Precipitation-Regulated Galaxies

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Fundamental Questions
What turns galaxies on and off?

What quenches star formation at $M_{\text{halo}} > 10^{12} M_{\text{Sun}}$?

What limits star formation in the most massive galaxies?

How are spheroids linked to black holes?

Why is star formation in small galaxies so inefficient?
What turns galaxies on and off?

What quenches star formation at $M_{\text{halo}} > 10^{12} \, M_{\odot}$?

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What limits star formation in the most massive galaxies?

How are spheroids linked to black holes?

How does feedback work?
Circumgalactic Conditions
Tumlinson+ 11 (COS-Halos)

Most of a galaxy’s baryons & metals are in the CGM
Precipitation & Cluster Cores
Cold Triggering of AGN Feedback
Cavagnolo+ 08

\[ K_0 = kTn_e^{-2/3} \]

Requires Chandra-like resolution

Black-Hole Power

Multiphase Gas

Core Entropy Index
If the medium is kept in global thermal balance by feedback, then the threshold for formation of multiphase gas is:

\[ \frac{t_{\text{cool}}}{t_{\text{ff}}} \sim 1 \] in a box  \[ \frac{t_{\text{cool}}}{t_{\text{ff}}} \sim 10 \] in a spherical potential

... but see Meece, O’Shea, & Voit 2015
Dependence of $L_{H\alpha}$ on $\min(t_c/t_{ff})$ looks more like a steep ramp than a threshold.

Implies a very stiff black-hole feedback response that maintains $t_c/t_{ff} \sim 10$ for most systems.

But there are outliers extending to $t_c/t_{ff} \sim 50$. 

Evidence for Precipitation

Voit & Donahue 2015; data: Cavagnolo thesis
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**Precipitation Threshold:**

1. Use 250 km/s singular isothermal sphere for the stars.

2. Use NFW halo with \( c_{500} = 3 \) for the dark matter.

3. Calculate \( t_{\text{ff}}(r) \).


**Baseline:** Voit+ 2005

**No Cooling:** Voit+ 2002

**Conduction:** Voit 2011
Precipitation-Regulated Galaxies

Cooling-Time Profiles
Voit+ 2015, Nature

![Graph showing cooling-time profiles with different regimes: Multiphase Gas and No Multiphase Gas, with various cooling scenarios like isothermal core, conductive balance, precipitation, and baseline.](image)
Precipitation-Regulated Galaxies

Cooling-Time Profiles
Voit+ 2015, Nature

 Requires Chandra-like resolution

Entropy Threshold

Precipitation Radius

no cooling
isothermal core
conductive balance
precipitation
baseline

Multiphase Gas

- 2-10 keV, Hα
- 0.5-2 keV, far-IR

K₀

r (kpc)

t_{\text{cool}} (\text{years})

Entropy Threshold

Precipitation Radius

no cooling
isothermal core
conductive balance
precipitation
baseline

Requires Chandra-like resolution
Precipitation-Regulated Feedback

Gaspari+ 2012, 2013, 2014; Li & Bryan 2014a, b; Li+ 2015

$t = 0.27$ Gyr

300 kpc

Temperature (K)

$10^6$ to $10^7$
Precipitation-Regulated Feedback

Gaspari+ 2012, 2013, 2014; Li & Bryan 2014a, b; Li+ 2015

t = 0.27 Gyr
Precipitation Cycles
Toward Cosmological Implementation
Meece Ph.D. Thesis

Precipitation-Regulated Galaxies
G M Voit
Precipitation & Quenching
Two Kinds of Massive Ellipticals
Werner+ 12, Werner+ 14

Single-Phase
NCG 1399

Multiphase
NGC 5044
**Entropy Profiles of Ellipticals**

Voit+ 15 (Apr 2015, ApJL), data: Werner+ 12,14

**Single-phase ellipticals:**

\[ K \approx (5 \text{ keV cm}^2) r_{\text{kpc}} \]

**Multiphase ellipticals:**

\[ K \approx (3.5 \text{ keV cm}^2) r_{\text{kpc}}^{2/3} \]
Precipitation Threshold
Voit+ 15 (Apr 2015, ApJL), data: Werner+ 12,14

AGN 100x more powerful than the others!
**Precipitation Threshold**

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AGN 100x more powerful than the others!
Precipitation & Regulation
Regulation via Precipitation

Precipitation Threshold

\[ n_e(r) \approx \frac{3kT}{10\ t_{ff}(r)\ \Lambda(T,Z)} \]

Enrichment increases cooling and triggers feedback that lowers CGM density
Regulation via Precipitation

Precipitation Threshold

\[ n_e(r) \approx \frac{3kT}{10 \, t_{ff}(r) \, \Lambda(T,Z)} \]

Precipitation Rate

\[ \dot{M}_p \sim \frac{\rho_{CGM} r_c^3}{10 \, t_{ff}(r_c)} \]

Reducing CGM density reduces gas supply for star formation

\[ \zeta \ll 1 \]

\[ \eta \sim 1 \]
Regulation via Precipitation

Precipitation Threshold

\[ n_e(r) \approx \frac{3kT}{10 \ t_{\text{ff}}(r) \ \Lambda(T,Z)} \]

Precipitation Rate

\[ \dot{M}_p \sim \frac{\rho_{\text{CGM}} r_c^3}{10 \ t_{\text{ff}}(r_c)} \]

Abundance Saturation

\[ \dot{Z}_{\text{gas}} \approx \frac{Y \dot{M}_* - Z_{\text{gas}} \dot{M}_{\text{in}}}{M_{\text{gas}}} \]

Saturation determines \( Z_{\text{gas}}(M) \) and \( f_*(M) \)
Mass-Metallicity Relation


Lower-mass systems reach saturation at low enrichment levels
Star formation rates in low-mass systems are limited by saturation.

Higher-mass systems transform gas into stars more quickly and quench sooner.
$M_{BH} - \sigma_v$ Relation


![Graph showing the relationship between black hole mass ($M_{BH}$) and velocity dispersion ($\sigma_v$). The graph includes symbols for different types of galaxies: Central Galaxies of Clusters, Ellipticals, Classical Bulges, and Pseudobulges. The equation $\epsilon_{BH} M_{BH} c^2 \sim L_{CGM} t_H$ is also displayed.]
Precipitation & X-Ray Surveyor
**Driver 1: Hot Gas at ~100 pc Resolution**

Resolving the Bondi radius in early-type galaxies requires Chandra-like optical quality and many photons.
Driver 2: CGM Imaging at < 0.5 keV

ROSAT stacks of SDSS LRGs indicate that $L_X - M_{\text{halo}}$ relation extends from cluster scales down to Milky Way scales.

Requires Chandra-like resolution, large effective area, low background, soft X-ray sensitivity.
What turns galaxies on and off?

Galaxies evolve in response to atmospheric conditions. High-resolution X-ray imaging is essential for studying galaxy evolution.