Galaxy Quenching and AGN Feedback
or, why the green valley is a red herring

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Star forming galaxies are on main sequence: $M_{\text{stellar}} \sim \text{SFR}^\beta$, with small scatter. Scatter small, holds out to at least $z \sim 2$, perhaps higher. See: Brinchmann+04; Elbaz+07,11, Noeske+07; Salim+07; Peng+10; Lee+12
Data
SDSS DR7
Galaxy Zoo 1 morphologies
GALEX GR6
MPA-JHU masses & SFRs
OSSY emission lines
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sSFRs in the Green valley: Both early- and late-types show same low sSFR
Measure* $d/dt \, sSFR(t)$ of green valley galaxies

* really, broadly constrain for now
UV-optical colours constrain $d/dt$ sSFR(t)
UV-optical colours constrain $d/dt \, sSFR(t)$
UV-optical colours constrain $\frac{d}{dt} sSFR(t)$

- All Galaxies
  - Green Valley Early-types
  - Green Valley Late-types

- Early-type Galaxies
  - Green Valley Early-types

- Late-type Galaxies
  - Green Valley Late-types

- Star formation rate:
  - $\tau_{\text{quench}} = 1$ Myr
  - $\tau_{\text{quench}} = 250$ Myr
  - $\tau_{\text{quench}} = 1$ Gyr
  - $\tau_{\text{quench}} = 2.5$ Gyr
What about environment?
(quick detour)
Environment

Halo masses from DR7 catalogue of Yang+

Early-type galaxies

\[ M_{\text{halo}} < 10^{12} \, \text{M}_{\odot}/h \]

Late-type galaxies

\[ M_{\text{halo}} > 10^{12} \, \text{M}_{\odot}/h \]
What about AGN?
Is there feedback?
Black Hole Growth

BPT AGN classification from Oh+12

-1 0 1 2 3 4

NUV-u colour (dust-corr.)

0.5 1.0 1.5 2.0 2.5

u-r colour (dust-corr.)

~10% of AGN hosts

~50% of AGN hosts

star formation rate

t_{\text{quench}} = 1 \text{ Myr}
250 \text{ Myr}
1 \text{ Gyr}
2.5 \text{ Gyr}

0.5 1.0 1.5 2.0 2.5 3.0

u-r colour (dust-corr.)

0 1 2 3 4

NUV-u colour (dust-corr.)

8 9 10 11 12 13

Time (Gyr)

BPT AGN classification from Oh+12
\[ \text{SFR} = \varepsilon M_{\text{gas}}/\tau_{\text{dyn}} \]

\[ > \text{SFR}(t) \sim \text{exponential} \]

\[ \varepsilon \sim 2\% \]
\[ \tau_{\text{dyn}} \sim \text{few 100 Myr} \]
(see Kaviraj+10!)
SDSS reveals an evolutionary sequence: Low-mass early-types migrate to the red sequence

Input: GALEX+SDSS+2MASS photometry, SDSS spectroscopy (Lick indices)
Result: 1-10% of stellar mass formed in most recent burst; leads to rapid quenching on ~100 Myr timescale and migration to red sequence

Schawinski+07
Deviations from the Schmidt Law: Clues to Feedback

SFR $\sim \epsilon M_{\text{gas}} / T_{\text{dyn}}$

(b)

Molecular gas mass $M_{\text{H}_2}$ vs Age of young burst $t_y$ [Gyr]

Schawinski+09a, Kaviraj, Schawinski, Silk & Shabala 2010
Can we model* these two quenching pathways?

* really, very roughly
1. Late-type galaxies
Late-type galaxies quench star formation slowly

Galaxy is on main sequence

\[ M_{\text{stellar}} \sim SFR^\beta \]

Inflows balance outflows:

system in quasi-equilibrium

(Bouche+10; Lilly+13)

could correspond to classical environmental mechanisms (strangulation, harassment, starvation).
Late-type galaxies quench star formation slowly

(2) $t = t_{\text{quench}}$

Either cosmological inflows or cooling from halo are stopped, galaxy gas reservoir is now no longer replenished.

Galaxy leaves main sequence

$$\text{SFR} = \frac{\epsilon M_{\text{gas}}}{\tau_{\text{dyn}}}$$

$\geq \text{SFR}(t) \sim \text{exponential}$

could correspond to classical environmental mechanisms (strangulation, harassment, starvation)
Late-type galaxies quench star formation slowly

(3) several 100-1000 Myr past quench

could correspond to classical environmental mechanisms (strangulation, harassment, starvation).

SFR goes into exponential decline, galaxy enters green valley

Gas reservoir is slowly used up
Late-type galaxies quench star formation slowly

(4) several Gyr past quench

could correspond to classical environmental mechanisms (strangulation, harassment, starvation).

Several Gyr later...

Passive, red spiral galaxy

No morphological transformation > “red spiral”

Very low SSFR
2. Early-type galaxies
Early-type galaxies quench star formation rapidly

(1) $\sim 100s$ Myr prior to $t_{\text{quench}}$

Two galaxies on main sequence are about to merge.

Both bring in gas reservoir and are connected to cosmic gas inflow.
Early-type galaxies quench star formation rapidly

Merger may drive SFR above main sequence, or not. Morphology is transformed to spheroid

Some process drives outflows of gas to rapidly deplete the cold gas reservoir, perhaps AGN feedback?

\[ \text{SFR} \neq \frac{\epsilon M_{\text{gas}}}{\tau_{\text{dyn}}} \]

Further cosmological inflows and/or cooling stopped
Early-type galaxies quench star formation rapidly

(3) \( \sim 100 \text{ s Myr post } t_{\text{quench}} \)

SFR drops rapidly to zero, galaxy moves to green valley

Gas reservoir is destroyed, further inflows not allowed to replenish

AGN active
Early-type galaxies quench star formation rapidly

(4) \( \sim 1-2 \) Gyr post \( t_{\text{quench}} \)

With no gas reservoir and no further gas inflows, new early-type becomes passive red sequence galaxy.
Summary

sSFR + UV/optical colours show **two different quenching pathways** though green valley associated with early- and late-type galaxies.

Late-type galaxies **quench slowly, without changing morphology** \((d/dt \text{sSFR} \text{ small})\) due to an external process that stops further inflow/cooling of gas; *could correspond to classical environmental mechanisms*.

Early-type galaxies **quench rapidly, during or after merger-driven change of morphology** \((d/dt \text{sSFR} \text{ large})\) due to an internal process that destroys the gas reservoir, possibly *AGN feedback*?
Mergers trigger the migration from the blue cloud to the red sequence