Covariance matrices for galaxy cluster weak lensing

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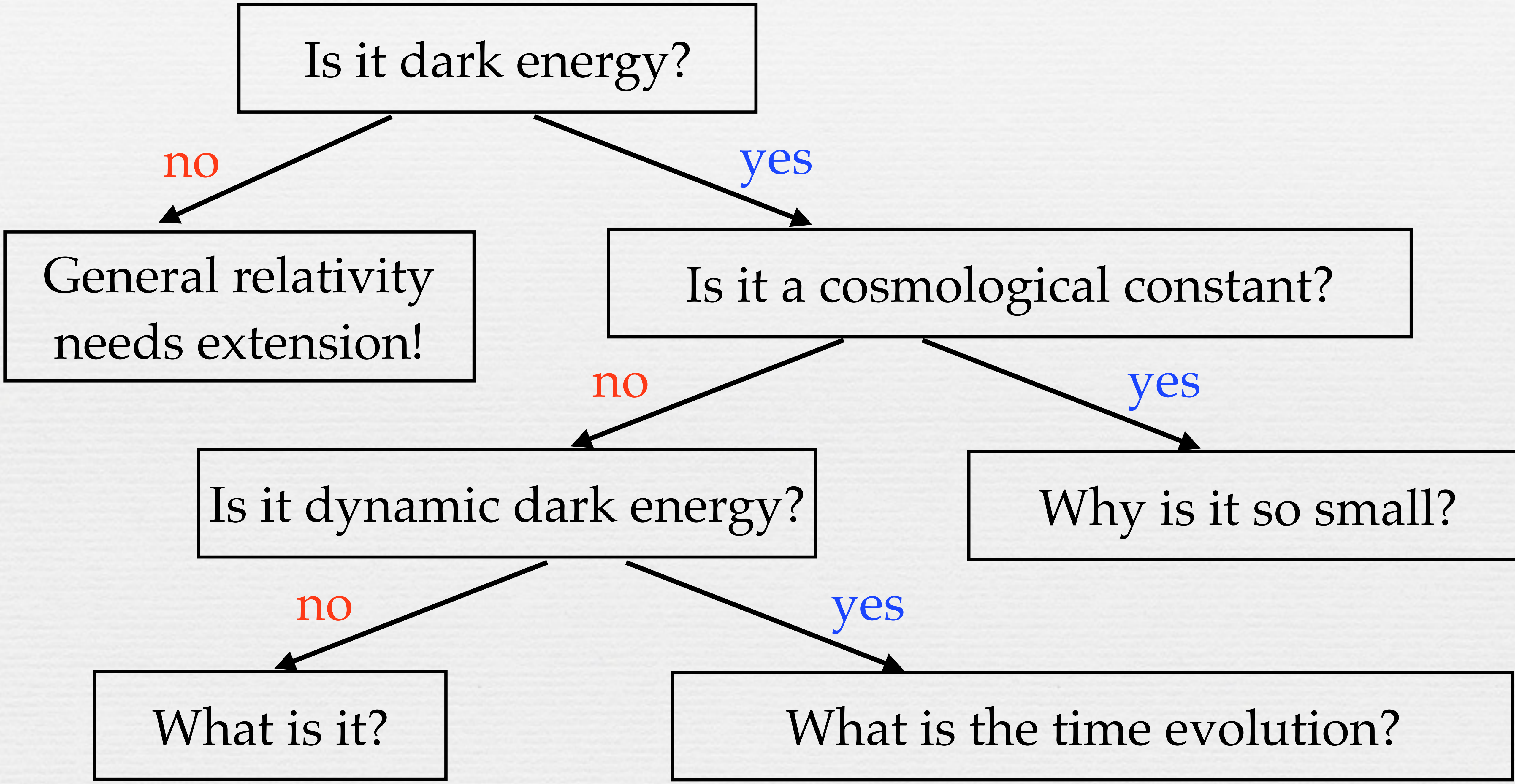
What causes cosmic acceleration?

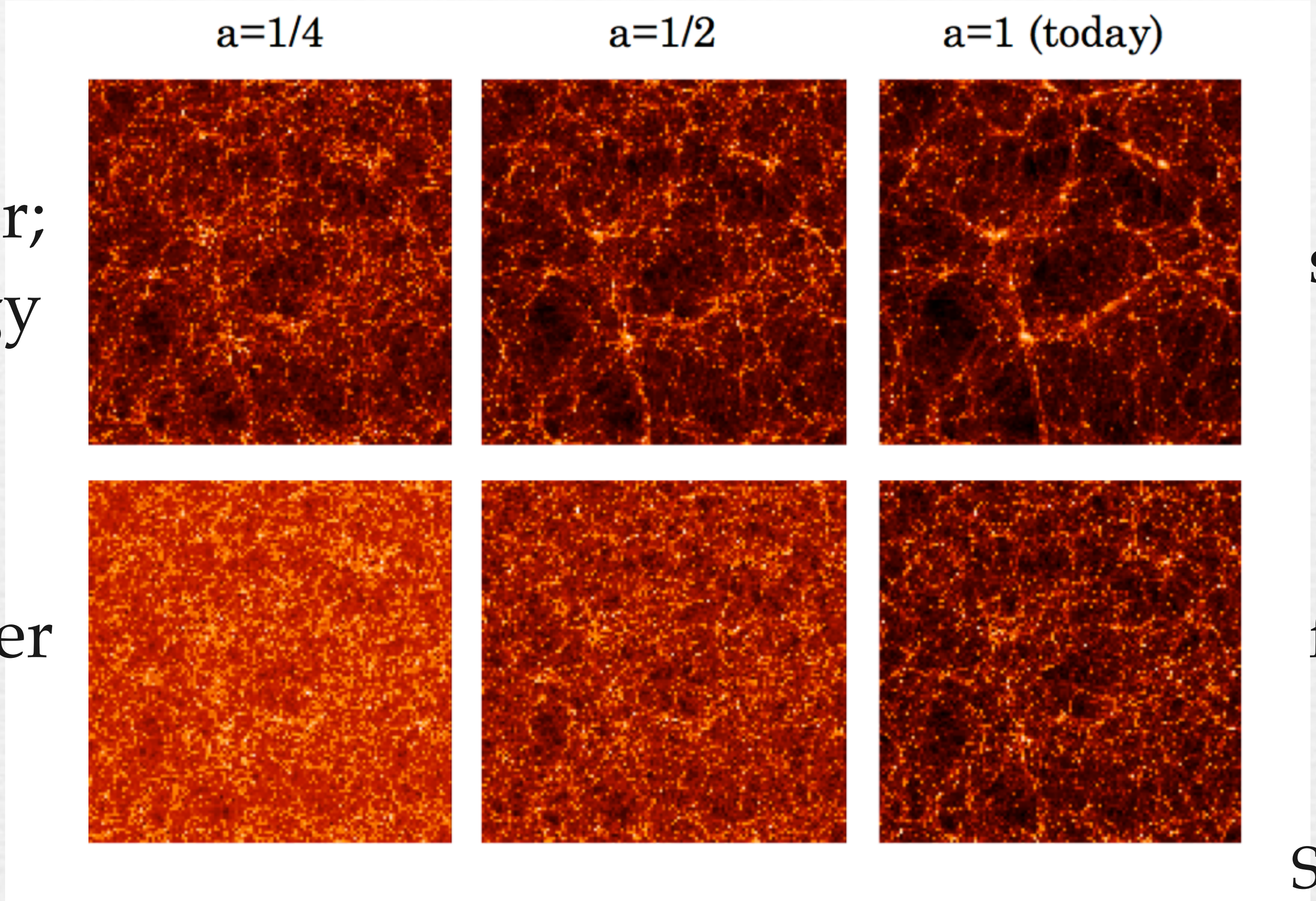


We need measurements other than the expansion rate.

Dark energy slows down the growth of large-scale structure

30% dark matter;
70% dark energy

100% dark matter



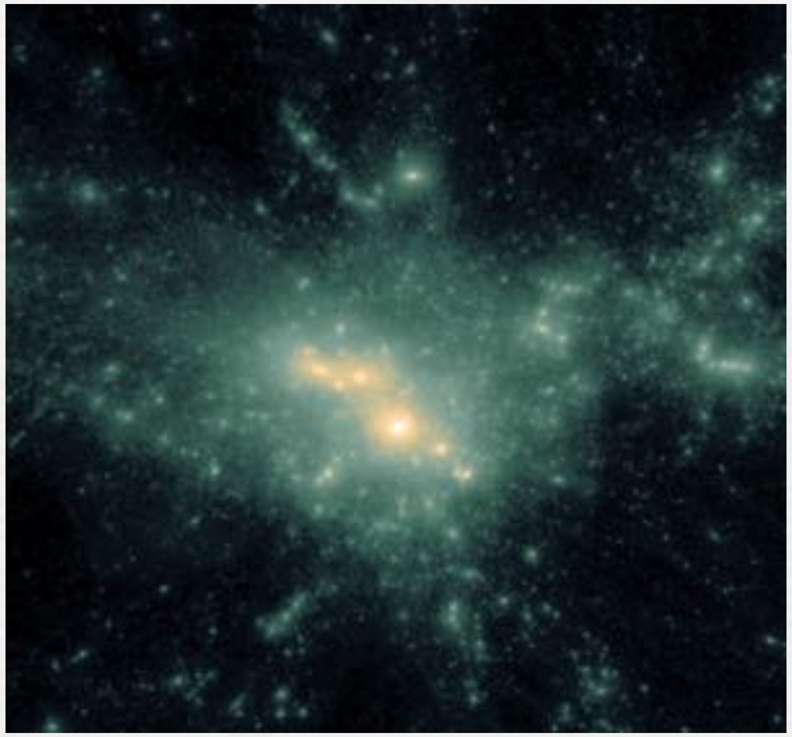
slower evolution

faster evolution

Sims: Jenkins et al. (1998)

Counting the density peaks as a function of time can help us constrain dark energy parameters.

Galaxy clusters: the highest density peaks

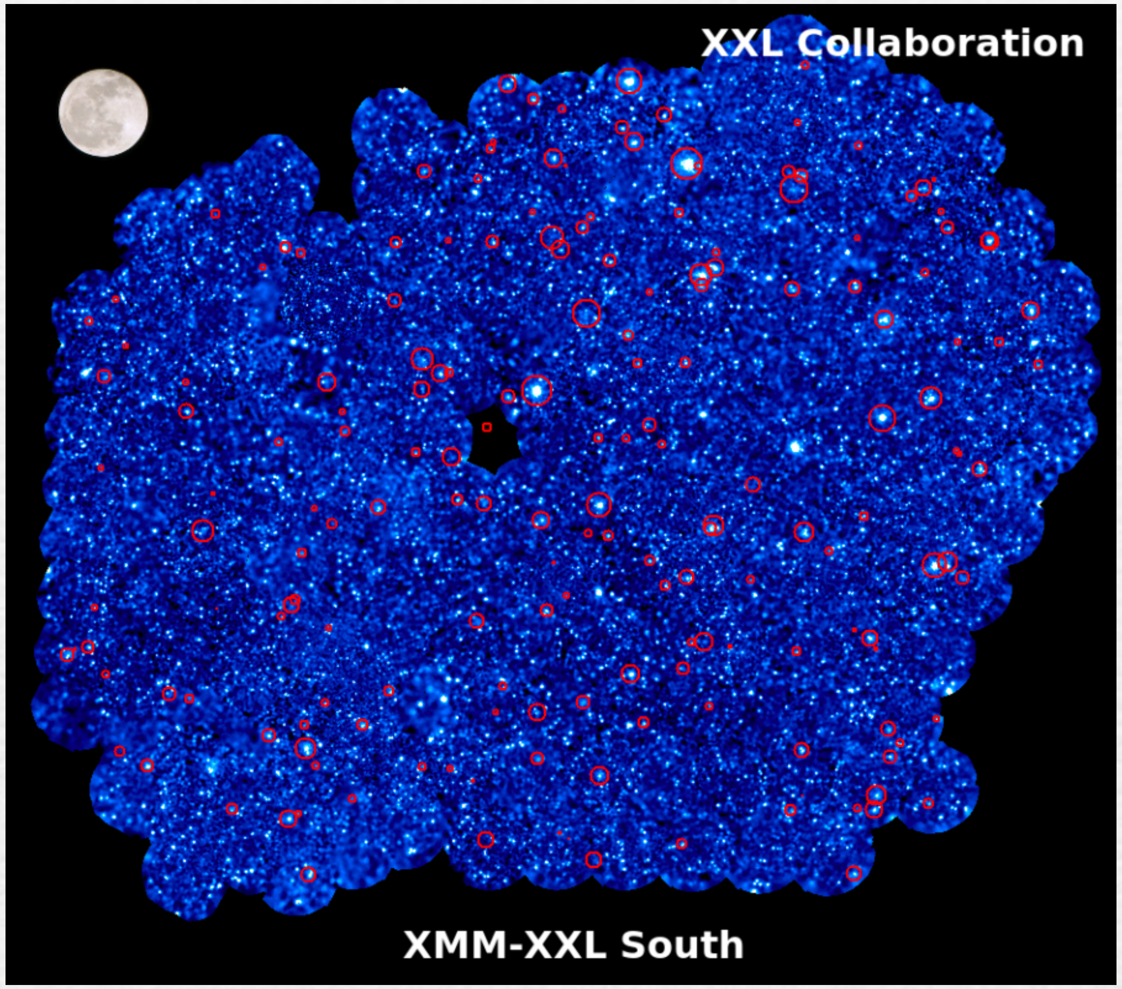
Galaxies	Hot gas	Dark matter halo
		
2%	10%	88%

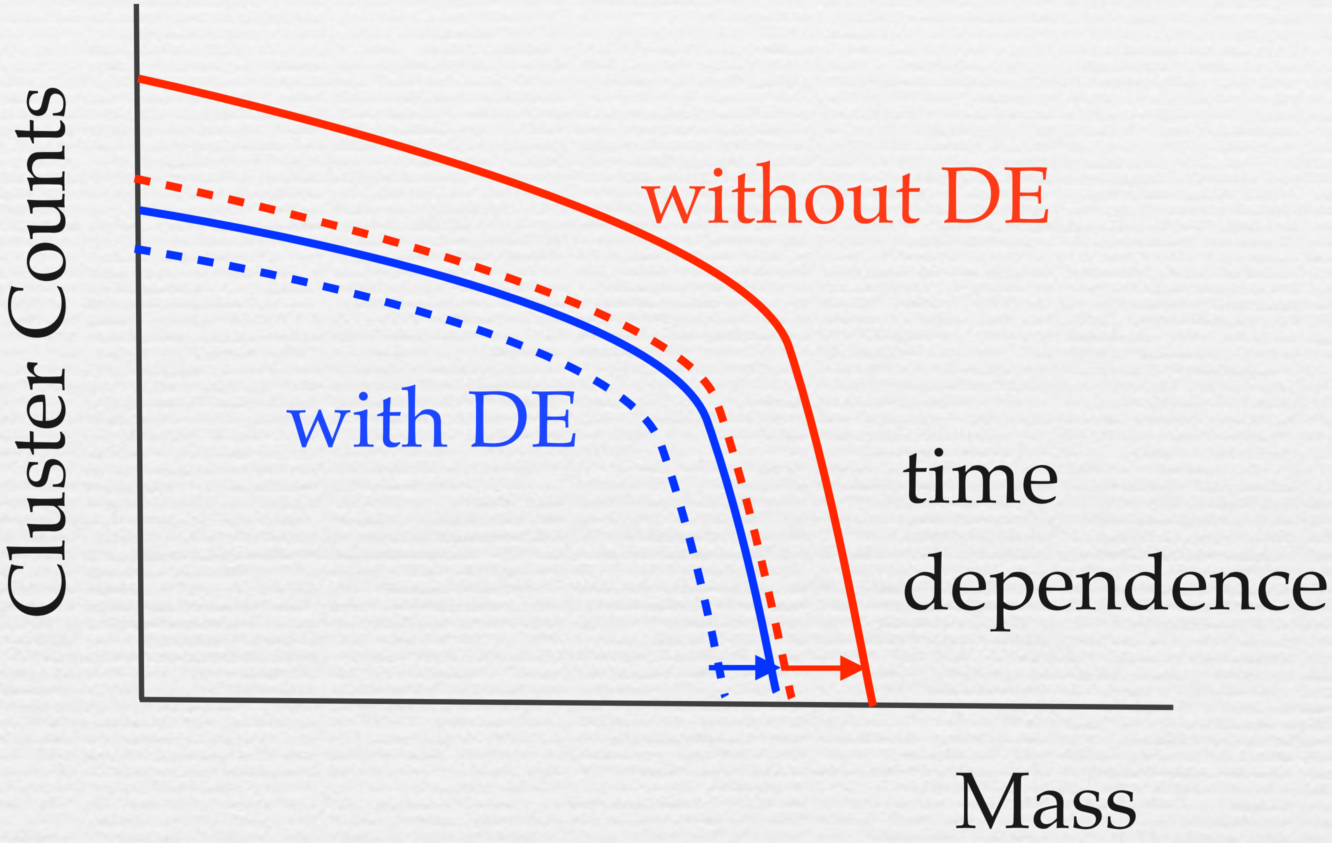
Mass ~ 10^{14} to 10^{15} $M_{\odot}$

Size ~ a few million parsecs (Mpc)

Richness ~ number of galaxies in a cluster

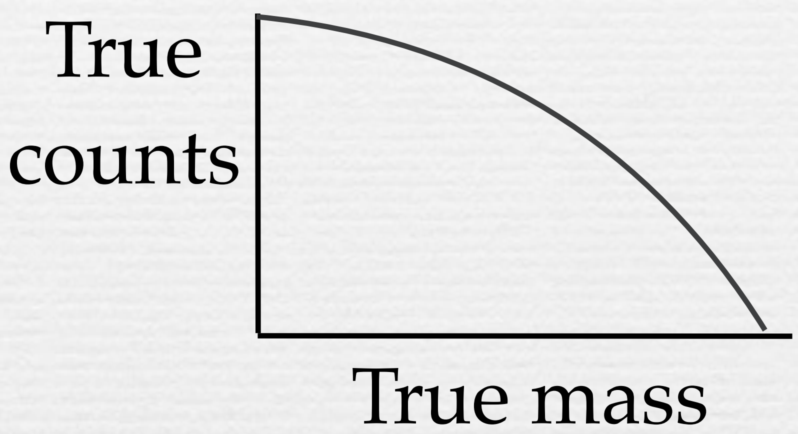
Measuring dark energy using the number counts of galaxy clusters



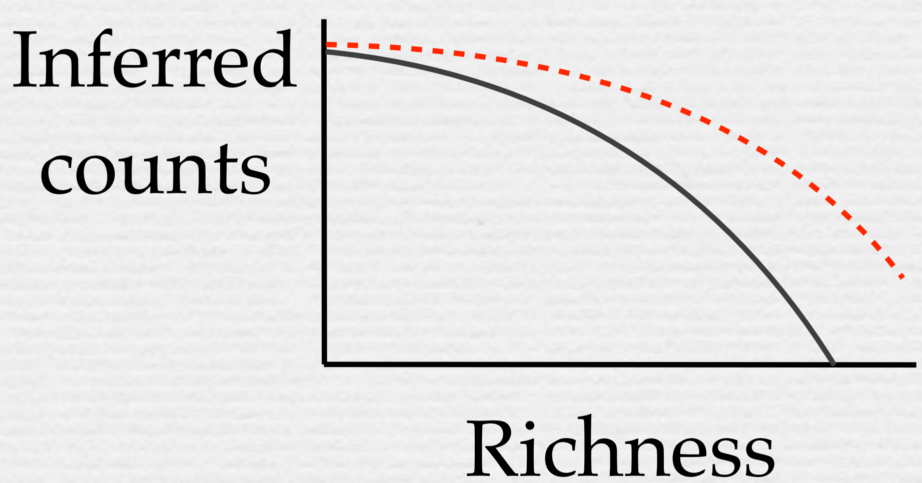


We need to infer cluster mass from observable properties.

Impact of scatter



Scatter between mass
and observable



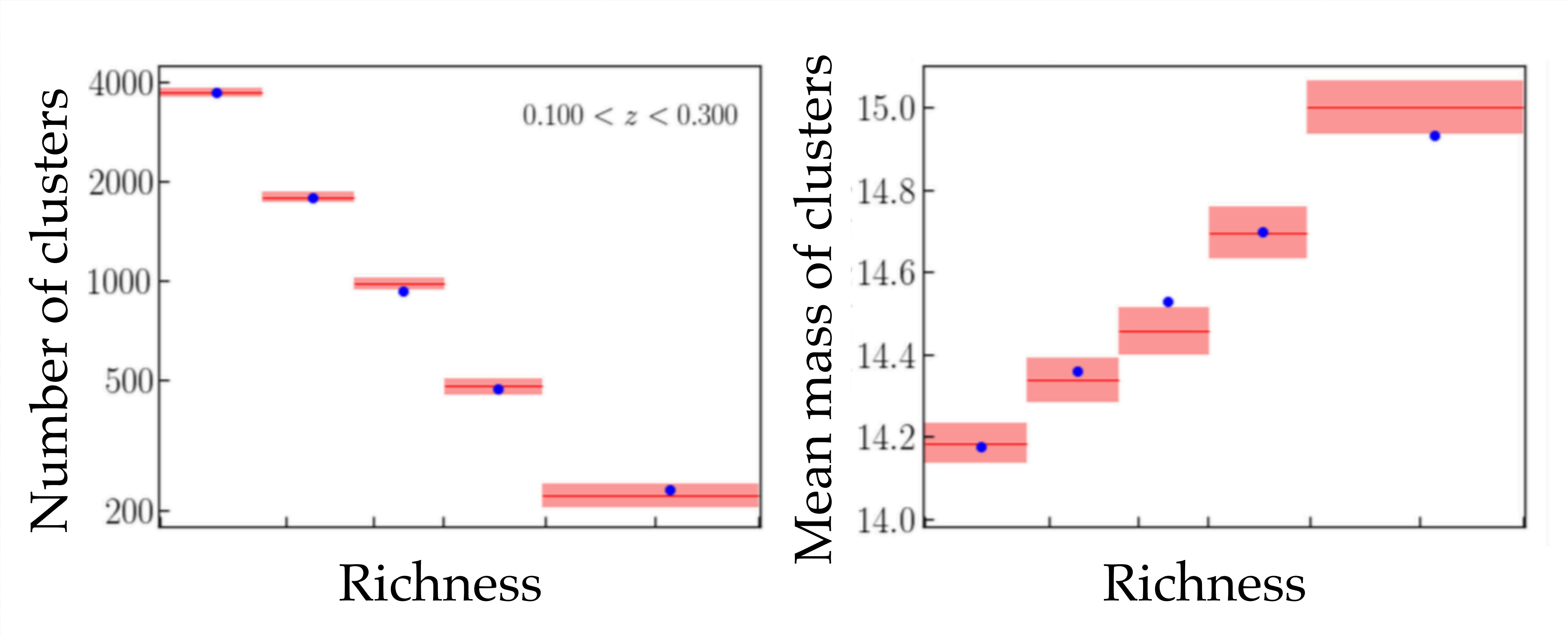
Scatter can mimic
the effect of low
dark energy!

Example from SDSS

DES results will be published in a few weeks!

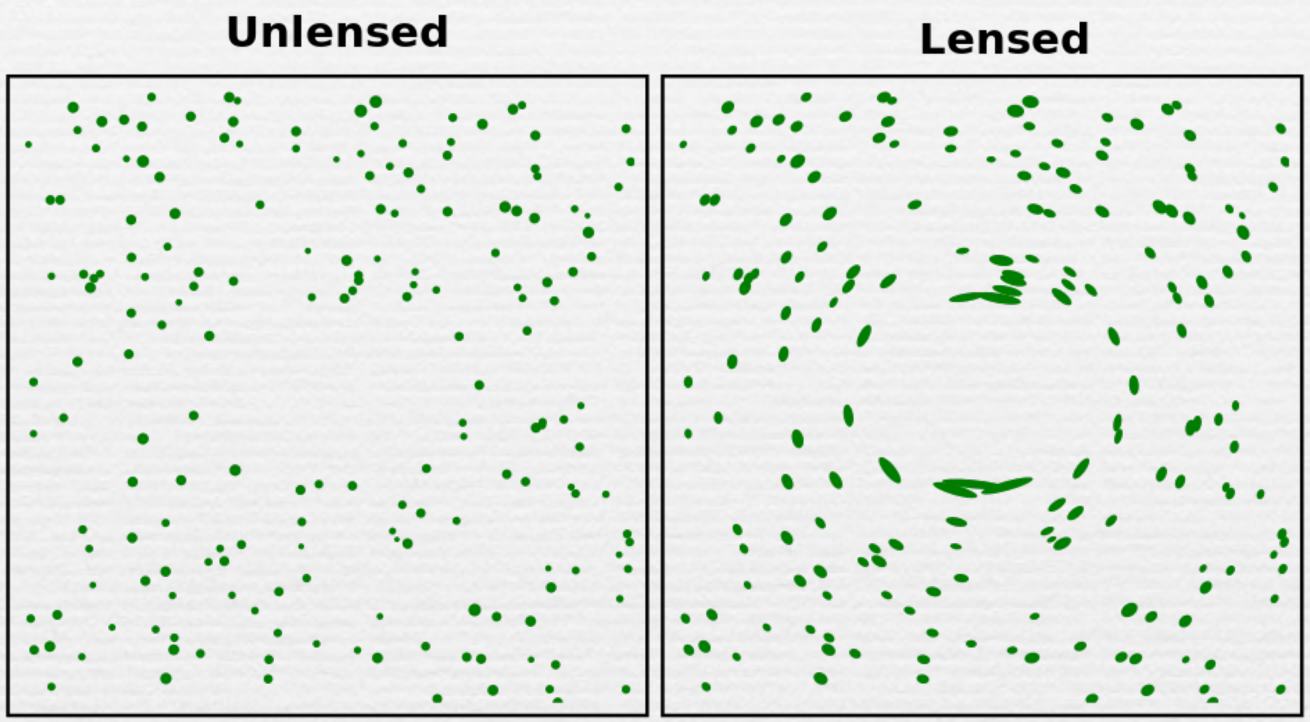
Bands: observation. Points: best-fitting model

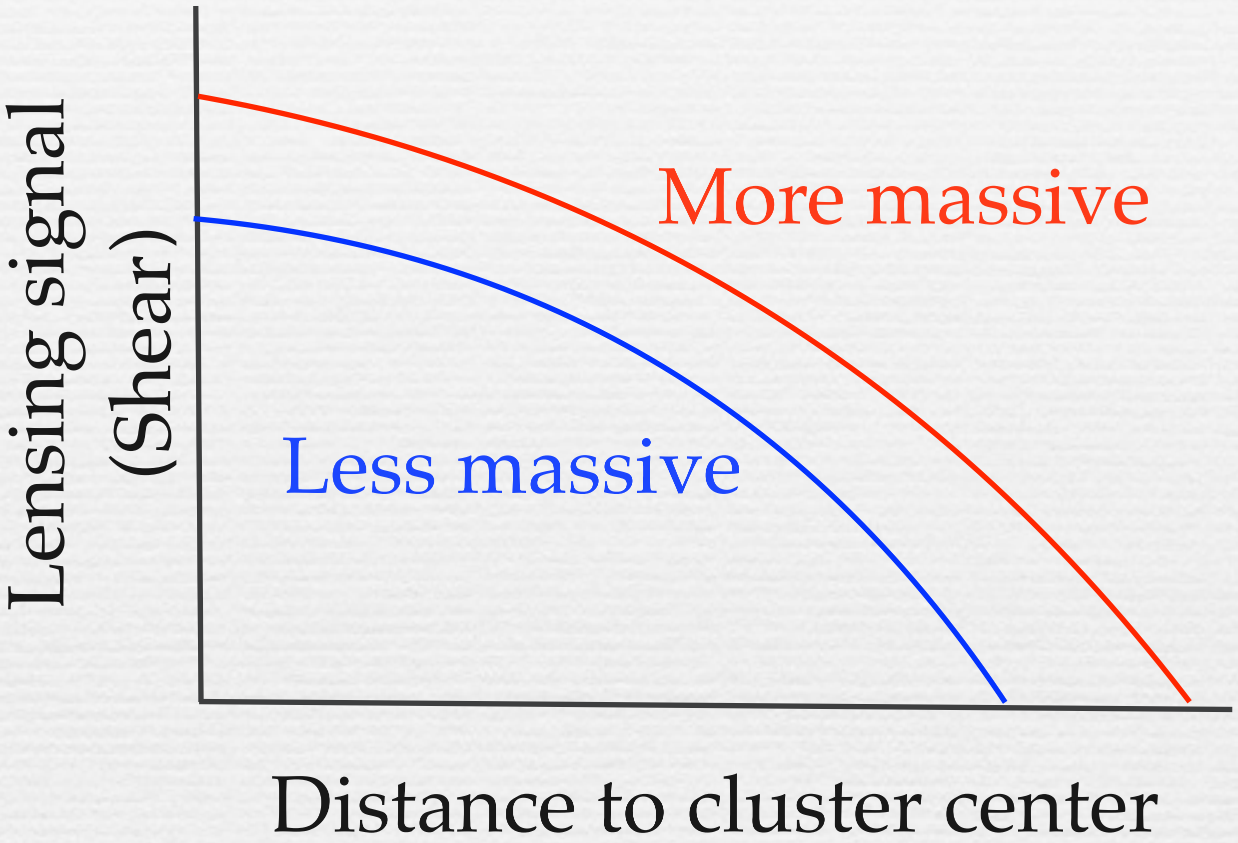
Mean mass comes from stacked lensing.



Costanzi et al. (2019)

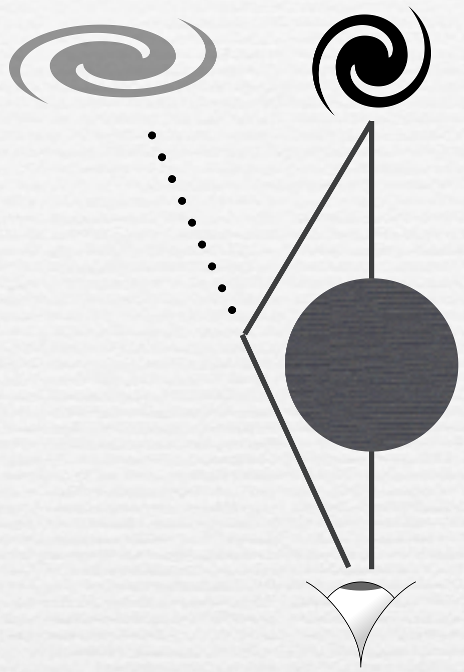
Inferring cluster mass from weak lensing

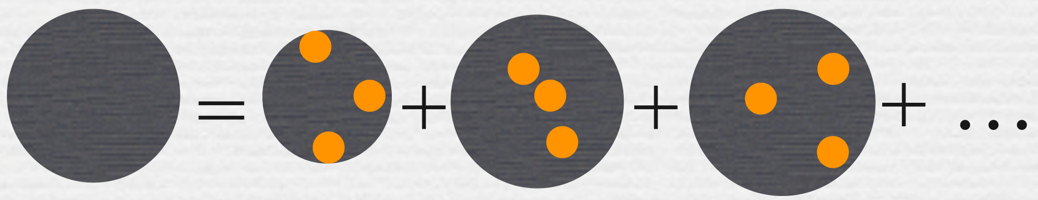




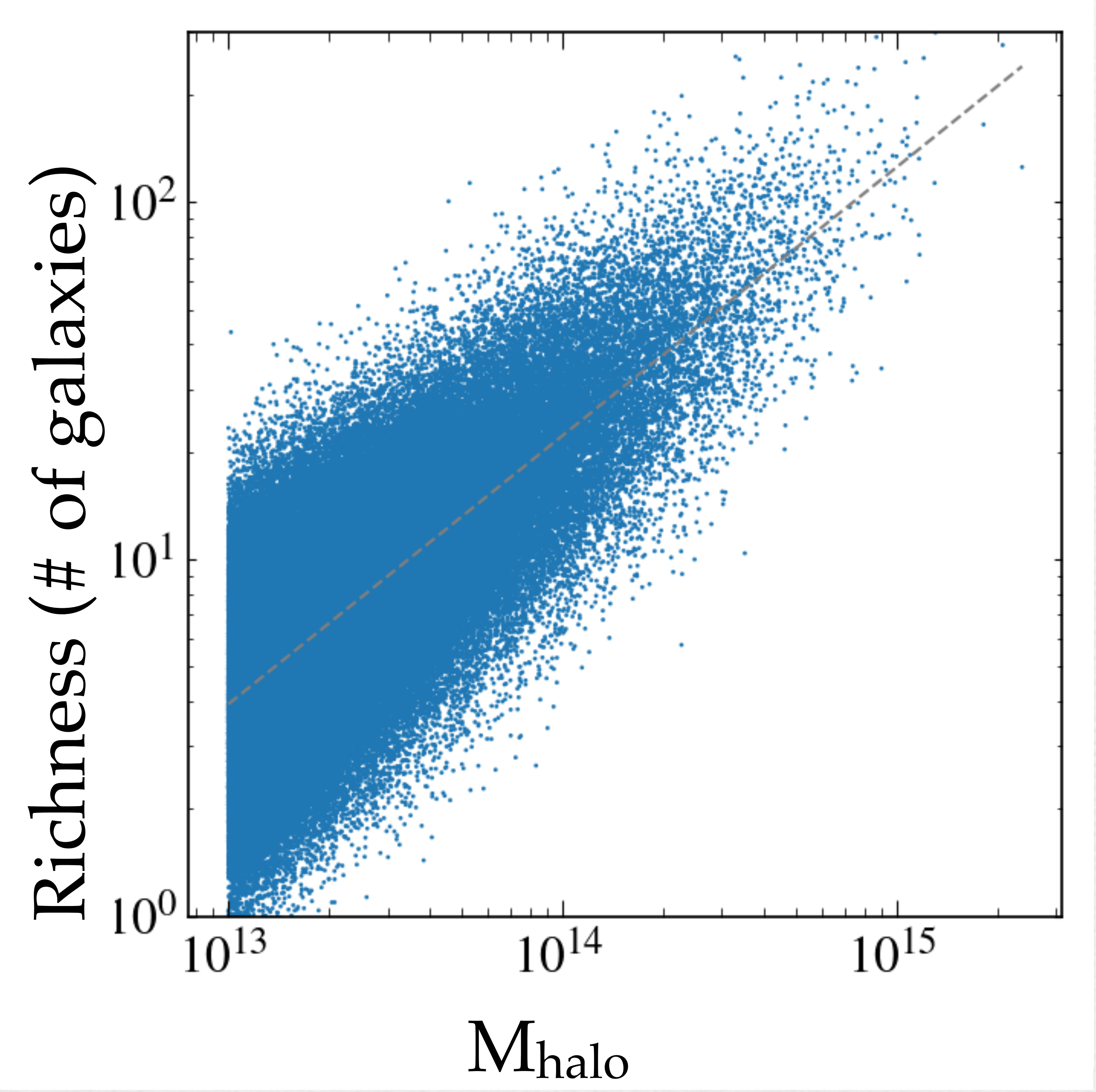
Lensing signal: tangential shear (γ_t)
$\propto$ excess surface mass density ($\Delta\Sigma$)

Stacking the weak lensing effect

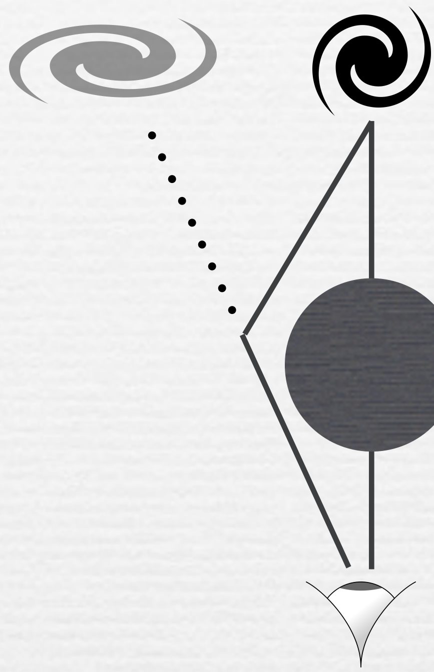


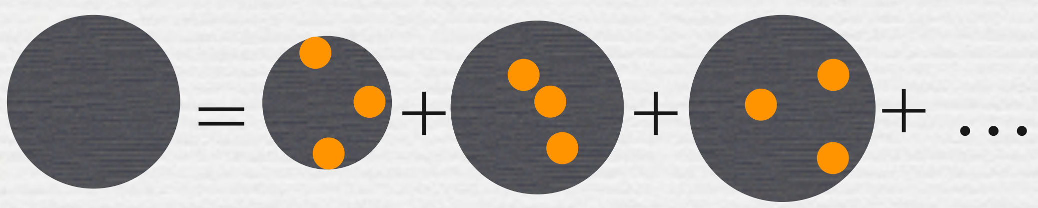


Combining the weak lensing signal of clusters of similar "richness" (# of galaxies)



Stacking the weak lensing effect





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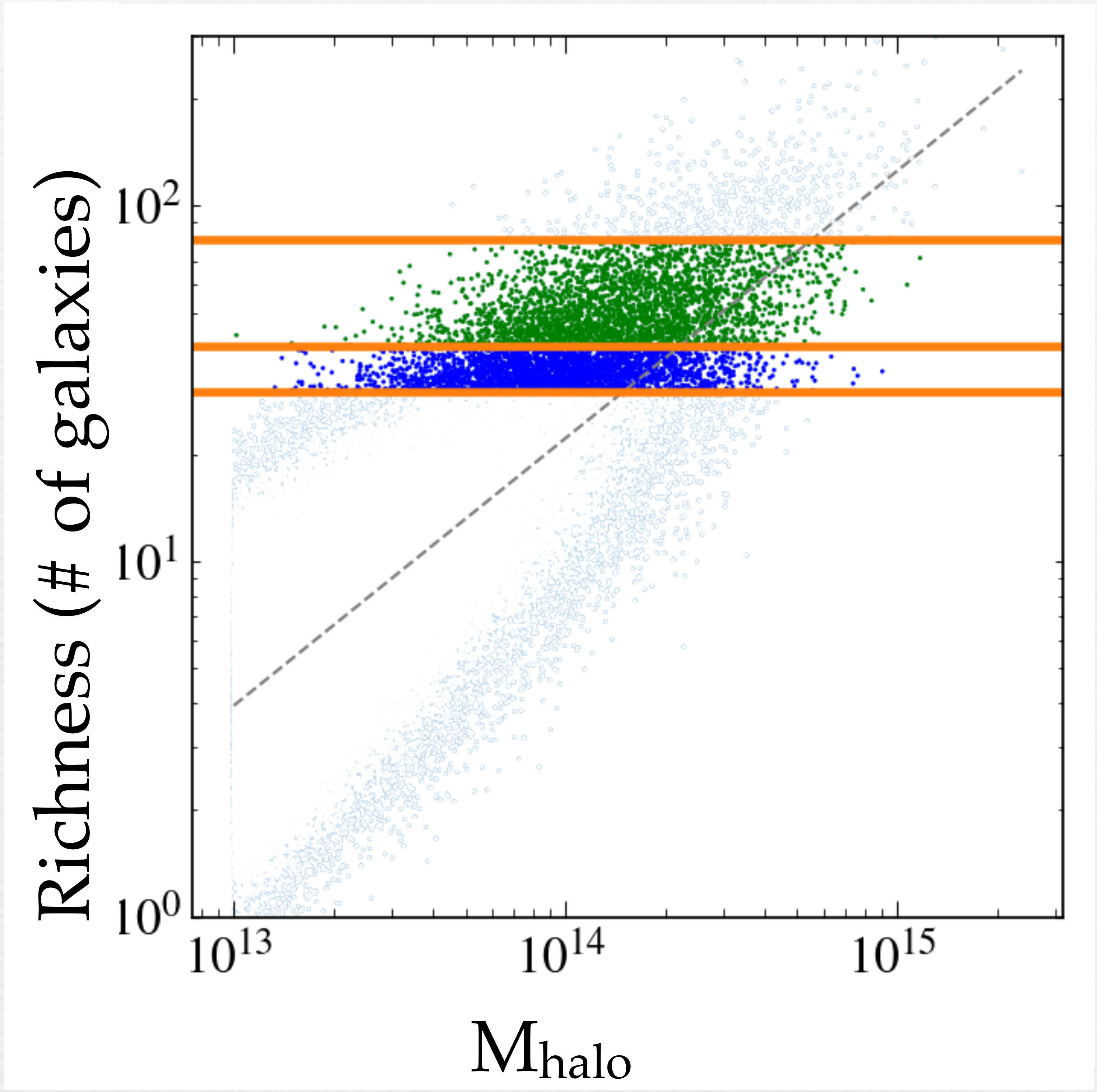
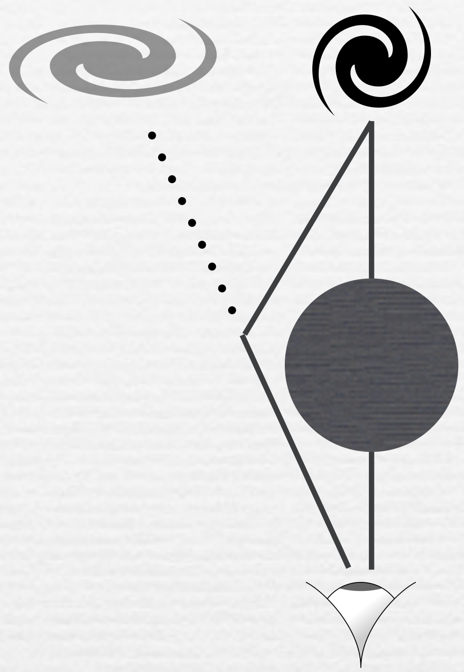
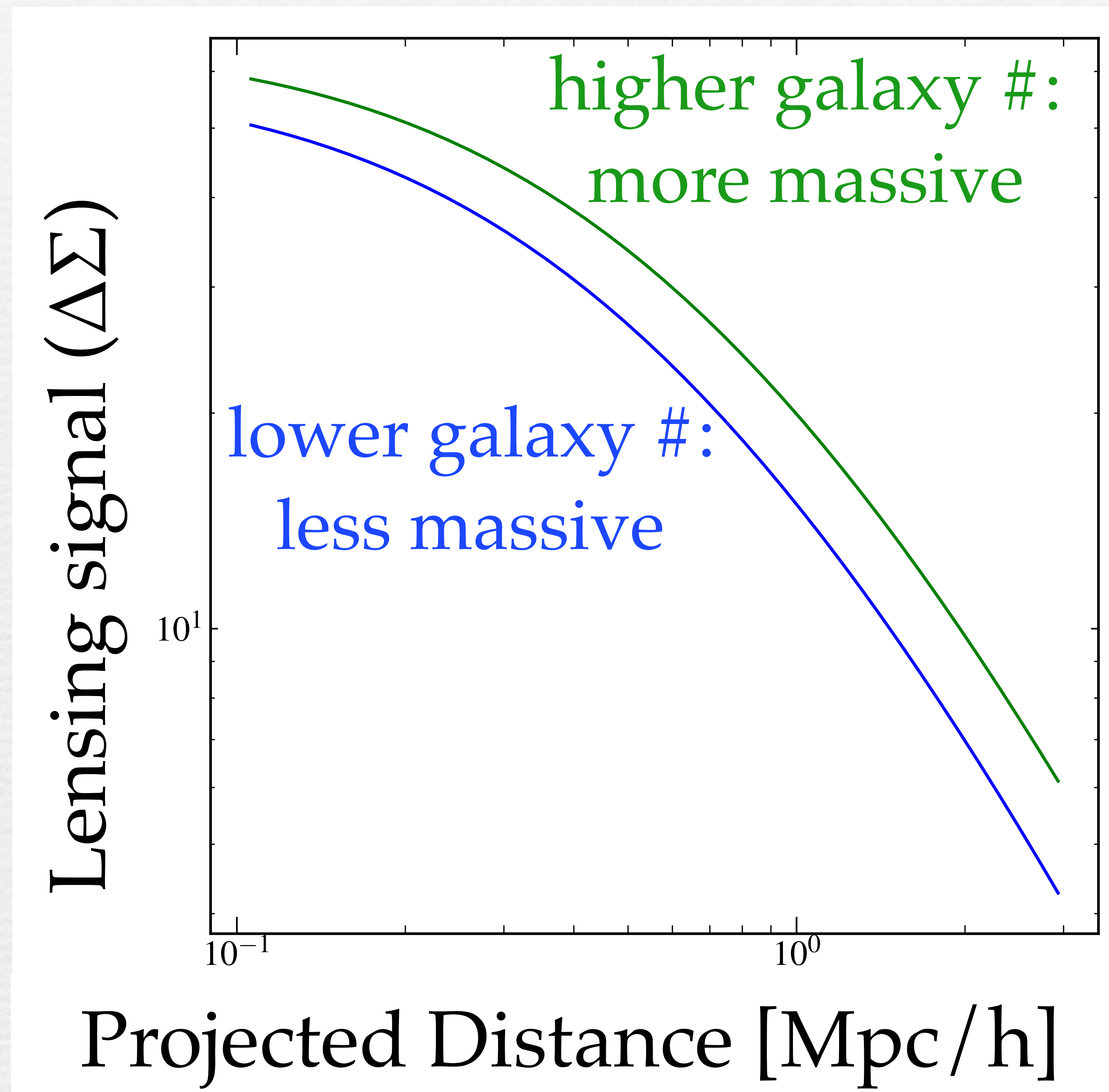


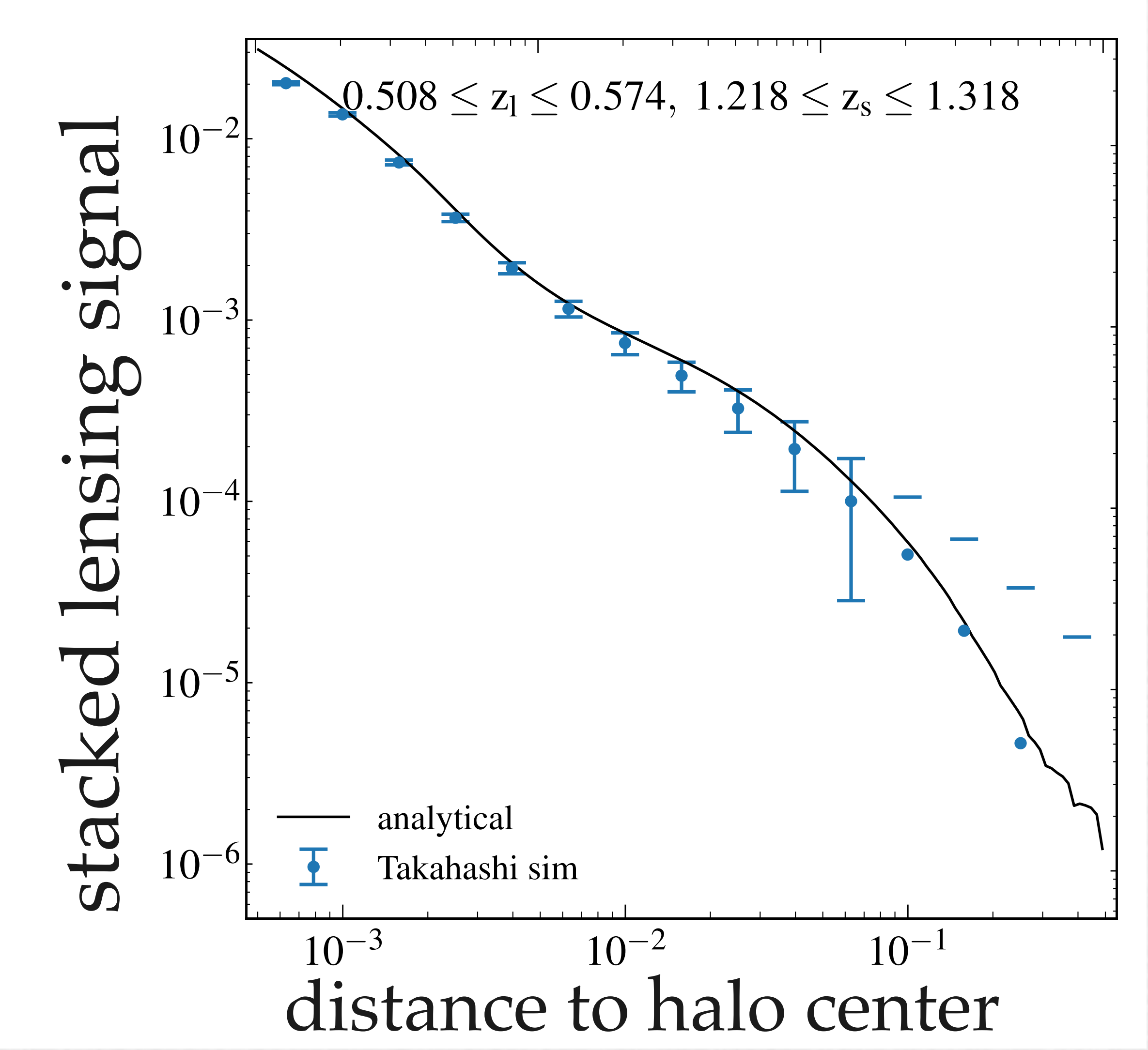
Stacking the weak lensing effect

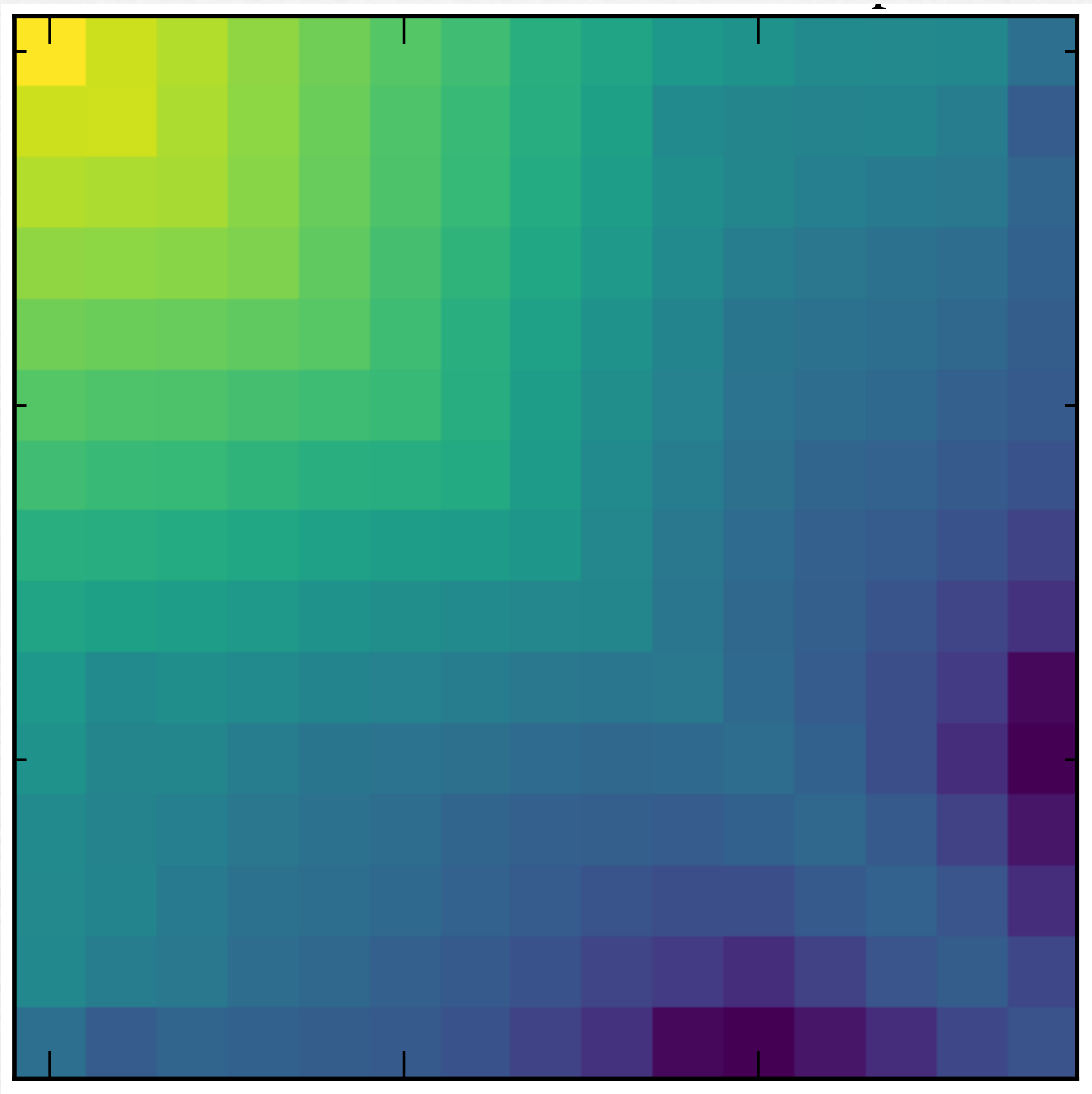


Deriving the mean mass of clusters in a richness bin from the stacked lensing



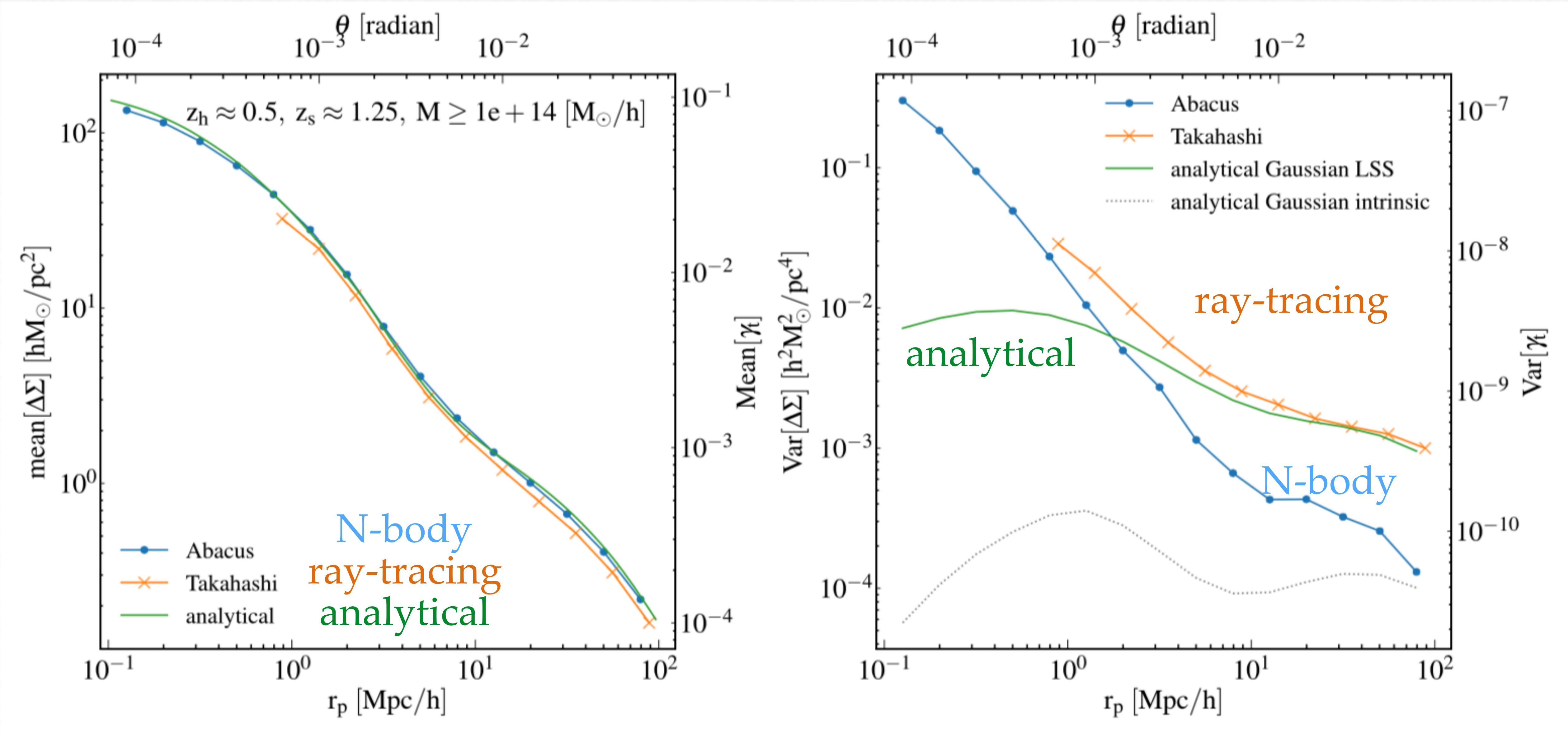
How do we calculate the error bars if we stack all clusters in our survey?





Ideally, we simulate many realizations of our survey (number of realizations >> number of data points) and calculate the covariance among realizations. It's incorrect to use halo-to-halo covariance.

Simulations vs. Analytical Calculations

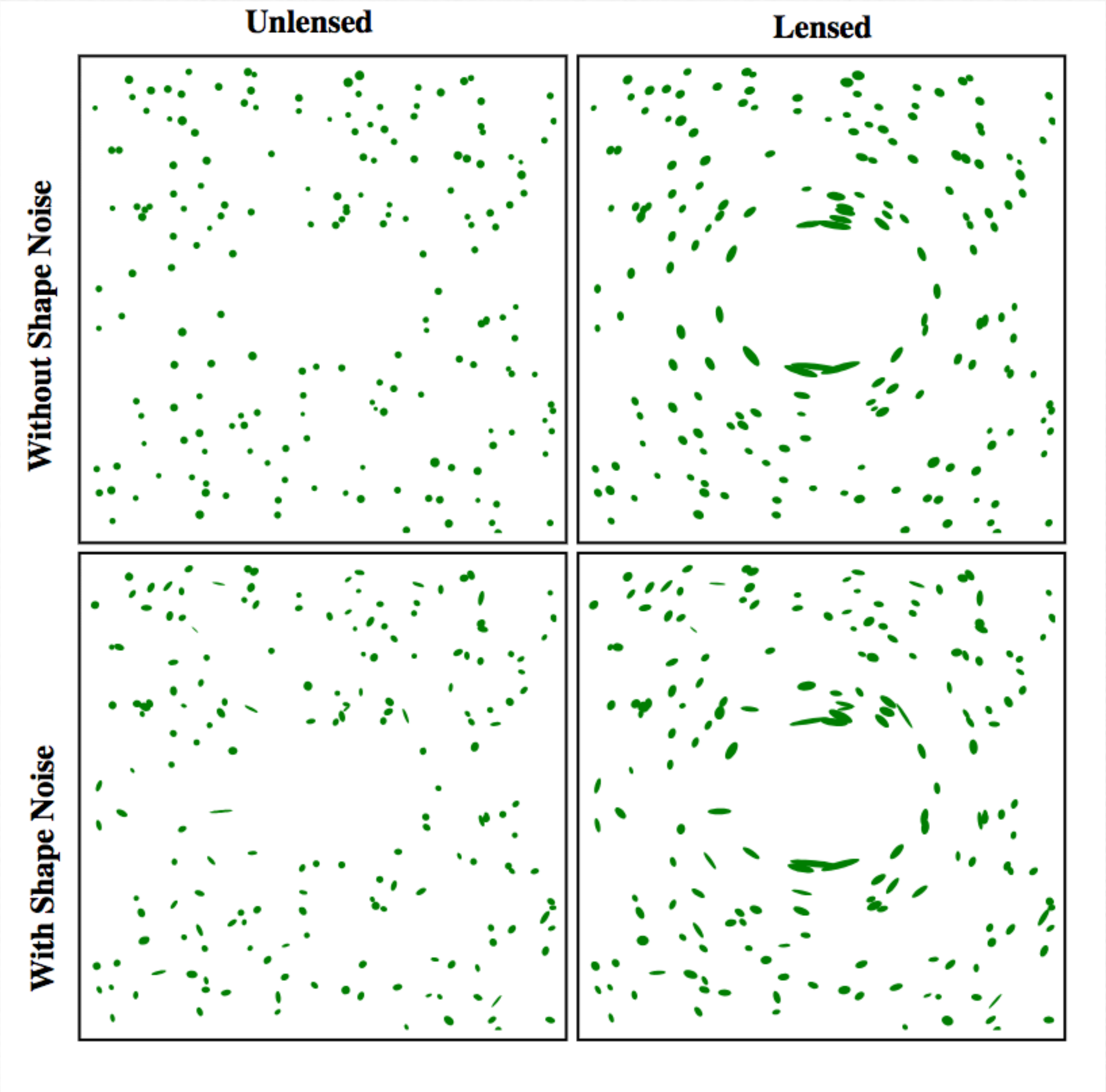


- Analytical calculations: inaccurate at medium/small scales
- Ray-tracing sims: limited to > 1 Mpc, expensive to run
- We combine high-resolution N-body sims with analytical calculations, cross-checking with ray-tracing sims.

Three major components of cluster lensing covariance matrices

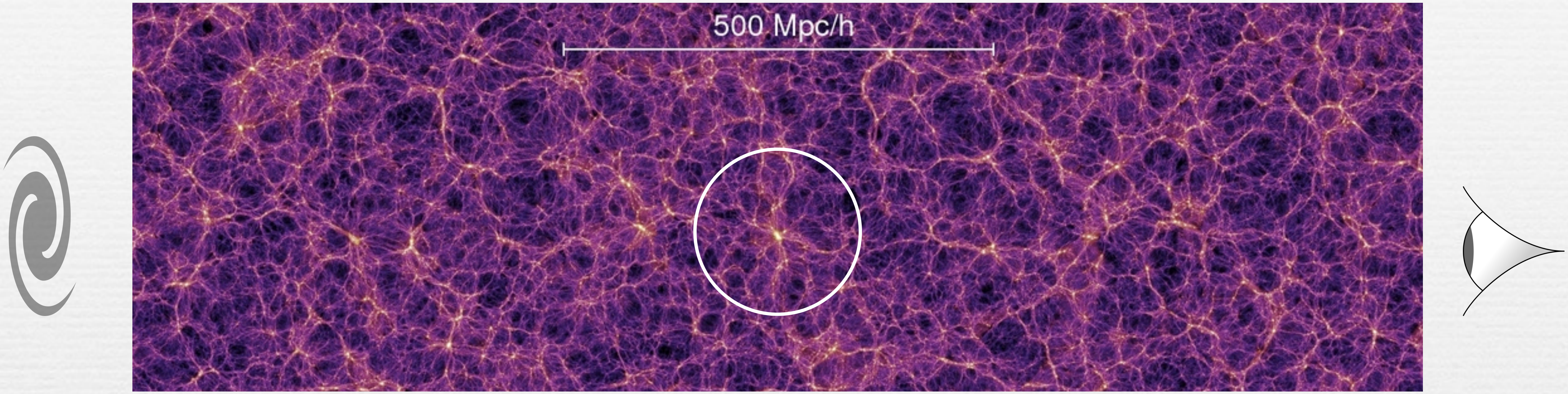
1. Shape noise ($\sim 1/N_{gal}$)
2. Large-scale structure (analytical calculations)
3. Intrinsic variation of halo density profile (small-scale, N-body sims)

Shape noise due to intrinsic galaxy ellipticities



- $\propto 1/N_{gal}$
- Dominating most of current surveys (n_{src}~10 gal/arcmin^2)
- Mostly diagonal

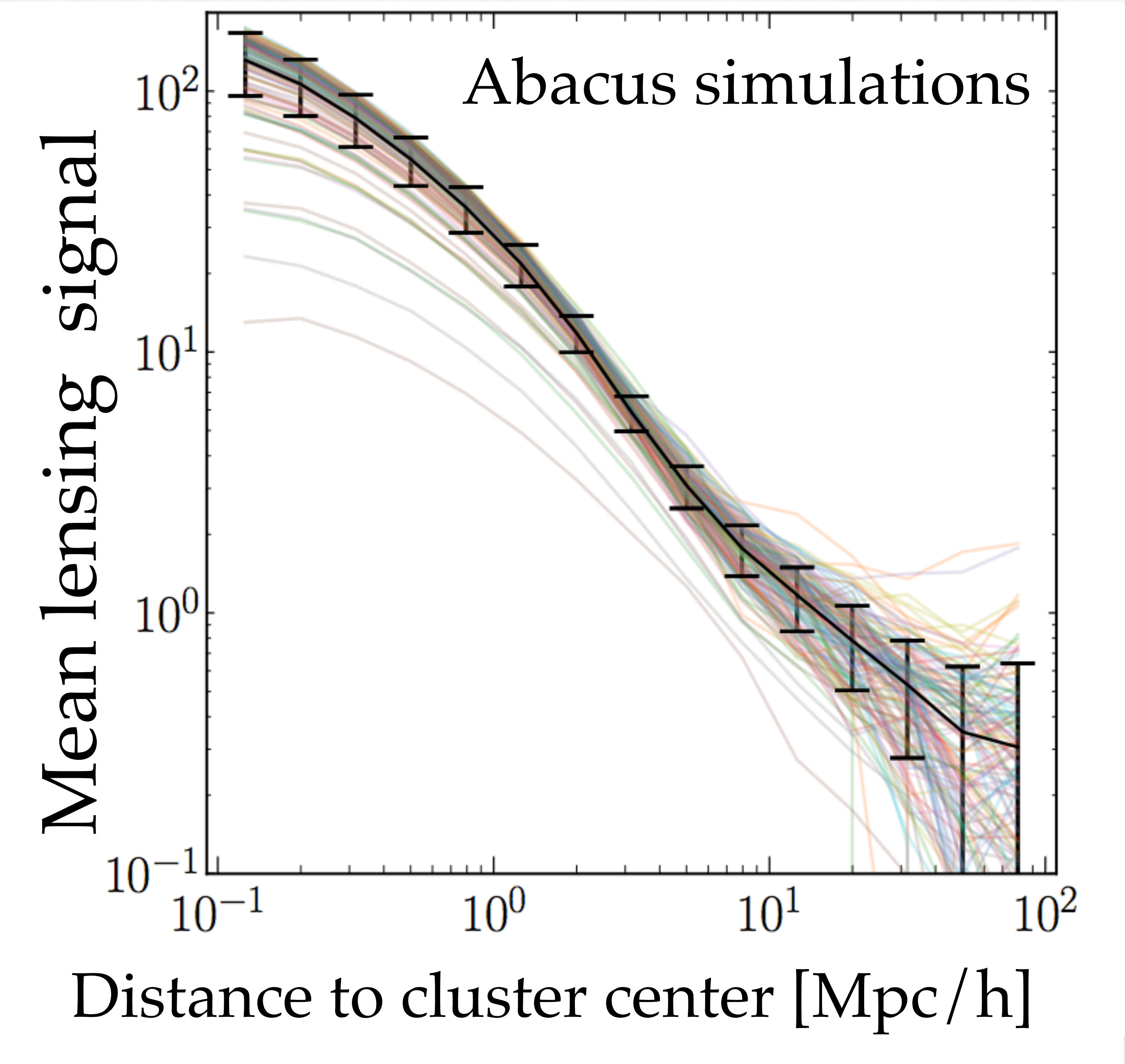
Noise from Large-Scale Structure



- It dominates large-scale lensing error (where cluster signal is low and shape noise is also low).
- It can be calculated analytically assuming Gaussian random field.

Figure from Millennium Simulation

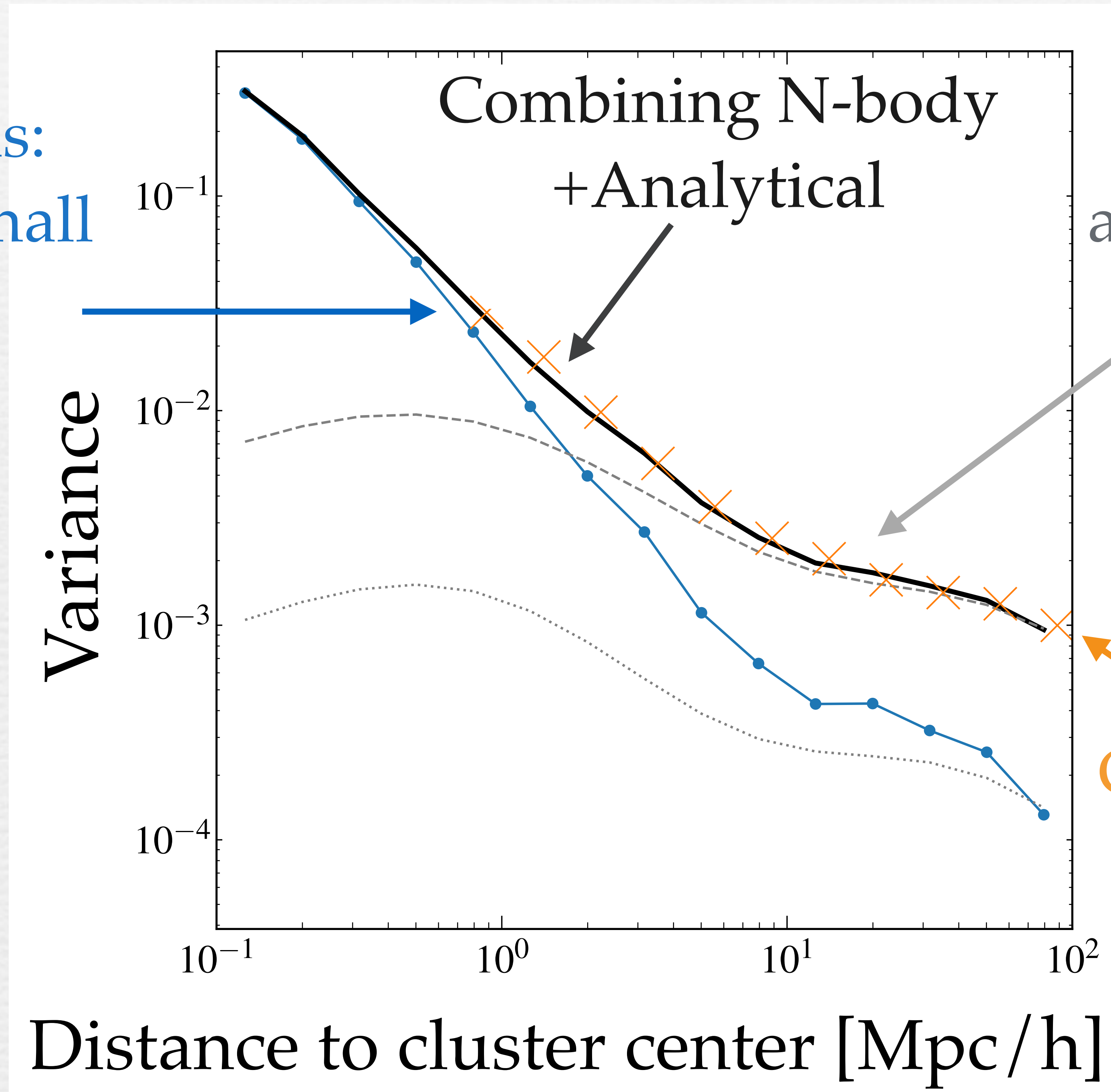
Noise from Intrinsic Variation of Halo Density Profiles



- Halos have diverse projected density profiles due to different concentration, triaxial shape, substructure, etc.

Combining N-body simulations and analytical calculations

N-body sims: accurate at small scales



Analytical: accurate at large scales

Cross-check with ray-tracing sims (Takahashi)

Wu et al. (1907.06611)

Analytical part: Gaussian random fields

Noise of cluster counts

Noise of shear

cross term (cluster profile)

$$\mathrm{Cov}[\gamma_t^h(\theta), \gamma_t^h(\theta')] = \frac{1}{4\pi f_{\rm sky}} \int \frac{\ell d\ell}{2\pi} J_2(\ell\theta) J_2(\ell\theta') \left[\boxed{\left(C_\ell^h + \frac{1}{\bar{n}_L} \right)} \boxed{\left(C_\ell^\kappa + \frac{\sigma_\gamma^2}{\bar{n}_S} \right)} + \left(C_\ell^{h\kappa} \right)^2 \right]$$

Both the cross term and the non-Gaussian contribution are calculated with N-body simulations.

replaced by simulations

LSS

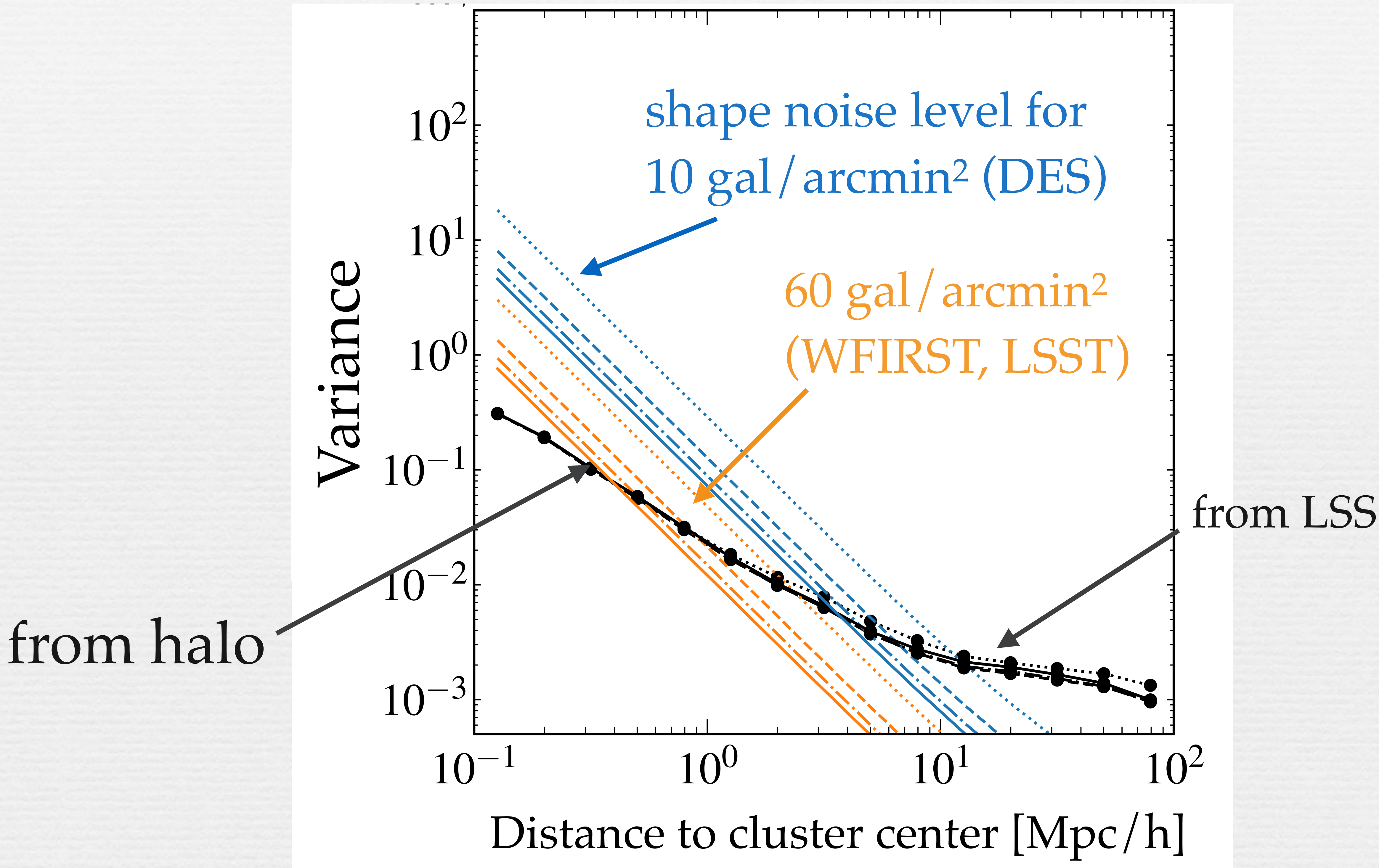
clustering of clusters

cluster shot noise

shape noise

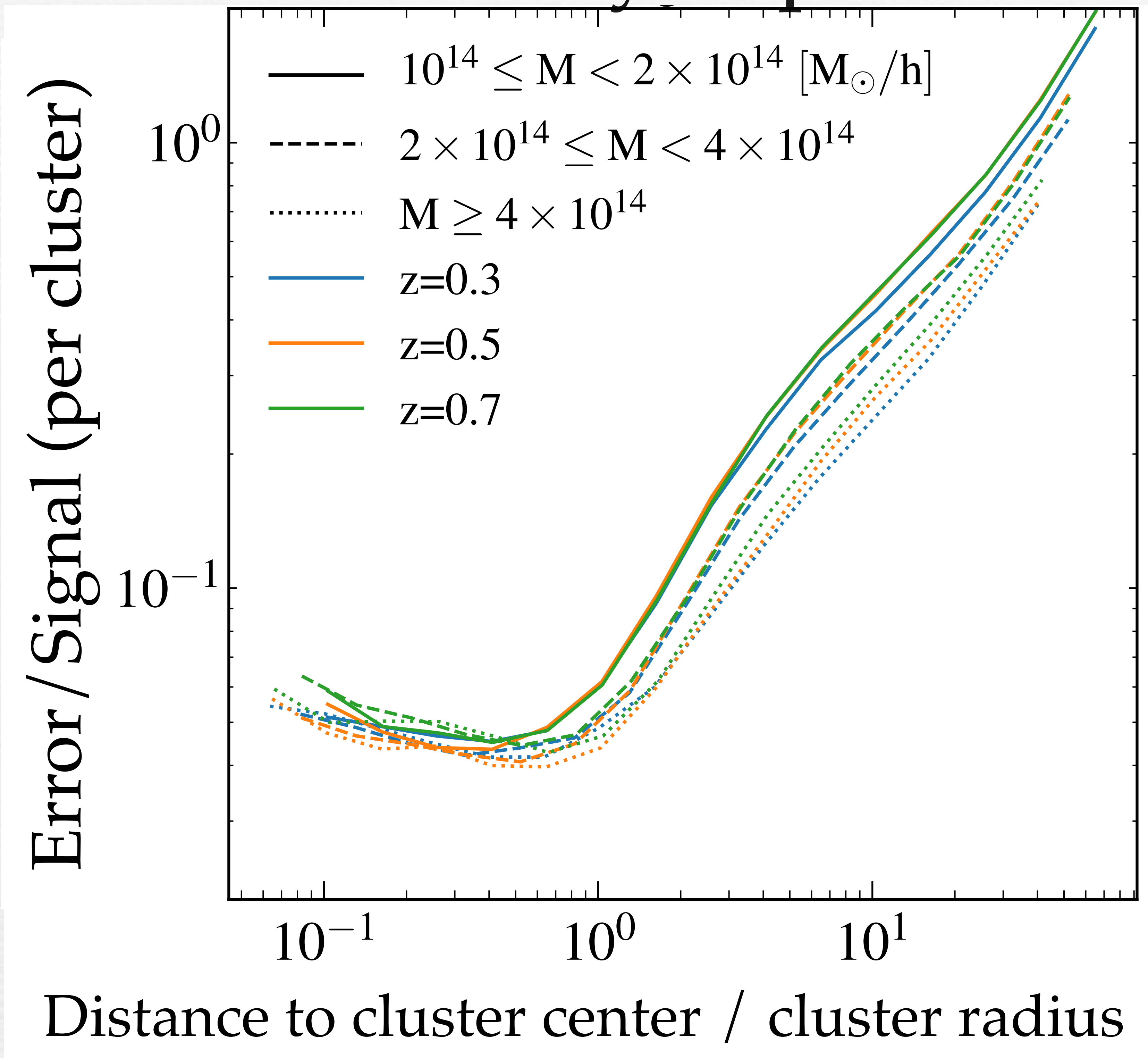
Wu et al. (1907.06611)

Importance of shape noise vs. density fluctuations



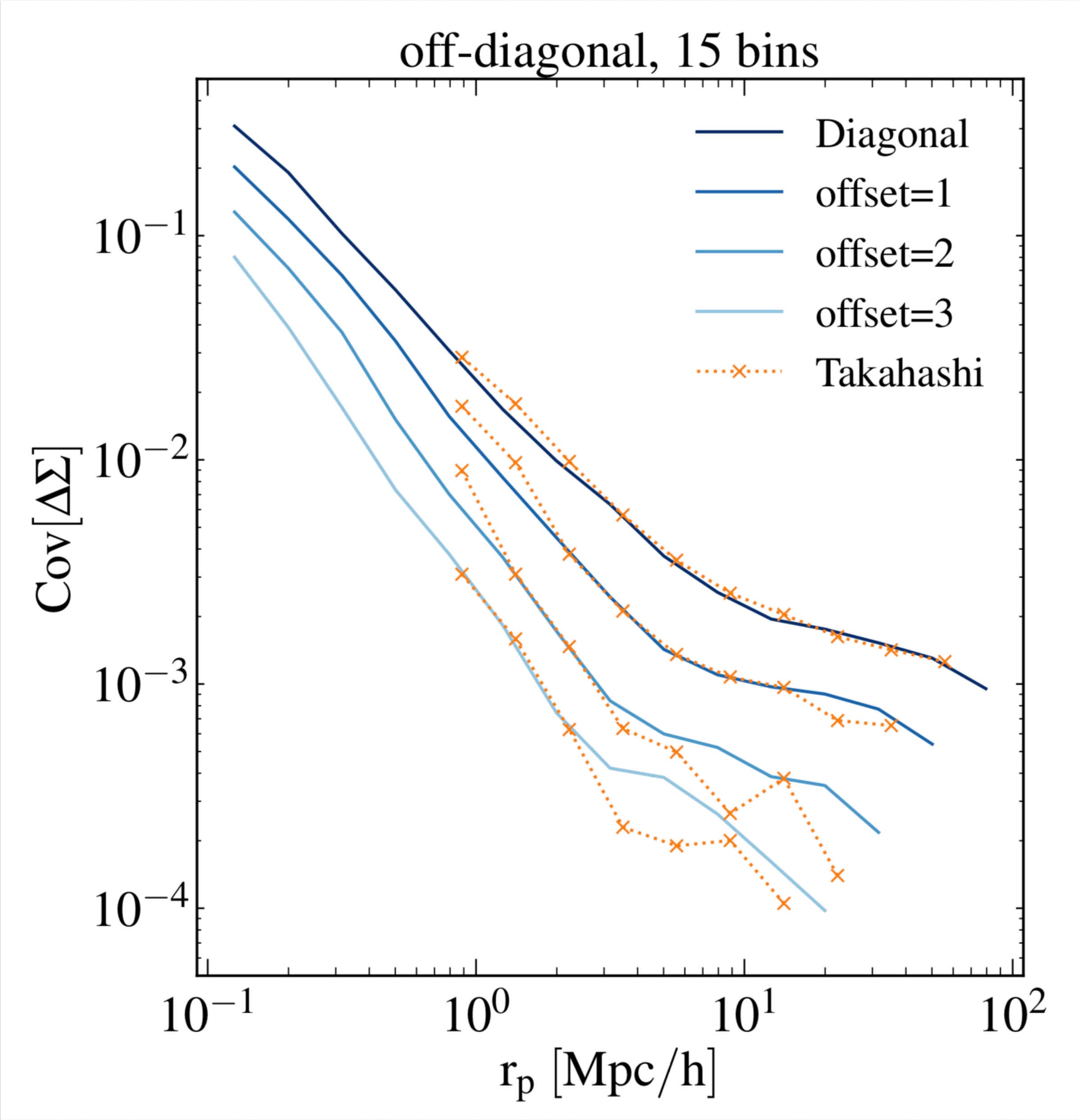
Wu et al. (1907.06611)

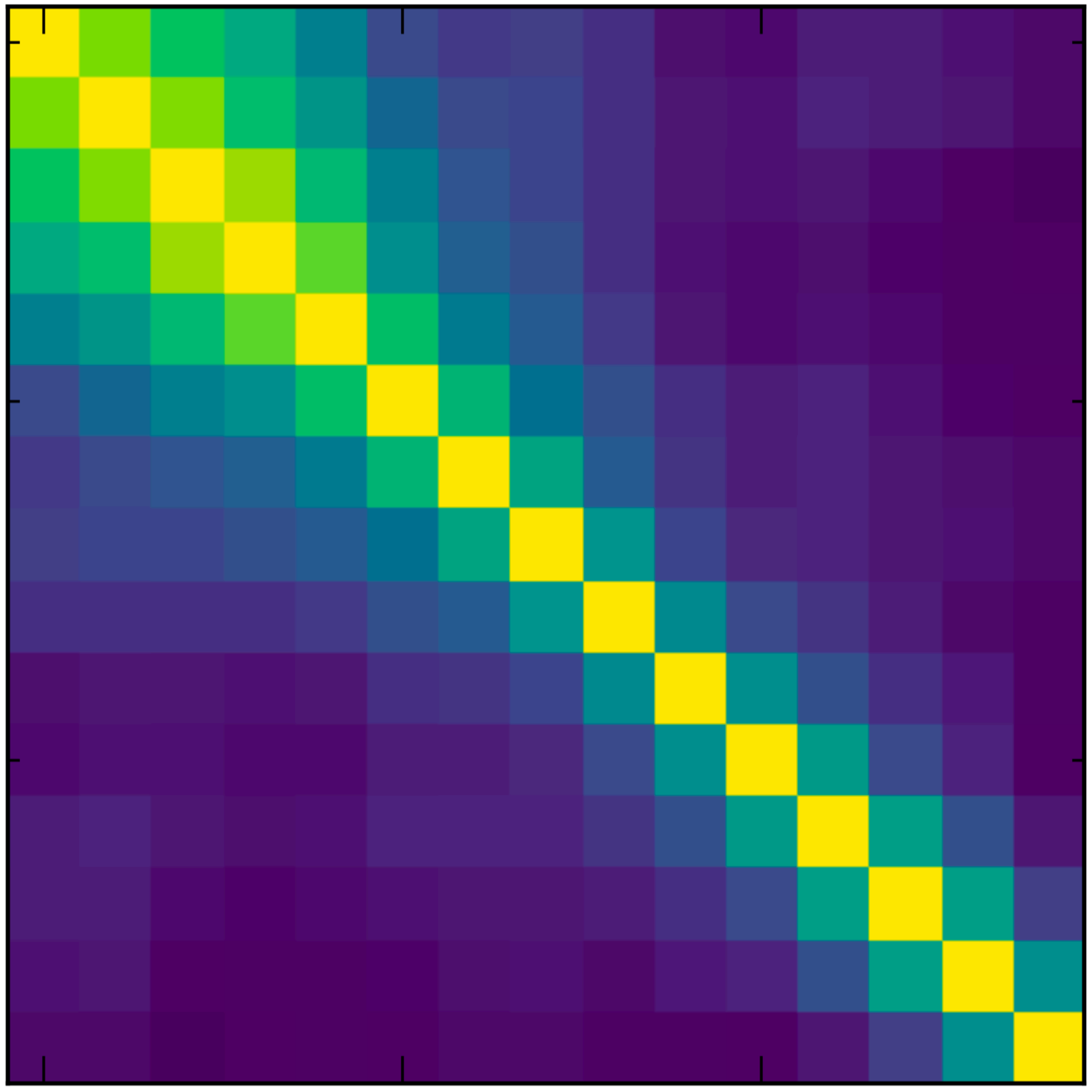
Fractional error is independent of redshift and weakly depends on mass



Wu et al. (1907.06611)

Diagonal vs. off-diagonal elements

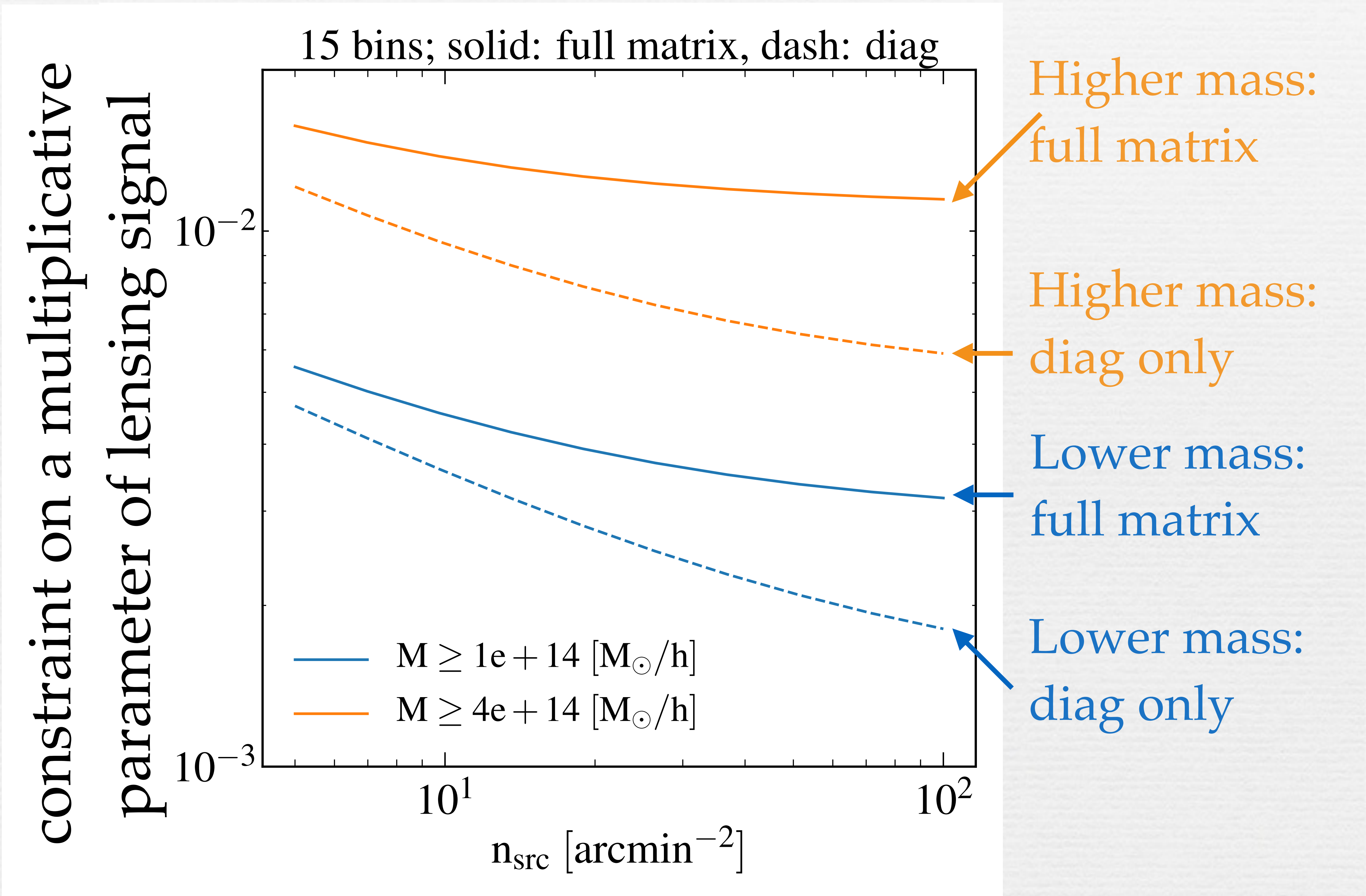




Off-diagonal elements decrease rapidly, especially at large-scales.

Wu et al. (1907.06611)

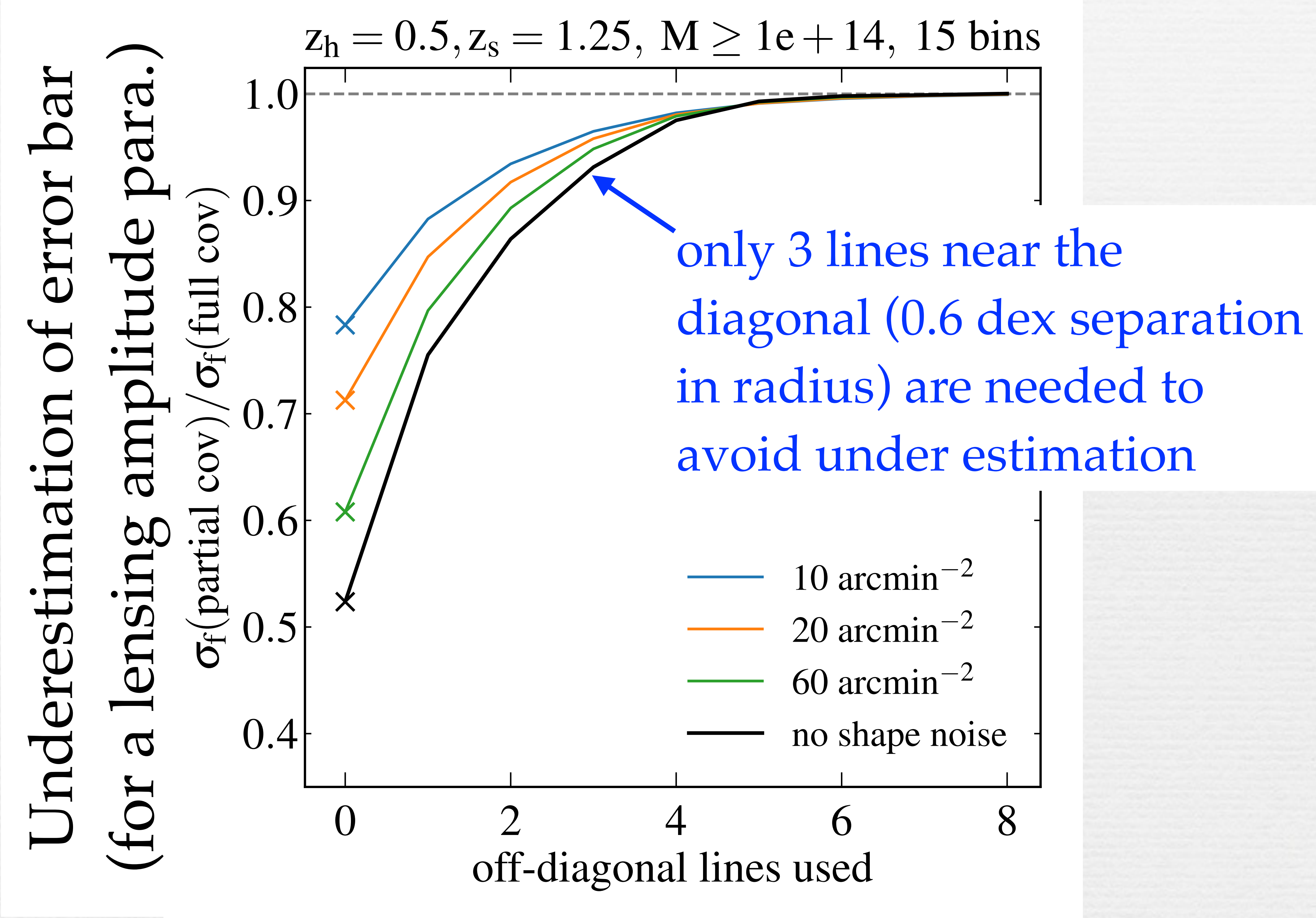
Importance of diagonal elements



lower shape noise ⟶

Wu et al. (1907.06611)

Importance of diagonal elements



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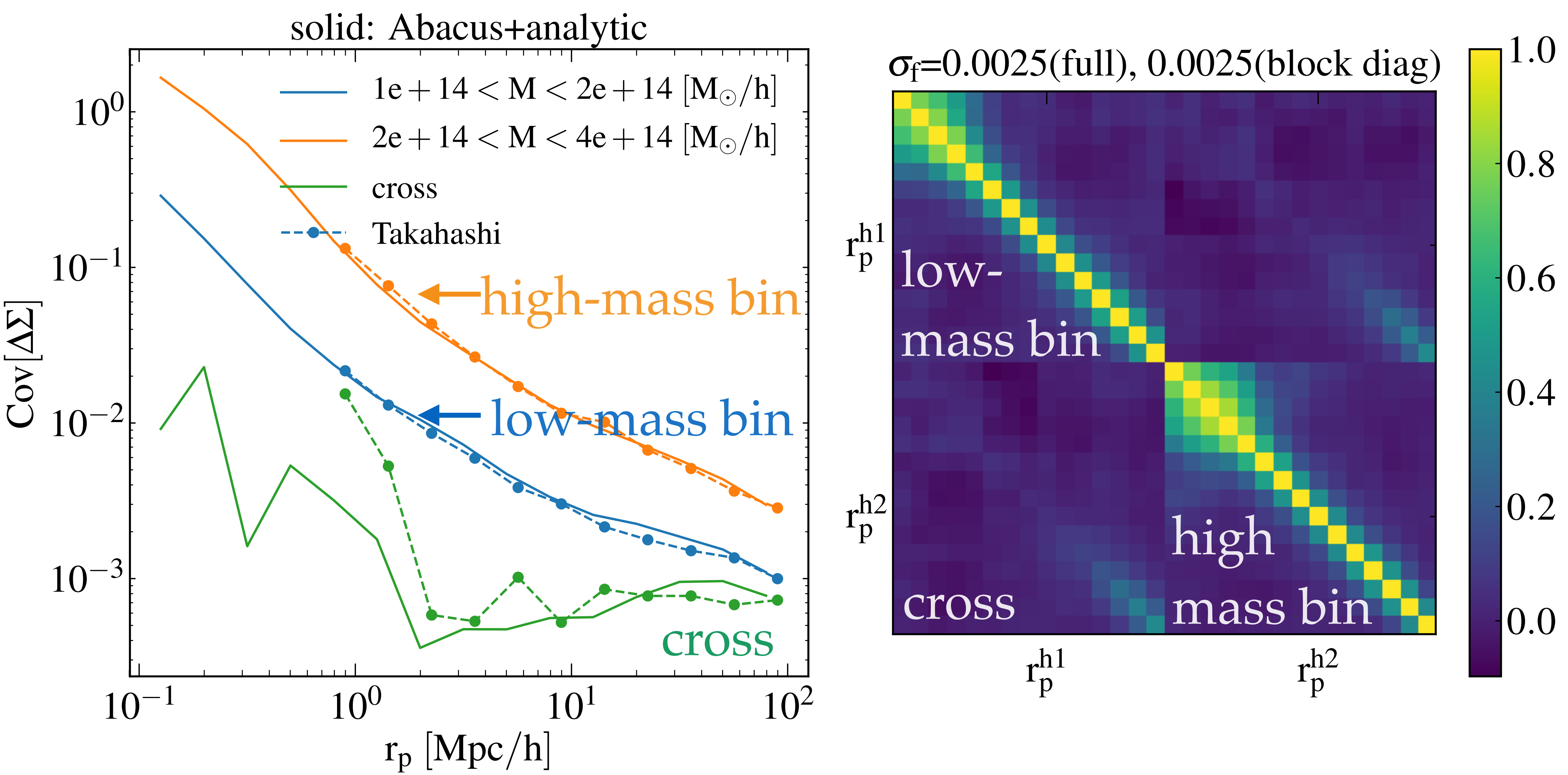
Cross-mass bin covariance



In the absence of shape noise, the cross-mass covariance is negligible.

Wu et al. (1907.06611)

Can we do cluster cosmology using only correlation functions (without number counts)?

Cosmology with Stacked Cluster Weak Lensing and Cluster-Galaxy Cross-Correlations

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Correlations between clusters, galaxies, and dark matter

Cluster lensing $$\Delta\Sigma \propto b_c \sigma_8^2,$$

Cluster galaxy cross correlation $$w_{p,cg} \propto b_c b_g \sigma_8^2,$$

Galaxy auto correlation $$w_{p,gg} \propto b_g^2 \sigma_8^2,$$

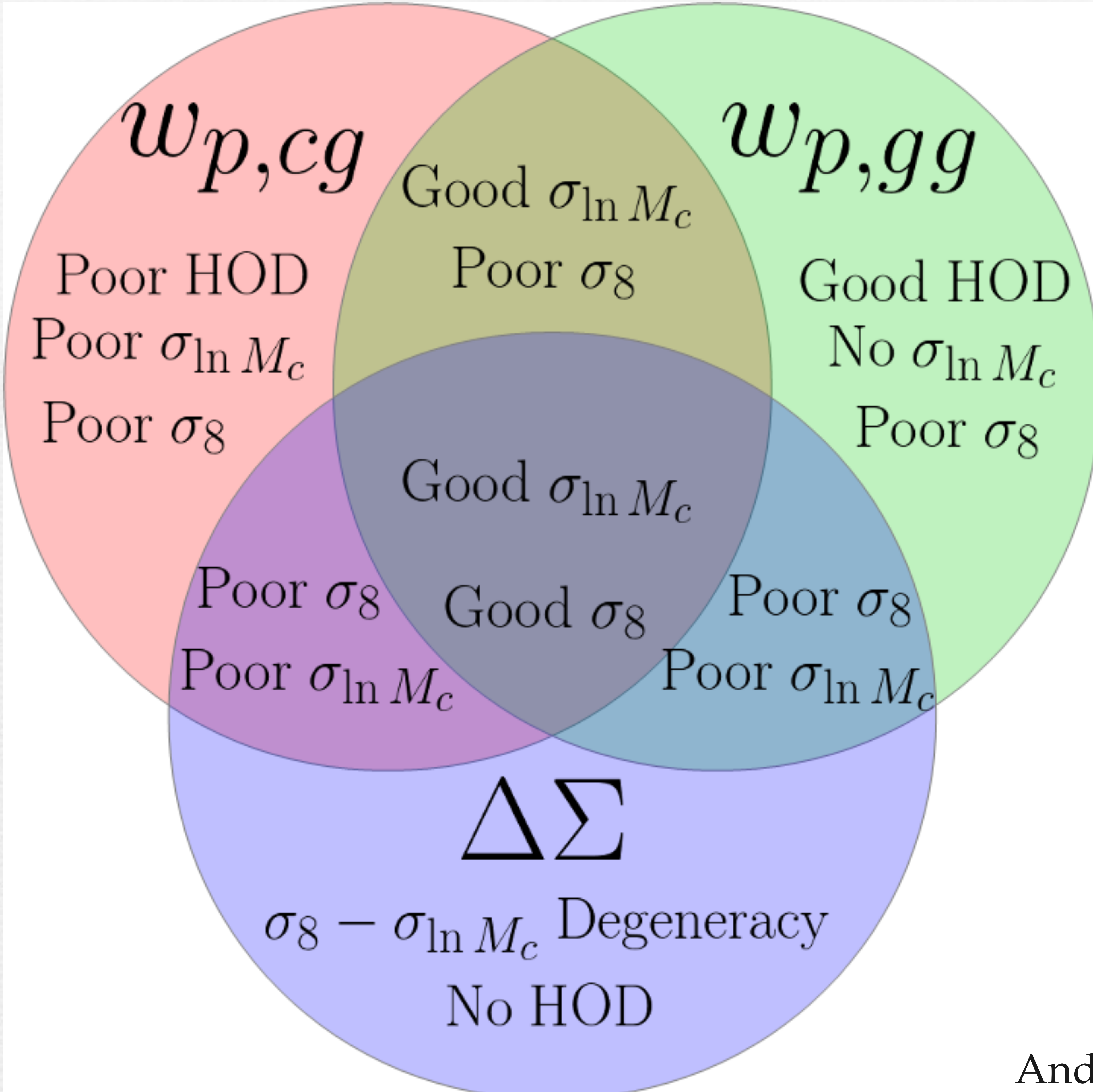
3 unknowns, 3 observables

Constraining nuisance parameters

Cluster lensing — observable-mass relation

Cluster galaxy cross correlation — both

Galaxy auto correlation — galaxy-halo connection



Andres Salcedo

Summary

- The number vs. mass of galaxy clusters is a sensitive probe of growth of structure and cosmic acceleration.
- Current surveys like DES are limited by shape noise. For future surveys like LSST and WFIRST, the noise will be dominated by large-scale structure and halo profile variance. We combine simulations and analytical calculations to achieve the required precision.
- Cross-correlation functions of clusters, galaxies, and lensing provide a promising method for constraining scatter and cosmology simultaneously.