The Nature of Massive Transition Galaxies in CANDELS, GAMA, and Cosmological Simulations

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CANDELS Team Meeting
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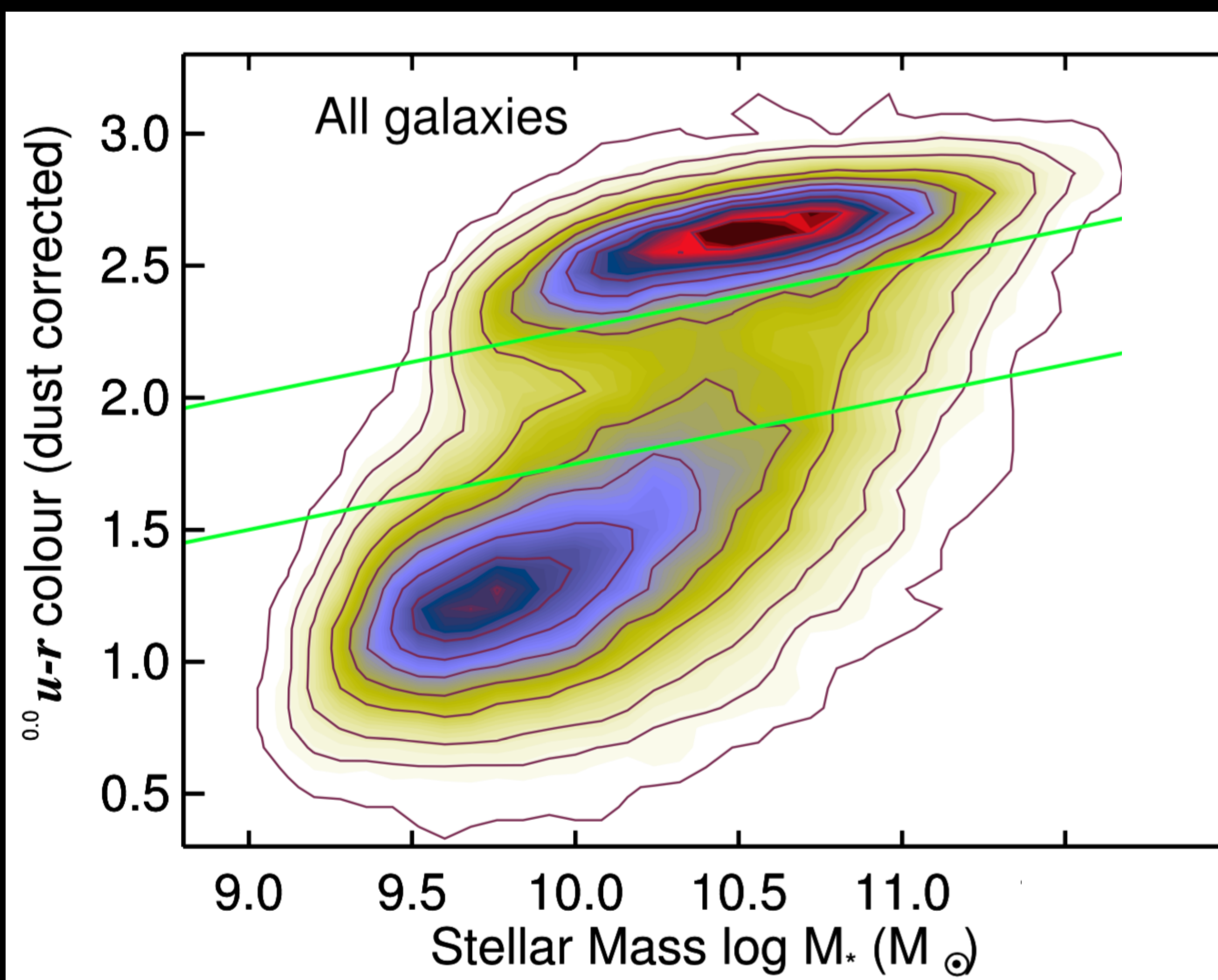
Paper just accepted Friday morning! (arXiv:1611.03869)

Physically motivating the green valley

Classical green valley thought to be an evolutionary bridge between the blue cloud and red sequence

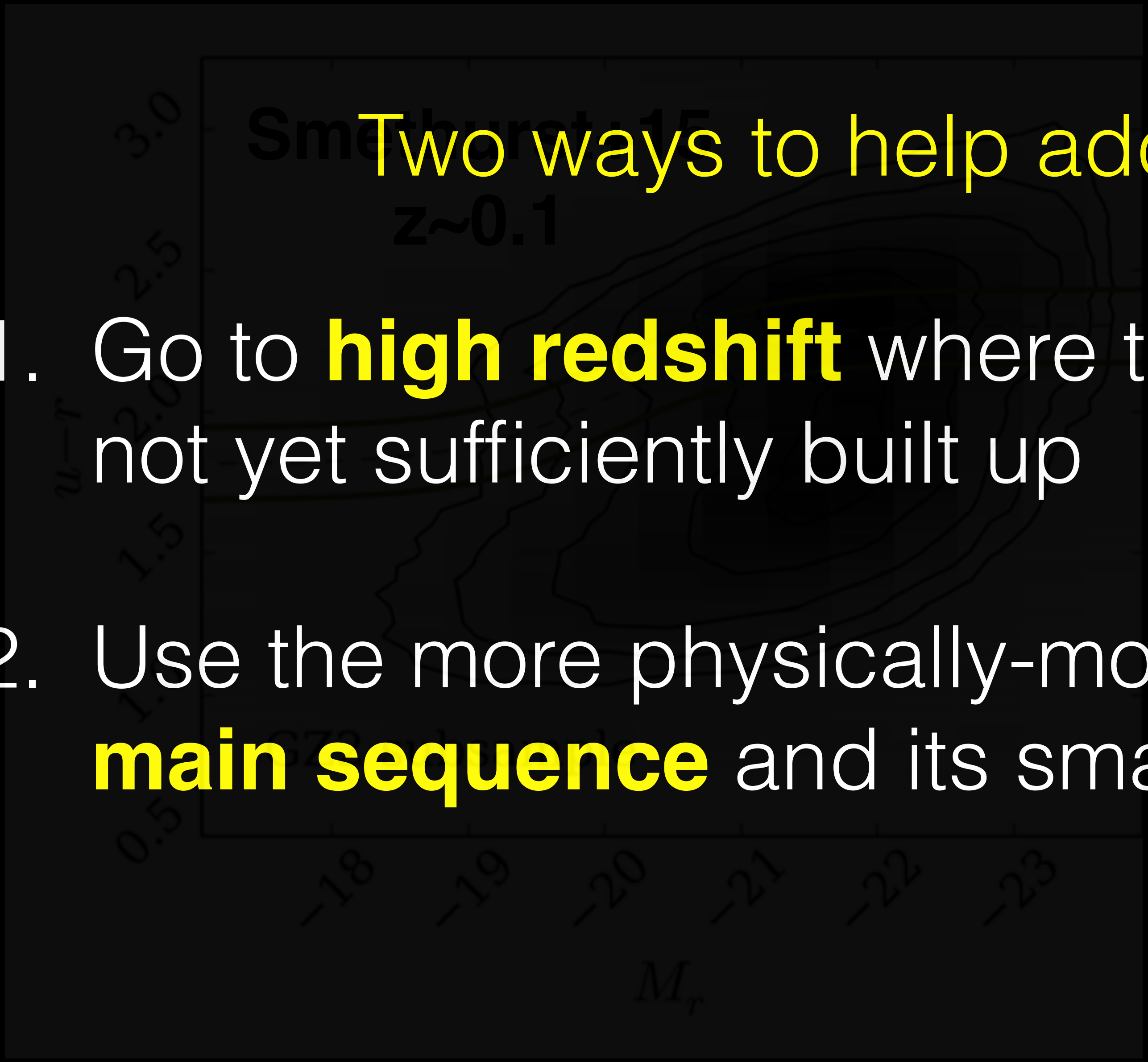


Schawinski+14
z~0.1

BUT: subject to many caveats…

- how do you draw your lines?
- what colors do you use?
- are colors dust-corrected?
- is there even a “statistically significant valley”?
- do all galaxies move in the same direction & on similar timescale?
- **purple valley**: merely super-position of blue & red galaxies with measurement errors

Physically motivating the green valley



Two ways to help address these concerns:

1. Go to **high redshift** where the red sequence is not yet sufficiently built up

2. Use the more physically-motivated **star-forming main sequence** and its small intrinsic scatter

The Observations

- Backbone: CANDELS (all 5 fields)
  - H < 25 AB mag
  - $M_{star} > 10^{10}\ M_{sun}$ (massive galaxies only)
  - SFRs from NUV+IR, or dust-corrected NUV
  - Six redshift slices from z=0.5 to z=3.0

- GAMA (z<0.12 anchor)
  - $M_{star} > 10^{10}\ M_{sun}$ (massive galaxies only)
  - ~2 magnitudes deeper than SDSS (r~19.5 mag)
  - SFRs from H-alpha emission line flux

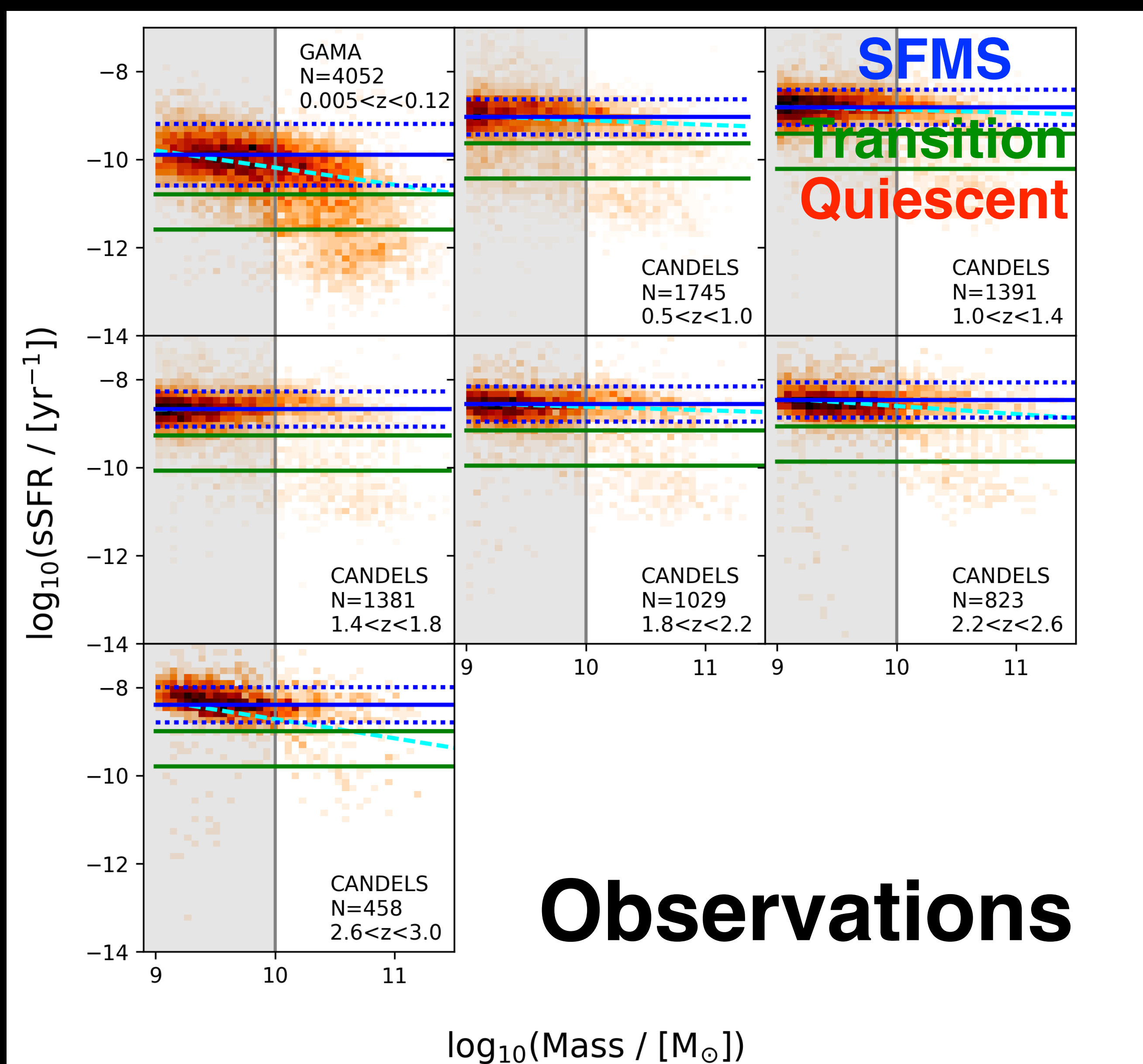
Santa Cruz Semi-Analytic Model

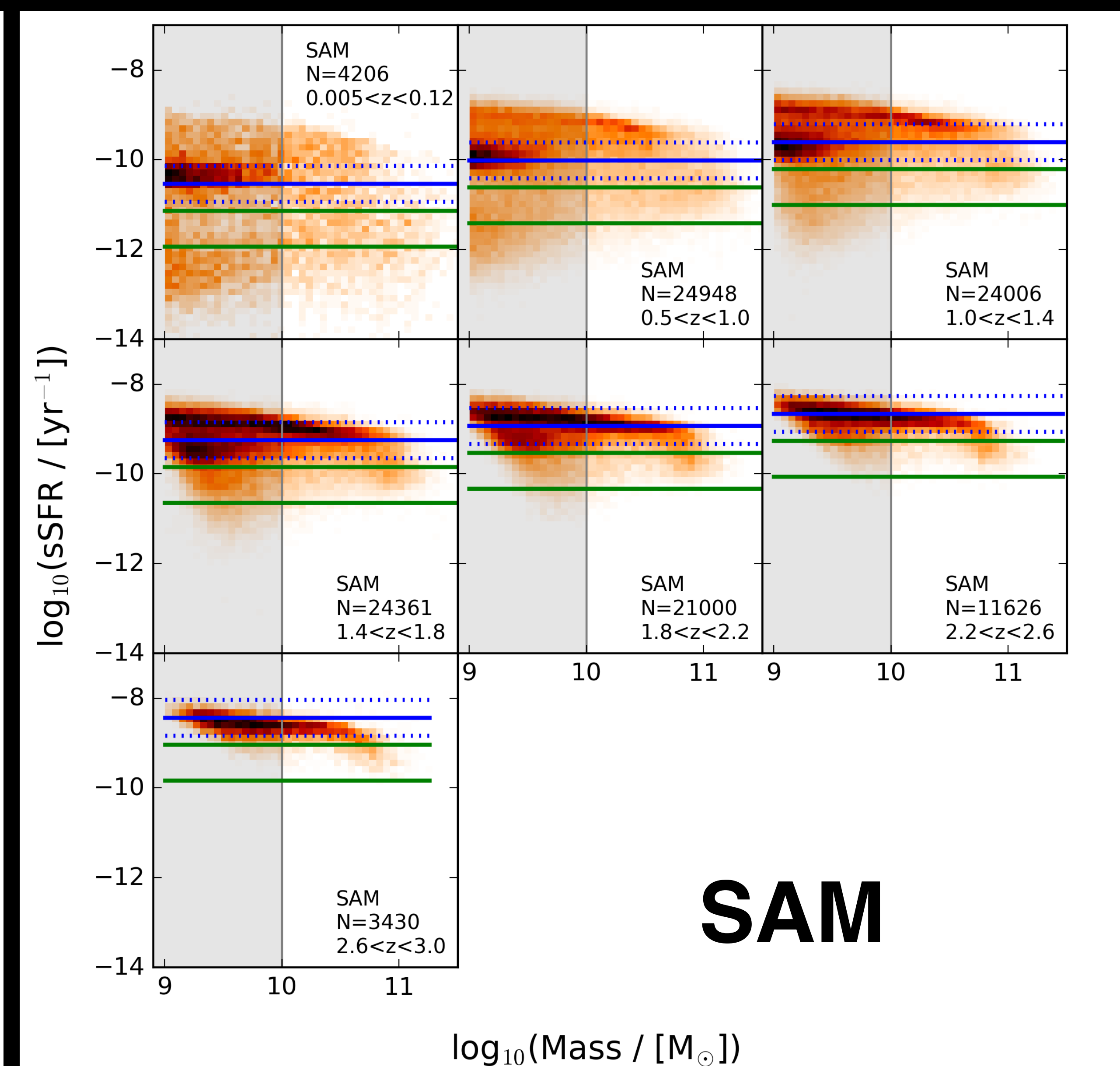
- Schematic prescriptions for tracking the hierarchical formation and evolution of galaxies within dark matter halos
  - Standard physical processes included, *and* disk instabilities, SMBH feedback, and novel composite galaxy size predictions
- Run on mock CANDELS light cones extracted from the full (dark matter only) Bolshoi-Planck simulation
- Key point: SAM analyzed in the EXACT same way as the observations so we can compare side by side

Somerville & Primack 99; Somerville+08; Somerville+12; Porter+14
Brennan, Pandya, Somerville+15

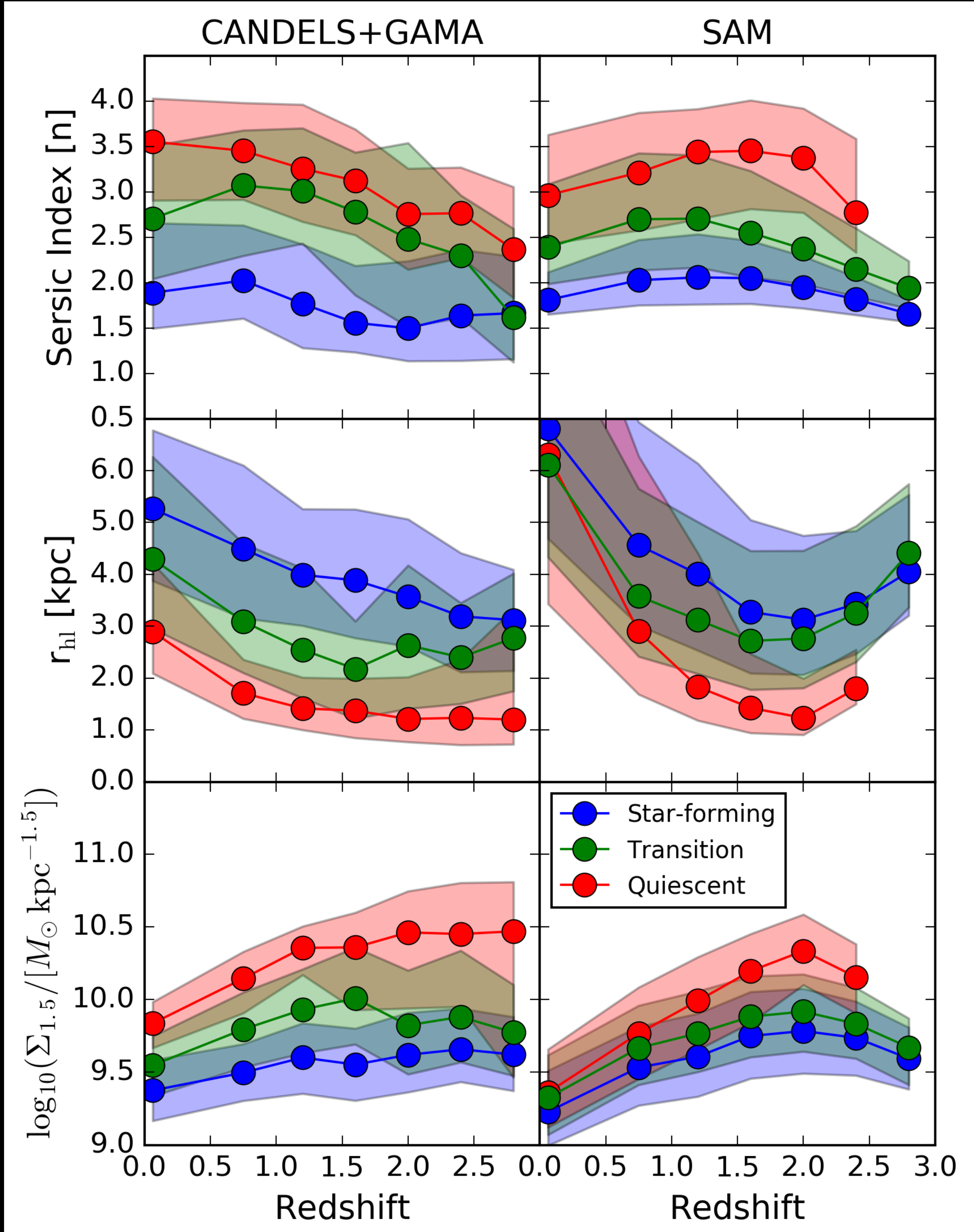
Defining Transition Galaxies

- Basically use an "n-sigma" approach to quantify the "degree of quiescence" of galaxies below the SFMS (assumed width = 0.4 dex)
- Define the **transition region** 1.5-3.5 sigma (0.6-1.4 dex) below SFMS (minimize contamination from SF galaxies in a statistical sense)
- See Brennan, Pandya, Somerville+17 for continuous approach





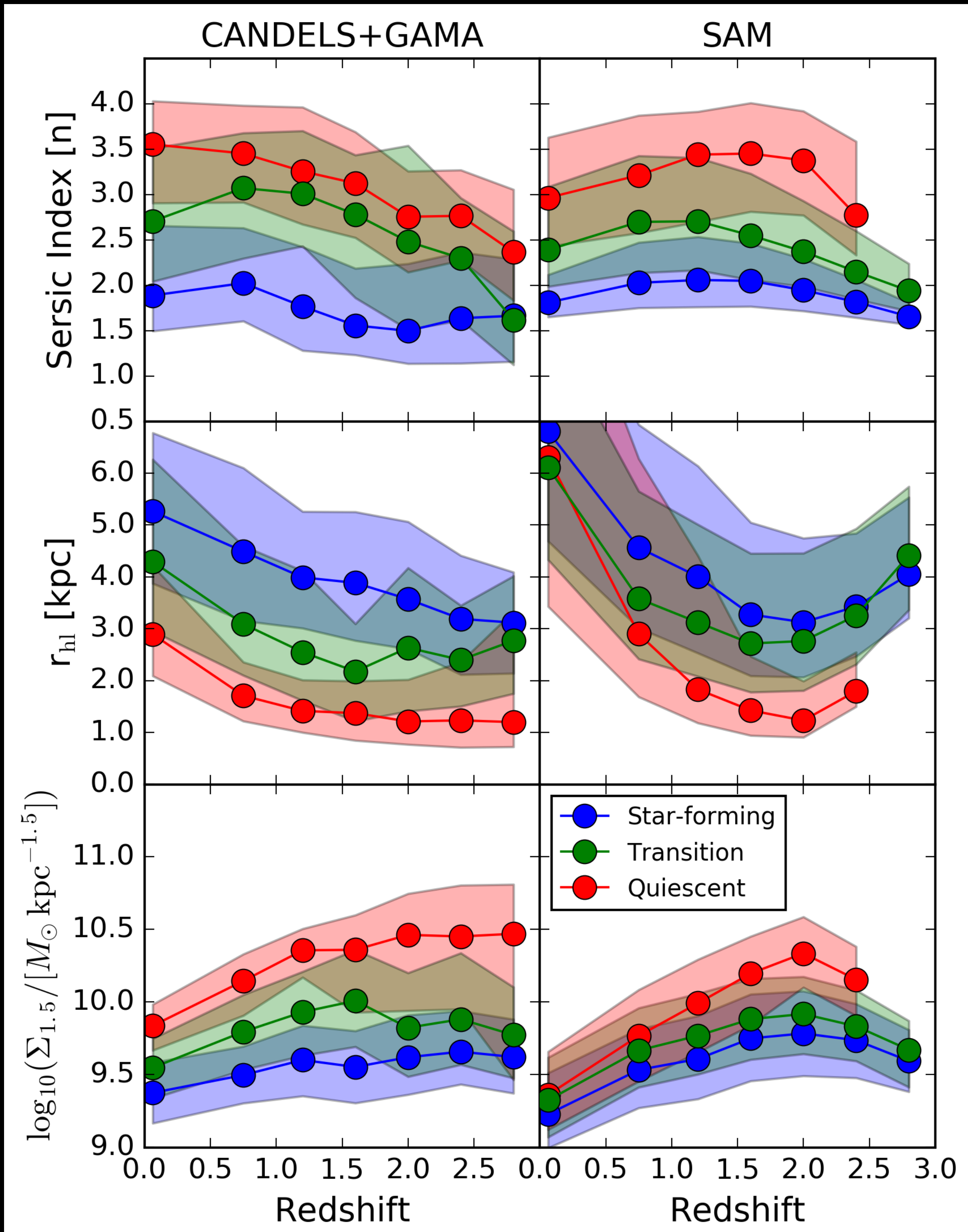
Structural Distinctiveness and Evolution



In observations and semi-analytic model: transition galaxies exhibit intermediate structural properties at 0<z<3 relative to SFMS and quiescent galaxies

(After controlling for stellar mass dependence)

Structural Distinctiveness and Evolution

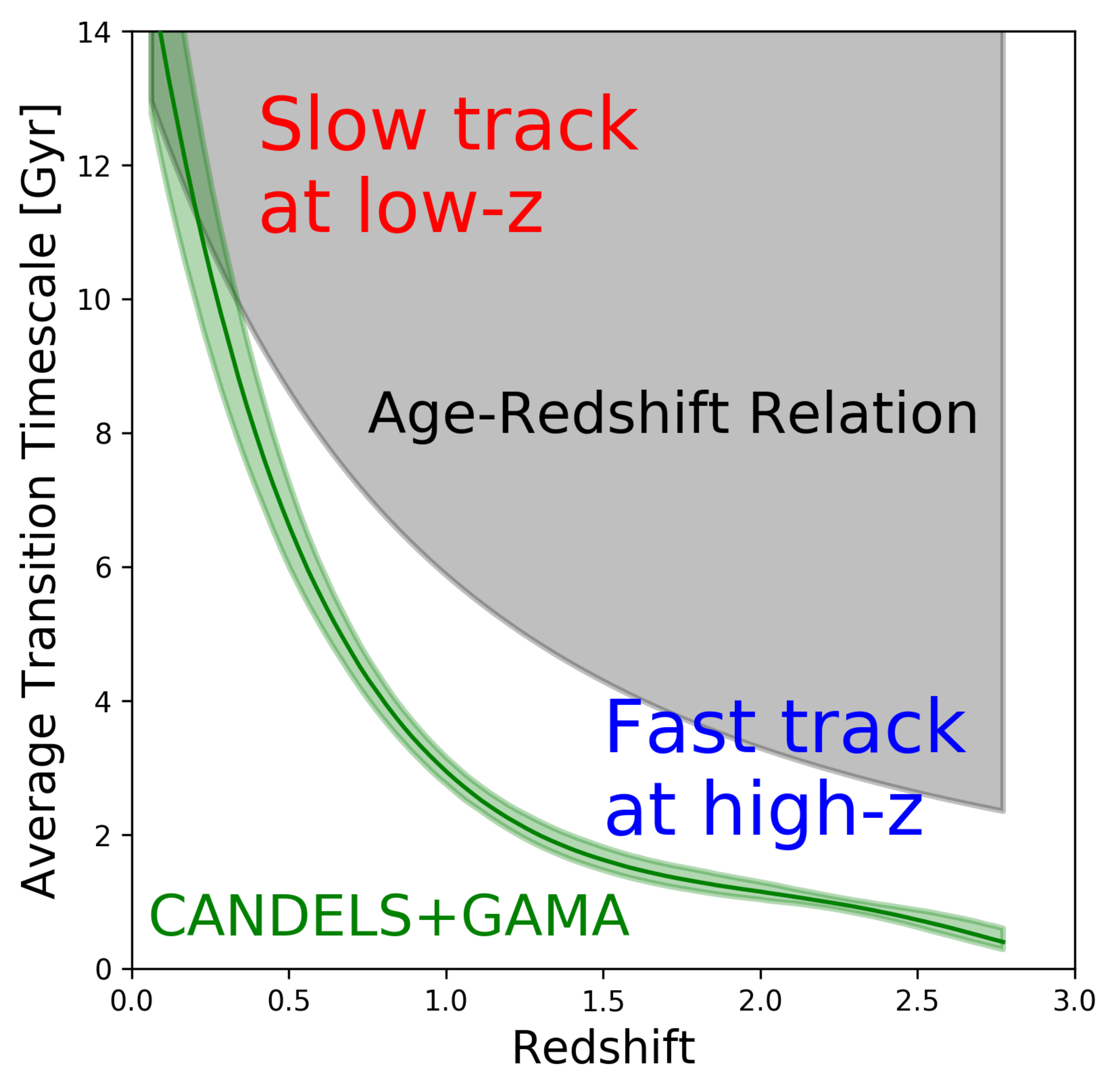


Morphological change accompanies/ precedes quenching.

Extreme high-z cases: "compaction" (growth of central stellar density via merger or disk instability) causes bulge growth first and *then* quenching (e.g., Barro +13, Tacchella+16)

But also "progenitor bias"

Observational **Upper Limit** on the Average Population Transition Timescale vs. Redshift



- Assume that all transition galaxies are moving from the SFMS toward quiescence
- Then the **average** galaxy between any two closely spaced redshifts has a transition timescale given by the formula below
- < 1 Gyr at z~2.5
- ~ 7 Gyr at z~0.5
- This is an **upper limit** for various reasons.

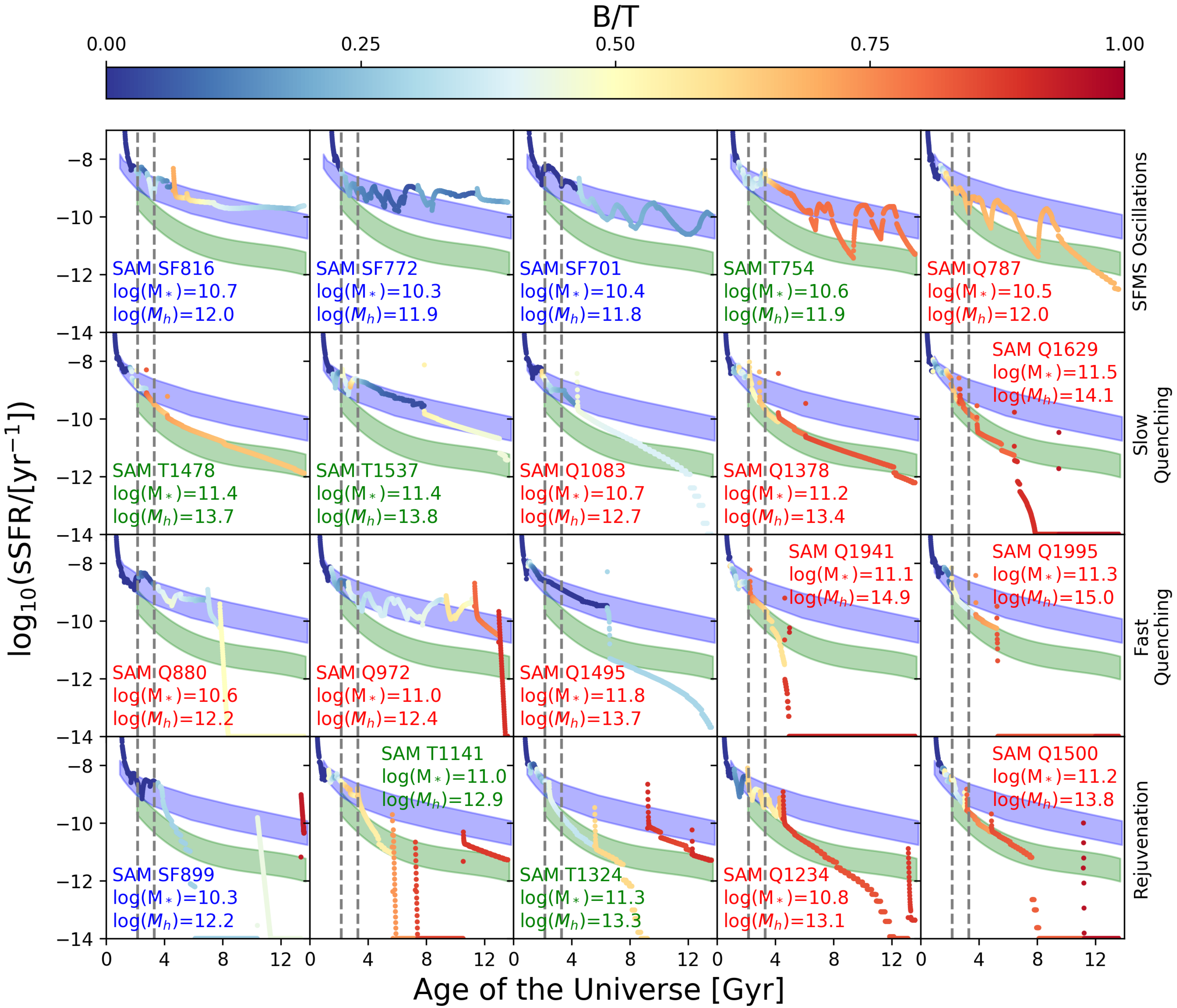
$$\langle t_{\mathrm{transition}} \rangle_{z_1,z_2} = \langle n_{\mathrm{transition}} \rangle_{z_1,z_2} \times \left(\frac{d\, n_{\mathrm{quiescent}}}{dt} \right)^{-1}_{z_1,z_2}$$

Physical Origin of Transition Galaxies in the SAM

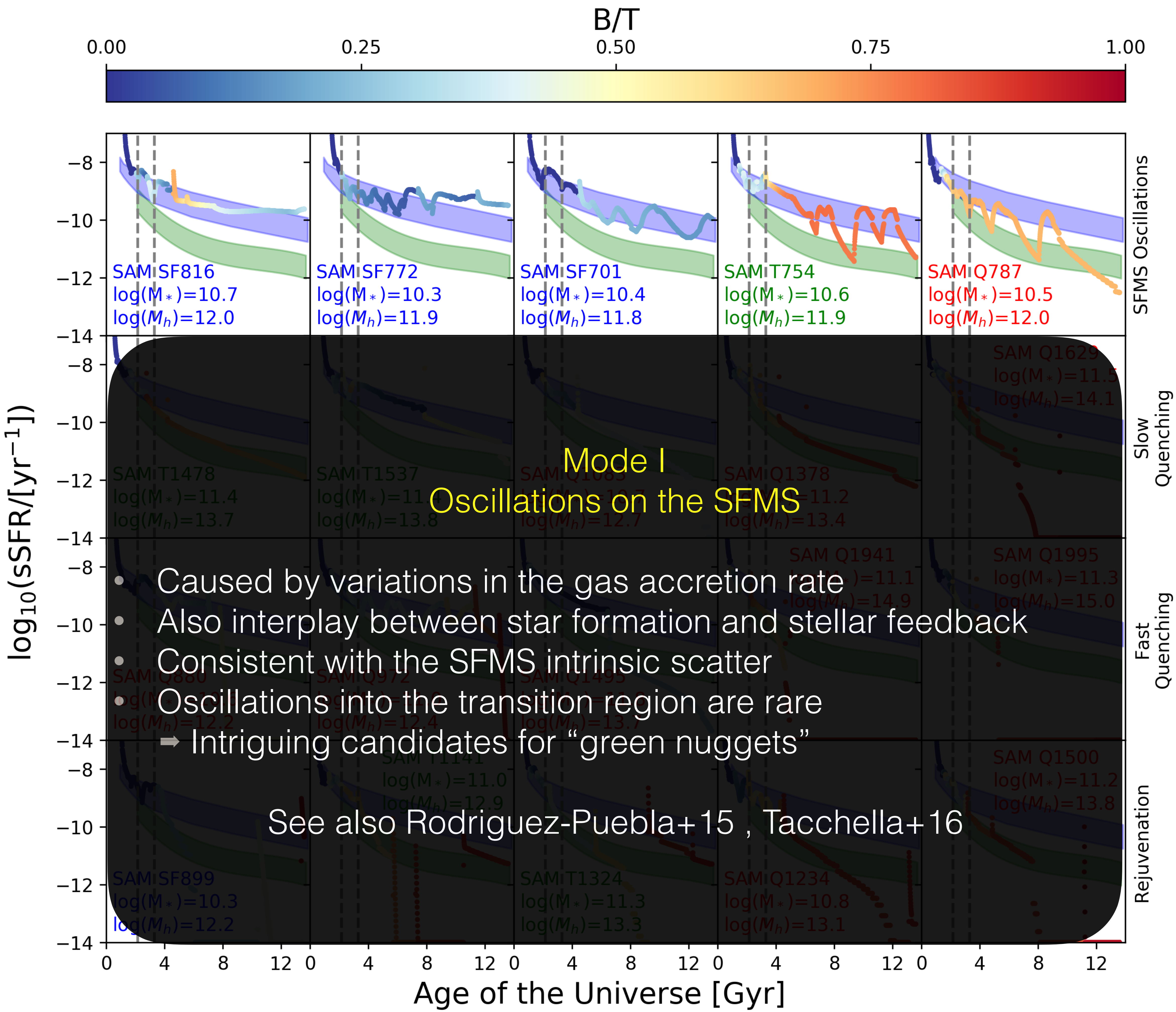
- What are all the different ways that galaxies can actually end up in the transition region in the SAM?

- We qualitatively identified four physical origin scenarios for transition galaxies in the SAM (restricted to $z<3$):

    1. Oscillations on the SFMS
    2. Slow Quenching
    3. Fast Quenching
    4. Rejuvenation



B/T
0.00
0.25
0.50
0.75
1.00
SFMS Oscillations
Slow Quenching
Fast Quenching
Rejuvenation
SAM SF816 log(M∗)=10.7 log(Mh)=12.0
SAM SF772 log(M∗)=10.3 log(Mh)=11.9
SAM SF701 log(M∗)=10.4 log(Mh)=11.8
SAM T754 log(M∗)=10.6 log(Mh)=11.9
SAM Q787 log(M∗)=10.5 log(Mh)=12.0
SAM T1478 log(M∗)=11.4 log(Mh)=13.7
SAM T1537 log(M∗)=11.4 log(Mh)=13.8
SAM Q1083 log(M∗)=10.7 log(Mh)=12.7
SAM Q1378 log(M∗)=11.2 log(Mh)=13.4
SAM Q1629 log(M∗)=11.5 log(Mh)=14.1
SAM Q880 log(M∗)=10.6 log(Mh)=12.2
SAM Q972 log(M∗)=11.0 log(Mh)=12.4
SAM Q1495 log(M∗)=11.8 log(Mh)=13.7
SAM Q1941 log(M∗)=11.1 log(Mh)=14.9
SAM Q1995 log(M∗)=11.3 log(Mh)=15.0
SAM SF899 log(M∗)=10.3 log(Mh)=12.2
SAM T1141 log(M∗)=11.0 log(Mh)=12.9
SAM T1324 log(M∗)=11.3 log(Mh)=13.3
SAM Q1234 log(M∗)=10.8 log(Mh)=13.1
SAM Q1500 log(M∗)=11.2 log(Mh)=13.8
log10(sSFR/[yr−1])
Age of the Universe [Gyr]



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SFMS Oscillations
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log10(sSFR/[yr−1])
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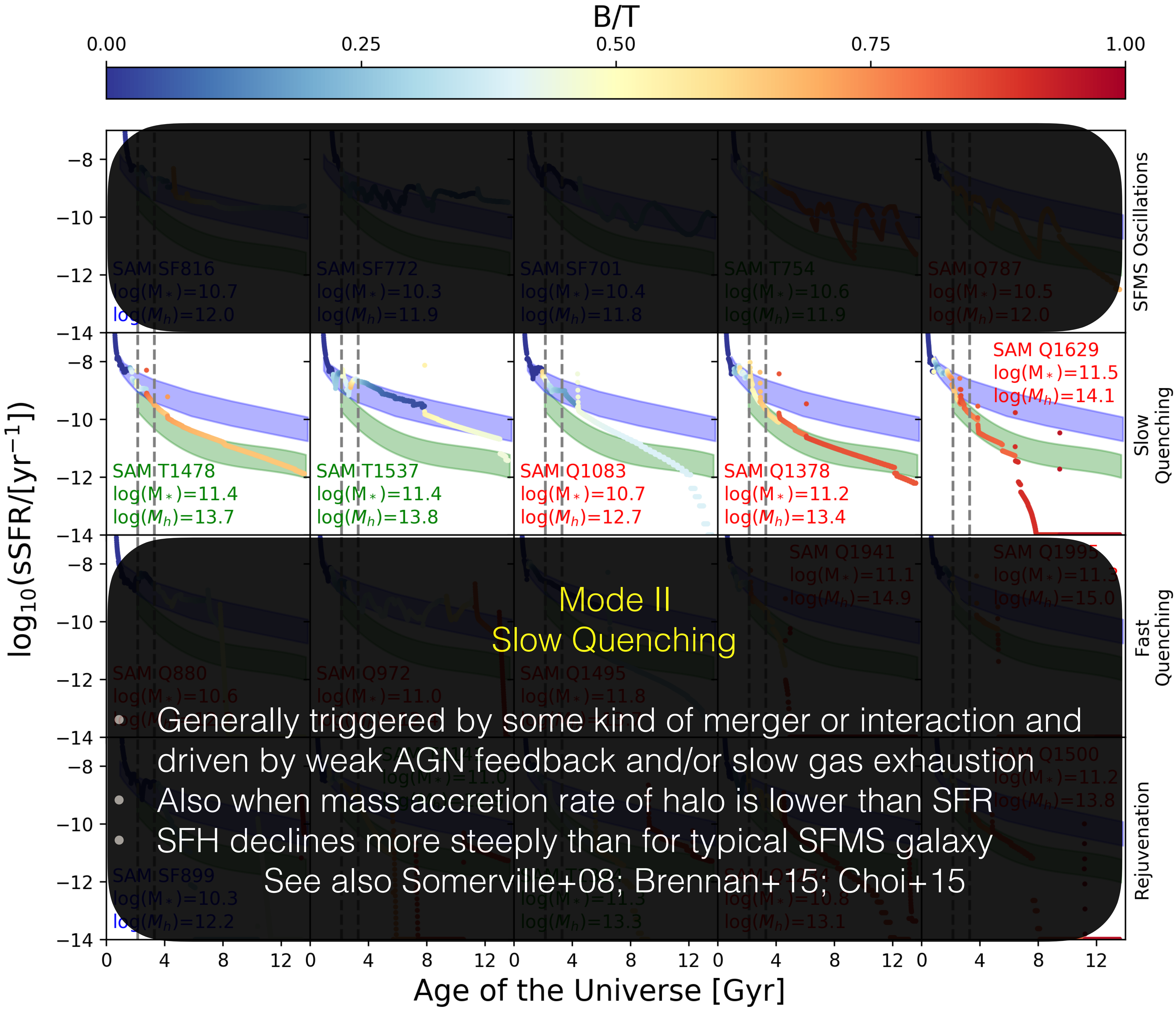
Mode I
Oscillations on the SFMS
Caused by variations in the gas accretion rate
Also interplay between star formation and stellar feedback
Consistent with the SFMS intrinsic scatter
Oscillations into the transition region are rare
➡ Intriguing candidates for “green nuggets”
See also Rodriguez-Puebla+15 , Tacchella+16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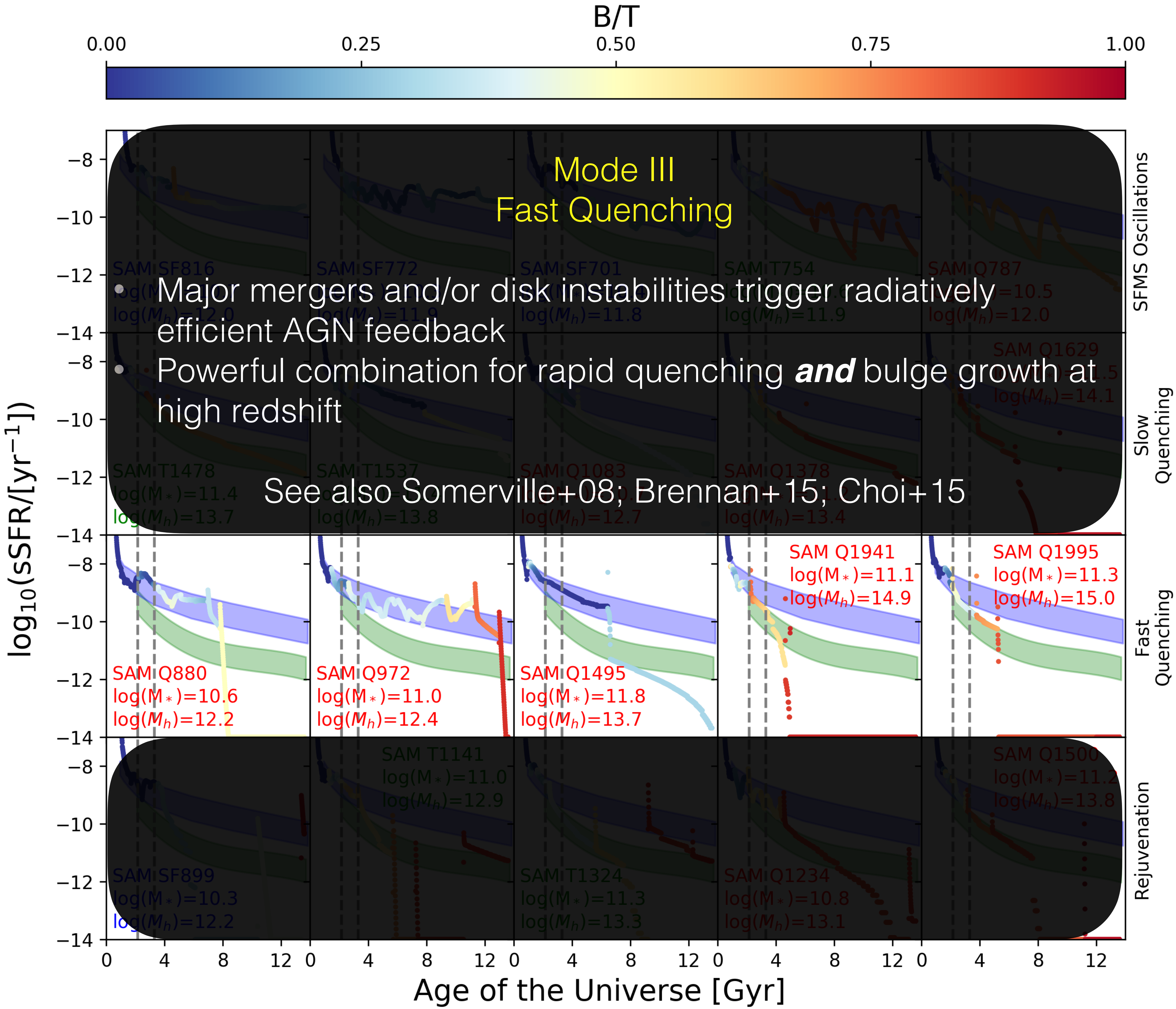
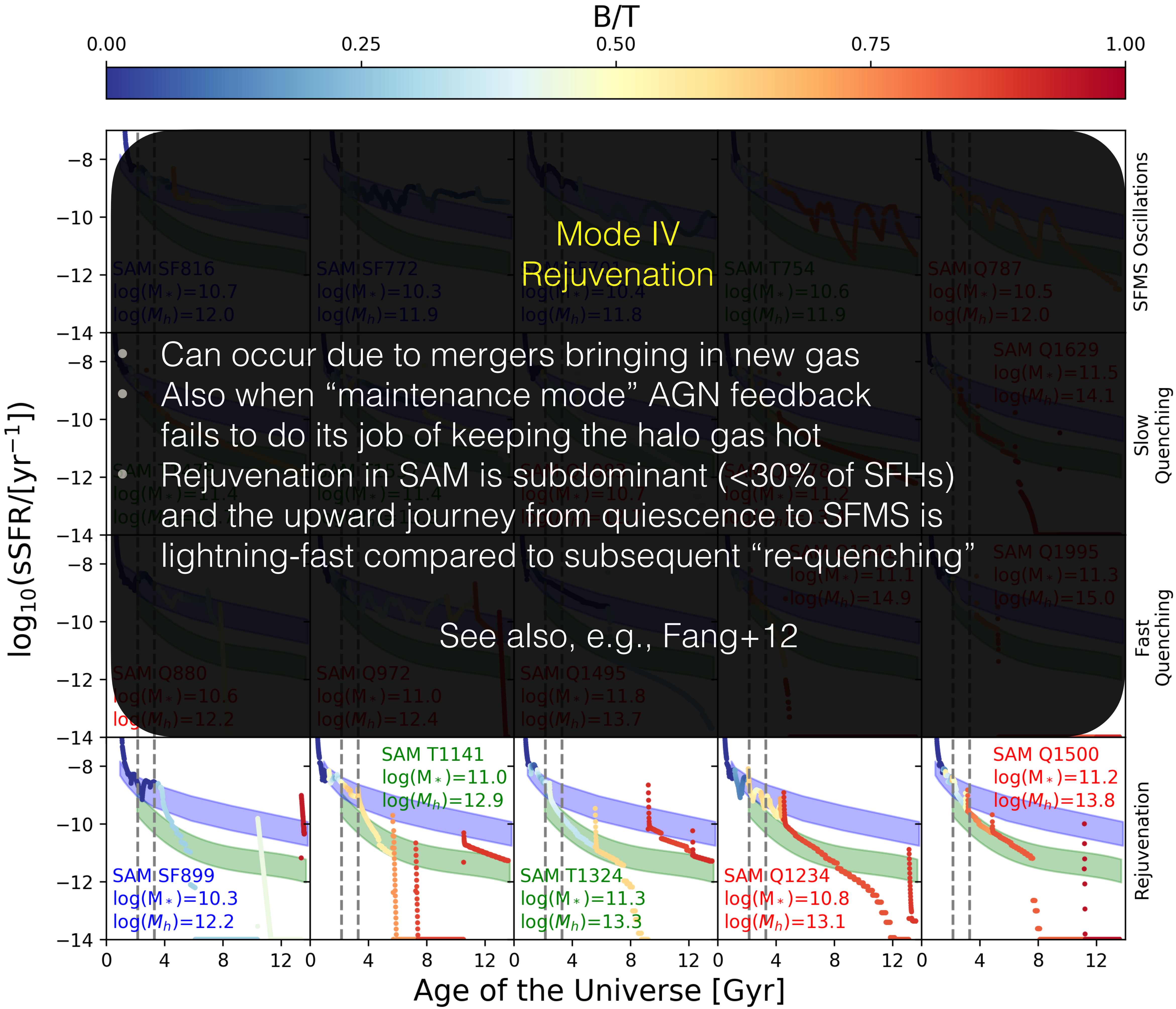
SAM Q1629
log(M*)=11.5
log(Mh)=14.1
Mode II
Slow Quenching
Generally triggered by some kind of merger or interaction and driven by weak AGN feedback and/or slow gas exhaustion
Also when mass accretion rate of halo is lower than SFR
SFH declines more steeply than for typical SFMS galaxy
See also Somerville+08; Brennan+15; Choi+15

Mode III
Fast Quenching

- Major mergers and/or disk instabilities trigger radiatively efficient AGN feedback
- Powerful combination for rapid quenching ***and*** bulge growth at high redshift

See also Somerville+08; Brennan+15; Choi+15





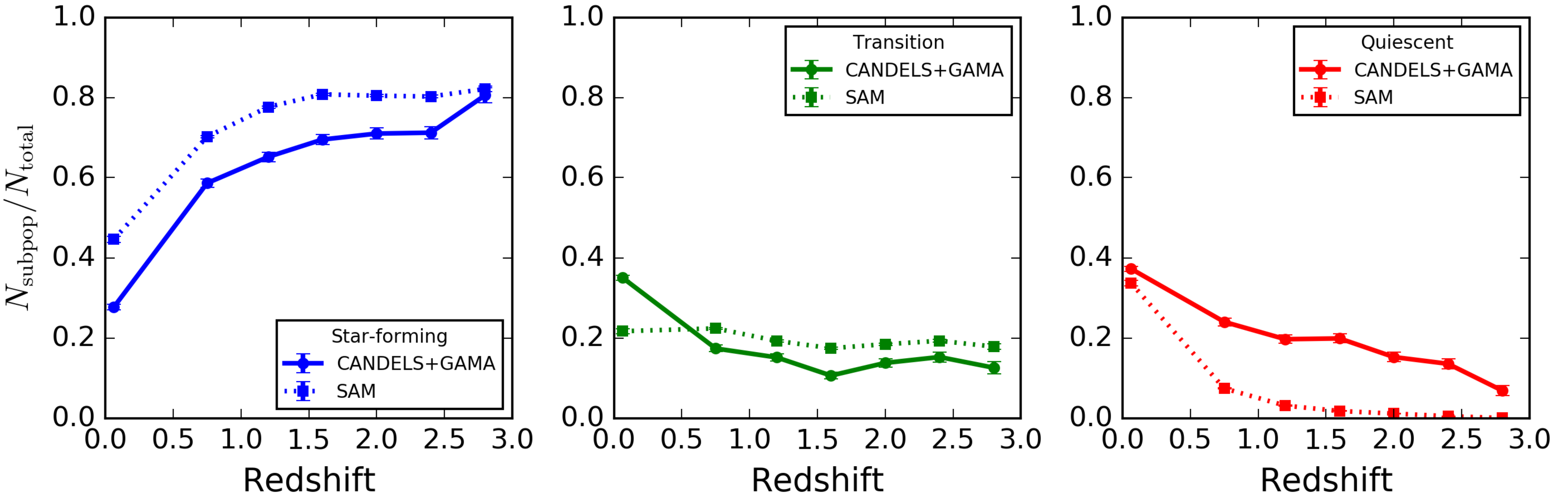
Mode IV
Rejuvenation

- Can occur due to mergers bringing in new gas
- Also when "maintenance mode" AGN feedback fails to do its job of keeping the halo gas hot
- Rejuvenation in SAM is subdominant (<30% of SFHs) and the upward journey from quiescence to SFMS is lightning-fast compared to subsequent "re-quenching"

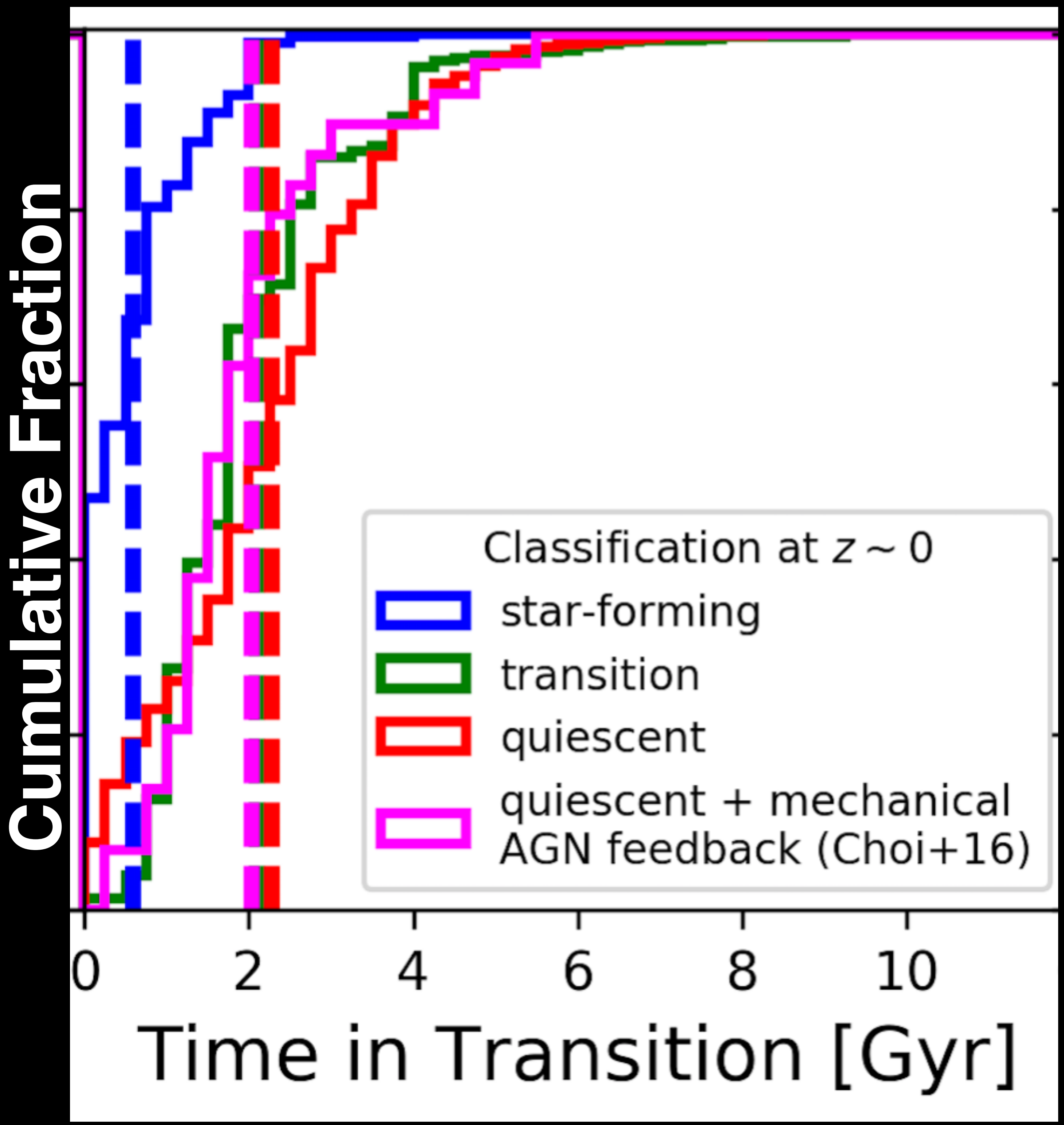
See also, e.g., Fang+12

The Transition Fraction Across Cosmic Time

- Interestingly, the transition fraction is roughly constant (in both the observations and the SAM)
- The SAM has a severe deficit of quiescent galaxies at z>1 relative to the observations, but it matches well at z~0.1



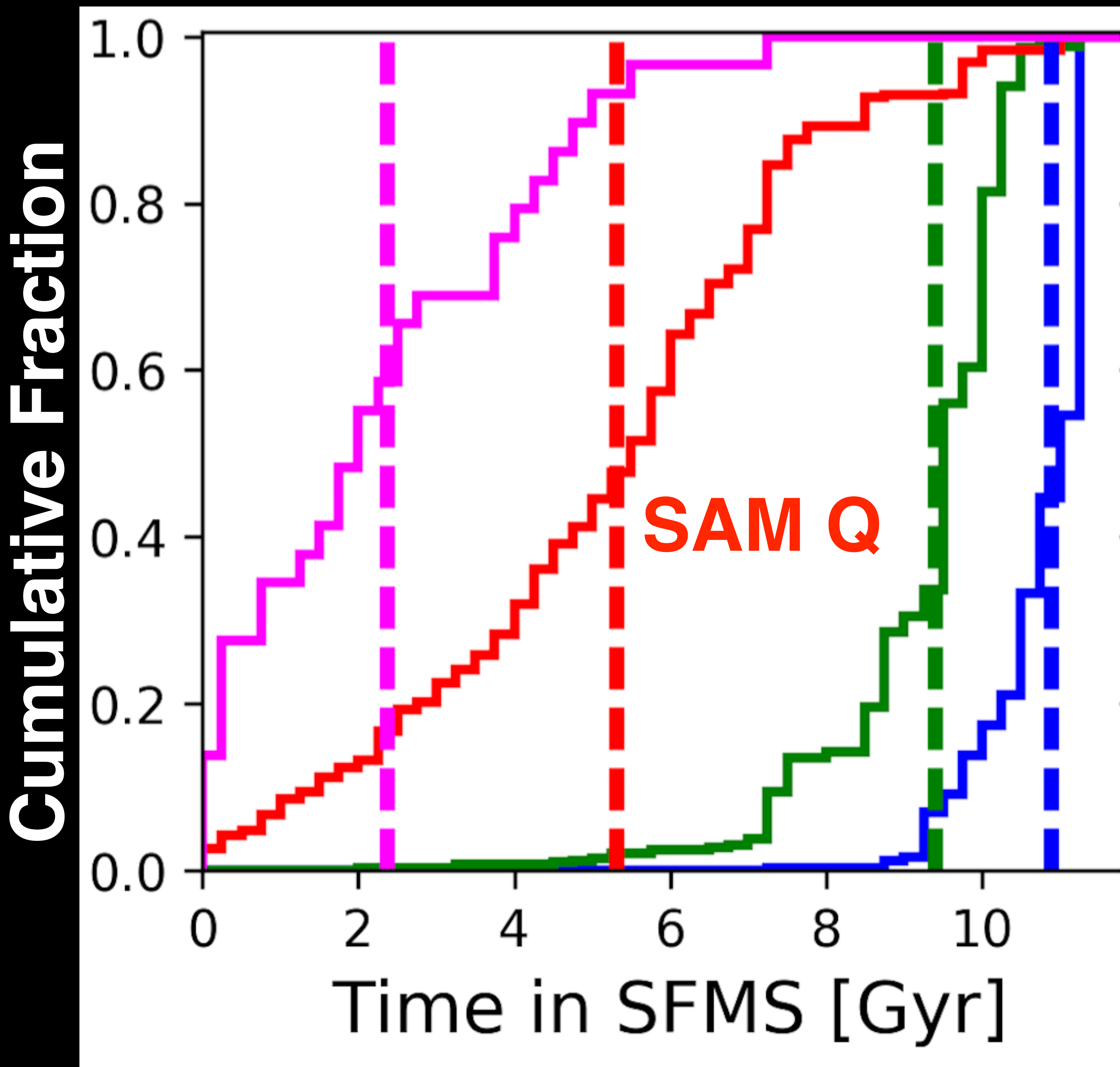
Why is the transition fraction constant in the SAM?



Since z=3

- For every z=0 SAM galaxy, we can simply trace its SFH back to z=3 and count up the total time it spent in the SFMS, transition region, and quiescence
- The transition fraction is constant in the SAM because galaxies are moving into and out of the transition region at various epochs on a wide variety of timescale
- Average transition region occupation timescale ~ 2 Gyr since z=3 (see left)

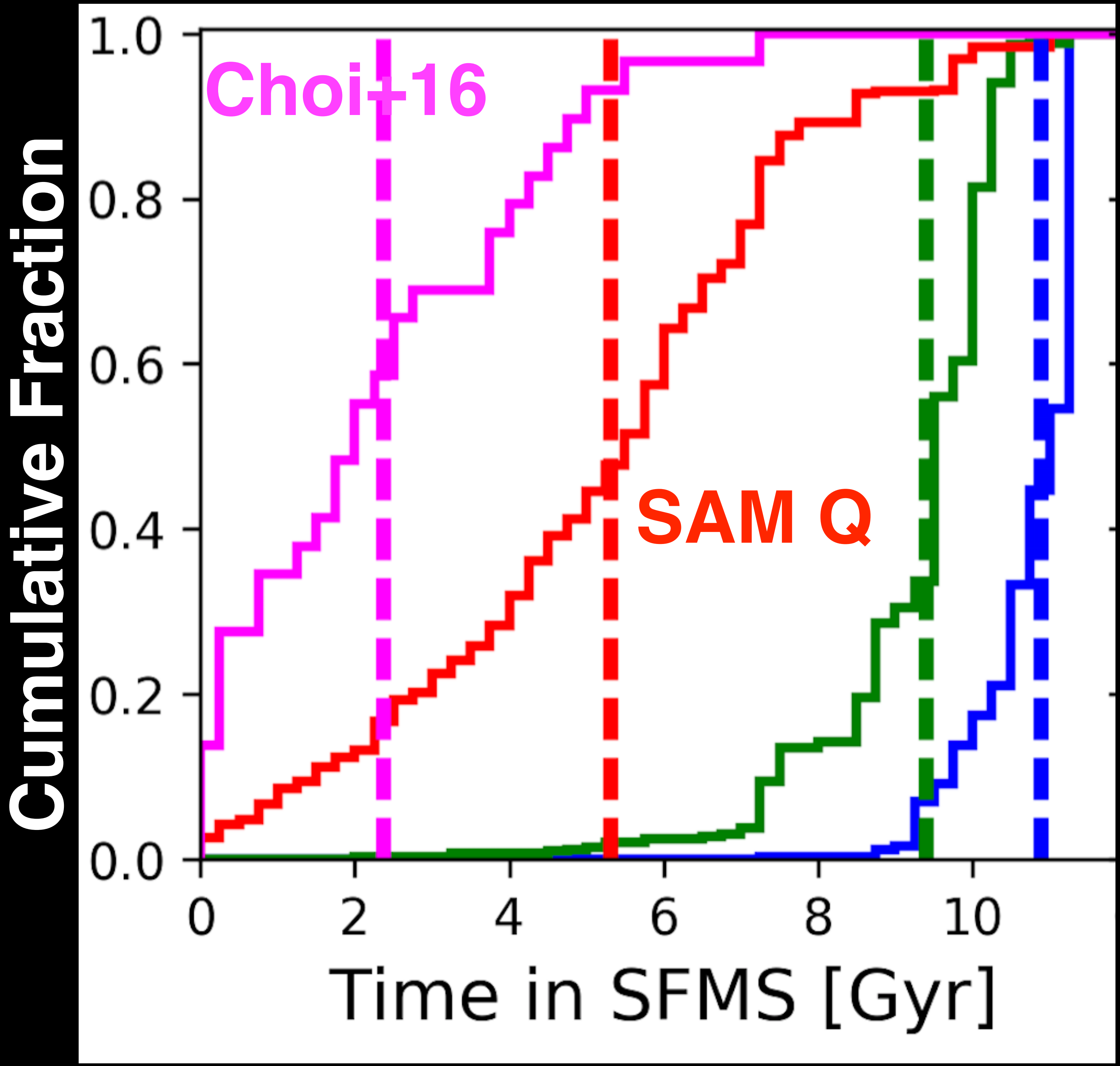
Why is the SAM missing high-z quiescent galaxies?



Since z=3

- Overall rate at which galaxies quench in SAM is correct: it matches the observed quiescent fraction at z~0.1
- But the average z=0 quiescent SAM galaxy did not begin to quench until z~0.7 (i.e., it stayed on the SFMS for ~5 Gyr since z=3; see left)
- Quenching timescales/events are too slow/late in the SAM

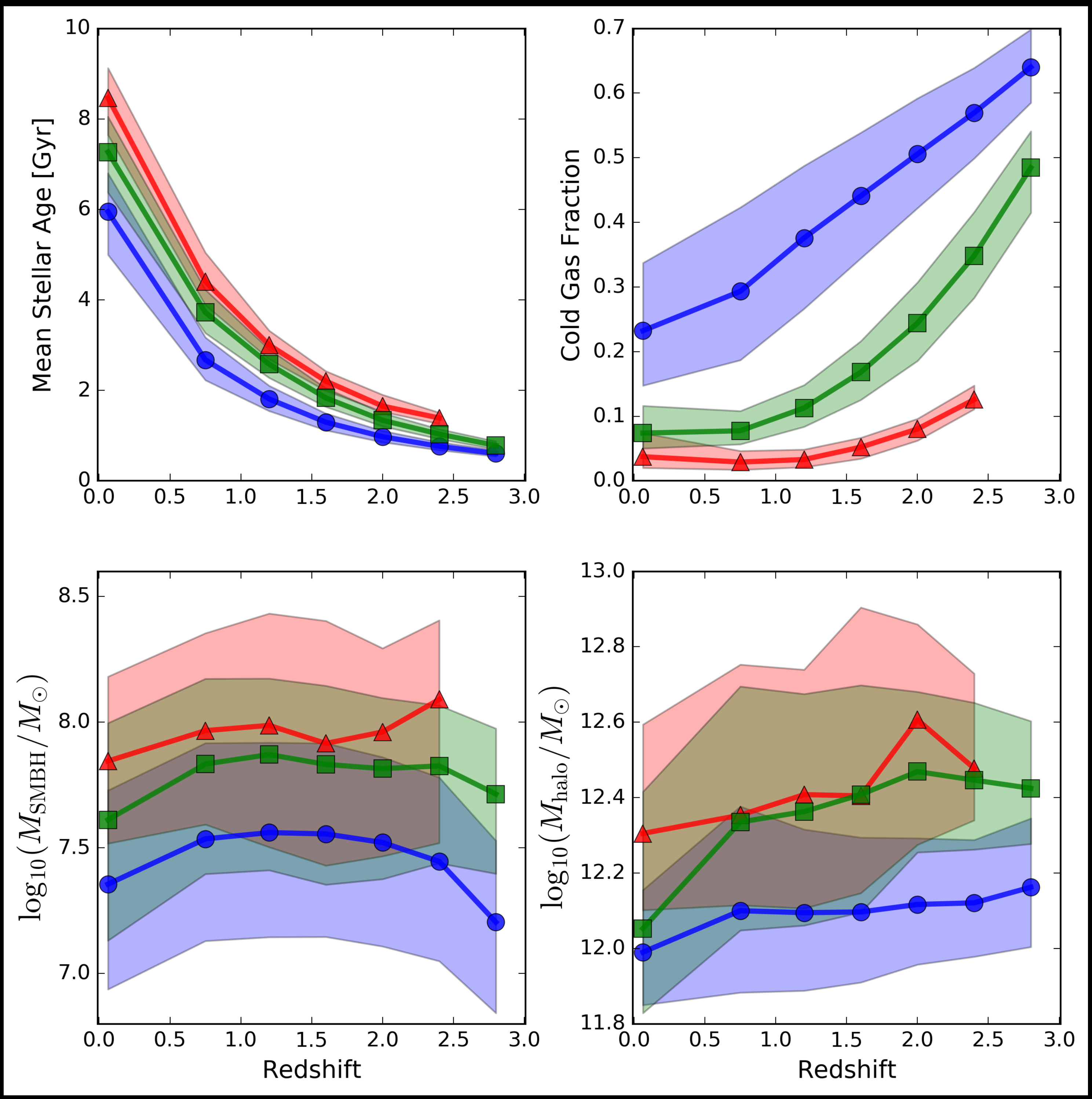
Can momentum-driven AGN feedback help?



Since z=3

- Choi+16 cosmological "zoom in" simulations include both thermal heating & momentum-driven winds due to radiation pressure from AGN
- On average, Choi+16 galaxies take ~2 Gyr since z=3 to quench, and then stay quiescent to z=0
- Thus a more sophisticated AGN model might help the SAM, but mostly at z<2

Could transition galaxies also be transitioning in other properties?



The SAM predicts that transition galaxies might exhibit intermediate:

- Mean stellar ages
- Cold gas fractions
- SMBH masses
- Halo masses

(After controlling for stellar mass dependence)

Suggests there are different ways to observationally probe the evolutionary significance of transition galaxies

Key Takeaways

- Most transition galaxies in the models, and perhaps the observations, seem to be transitioning in most properties
- The transition fraction is roughly constant out to z=3; in the SAM, this is because galaxies are moving into and out of the transition region at various epochs on a variety of timescales (*not* all rapid quenching)
- Observational upper limit on the average population transition timescale as a function of z: fast track at high-z and slow track at low-z
- In the SAM, transition galaxies have four physical origins: SFMS oscillations, slow quenching, fast quenching, and rejuvenation

See paper at arXiv:1611.03869