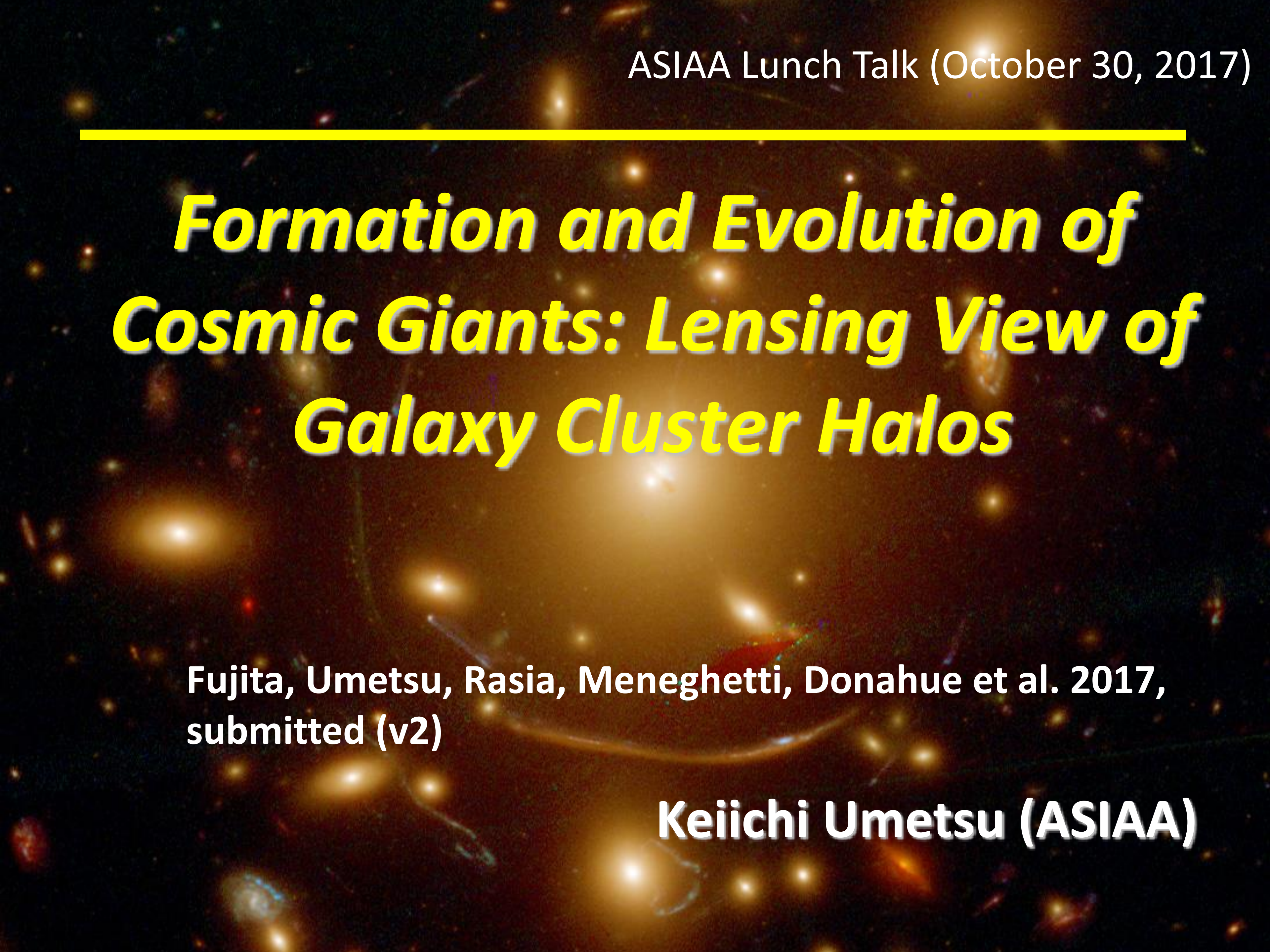


ASIAA Lunch Talk (October 30, 2017)

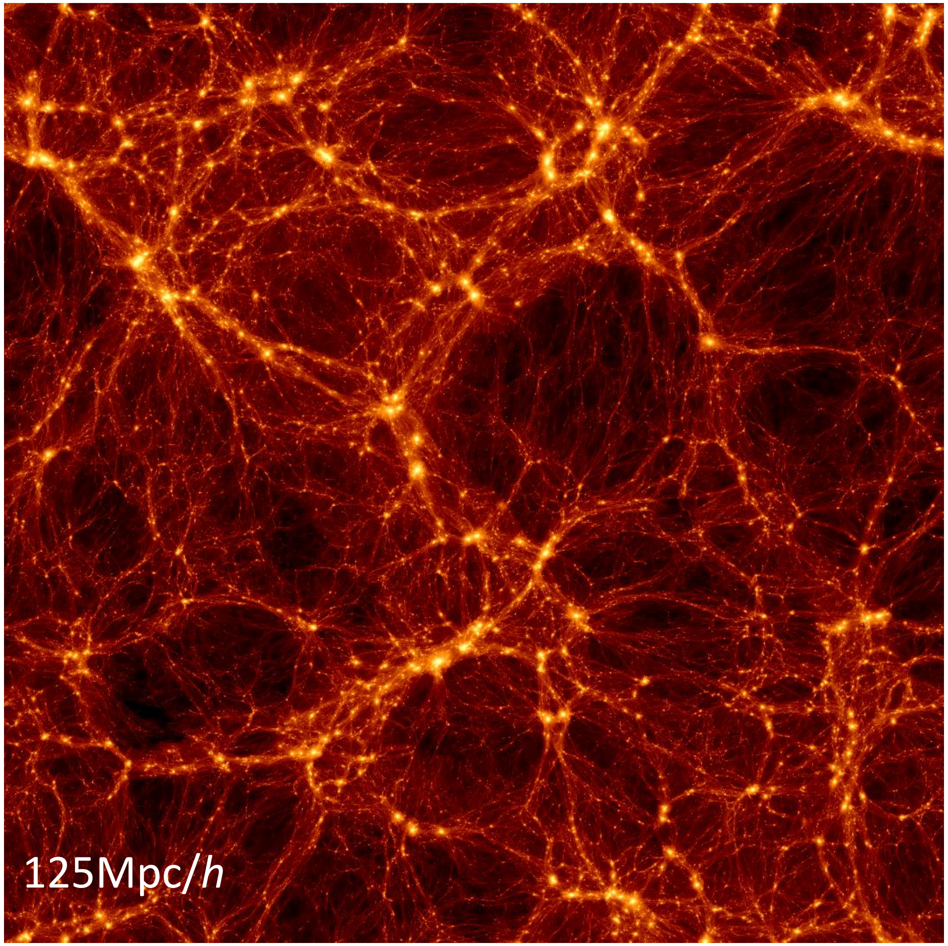
# Formation and Evolution of Cosmic Giants: Lensing View of Galaxy Cluster Halos

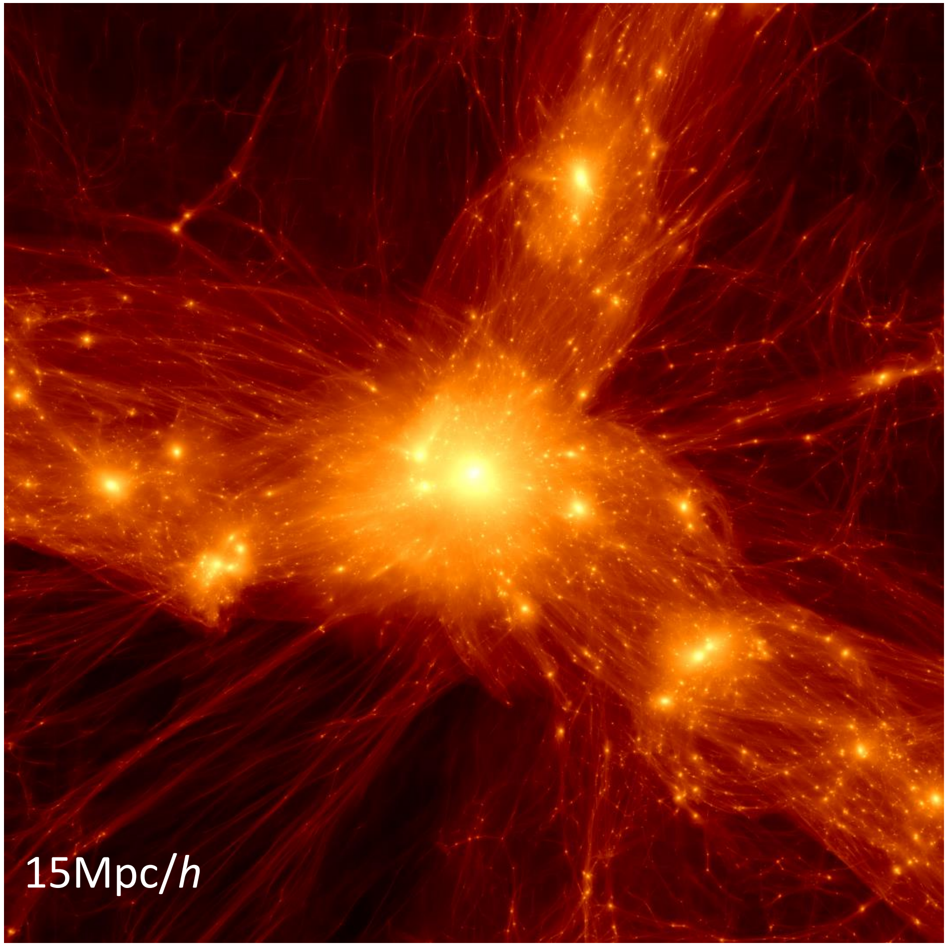
Fujita, Umetsu, Rasia, Meneghetti, Donahue et al. 2017, submitted (v2)

**Keiichi Umetsu (ASIAA)**

# High-mass Galaxy Clusters: “Cosmic Giants”

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





N-body simulations (B. Diemer)

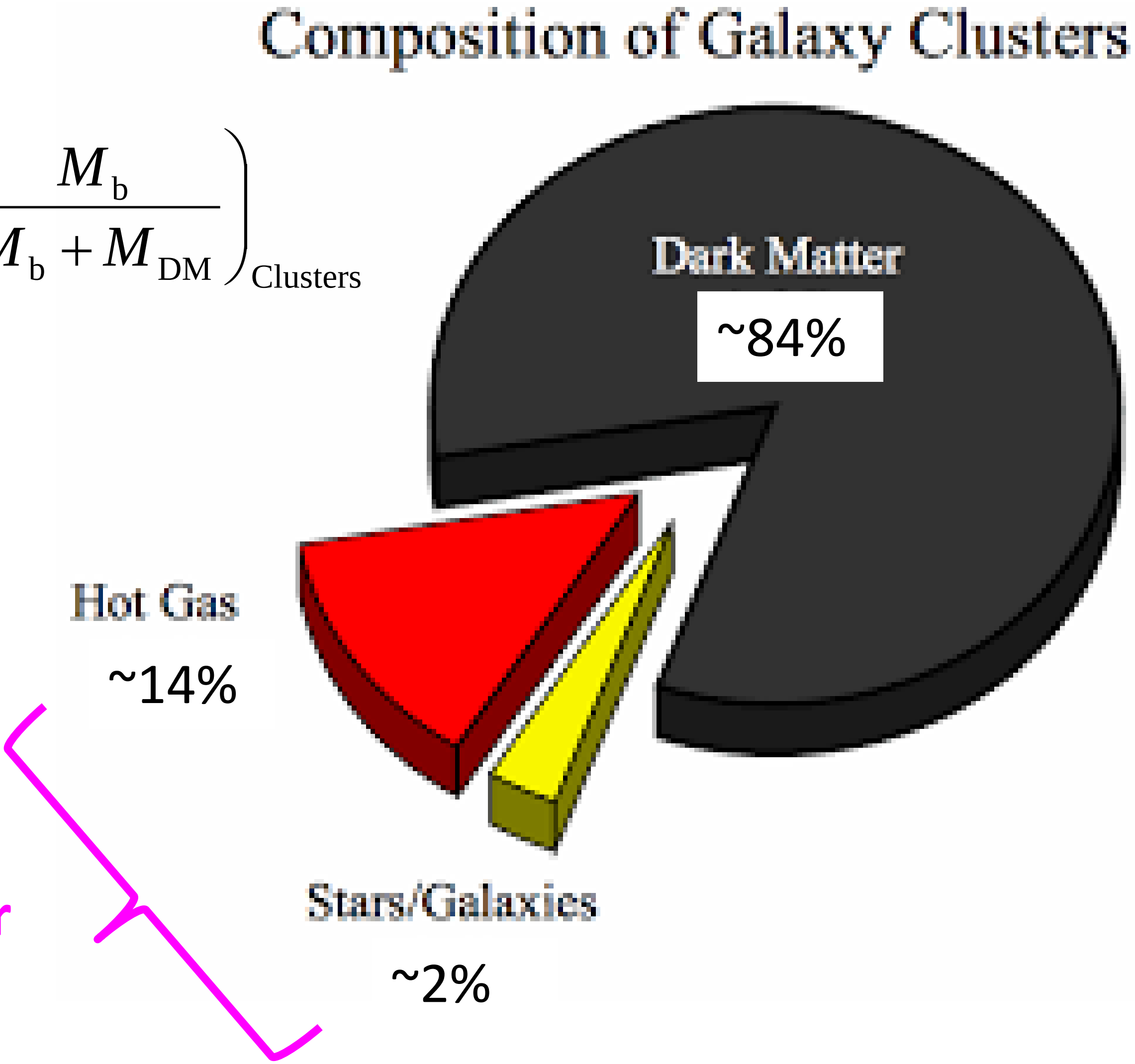
# What are clusters made of?

**Baryon fraction**

$$f_\mathrm{b} \equiv \left( \frac{M_\mathrm{b}}{M_\mathrm{b} + M_\mathrm{DM}} \right)_\mathrm{Universe} \approx \left( \frac{M_\mathrm{b}}{M_\mathrm{b} + M_\mathrm{DM}} \right)_\mathrm{Clusters}$$

$$f_\mathrm{b} = \frac{\Omega_\mathrm{b}}{\Omega_\mathrm{m}} \approx 15.6\%$$

(*Planck* cosmology)

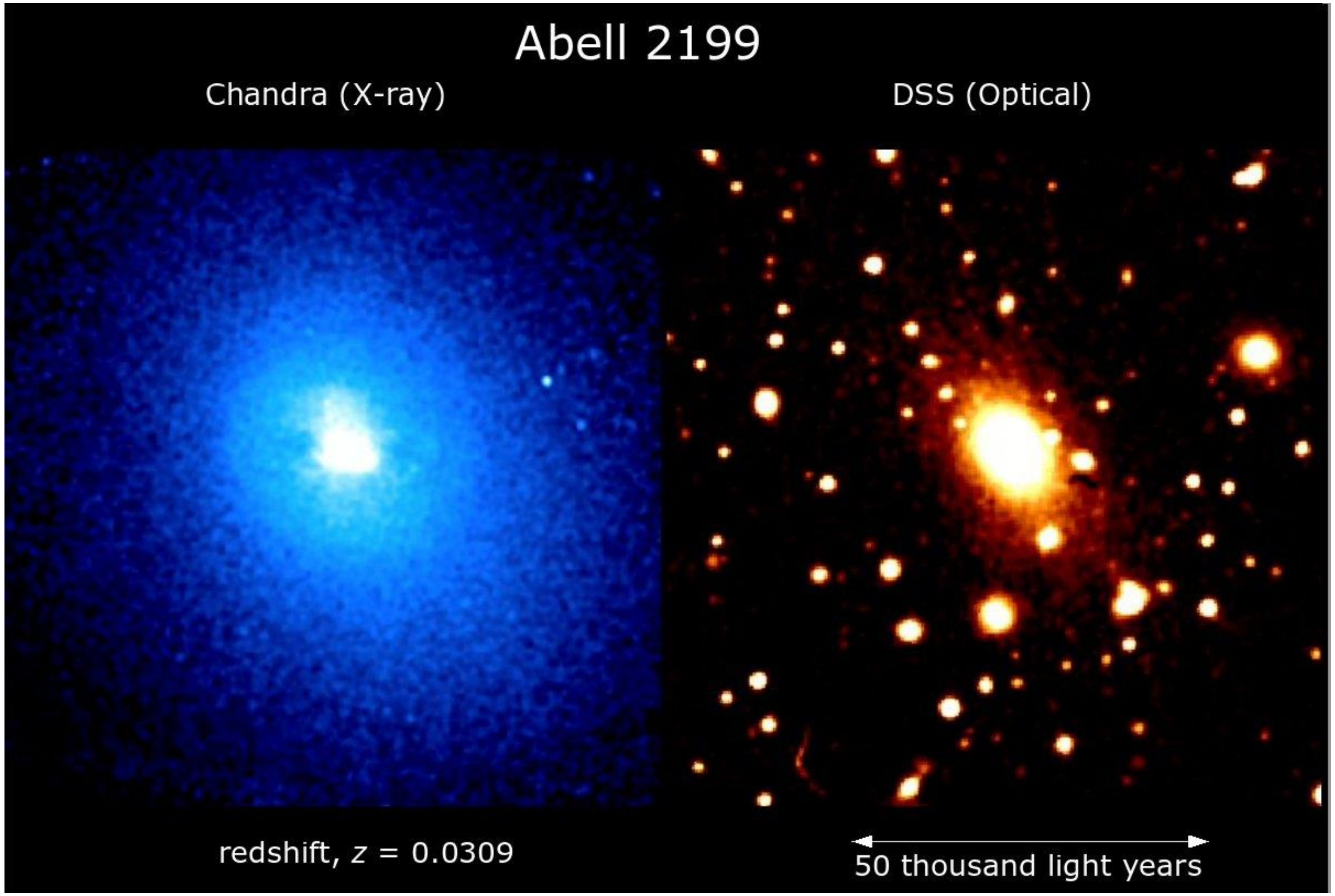


**Ordinal Matter (baryons)**

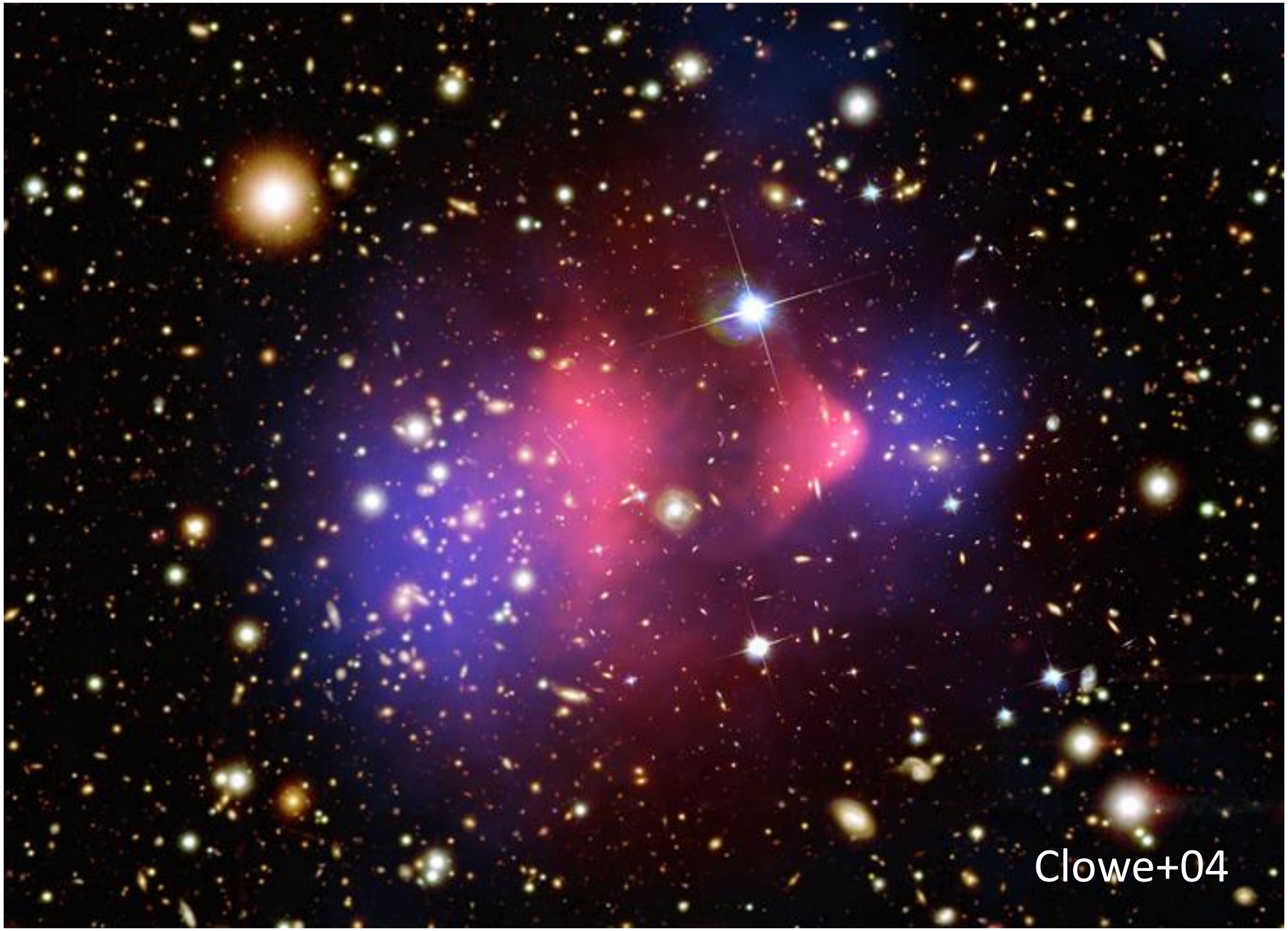
# Intracluster Medium (ICM)

**ICM** = fully ionized H-He plasma ($T_e$=3-15keV, $n_e$=$10^{-2}$-$10^{-3}$cm$^{-3}$)

~ nonrelativistic ideal gas with $\gamma$=5/3



# The Bullet Cluster: Evidence of DM



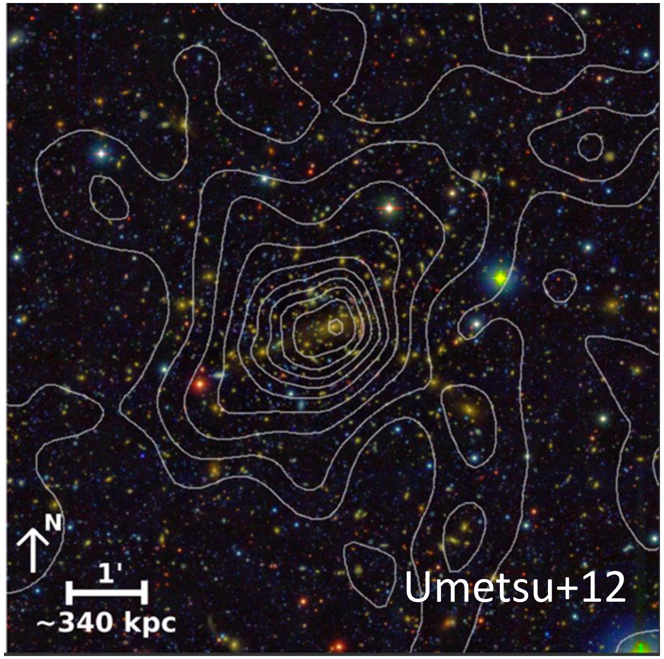
**Blue: DM**

**Red: ICM**

$(\sigma/m)_{\mathrm{SIDM}} < 1/\langle L\rho\rangle \sim 1\mathrm{cm}^2/\mathrm{g}$ (Randall+08)

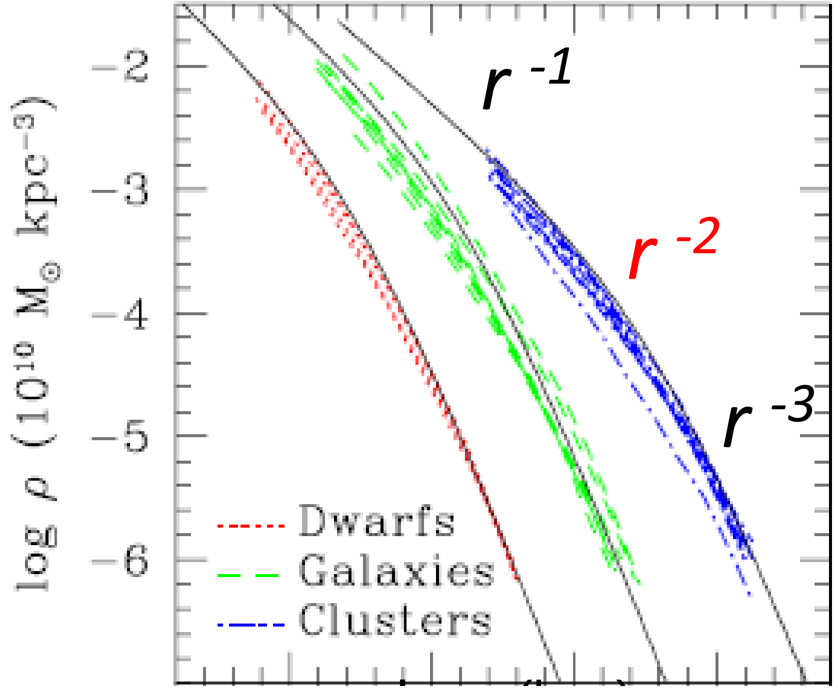
# High-mass clusters probing nonlinear structure formation

- 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
  - Substructure distribution
  - DM-galaxy-ICM offset



# Halo density profile

**N**avarro-**F**renk-**W**hite ‘96 profile (CDM)

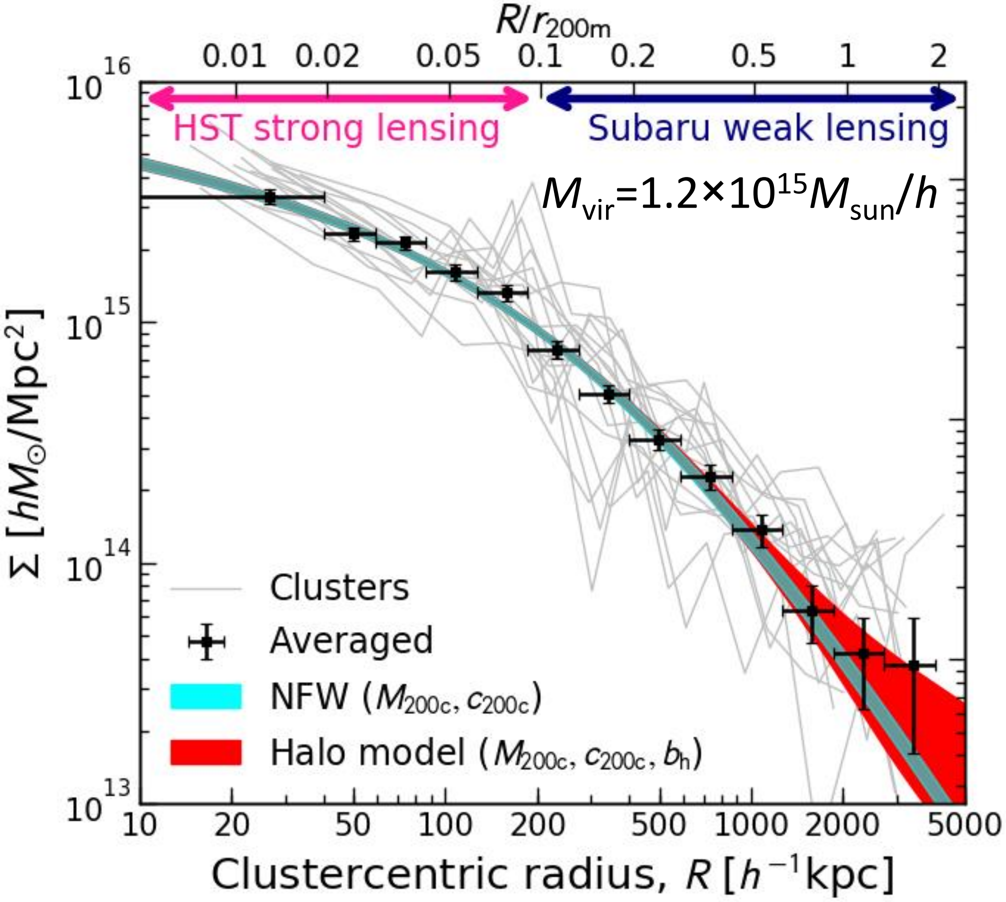


log $r$

$$\boxed{\frac{d\ln\rho(r)}{d\ln r} = -2 \;@\; r = r_s}$$

$$\max(V_c)\;@\;r \approx 2r_s$$

**CLASH lensing survey**



Umetsu et al. 2016, *ApJ*, 821, 116

# How DM halos form and evolve?

## "Inside-out" growth scenario ($\Lambda$CDM):

- DM halos are assembled from the inside out (Zhao+03).
- Internal structure of halos reflects their growth history (Ludlow+13).

### (1) **Fast-growth phase**

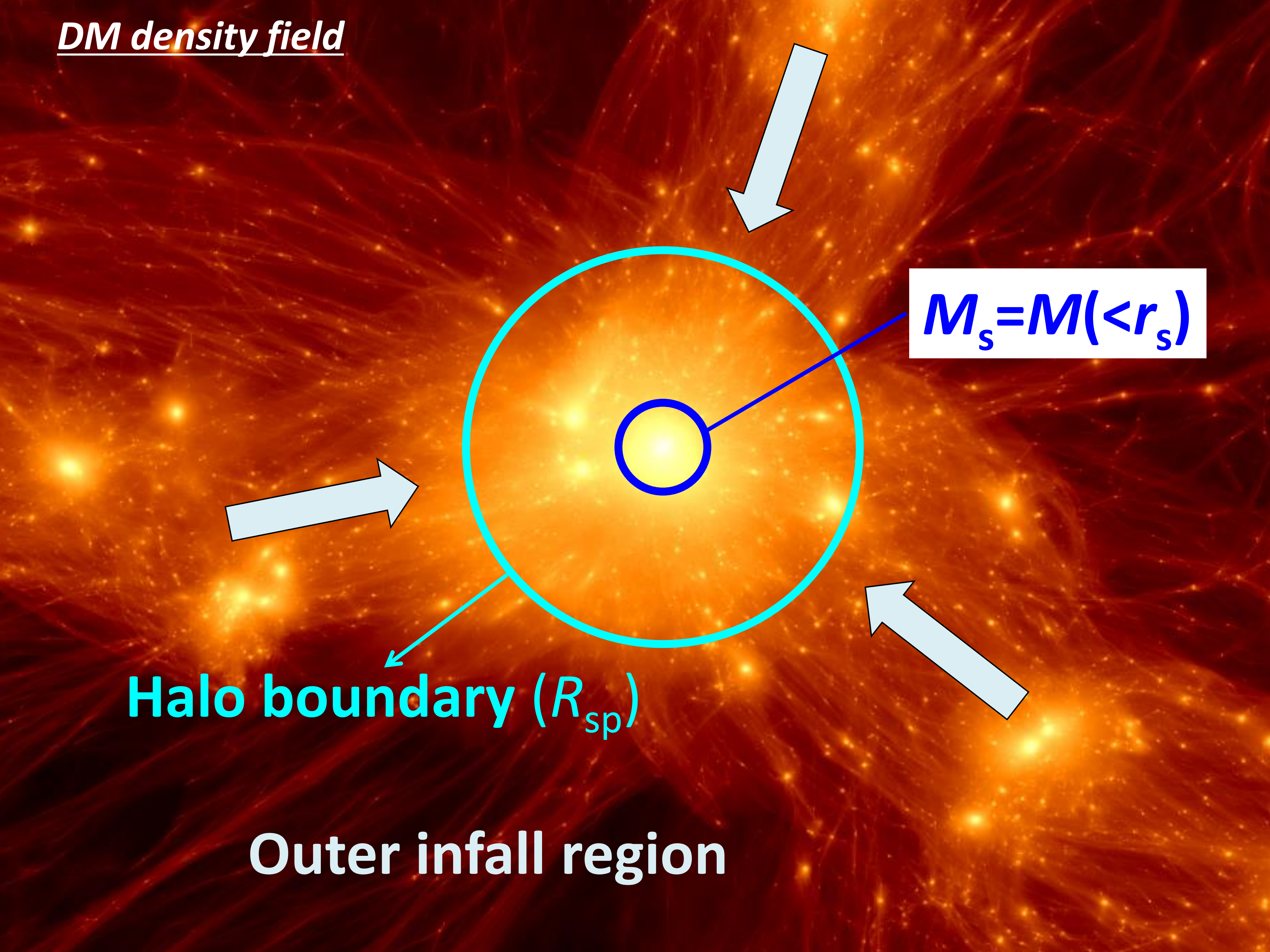
Halos grow rapidly through gravitational collapse and major mergers.

***Halo formation time*** : End of fast-growth phase (e.g., the last merger)

### (2) **Slow-growth phase**

The outskirts of halos ($r > r_s$) gradually grow through smooth matter accretion from surroundings, without changing the potential significantly.

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



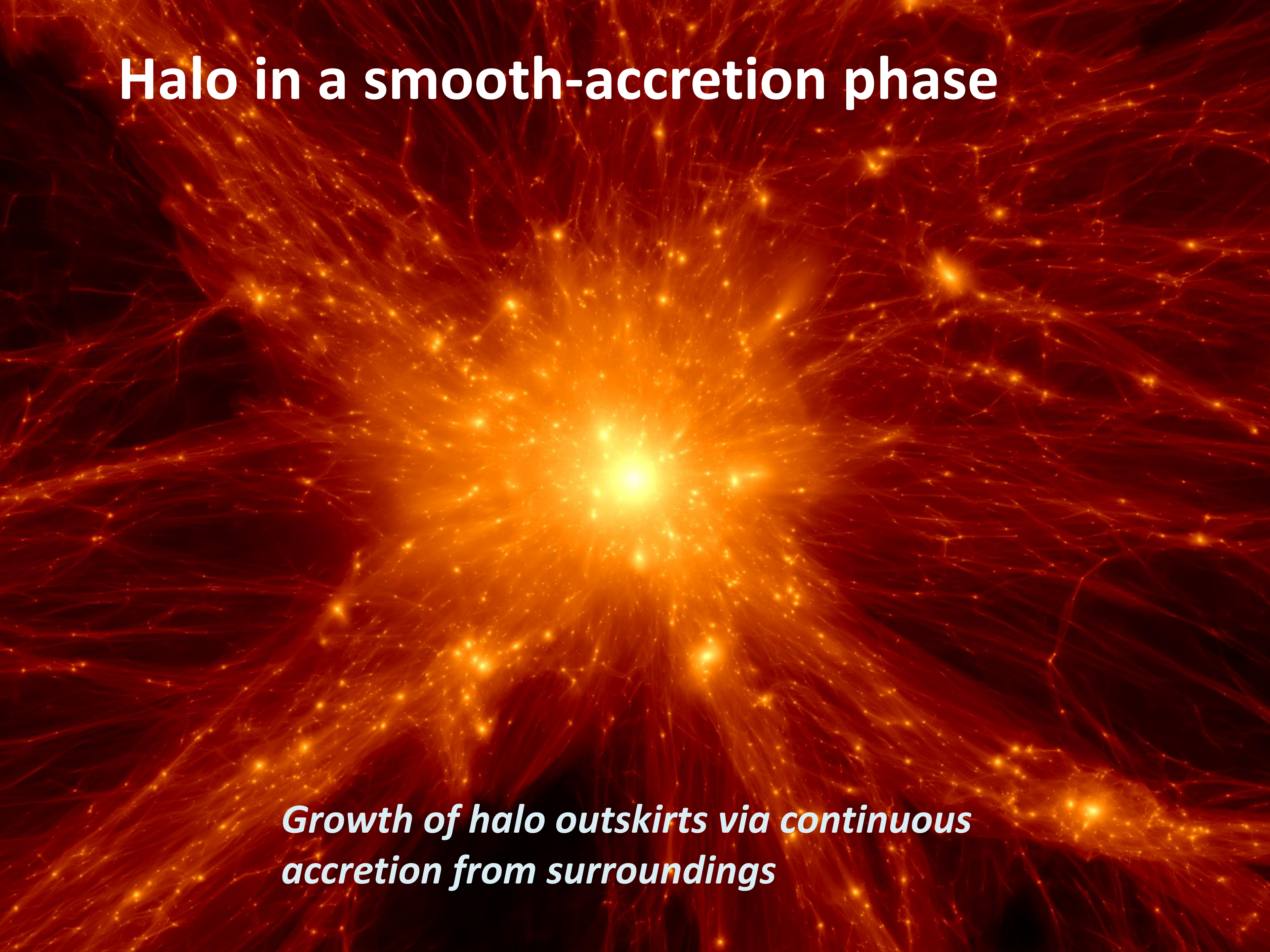
*DM density field*

$M_s=M(<r_s)$

**Halo boundary** ($R_{sp}$)

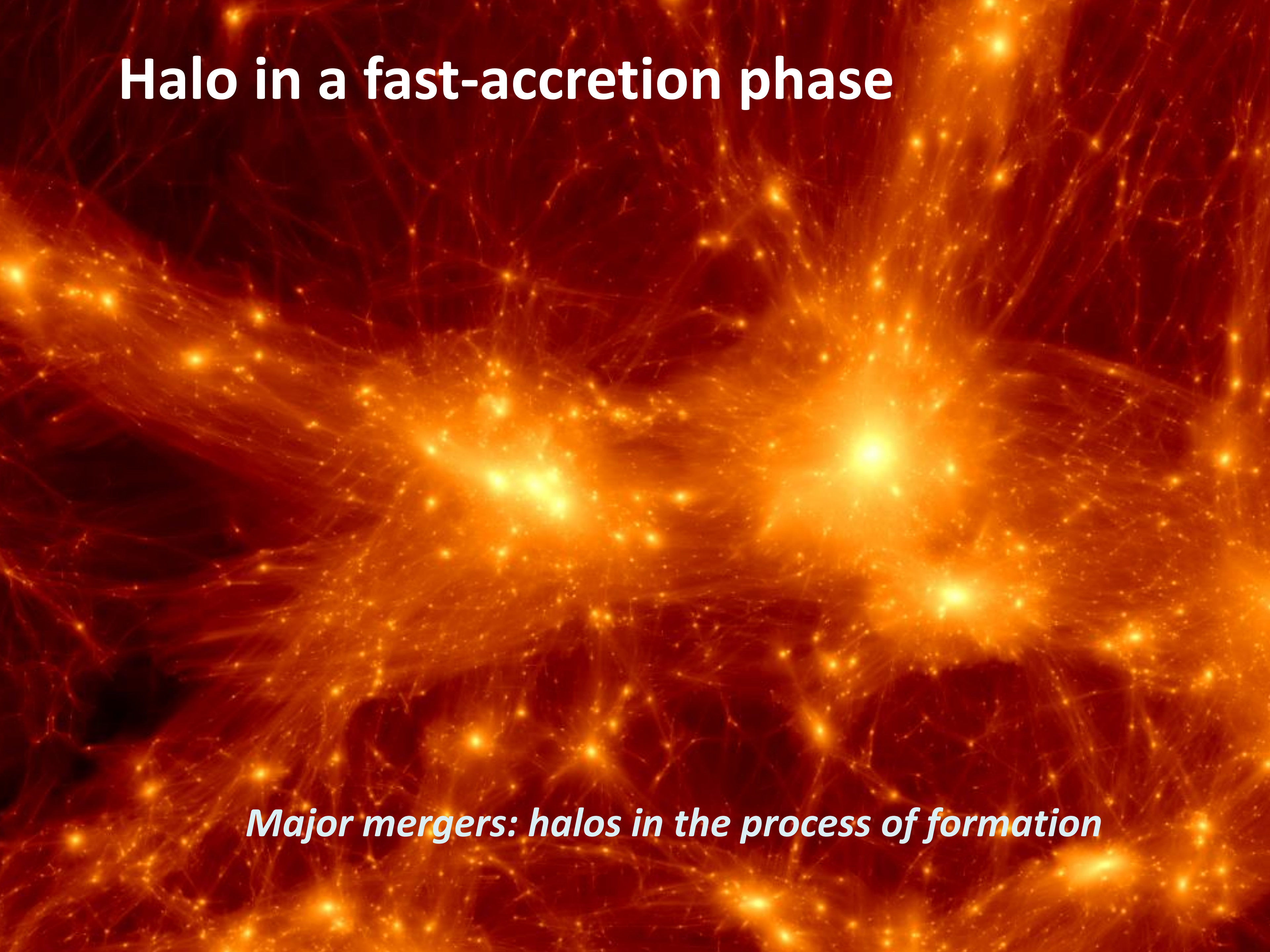
**Outer infall region**

# 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*

# Key Questions

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

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

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

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

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

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

$$T_X \propto \frac{M_s}{r_s} \quad \text{; or} \quad T_X \propto \rho_{\mathrm{crit}}(t_f) \propto \frac{M_s}{r_s^3}$$

# Data: deep multi-wavelength data sets from the CLASH survey

**High-resolution strong lensing & weak shear lensing analysis with deep 16-band *HST* ACS/WFC3 imaging** (Zitrin+15, *ApJ*, 795, 163)

**Wide-field weak-lensing shear & magnification analysis with deep 5—6 band Subaru/Suprime-Cam imaging** (Umetsu+14, *ApJ*, 795, 163)

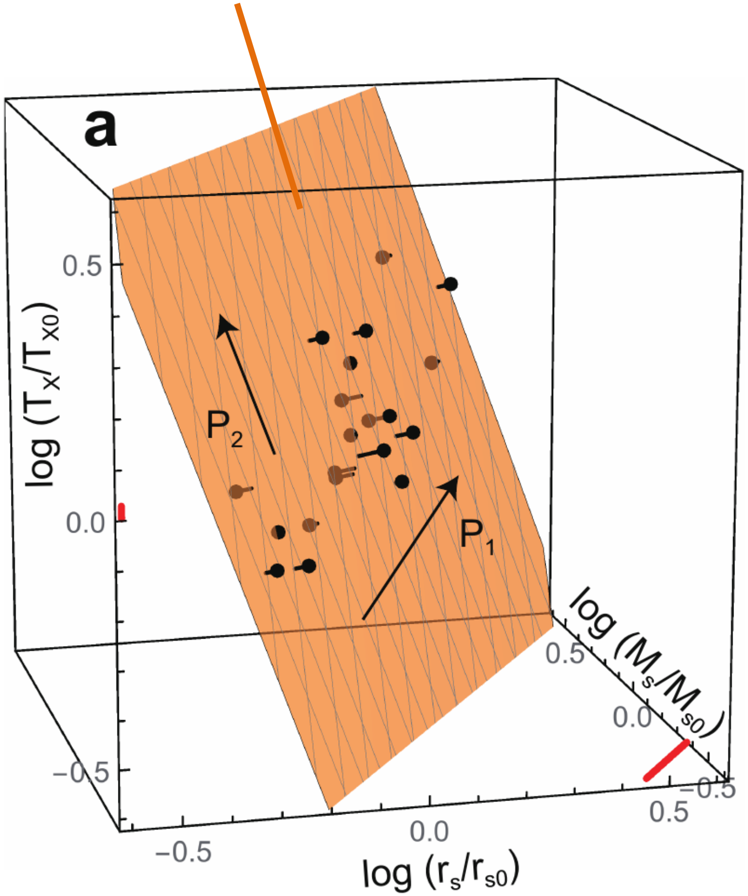
***HST*+Subaru-combined, strong-lensing, weak-lensing shear & magnification analysis** on 20 high-mass CLASH clusters (Umetsu+16, *ApJ*, 821, 116)

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

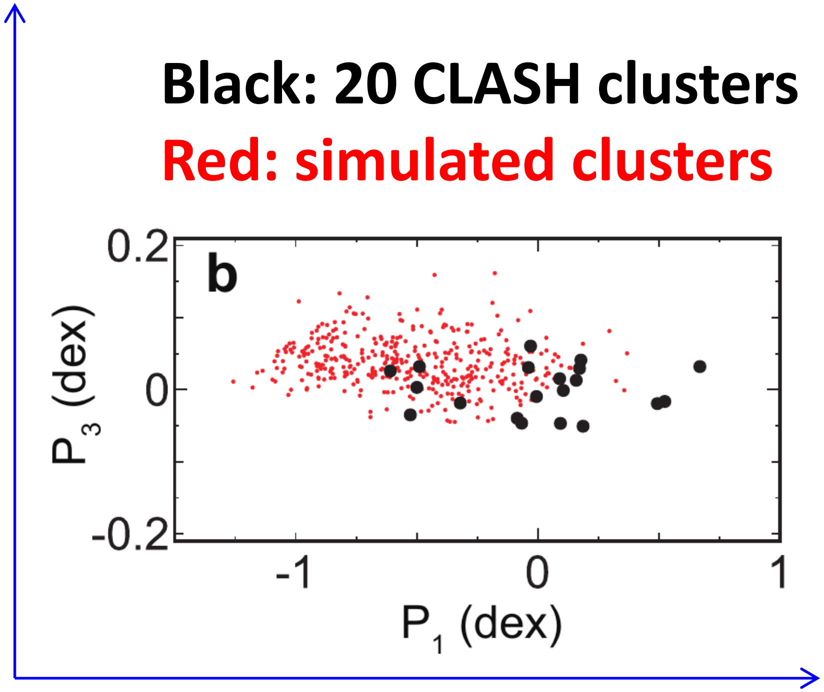
# Results: Principal Component Analysis

**A tight fundamental plane (FP) exists with 0.045 dex scatter!!!**

**FP of clusters halos**



$P_3$ (orthogonal to FP)



**Black: 20 CLASH clusters**

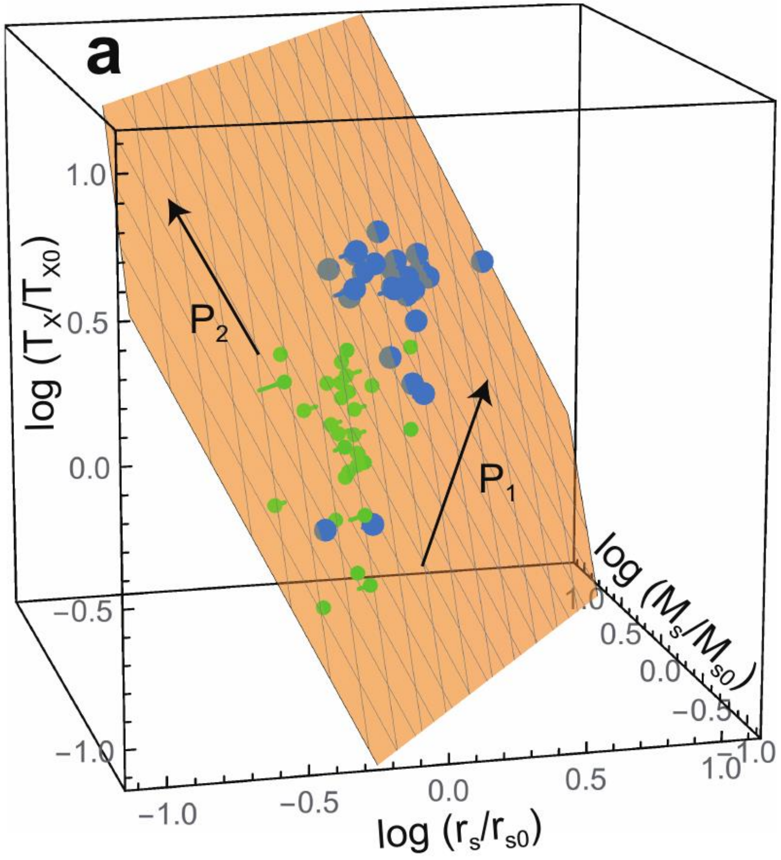
**Red: simulated clusters**

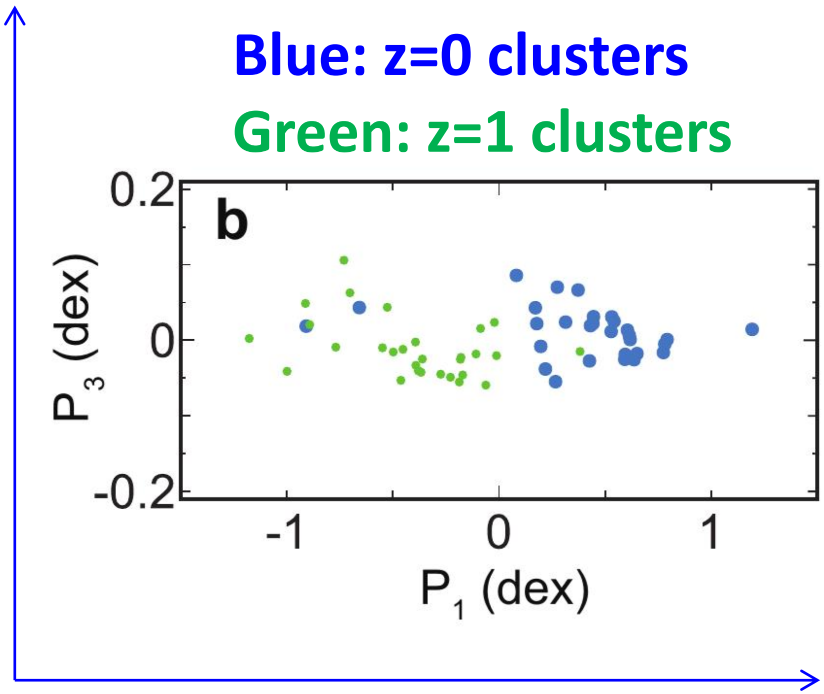
Direction of evolution

Fujita, Umetsu, Rasia+17

# FP in simulated cluster halos

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





$P_3$ (orthogonal to FP)

**Blue: z=0 clusters**

**Green: z=1 clusters**

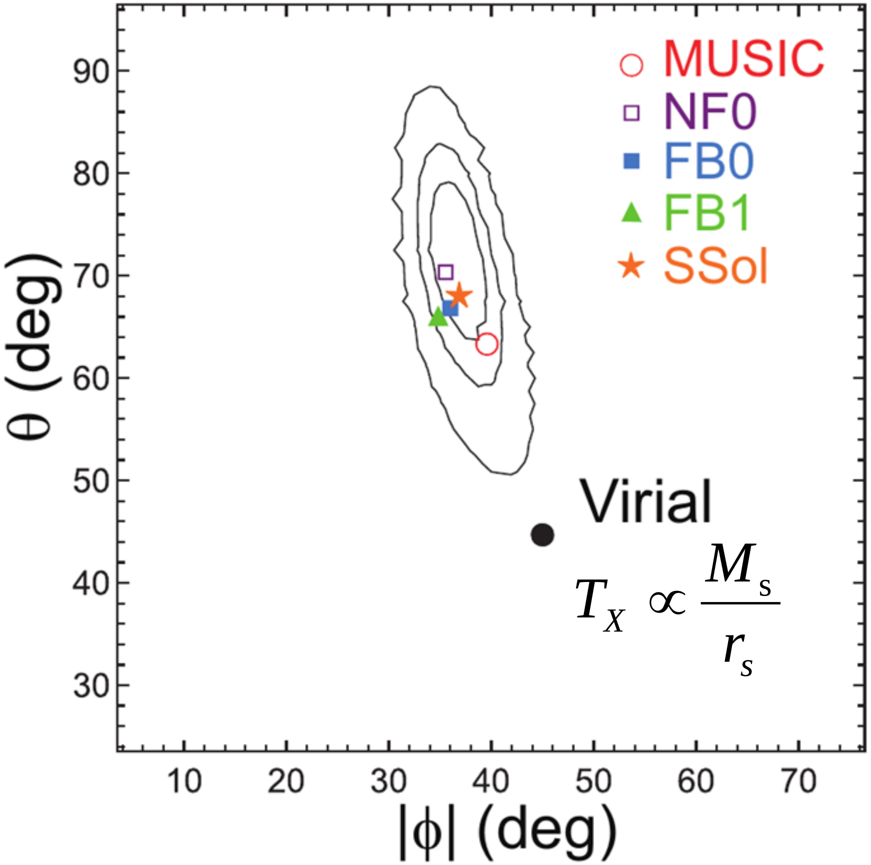
Direction of evolution

Fujita, Umetsu, Rasia+17

# Observed vs. simulated FP

$$\boxed{a\log_{10}(r_s)+b\log_{10}(M_s)+c\log_{10}(T_X)=\text{const.}}$$

**Direction of the FP normal P$_3$ (*a*,*b*,*c*)**



## Observed FP

$$T_X \propto \frac{M_s^{1.8\pm0.5}}{r_s^{2.3\pm0.7}} \propto (M_s/r_s)^2 \times M_s^{-0.2} r_s^{-0.3}$$

| | Observation | Simulations | | | | |
|---|---|---|---|---|---|---|
| | | MUSIC | NF0 | FB0 | FB1 | FB0+FB1 |
| Non-gravitational effects | – | no | no | yes | yes | yes |
| Redshift | $0.377^{+0.309}_{-0.190}$ | 0.25 | 0 | 0 | 1 | $0+1$ |
| Dispersion around the plane (dex) | $0.045^{+0.008}_{-0.007}$ | $0.025^{*}$ | 0.023 | 0.031 | 0.035 | 0.037 |

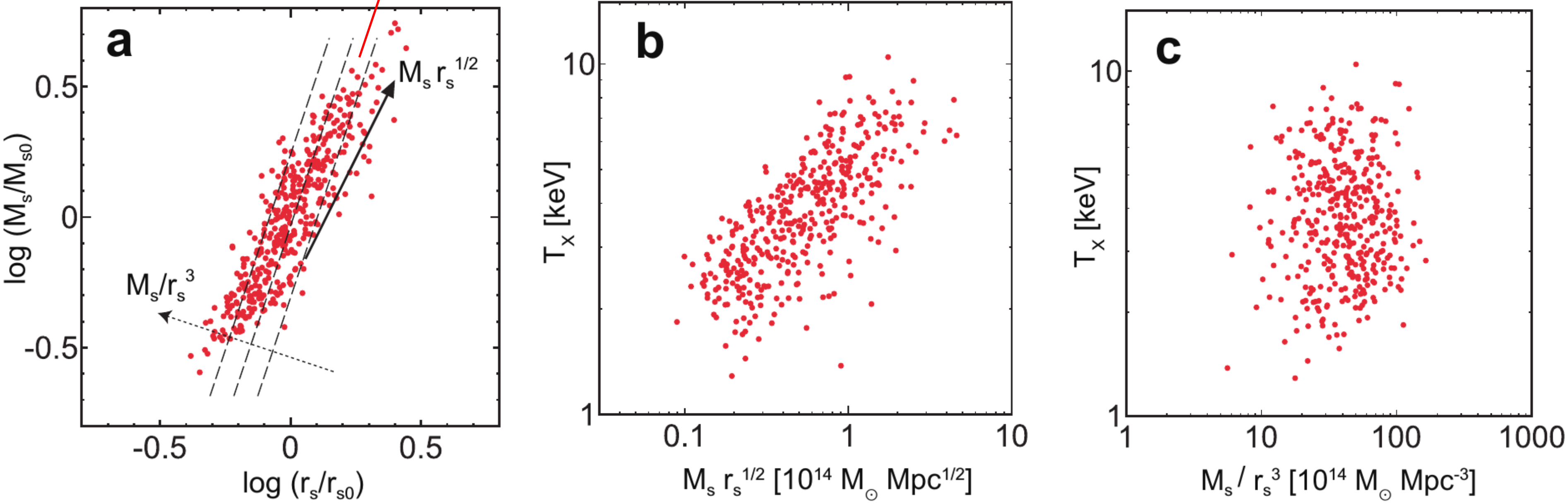
Fujita, Umetsu, Rasia+17

# Projections of simulated clusters

Halos evolve with (Zhao+09)

$$r_s \propto M_s^{1/2}$$

$$\rho_{\mathrm{crit}}(t_{\mathrm{f}}) \sim \frac{M_{\mathrm{s}}}{r_{\mathrm{s}}^{3}}$$

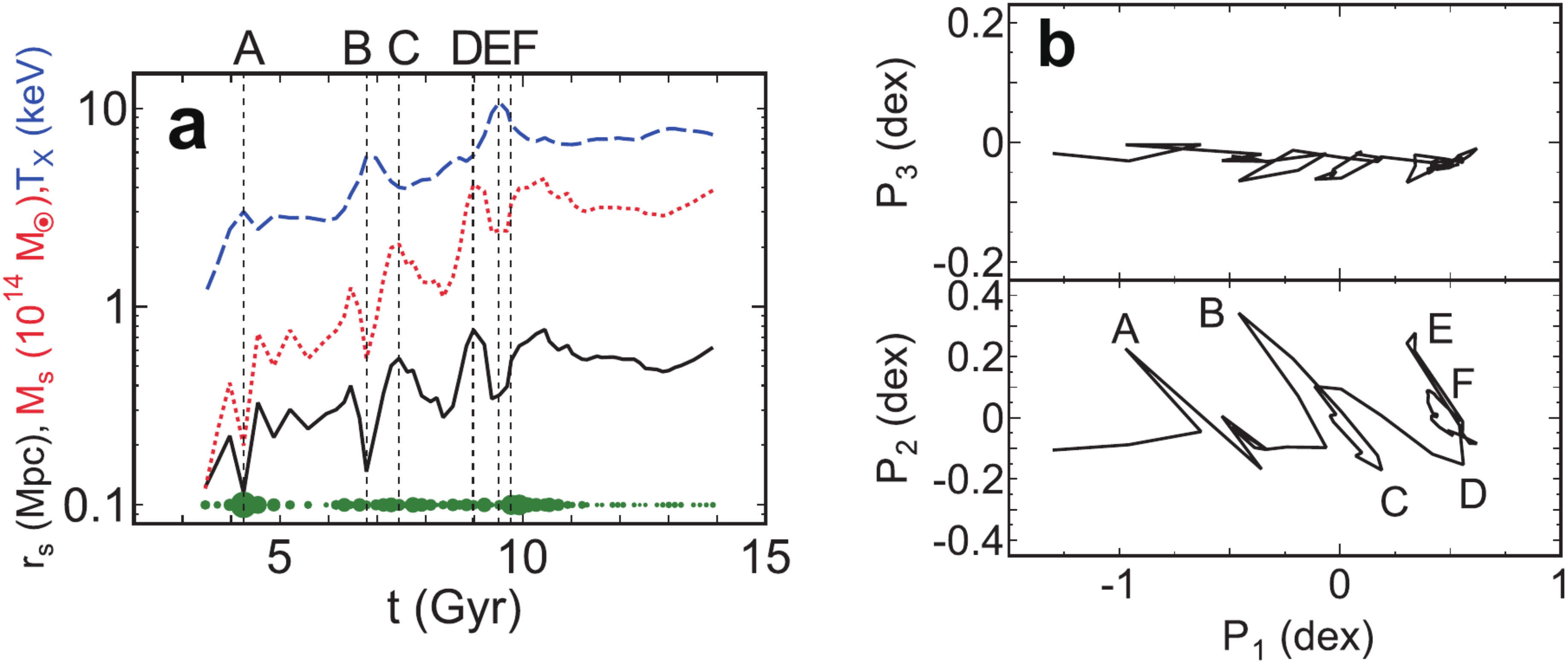


**MUSIC cosmological simulations (DM + adiabatic gas)**

Fujita, Umetsu, Rasia+17

# Stability of FP against mergers

Evolutionary track of a typical halo in the sample FB0+FB1

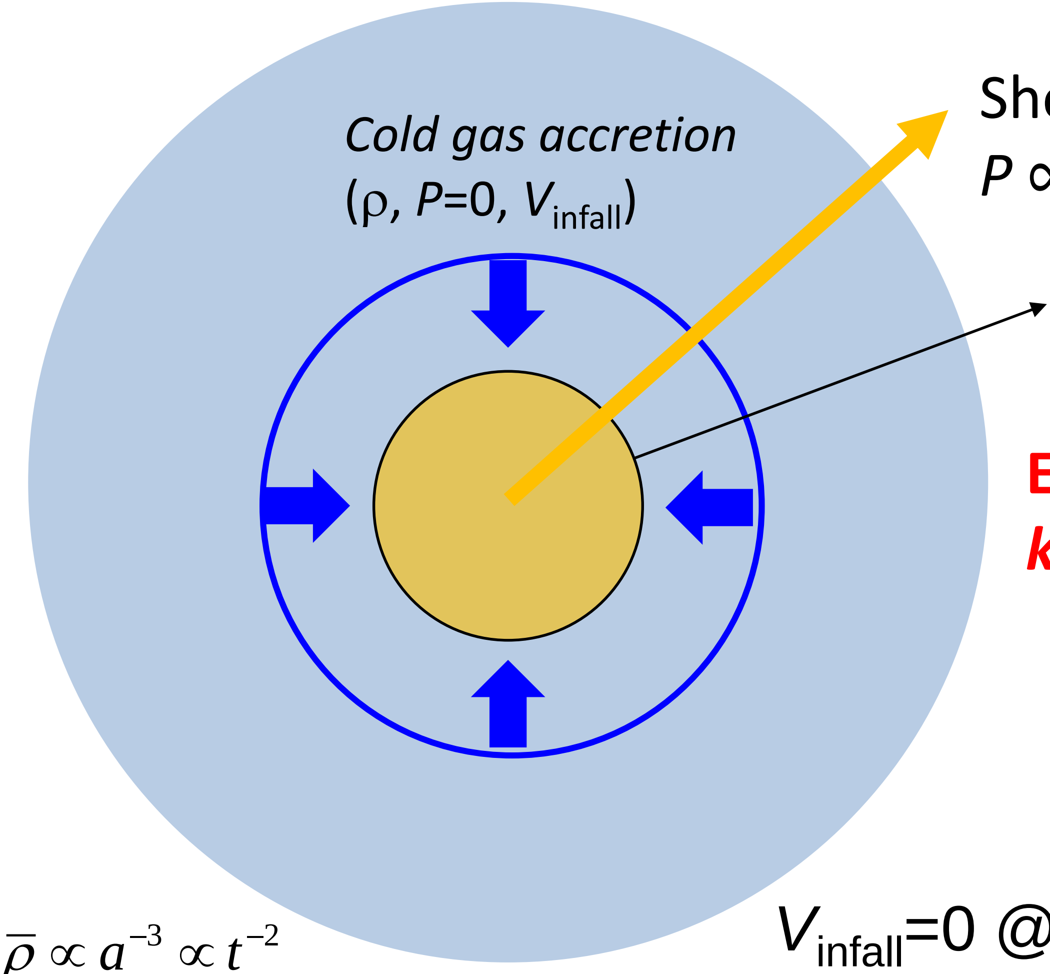


Direction of evolution →

Fujita, Umetsu, Rasia+17

# 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



*Cold gas accretion*
($\rho$, $P$=0, $V_{\mathrm{infall}}$)

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

Accretion shock radius (shock jump conditions satisfied)

**Entropy integral (B85) & *P*(*k*) ∝ $k^{-2}$ at cluster scales yield**

$$T_X \propto \frac{M_s^{1.5}}{r_s^{2.}}$$

$V_{\mathrm{infall}}$=0 @ turn-around radius $R_{\mathrm{t.a.}}$

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

# Summary

1. A tight fundamental plane exists in DM-ICM parameter space ($r_s$, $M_s$, $T_x$)
   - In the "inside-out" growth picture of $\Lambda$CDM, $T_x$ was determined at the halo formation epoch ($\rho_{crit} \sim M_s/r_s^3$) and has been conserved during halo evolution.
2. The fundamental plane is significantly tilted from the canonical virial expectation, $T_x \propto M_s/r_s$
   - 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

# Splashback radius, $R_{\mathrm{sp}}$: Physical halo boundary

$r > R_{\mathrm{sp}}$: infall region
$r < R_{\mathrm{sp}}$: multi-stream intra-halo region

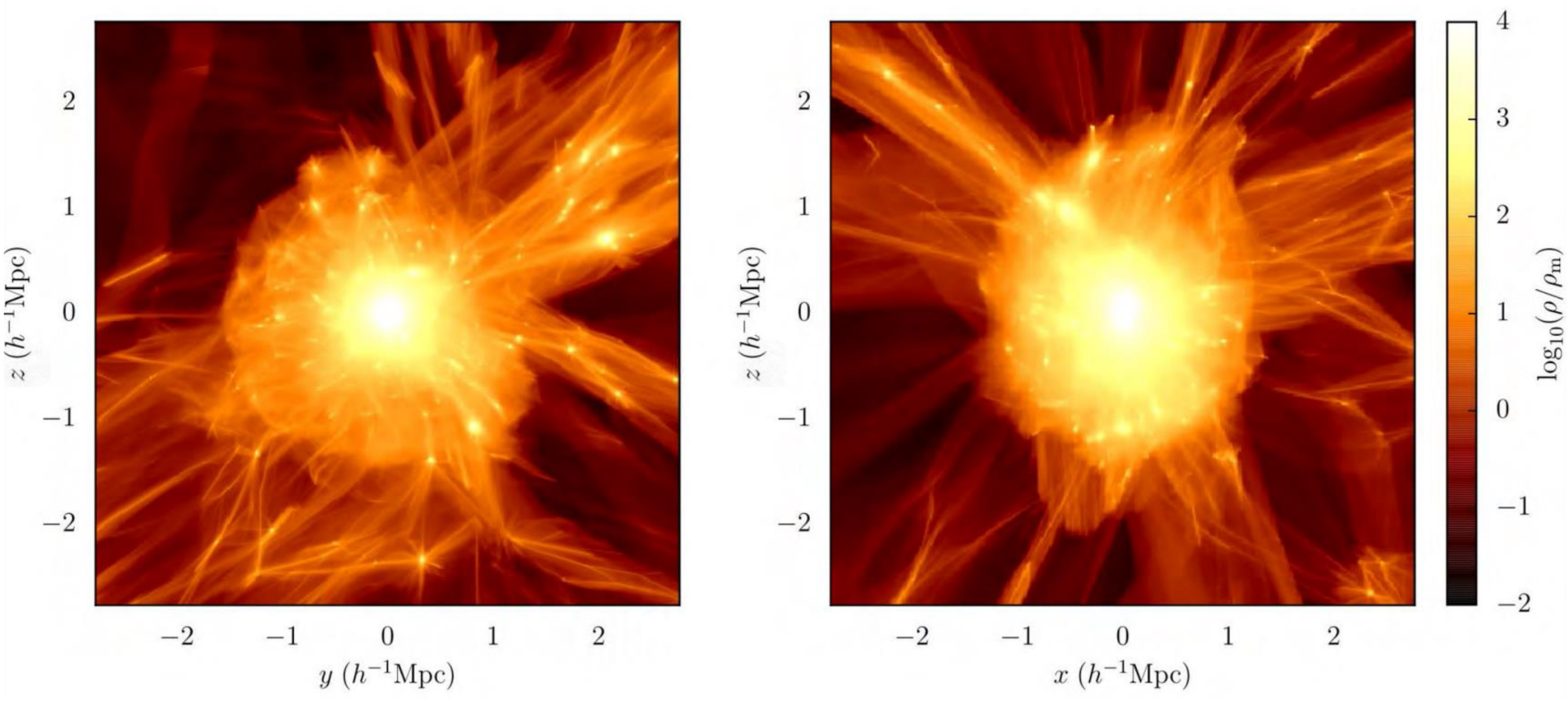
Splashback radius depends on MAR, halo peak height, cosmology ($\Omega_m$)

Slow accreting halos

$R_{\mathrm{sp}} > r_{200\mathrm{m}}$

Fast accreting halos

$R_{\mathrm{sp}} \sim r_{200\mathrm{m}}$

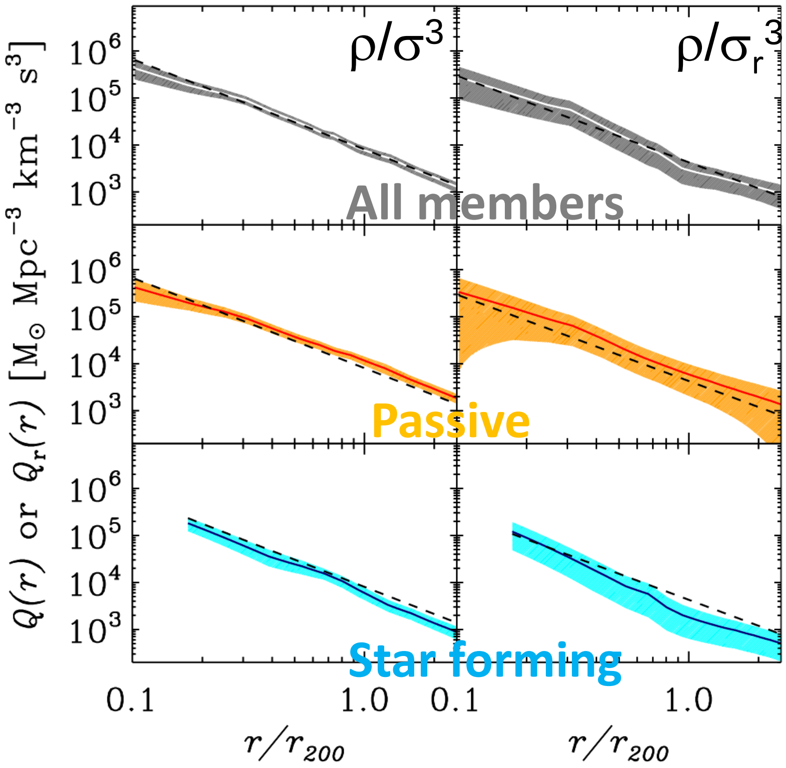


*N*-body simulations from S. More, Diemer, & Kravtsov 2015

# 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

Biviano et al. 2013 (CLASH-VLT), A&A, 558, A1

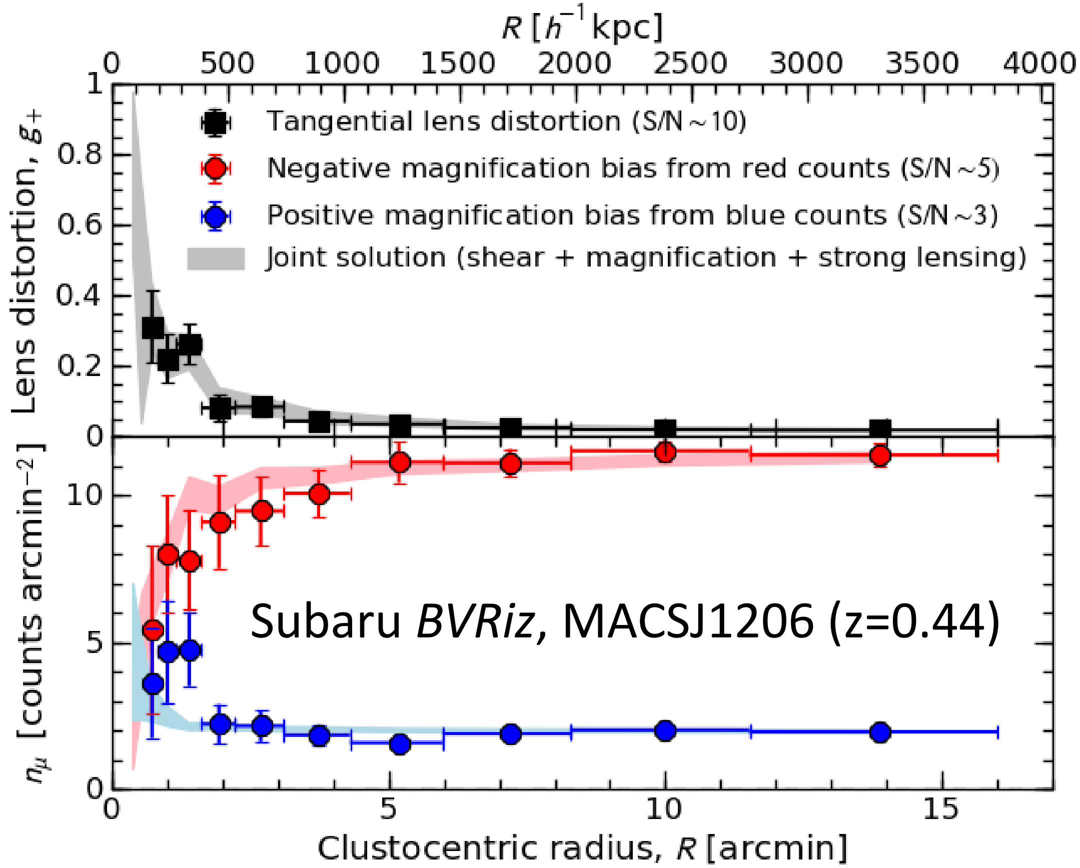
(See also Munari+15)

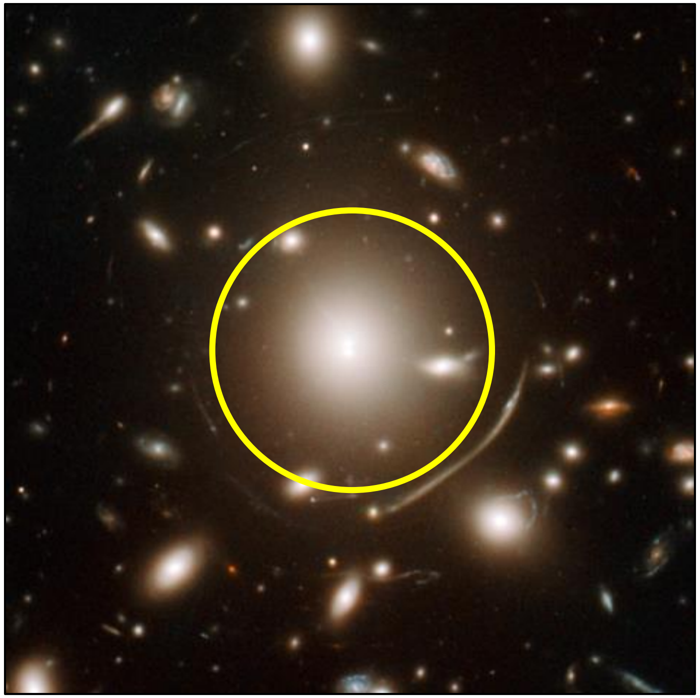
# CLUMI (CLUster lensing Mass Inversion): Multi-probe lensing analysis

**Combining strong-lensing, weak-lensing shear and magnification**

$$\{M_{2\mathrm{D},i}\}_{i=1}^{N_{\mathrm{SL}}}, \{\langle g_{+,i}\rangle\}_{i=1}^{N_{\mathrm{WL}}}, \{\langle n_{\mu,i}\rangle\}_{i=1}^{N_{\mathrm{WL}}}.$$

$$\boxed{P(\boldsymbol{\Sigma}|\mathrm{WL},\mathrm{SL}) \propto P(\mathrm{WL},\mathrm{SL}|\boldsymbol{\Sigma})P(\boldsymbol{\Sigma}) = P(\boldsymbol{n}_{\mu}|\boldsymbol{\Sigma})P(\boldsymbol{g}_{+}|\boldsymbol{\Sigma})P(\boldsymbol{M}_{2D}|\boldsymbol{\Sigma})P(\boldsymbol{\Sigma})}$$

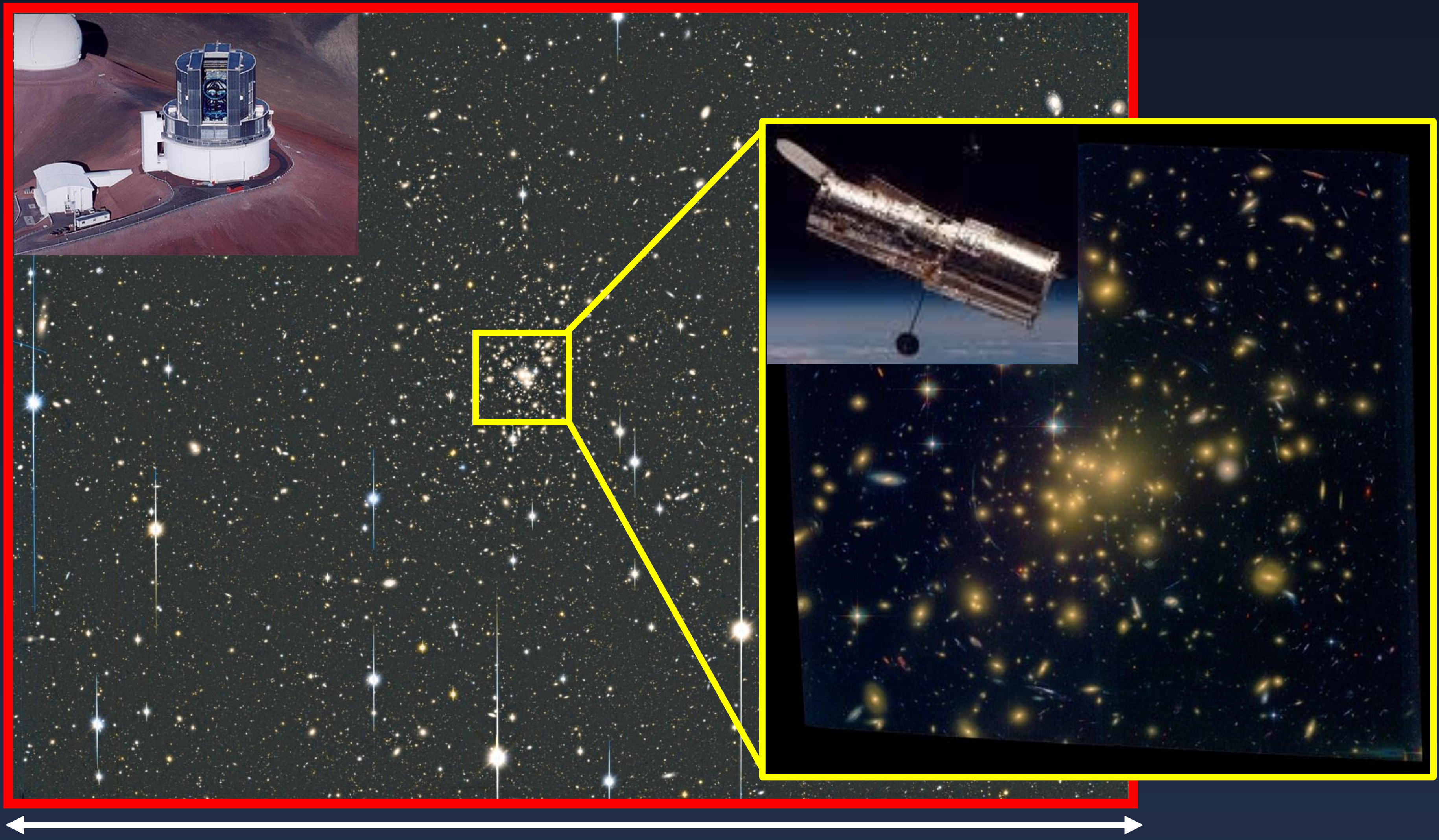




Umetsu 2013, *ApJ*, 769, 13

Subaru/Suprime-Cam multi-color imaging for wide-field weak lensing

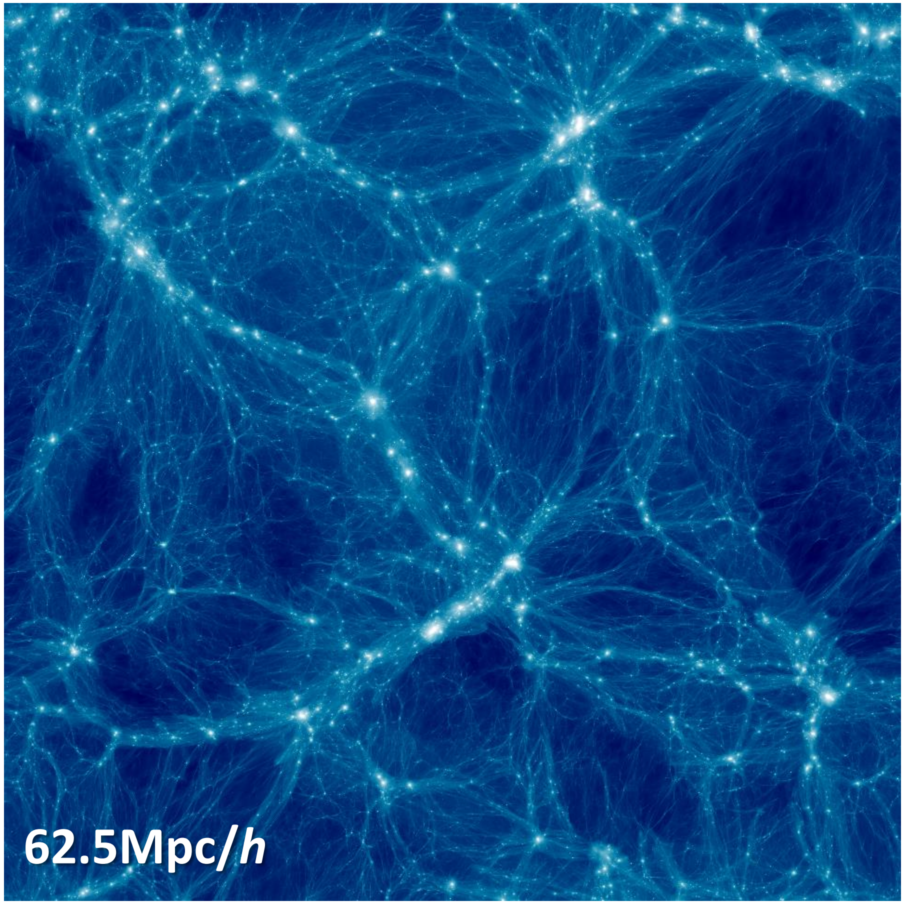
High-resolution space imaging with *HST* (ACS/WFC3) for strong lensing

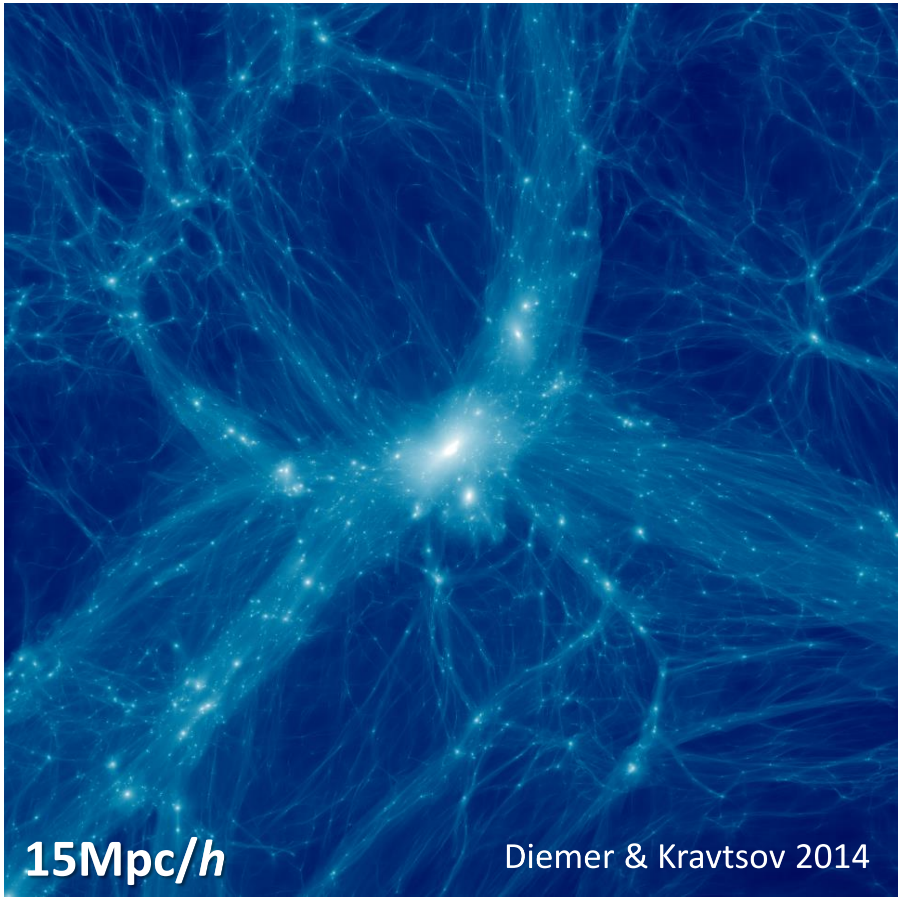


34 arcmin

# Galaxy Clusters as Cosmological Probes

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

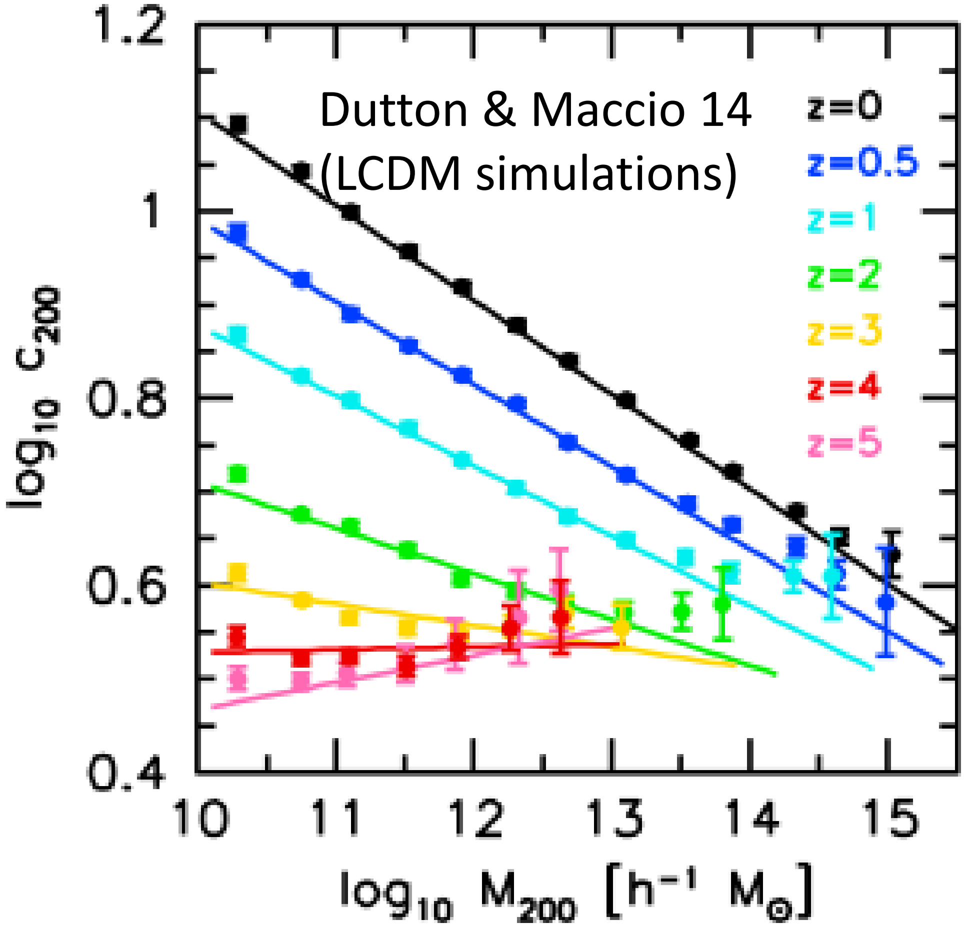




Diemer & Kravtsov 2014

# 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:*

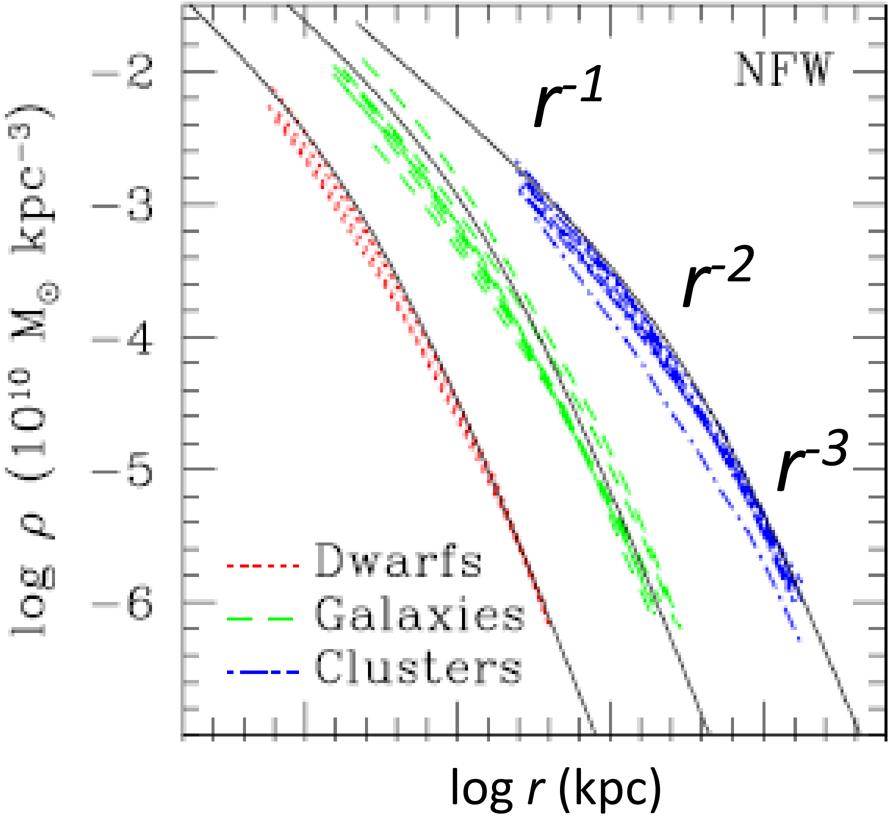
DM halos that are more massive collapse later on average, when the mean background density of the universe is correspondingly lower.

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

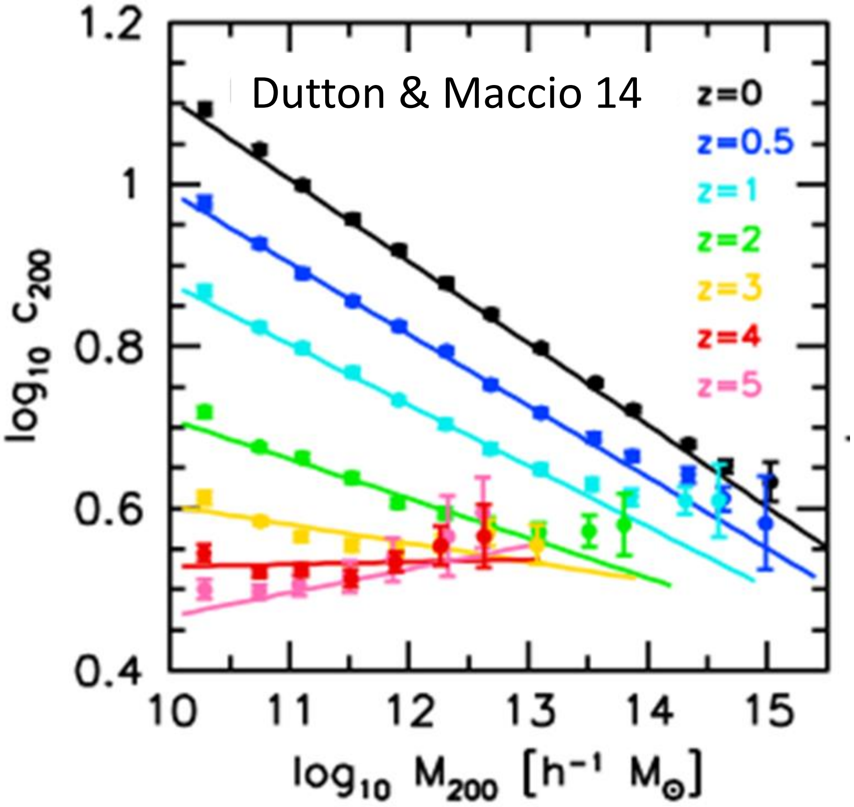
# Density structure of CDM halos

- 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**



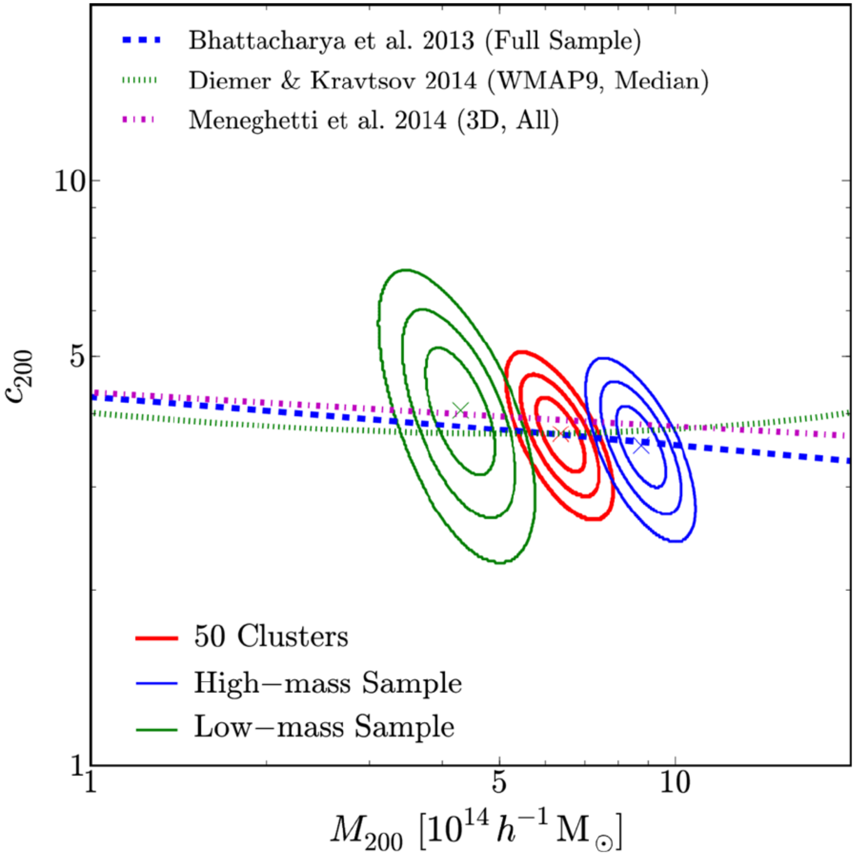
**The concentration-mass relation**



# Cluster concentration-mass relation $c_\Delta \equiv \frac{r_\Delta}{r_s}$

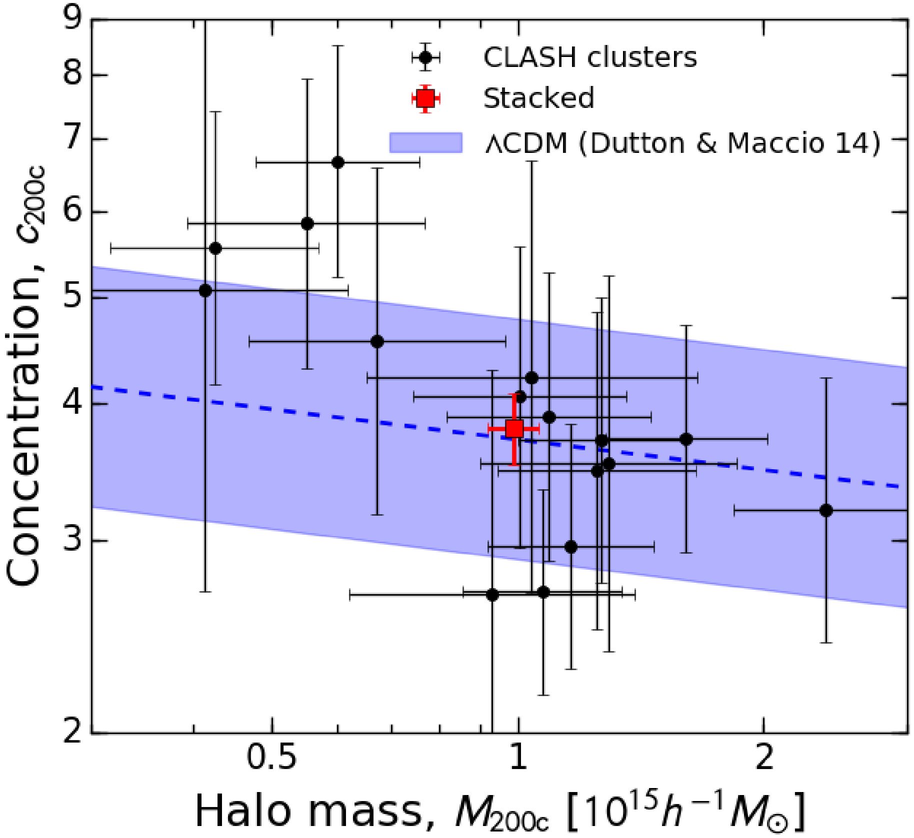
*Targeted lensing surveys of X-ray-selected clusters*

**LoCuSS** (<*z*>~0.2)



Okabe & Smith 15

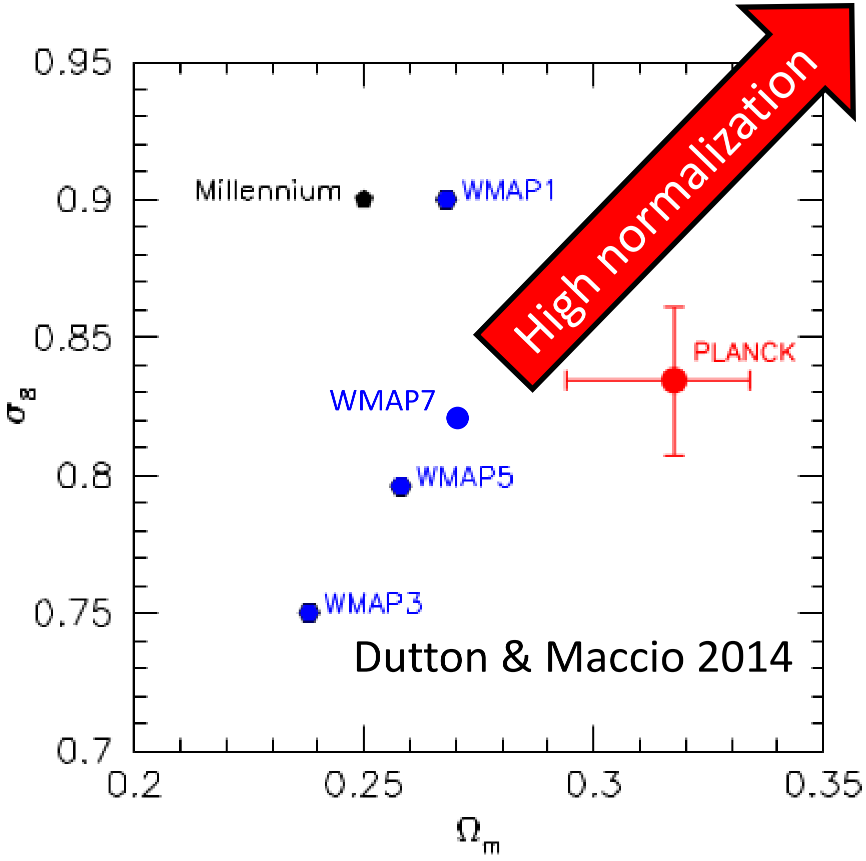
**CLASH** (<*z*>~0.35)



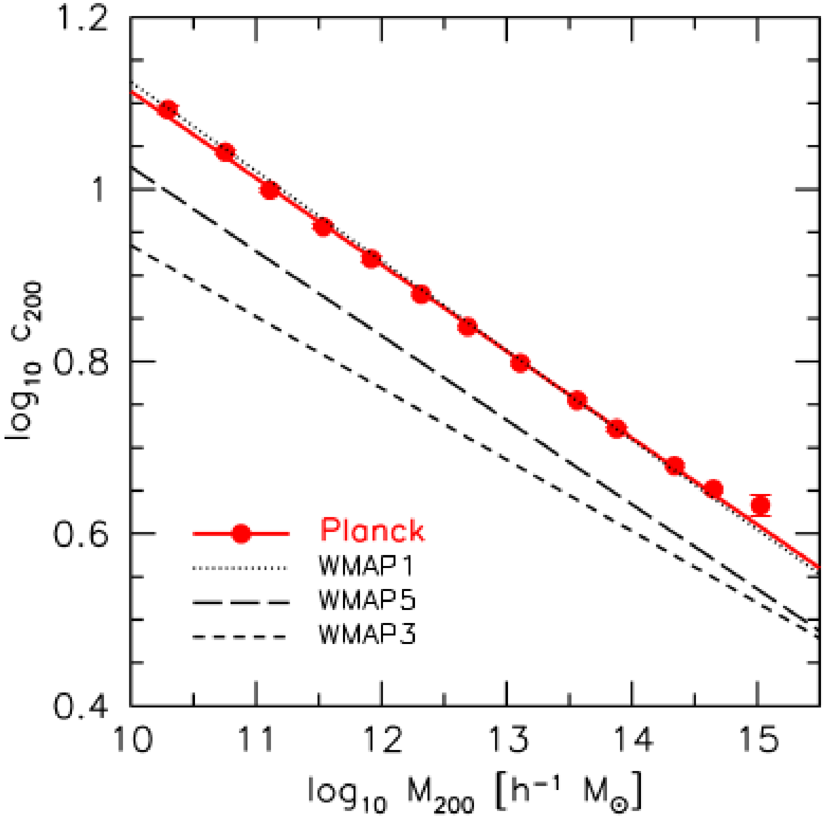
Umetsu+16, Merten+15

# Halo cooncentration 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