LoCuSS: The slow quenching of star formation in cluster galaxies at z~0.2

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How long are ~L* spiral galaxies able to continue forming stars after they have been accreted into a massive galaxy cluster ?

Rapid quenching ($t_Q < 10^8$ yr)

Violent processes:
e.g. mergers, extreme ram-pressure stripping events

Slow quenching ($t_Q > 10^9$ yr) ?

Gentle processes:
e.g. starvation, incremental ram-pressure stripping

LoCuSS: The Local Cluster Substructure Survey

- Survey of 30 X-ray luminous clusters at $0.15<z<0.30$ from ROSAT All Sky Survey cluster catalogues ($M_{200} > 3\times10^{14}\,M_\odot$; Okabe *et al.* 2010)

- *Spitzer* 24μm maps over 25′x25′ (2-3r_{200}) => obscured star formation

  $SFR(M_\odot yr^{-1}) = 7.8\times10^{-10}\, L(24\mu m, L_\odot)$ (Rieke *et al.* 2009)

- Deep GALEX NUV data for 23/30 clusters => unobscured SF

- *Chandra/XMM* X-ray data => $\rho_{ICM}(r)$ and r_{500} for each cluster

  $r_{200} \approx 1.50\, r_{500}$ (Sanderson & Ponman 2003)

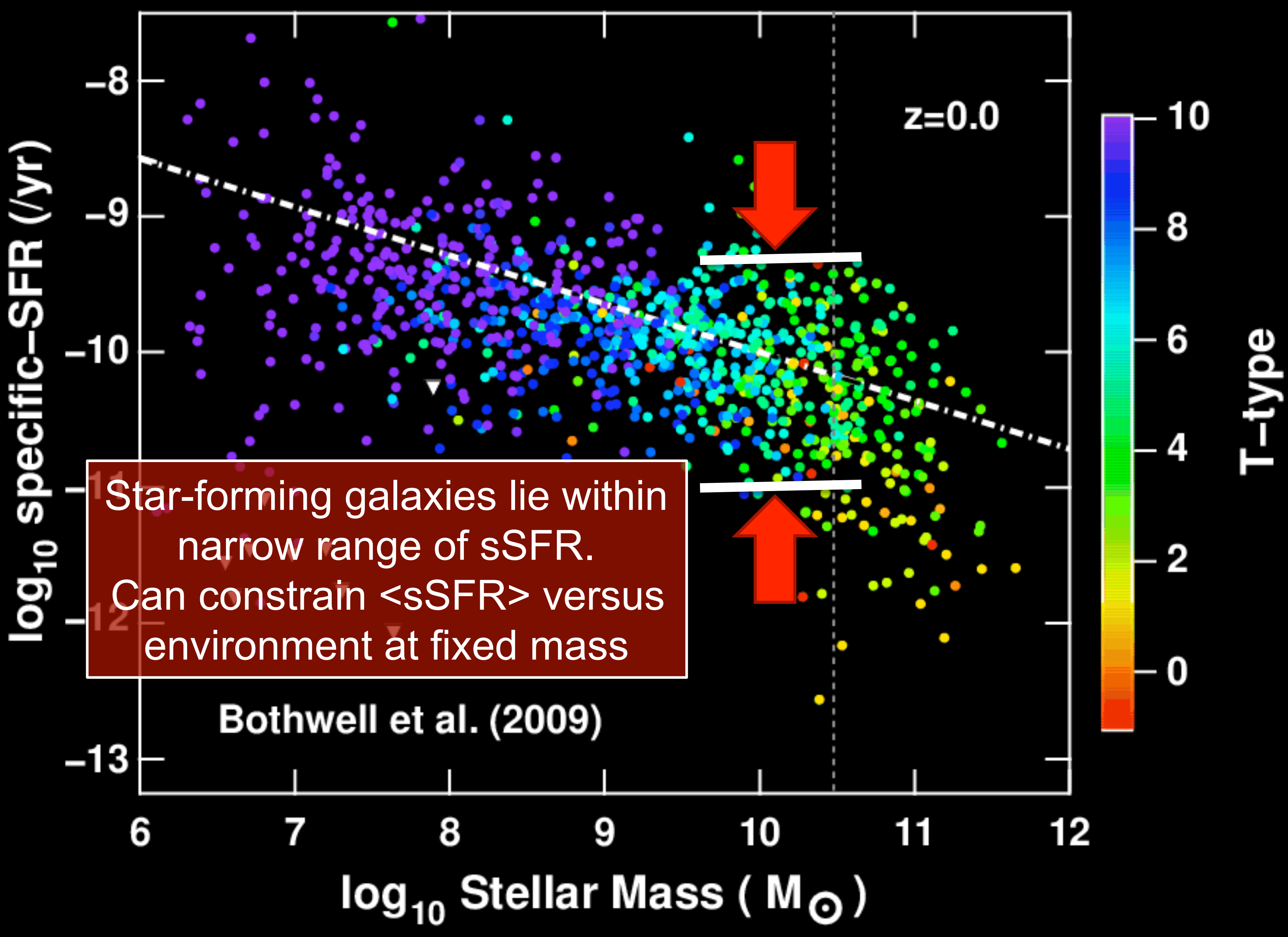
  Identify X-ray AGN as point sources in *Chandra* data

- Wide field *J,K* and optical imaging (stellar masses, photo-z)

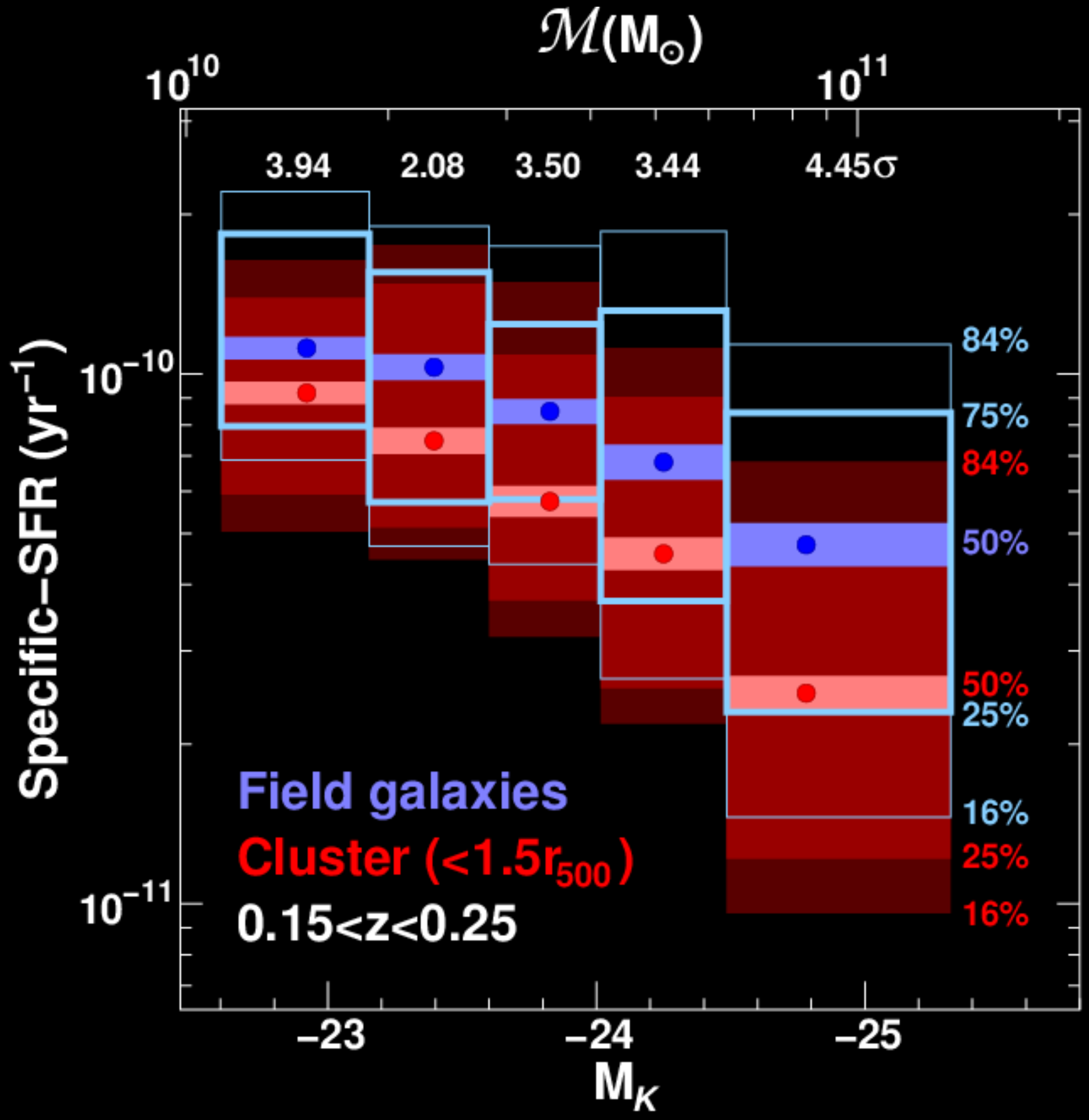
ACReS: Arizona Cluster Redshift Survey

- ACReS : Long term survey program with Hectospec on the 6.5m MMT obtaining spectra over 1-deg field for each cluster, providing ~24,000 redshifts, including 10,950 cluster members (126-1083 per cluster)
- K-band selected, reaching K*(z)+2.0 for each cluster => approximate stellar mass selection with $M_* > 10^{10} M_\odot$
- Prioritize 24μm-detected sources to provide complete census of obscured star-formation down to 2 $M_\odot$ yr^{-1}.
- 96.4% complete for cluster galaxies detected at 24μm
- 80% complete for overall cluster population to K*+1.5
- Obtain coeval field galaxy sample by considering narrow redshift slices either side of each cluster for which survey is still complete

LoCuSS: The main sequence of star-forming galaxies



Comparison of cluster and field sSFRs at fixed stellar mass

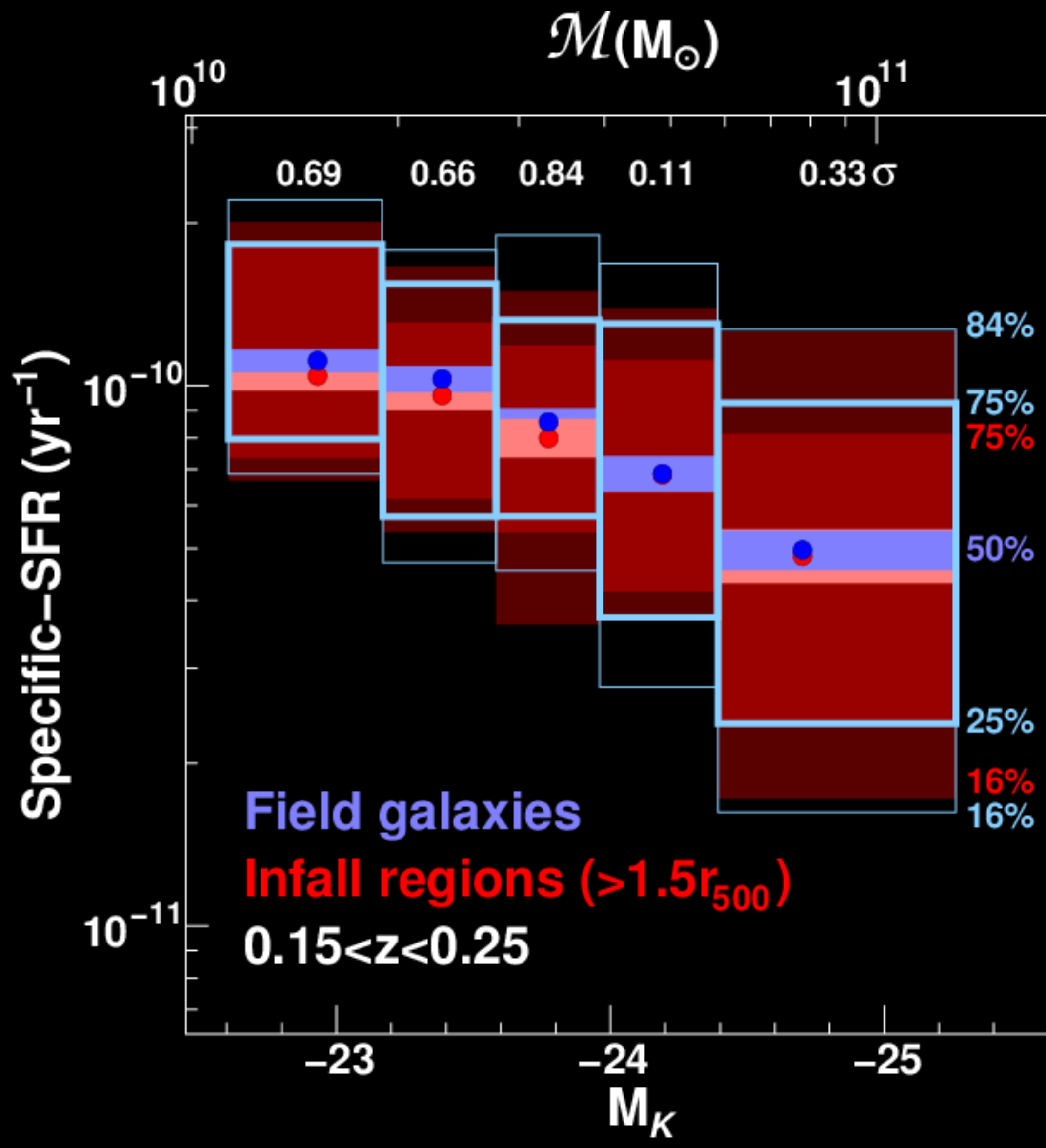


The sSFRs of star-forming galaxies in clusters ($r_{proj}<r_{200}$) are *systematically* 30% lower than star-forming field galaxies of the same stellar mass and redshift (8.7σ significance)

Does this reduction in sSFRs extend beyond r_{200} and into the cluster infall regions ?

Haines et al. (2013), ApJ, 775, 126

Comparison of cluster infall region and field sSFRs



No, the sSFRs of star-forming galaxies in the infall regions of clusters are indistinguishable from those in the field.

The systematic reduction of sSFRs appears to be a cluster-specific phenomenon

Haines et al. (2013), ApJ, 775, 126

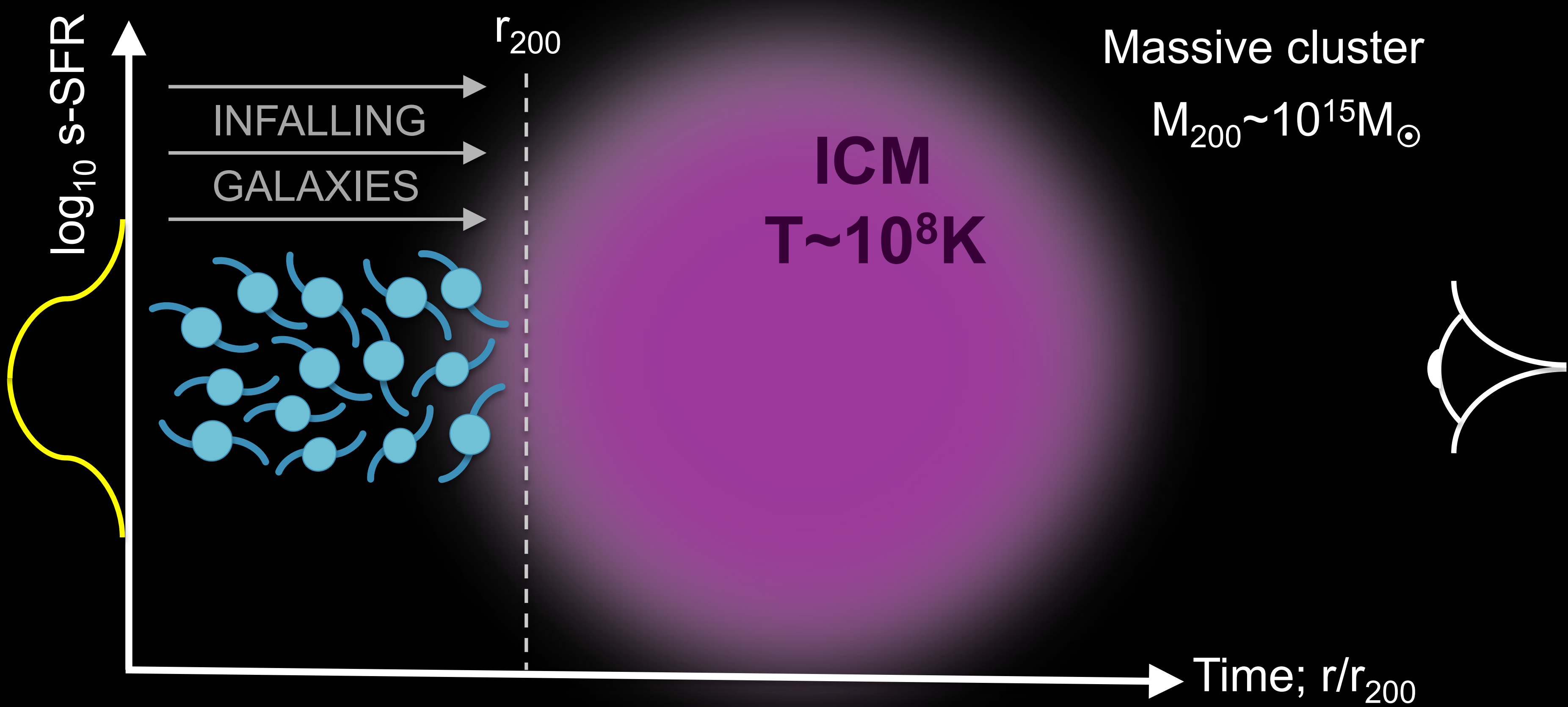
The systematic reduction in sSFRs suggests that many if not most of the star-forming galaxies in clusters are observed <u>in</u> <u>the</u> <u>process</u> <u>of</u> being quenched

This implies that the quenching is a long, slow process

How can we estimate this quenching time-scale?

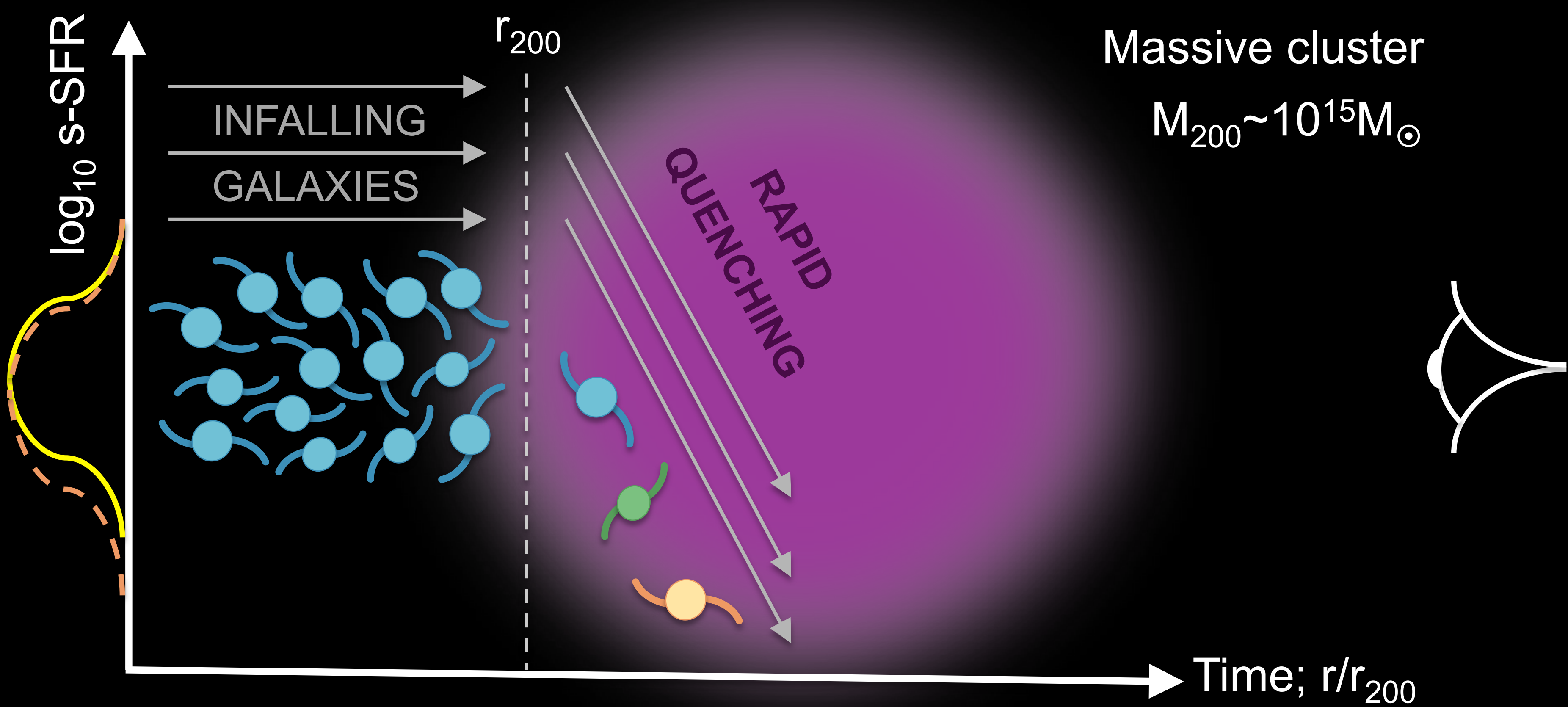
LoCuSS: The infall of galaxies onto clusters

- In a ΛCDM Universe, star-forming galaxies are continually being accreted onto clusters from the surrounding infall regions. Their specific-SFRs should be the same as coeval field galaxies.



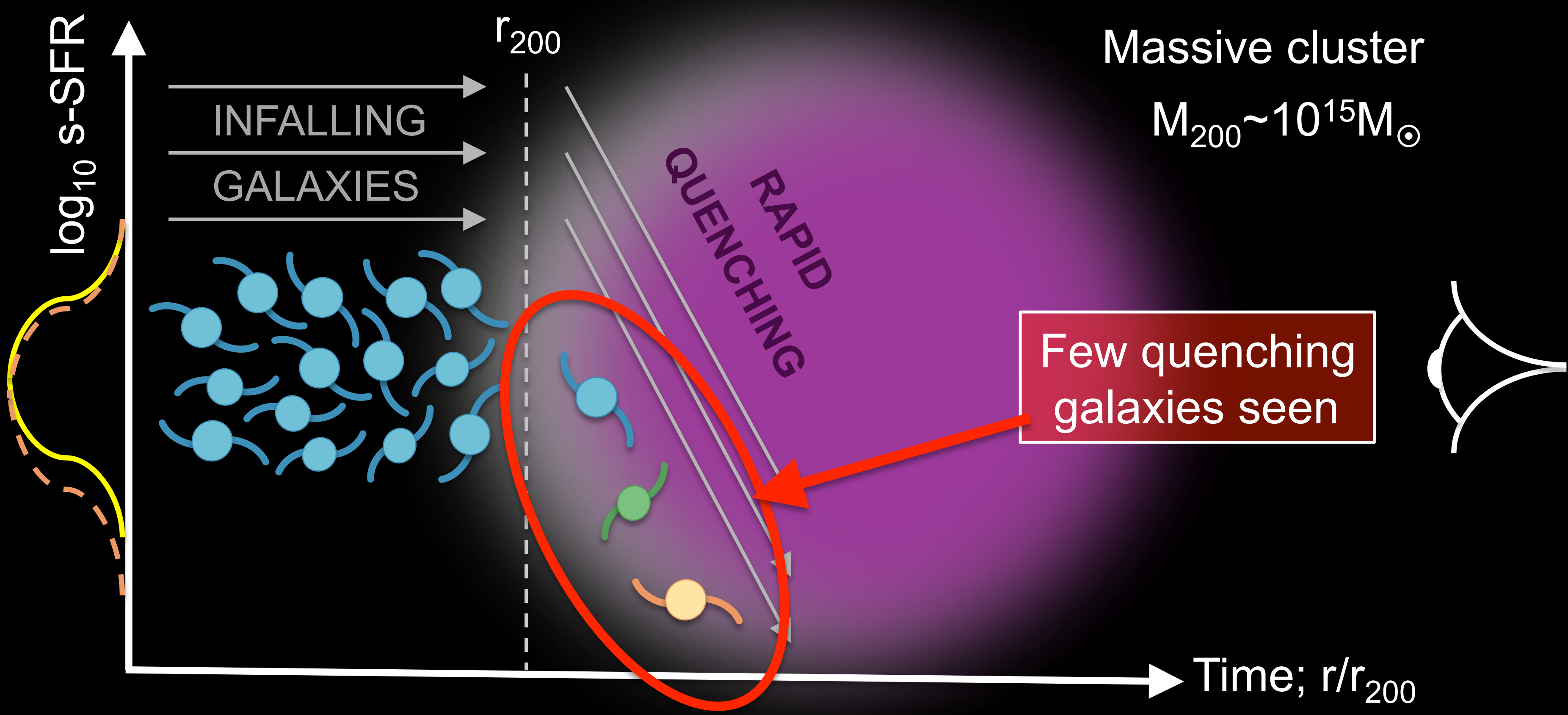
LoCuSS: Rapid quenching of star formation

- If star-formation is quenched rapidly (<10^8 yr) when galaxies are accreted into clusters...



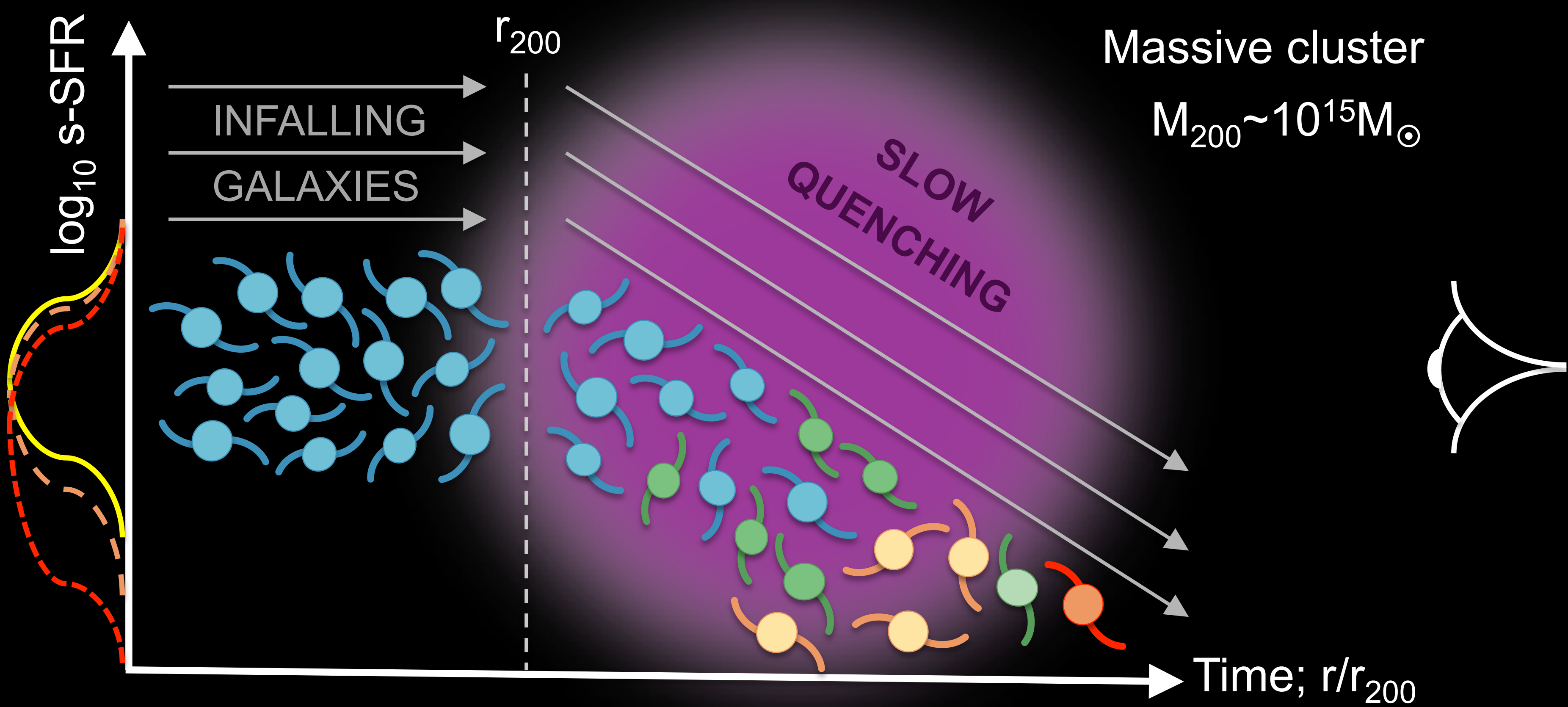
LoCuSS: Rapid quenching of star formation

- If star-formation is quenched rapidly ($<10^8$ yr) when galaxies are accreted into clusters, we will see *few* cluster galaxies *in the process of* being quenched, leaving the specific-SFR distribution almost unaltered



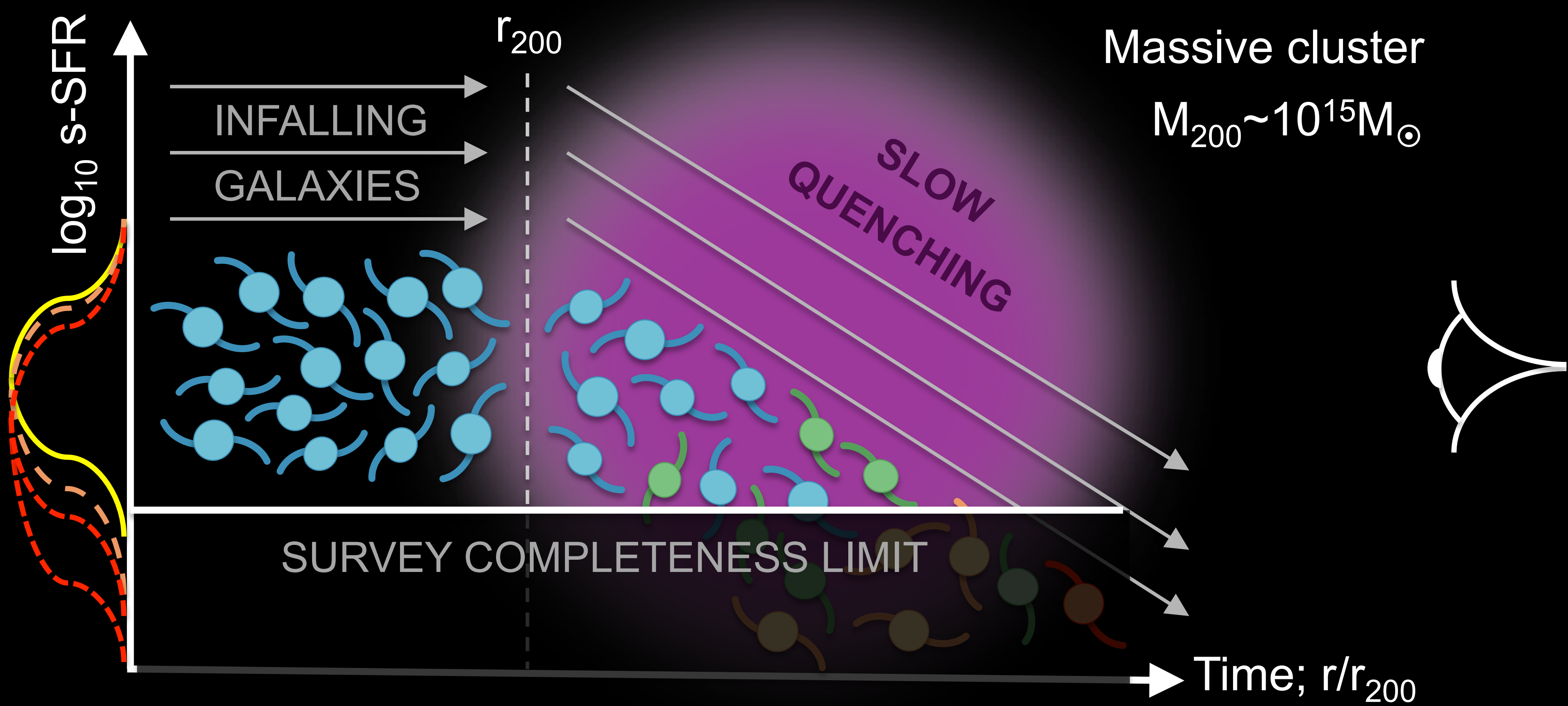
LoCuSS: Slow quenching of star formation

- If instead the quenching occurs slowly over $>10^9$ yr time-scales, we should see *many* cluster galaxies *in the process of* being quenched, with *reduced* s-SFRs, *skewing* the overall s-SFR distribution downwards



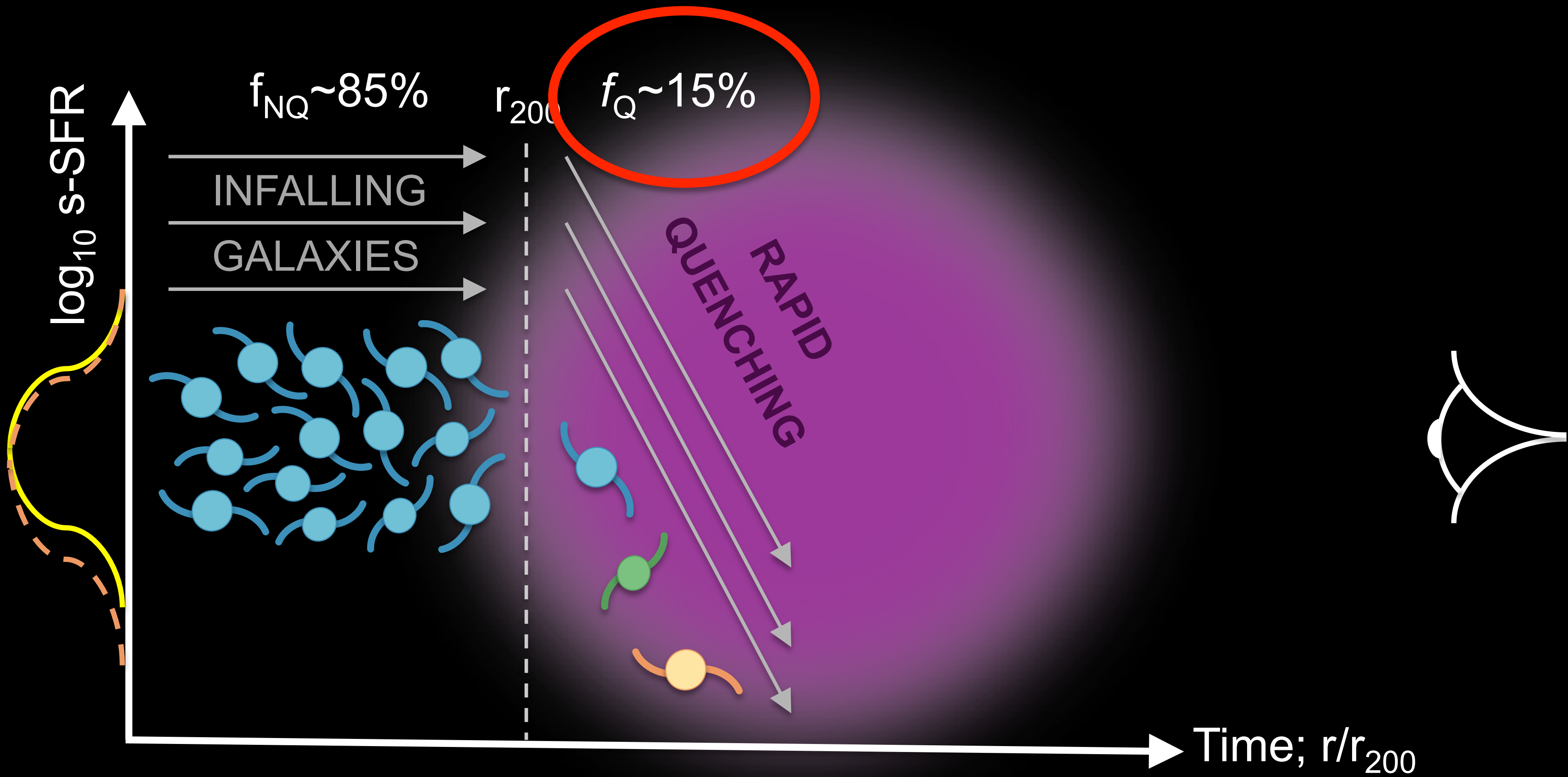
LoCuSS: The effect of a decrease in sensitivity

- The level of skewing and number of quenching galaxies depends on the depth of the SFR completeness limit relative to the SF main sequence. Both are reduced as the survey becomes shallower...



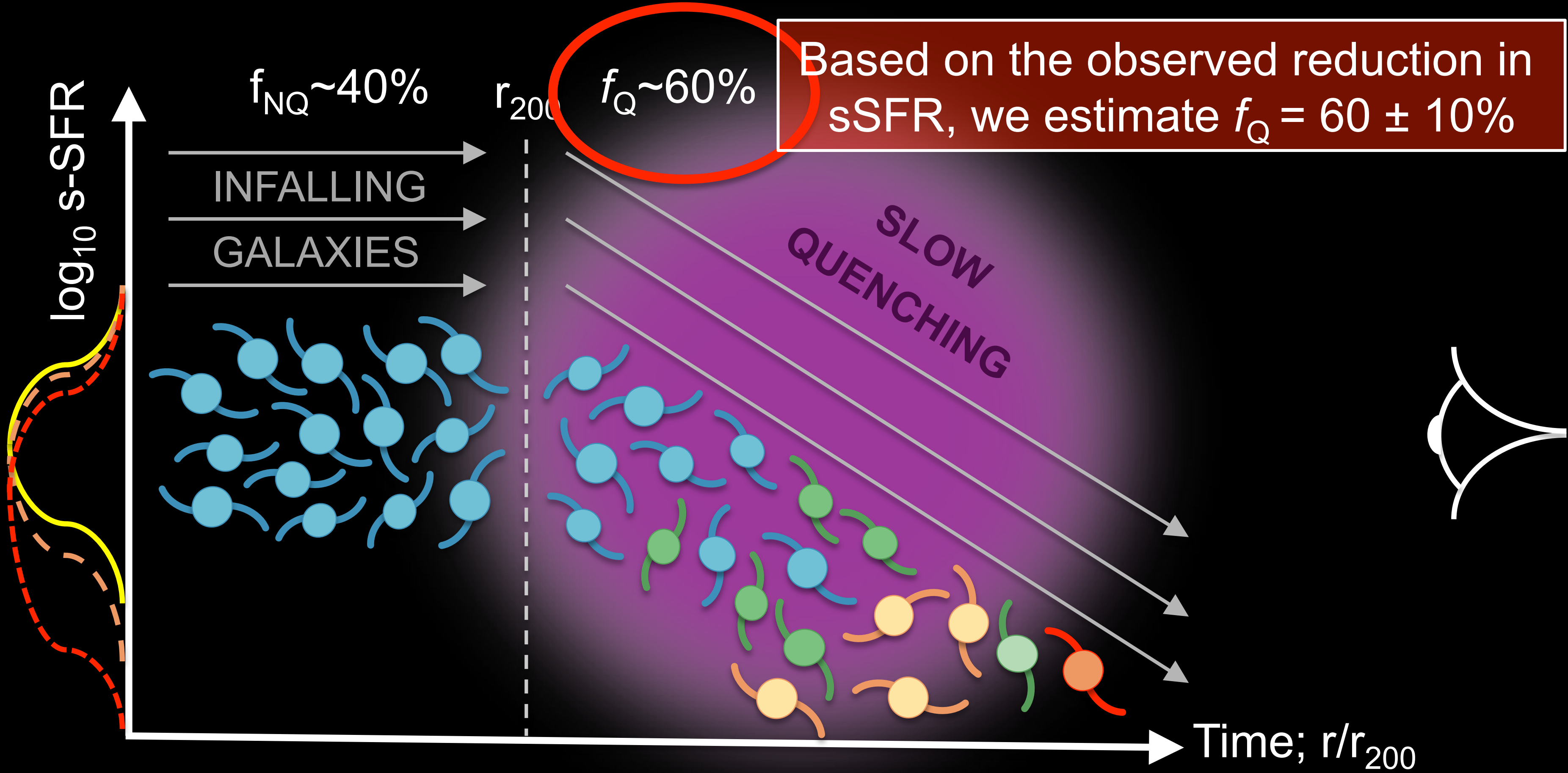
LoCuSS: Rapid quenching of star formation

- The fraction of star-forming cluster galaxies observed while being quenched, $f_{Q,}$ increases roughly linearly with the quenching time-scale t_Q



LoCuSS: Slow quenching of star formation

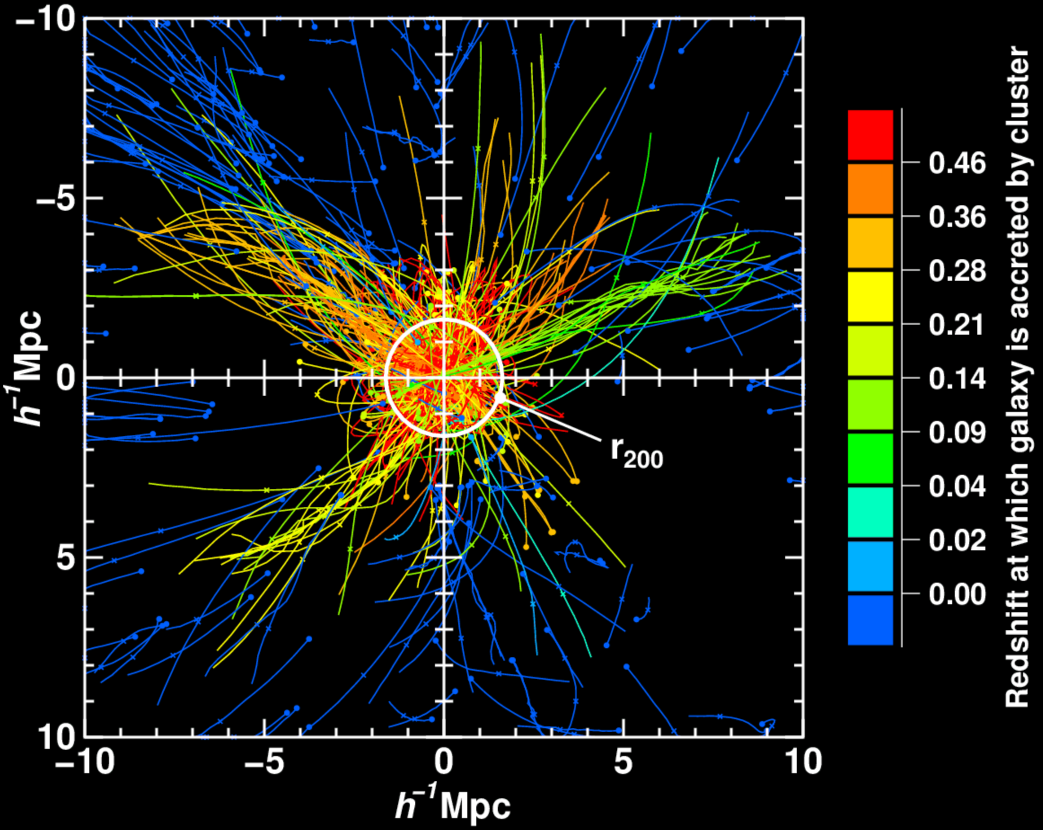
- …and thus should provide a way of estimating the typical e-folding quenching time t_Q of star-forming galaxies when they are accreted



To convert f_Q into a quenching time-scale, we need to use cosmological simulations to follow how star-forming galaxies are accreted into clusters

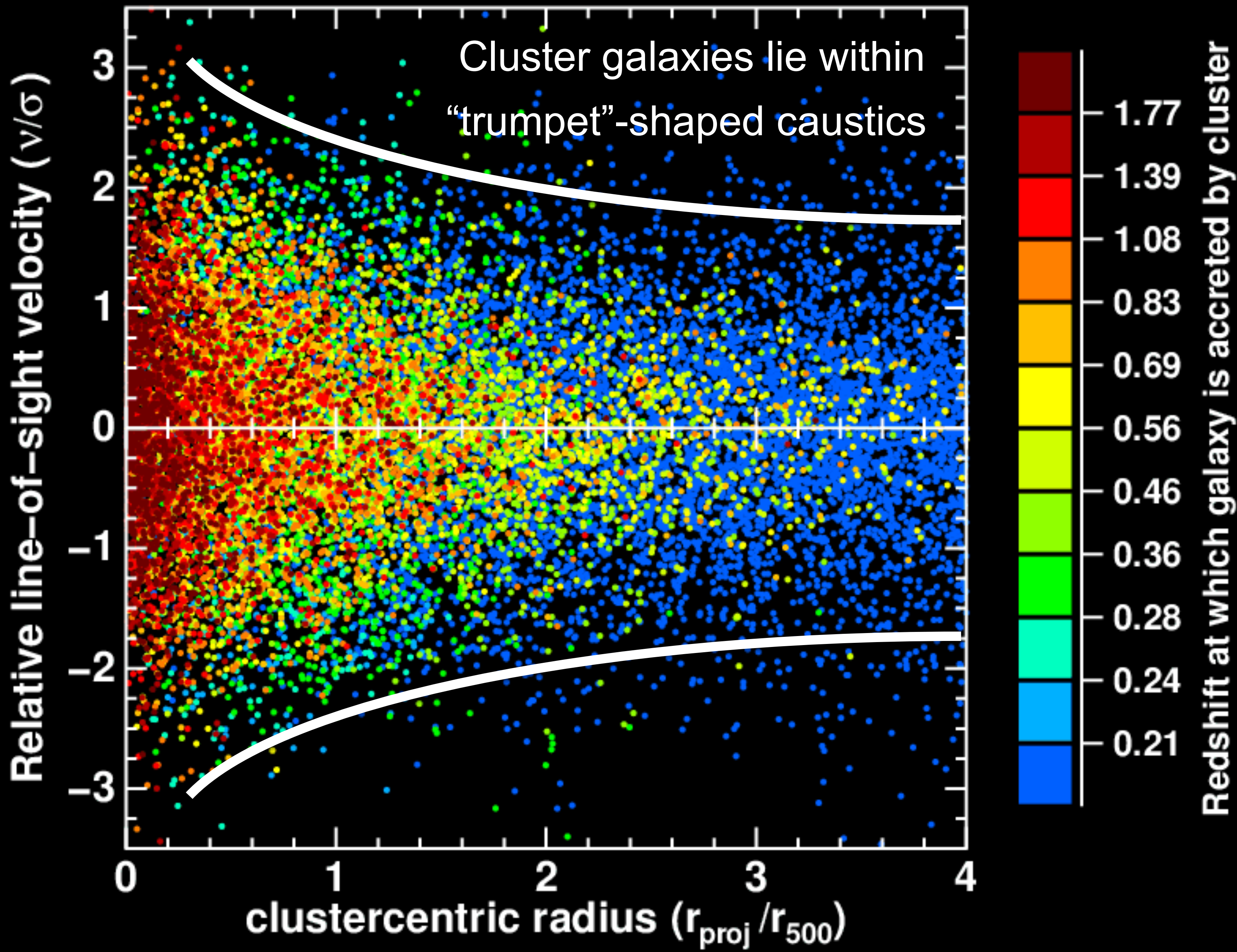
LoCuSS: Millennium simulation

- Need to place clusters in the cosmological context of continually accreting galaxies and groups from the surrounding large-scale structure
- The Millennium DM-only cosmological simulation covers ($500h^{-1}$Mpc)^3 contains many massive clusters, while SAMs populate the DM halos with galaxies
- Database gives positions, masses, velocities of galaxies, halos at 63 snapshots



- Extract volumes around the 75 most massive clusters at z=0
- Follow the orbits of galaxies around each cluster halo to determine $z_{acc}(<r_{200})$, vel(z)
- Create “observations” of each cluster for a distant observer along z-axis, including all galaxies projected along the line-of-sight
- Stack all 75 systems (scaling by r_{200}, σ) to reduce impact of cluster-to-cluster scatter

Simulations: Redshift-space of cluster galaxies



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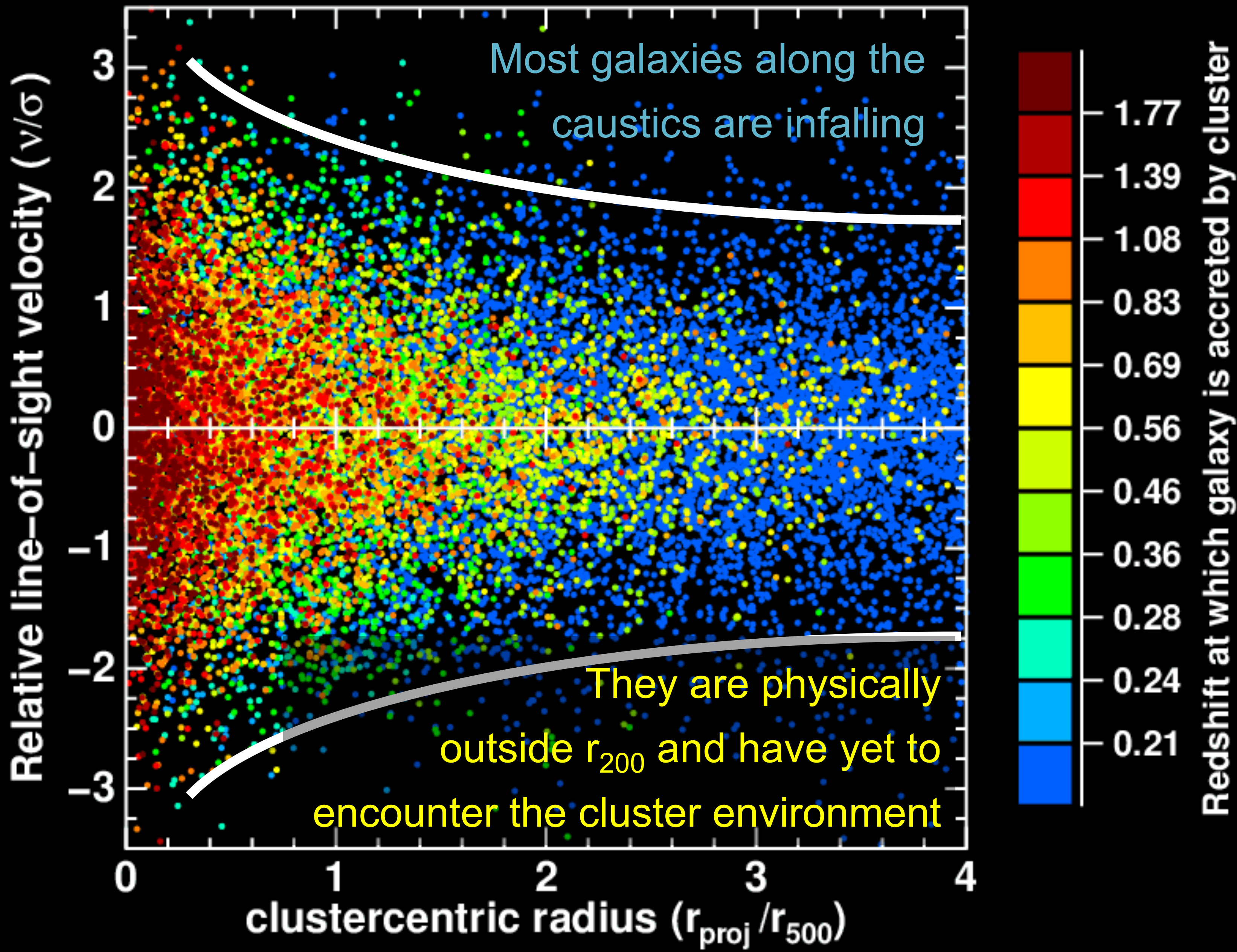

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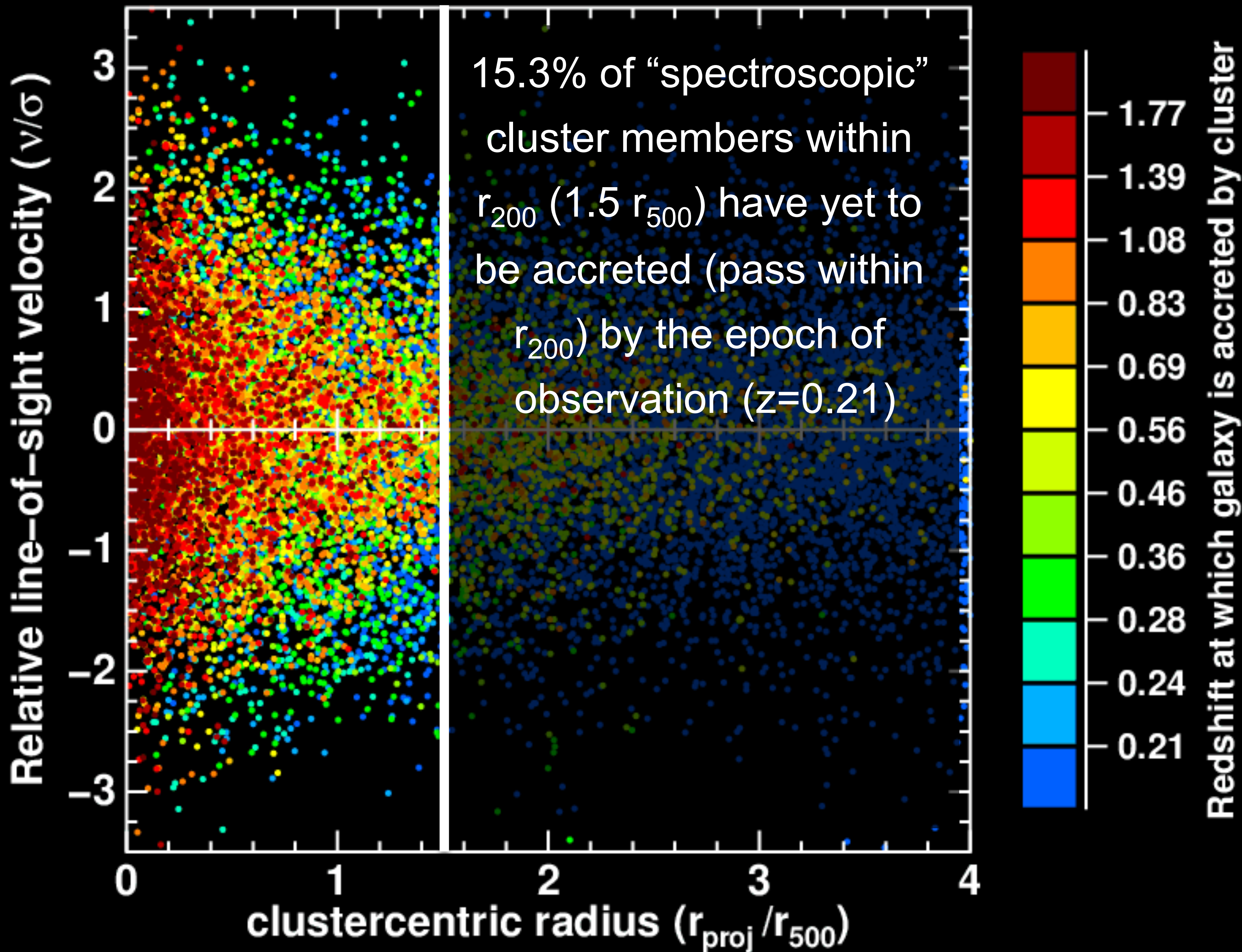
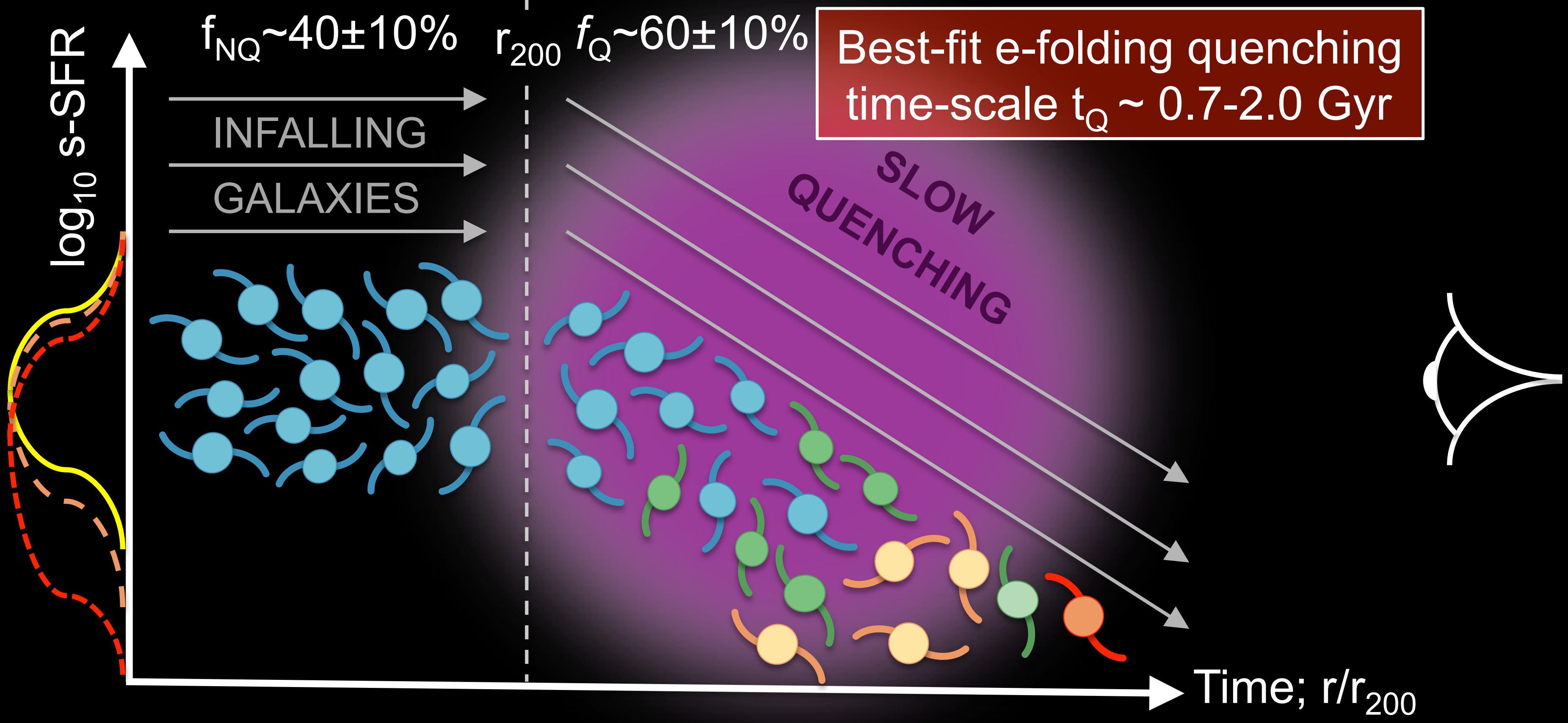


LoCuSS: An estimate for t_Q

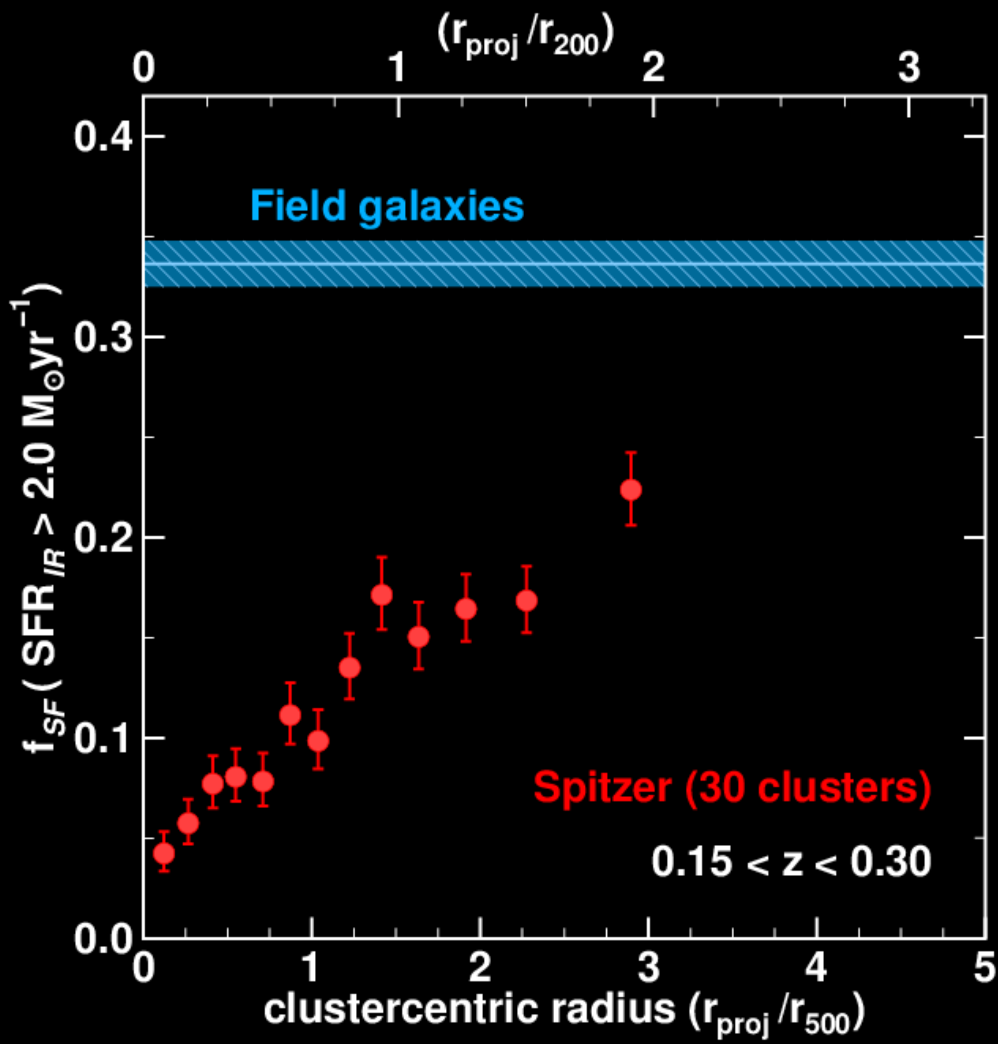
15.3% of “spectroscopic” cluster members at $r_{proj}<1.5r_{500}$ that are yet to be accreted

The 22.9% of “spectroscopic” cluster members at $r_{proj}<1.5r_{500}$ that were most recently accreted into the cluster



Haines et al. (2013), ApJ, 775, 126

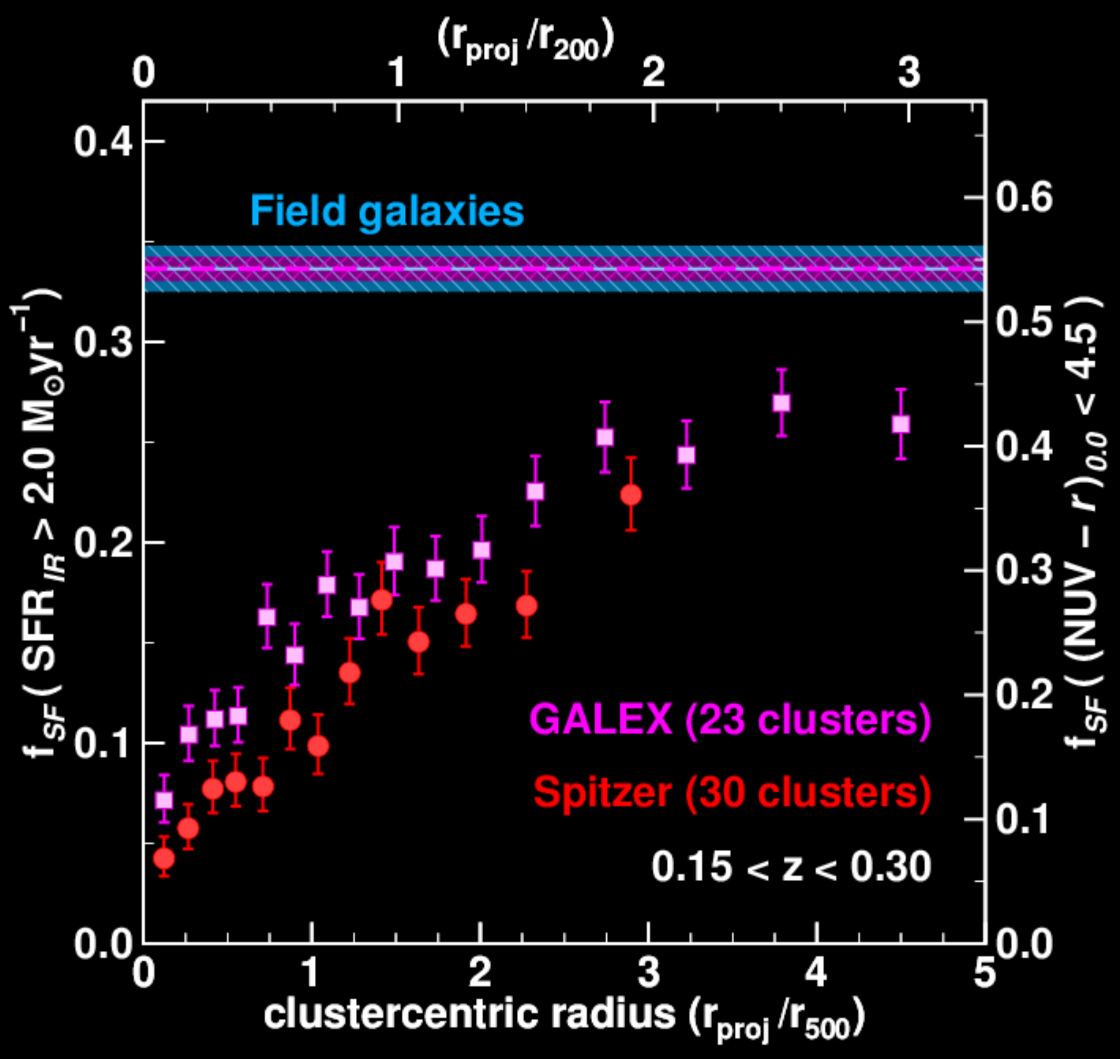
Results: The observed SF-radius relation



The f_{SF} increases steadily with radius out to 2 r_{200}

Star forming galaxies are found at all radii, even the very cores of clusters

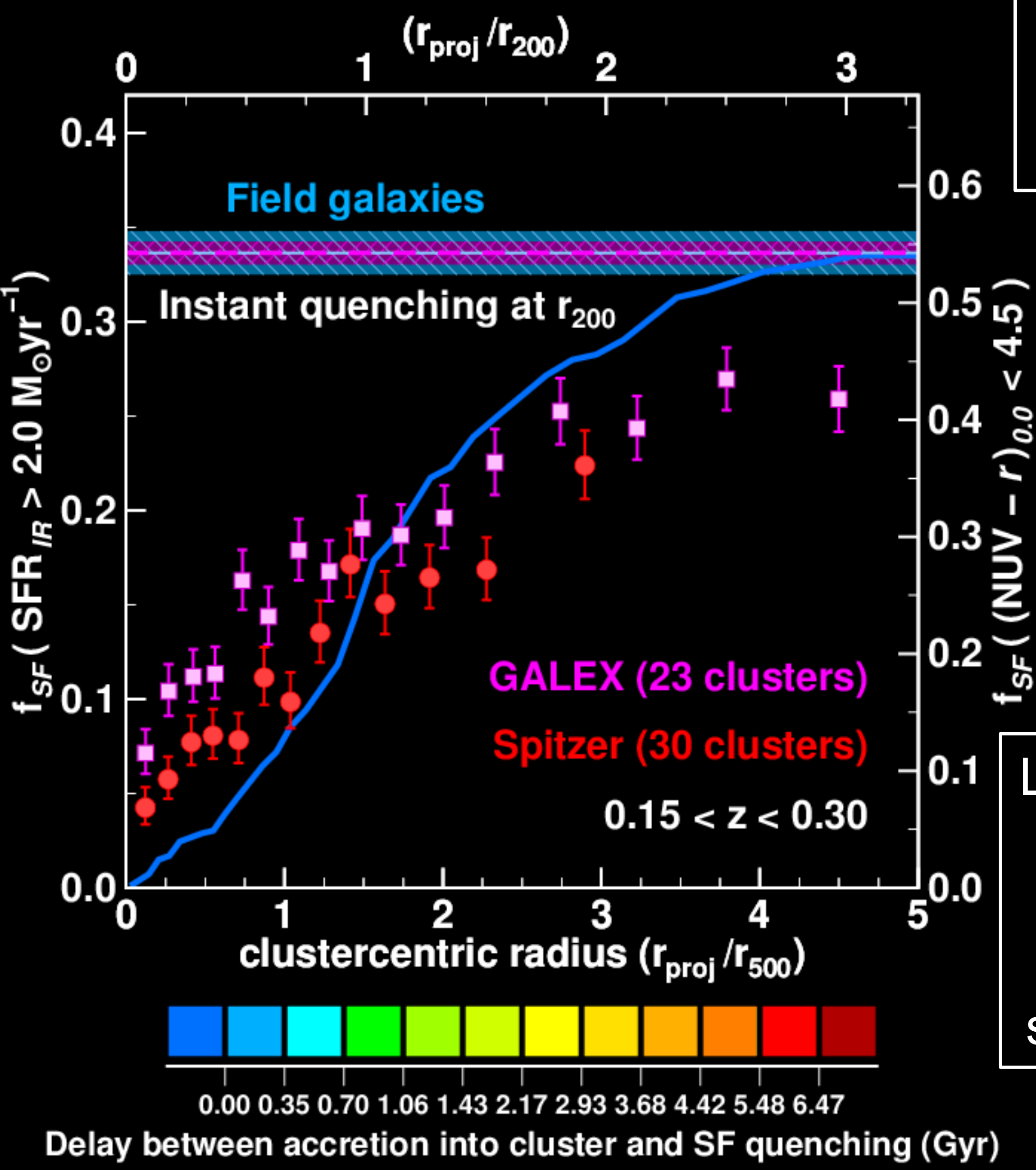
Results: The observed SF-radius relation



GALEX UV data provides a complementary selection of star-forming galaxies for 23 out of our 30 clusters

Even out at 3 r_{200}, the f_{SF} remains well below that seen in the coeval field population

Results: Modelling the SF-radius relation

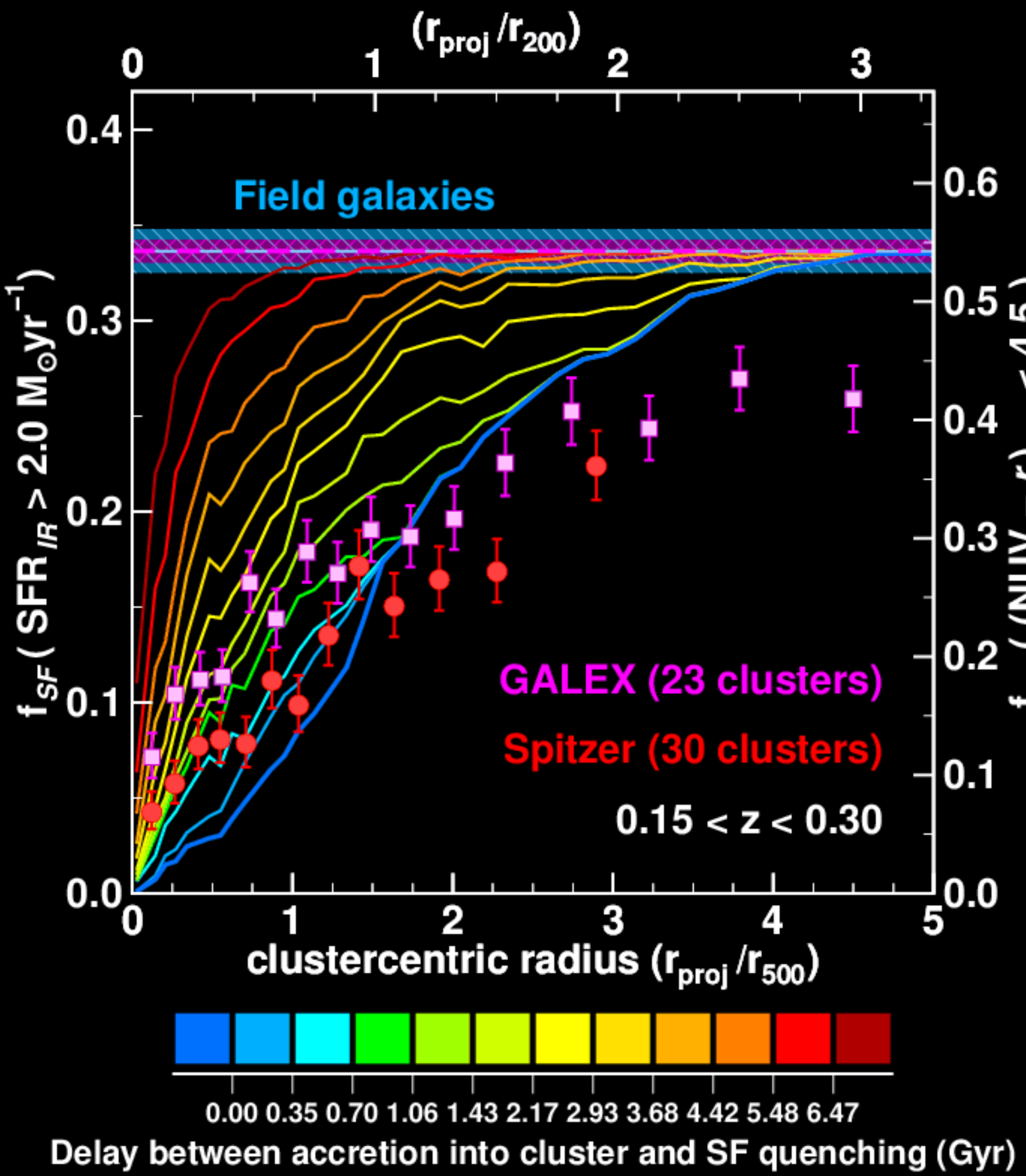


Use Millennium simulation to predict SF-radius relation for the 75 most massive clusters

Simplest model: Assume infalling galaxies have the same f_{SF} as our coeval field population, and are instantaneously quenched upon passing within r_{200} for the first time

Linear trend extending to 3 r_{200} shaped by contribution from “back-splash” galaxies, is qualitatively similar but much steeper than observed relation

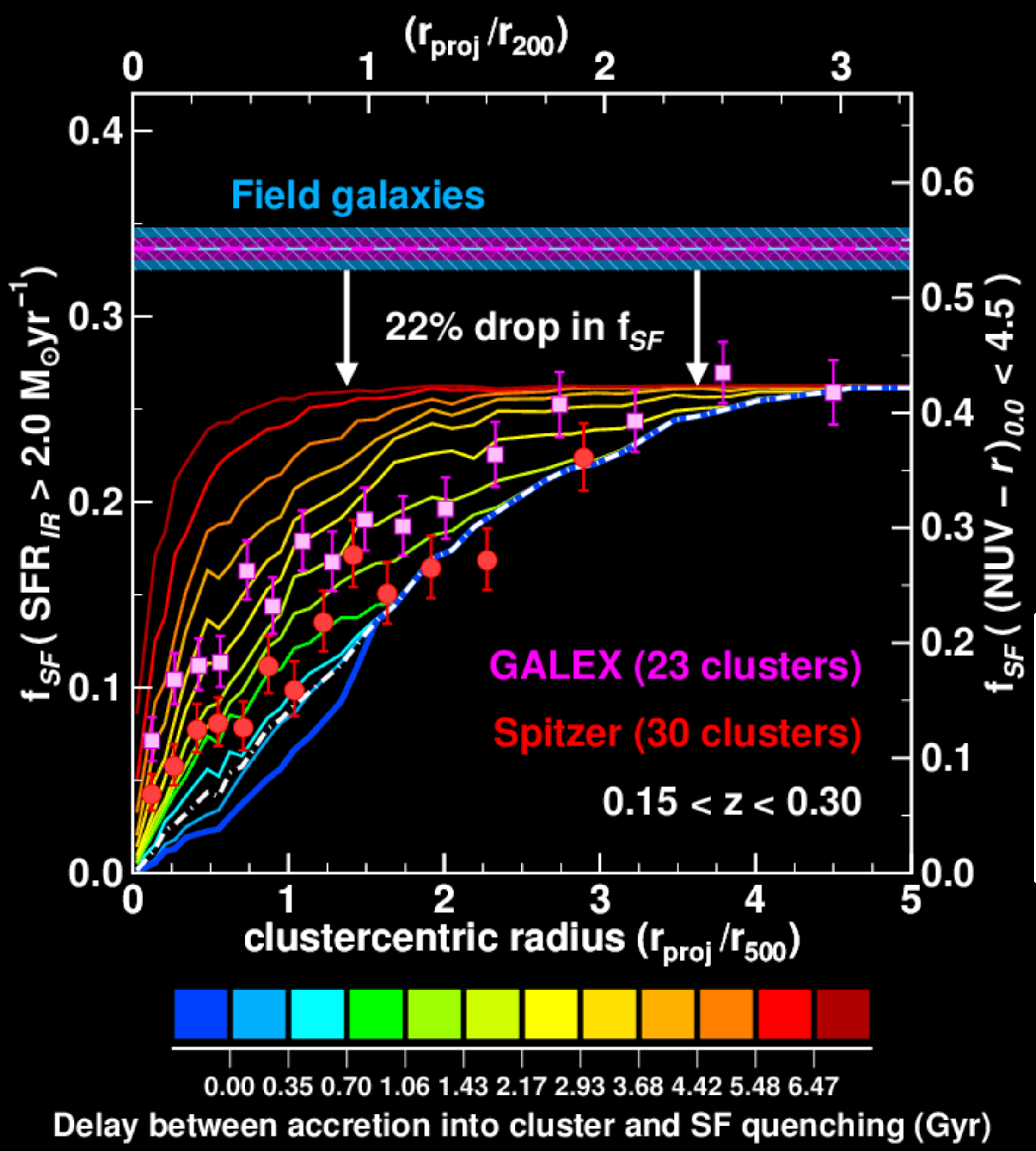
Results: Modelling the SF-radius relation



Delayed quenching models: The star formation in infalling SF galaxies is rapidly quenched, but only after a delay of Δt Gyr after passing within r_{200}

A short delay of 0.7-2.2 Gyr is able to reproduce the f_{SF} in the cluster cores, but no model can fit the shortfall of star-forming galaxies at large radii (r_{proj} > 2 r_{200})

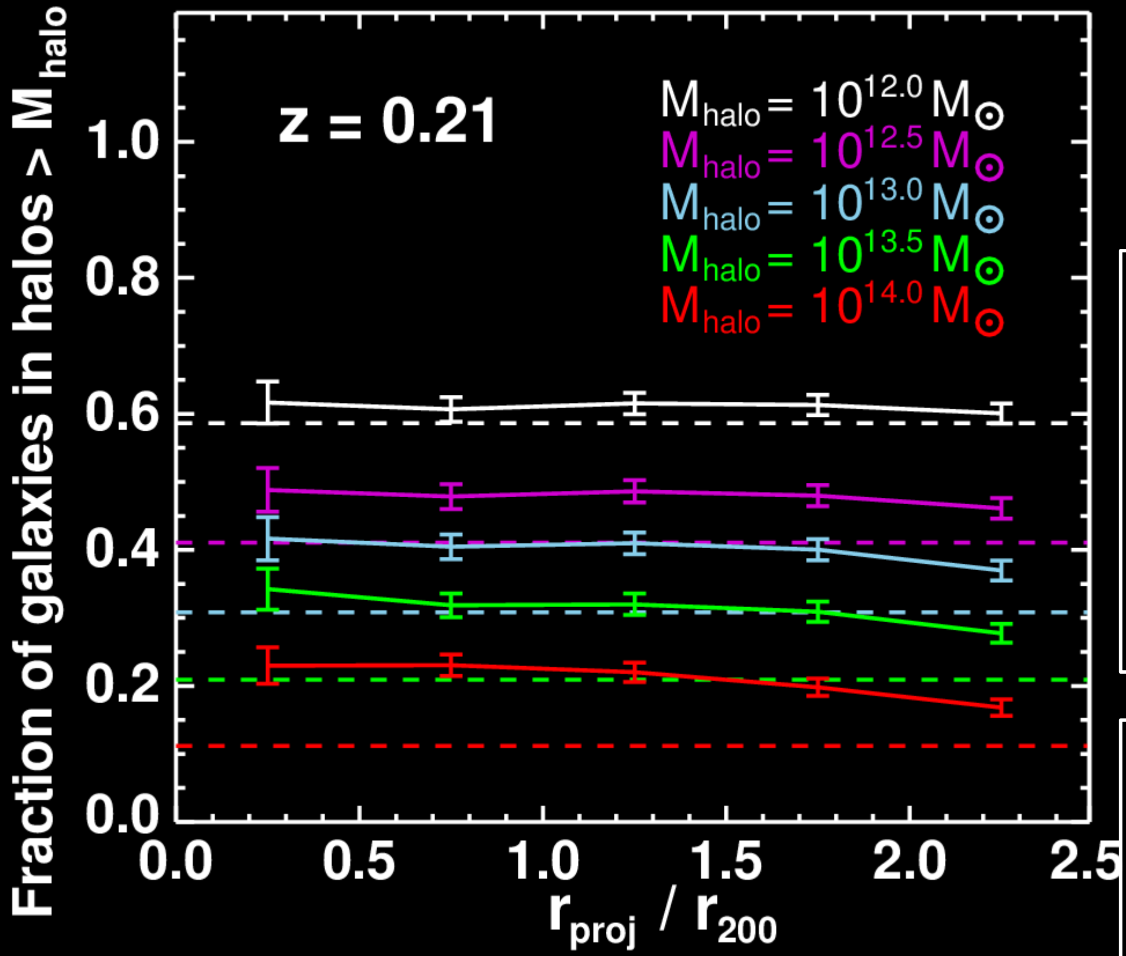
Results: Modelling the SF-radius relation



Pre-processing models:
To reproduce observations, the f_{SF} of the galaxies arriving onto the cluster must be lower than that of the coeval field population

Evidence for pre-processing in galaxy groups prior to their arrival into massive clusters?

Results: Increased scope for pre-processing in groups



Accretion bias: The halo mass function near clusters will be biased to higher masses than average

We measure the mass function of halos hosting ~L* galaxies in the infall regions of clusters (not including those galaxies already accreted into the cluster)

Galaxies infalling into clusters are more likely to already be hosted in group-mass halos than coeval field galaxies of the same stellar mass, and being pre-processed

Results: The ongoing assembly of Abell 1763

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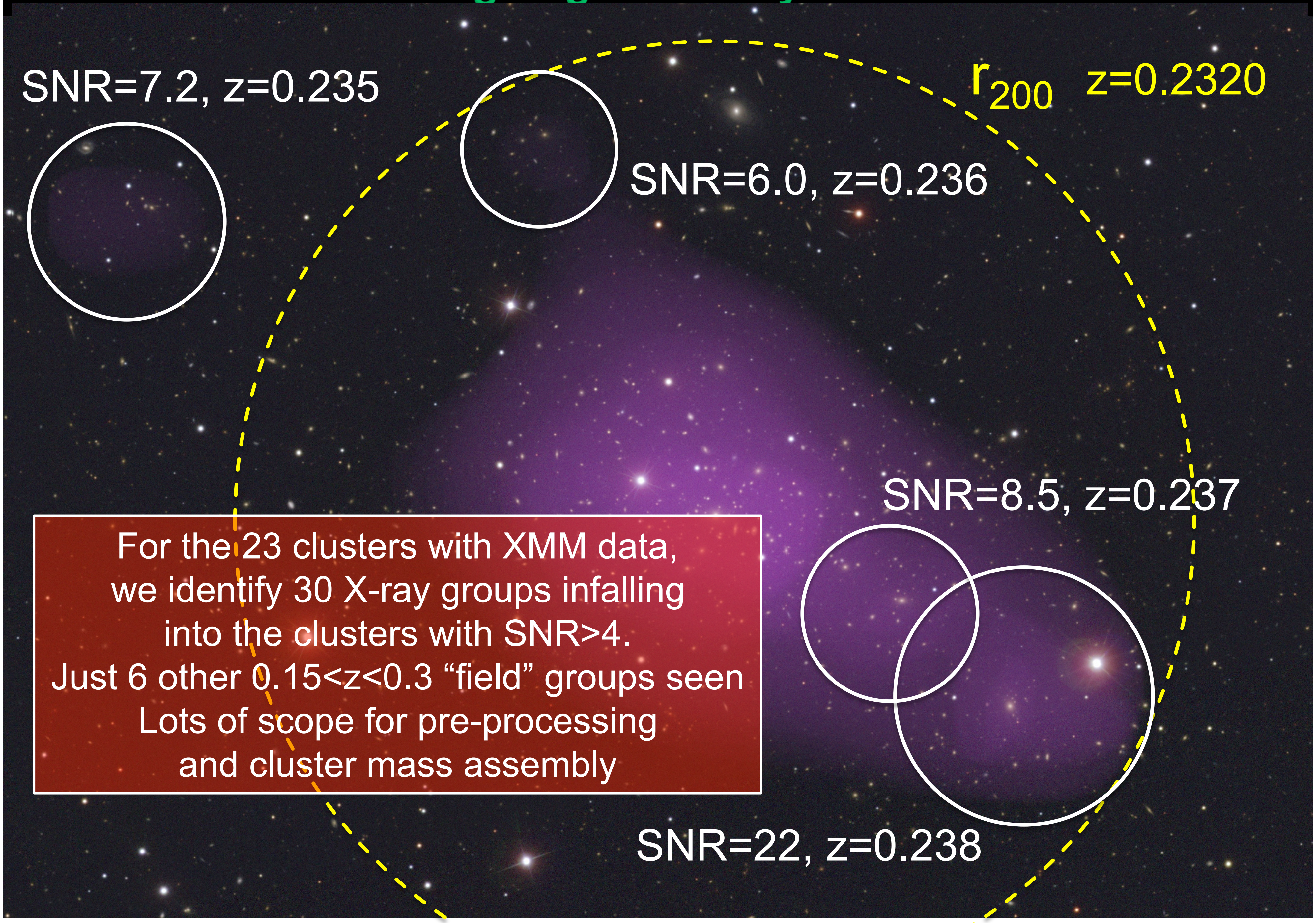
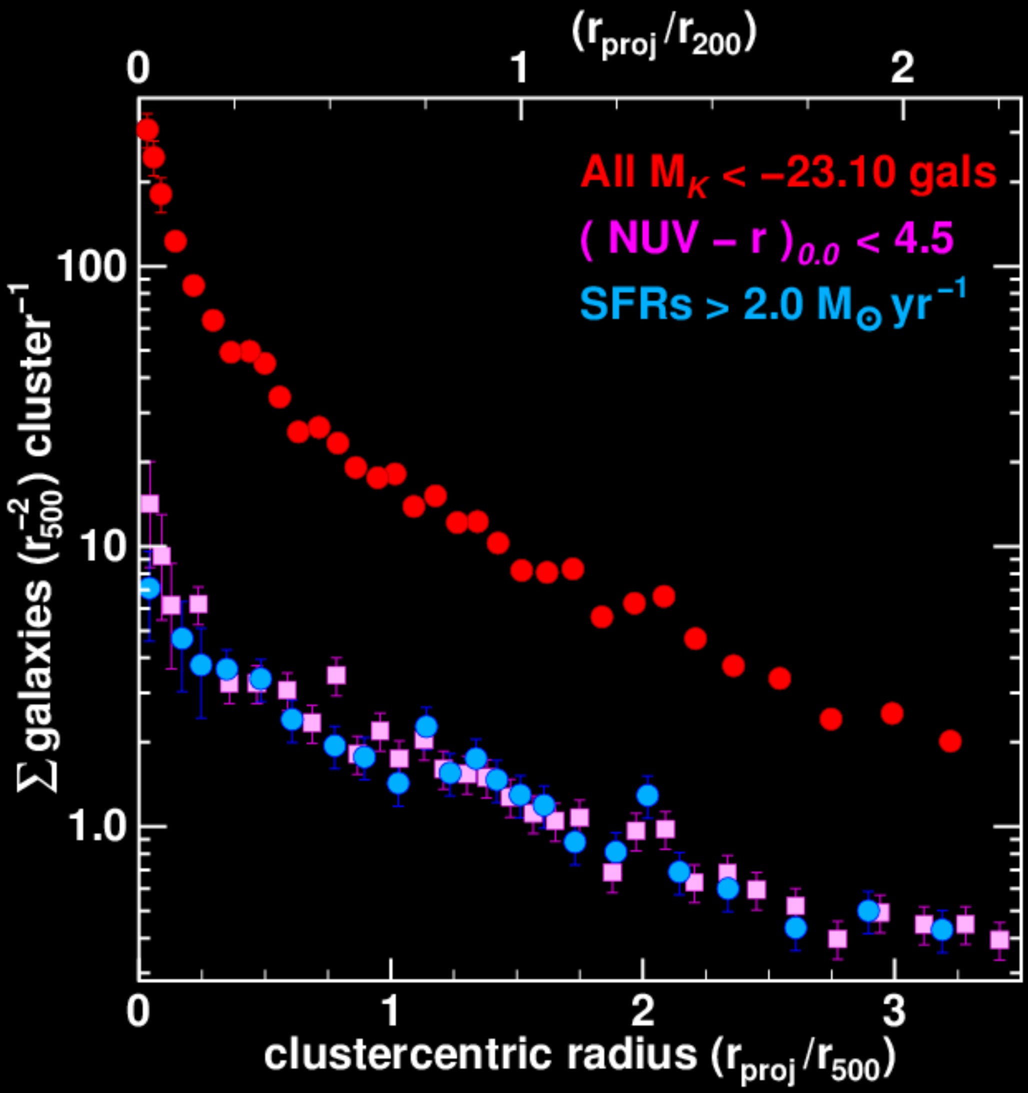


Results: Radial galaxy surface-density profiles



The surface density of star-forming galaxies declines steadily with radius, falling ~15x from core to 2 r_{200}

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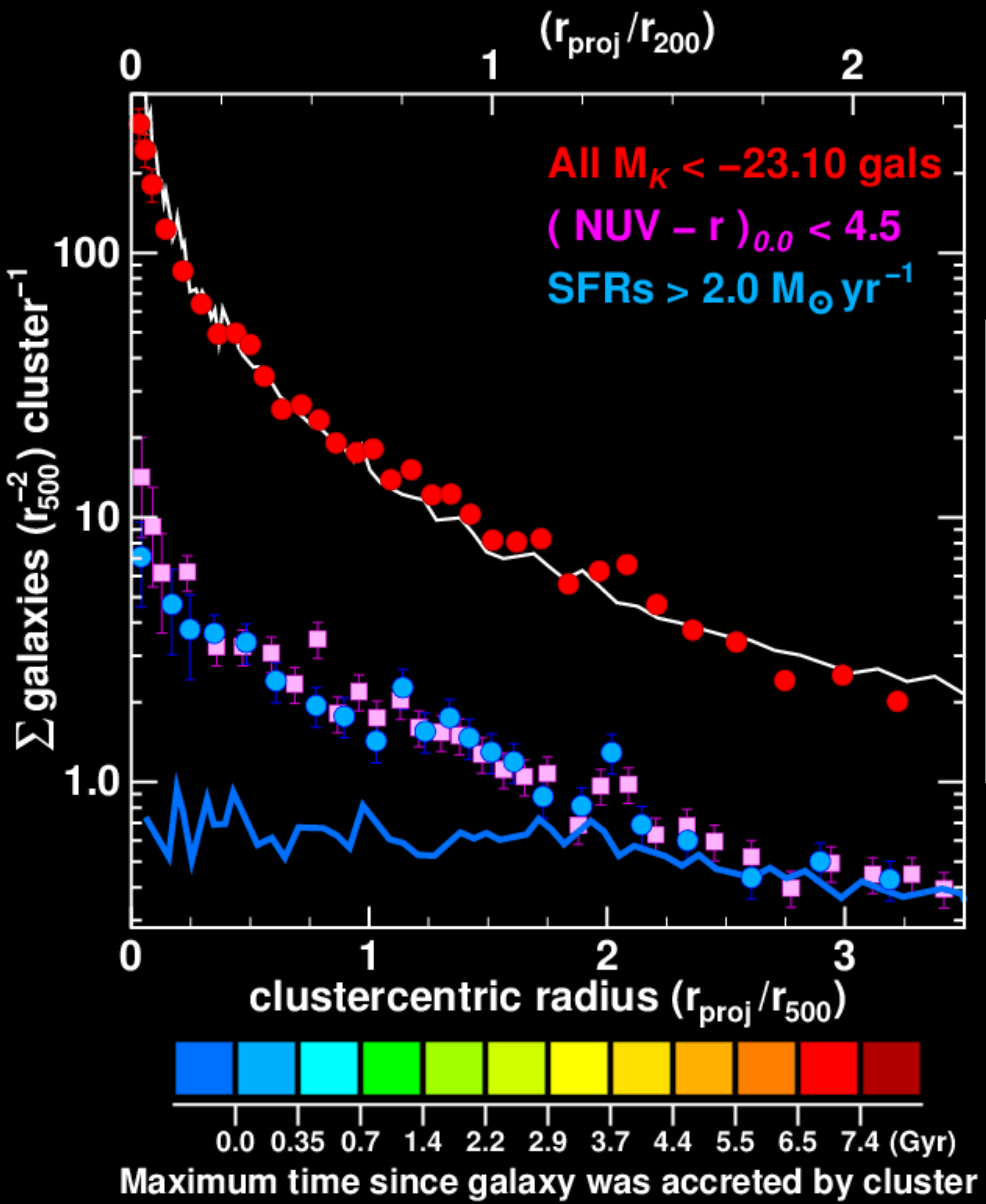

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If infalling star-forming galaxies are instantly quenched upon accretion, we expect flat $\Sigma(r)$ profile for star-forming cluster galaxies. We can exclude such immediate quenching models

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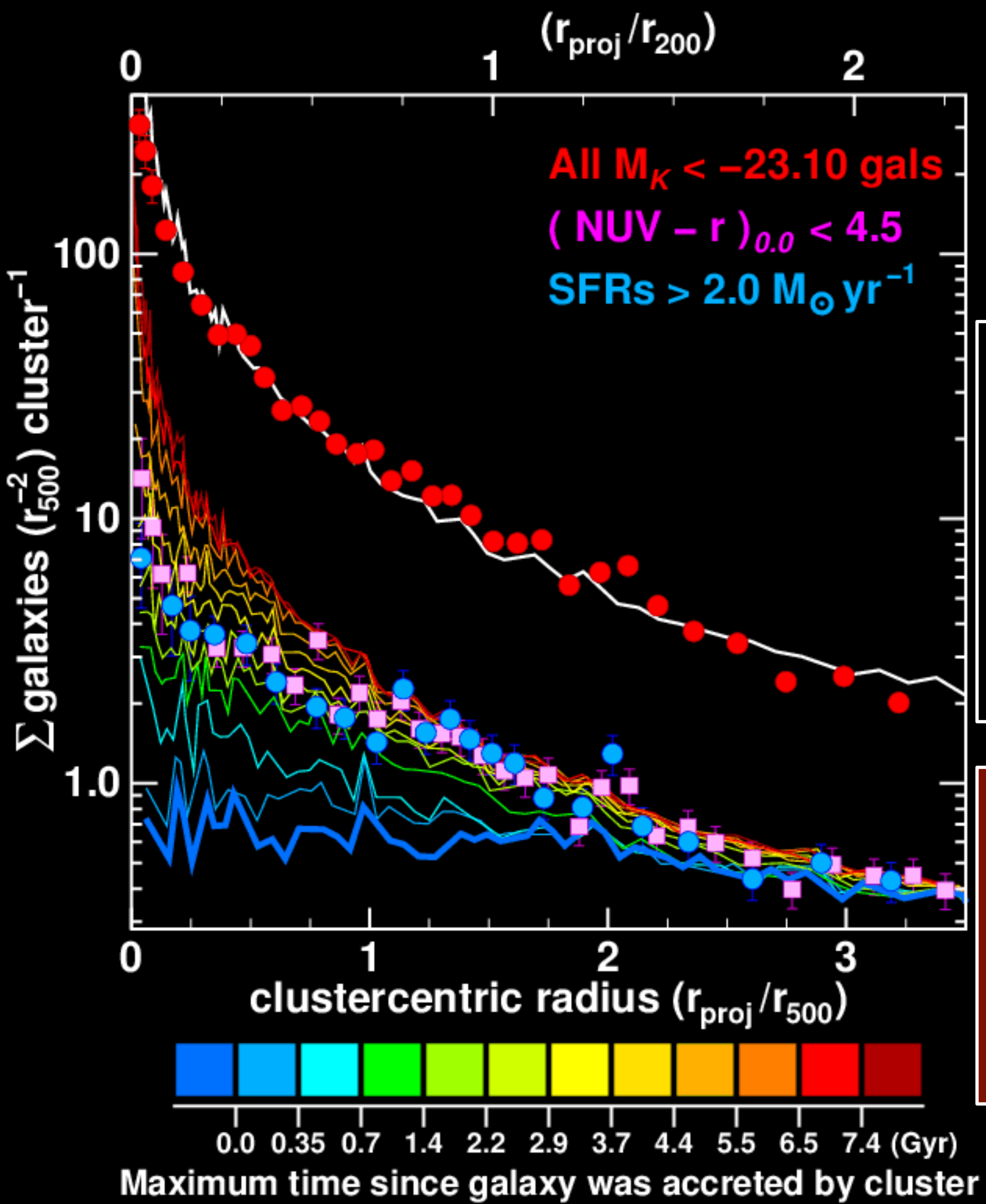

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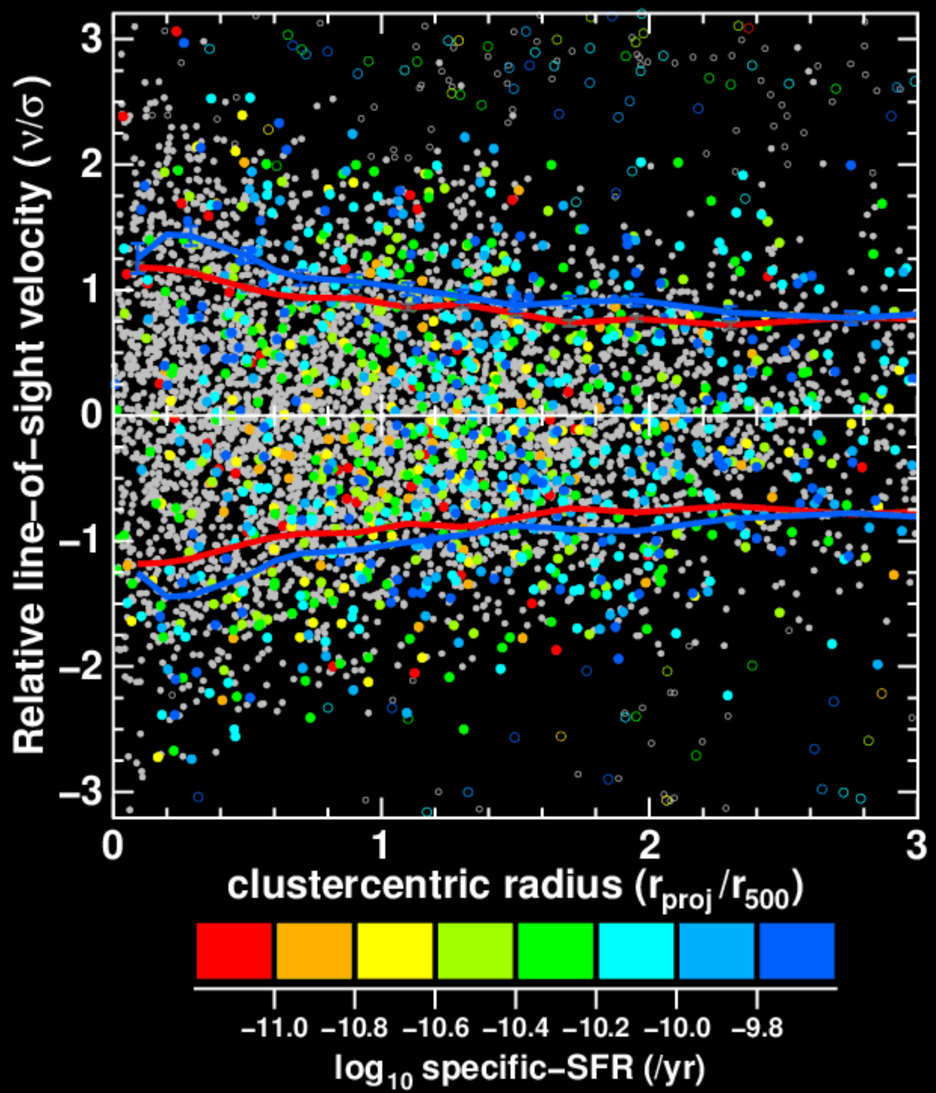
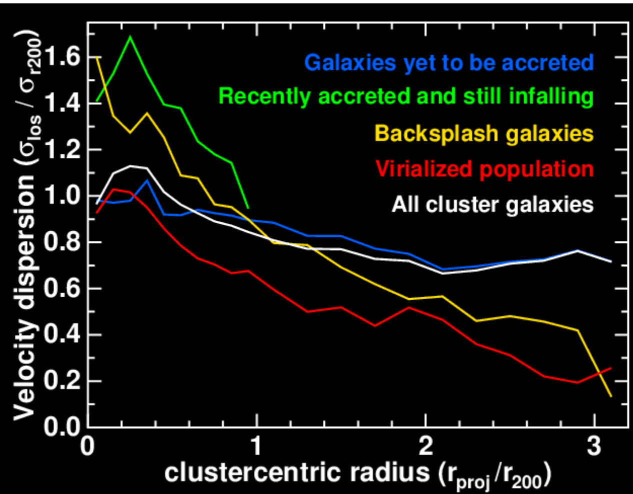
Star-forming galaxies must survive for 2-3 Gyr after accretion to build up the apparent "over-density" of star-forming galaxies in clusters

Results: The phase-space distribution of SF galaxies



Star-forming galaxies have l-o-s velocity dispersions which are 10-35% higher than their passive counterparts at all cluster-centric radii

The $\sigma_{los}(r)$ profile of star-forming galaxies shows a sharp peak at r_{proj}~$0.3r_{500}$, consistent with model predictions including recently accreted galaxies



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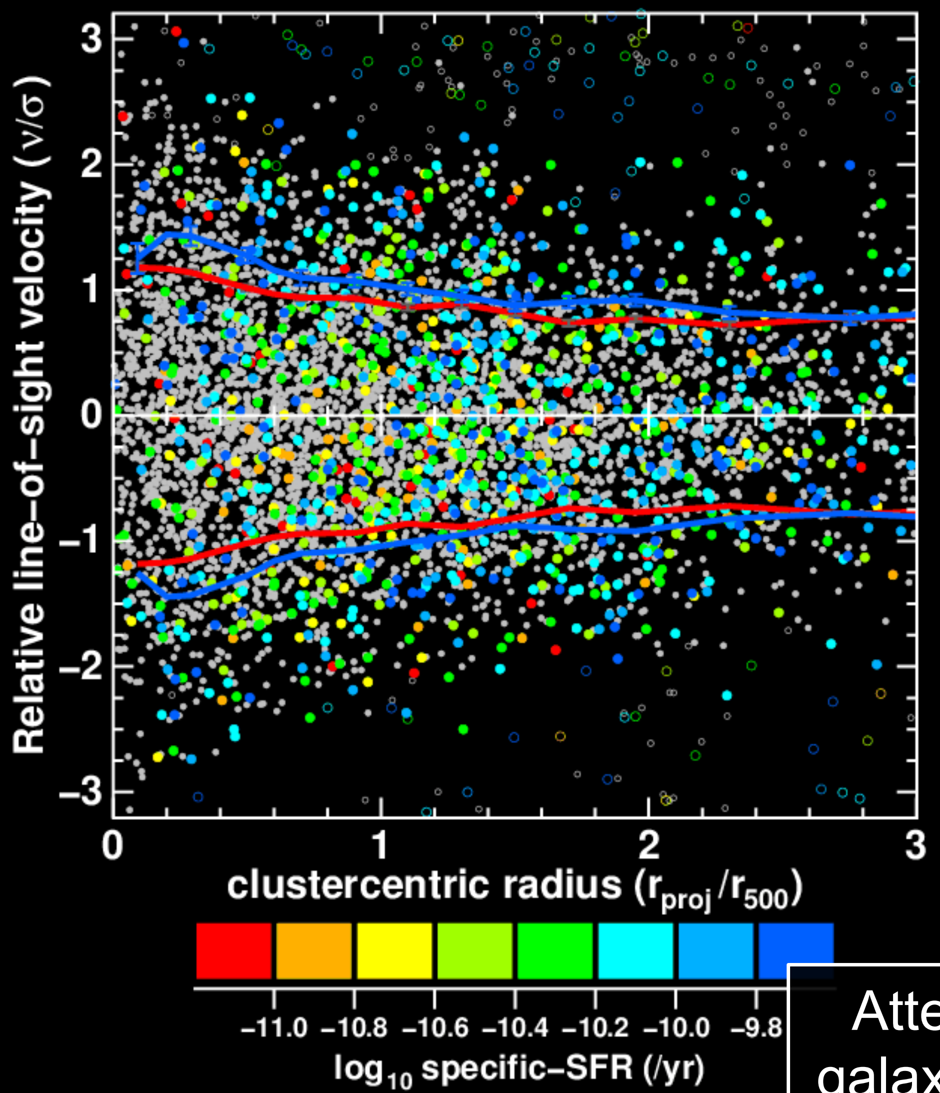
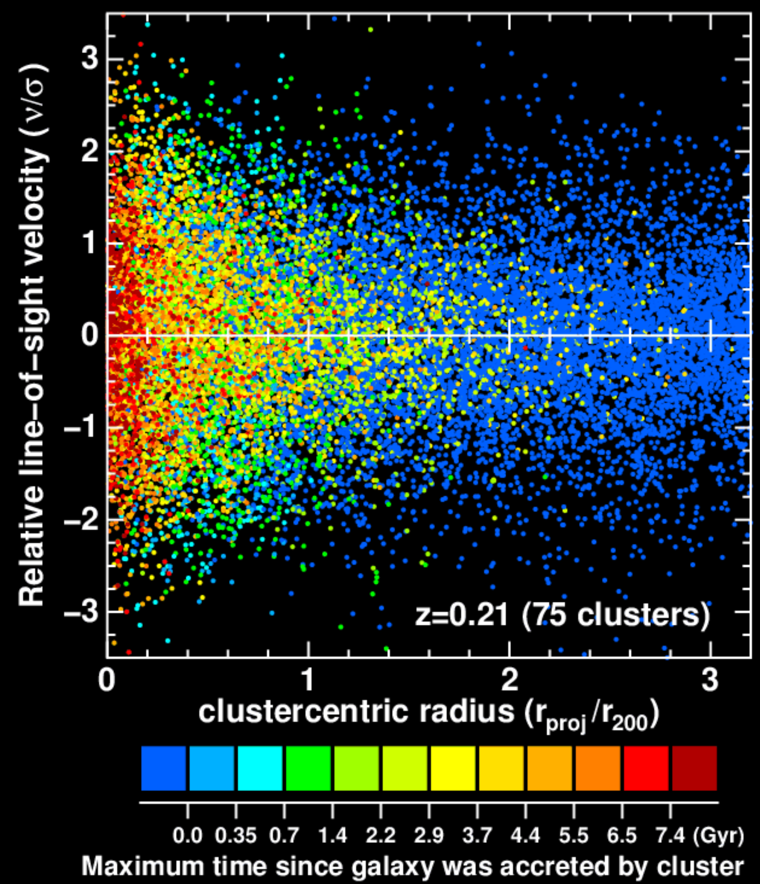
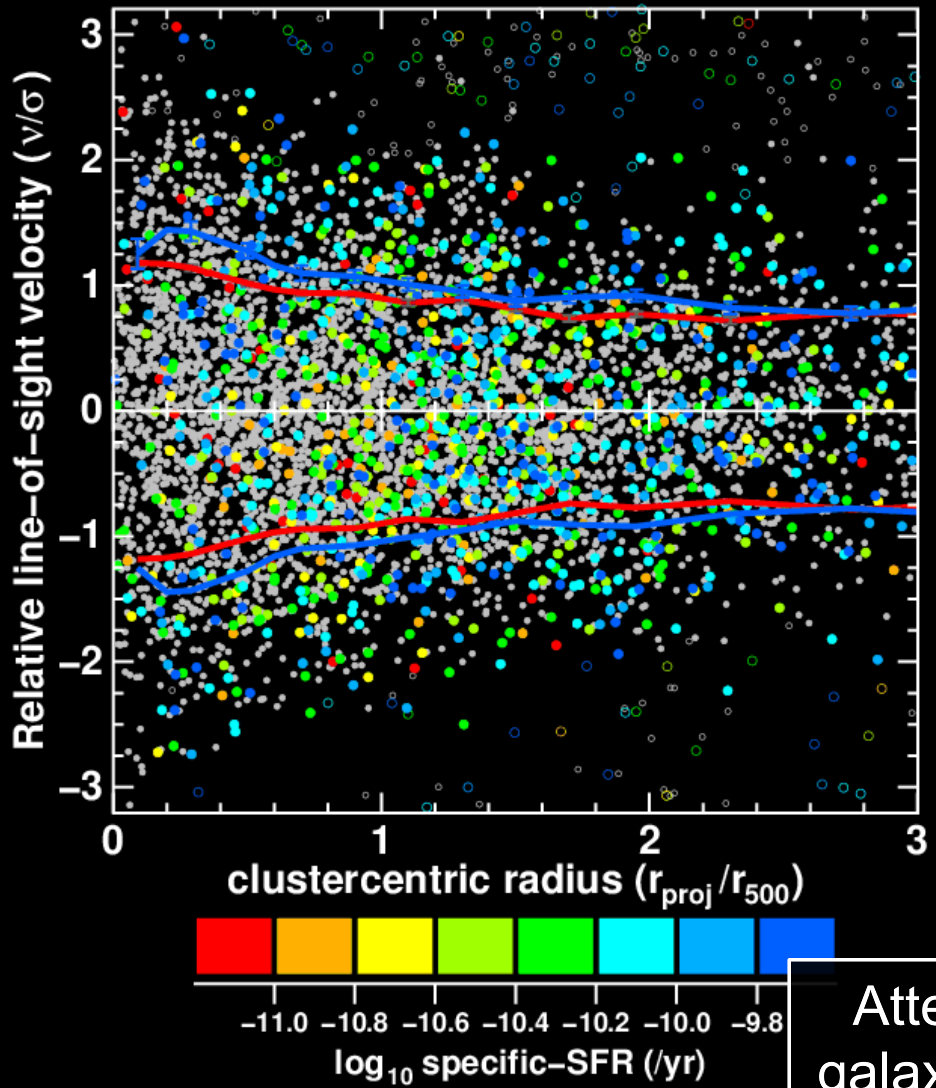
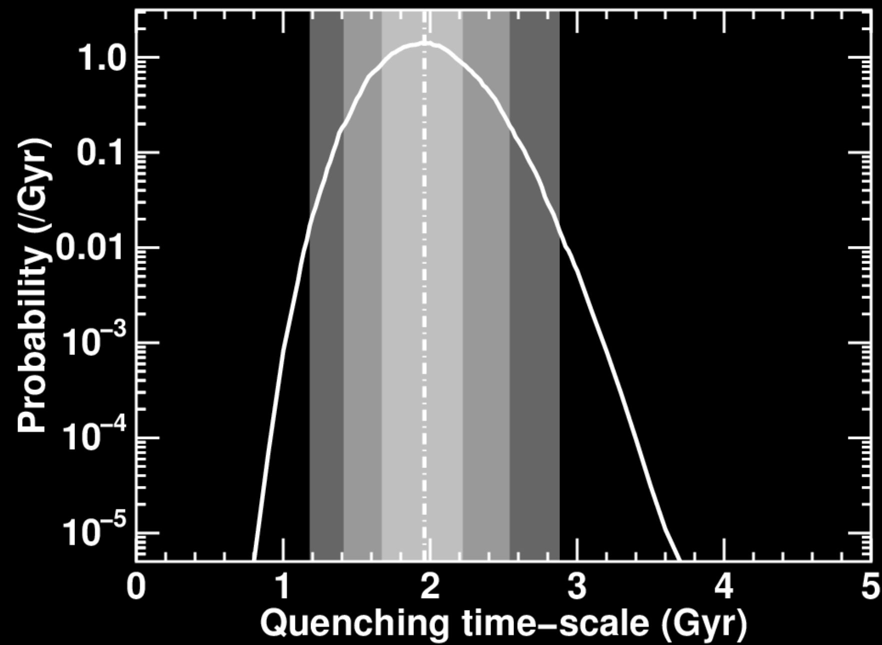




Attempt to match the distribution of SF galaxies in the caustic diagram, by model infalling cluster galaxy populations whose SF declines exponentially upon accretion

Results: Constraining t_Q from z-space dist. of SF gals





Best fit by models with t_Q=1.96 ± 0.27 Gyr

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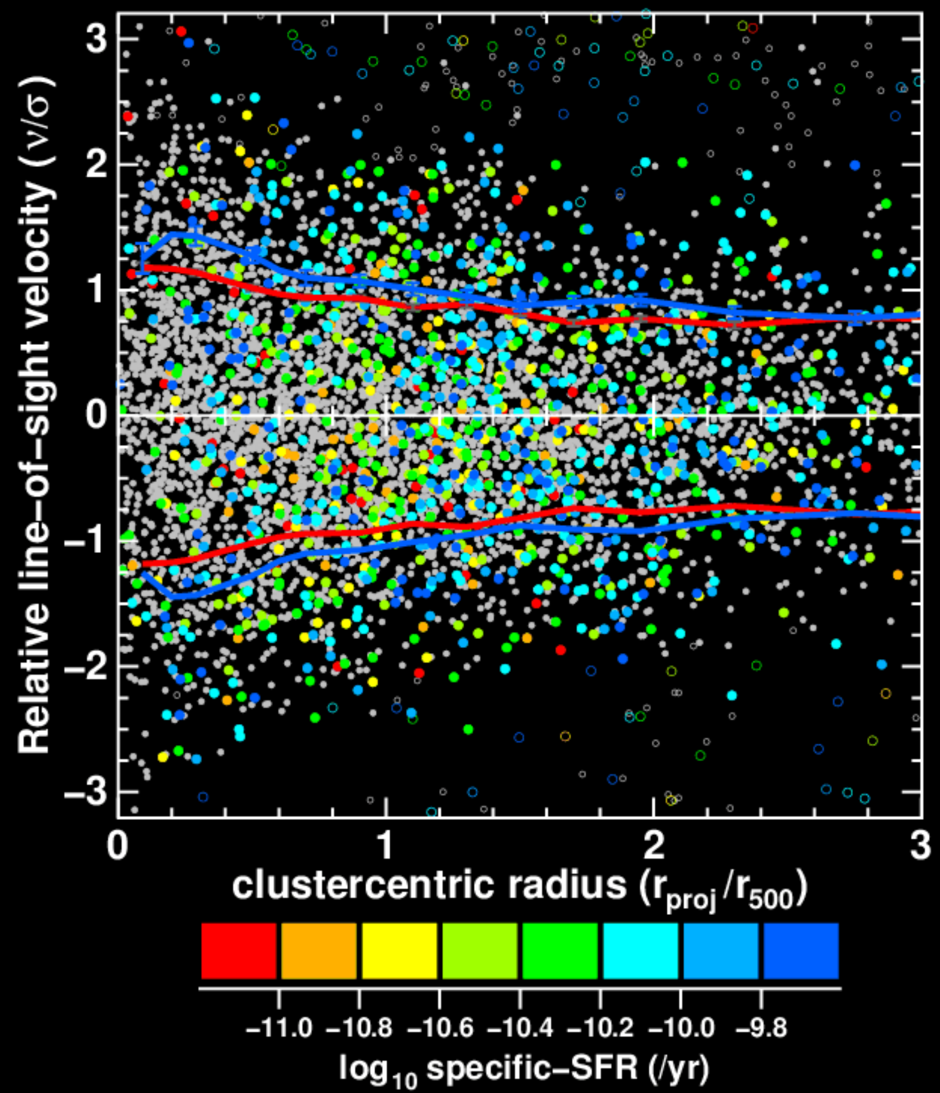
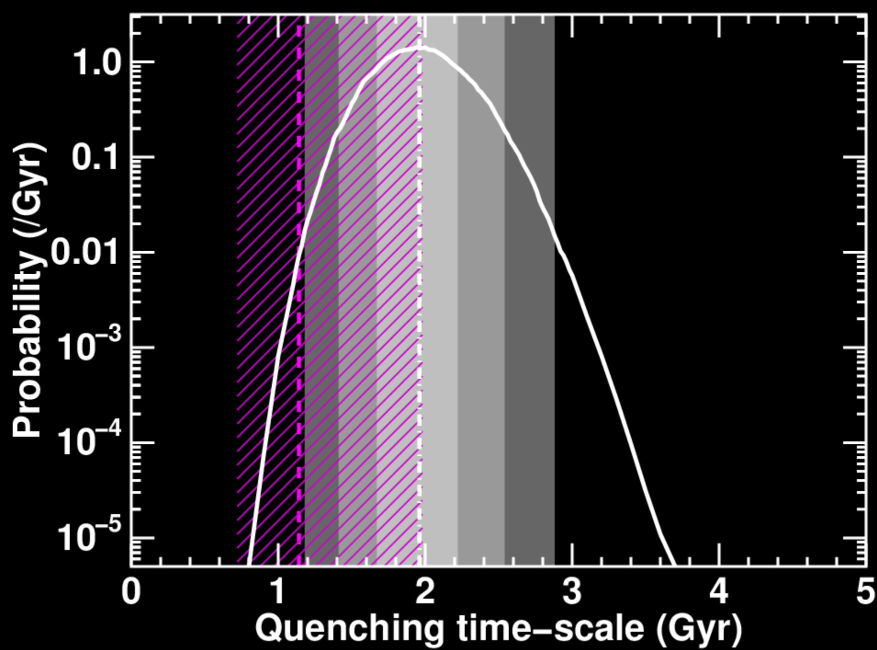




Best fit by models with t_Q=1.96 ± 0.27 Gyr

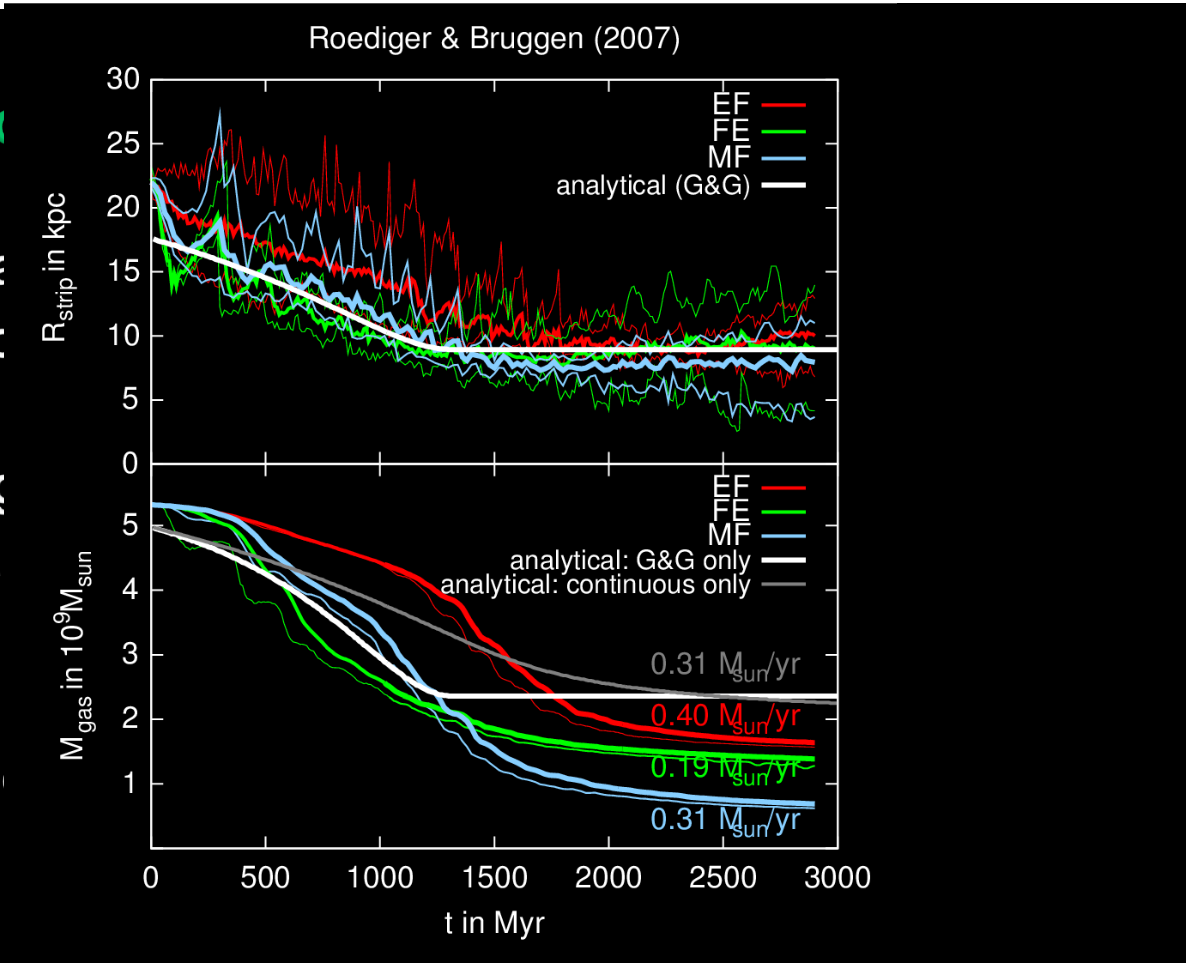
Consistent with t_Q=1.14 Gyr implied by 30% reduction in sSFRs of cluster galaxies within r_{200}

Discussion: Relati

- Infalling star-forming L* gala
time-scales of 0.7-2.5 Gyr upo

- The hot diffuse gas halo of g
preventing further gas accret

- The galaxy then uses up its
formation. Local spiral galaxi
time-scales of 2-3 Gyr (Bigiel



- Infalling spirals encounter gradually increasing ICM densities and ram pressures which incrementally strip gas from their disks from the outside-in as they travel from the cluster outskirts to the core.

- Effective time-scale for ram-pressure stripping is the ~0.5-1 Gyr time required for infalling spirals to travel from ~r_{200} to the cluster core

Take-home points

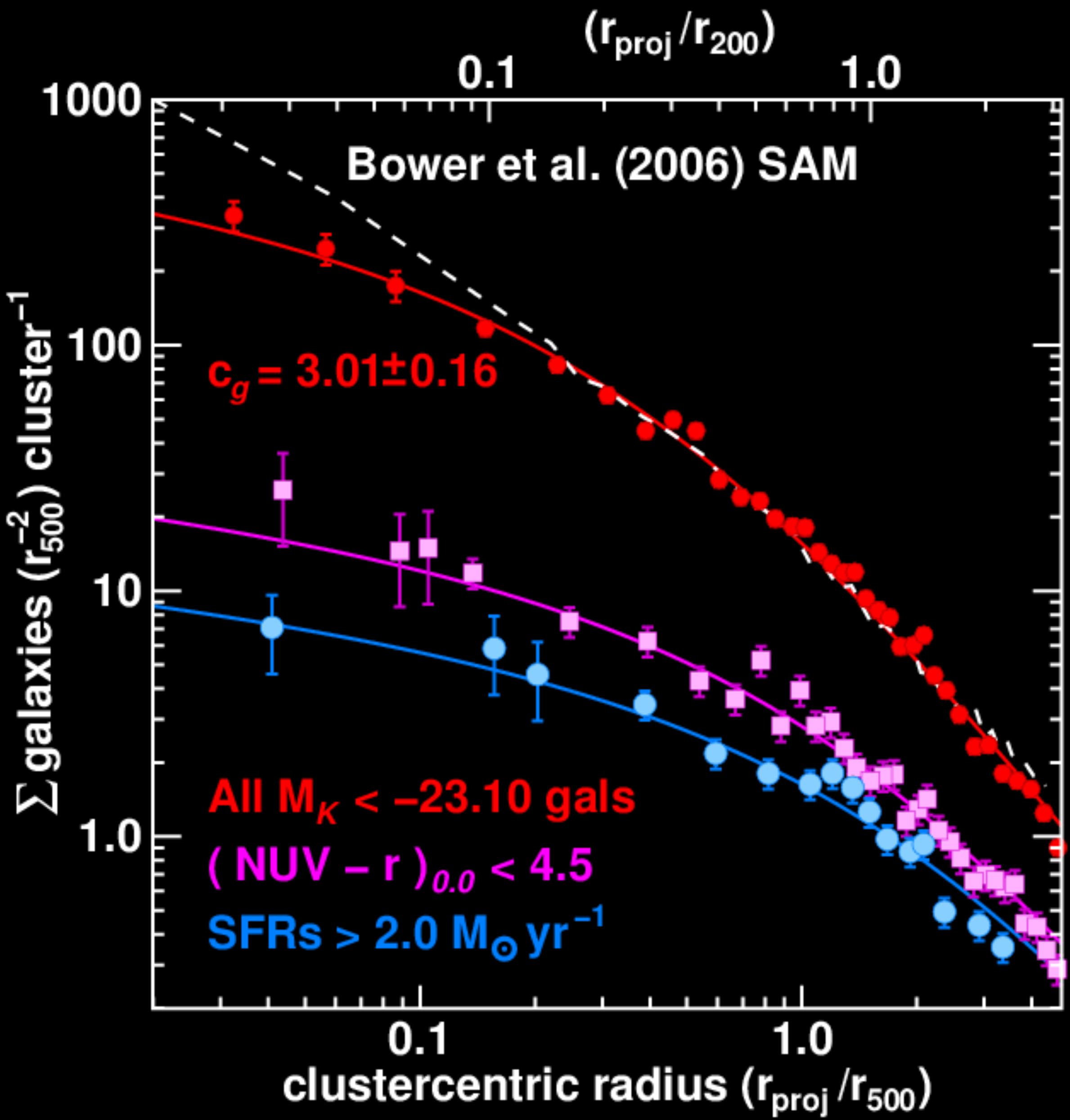
- Star-formation in high-mass ($>10^{10}M_{\odot}$) spiral galaxies is slowly quenched on ~2 Gyr time-scales when they are accreted into massive clusters at low redshifts

- Consistent picture of slow quenching on 2 Gyr time-scales from:
- (i) reduction in specific-SFRs of star-forming cluster galaxies,
- (ii) radial surface density profile of star-forming galaxies and
- (iii) distribution of star-forming galaxies within caustic diagram

- Caveat: t_Q may vary with stellar mass, halo mass and redshift

- Pre-processing in infalling galaxy groups may halt star formation in galaxies prior to their arrival into clusters

Results: The radial surface density profile of galaxies

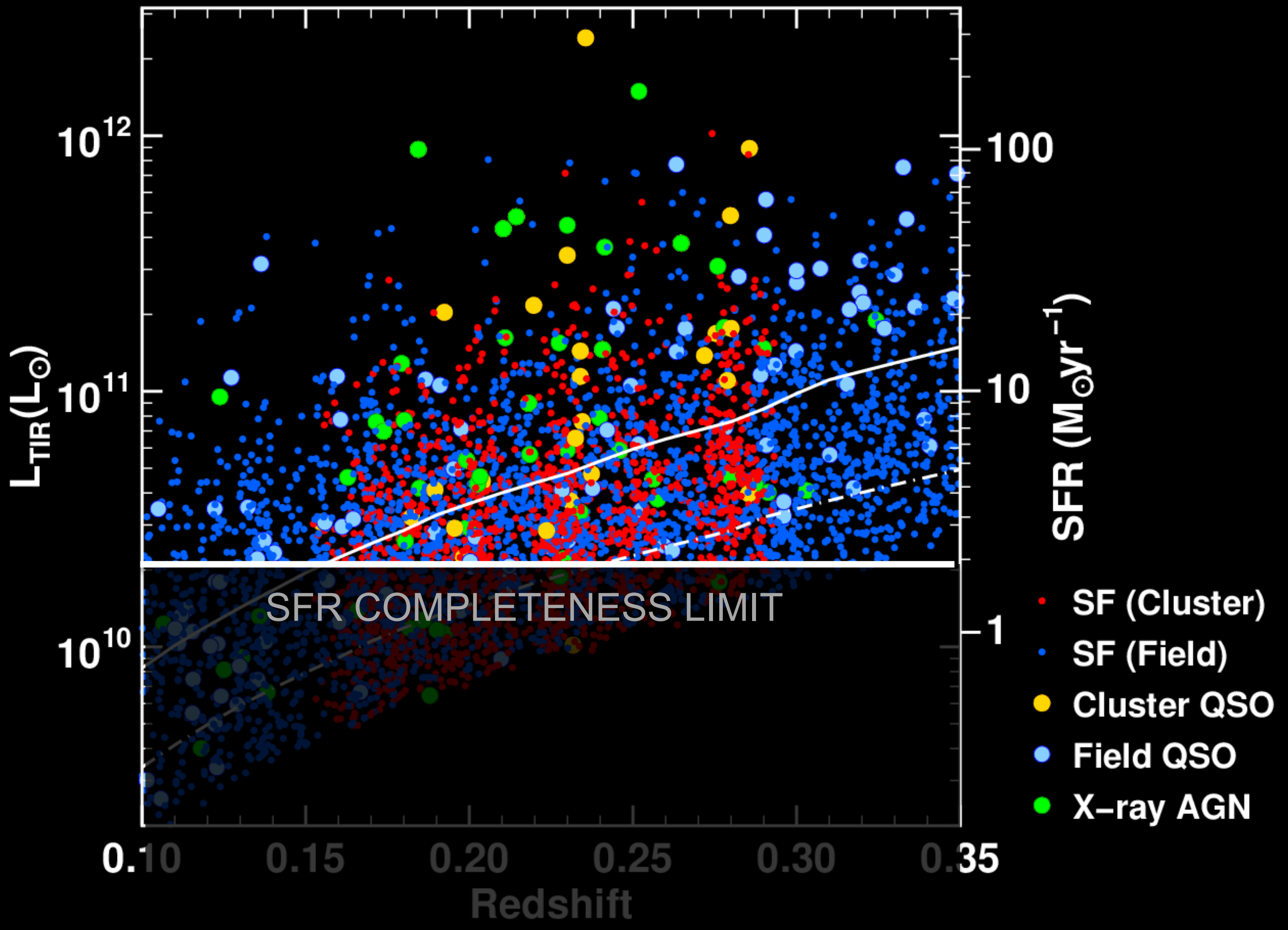


The radial surface density profile $\Sigma(r)$ of cluster galaxies can be well fit by an NFW profile with c_g=3.0

The $\Sigma(r)$ profile for cluster galaxies predicted by the Bower et al. SAM is too steep for r_{proj}<0.1r_{500}

The DM halos hosting galaxies are continually stripped over ~5Gyr after accretion into clusters. SAMs introduce "orphan galaxies" who lack a DM sub-halo. Affects our model trends within 0.1 r_{500}.

LoCuSS: A census of star-formation at 0.1<z<0.35



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