Fast, Slow, Early Late: Quenching Massive Galaxies at $z \sim 0.8$

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in collaboration with C. Conroy, S. Faber, L. Hernquist, D. Eisenstein, B. Johnson, J. Leja, et al.
Galaxy growth needs to be regulated: Quenching at high masses

quenching ≈ suppression of star formation ➔ solves two problems

1.) more massive galaxies have systematically older stars

2.) observed galaxy mass function vs theoretical halo mass function

Schawinski+ 2014

Bell et al. (2003) SMF

Millenium Sim (M_h x f_b)

adopted from Mutch et al. (2013)
How quickly do galaxies quench?

- current theoretical models (e.g. IllustrisTNG, Simba, EAGLE, …) are able to reproduce the buildup of the quiescent sequence with cosmic time
- need to go beyond simple number densities → timescale for quenching & spatial information

IllustrisTNG (Nelson+ 2018)
Simba (Rodríguez Montero+ 2019)
EAGLE (Wright+ 2019)
Constraining the timescale for quenching

adopted from Ilbert et al. (2013)
Constraining the timescale for quenching

- study the number densities of star-forming and quiescent galaxies (e.g., Pandya+ 2017): galaxies at early times quench on timescales of ~1-2 Gyr

adopted from Ilbert et al. (2013)
Constraining the timescale for quenching

- study the number densities of star-forming and quiescent galaxies (e.g., Pandya+ 2017): galaxies at early times quench on timescales of ~1-2 Gyr
- studying star-forming galaxies at the verge of quenching on spatially resolve scales (e.g., Tacchella+ 2015): galaxies quench inside-out on timescales of a few hundred Myr

Tacchella+ (2015; 2018) massive galaxies at z~2 have mature bulges embedded in a star-forming disk ➔ quench inside out

➜ powerful nuclear outflows

Förster Schreiber+ (2014); Genzel+ (2014): black hole activity?

adopted from Ilbert et al. (2013)
Constraining the timescale for quenching

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- archaeological approach: star-formation histories and quenching timescale in quiescent galaxies

⇒ we want to do this at z~1 in order to “resolve” the quenching timescale
HALO7D Survey

some of the deepest spectra for quiescent galaxies at z~1 while looking at the remote Milky Way stellar halo with HST and Keck/DEIMOS

- massive, mostly quiescent galaxies at z~0.8
- 161 objects with S/N>5 per Å
Modeling photometry + spectroscopy

- fully Bayesian framework
- combine photometric and spectroscopic data rigorously using a spectroscopic calibration model

We fit an advanced physical model with 27 parameters:

- standard: redshift, stellar mass, velocity dispersion, metallicity
- flexible dust attenuation model: $A_V$ and multiplicative of Calzetti attenuation law
- dust emission: 3 parameters
- AGN emission in IR model: 2 parameters
- “non-parametric” SFH (10 bins in time)
- emission line model: fit for prominent emission lines
  - fit for velocity dispersion, optimize out amplitude
- outlier model: skylines residuals, detector artifacts, data-model inconsistencies
  - fraction of outlier pixels in spectrum
Example

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Tacchella+ (2021)
Average star-formation histories of massive z~1 galaxies

- match direct measurements of the sSFR at early times
- SFH of star-forming galaxies follows specific dark matter accretion rate
- quiescent galaxies typically decouple from the star-forming main sequence around z~2-3
Star-formation histories of massive quiescent galaxies

large diversity of quenching paths: galaxies quench fast, slow, early & late
Quenching timescales

large diversity of quenching timescale and quenching epochs

→ consistent with other studies showing fast and slow quenching paths (i.e., Wu+18, Belli+19)
→ combination of internal and external quenching mechanism
→ dark matter halo as a gate keeper, internal processes (black hole/stellar feedback) as the agent
large diversity of quenching timescale and quenching epochs
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Implications

large diversity of quenching timescale and quenching epochs

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Tacchella+ (2016)
**Conclusions**

Galaxies at early cosmic times “quench” inside-out, black hole feedback?

Large diversity of quenching timescales and epochs, pointing toward a combination of internal and external quenching mechanisms.

**Future:**
- Timing how quickly galaxies transition
- More careful comparisons between observations and theory
- Formation of first quiescent galaxies with JWST
- Spatially resolved quenching (ELT)
Extra Slides
Galaxies relative to the star-forming main sequence

$\Delta_{\text{MS}} = \log \frac{sSFR}{sSFR_{\text{MS}}}$ [dex]

- $t_{\text{fb}} = 0.0\,\text{Gyr} \ (z \approx 0.8)$
- $t_{\text{fb}} = 0.1\,\text{Gyr} \ (z \approx 0.8)$
- $t_{\text{fb}} = 1.0\,\text{Gyr} \ (z \approx 1.0)$
- $t_{\text{fb}} = 2.0\,\text{Gyr} \ (z \approx 1.3)$
- $t_{\text{fb}} = 3.0\,\text{Gyr} \ (z \approx 1.7)$
- $t_{\text{fb}} = 4.0\,\text{Gyr} \ (z \approx 2.4)$
- $t_{\text{fb}} = 4.5\,\text{Gyr} \ (z \approx 2.9)$

$\log \text{SFR} \ [M_\odot \, \text{yr}^{-1}]$

$\log M_* \ [M_\odot]$

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Tacchella+ (2021)
Redshift of formation and star-formation timescale

$z_f$: redshift of $t_{50}$ (when 50% of the mass formed)

$\tau_{SF}$: star-formation timescale ($t_{20}$-$t_{80}$)

JWST science!
Star-formation timescale

Shorter star-formation timescale for more massive and early-forming galaxies:

\[
\tau_{\text{SF}/\text{GYR}} = (4.1 \pm 0.2) - (0.3 \pm 0.2) \cdot \log \left( \frac{M_*}{10^{11} \, M_\odot} \right) \\
- (3.1 \pm 0.2) \cdot \log(1 + z_f)
\]

where:
- \(z_f\): redshift of \(t_{50}\) (when 50\% of the mass formed)
- \(\tau_{\text{SF}}\): star-formation timescale (\(t_{20}-t_{80}\))
Late bloomers are rare, i.e. galaxies typically grow along the star-forming main sequence.

So on which timescale do galaxies oscillate about the SFMS?

Tacchella+ (2021)
Fitting results: parametric versus non-parametric

Tacchella+ (2021)
Fitting results: parametric versus non-parametric

Tacchella+ (2021)
Fitting results: with and without spectroscopic data

Tacchella+ (2021)
Fitting results: with versus without spectra
Prior on the star-formation history

randomly sampling the SFH prior:
our fiducial prior is a constant SFR

see also Carnall+ (2019), Leja+ (2019)
Prior on the star-formation history

\[ K = \frac{Z_{np,14}}{Z_{np,10}} = 1.3 \]

\[ K = \frac{Z_{np,\text{dir}}}{Z_{np,10}} = 6 \times 10^{-4} \]

\[ K = \frac{Z_{\text{delayed-\tau}}}{Z_{np,10}} = 0.14 \]

see also Carnall+ (2019), Leja+ (2019)
Prior on the star-formation history