The Green Valley is a Red Herring: Galaxy Zoo reveals two evolutionary pathways towards quenching of star formation in early- and late-type galaxies

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Jonathan D.
Hernández Fernández

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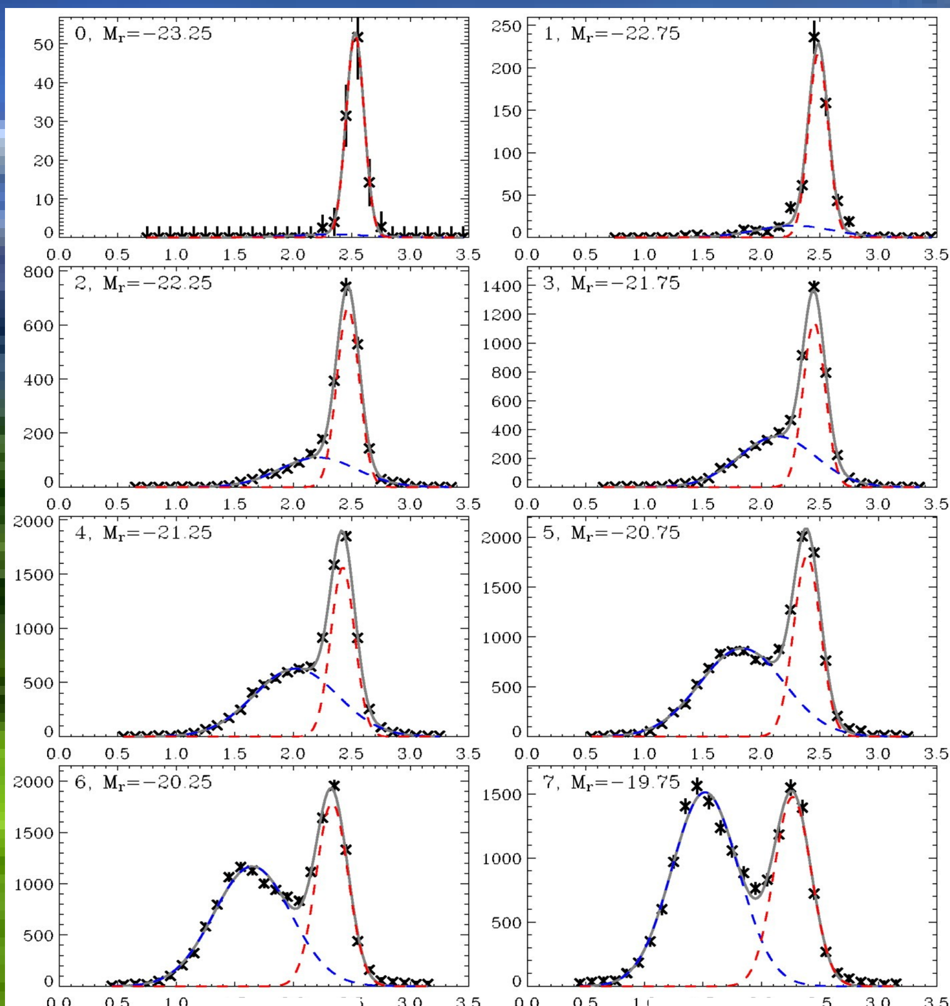
Two evolutionary pathways through the green valley

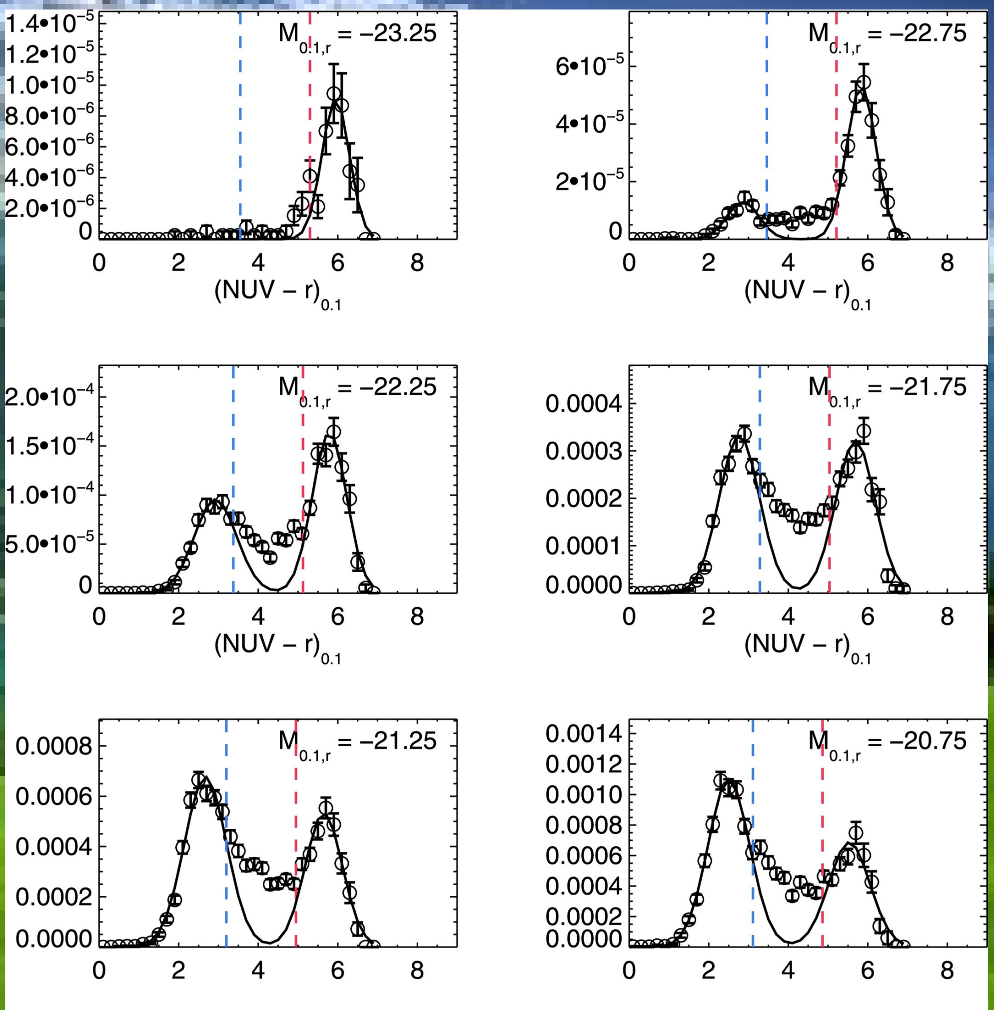
Green valley population appears
in the frame of
the ultraviolet-optical color-magnitude diagram
GALEX & SDSS
Wyder et al. (2007)

Two evolutionary pathways through the green valley



u'-r'

u'-r'



NUV-r'

NUV-r'

Baldry et al. 2003

Wyder et al. 2007

Morphology vs. color

early-types

blue

red

late-types

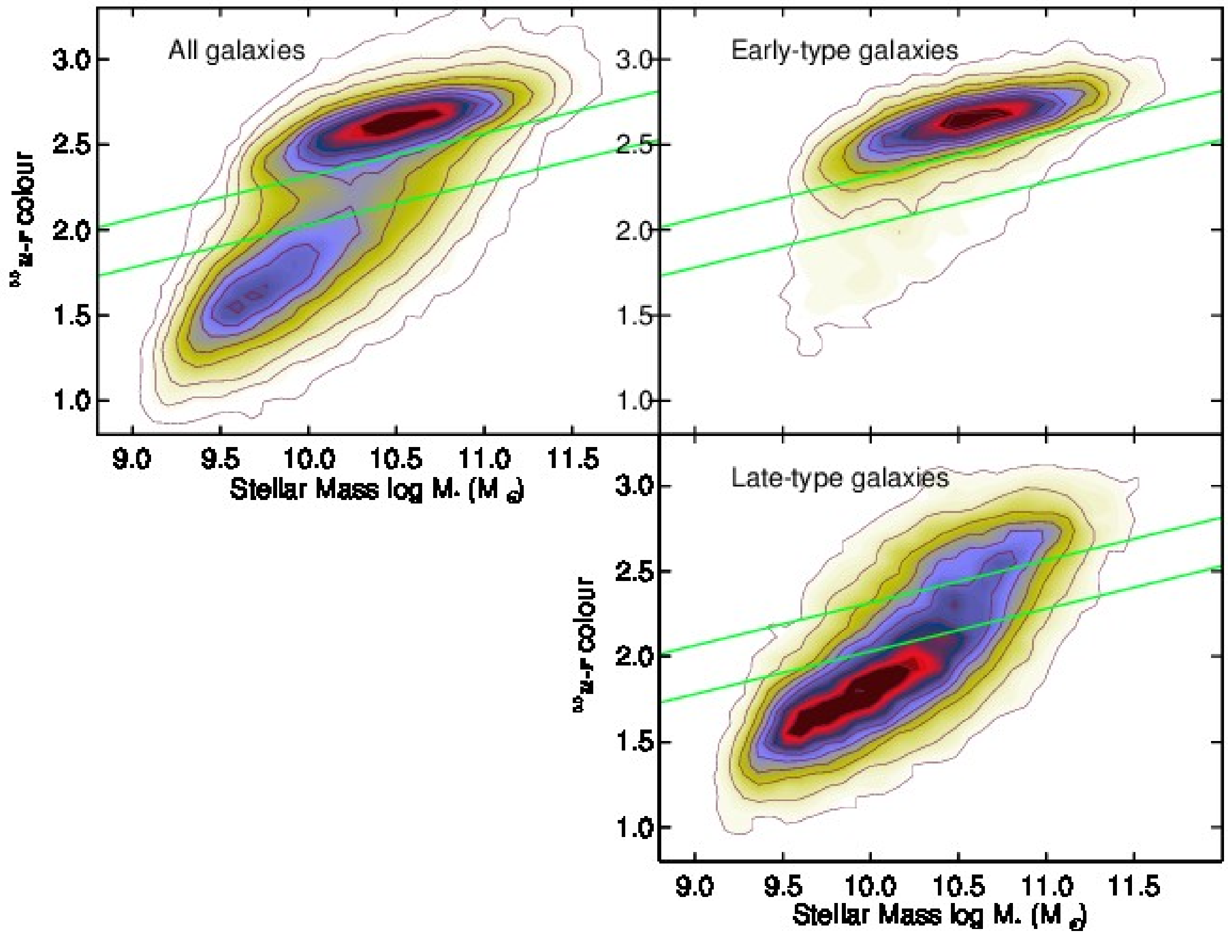
Morphology classification provides by the Galaxy Zoo project (Lintott et al. 2008, 2011)

The sample

The sample is limited in redshift to
$0.02 < z < 0.05$ and limited in absolute luminosity to
$M_{z,petro} < -19.50$ AB (~ giants;
for dwarfs see Boselli et al. 2008)

Galaxy sample	Number	% of population
Early blue	464	5.2%
Early green	1,110	12.4%
Early red	7,404	82.5%
Early all	**8,978**	
Late blue	12,380	74.1%
Late green	3,152	18.9%
Late red	1,175	7.0%
Late all	**16,707**	

u-r vs. M$_*$


All galaxies
Early-type galaxies
Late-type galaxies
$^{0.0}u-r$ colour
Stellar Mass log M$_*$ (M$_\odot$)
3.0
2.5
2.0
1.5
1.0
9.0
9.5
10.0
10.5
11.0
11.5

u-r vs. M_*

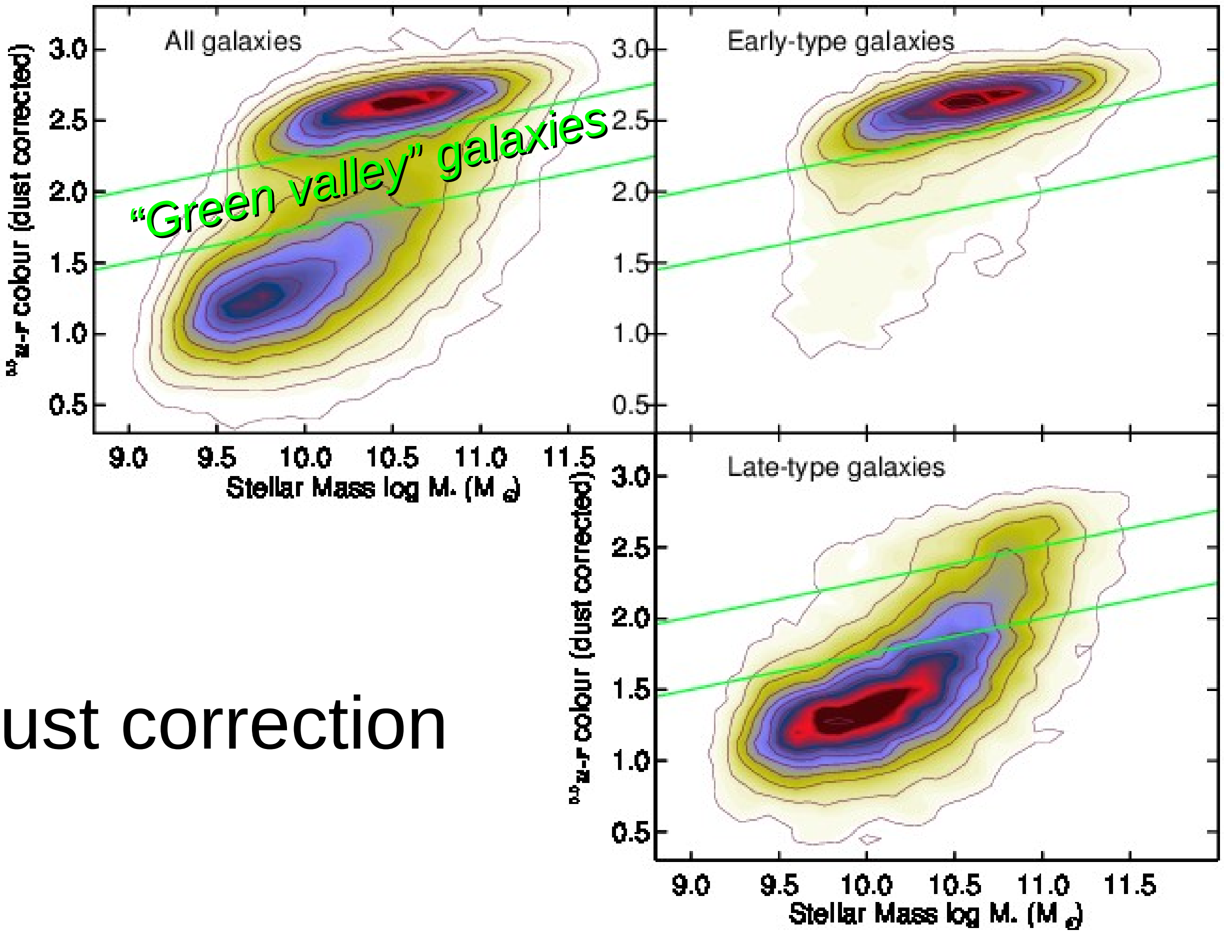
(i) Both early- and late-type galaxies span almost the entire u-r colour range; that is, the classification by morphology reveals populations of blue early-type galaxies and of red late-type galaxies (e.g., Schawinski et al. 2009a; Masters et al. 2010a).

(ii) The green valley appears as a dip between bimodal colours only in the all-galaxies panel; within a given morphological class, there is no green valley, just a gradual decline in number density.

- Most early types lie in the red sequence with a long tail of 10% of the population reaching the blue cloud, which could represent a population in rapid transition, commensurate with the original idea of the green valley as a transition zone.

- The late-type galaxies, however, do not separate into a blue cloud and a red sequence, but rather form a continuous population ranging from blue to red without a gap or valley in between.

u-r vs. M$_*$



Dust correction

We take the measured E(B-V) values from Oh et al. 2011 (based on the GANDALF code Cappellari & Emsellem 2004; Sarzi et al. 2006), and use the Calzetti et al. (2000) extinction law; for the GALEX magnitudes, we use the Cardelli et al. (1989) law.

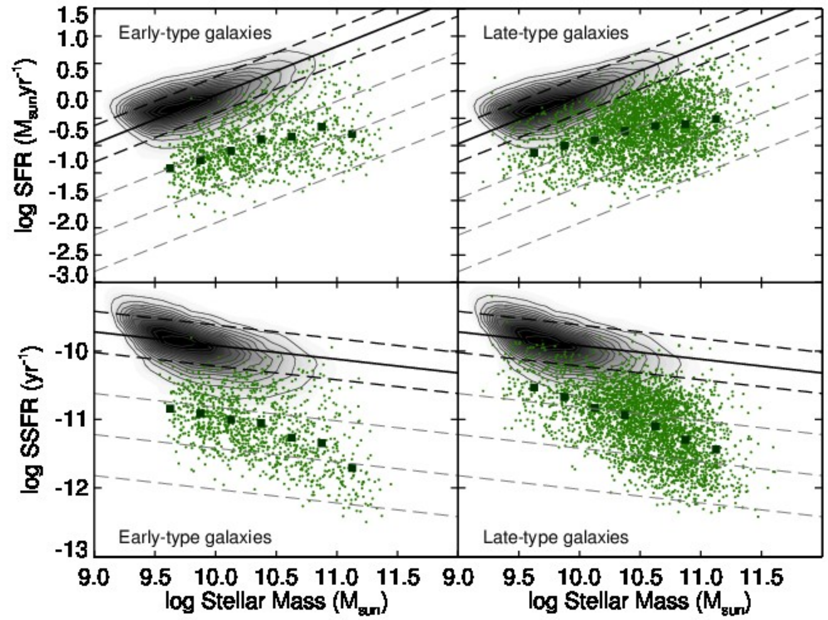
u-r vs. M_*

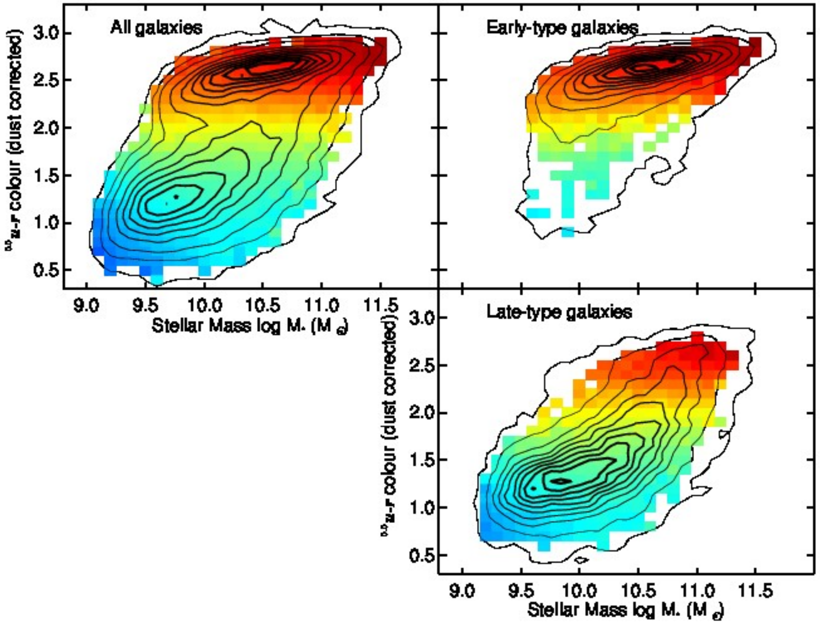
The main differences after correcting for dust reddening are that the blue cloud (i.e., the main sequence) is now bluer, and the slope to redder colours with increasing mass flattens (presumably driven by dust from higher SFRs).

The separation of the blue cloud and red sequence also becomes more prominent. Vitally, the green valley population in both the early- and late-type population does not disappear, and red late-type galaxies remain; not all of them were dusty starformers.

Thus, dust correction is important but does not greatly change the global picture

Star formation activity

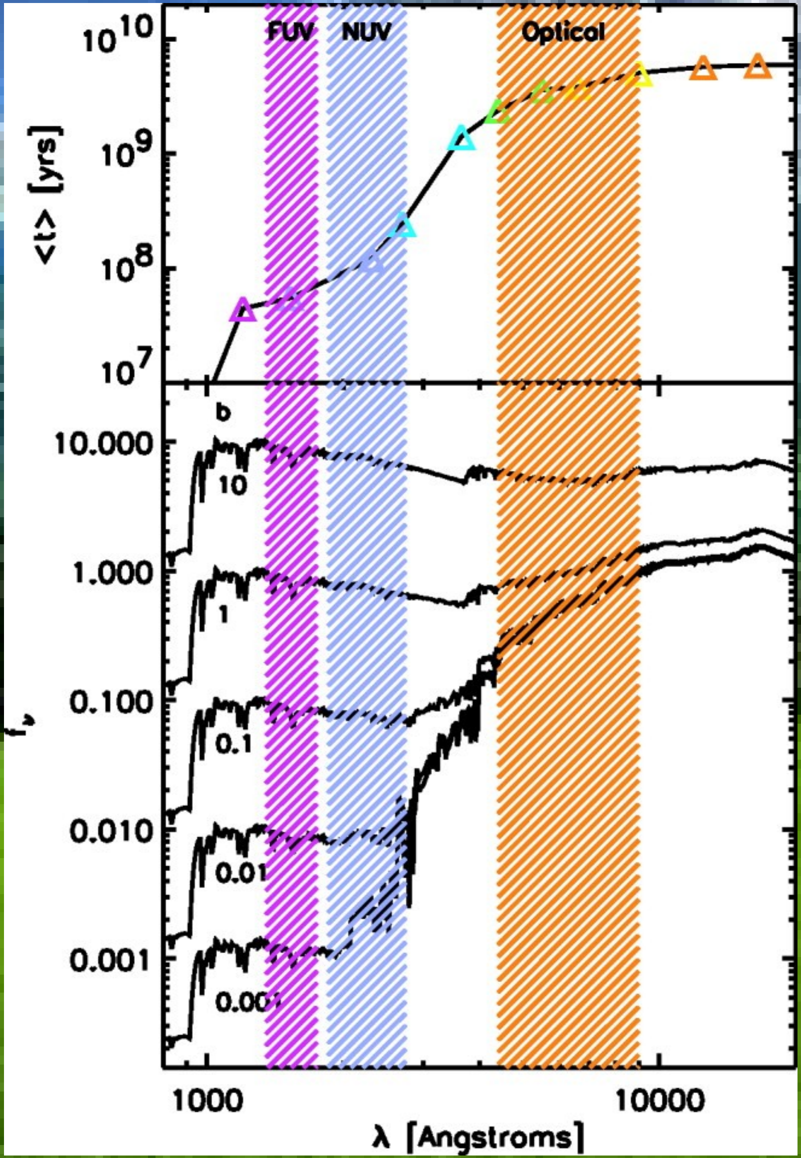




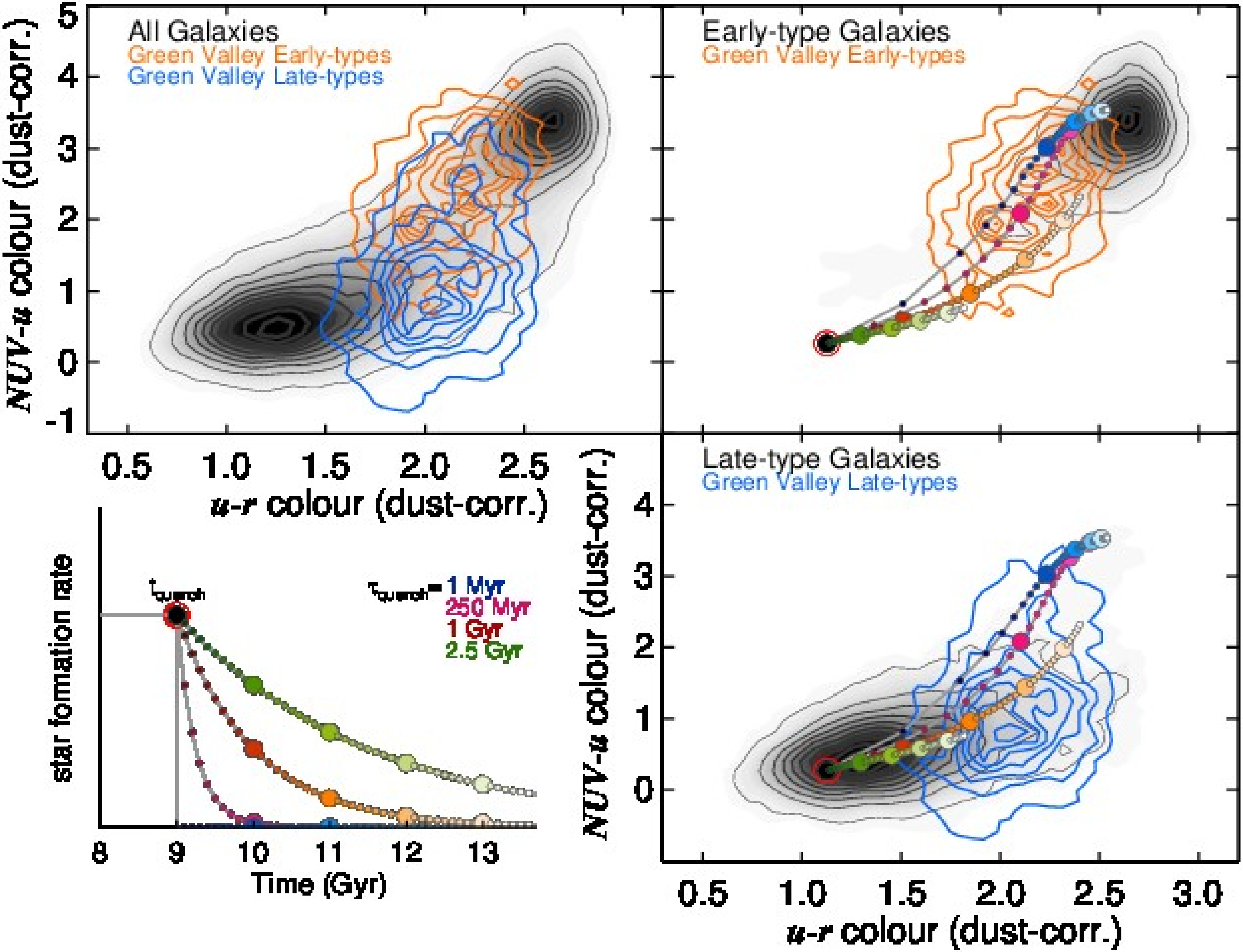
Specific star formation rate:
SSFR = SFR / M_*

UV bands & recent SF

<t> is the average age t_{age} weighted by the flux f_λ of a simple composite stellar population

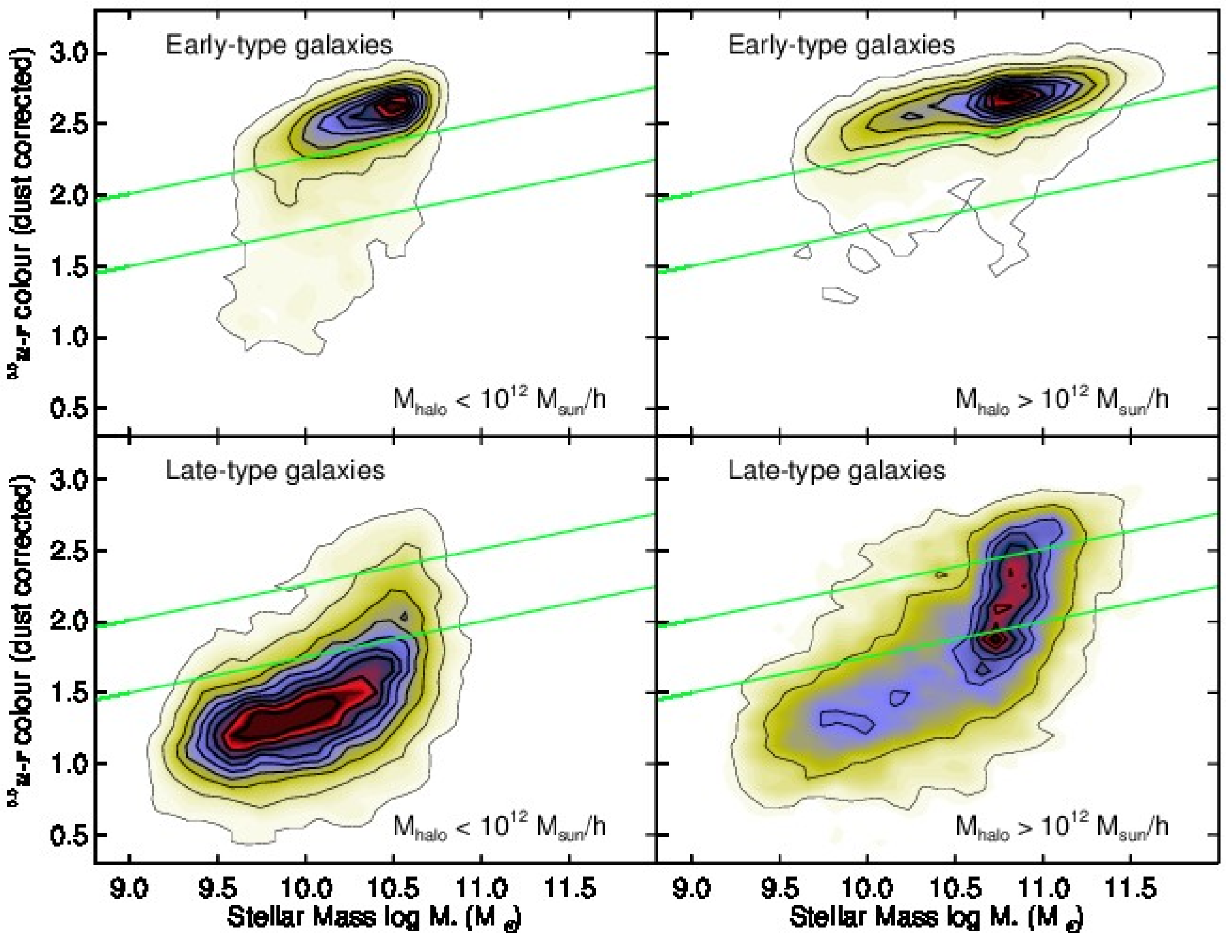


Martin et al. 2005



All Galaxies
Green Valley Early-types
Green Valley Late-types
NUV-u colour (dust-corr.)
u-r colour (dust-corr.)
Early-type Galaxies
Green Valley Early-types
Late-type Galaxies
Green Valley Late-types
NUV-u colour (dust-corr.)
u-r colour (dust-corr.)
star formation rate
Time (Gyr)
t_{quench}
τ_{quench}= 1 Myr
250 Myr
1 Gyr
2.5 Gyr

Environment – Halo mas



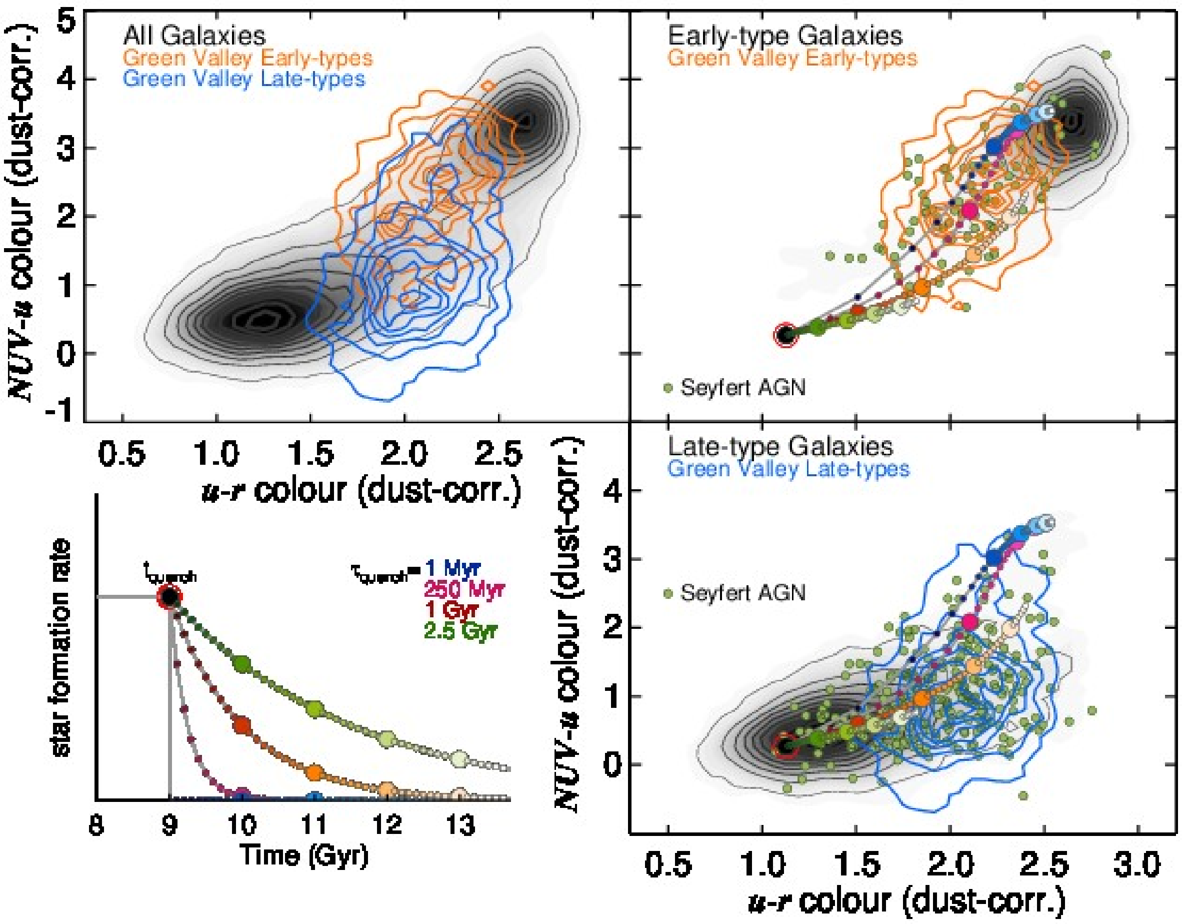
Critical halo mass ~ $10^{12}\ M_\odot$ (Cattaneo et al. 2006, Sec. 4; Dekel & Birnboim 2006).

HI content

Green valley	Number covered	Number detected	Number un-detected	HI Detection fraction
Early-type	349	28	321	9 %
Late-type	912	435	477	48 %

HI data from the Arecibo Legacy Fast ALFA Survey (ALFALFA; Haynes et al. 2011).

AGN activity



Summary with “Cartoons”

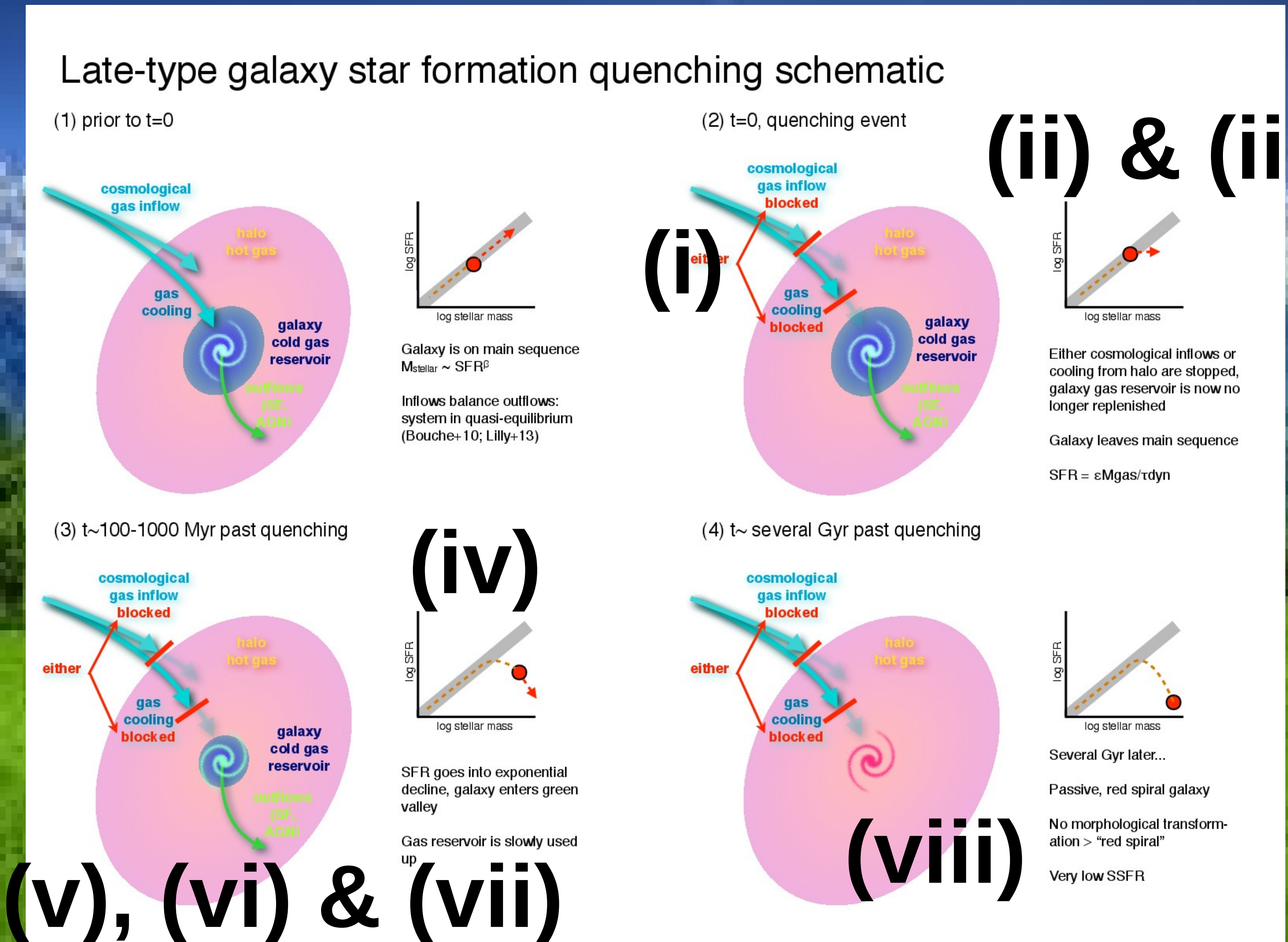
From a detailed analysis of specific star formation rates, dust-corrected UV-optical colours and other properties, we traced the evolution of early- and late-type galaxies through the green valley.

- Both leave the main sequence and enter the green valley as their sSFR drops, but they do so with very different rates of change.

- UV-optical colours show that the rate of change in sSFR (d/dt sSFR) - i.e., the quenching time scale - is rapid in early-type galaxies (< 250 Myr), while late-type galaxies undergo a much more gradual decline in star formation (~ Gyrs).

Proposed evolutionary scenarios for late-type and early-type green valley galaxies

Late-type quenching scenario



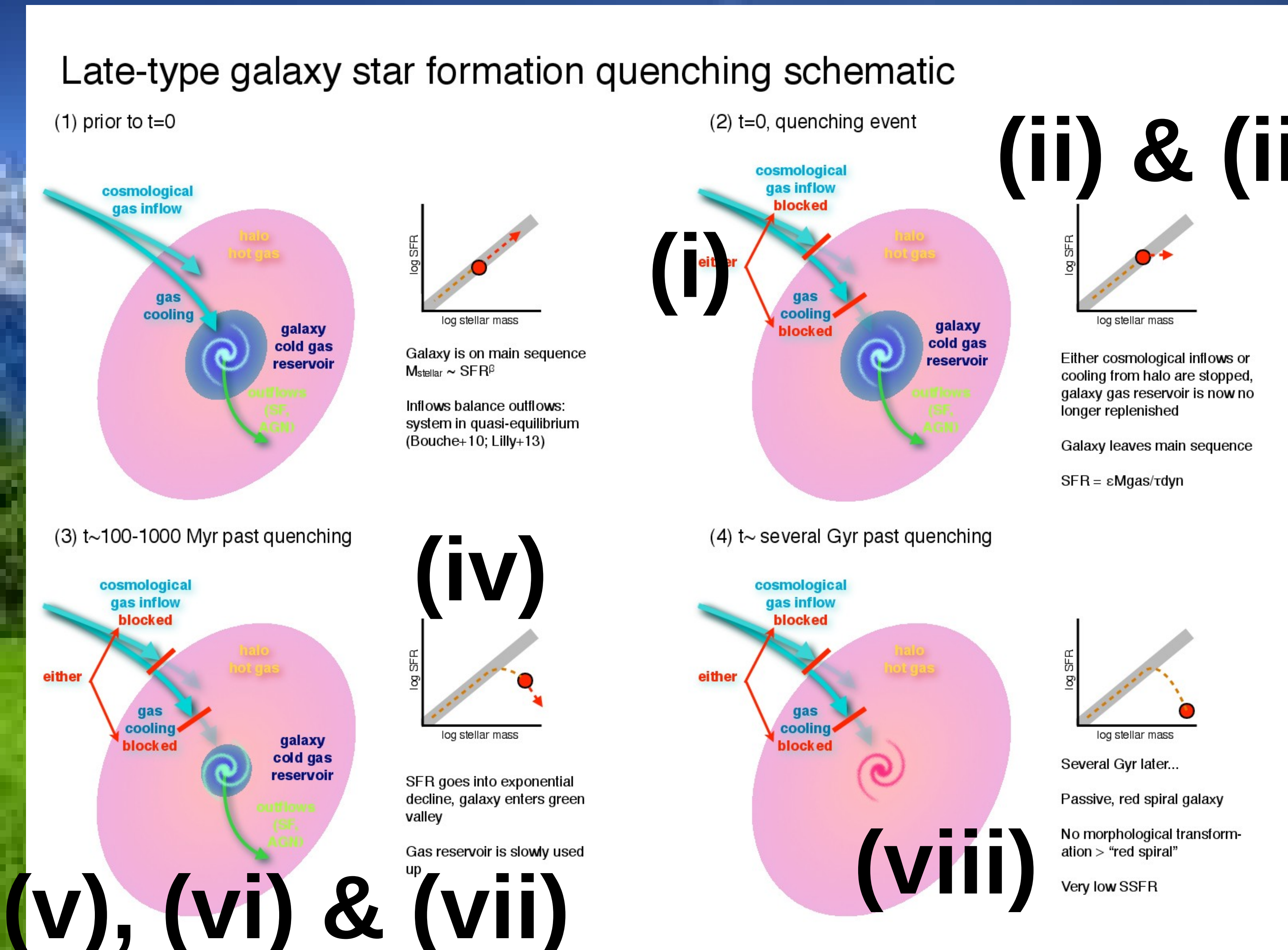
Late-type quenching scenario

(i) The quenching of star formation is initiated by a cutoff of the galaxy gas reservoir from the cosmic supply of fresh gas. This cutoff could be due, for example, to the halo mass reaching 10^{12} M, preventing further accretion of gas onto the galaxy, or to cooling of the hot halo gas becoming inefficient.

(ii) This disturbance of the balance of inflows and outflows moves the galaxy off the main sequence, as star formation uses up the remaining gas and the gas reservoir is not replenished. Where initially the galaxy SFR scales nearly linearly with the stellar mass (the main sequence), it then declines exponentially after quenching commences, with a long characteristic time scale that to first order is set by the gas reservoir at the time quenching begins and the dynamical time scale of the galaxy disk.

(iii) Since the SFR is declining, but not zero, the stellar mass may continue to increase as star formation converts the remaining gas reservoir to stars.

Late-type quenching scenario



Late-type quenching scenario

(iv) The galaxy moves slowly out of the blue cloud and into the green valley. Objects that were quenched this way at high redshift may by now have reached the red sequence, accounting for the red spiral population.

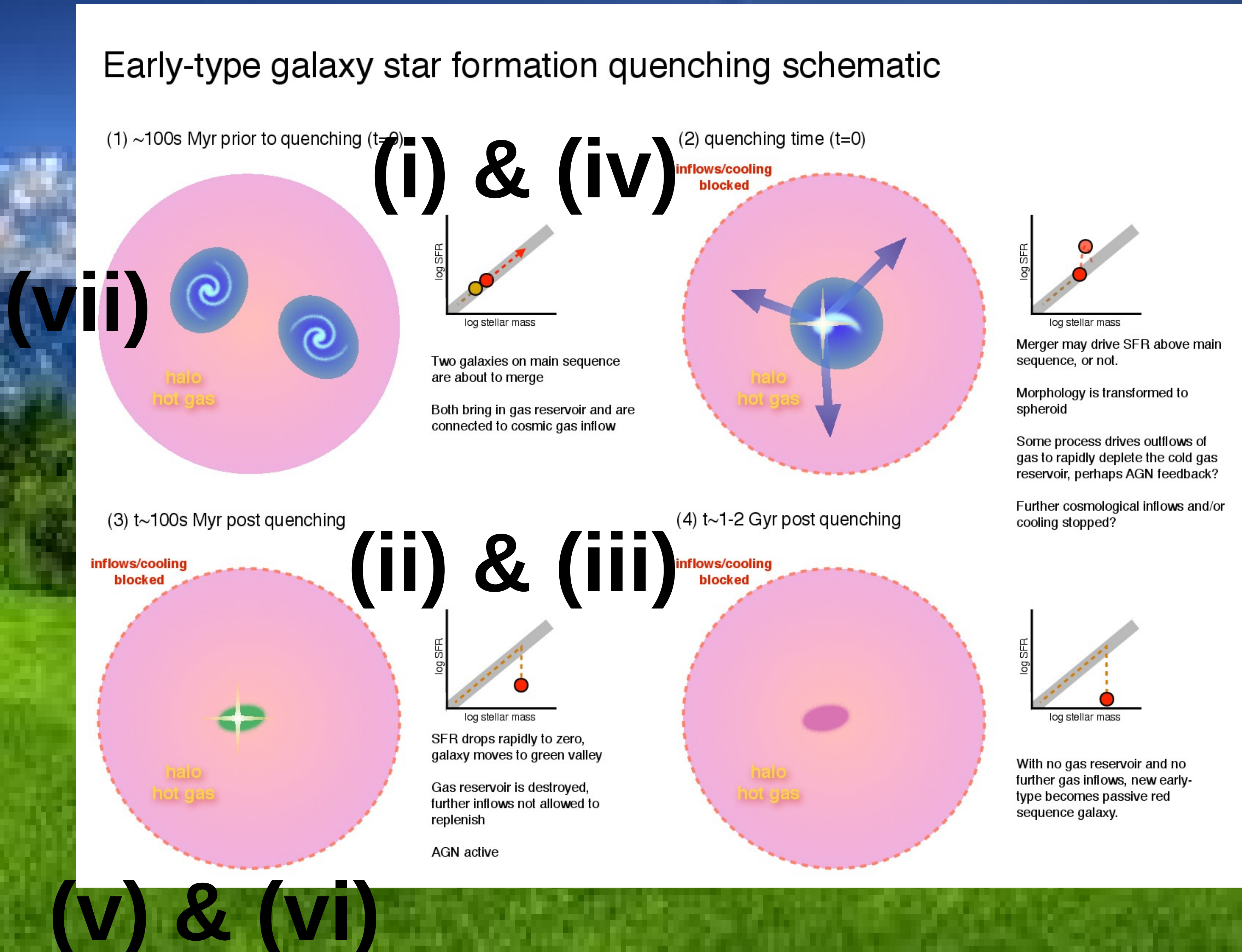
(v) The gas-depletion process can be accelerated by other physical processes, in particular secular processes and environmental processes.

(vi) Black hole accretion appears to be favoured in late types that have been quenched and are in the exponential decline phase.

(vii) Observations of still-significant gas reservoirs and high dark matter halo masses support this evolutionary scenario.

(viii) The time delay between the quenching event (i.e., the point at which the external gas supply to the galaxy reservoir is cut off) and the time that the quenching becomes apparent (by movement out of the blue cloud and into the green valley) is long, on the order of several gigayears. This means that studying the local green valley galaxies will not allow us to understand this quenching mode or directly observe it in action. It also means that the green and red late types we see today may be the amongst the first to have quenched. The Milky Way may be on a similar trajectory to quiescence.

Early-type quenching scenario



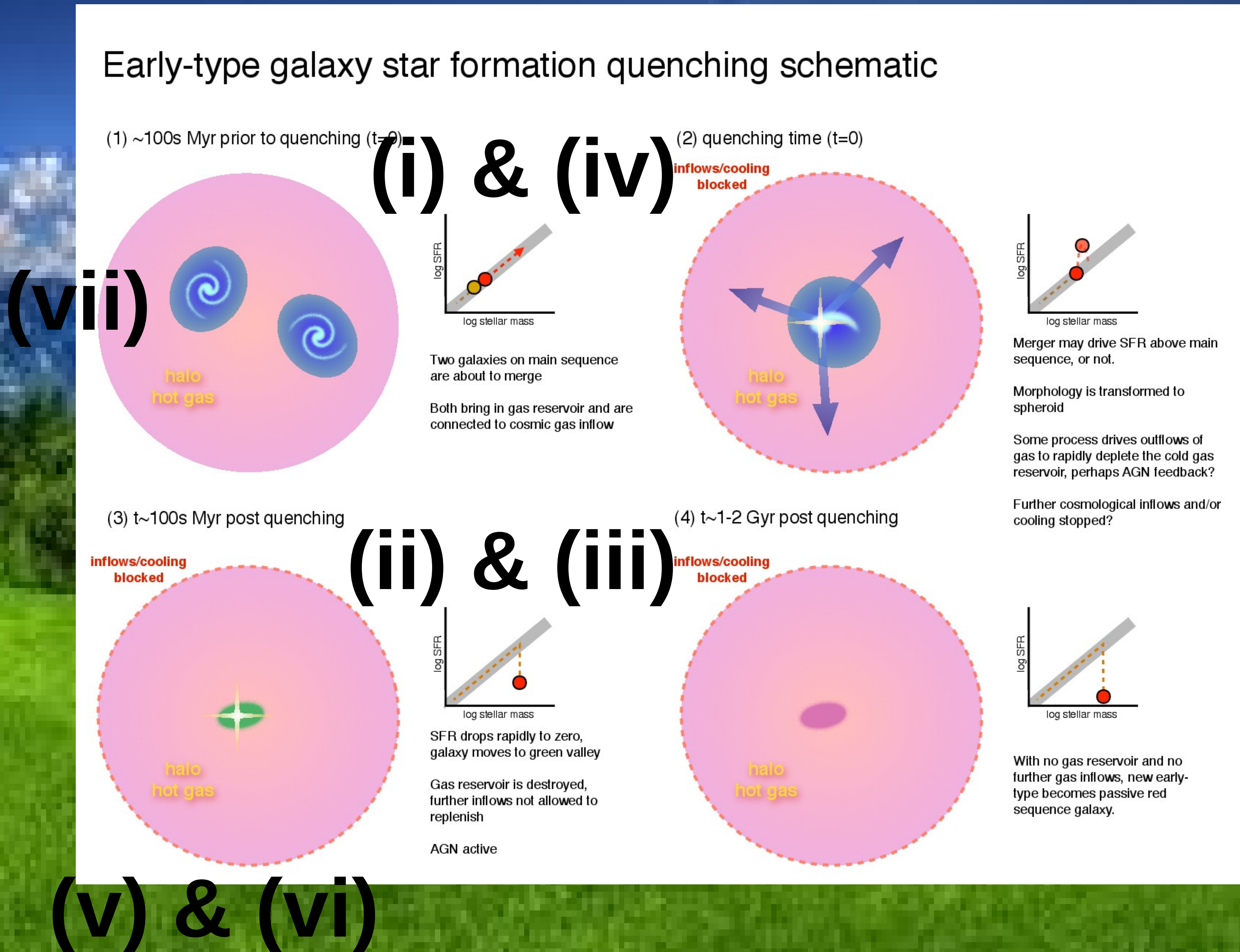
Early-type quenching scenario

(i) The quenching of star formation is triggered by the rapid destruction of the galaxy gas reservoir. This must occur rapidly and can not be due to gas exhaustion by star formation alone.

(ii) The destruction of the gas reservoir triggers the immediate departure from the main sequence of the galaxy. The SFR rapidly approaches zero, which means the galaxy no longer increases its stellar mass.

(iii) The drop in SFR corresponds to the galaxy moving out of the blue cloud, into the green valley and to the red sequence as fast as stellar evolution allows. The transition process in terms of galaxy colour takes about 1 Gyr.

Early-type quenching scenario



Early-type quenching scenario

(iv) The rapid quenching event is effectively simultaneous with the morphological transformation, since there are very few blue early-type galaxies. This suggests a common origin in a major merger.

(v) Visible radiation from black hole accretion is associated with the green valley, i.e., only after the quenching event.

(vi) The rapidity of the gas reservoir destruction suggests that unusually strong stellar process and/or AGN feedback (winds, ionization) are involved, perhaps in a kinetic or highly obscured phase.

(vii) To understand the physics of quenching in early types more fully requires observations of the progenitors of the blue early types - most likely major, gas-rich mergers - where we can see which processes (AGN or not) destroying the gas reservoir.