How do Central and Satellite Galaxies Quench?
Evidence for AGN-Feedback and Environmental Quenching in MaNGA

M83 – HST Image  M87 – HST Image

"Quenching"

Introduction: The “Big” Theoretical Problem

Gas Inflow (along DM streams)

Only ~5-10% of baryons in Stars
Up to ~90% of baryons in ionized hot halo
→ Why so few baryons in stars?

AGN Feedback Observed

Credit: McNamara et al.

AGN

φ = dn/dM

Mutch+13

Galaxy Cluster MS 0735.6+7421

AGN Feedback Observed

Credit: McNamara et al.

NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University) / STScI-FRC06-51

Radio Jets

shocks

outflows
Introduction: The “Big” Theoretical Problem

1) Why is star formation so inefficient? (Theoretical / Cosmological Perspective)

2) Why is the hot gas halo stable to cooling and collapse? (Galaxy Clusters / X-ray & Radio Perspective)

3) Why do quenched galaxies exist? (Galaxy Evolution / Optical – NIR Perspective)

Only ~5-10% of baryons in Stars
~90% of baryons in ionized hot halo → Why so few baryons in stars?

Credit: McNamara et al.
Introduction: Theoretical Mechanisms for Quenching

“Intrinsic” - Centrals and Satellites
- Halo Mass Quenching ($M_{\text{Halo}}$)
- AGN Feedback: Radio-Mode ($M_{\text{BH}}$)
- AGN Feedback: Quasar-Mode ($\frac{dM_{\text{BH}}}{dt}_{\text{max}}$)
- Stellar & Supernova Feedback ($M_*$)
- Morphological Quenching ($M_{\text{Bulge}}/(R_d)^3$)
- Mergers & Gas Depletion ($B/T; \Gamma_m$)

“Environmental” - Satellites Mostly
- Ram Pressure Stripping ($\rho_{\text{gas}}, V_{\text{sat}}$)
- Galaxy – Galaxy Harassment ($\delta_{\text{gal}}$)
- Host Halo Tidal Stripping ($M_{\text{Halo}}, D_{\text{cen}}$)
- Location in Cosmic Web (cen. – sat. class)

More Exotic Alternatives
- e.g. DM Annihilation, DM Interactions, Magnetic Fields, Cosmic Rays etc.
Wisdom from Hydrodynamical Simulations
Work done by: Joanna Piotrowska (Cambridge)

Random Forest Classification Analysis

AGN Feedback $\rightarrow$ $M_{BH}$ Dependence

NOT $dM_{BH}/dt$ Dependence

Key Insight: Central galaxy quenching is governed by $M_{BH}$ modern simulations
$\rightarrow$ Role of integrated impact of AGN feedback over cosmic time

Piotrowska, Bluck et al. (2020b, in prep.)
The MaNGA Survey:
- SDSS IV Ongoing Large Program
- ~10,000 Local (z < 0.1) Galaxies Observed with IFU Spectroscopy
- Flat Mass Distribution ($10^9 - 10^{11.5} M_{\text{sun}}$)
- 3600 – 10000 A Spectral Range (R = 2000)
- ~1kpc Spatial Resolution (0.5 arcsec)
- Largest IFU Survey to date!

Pipe3D DR15 VAC:
- ~4500 Galaxies Observed
- ~10 Million Spectra Analysed:
  - Emission Line Strengths (Flux & EW)
  - Absorption Lines & Spectral Indices
  - Kinematics ($V_{\text{los}}, \sigma_{\text{los}}$)
  - SSP Fitting Parameters: stellar mass densities, stellar ages $M, L, M$, stellar metallicities, SFHs...

Bundy et al. (2015); Sanchez et al. (2016a,b)
Star Forming Main Sequence: Resolved vs. Global

SFR
Hα | D4000
Brinchmann+04

Σ_{SFR}
Hα | D4000
Bluck+20a

Bluck et al. (2020b, submitted)
How is Star Formation Distributed within Galaxies?

- Star forming systems are star forming everywhere in radius (out to $r \sim 1.5R_e$)
- Quenched systems are quenched everywhere in radius (out to $r \sim 1.5R_e$)
- But, green valley systems have quenched cores and star forming outskirts -> “inside-out” quenching (see also Tacchella+15, Ellison+18, Medling+18)

- High levels of star formation lead to young stellar ages
- Low levels of star formation lead to old stellar ages
- But, green valley systems have older cores and younger outskirts → Consistency with SFR results
Comparing Central & Satellite Galaxies

Take Away: “Central galaxies quench “inside-out”; but satellite galaxies have much flatter profiles in transition”

Bluck et al. (2020b, submitted)
Star Formation & Quenching as a Function of Mass

All Galaxies

Take Away: “High mass quenching proceeds inside-out but low mass quenching proceeds outside-in”

Bluck et al. (2020b, submitted)
Setting up the Machine Learning Problem: Quenching Classification & Star Formation Rate Regression in ANN & RF

**Quenching:**
1) Identify which parameters, and groups of parameters, are particularly effective at predicting whether regions will be star forming or quenched
   “Classification”

**Star Formation:**
2) Identify which parameters, and groups of parameters, are particularly effective at predicting actual SFR surface densities in star forming regions
   “Regression”

See also Teimoorinia, Bluck & Ellison (2016) & Bluck et al. (2019a) for similar ML approaches
Insights from Machine Learning:
Star Formation vs. Quenching in ANN & RF for Centrals Only

ANN: Quench
RF: Quench

ANN: Star Formation
RF: Star Formation

Bluck et al. (2020a)
Insights from Machine Learning:
Star Formation vs. Quenching in ANN & RF for Centrals Only

ANN: Quench
Quenching is GLOBAL

RF: Quench
Most Predictive: $\sigma_c$

ANN: Star Formation
Star Formation is LOCAL

RF: Star Formation
Most predictive: $\Sigma*$

Bluck et al. (2020a)
Insights from Machine Learning:
PCA Test of GLOBAL vs. LOCAL Star Formation & Quenching

"Quenching is a global process"

"Star formation is a local process"
Insights from Machine Learning: Quenching of Centrals & Satellites in a Random Forest Classification

Bluck et al. (2020b, submitted)
Insights from Machine Learning:
Quenching of Centrals & Satellites in a Random Forest Classification

**Take Away:** “Central galaxy quenching depends primarily on central velocity dispersion; but low mass satellite galaxy quenching depends primarily on local density”
Insights from Machine Learning: Visualizing the Machine Learning Results

Central Velocity Dispersion: $\sigma_c$

There is a striking separation in $\sigma_c$ between star forming and quenched centrals. But no separation for low mass satellites.

Local Galaxy Over-Density: $\delta_5$

There is a clear separation in $\delta_5$ between star forming and quenched low mass satellites. But essentially no separation for centrals.
Insights from Machine Learning: Important Test -- Partial Correlation Coefficient Analysis in SDSS

**Note:** negligible importance of both stellar and halo mass, at fixed central velocity dispersion

Bluck et al. (2020b, submitted)

**Note:** negligible importance of central velocity dispersion at fixed local galaxy density
Interpreting the Importance of $\sigma_c$ & $\delta_5$

Strong dependence on $\sigma_c \rightarrow$ Strong dependence on $M_{\text{BH}}$

(see also Bluck+14,16; Teimoorinia, Bluck & Ellison 2016)
Central galaxy quenching is governed by supermassive black hole mass (which is a natural prediction of AGN feedback models, yet highly challenging for models utilising virial shocks and/or supernovae heating to explain!)

**Key Result:**
Central galaxy quenching is governed by supermassive black hole mass.
Brining It All Together: \( \Delta \Sigma_{\text{SFR}} \) Profiles in Ranges of Black Hole Mass and Local Galaxy Density

**Black Hole Mass:**
“Inside-out” Quenching

- Effective in all high mass galaxies

**Local Density:**
“Outside-in” Quenching

- Effective in low mass satellites only

Bluck et al. 2020b, submitted
Conclusions

- Central (and high mass satellite) quenching is governed by intrinsic processes, especially those connected with $\sigma_c$

- Low mass satellite quenching is governed by environmental processes, especially those connected with $\delta_5$

- High mass quenching operates “inside-out”

- Low mass quenching operates “outside-in”

- Both forms of quenching encompass the entire galaxy over time...

  → Globally Quenched Systems

  (with no dependence on resolved parameters)

**Papers:** Bluck+20a; Bluck+20b, submitted; Piotrowska, Bluck+20b, in prep.