THE DARK ENERGY SURVEY

LSST DESC
Dark Energy Science Collaboration

Impact of Property Covariance on Galaxy Cluster Weak-lensing Mass Calibration

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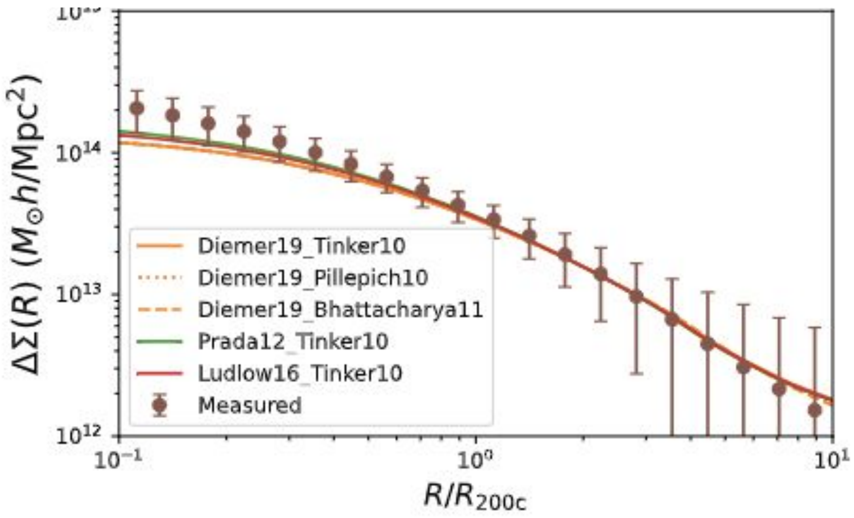
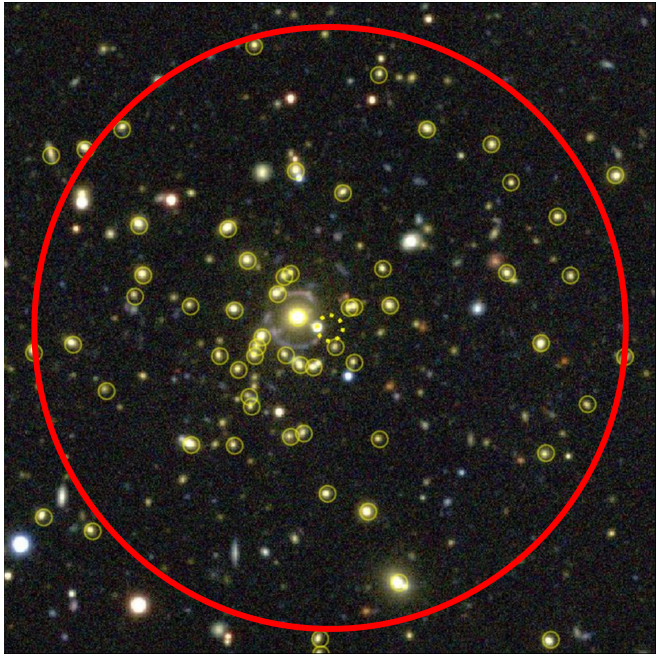
Weak lensing Observables



Cluster lensing – excess shear measurement of source galaxies when lensed by galaxy clusters.

$$\Sigma(R) = \Omega_m \rho_{\rm crit} \int_{-\infty}^{+\infty} dz\, \xi_{\rm hm}(\sqrt{R^2 + z^2}).$$

$$\Delta\Sigma = \bar{\Sigma}(< R) - \Sigma(R)$$

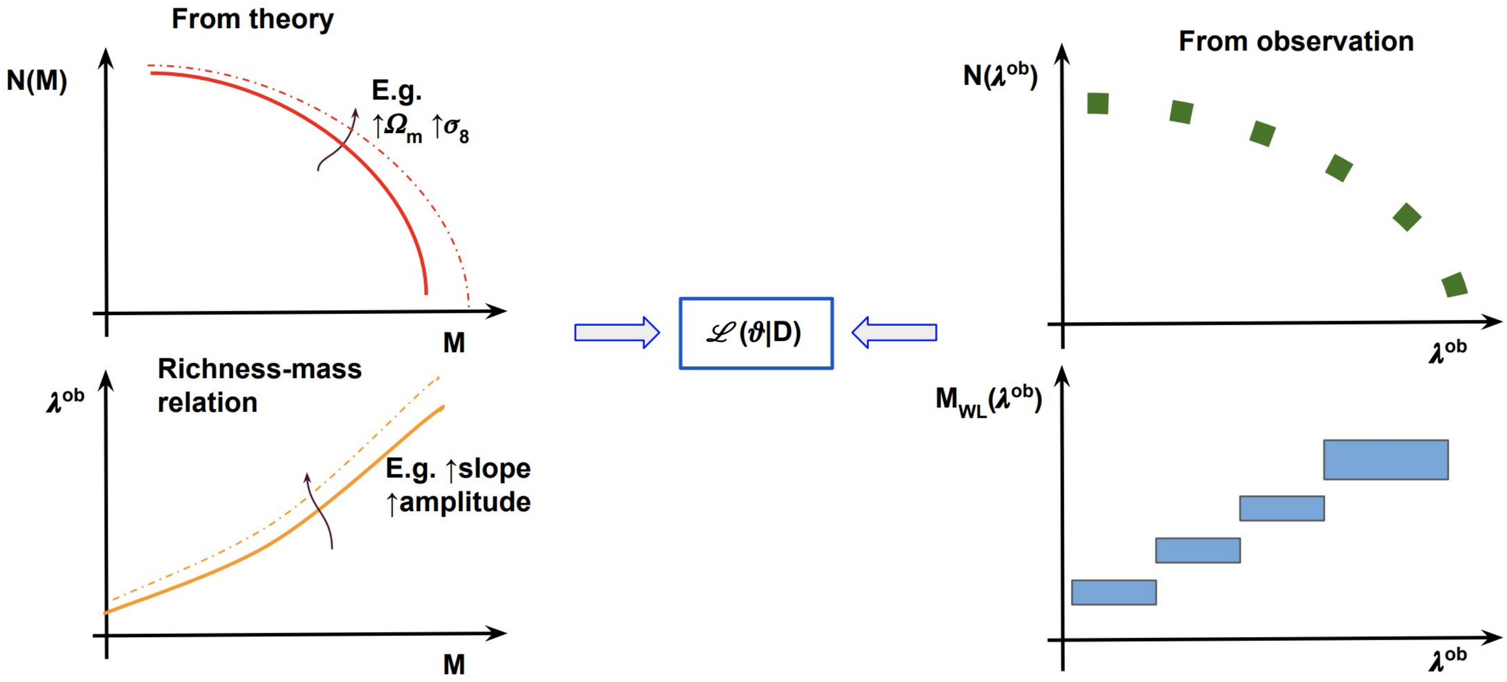


Richness – probabilistic number count of galaxies detected using red-sequence

$$\lambda = \sum p(\boldsymbol{x}|\lambda) = \sum_{R<R_c(\lambda)} \frac{\lambda u(\boldsymbol{x}|\lambda)}{\lambda u(\boldsymbol{x}|\lambda) + b(\boldsymbol{x})}.$$

Cluster Cosmology with optical surveys

- Combine cluster abundance and Weak lensing cluster mass estimates to simultaneously constrain cosmology and the richness-mass relation



PC: Matteo Costanzi

Systematic Biases with Cluster Observables

- Uncertainty shear measurements
- Photo-z uncertainty
- Triaxiality
- Miscentering
- Line-of-sight projection
- Membership dilution
- Modeling systematics
- Cosmology dependence

In DES Y1:
Total systematic uncertainty: 4.3%
Statistical: 2.4%

T. McClintock+19

Statistical uncertainty dominated by shape noise:

- n_s = ~5 galaxies/arcmin^2
- n_s = ~30 galaxies/arcmin^2 for next-gen optical survey, e.g. Rubin (LSST)

Systematics on par with statistical errors, soon to dominate for near future surveys

Unconstrained systematic — Correlated scatter

$$\mathrm{hmf}(\ln M, z) = \frac{\mathrm{d}n_{\mathrm{hmf}}(\ln M, z)}{\mathrm{d}\ln M} \approx A(z)\exp\left[-\gamma(m, z)\ln M\right]$$

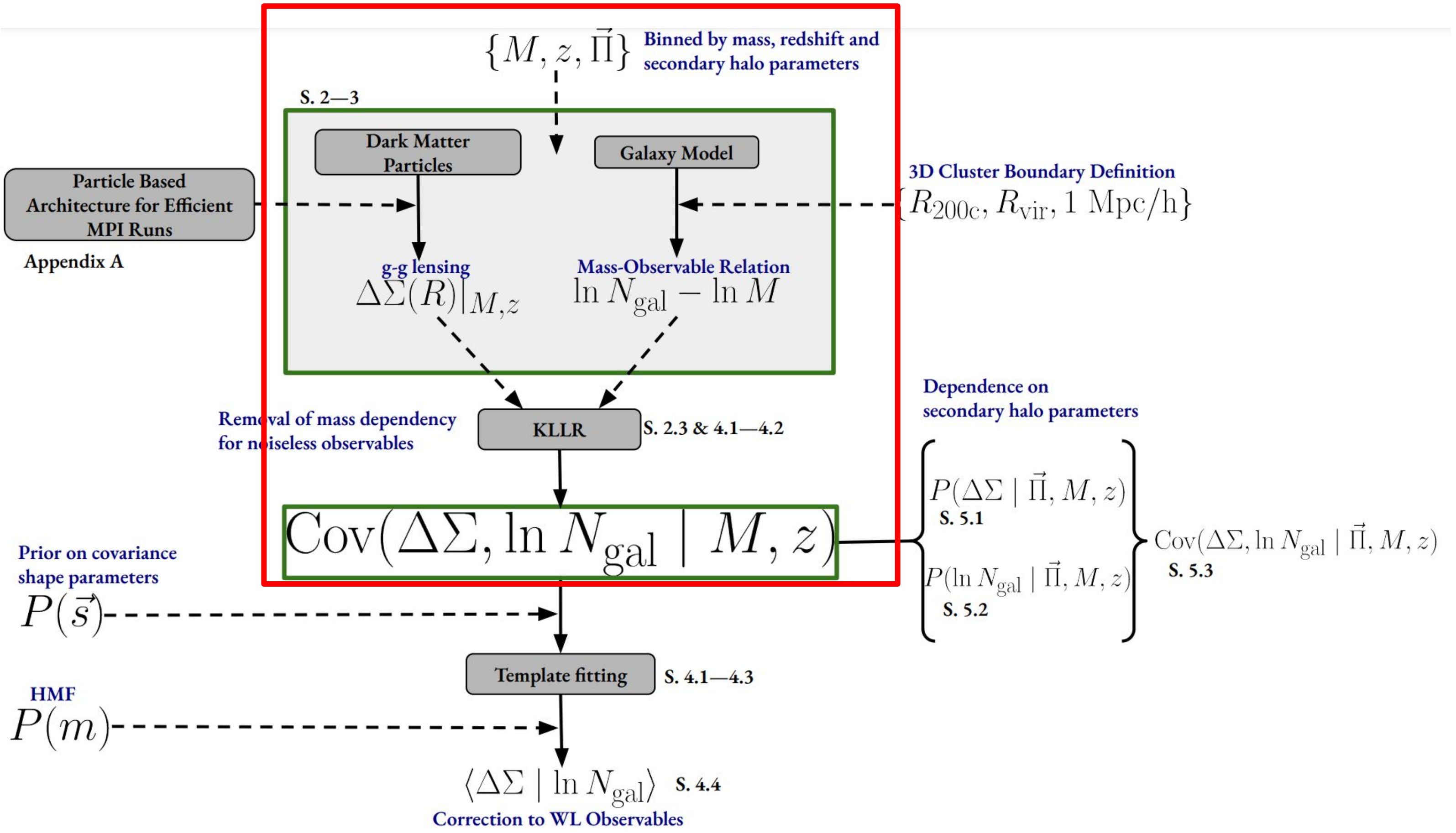
$$\langle \Delta\Sigma \mid N_{\mathrm{gal}} \rangle_1 = \langle \Delta\Sigma \mid M \rangle + \boxed{\frac{\gamma_1}{\alpha_n} \times \mathrm{Cov}(\Delta\Sigma, \ln N_{\mathrm{gal}} \mid M, z),}$$

This term left unconstrained by McClintock+19, DES 2020

Dataset: MDPL2 N-body simulation with SAGE semi-analytic galaxy model

Goal: Set informative priors using mock measurements of the correlated scatter between WL-observables

Outline: Data Vector



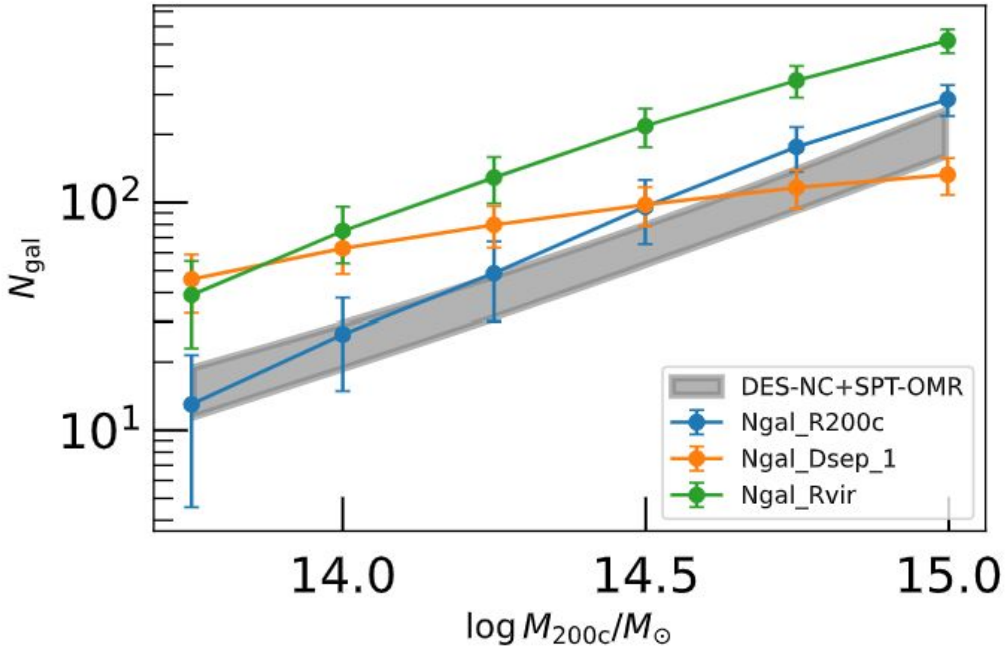
Ngal: True Richness Estimator

- Number count of galaxies enclosed inside a radius

3D Cluster Boundary Definition

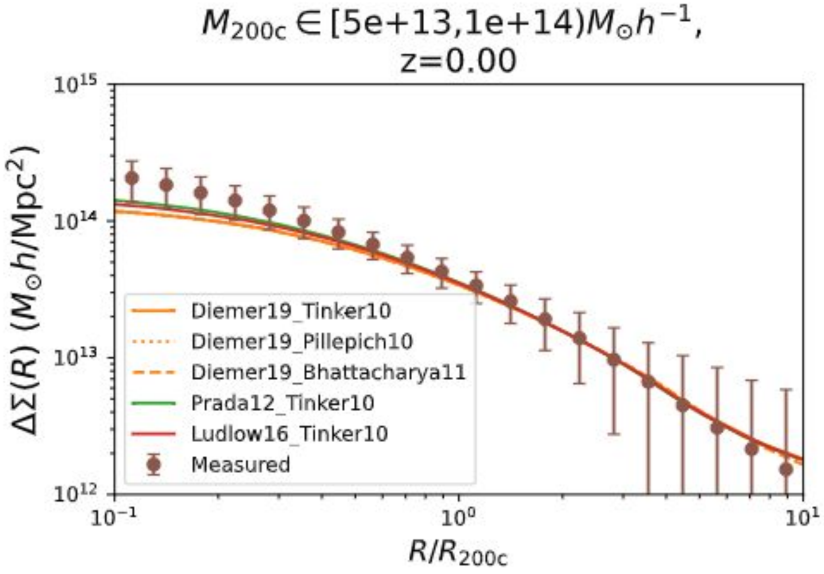
$$\{R_{200c}, R_{vir}, 1\ \mathrm{Mpc/h}\}$$

- No stellar, color cut; no projected galaxies along LOS
- Test for robustness against different radius definitions.



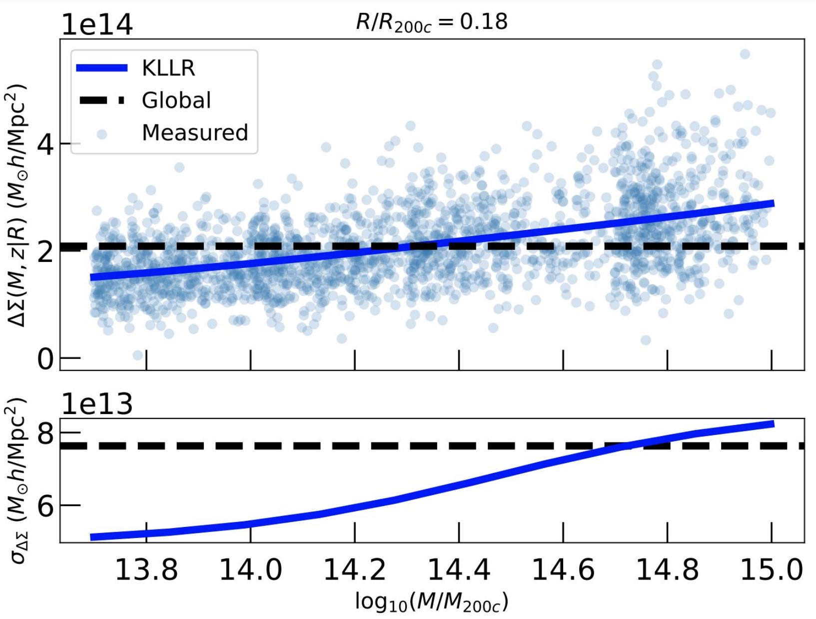
cluster lensing

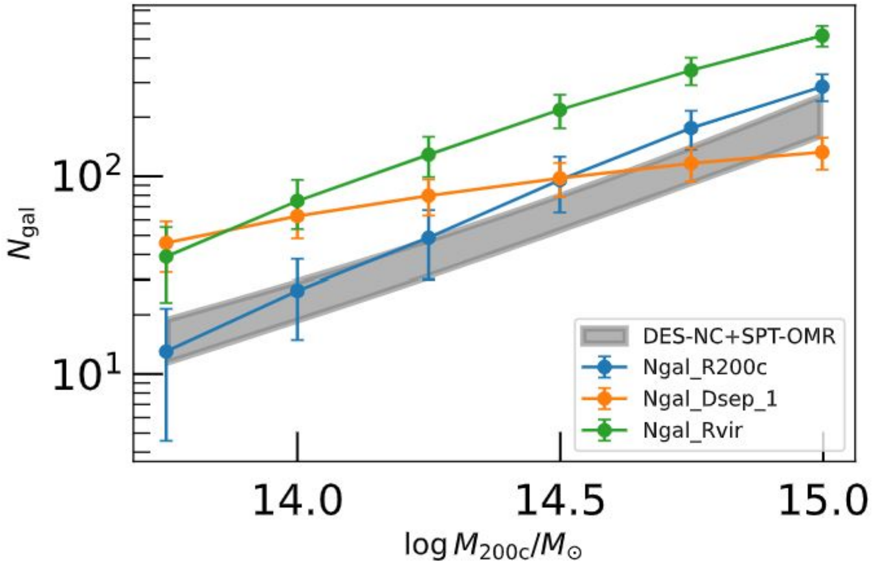
- Computed directly from DM particles
- (M,z) span optical cluster range
- Plotted against cosmology dependent models
  - c-M relation
  - halo bias
- Given errors are consistent with models but unable to distinguish



KLLR – Kernel Local Linear Regression

A. Farahi+21

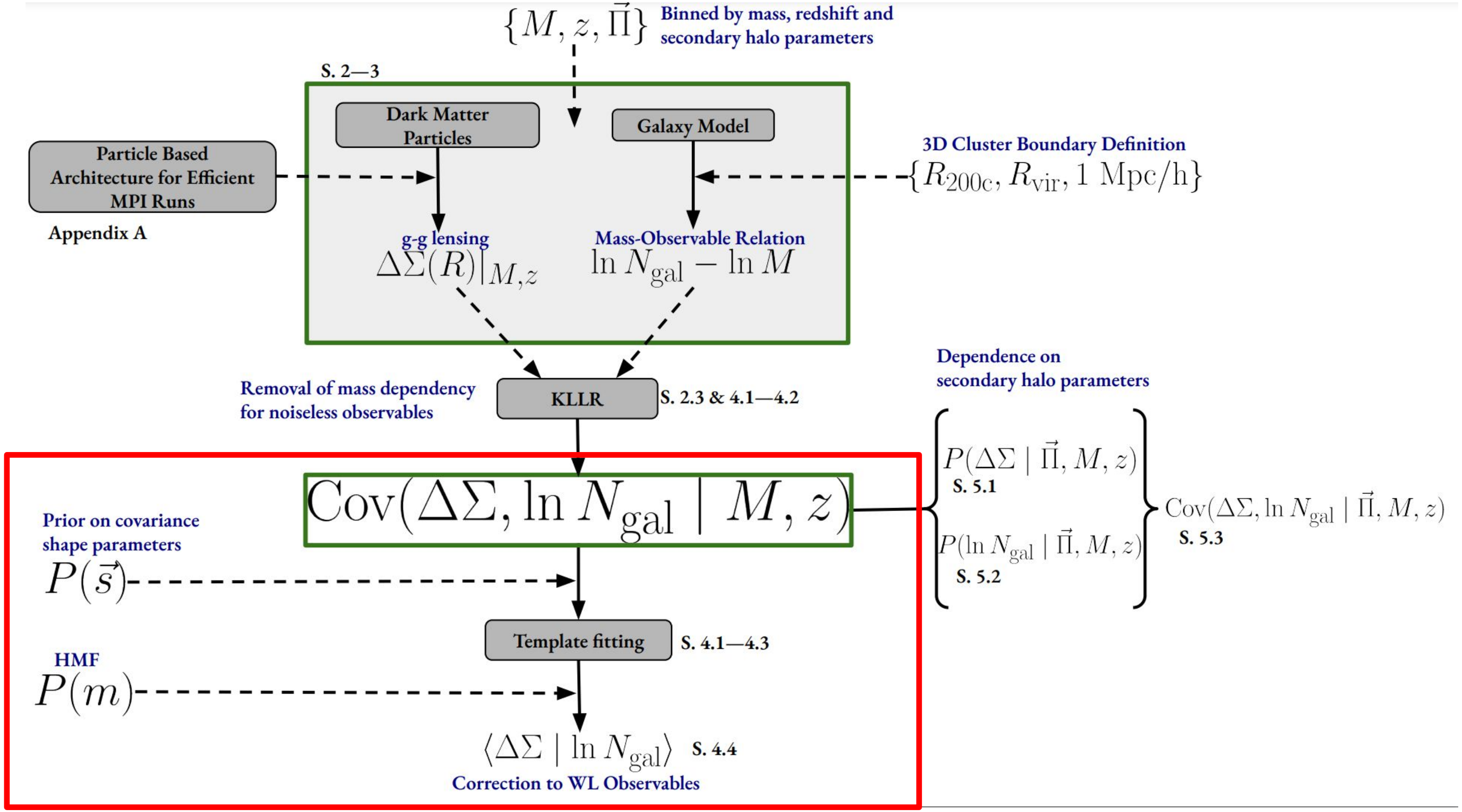


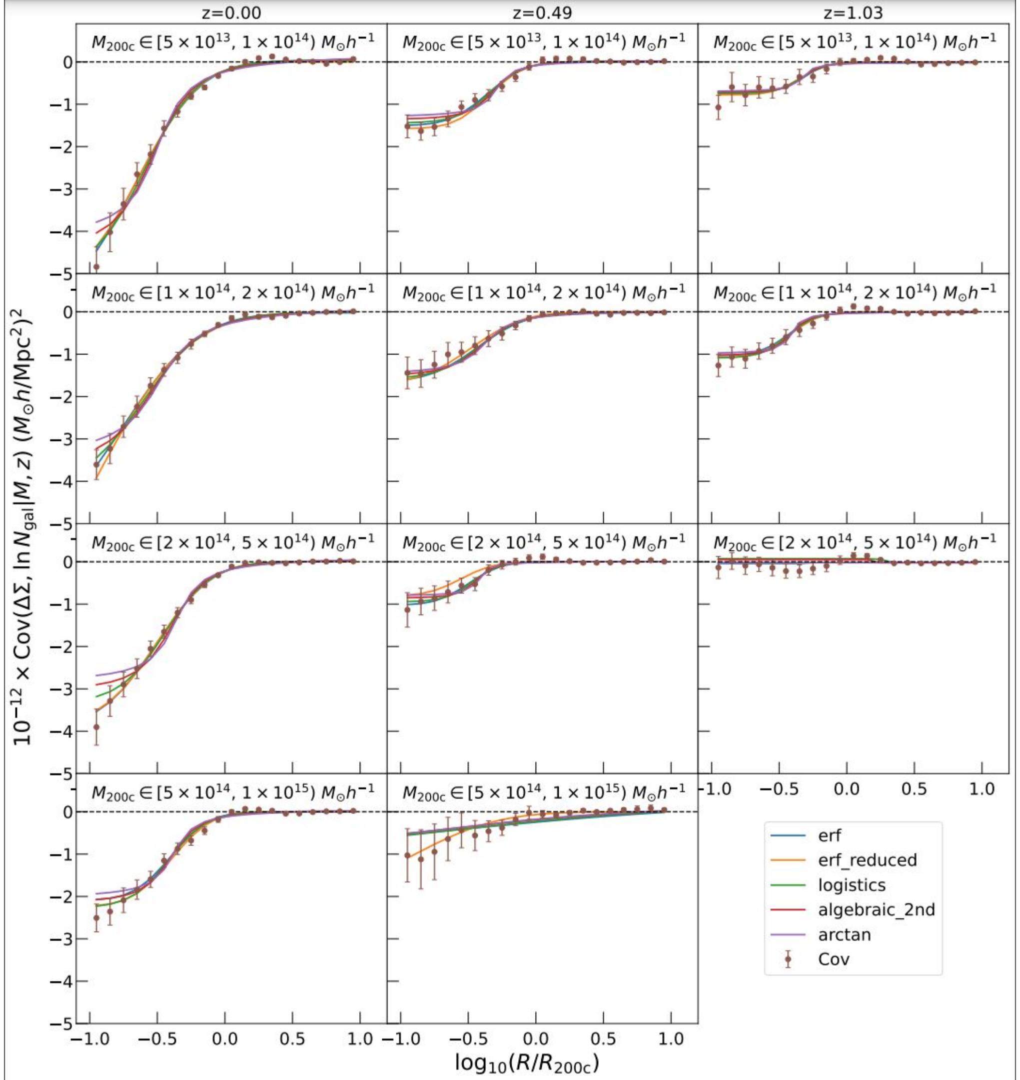


Local/global scatter of cluster lensing using KLLR

Local log-linear richness-mass relation using KLLR

Outline: Cov. measurement and modeling





- Negative at small scales, null at large scales
- Modeled as an offset error function
- Four parameter model

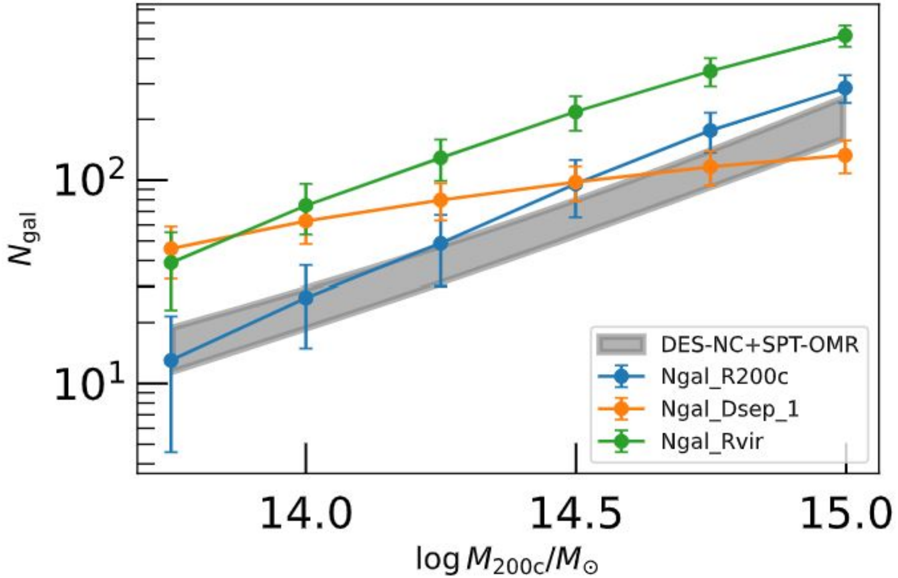
$$\tilde{x} = (x-\gamma)/\tau.$$

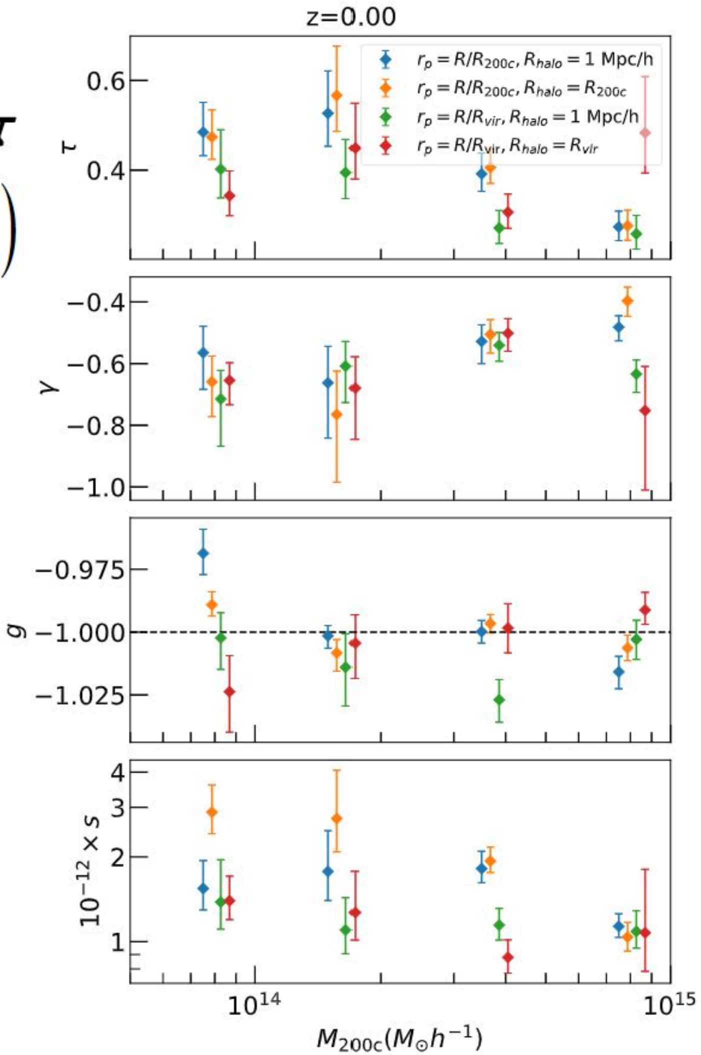
$$s\left(\mathrm{erf}\left(\frac{\sqrt{\pi}}{2}\tilde{x}\right) + g\right)$$

Modeling: Impact of Radius definition

$$\tilde{x} = (x - \gamma)/\tau$$

$$s\left(\mathrm{erf}\left(\frac{\sqrt{\pi}}{2}\tilde{x}\right) + g\right)$$

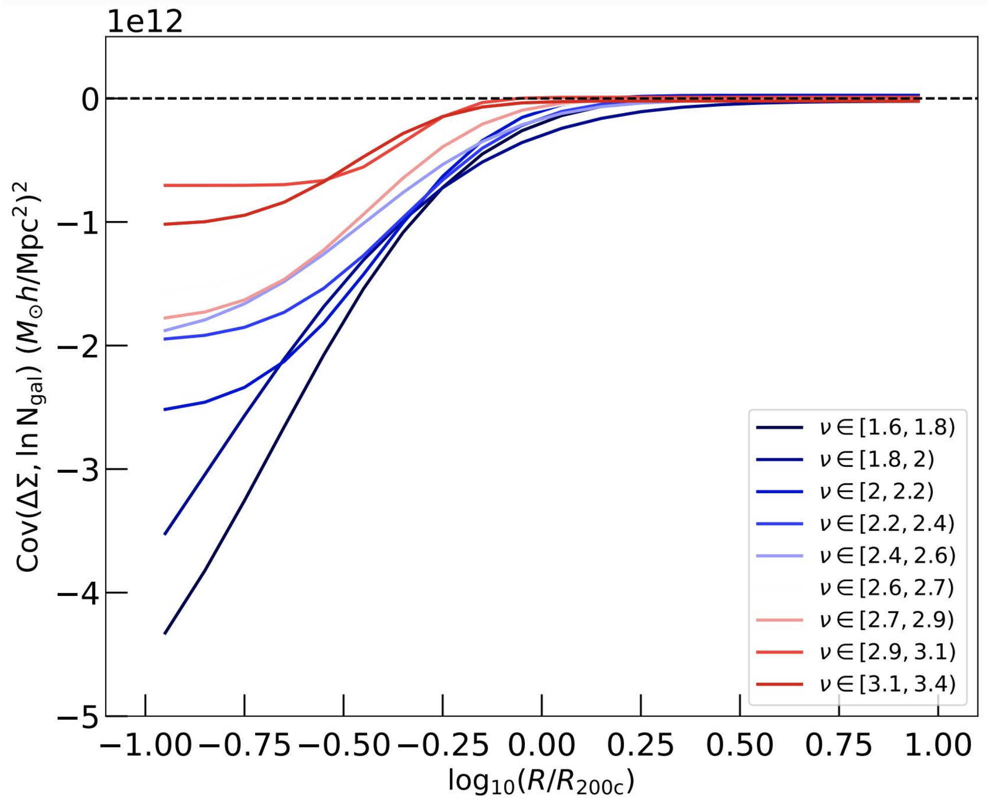


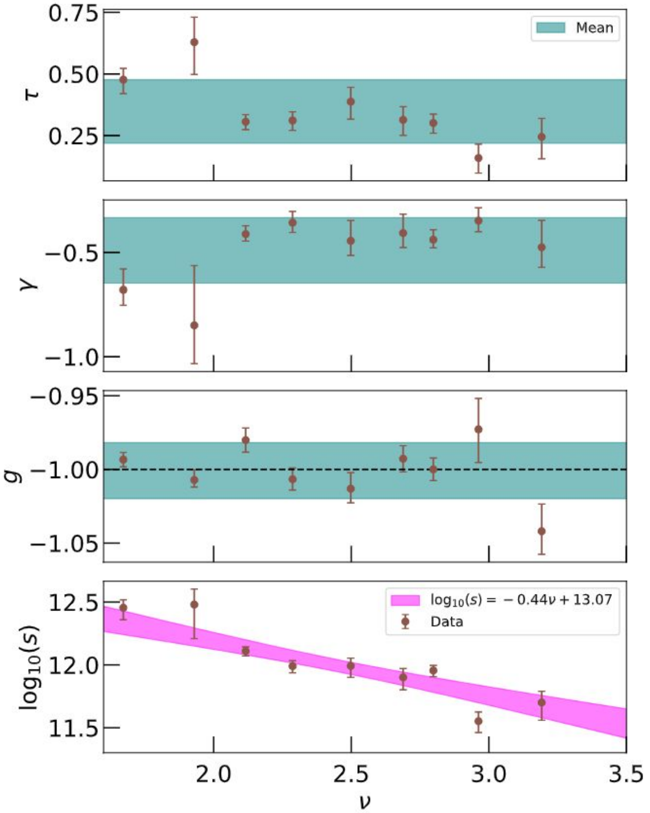


Binning by halo peak height $\nu = \frac{\delta_c}{\sigma(R, a)}$

$$\tilde{x} = (x - \gamma)/\tau$$

$$s\left(\mathrm{erf}\left(\frac{\sqrt{\pi}}{2}\tilde{x}\right) + g\right)$$

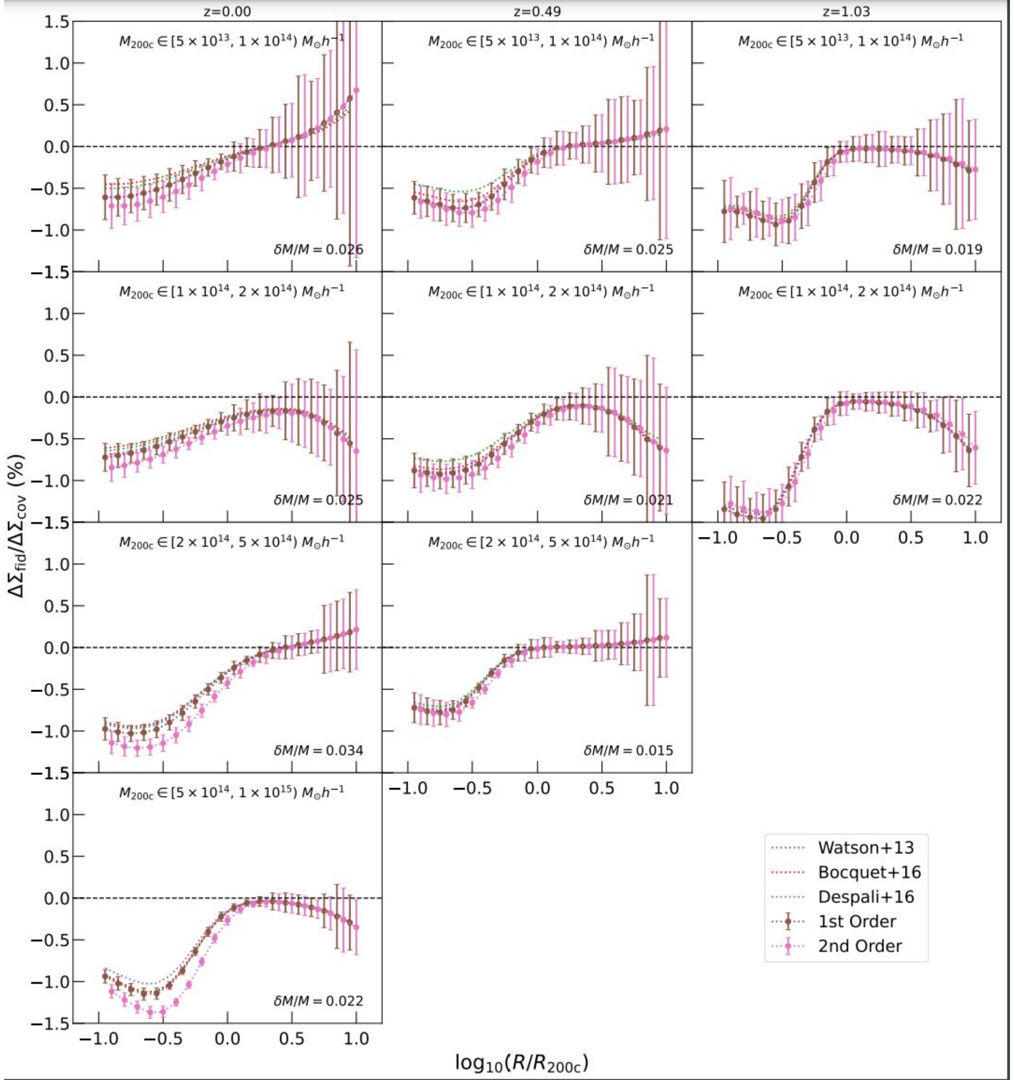




$$\langle \Delta\Sigma \mid N_{\rm gal}\rangle_1 = \langle \Delta\Sigma \mid M\rangle + \frac{\gamma_1}{\alpha_n} \times \mathrm{Cov}(\Delta\Sigma, \ln N_{\rm gal} \mid M, z)$$

$$\langle \Delta\Sigma|N_{\rm gal}\rangle_2 = \langle \Delta\Sigma|N_{\rm gal}\rangle_{\rm fid} + [\frac{x_s}{\alpha_n}(\gamma_1+\gamma_2\delta_n)\mathrm{Cov}(\Delta\Sigma, \ln N_{\rm gal}|M,z)].$$

- ~1% bias on stacked lensing at small scales
- Propagated into 2-3% mass bias

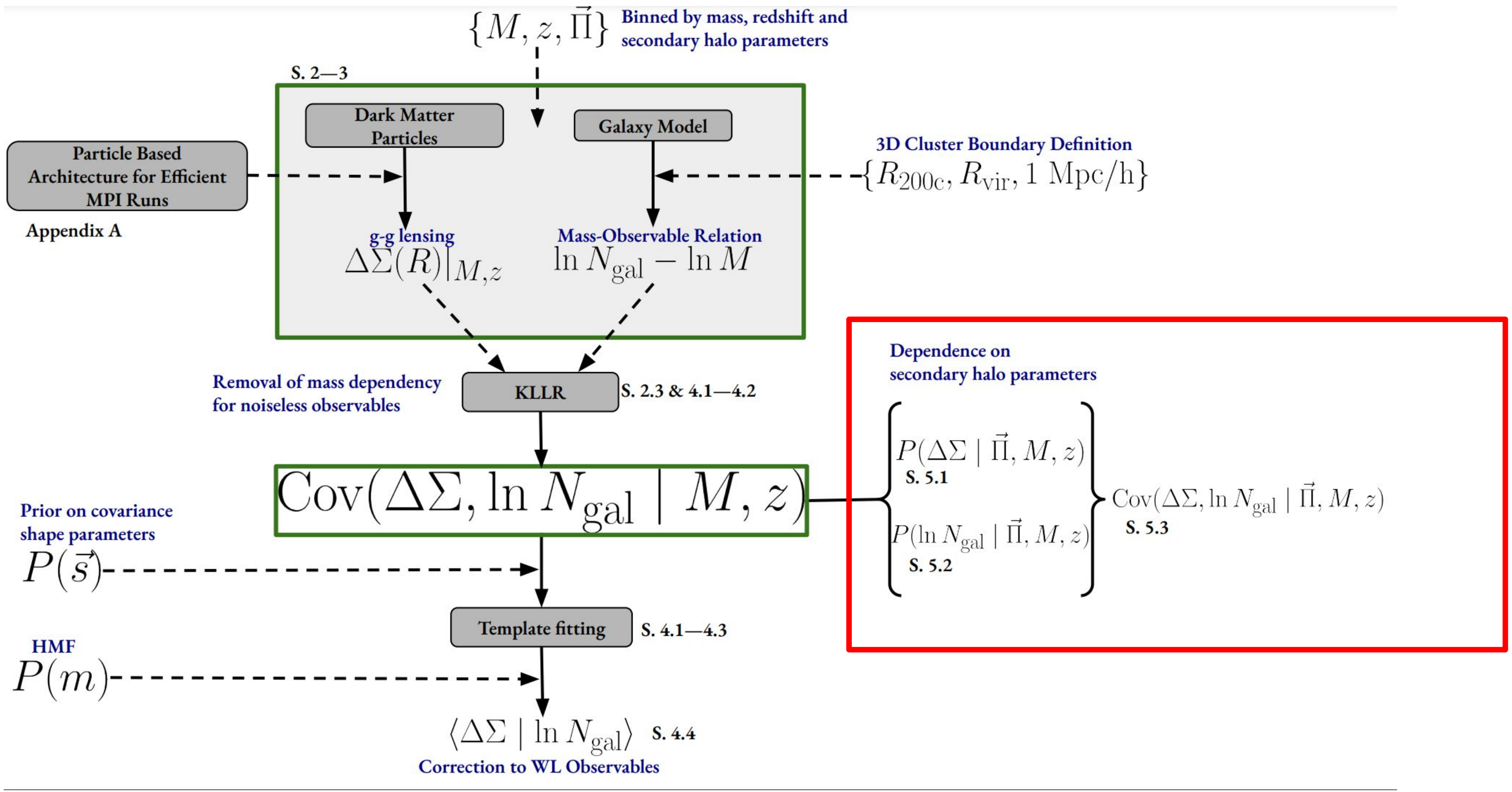


Source of systematic	SV Amplitude uncertainty	Y1 Amplitude Uncertainty
Shear measurement	4%	1.7%
Photometric redshifts	3%	2.6%
Modeling systematics	2%	0.73%
Cluster triaxiality	2%	2.0%
Line-of-sight projections	2%	2.0%
Membership dilution + miscentering	$\leqslant$ 1%	0.78%
Total Systematics	6.1%	4.3%
Total Statistical	9.4%	2.4%
Total	11.2%	5.0%

McClintock+19

Uncorrelated scatter 2-3% bias needs to be modeled!

Outline: Secondary halo parameter dependence



Secondary halo parameter dependence

$$\langle \ln N_{\rm gal} \mid \Pi, M, z\rangle = \pi_n(m,z) + \alpha_n(m,z)\ln M + \vec{\beta}_n^{\mathsf{T}}(m,z)\cdot\vec{\Pi} + \epsilon_n;$$

$$\langle \Delta\Sigma \mid \Pi, M, z\rangle = \pi_\tau(m,z) + \alpha_\tau(m,z)\ln M + \vec{\beta}_\tau^{\mathsf{T}}(m,z)\cdot\vec{\Pi} + \epsilon_\tau,$$

$$\mathrm{Cov}(\Delta\Sigma, \ln N_{\rm gal} \mid M, z) = \mathrm{Cov}(\vec{\beta}_\tau^{\mathsf{T}}\cdot\vec{\Pi}, \vec{\beta}_n^{\mathsf{T}}\cdot\vec{\Pi}) = \vec{\beta}_\tau^{\mathsf{T}}\mathrm{Cov}(\vec{\Pi},\vec{\Pi})\vec{\beta}_n.$$

Parameter	Explanation
$\vec{\Pi}$	Set of secondary halo parameters
$\Gamma_{\rm inst}$	instantaneous mass accretion rate (MAR)
$\Gamma^*_{\rm 100Myr}$	mean MAR over the past 100 Myr
$\Gamma^*_{\rm dyn}$	mean MAR over virial dynamical time
$\Gamma^*_{\rm 2dyn}$	mean MAR over two virial dynamical time
$\Gamma_{\rm peak}$	Growth rate of peak mass from current z to z+0.5
$a_{1/2}$	Half mass scale factor
$c_{\rm vir}$	$R_{\rm vir}$ concentration
T/|U|	Absolute value of the kinetic to potential energy ratio
$X_{\rm off}$	Offset of density peak from mean particle position (kpc h^{-1})
ρ_{Π_a,Π_b}	Correlation coefficient between secondary halo parameters

Shin & Diemer+23 quantified correlation of secondary halo parameters

This project provides the slopes β

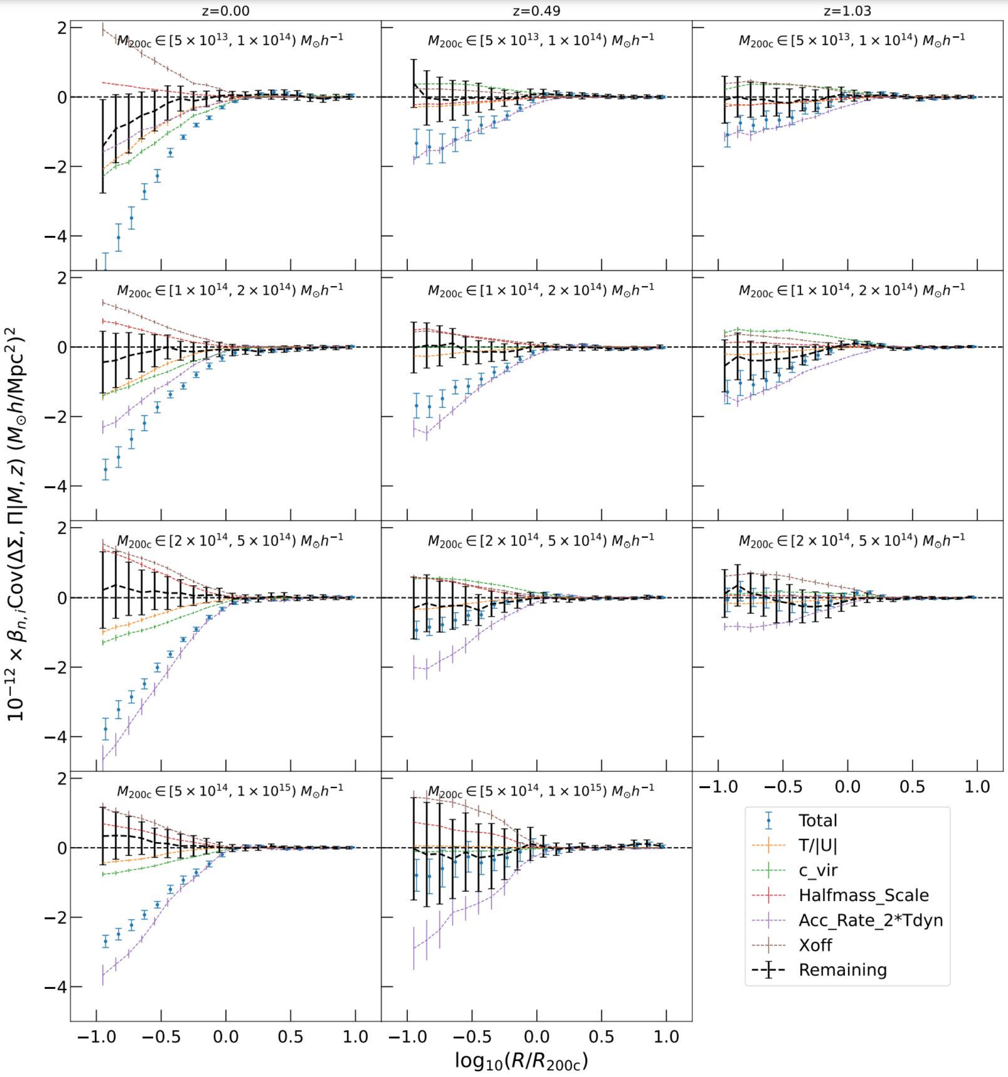
Cov. dependence on secondary halo parameters

$$\mathrm{Cov}(\Delta\Sigma, \ln N_{\mathrm{gal}}|M, z) = \sum_i \beta_{n,i}(m, z)\mathrm{Cov}(\Delta\Sigma, \Pi_i|M, z).$$

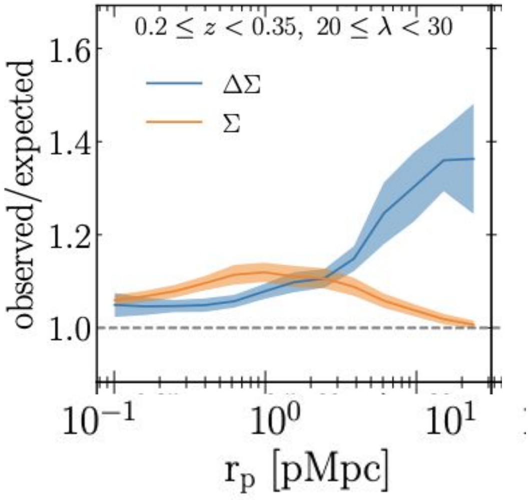
Secondary parameters **fully** explain the covariance

- i.e. Cov remaining = 0

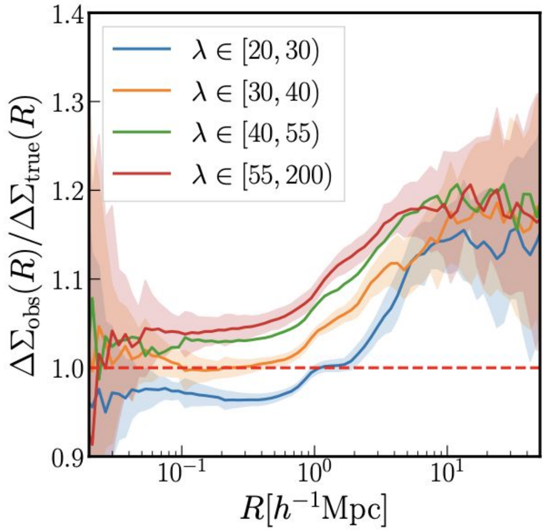
No dominant secondary halo parameter; all noisy and bias indicators of time formation



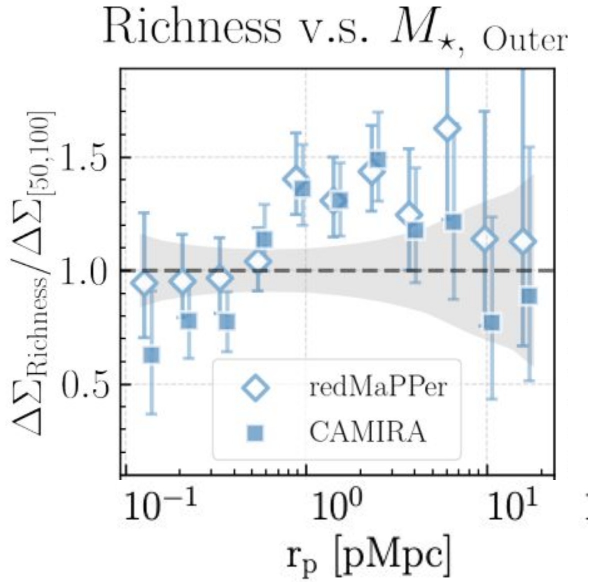
Comparison with other works: Projection effects?



Heidi Wu+2022



Tomomi Sunayama+2020



Song Huang+2021

Takeaways from this project

- Negative covariance at small scales, null at large scales.
- Folds into a mass bias of 2-3% in the halo mass estimates in most bins.
- Dependence with peak height suggests time formation history dependence of the covariance
- Physical origin fully explained by the secondary halo parameter
- Difference between other works likely due to projection effects