Phase-Space Analysis:
Revealing
The Quenching History
of Cluster Galaxies

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Image credit@SDSS DR10
Observational Reports

Morphological fractions

Star Forming Fraction

Fasano et al. 2000

Haines et al. 2015
Observational Reports

Bimodal distribution of cluster galaxies’ sSFR

- How fast galaxies are quenched in clusters?
Observational Reports

- Which process is a main driver for quenching?
Quenching History Model

Two Phases of Quenching
Delayed-then-Rapid model (Wetzel+13)

- ‘Infall (T_{inf})’
- ‘Delayed (T_{delay})’
- ‘Phase-change’

Central-decaying

Satellite-decaying

Main parameter: \( T_{inf} \)
Model dependencies: \( T_{cen} \), \( T_{sat} \), \( T_{delay} \)
$T_{\text{inf}}$ - SFR relation

"Toy Model for Quenching"

$z = 1.00$
$\tau_{\text{cen}} = 4.0 \text{ Gyr}$
$\tau_{\text{sat}} = 1.5 \text{ Gyr}$
$T_{\text{delay}} = 3.0 \text{ Gyr}$

Star Forming  Quenched

Virial radius  Satellites
$T_{\text{inf}} - \text{SFR relation}$

- **Recent Infallers**
  - $\tau_{\text{cen}} = 4.0$ Gyr
  - $\tau_{\text{sat}} = 1.5$ Gyr
  - $T_{\text{delay}} = 3.0$ Gyr

- **Ancient Infallers**

**Central-decaying**
- $\tau_{\text{sat}} = 3$ Gyr
- $T_{\text{delay}} = 0$ Gyr

**Satellite-decaying**
- $\tau_{\text{sat}} = 1$ Gyr

**Fast-Quenching**

**Slow-Quenching**

$T_{\text{delay}} = 3.0 (1+z)^{-1.5}$ Gyr

$T_{\text{delay}} = 0$ Gyr
[Simulation]

- YZiCS (Yonsei Zoom-in Cluster Simulations) Using RAMSES, Choi & Yi (2017)
- 15 Clusters in a 200 Mpc/h cubic box
- dM_{DM}=8e7 M_{sun}, dM_{Star}=5e6 M_{sun}, dx=0.76 kpc/h
- Over-quenching problem

[Observation]

- Cluster Catalogue in Tempel et al. 2014
  Used SDSS DR10 Galaxies
- 421 Clusters (z < 0.166 & M_{vir} > 5e13 M_{sun})
- 17,218 Satellite Disk galaxies (log(M_{star}) > 9.5)
Quantile Matching Method

A method to infer the relation between two parameters

Assumptions

1. Two parameters are correlated, that is, Y is driven by X ("Causality")
2. The relation is monotonic
Phase-space Analysis for Causality

Inside Cluster

- Accreted earlier
- More quenched

Outside Cluster

- Accreted recently
- Less quenched

Rhee et al. 2017

Trajectory of a galaxy
Caustic curve
Phase-space Analysis for Causality

**Boundary**

\[ dX = 0.2 \]

- **Time since Infall [Gyr]**
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10
  - 12

- **log (SFR) \[ \log(M_\odot \text{yr}^{-1}) \]**
  - -2
  - -1
  - 0
  - 1
  - 2
  - 3

- **\( |V_{\text{LOS}}| / \sigma_{\text{LOS}} \)**
  - 0.0
  - 0.5
  - 1.0
  - 1.5
  - 2.0

- **\( R_{\text{proj}} / R_{\text{vir}} \)**
  - 0.0
  - 0.5
  - 1.0
  - 1.5
  - 2.0

**T\text{inf} from YZiCS Gals**

**SFR from SDSS Gals**
Derived $T_{\text{inf}}$ - SFR relation

- Result from ~ 50 pixels (9 points per each pixel)
- Each data point has different weight
Quenching Parameters

- **Central phase**: Roughly 4 Gyrs, comparable to other studies (Wetzel+13, Oman)

Rhee et al. 2018, in prep
Take Home Messages

- We measure time since infall and SFR, in a statistical context
- We derive the relation of $T_{\text{inf}}$ versus SFR, using the quantile matching method
- We constrain a quenching model
Phase-space Analysis for **Causality**

Rhee et al. 2017

- **Bar length** ~ number density of each population
- **Numbers** ~ mean $t_{\text{inf}}$, mass loss
Phase-space Analysis for Causality

Normalized Number Density

YZiCS Galaxies

SDSS Galaxies

Comparison

Normalized Number Density

Relative Fraction

$R_{\text{proj}} / R_{\text{vir}}$

$I_{\text{los}} / i_{\text{los}}$

Ramses User Meeting 2018