Starvation as the primary quenching mechanism in galaxies

James Trussler al.

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Speaker: Guangwen Chen

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Quenching mechanism

Quench: star-forming galaxies → passive galaxies
How? remain unclear.
Mass quenching (internal process):

- Low mass: stellar feedback, shallower potential.
- Massive: AGN feedback (stronger outflow, jets and winds heat CGM)
- Halo quenching (infalling gas from IGM shock-heated)

Environmental quenching (external process):

- tidal interactions other galaxies
- intracluster medium (ICM): ram pressure stripping

Tracer: chemical abundance

Properties: SFR, Z_* (Stellar metallicity), $Z_{\rm ISM}$ (gas metallicity)

- Star formation: gas $\rightarrow$ stars
- Star (stellar nucleosynthesis) death $\rightarrow Z_{\rm ISM}\uparrow$
- Accretion of gas from the IGM into ISM $\rightarrow Z_{\rm ISM}\downarrow$, $M_{gas}\uparrow$
- $M_{gas}\uparrow\rightarrow$ star formation$\uparrow$

SFMS (cycle) evolution: $M_{gas}\downarrow$ or $-$, $M_*\uparrow$, $Z\uparrow$

- Leave SFMS, SFG $\rightarrow$ PG: $M_*, Z\uparrow$ or keep constant?

△ The stellar metallicity difference between SFG and PG determine the nature of the primary quenching mechanism.

- another benefit of Z_*: reliably measured for PG.

Data

Main sample: SDSS DR7

- $r_{petro} = 17.77$, added LRG sample up to $r = 19.2$
- $M_* > 10^9 M_\odot$, $0.02 < z < 0.085$
- median S/N per spectral pixel > 20
- exclude objects hosting an AGN

Parameters:

- M_*, aperture-corrected total SFR from MPA-JHU DR7.
- Z, Age, fitted from the spectral fitting code FIREFLY.
- Central-satellite classification from the galaxy group catalogue of Yang et al. (2005, 2007)
- Overdensities estimated by Peng et al. (2010).

Sample

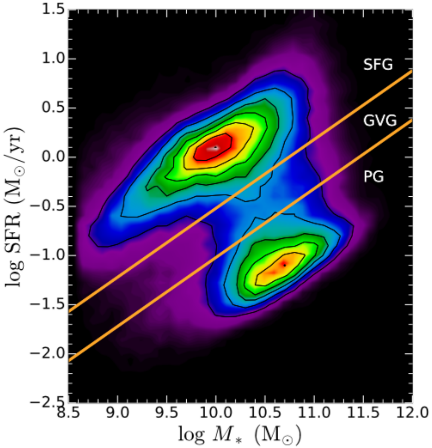
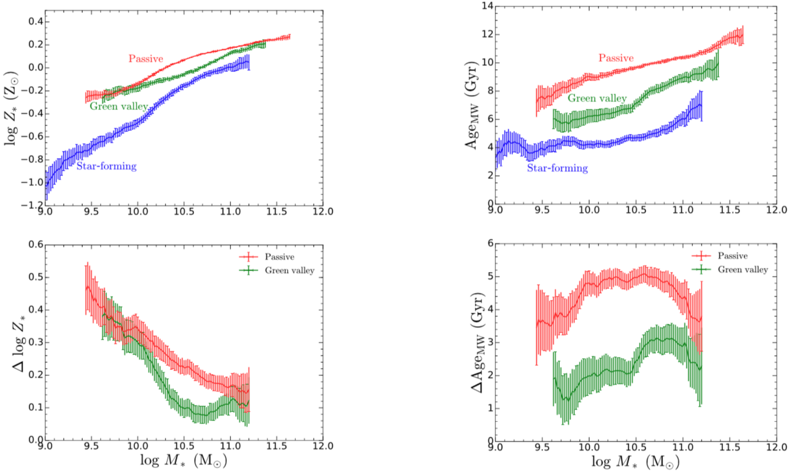


Figure 1. The bimodality of local galaxies in the star formation rate–stellar mass (SFR–M_*) plane. We only show the subsample of SDSS DR7 galaxies in the redshift range $0.02 < z < 0.085$. The colour shown reflects the number of galaxies in each SFR-M_* bin, ranging from low counts (purple) to high counts (red). The orange lines mark the boundaries of the star-forming, green valley and passive regions of the plane. Galaxies in the upper left are classified as star-forming (SFG), intermediate galaxies are classified as green valley (GVG), and galaxies in the lower right are classified as passive (PG).

9,955 SFG, 4,567 GVG and 28,052 PG at 0.5dex

Scaling Relations



Quenching through starvation rather than through simple gas removal.

For gas in ISM, $\sim$ -(1-return fraction) x SFR - outflow + inflow

$$\frac{\mathrm{d}g}{\mathrm{d}t} = -(1-R)\Psi - \Lambda + \Phi, \Lambda = \lambda_{\mathrm{eff}}\Psi \quad (1)$$

$$g\frac{\mathrm{d}Z_g}{\mathrm{d}t} = (1-R)y\Psi - (Z_\Lambda - Z_g)\Lambda - (Z_g - Z_\Phi)\Phi, \quad (2)$$

For metallicity in ISM, $\sim$ - (SFR) - ΔZ (outflow) + ΔZ (inflow)

- Assumptions: inflow = 0, $Z_\Lambda = Z_g$

$$\frac{\mathrm{d}g}{\mathrm{d}t} = -(1-R)\Psi - \Lambda, \frac{\mathrm{d}Z_g}{\mathrm{d}t} = (1-R)y\epsilon \quad (3)$$

$$\frac{\mathrm{d}s}{\mathrm{d}t} = (1-R)\Psi, \frac{\mathrm{d}Z_*}{\mathrm{d}t} = \frac{\Psi}{s}(1-R)(Z_g - Z_*). \quad (4)$$

- Closed-box models: pure starvation ($\lambda_{\mathrm{eff}} = 0$)
- Leaky-box models: starvation with outflows ($\lambda_{\mathrm{eff}} > 0$)

ICs and Onset of Models

Evolution: high redshift progenitors$\rightarrow$ local galaxies.
z_q (Onset of quenching): high redshift progenitors began quenching through starvation $\leftarrow$ lookback time $t_{\mathrm{lb}}(M_*)$.

$$t_0(M_*) = t(z_{\mathrm{q}}, M_*) + t_{\mathrm{lb}}(M_*). \tag{5}$$

- For PG, $t(z_{\mathrm{q}}, M_*) \ll t_{\mathrm{lb}}(M_*)$, set $t_{\mathrm{lb}}(M_*) = t_0(M_*)$.
- For GVG, $t(z_{\mathrm{q}}, M_*) \sim t_{\mathrm{lb}}(M_*)$, set $t_{\mathrm{lb}}(M_*) = t_{0,\mathrm{GVG}}(M_*) - t_{0,\mathrm{SFG}}(M_*)$.

Local galaxies (PG & GVG) + z evolution $\rightarrow$ Initial conditions.

Table 1. Summary of the initial conditions and other key quantities used in the gas regulator model.

Quantity	Description	Passive galaxies	Green valley galaxies
g	Initial total gas mass (molecular and atomic)	Molecular gas mass: Tacconi et al. (2018)	Molecular gas mass: Boselli et al. (2014)
		Atomic gas mass: Popping et al. (2014)	Atomic gas mass: Boselli et al. (2014)
		Redshift-evolution: Tacconi et al. (2018)	Redshift-evolution: Tacconi et al. (2018)
t_{depl} $(= \epsilon^{-1})$	Total gas depletion time (molecular and atomic)	Molecular gas depletion time: Tacconi et al. (2018)	Molecular gas depletion time: Boselli et al. (2014)
		Atomic gas depletion time: Popping et al. (2014)	Atomic gas depletion time: Boselli et al. (2014)
		Redshift-evolution: Tacconi et al. (2018)	Redshift-evolution: Tacconi et al. (2018)
Z_*	Initial mass-weighted stellar metallicity	Local Z_*: Z_{MW} for star-forming galaxies from this work	Local Z_*: Z_{MW} for star-forming galaxies from this work
		Redshift-evolution: Maiolino et al. (2008)	Redshift-evolution: Maiolino et al. (2008)
Z_g	Initial gas-phase metallicity	0.25 dex larger than Z_*	Offset from Z_* given by difference between Z_{LW} and Z_{MW} for star-forming galaxies from this work
z_{q}	Redshift when the star-forming progenitor began quenching through starvation (i.e. when the accretion of gas is halted)	Given by the mass-weighted age of local passive galaxies from this work	Given by the mass-weighted age difference between local green valley and star-forming galaxies from this work
t_{quench}	Duration of quenching (i.e. how long a star-forming progenitor must quench before its stellar metallicity is equal to the stellar metallicity of local passive/green valley galaxies)	Given by the time elapsed since the onset of quenching when $Z_{*,\mathrm{model}} = Z_{*,\mathrm{passive}}$	Given by the time elapsed since the onset of quenching when $Z_{*,\mathrm{model}} = Z_{*,\mathrm{green\ valley}}$

Onset of quenching

PG: quenching at high redshift, GVG: quenching in local universe

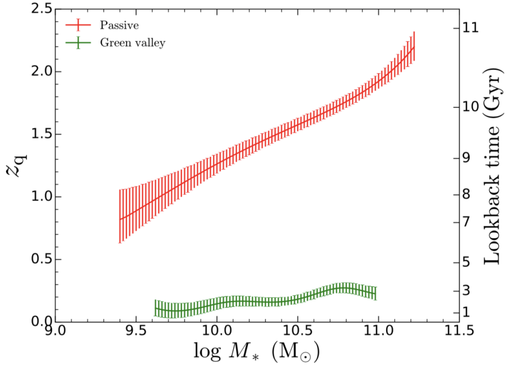


Figure 4. The redshift z_q when the star-forming progenitors of local passive galaxies (red) and local green valley galaxies (green) begin quenching through starvation, as a function of stellar mass, as inferred by our analysis. The onset of quenching for passive and green valley galaxies were estimated from the mass-weighted

Stellar metallicity difference

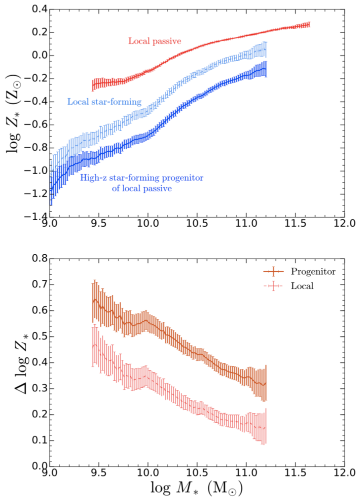
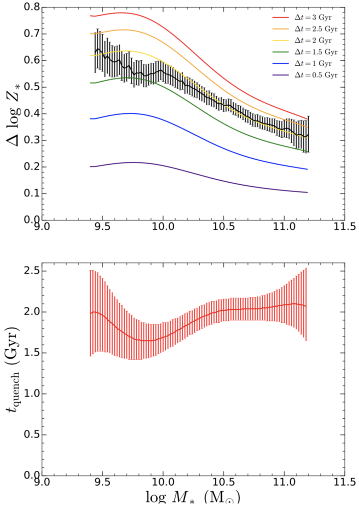


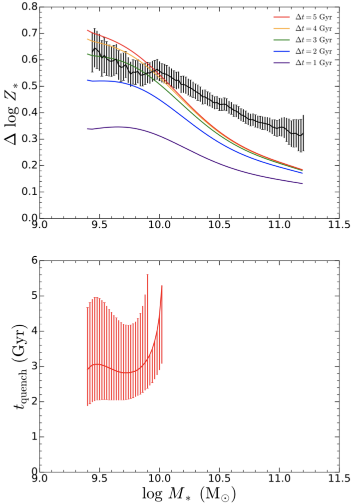
Figure 5. Top panel: The stellar mass–stellar metallicity relation observed for local passive galaxies (red) and local star-forming galaxies (light blue), as well as our estimates for the stellar metallicities for the star-forming progenitors of local passive galaxies (dark blue). Bottom panel: The observed difference in stellar metallicity between local star-forming and local passive galaxies (red) and the estimated difference in stellar metallicity between local passive galaxies and their star-forming progenitors at higher redshift (orange).

Since SFG at higher redshift are less metal-rich than their local counterparts, the observed stellar metallicity differences between local PG and their progenitors are even larger than that between local PG and local SFG.

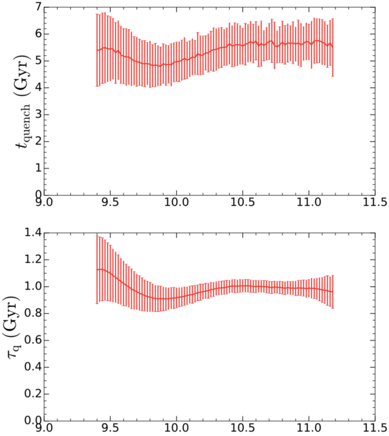
Pure starvation (2Gyr)



Starvation with outflows (3.5Gyr)



Joint metallicity-SFR analysis



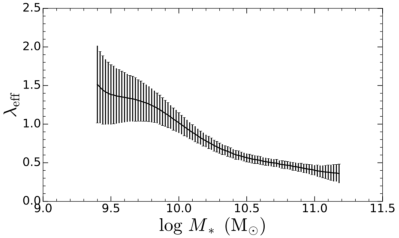


Figure 8. Top panel: Similar to the bottom panel in Fig. 6, but we now apply our joint metallicity-SFR analysis. Middle panel: The *e*-folding time-scales $\tau_{\rm q}$, which indicate the typical time-scale over which the star formation rate declines and the stellar metallicity enriches, as a function of stellar mass. Bottom panel: The mass-loading factors $\lambda_{\rm eff}$ required to simultaneously satisfy the ΔZ_* and the SFR quenching criteria. We show the median *e*-folding time-scale and mass-loading factor in each stellar mass bin, with the error bars representing the standard deviation.

$t_{\rm quench} \sim 5.5$ Gyr, the typical time-scale $\tau_{\rm q} \sim 1$ Gyr. $\lambda_{\rm eff} \sim 1.5$ for low-mass region

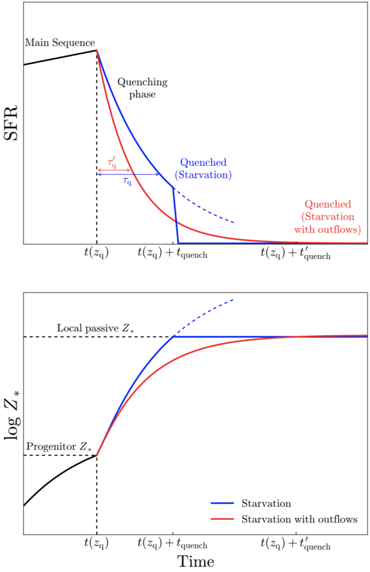
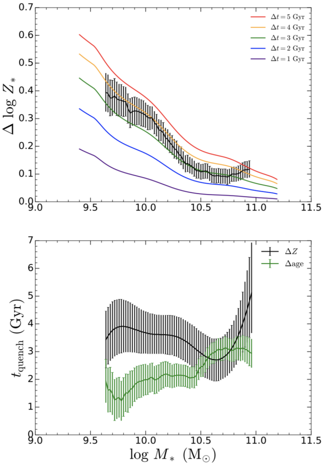


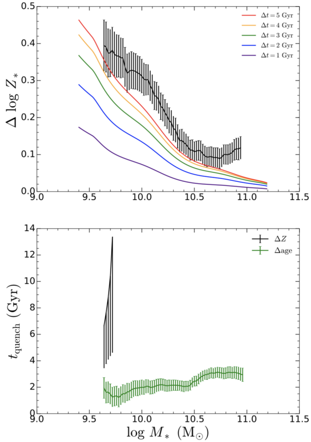
Figure 9. A schematic illustration of the evolution of the star formation rate (SFR, top panel) and the evolution of the logarithmic stellar metallicity ($\log Z_*$, bottom panel) during the quenching phase in our models. The galaxy initially evolves along the star-forming main sequence. At a time $t(z_q)$, the accretion of cold gas is halted and the galaxy begins quenching through starvation ($\lambda_{eff}=0$, blue) or through starvation with outflows ($\lambda_{eff}>0$, red). In the starvation scenario, the galaxy quenches for a time-scale t_{quench} before it reaches the level of chemical enrichment seen in local passive galaxies, at which point the onset of an ejective or heating mode prevents any further star formation and chemical enrichment, and the galaxy is quenched. In the starvation with outflows scenario, after a time t'_{quench} has elapsed the galaxy has completed quenching, and both its stellar metallicity and star formation rate are similar to that seen in local passive galaxies. τ_q and τ'_q represent the e-folding time-scales in the starvation, and starvation with outflows scenarios, respectively.

SFMS $\rightarrow$ PG:
Starvation: in order to prevent further star formation and chemical enrichment, an ejective or heating mode is required, which completely quenches the galaxy (SFR $\rightarrow$ 0 and Z_* keep constant).

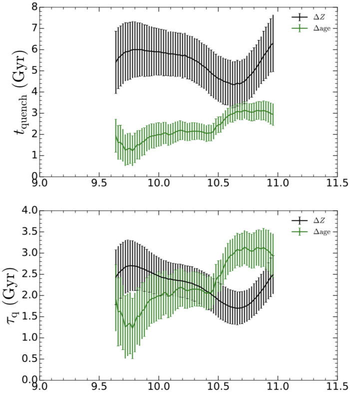
Pure starvation (3.5 Gyr)



Starvation with outflows (5.5 Gyr)



Joint metallicity-SFR analysis for GVG



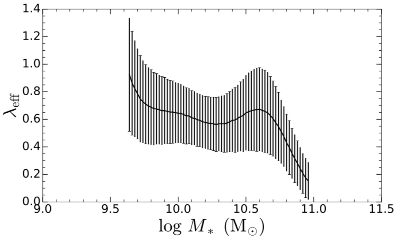


Figure 12. Top panel: Similar to the bottom panel in Fig. 10, but we now apply our joint metallicity-SFR analysis. Middle panel: The *e*-folding time-scales τ_q, which indicate the typical time-scale over which the star formation rate declines and the stellar metallicity enriches, as a function of stellar mass. Bottom panel: The mass-loading factors $\lambda_{\rm eff}$ required to simultaneously satisfy the ΔZ_* and the SFR quenching criteria. We show the median *e*-folding time-scale and mass-loading factor in each stellar mass bin, with the error bars representing the standard deviation.

Central-satellite

Starvation mechanism operates similarly for central and satellite galaxies.

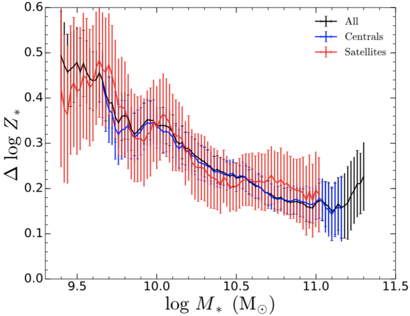


Figure 13. The difference in stellar metallicity between star-forming and passive galaxies, for the total galaxy population (black), the central sub-population (blue) and the satellite sub-population (red).

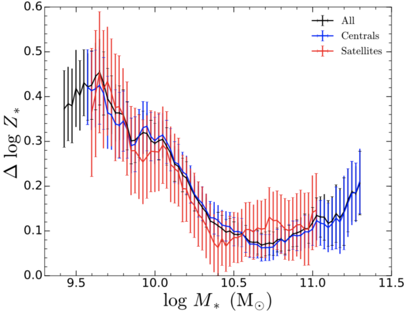


Figure 14. The difference in stellar metallicity between star-forming and green valley galaxies, for the total galaxy population (black), the central sub-population (blue) and the satellite sub-population (red).

Stellar metallicity difference with local overdensity for PG

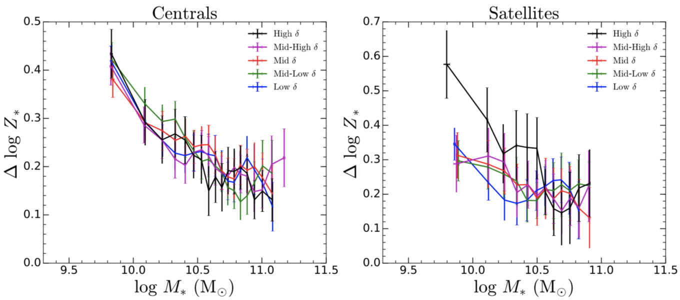


Figure 15. Galaxies are divided into quintiles of the local overdensity $1 + \delta$, ranging from the smallest (blue) to the largest overdensities (black). The stellar metallicity differences between star-forming and passive galaxies is plotted for the five overdensity quintiles as a function of M_*. Left panel: the stellar metallicity differences for central galaxies are shown. Right panel: the stellar metallicity differences for satellite galaxies are shown.

Stellar metallicity difference with local overdensity for GVG

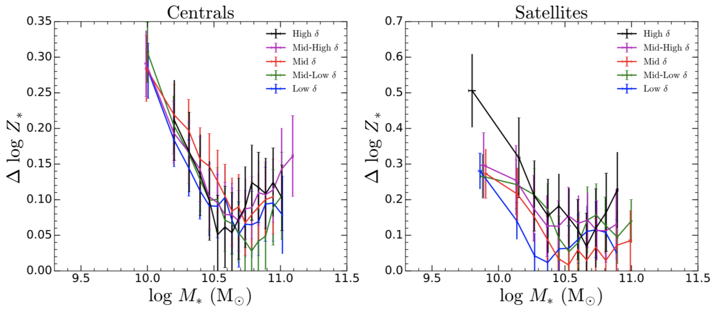


Figure 16. Similar to Fig. 15, but we now study the stellar metallicity difference between star-forming and green valley galaxies.

Environmental effects contributed to the starvation of galaxies primarily in very dense environments.

Conclusion

1 The stellar metallicity of passive galaxies is higher than that of local star-forming galaxies, and even higher compared with their star-forming progenitors at high-redshift. The metallicity difference is a strong function of stellar mass.

2 For galaxies at all masses, quenching involved an extended phase of starvation.Together with starvation, effective outflows are of increasing importance in low-mass galaxies.

3 In massive galaxies, quenching started about 10 Gyr ago and it lasted about 2 Gyr primarily through starvation. In low-mass galaxies, the quenching started later and the quenching time-scale was up to about 6 Gyr.

4 In local universe, the quenching process also involve an extensive period of starvation with a longer time-scale, at least 3-6 Gyr.

5 Environmental effects contributed to the starvation of galaxies primarily in very dense environments.