Collaborators

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UC Santa Cruz

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Evolution of Star Formation in Galaxies

Faber et al 2007

Andrew Wetzel   *Yale University*
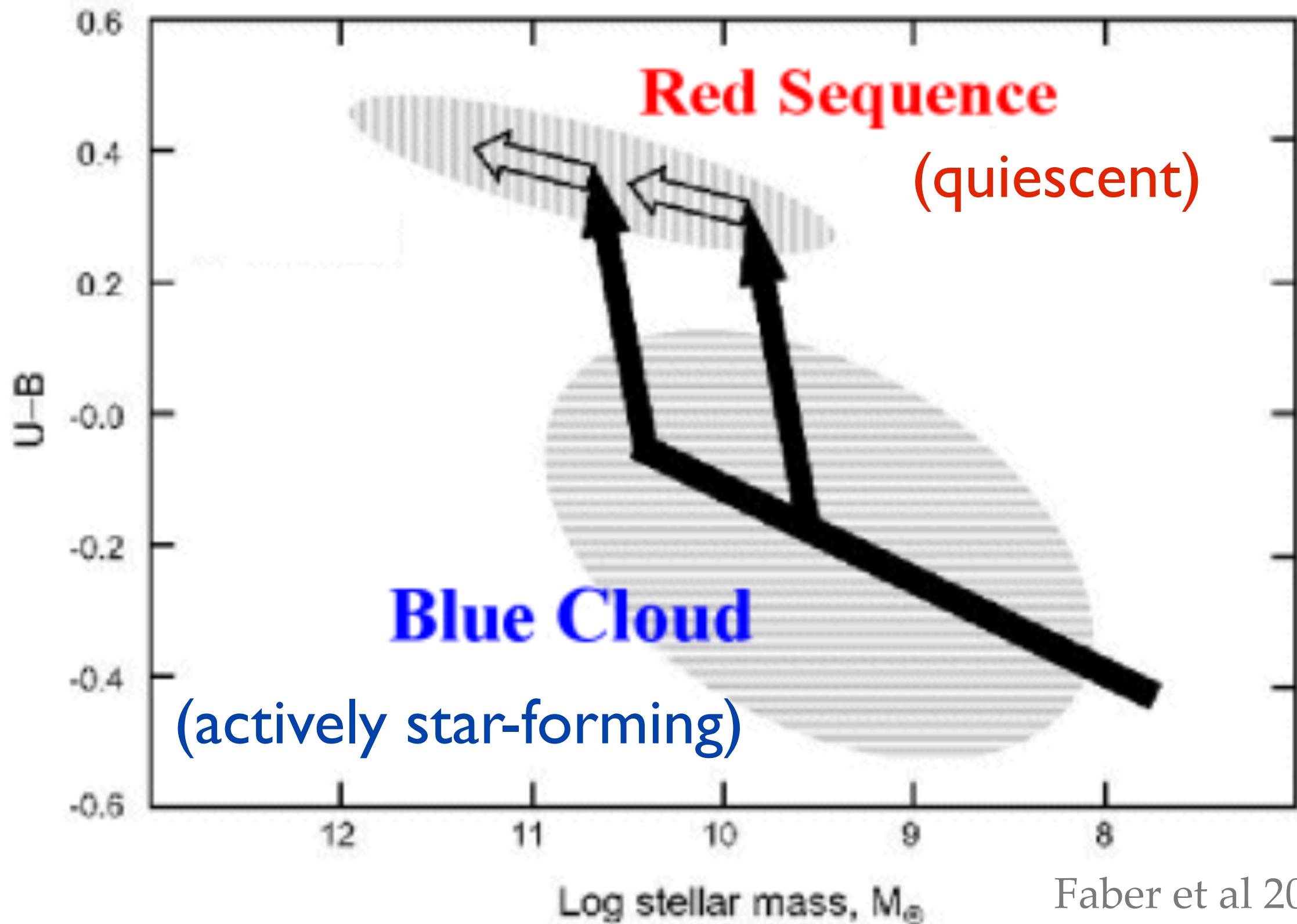
Galaxy SFR/color depends on environment
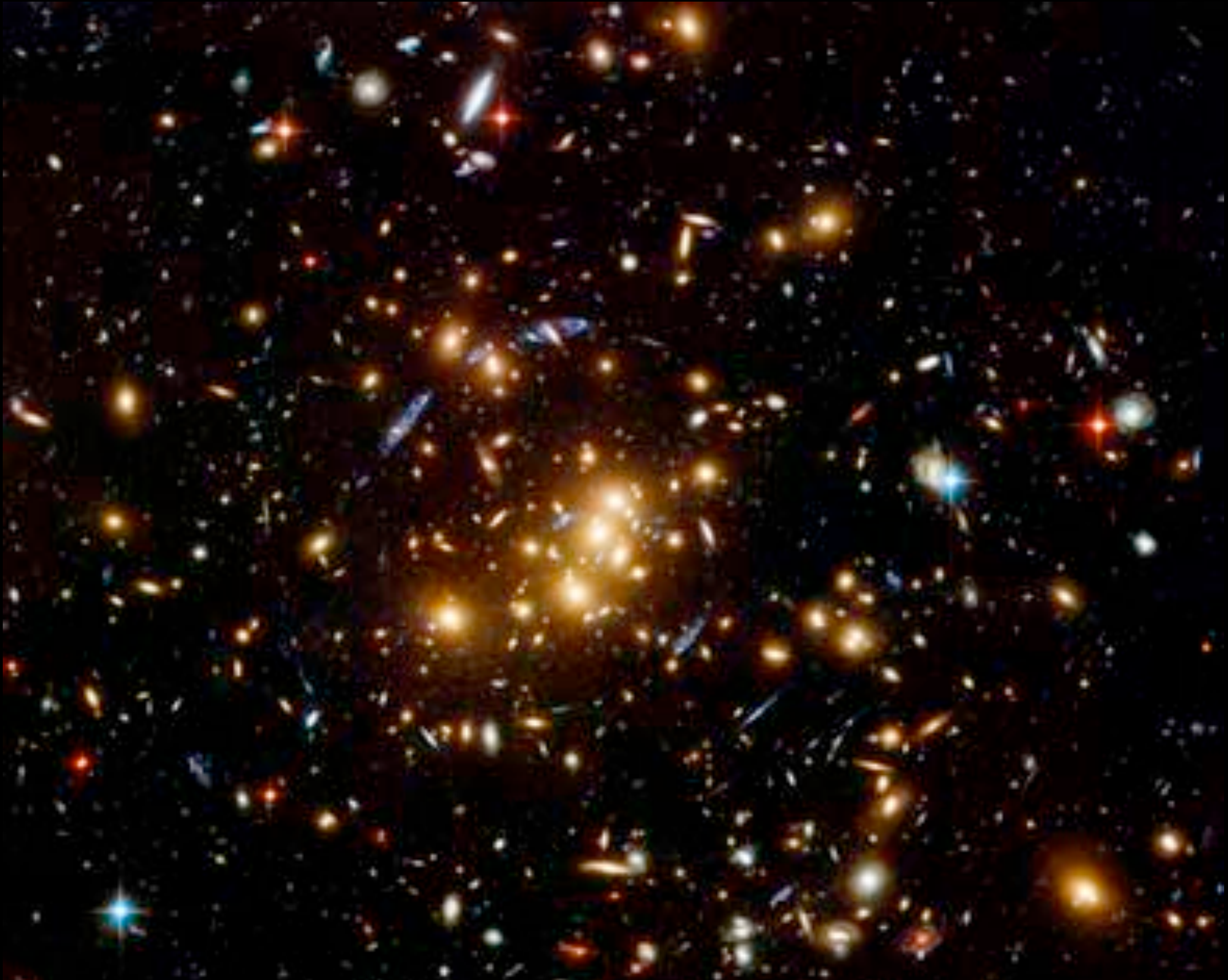
Galaxy properties depend on their environmental density
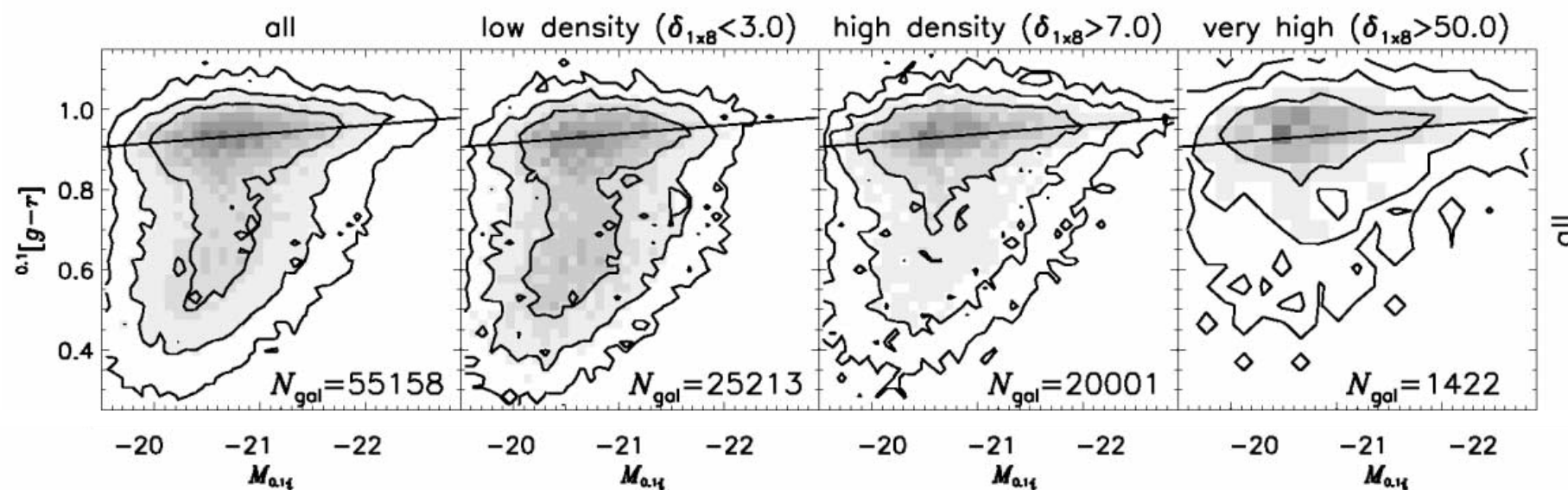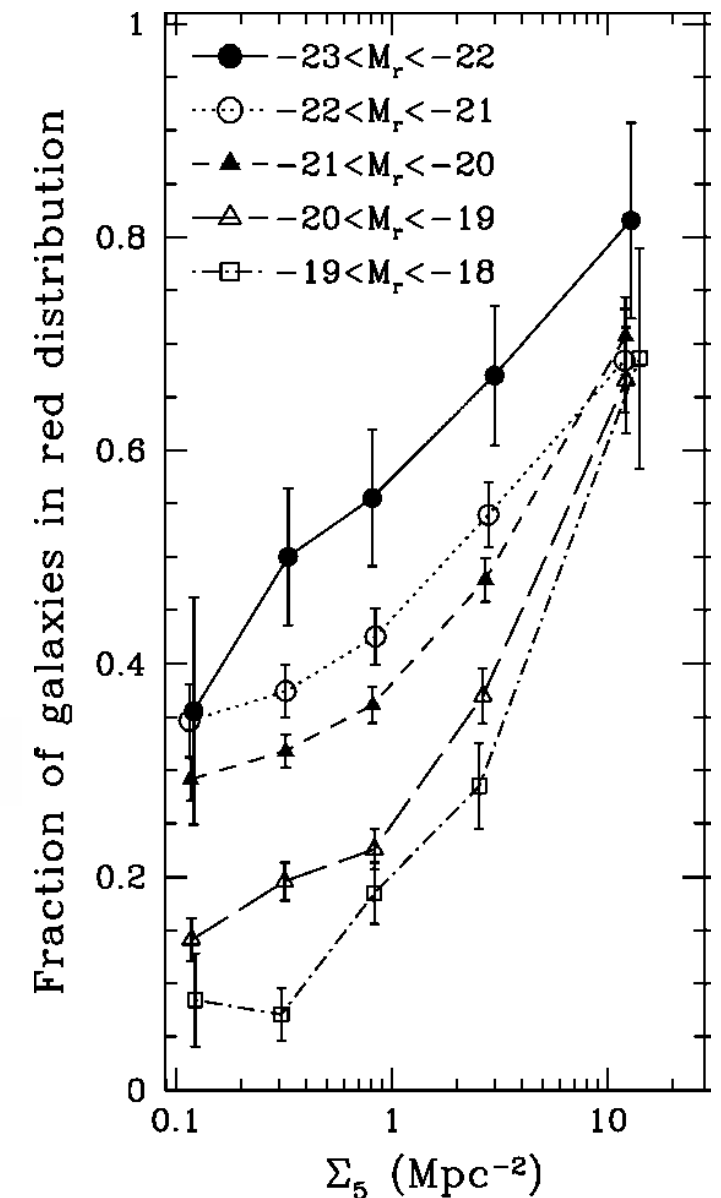
Abel 1965
Oemler 1974
Dressler 1980
Postman & Geller 1984

Hogg et al 2004

Balogh et al 2004

Outstanding questions about environmental quenching

What is the physical extent of environmental dependence?

Where / when does environmental quenching begin?

How long does the quenching process take?

How does SFR evolve in detail?

What is the physical mechanism?

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   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
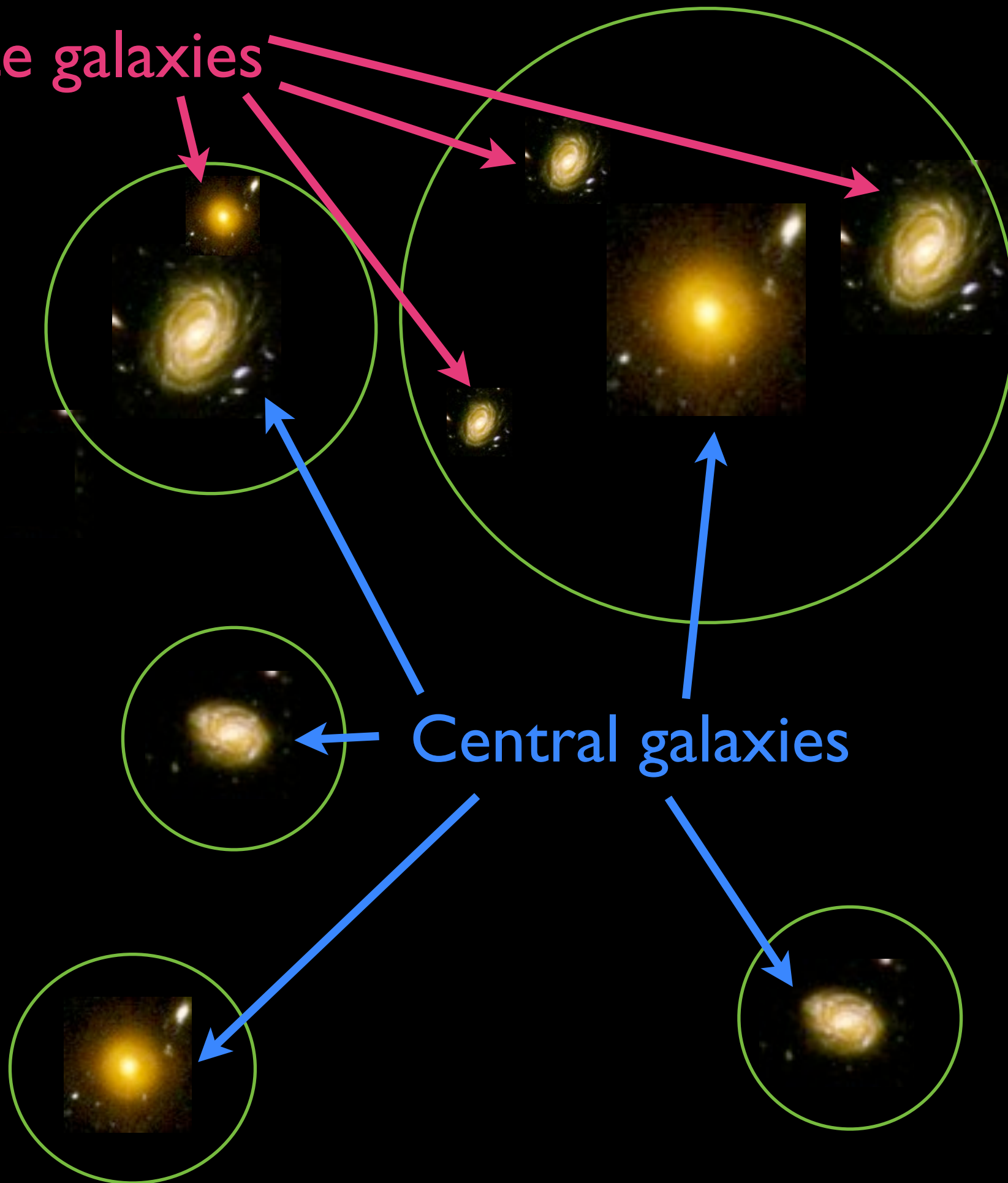
Central galaxies

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What is the physical extent of environmental dependence?

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How long does the quenching process take?
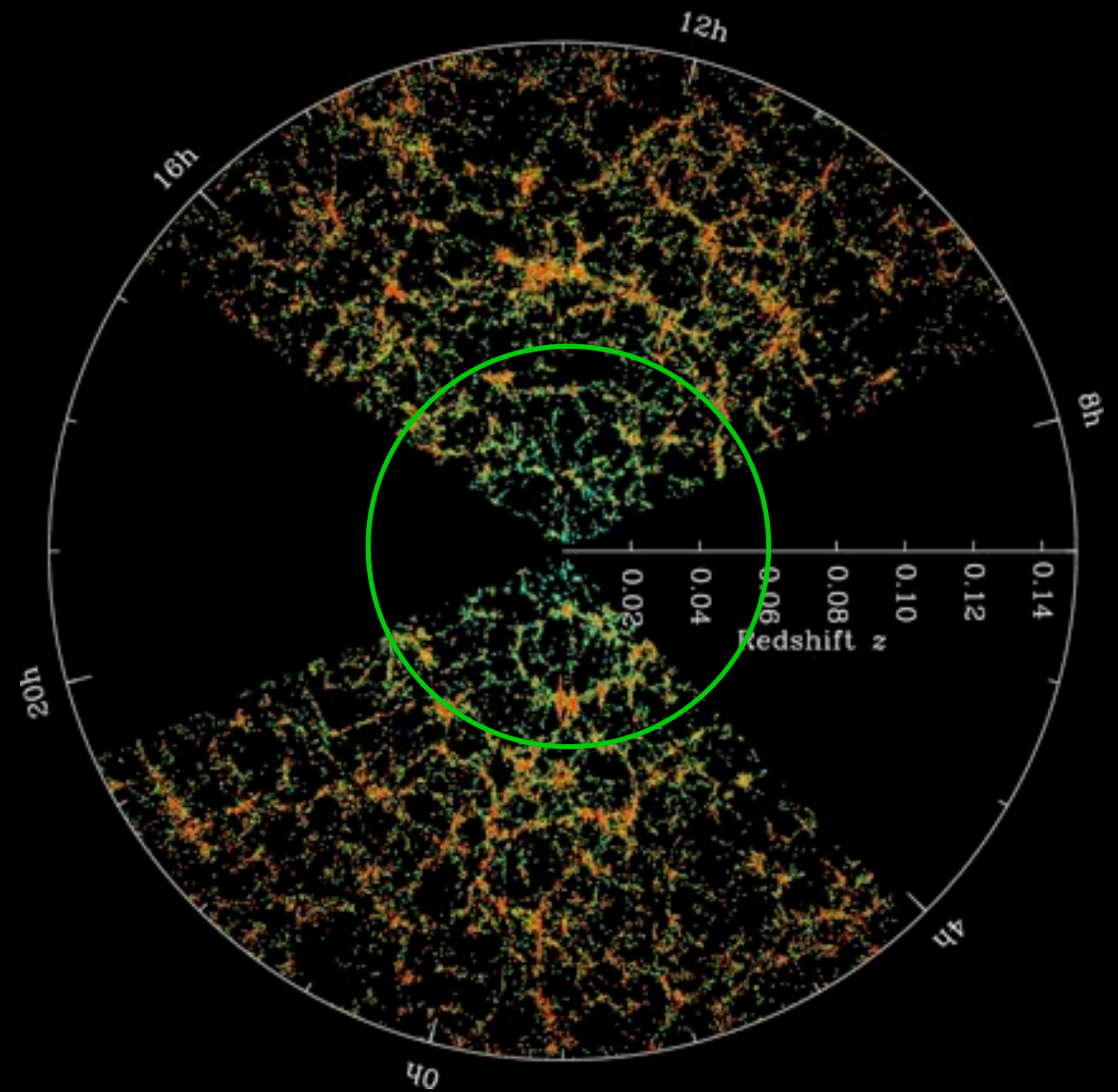
How does SFR evolve in detail?

What is the physical mechanism?

Andrew Wetzel   *Yale University*

Environmental dependence of galaxy star formation

Tinker, Wetzel & Conroy 2011

Andrew Wetzel   *Yale University*

Environmental dependence of galaxy star formation

Tinker, Wetzel & Conroy 2011
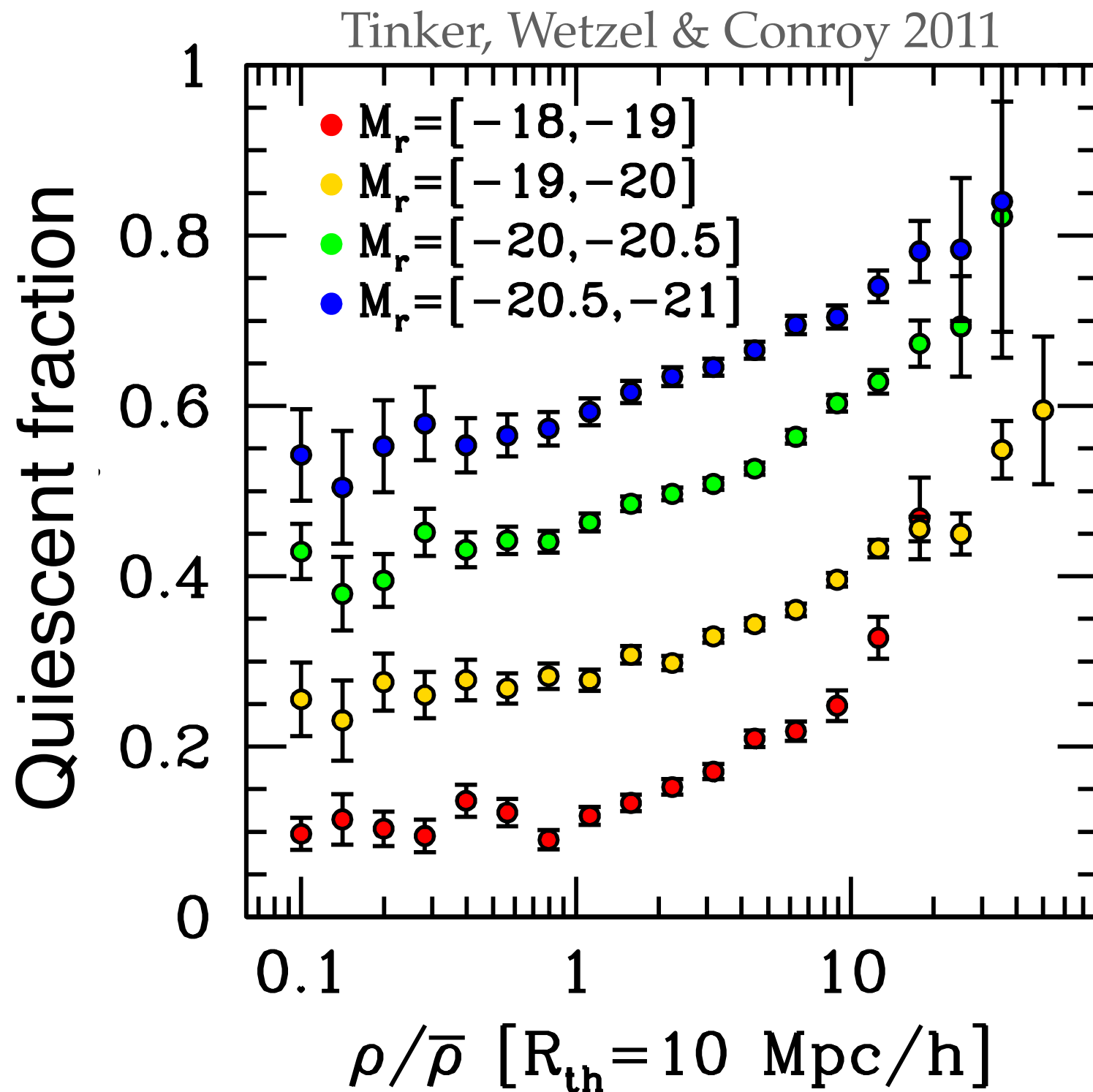
Environmental dependence = satellite galaxies

Andrew Wetzel   *Yale University*

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

Andrew Wetzel   *Yale University*

Is SFR affected beyond the virial radius?

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

cosmic average

$M_{halo} = [14, 15]$

$M_{star} = [10.5, 10.9]$
$M_{star} = [10.1, 10.5]$
$M_{star} = [9.7, 10.1]$

Quiescent fraction

Distance/R_{200m}
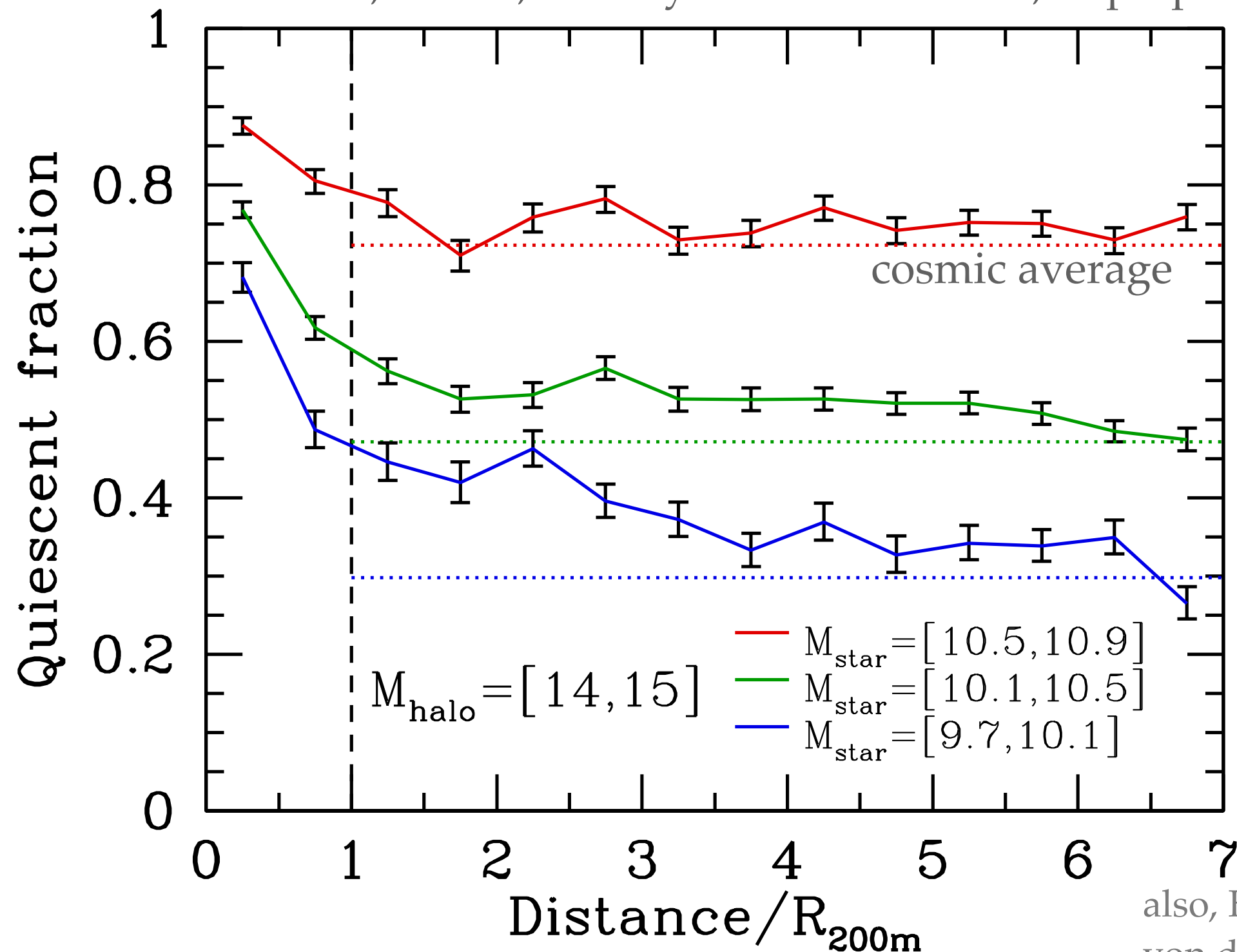
also, Hansen et al 2009
von der Linden et al 2010

Andrew Wetzel

Yale University

Is SFR affected beyond the virial radius?

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

$M_{halo} = [14, 15]$
$M_{star} = [9.7, 10.1]$

— all
— centrals
— satellites

Quiescent fraction

Distance/R_{200m}

Andrew Wetzel

Yale University

Outstanding questions about environmental quenching

What is the physical extent of environmental dependence?

Where/**when does environmental quenching begin?**
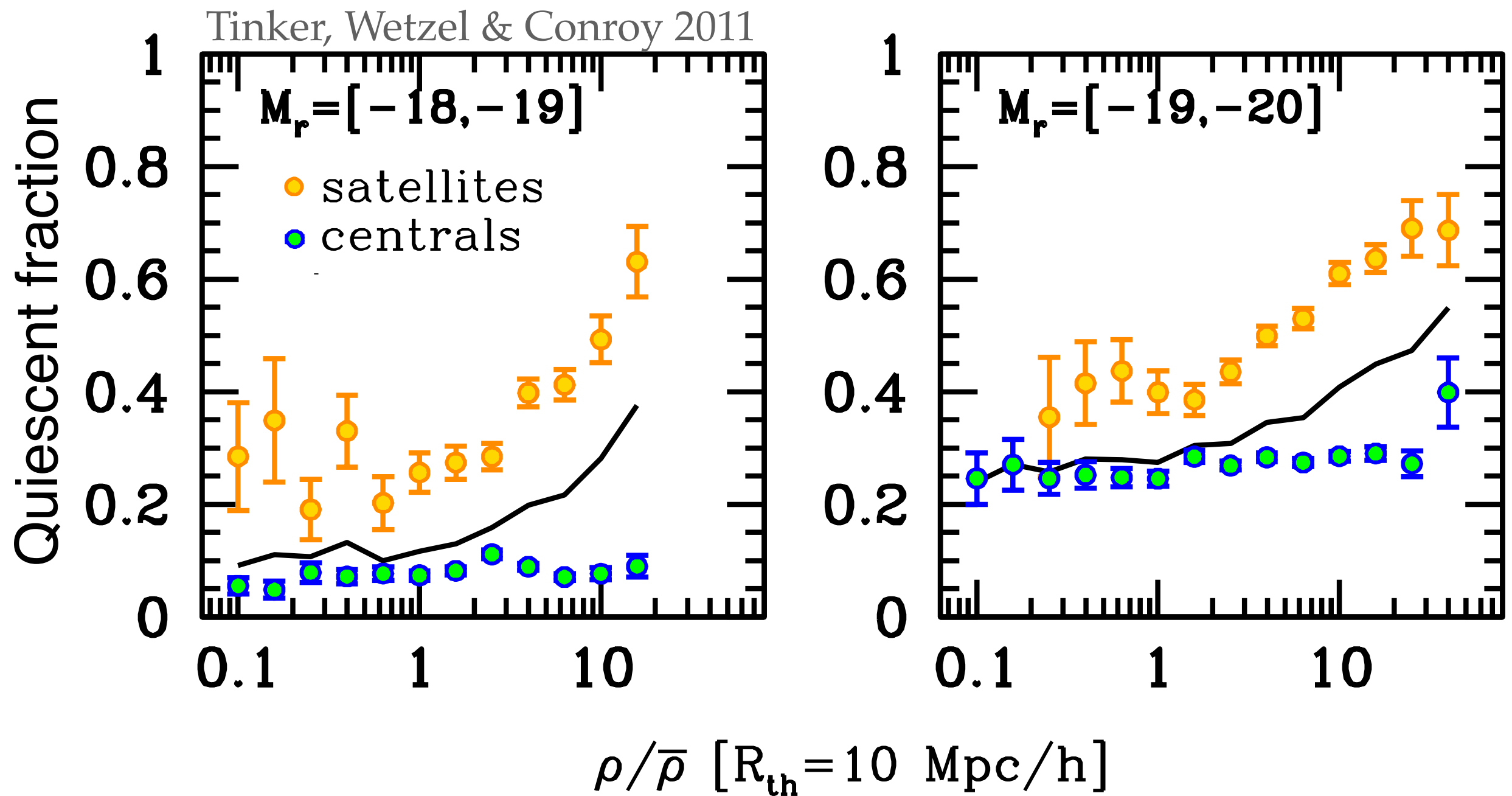
How long does the quenching process take?

How does SFR evolve in detail?

What is the physical mechanism?

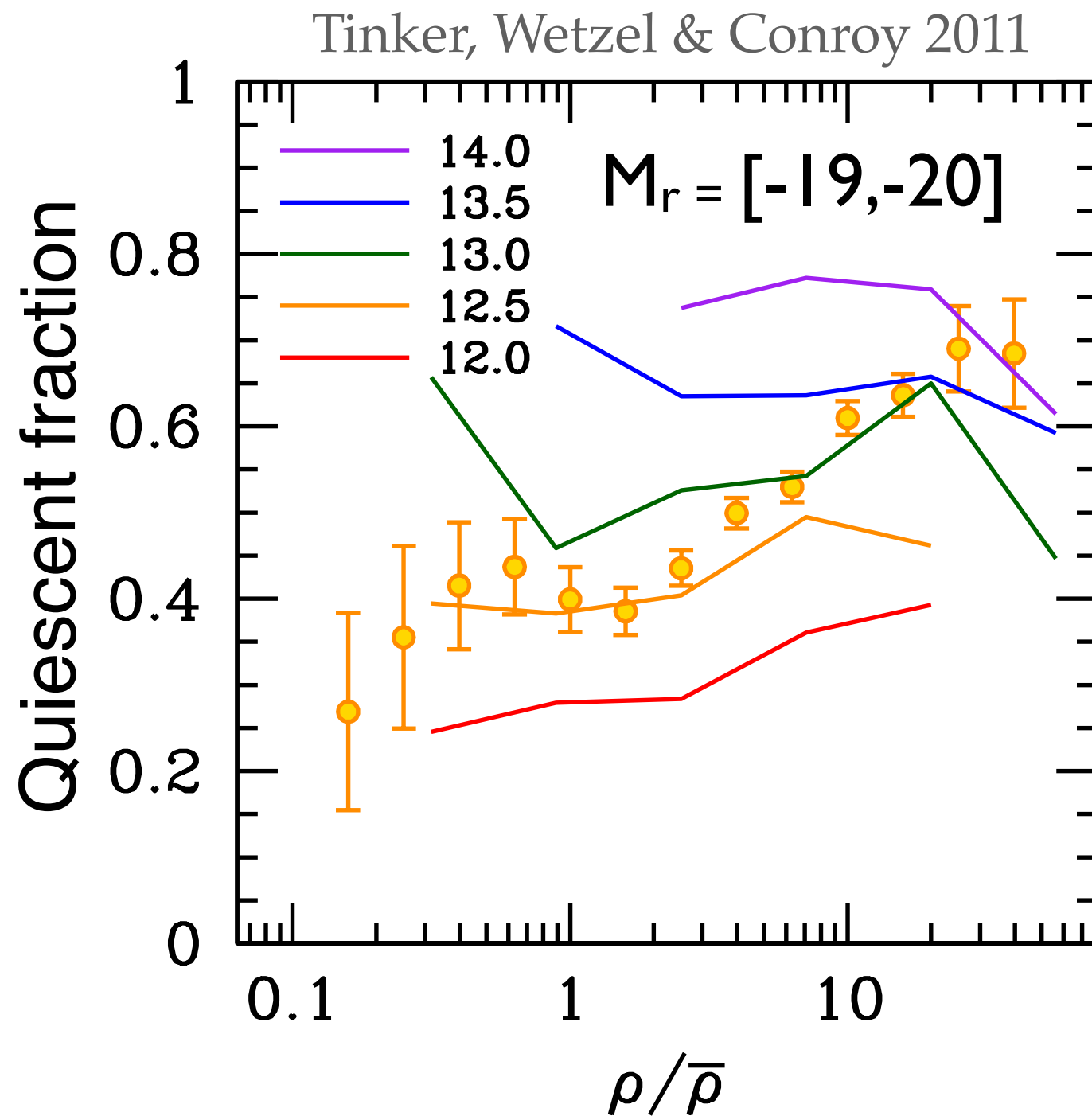*Andrew Wetzel*   *Yale University*

Wetzel, Tinker & Conroy 2011
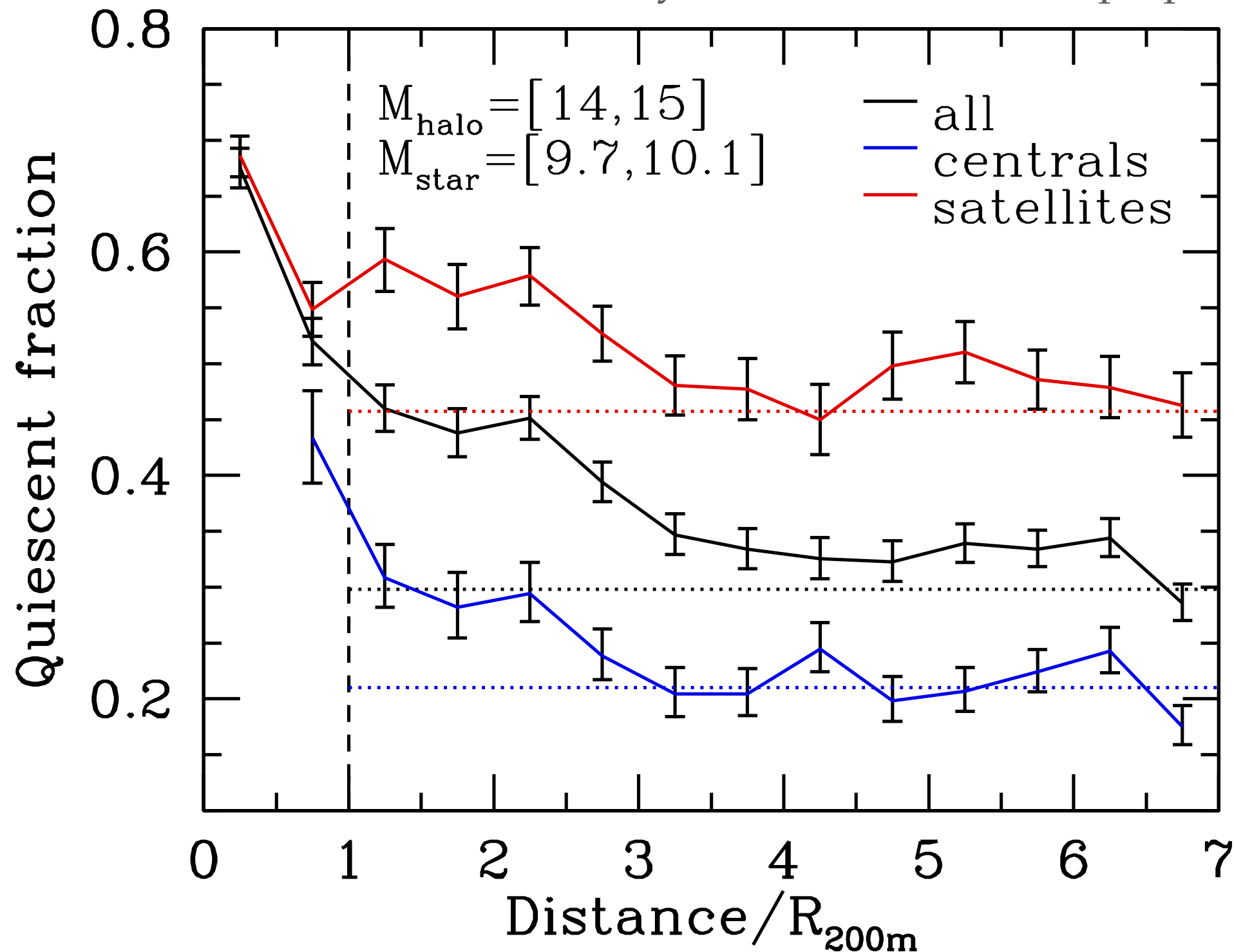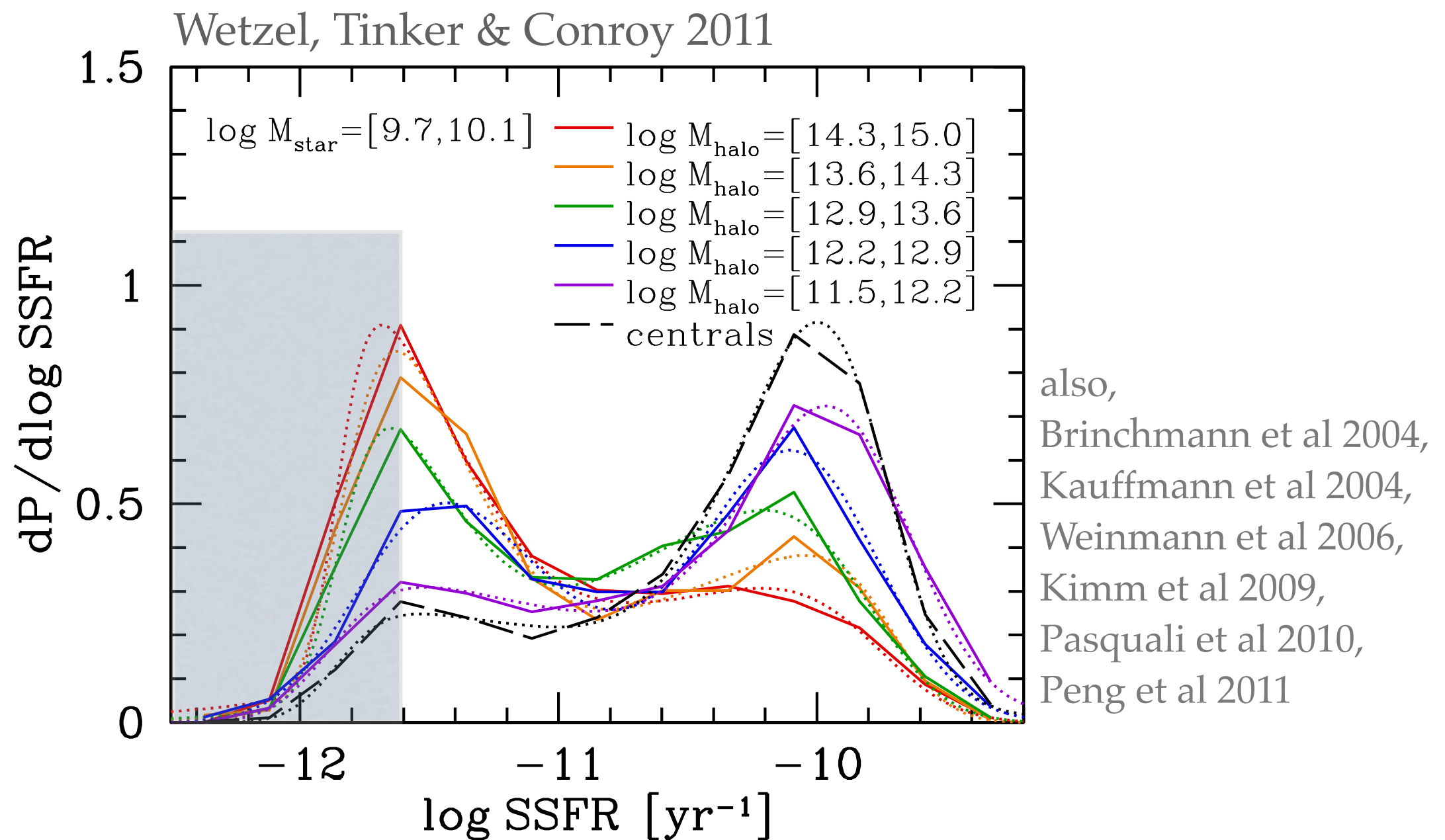
Satellite SFR depends on mass of host halo
SFR bimodality persists across **all** host halo masses
No lower limit of host halo mass for affecting satellite SFR

Andrew Wetzel   *Yale University*

Satellite SFR depends on halo-centric distance

Wetzel, Tinker & Conroy 2011
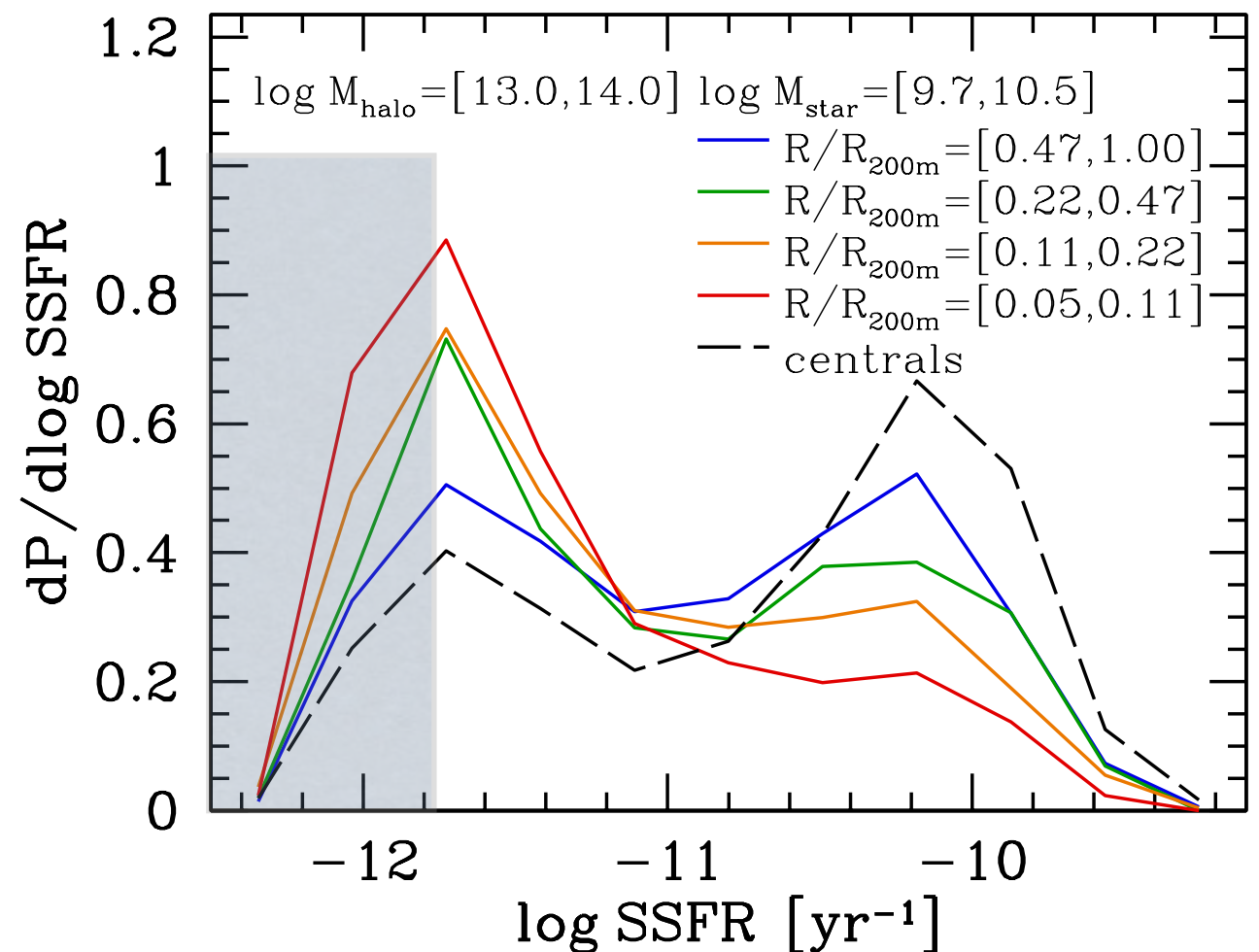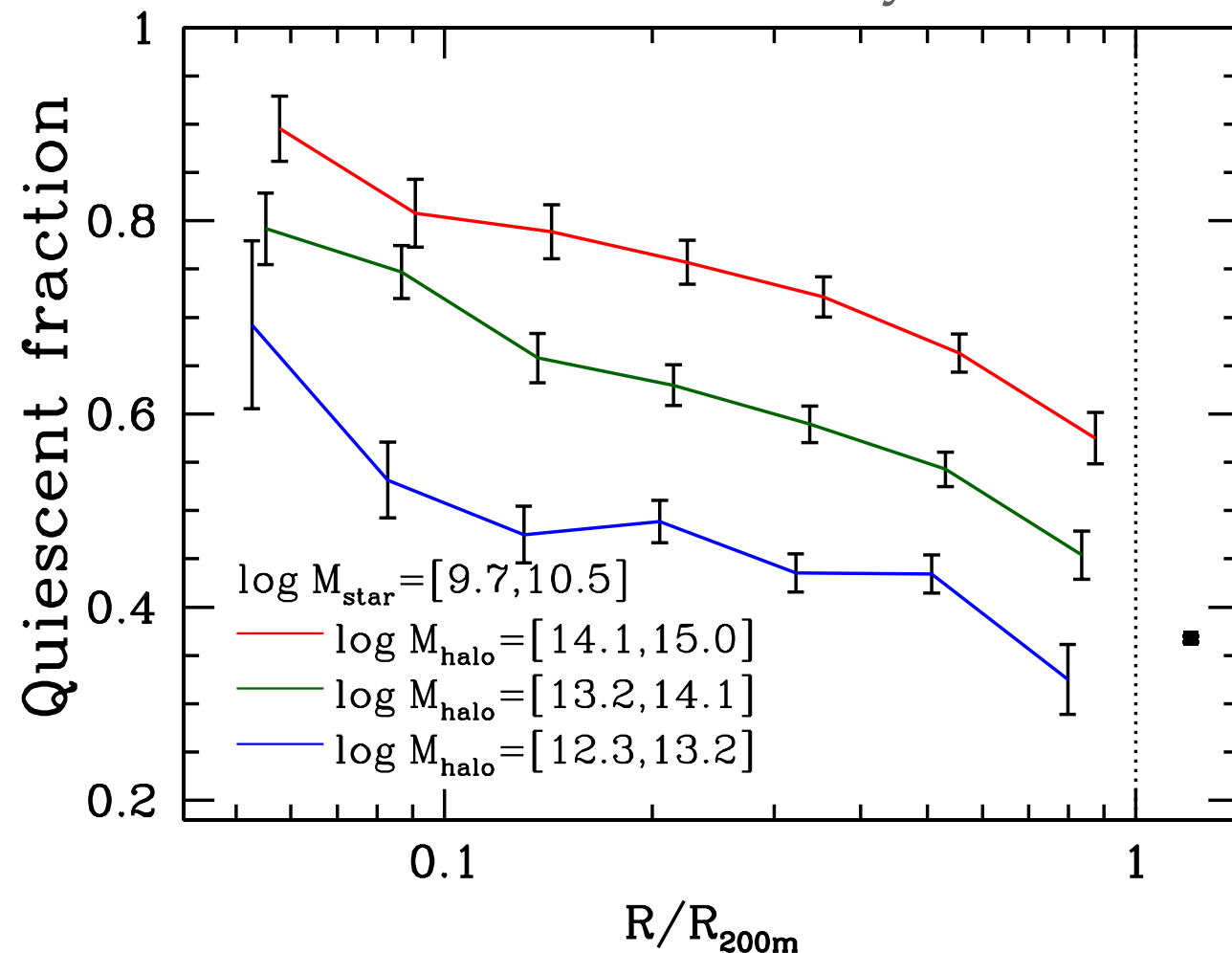
but SFR bimodality persists at all halo-centric distances

~constant fraction at intermediate SFR ('green valley')

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

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
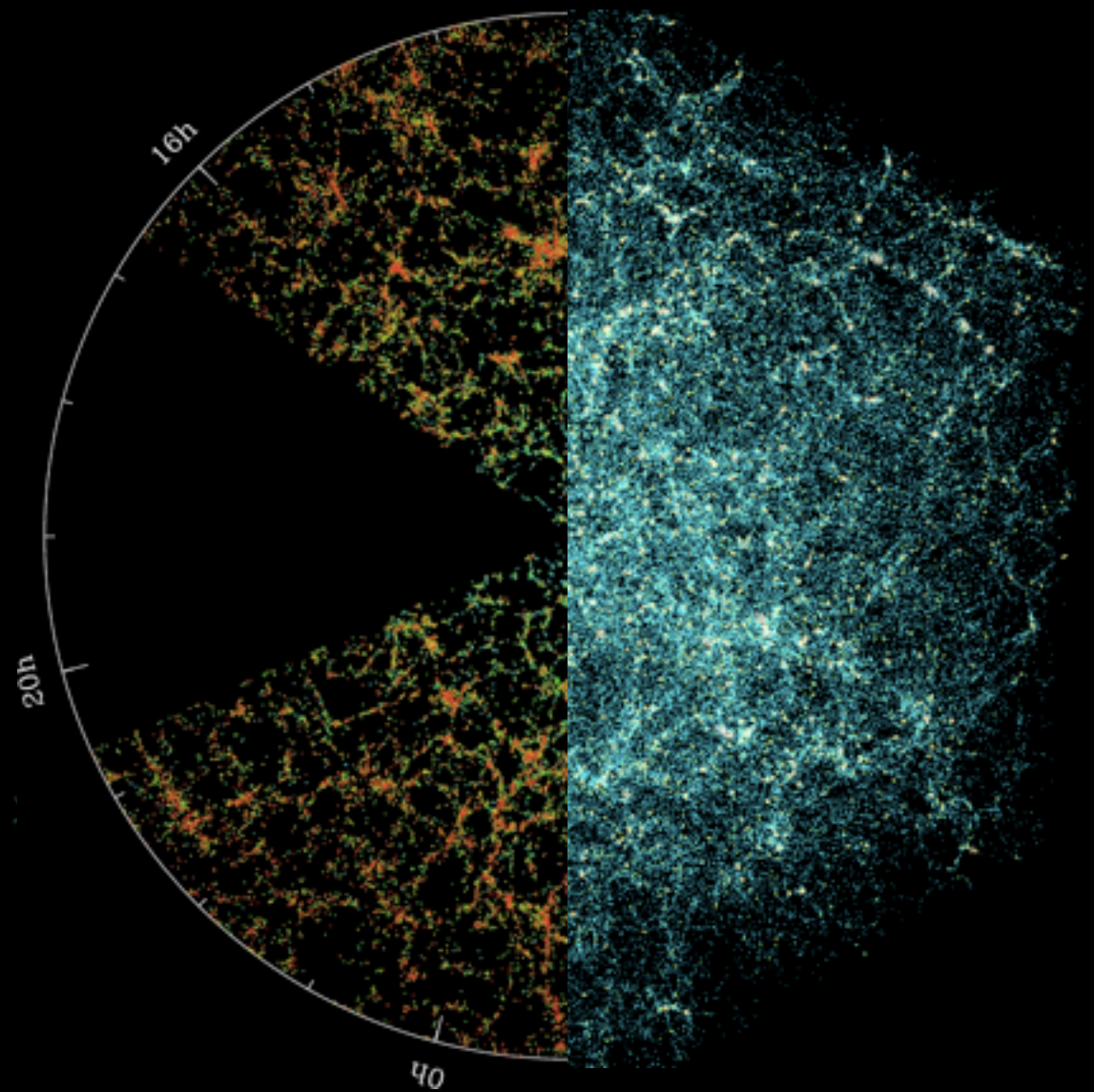
How do satellites fall into halos?

Wetzel, Tinker, Conroy & van den Bosch 2012

$\log M_{star} > 9.7$
— first infall central
— re-infall ejected satellite
— satellite in group
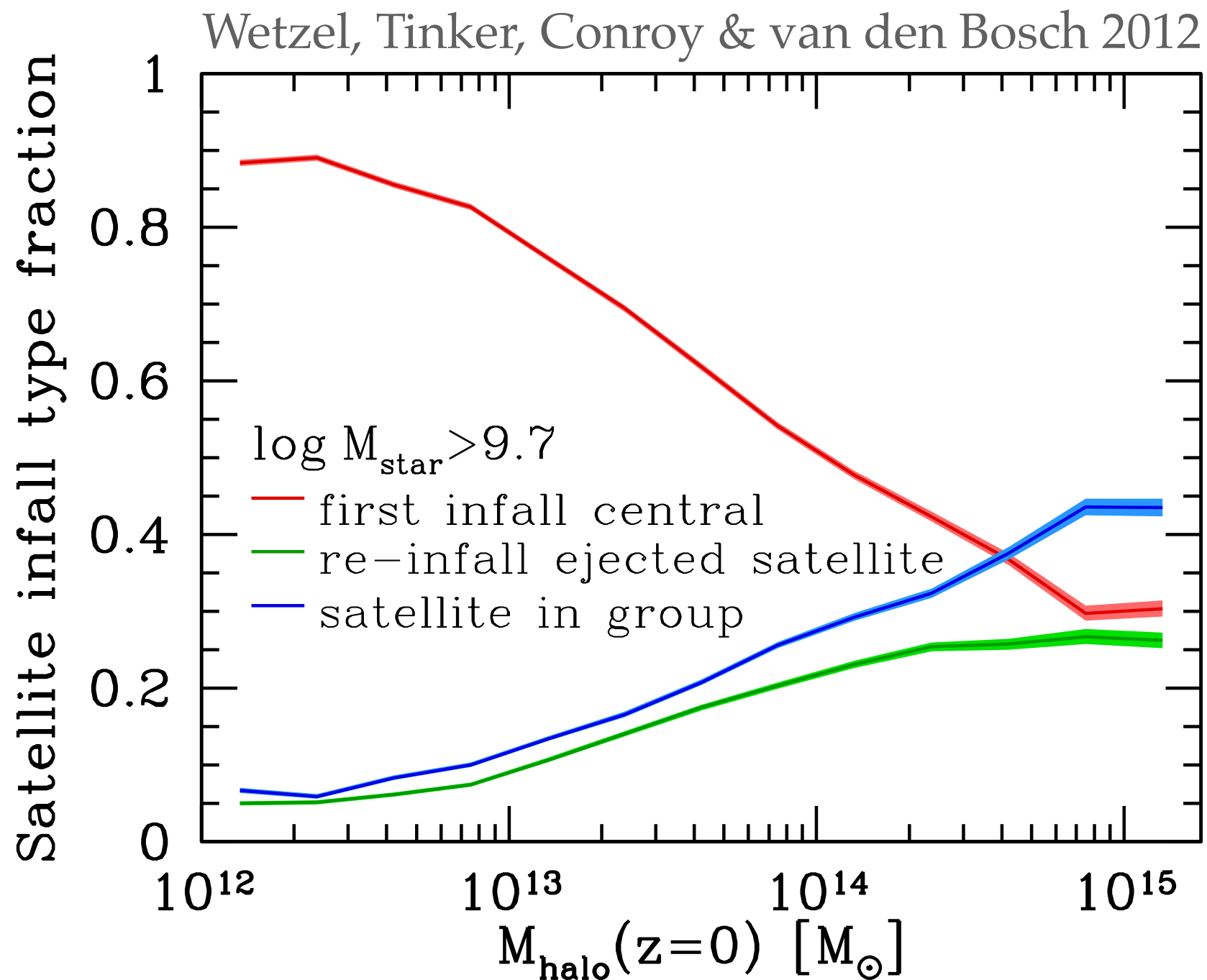
also,
Berrier et al 2009
McGee et al 2009

y-axis: Satellite infall type fraction

x-axis: $M_{halo}(z=0)$ [$M_\odot$]

In halos > 10^{14} M$_\odot$, most satellites do not fall in directly from the field
Importance of satellite *first* infall

Wetzel, Tinker, Conroy & van den Bosch, in prep
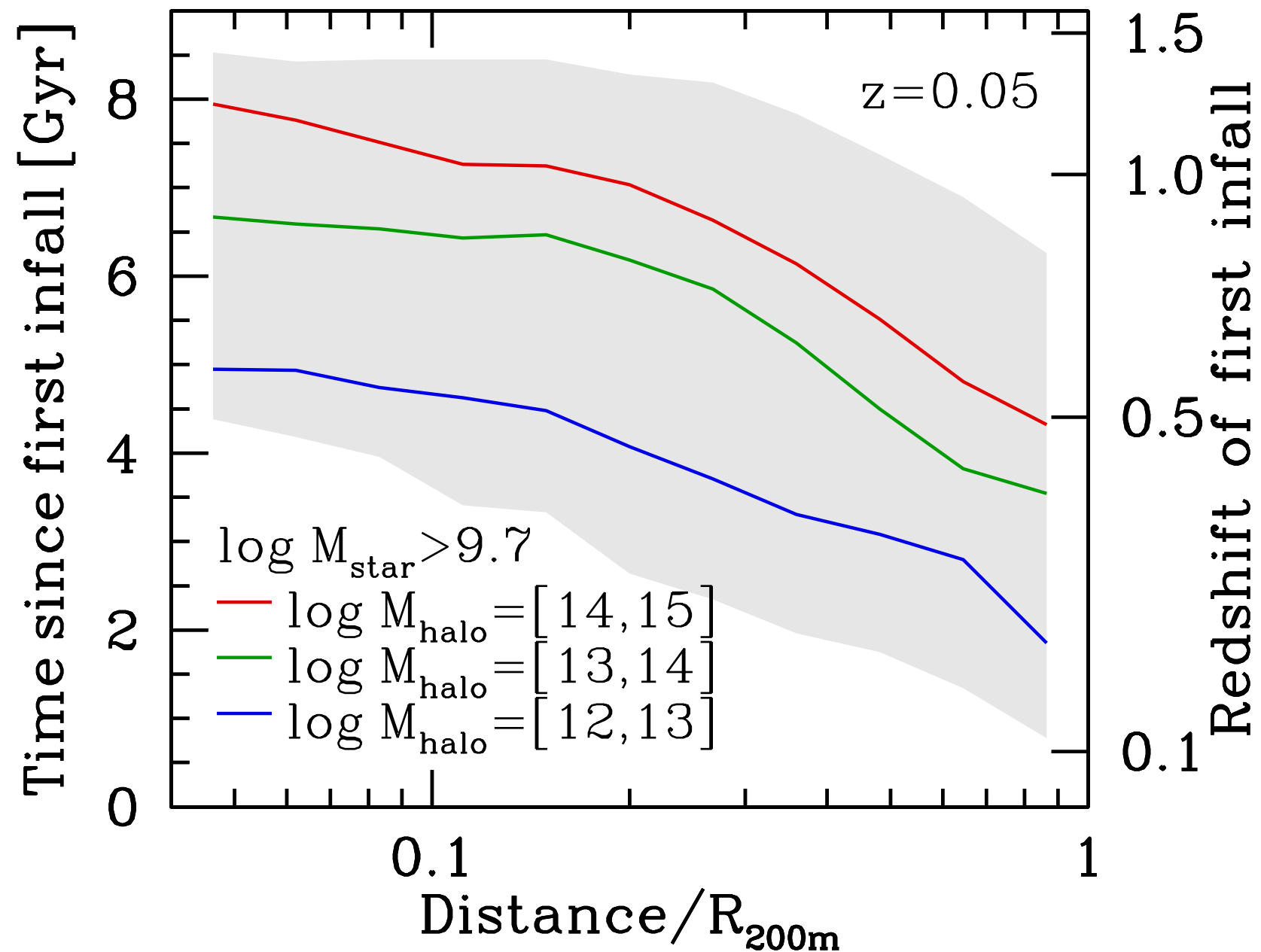
Earlier infall times in more massive host halos &
at smaller halo-centric distance

Andrew Wetzel

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 ~ 0.5, with a broad tail out to z ~ 1

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

Evolution of SFR for central galaxies
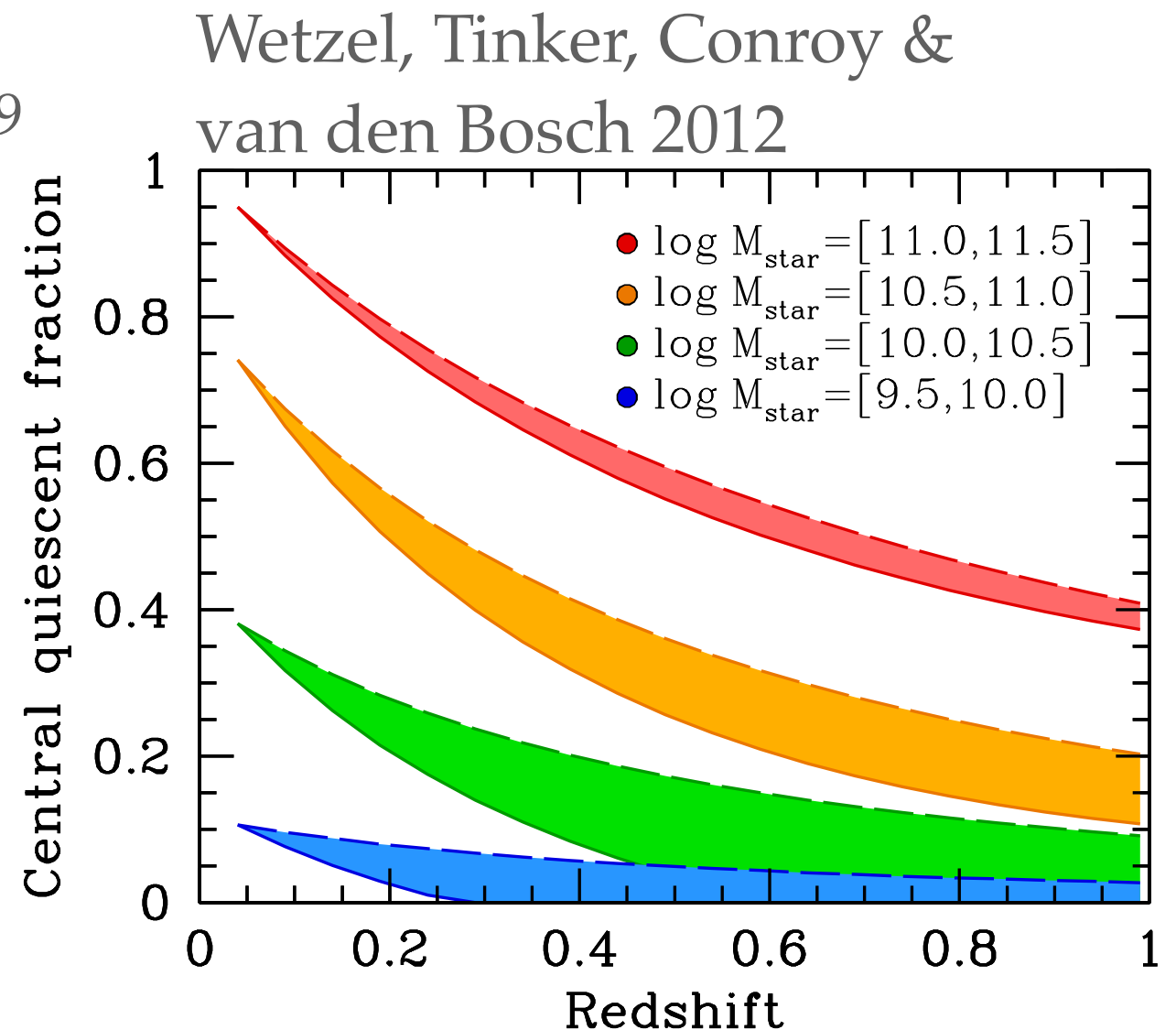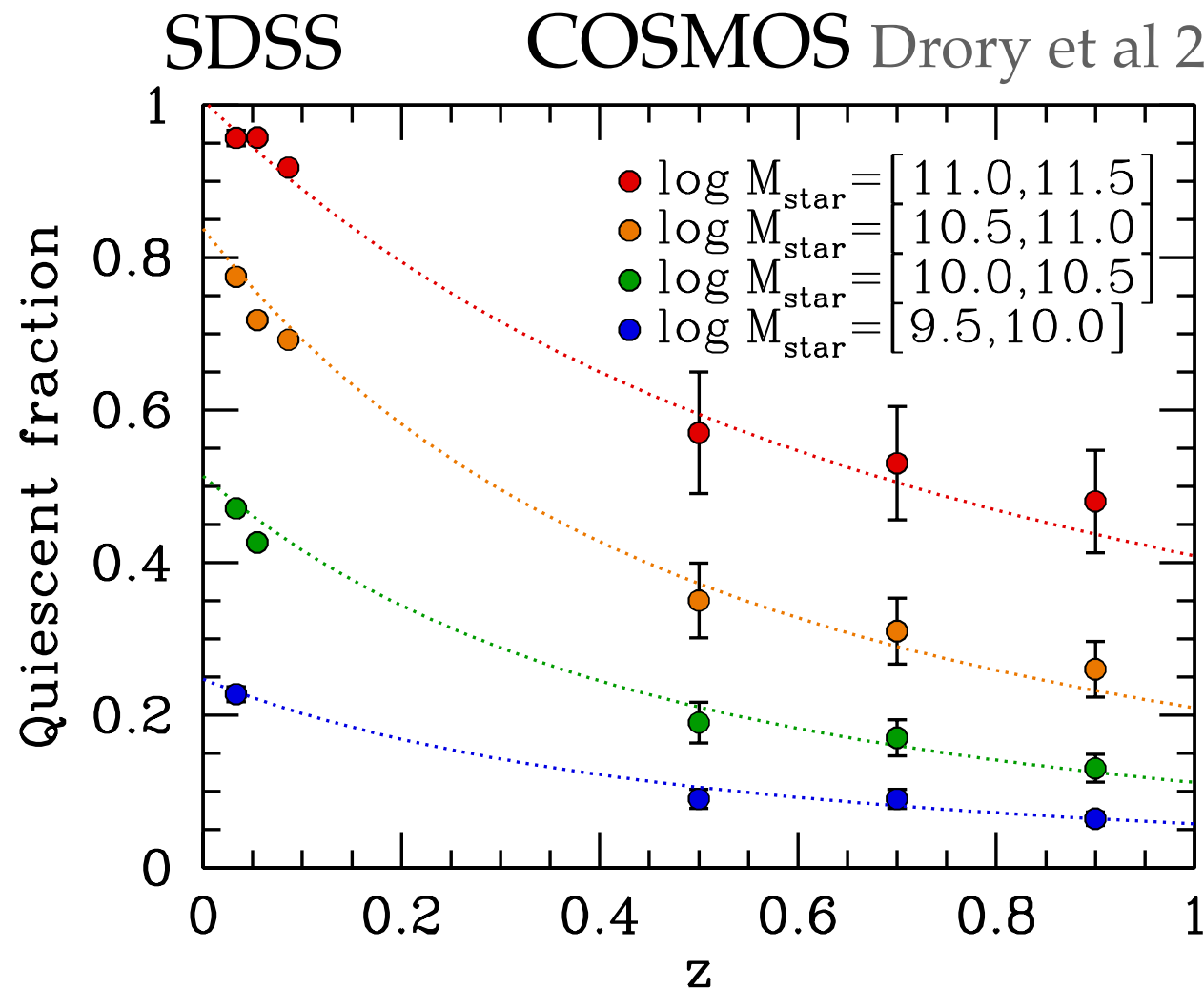
Use group catalogs & spatial clustering to disentangle quiescent fractions of central & satellite galaxies Tinker & Wetzel 2010

Central galaxy quiescent fraction grows by at least 2x since z ~ 1

Andrew Wetzel

Evolution of SFR for central galaxies

0.85 <= z < 1.10

0.70 <= z < 0.85

$z_f = 2, \tau \alpha M^{-1}$
(lowest z bin)

0.45 <= z < 0.70

$z_f = 1.2, \tau \alpha M^{-1}$
$z_f = 2, \quad \tau \alpha M^{-1}$
$z_f = 2, \quad \tau \alpha M^{-0.5}$

0.20 <= z < 0.45

$\log (\mathrm{SFR}/M_*[\mathrm{yr}^{-1}])$

$\log (M_*[M_{sun}])$

Noeske et al 2007

$\log M_{star} = [10.0, 10.5]$

z=0.0
z=0.1
z=0.3
z=0.5
z=0.7
z=0.9

$P(\log \mathrm{SSFR})$

$\log \mathrm{SSFR} \ [\mathrm{yr}^{-1}]$

Wetzel, Tinker, Conroy &
van den Bosch 2012

Andrew Wetzel

Yale University
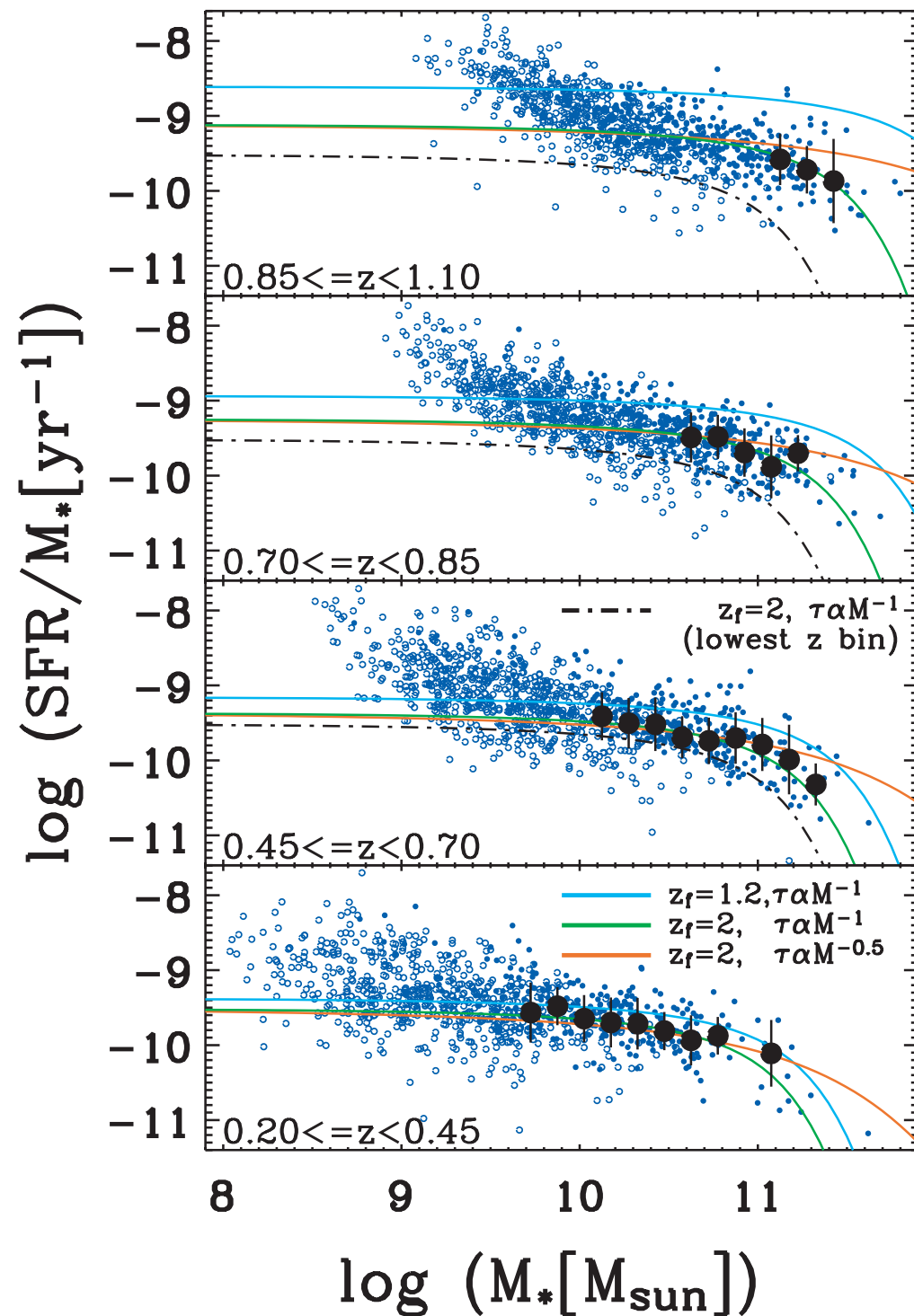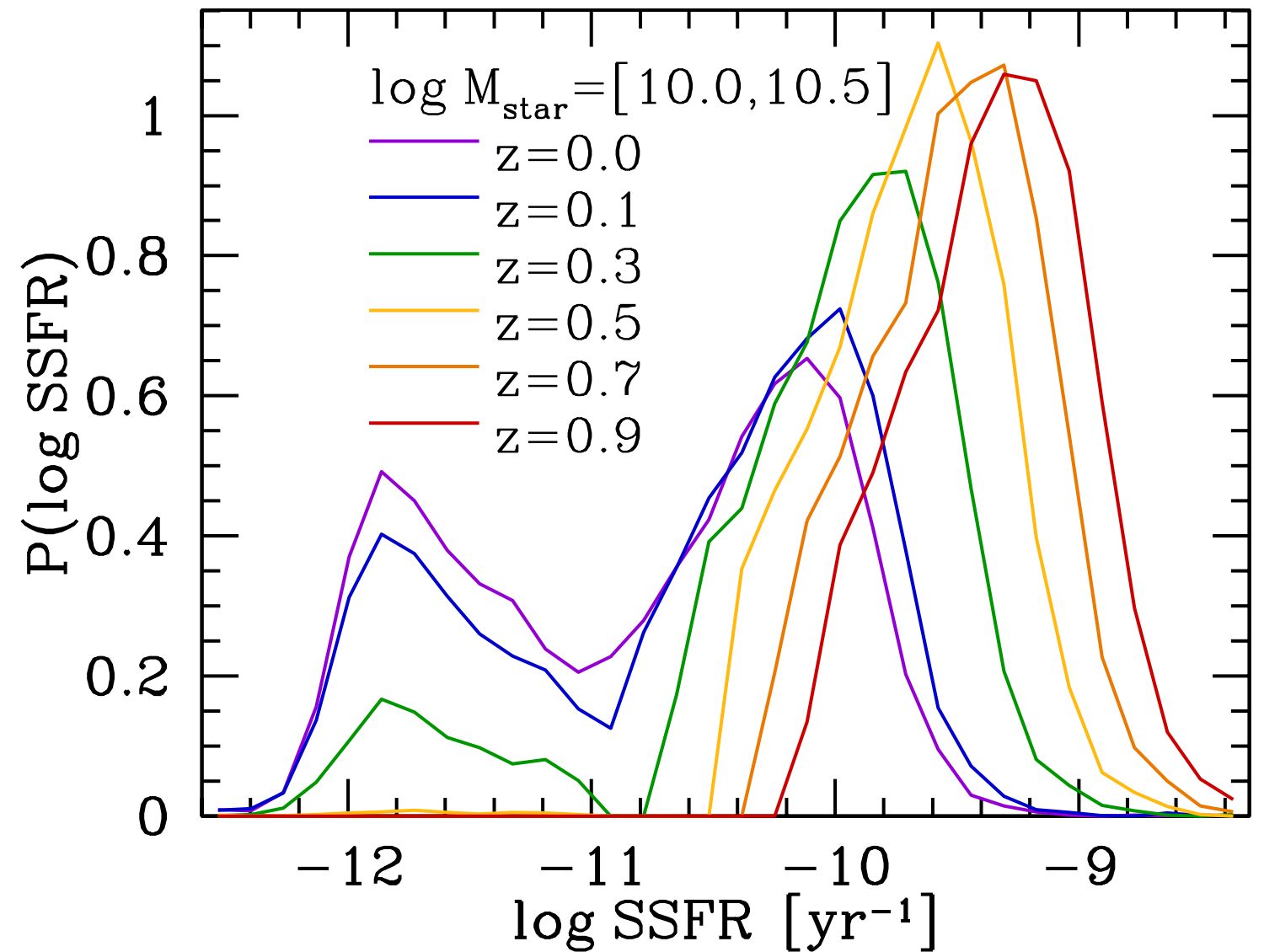
Importance of satellite quenching in building up the red-sequence population

Wetzel, Tinker, Conroy & van den Bosch 2012

Frac that quenched as sat

quiescent sats at z=0
quiescent gals at z=0

$M_{star}(z=0)$ [$M_\odot$]
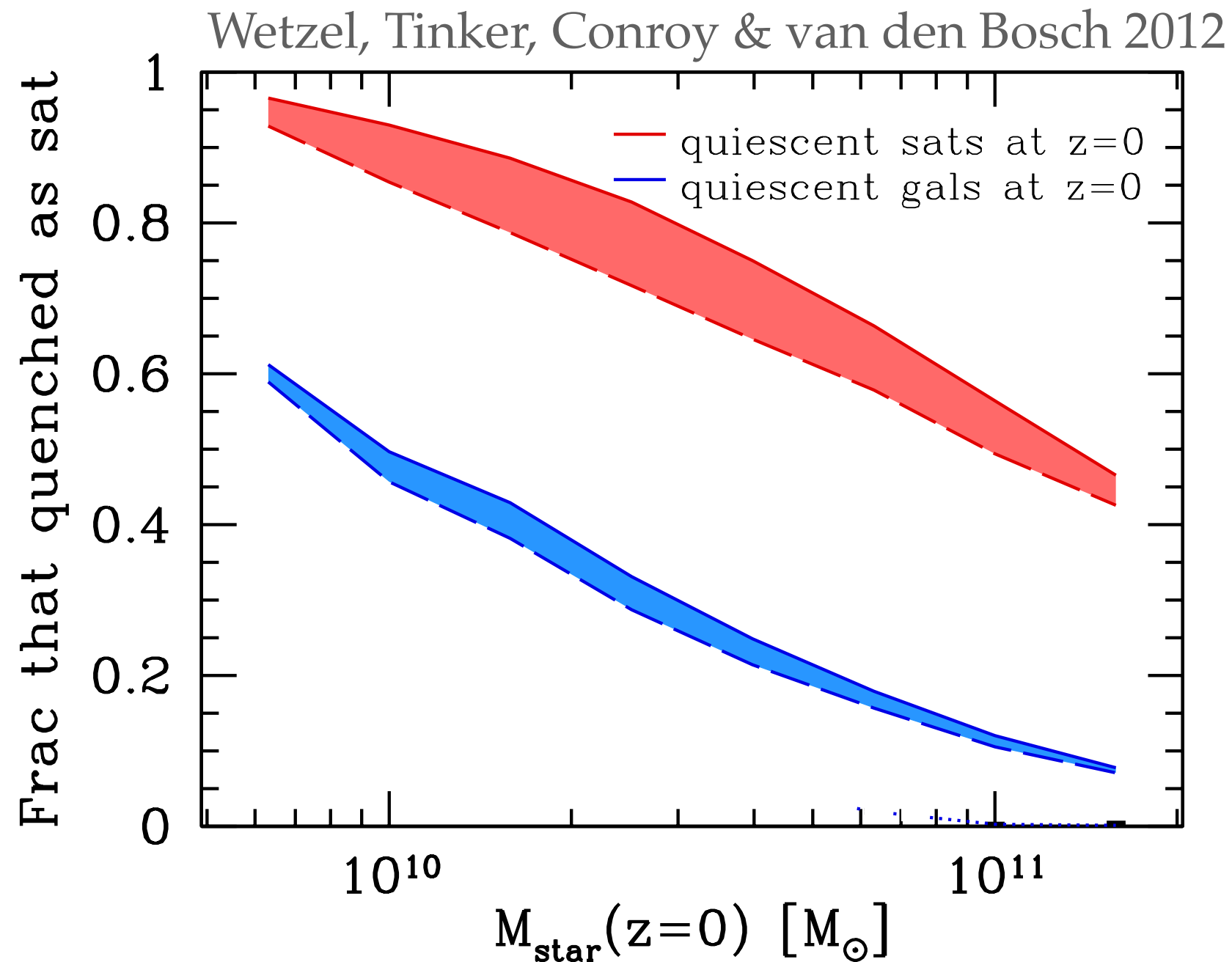
At $M_{star} < 10^{10} M_\odot$, most quiescent galaxies quenched as satellites

Andrew Wetzel   *Yale University*

Modeling satellite SFR histories

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

(1) Identify all surviving satellites in the simulation
that were actively star-forming at the time of infall

(2) Quench their star formation if they fell in prior to
some time-since-infall threshold

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

Andrew Wetzel
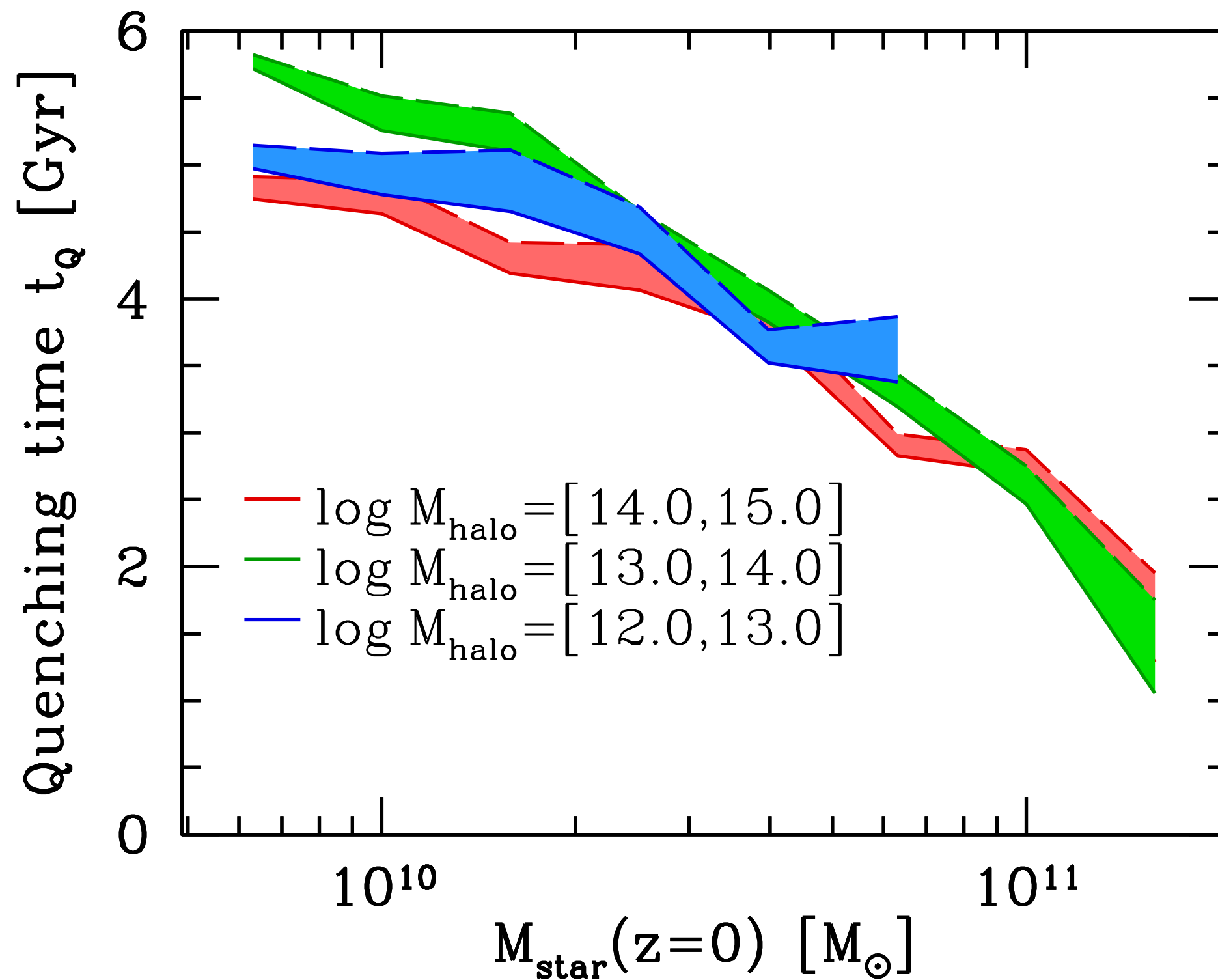
Wetzel, Tinker, Conroy & van den Bosch 2012

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

Andrew Wetzel

Outstanding questions about environmental quenching

What is the physical extent of environmental dependence?

Where / when does environmental quenching begin?

How long does the quenching process take?

How does SFR evolve in detail?

What is the physical mechanism?

Andrew Wetzel

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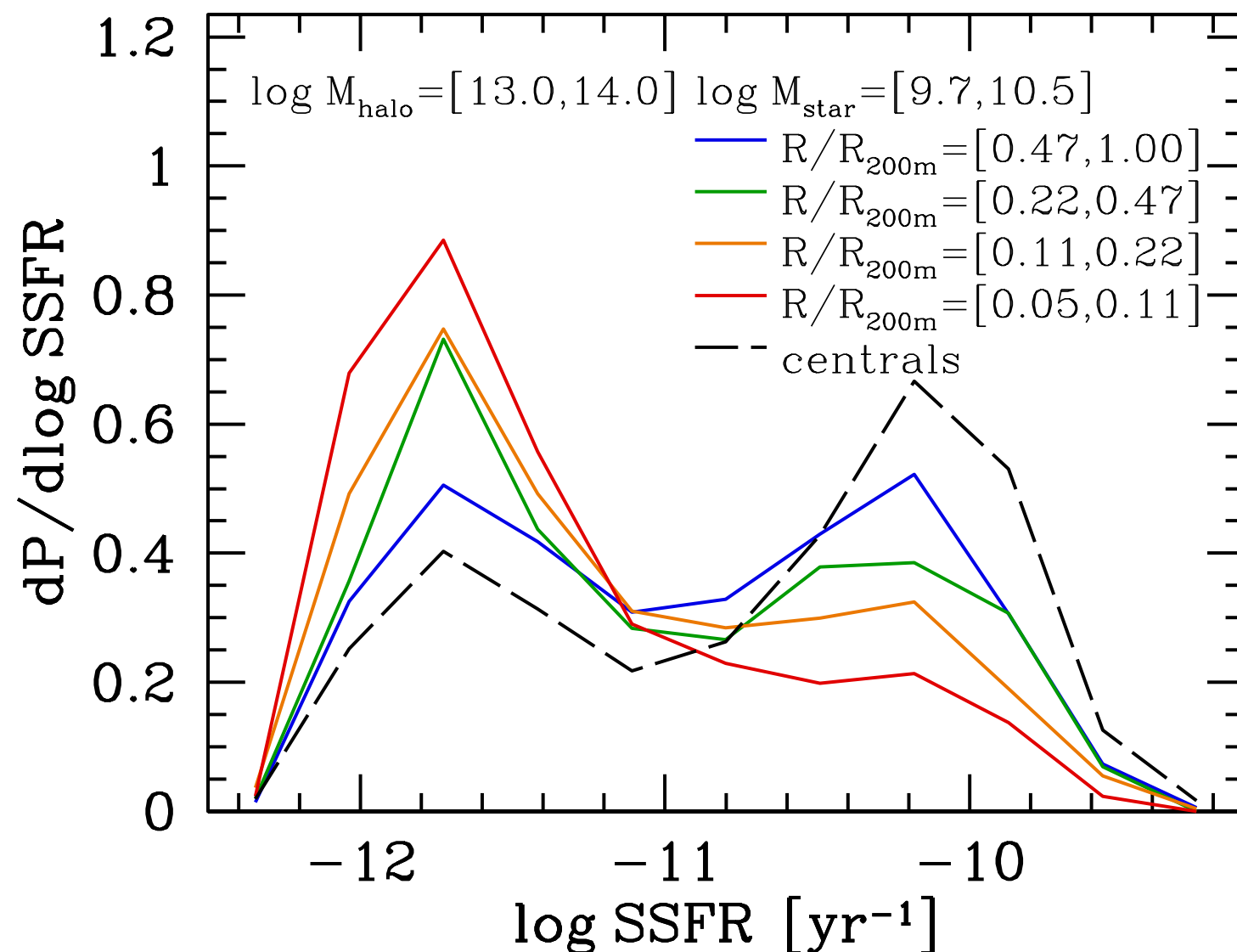
(1) Satellite SFR evolves unaffected for roughly a halo crossing time (several Gyrs)

(2) Once begun, satellite SFR quenching is rapid

Andrew Wetzel   *Yale University*

fade

$M_{star}(z=0) \ [M_{\odot}]$

$M_{star}(z=0) \ [M_{\odot}]$

10^{11}

1.2

$\log M_{halo} = [13.0, 14.0]$ $\log M_{star} = [9.7, 10.5]$

- $R/R_{200m} = [0.47, 1.00]$
- $R/R_{200m} = [0.22, 0.47]$
- $R/R_{200m} = [0.11, 0.22]$
- $R/R_{200m} = [0.05, 0.11]$
- centrals

dP/dlog SSFR

$\log$ SSFR $[yr^{-1}]$
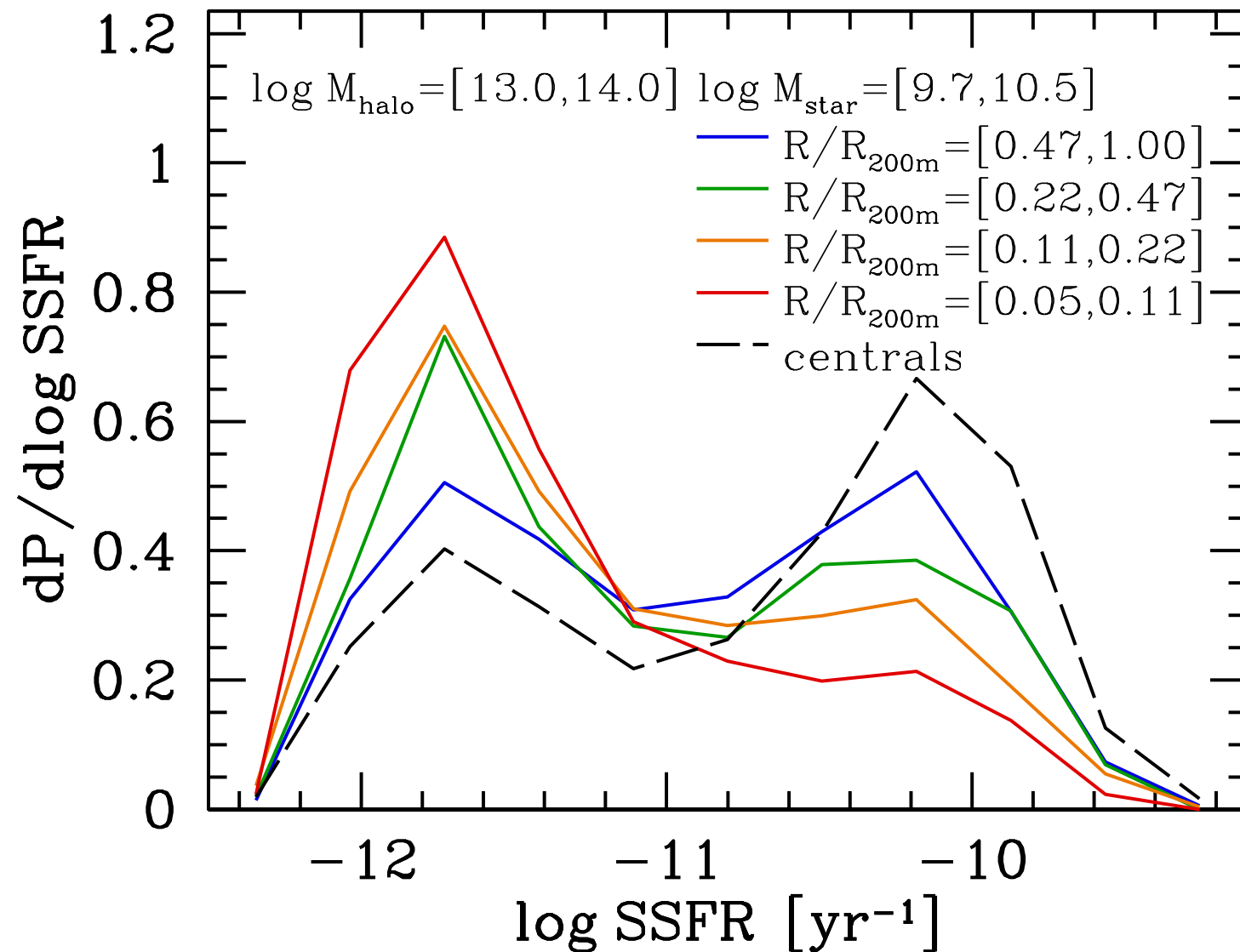
$$\mathrm{SFR}_{\mathrm{sat}}(t) = \begin{cases} \mathrm{SFR}_{\mathrm{cen}}(t) & t < t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \\ \mathrm{SFR}_{\mathrm{cen}}(t_{Q,\,\mathrm{start}})\, e^{\left\{ -\frac{(t - t_{Q,\,\mathrm{start}})}{\tau_{Q,\,\mathrm{fade}}} \right\}} & t > t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \end{cases}$$

simple fading SFR - no bimodality

$M_{star}(z=0)$ $[M_\odot]$

$M_{star}(z=0)$ $[M_\odot]$

10^{11}

log M_{star}=[9.7,10.1]

$t_{Q,delay}$

$\tau_{Q,fade}$

observed

log M_{star}=[10.1,10.5]

$t_{Q,delay}$=0.0 Gyr

$\tau_{Q,fade}$=1.7 Gyr

log M_{star}=[10.5,10.9]

$t_{Q,delay}$=0.0 Gyr

$\tau_{Q,fade}$=1.4 Gyr

log M_{star}=[10.9,11.3]

$t_{Q,delay}$=0.0 Gyr

$\tau_{Q,fade}$=1.2 Gyr

P(log SSFR)

log SSFR $[yr^{-1}]$

log SSFR $[yr^{-1}]$

Wetzel, Tinker, Conroy
& van den Bosch 2012

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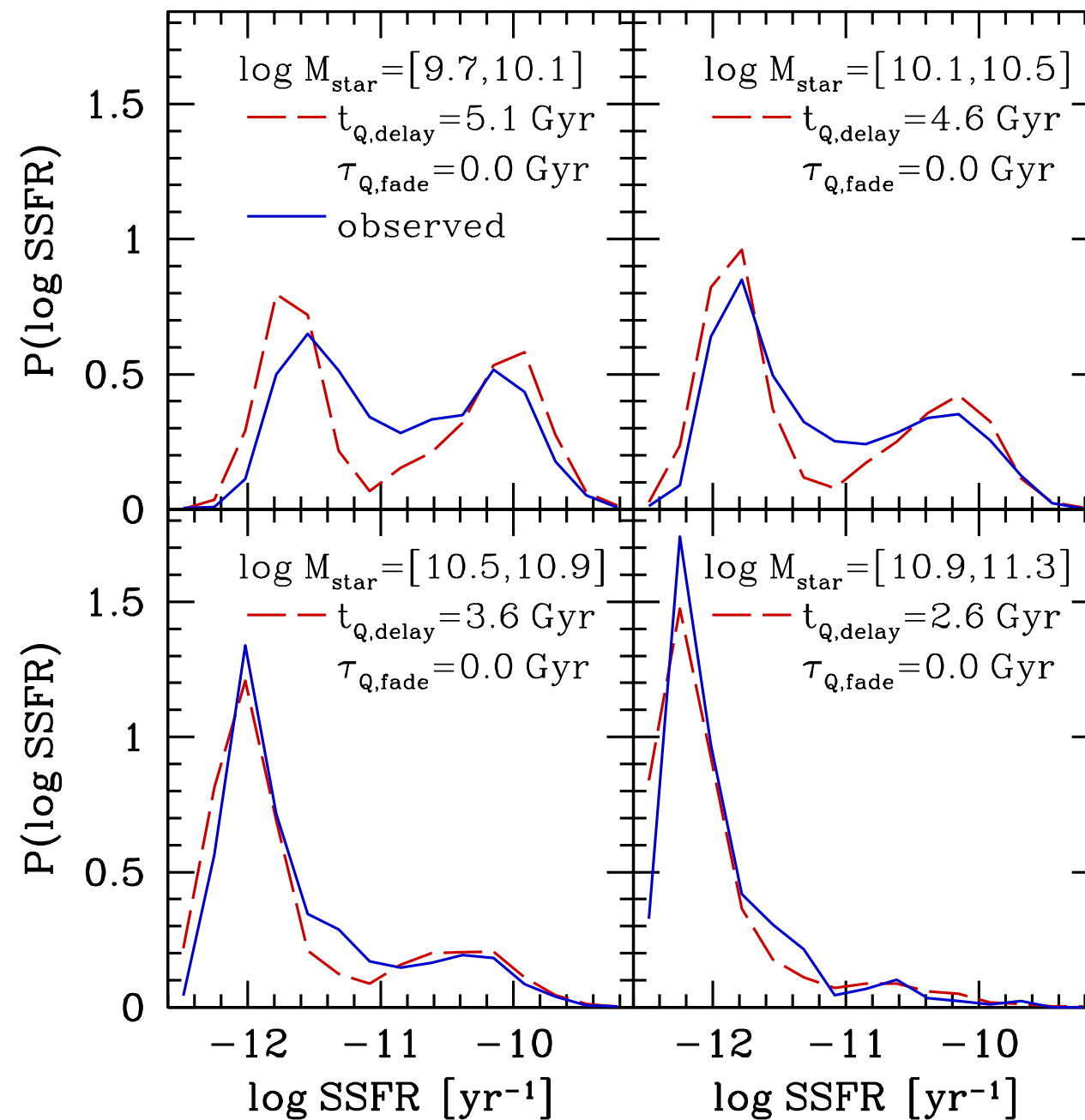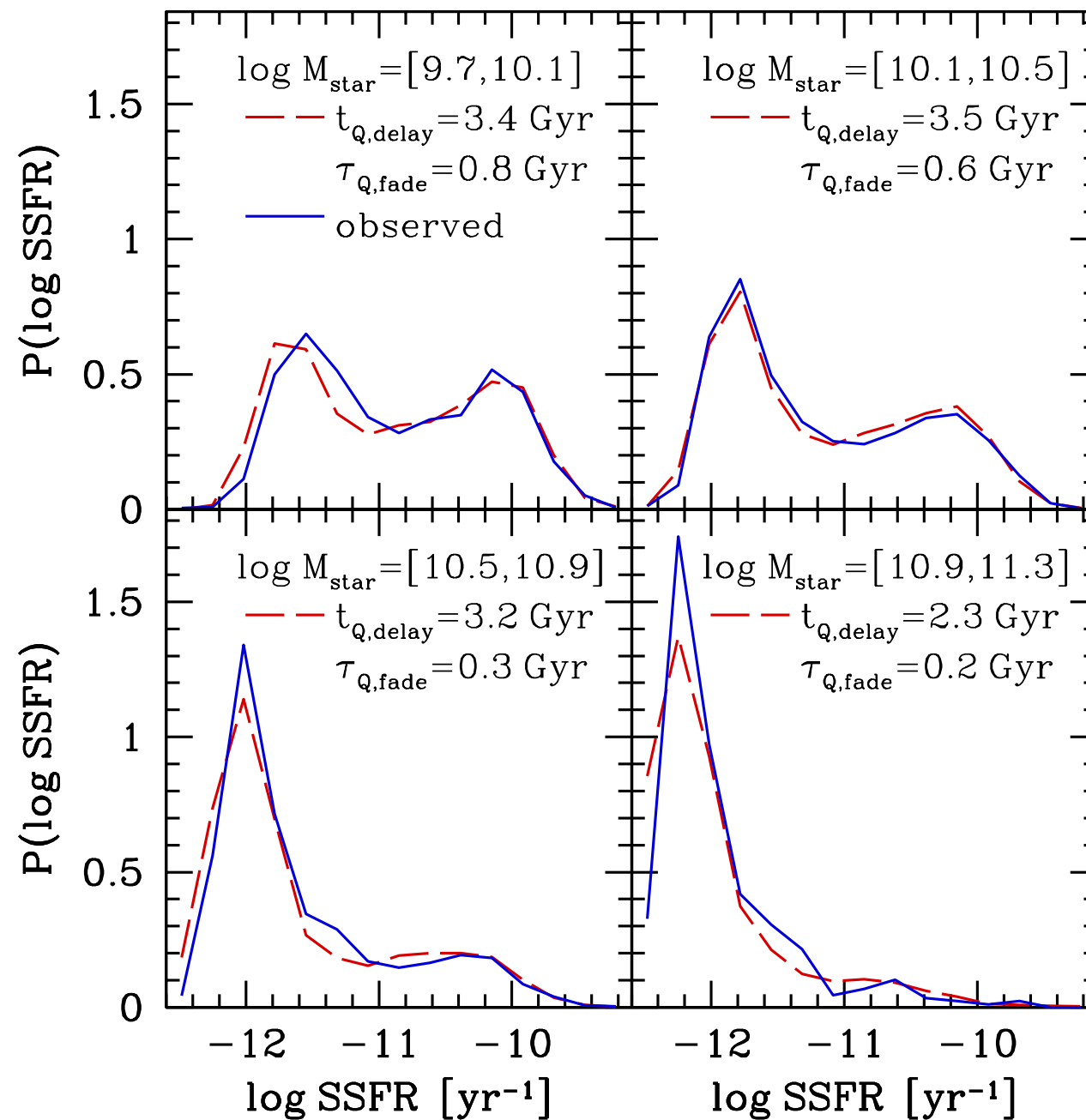
Andrew Wetzel   *Yale University*

$M_{\mathrm{star}}(z=0) \ [M_\odot]$

$M_{\mathrm{star}}(z=0) \ [M_\odot]$

10^{11}

log M$_{\mathrm{star}}$=[9.7,10.1]

log M$_{\mathrm{star}}$=[10.1,10.5]
t$_{\mathrm{Q,delay}}$=4.6 Gyr
$\tau_{\mathrm{Q,fade}}$=0.0 Gyr

observed

log M$_{\mathrm{star}}$=[10.5,10.9]
t$_{\mathrm{Q,delay}}$=3.6 Gyr
$\tau_{\mathrm{Q,fade}}$=0.0 Gyr

log M$_{\mathrm{star}}$=[10.9,11.3]
t$_{\mathrm{Q,delay}}$=2.6 Gyr
$\tau_{\mathrm{Q,fade}}$=0.0 Gyr

P(log SSFR)

log SSFR [yr^{-1}]

log SSFR [yr^{-1}]

Wetzel, Tinker, Conroy
& van den Bosch 2012

$$\mathrm{SFR}_{\mathrm{sat}}(t) = \begin{cases} \mathrm{SFR}_{\mathrm{cen}}(t) & t < t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \\[2mm] \mathrm{SFR}_{\mathrm{cen}}(t_{Q,\,\mathrm{start}})\, e^{\left\{ -\frac{(t - t_{Q,\,\mathrm{start}})}{\tau_{Q,\,\mathrm{fade}}} \right\}} & t > t_{\mathrm{inf}} + t_{Q,\,\mathrm{delay}} \end{cases}$$

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...rapid quenching - successful

$M_{star}(z=0)$ [$M_\odot$]

$M_{star}(z=0)$ [$M_\odot$]

10^{11}

log M_{star}=[9.7,10.1]

... yr

$\tau_{Q,fade}$ ... yr

observed

log M_{star}=[10.1,10.5]

$t_{Q,delay}$=3.5 Gyr

$\tau_{Q,fade}$=0.6 Gyr

P(log SSFR)

log M_{star}=[10.5,10.9]

$t_{Q,delay}$=3.2 Gyr

$\tau_{Q,fade}$=0.3 Gyr

log M_{star}=[10.9,11.3]

$t_{Q,delay}$=2.3 Gyr

$\tau_{Q,fade}$=0.2 Gyr

−12 −11 −10

log SSFR [yr⁻¹]
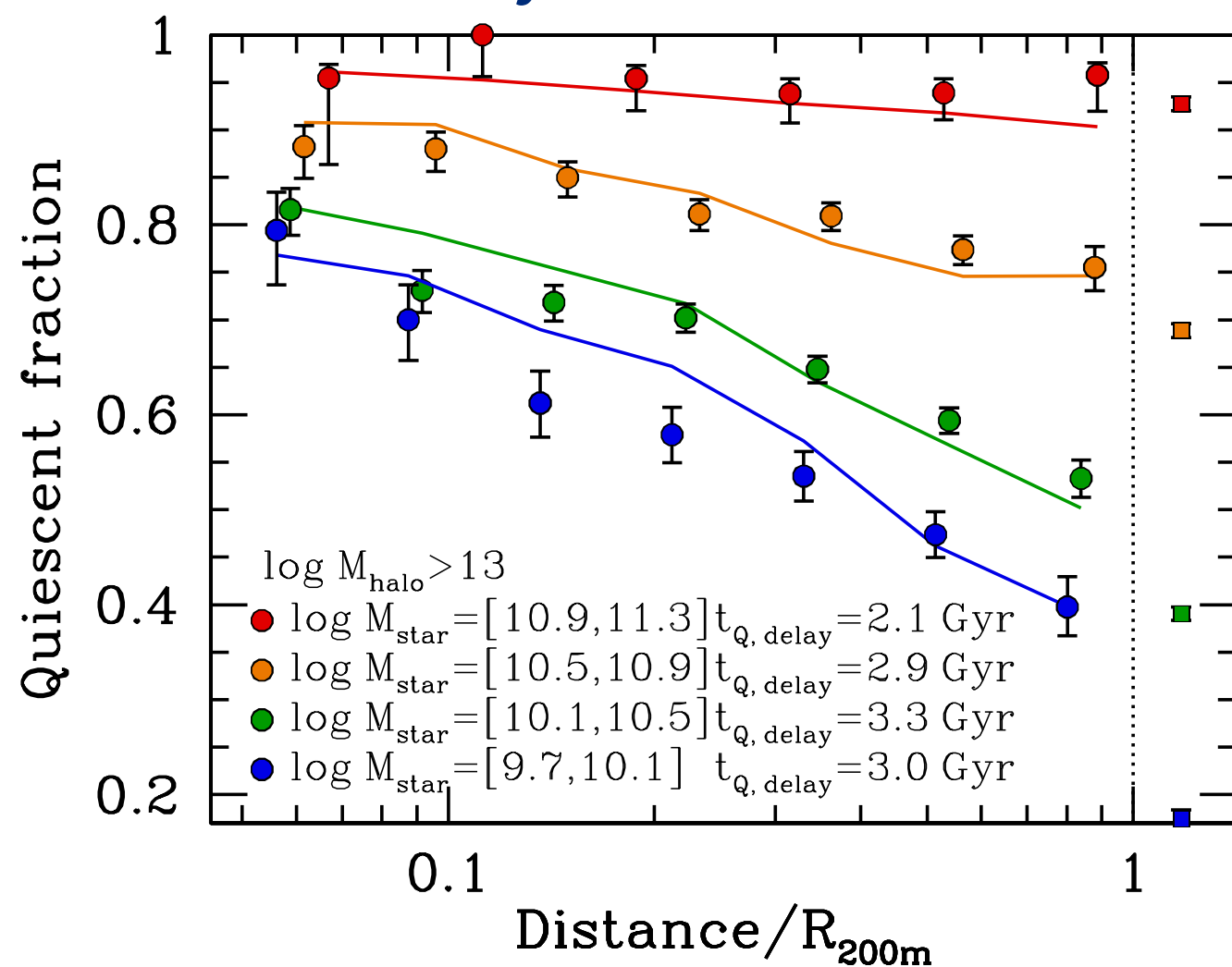
−12 −11 −10

log SSFR [yr⁻¹]

Wetzel, Tinker, Conroy
& van den Bosch 2012

$$\text{SFR}_{\text{sat}}(t) = \begin{cases} \text{SFR}_{\text{cen}}(t) & t < t_{\text{inf}} + t_{Q,\,\text{delay}} \\ \text{SFR}_{\text{cen}}(t_{Q,\,\text{start}})e^{\left\{-\frac{(t-t_{Q,\,\text{start}})}{\tau_{Q,\,\text{fade}}}\right\}} & t > t_{\text{inf}} + t_{Q,\,\text{delay}} \end{cases}$$
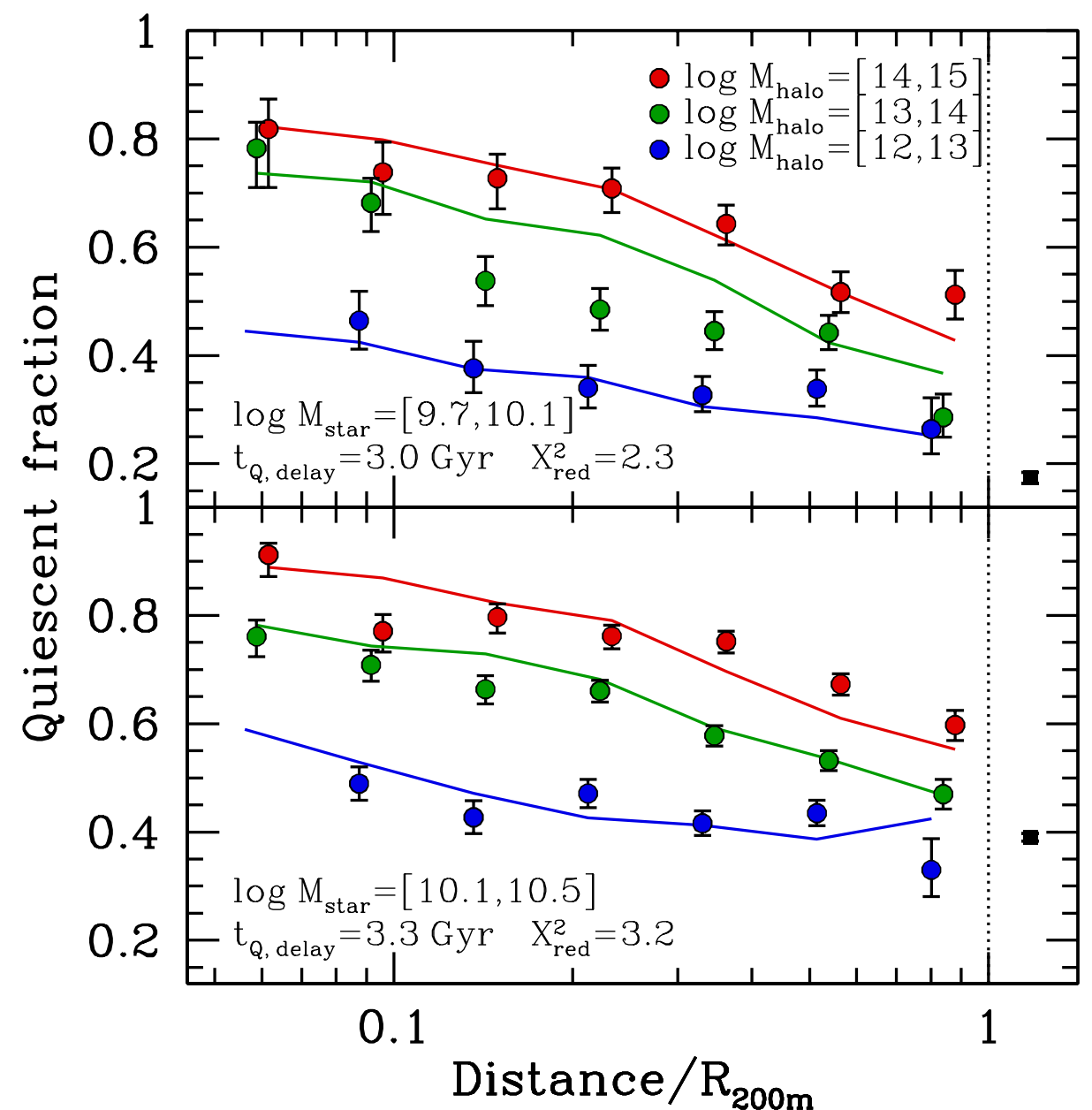
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Satellite quenching based on time since first infall

Vary satellite mass

Vary host halo mass

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

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`Delayed' satellite quenching scenario
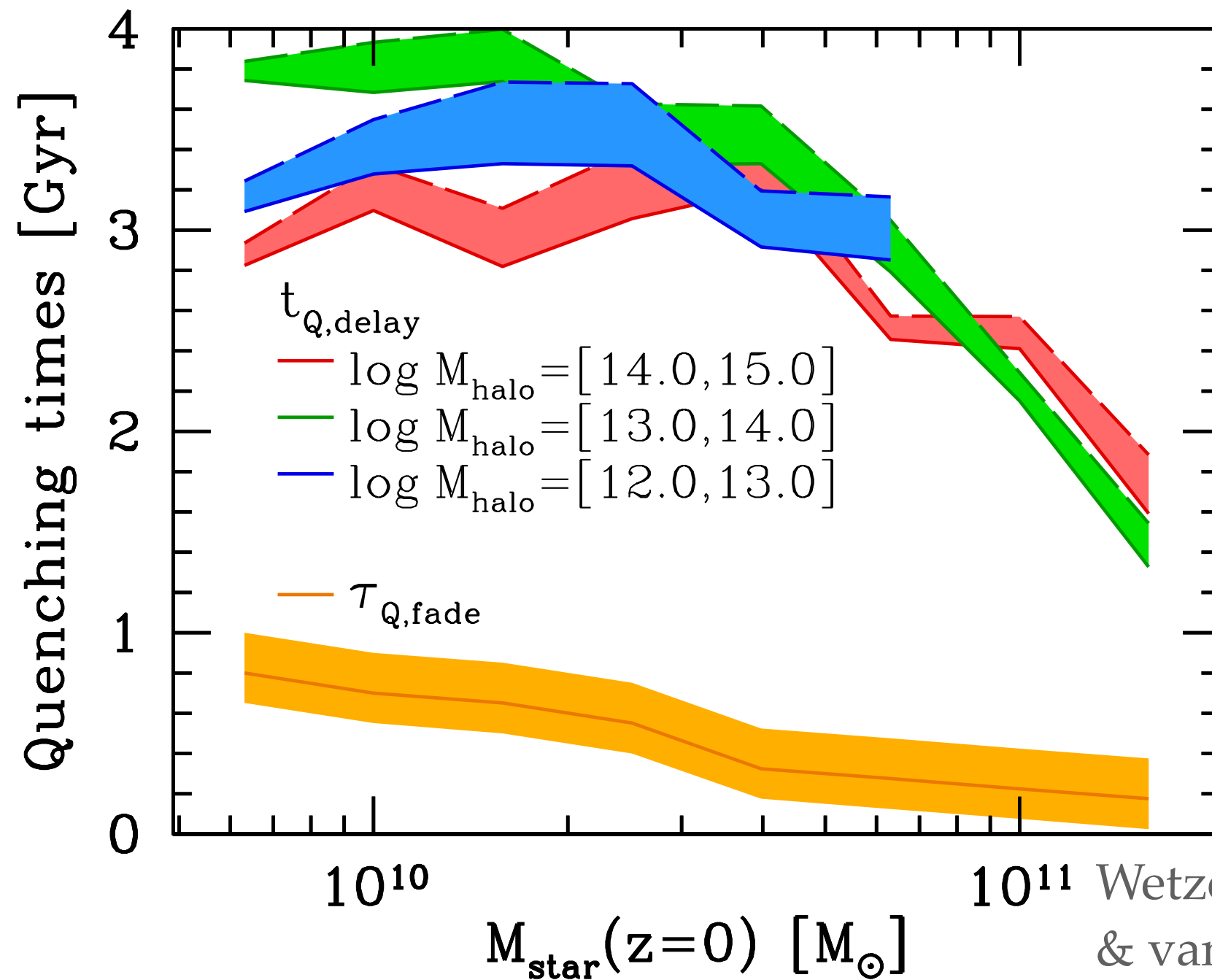
$\tau_{Q,\text{delay}}$
— log $M_{\text{halo}} = [14.0, 15.0]$
— log $M_{\text{halo}} = [13.0, 14.0]$
— log $M_{\text{halo}} = [12.0, 13.0]$

— $\tau_{Q,\text{fade}}$

Quenching times [Gyr]

$M_{\text{star}}(z=0)$ [$M_\odot$]

Wetzel, Tinker, Conroy & van den Bosch 2012

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

Andrew Wetzel   *Yale University*
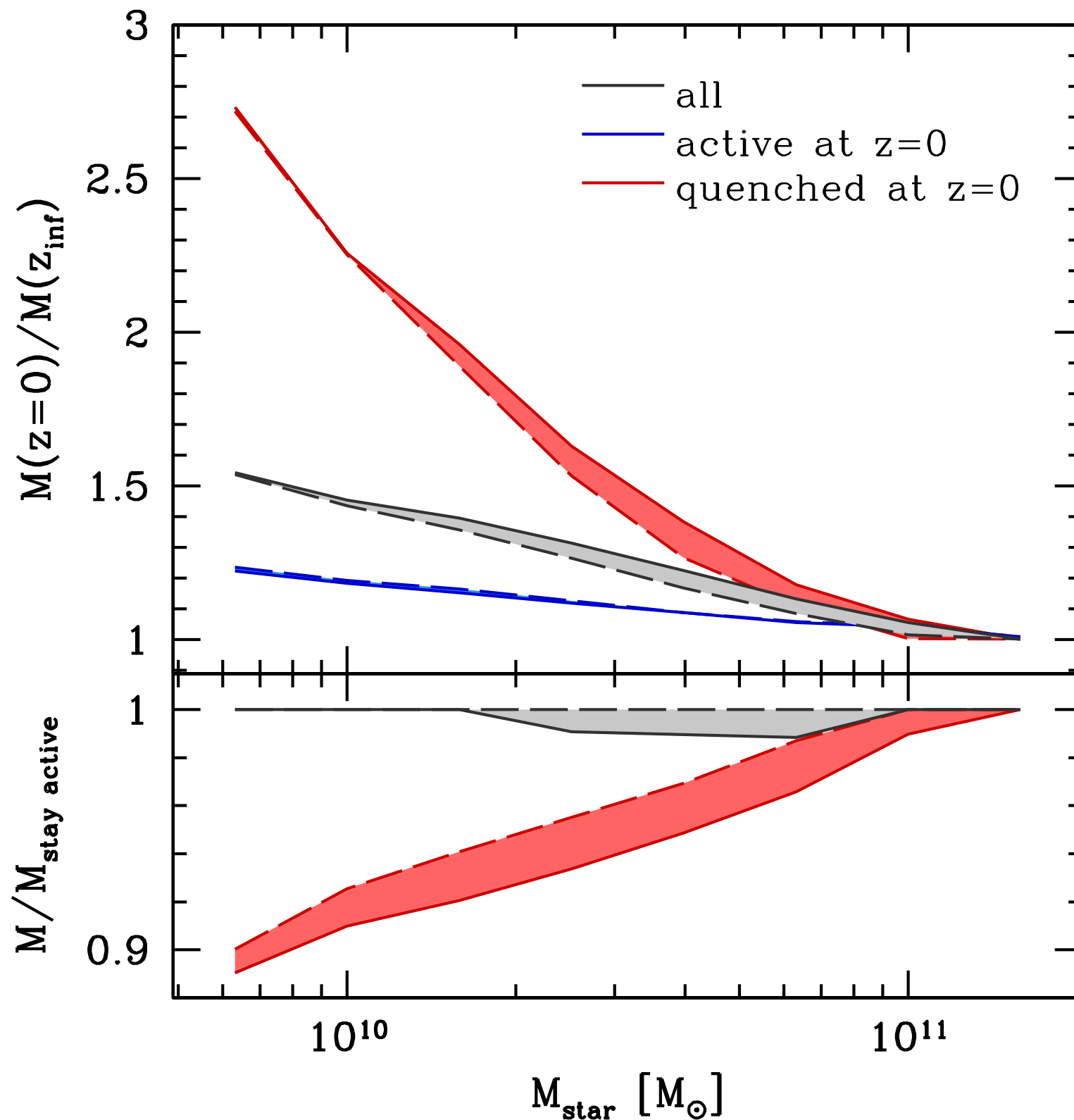
Satellites experience significant stellar mass growth after infall, similar to central galaxies

Andrew Wetzel

Outstanding questions about environmental quenching

What is the physical extent of environmental dependence?
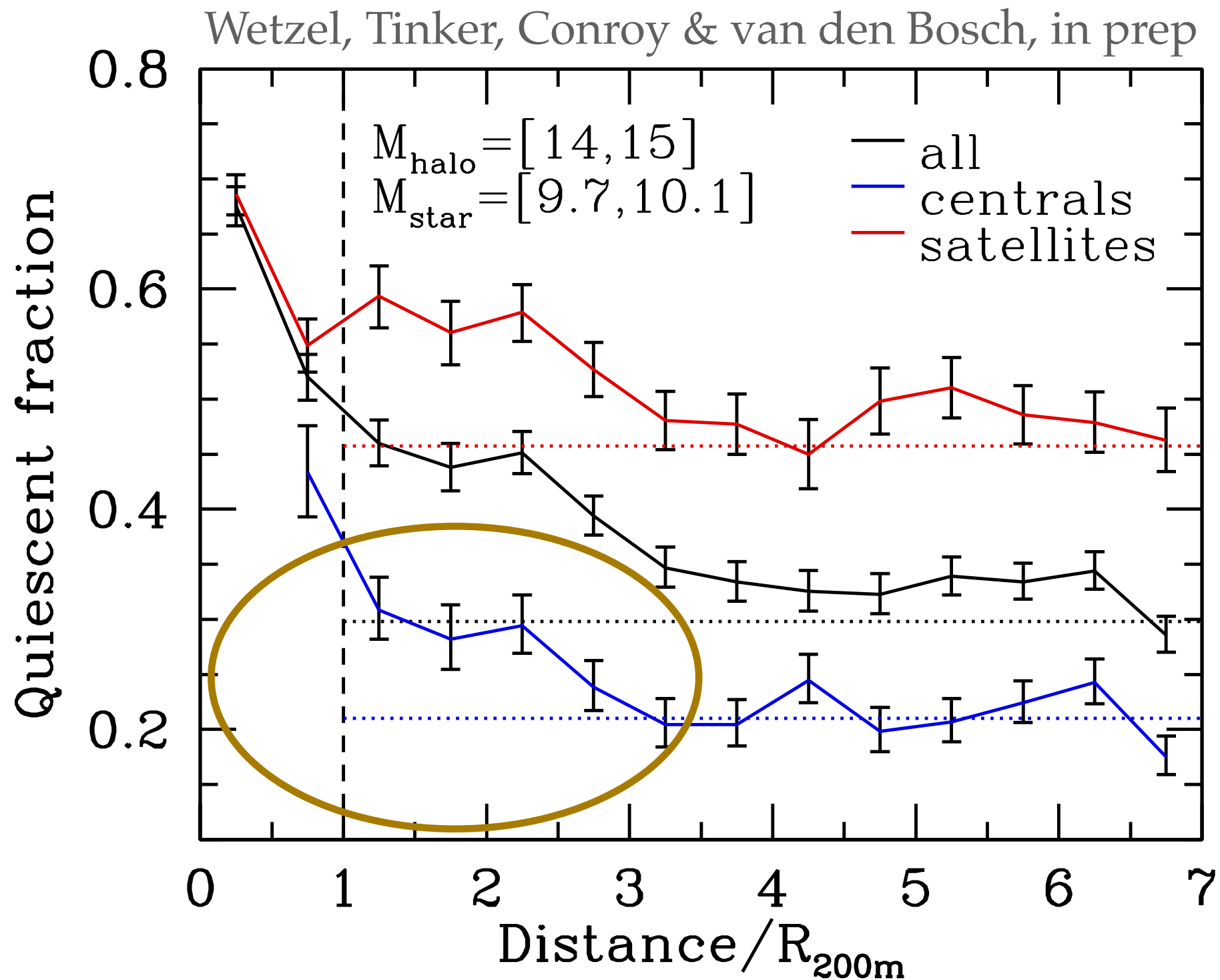
Where / when does environmental quenching begin?

How long does the quenching process take?
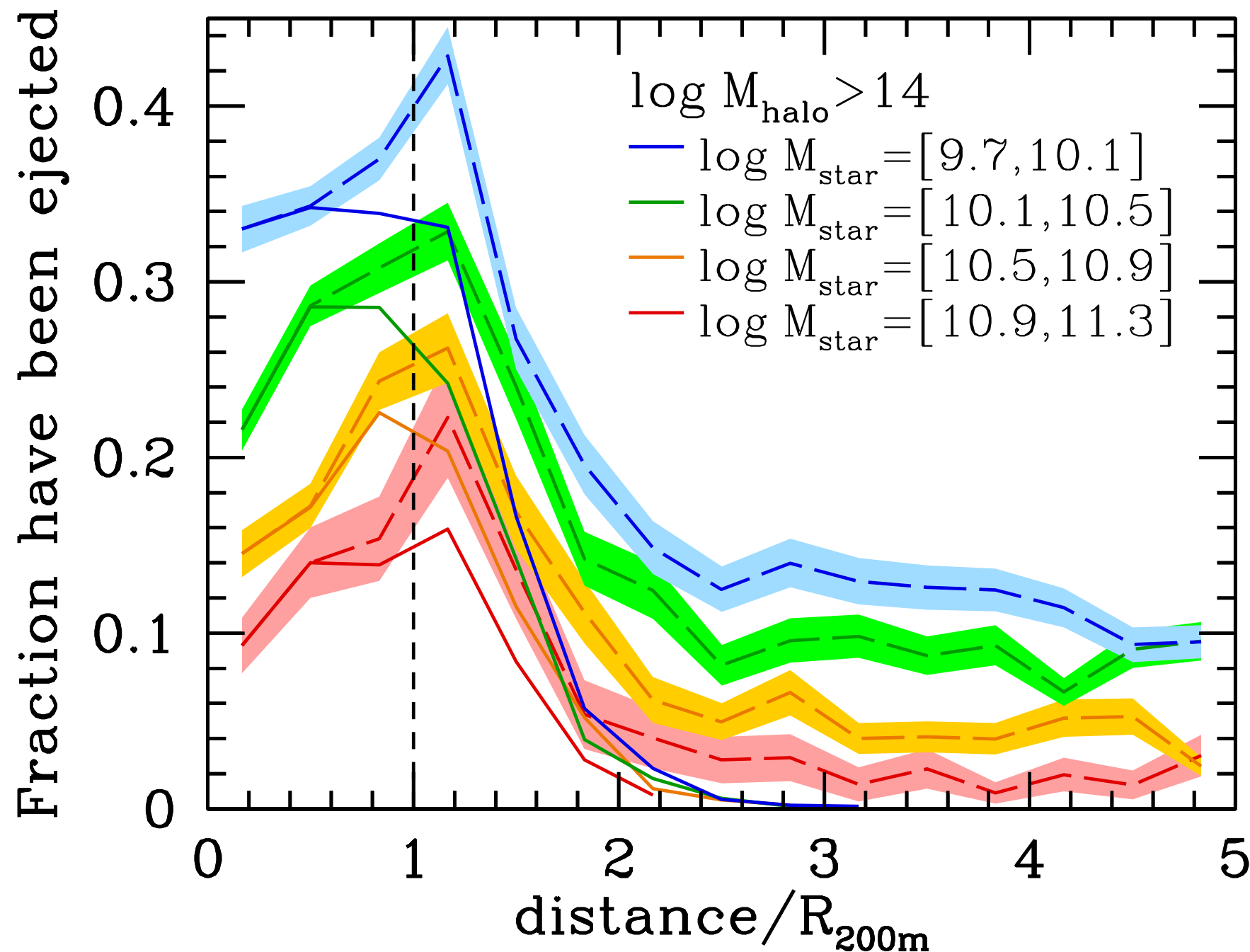
How does SFR evolve in detail?

What is the physical mechanism?

Andrew Wetzel

SFR in central galaxies beyond R_{vir}

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

$M_{halo} = [14, 15]$
$M_{star} = [9.7, 10.1]$

all
centrals
satellites

Quiescent fraction

Distance/R_{200m}

Andrew Wetzel

Yale University

Ejected satellite excess persists out to 2.5 R$_{vir}$

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

log M$_{halo}$ > 14

log M$_{star}$ = [9.7, 10.1]
log M$_{star}$ = [10.1, 10.5]
log M$_{star}$ = [10.5, 10.9]
log M$_{star}$ = [10.9, 11.3]

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

>90% continue to lose mass after being ejected

Andrew Wetzel   *Yale University*

If SFR in ejected satellites evolves same as central galaxies
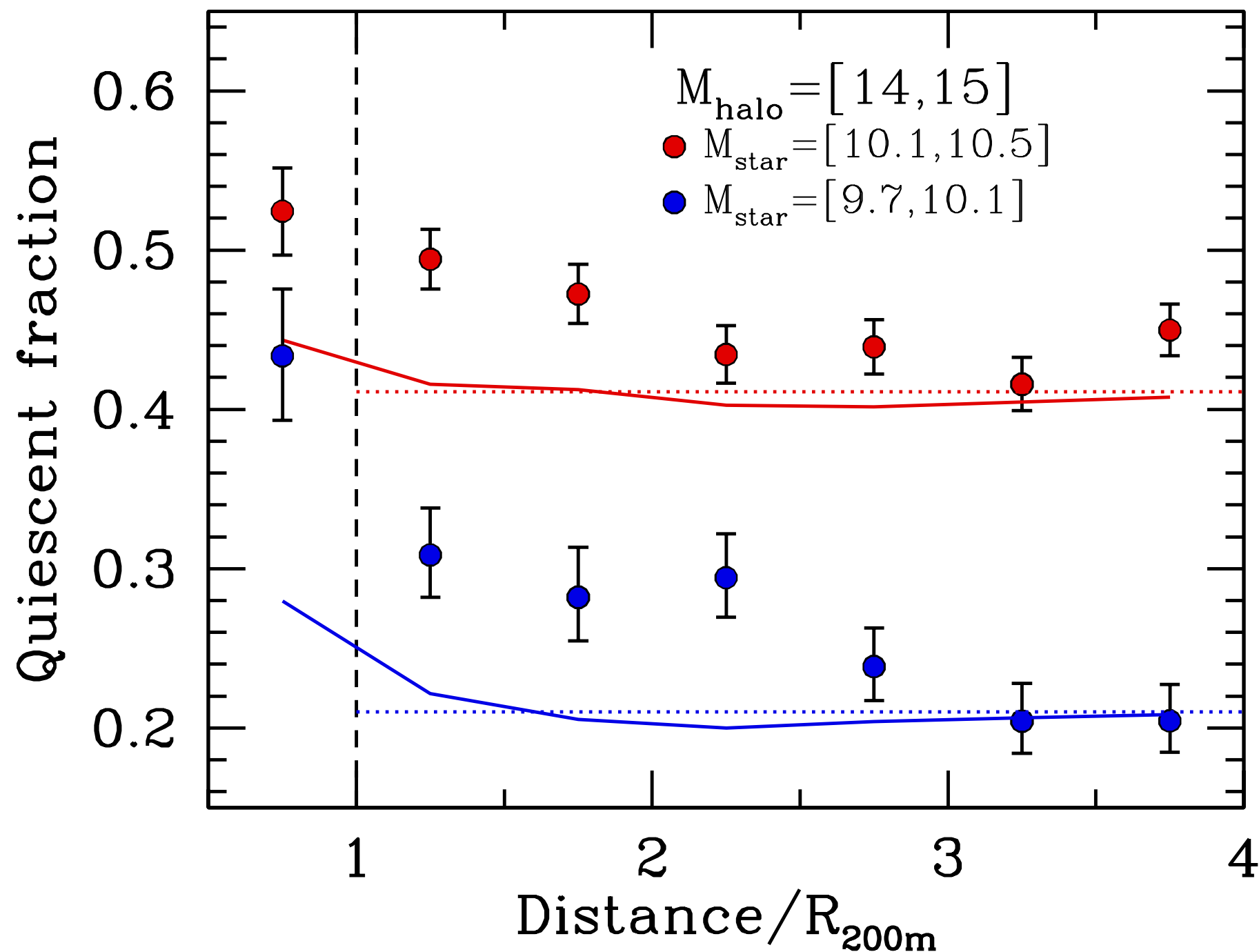
If SFR in ejected satellites evolves same as those within R_{vir}
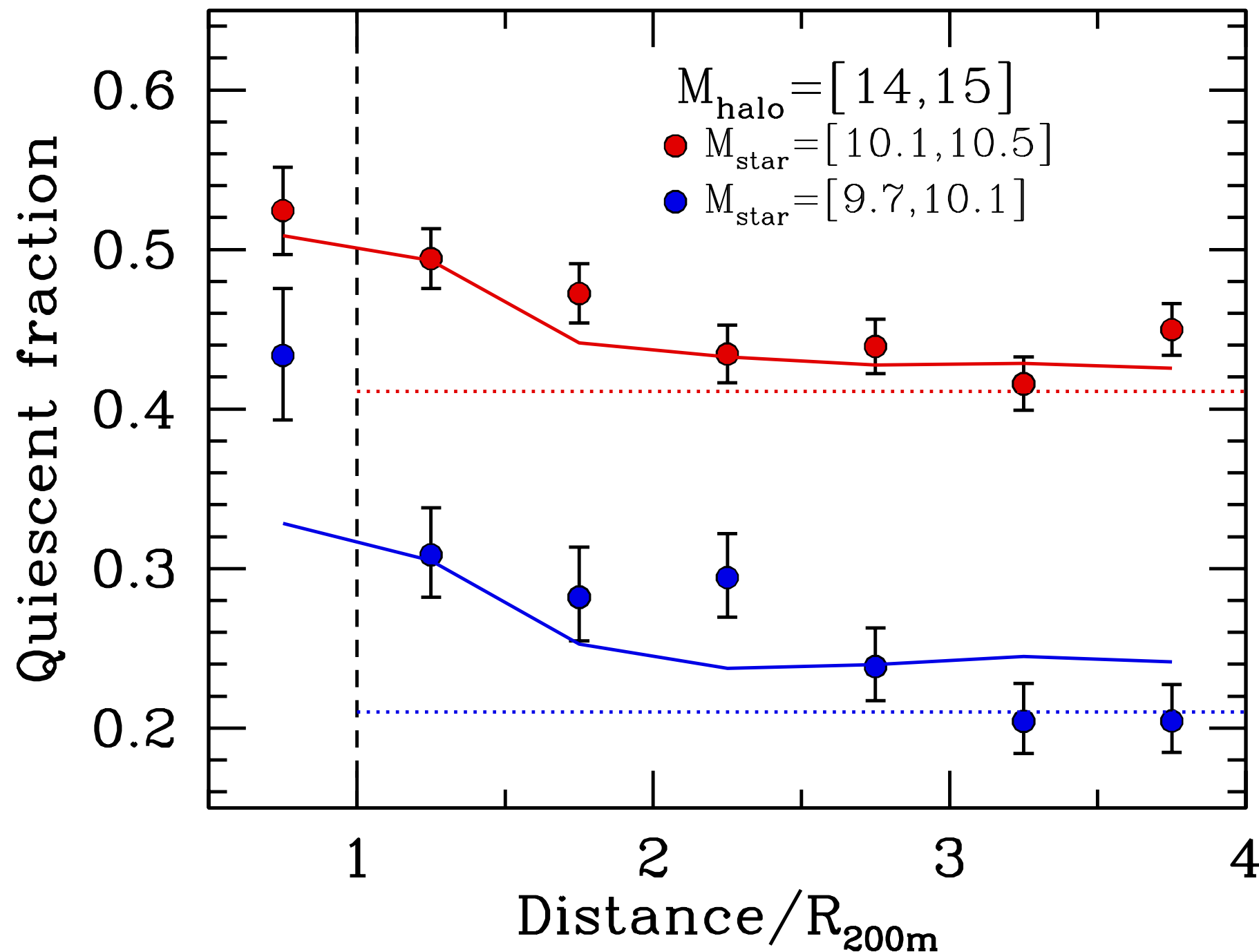
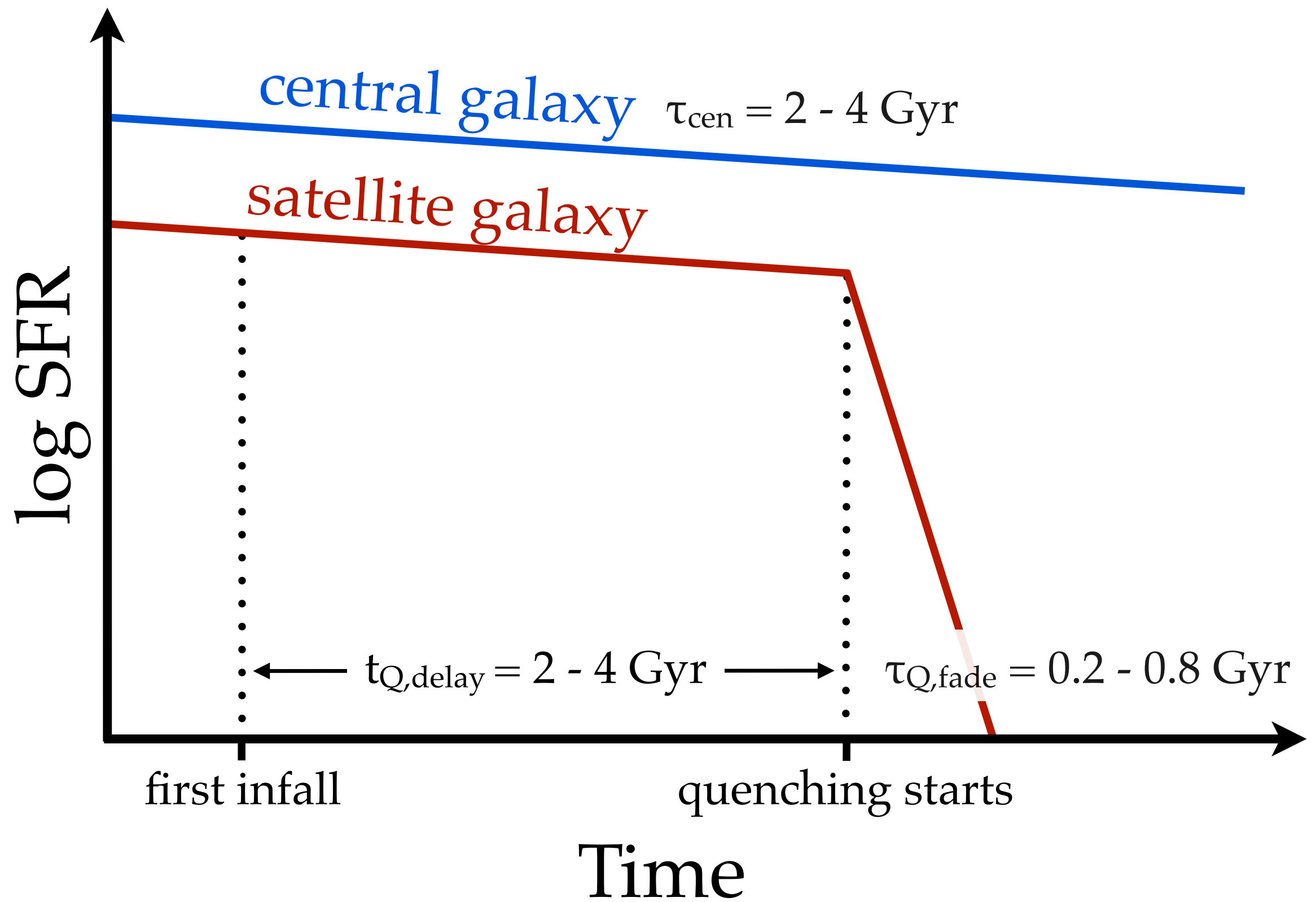# Outstanding questions about environmental quenching

What is the physical extent of environmental dependence?

Where / when does environmental quenching begin?

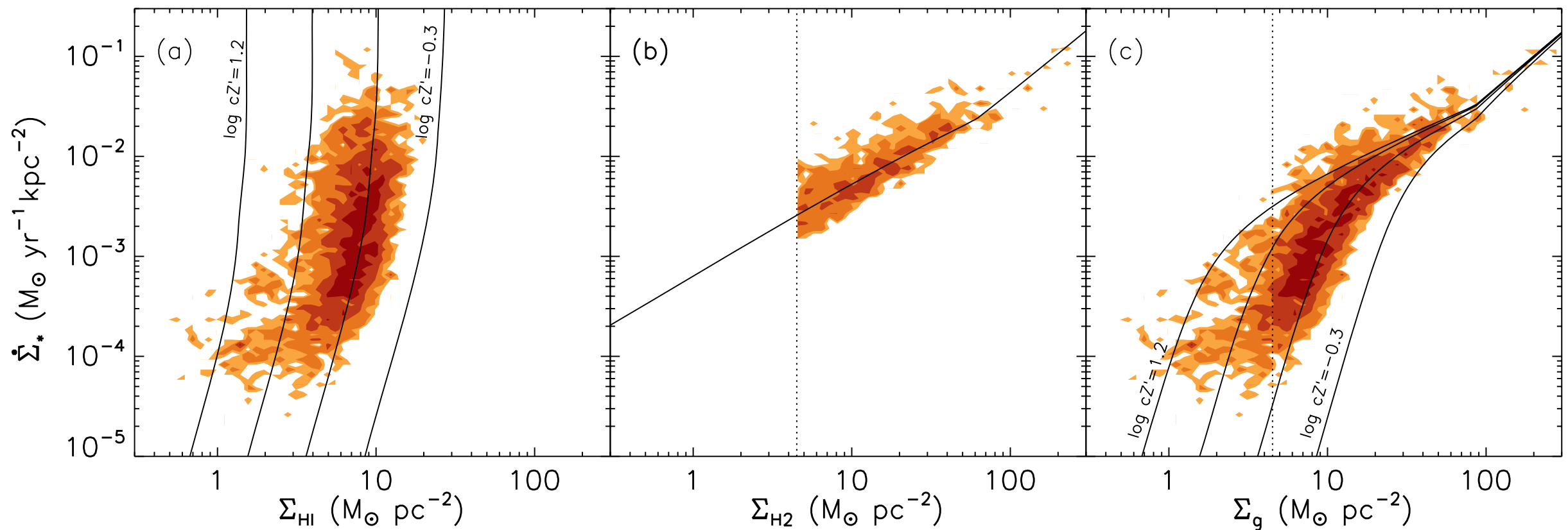How long does the quenching process take?

How does SFR evolve in detail?

What is the physical mechanism?

Andrew Wetzel

Yale University

central galaxy τ_{cen} = 2 - 4 Gyr

satellite galaxy

log SFR

$t_{Q,delay}$ = 2 - 4 Gyr

$\tau_{Q,fade}$ = 0.2 - 0.8 Gyr

first infall

quenching starts

Time

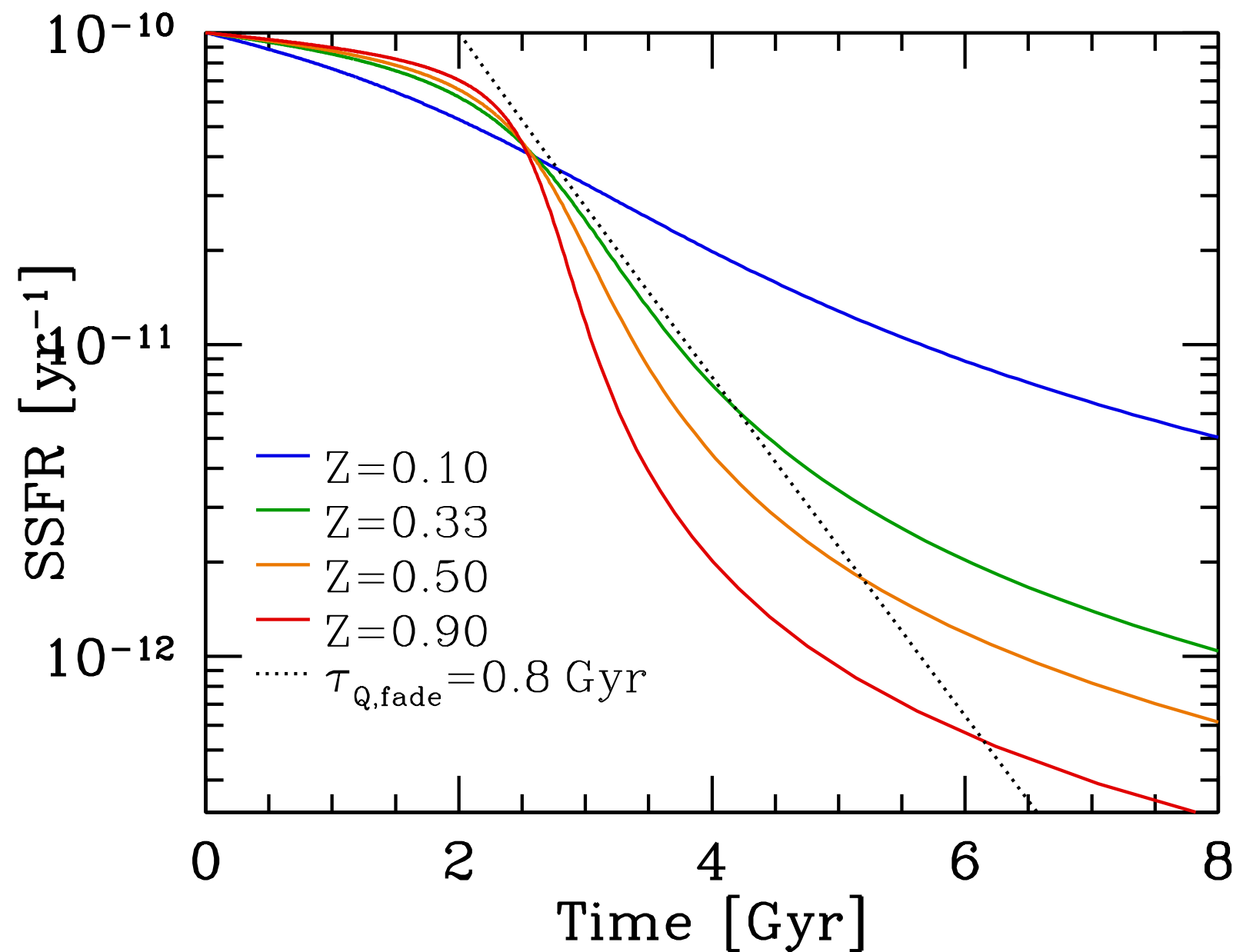# Mechanism of satellite quenching: time since infall?

Relating galaxy SFR to gas content

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

Mechanism of satellite quenching: time since infall?

Galaxy SFR evolution in absence of gas accretion

Galaxy Evolution in Groups & Clusters

Satellites drive ~all environmental dependence of galaxy star formation

At $M_{star} < 10^{10}\ M_\odot$, satellite quenching is the dominant process for building up the red sequence

Satellite SFR distribution is *always* bimodal - satellite quenching is delayed (2 - 4 Gyr) then rapid (< 800 Myr)

Satellite stellar mass growth is ~same as that of central galaxies

Satellite ejected beyond R_{vir} evolve in the same way as those within R_{vir}

Andrew Wetzel

Yale University