



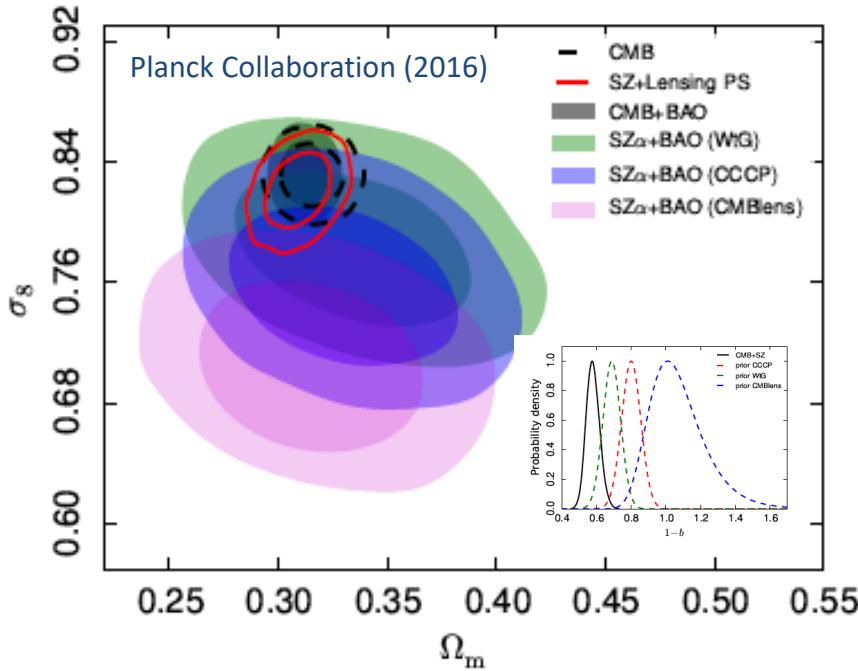
Probing Cosmology with Galaxy Cluster Sparsity

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Cosmology with Clusters

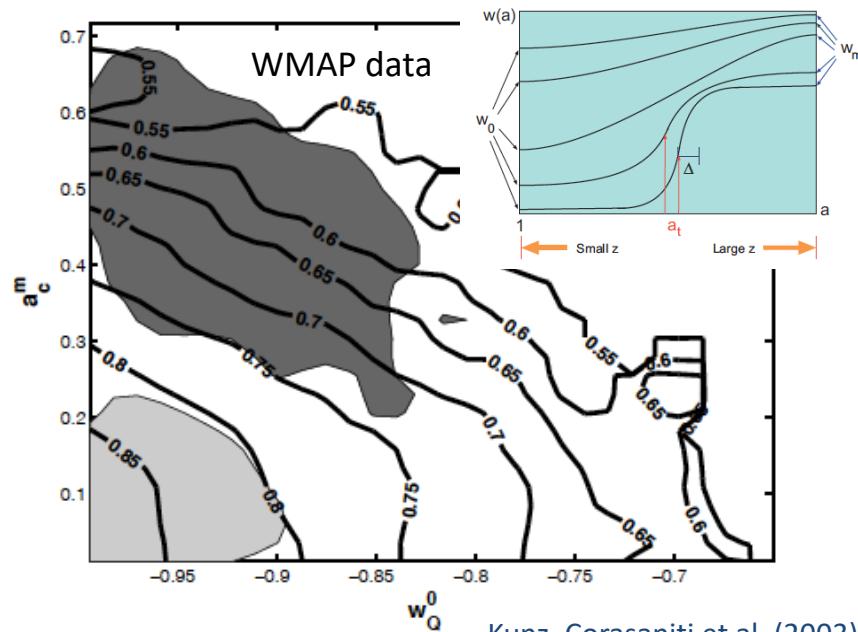
Cluster Number Counts



- Low σ_8 from non-CMB probes would favor non-LCDM like scenarios (or very high > 1)
- The importance of testing cosmology with alternative cluster probes

- Test of the Concordance Model
- Tension & Cluster Systematics
- Beyond LCDM (m_ν)

CMB-independent σ_8 estimates & Dark Energy



Kunz, Corasaniti et al. (2003)

Cluster Internal Mass Distribution

Navarro-Frenk-White Profile

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

$$c = \frac{r_{200}}{r_s} \quad \text{halo concentration}$$

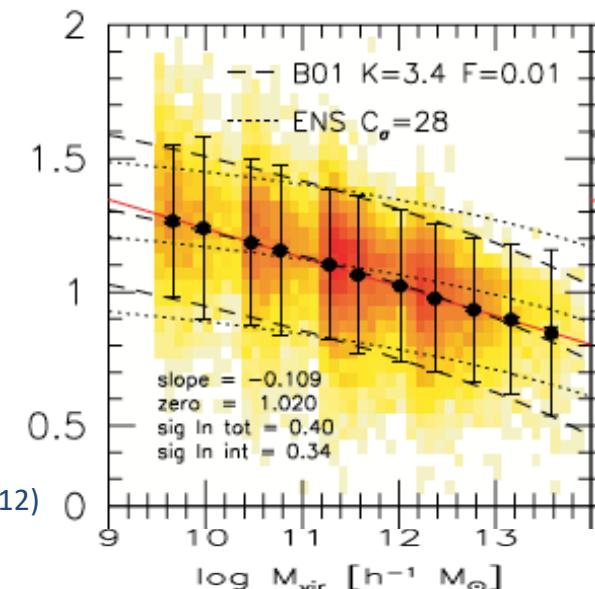
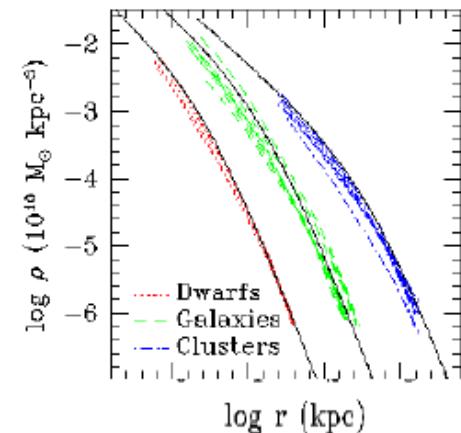
c – M relation: $c(M, z) = \frac{c_0}{1+z} \left(\frac{M}{10^{14} h^{-1} M_{Sun}} \right)^\alpha$

$\alpha \sim -0.1$; c_0 : cosmology dependent; Klypin et al. (2003); Dolag et al. (2004)

Limitations:

- Large Scatter
- Astrophysical Effects e.g. Gnedin et al. (2004); Duffy et al. (2010); De Boni et al. (2013)
- Lensing Observations: Shape & Orientation e.g. Oguri et al. (2005); Corless, King & Clowe (2009), Sereno et al. (2013)
- X-ray Observations: Deviations from HE e.g. Rasia et al. (2012)
- Selection Effects Sereno et al. (2014)

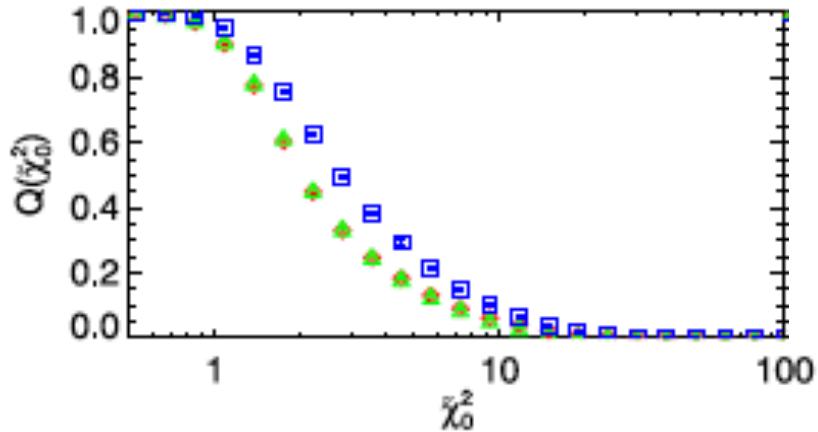
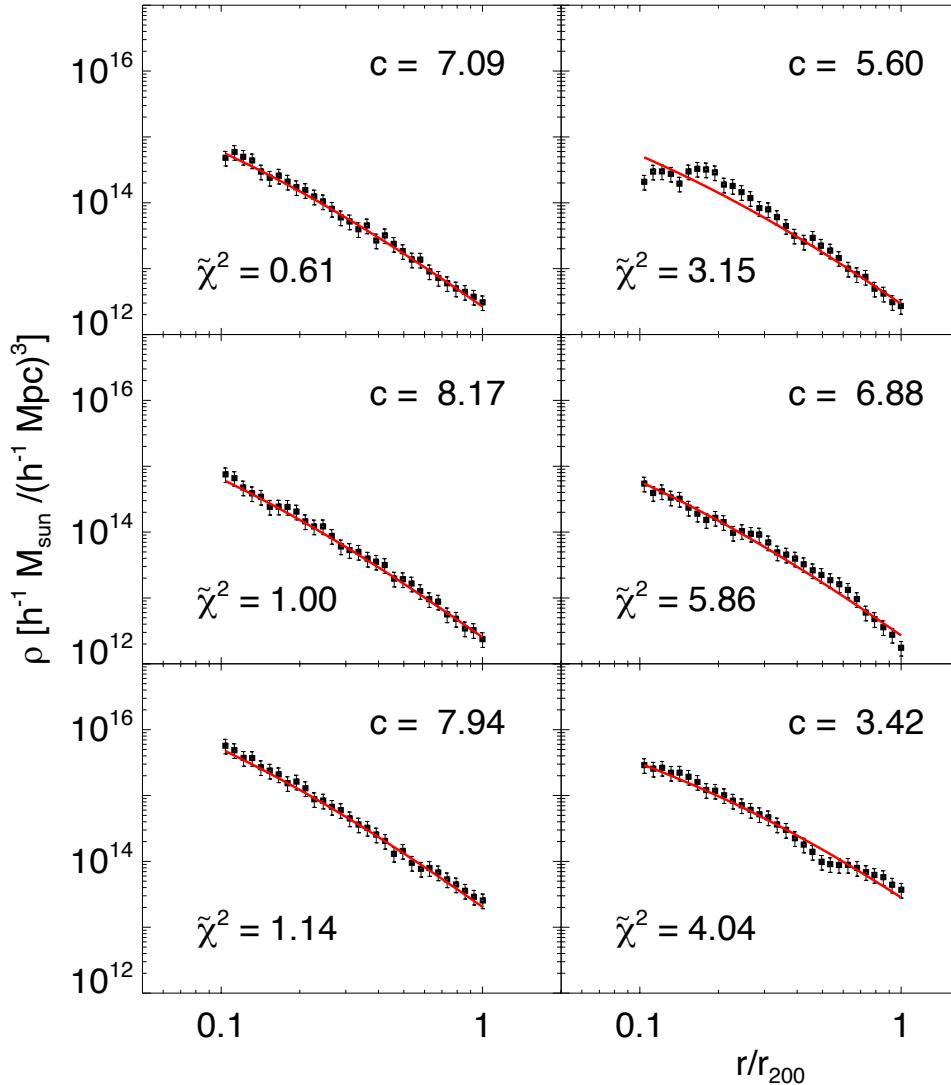
Navarro, Frenk & White (1997)



Maccio et al. (2007)

The Core of the Problem

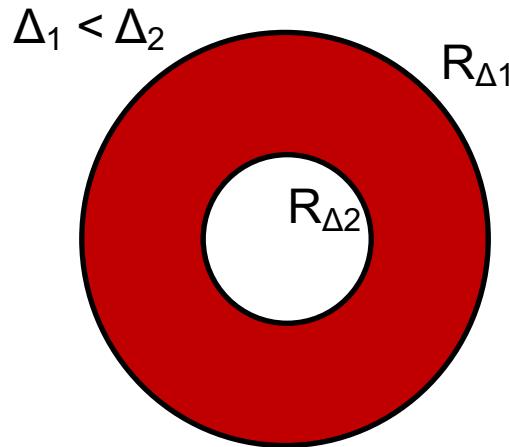
Balmes, Rasera, Corasaniti, Alimi (2014)



- distribution of c correlates with goodness-of-fit

See also Ragagnin et al. (2020)

Halo Sparsity



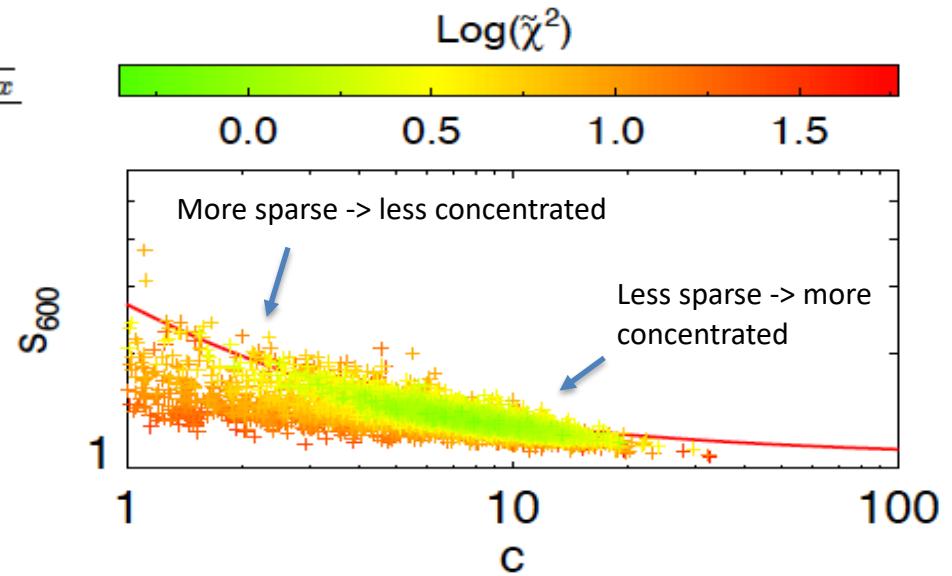
Mass Ratio $S_{\Delta_1 \Delta_2} = \frac{M_{\Delta_1}}{M_{\Delta_2}} \equiv 1 + \frac{\Delta M}{M_{\Delta_2}}$

- $\Delta_1 \geq 100$ (preserve halo individuality)
- $\Delta_2 \leq 2000$ (avoid baryon dominated region)

Sparsity of NFW Halos

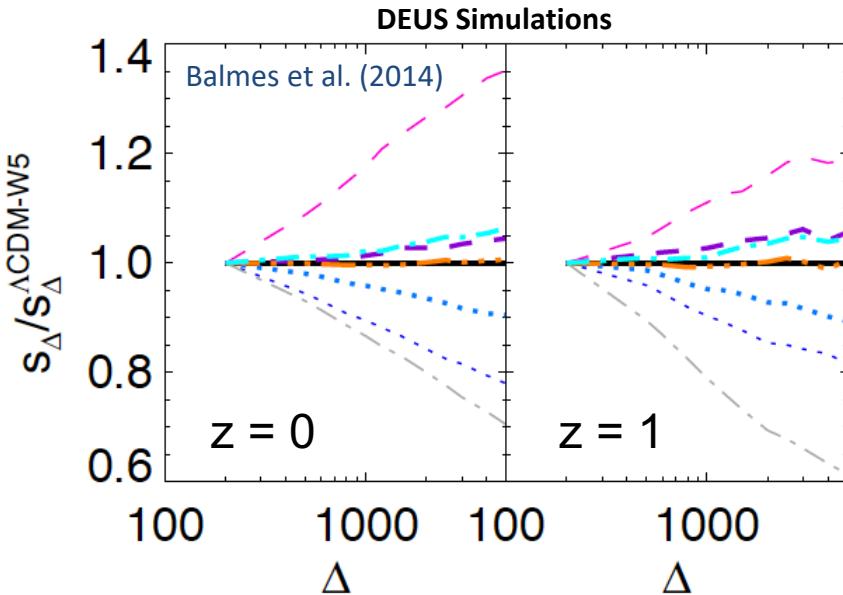
$$S_\Delta = \frac{200}{x^3 \Delta} \quad \& \quad x^3 \frac{\Delta}{200} = \frac{\ln(1 + cx) - \frac{cx}{1+cx}}{\ln(1 + c) - \frac{c}{1+c}}$$

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

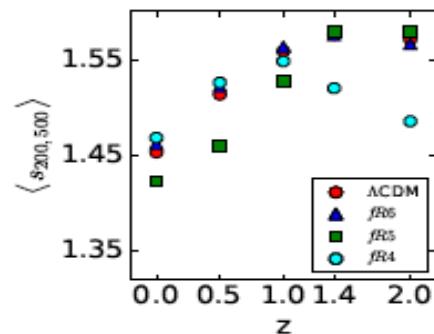


Cosmological Imprint

Stacked Halo Sparsity



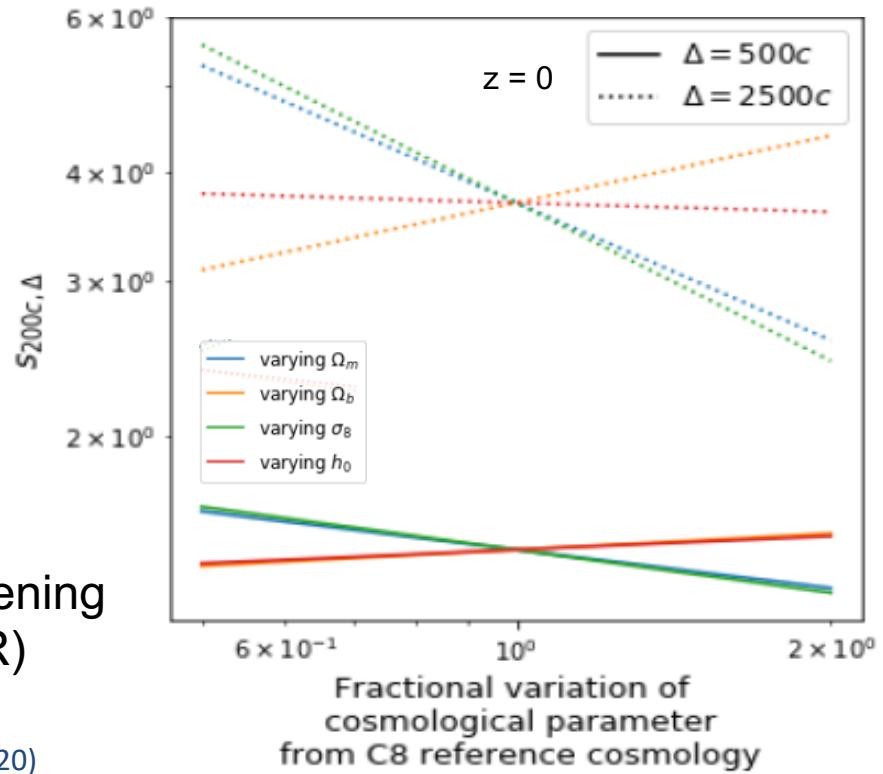
- Cosmological signal stands despite baryon physics (Magneticum Simulations) Ragagnin et al. (2020)



- Sensitive to screening mechanism in $f(R)$ scenarios

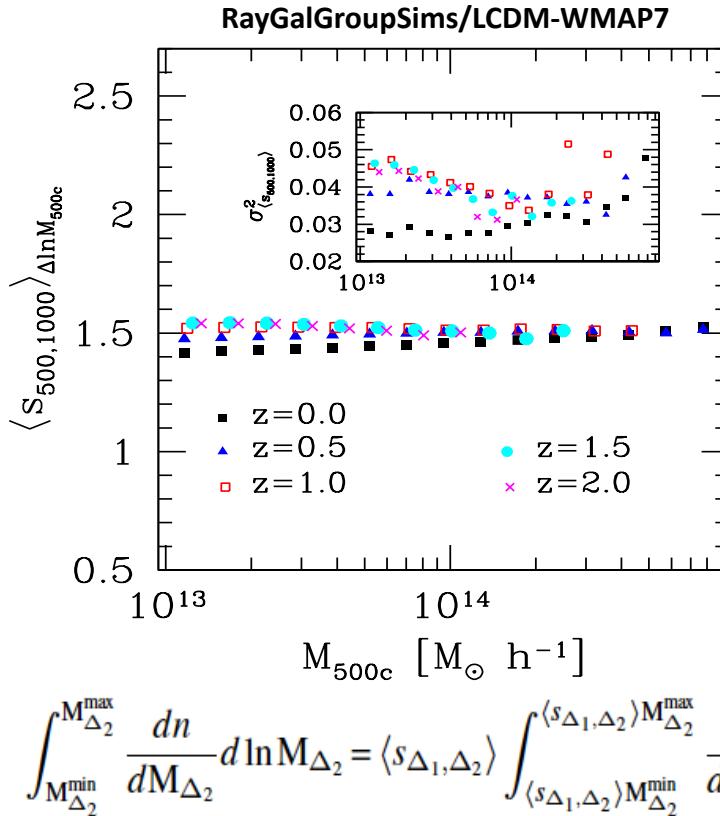
Corasaniti, Giocoli, Baldi (2020)

- Sparsity evolution correlates with linear growth history
- The earlier the formation of structures the smaller the sparsity

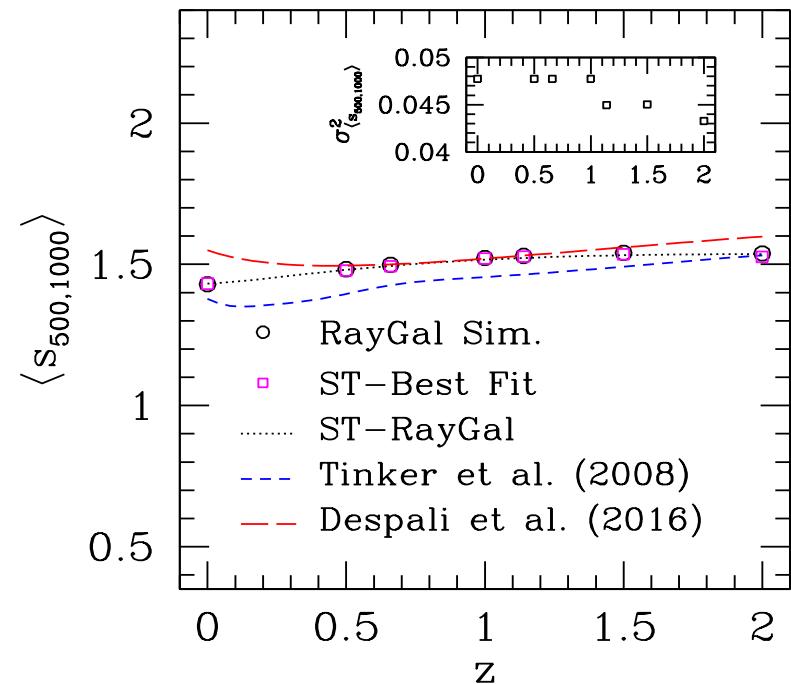


Sparsity Ensemble Properties

Halo Mass Independence



- Nearly constant (<10% variation across 2 orders in mass)
- Intrinsic scatter bounded to ~20%
- Trend independent of Δ_1 and Δ_2

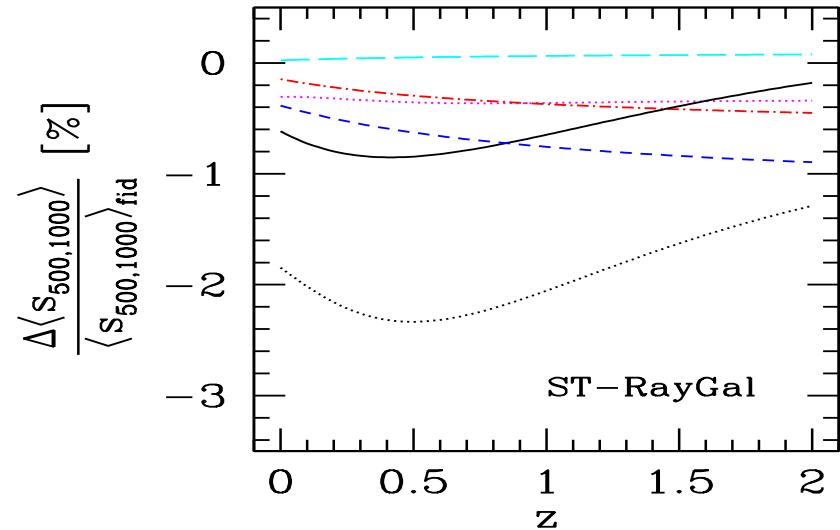


- Accurate to sub-percent level
- Quantitative Framework

Probing Cosmology with Cluster Sparsity

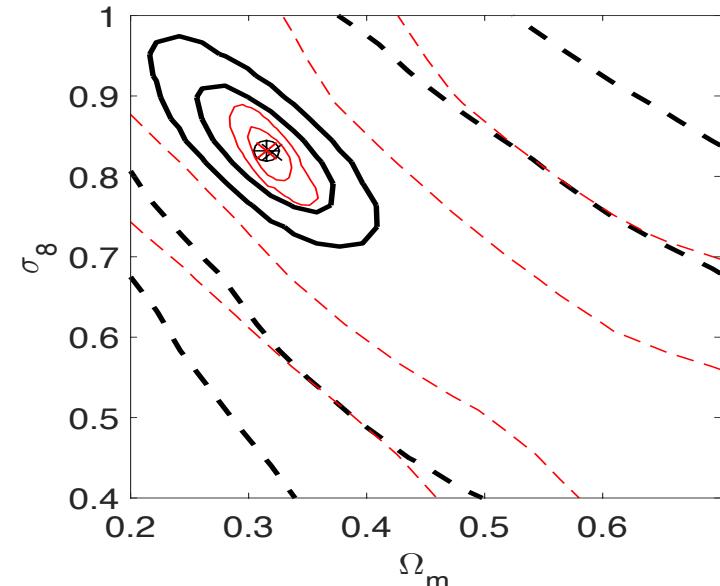
Redshift Evolution and Cosmological Parameters

- $\Omega_m, \sigma_8, n_s, h, \Omega_b$
- Primarily sensitive to $S_8 = \sigma_8 \sqrt{\Omega_m}$



Synthetic Data Analysis

- Planck-LCDM Fiducial Cosmology
- Mass Function Parametrization
- Statistical Errors: 1%, 20%
- Recover Input Fiducial Cosmology



Systematic Effects

Radial Dependent Mass Bias

- Baryonic Processes Altering Halo Mass Distribution (AGN feedback)

Velliscig et al. (2014)

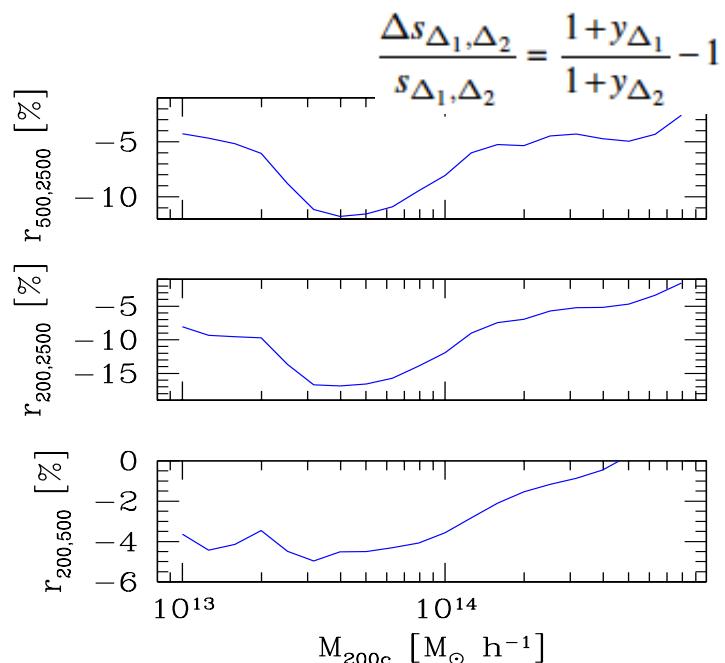
- Hydrostatic Mass Bias

Biffi et al. (2016)

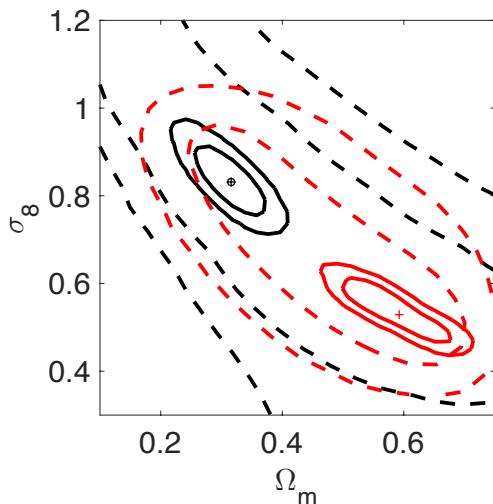
- Tangential Shear Profile

Becker & Kravtsov (2011)

Cluster State	$r_{500,1000}$ [%]
CC	-3.7
NCC	0.1
Regular	0.3
Disturbed	-2.0



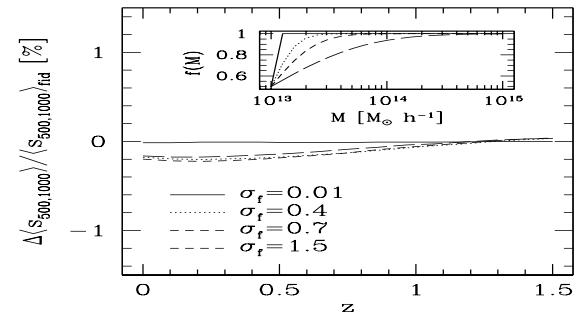
Mass Function Model



- ST-Despali vs ST-RayGal
- Need to Resolve the High-Mass End <5%

Selection Effects

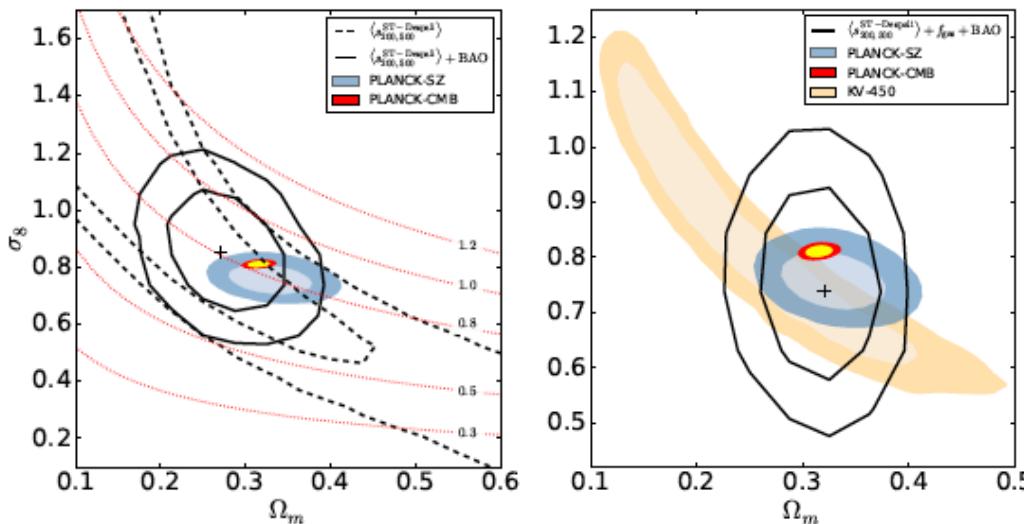
- Sub-percent level
- Can be easily included in data analysis



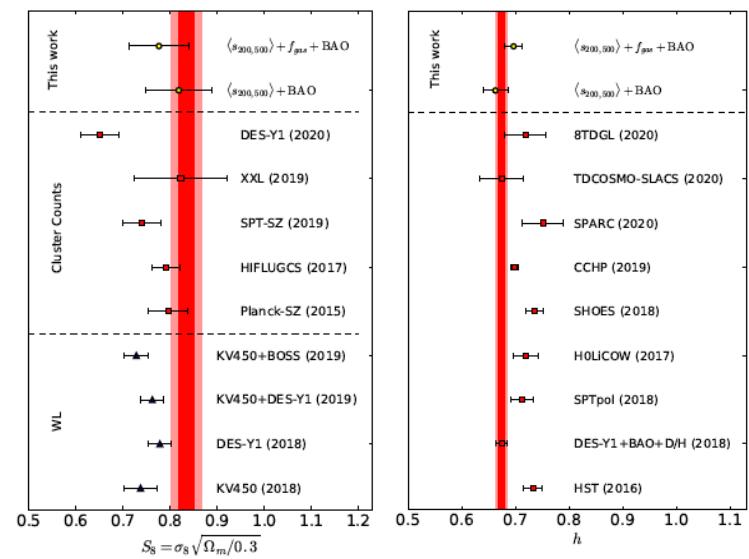
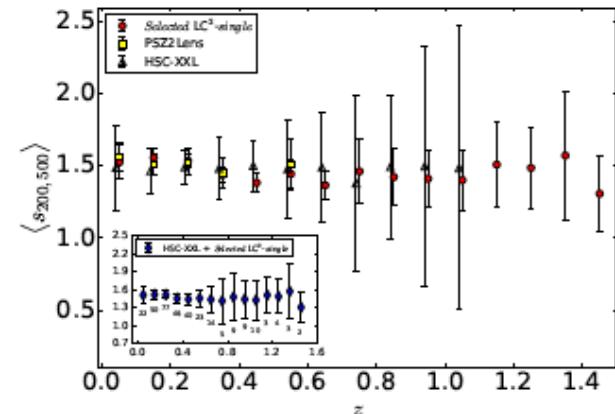
Cosmological Constraints

Weak Lensing Cluster Masses

- Selected LC²-Single + HSC-XXL Catalogs (317)
- $0 < z < 1.5$; $M_{200c} > 10^{13} M_{\text{sun}} h^{-1}$
- Joint BAO & f_{gas} analysis
- Constraints on flat LCDM model parameters



- Marginalised on f_{gas} parameters (K & Y_b)
- $\Omega_m = 0.32 \pm 0.02$; $\sigma_8 = 0.76 \pm 0.07$; $h = 0.70 \pm 0.02$
- No tension with Planck-CMB
- Assuming $K_{\text{CLASH}} \sim G(0.79, 0.09)$ $\rightarrow Y_b > 0.89$



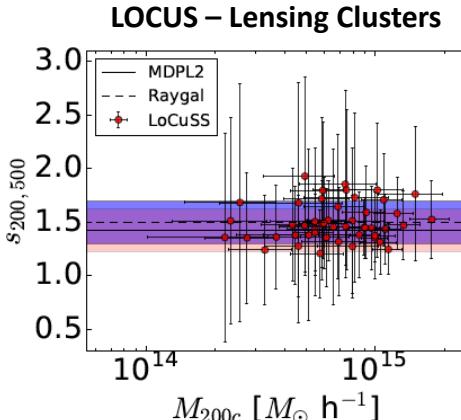
Consistency Relations

Distinct Average Sparsity Estimators

$$\langle s_{\Delta_1, \Delta_2} \rangle \equiv \left\langle \frac{M_{\Delta_1}}{M_{\Delta_2}} \right\rangle = \frac{1}{N_h} \sum_i \frac{M_{\Delta_1}^i}{M_{\Delta_2}^i}$$

$$\langle s_{\Delta_1, \Delta_2} \rangle \cong \frac{\langle 1/M_{\Delta_2} \rangle}{\langle 1/M_{\Delta_1} \rangle} = \frac{\sum_i 1/M_{\Delta_2}^i}{\sum_i 1/M_{\Delta_1}^i}$$

$$\langle s_{\Delta_1, \Delta_2} \rangle \cong \frac{\langle M_{\Delta_1} \rangle}{\langle M_{\Delta_2} \rangle} = \frac{\sum_i M_{\Delta_1}^i}{\sum_i M_{\Delta_2}^i}$$



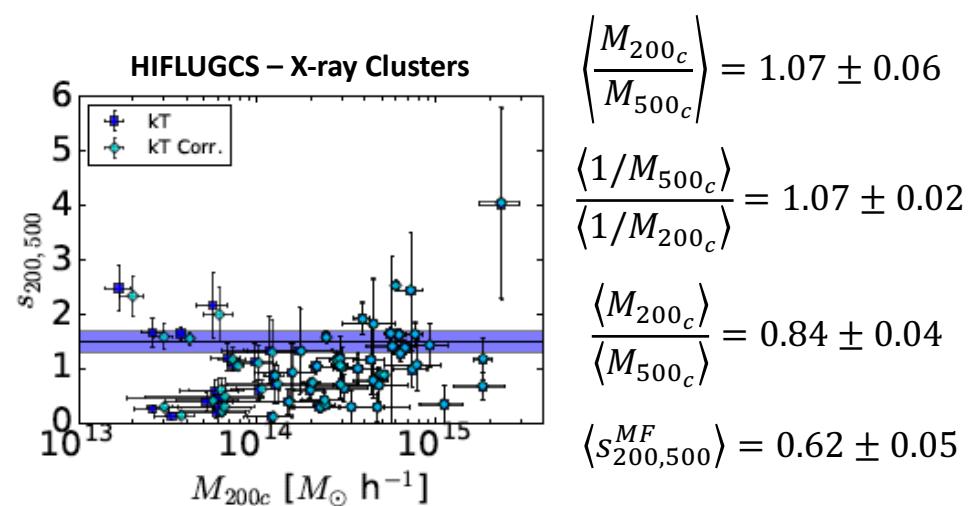
$$\left\langle \frac{M_{200c}}{M_{500c}} \right\rangle = 1.50 \pm 0.08$$

$$\frac{\langle 1/M_{500c} \rangle}{\langle 1/M_{200c} \rangle} = 1.49 \pm 0.12$$

$$\frac{\langle M_{200c} \rangle}{\langle M_{500c} \rangle} = 1.49 \pm 0.07$$

$$\int_{M_{\Delta_2}^{\min}}^{M_{\Delta_2}^{\max}} \frac{dn}{dM_{\Delta_2}} d\ln M_{\Delta_2} = \left\langle s_{\Delta_1 \Delta_2} \right\rangle \int_{\langle s_{\Delta_1 \Delta_2} \rangle M_{\Delta_2}^{\min}}^{\langle s_{\Delta_1 \Delta_2} \rangle M_{\Delta_2}^{\max}} \frac{dn}{dM_{\Delta_1}} d\ln M_{\Delta_1}$$

	z	$\left\langle \frac{M_{200c}}{M_{500c}} \right\rangle$	$\frac{\langle 1/M_{500c} \rangle}{\langle 1/M_{200c} \rangle}$	$\left\langle \frac{M_{200c}}{M_{500c}} \right\rangle$	$\langle s_{200,500}^{\text{MF}} \rangle \pm \sigma_{\langle s_{200,500} \rangle}^{\text{MF}}$
MDPL2	0.0	1.42	1.41	1.42	1.40 ± 0.01
	0.5	1.47	1.46	1.46	1.48 ± 0.02
	1.0	1.51	1.51	1.48	1.52 ± 0.03
Raygal	0.0	1.50	1.48	1.49	1.49 ± 0.03
	0.5	1.54	1.53	1.53	1.54 ± 0.05
	1.0	1.55	1.54	1.52	1.54 ± 0.05



$$\left\langle \frac{M_{200c}}{M_{500c}} \right\rangle = 1.07 \pm 0.06$$

$$\frac{\langle 1/M_{500c} \rangle}{\langle 1/M_{200c} \rangle} = 1.07 \pm 0.02$$

$$\frac{\langle M_{200c} \rangle}{\langle M_{500c} \rangle} = 0.84 \pm 0.04$$

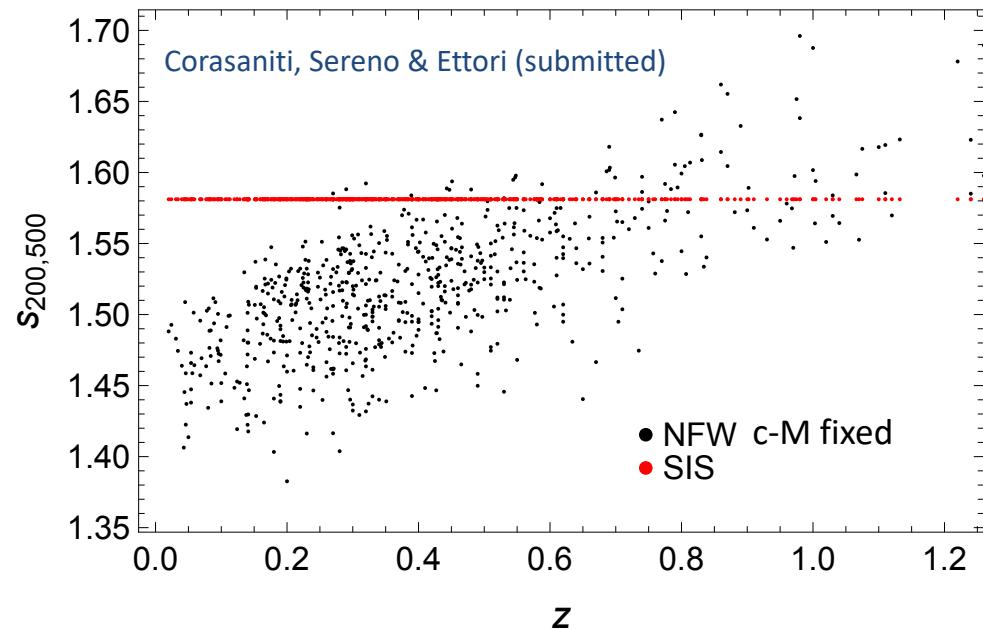
$$\langle s_{200,500}^{\text{MF}} \rangle = 0.62 \pm 0.05$$

Biases and Outliers

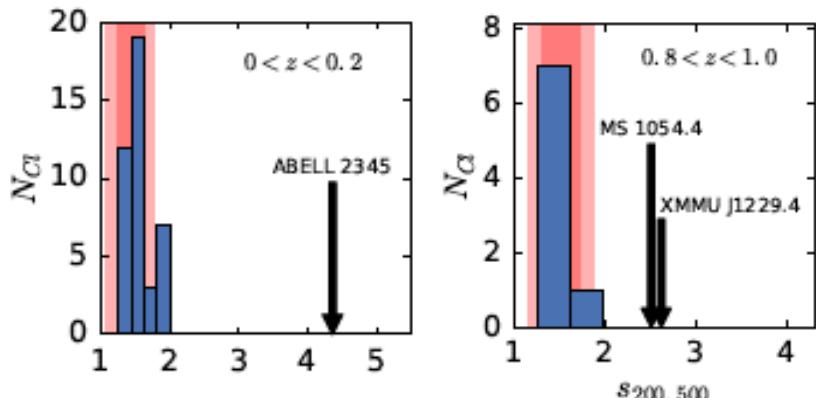
Lensing Masses

Shear Lensing Profile

- LC² clusters
- SIS profile: $s_{\Delta_1, \Delta_2} = \sqrt{\frac{\Delta_2}{\Delta_1}}$
- NFW with fixed c-M relation

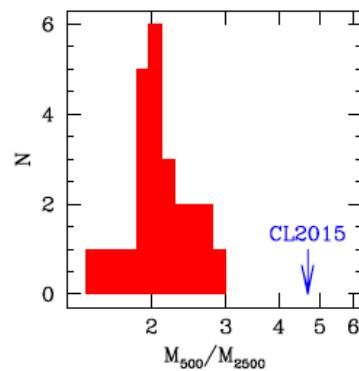


Major Merger & Dynamical State



- Clusters undergoing merger

X-ray Masses



- ### Hydrostatic Equilibrium
- Morphologically Relaxed Clusters vs CL2015

Andreon et al. (2019)

Conclusions

- Cluster sparsity as cosmological proxy
- Insensitive to selection effects
- Limited impact of radial dependent mass bias
- Mostly sensitive to degenerate combination $\Omega_m - \sigma_8$
- Constraints from lensing mass cluster catalogs
- Identification of outliers