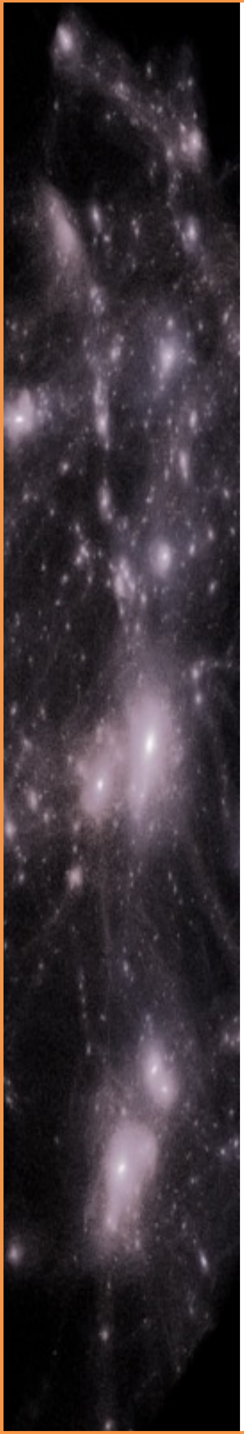


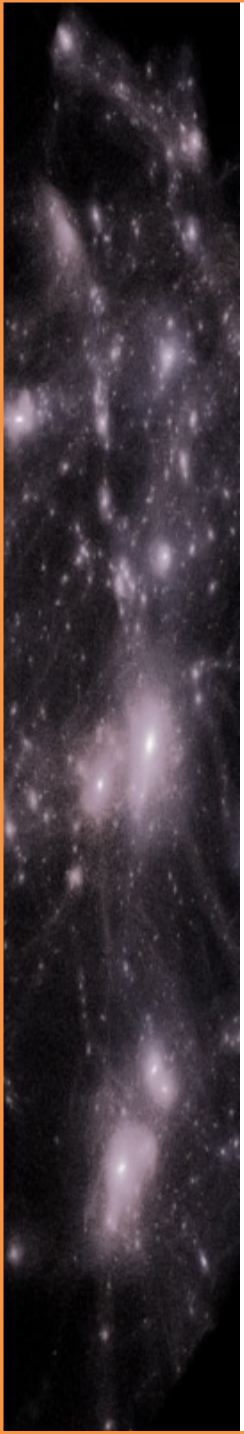
Dark Matter Halos and Sparsity

Pier Stefano Corasaniti

CNRS and Observatoire de Paris

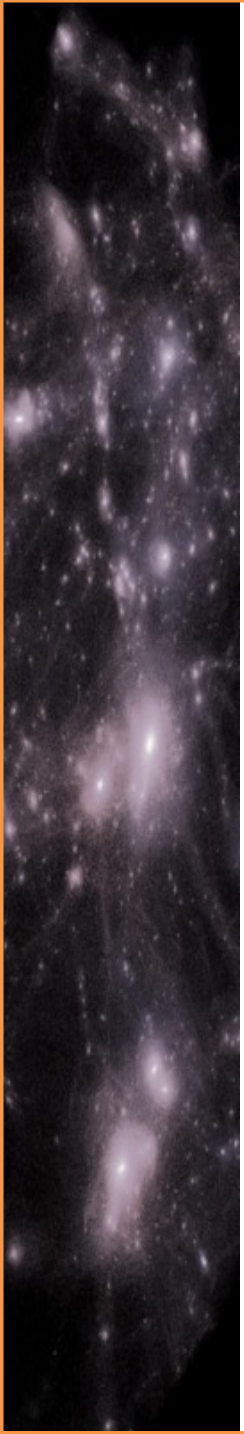
“News from the Dark”

Marseille 13-15/11/22



Outline

- Motivations
- Halo Mass Profiles & Sparsity
- Halo Assembly & Cosmology
- Impact of Baryons & Astrophysical Aspects



Collaborators:

Tamara Richardson (DIPC), Stefano Ettori (INAF-Bologna), Mauro Serena(U. Bologna), Y. Rasera (LUTH), Amandine Le Brun (LUTH), Inigo Saez (INAF-Milan), Michel-Andres Breton (CEA)

Carlo Giocoli (INAF-Bologna), Marco Baldi (U. Bologna), D. Eckert (U. Geneva), M. Arnaud, G. Pratt (CEA)

Marco De Petris (U. Roma I), Elena Rasia (INAF-Trieste), Gustavo Yepes (U. Madrid), Weiguang Cui (U. Madrid)

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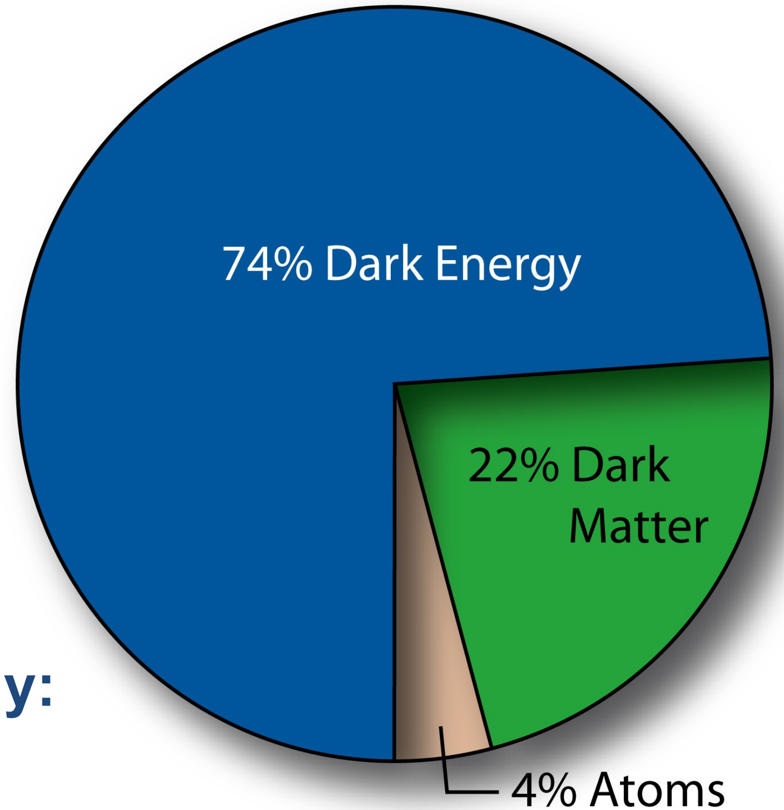
Richardson & Corasaniti, A&A 674, A173 (2023)

Corasaniti, Richardson et al. in preparation

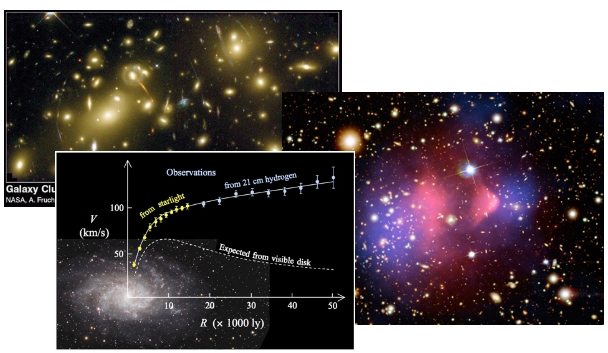
Stressing the LCDM paradigm

The Universe in 6 parameters:

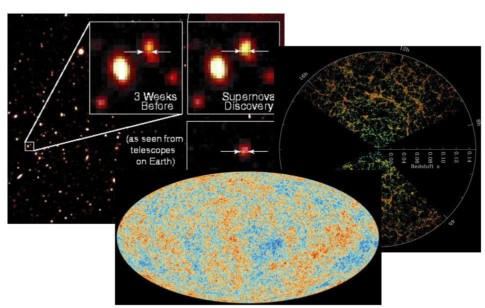
$$\Omega_b h^2 = 0.0223 \pm 0.0001$$
$$n_s = 0.965 \pm 0.004$$
$$\Omega_m = 0.317 \pm 0.008$$
$$\sigma_8 = 0.812 \pm 0.007$$
$$\text{h} = 0.673 \pm 0.006$$
$$\tau = 0.054 \pm 0.008$$



Dark Matter :



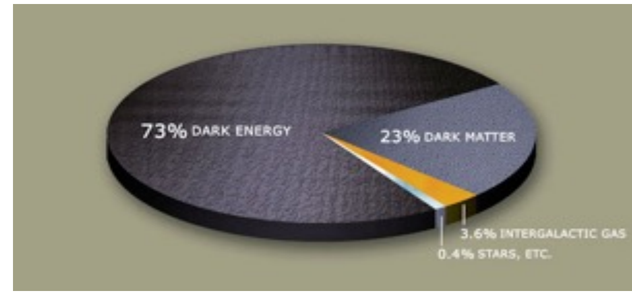
Dark Energy:



Structures in the Universe

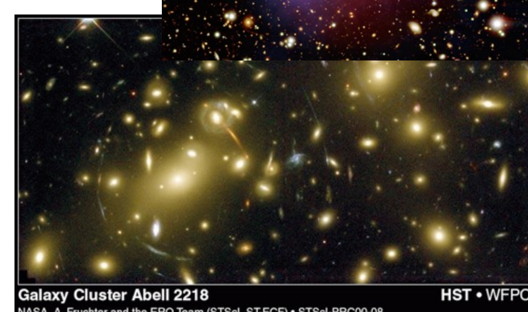
Dark Matter in the Universe:

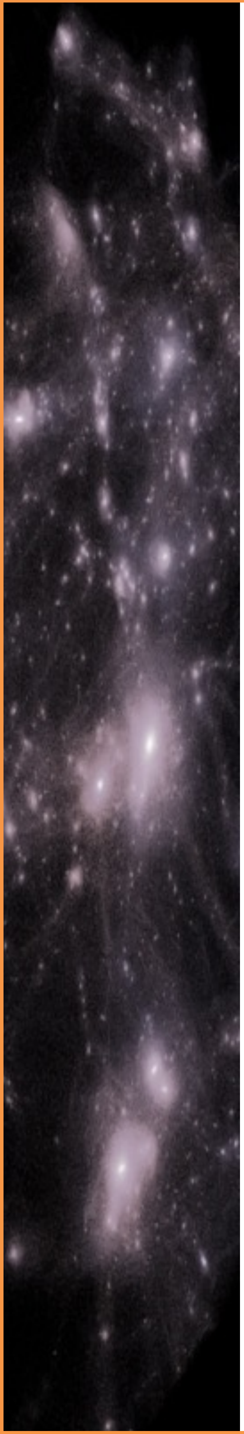
- Makes ~30% of total matter content
- Foster gravitational collapse of ordinary matter
- Resides in virialized clumps (halos)



Dark Matter Halos:

- Result of non-linear gravitational collapse
- Building blocks of cosmic structure formation
- Formation and evolution process depends on cosmology
- Halos host galaxies, dwarfs to massive, groups to clusters

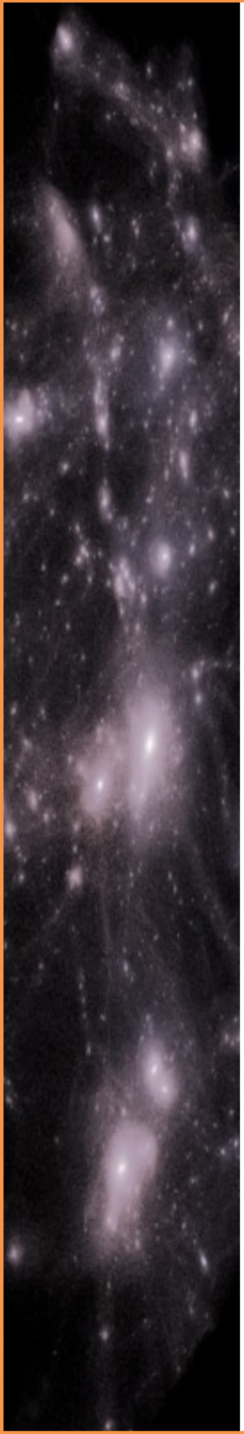




Galaxy Cluster Cosmology

Cosmic Probes

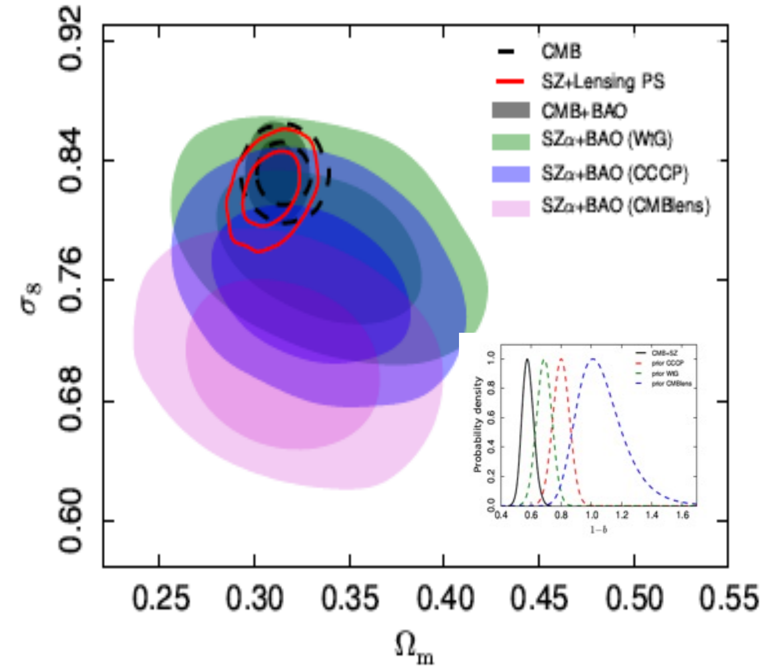
- Largest Most Massive Structures in the Universe
- Ultimate Result of Hierarchical Bottom-Up Structure Formation Process
- X-ray, SZ, Optical & Near-IR
- Cluster Abundance, Baryon Fraction, Spatial Clustering & Internal Mass Distribution



Cluster Number Counts

- *Planck*-SZ Catalog
- SPT-SZ, XXL, DES
- Low Ω_m & σ_8
- Primary Systematics: Mass Calibration Bias, Selection, Halo Mass Function Model

Planck Collaboration (2016)



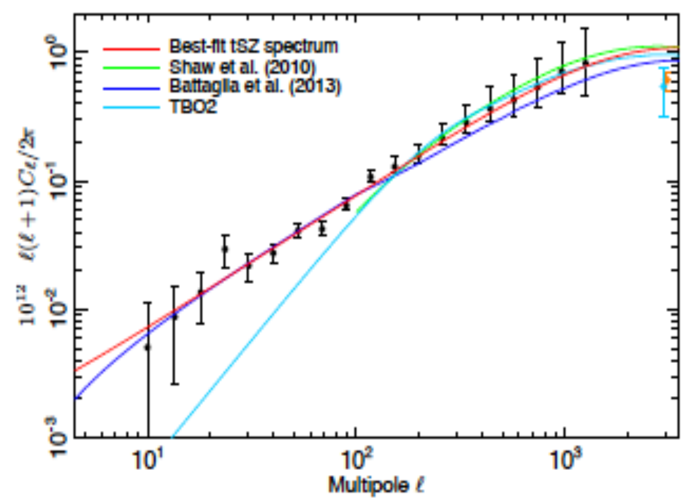
Baryon Fraction

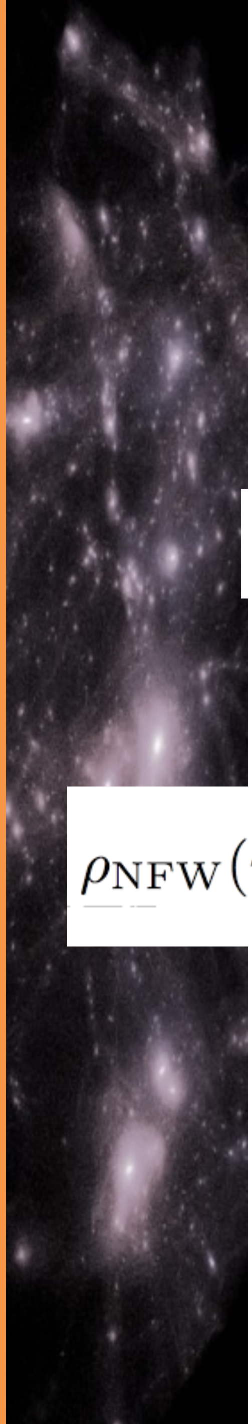
- $f_{gas} = M_{gas}/M_{tot} \sim f_{baryon} = \Omega_b / \Omega_m$
- Primary Systematics: Mass Calibration Bias, Gas Depletion

Spatial Clustering

- 2-Point Correlation Function SZ Sources
- Primary Systematics: Selection Function, Halo Bias Model, Secondary Sources

Planck Collaboration (2016)





NFW-Profile

Universal Profile

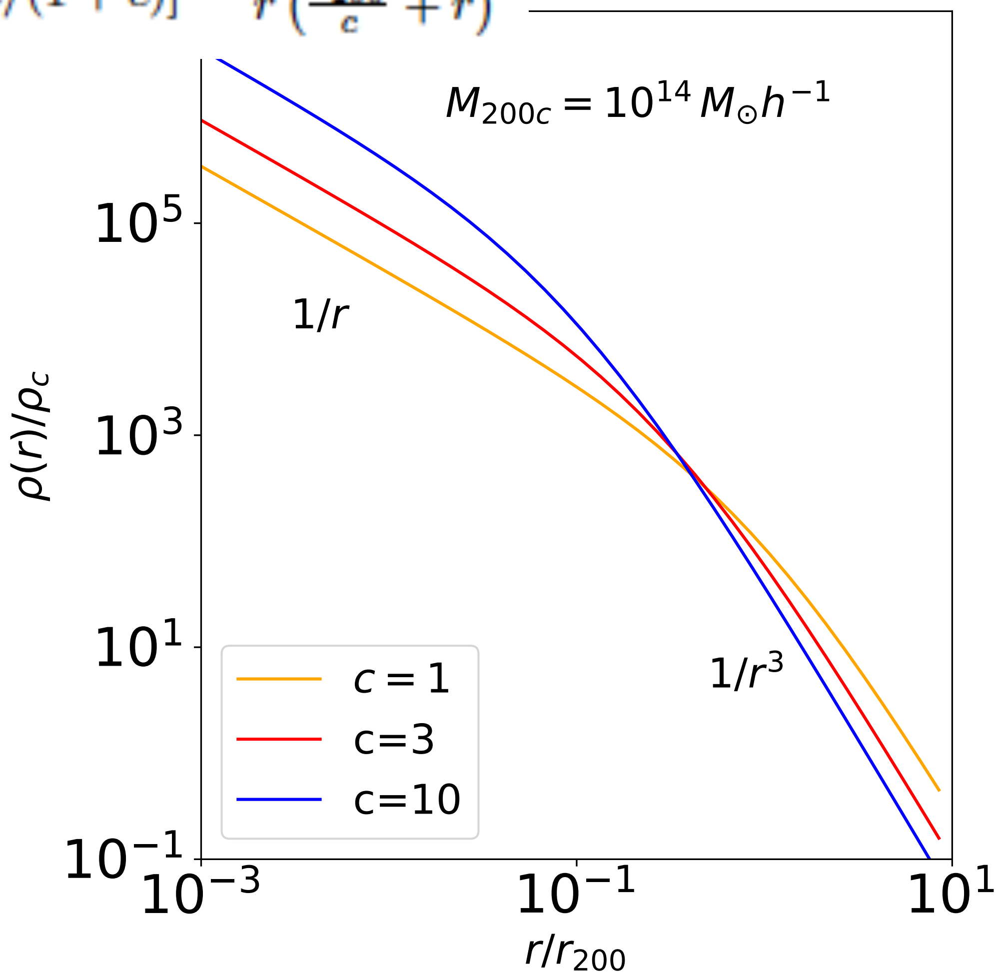
$$\rho_{\rm NFW}(r) = \frac{M_{200}}{4\pi[\ln(1+c) - c/(1+c)]} \times \frac{1}{r\left(\frac{r_{200}}{c} + r\right)^2}$$

$$c = \frac{r_{200}}{r_s}$$

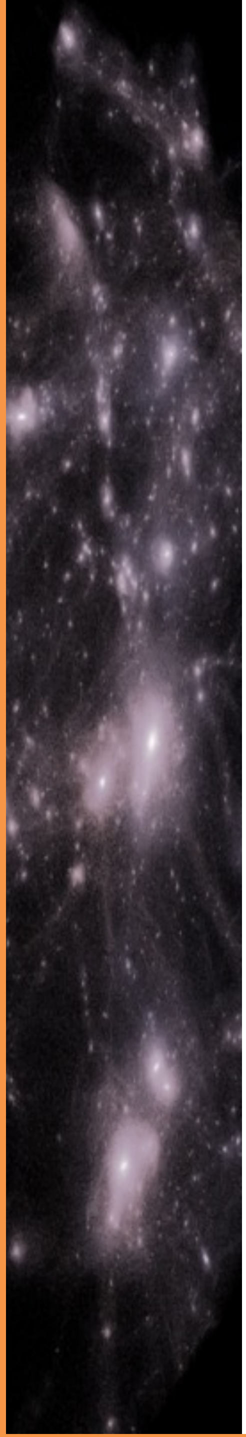
Navarro, Frenk & White (1997)

$$\rho_{\rm NFW}(r) \propto \begin{cases} r^{-1} & r \ll r_{\rm s} \\ r^{-3} & r \gg r_{\rm s}, \end{cases}$$

- The smaller r_s the more compact the halo
- c is a proxy of halo concentration



Universality of Halo Profile

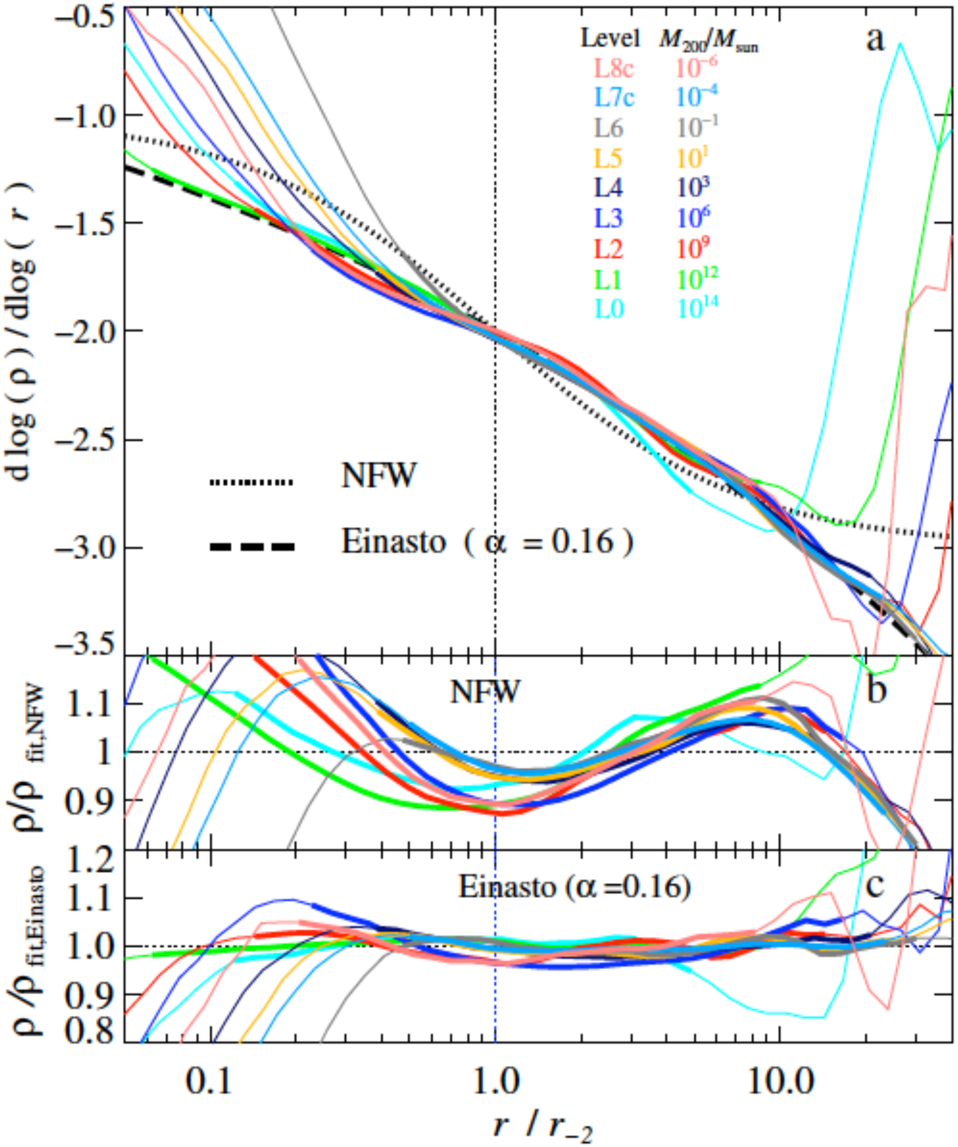


- Successive N-body zoom simulations
- Average profile of dozen most massive halos at each refinement level
- Spans 20 order mass scales

  - NFW (< 10%)
  - Einasto (< 5%)

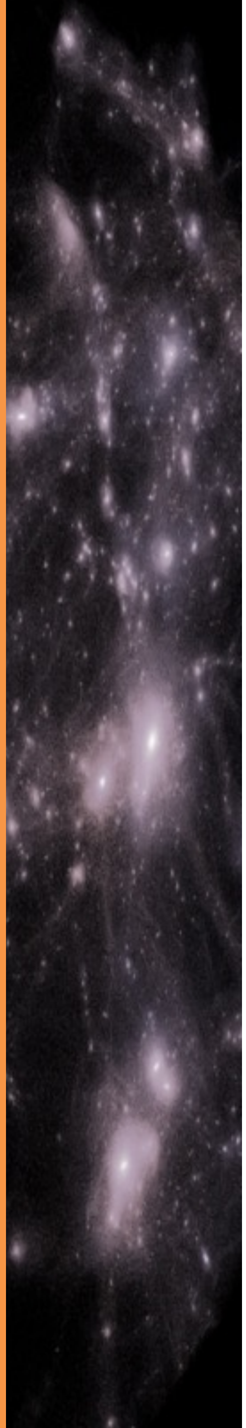
Origin of Universality?

- Gravity + Initial Scale Invariant Spectrum



Wang et a. (2020)

Concentration-Mass Relation



Halo Density Profile

- c = random variate

- Median

$$c(M,z) = \frac{c_0}{1+z}\left(\frac{M}{10^{14}h^{-1}M_{Sun}}\right)^{\alpha}$$

- scatter

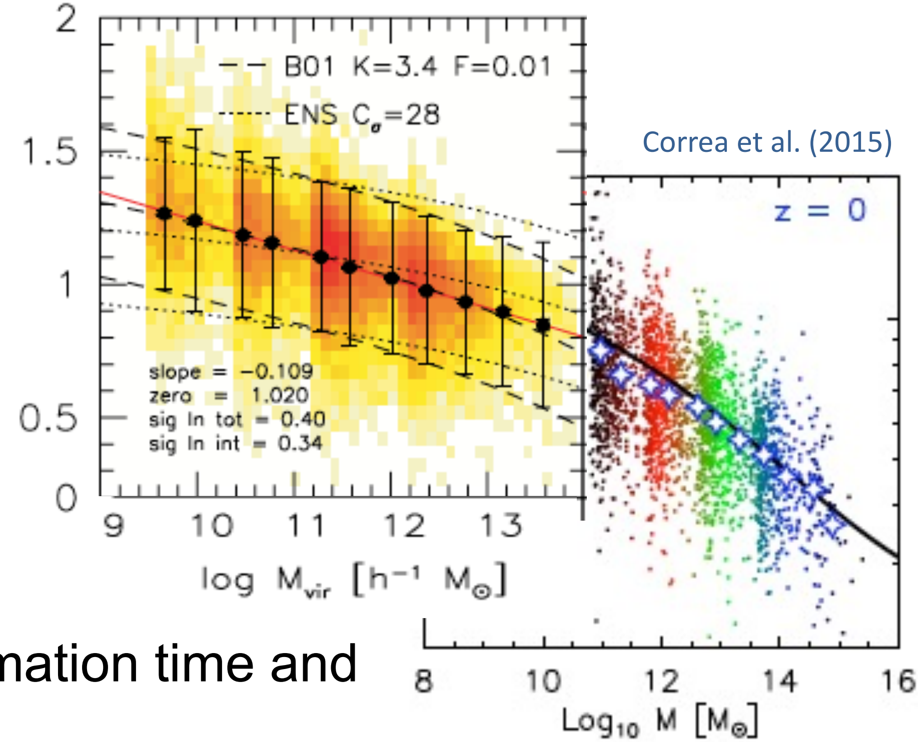
$\sigma_{\ln c}$ ~ 0.3 (large)

- Correlates with halo formation time and mass assembly history

see e.g. Zhao et al. (2003), Ludlow et al. (2012)

Maccio et al. (2007)

Correa et al. (2015)

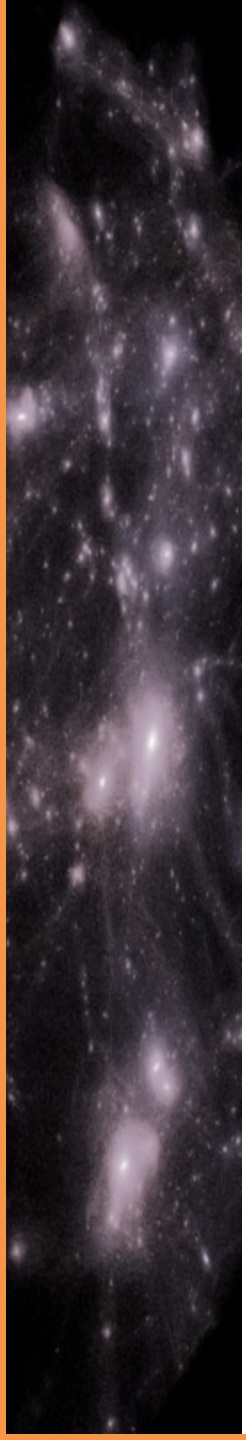


Cosmology

- α ~ -0.1;
- c_0 : cosmology dependent;

$$c_0 \rightarrow c_0^{\Lambda CDM} \cdot \frac{D_+(z_{coll})}{D_+^{\Lambda CDM}(z_{coll})}$$

Klypin et al. (2003); Dolag et al. (2004)



Observational Challenges

Systematic Effects

- Impact of Cooling, Star Formation, SN & AGN feedback

- X-ray Observations: Deviations from HE

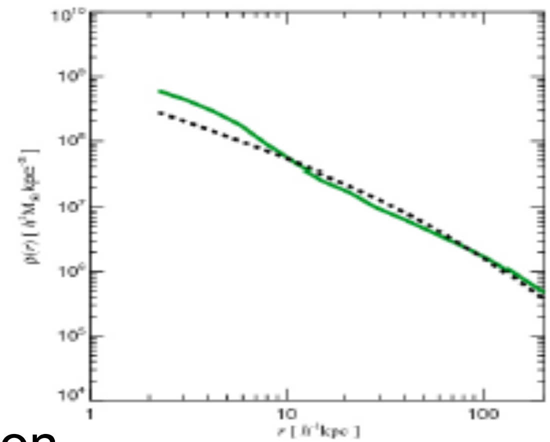
  e.g. Gnedin et al. (2004); Duffy et al. (2010); De Boni et al. (2013); Rasia et al. (2013)

- Lensing Observations: Shape & Orientation

  e.g. Oguri et al. (2005); Corless, King & Clowe (2009), Sereno et al. (2013)

- Selection Effects

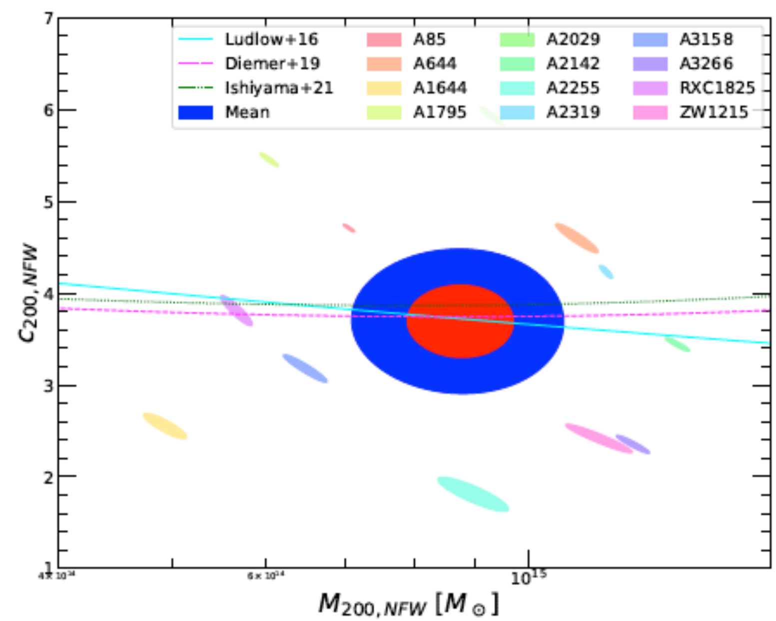
  Sereno et al. (2014)



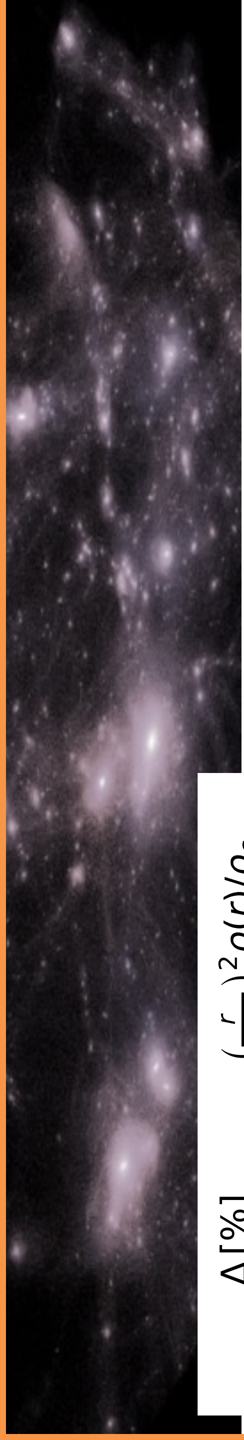
Mead et al. (2010)

X-COP Concentrations

- Large Scatter
- Consistent with c-M relations in literature
- No cosmological constraints out of it



Eckert, Ettori, Pointecouteau, van der Bourg, Loubser (2022)

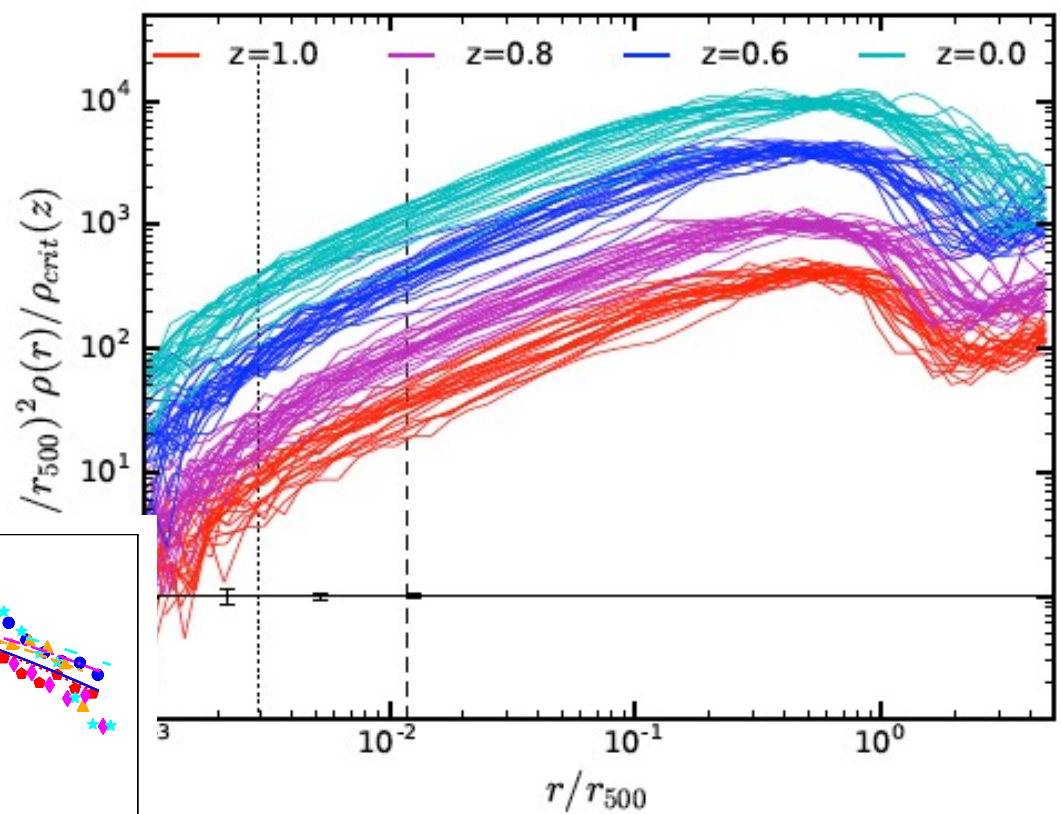


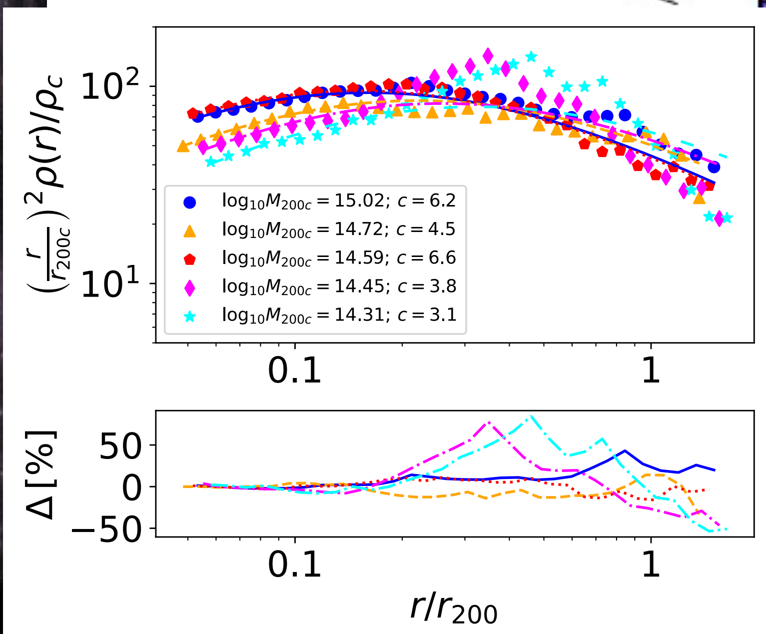
N-body Halo Density Profiles

Perturbed Profile

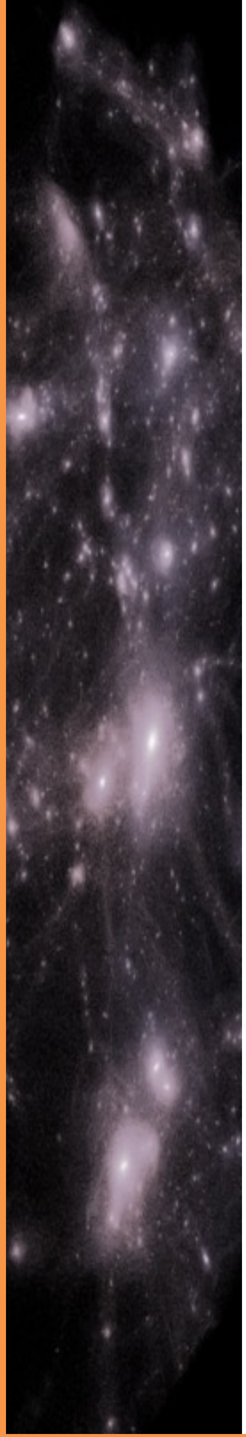
Le Brun et al. (2018)

- Zooms of 25 massive halos ~10^{15} M_{sun} h
- Negligible Poisson Errors
- Scatter: sub-structures and perturbed state



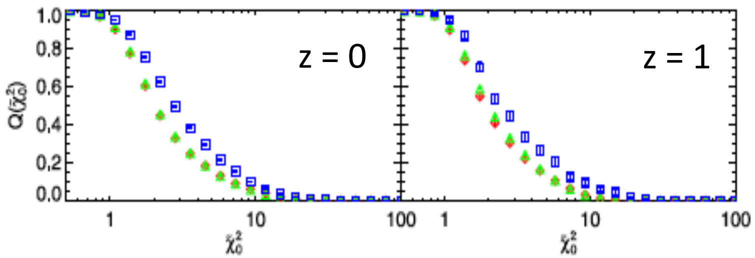


- Five most massive Bolshoi halos
- Impact NFW goodness-of-fit



Perturbed Halo Profiles

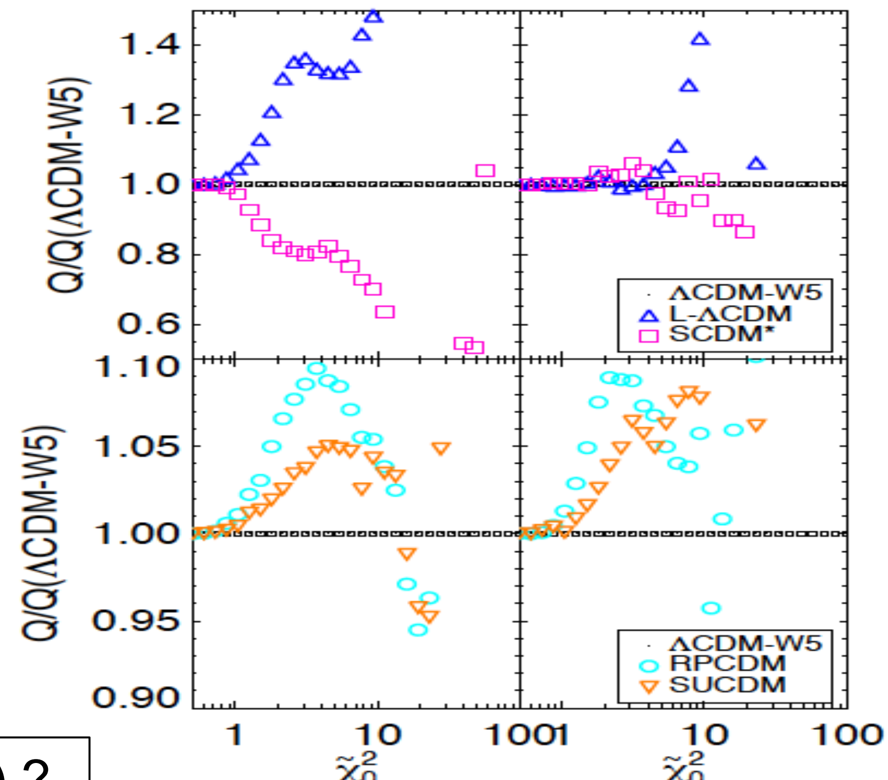
NFW Goodness-of-fit



- Cumulative Reduced χ^2-distribution
- 10% of halos >2σ deviation from NFW
- Deviations larger for massive halos

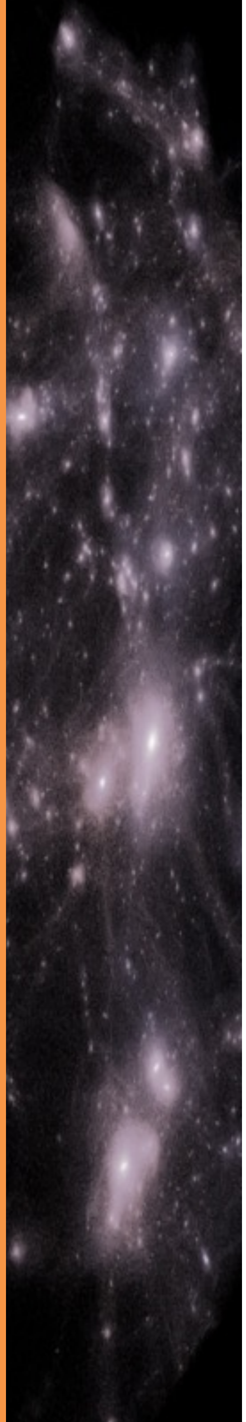
- Deviations strongly correlates with underlying model

- The less efficient the structure formation with respect to reference model the larger the fraction of halos deviating from NFW



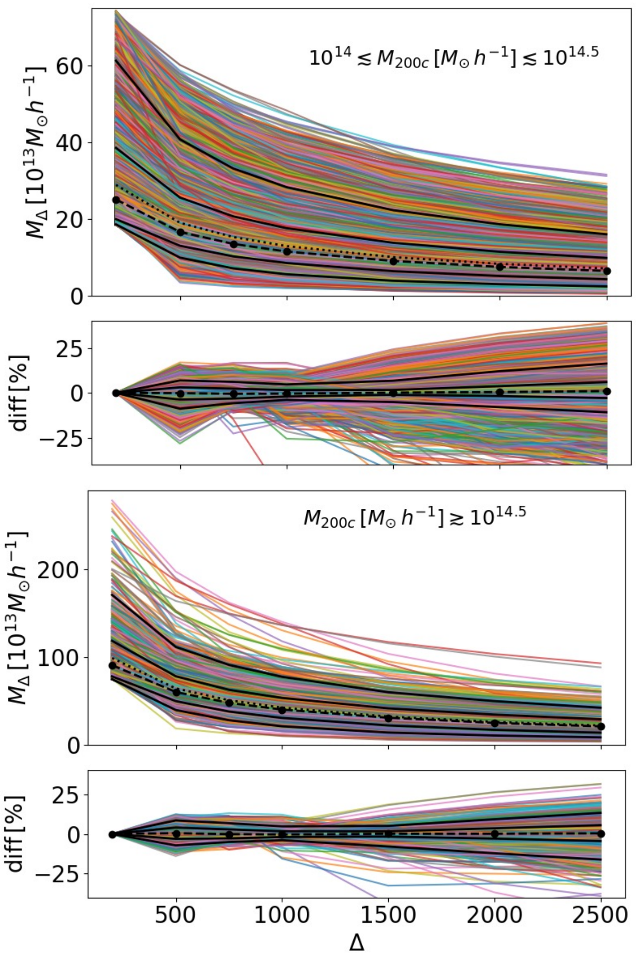
Are these relevant on M(<r) ?

Balmes, Rasera, Corasaniti, Alimi (2014)

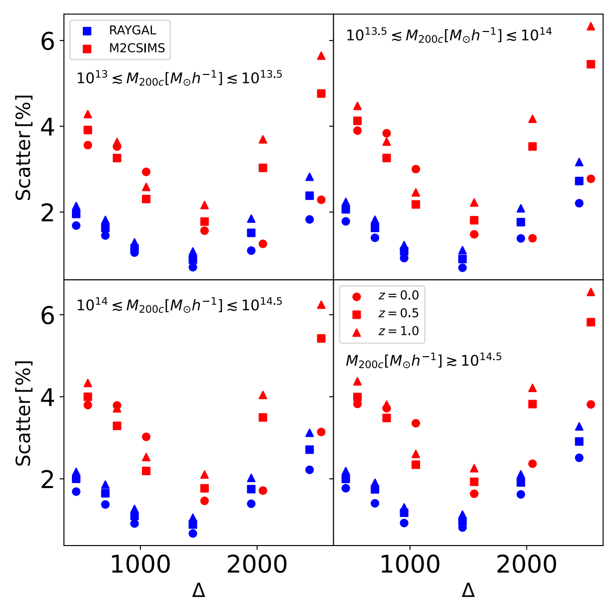


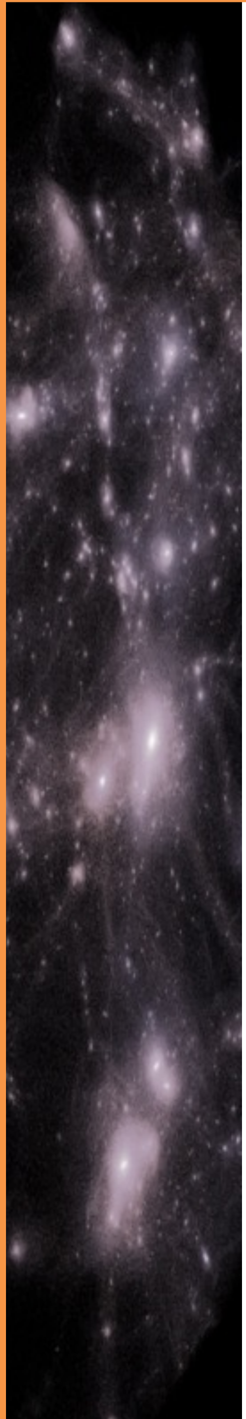
Halo Mass Profile

Deviations from NFW



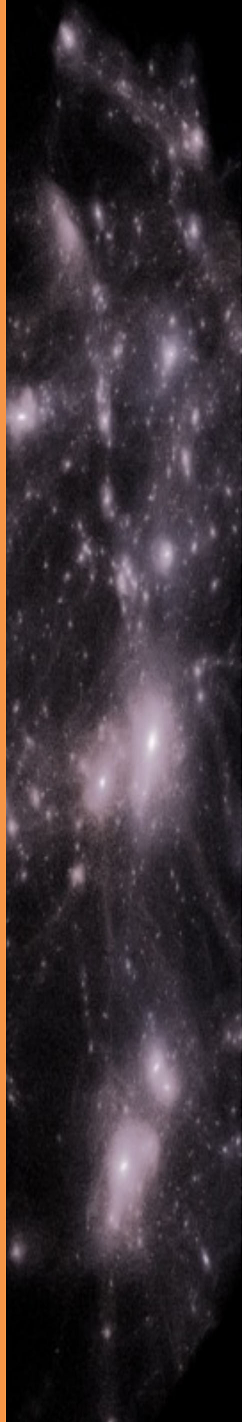
- Mass Profile ~10000 halos from RAYGAL simulation
- Scatter varies with radial distance / cosmology dependent
- Deviations > expected mass measurement errors





Proxy of Halo Mass Profile

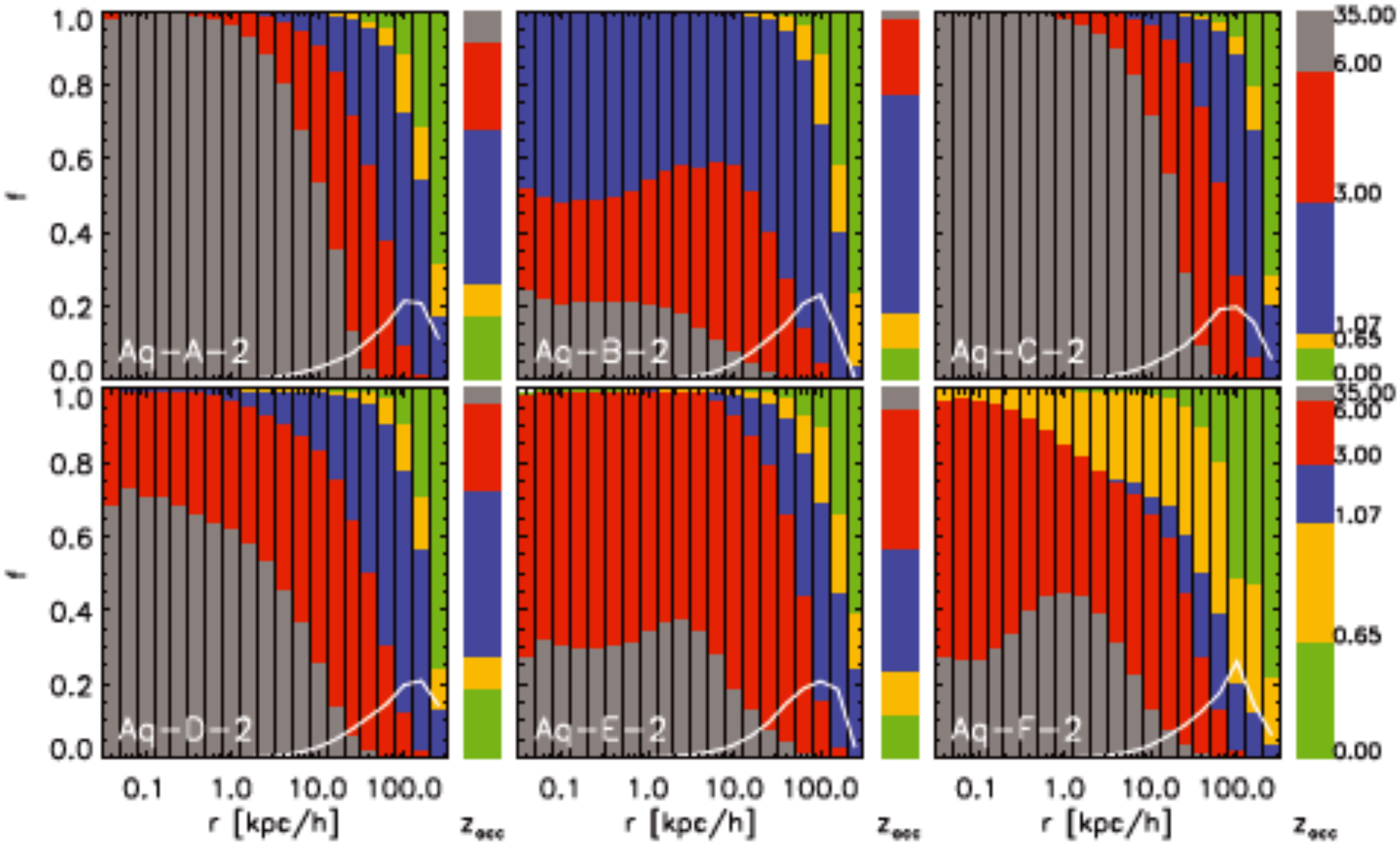
- Non-parametric Observable Estimator
- Capture differences in radial halo mass distribution
- Probe region of choice
- Retrieve cosmological information
- Easily predictable



Halo Structure

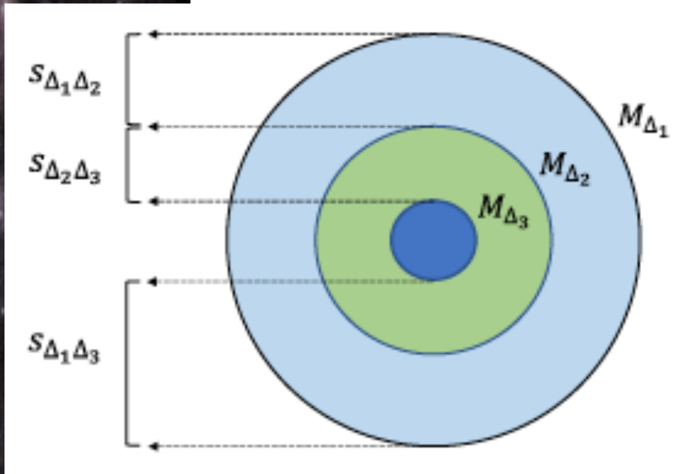
Aquarius Halos

- Halo form inside-out (Onion-like structure)



J. Wang et al. (2011)

Halo Sparsity



Mass Ratio:

$$s_{\Delta_i\Delta_j} = \frac{M_{\Delta_i}}{M_{\Delta_j}} \equiv \frac{\Delta M}{M_{\Delta_j}} + 1$$

- $\Delta_i < \Delta_j$
- $\Delta_i \geq 100$ (preserve halo individuality)
- $\Delta_j \leq 2000$ (avoid baryon dominated region)

Balmes, Rasera, Corasaniti, Alimi (2014)

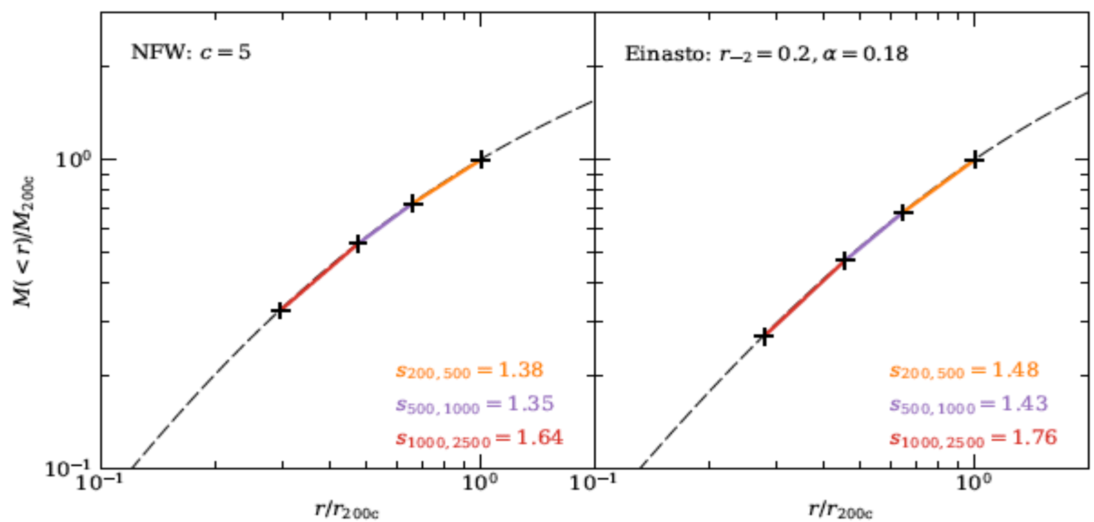
Physical Interpretation:

$$\gamma \equiv \frac{\Delta \ln M}{\Delta \ln R} = \frac{3 \ln s_{\Delta_1\Delta_2}}{\ln(\Delta_2/\Delta_1) + \ln s_{\Delta_1\Delta_2}}$$

- $s_{\Delta_i,\Delta_j} > 1$
- $0 < \gamma < 3$

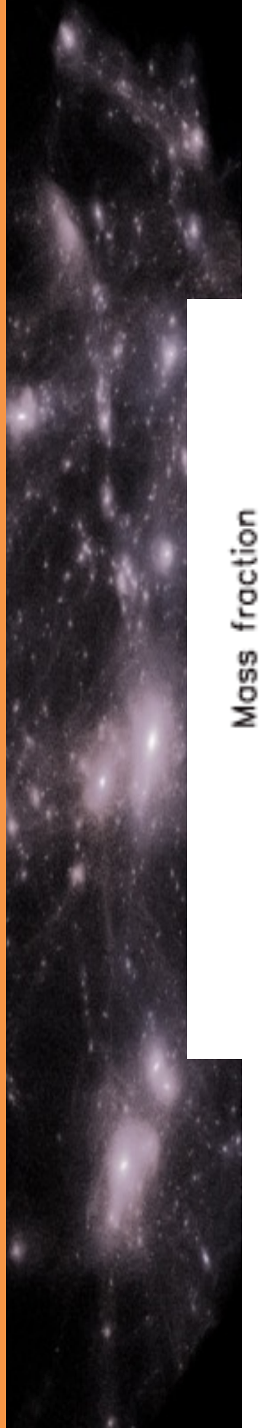
Chain Rule

- $s_{\Delta_2,\Delta_1} = \frac{1}{s_{\Delta_1,\Delta_2}}$
- $s_{\Delta_1,\Delta_2} = \frac{s_{\Delta_1,\Delta_3}}{s_{\Delta_2,\Delta_3}}$

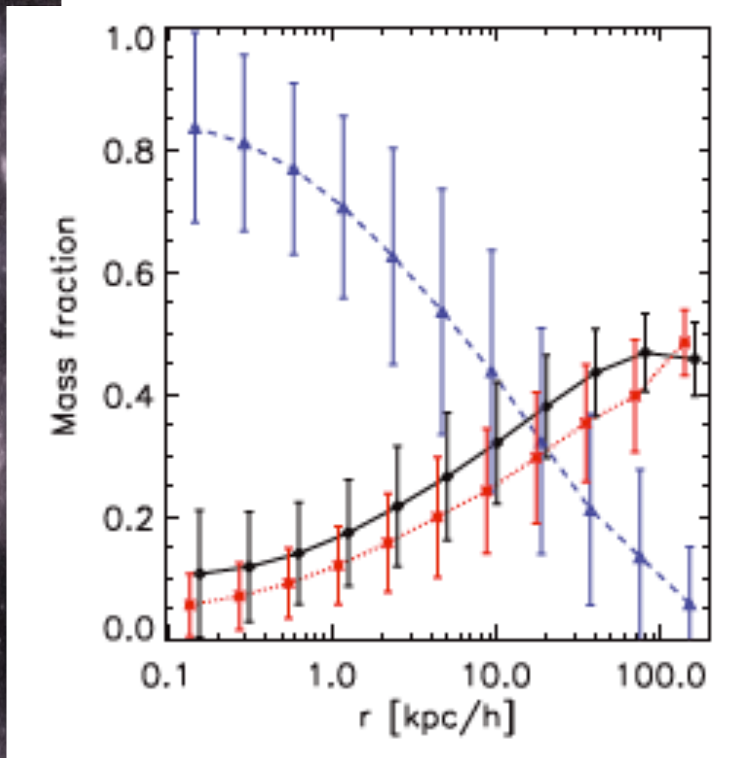


T. Richardson *thesis*

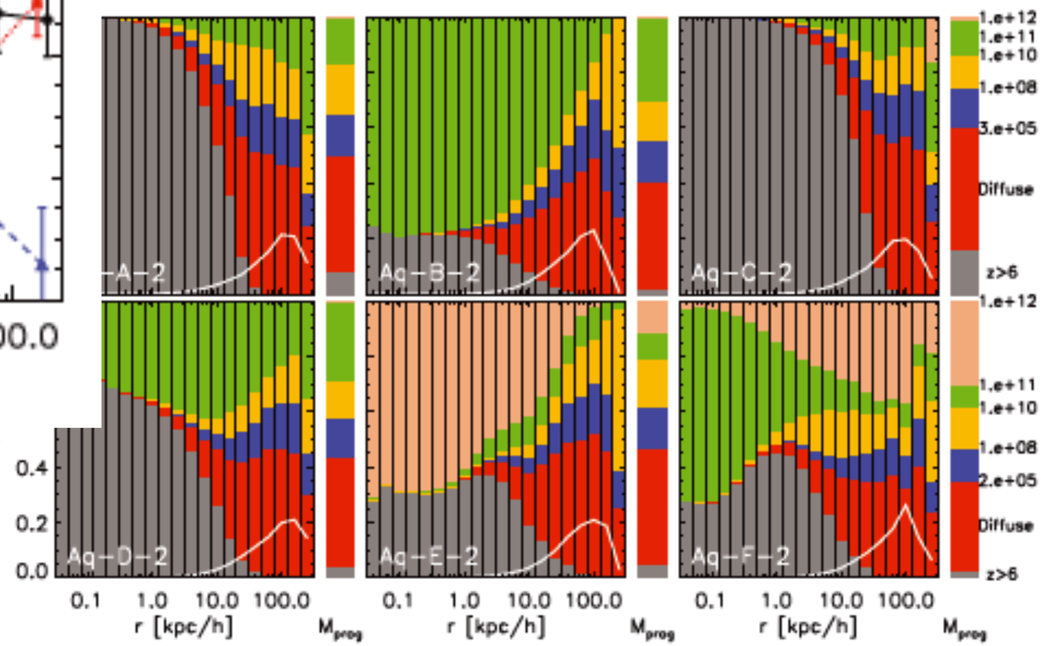
Halo Mass Distribution



Aquarius Halos

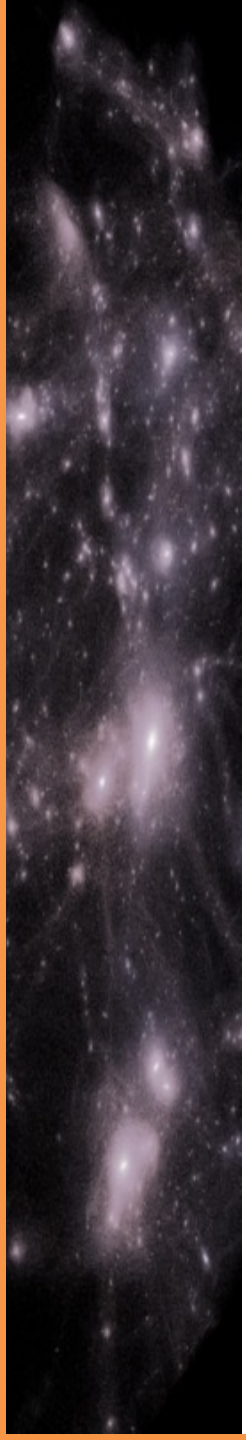


- Major Mergers (~inner regions)
- Diffuse Matter Accretion & Minor Mergers (~external regions)



- Diffuse Matter contributes non-negligibly to final halo mass

J. Wang et al. (2011)



Halo Assembly History

Halo Growth

- Fast Accretion (Major Mergers)
- Slow Smooth Accretion (Minor Mergers & Diffuse Matter)

see e.g. Zhao et al. (2003), Li et al. (2007)

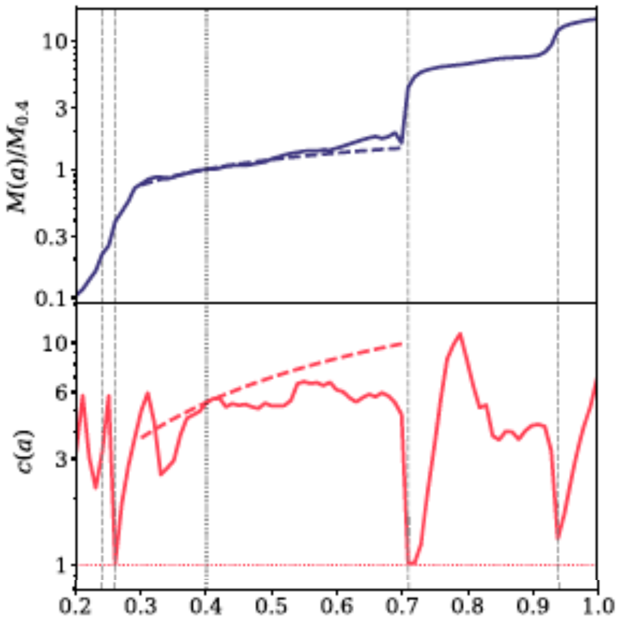
Pseudo-Evolution

- Halo mass evolution due to reference density $M_\Delta(z) = \frac{4}{3}\pi R_\Delta^3(z)\Delta(z)\rho_{\rm ref}(z)$

Diemer, More, Kravtsov (2013)

Slow vs Fast Accretion

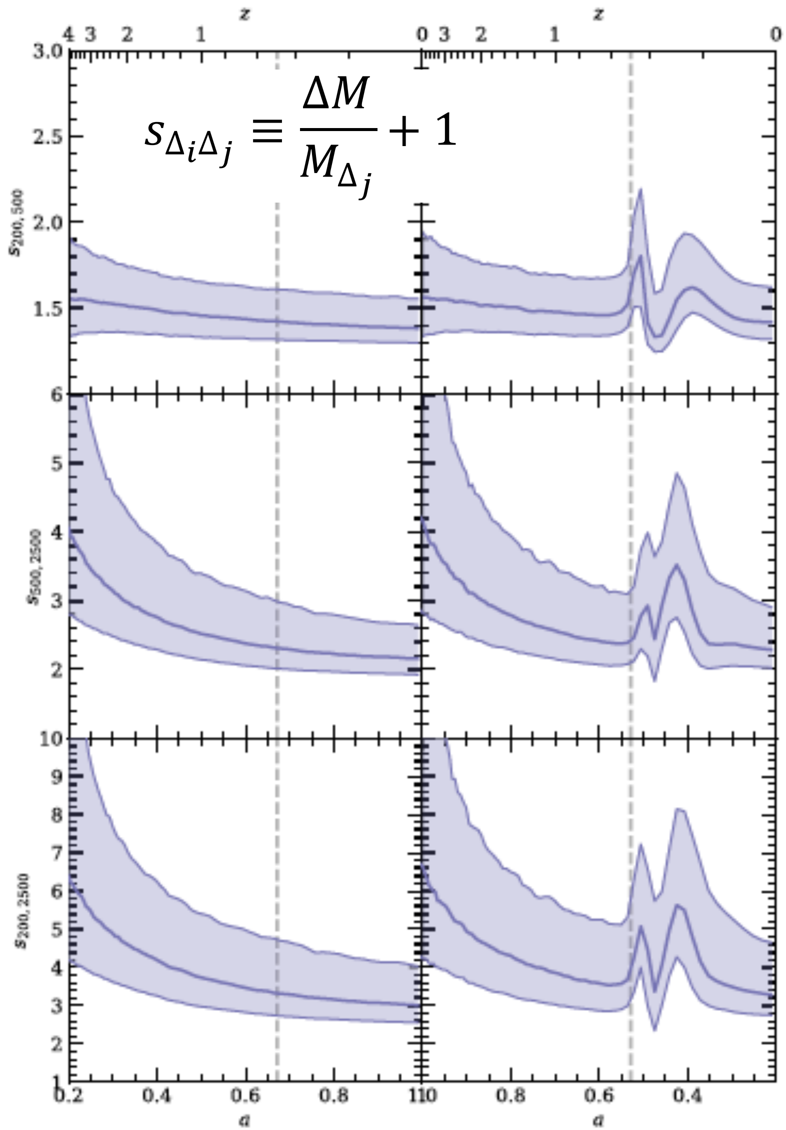
- Concentration deviates from pseudo-evolution
- Scatter due to stochastic minor mergers during slow accretion
- Universal response during major mergers with large excursion



K. Wang et al. (2020)

Halo Sparsity Evolution

Slow vs Pulse-like Evolution (Uchuu Simulations)



$$s_{\Delta_i\Delta_j} \equiv \frac{\Delta M}{M_{\Delta_j}} + 1$$

Quiescent Halos Average Sparsities:

- Nearly Constant Evolution Outer Region
- Decreasing Trend Inner Region

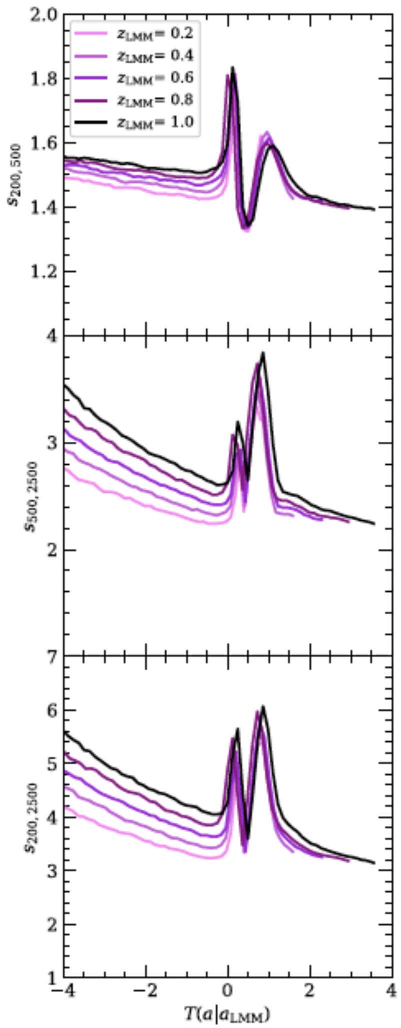
Average Sparsities of Major Mergers z = 0.5:

- Quiescent Evolution Before Merger
- Pulse-like Shape:
  - First Peak = Merger Enters Outer Region
  - First Dip = Merger Arrives Cores
  - Second Peak = Merger within < R_{500c}

Richardson & Corasaniti (2022)

Major Merger Response

Universality



- Identical Behavior (in units of dynamical time)

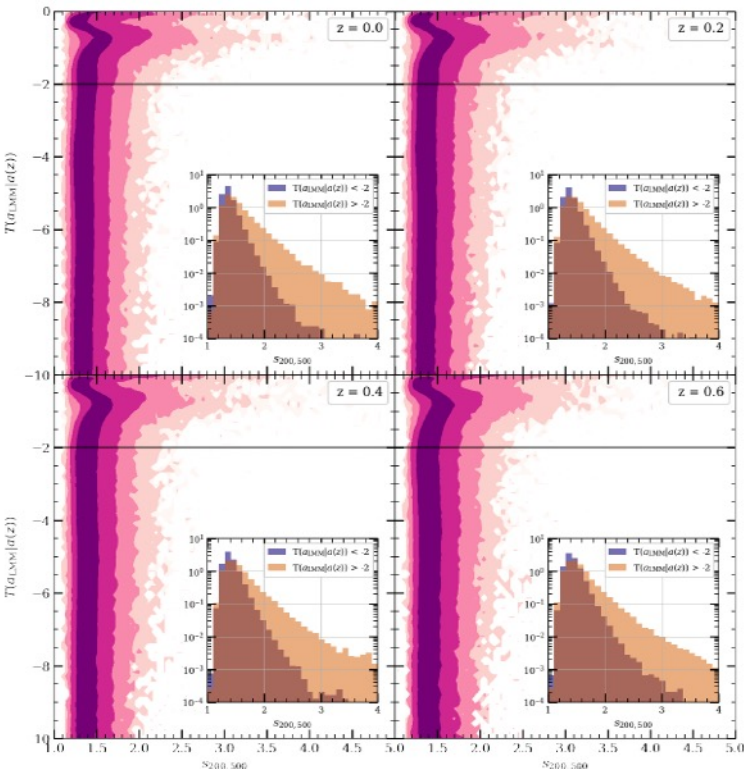
$$T(z; z_{\rm LMM}) = \frac{\sqrt{2}}{\pi}\int_{z_{\rm LMM}}^{z}\frac{\sqrt{\Delta_{\rm vir}(z)}}{z+1}dz$$

see also Wang et al. (2020) for concentration

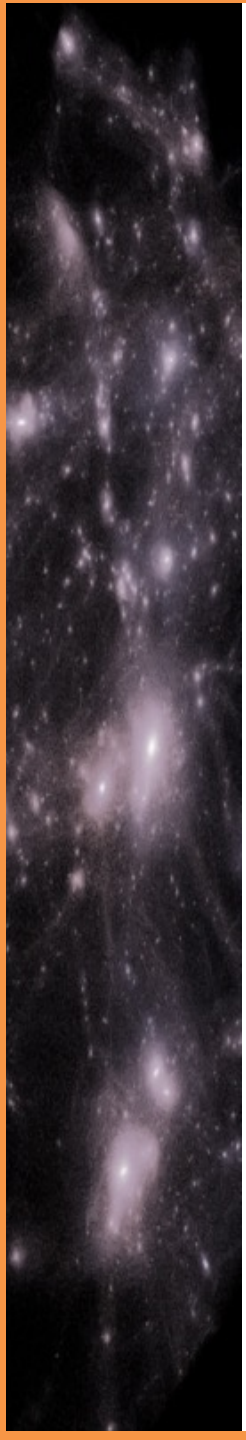
- Quiescent Evolution Recovered t > 2T

- Halo Population:

- Perturbed Halos (<2T from last major merger)
- Contribute to scatter in sparsity
- Quiescent Halos

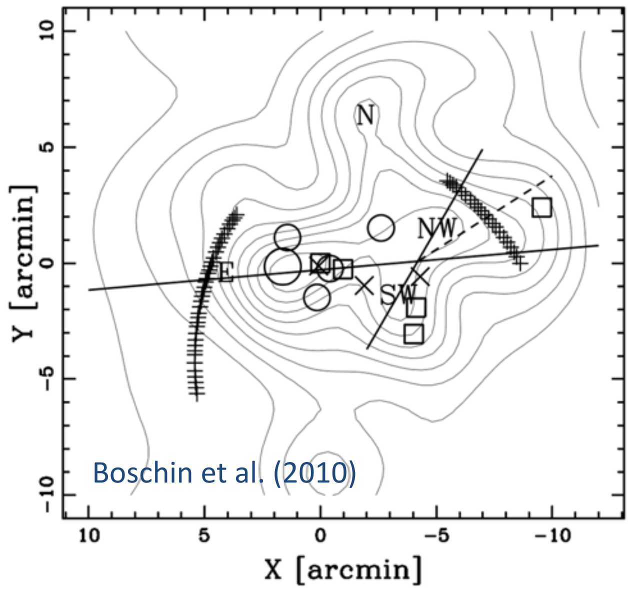


Richardson & Corasaniti (2022)



ABELL 2345

Lensing & Radio Relics



- Redshift z = 0.176
- Lensing Masses (10^{13} M_{sun}/h)

M_{2500c} = 0.32 ± 0.12 Okabe et al. (2010)
M_{500c} = 6.52 ± 2.47
M_{200c} = 28.44 ± 10.76

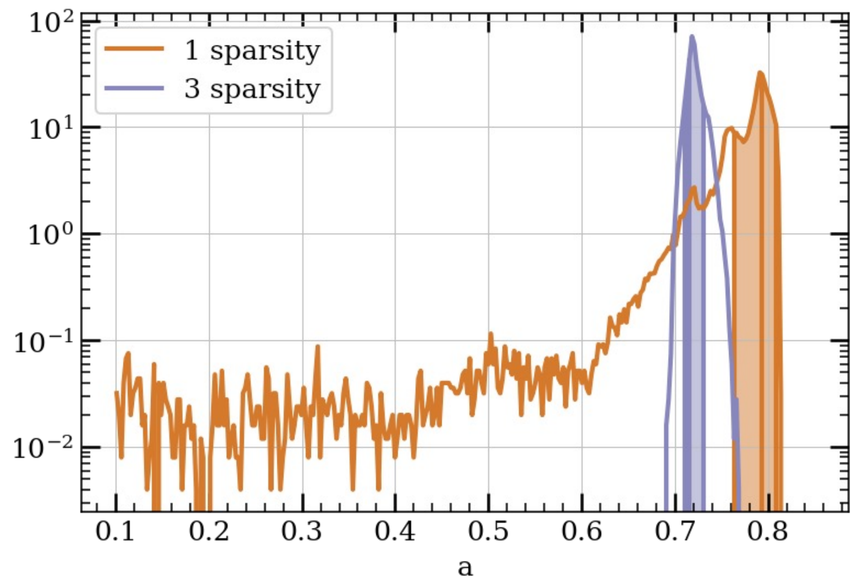
- Sparsities: $s_{200,500}$ = 4.26 ± 2.33
$s_{200,2500}$ = 87.50 ± 46.83
$s_{500,2500}$ = 20.06 ± 10.93

- Uchuu Simulations Calibrated Distributions
- Timing the merger event:

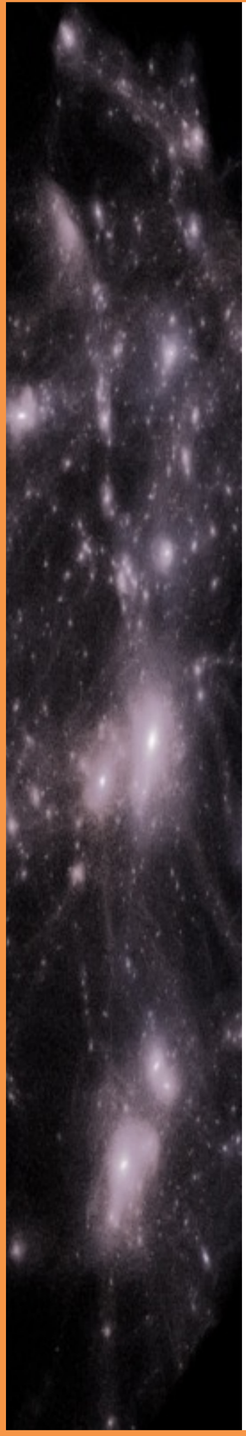
$$z_{LMM} = 0.396 \pm^{0.01}_{0.03}$$

$$|T| = 0.86\ \tau_{dyn}$$

$$\tilde{t}_{LMM} = 2.14 \pm^{0.08}_{0.2}\ \text{Gyr (LCDM)}$$



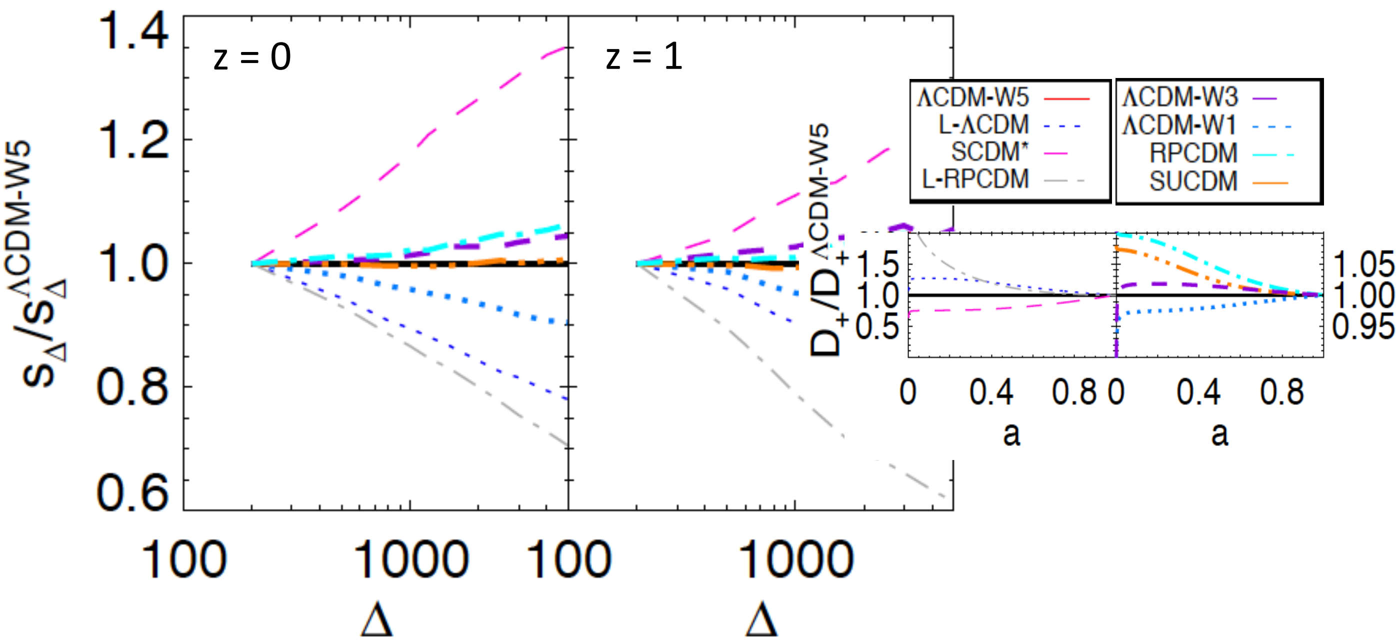
https://gitlab.obspm.fr/trichardson/lammas



Cosmological Imprint

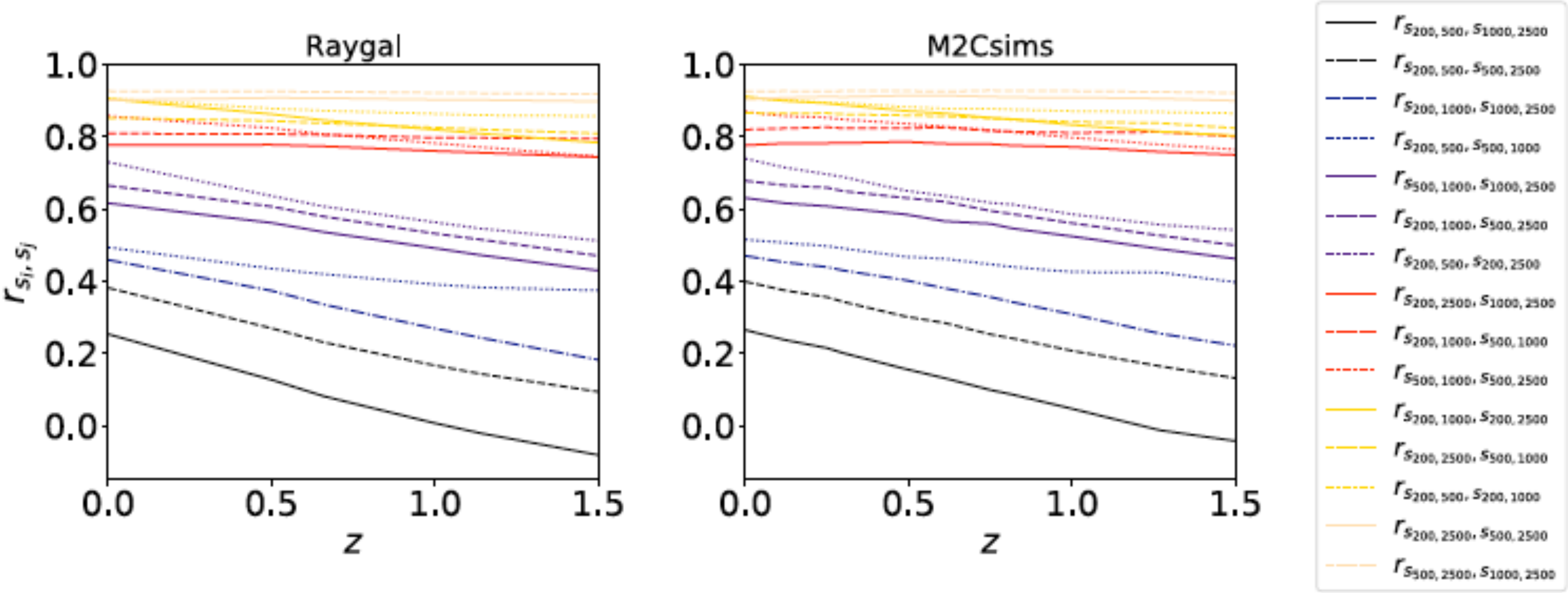
Average Sparsity

- Cosmological signal increases for $\Delta_2 >> \Delta_1$
- Sparsity evolution correlates with linear growth history
- The earlier the formation of structures the smaller the sparsity



Balmes, Rasera, Corasaniti, Alimi (2014)

Sparsity Correlations



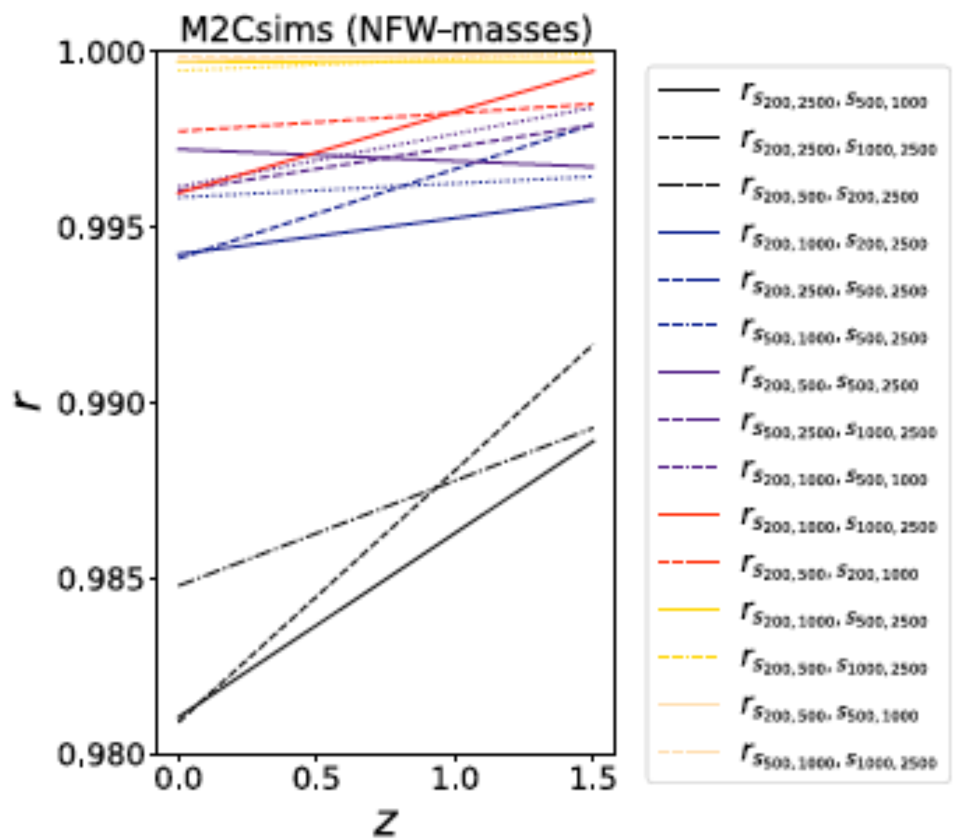
- Correlations increases at lower redshift (consistent with halo mass assembly process)
- Sparsities probing distant halo shells have low correlations (inner vs outer region)
- Expected from mass accretion history (inner region contains mass from major merger events, outer from minor and diffuse matter accretion)

Corasaniti, Le Brun, Richardson et al. (2022)

NFW-induced Correlations

Sparsity of NFW Halos

$$s_\Delta = \frac{200}{x^3 \Delta} \quad \& \quad x^3 \frac{\Delta}{200} = \frac{\ln(1+cx) - \frac{cx}{1+cx}}{\ln(1+c) - \frac{c}{1+c}}$$

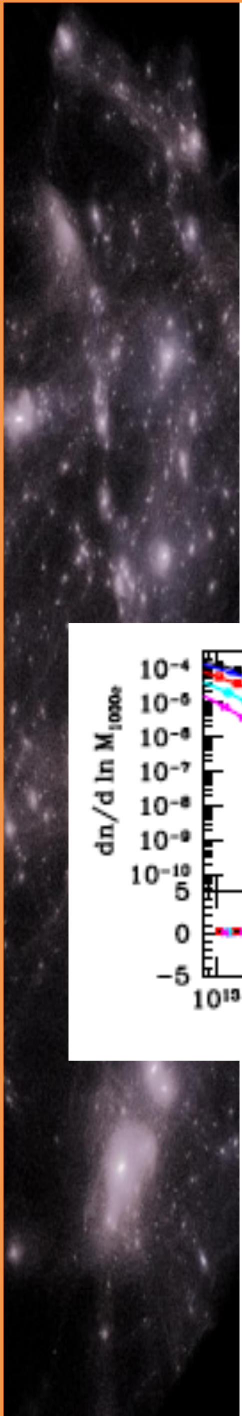


Corasaniti, Le Brun, Richardson et al. (2022)

- Best-fit M2Csims halos at given z with NFW
- Estimate corresponding sparsities halo by halo
- Compute correlations among NFW halo sparsities at given redshift

Results

- Assuming NFW suppress information encoded in different halo mass shells
- Impose Spurious Correlations: r ~1
- There is more information on the halo mass profile than encoded in the NFW profile

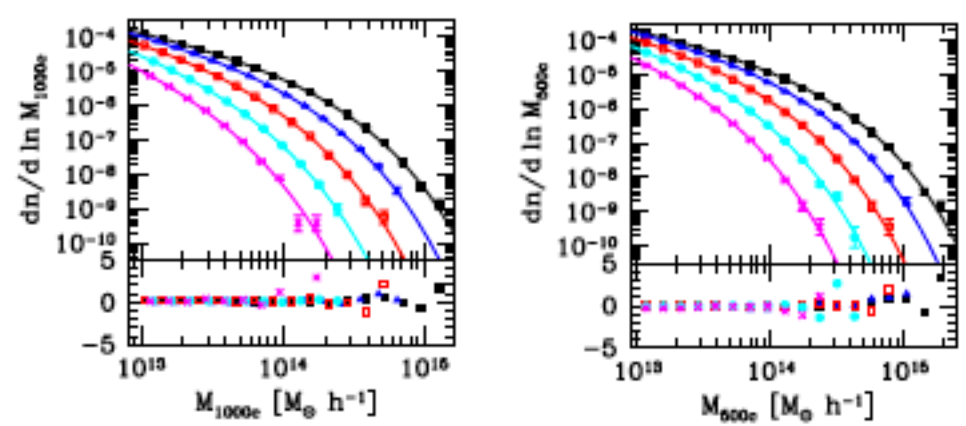


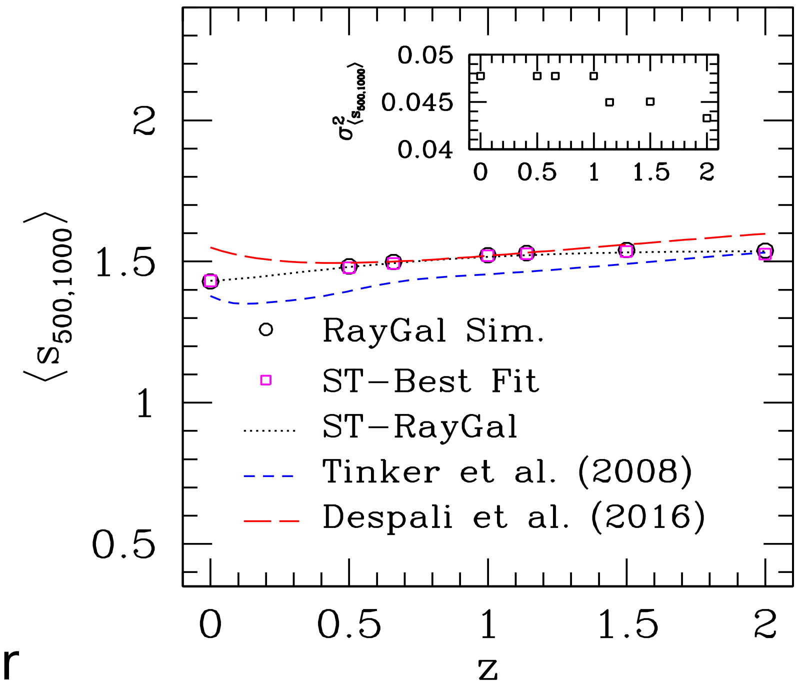
Average Halo Sparsity

Sparsity – Mass Function Relation

$$\frac{dn}{dM_{\Delta_2}} = s_{\Delta_1\Delta_2}\frac{dn}{dM_1}\frac{dlogM_1}{dlogM_{\Delta_2}} \rightarrow \int_{M_{\Delta_2}^{min}}^{M_{\Delta_2}^{max}} \frac{dn}{dM_{\Delta_2}} d\ln M_{\Delta_2} = \langle s_{\Delta_1,\Delta_2}\rangle \int_{\langle s_{\Delta_1,\Delta_2}\rangle M_{\Delta_2}^{min}}^{\langle s_{\Delta_1,\Delta_2}\rangle M_{\Delta_2}^{max}} \frac{dn}{dM_{\Delta_1}} d\ln M_{\Delta_1}$$

- N-body Calibrated Halo Mass Functions at Δ_1 and Δ_2

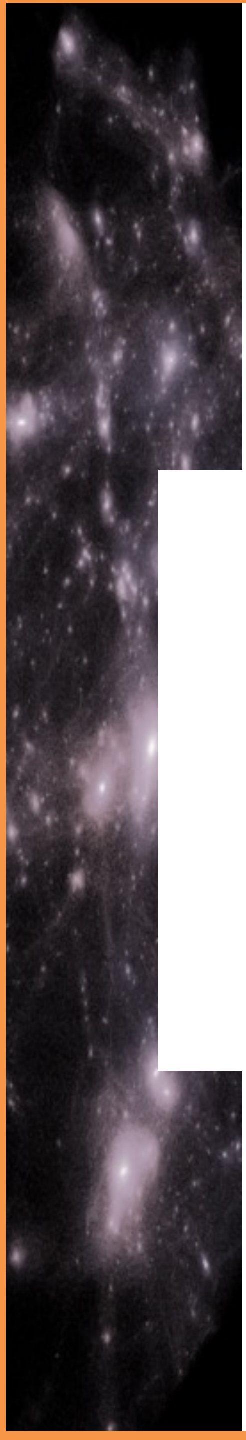




- Accurate to sub-percent level
- Quantitative Framework for Cosmological Model Predictior

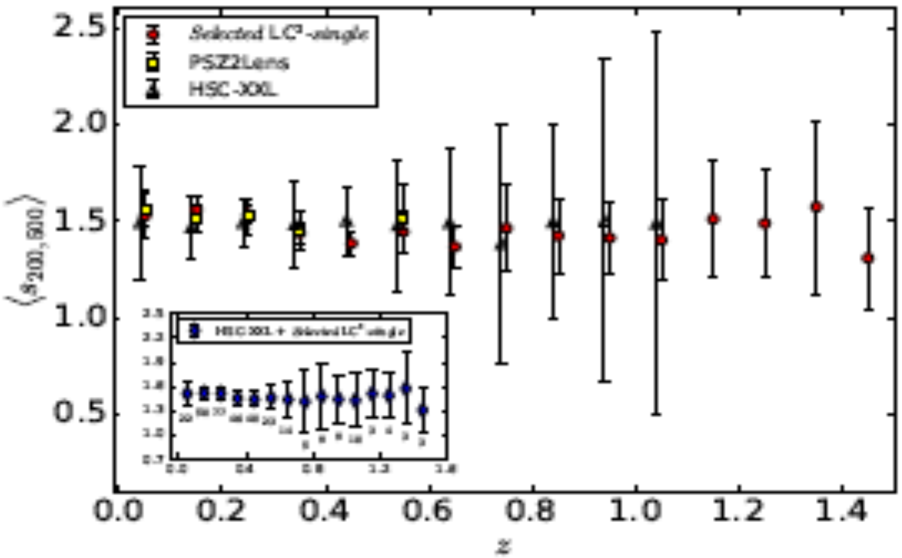
Corasaniti et al. (2018)

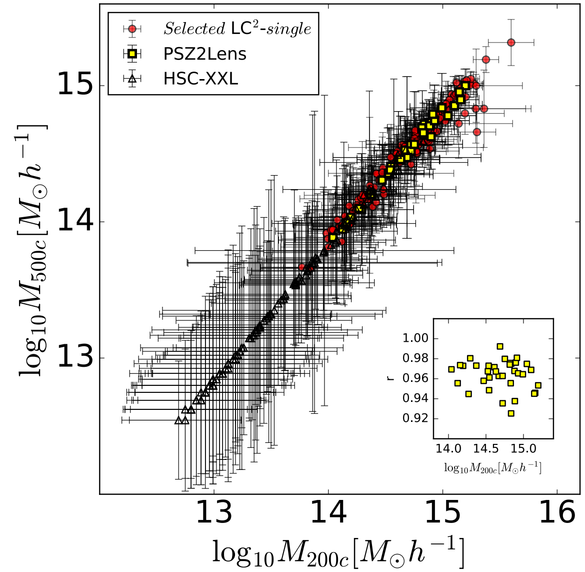
Cosmological Parameter Analysis



Sparsity Cosmological Sample

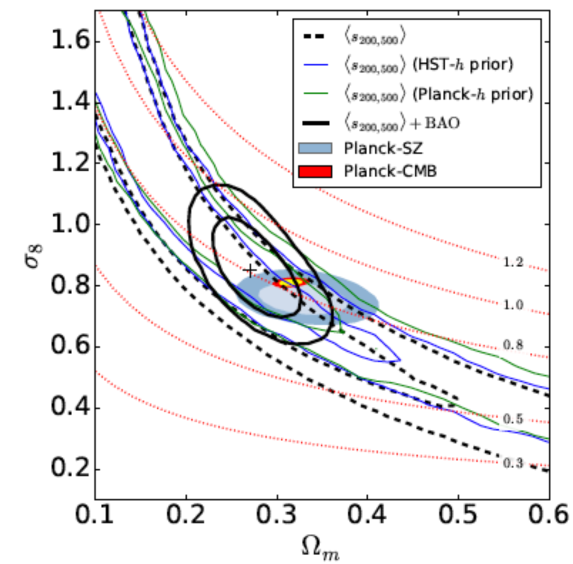
- *Selected* LC^2-*single* (317 ⊃ PSZ2Lens) + HSC-XXL (136, z<1.03)
- $0 < z < 1.5$; $M_{200c} > 10^{13}\ M_{sun}\ h^{-1}$





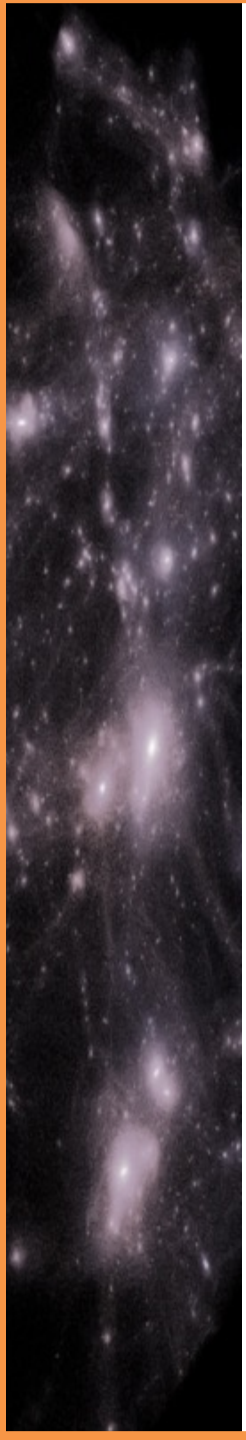
Constraints

- $S_8 = 0.75 \pm 0.20$
- $S_8 = 0.80 \pm 0.18$ (HST-prior)
- $S_8 = 0.82 \pm 0.16$ (Planck h-prior)

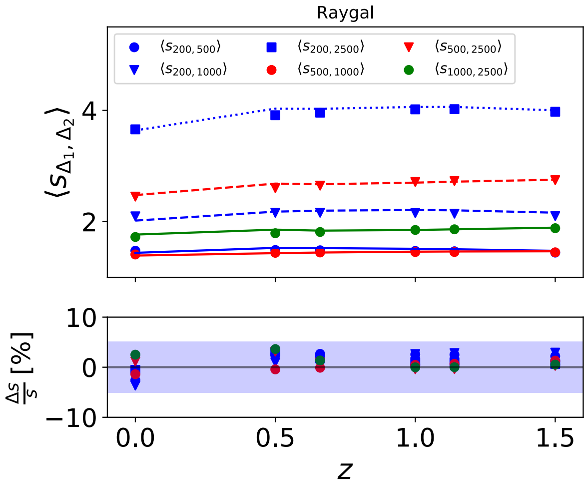


Corasaniti, Sereno & Ettori (2021)

Multiple Sparsity Measurements



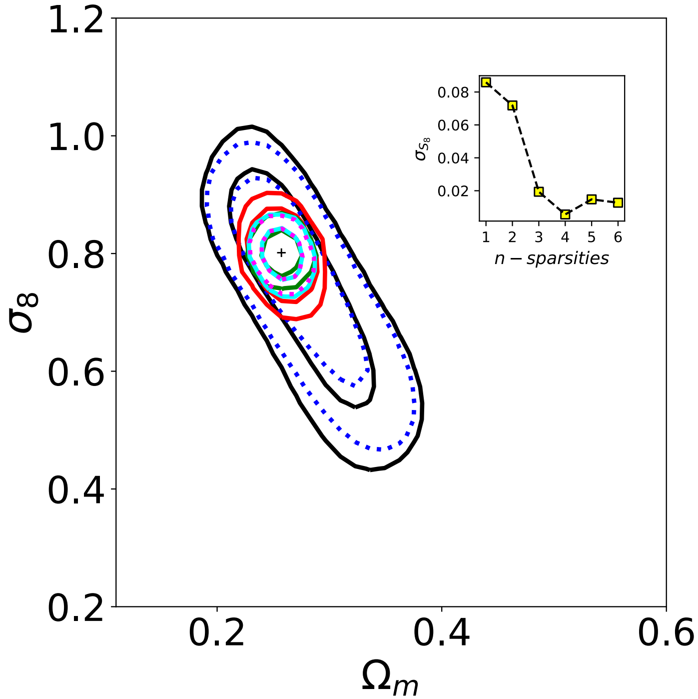
Non-Parametric Cluster Mass Estimates



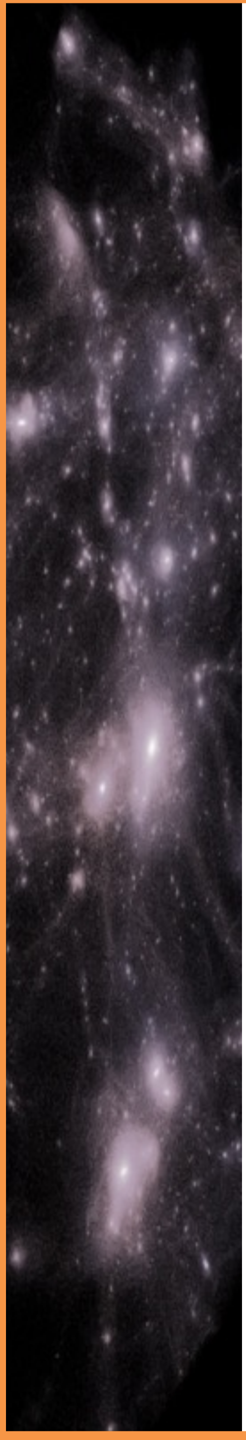
- Mass Estimates Δ = 200, 500, 1000, 2500
- N_s = 6 sparsities
- Correlations + Propagation of theoretical model errors

MCMC Analysis

- Additional sparsities break S_8 degeneracy
- Constraints saturate at N_s = 4
- Practically requires mass measurements beyond 2-parameter profile fit

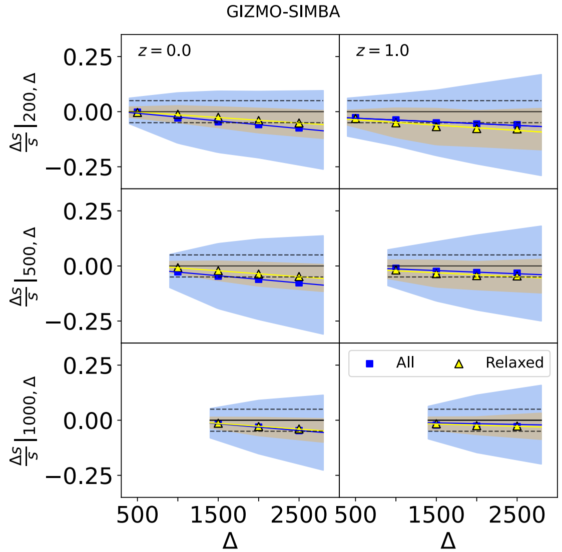


Corasaniti, Le Brun, Richardson, Rasera, Pratt, Arnaud (2022)

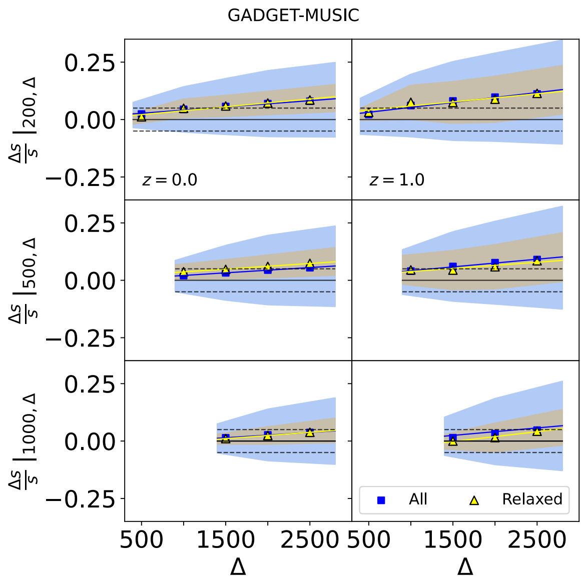


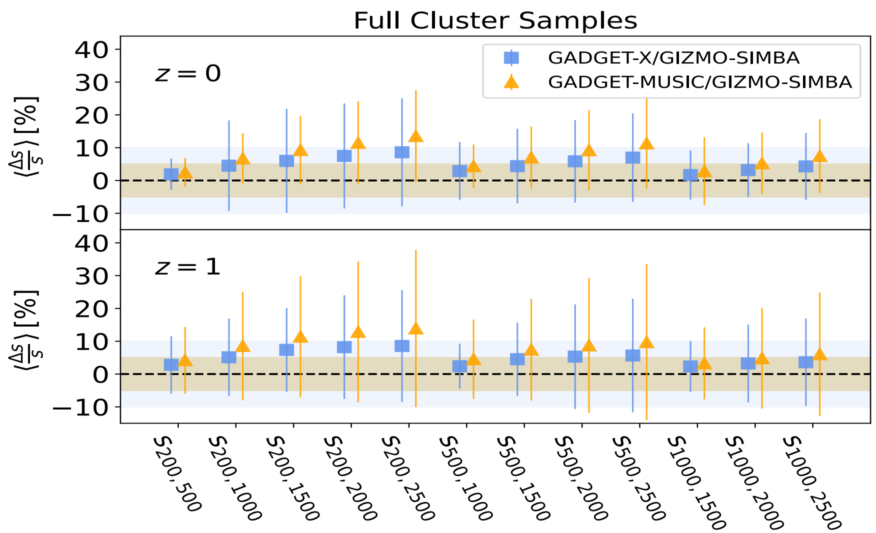
What about Baryons?

The300 Simulations



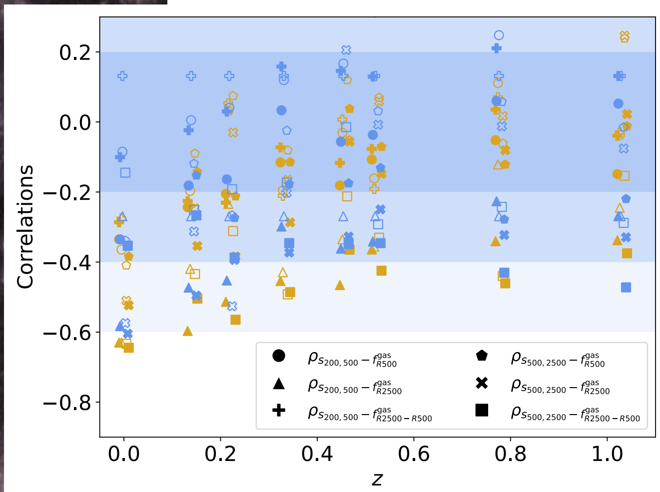
- 324 Most Massive Clusters from MDPL2
- 3 Hydro (2 AGN, 1 no-AGN) and 1 DM-Only Runs
- $(s_{DM\text{-}Only} - s_{Hydro}) / s_{DM\text{-}Only}$
- < 5% in external cluster regions & contiguous shells
- inner regions sensitive to baryon feedback





Probing Cluster Astrophysics

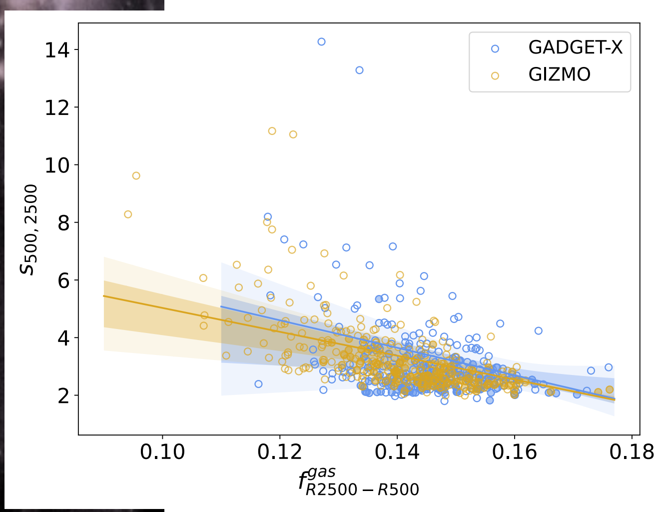
Sparsity vs Gas Fraction



- weakly correlated $s_{200,500}$ and f_{500}

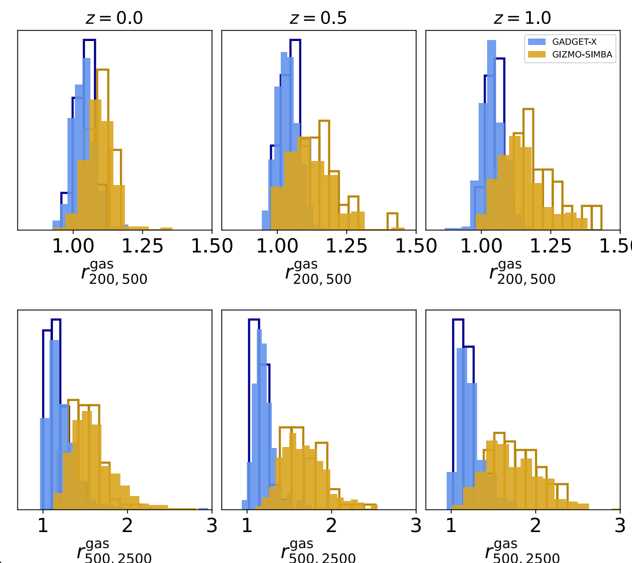
- strongly to moderately correlated $s_{500,2500}$ and $f_{R2500-R500}$

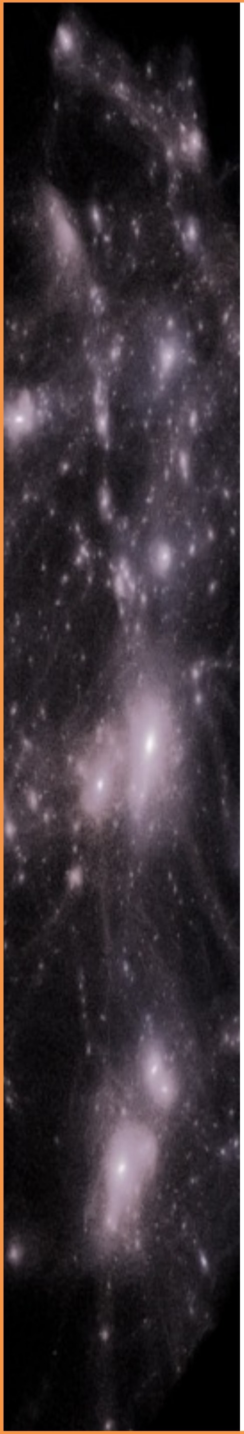
- test presence of AGN feedback



- gas mass fraction ratio bias probe of sparsity $r = f_{200}/f_{500} = s_{gas} / s_{tot}$

- probe AGN feedback scenario





Conclusions

- Non-parametric Probe of Halo Mass Assembly History
- Capture Information Beyond Concentration Parameter
- Minimal Systematics
- Observational Proxy of Cluster Cosmology and Astrophysics