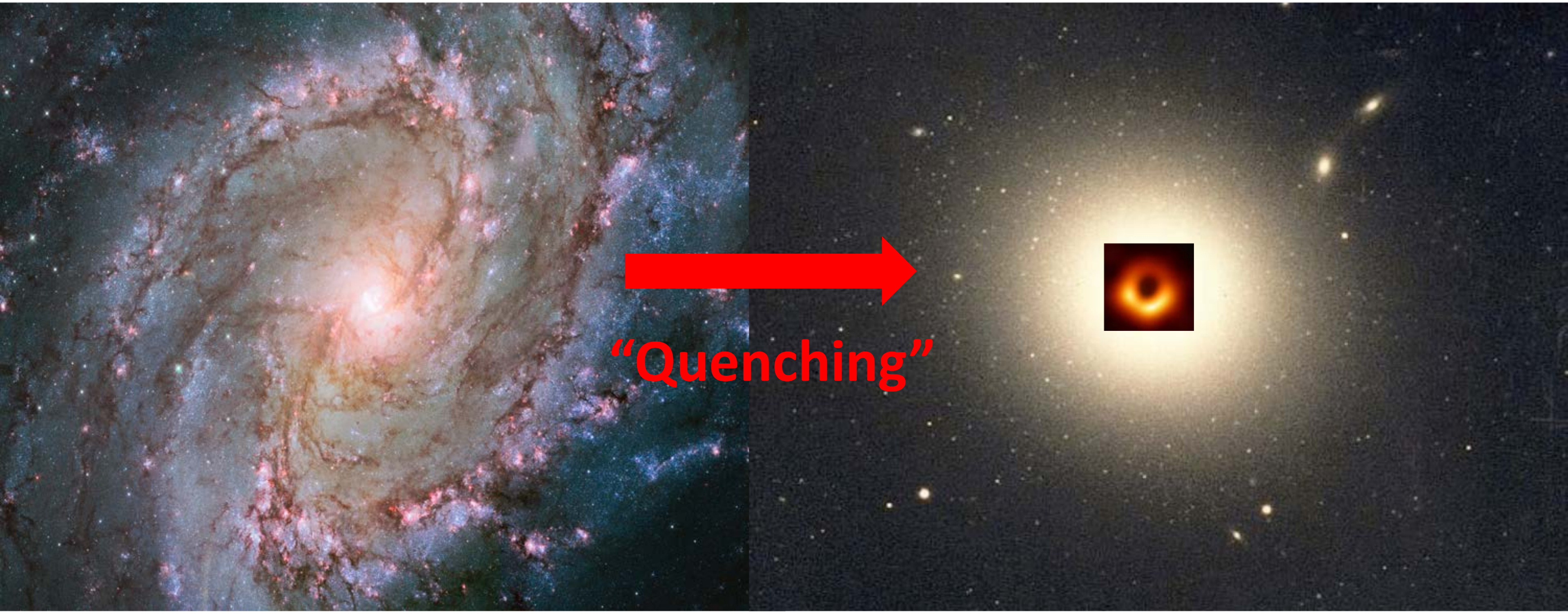
How do Central and Satellite Galaxies Quench?

Evidence for AGN-Feedback and Environmental Quenching in MaNGA



M83 – HST Image

M87 – HST Image

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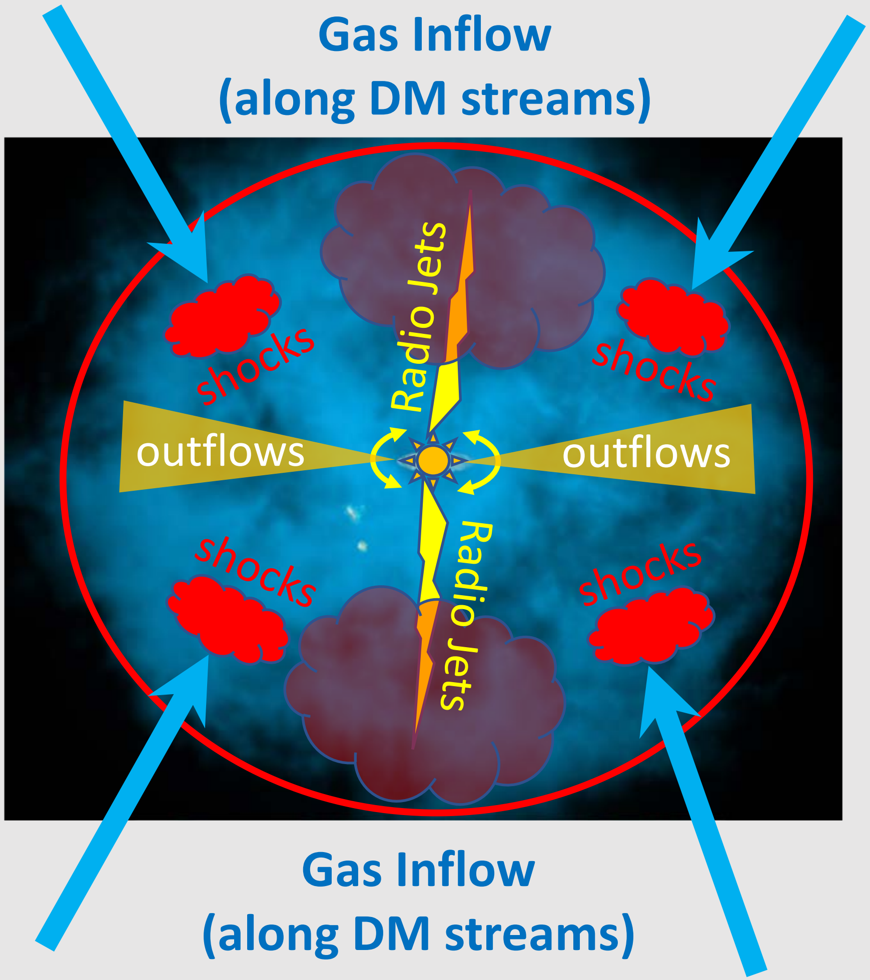
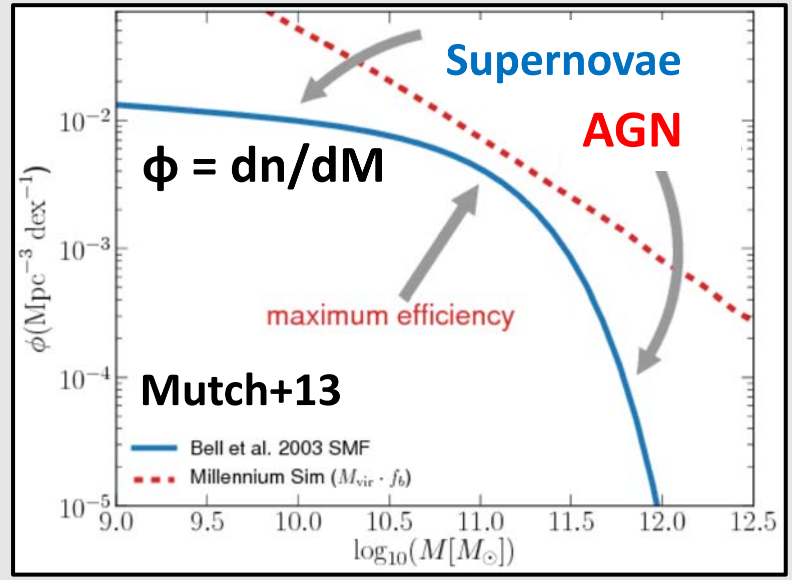
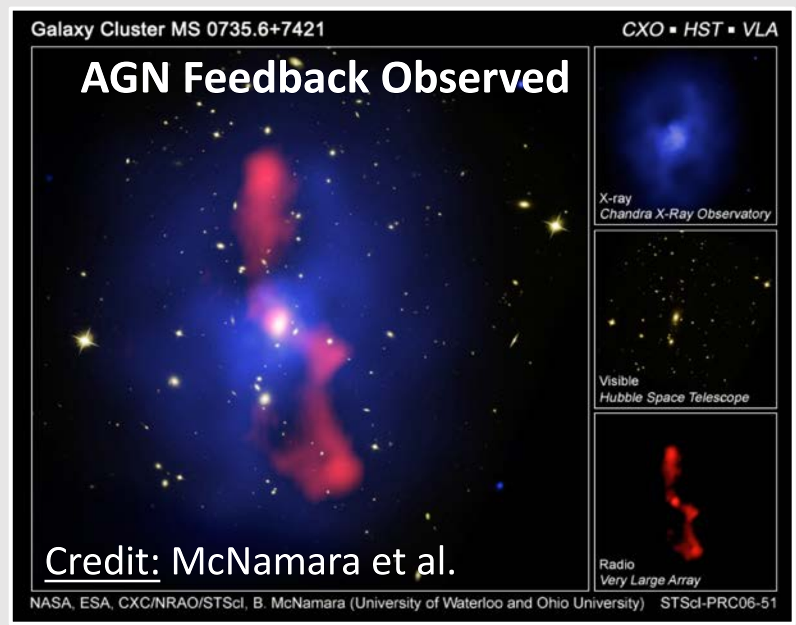
Collaborators: R. Maiolino, J. M. Piotrowska, J. Trussler, M. Thorp, S. Brownson, S. L. Ellison, S. Sanchez, H. Teimoorinia, K. Bundy, C. J. Conselice, J. Moreno, et al.

Introduction: The "Big" Theoretical Problem

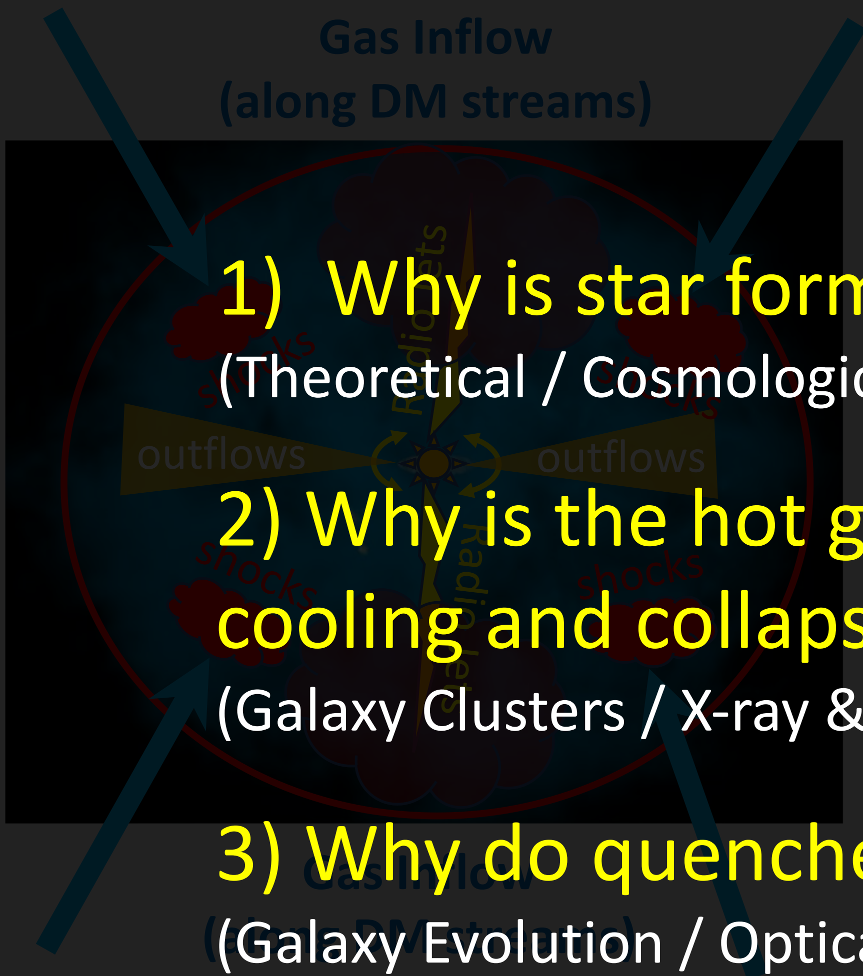


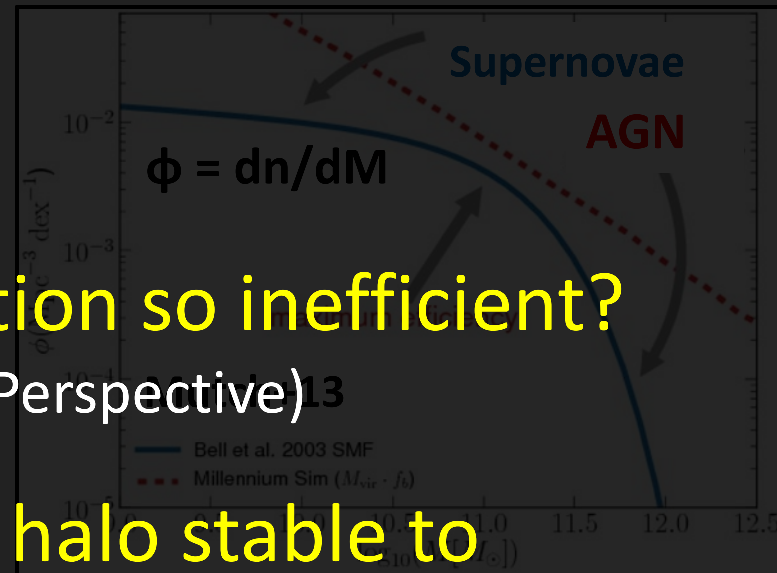




Only ~5-10% of baryons in Stars
Up to ~90% of baryons in ionized hot halo
→ **Why so few baryons in stars?**

Introduction: The "Big" Theoretical Problem



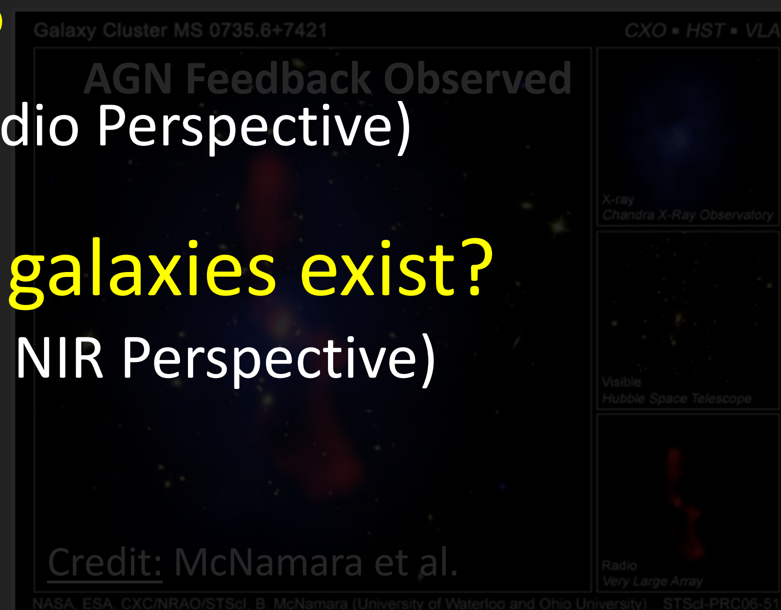


1) Why is star formation so inefficient?

(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?**

Introduction: Theoretical Mechanisms for Quenching

➢ "Intrinsic" - Centrals and Satellites

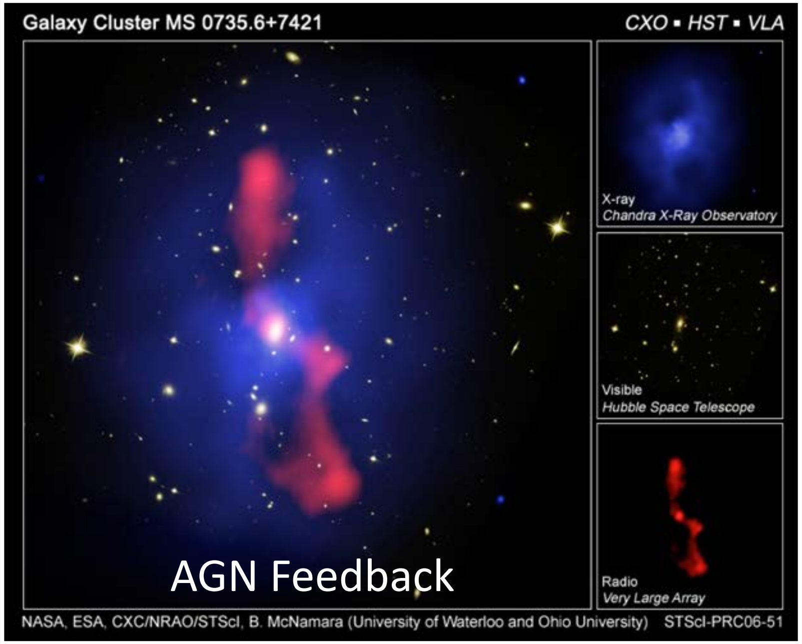
- ➢ Halo Mass Quenching (M_{Halo})
- ➢ AGN Feedback: Radio-Mode (M_{BH})
- ➢ AGN Feedback: Quasar-Mode $(dM_{BH}/dt)_{max}$
- ➢ Stellar & Supernova Feedback (M_*)
- ➢ Morphological Quenching ($M_{Bulge}/(R_d)^3$)
- ➢ Mergers & Gas Depletion (B/T; Γ_m)

➢ "Environmental" - Satellites Mostly

- ➢ Ram Pressure Stripping (ρ_{gas}, V_{sat})
- ➢ Galaxy – Galaxy Harassment (δ_{gal})
- ➢ Host Halo Tidal Stripping (M_{Halo}, D_{cen})
- ➢ Location in Cosmic Web (cen. – sat. class)

➢ More Exotic Alternatives

- ➢ e.g. DM Annihilation, DM Interactions, Magnetic Fields, Cosmic Rays etc.



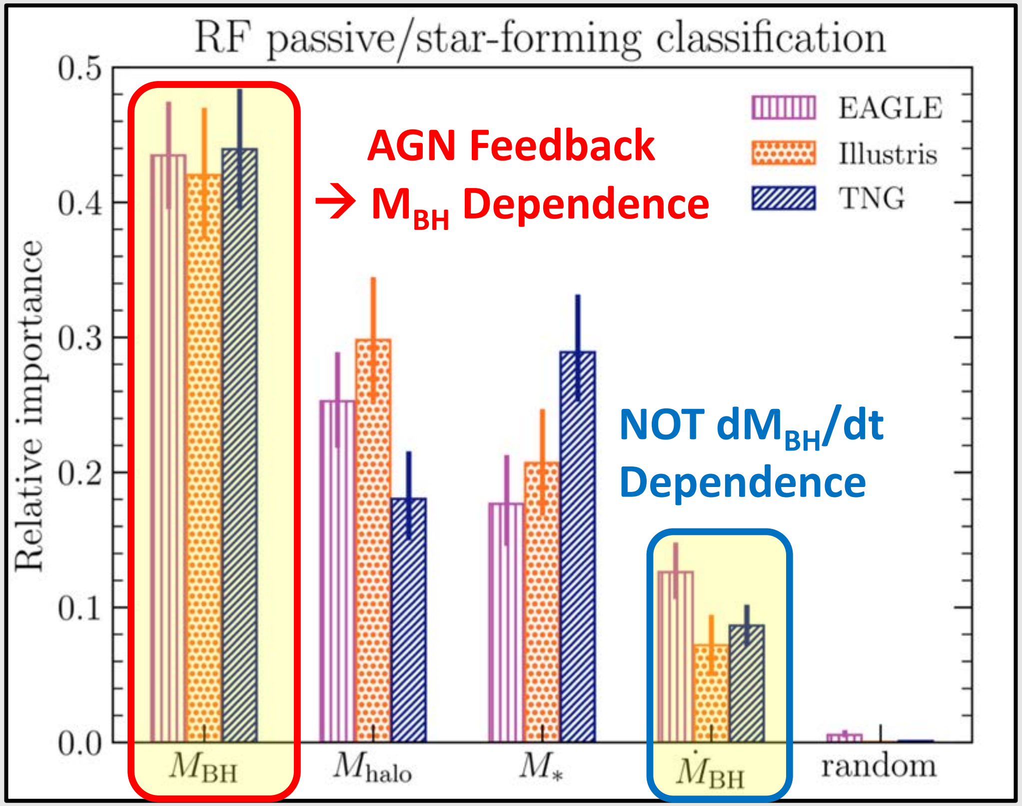
AGN Feedback

Galaxy-Galaxy Interactions

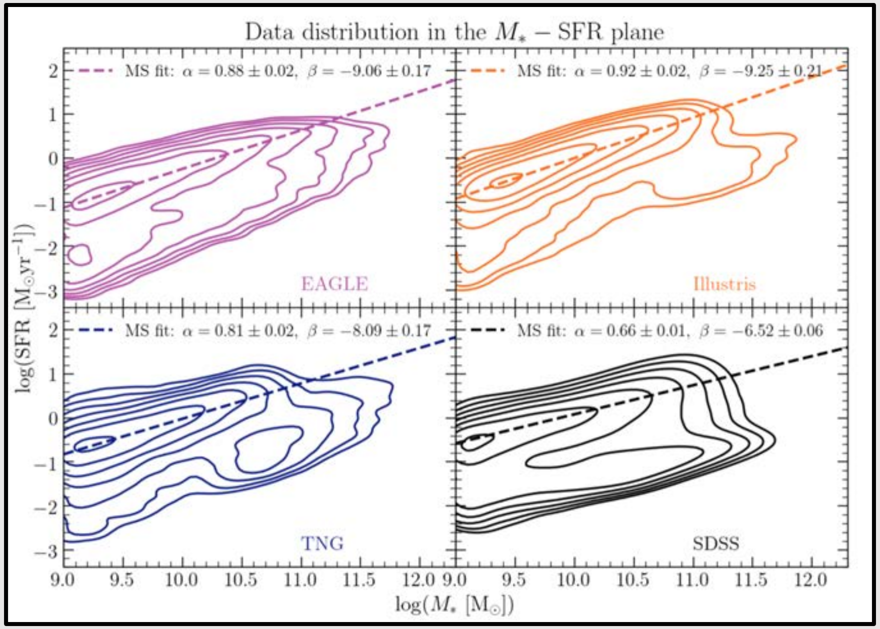
Wisdom from Hydrodynamical Simulations

Work done by: Joanna Piotrowska (Cambridge)

Random Forest Classification Analysis



SFMS in Simulations



Key Insight: Central galaxy quenching is governed by M_{BH} modern simulations

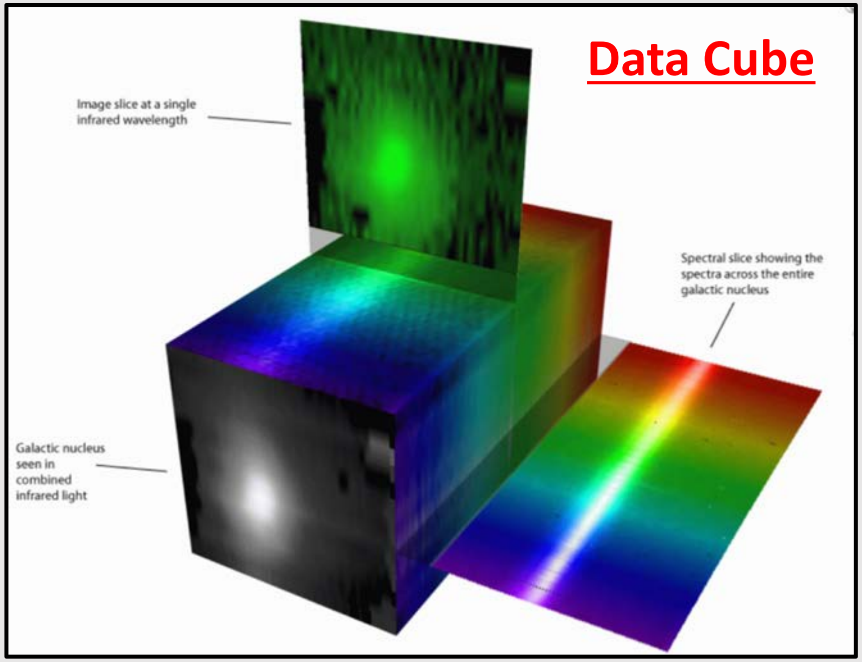
→ Role of *integrated* impact of AGN feedback over cosmic time

Piotrowska, Bluck et al. (2020b, in prep.)

MaNGA IFU Survey – DR15

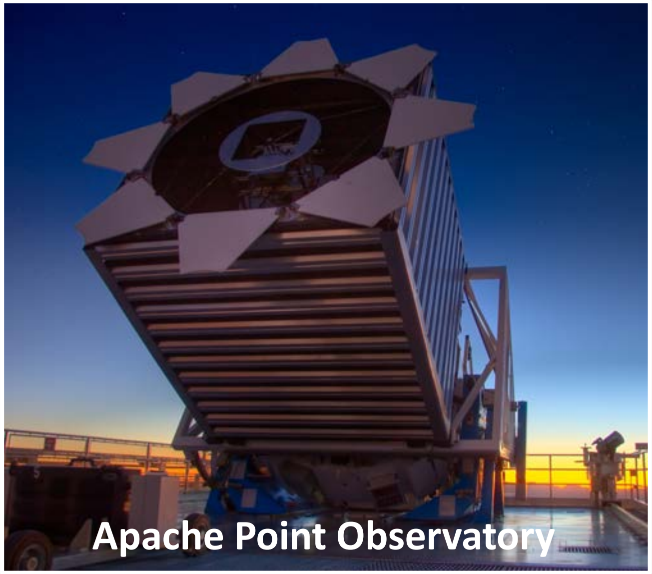
The MaNGA Survey:

- SDSS IV Ongoing Large Program
- ~10,000 Local ($z < 0.1$) Galaxies Observed with IFU Spectroscopy
- Flat Mass Distribution ($10^9 - 10^{11.5} M_{sun}$)
- 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_{los}, σ_{los})
  - SSP Fitting Parameters: stellar mass densities, stellar ages$_{L,M}$, stellar metallicities, SFHs…

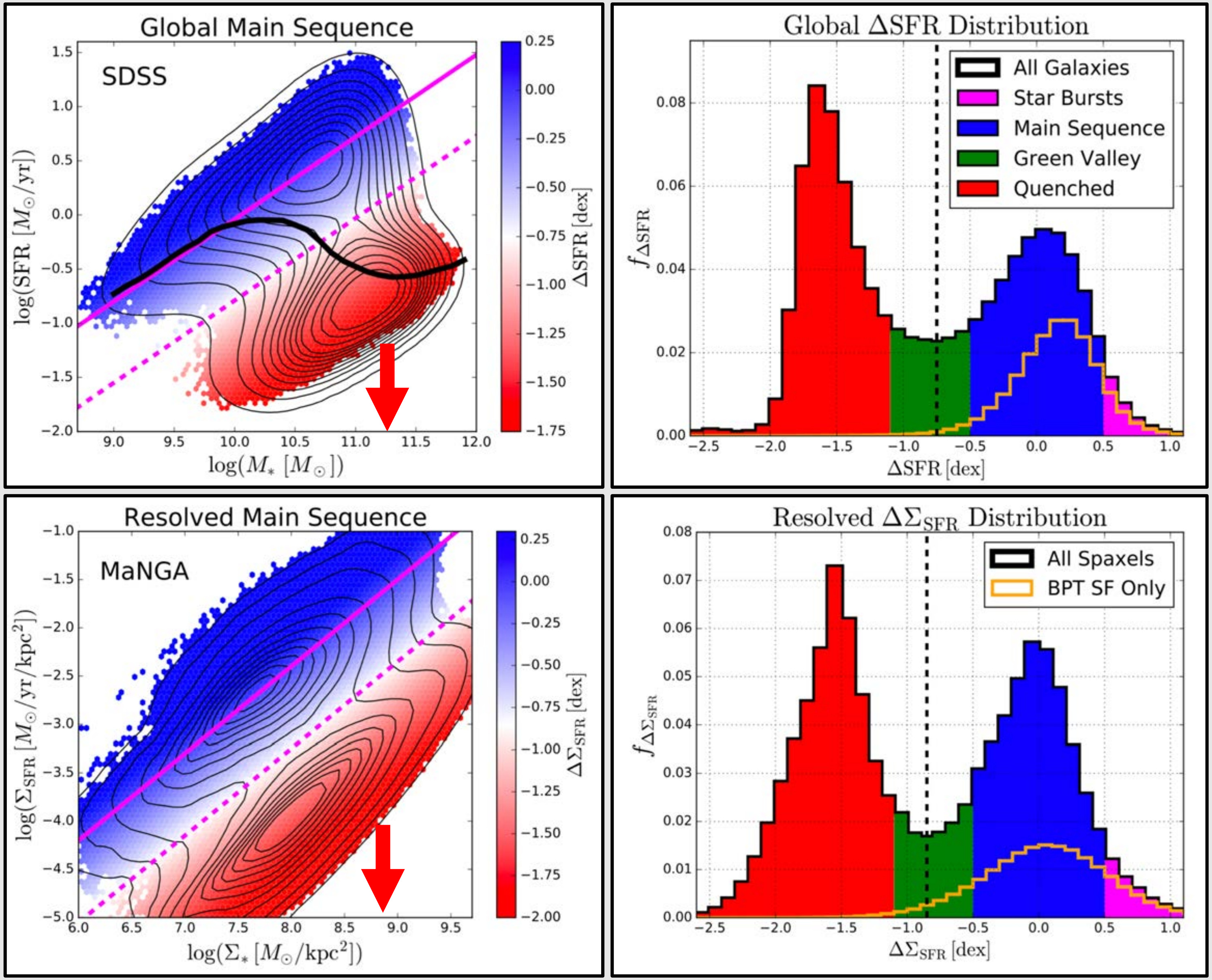


Bundy et al. (2015); Sanchez et al. (2016a,b)

Star Forming Main Sequence: Resolved vs. Global

SFR
Hα | D4000
Brinchmann+04

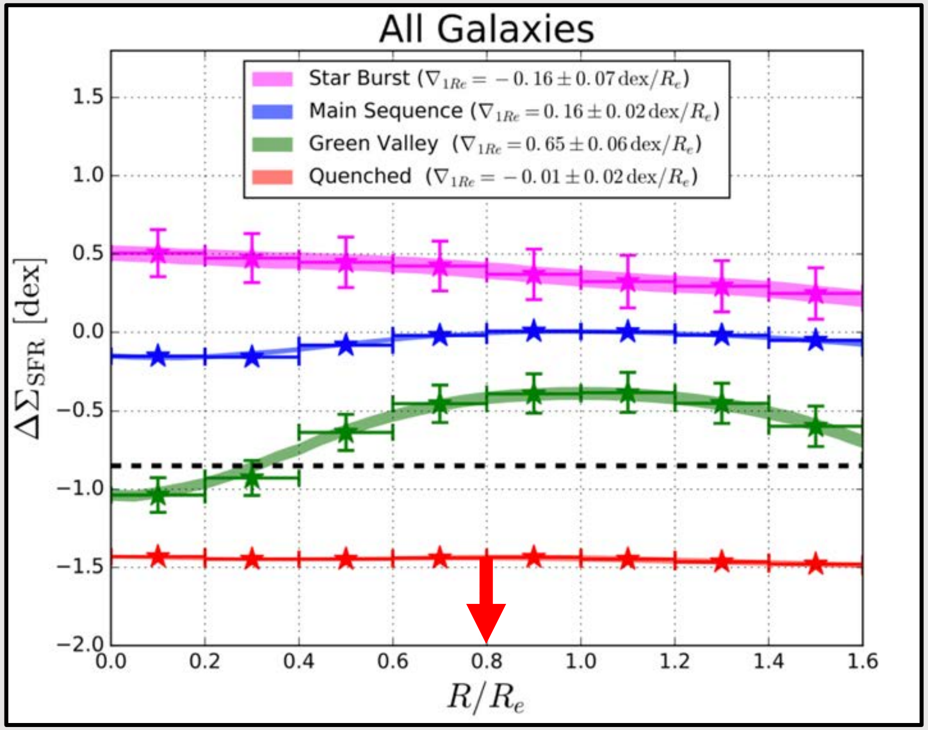
Σ_{SFR}
Hα | D4000
Bluck+20a



Bluck et al. (2020b, submitted)

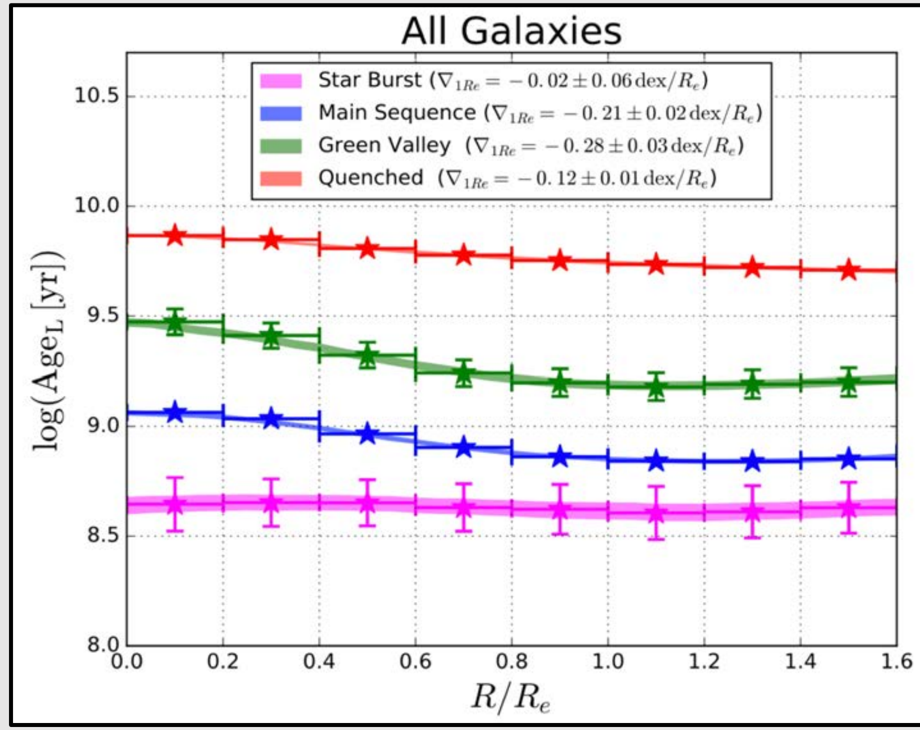
How is Star Formation Distributed within Galaxies?

Offset from Resolved SFMS



- Star forming systems are star forming everywhere in radius (out to r ~ 1.5Re)
- Quenched systems are quenched everywhere in radius (out to r ~ 1.5Re)
- **But, green valley systems have quenched cores and star forming outskirts**
  -> "inside-out" quenching
  (see also Tacchella+15, Ellison+18, Medling+18)

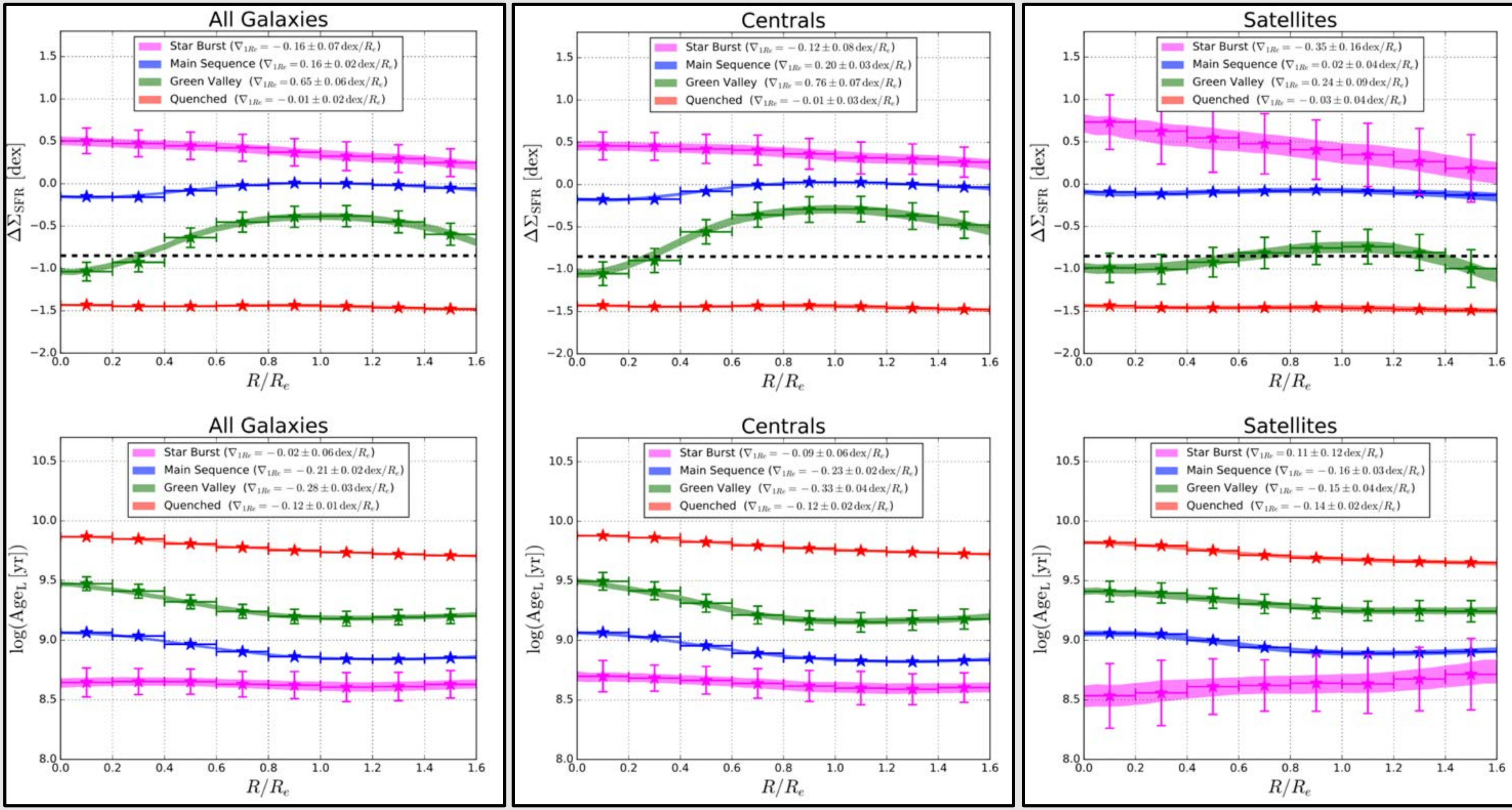
Luminosity Weighted Stellar Age



- 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

All Galaxies | **Centrals** | **Satellites**



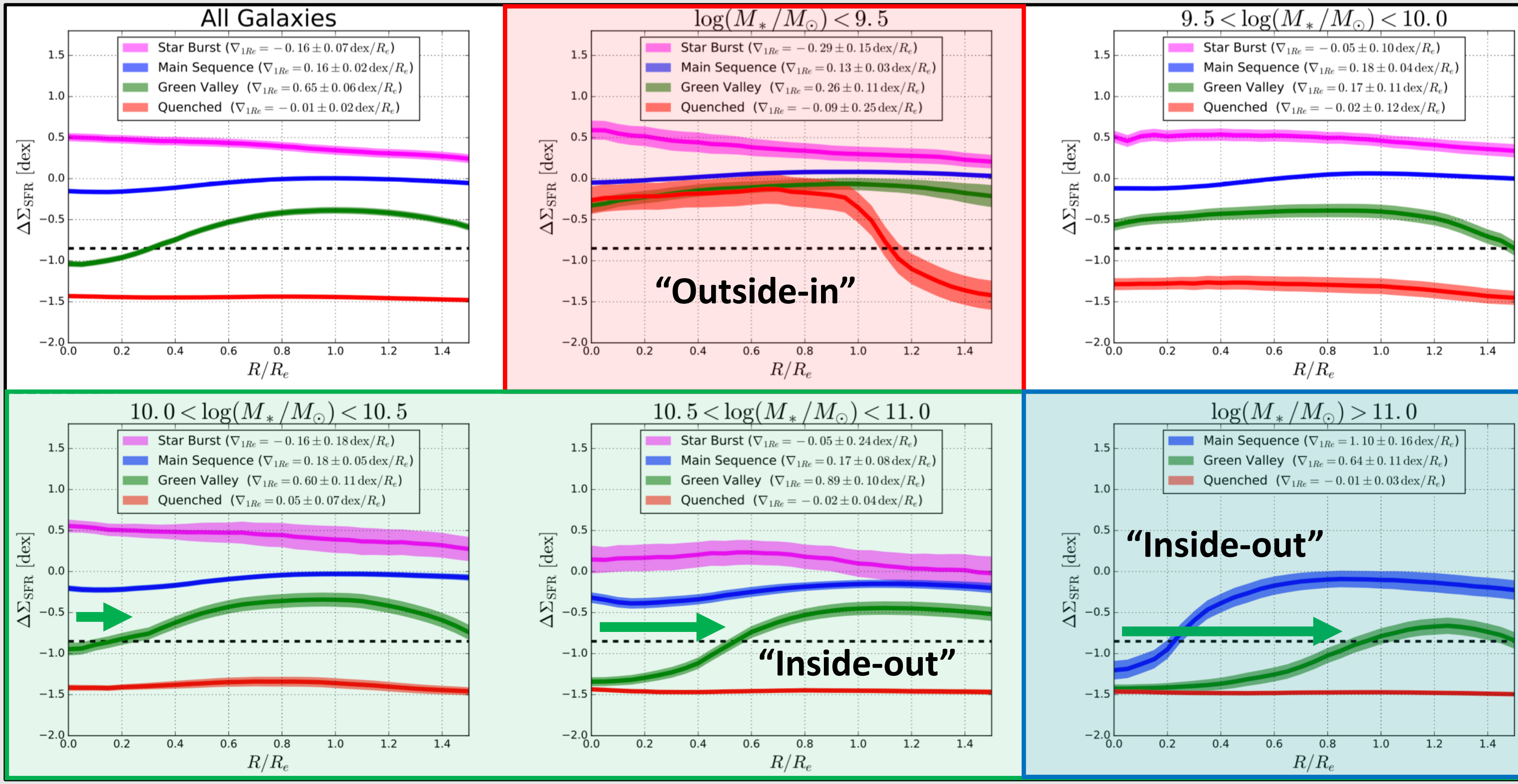
Take Away: **"Central galaxies quench "inside-out"; but satellite galaxies have much flatter profiles in transition"**

Bluck et al. (2020b, submitted)

Star Formation & Quenching as a Function of Mass

All Galaxies

Increasing M_*



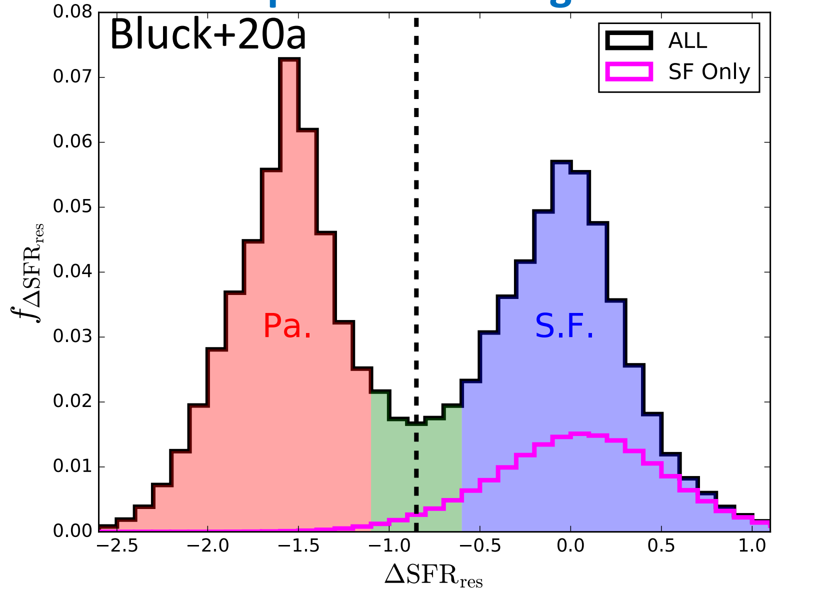
Take Away: **"High mass quenching proceeds inside-out but low mass quenching proceeds outside-in"**

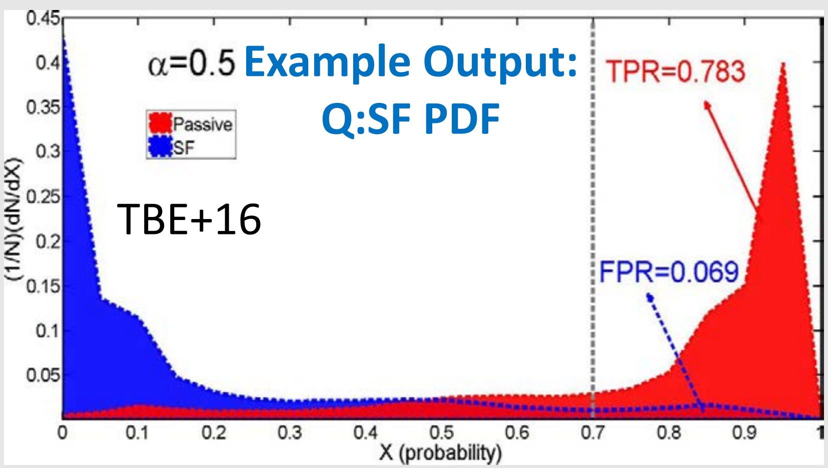
Bluck et al. (2020b, submitted)

Setting up the Machine Learning Problem:

Quenching Classification & Star Formation Rate Regression in ANN & RF

Input for Training:





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:

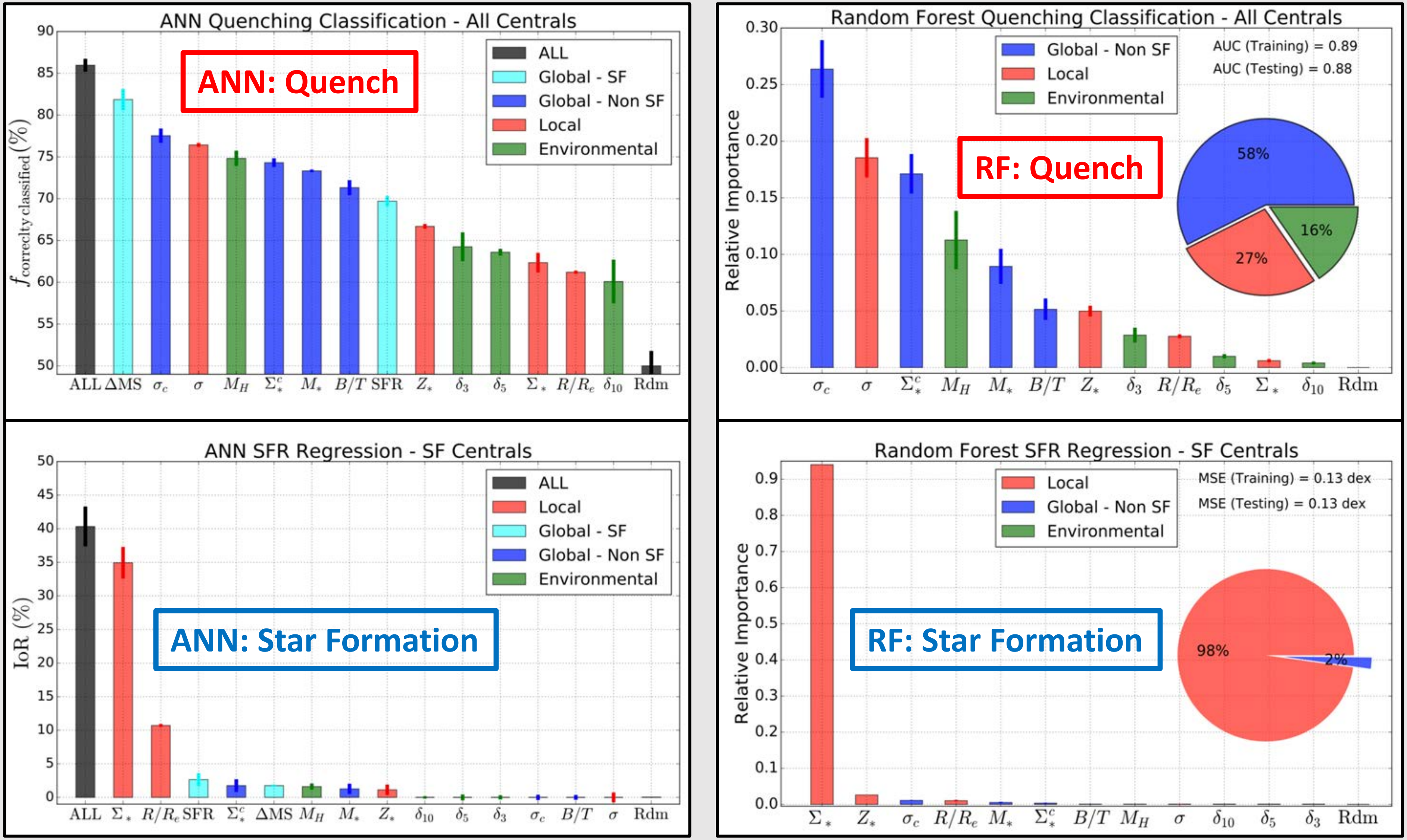
2) Identify which parameters, and groups of parameters, are particularly effective at predicting actual SFR surface densities in star forming regions

"Regression"

See also Teimoorinia, Bluck & Ellison (2016) & Bluck et al. (2019a) for similar ML approaches

Insights from Machine Learning:

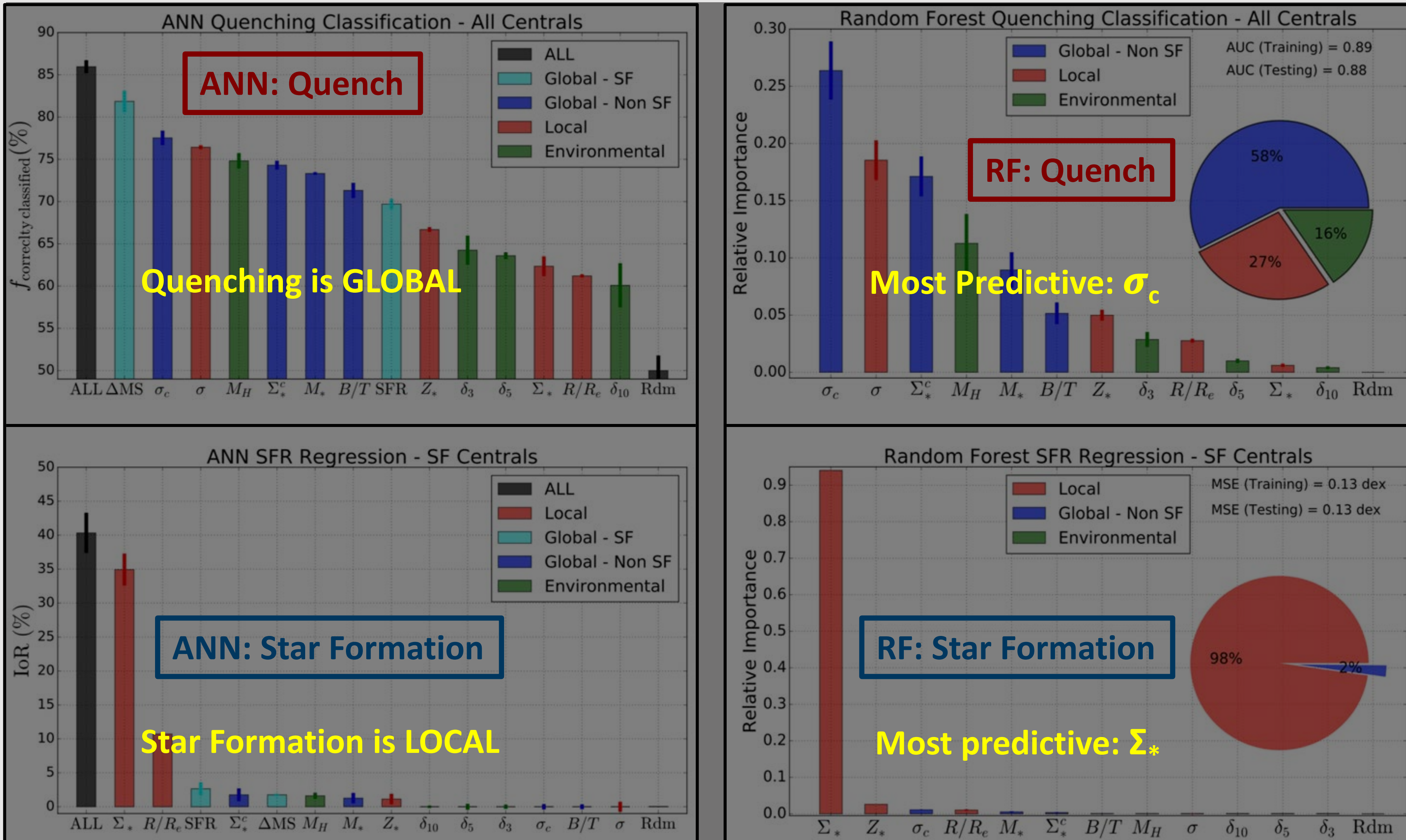
Star Formation vs. Quenching in ANN & RF for Centrals Only



Bluck et al. (2020a)

Insights from Machine Learning:

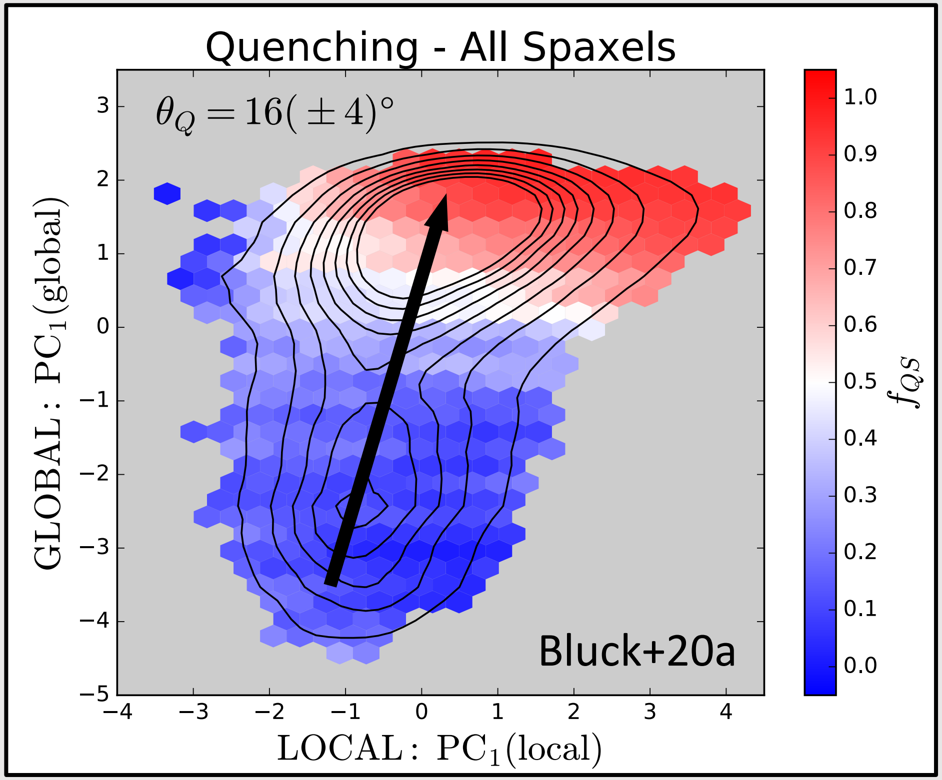
Star Formation vs. Quenching in ANN & RF for Centrals Only

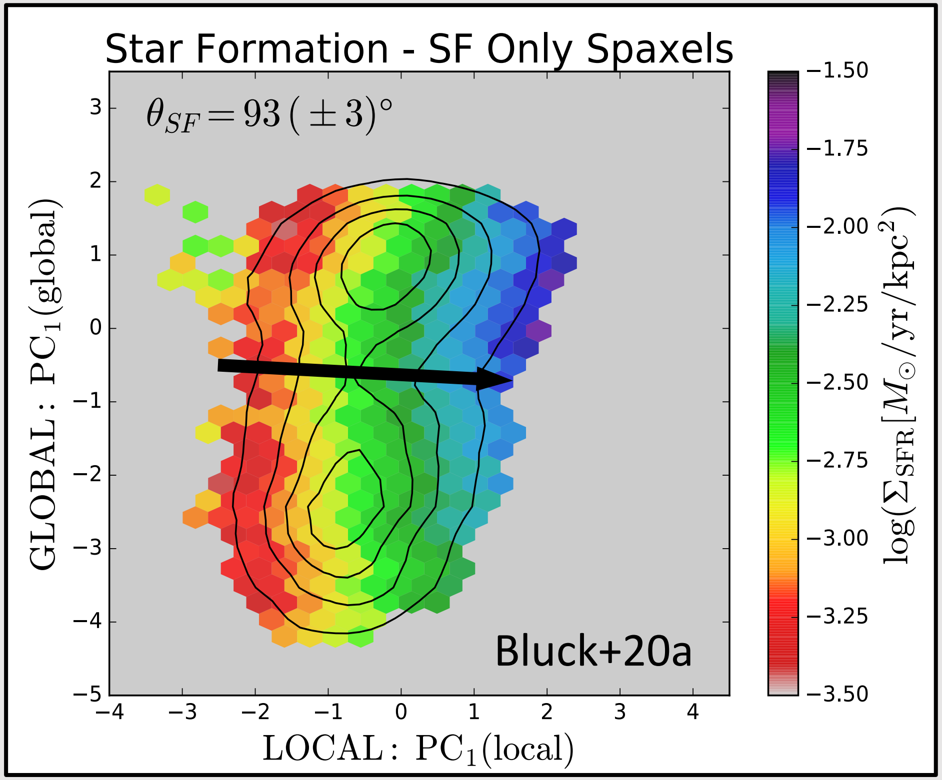


Bluck et al. (2020a)

Insights from Machine Learning:

PCA Test of GLOBAL vs. LOCAL Star Formation & Quenching





$$\theta_Q = \tan^{-1}\left(\frac{\rho_{Y f_{QS},X}}{\rho_{X f_{QS},Y}}\right)$$

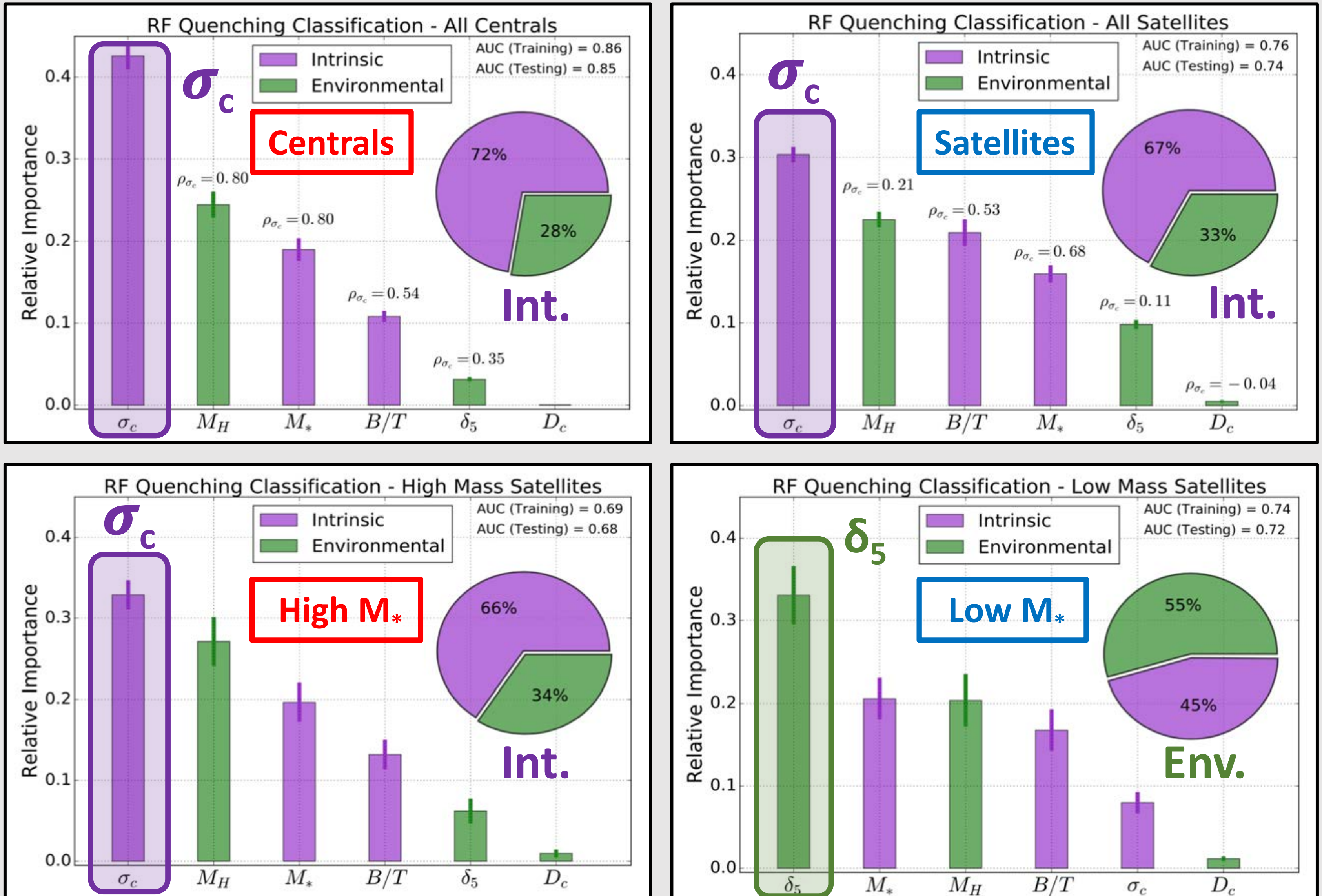
$$\theta_{SF} = \tan^{-1}\left(\frac{\rho_{Y \Sigma_{\rm SFR},X}}{\rho_{X \Sigma_{\rm SFR},Y}}\right)$$

“Quenching is a global process”

“Star formation is a local process”

Insights from Machine Learning:

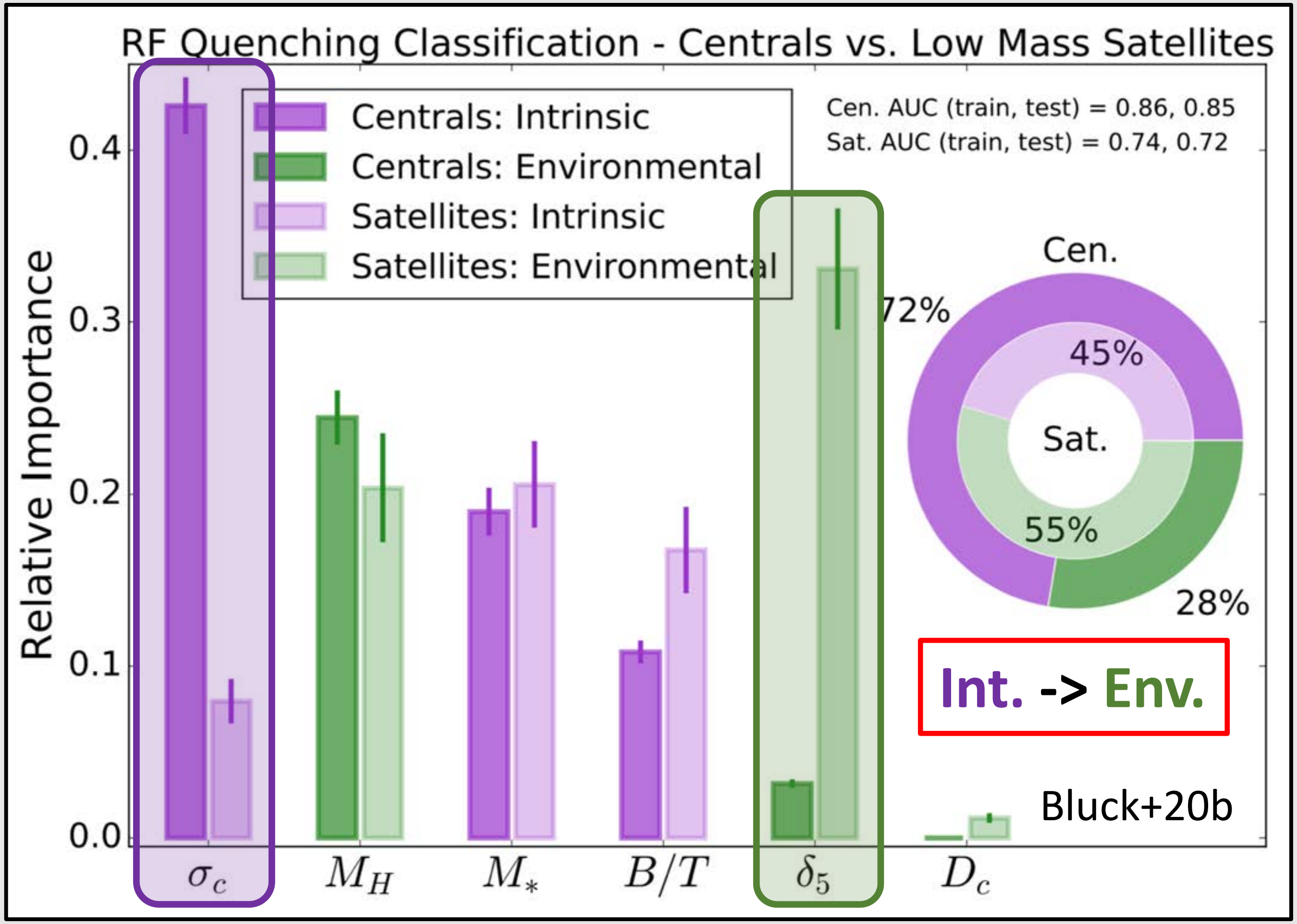
Quenching of Centrals & Satellites in a Random Forest Classification



Bluck et al. (2020b, submitted)

Insights from Machine Learning:

Quenching of Centrals & Satellites in a Random Forest Classification

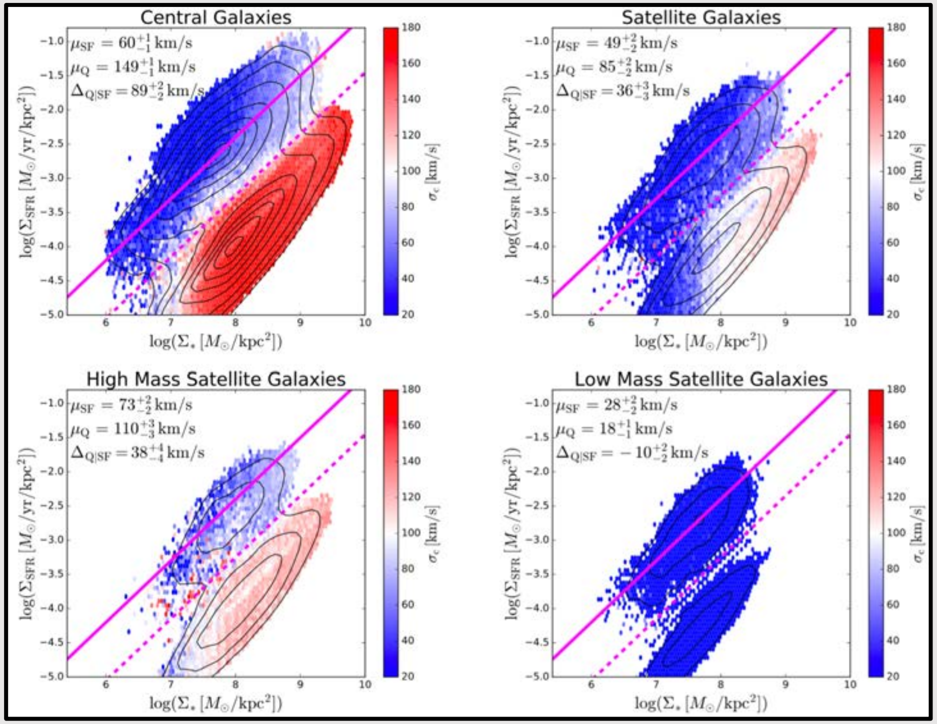


Take Away: **"Central galaxy quenching depends primarily on central velocity dispersion; but *low mass* satellite galaxy quenching depends primarily on local density"**

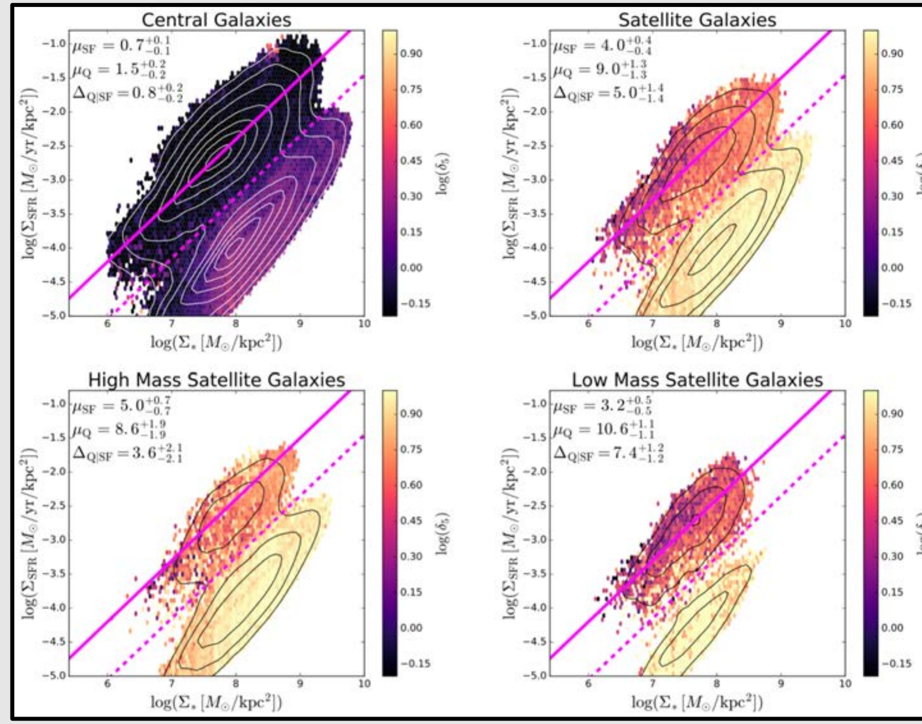
Insights from Machine Learning:

Visualizing the Machine Learning Results

Central Velocity Dispersion: σ_c



Local Galaxy Over-Density: δ_5

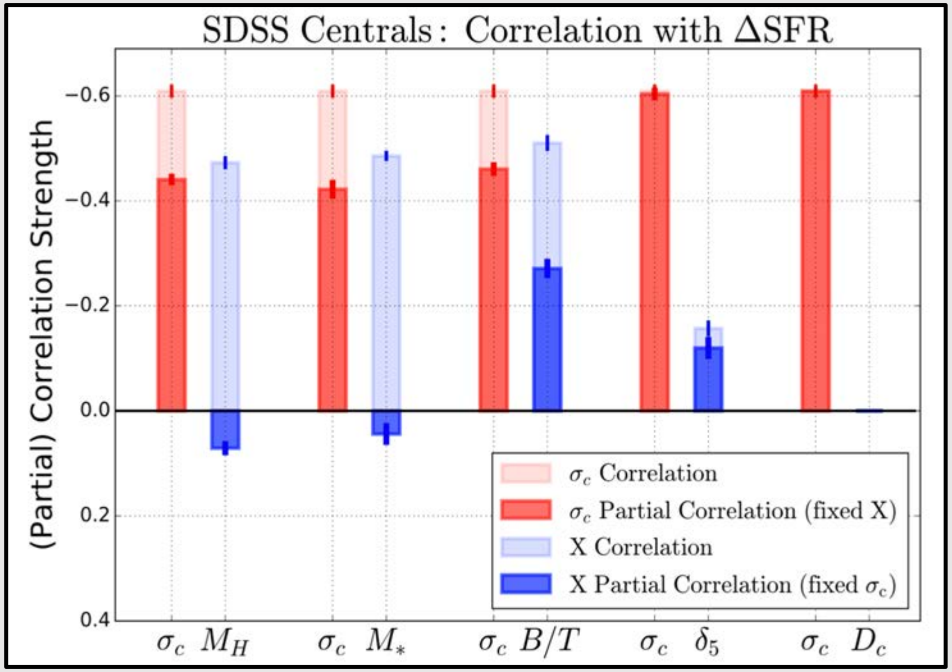


There is a striking separation in σ_c between star forming and quenched *centrals*. But no separation for low mass satellites.

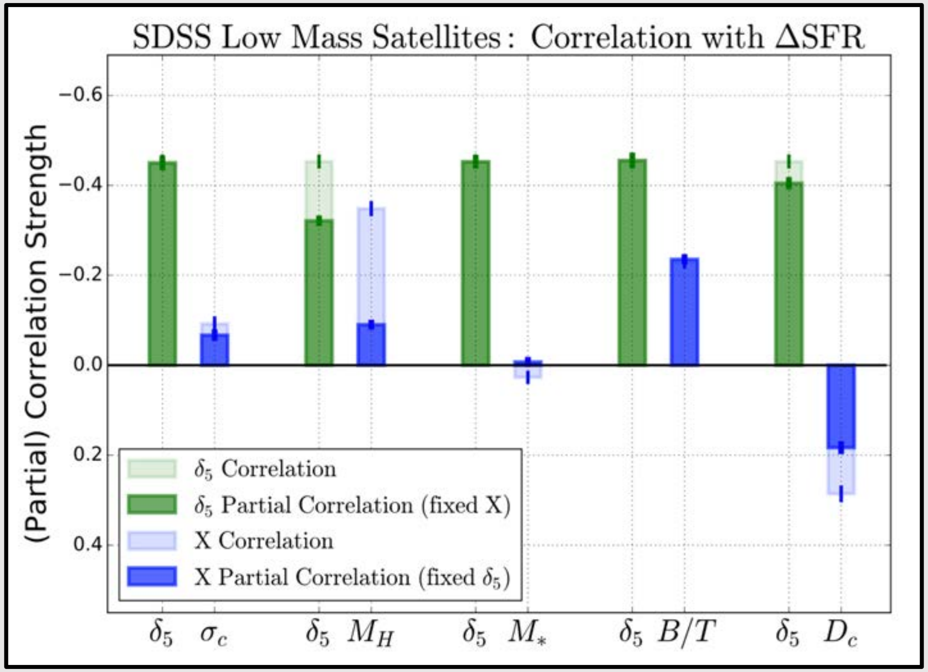
There is a clear separation in δ_5 between star forming and quenched *low mass satellites*. But essentially no separation for centrals.

Insights from Machine Learning:
Important Test -- Partial Correlation Coefficient Analysis in SDSS

All Centrals



Low Mass Satellites



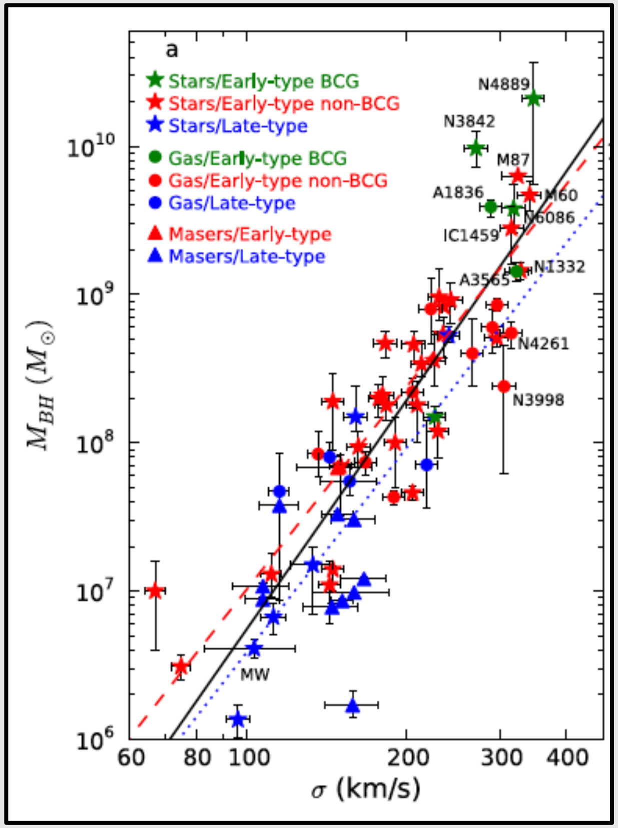
Note: negligible importance of both stellar and halo mass, at fixed central velocity dispersion

Note: negligible importance of central velocity dispersion at fixed local galaxy density

Bluck et al. (2020b, submitted)

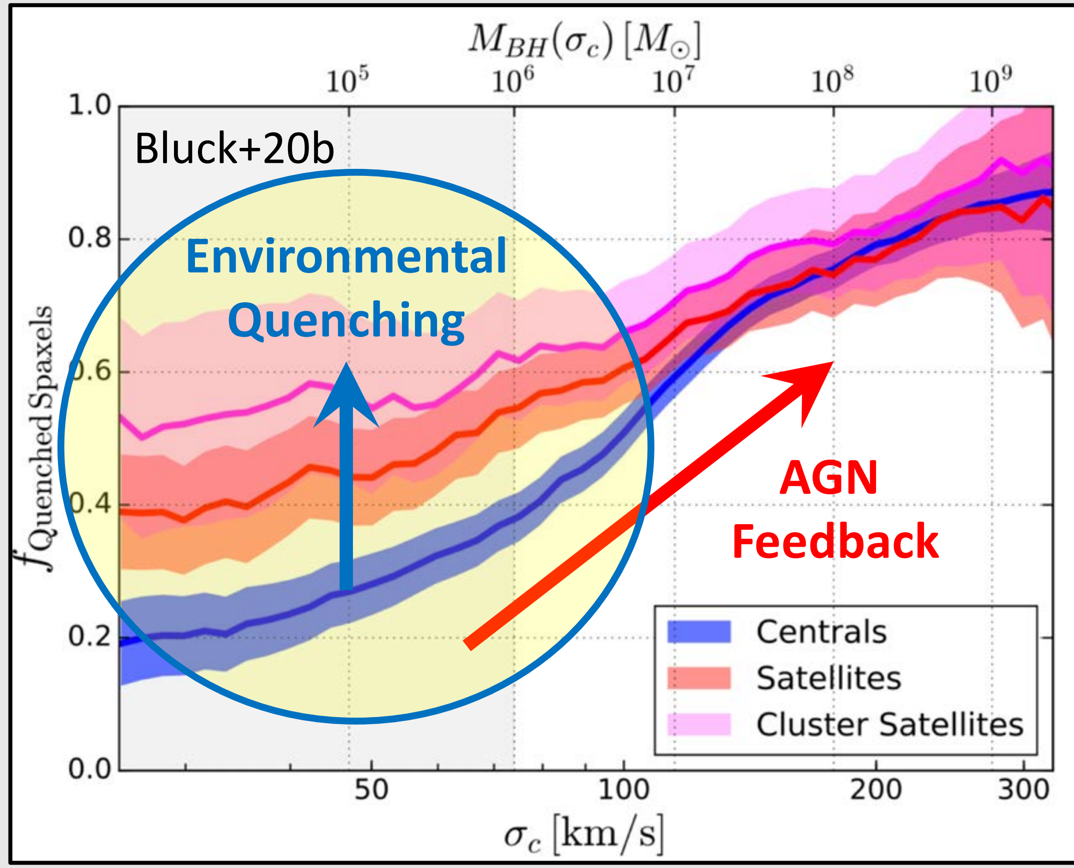
Interpreting the Importance of σ_c & δ_5

MBH – σ Relation



McConnell et al. (2011)

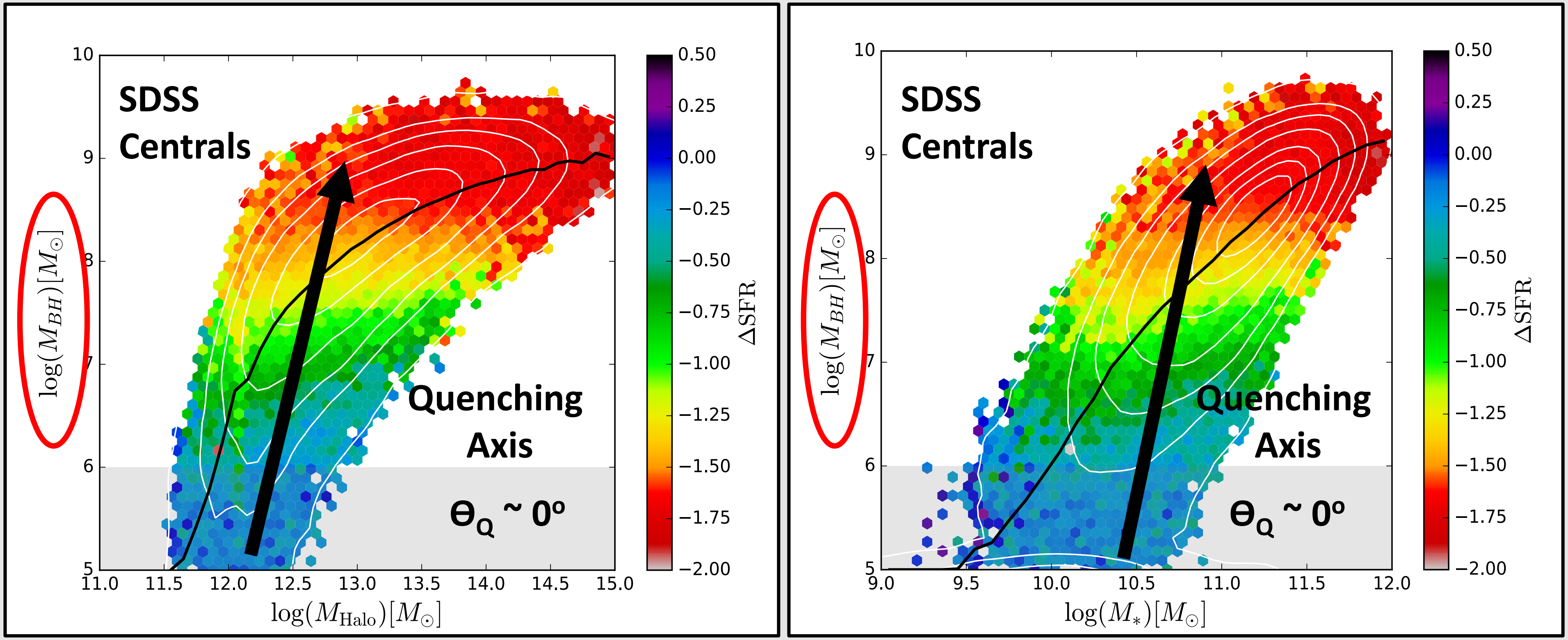
Quenched Fraction – MBH Dependence



Strong dependence on σ_c → Strong dependence on M_{BH}

(see also Bluck+14,16; Teimoorinia, Bluck & Ellison 2016)

Comparing M_{BH}, M_{Halo} & M_* as Drivers of Quenching



Bluck et al. (2020a)

Key Result:

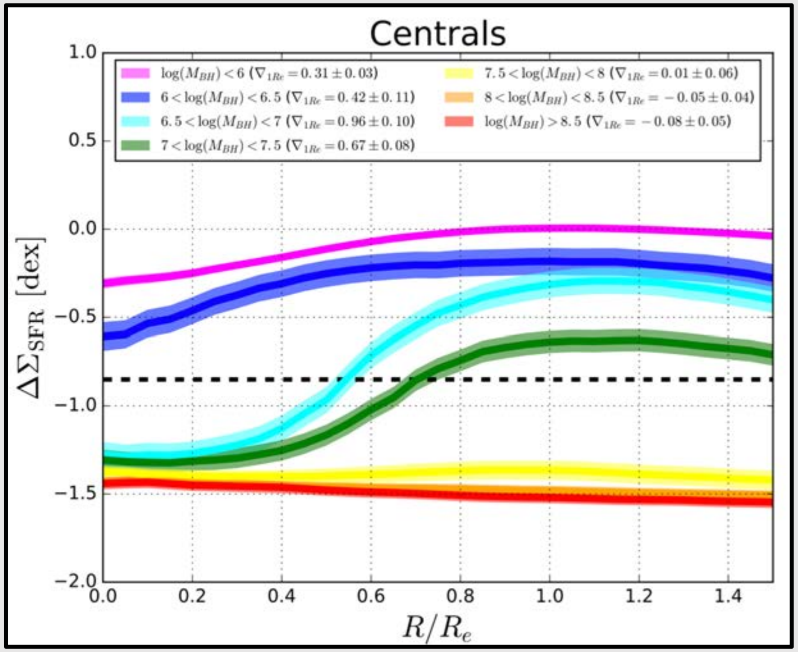
Central galaxy quenching is governed by supermassive black hole mass

(which is a natural prediction of AGN feedback models, yet highly challenging for models utilising virial shocks and/or supernovae heating to explain!)

Bringing It All Together:

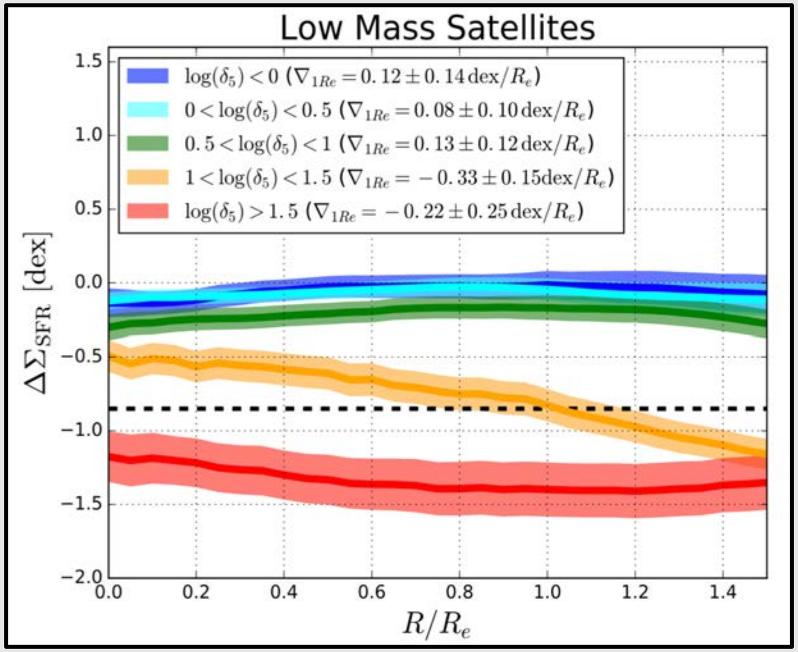
$\Delta\Sigma_{SFR}$ Profiles in Ranges of Black Hole Mass and Local Galaxy Density

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 <u>intrinsic processes</u>, especially those connected with σ_c
- Low mass satellite quenching is governed by <u>environmental processes</u>, especially those connected with δ_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)

<u>Papers</u>: Bluck+20a; Bluck+20b, submitted; Piotrowska, Bluck+20b, in prep.