TPS2018, O6-AG6 (January 26, 2018)

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

Fujita, Umetsu, Rasia, Meneghetti, Donahue et al. 2018, submitted to *ApJ* (arXiv:1801.03943)

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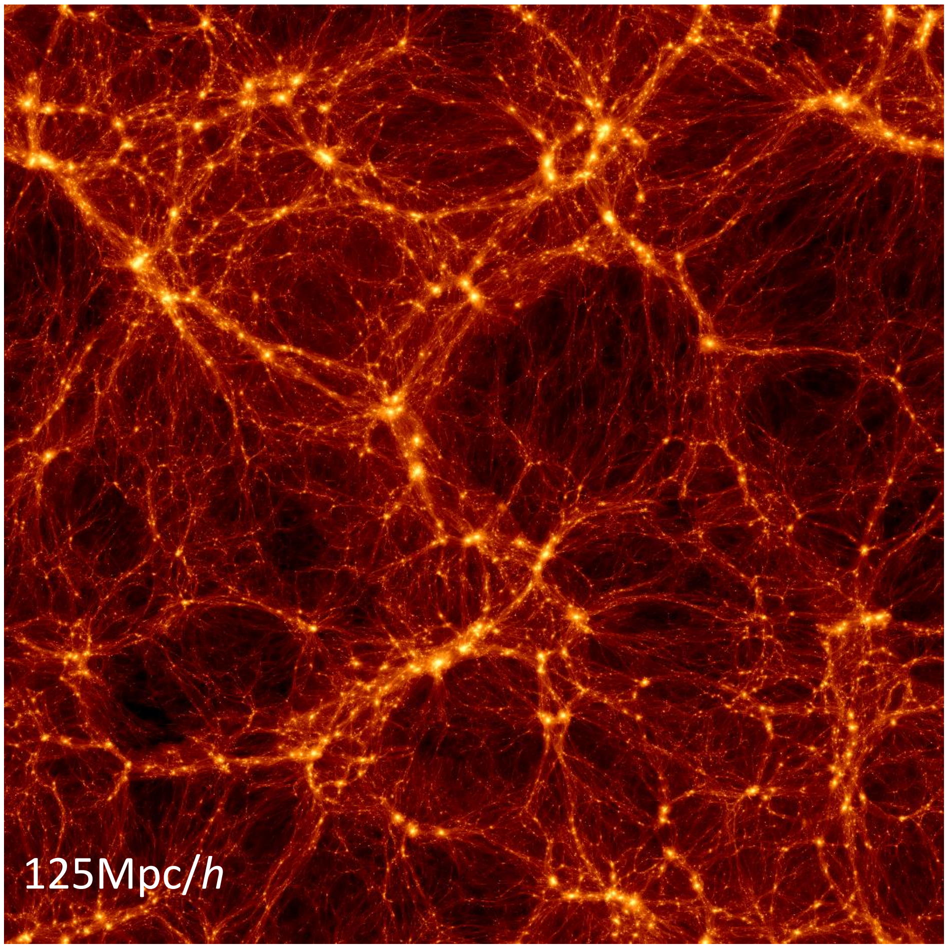
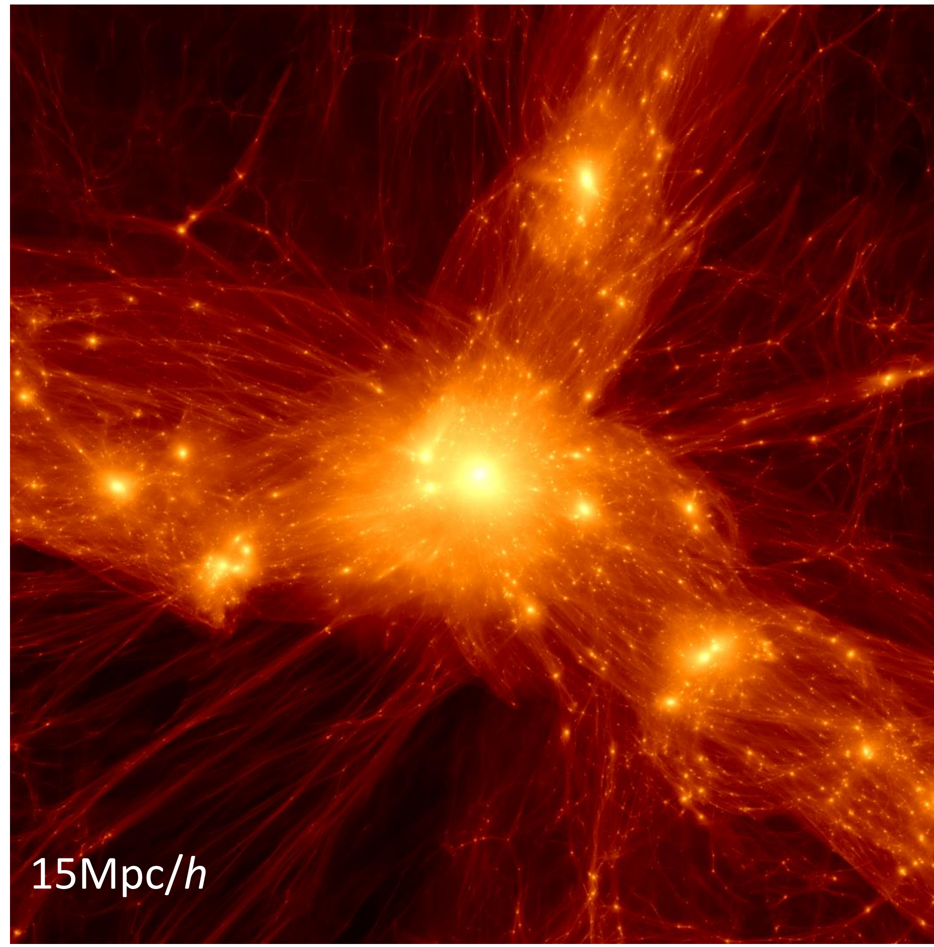
High-mass Galaxy Clusters: “Cosmic Giants”

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





N-body simulations (B. Diemer)

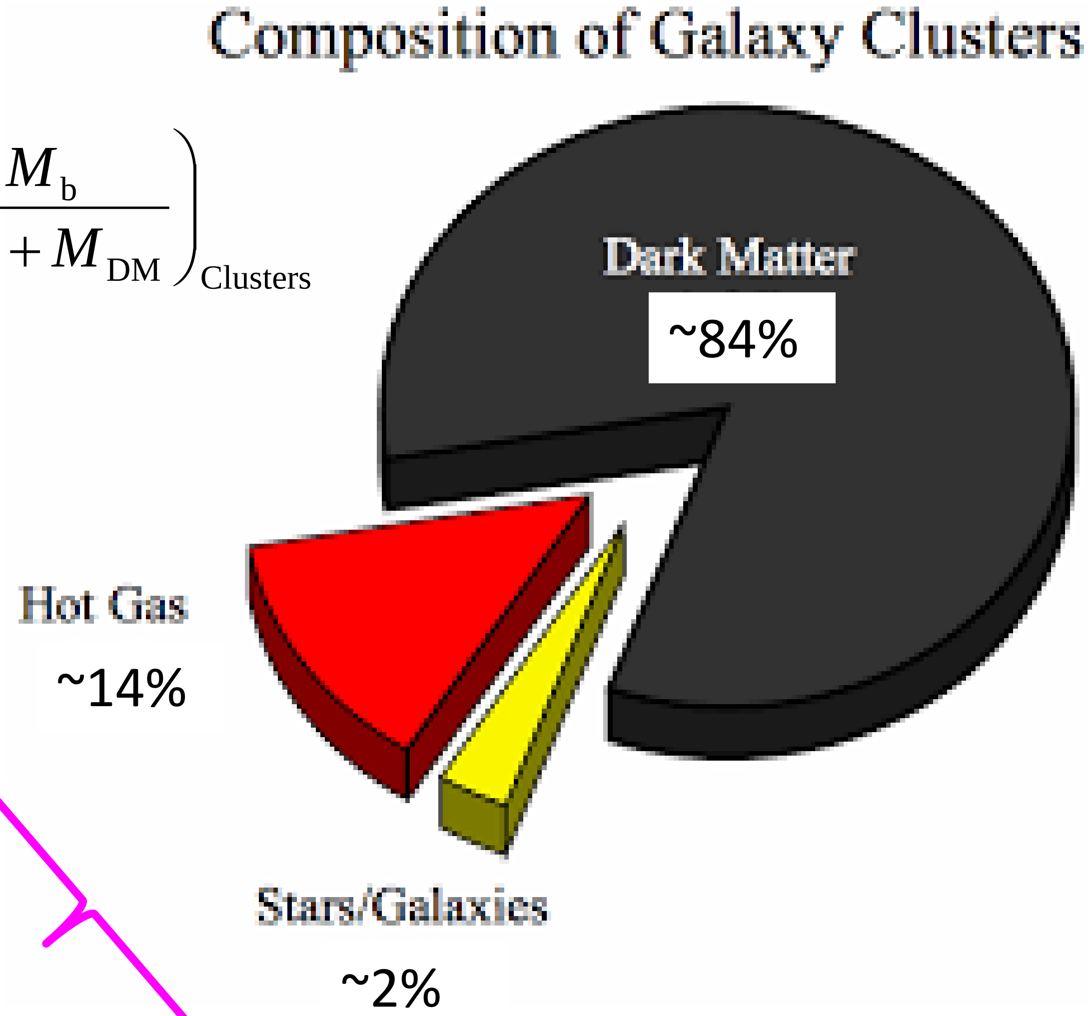
What are clusters made of?

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)

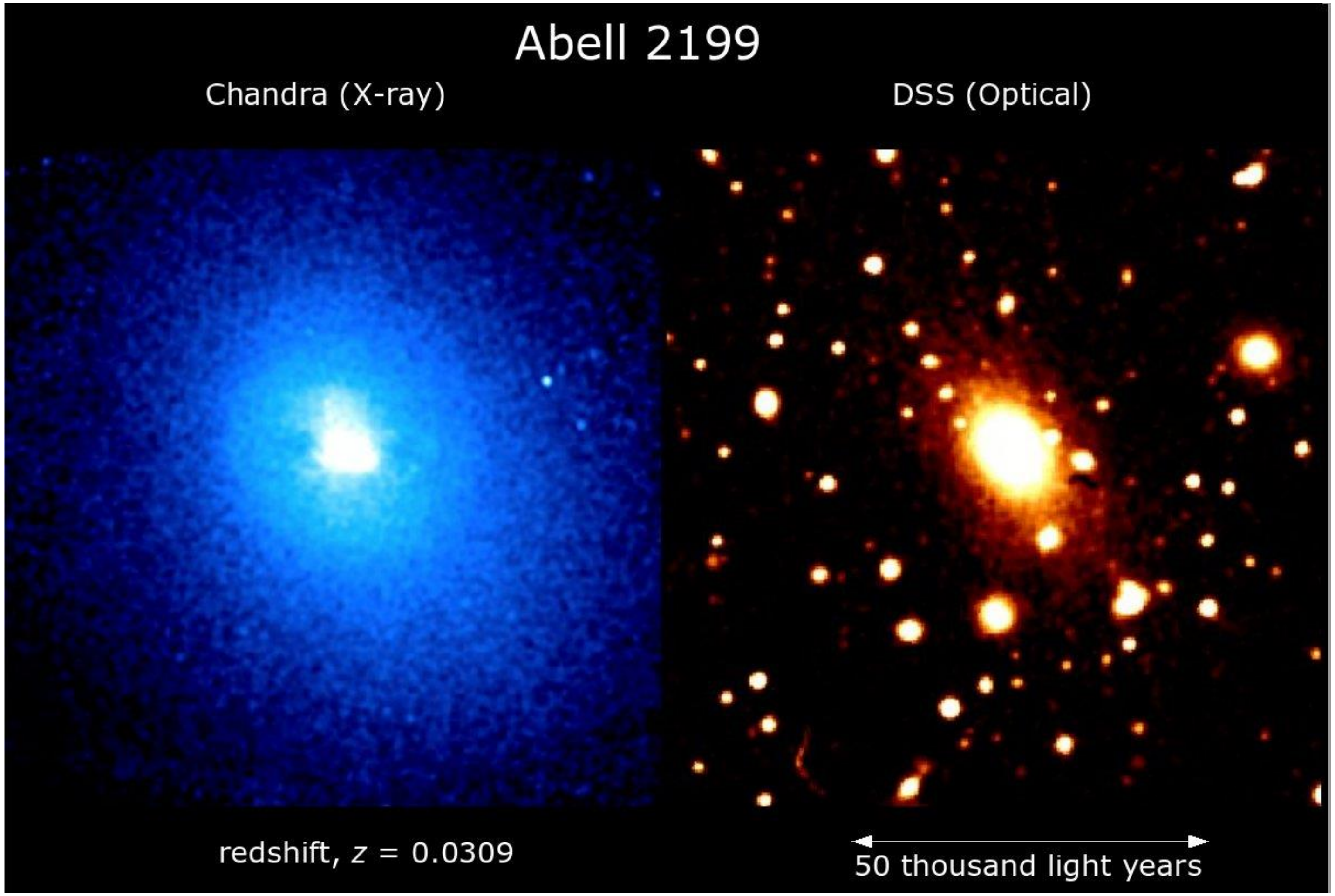


Ordinal Matter
(baryons)

Intracluster Medium (ICM)

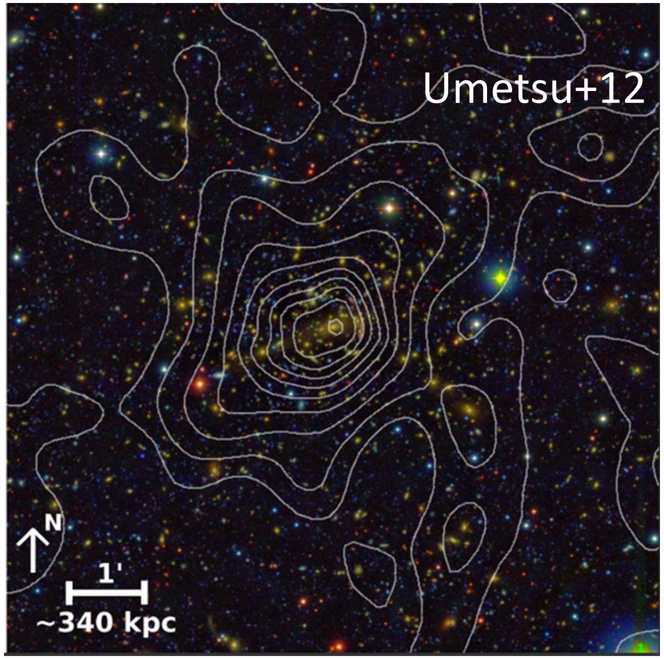
ICM = fully ionized H-He plasma (T_e=3-15keV, n_e=10^{-2}-10^{-3}cm^{-3})

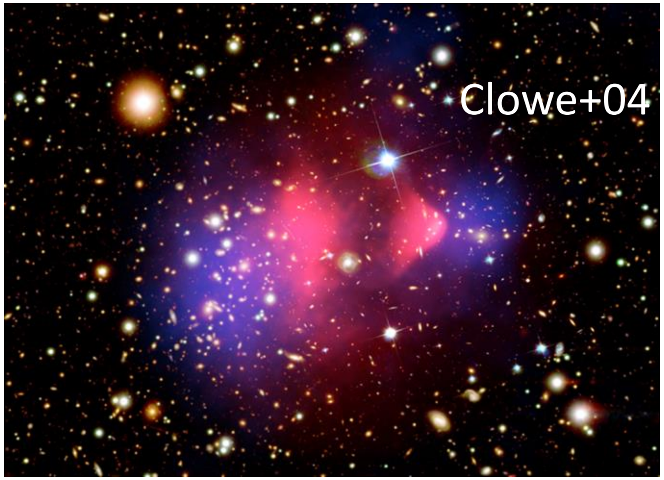
~ nonrelativistic ideal gas with γ=5/3



High-mass clusters probing nonlinear structure formation

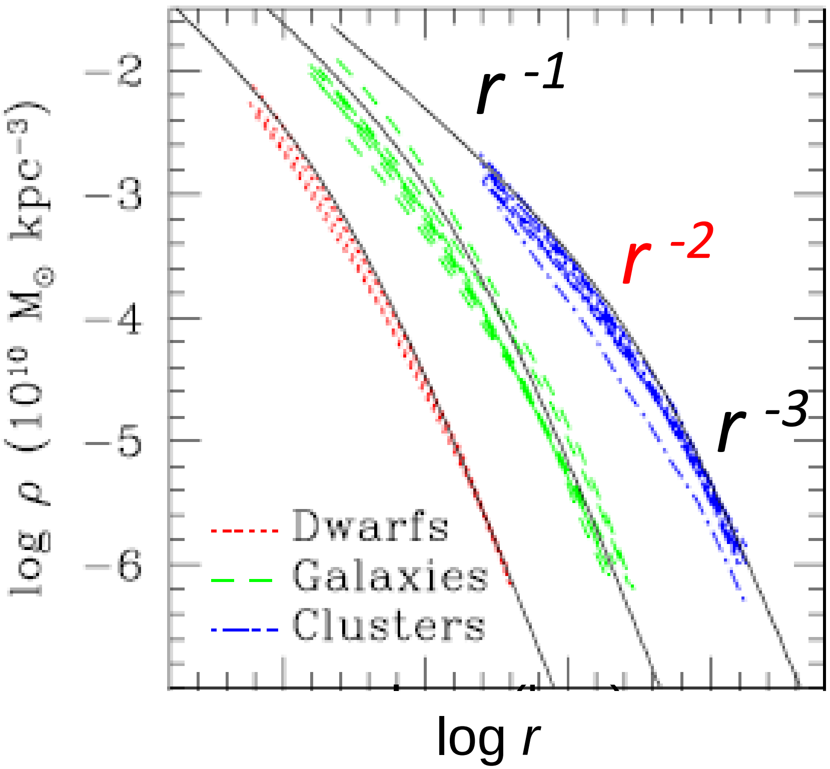
- Standard paradigm for structure formation: ΛCDM
  - Collisionless, cold dark matter
- Clusters offer fundamental tests of assumed DM properties:
  - DM density profile shape, $\rho(r|M)$
  - Phase-space distribution of DM
  - Halo shape and alignments
  - Substructure distribution $N(m,r|M)$
  - DM-galaxy-ICM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





Halo density profile

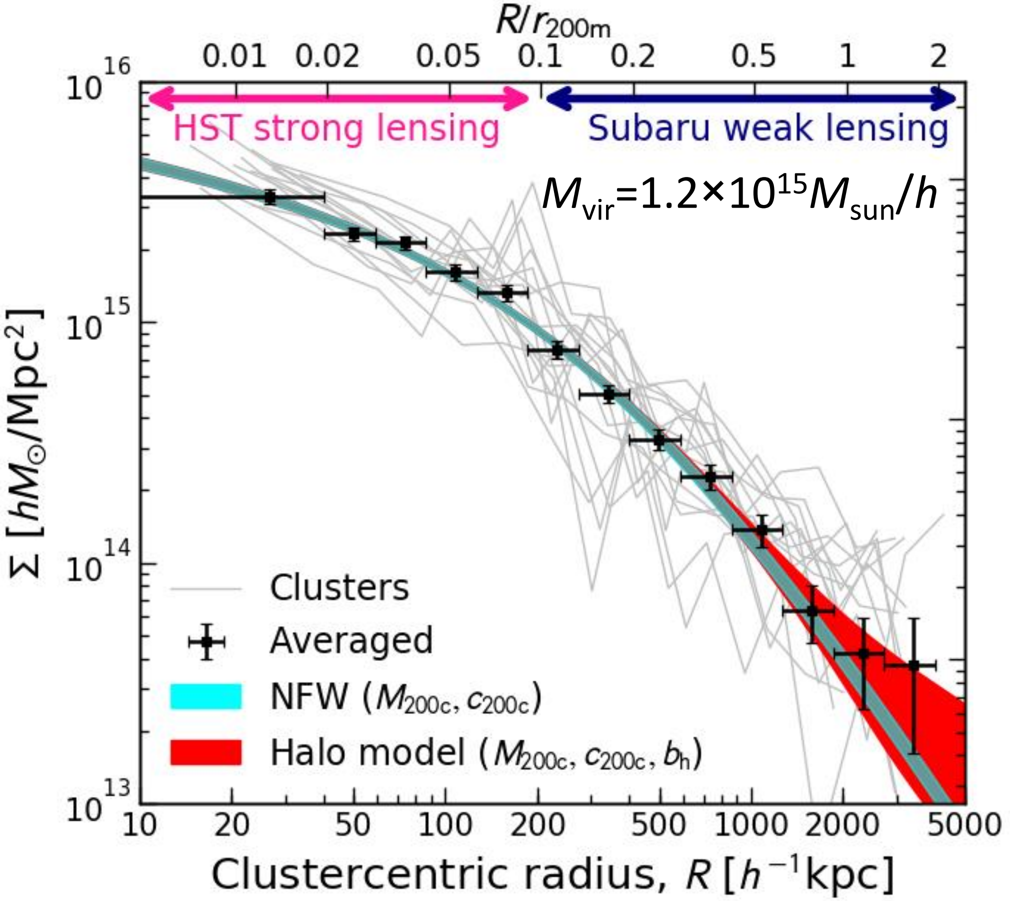
Navarro-**F**renk-**W**hite '96 profile (CDM)



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

$$\max(V_{circ})\ @\ r \approx 2r_s$$

CLASH lensing survey



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

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**

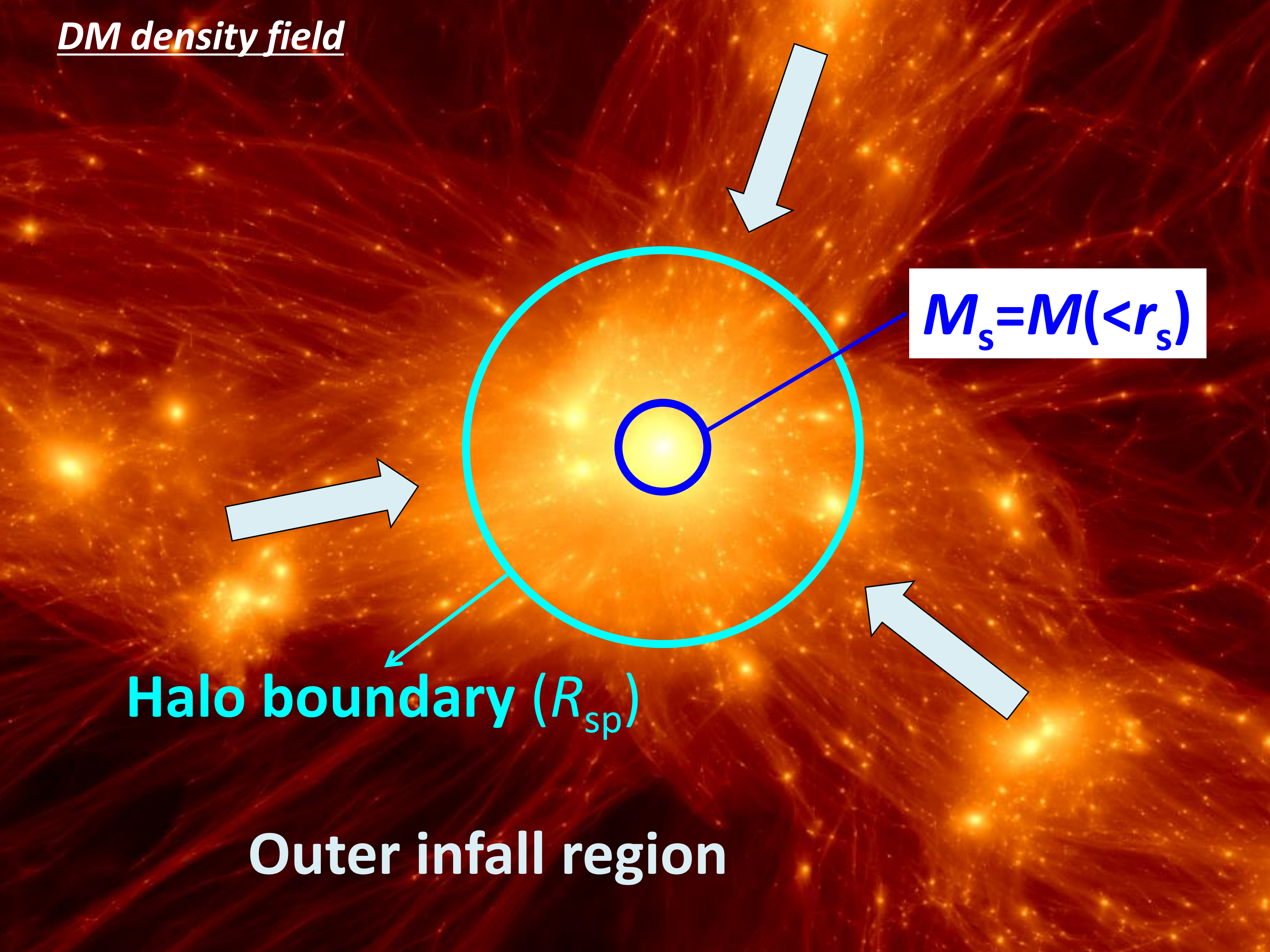
Halos grow rapidly through gravitational collapse and major mergers.

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.


DM density field
$M_s = M(<r_s)$
Halo boundary (R_{sp})
Outer infall region

Key Questions

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

- **X-ray observable**: Core-excised $T = T_{\mathrm{ICM}}(50\text{-}500\mathrm{kpc})$
- **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) 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

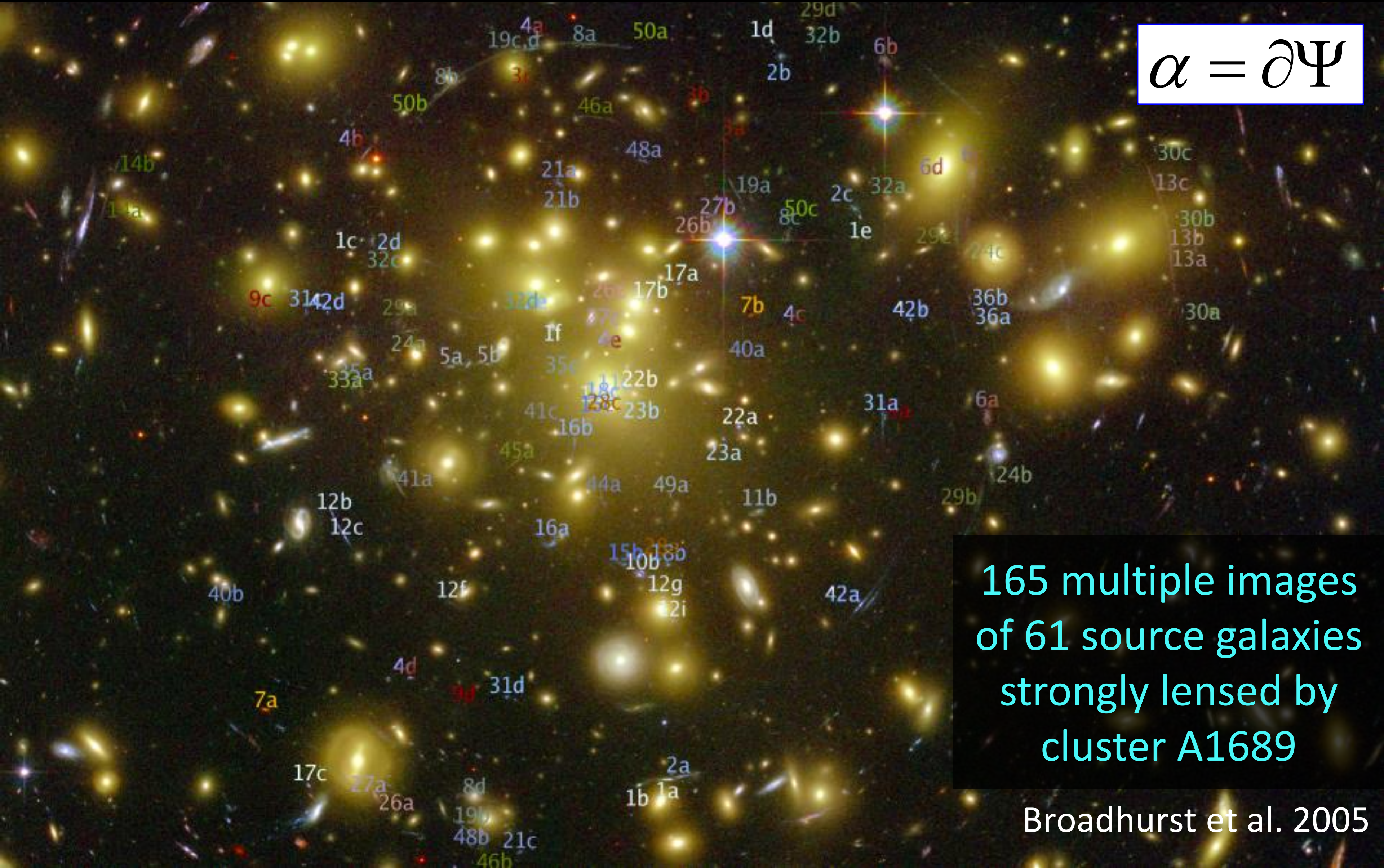
High-resolution strong lensing & weak shear lensing analysis with deep 16-band *HST* ACS/WFC3 imaging
(Zitrin+15, *ApJ*, 795, 163)

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 with $\langle M_{vir} \rangle \sim 1.2 \times 10^{15} M_{sun}/h$ (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)



$$\alpha = \partial \Psi$$

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

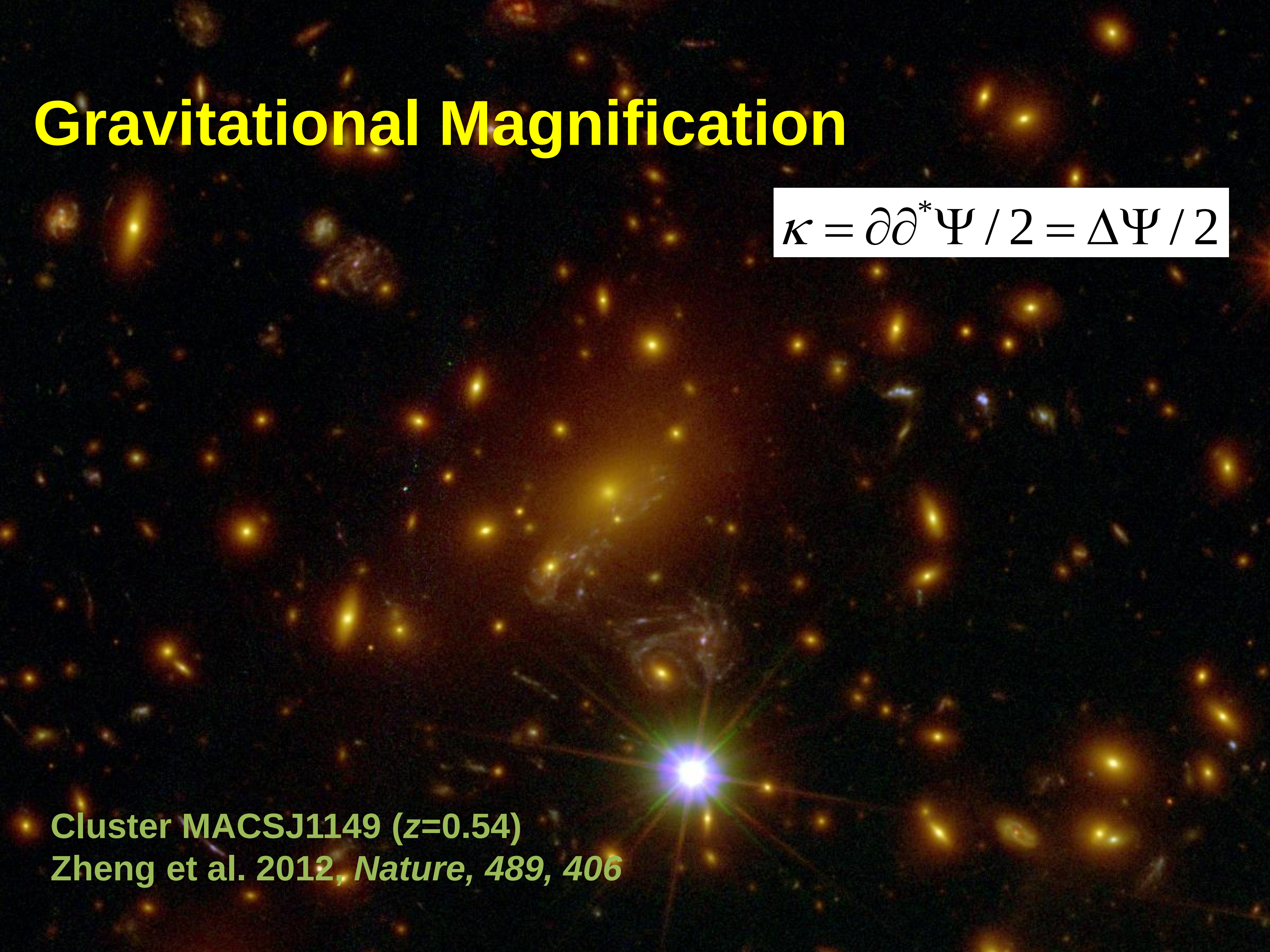
Broadhurst et al. 2005

Gravitational Shear

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

Gravitational Magnification

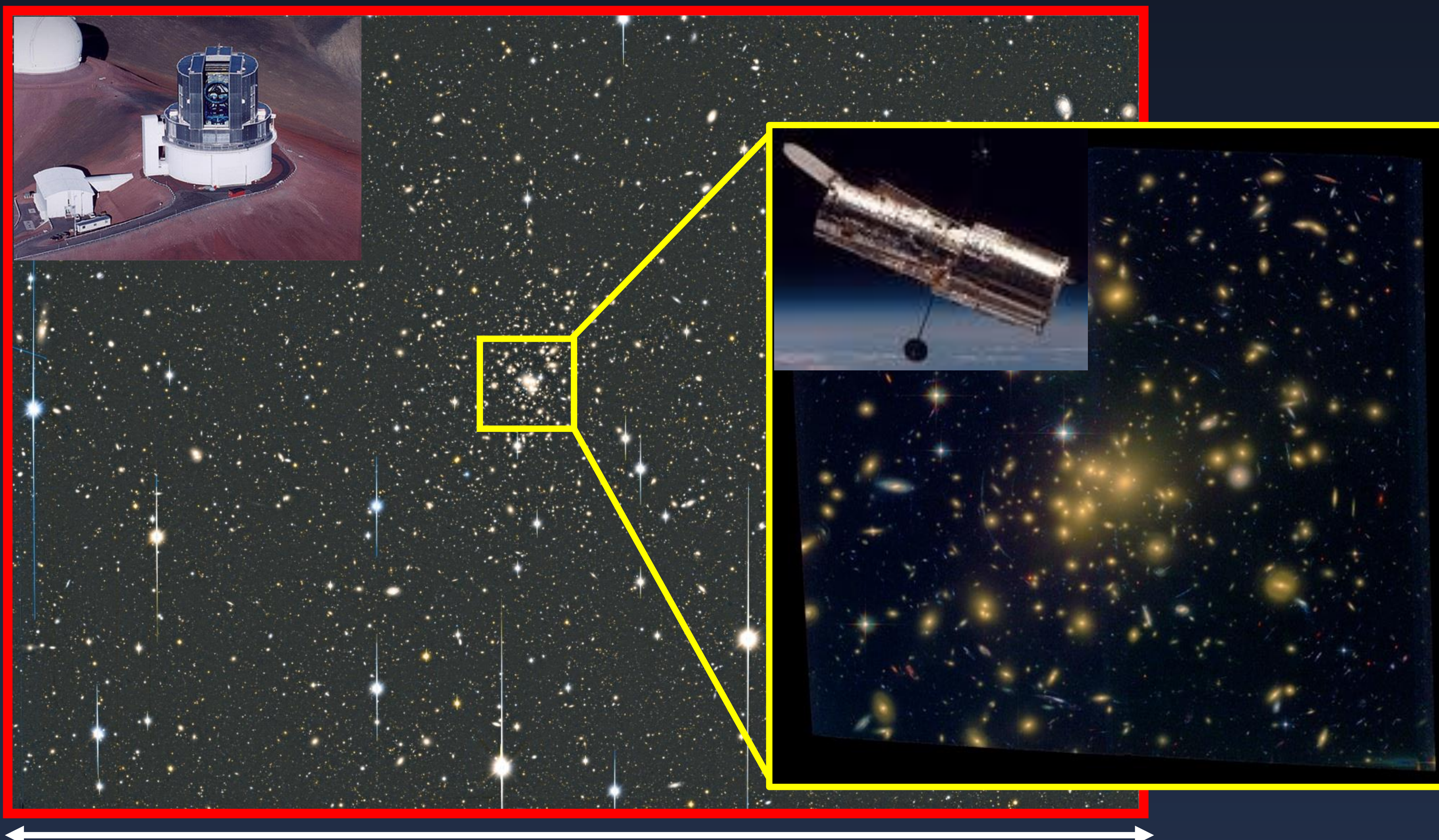
$$\kappa = \partial\partial^{*}\Psi / 2 = \Delta\Psi / 2$$



Cluster MACSJ1149 (*z*=0.54)
Zheng et al. 2012, *Nature, 489, 406*

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

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



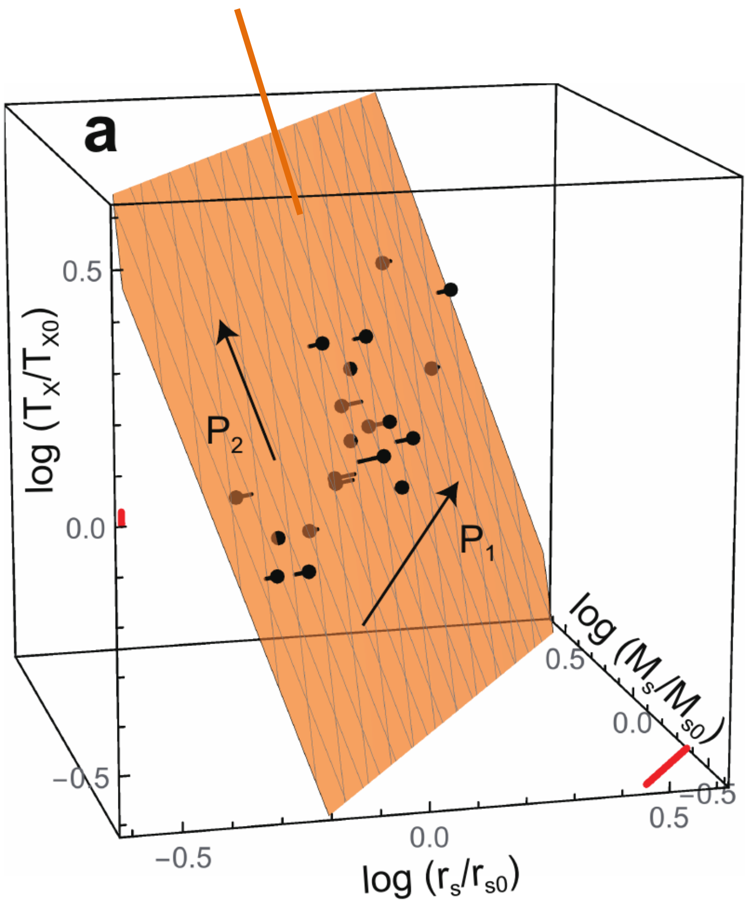
34 arcmin

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

Results: Principal Component Analysis

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

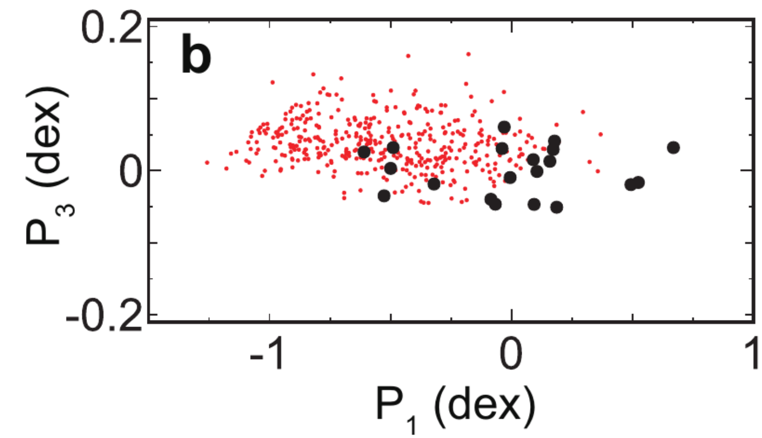
FP of clusters halos



P_3 (orthogonal to FP)

Black: 20 CLASH clusters

Red: adiabatic simulations

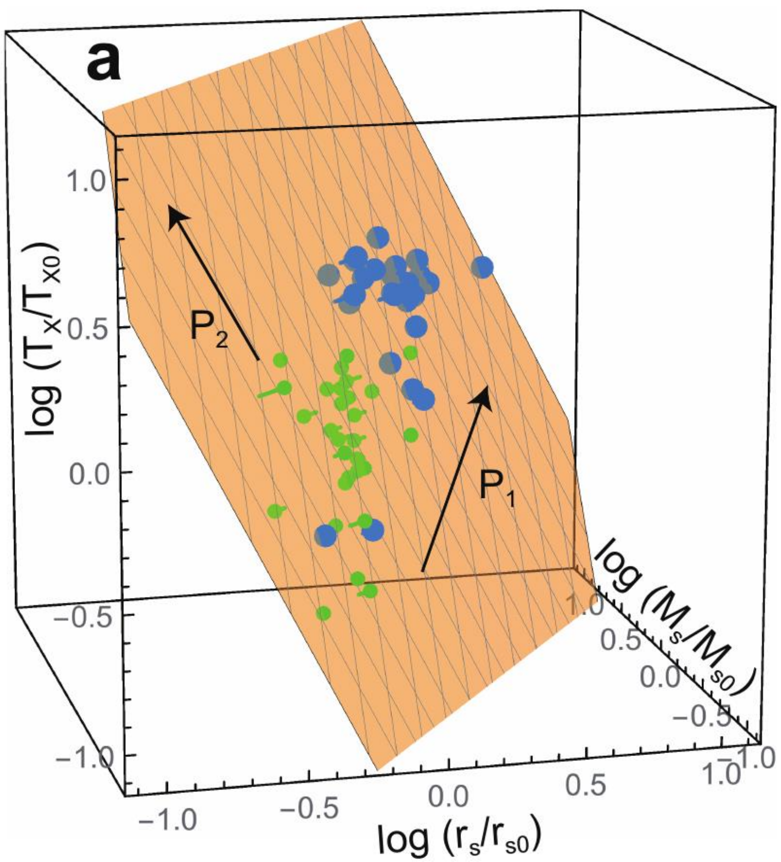


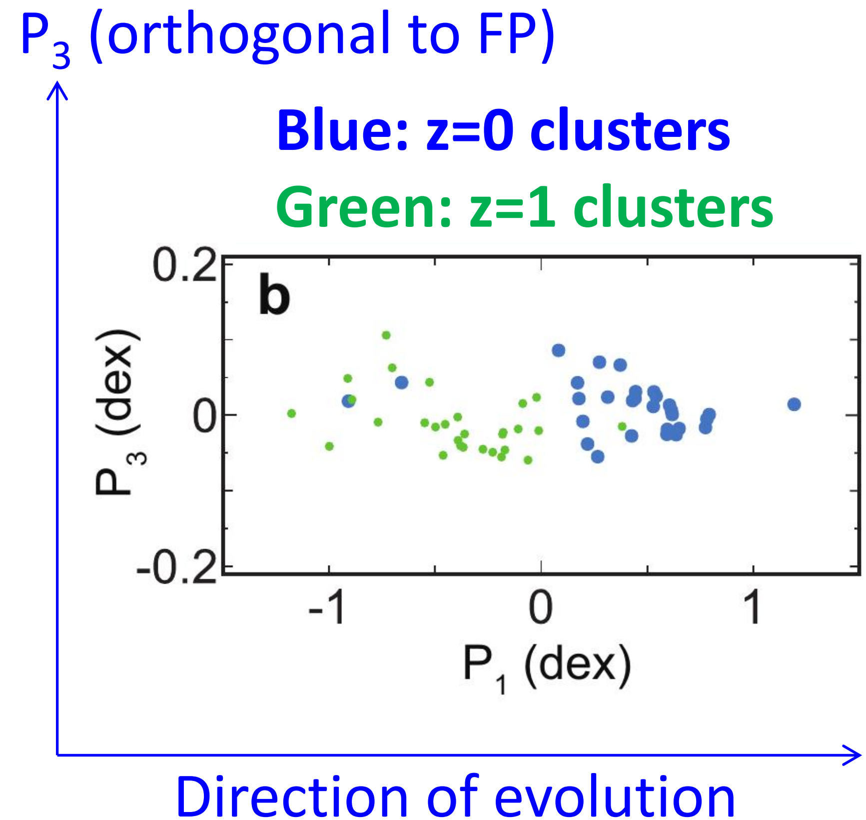
Direction of evolution

Fujita, Umetsu, Rasia+18

FP in simulated cluster halos

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



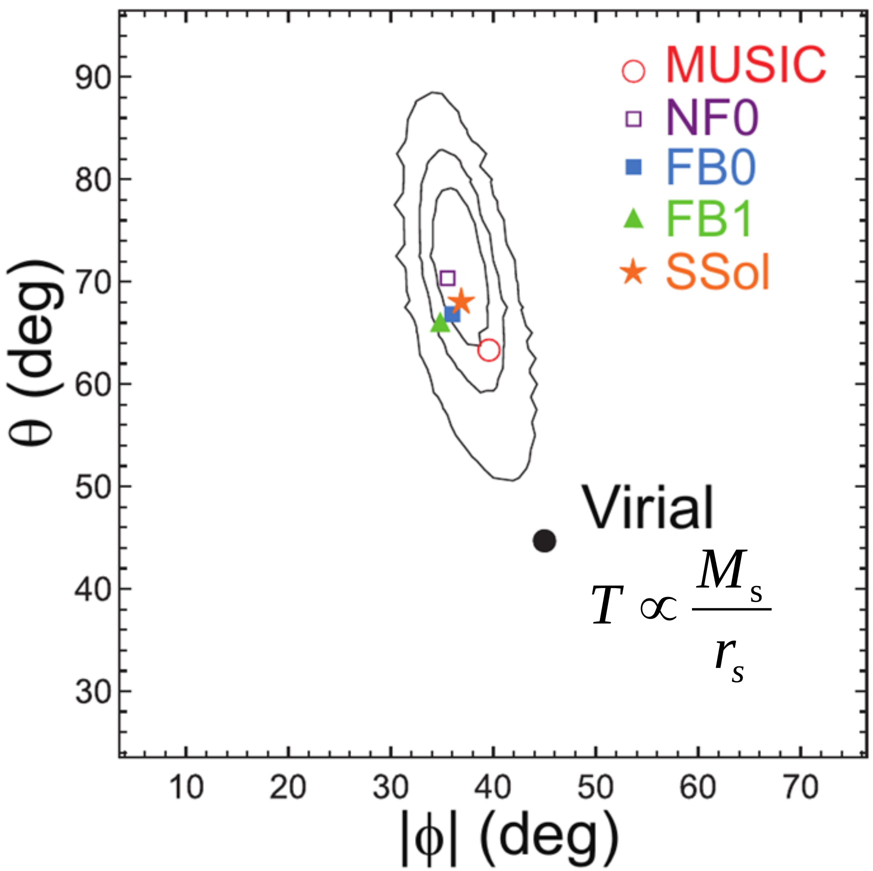


Fujita, Umetsu, Rasia+18

Observed vs. simulated FP

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

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



Observed FP

$$T \propto \frac{M_s^{1.8\pm0.5}}{r_s^{2.3\pm0.7}}$$

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

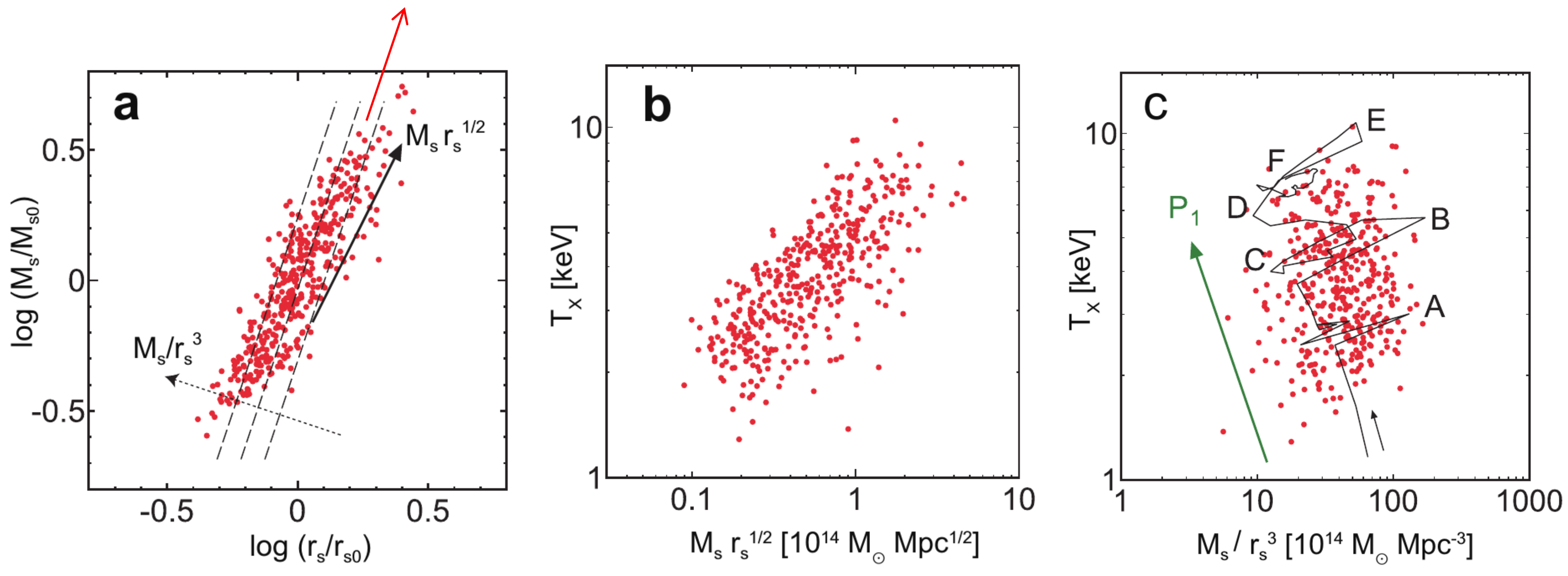
	Observation	Simulations				
		MUSIC	NF0	FB0	FB1	FB0+FB1
Non-gravitational effects	–	no	no	yes	yes	yes
Redshift	$0.377^{+0.309}_{-0.190}$	0.25	0	0	1	$0+1$
Dispersion around the plane (dex)	$0.045^{+0.008}_{-0.007}$	0.025*	0.023	0.031	0.035	0.037

Fujita, Umetsu, Rasia+18

Projections of simulated clusters

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

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

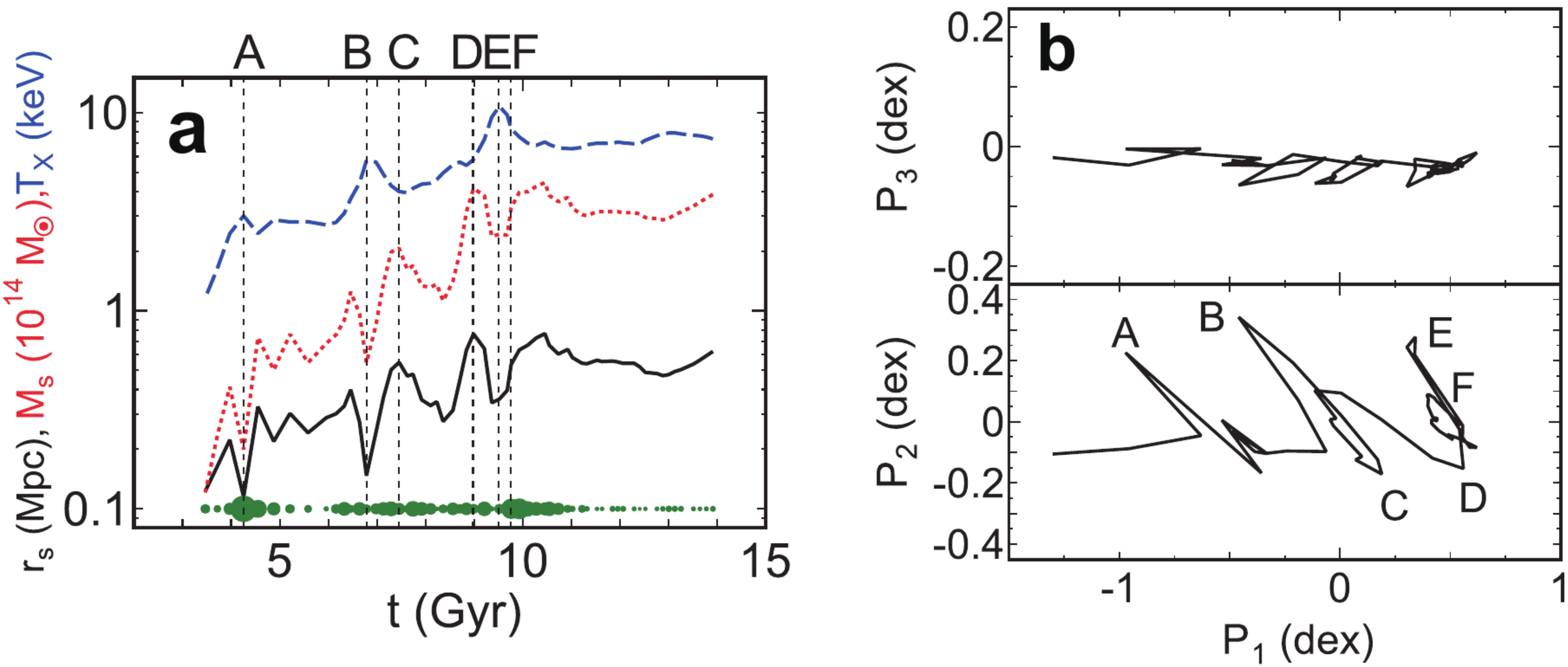


MUSIC cosmological simulations (DM + adiabatic gas)

Fujita, Umetsu, Rasia+18

Stability of FP against mergers

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



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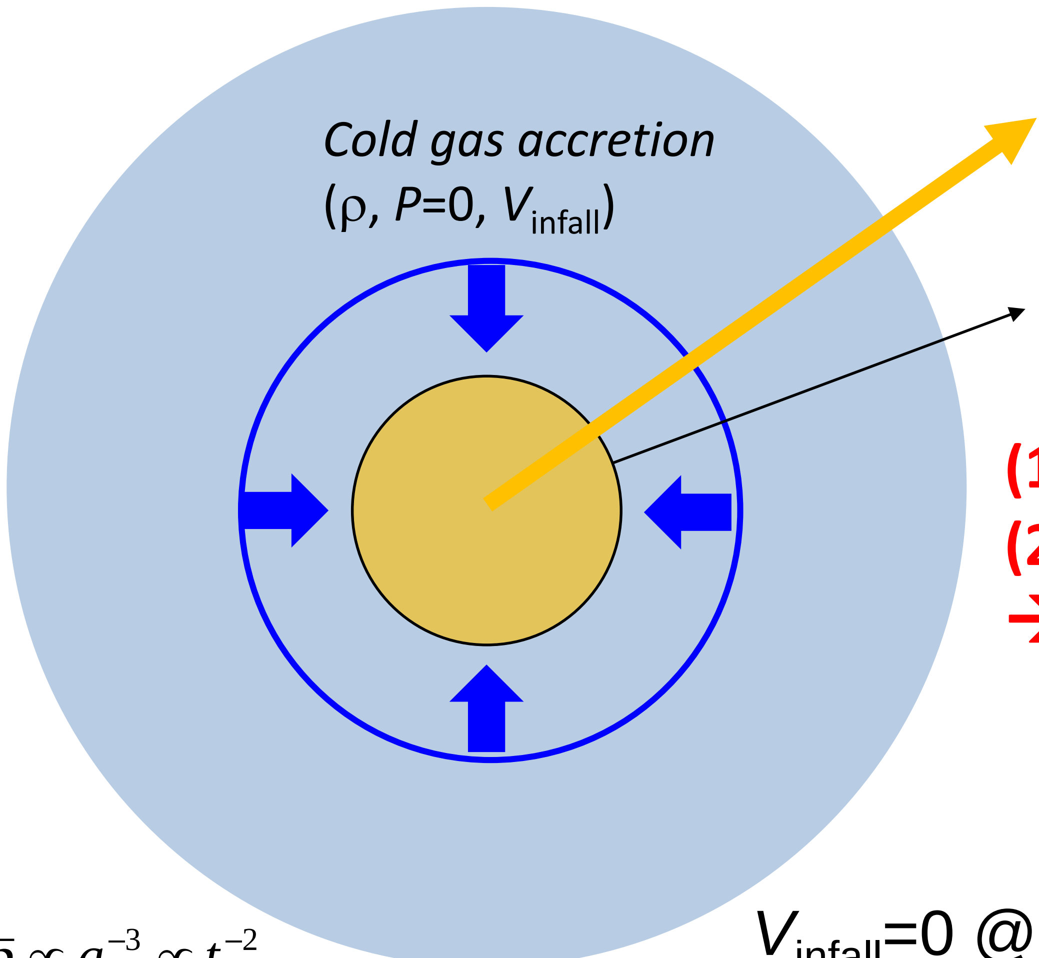
Direction of evolution

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
→ (1)+(2) yield

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

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

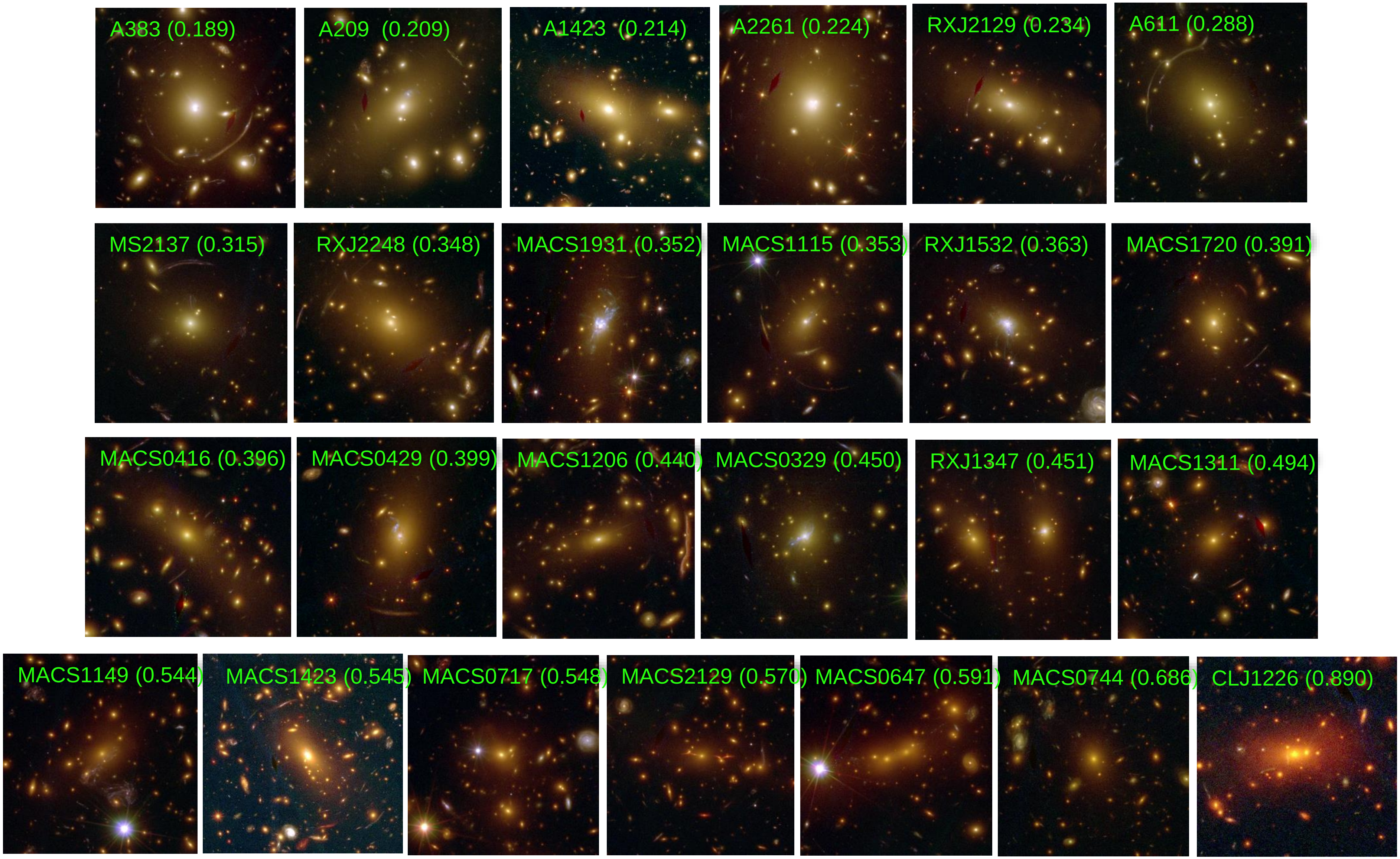
V_{infall}=0 @ turn-around radius $R_{t.a.}$

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 ($\rho_{crit} \sim M_s/r_s^3$) 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



Zitrin et al. 2015, *ApJ*, 801, 44

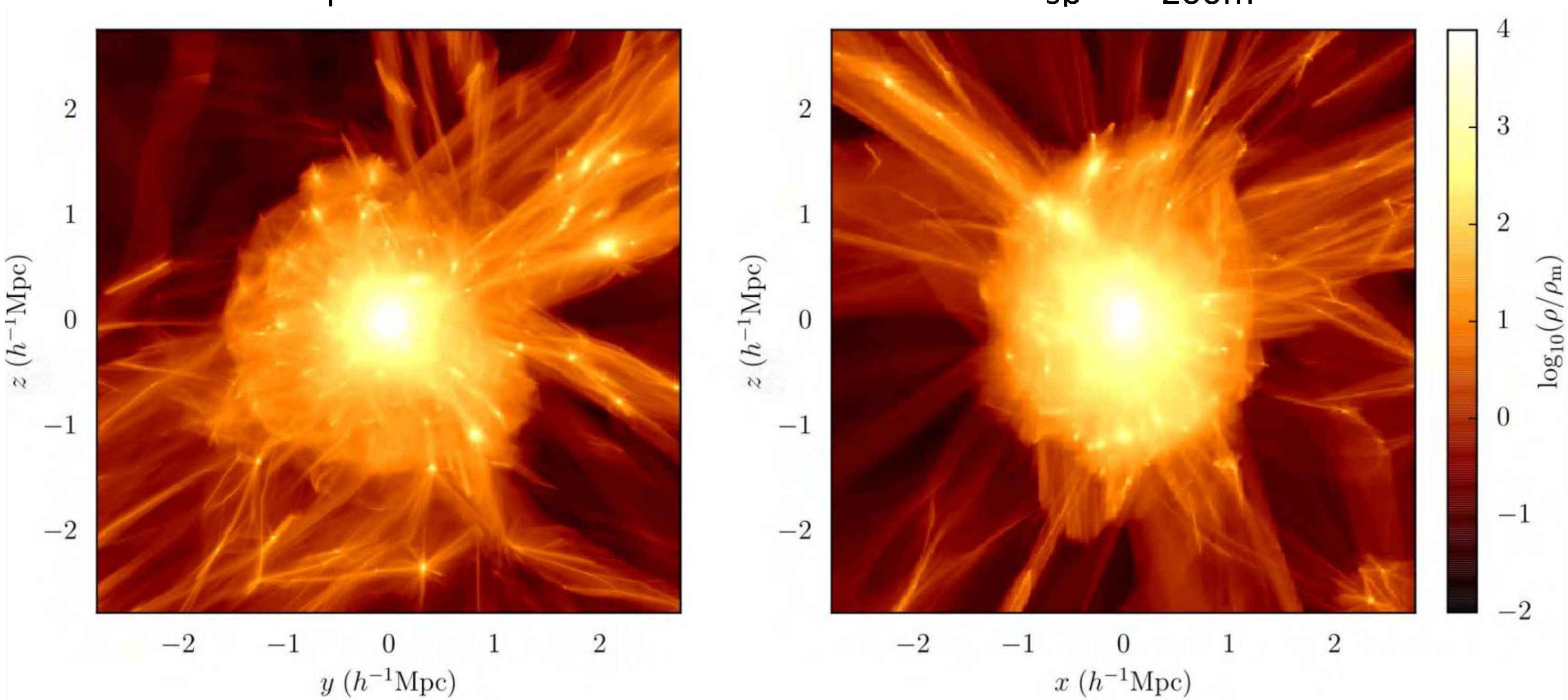
Splashback radius, R_{sp}: Physical halo boundary

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

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

<u>Slow accreting halos</u> — $R_{sp} > r_{200m}$

<u>Fast accreting halos</u> — $R_{sp} \sim r_{200m}$

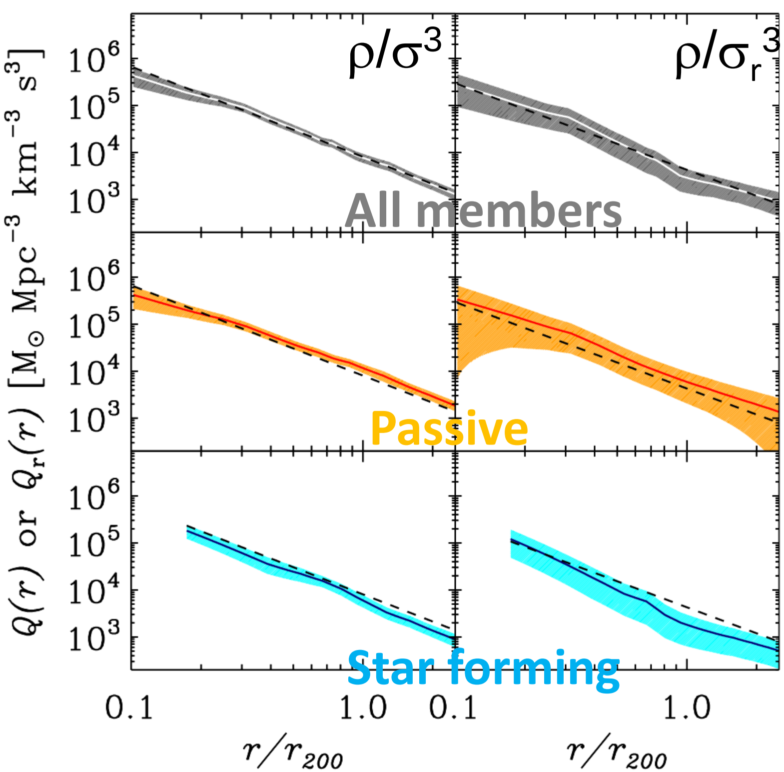


N-body simulations from S. More, Diemer, & Kravtsov 2015

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

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

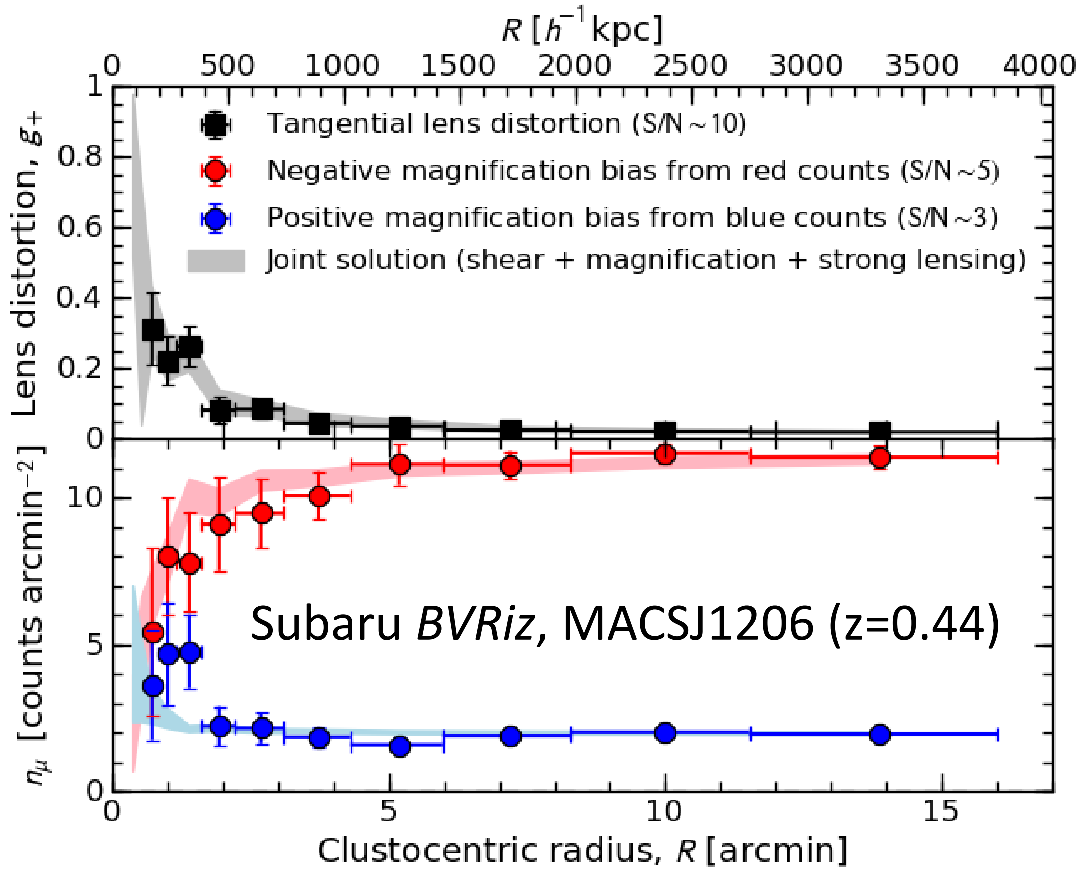
(See also Munari+15)

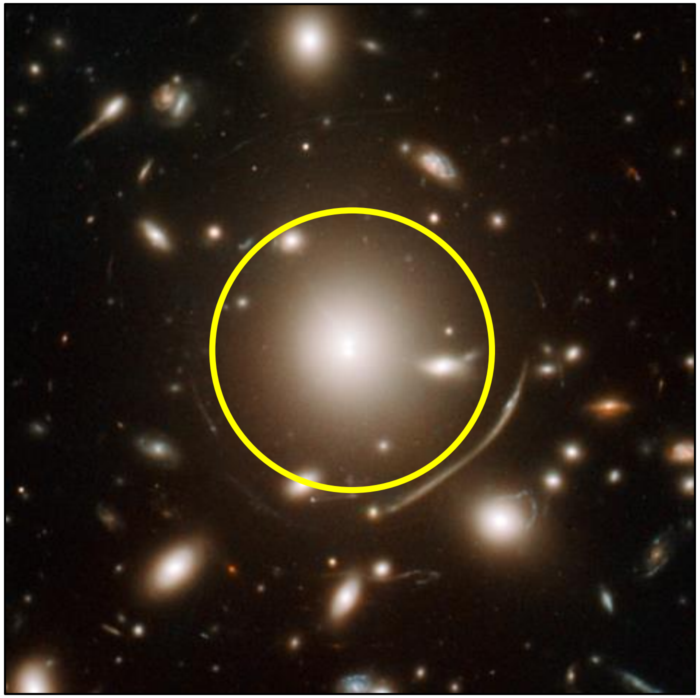
CLUMI (CLUster lensing Mass Inversion): Multi-probe lensing analysis

Combining strong-lensing, weak-lensing shear and magnification

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

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

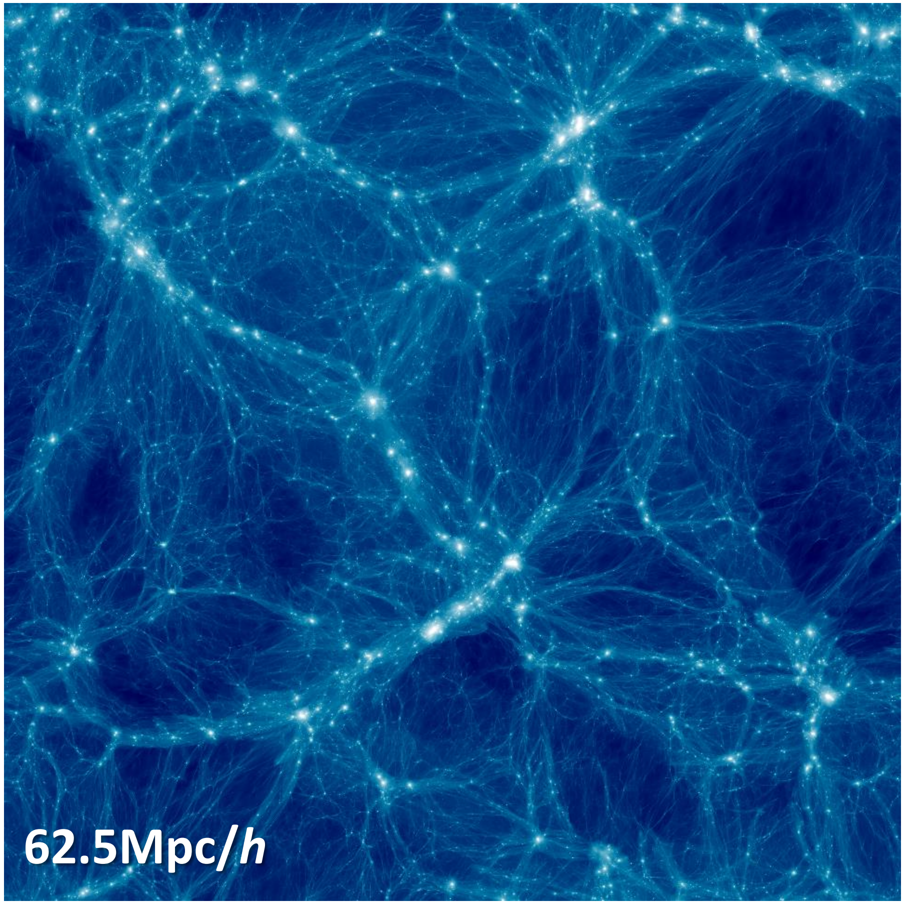


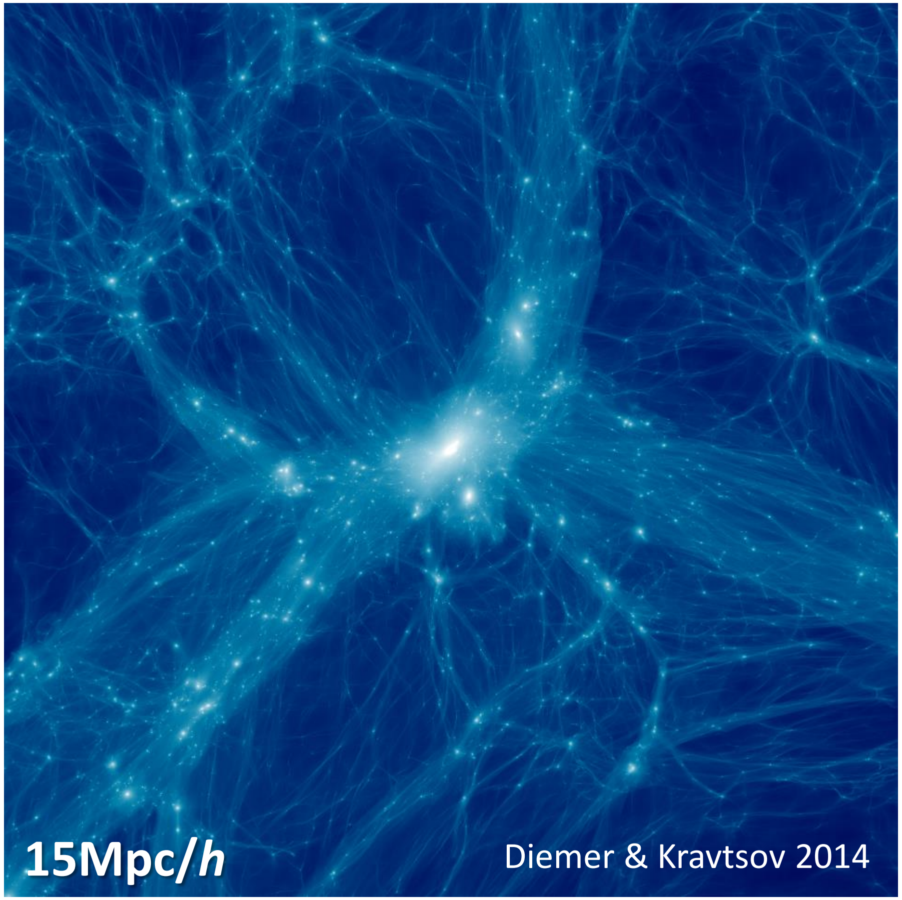


Umetsu 2013, *ApJ*, 769, 13

Galaxy Clusters as Cosmological Probes

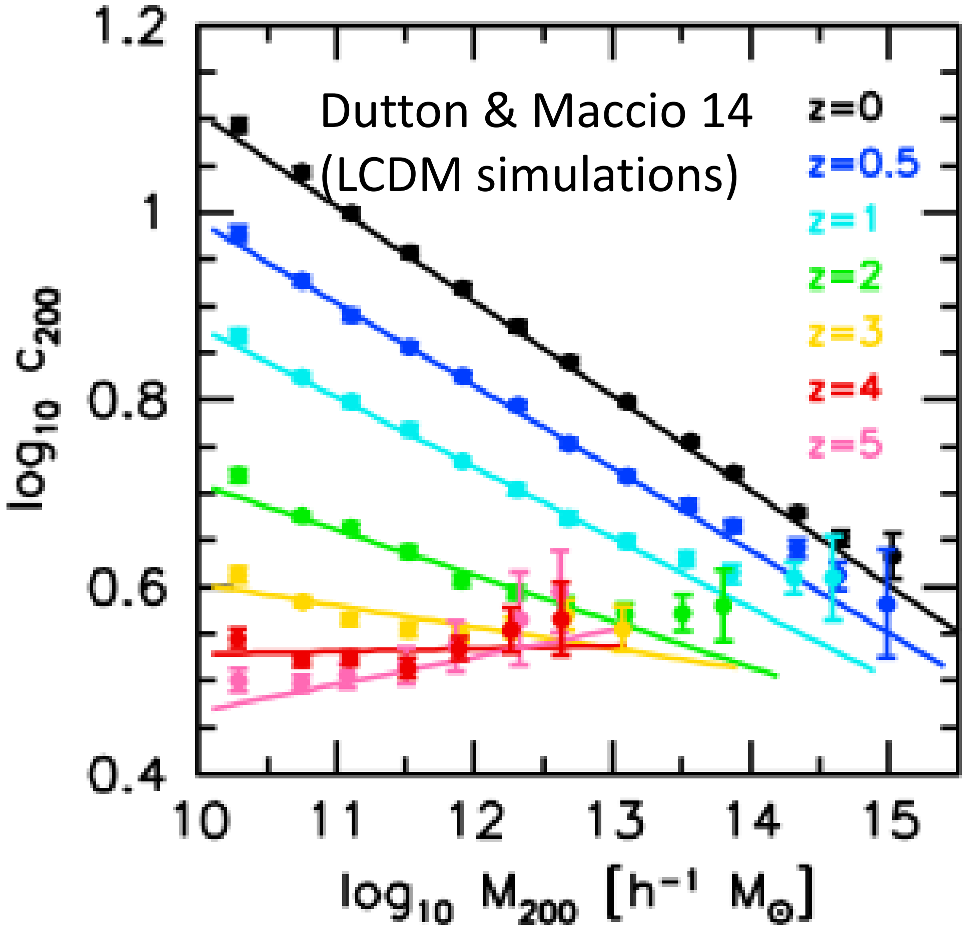
Statistical and individual properties of rare massive clusters are sensitive to cosmology





Halo concentration, c_Δ

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



In hierarchical structure formation, <*c*> is predicted to correlate with *M*:

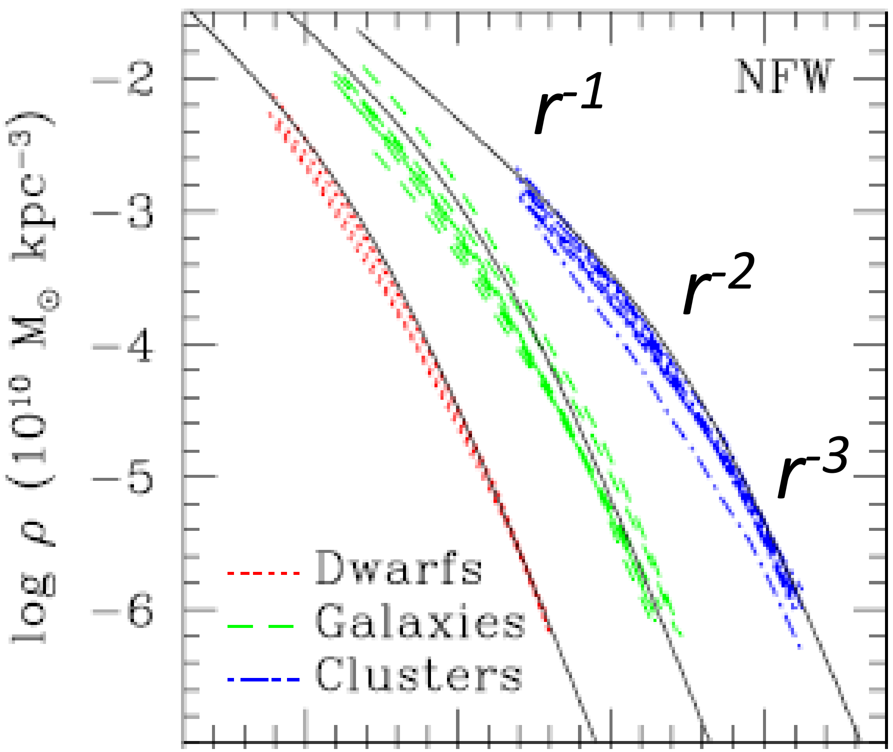
DM halos that are more massive collapse later on average, when the mean background density of the universe is correspondingly lower.

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

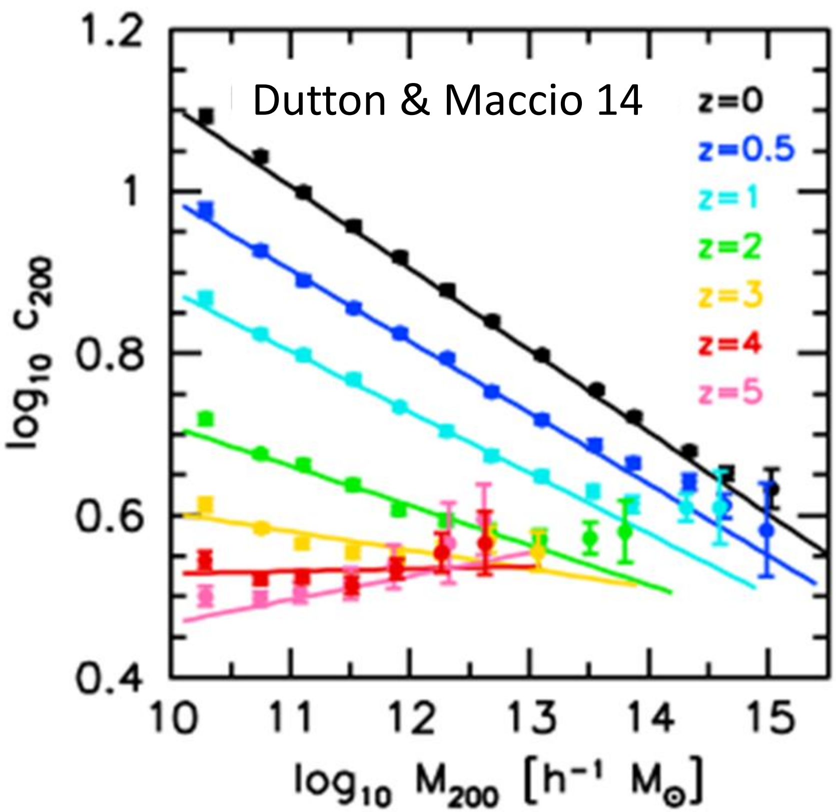
Density structure of CDM halos

- 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



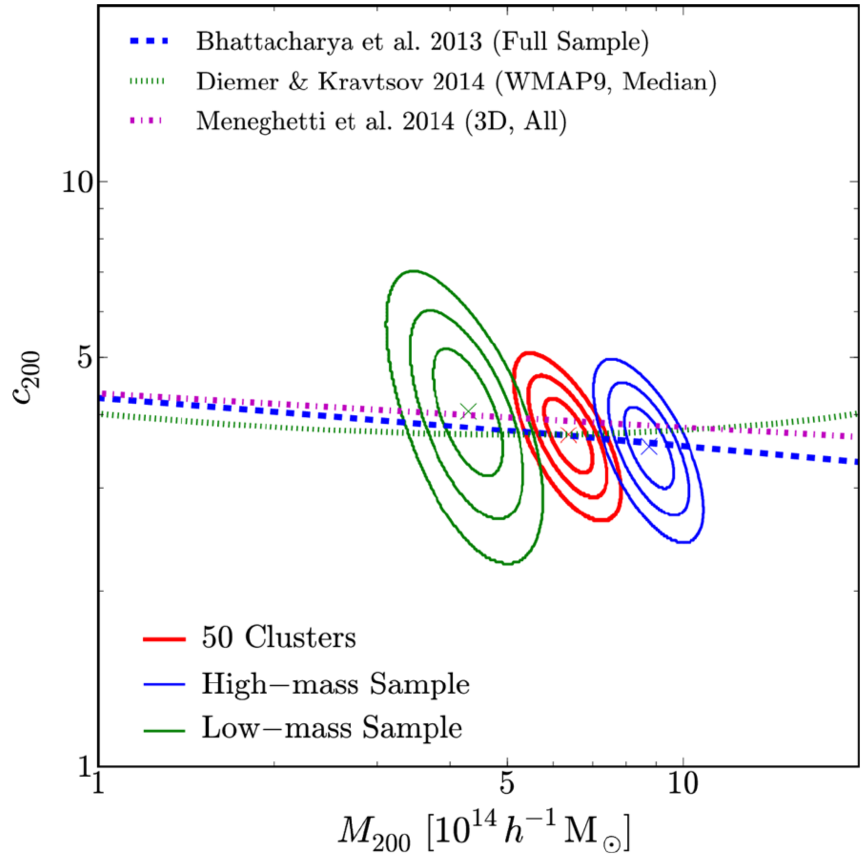
The concentration-mass relation



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

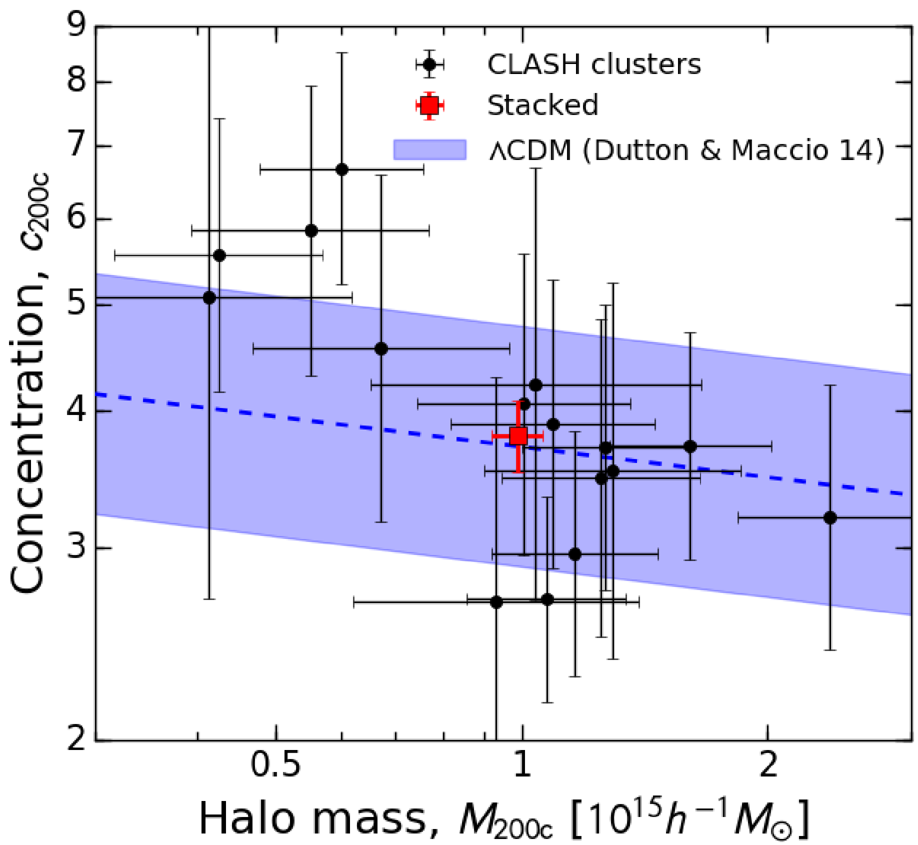
Targeted lensing surveys of X-ray-selected clusters

LoCuSS (<*z*>~0.2)



Okabe & Smith 15

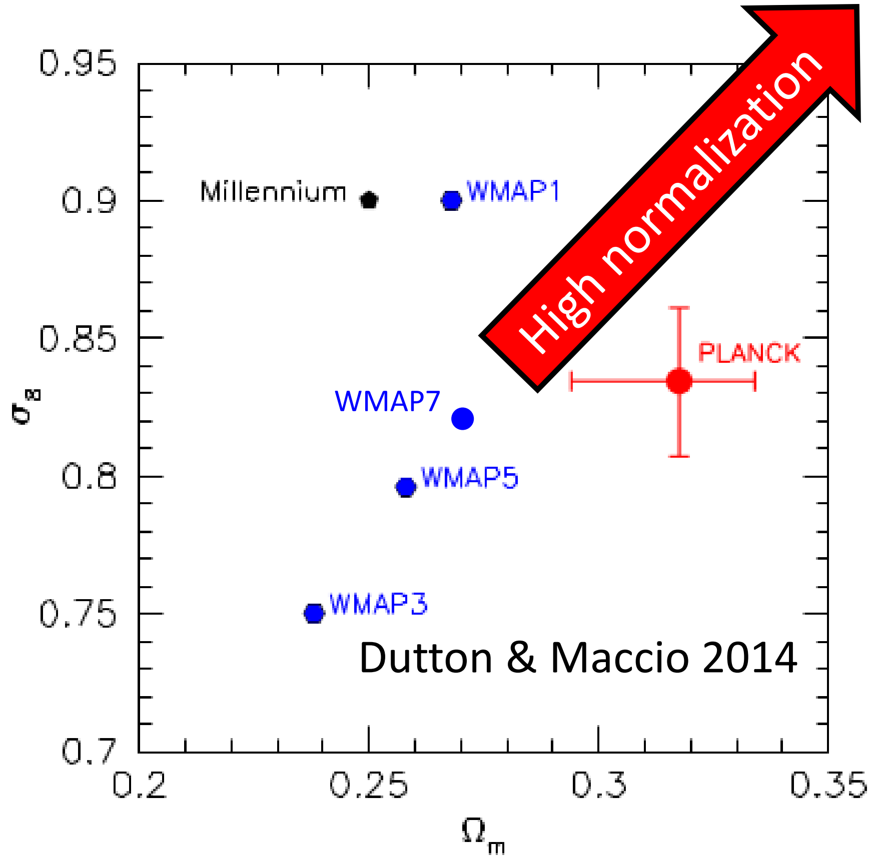
CLASH (<*z*>~0.35)

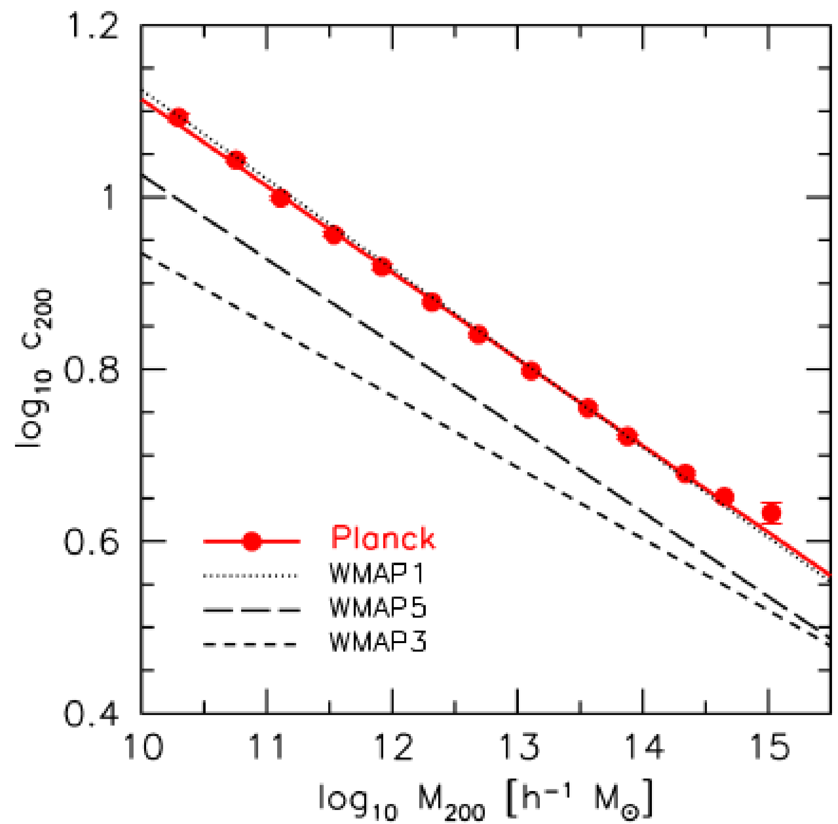


Umetsu+16, Merten+15

Halo cooncentration is sensitive to cosmology

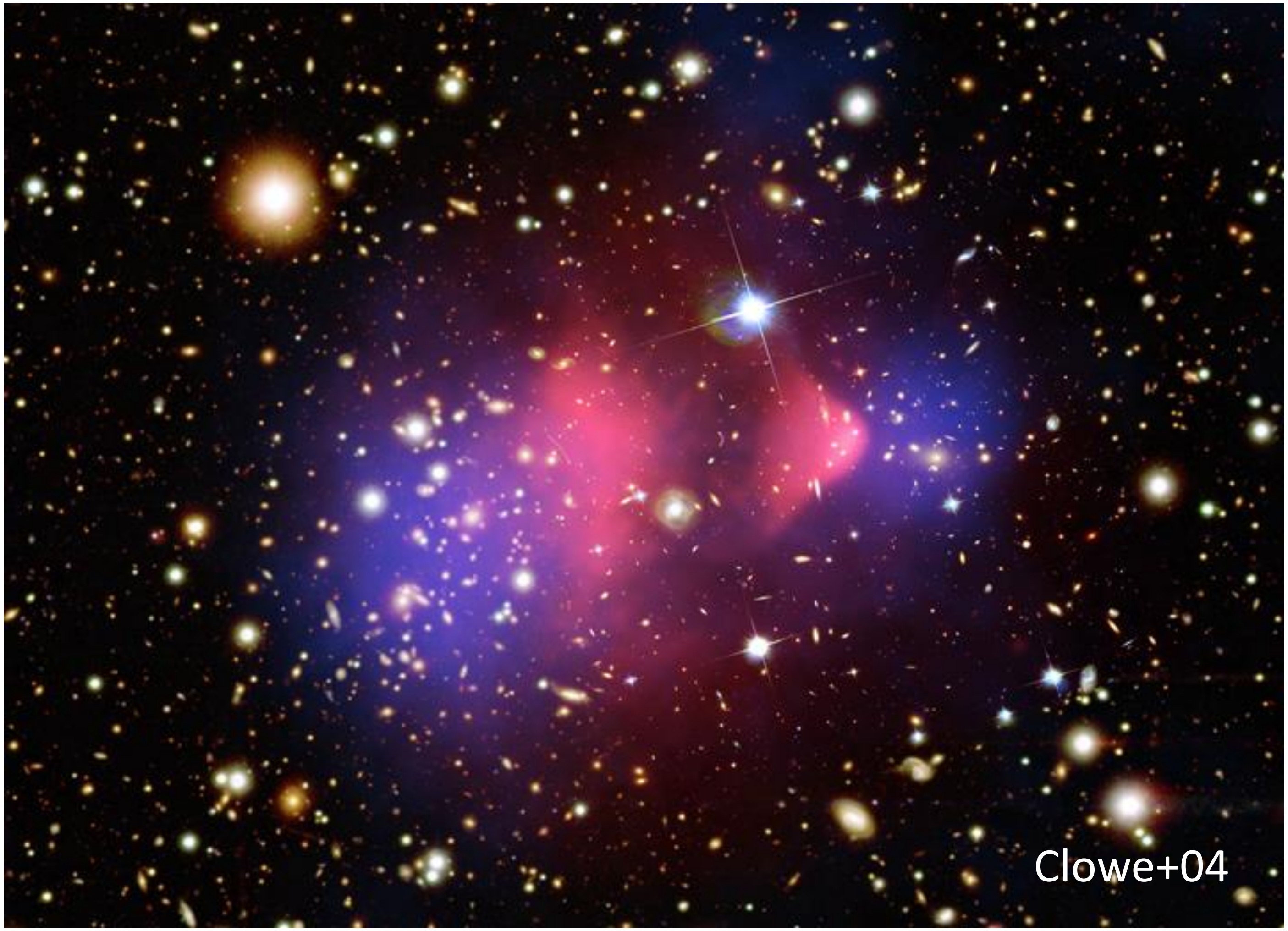
$$c_\Delta \equiv \frac{r_\Delta}{r_s} = \frac{\text{(Outer halo radius)}}{\text{(Inner scale radius)}}$$





Dutton & Maccio 2014

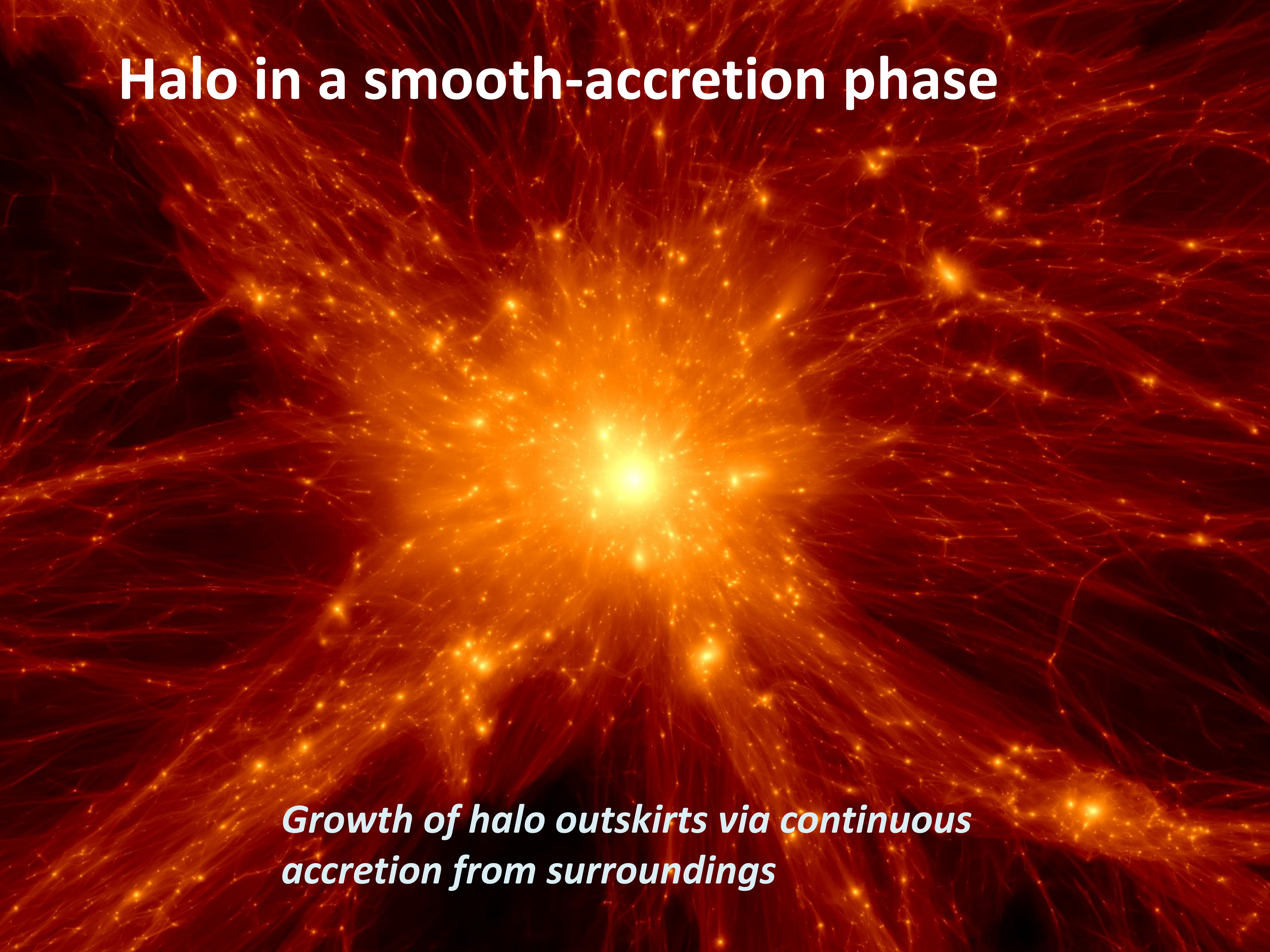
The Bullet Cluster: Evidence of DM



Blue: DM
Red: ICM

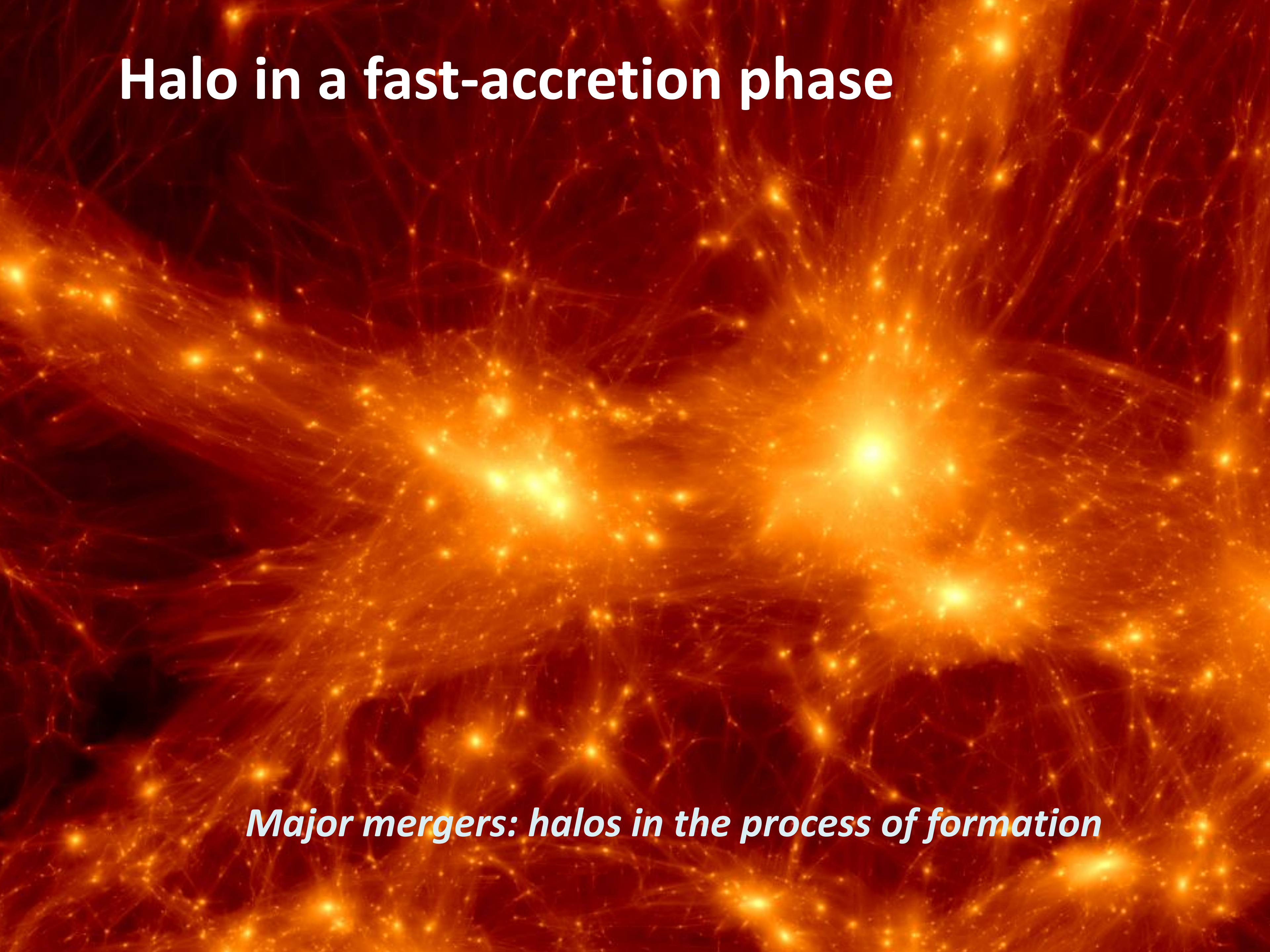
$(\sigma/m)_{SIDM} < 1/\langle L\rho \rangle \sim 1 \mathrm{cm}^2/\mathrm{g}$ (Randall+08)

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