What satellite galaxy evolution tells us about the baryon cycle of galaxies

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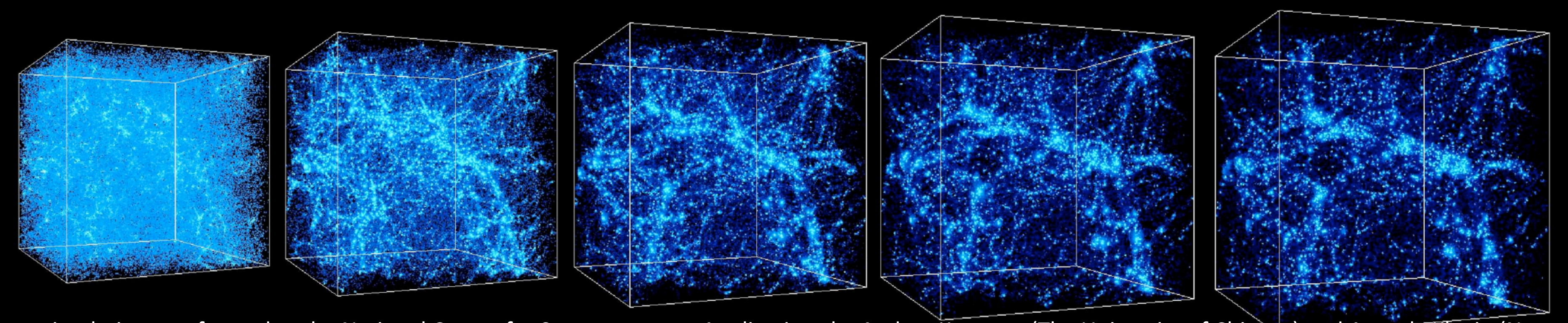
Outline

1. Background
   - Structure formation and the halo model
   - Galaxy formation
   - The overquenching problem
   - Insight from toy models based on accretion histories
2. Results from the GCLASS and GEEC2 cluster & group redshift surveys at $0.8<z<1.2$
3. *Overconsumption*: The role of outflows and new predictions for cluster populations at $z>1$
4. GOGREEN: A Gemini Large Program to test predictions of this model, $1<z<1.5$

Background



From simulations performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.

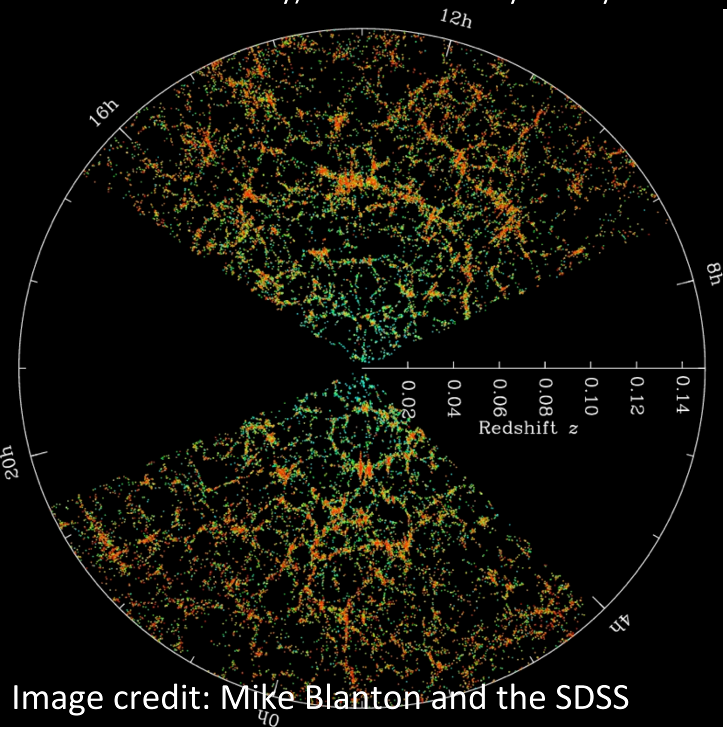
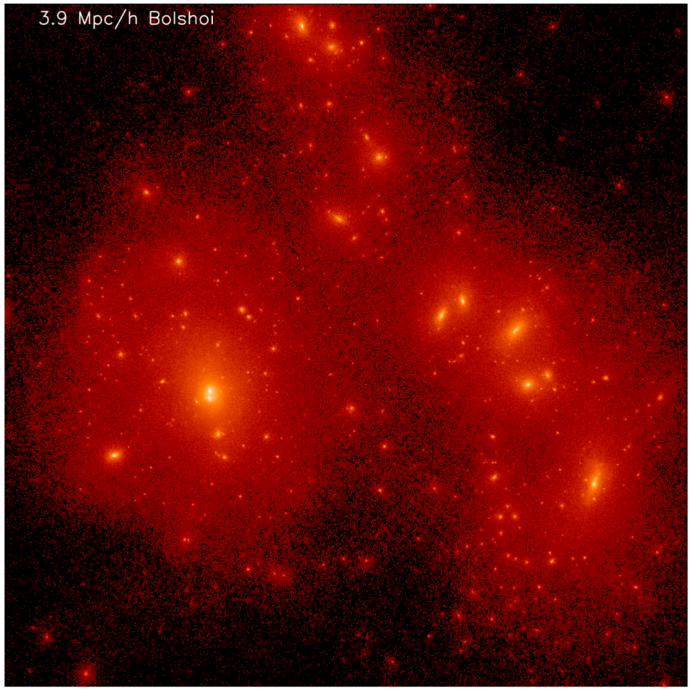


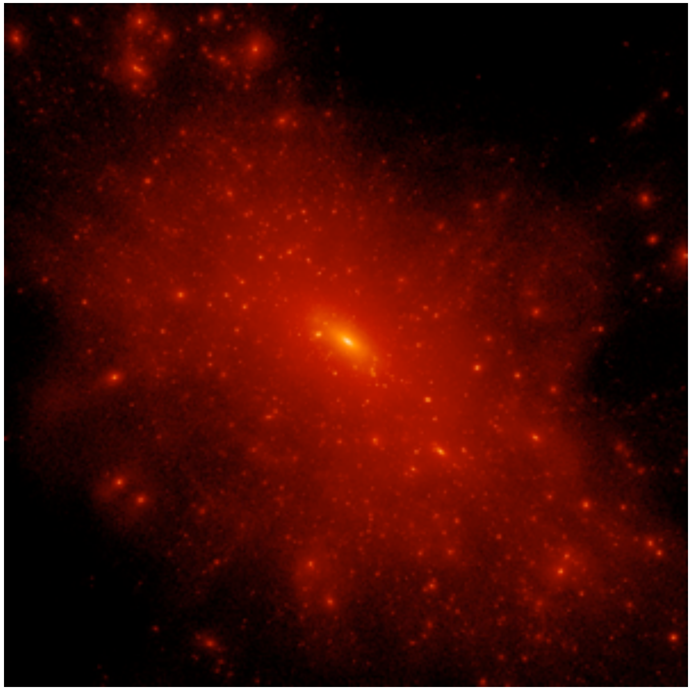
Image credit: Mike Blanton and the SDSS

Observed large-scale structure is reproduced well by dark matter simulations

The halo model

Simulated structure consists of virialized "haloes", with a dominant central object and many satellites.

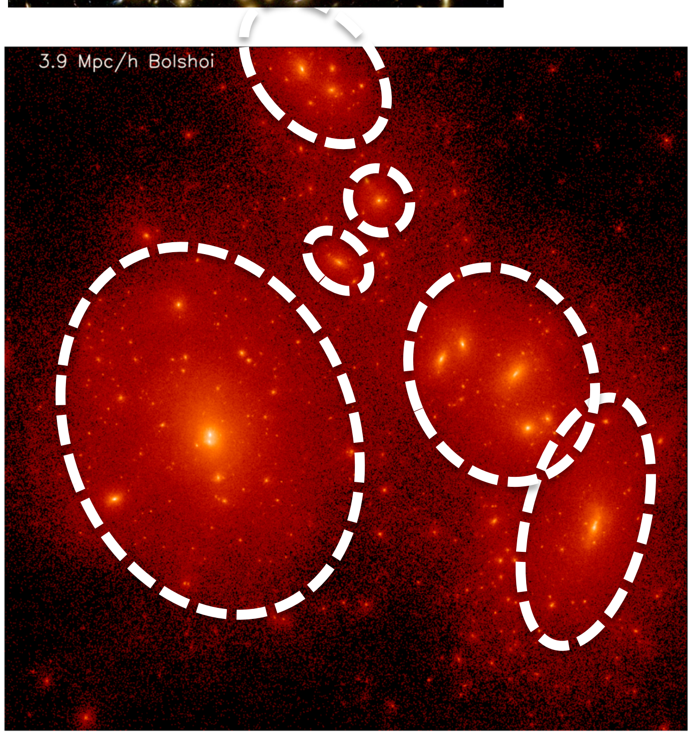


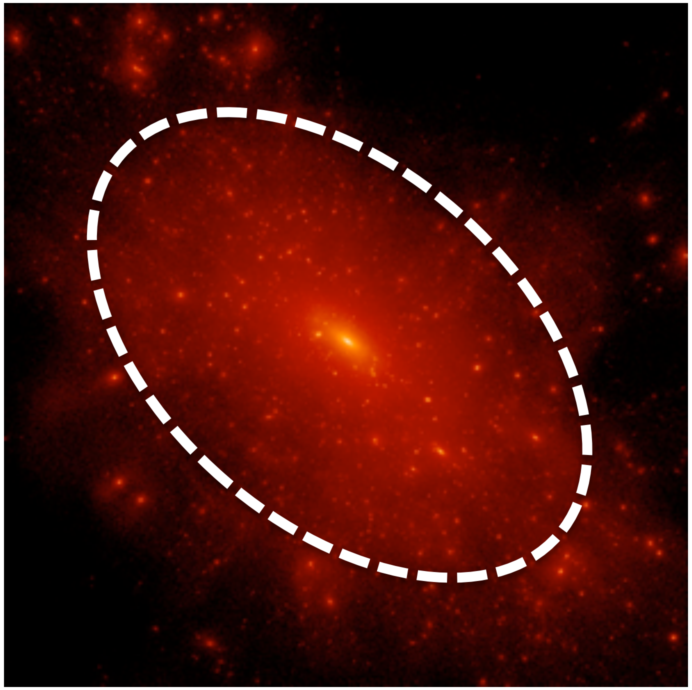


Bolshoi simulations

The halo model

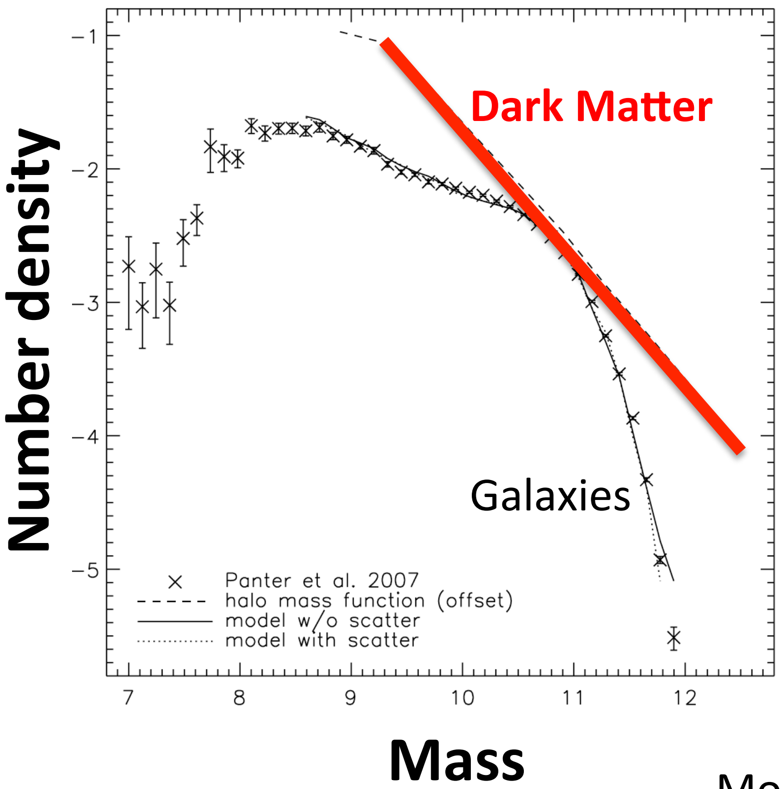
This provides an excellent description of clustering in the observed Universe.

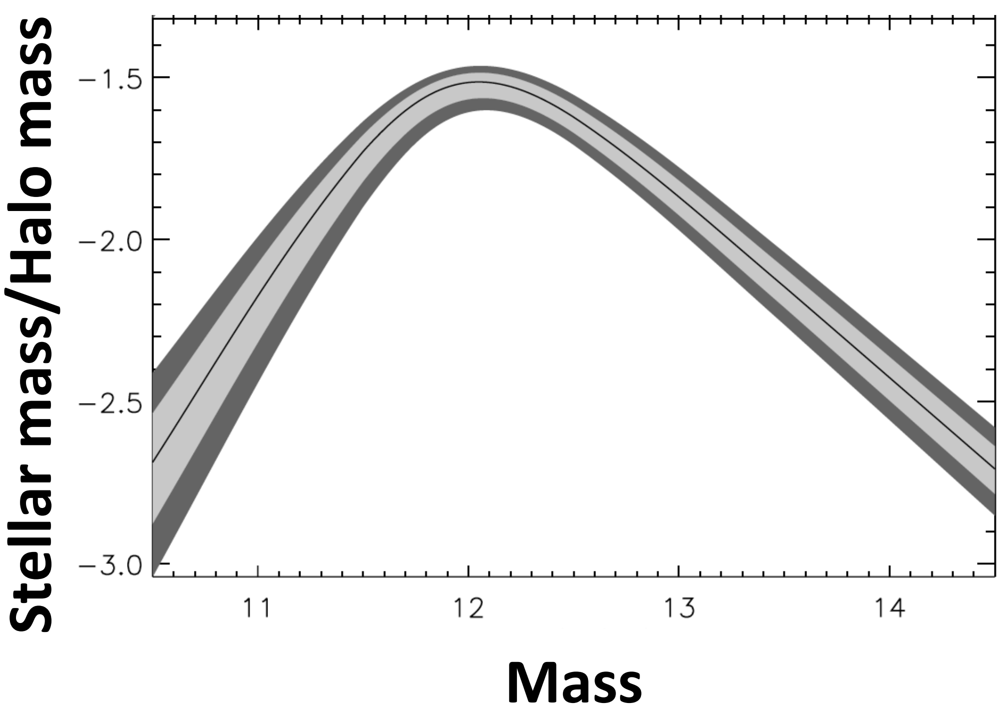




Bolshoi simulations

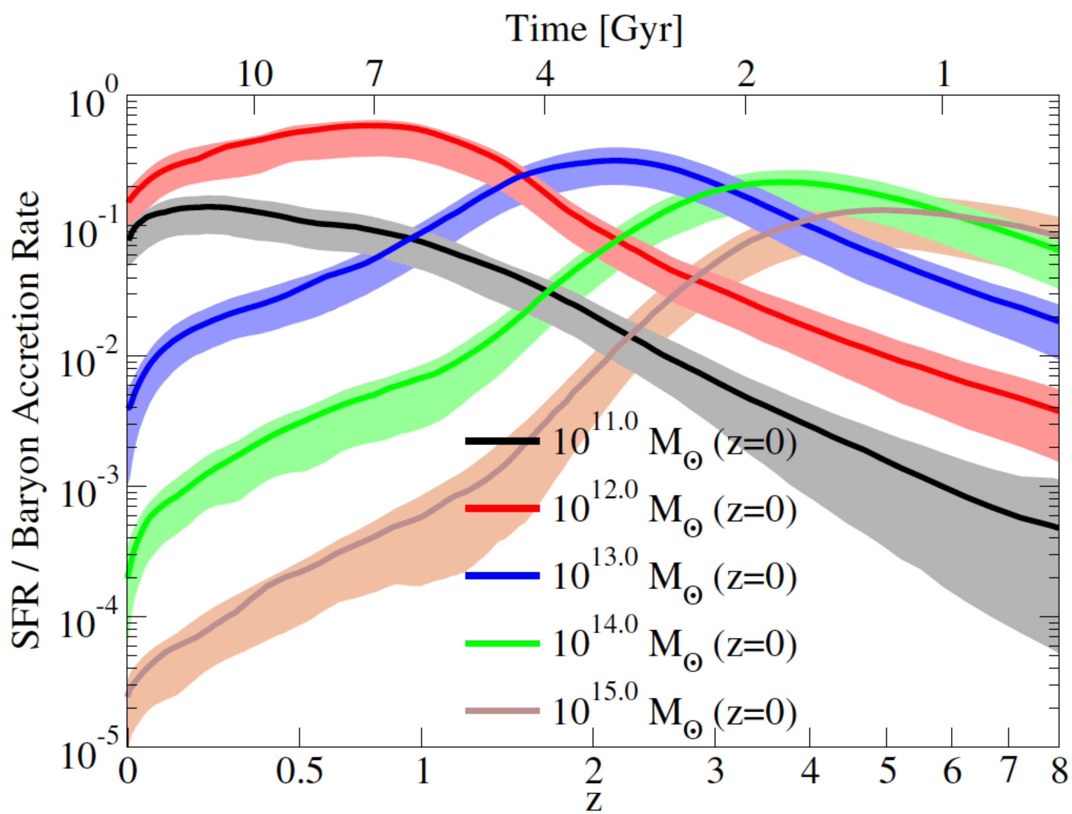
But the efficiency of galaxy formation within these haloes varies by orders of magnitude.





Moster et al. (2010)

The rate of star formation is decoupled from the rate of mass accretion.



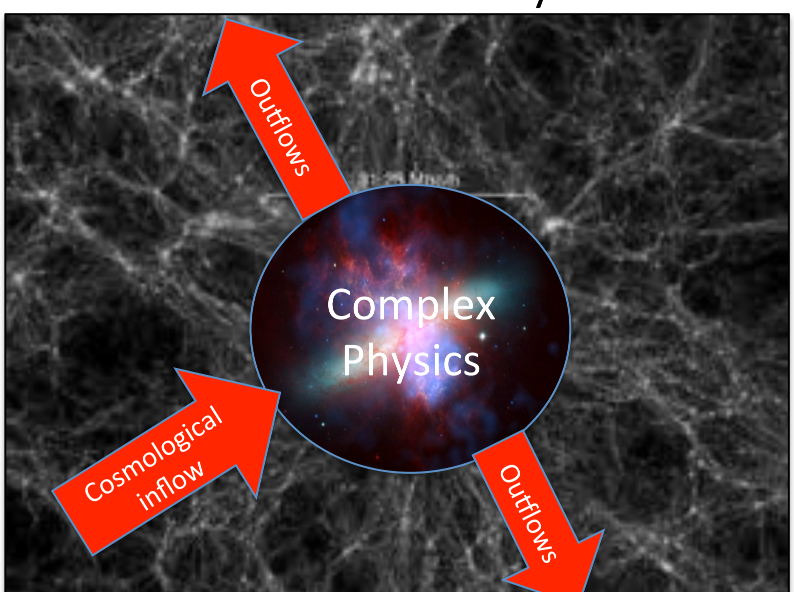
Requires energetic feedback, and expulsion of large amounts of gas from the halo at early times.

Behroozi et al. (2013)

Central galaxies

Star formation rates are determined by a variety of processes occurring over a wide range of time and spatial scales. Interpretations rely on sophisticated, parameterised models that have little predictive power.

Central Galaxy



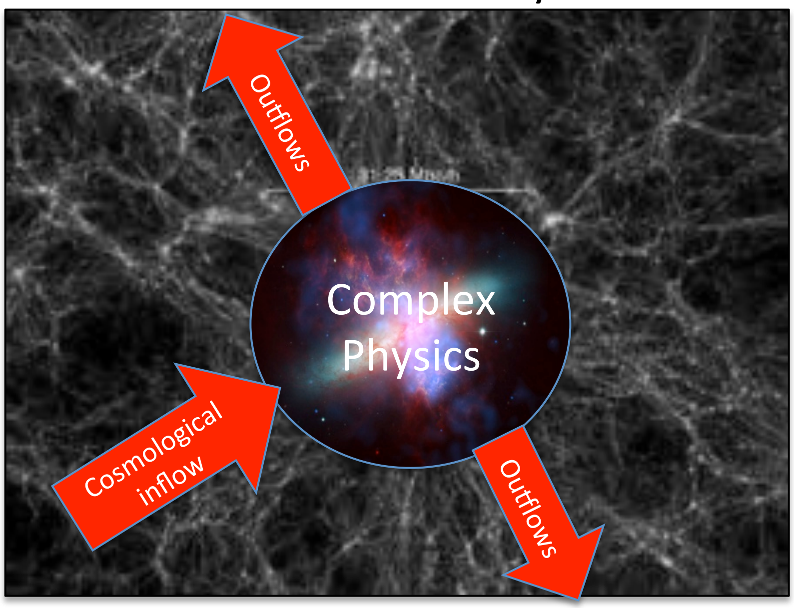
The physics is simpler on the largest scales, and inflow rates from the cosmic web may be more predictable

Satellite galaxies

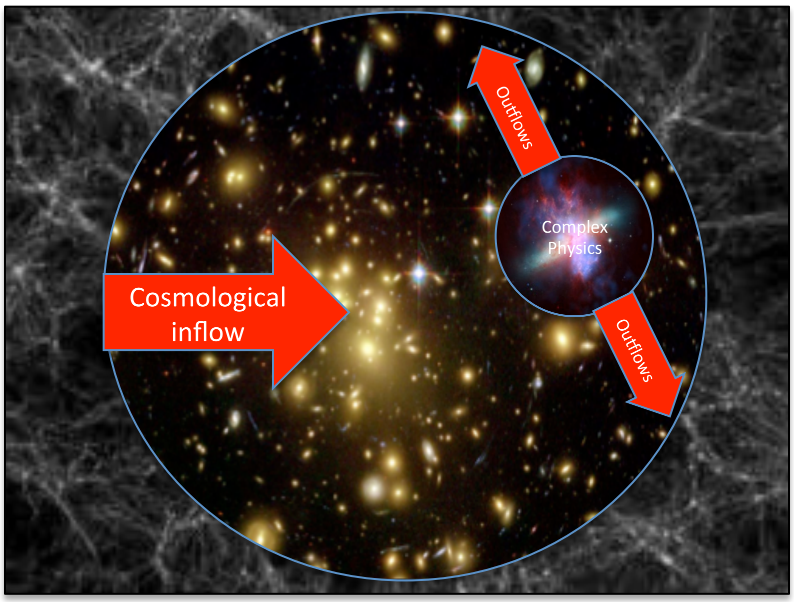
A satellite galaxy loses its source of fresh gas from cosmological accretion.

- For most satellites, everything else may be largely unaffected.
- We can test predictions of the “complex physics”

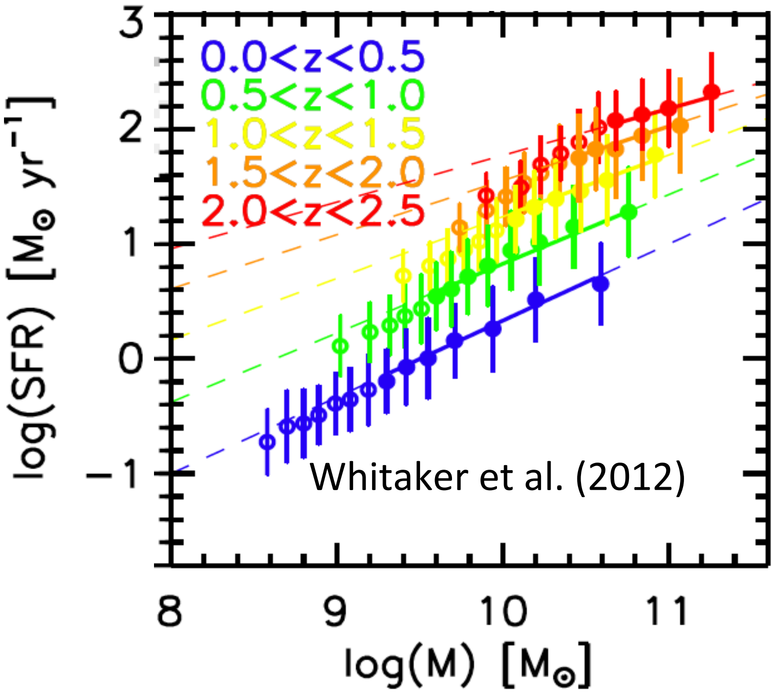
Central Galaxy

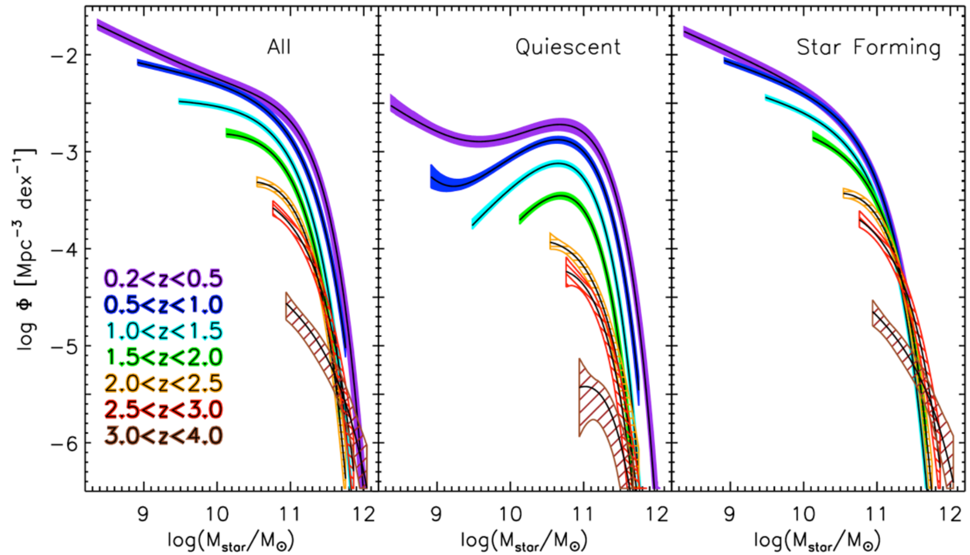


Satellite Galaxy



Galaxies





Muzzin et al. (2014)

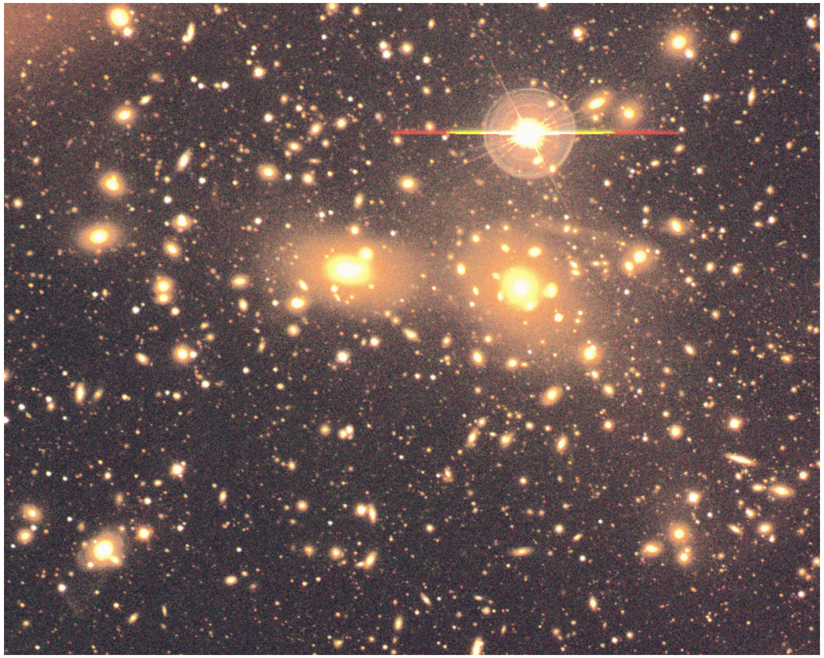
The SFR of star-forming galaxies decreases…

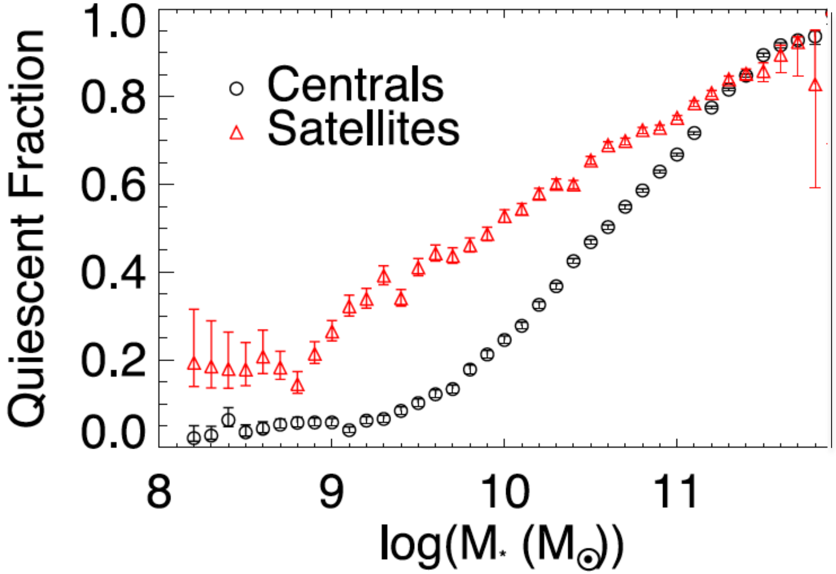
…while the number density of quiescent galaxies grows strongly with time…

Requires two types of evolution:

1. Steady evolution of SFR with time
2. Relatively sudden transition from SF to Quiescent

Quenching as a clock



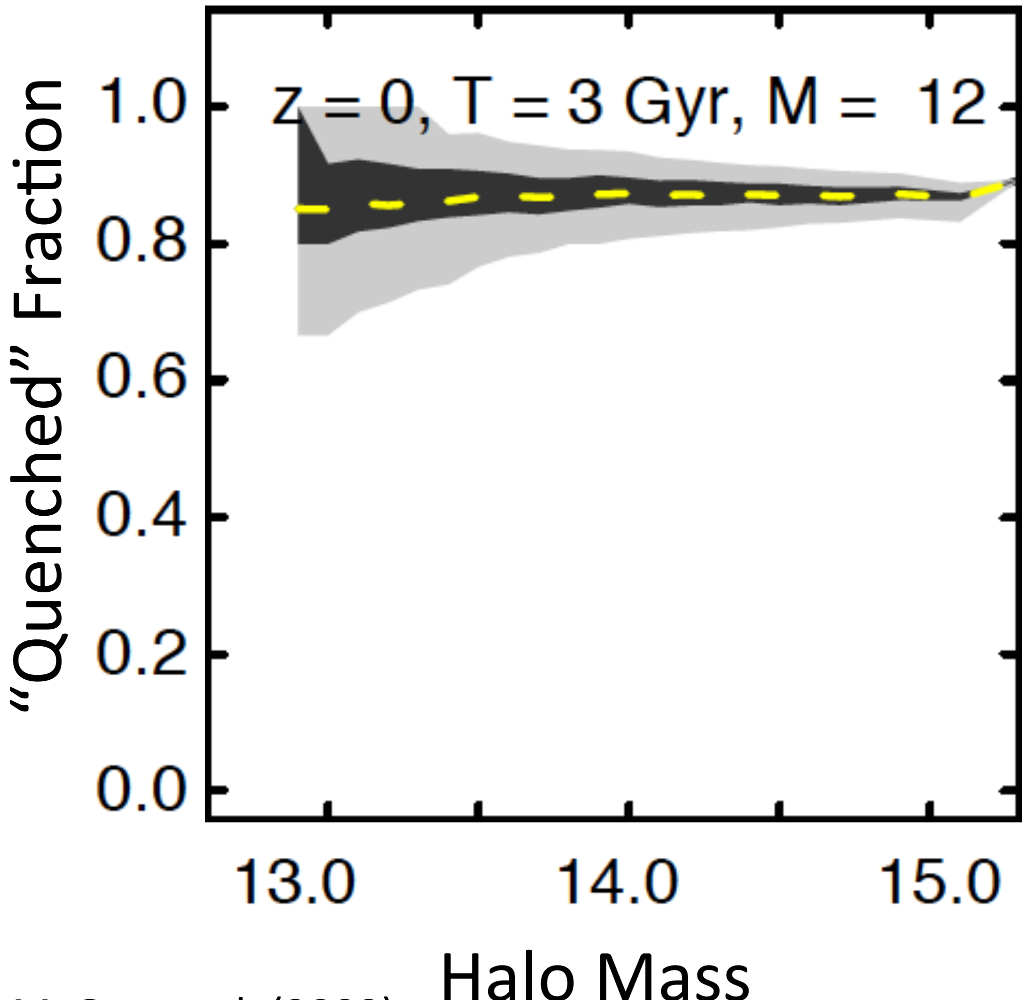


Omand, Balogh & Poggianti (2014)

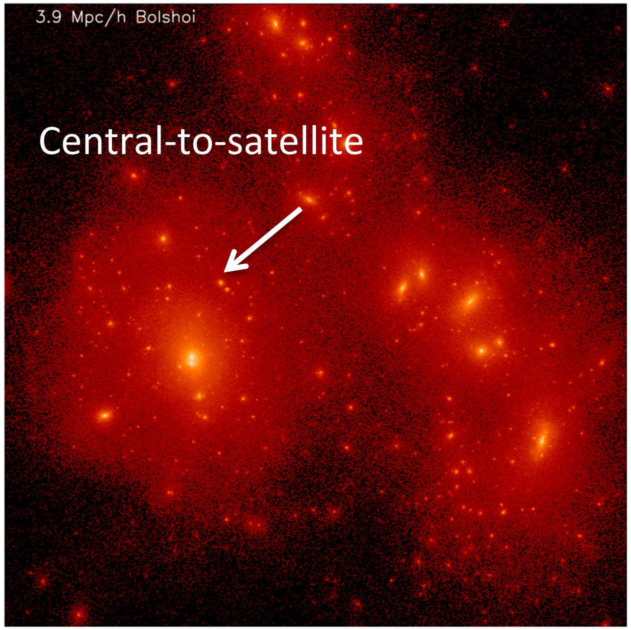
An important feature of galaxy evolution is a one-way quenching of star formation, leading to growth in abundance of quiescent galaxies with time

If a component of this transformation is associated with structure formation, we can use models of cluster growth to time the process

Linking accretion to quenching

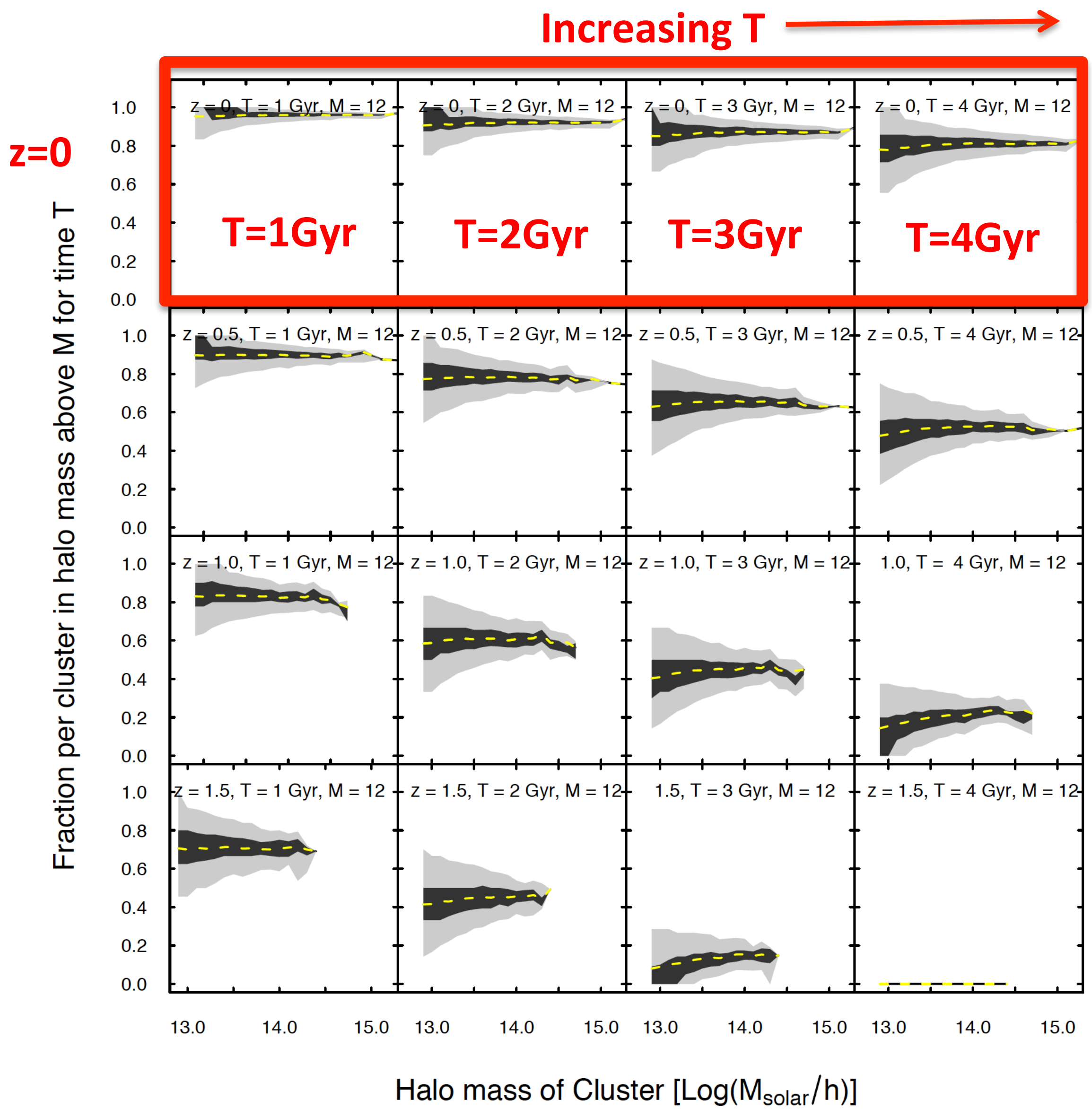


McGee et al. (2009)



From N-body accretion histories, we can consider how many galaxies have been in a massive halo for some time T

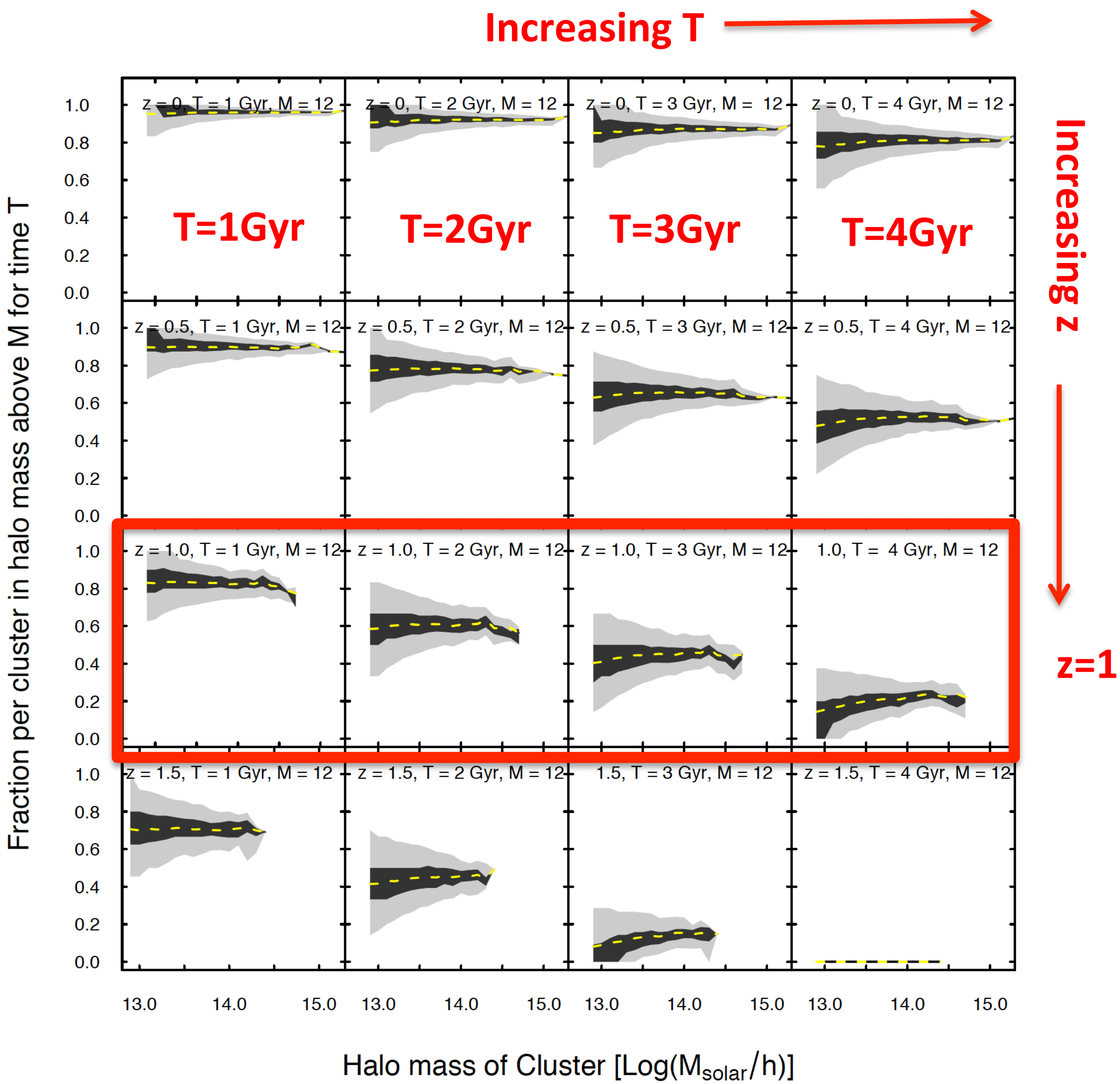
Linking accretion to quenching



At z=0, as T increases, fraction decreases.

McGee et al. (2009)

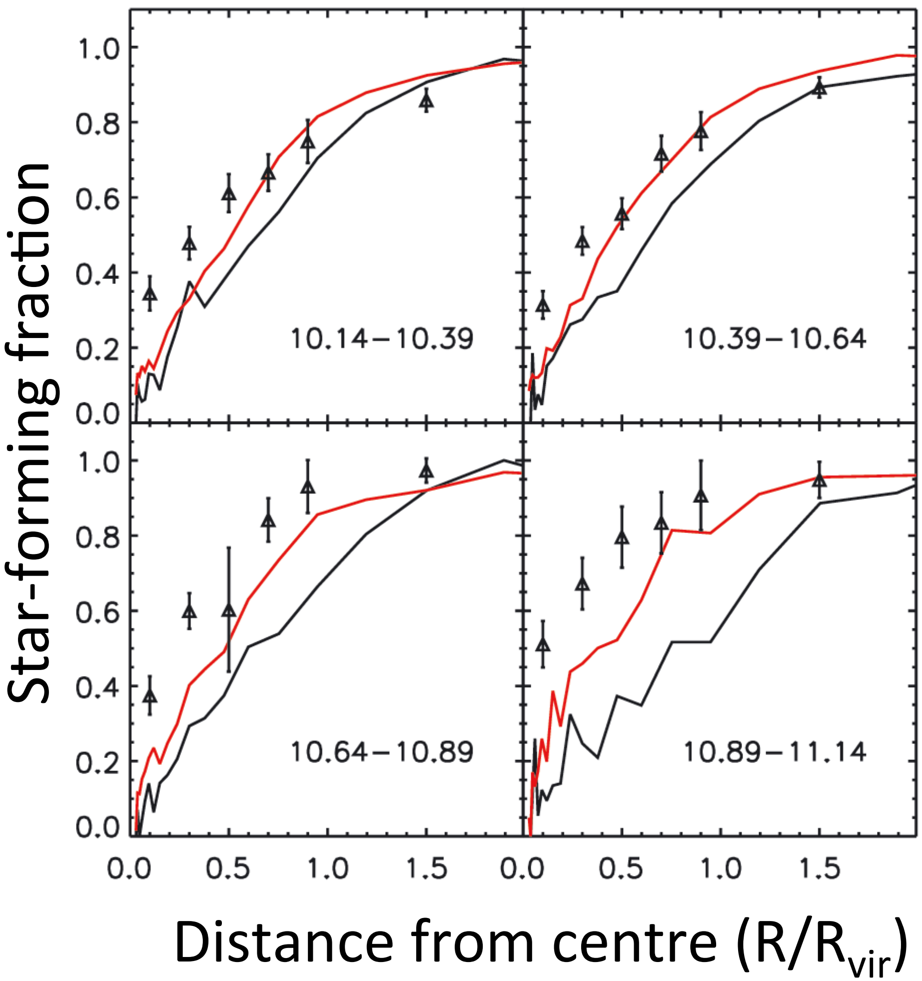
Linking accretion to quenching



Sensitivity to T increases dramatically with redshift

McGee et al. (2009)

The overquenching problem



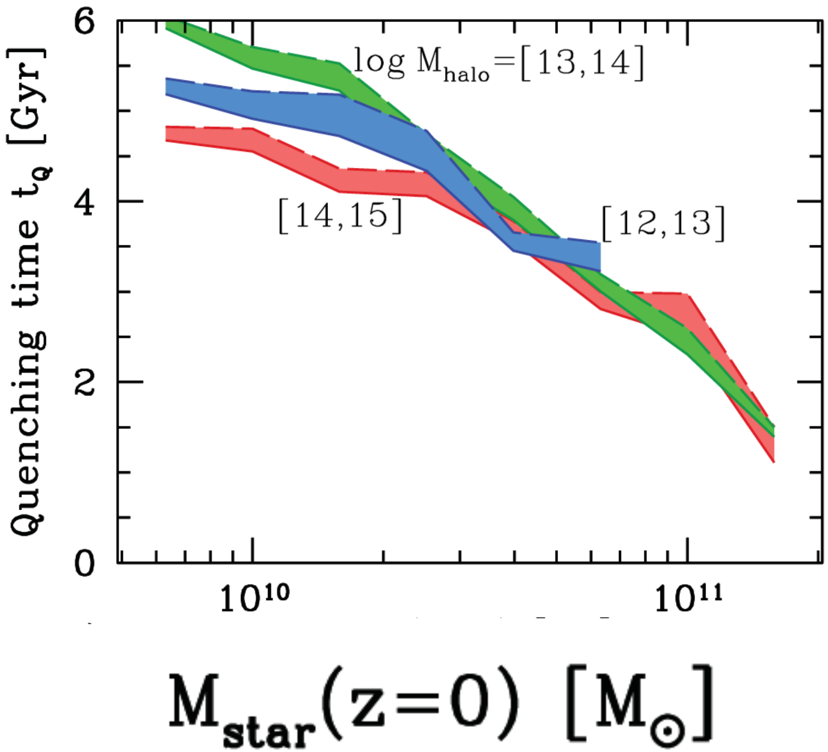
Guo et al. (2011)

Models predict more quiescent galaxies in clusters than observed

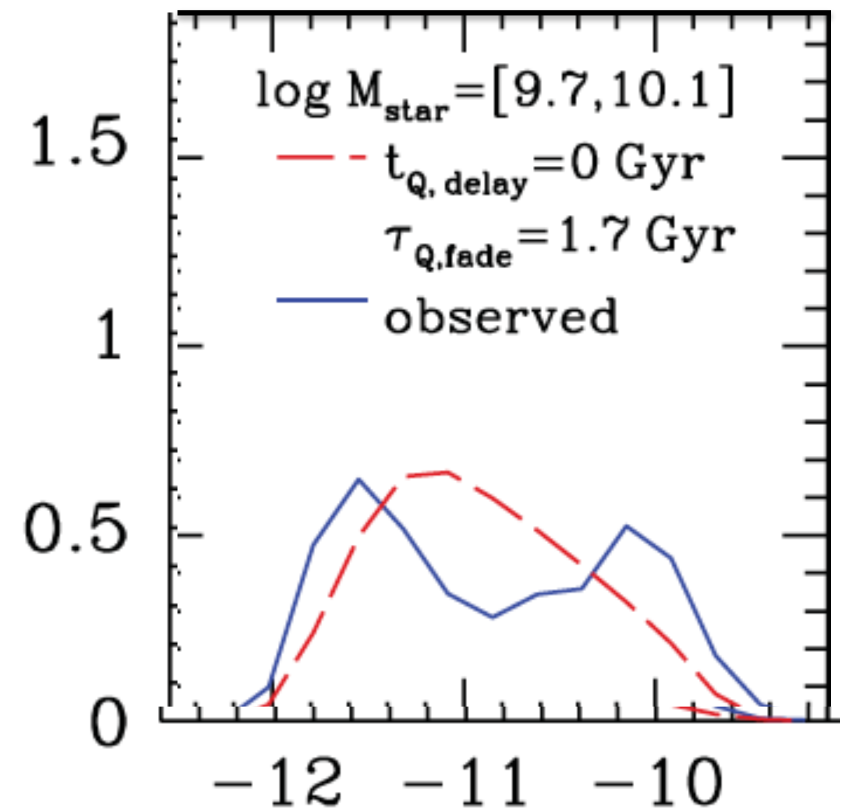
This is a persistent problem that has been hard to solve by just adjusting parameters

The timescale problem

Low-z data require T>3 Gyr to avoid overquenching.

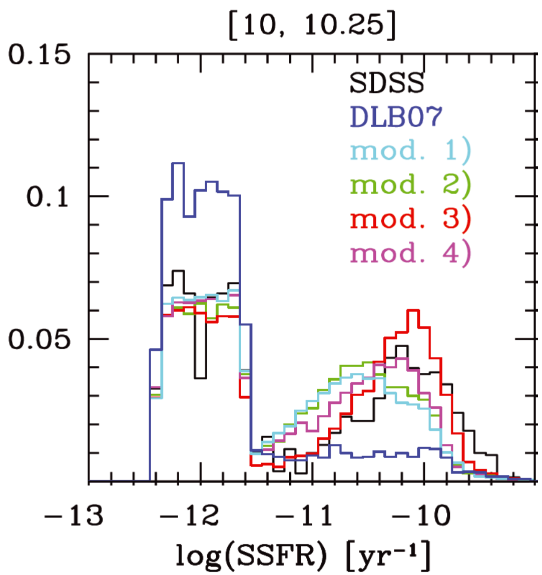


But how does this happen without distorting the SFR distribution?

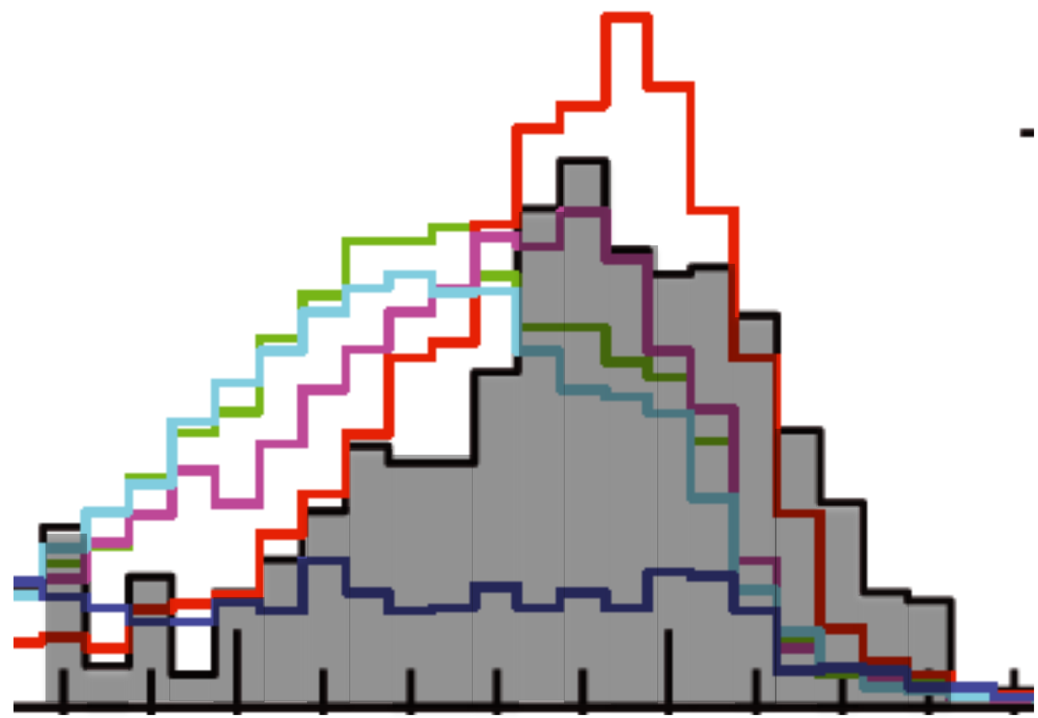


Wetzel et al. (2013)

The overquenching problem



Attempts to reduce the quenching generally predict too many galaxies with low (but non-zero) SFR.



log(sSFR)

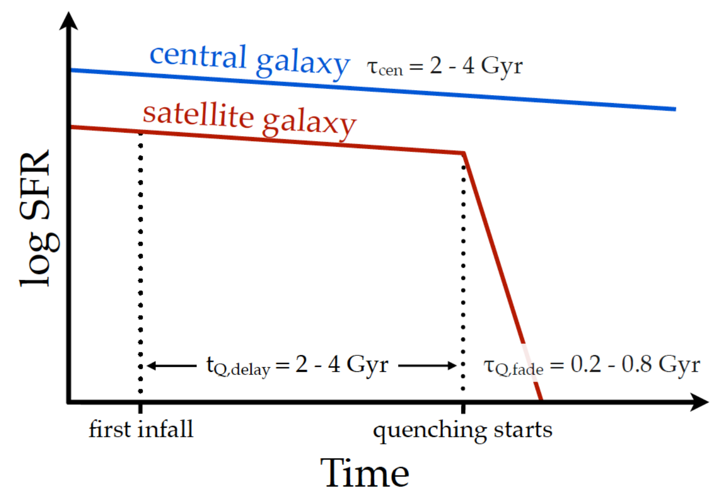
Weinmann et al. (2010)

also Font et al. (2008)

Two relevant timescales

$T = t_{delay} + \tau_Q$

T is the time between when a SF galaxy is accreted, to when it turns passive.



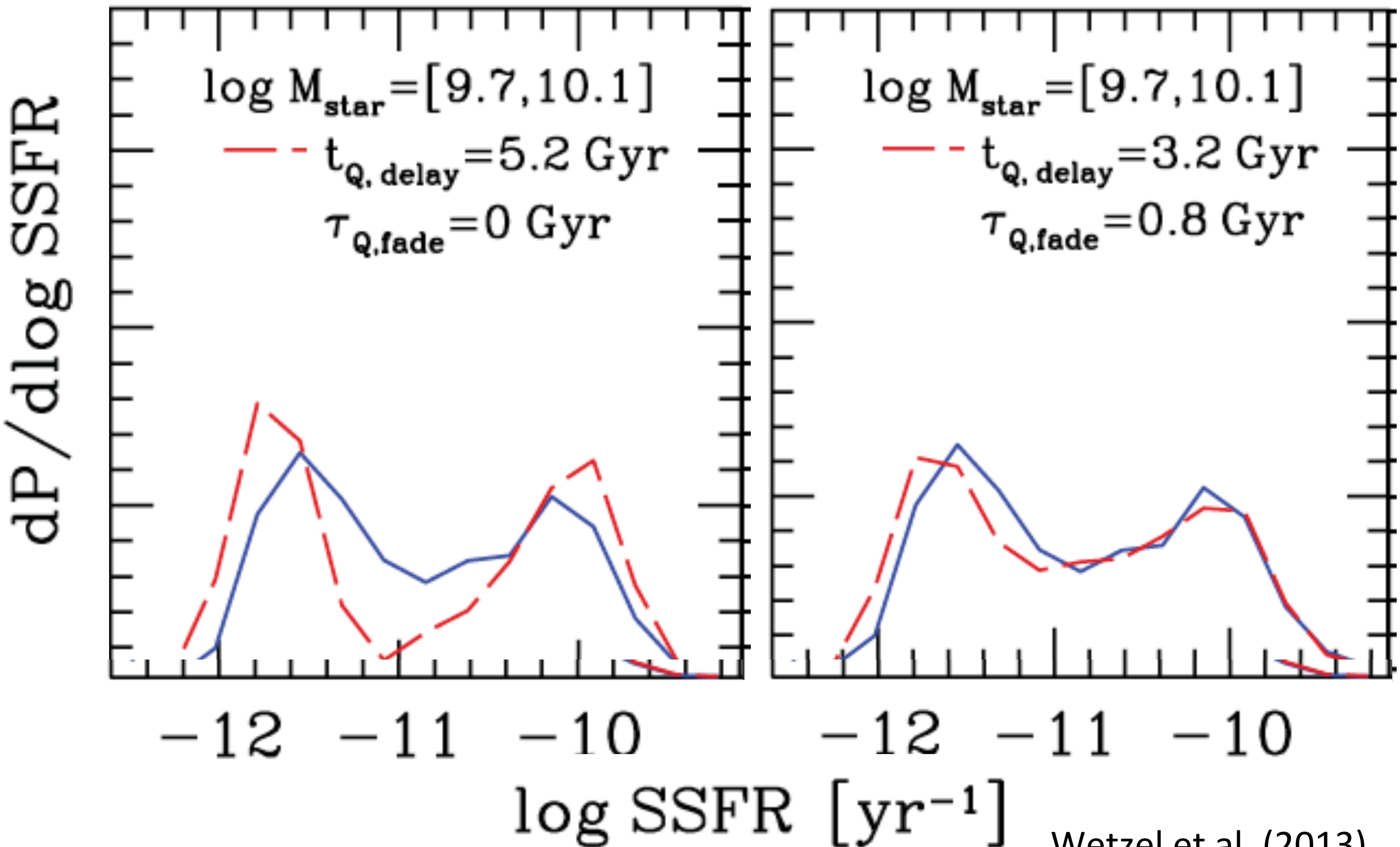
Wetzel et al. (2013)

At z=0:

- T must be large, 3-7 Gyr, to explain presence of SF galaxies in clusters
- τ_Q must be short, <1 Gyr to avoid overpopulating the “green valley”

t_{delay}>0 allows us to reconcile these apparently conflicting requirements.

Solution requires a long delay time, with short fade time.



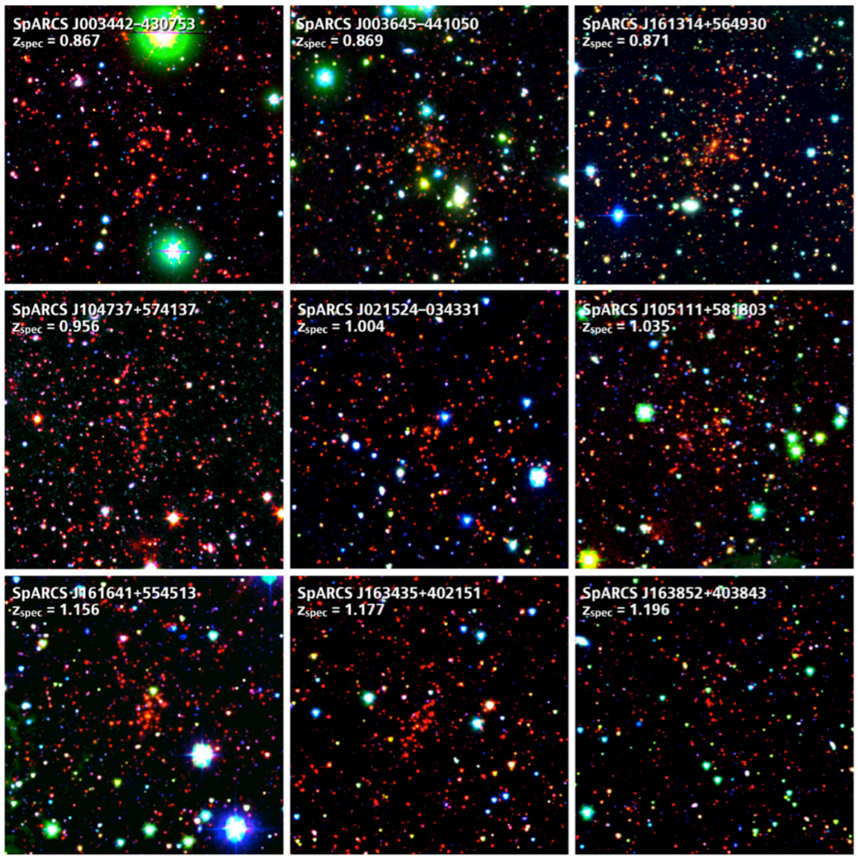
Wetzel et al. (2013)

The delay time puzzle

Why such a long delay time? How can satellite galaxies persist in a larger halo for several Gyr without changing?

Observing its evolution can provide important clues. Is it associated with the orbit, or internal galaxy properties, or something else?

GCLASS clusters



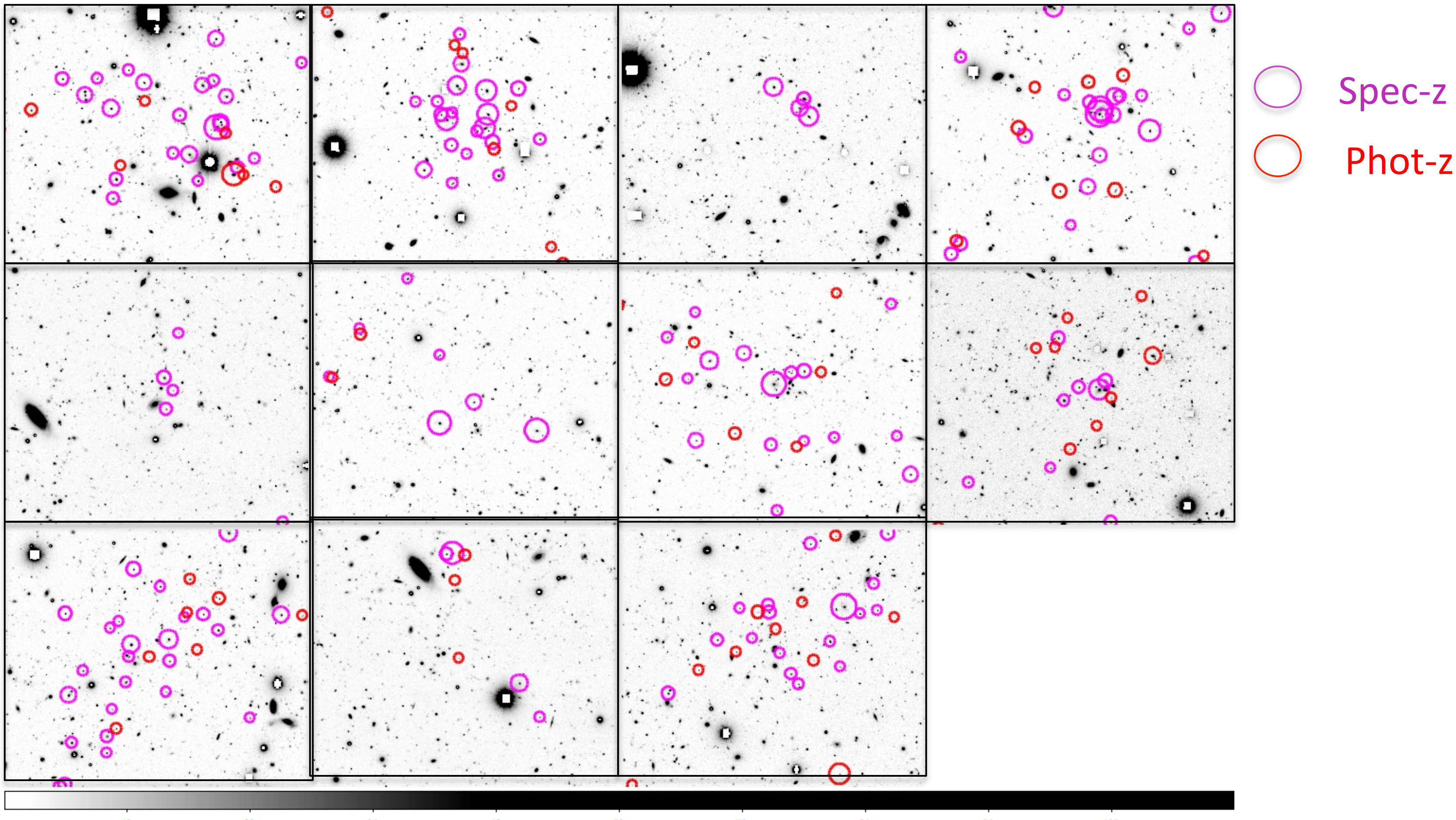
10 rich clusters at $0.85<z<1.25$ from SpARCS

Gemini GMOS n&s spectroscopy (IRAC <22) confirms 30-100 members per cluster

Muzzin et al. (2012)

GEEC2 groups

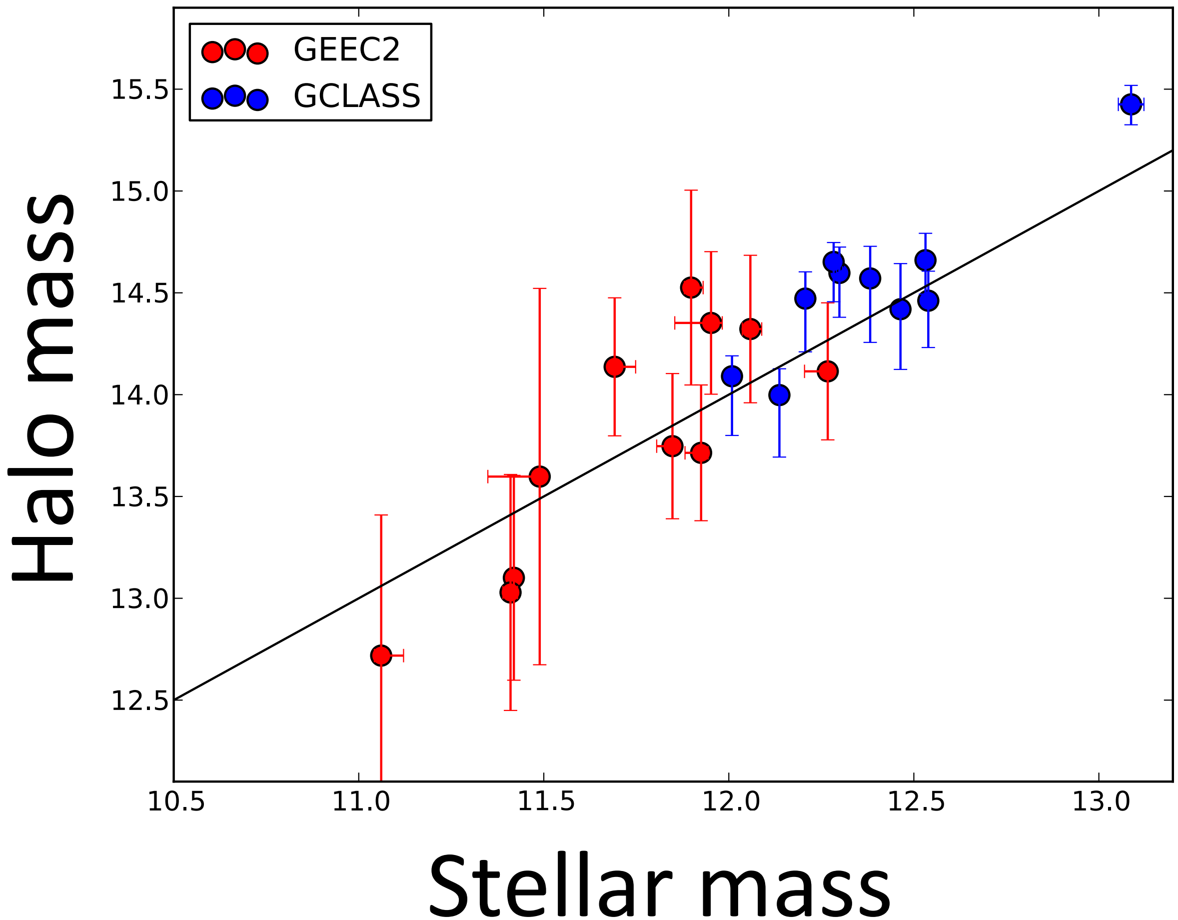
11 groups at 0.8<z<1 selected from deep X-ray images in COSMOS
Highly-complete spectroscopy, excellent photo-z for the rest.



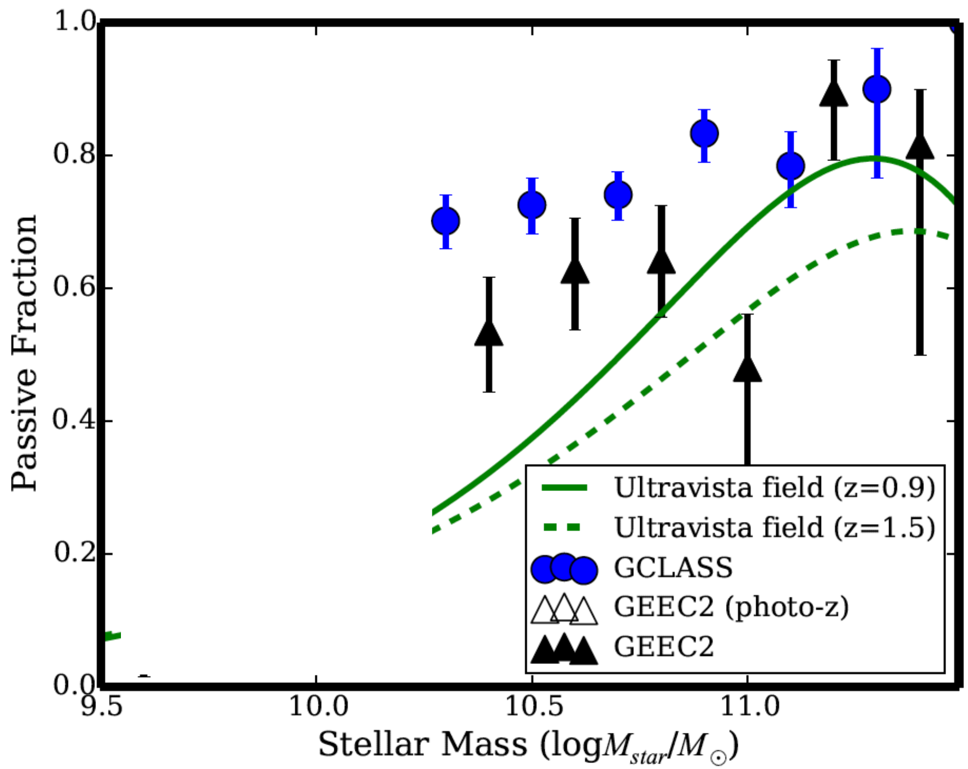
Dynamical and stellar masses

- Dynamical masses (M_{200}) and R_{200} measured from velocity dispersions
- Stellar mass measured within R_{200}

Combined with GCLASS, shows 1% stellar content, over 3.5 orders of magnitude in mass



Passive Fraction



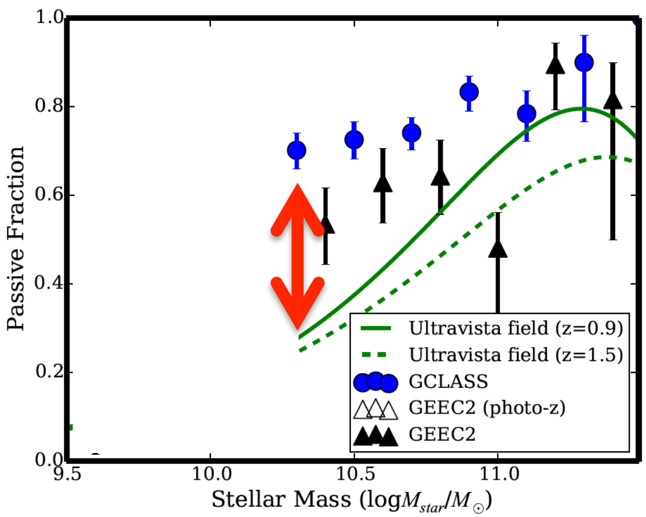
High fraction of passive galaxies. Very similar to local measurements!

Immediately rules out a t=4Gyr delay time at z=1

Conversion Fraction

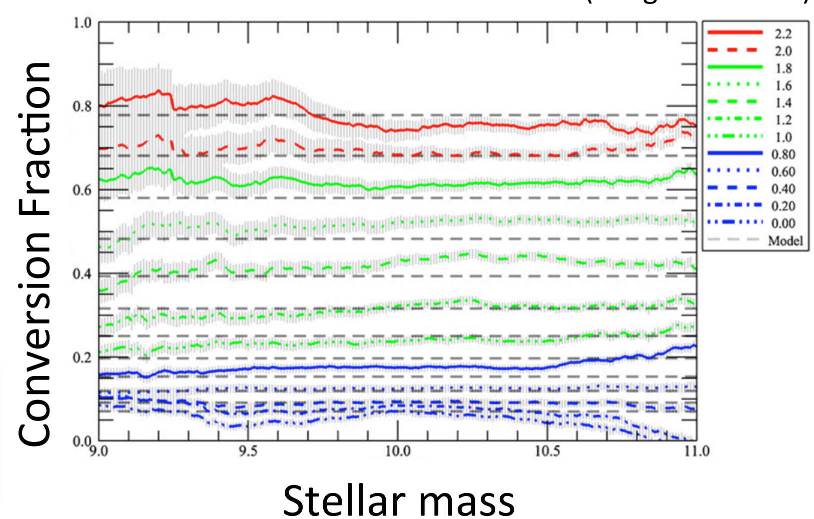
Massive galaxies are more likely to be quenched, independent of environment.

$$f_{convert} = \frac{Q_{cluster} - Q_{field}}{1 - Q_{field}}$$



The conversion fraction measures the excess quenching caused by environment

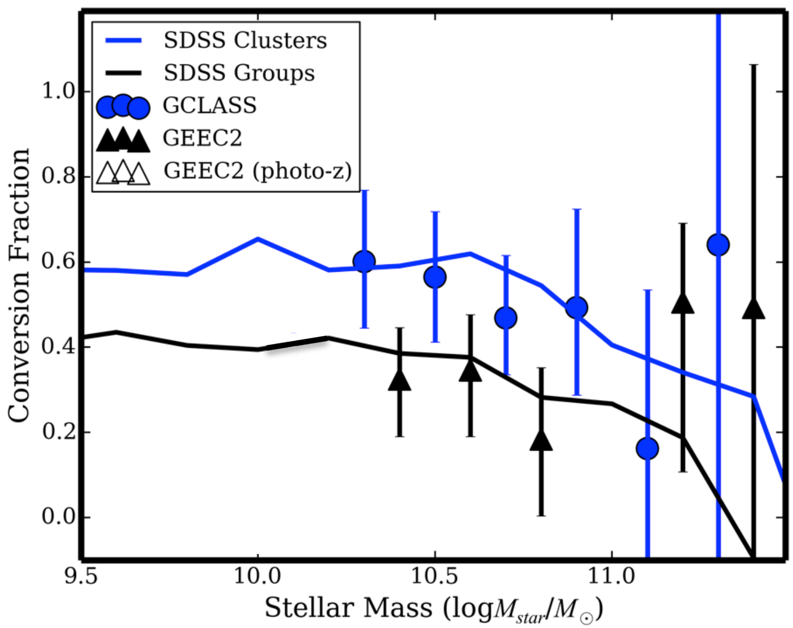
z=0: SDSS (Peng et al. 2010)



At low-z, this is independent of stellar mass

Conversion fraction

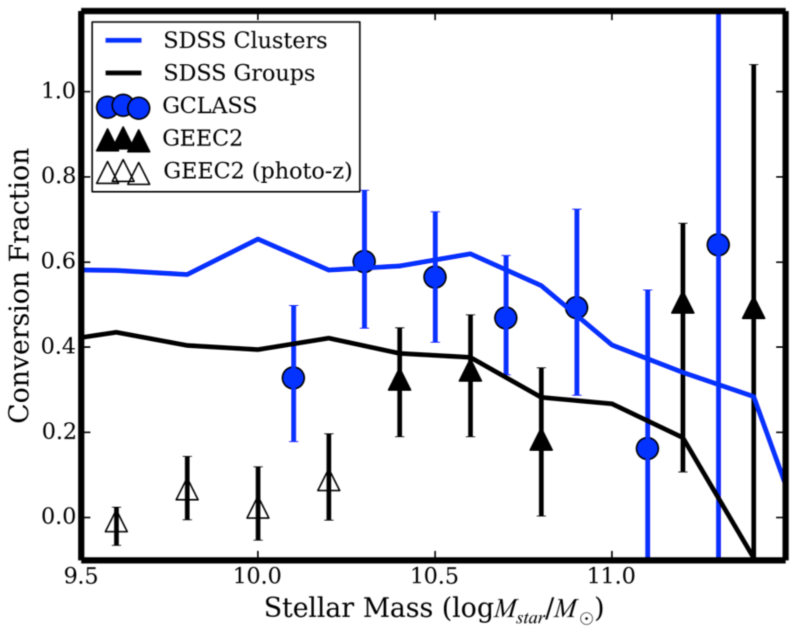
We find almost identical results for massive galaxies, at z=1

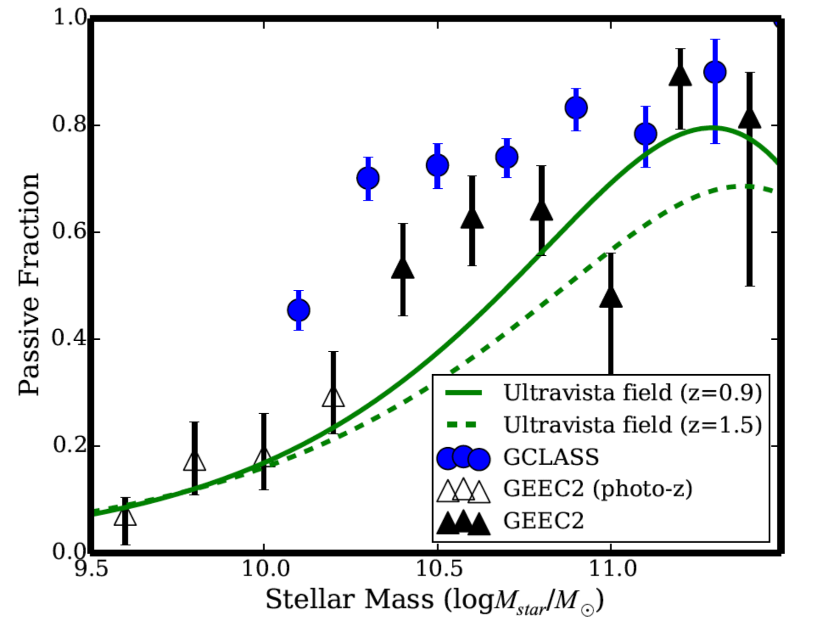


z=1: GEEC2 and GCLASS (Balogh et al. 2016)
z=0: SDSS from Omand, Balogh & Poggianti (2014)

Conversion fraction

Strong suggestion that the fraction drops sharply below $\log(M_*)=10.3$



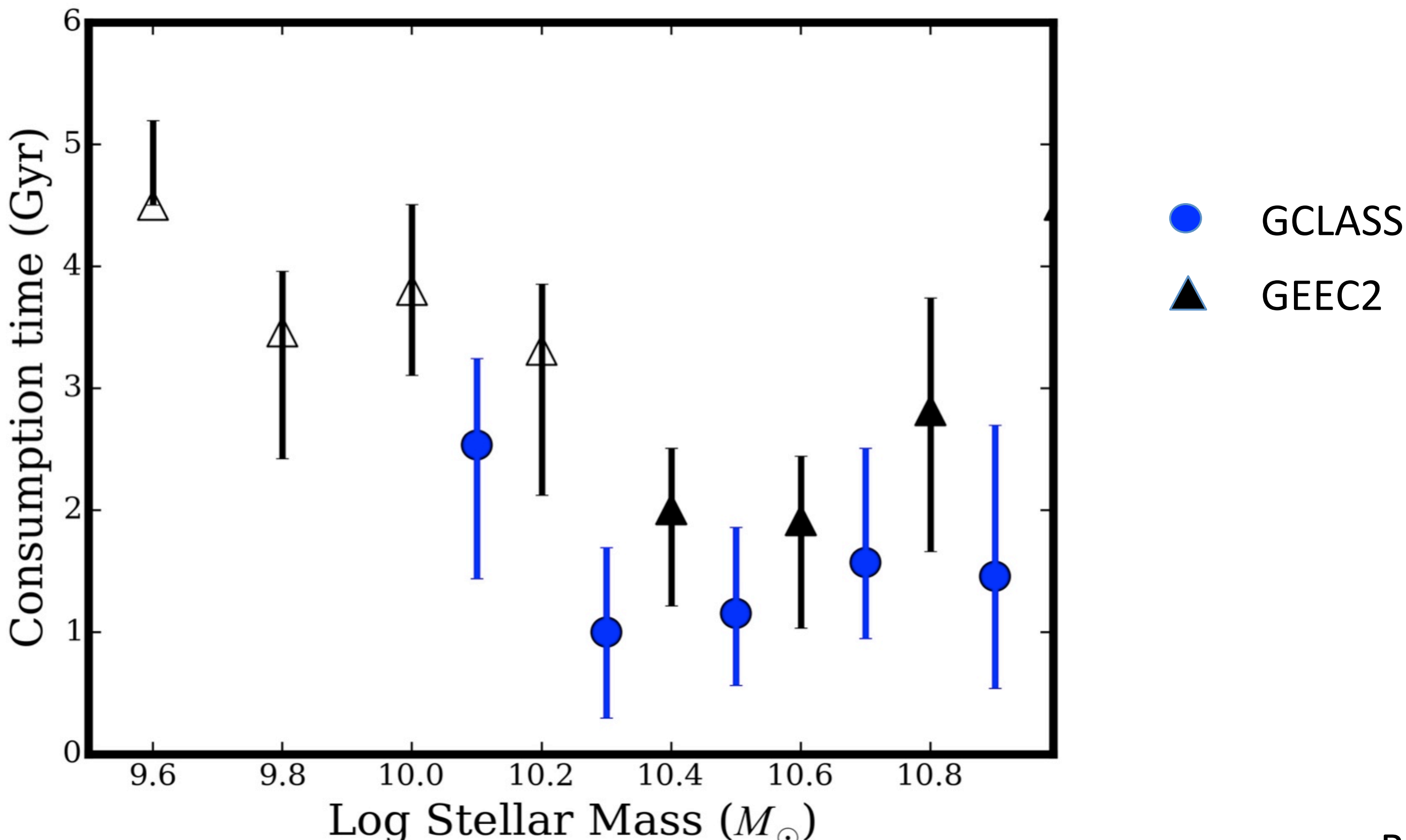


z=1: GEEC2 and GCLASS (Balogh et al. 2016)

z=0: SDSS from Omand, Balogh & Poggianti (2014)

Timescales

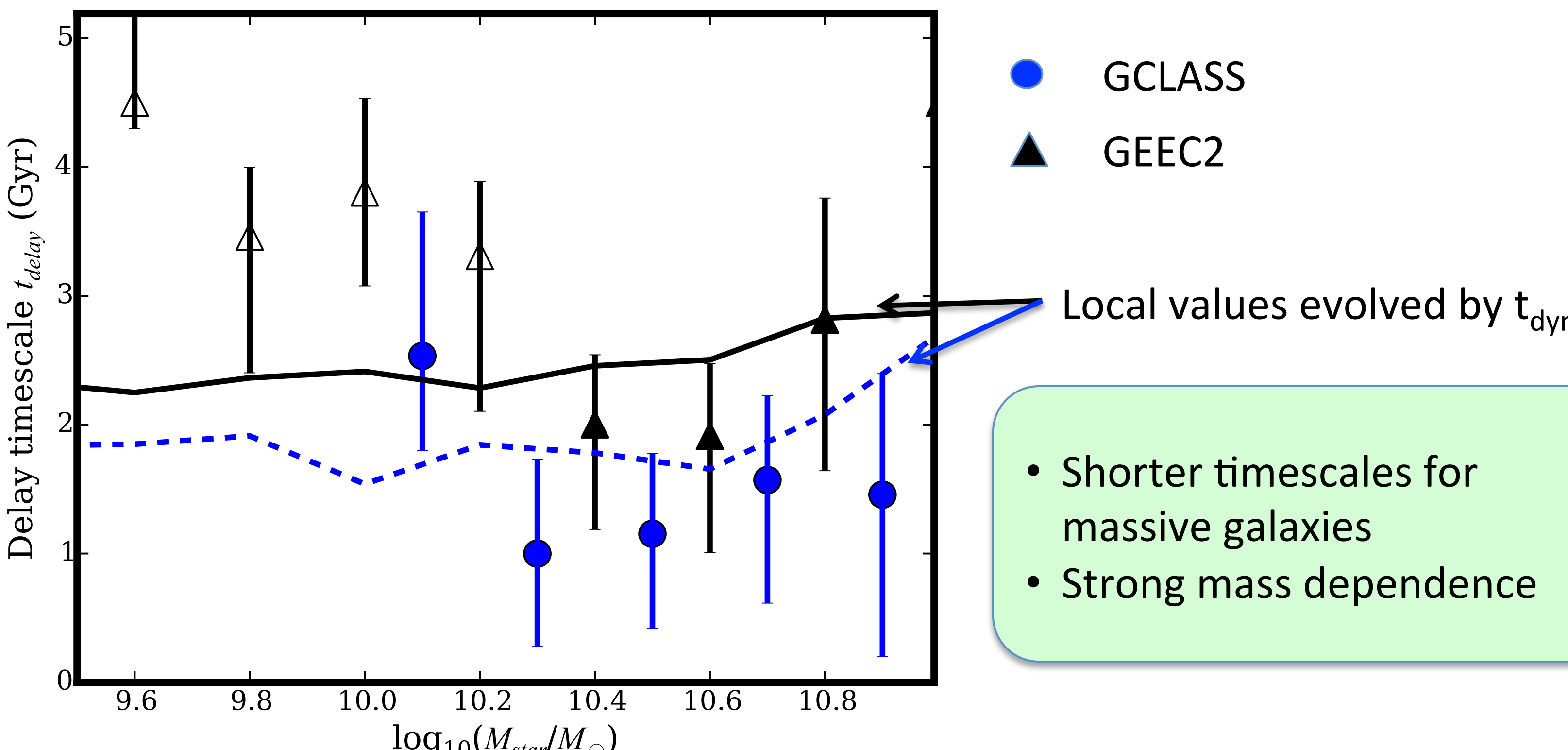
With some assumptions and the use of cluster mass growth predictions we can relate the relative passive fractions to the time between accretion and quenching



Balogh et al. (2016)

Timescales

The result is very different from what would be predicted if local values evolved like the dynamical time.



- Shorter timescales for massive galaxies
- Strong mass dependence

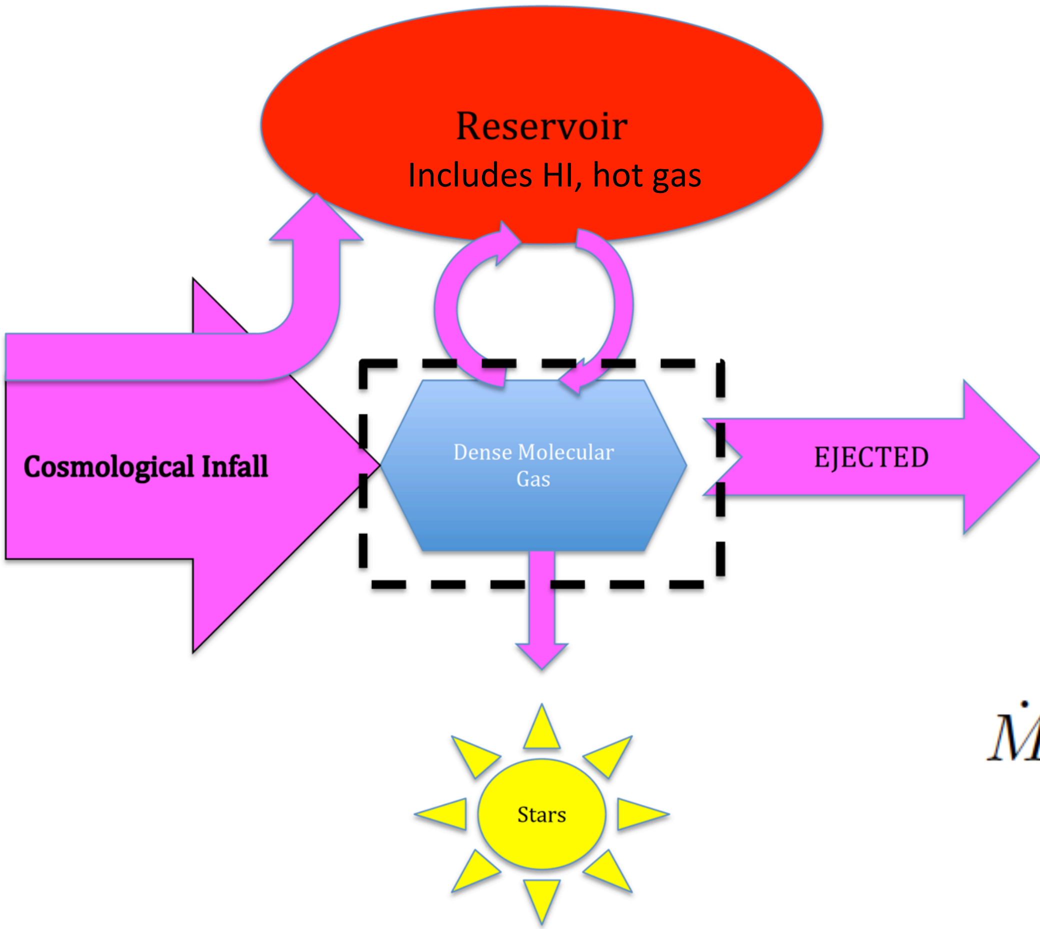
Balogh et al. (2016)

A new solution to an old problem?

1) At low redshift, the delay time is longer than the dynamical time
2) There are indications that the delay time evolves more quickly than the dynamical time for massive galaxies, and more slowly for low-mass galaxies.

Perhaps the relevant physical process is unrelated to the satellite orbit

The baryon cycle



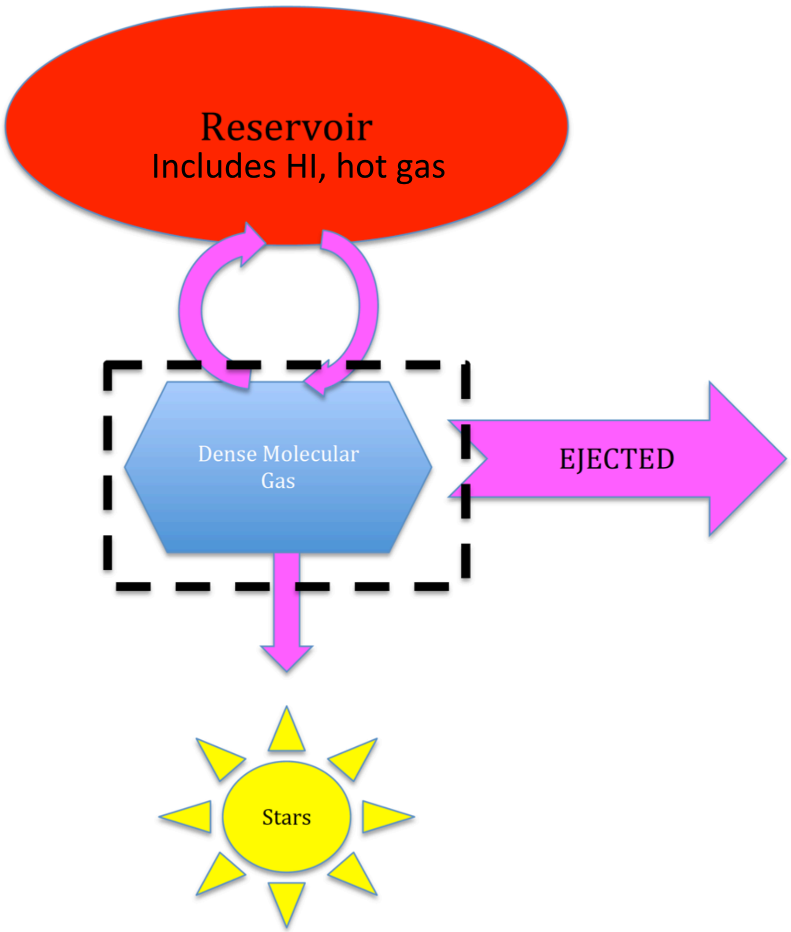
Consider our system to be the direct source of star formation: dense, molecular gas

$$\dot{M}_{in} + \dot{M}_{res} = \dot{M}_{*} + \dot{M}_{out}$$

$$\eta \equiv \frac{\dot{M}_{out}}{\dot{M}_{*}}$$

McGee, Bower & Balogh (2014)

Satellite galaxies



Almost by definition, cosmological inflow is shut off in satellite galaxies (e.g. Behroozi et al. 2013). This is a robust prediction of the model

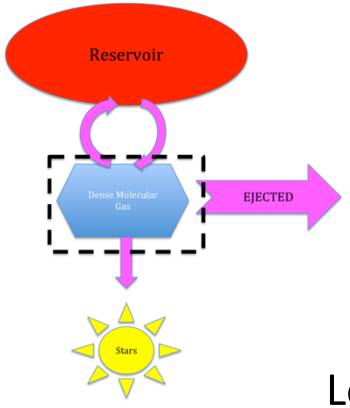
- In addition, the reservoir may or may not be stripped

Satellite galaxies provide a relatively clean test of the parameters in this cycle

$$\dot{M}_{res} = \dot{M}_{*} + \dot{M}_{out} = \dot{M}_{*}(1+\eta)$$

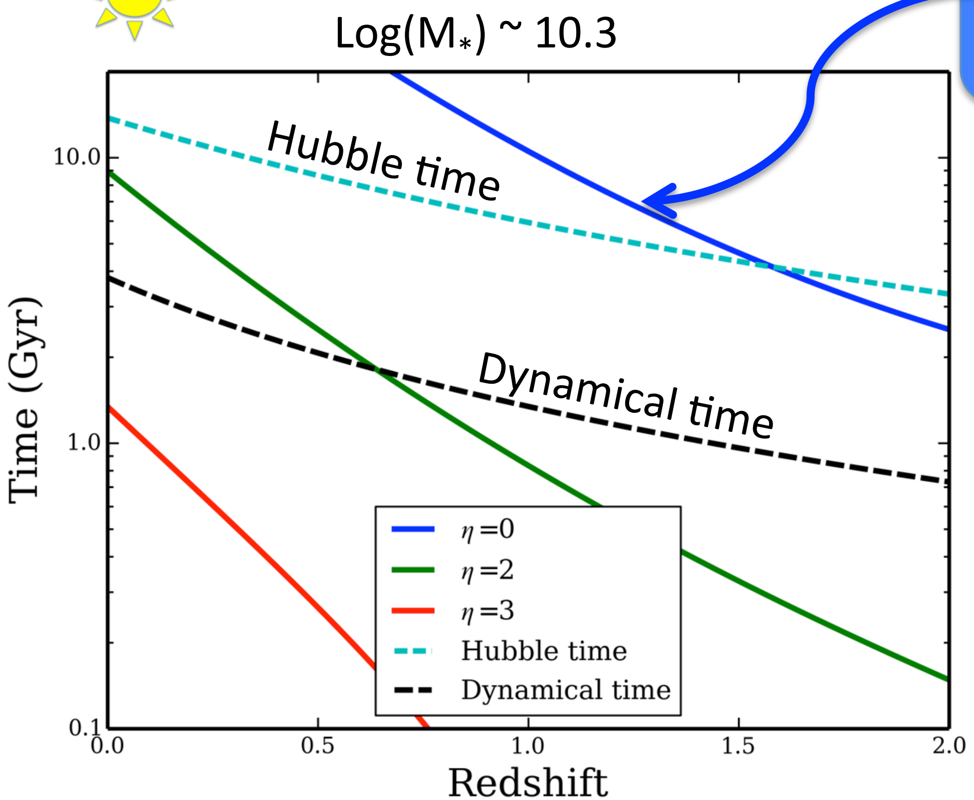
$$T_{\rm delay} = \frac{M_{res}}{\dot{M}_{res}}$$

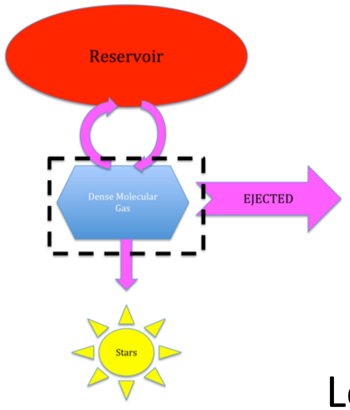
McGee, Bower & Balogh (2014)



The role of outflows

Ignoring the role of outflows, satellites potentially have lots of fuel to maintain star formation

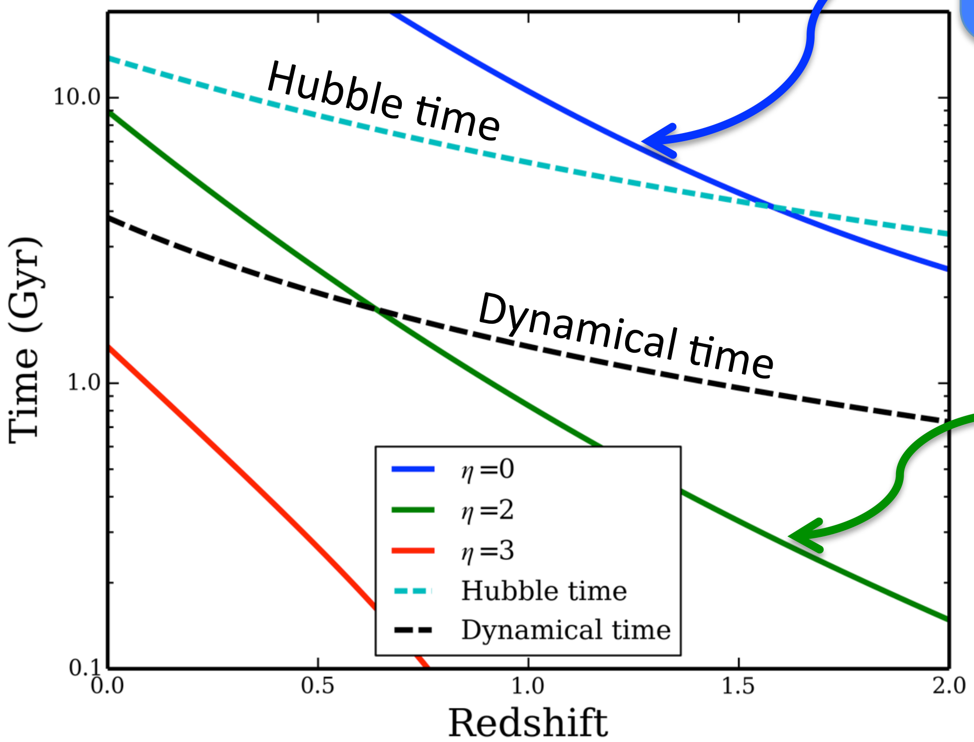




The role of outflows

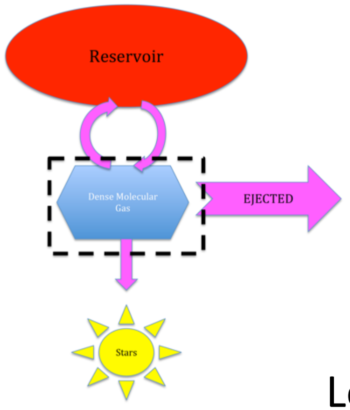
Ignoring the role of outflows, satellites potentially have lots of fuel to maintain star formation

Log(M_*) ~ 10.3

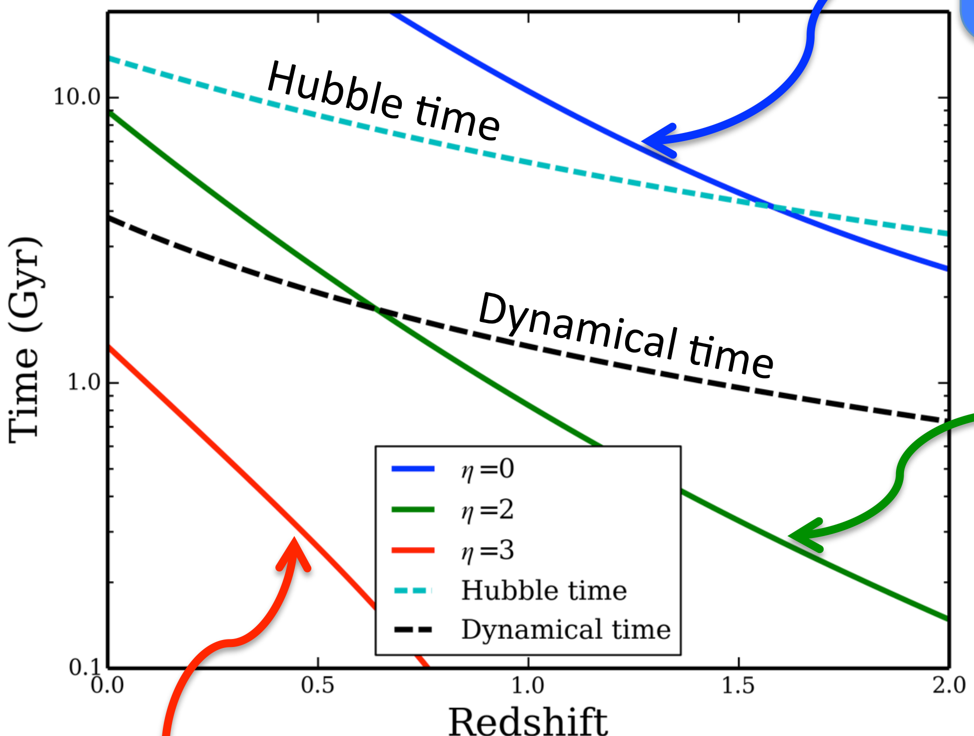


At high redshift, the high SFR imply strong associated feedback. This can limit the lifetime for star formation in the absence of inflow.

The role of outflows



Log(M$_*$) ~ 10.3



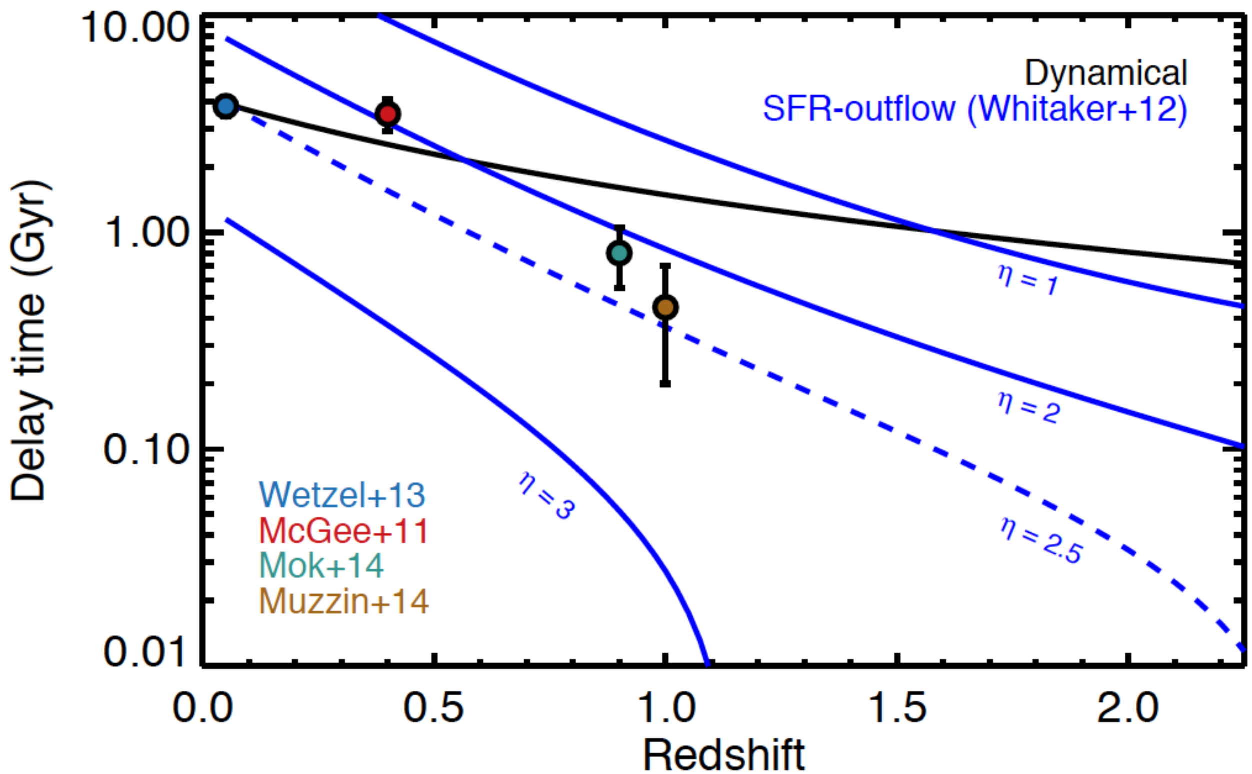
Ignoring the role of outflows, satellites potentially have lots of fuel to maintain star formation

At high redshift, the high SFR imply strong associated feedback. This can limit the lifetime for star formation in the absence of inflow.

With the high mass-loading factors preferred by many models, this dominates the quenching at all redshifts

“Overconsumption”

Evolution in delay times may be more rapid then expected dynamically, but as expected for η~2



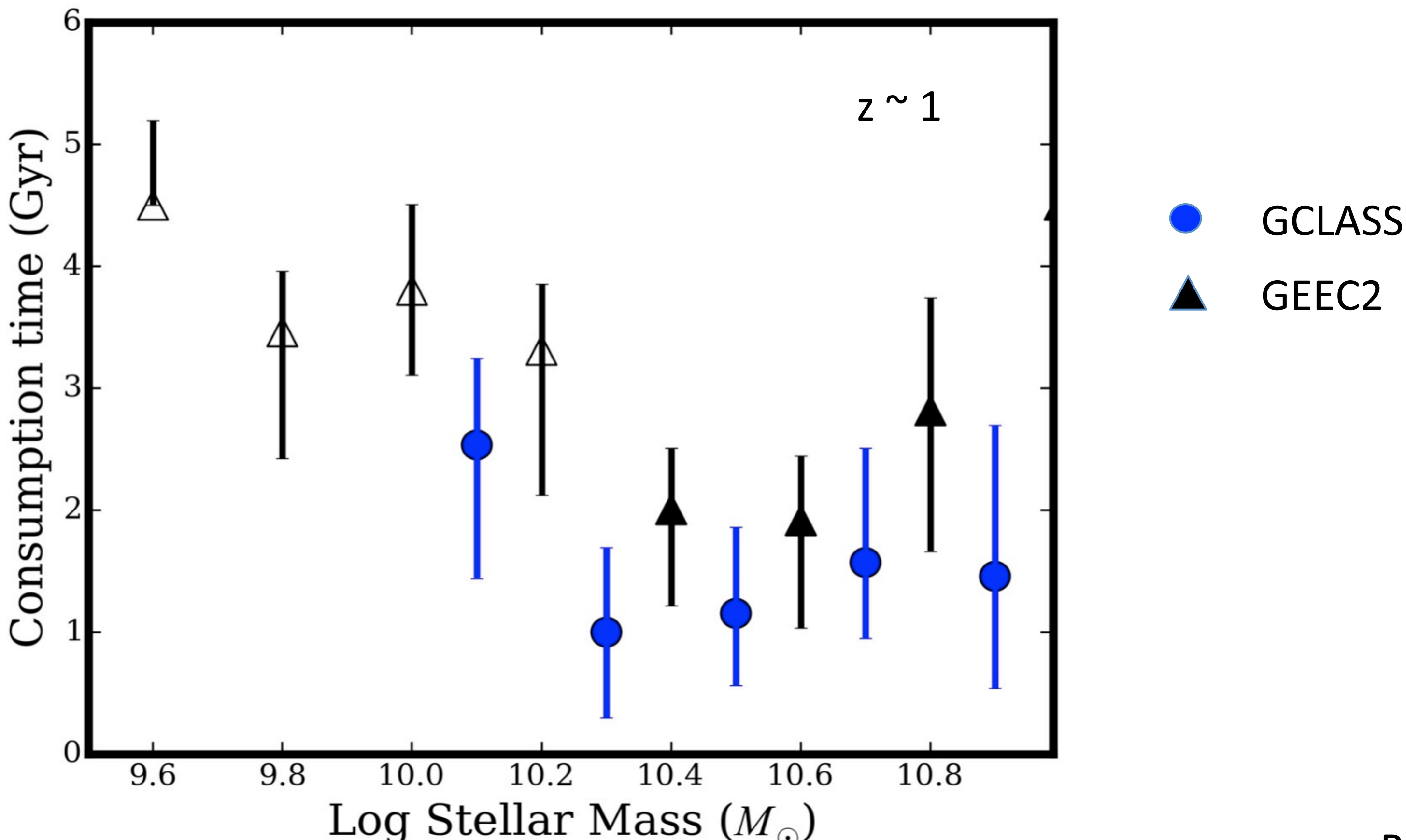
McGee, Bower & Balogh (2014)

The overquenching problem at z=0 may be associated with outflows that are too strong

Log(M*) ~ 10.3

Recall: Timescales

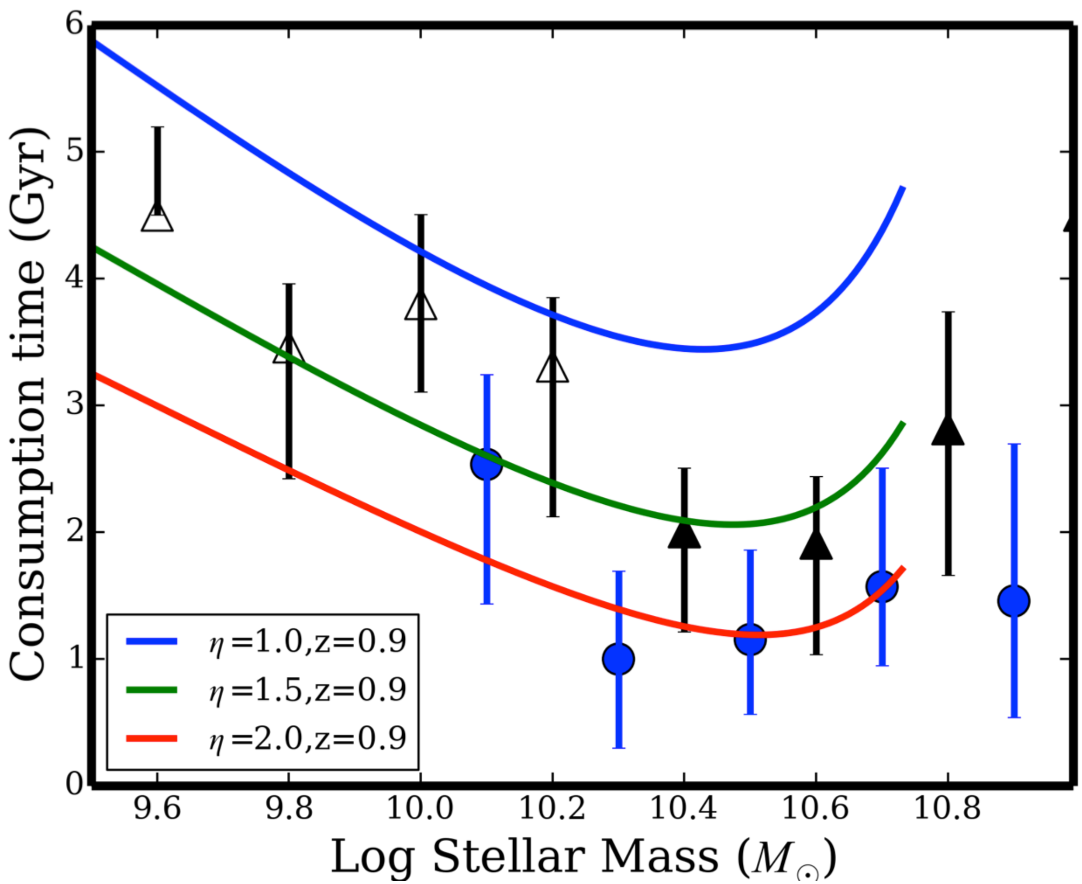
With some assumptions and the use of cluster mass growth predictions we can relate the relative passive fractions to the time between accretion and quenching



Balogh et al. (2016)

Timescales

The observed mass dependence is predicted by the overconsumption model with modest outflow rates



Low passive fraction in low-mass galaxies is due to their inefficient star formation and associated outflow rate

- Very different from z=0 behaviour

Balogh et al. (2016)

GOGREEN

A Gemini Large Program

Data Acquisition and Reduction

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Greg Rudnick, Kansas
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Adam Muzzin, York University

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Mike Cooper (UC Irvine)
Ricardo Demarco (Concepcion)
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Richard Bower (Durham)
Charlie Conroy (UCSC)
Warrick Couch (AAO)
Andrew de Groot (UCR)
Gabriella De Lucia (Trieste)
Erica Ellingson (UC Boulder)
Alexis Finoguenov (Helsinki)
Ryan Foltz (UCR)
Henk Hoekstra (Leiden)
Mark David Lacy (NRAO)
Diego Garcia Lambas (Cordoba)

Ian McCarthy (LJMU)
Hernan Muriel (Cordoba)
Matt Owers (AAO)
Laura Parker (McMaster)
Bianca Poggianti (Padova)
Alessandro Rettura (JPL)
Ian Smail (Durham)
Jason Surace (IPAC)
Jeremy Tinker (NYU)
Carlos Valotto (Cordoba)
Tracy Webb (McGill)
Andrew Wetzel (Caltech/Carnegie)
Jon Willis (Victoria)
Dennis Zaritsky (Arizona)

Survey description: Balogh et al. (2017 – coming soon!)

What we learn from galaxy clusters and groups

- Cosmology, through masses/abundance
- Plasma physics (X-ray emitting ICM)
- Supermassive black hole growth (radio jets)
- Nature of dark matter (lensing comparisons)
- Host the most massive galaxies in the Universe
- Rare perturbations to galaxy evolution
- Laboratories for study of galaxy and structure formation

GMOS is the perfect instrument:

- Field of view matches distant cluster sizes
- Nod and shuffle allows high target densities
- Red sensitivity allows to push out in redshift

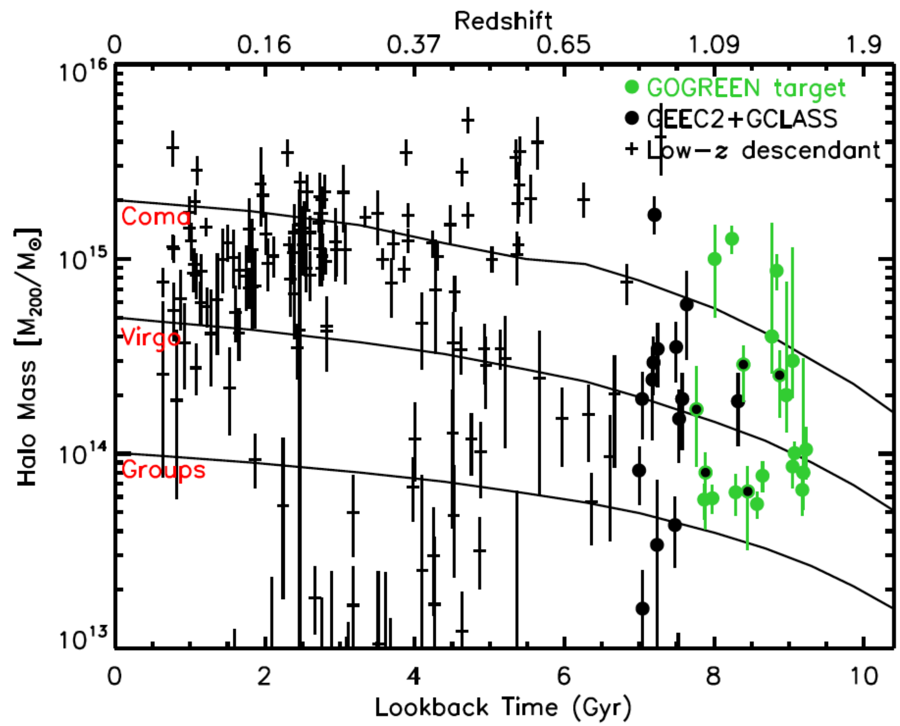
GOGREEN

We are engaged in a Gemini Large Program to observe 21 clusters at 1<z<1.5: *Gemini Observations of Galaxies in Rich Early ENvironments (GOGREEN)*

Awarded 440h over 3 years 2014-2017 on Gemini N&S (extended to 2018A)

- Will measure quiescent fraction for $M>10^{10}$ M_{sun} in 21 systems
- Extend lookback time by 1.5 Gyr: large relative to the quenching times

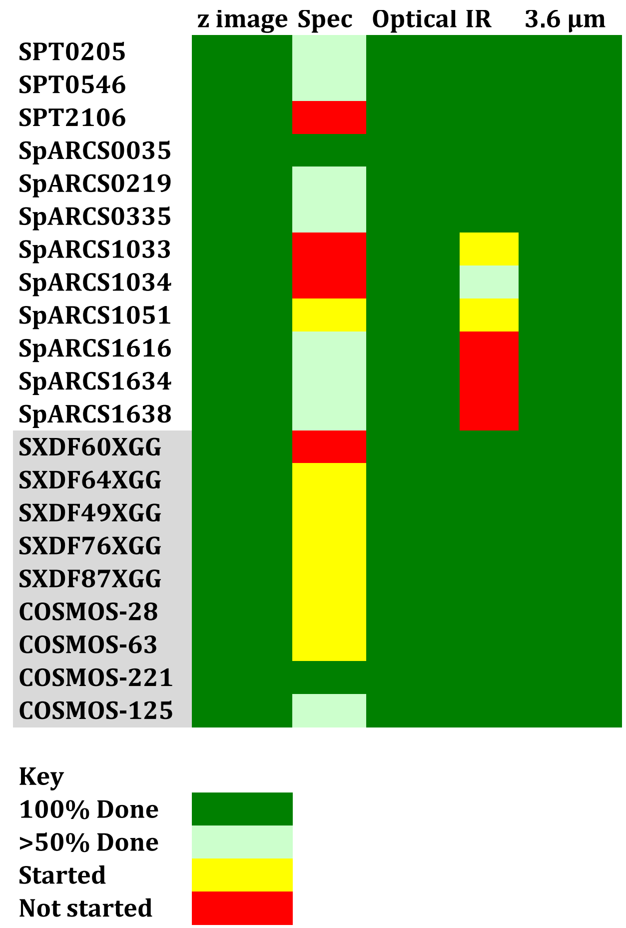
Sample	ID	RA	Dec	z	Nm x t(h)
		Groups			
SXDF	64XGG	34.3238	-5.1714	1.0300	3x5
SXDF	49XGG	34.5347	-5.0714	1.0590	3x5
COSMOS	221	150.5702	2.4986	1.1460	3x5
COSMOS	63	150.3533	1.9334	1.2340	3x5
COSMOS	28	149.4576	1.6724	1.2580	3x5
SXDF	76XGG	34.7413	-5.3233	1.4000	3x5
SXDF	60XGG	34.1894	-5.1635	1.4100	3x5
COSMOS	125	150.6272	2.1592	1.4500	3x5
CDFS	2	53.0017	-27.5790	1.4700	3x5
		Virgo Progenitors			
GCLASS	J0215	33.8500	-3.7256	1.0040	3x5
GCLASS	J1051	162.7968	58.3009	1.0350	3x5
GCLASS	J1634	248.6475	40.3643	1.1770	3x5
GCLASS	J1638	249.7152	40.6453	1.1960	3x5
SpARCS	XMM-67	34.9316	-5.5249	1.3000	5x3
GCLASS	J0035	8.9571	-43.2068	1.3350	5x3
SpARCS	CDFS-41	53.7649	-29.4822	1.3680	5x3
SpARCS	L-77	158.7060	58.3092	1.4000	5x3
SpARCS	L-100	158.3565	57.8900	1.4550	5x3
		Coma Progenitors			
SPT-CL	J0546-5345	86.5000	-53.9000	1.0670	5x3
SPT-CL	J2106-58	316.5000	-58.7300	1.1320	5x3
SPT-CL	J0205-5829	31.2500	-58.4800	1.3200	5x3



GOGREEN status

194.3h used over 5 semesters (44%)

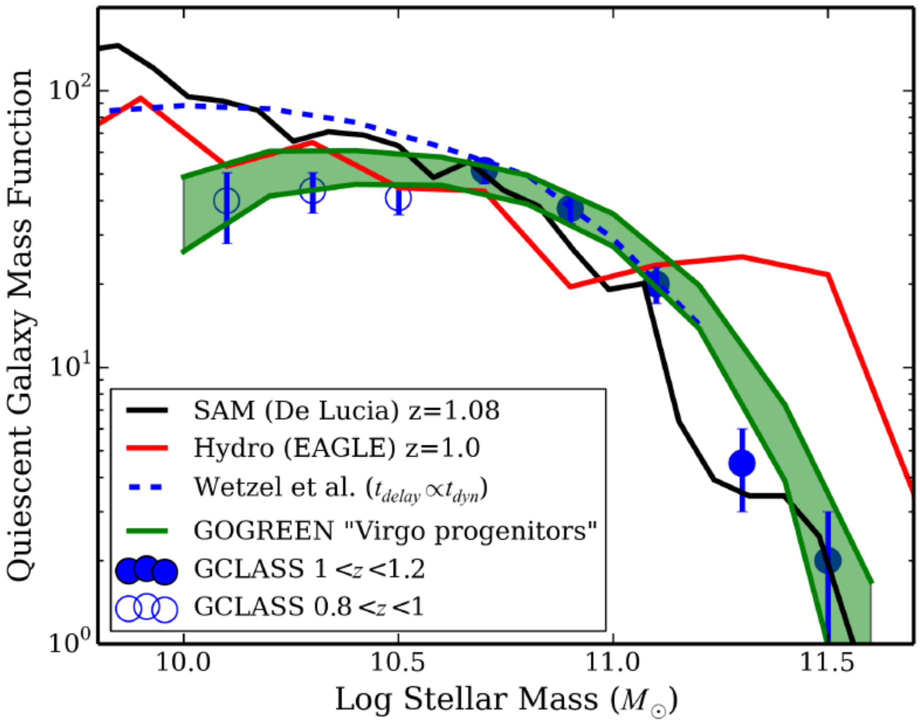
- Have acquired all the deep (AB=25, 5σ) z-band and optical imaging. All NIR except northern clusters
- Plus 35 masks of spectroscopy, ~600 spectra.

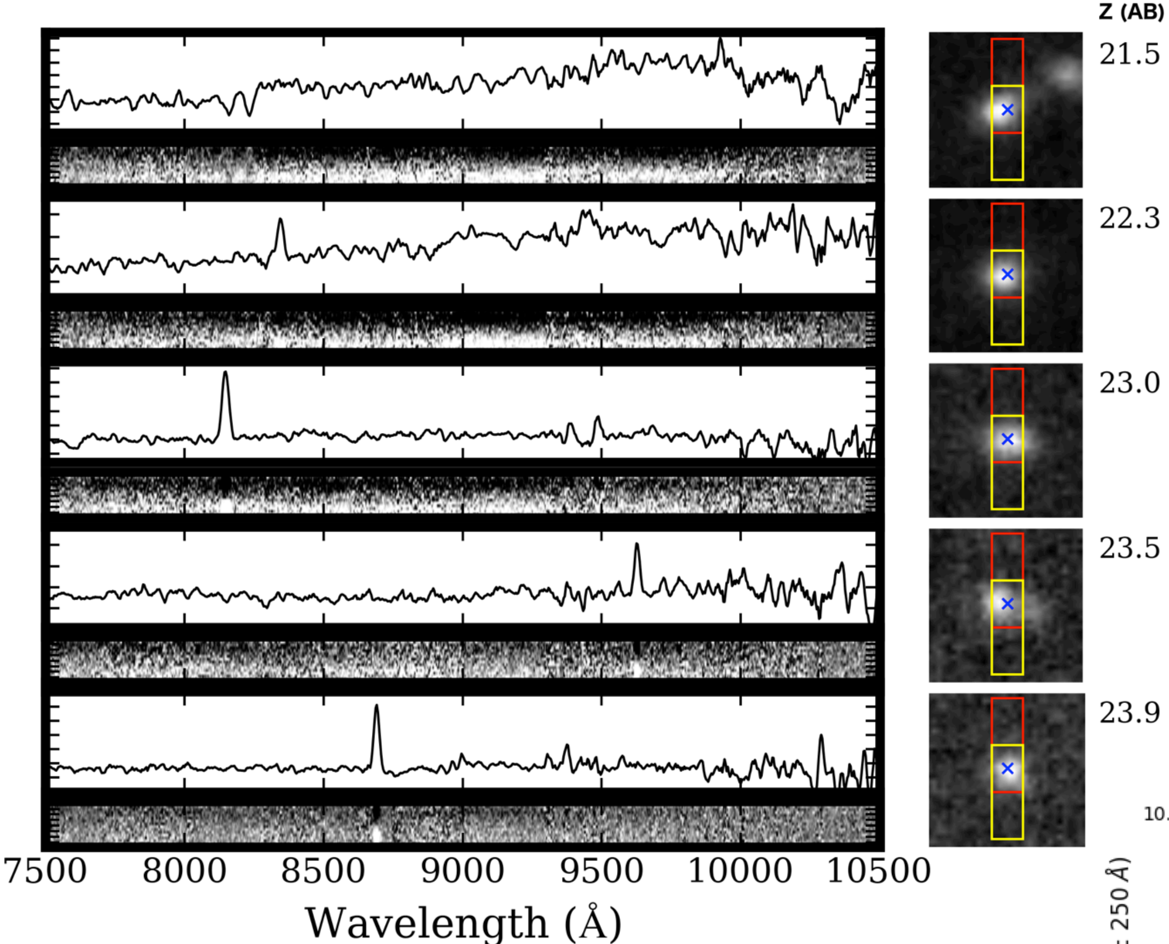


GOALS

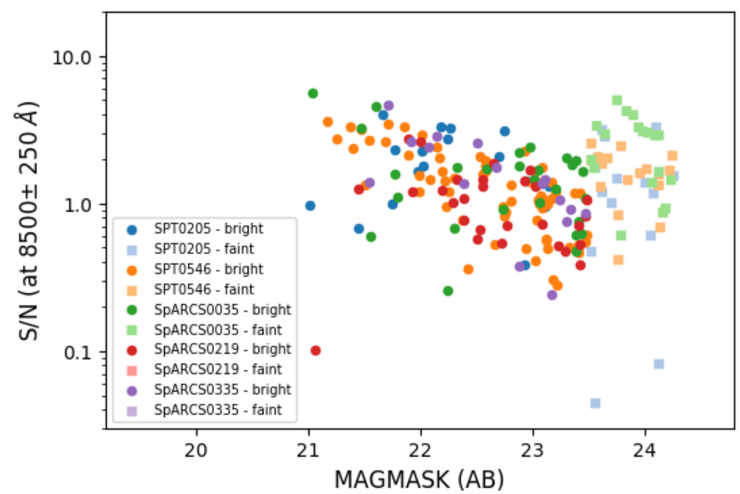
Expect to add ~700 confirmed cluster members, in 21 systems 1<z<1.5. Over 1000 when combined with existing data

- Most massive clusters will have >50 members; groups will have >20.
- Targets are selected to have z<24.25, with up to 15h integration on the faintest



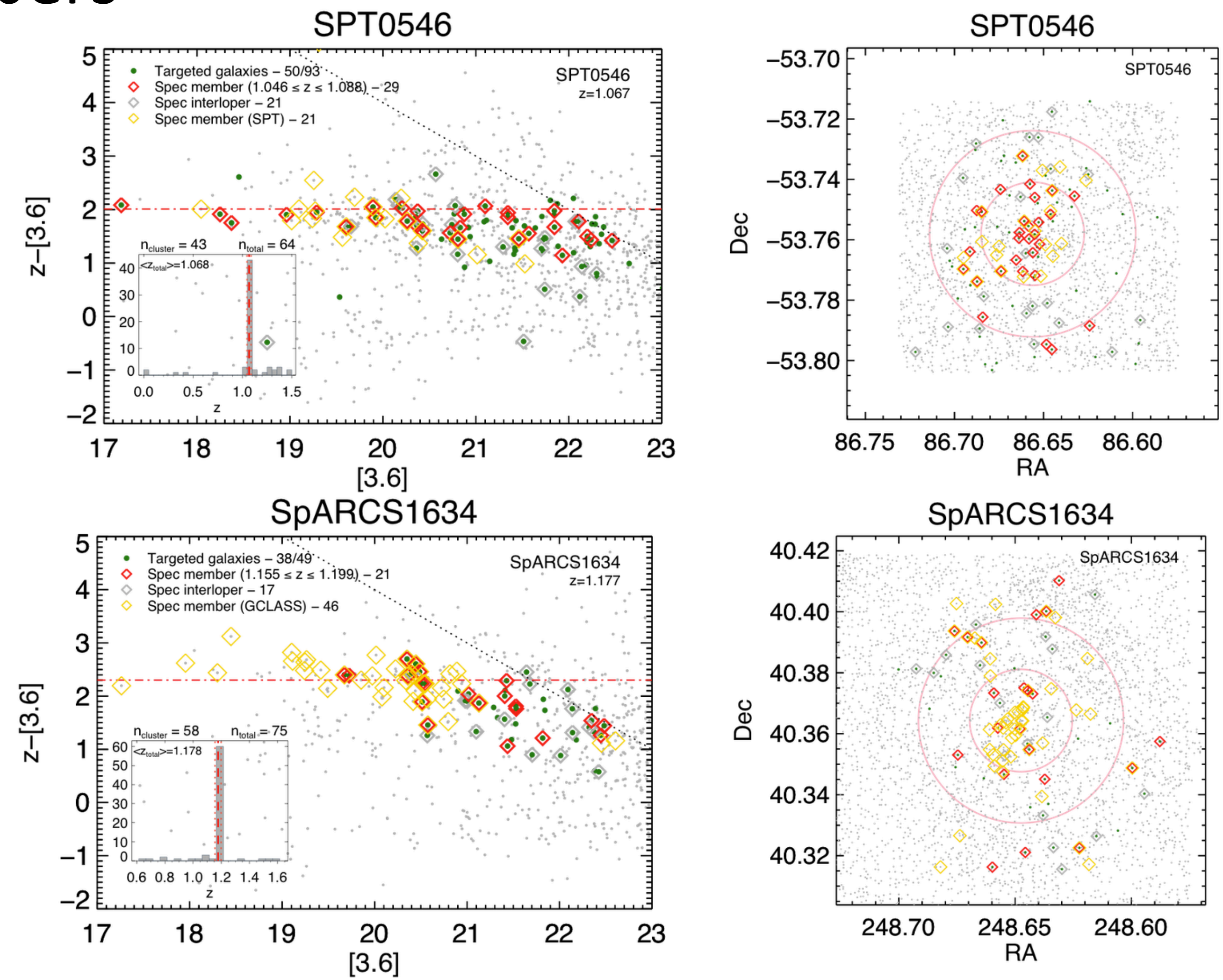


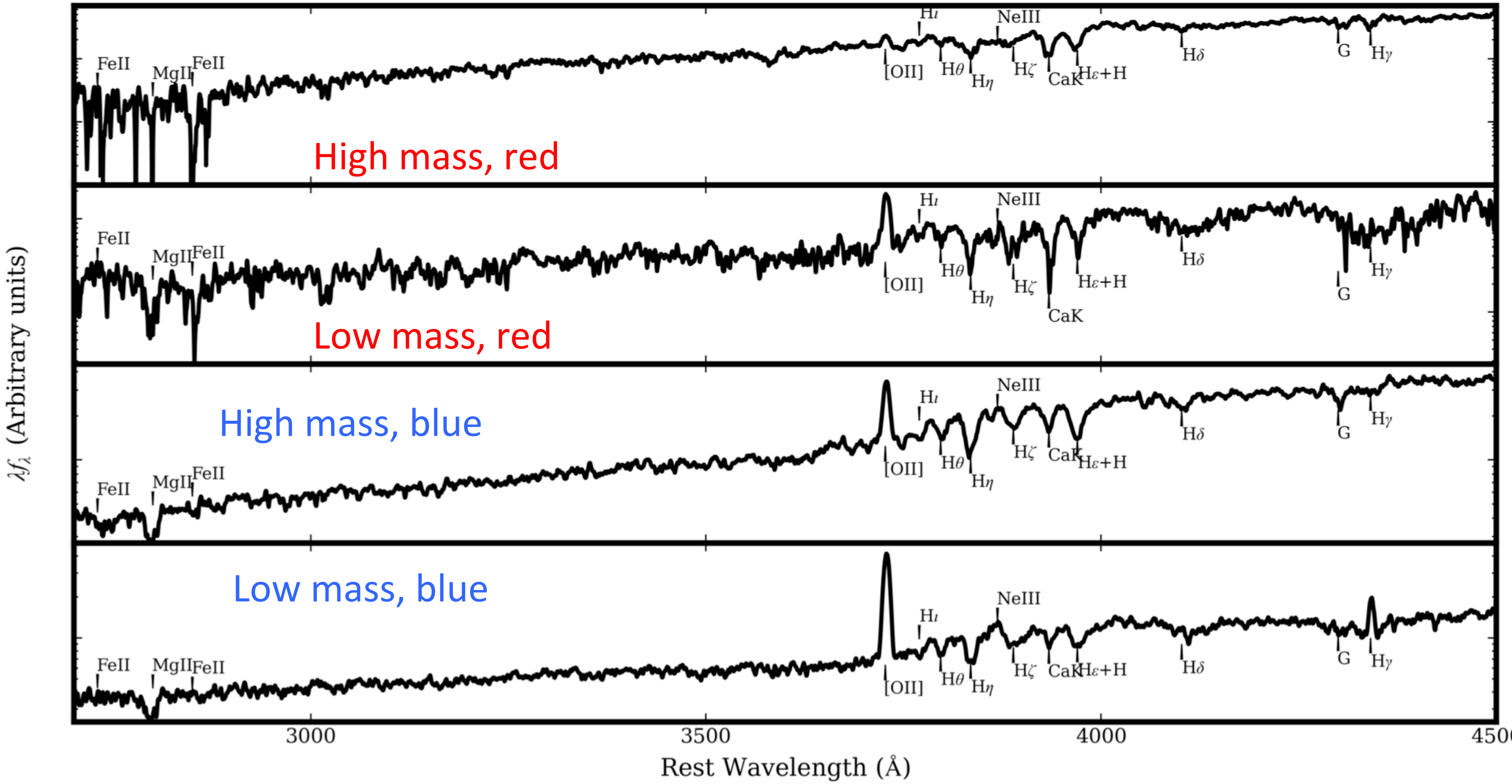
15h exposure times on the faintest galaxies, observed on multiple masks



Enabled by nod&shuffle with red-sensitive detectors

Combining with GCLASS, SPT, zCOSMOS redshifts as the bright end for a sample of >1000 cluster members





Spectra are low resolution (~440), but stacks by mass are high S/N, high resolution

Conclusions

1. At z=0, satellite quenching is likely dominated by dynamical effects: stripping, tidal disruption etc.
2. Average SFR evolves more strongly with dynamical time; at higher redshift overconsumption becomes dominant
3. Both the redshift and mass-dependence of t_{delay} suggest that $\eta \equiv \frac{\dot{M}_{out}}{\dot{M}_{*}} \sim 2$