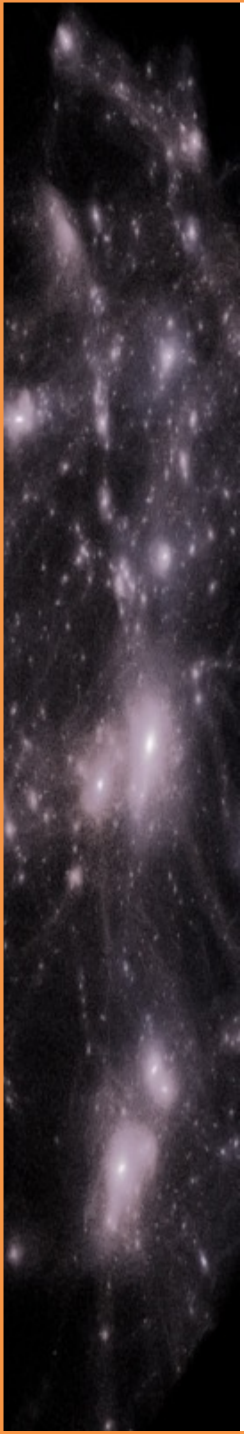


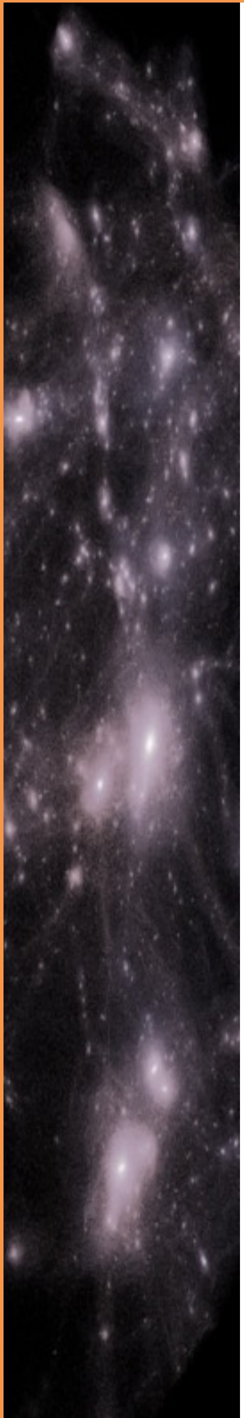
Cosmological Constraints from Galaxy Cluster Mass Profiles

Pier Stefano Corasaniti

CNRS and Observatoire de Paris

AstroParticle Symposium 2022

Institut Pascal – 09/11/22



Why and How ?

Bibliography:

Balmes et al., MNRAS, 437, 2328 (2014)

Corasaniti, Ettori et al., ApJ, 862, 40 (2018)

Corasaniti & Rasera, MNRAS, 487, 4382 (2019)

Corasaniti, Giocoli, Baldi, PRD, 102, 043501 (2020)

Corasaniti, Sereno, Ettori, ApJ, 911, 82 (2021)

Richardson & Corasaniti, MNRAS, 513, 4951 (2022)

Corasaniti, Le Brun, Richardson et al., MNRAS, 516, 427 (2022)

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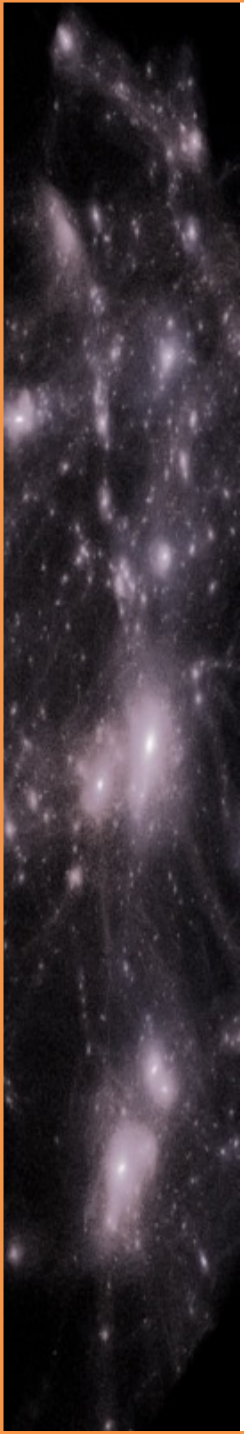


Galaxy Cluster Cosmology

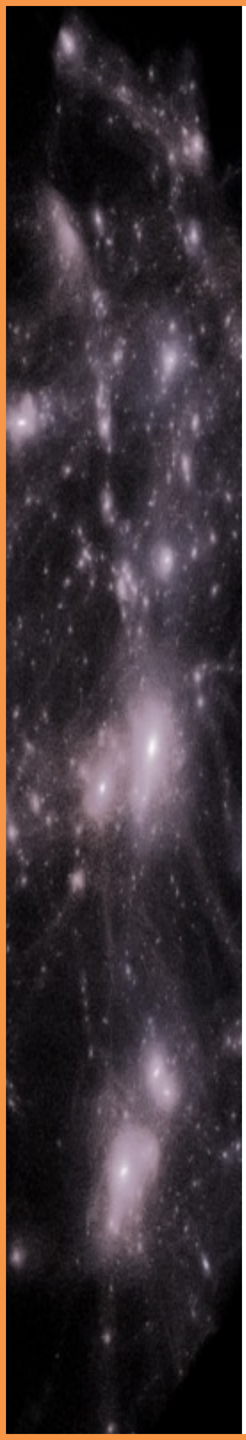
Cosmic Probes

- Largest Most Massive Structures in the Universe

- Ultimate Result of Hierarchical Bottom-Up Structure Formation Process

- X-ray, SZ, Optical & Near-IR

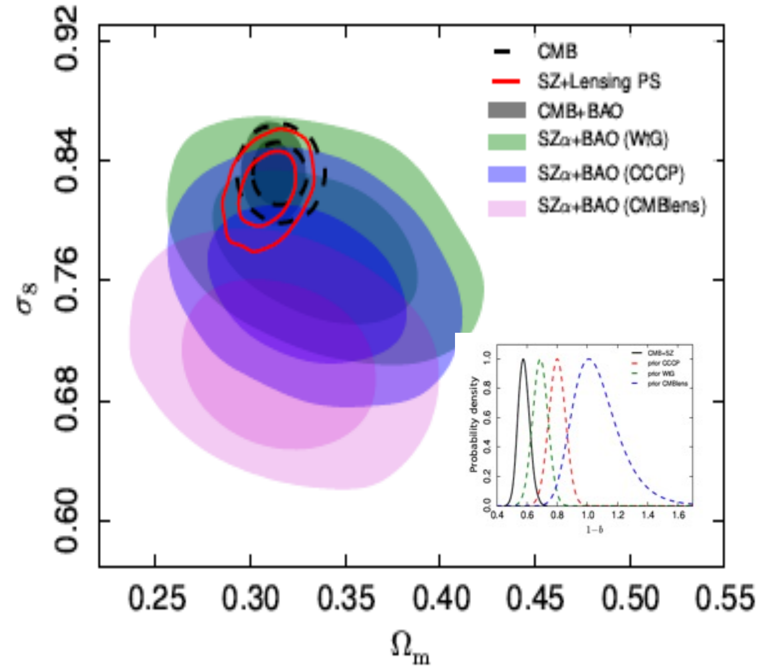
- Cluster Abundance, Baryon Fraction, Spatial Clustering & Internal Mass Distribution



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)



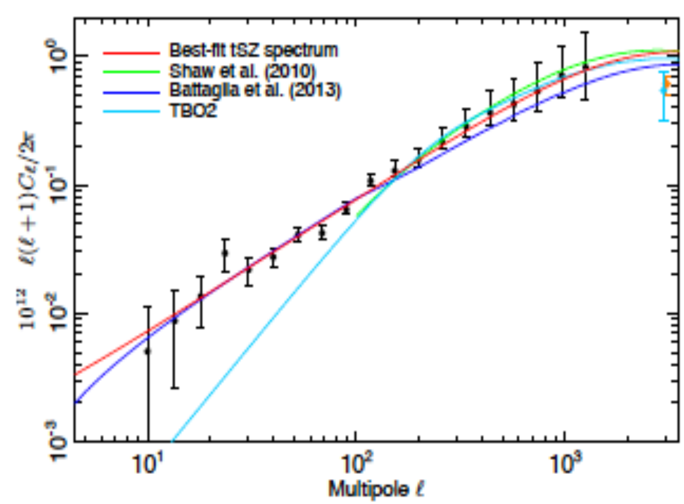
Baryon Fraction

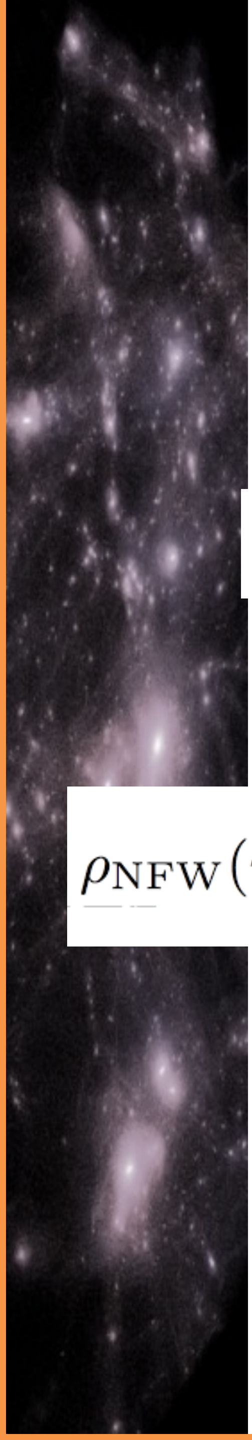
- $f_{gas} = M_{gas}/M_{tot} \sim f_{baryon} = \Omega_b / \Omega_m$
- Primary Systematics: Mass Calibration Bias, Gas Depletion

Spatial Clustering

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

Planck Collaboration (2016)





NFW-Profile

Universal Profile

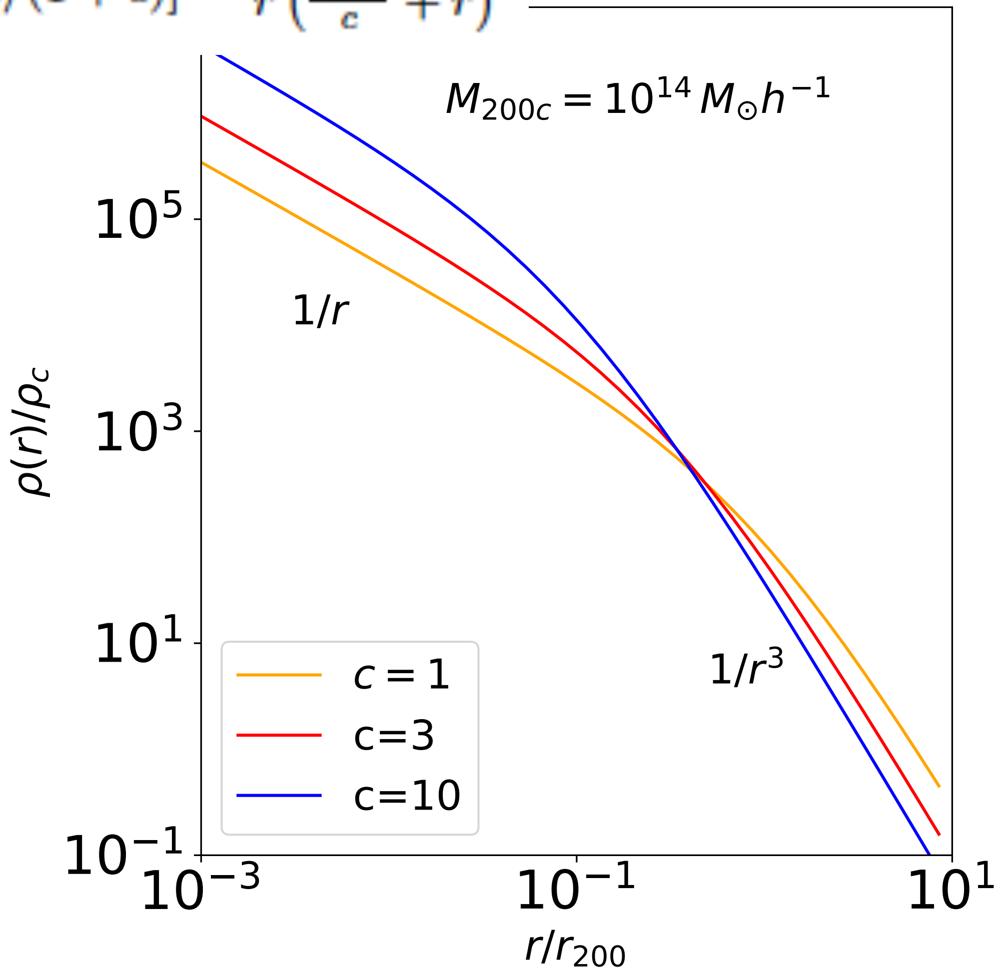
$$\rho_{\rm NFW}(r) = \frac{M_{200}}{4\pi[\ln(1+c) - c/(1+c)]} \times \frac{1}{r\left(\frac{r_{200}}{c} + r\right)^2}$$

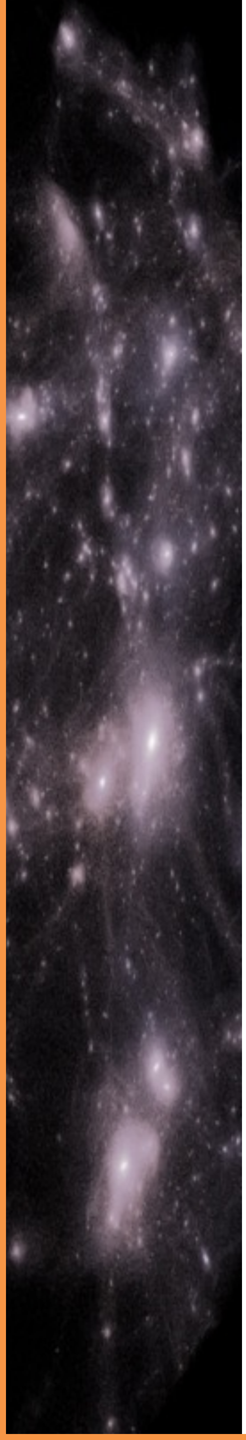
$$c = \frac{r_{200}}{r_s}$$

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





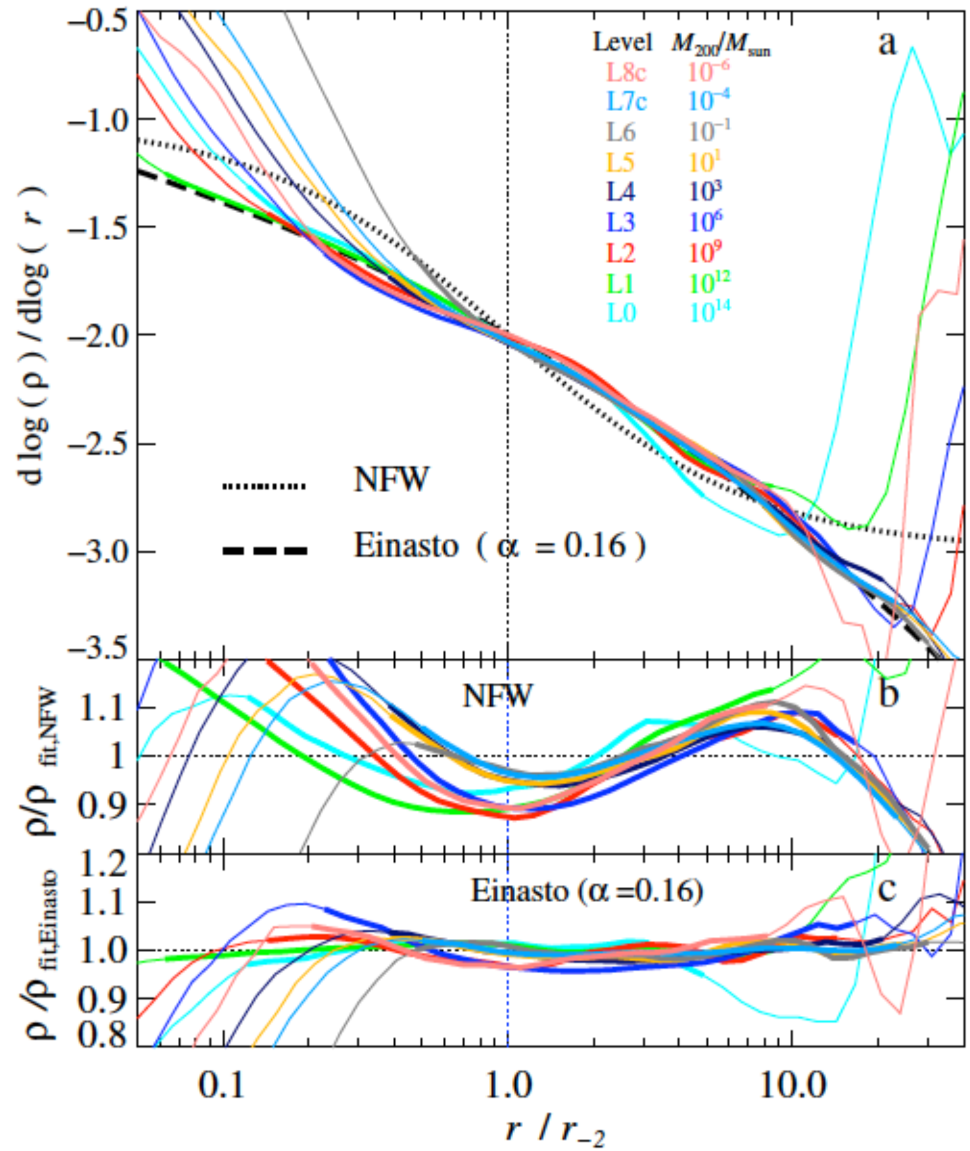
Universality of Halo Profile

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

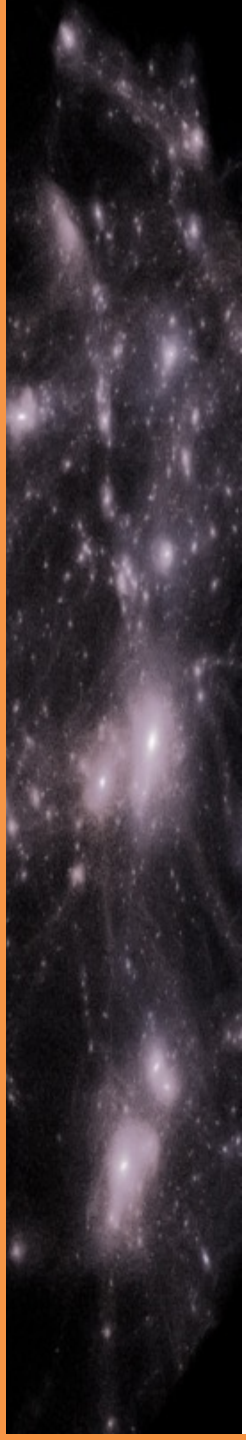
  - NFW (< 10%)
  - Einasto (< 5%)

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

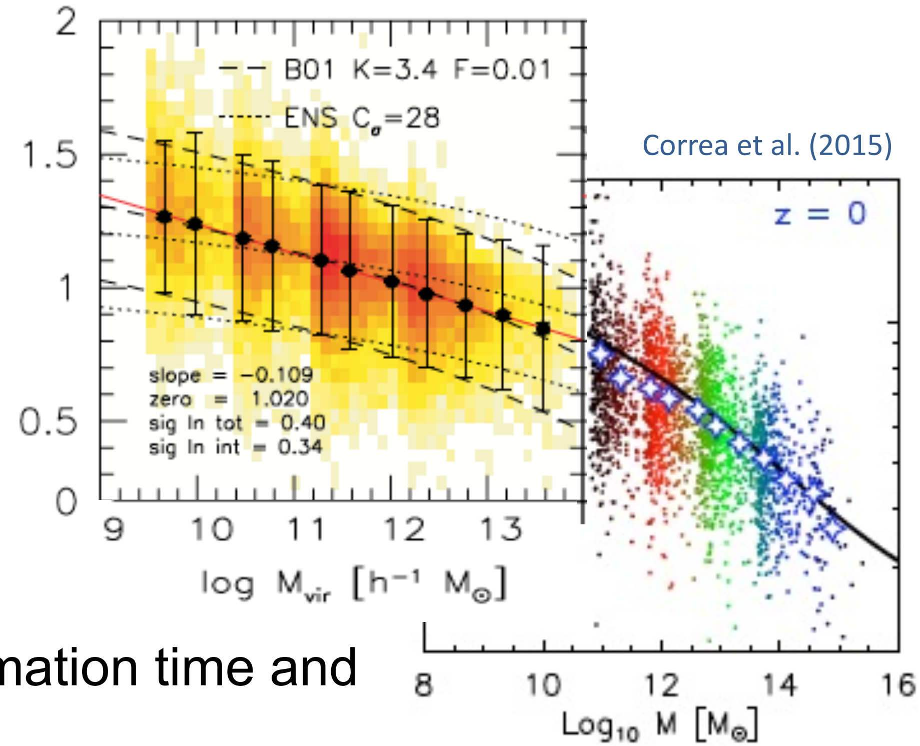
$\sigma_{\ln c}$ ~ 0.3 (large)

- 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)

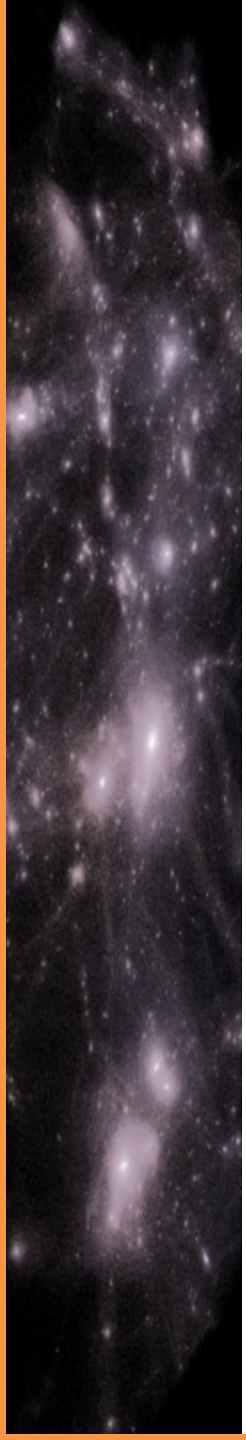


Cosmology

- 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

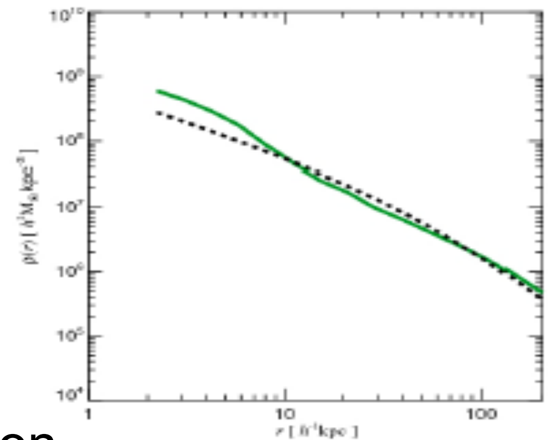
Systematic Effects

- 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)

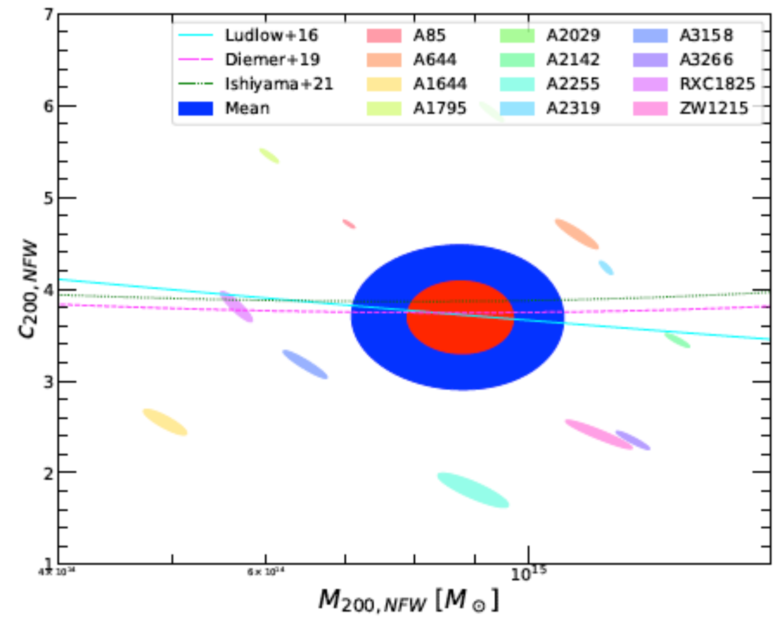
- Selection Effects
  Sereno et al. (2014)



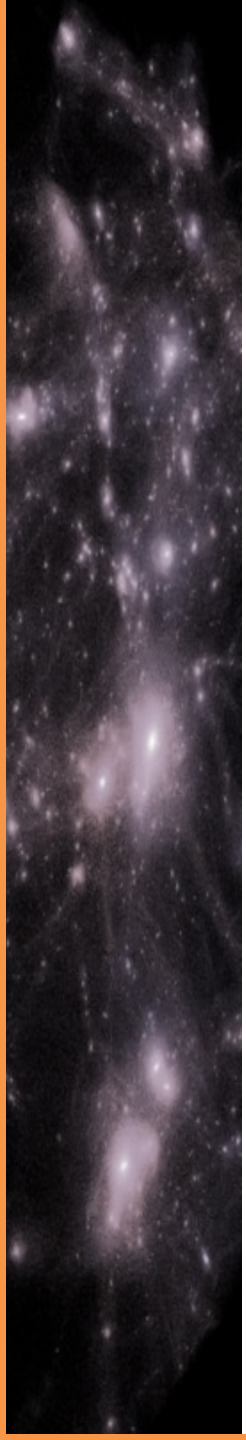
Mead et al. (2010)

X-COP Concentrations

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

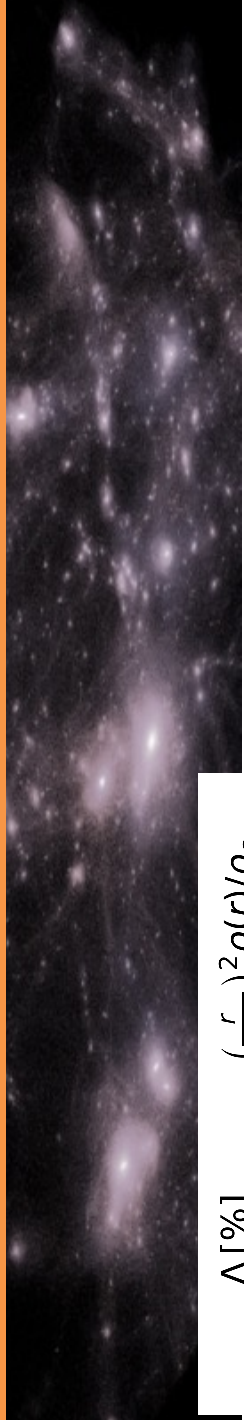


Eckert, Ettori, Pointecouteau, van der Bourg, Loubser (2022)



Claim

There is cosmological and astrophysical information encoded in the mass profile of halos which goes beyond what is parametrized by the NFW profile!

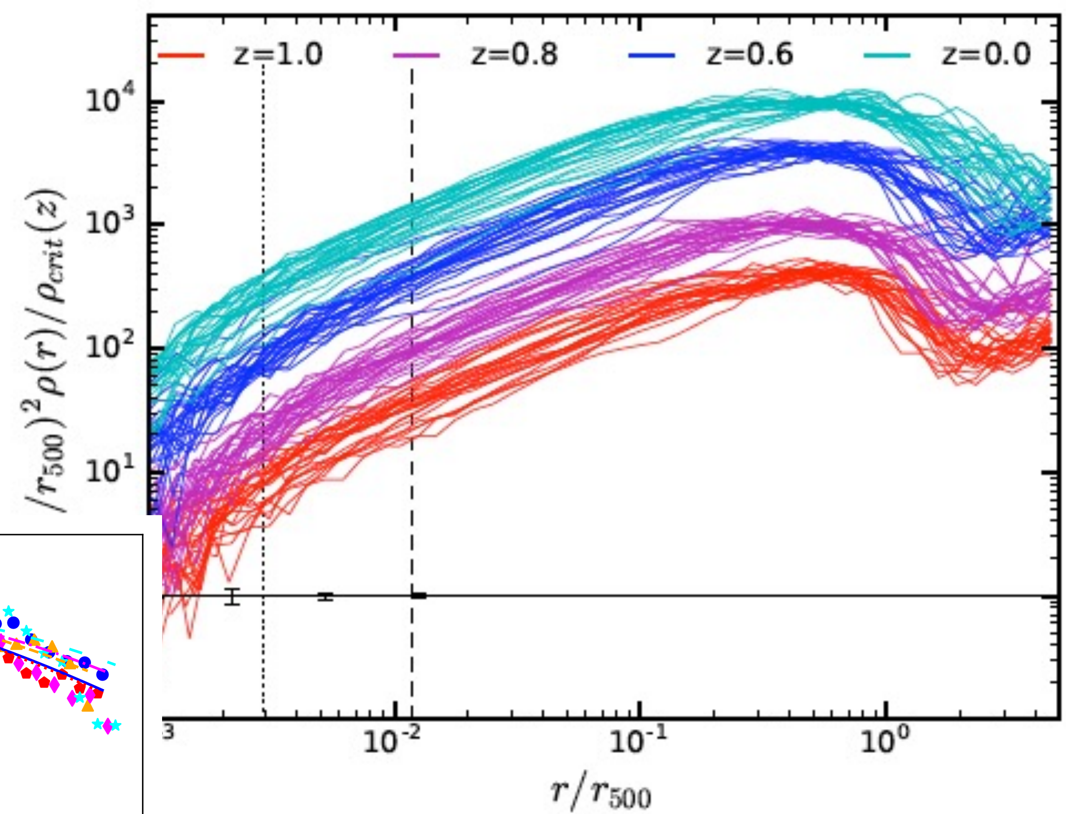


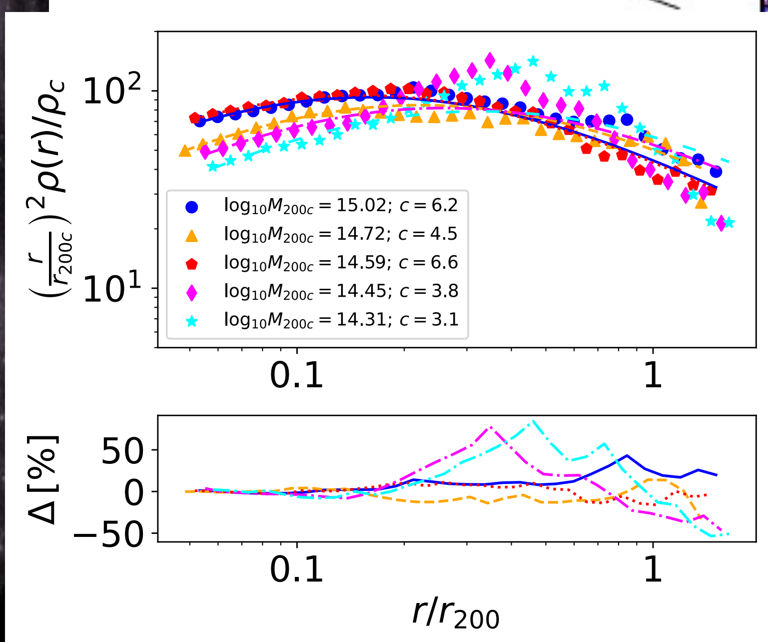
N-body Halo Profiles

Perturbed Profile

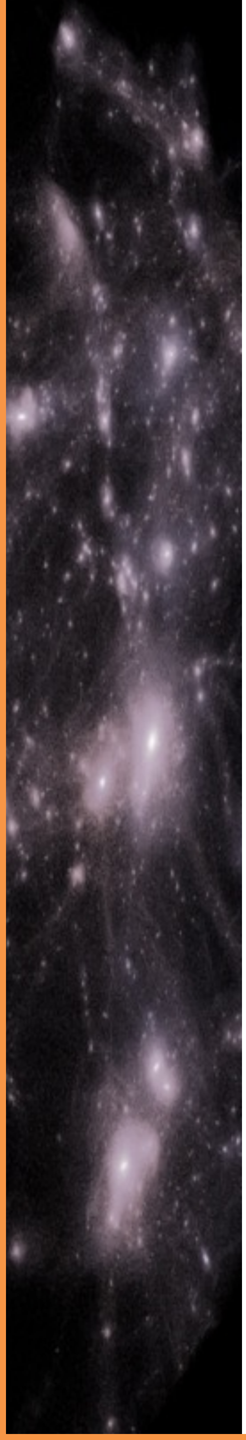
- Zooms of 25 massive halos ~10^{15} M_{sun} h
- Negligible Poisson Errors
- Scatter: sub-structures and perturbed state

Le Brun et al. (2018)



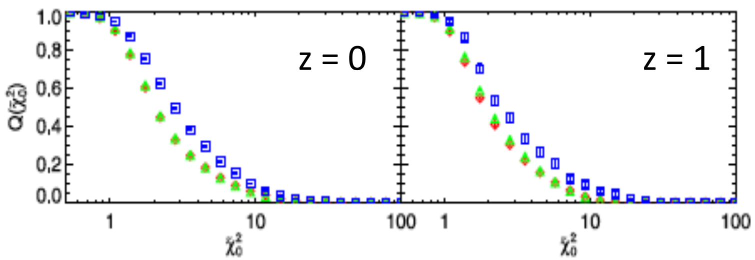


- Five most massive Bolshoi halos
- Deviations ~10% relaxed halos
- Impact NFW goodness-of-fit



Perturbed Halo Profiles

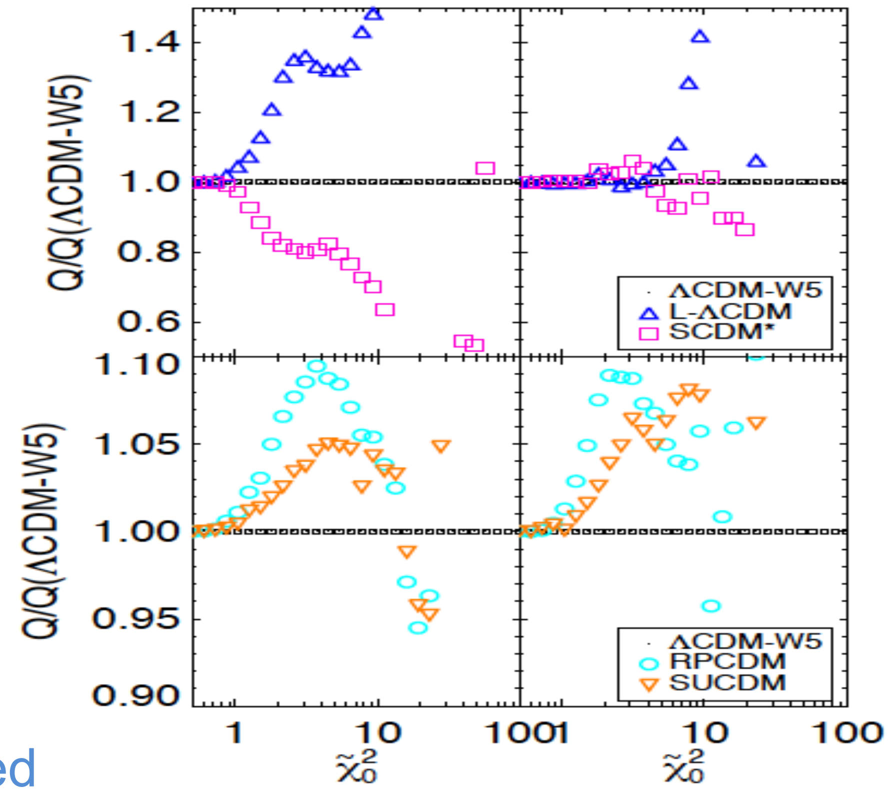
NFW Goodness-of-fit



- 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

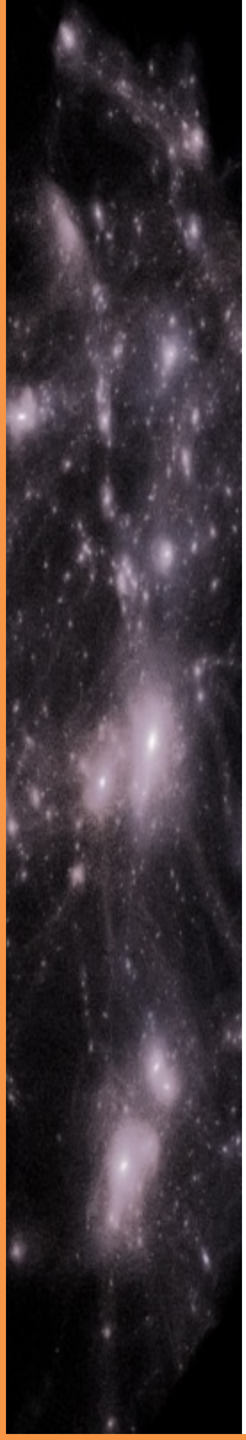


Non-parametric proxy needed

Balmes, Rasera, Corasaniti, Alimi (2014)

Proxy of Halo Mass Profile

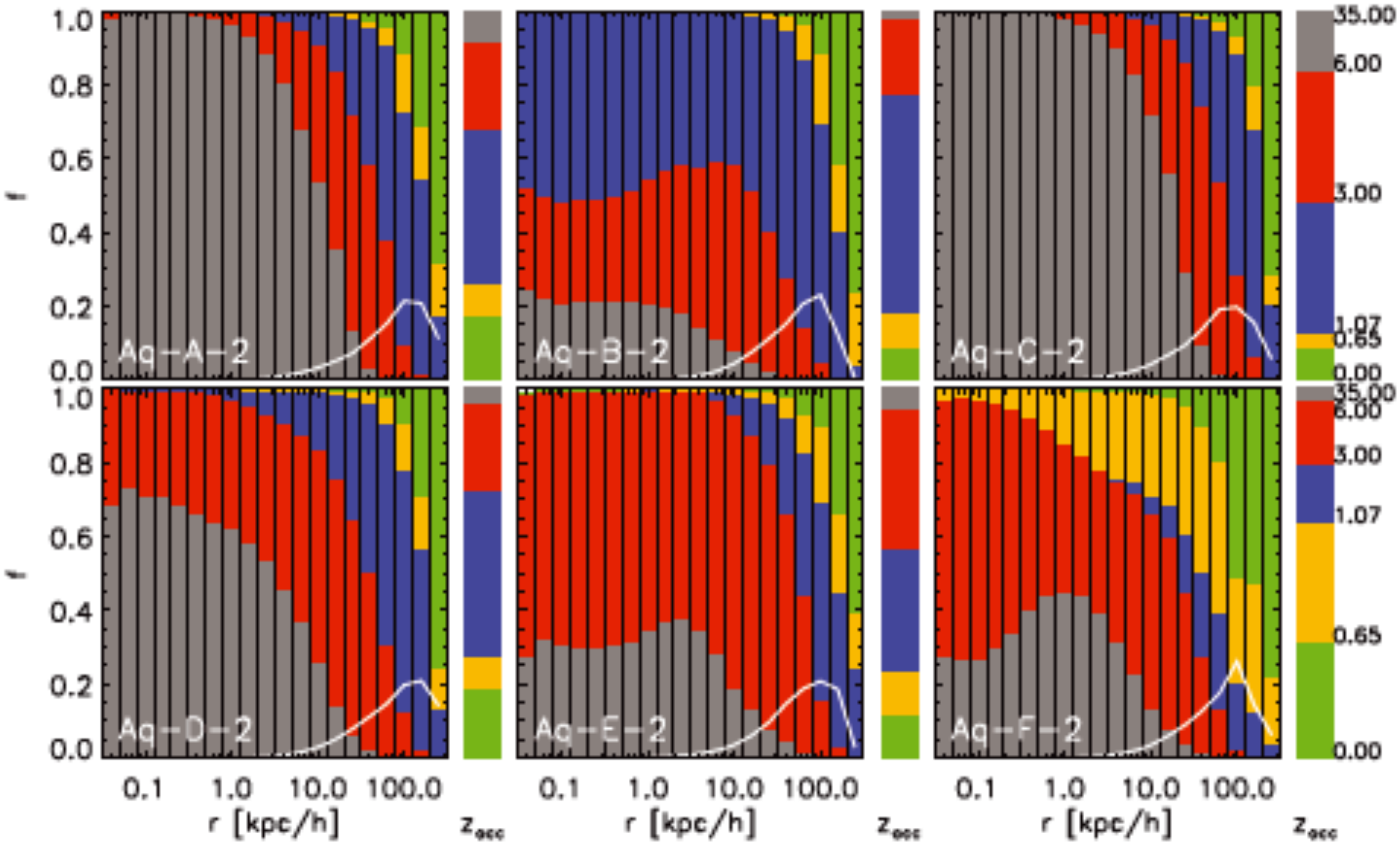
- Non-parametric Observable Estimator
- Capture differences in radial halo mass distribution
- Probe region of choice
- Retrieve cosmological information
- Easily predictable



Halo Structure

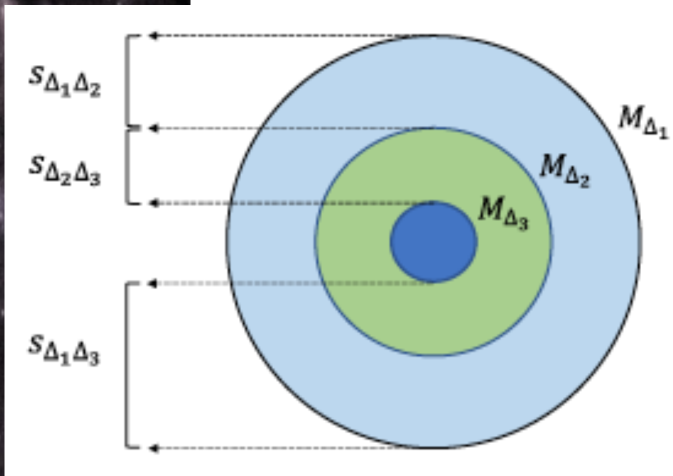
Aquarius Halos

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



J. Wang et al. (2011)

Halo Sparsity



Mass Ratio:

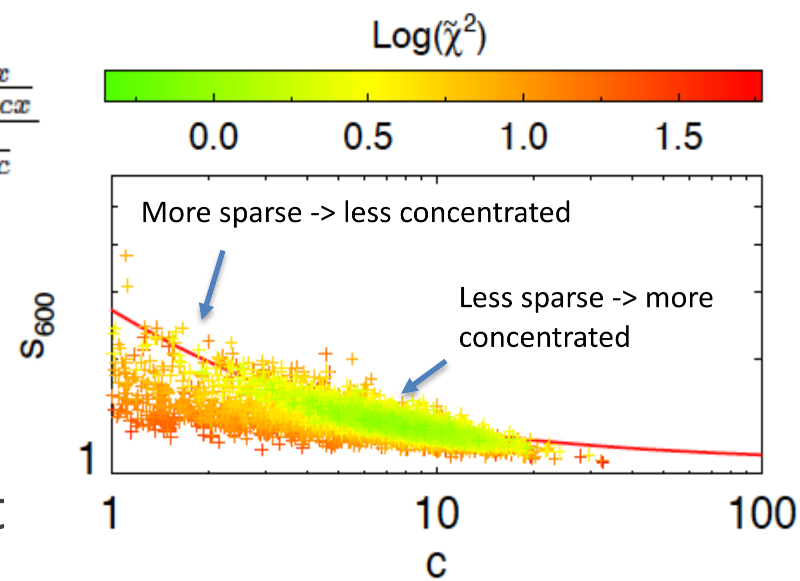
$$s_{\Delta_i\Delta_j} = \frac{M_{\Delta_i}}{M_{\Delta_j}} \equiv \frac{\Delta M}{M_{\Delta_j}} + 1$$

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

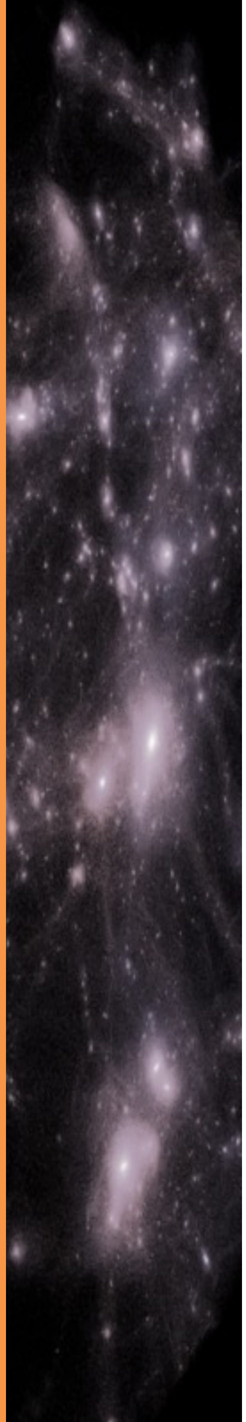
Sparsity of NFW Halos

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

- Halos with <1σ NFW along the expected relation
- Distributed nearly constant value with small scatter

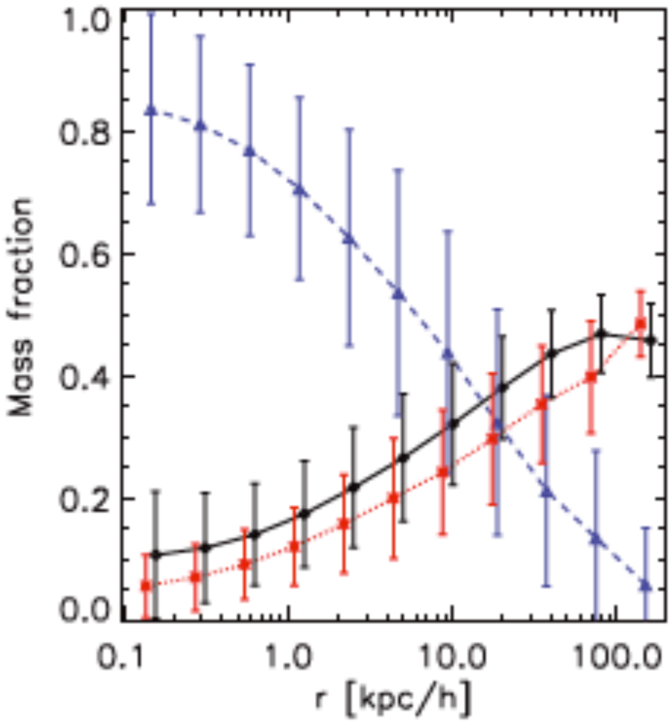


Balmes, Rasera, Corasaniti, Alimi (2014)

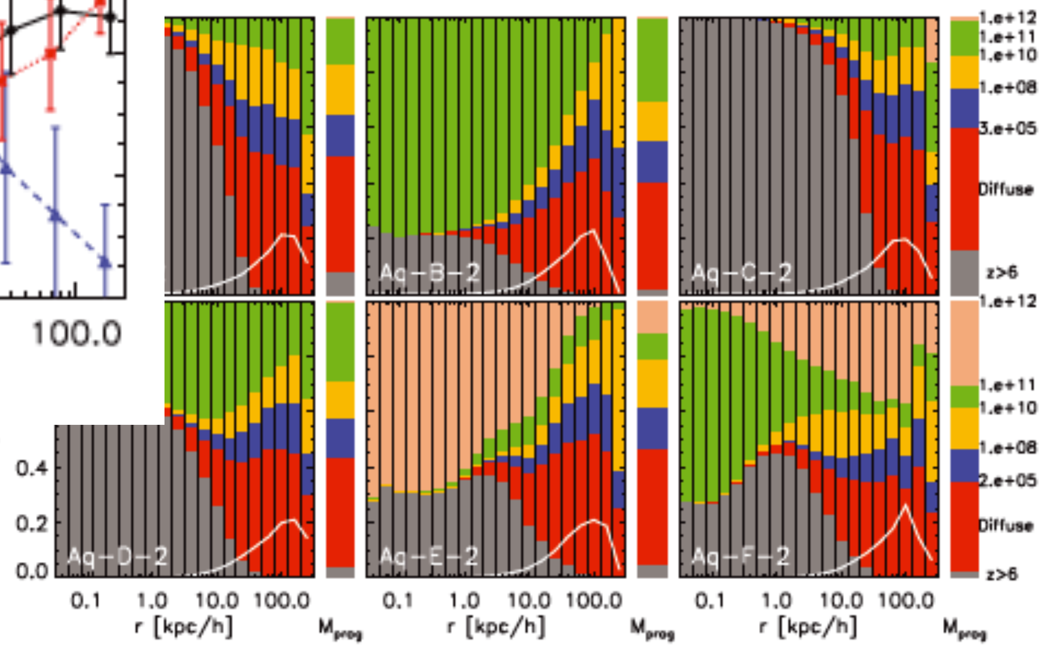


Halo Mass Distribution

Aquarius Halos

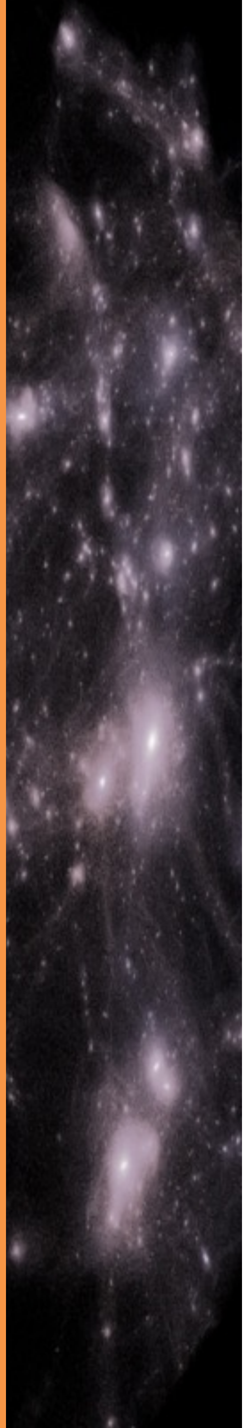


- Major Mergers (~inner regions)
- Diffuse Matter Accretion & Minor Mergers (~external regions)



- 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)

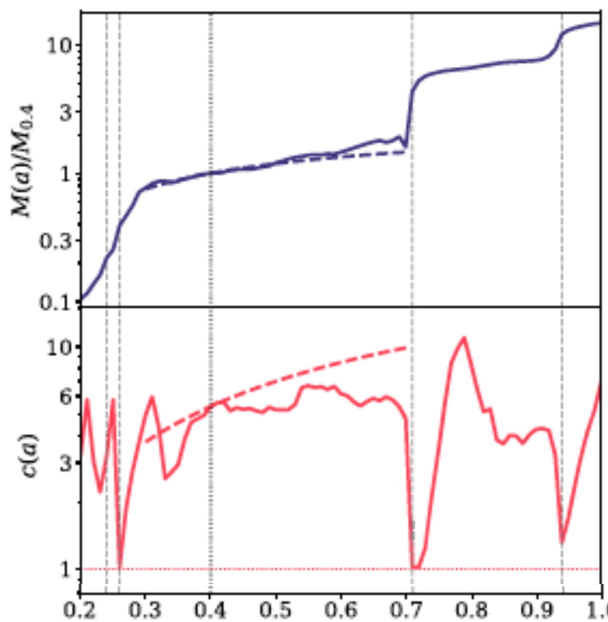
Pseudo-Evolution

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

Diemer, More, Kravtsov (2013)

Slow vs Fast Accretion

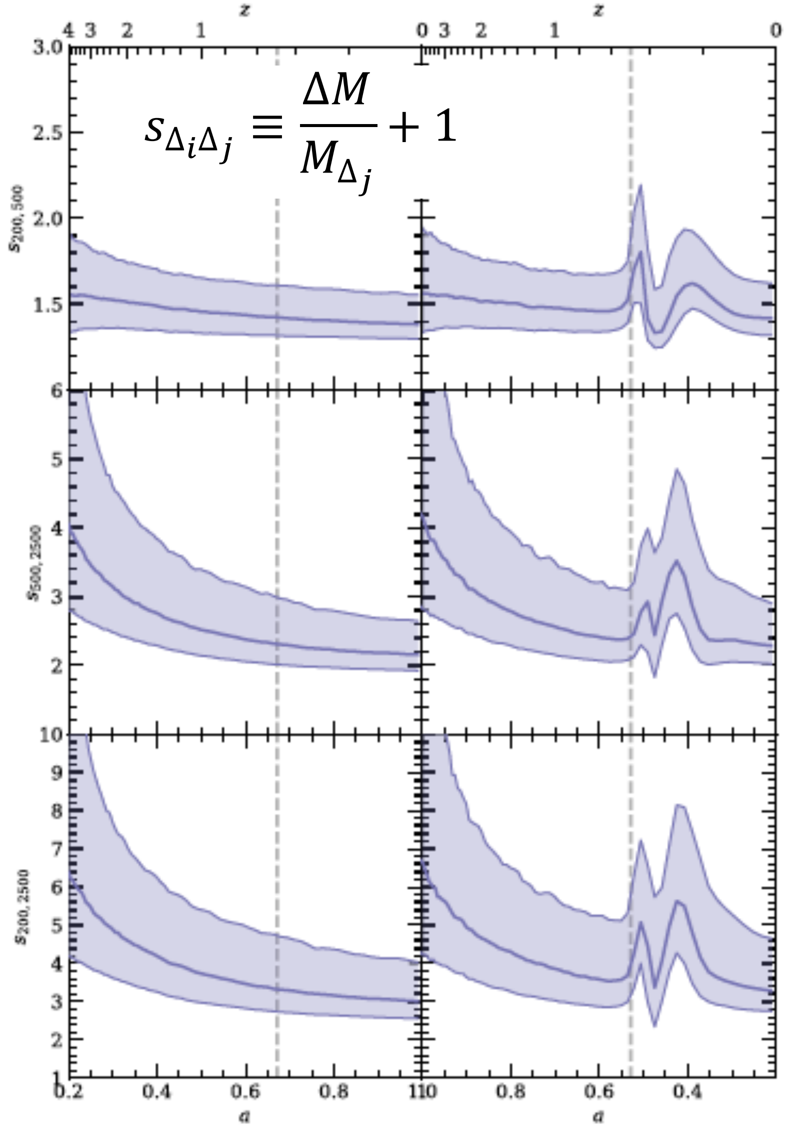
- Concentration deviates from pseudo-evolution
- Scatter due to stochastic minor mergers during slow accretion
- Universal response during major mergers with large excursion



K. Wang et al. (2020)

Halo Sparsity Evolution

Slow vs Pulse-like Evolution



Quiescent Halos Average Sparsities:

- Nearly Constant Evolution Outer Region
- Decreasing Trend Inner Region

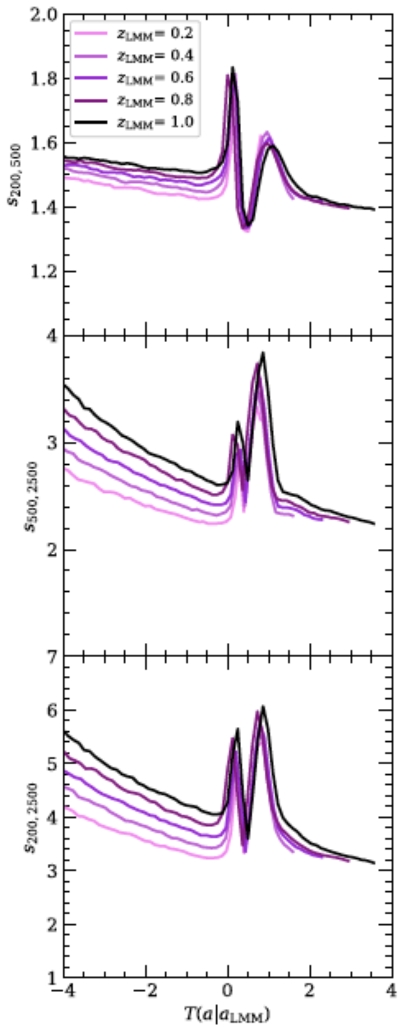
Average Sparsities of Major Mergers z = 0.5:

- 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)

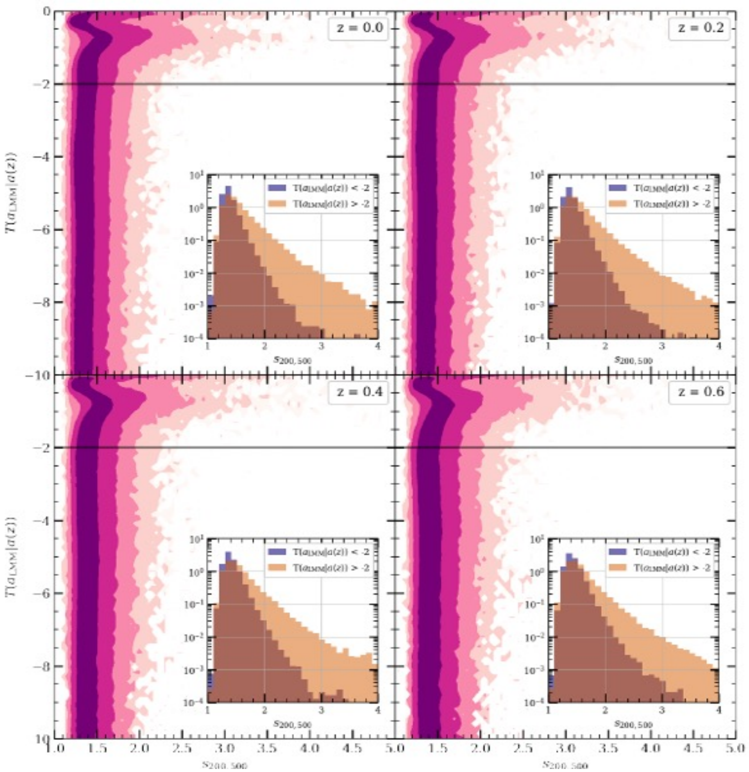
$$T(z; z_{LMM}) = \frac{\sqrt{2}}{\pi} \int_{z_{LMM}}^{z} \frac{\sqrt{\Delta_{vir}(z)}}{z+1} dz$$

see also Wang et al. (2020) for concentration

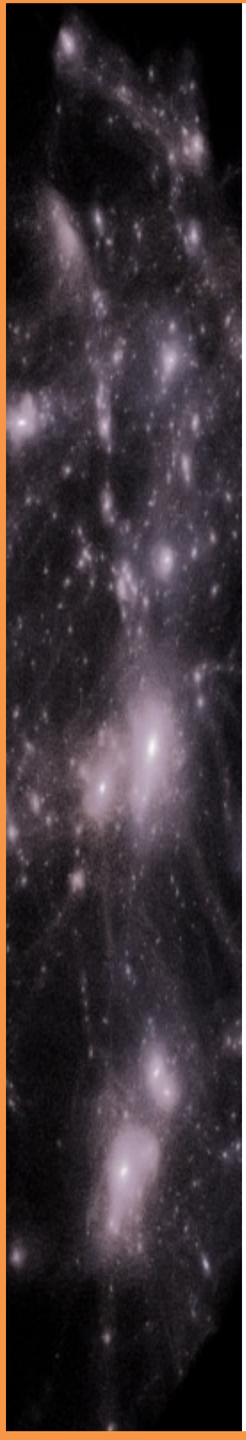
- Quiescent Evolution Recovered t > 2T

- Halo Population:

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

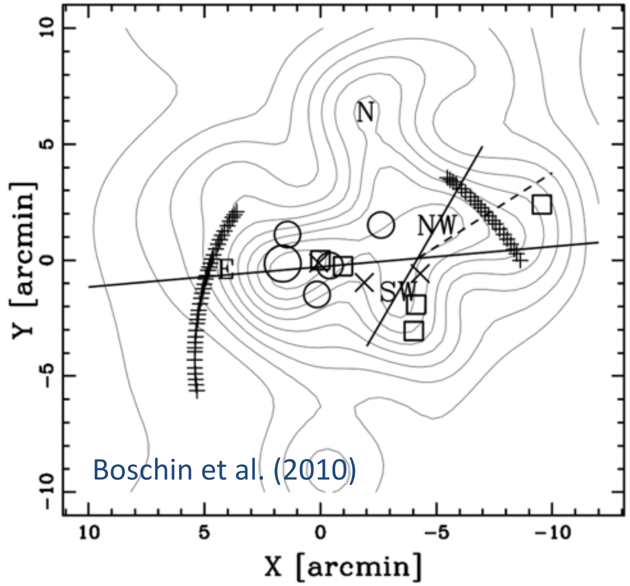


Richardson & Corasaniti (2022)



ABELL 2345

Lensing & Radio Relics



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

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

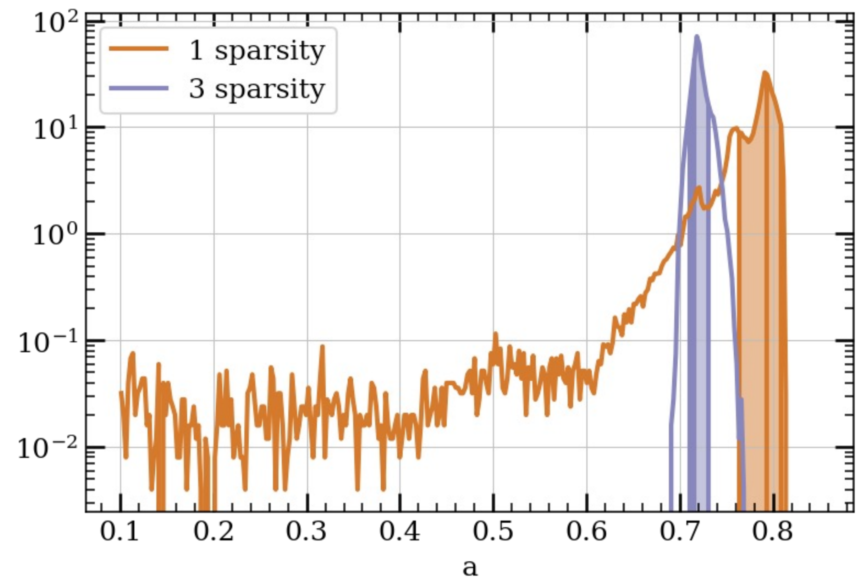
- Sparsities: $s_{200,500} = 4.26 \pm 2.33$
$s_{200,2500} = 87.50 \pm 46.83$
$s_{500,2500} = 20.06 \pm 10.93$

- Uchuu Simulations Calibrated Distributions
- Timing the merger event:

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

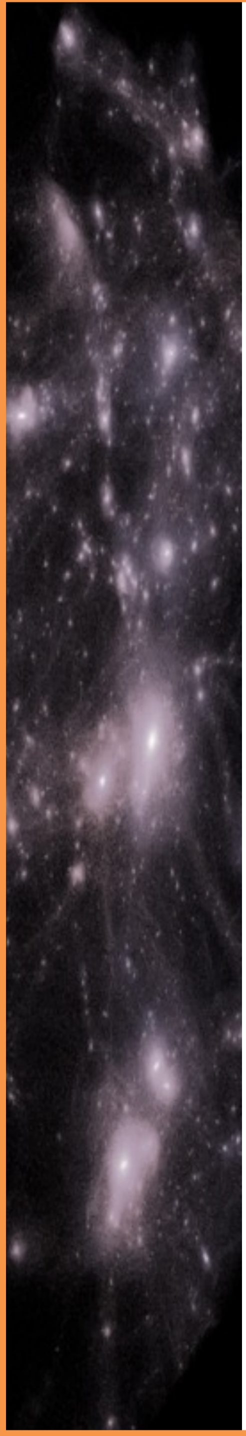
$$|T| = 0.86\ \tau_{dyn}$$

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



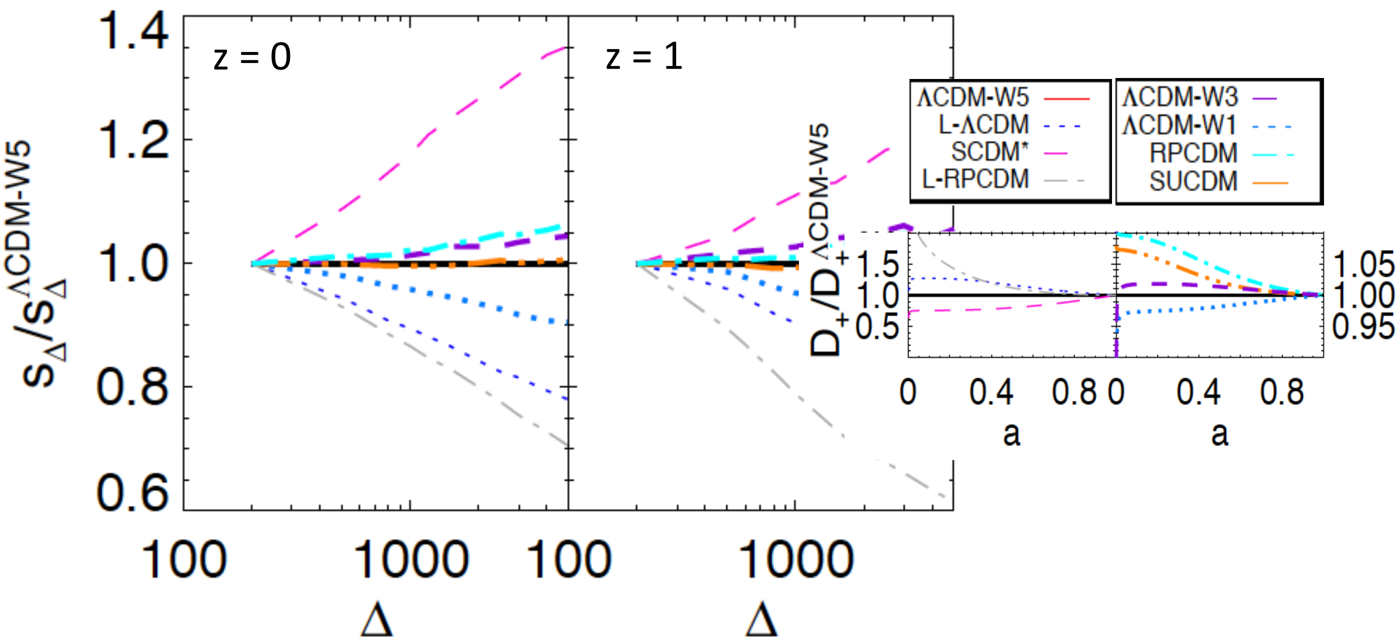
https://gitlab.obspm.fr/trichardson/lammas

Cosmological Imprint



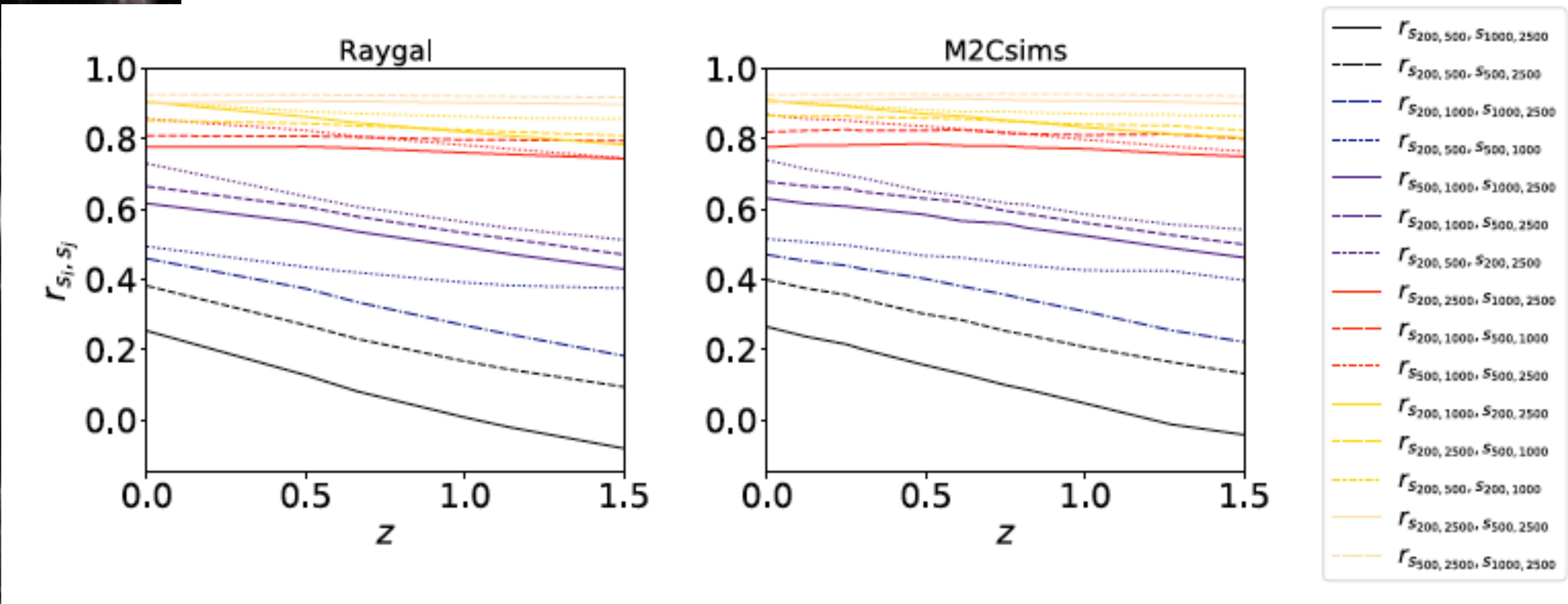
Average Sparsity

- 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)

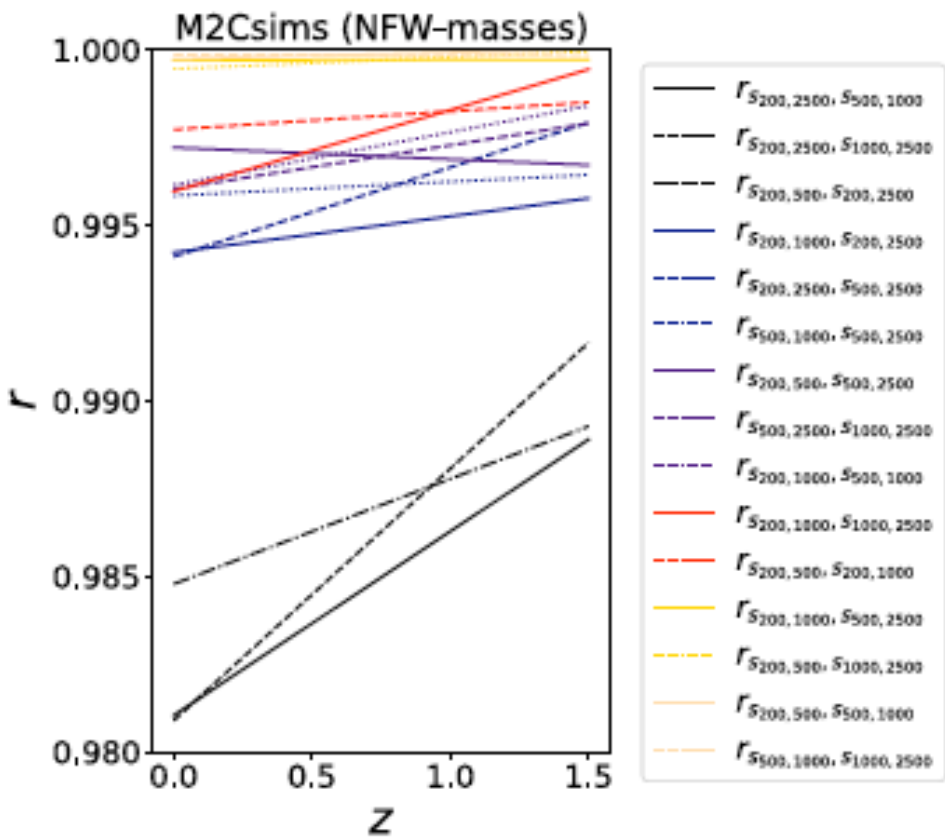
Sparsity Correlations



- 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

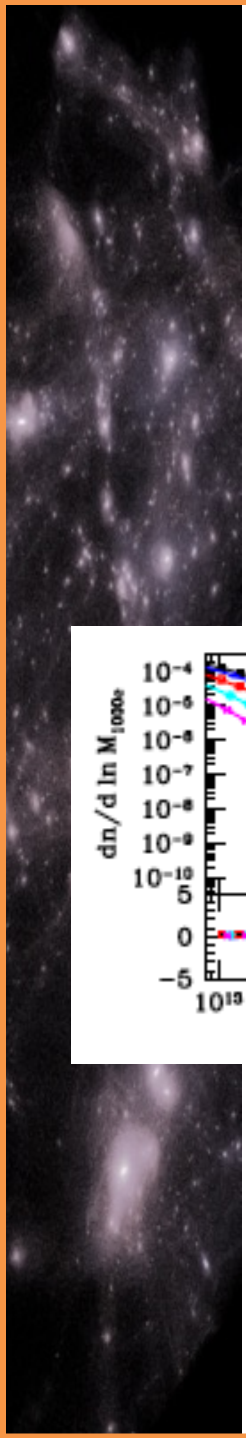


Corasaniti, Le Brun, Richardson et al. (2022)

- 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 destroys all 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

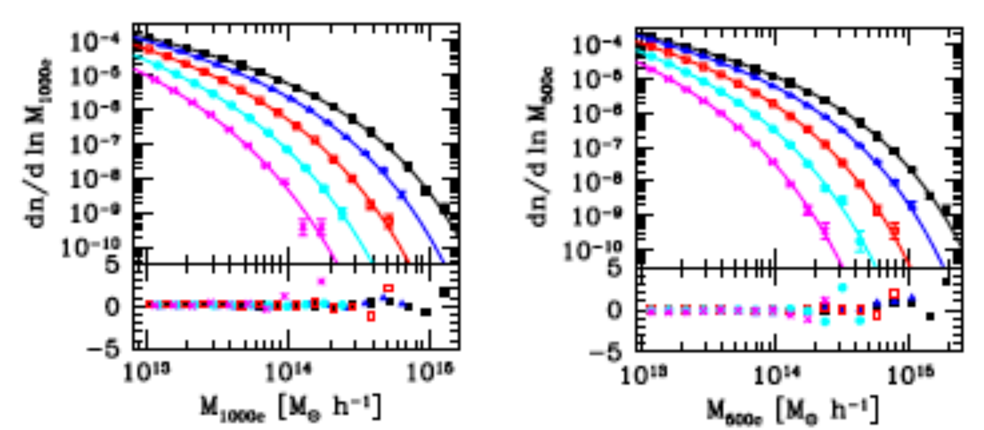


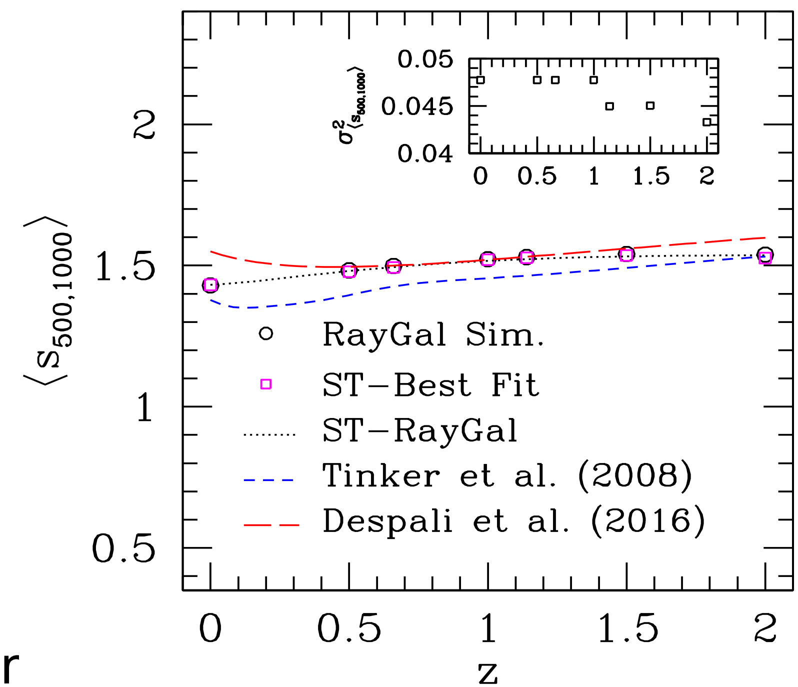
Average Halo Sparsity

Sparsity – Mass Function Relation

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

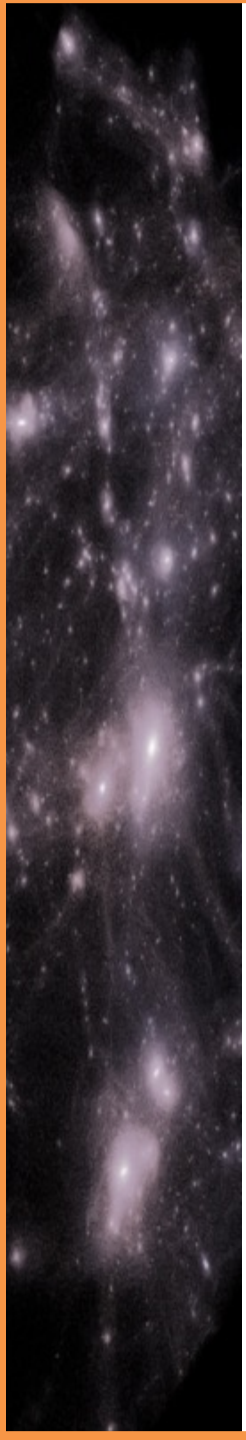
- N-body Calibrated Halo Mass Functions at Δ_1 and Δ_2





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

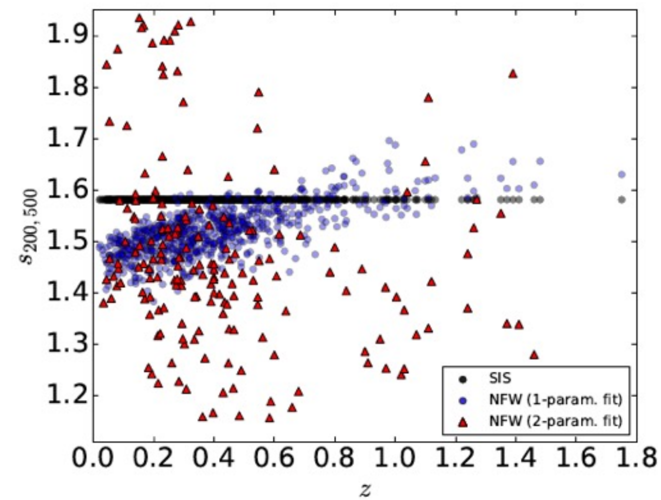
Corasaniti et al. (2018)



Cosmological Parameter Analysis

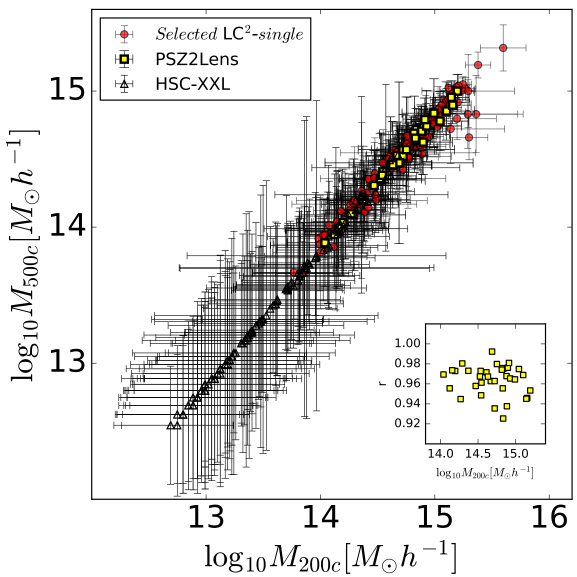
Weak Lensing Cluster Masses

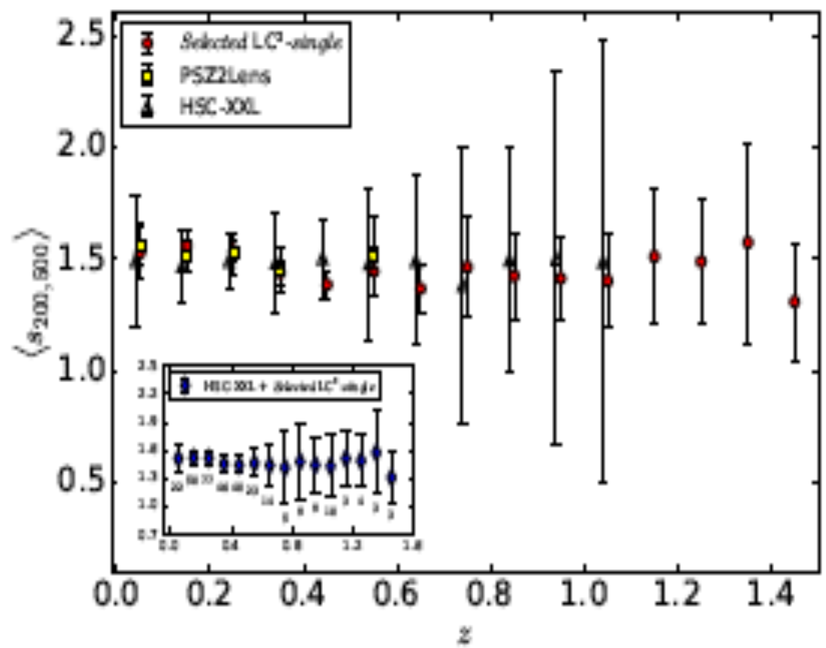
- LC^2 catalog (672 clusters, z<1.7)
  Sereno (2015)
- Removing Biased Estimates



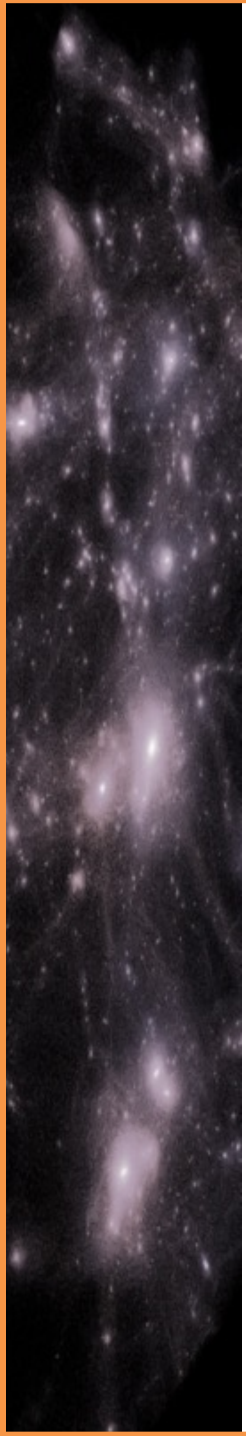
Sparsity Cosmological Sample

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





Corasaniti, Sereno & Ettori (2021)

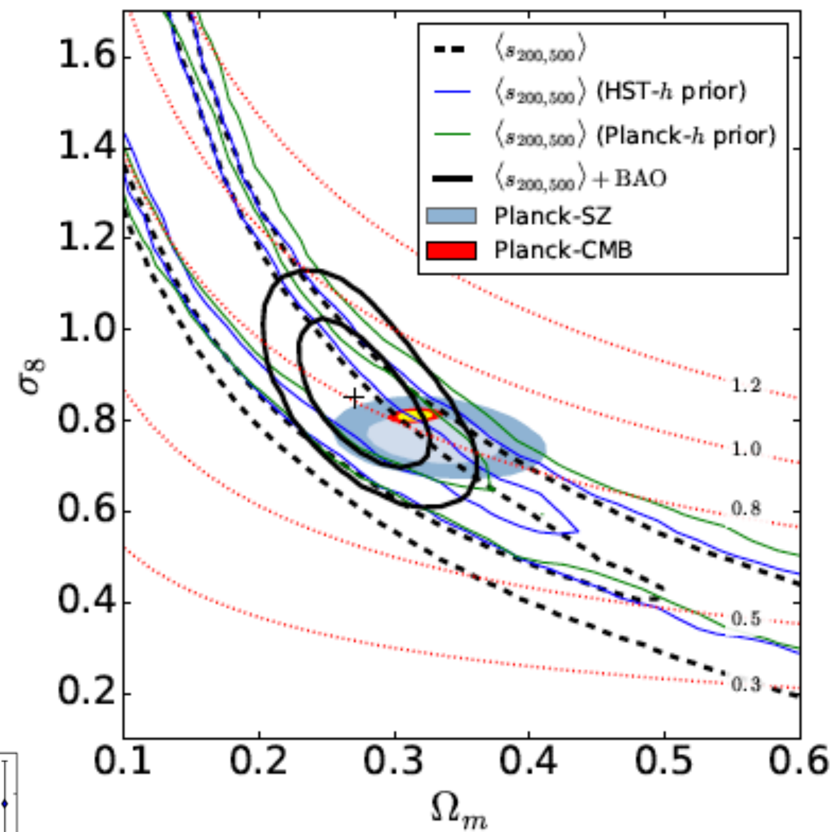


MCMC - Sparsity + BAO

Model Parameters & Priors

- Ω_m , σ_8 , h (+ n_s-Planck prior & $\Omega_b h^2$-BBN prior)
- S_8 degeneracy

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

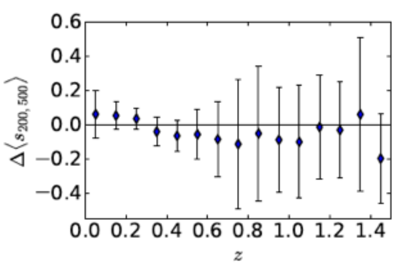


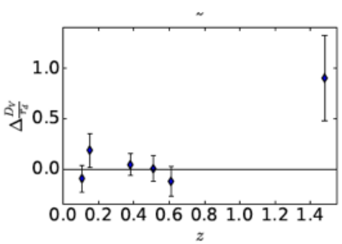
Pre-reconstruction BAO Data

- Marginal Stats:

$\Omega_m = 0.28 \pm 0.03$
$\sigma_8 = 0.86 \pm 0.10$
$h = 0.66 \pm 0.02$

- Residuals



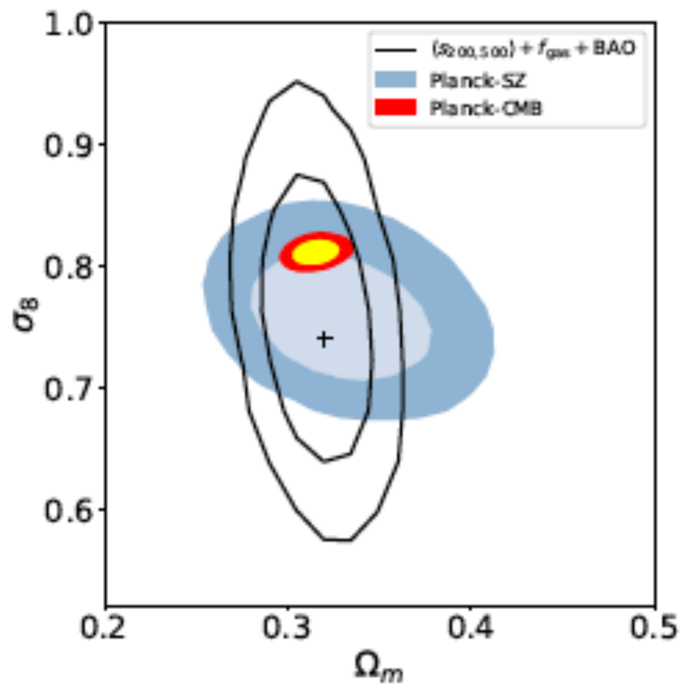


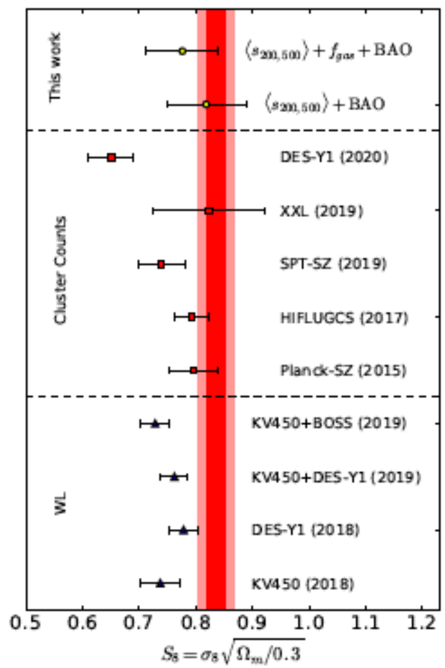
Corasaniti, Sereno & Ettori (2021)

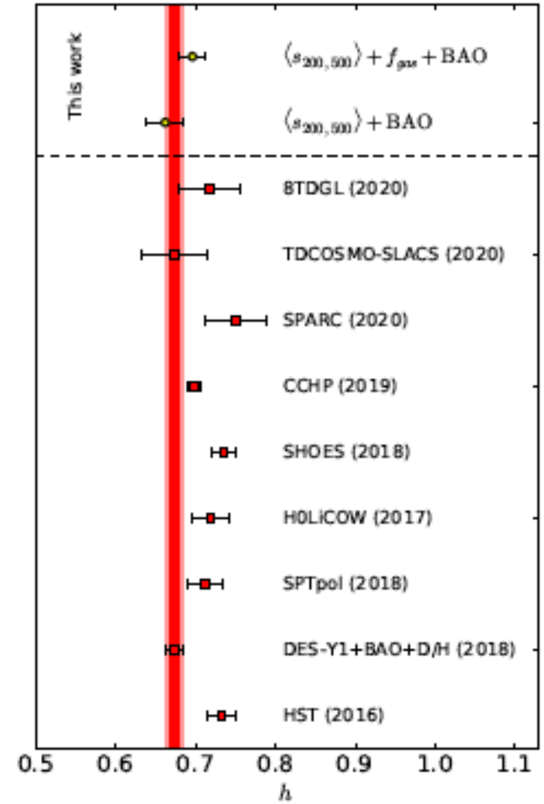
MCMC – Sparsity + f_{gas} + BAO

Joint Analysis

- Marginalized on f_{gas} parameters (K & Y_b)
- $\Omega_m = 0.32 \pm 0.02$; $\sigma_8 = 0.76 \pm 0.07$; $h = 0.70 \pm 0.02$

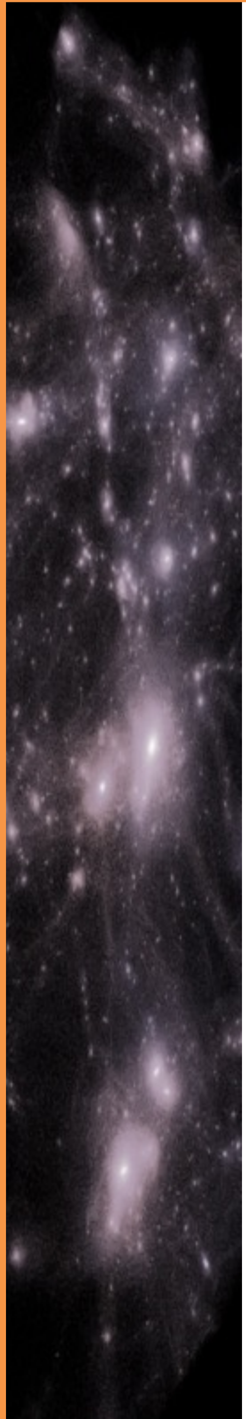






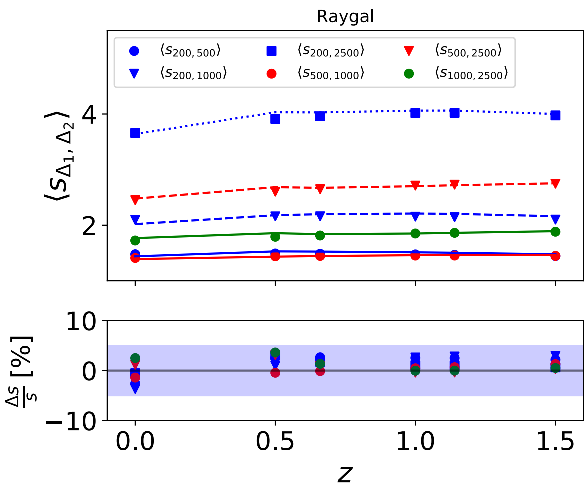
- Assuming $K_{CLASH} \sim G(0.79,0.09) \rightarrow Y_b > 0.89$

Corasaniti, Sereno & Ettori (2021)



Multiple Sparsity Measurements

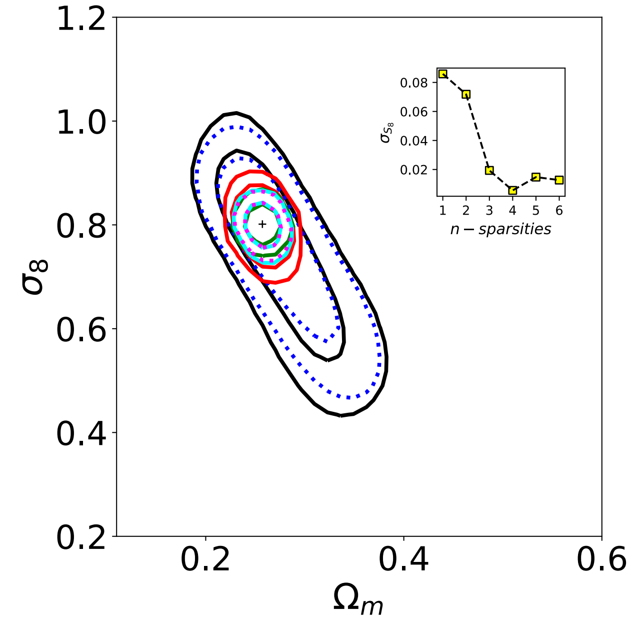
Non-Parametric Cluster Mass Estimates



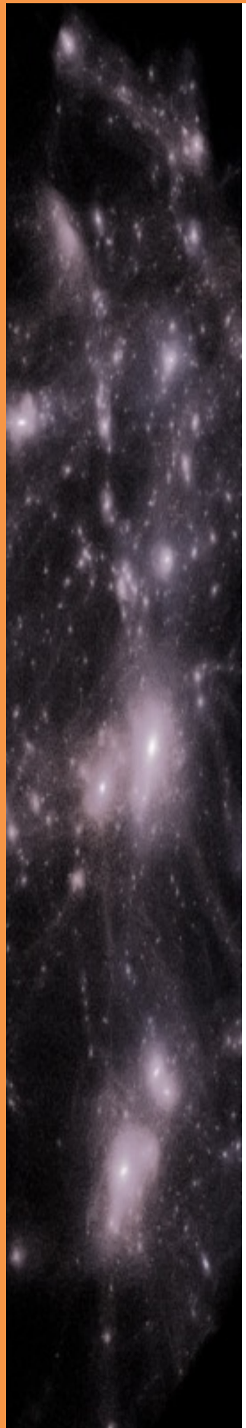
- Mass Estimates Δ = 200, 500, 1000, 2500
- N_s = 6 sparsities
- Correlations + Propagation of theoretical model errors

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)

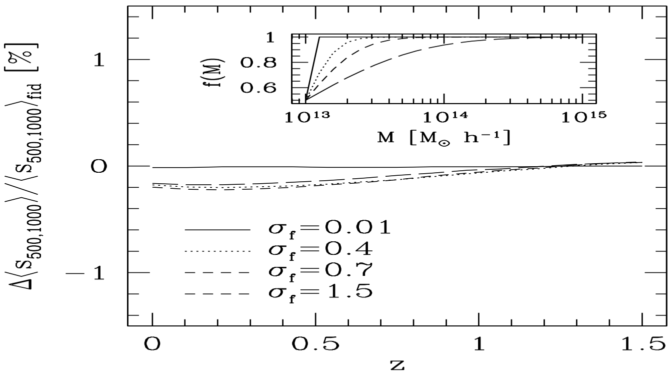


Sparsity Systematic Effects

Selection Effects

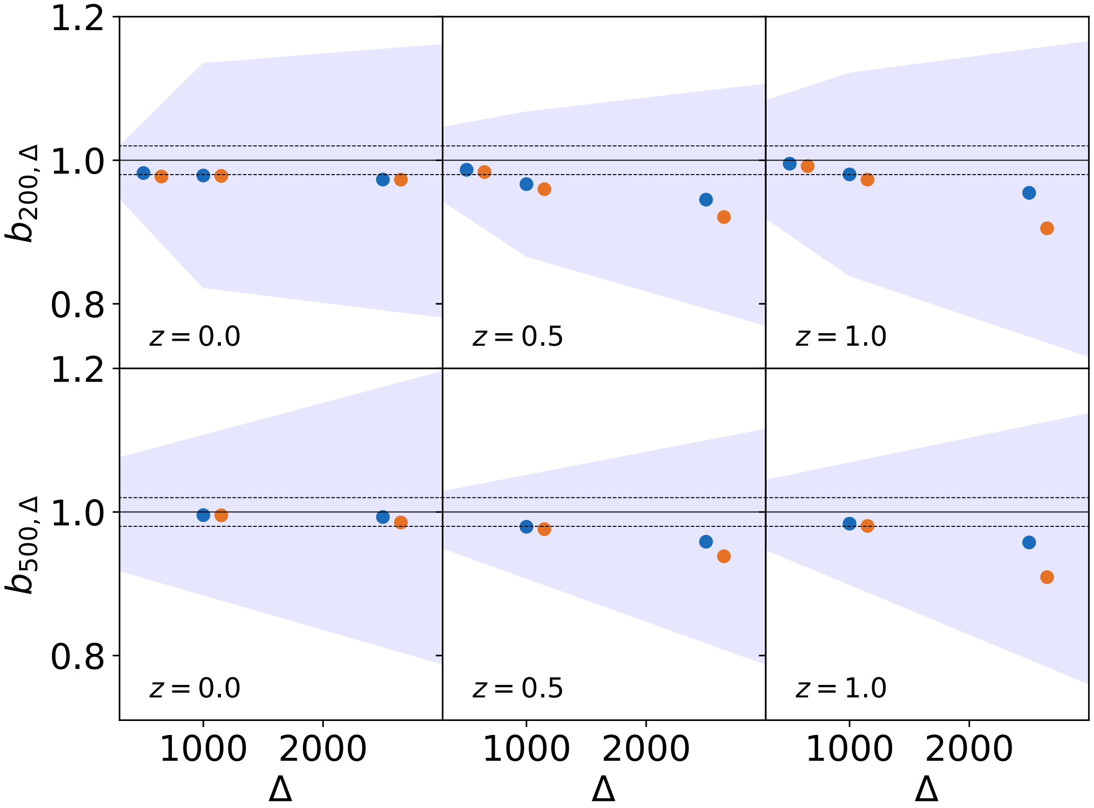
- Sub-percent level
- Consistent with near constant sparsity – mass relation

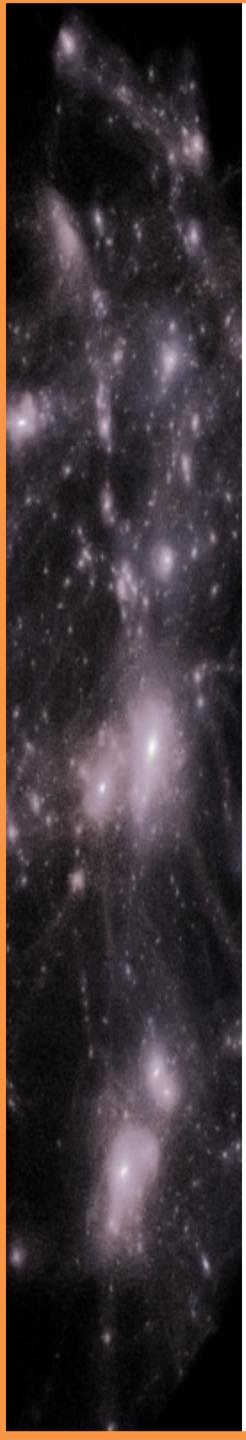
Corasaniti et al. (2018)



Radial Dependent Mass Bias

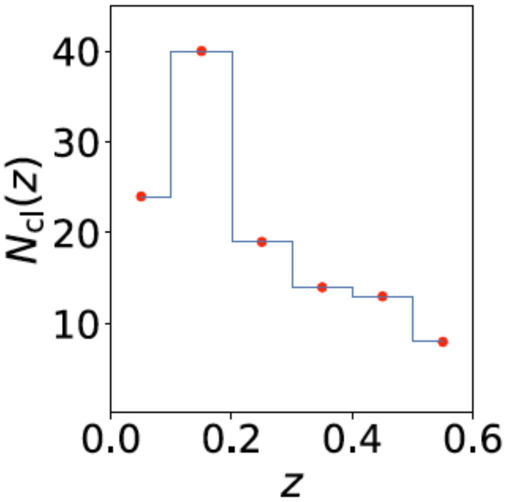
- Preliminary analysis of The300
- < 1-2% at z = 0
- Increases at z > 0 and larger overdensities
- Baryons induce correlations in the inner halo region





Impact on Cosmological Inference

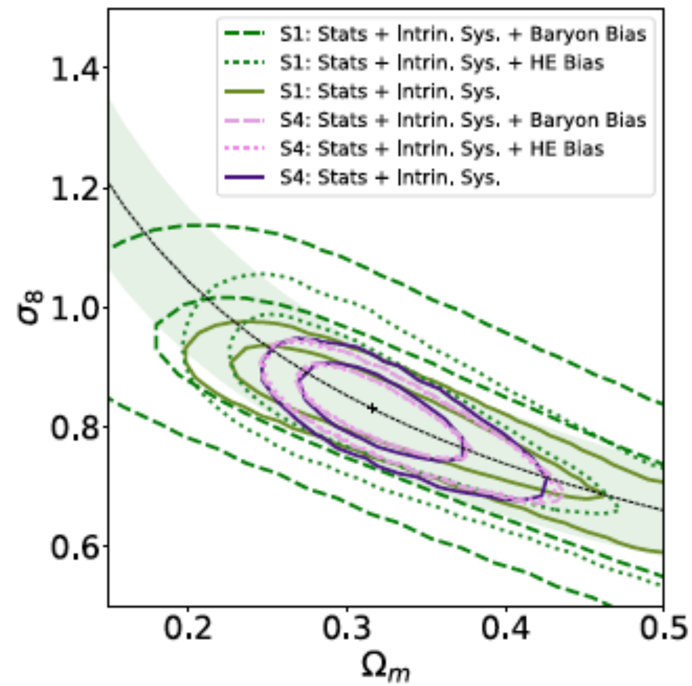
CHEXMATE-like Sample



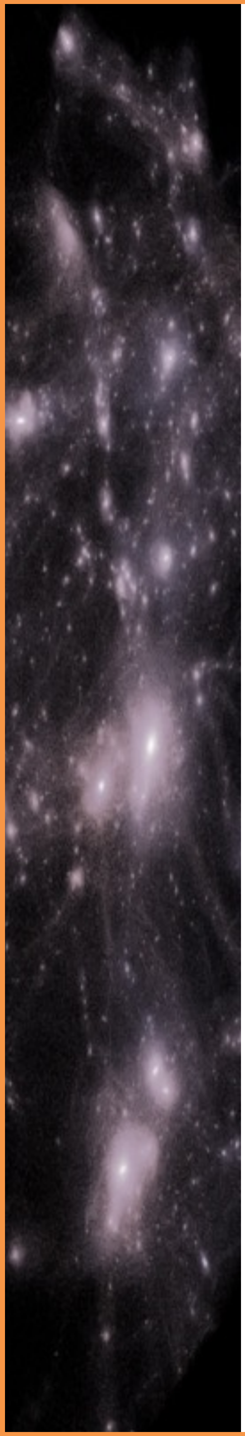
- 118 Clusters in $0 < z < 0.6$
- $e_{M\Delta}$ = 0.23, 0.15, 0.11 & 0.10 (for Δ = 200, 500, 1000 & 2500)
- Propagate radial mass bias & HE bias
- Single vs Multiple (n=4) sparsities

MCMC Constraints

- Significant Effect on Single Sparsity inferred constraints
- Negligible Effect on Multiple Sparsity case
- ~ percent level errors on $\mathbf{\Omega}_{\rm m}$ and $\boldsymbol{\sigma}_8$

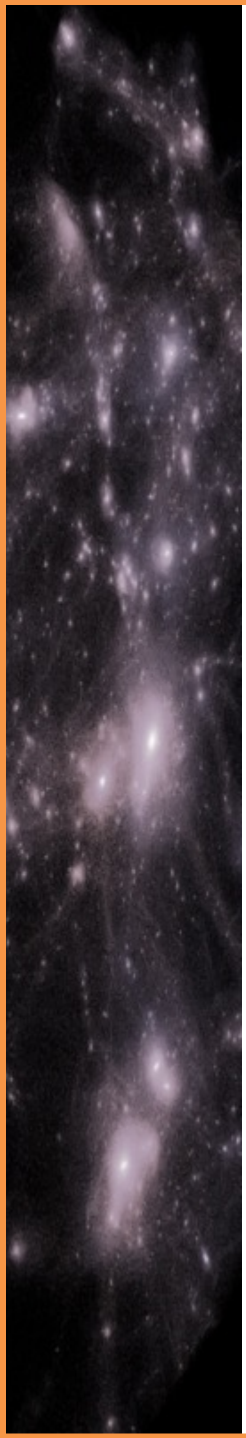


Corasaniti, Le Brun, Richardson, Rasera, Pratt, Arnaud (2022)



Conclusions

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

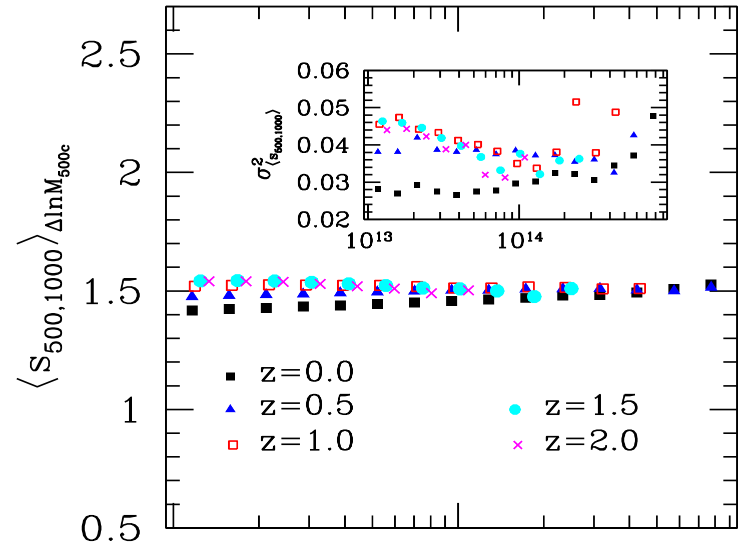


Sparsity Ensemble Properties

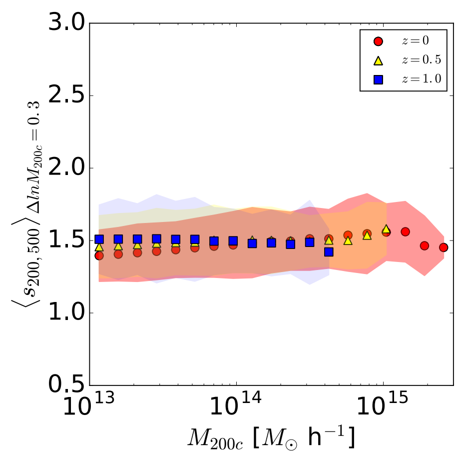
RayGalGroupSims Analysis

- L_{box} = 2.6 Gpc/h; $N_p = 4096^3$
- SOD Halos ($M_{200c} > 10^{13}$ M_{sun}/h)
- Nearly constant (<10% variation across 2 orders in mass)
- Intrinsic scatter bounded to ~20%
- Trend independent of Δ_1 and Δ_2

Corasaniti et al. (2018)



MultiDark-Planck2 Analysis



- L_{box} = 1 Gpc/h; $N_p = 3840^3$
- SOD Halos ($M_{200c} > 10^{13}$ M_{sun}/h)

Corasaniti & Rasera (2019)