Formation and Growth of Cosmic Giants: Lensing View of Galaxy Cluster Halos


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High-mass Galaxy Clusters: “Cosmic Giants”

Rare largest class ($\sim 10^{15} M_{\text{sun}}$) of bound objects formed in the universe

N-body simulations (B. Diemer)
What are clusters made of?

**Baryon fraction**

\[ f_b \equiv \left( \frac{M_b}{M_b + M_{DM}} \right) \text{Universe} \approx \left( \frac{M_b}{M_b + M_{DM}} \right) \text{Clusters} \]

\[ f_b = \frac{\Omega_b}{\Omega_m} \approx 15.6\% \]

*(Planck cosmology)*
Intracluster Medium (ICM)

**ICM** = fully ionized H-He plasma \( T_e = 3-15 \text{keV}, \ n_e = 10^{-2}-10^{-3} \text{cm}^{-3} \)
~ nonrelativistic ideal gas with \( \gamma = 5/3 \)
High-mass clusters probing nonlinear structure formation

- Standard paradigm for structure formation: $\Lambda$CDM
  - Collisionless, cold dark matter
- Clusters offer fundamental tests of assumed DM properties:
  - DM density profile shape, $\rho(r|M)$
  - Phase-space distribution of DM
  - Halo shape and alignments
  - Substructure distribution $N(m,r|M)$
  - DM-galaxy-ICM offset

Umetsu+12
Clowe+04
Halo density profile

Navarro-Frenk-White '96 profile (CDM)

\[
\frac{d \ln \rho(r)}{d \ln r} = -2 \quad @ \quad r = r_s
\]

\[
\max(V_{\text{circ}}) \quad @ \quad r \approx 2r_s
\]

CLASH lensing survey

How DM halos form and evolve?

ΛCDM: “Inside-out” growth scenario
– DM halos are assembled from the inside out (Zhao+03).
– Internal structure of halos reflects their growth history (Ludlow+13).

(1) Fast-growth phase
Halos grow rapidly through gravitational collapse and major mergers.

Halo formation time: End of fast-growth phase

(2) Slow-growth phase
The halo outskirts ($r > r_s$) gradually grow via smooth matter accretion from surroundings, without changing the inner potential significantly.

Halo’s characteristic radius $r_s$ and $M_s=M(< r_s)$ preserve a memory of its formation time.
$M_s = M(<r_s)$

Halo boundary ($R_{sp}$)

Outer infall region

DM density field
Key Questions

Do halos preserve a record of the thermodynamic history of ICM (~90% of the cluster baryons)?

- **X-ray observable**: Core-excised $T = T_{\text{ICM}}(50-500\text{kpc})$
- **Lensing observable**: Halo characteristic radius, $<r_s> = 500-600\text{kpc}$ for high-mass clusters (~1/5 of the halo boundary)

Does the ICM temperature ($T$) correlate with DM halo progenitor quantities ($M_s, r_s$)?

- **If yes**: The ICM was likely heated during the fast-growth phase, and $T$ was conserved in the subsequent slow-growth phase.

If so, how do ($M_s, r_s, T$) correlate? What is the degree of scatter?

**Canonical predictions** (e.g., virial theorem, Komatsu-Seljak pressure model):

$$T \propto f(c) \frac{M_s}{r_s} \sim \frac{M_s}{r_s}$$
Data: deep multi-wavelength data sets from the CLASH survey


*HST*+Subaru-combined, strong-lensing, weak-lensing shear & magnification analysis on 20 high-mass CLASH clusters with \(<M_{\text{vir}}＞\sim 1.2 \times 10^{15} M_{\odot}/h\) (Umetsu+16, *ApJ*, 821, 116)

**X-ray analysis** with deep *Chandra*/XMM X-ray imaging and spectroscopy (Donahue+14, *ApJ*, 797, 34)
Strong Lensing (multiple imaging)

165 multiple images of 61 source galaxies strongly lensed by cluster A1689

Broadhurst et al. 2005

$\alpha = \partial \Psi$
Gravitational Shear

\[ \gamma = |\gamma| e^{2i\phi} = \partial \partial \Psi / 2 \]

Cluster A2218 (NASA/ESA)
Gravitational Magnification

\[ \kappa = \partial \partial^* \Psi / 2 = \Delta \Psi / 2 \]

Cluster MACSJ1149 (z=0.54)
High-resolution space imaging with *HST* (ACS/WFC3) for strong lensing

Subaru/Suprime-Cam multi-color imaging for weak lensing shear & magnification

Results: Principal Component Analysis

A tight fundamental plane (FP) exists with 0.045 dex scatter!!!
FP in simulated cluster halos

Cosmological $N$-body + hydro simulations with radiative cooling + nongravitational feedback (AGNs/SNe) by Rasia+2015

Fujita, Umetsu, Rasia+18
Observed vs. simulated FP

$$a \log(r_s) + b \log(M_s) + c \log(T) = \text{const.}$$

**Observed FP**

$$T \propto \frac{M_s^{1.8 \pm 0.5}}{r_s^{2.3 \pm 0.7}}$$

$$\propto (M_s / r_s)^2 \times M_s^{-0.2} r_s^{-0.3}$$

<table>
<thead>
<tr>
<th></th>
<th>Observation</th>
<th>Simulations</th>
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<tbody>
<tr>
<td></td>
<td>MUSIC</td>
<td>NF0</td>
</tr>
<tr>
<td>Non-gravitational effects</td>
<td>–</td>
<td>no</td>
</tr>
<tr>
<td>Redshift</td>
<td>$0.377^{+0.309}_{-0.190}$</td>
<td>0.25</td>
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<tr>
<td>Dispersion around the plane (dex)</td>
<td>$0.045^{+0.008}_{-0.007}$</td>
<td>0.025*</td>
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Projections of simulated clusters

Halos evolve with \( r_s \propto M_s^{1/2} \) (Zhao+09)

Formation epoch of halos \( \rho_{\text{crit}}(t_f) \sim \frac{M_s}{r_s^3} \)

MUSIC cosmological simulations (DM + adiabatic gas)

Fujita, Umetsu, Rasia+18
Stability of FP against mergers

Evolutionary track of a typical halo in the FB0+FB1 sample
What’s the physics governing FP?

A possible explanation: Bertschinger (1985) similarity solution for secondary infall and accretion of gas in an E-de S universe

Shock-heated, virialized ideal gas, $P \propto \rho^{5/3}$, with $M(<r)$

Accretion shock radius (shock jump conditions satisfied)

1. Entropy integral of B85
2. $P(k) \propto k^{-2}$ at cluster scales

$\Rightarrow$ (1)+(2) yield

$$T \propto \frac{M_{s}^{1.5}}{r_{s}^{2}}$$

$\bar{\rho} \propto a^{-3} \propto t^{-2}$

$V_{\text{infall}}=0 @ \text{turn-around radius } R_{\text{T.a.}}$
Summary

1. A tight fundamental plane exists in DM-ICM parameter space $(r_s, M_s, T)$
   - In the “inside-out” growth picture of ΛCDM, this indicates that $T$ was determined at the halo formation epoch ($\rho_{\text{crit}} \sim M_s/r_s^3$) and has been conserved during halo evolution.

2. The observed FP is tilted from the virial expectation, $T \propto M_s/r_s$, and can be explained by a similarity solution (Bertchinger85):
   - Contributions from the momentum flux at the cluster boundary should be included (e.g., Bertschinger 85)
   - For a self-consistent treatment of collisional gas + collisionless DM, see Shi (2016).

3. Numerical simulations reproduce the observed plane, regardless of the gas physics implemented in the code.

4. The plane is stable even against major mergers
   - Clusters evolve on FP along the direction of P1.
Supplemental slides
CLASH HST dataset

Splashback radius, \( R_{sp} \): Physical halo boundary

\[
\begin{align*}
    r > R_{sp} &: \text{infall region} \\
    r < R_{sp} &: \text{multi-stream intra-halo region}
\end{align*}
\]

Splashback radius depends on MAR, halo peak height, cosmology (\( \Omega_m \))

**Slow accreting halos**

\( R_{sp} > r_{200m} \)

**Fast accreting halos**

\( R_{sp} \sim r_{200m} \)

\(N\)-body simulations from S. More, Diemer, & Kravtsov 2015
Pseudo phase-space density profile

Scale-free behavior with $Q(r) := \rho/\sigma^3 \propto r^{-1.875}$ expected for self-gravitating collisionless systems in equilibrium (Taylor & Navarro 01)

Dynamical Jeans + lensing analysis of a relaxed cluster to solve for $M(r)$ and velocity orbital anisotropy, $\beta(r)$

- Observed $Q(r)$ consistent with a power-law with the theoretically predicted index!!
- Better agreement for passive galaxy members than star forming ones

(See also Munari+15)
CLUMI (CLUster lensing Mass Inversion): Multi-probe lensing analysis

Combining strong-lensing, weak-lensing shear and magnification

\[
P(\Sigma|WL, SL) \propto P(WL, SL|\Sigma)P(\Sigma) = P(n_\mu|\Sigma)P(g_+|\Sigma)P(M_{2D}|\Sigma)P(\Sigma).
\]

Subaru BVRiz, MACSJ1206 (z=0.44)

Galaxy Clusters as Cosmological Probes

Statistical and individual properties of rare massive clusters are sensitive to cosmology

Diemer & Kravtsov 2014
Halo concentration, $c_\Delta$

$$c_\Delta \equiv \frac{R_\Delta}{r_s} = \frac{\text{(Outer halo radius)}}{\text{(Inner scale radius)}}$$

Dutton & Maccio 14 (LCDM simulations)

In hierarchical structure formation, $<c>$ is predicted to correlate with $M$:
DM halos that are more massive collapse later on average, when the mean background density of the universe is correspondingly lower.

Sizable intrinsic scatter (at fixed $M$) ~30%-40%, reflecting diversity of mass accretion history & formation epoch.
Density structure of CDM halos

- Cuspy density profiles with outwardly steepening slopes
- Higher mass halos form later and are less concentrated
- Triaxial halo shape: massive halos being more prolate

Radial density profiles of DM halos

The concentration-mass relation

Dutton & Maccio 14
Cluster concentration-mass relation

\[ c_\Delta \equiv \frac{r_\Delta}{r_s} \]

Targeted lensing surveys of X-ray-selected clusters

LoCuSS \((<z>\sim 0.2)\)

CLASH \((<z>\sim 0.35)\)

Okabe & Smith 15

Umetsu+16, Merten+15
Halo concentration is sensitive to cosmology

\[ c_\Delta \equiv \frac{r_\Delta}{r_s} = \frac{\text{(Outer halo radius)}}{\text{(Inner scale radius)}} \]

Dutton & Maccio 2014

Dutton & Maccio 2014
The Bullet Cluster: Evidence of DM

$(\sigma/m)_{\text{SIDM}} < 1/\langle L_\rho \rangle \sim 1 \text{cm}^2/\text{g}$ (Randall+08)
Halo in a smooth-accretion phase

Growth of halo outskirts via continuous accretion from surroundings
Halo in a fast-accretion phase

Major mergers: halos in the process of formation