Galaxy clusters in the Dark Energy Survey

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THE UNIVERSITY OF ARIZONA
COLLEGE OF SCIENCE
Physics

DES - Cerro Tololo Inter-American Observatory

Dark Energy Survey:

- 5000 sq. deg.
- Project lifetime of 5.5 years
- Goal is to measure dark energy
- Optically selected galaxy clusters with **redMaPPer** algorithm

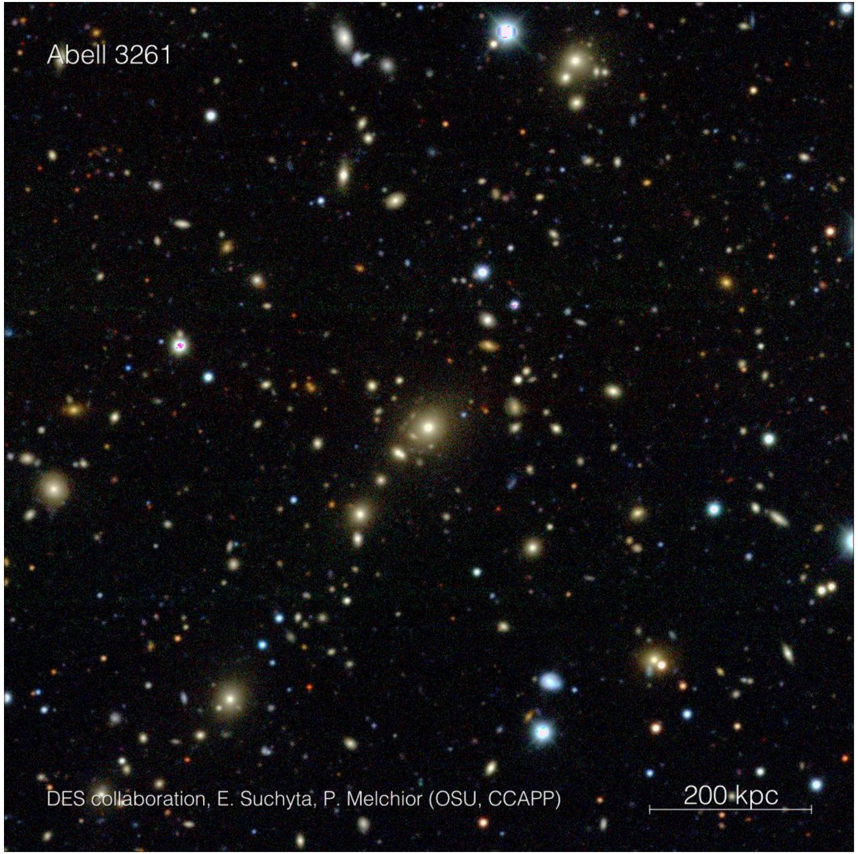
Image courtesy of DES

Galaxy clusters & cosmology

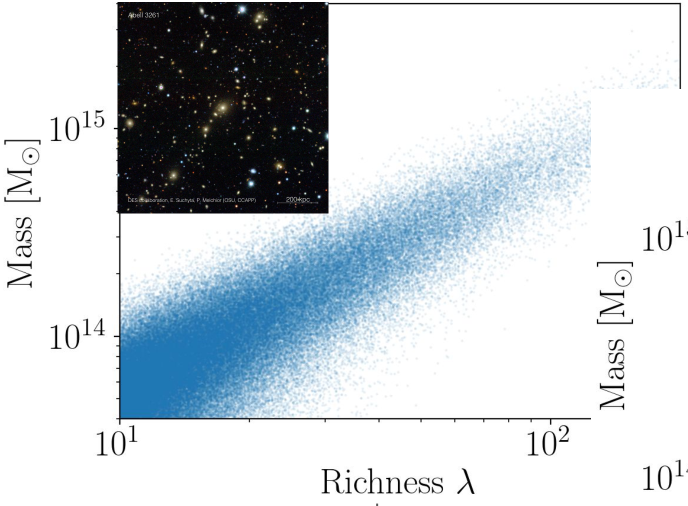
Cosmic Visions Report:

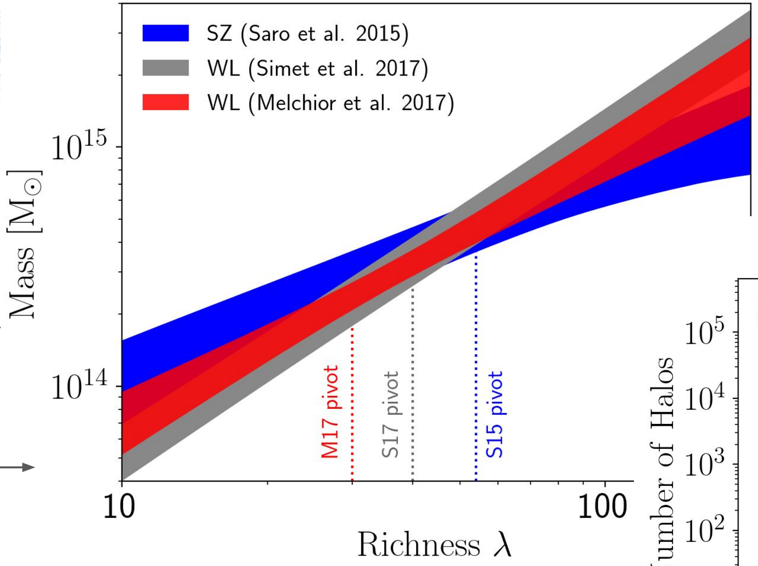
"galaxy clusters could emerge as the most powerful cosmological probe"

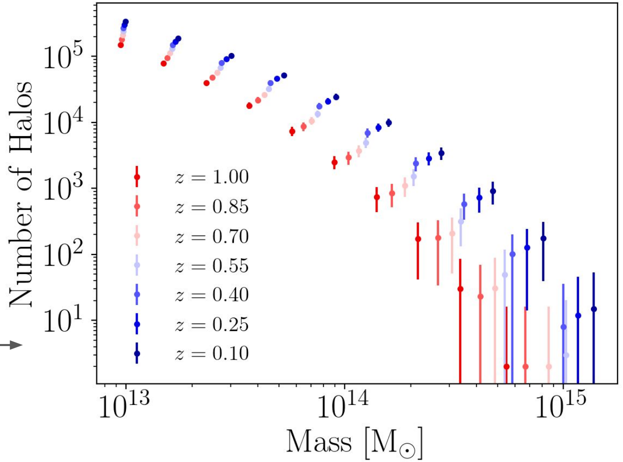
$$\sigma_{\ln \sigma_8 \Omega_m^{0.5}} \approx \frac{1}{2}\sigma_{\ln M}$$



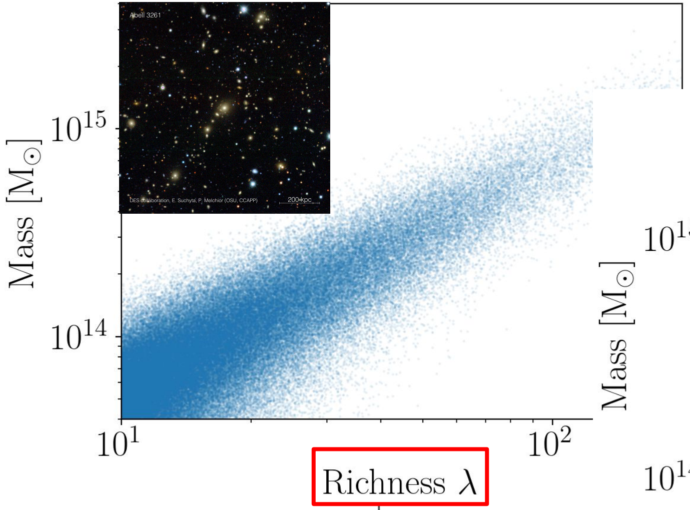
Cluster cosmology 101

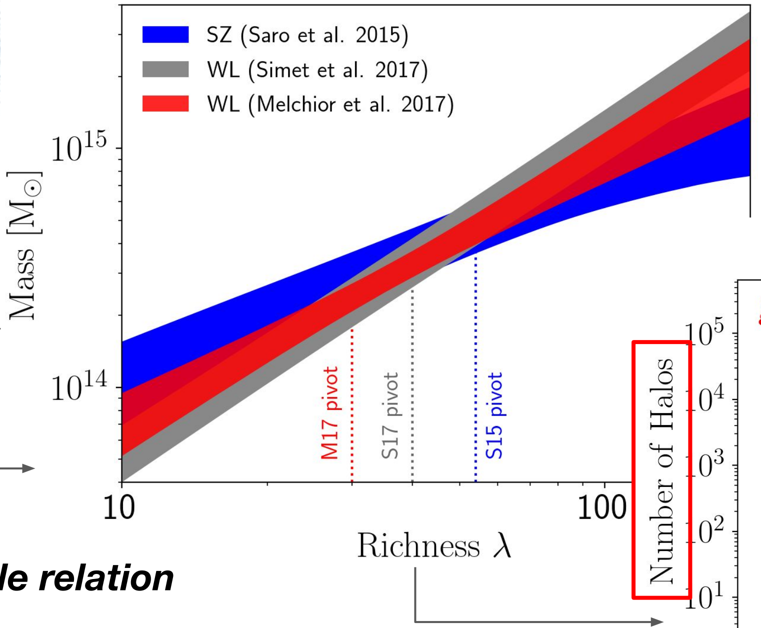


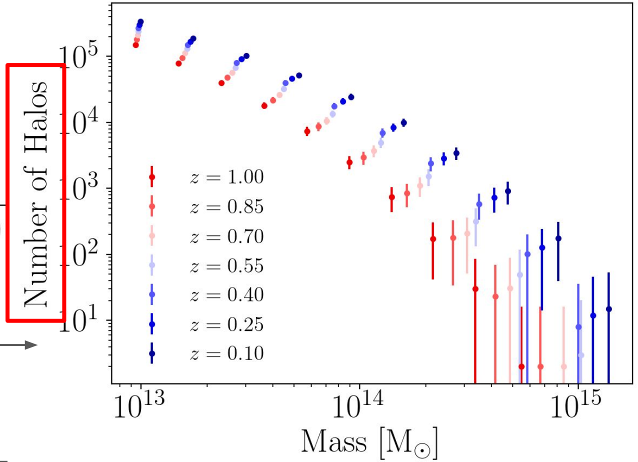




Cluster cosmology 101

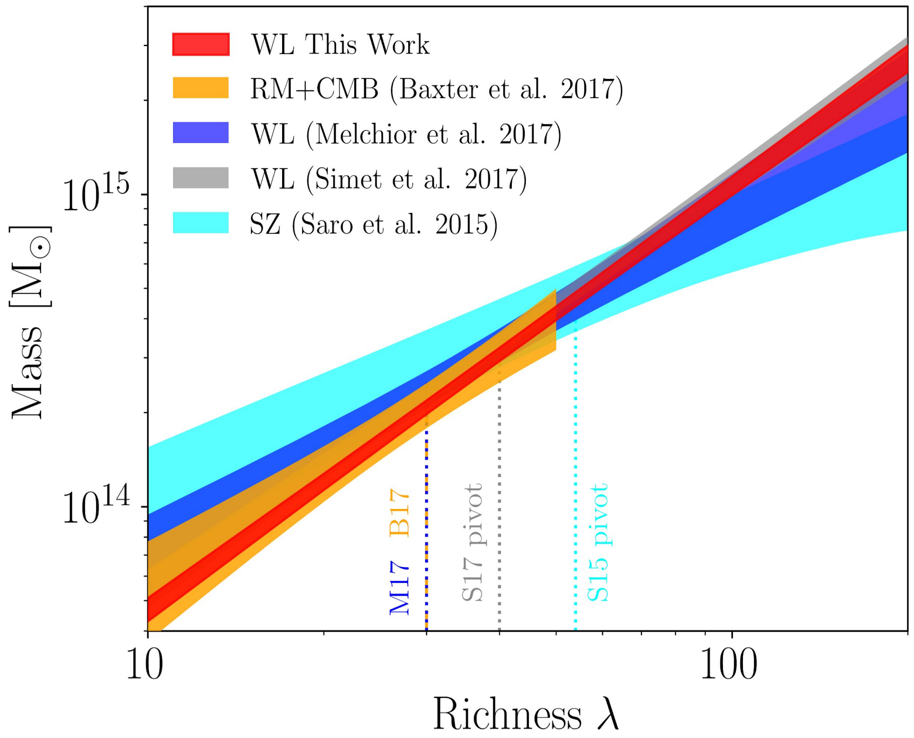




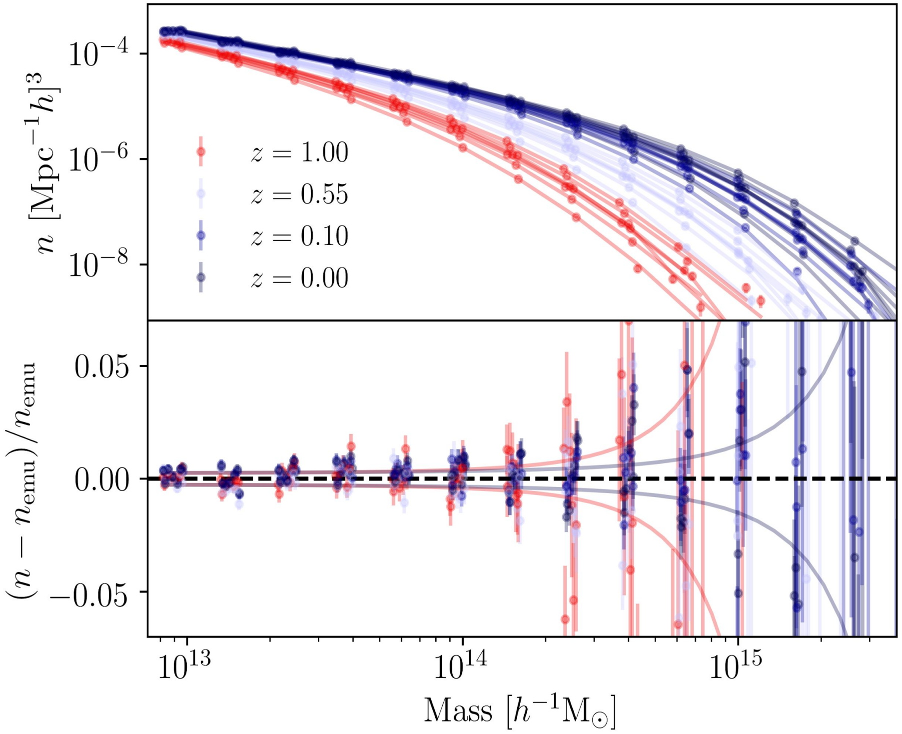


Step 1: *cluster observable*
Step 2: *halo mass--observable relation*
Step 3: *mass function*

My projects

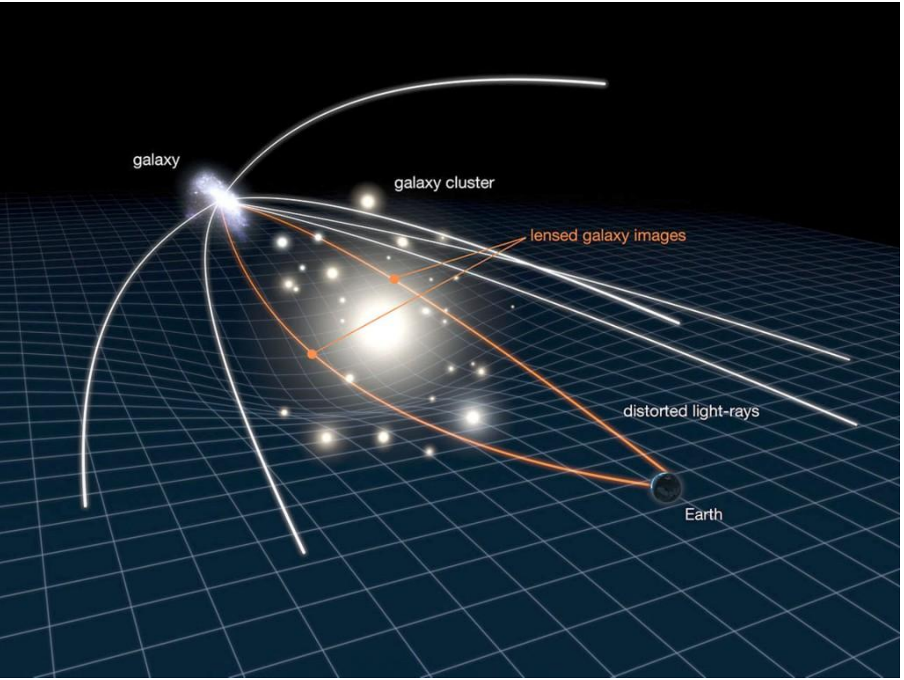


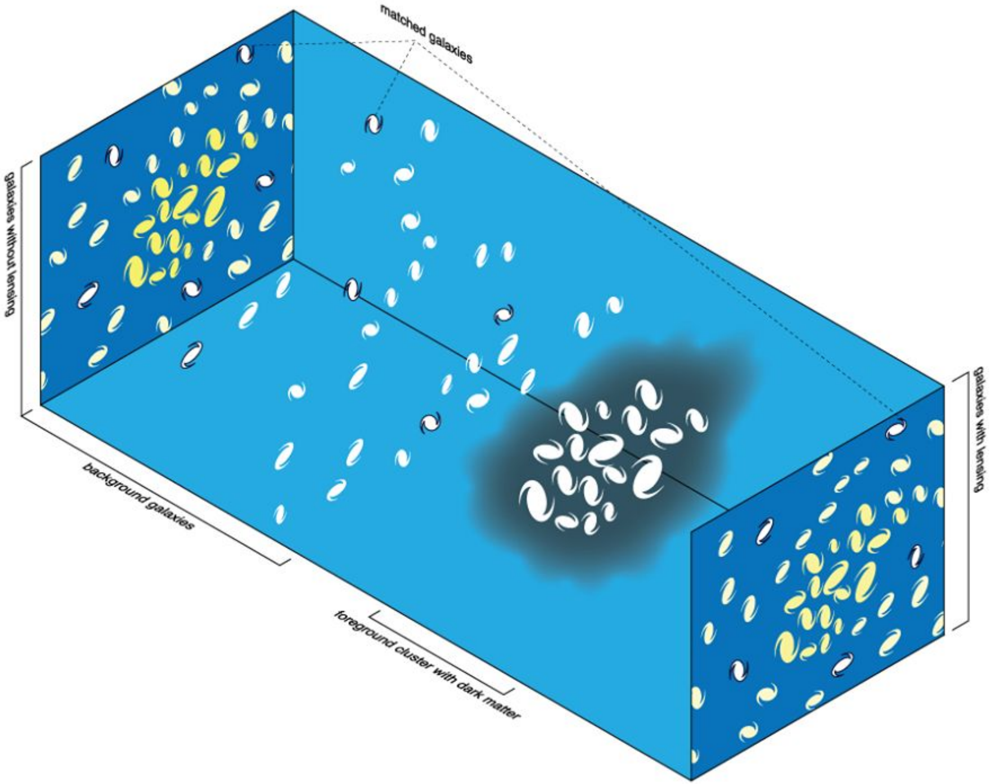
Gravitational lensing mass measurements



Halo mass function emulation

First project: cluster masses from gravitational lensing



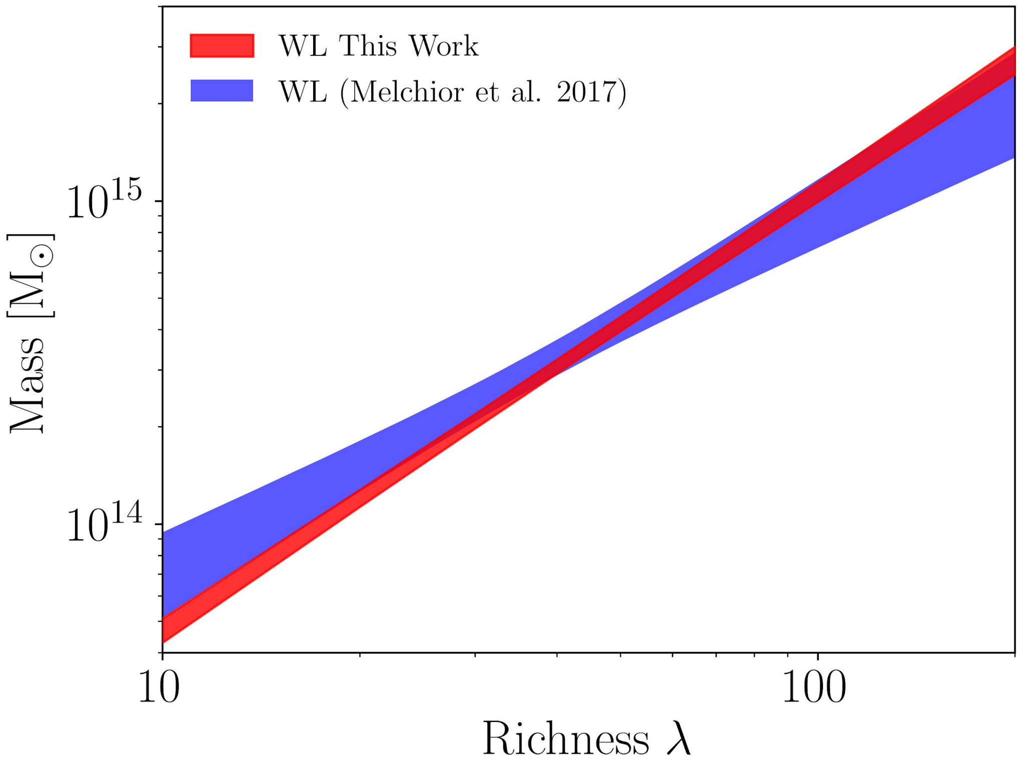


Upgrades compared to SV (Melchior+)

1. Many clusters
2. Semi-analytic covariance matrix
3. Calibration of modeling systematics

Results:

- Tight mass calibration
- Well understood error budget



Cluster weak lensing profiles

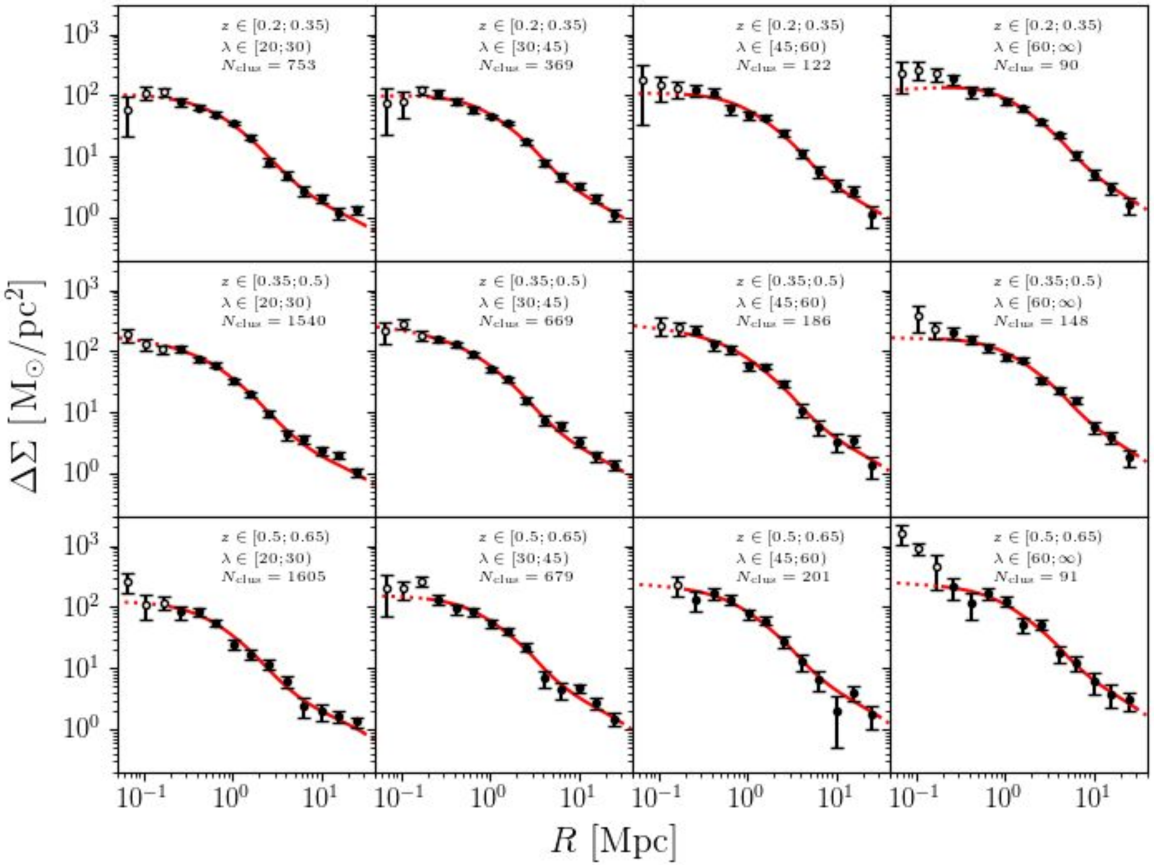
Differential surface density

- Proportional to galaxy tangential shear
- 1-halo + 2-halo profile

Black points - used in fit

Unfilled points - not fit

Red line - best fit model



Lensing model + systematics

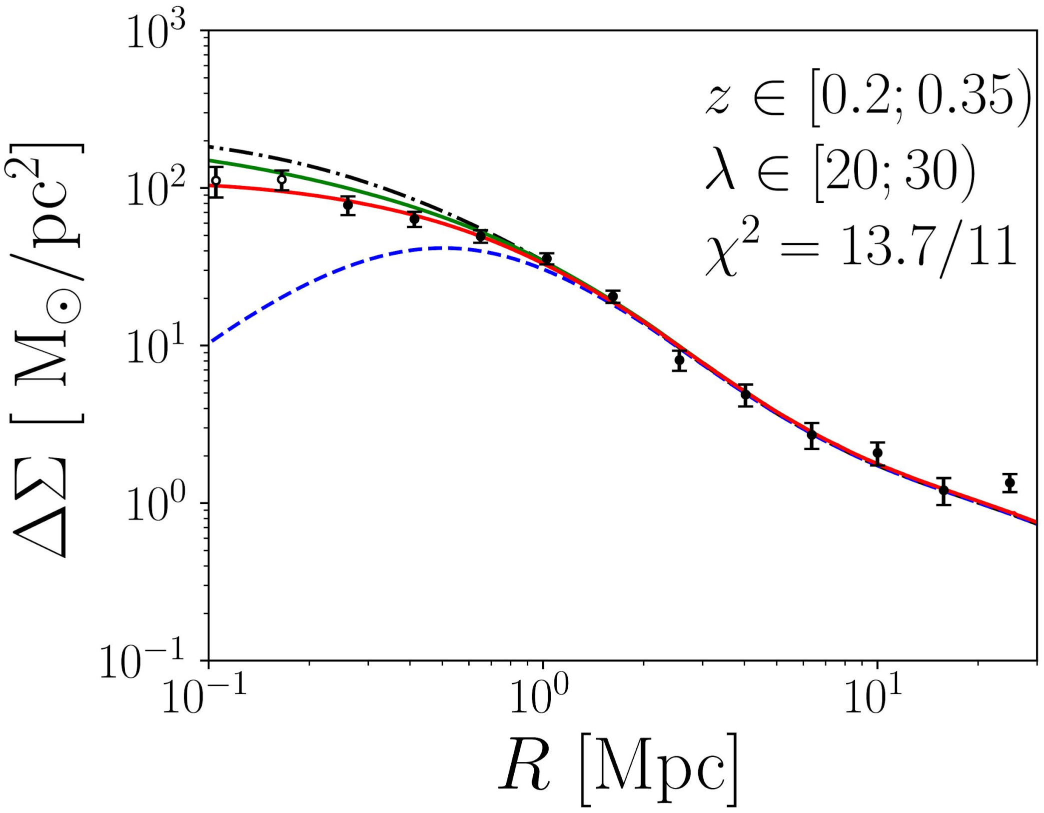
Lensing model:

- centered (black .-)
- miscentered (blue -)
- boost factor, shear+pz (red)
- triaxiality+proj. (not shown)

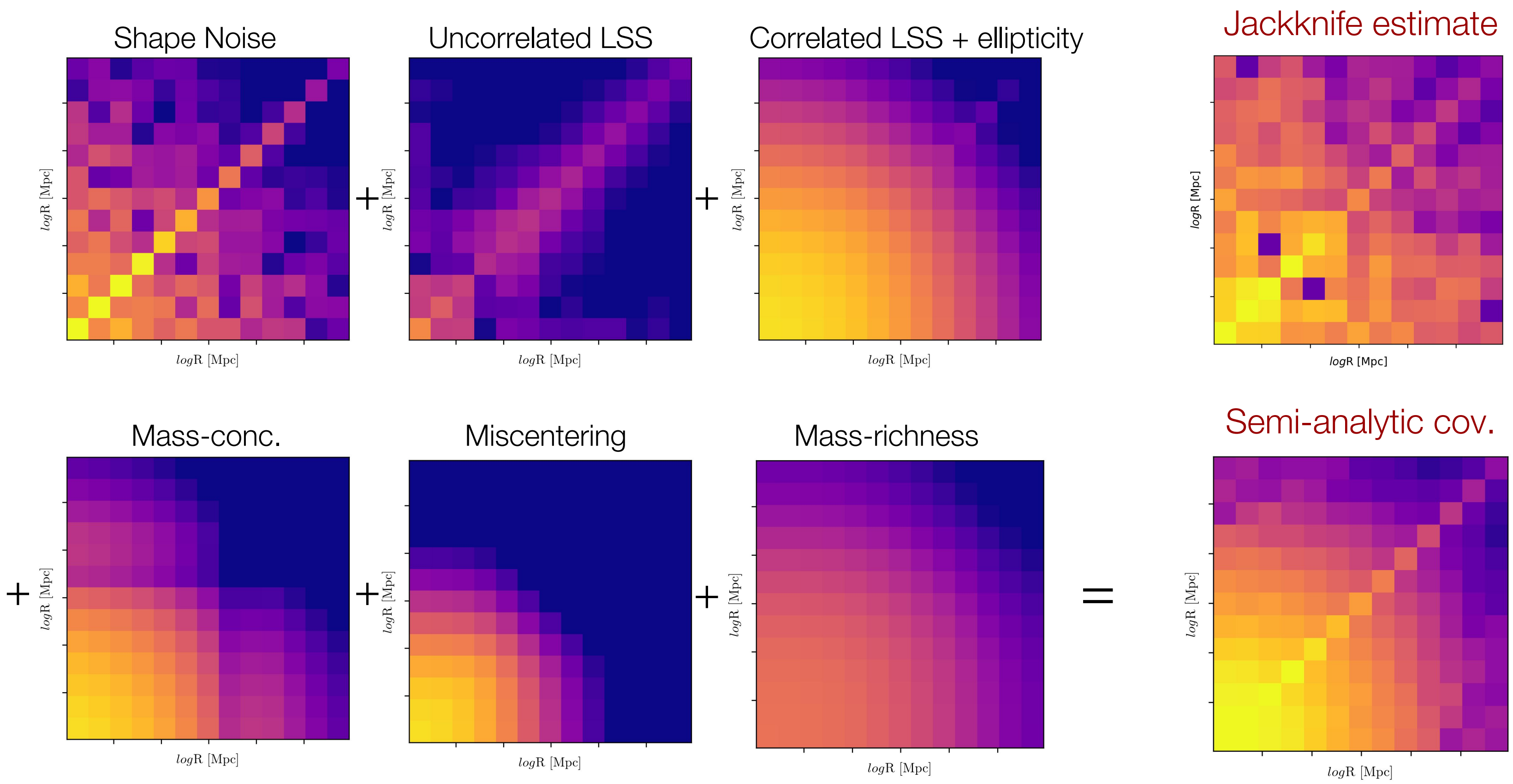
Boost factor model (not shown):

- NFW 2-parameter model

De-boosted the lensing profile to match the data points



Semi-analytic covariance matrix

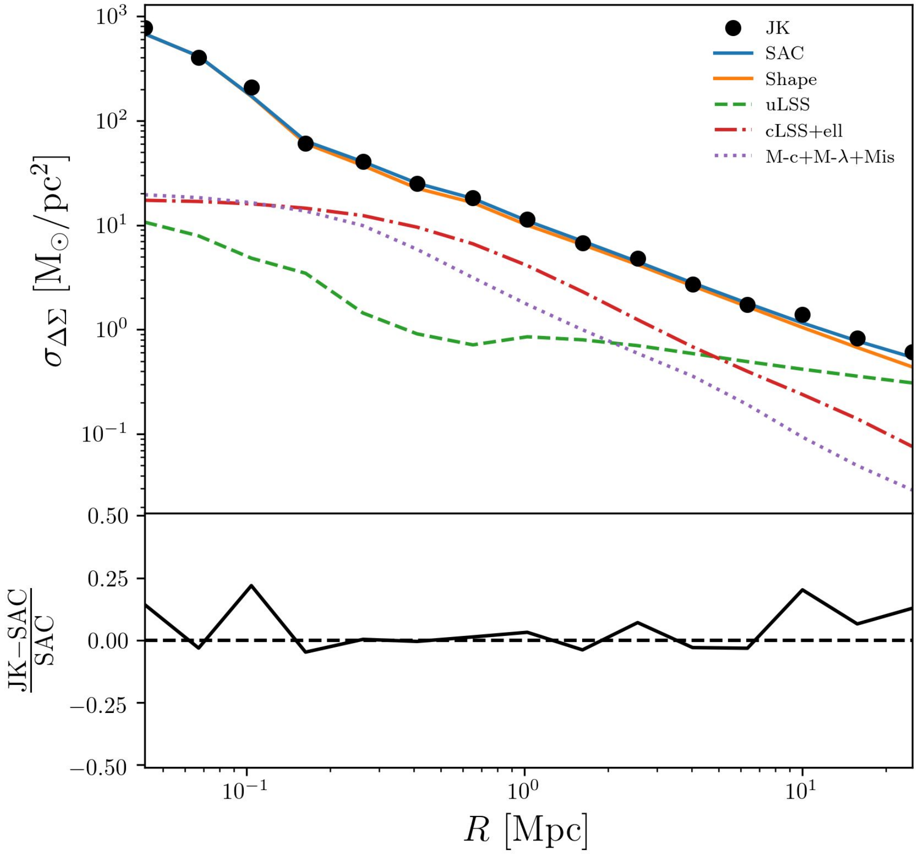


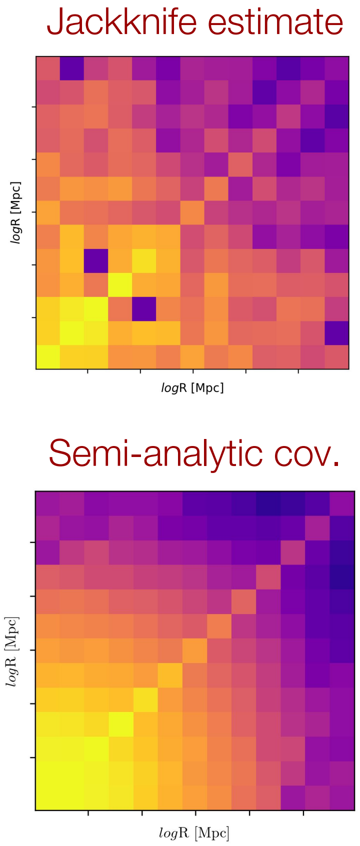
Semi-analytic covariance matrix

Dominant component is **shape noise**.

Largest scales limited by **uncorrelated large scale structure**.

Covariance matrices are **consistent** but **noise is reduced**.





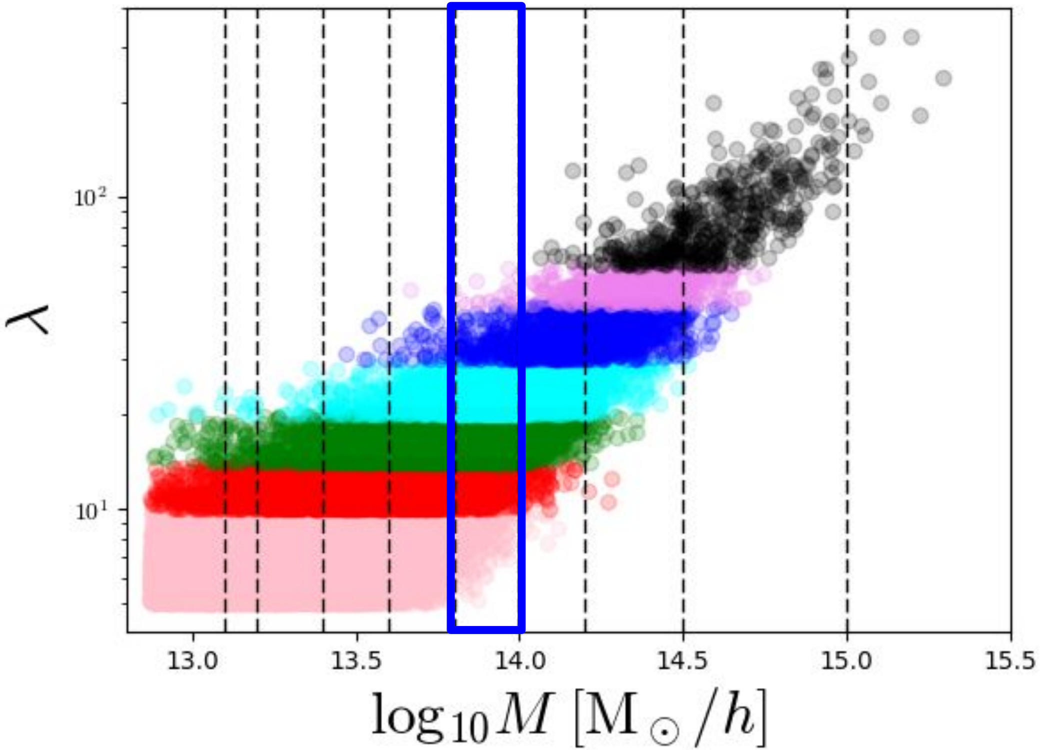
Modeling systematics calibration

Modeling systematic - mass correction based on simulations.

$$\mathcal{C} = \frac{M_{\rm true}}{M_{\rm obs}}$$

Blue box and blue points have the same average (i.e. “true”) mass, but their clustering properties are very different.

Difference in clustering results in a change of ~4% in the mass bias.

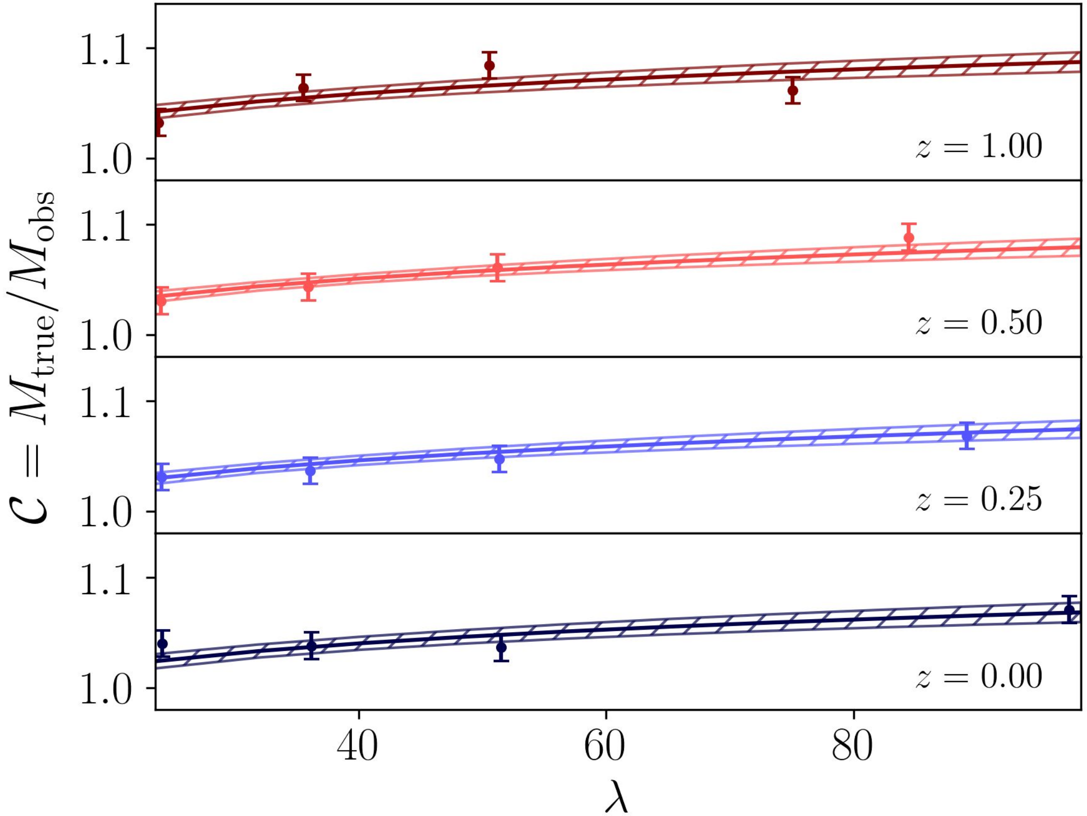


Modeling systematics calibration

Typical calibration was ~4%.

Up from <1% in Melchior+ (2017).

Not a significant contributor to the error budget, but is motivation for a **lensing emulator**.

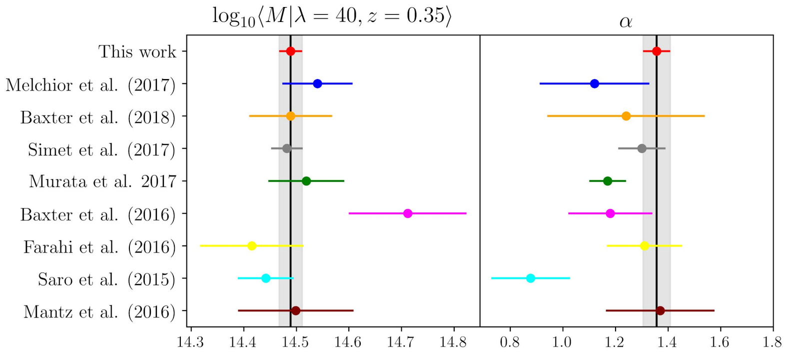


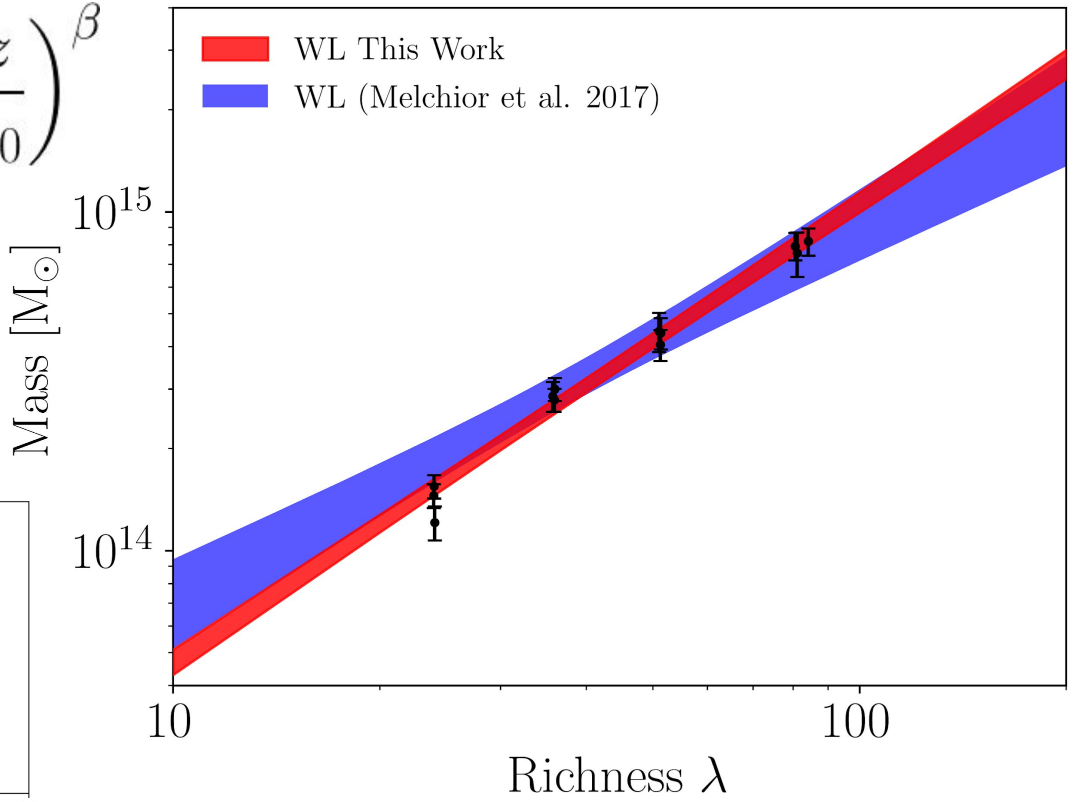
Final result: mass--richness relation

$$\langle M|\lambda, z\rangle = M_0 \left(\frac{\lambda}{\lambda_0}\right)^{\alpha} \left(\frac{1+z}{1+z_0}\right)^{\beta}$$

Stacked masses measured at the 8% level.

Normalization constrained at the 5% level.



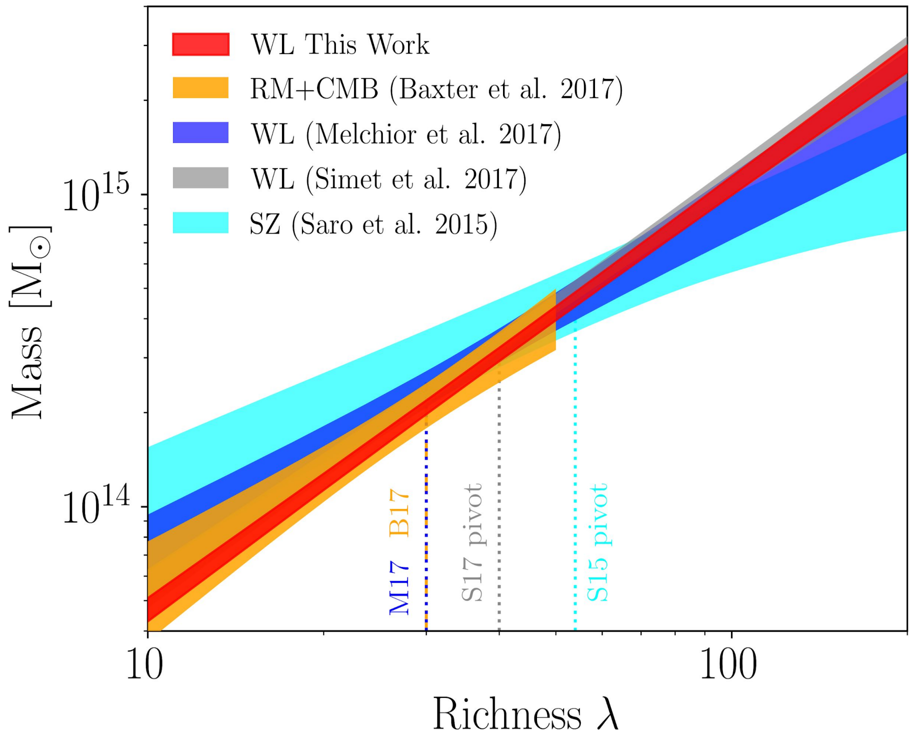


Error budget & looking forward

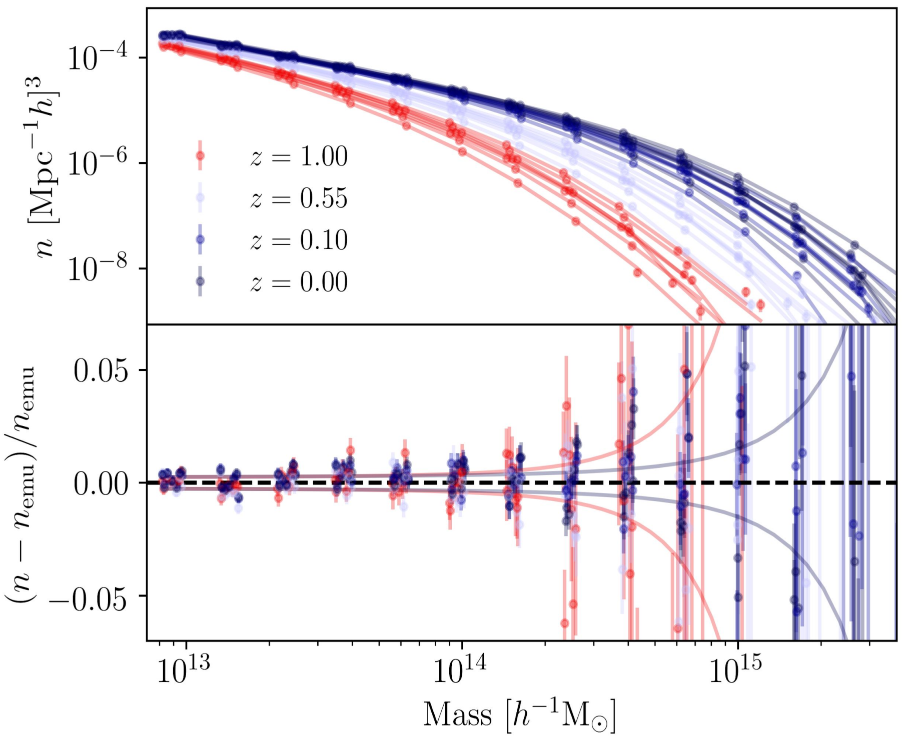
Source of systematic	SV Amplitude uncertainty	Y1 Amplitude Uncertainty
Shear measurement	4%	1.7%
Photometric redshifts	3%	2.6%
Modeling systematics	2%	0.73%
Cluster triaxiality	2%	2.0%
Line-of-sight projections	2%	2.0%
Membership dilution + miscentering	$\leqslant$ 1%	0.78%
Total Systematics	6.1%	4.3%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

Future plans:
- prioritize improving photometric redshifts
- model triaxiality and projection effects
- emulate lensing signal to reduce mass calibration
- covariance between the sources of systematic uncertainty

My projects

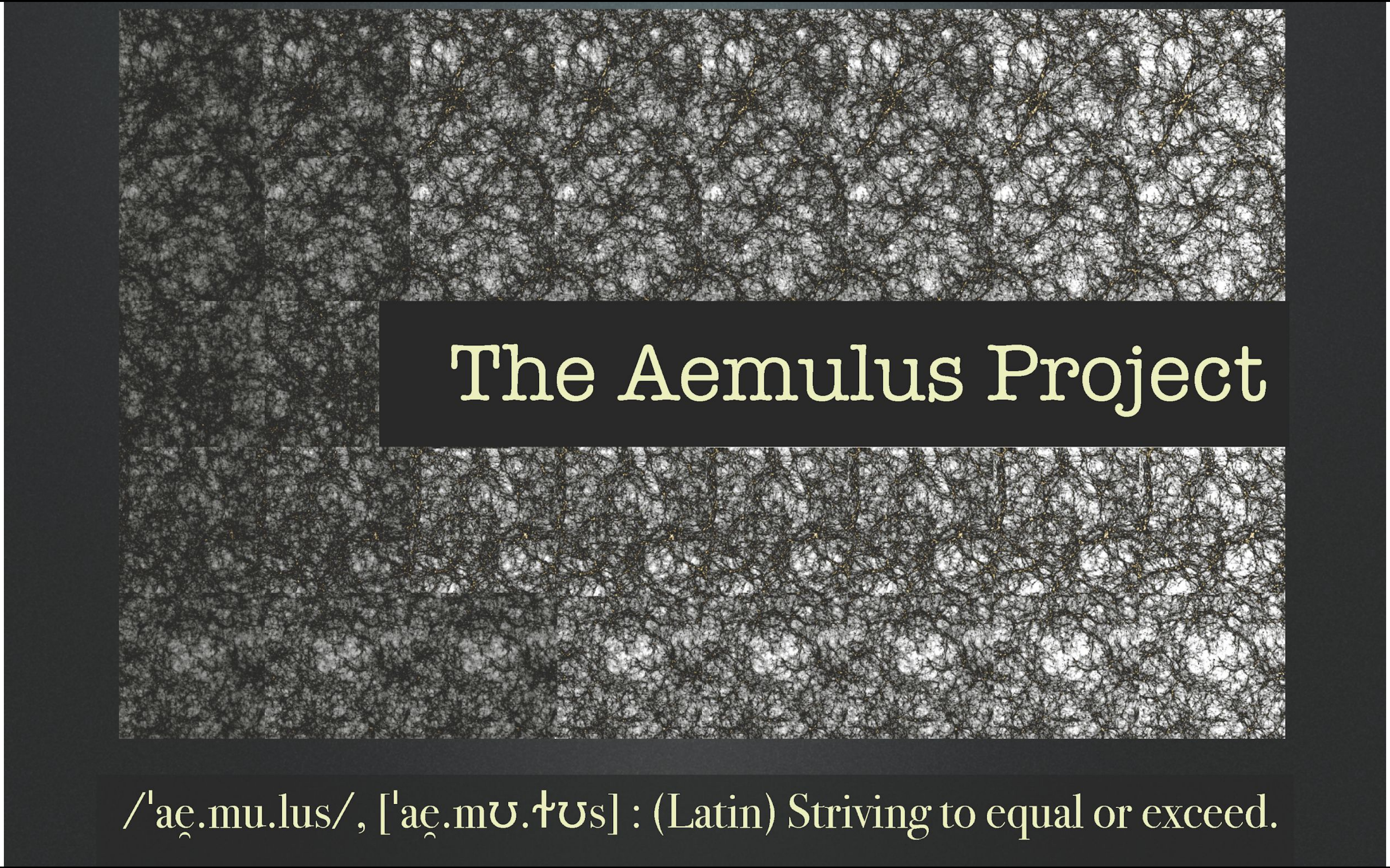


Gravitational lensing mass measurements



Halo mass function emulation

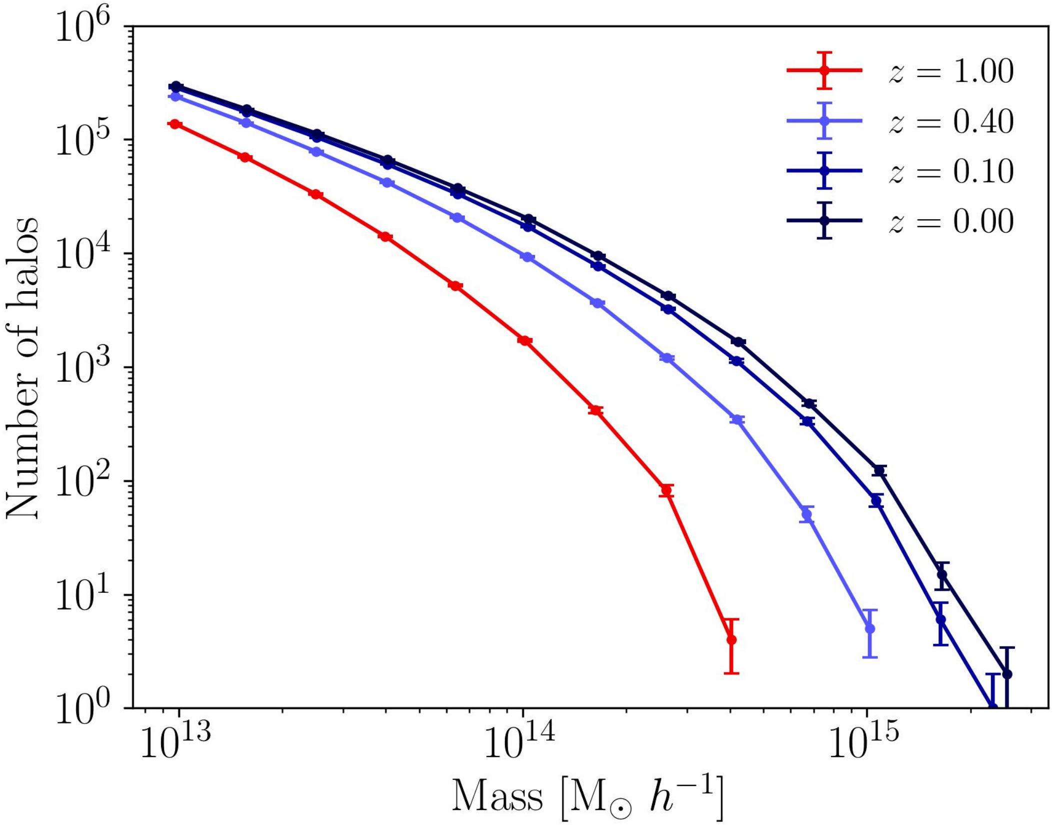
Second project: emulating the halo mass function



Second project: emulating the halo mass function

Goals:

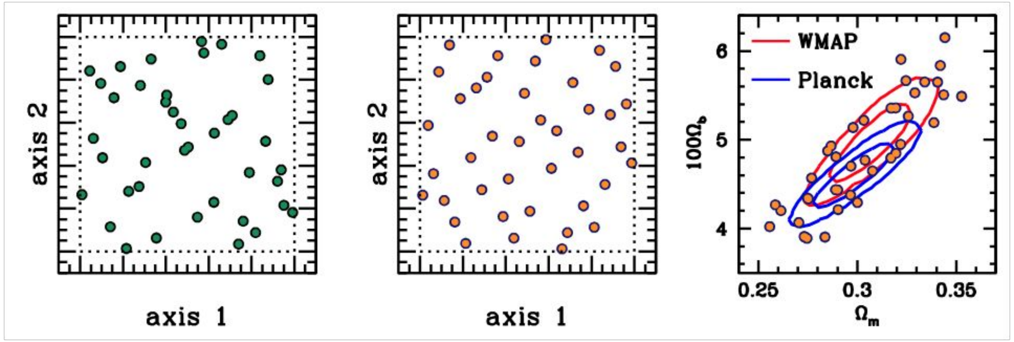
1. Measure **halo mass function** in simulations.
2. Connect simulation outputs by **interpolating**, thus building an emulator
3. Verify we achieve accuracy required by **DES** and **LSST**
4. Model the emulator accuracy

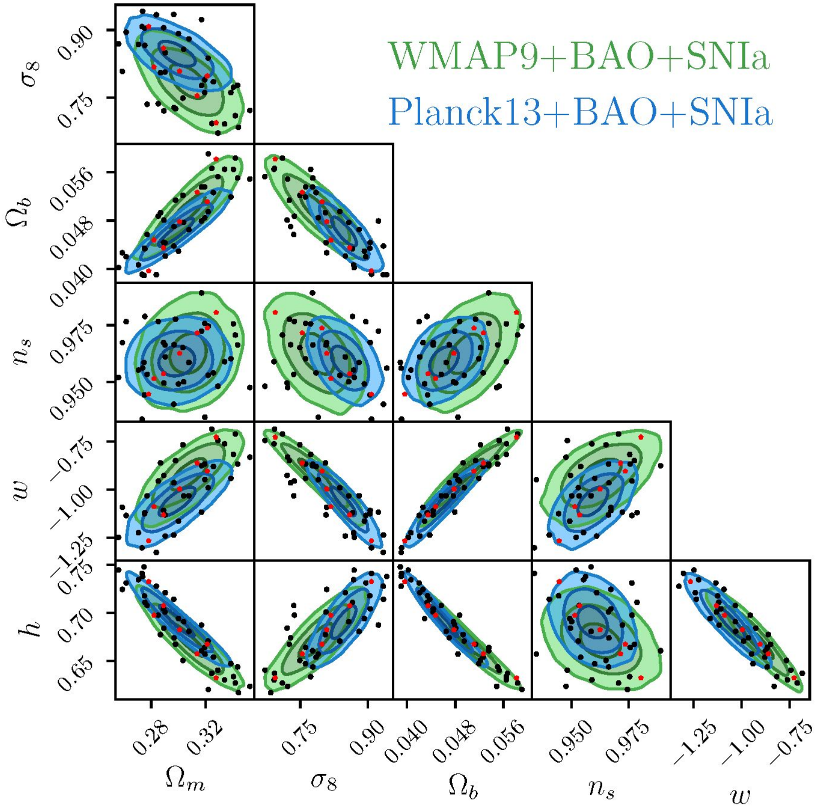


Simulations

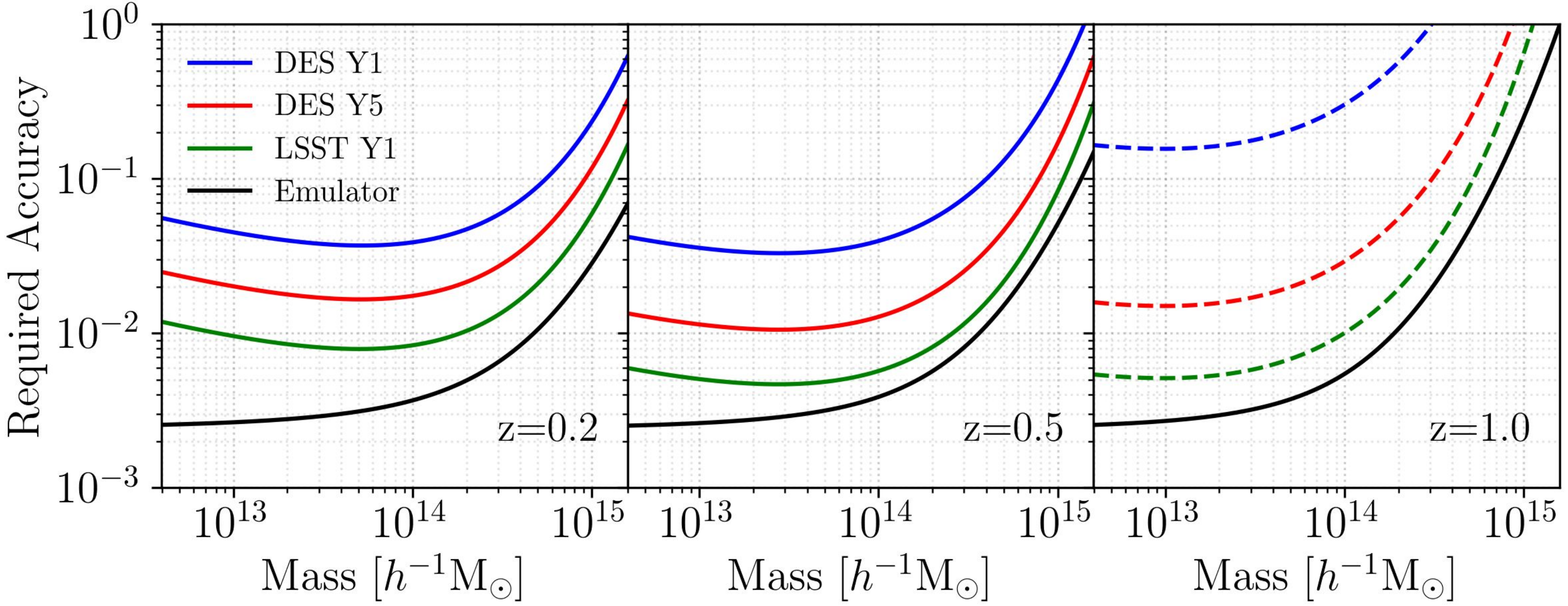
7 parameter wCDM

Cosmologies sampled from Latin Hypercube rotated into CMB + BAO + SNIa eigenspace





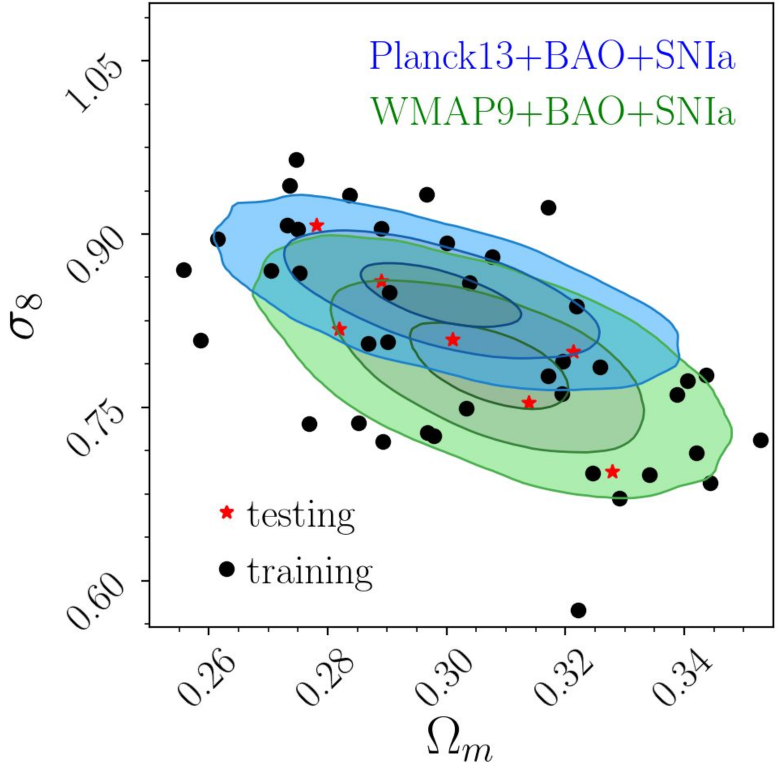
Mass function accuracy requirements



Dominant systematic for clusters is mass calibration (previous project).

Requirement for HMF is set by not increasing total error by more than 10%.

Approach: interpolate between models



$$\frac{dn}{dM} = \boxed{G(\sigma)}\frac{\rho_m}{M}\frac{d\ln\sigma^{-1}}{dM}$$

$$G(\sigma) = B\left[\left(\frac{\sigma}{\boxed{e}}\right)^{-\boxed{d}} + \sigma^{-\boxed{f}}\right]\exp(-\boxed{g}/\sigma^2)$$

Free parameters measured in each sim.

All written as linear functions of scale factor.

4x2=8 free parameters total.

2 held fixed -> 6 independent GPs.

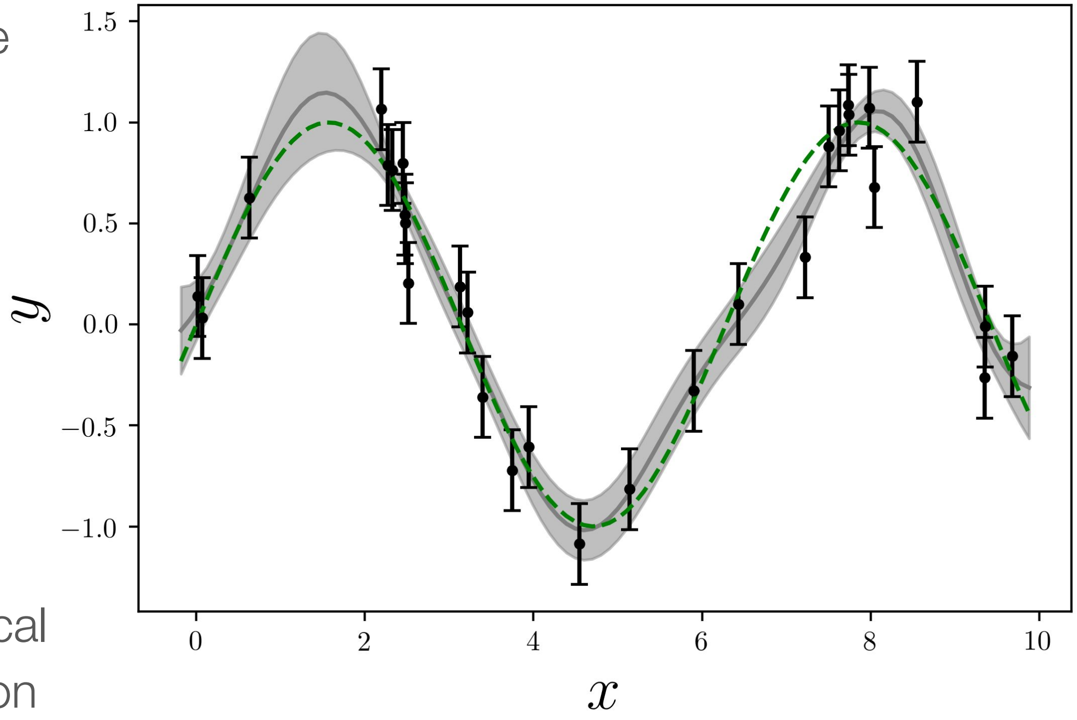
Interpolation using Gaussian Processes

Gaussian Processes: exploit covariance between training data.

<u>Probabilistic regression</u>

Example: given training data (black points) drawn from a true distribution (green), the *Gaussian Process* models the data (gray line+band).

For the emulator, ‘x’ are the cosmological parameters and ‘y’ are the fitting function parameters.

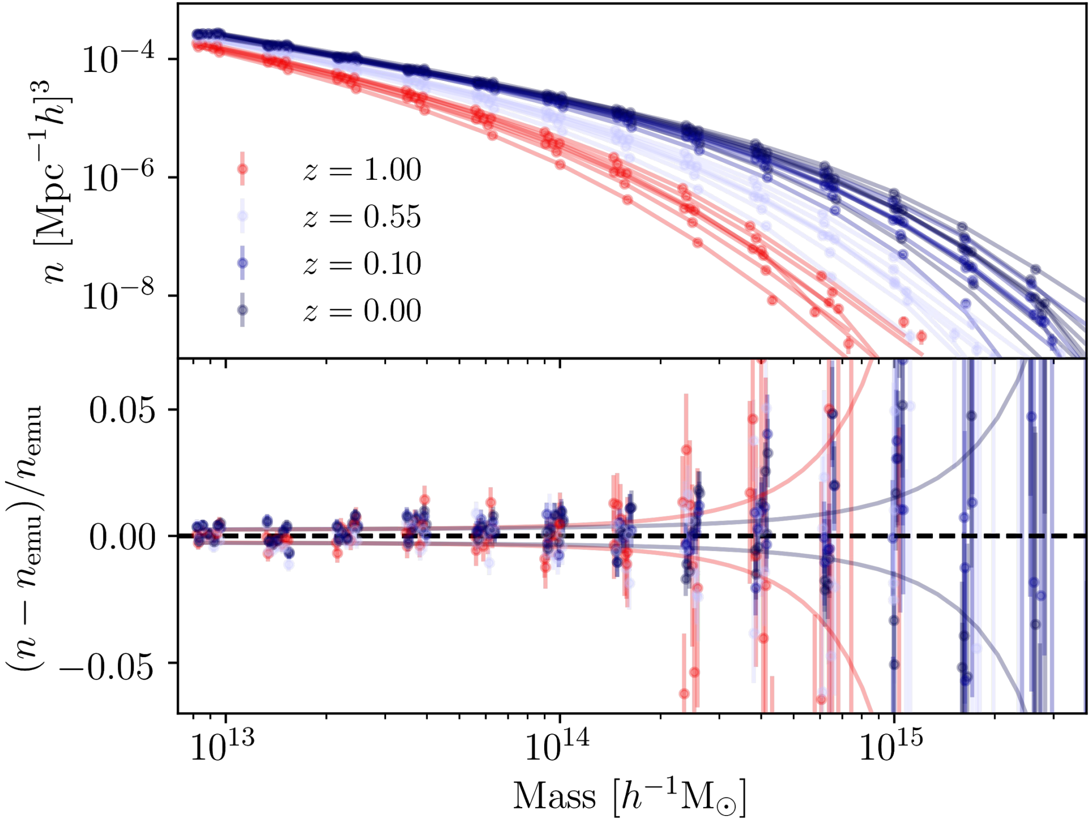


Test against independent simulations

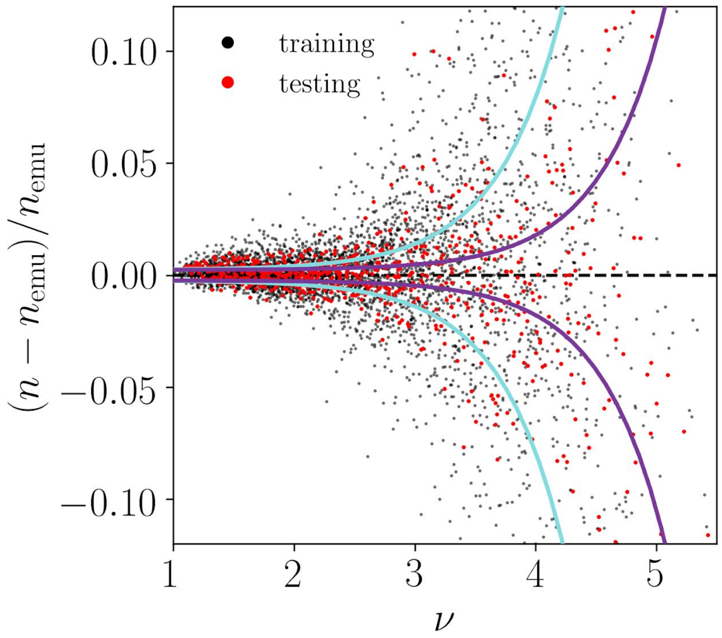
Averaged realizations of test simulations.

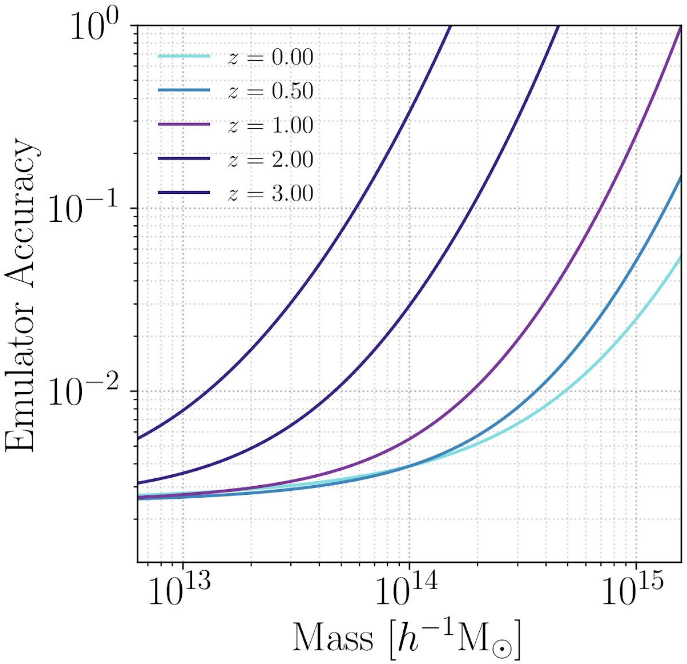
Training simulations were less accurate than the testing simulations.

More halos -> more accurate.



Modeling the uncertainty



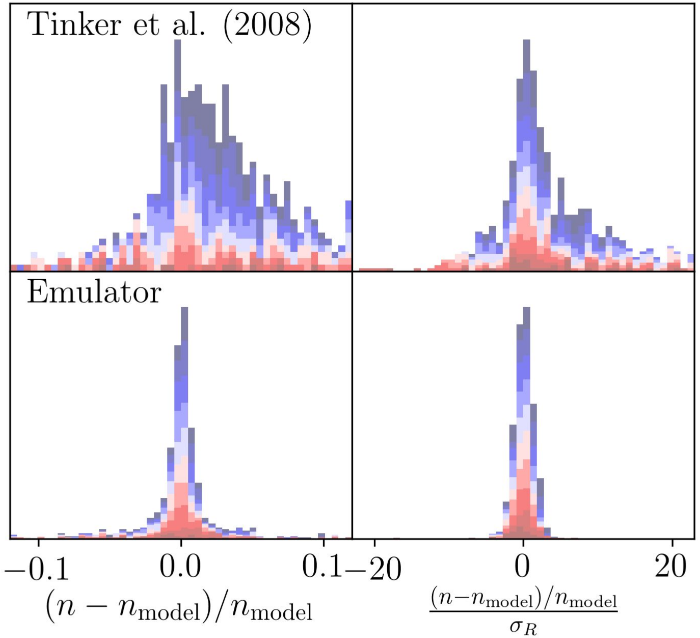


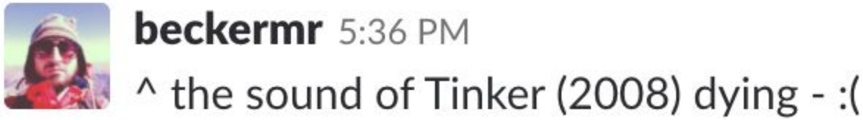
Modeling the mass and redshift dependent uncertainty allows the modeling uncertainty to be correctly propagated. Rather than reducing it to a single number (e.g. “5% accuracy”).

Project results

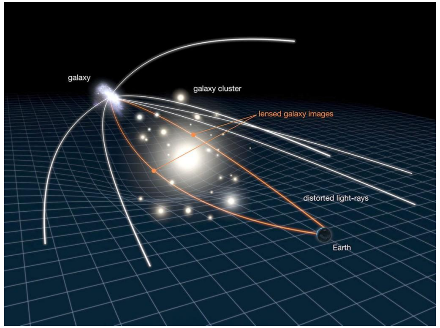
Achieved our goals!

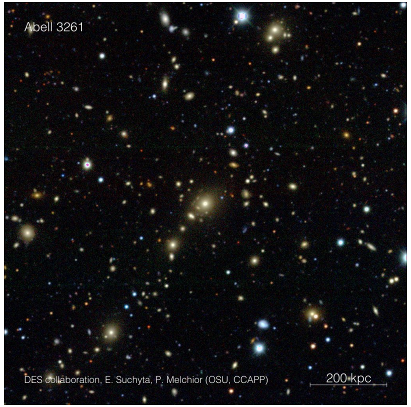
- Built an emulator to **enable cluster cosmology** in the LSST era
- Emulators can be more accurate than individual simulations
- A full understanding of modeling accuracy is necessary

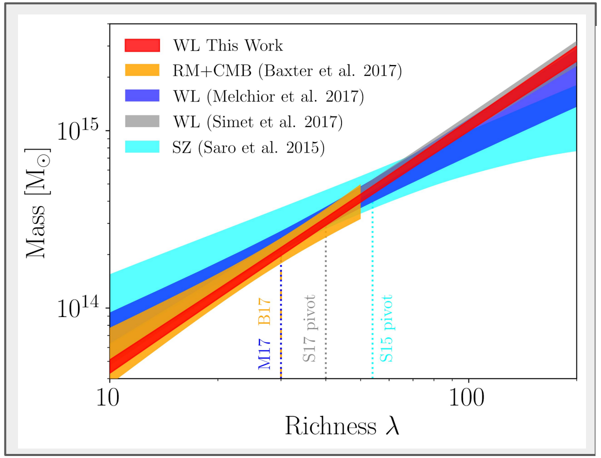


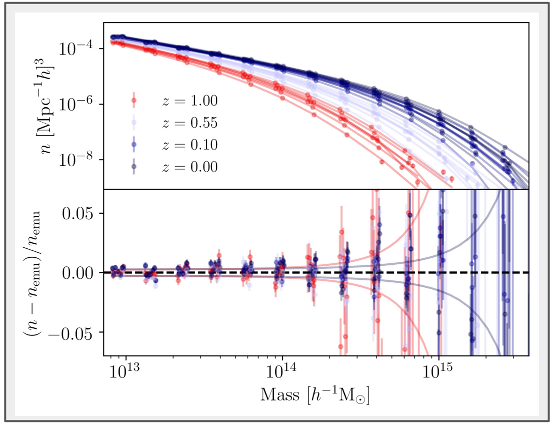


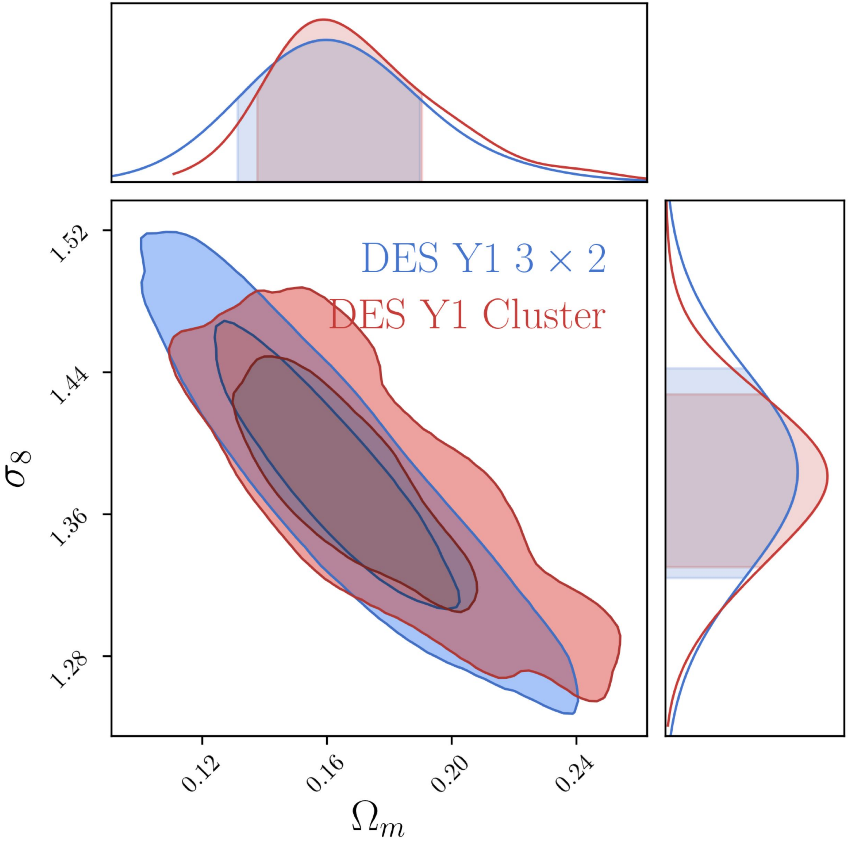
Enabling galaxy cluster cosmology in DES











Thanks!

UA Cosmology:

Eduardo Rozo, Youngsoo Park, Matt Kirby, Erika Wagoner, Rafael Garcia Mar, Pier Fiedorowicz, Sasha Safonova

DES working group:

Tamás N. Varga, Matteo Costanzi, Peter Melchior, Daniel Gruen, Erin Sheldon, Yuanyuan Zhang, +others

Aemulus Project:

Joe DeRose, Zhongxu Zhai,
Sean McLaughlin, Risa Wechsler,
Jeremy Tinker

Extra slides

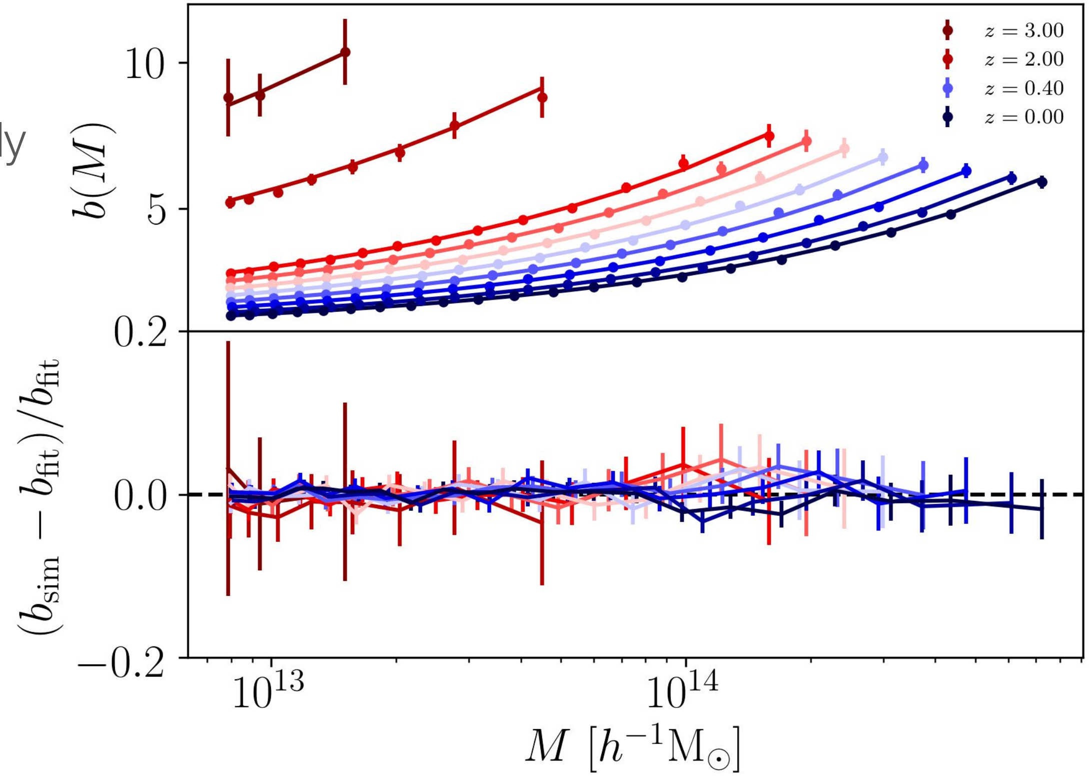
Additional emulators - halo bias

Halo bias = halos/dark matter

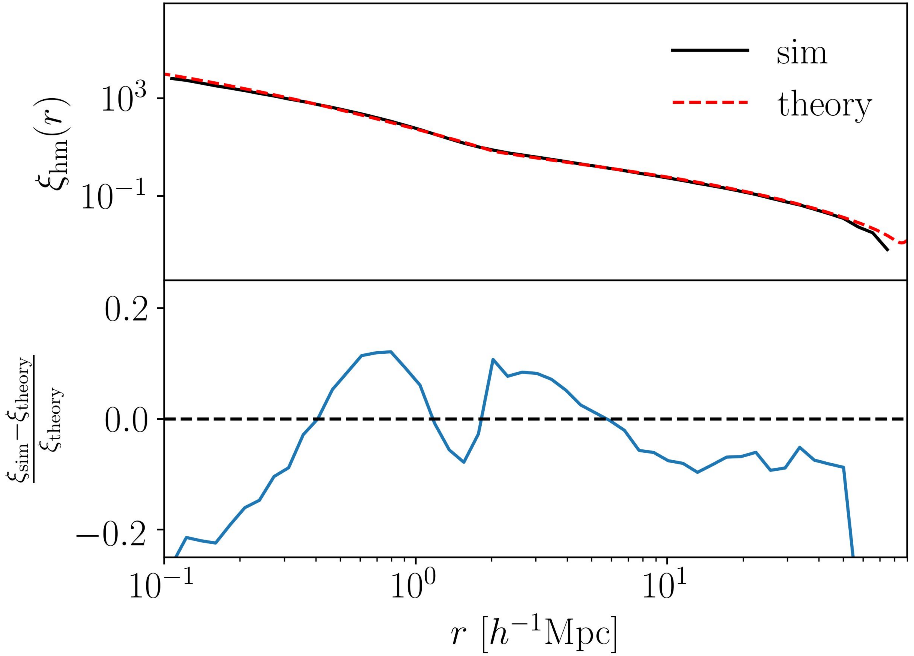
Cluster clustering is systematically limited by accuracy of the halo bias.

Baxter+ (2016) mass calibration: halo bias **increased error budget** from 7% to 18%!

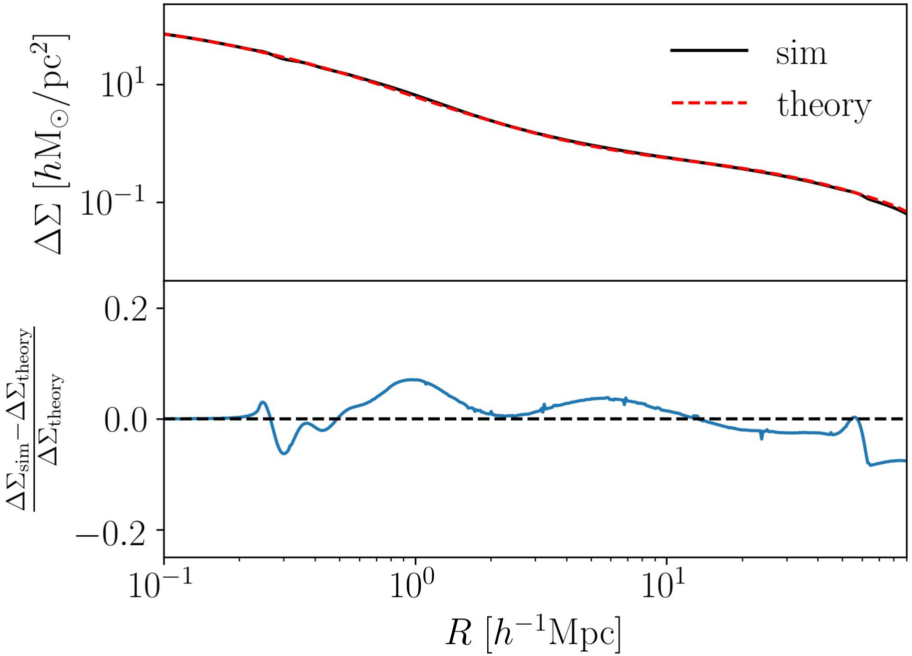
Perfect for the Aemulus Project.



Additional emulators - cluster lensing



Halo-matter correlation function



Weak lensing profiles