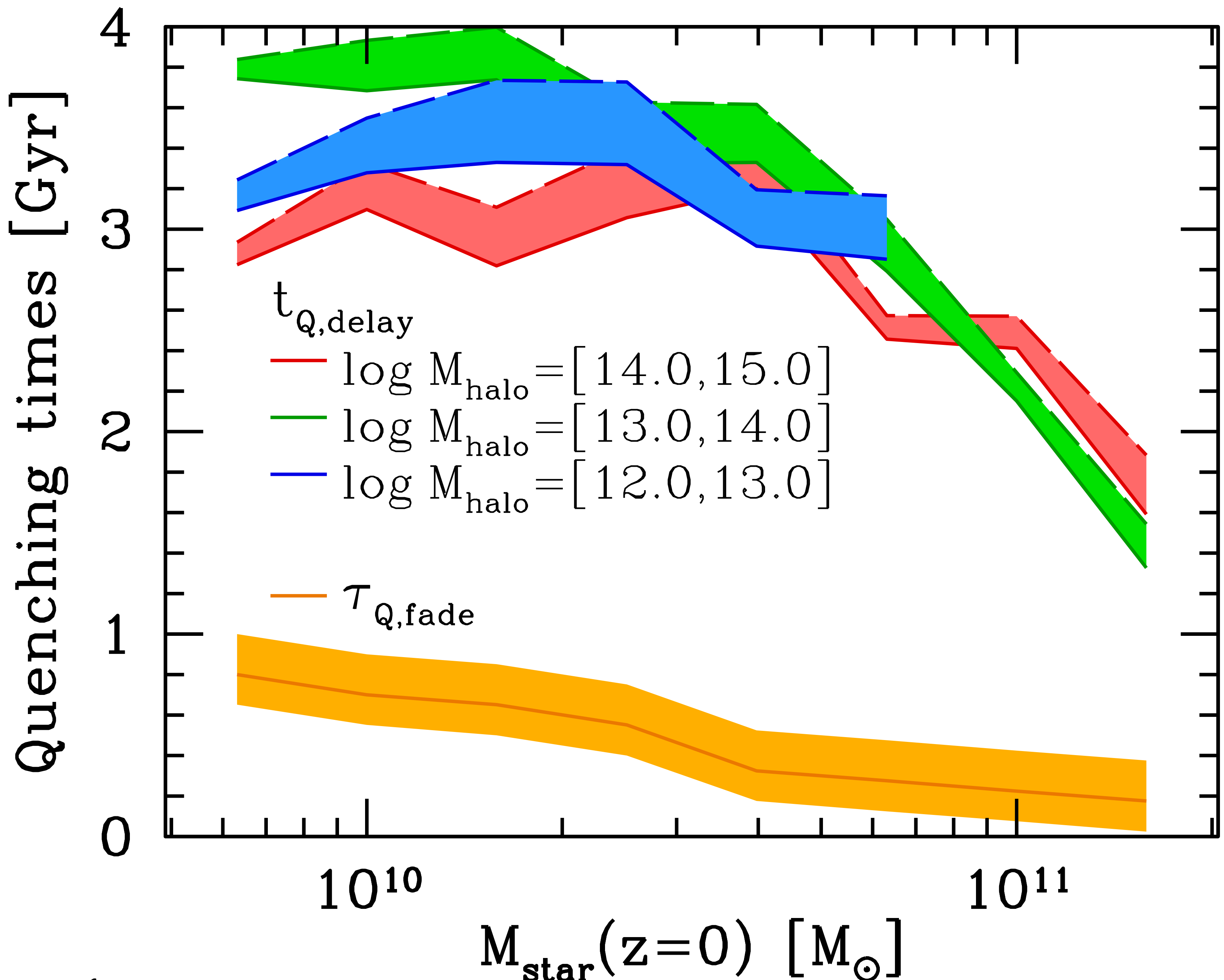
Delayed-then-rapid quenching - successful



Wetzel, Tinker, Conroy & van den Bosch 2012

$$\mathrm{SFR_{sat}}(t) = \begin{cases} \mathrm{SFR_{cen}}(t) & t < t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \\ \mathrm{SFR_{cen}}(t_{Q,\,\mathrm{start}})\, e^{\left\{-\frac{(t - t_{Q,\,\mathrm{start}})}{\tau_{Q,\,\mathrm{fade}}}\right\}} & t > t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \end{cases}$$

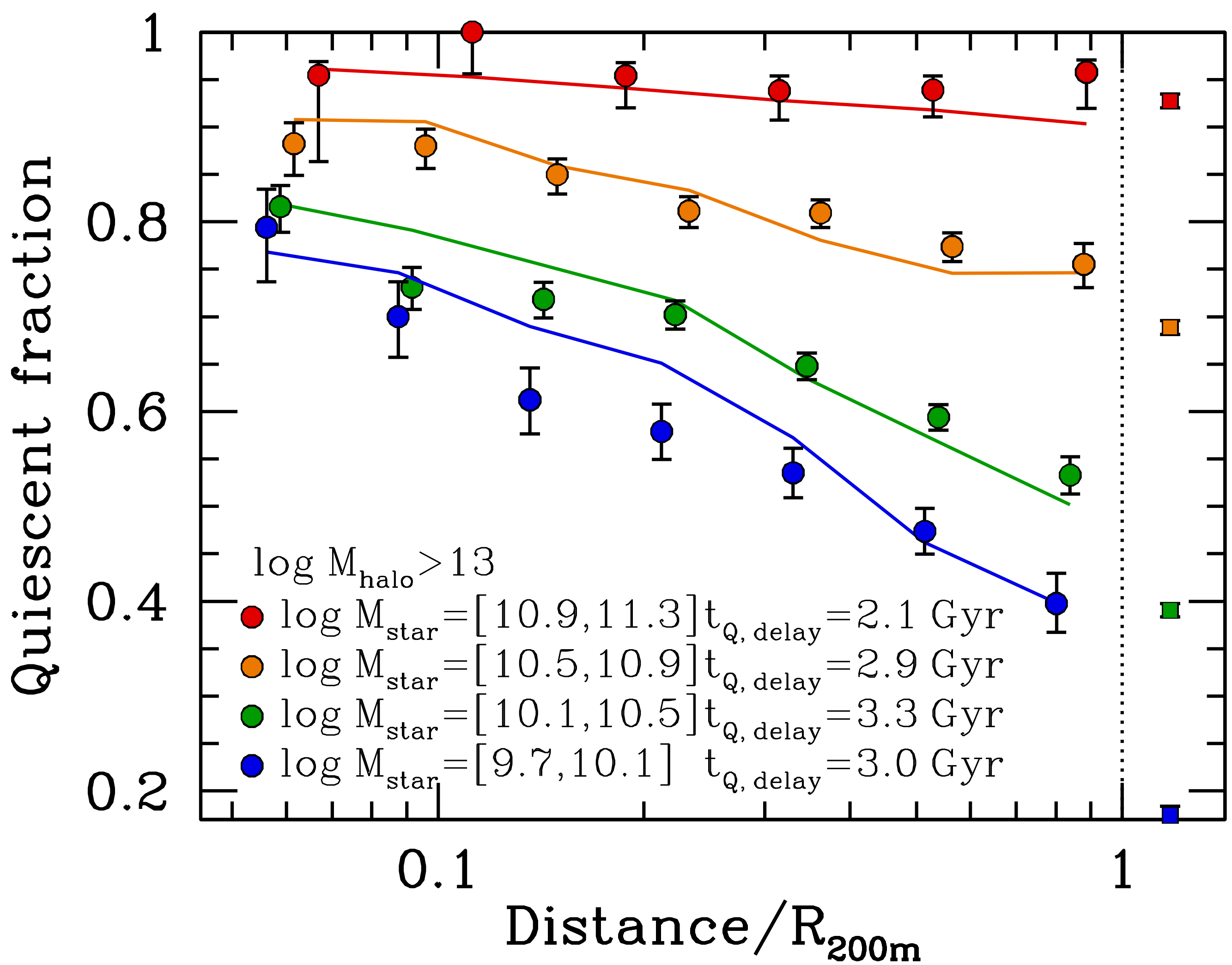
`Delayed-then-rapid' satellite quenching scenario



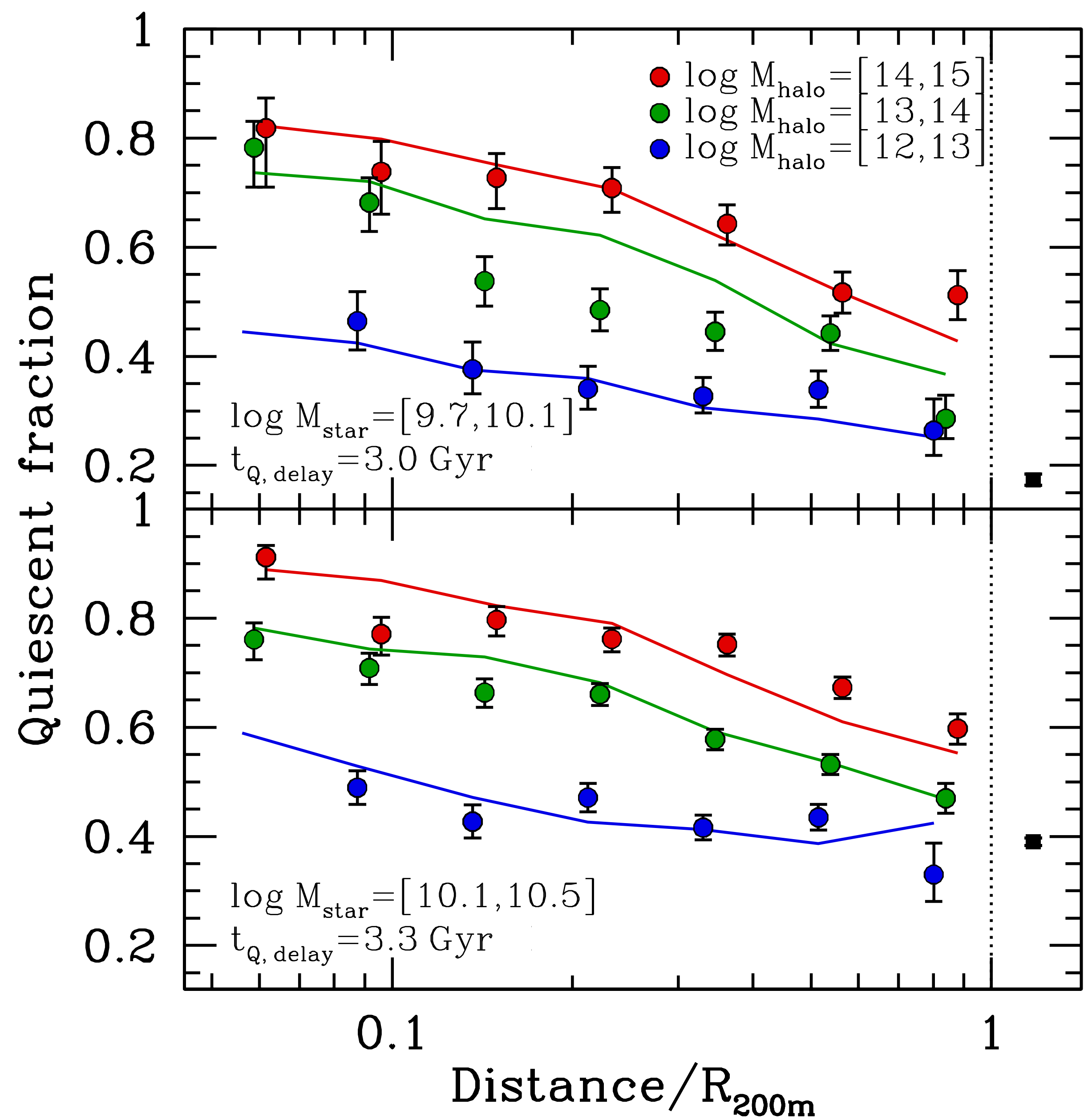
$$\mathrm{SFR_{sat}}(t) = \begin{cases} \mathrm{SFR_{cen}}(t) & t < t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \\ \mathrm{SFR_{cen}}(t_{Q,\,\mathrm{start}})\, e^{\left\{-\frac{(t-t_{Q,\,\mathrm{start}})}{\tau_{Q,\,\mathrm{fade}}}\right\}} & t > t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \end{cases}$$

Successfully reproduces dependence on halo-centric distance

Across satellite mass



Across host halo mass



Outstanding questions about environmental quenching

What is the physical extent of environmental dependence?

How long does it take satellites to quench after infall?
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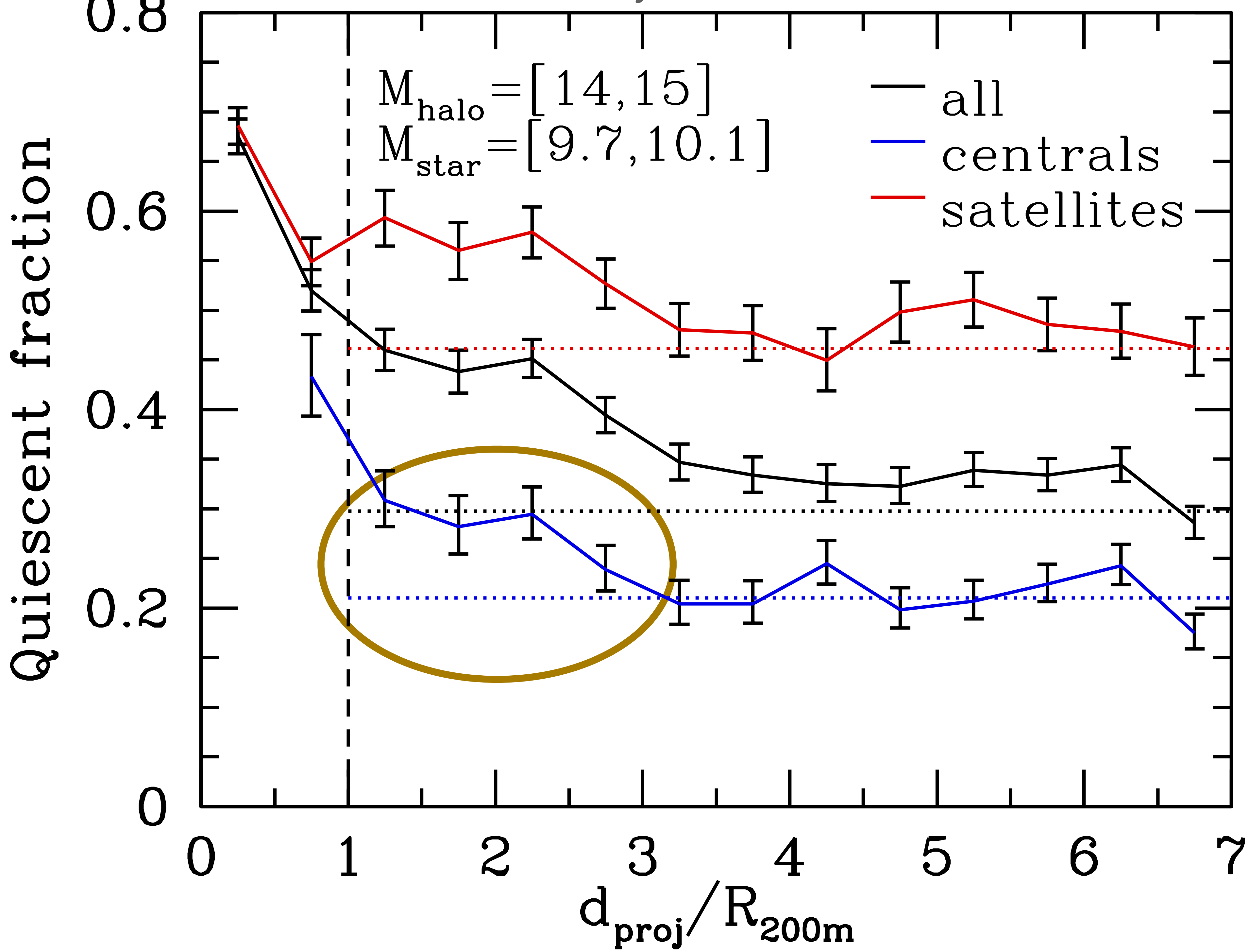
What is the physical mechanism for quenching satellites?

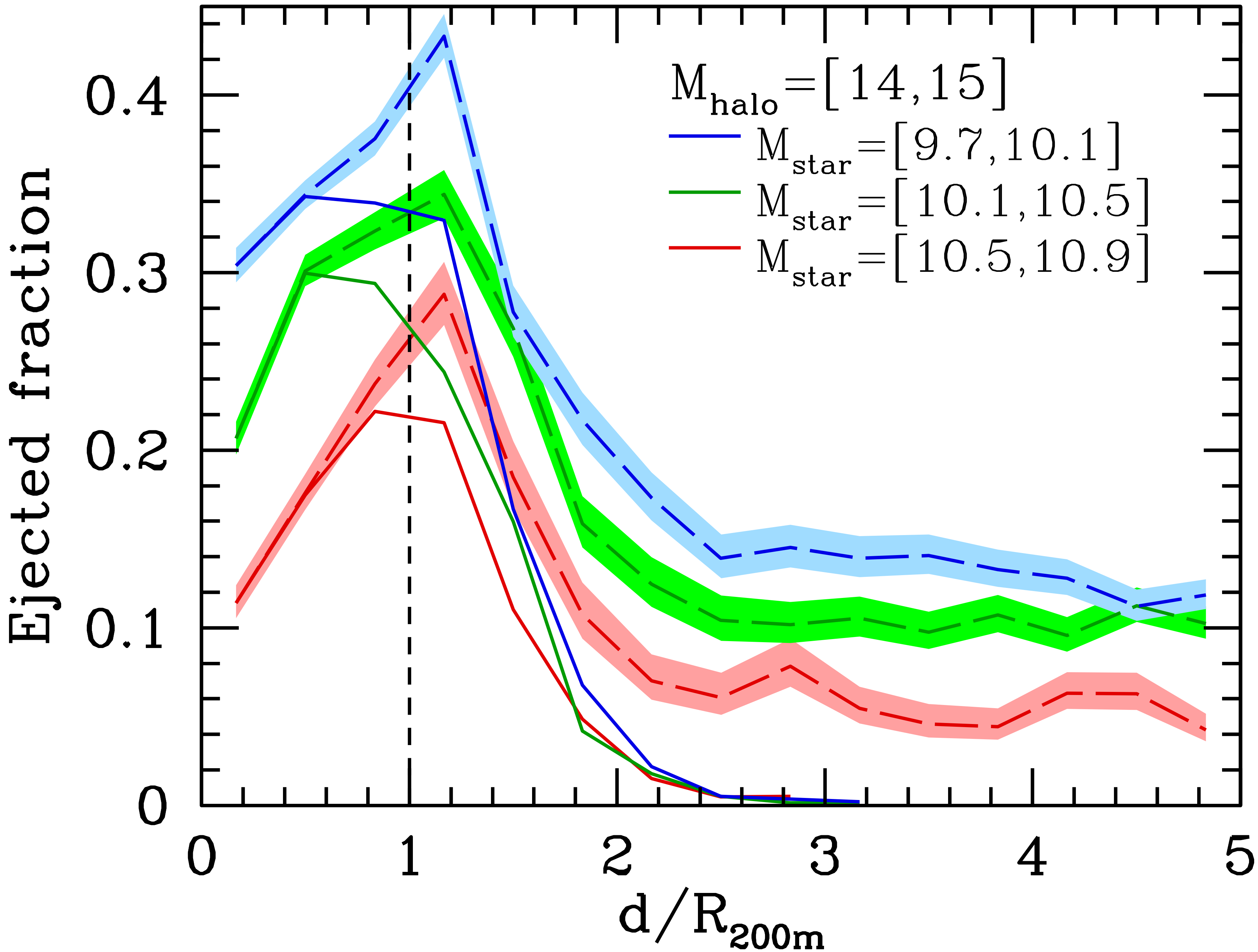
SFR in central galaxies beyond R_{vir}

Wetzel, Tinker, Conroy & van den Bosch 2013



Ejected satellite excess persists out to 2.5 R_{vir}

Wetzel, Tinker, Conroy & van den Bosch 2013

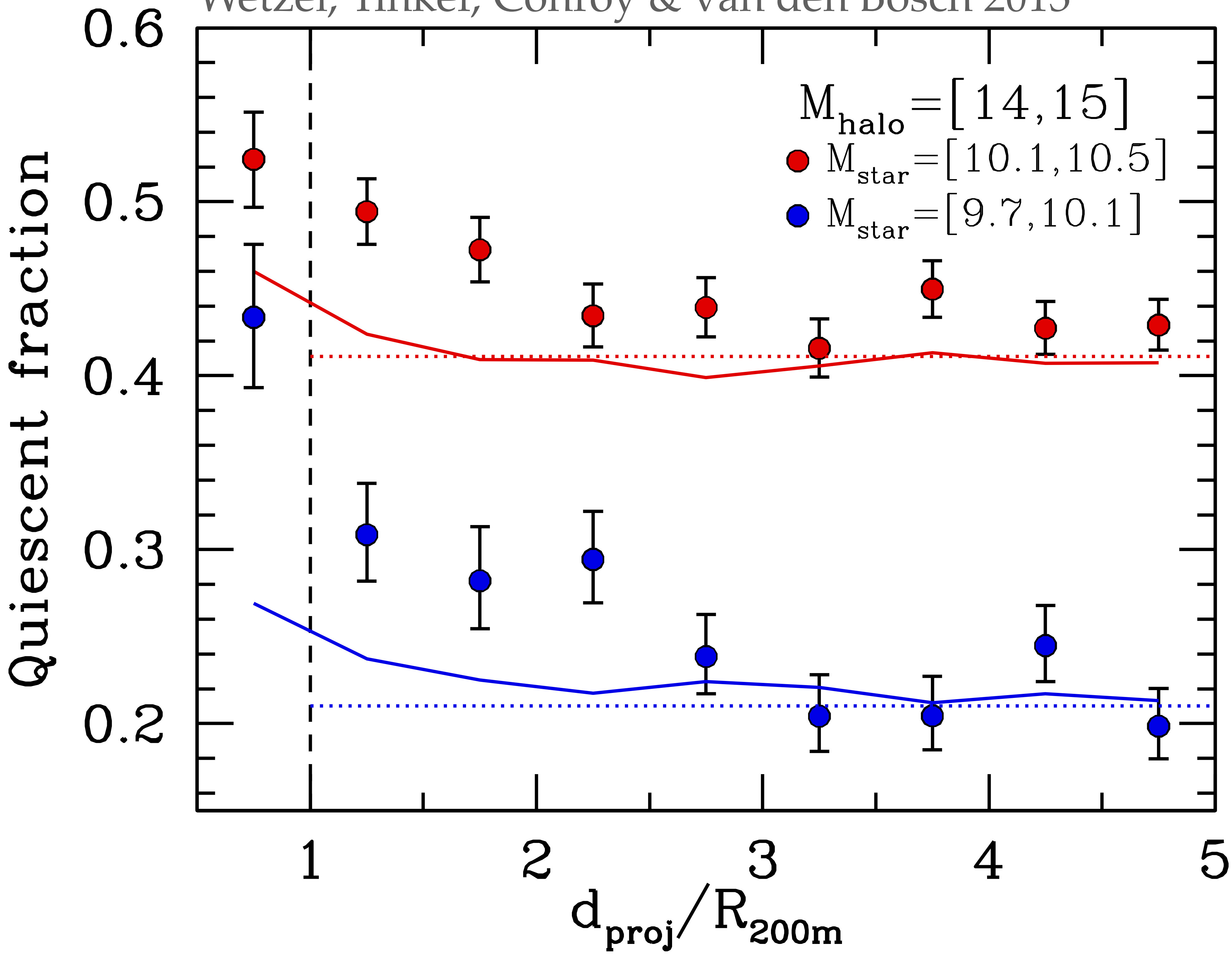


also,
Gill et al 2005
Ludlow et al 2009
Wang et al 2009
Teyssier et al 2012

- >90% continue to lose mass after being ejected

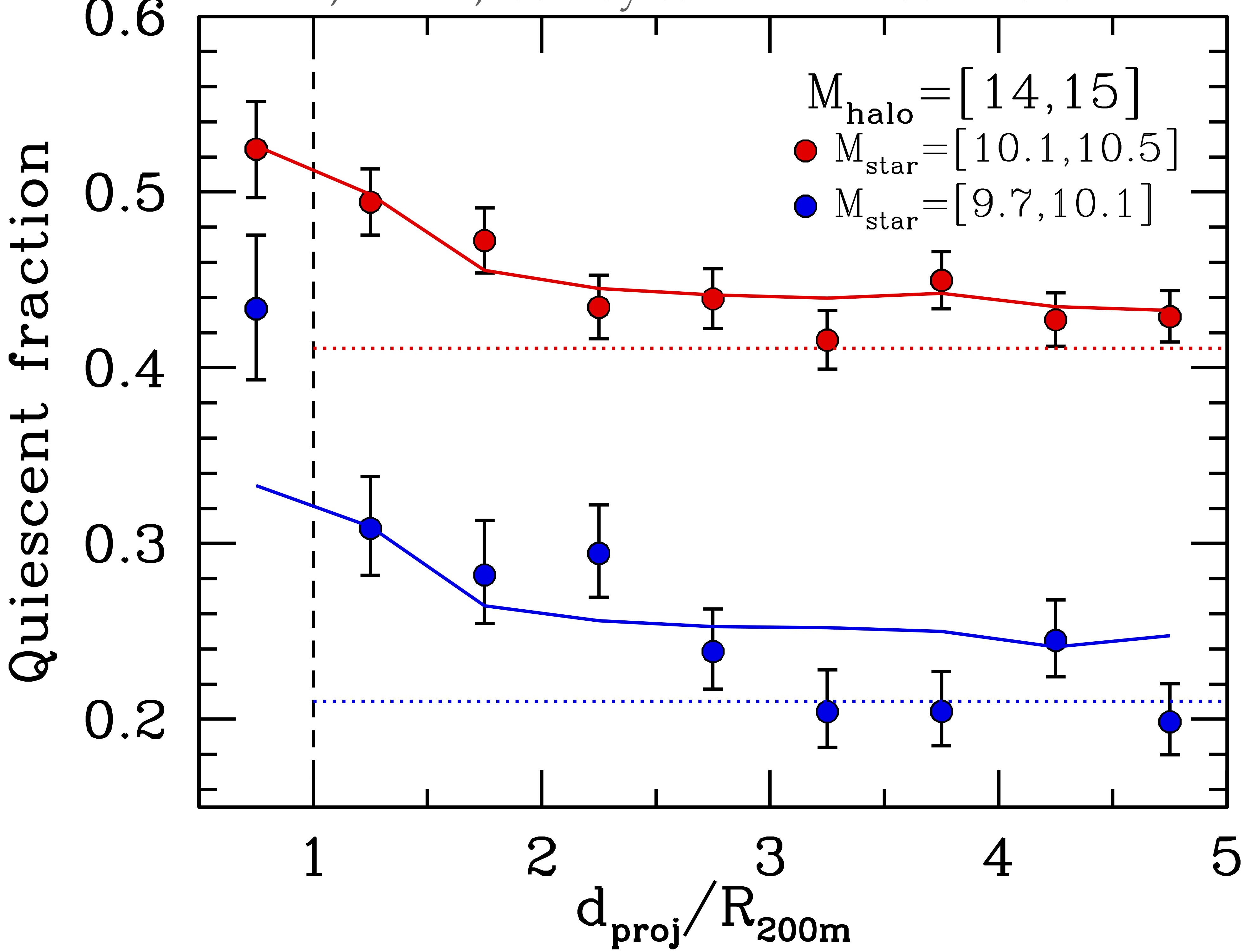
If SFR in ejected satellites evolves same as central galaxies

Wetzel, Tinker, Conroy & van den Bosch 2013



If SFR in ejected satellites evolves same as satellites within R_{vir}

Wetzel, Tinker, Conroy & van den Bosch 2013



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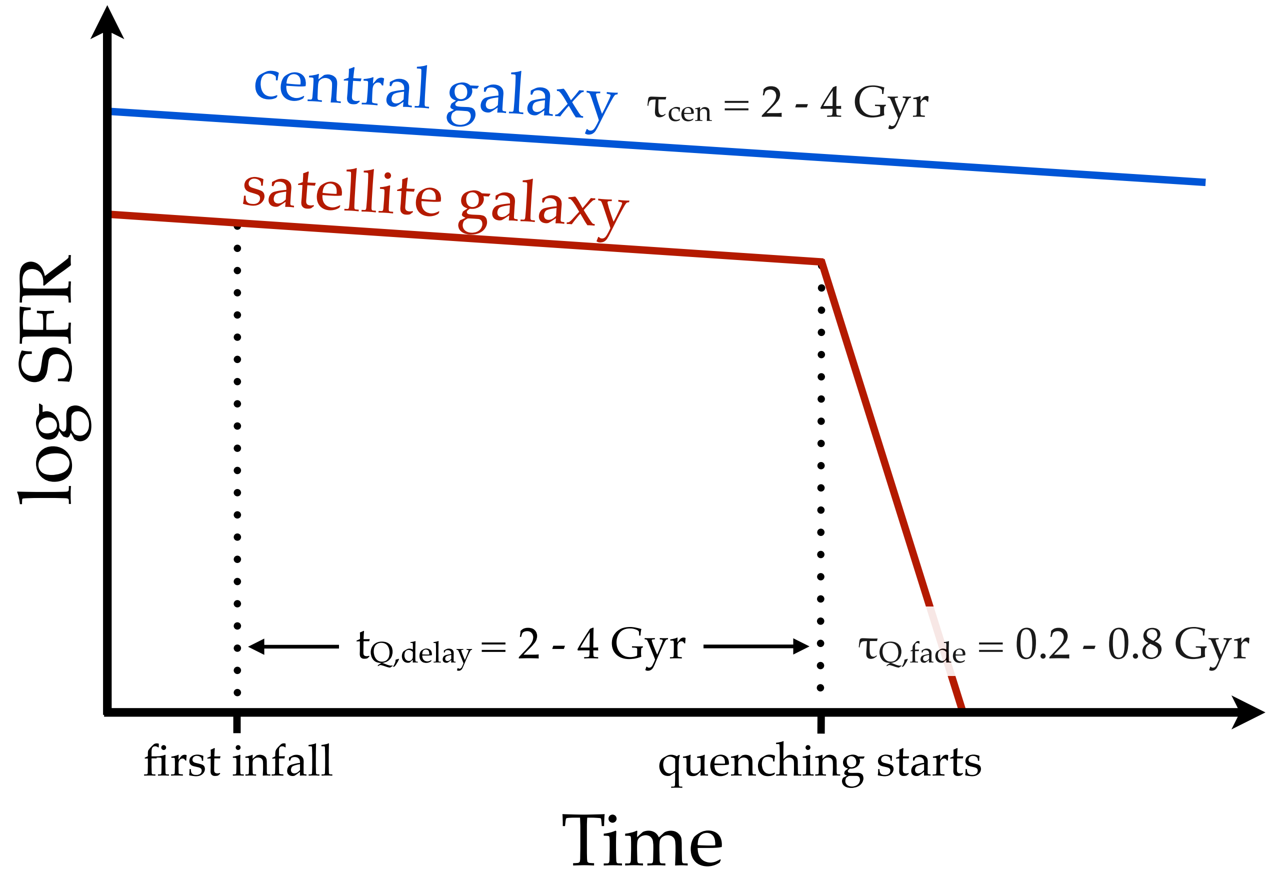
Empirical constraints on satellite quenching mechanism



(1) Quenching correlates strongly with time since infall

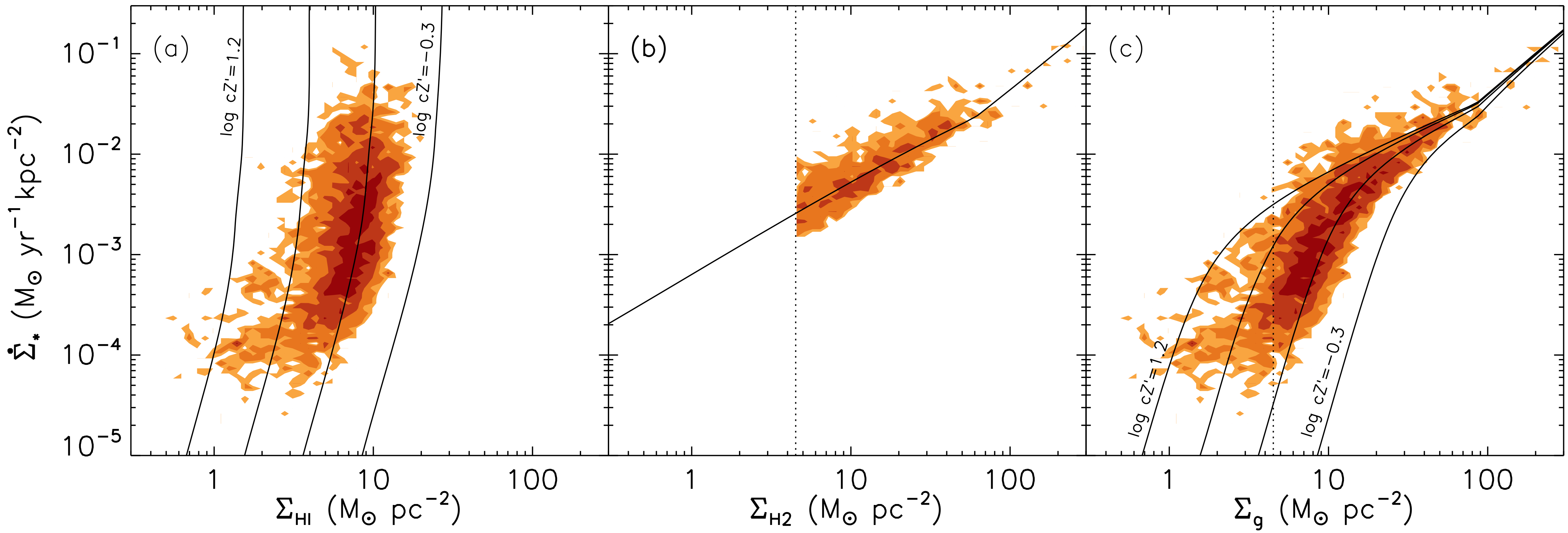
(2) Quenching process is ‘delayed-then-rapid’

(3) Longer quenching times for less massive satellites

(4) No dependence on host halo mass

Mechanism of satellite quenching: time since infall?

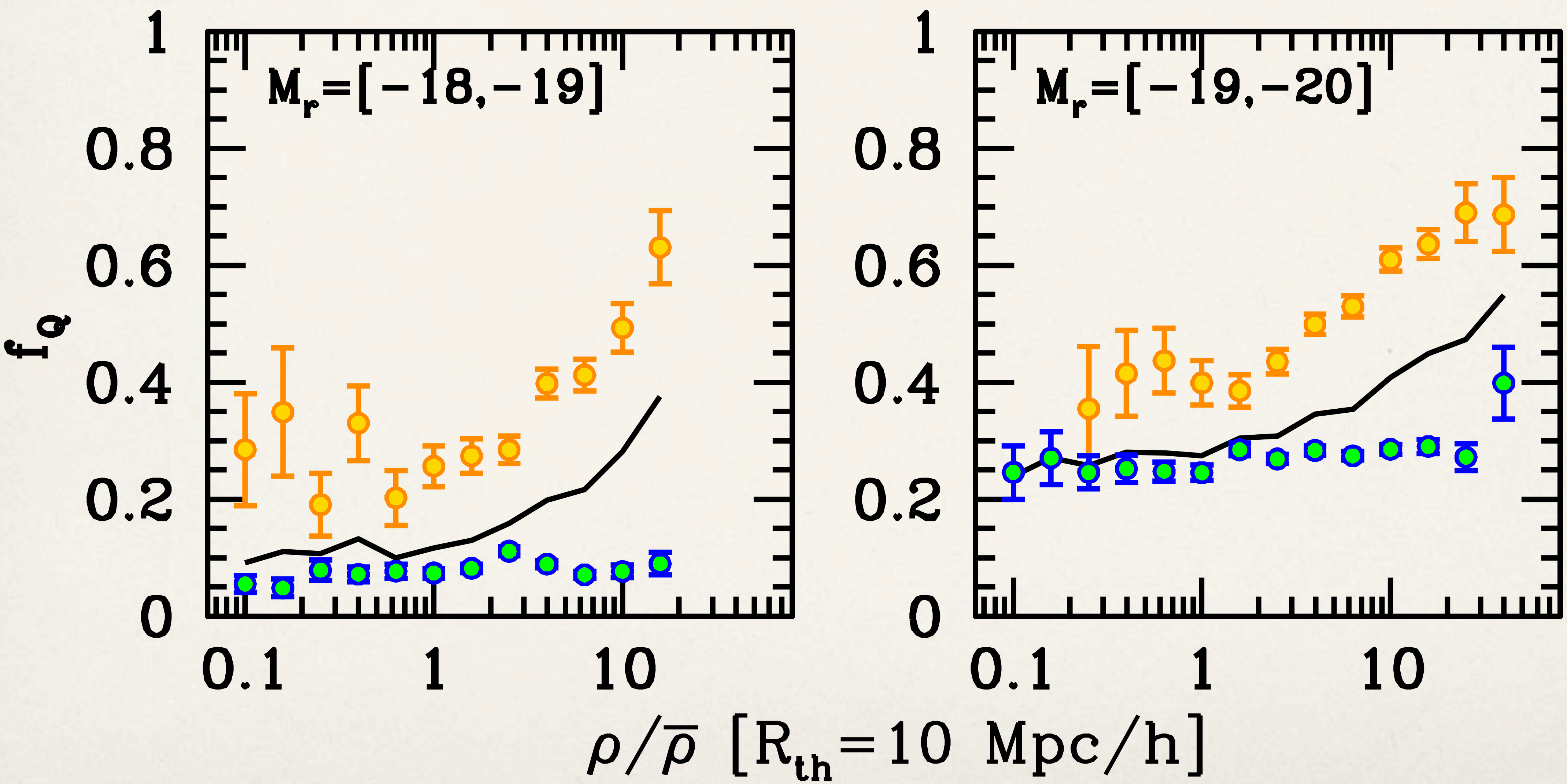
Relating galaxy SFR to gas content



Krumholz, McKee & Tumlinson 2009
Bigiel et al 2008 (THINGS survey)

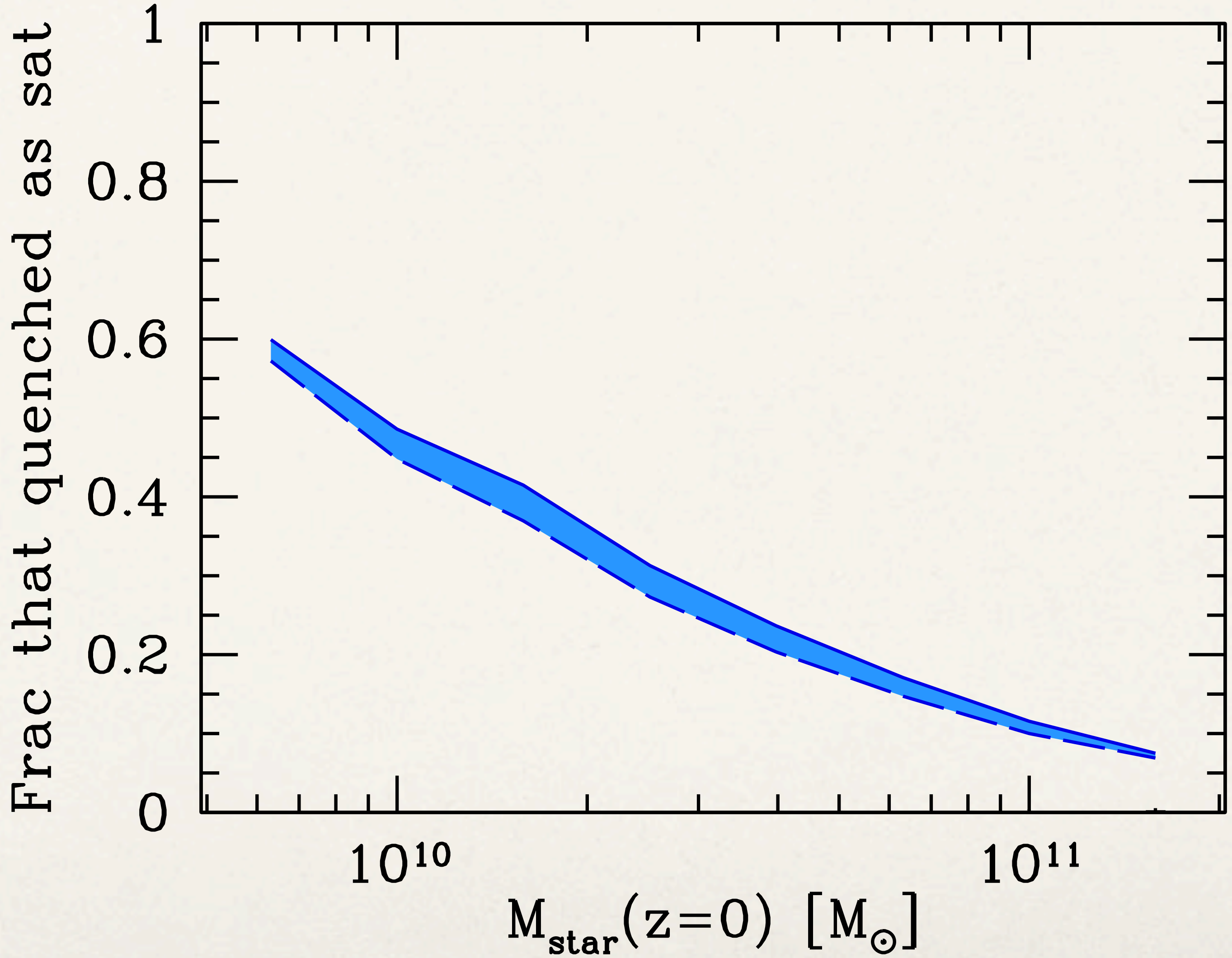
Galaxy Evolution in Groups & Clusters

Satellite galaxies drive essentially **all** environmental dependence of galaxy star formation



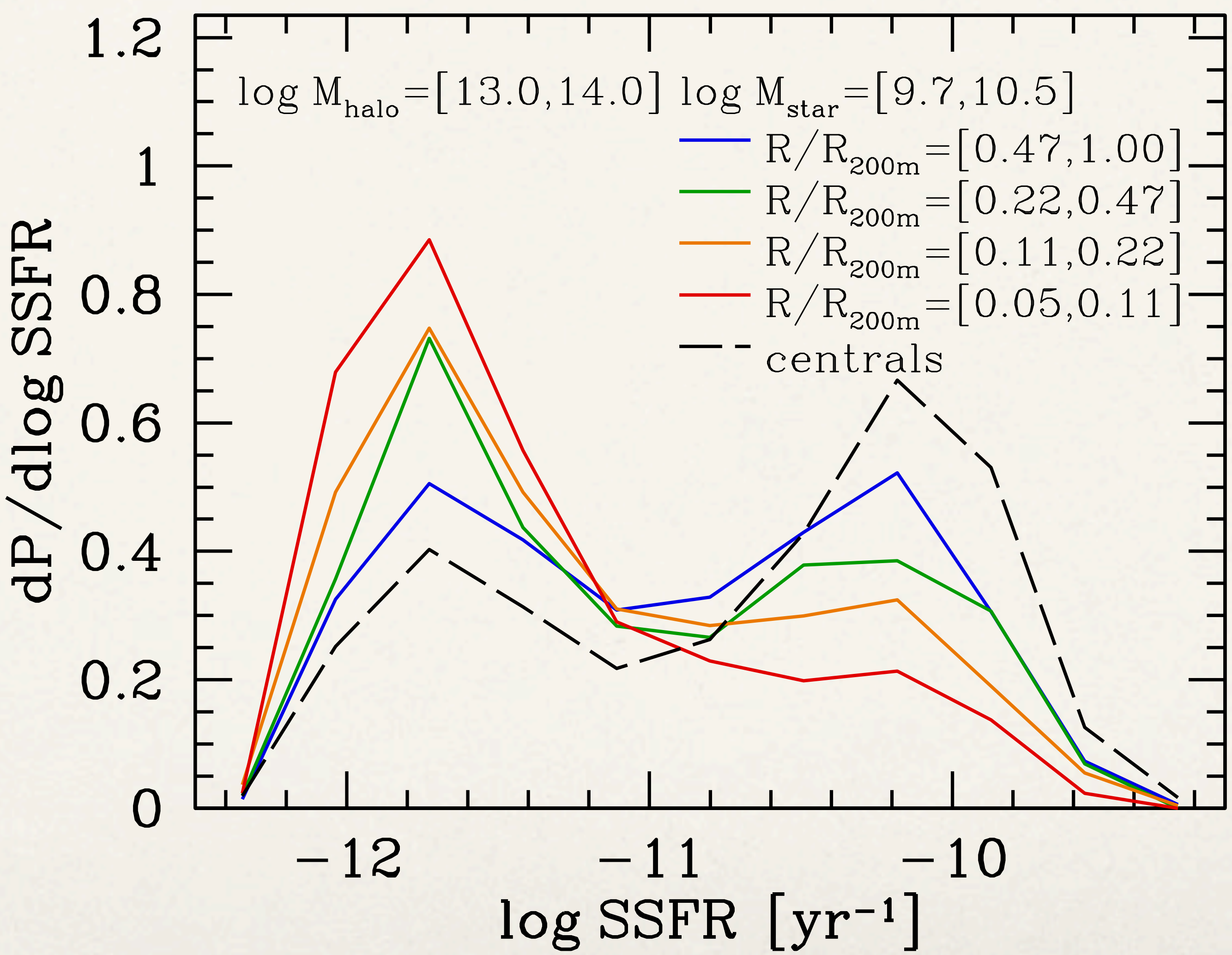
Galaxy Evolution in Groups & Clusters

Satellite quenching is the **dominant** process for building up the red sequence at $M_{star} < 10^{10}\ M_{\odot}$



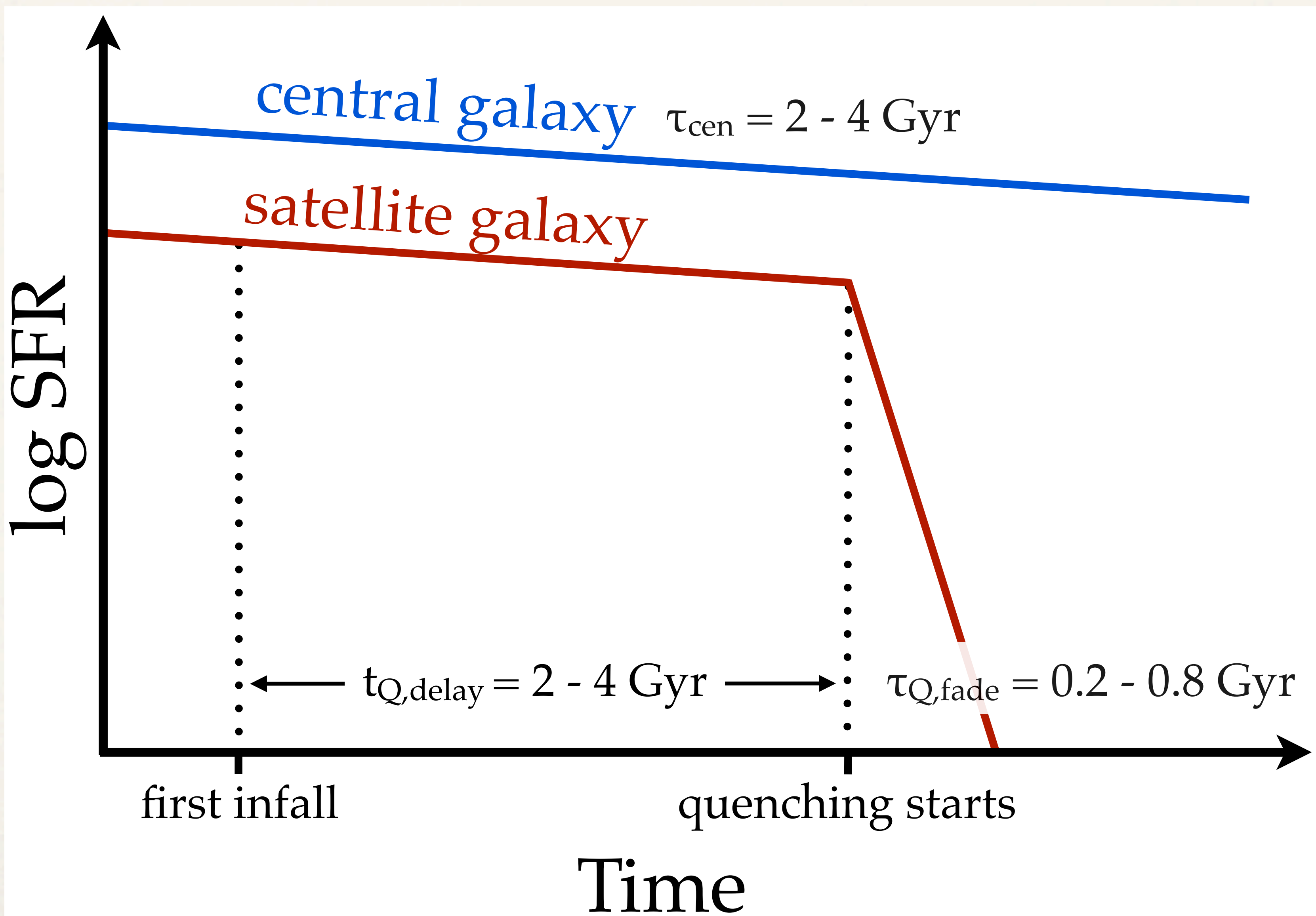
Galaxy Evolution in Groups & Clusters

Satellite quiescent fraction increases with host halo mass & toward halo center, but SFR bimodality **always** persists



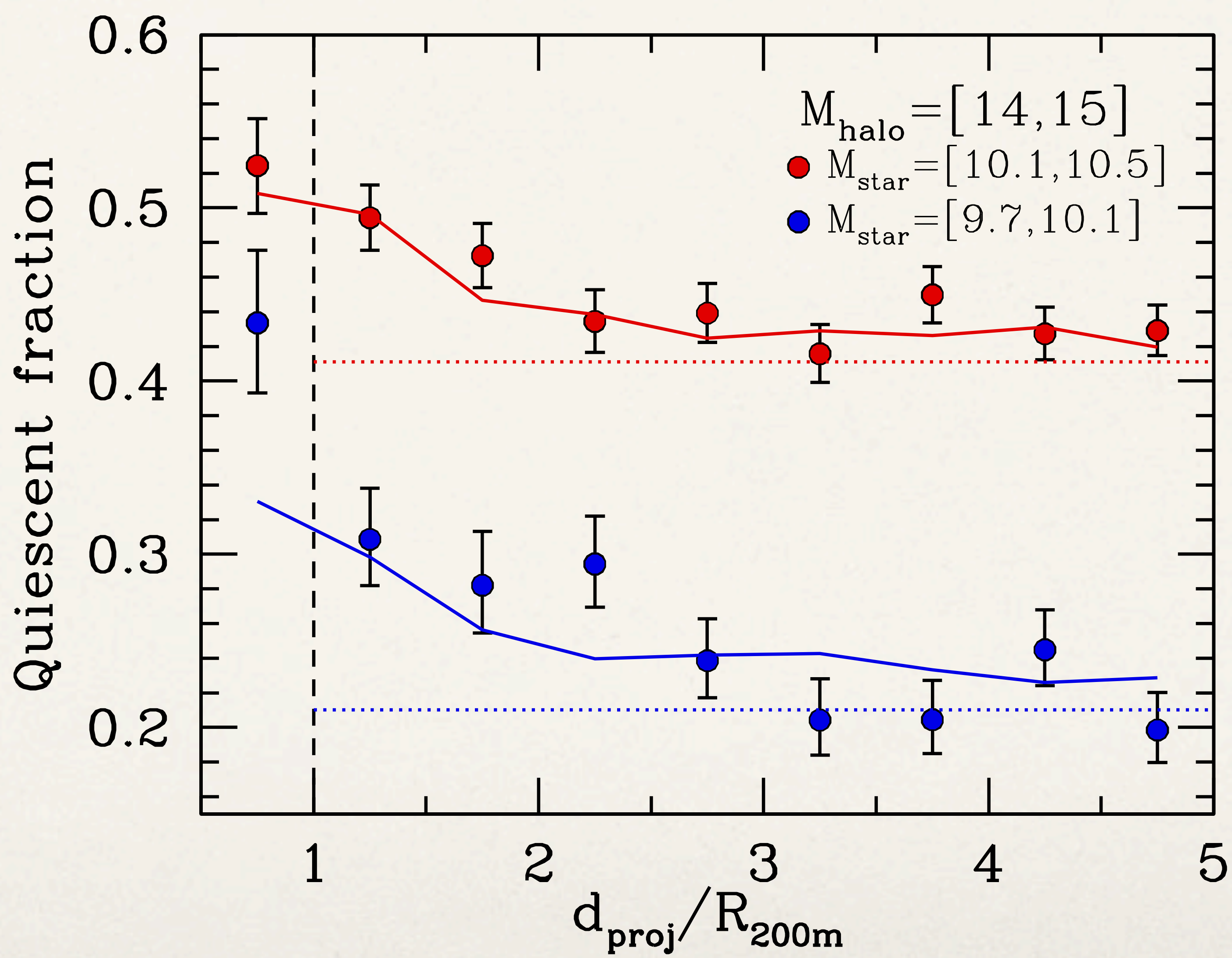
Galaxy Evolution in Groups & Clusters

`Delayed-then-rapid' satellite quenching scenario



Galaxy Evolution in Groups & Clusters

Satellite galaxies ejected outside the virial radius evolve/quench **same** as those inside



Galaxy Evolution in Groups & Clusters

Satellite galaxies drive essentially **all** environmental dependence of galaxy star formation

Satellite quenching is the **dominant** process for building up the red sequence at $M_{star} < 10^{10}\ M_{\odot}$

Satellite quenching is **delayed** (2 - 4 Gyr) then **rapid** (< 800 Myr)

Satellites ejected beyond R_{vir} evolve **same** as those within R_{vir}