Probing Cosmic Acceleration with Galaxy Clusters

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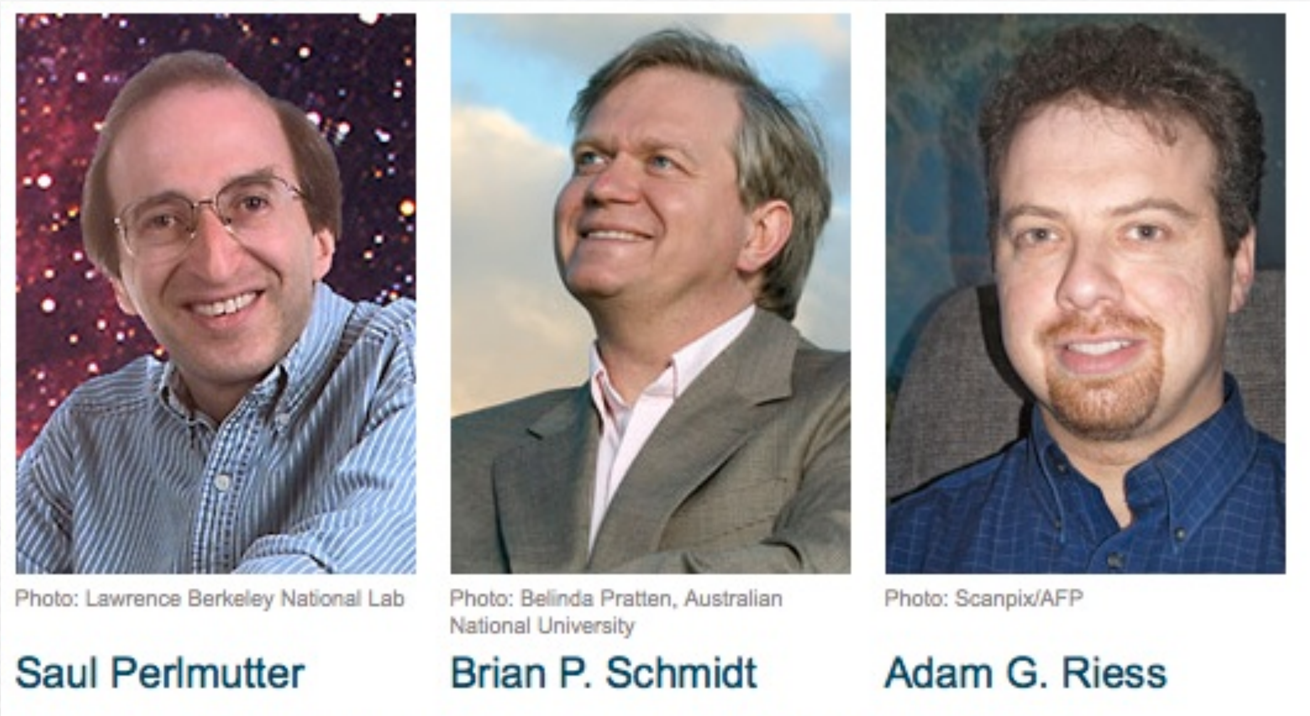
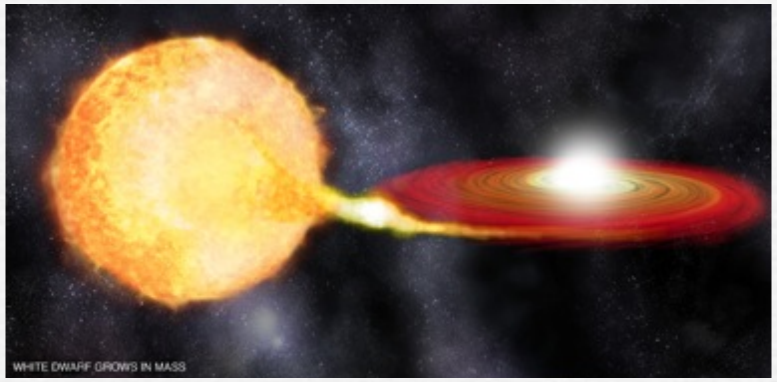
Overview

- Introduction
  - Cosmic acceleration
  - Galaxy cluster surveys
- Gravitational lensing for current & next generation cluster cosmology
  - Part I: Cluster lensing signals
  - Part II: Covariance matrices

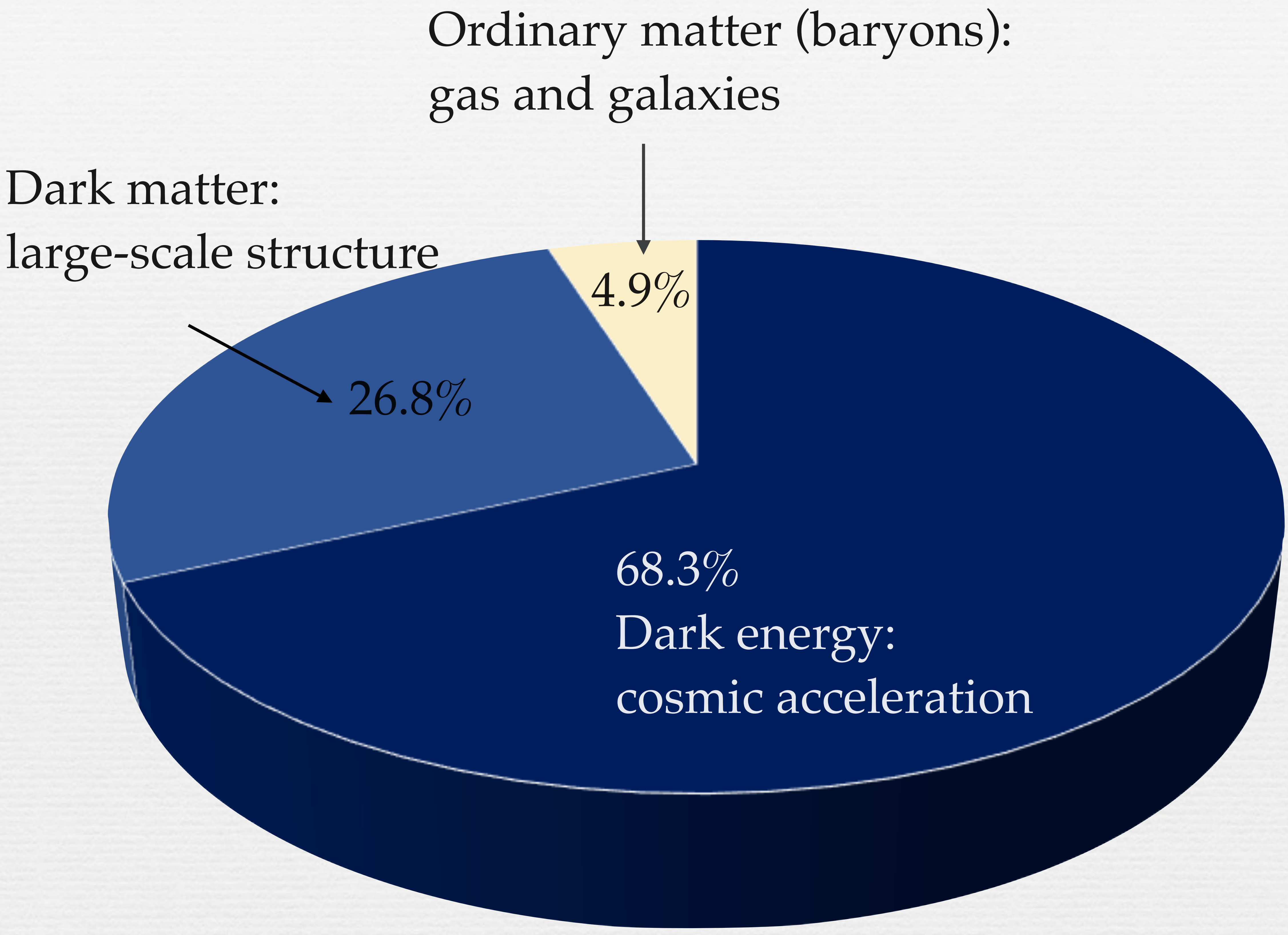
Discovery of cosmic acceleration



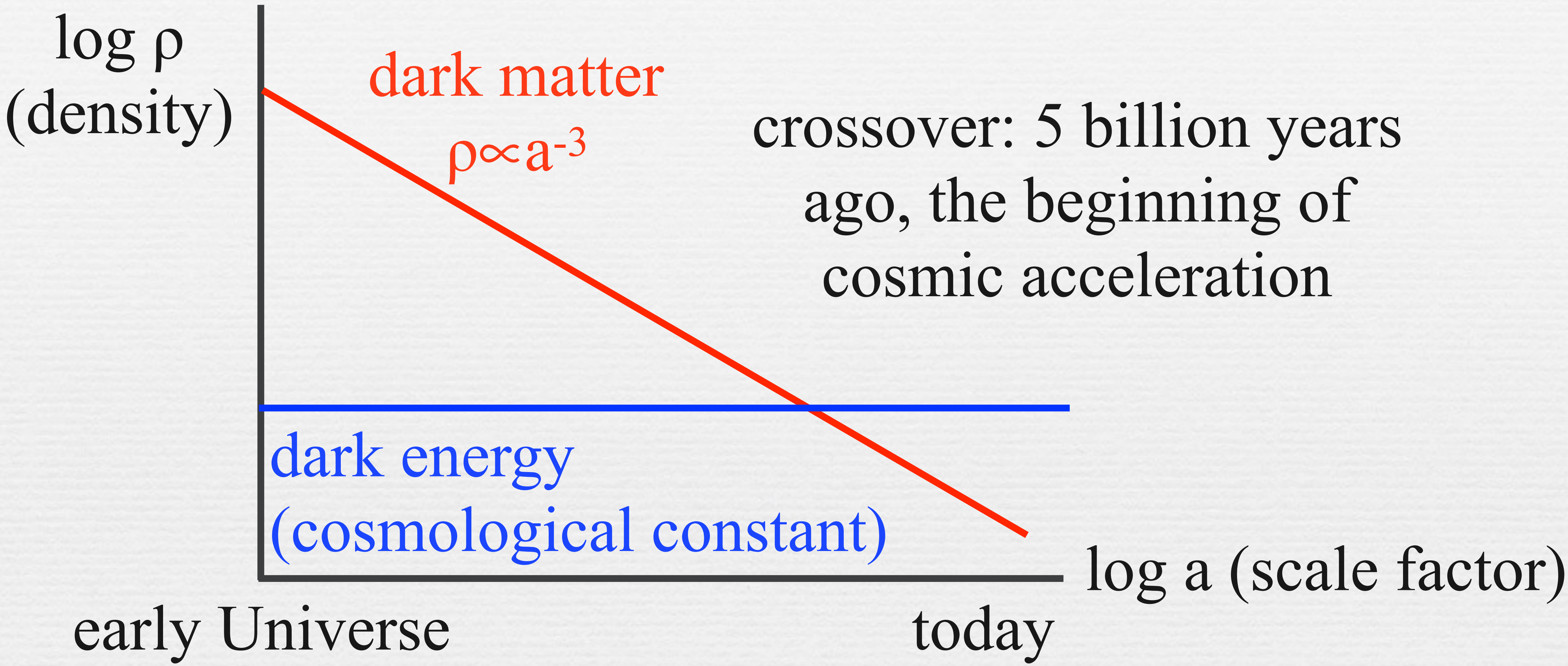
2011 Nobel Prize in Physics



Perlmutter, Schmidt, and Riess used Type Ia Supernovae to accurately determine the **redshift-distance relation**. They found that the Universe is accelerating.


Ordinary matter (baryons):
gas and galaxies
Dark matter:
large-scale structure
4.9%
26.8%
68.3%
Dark energy:
cosmic acceleration

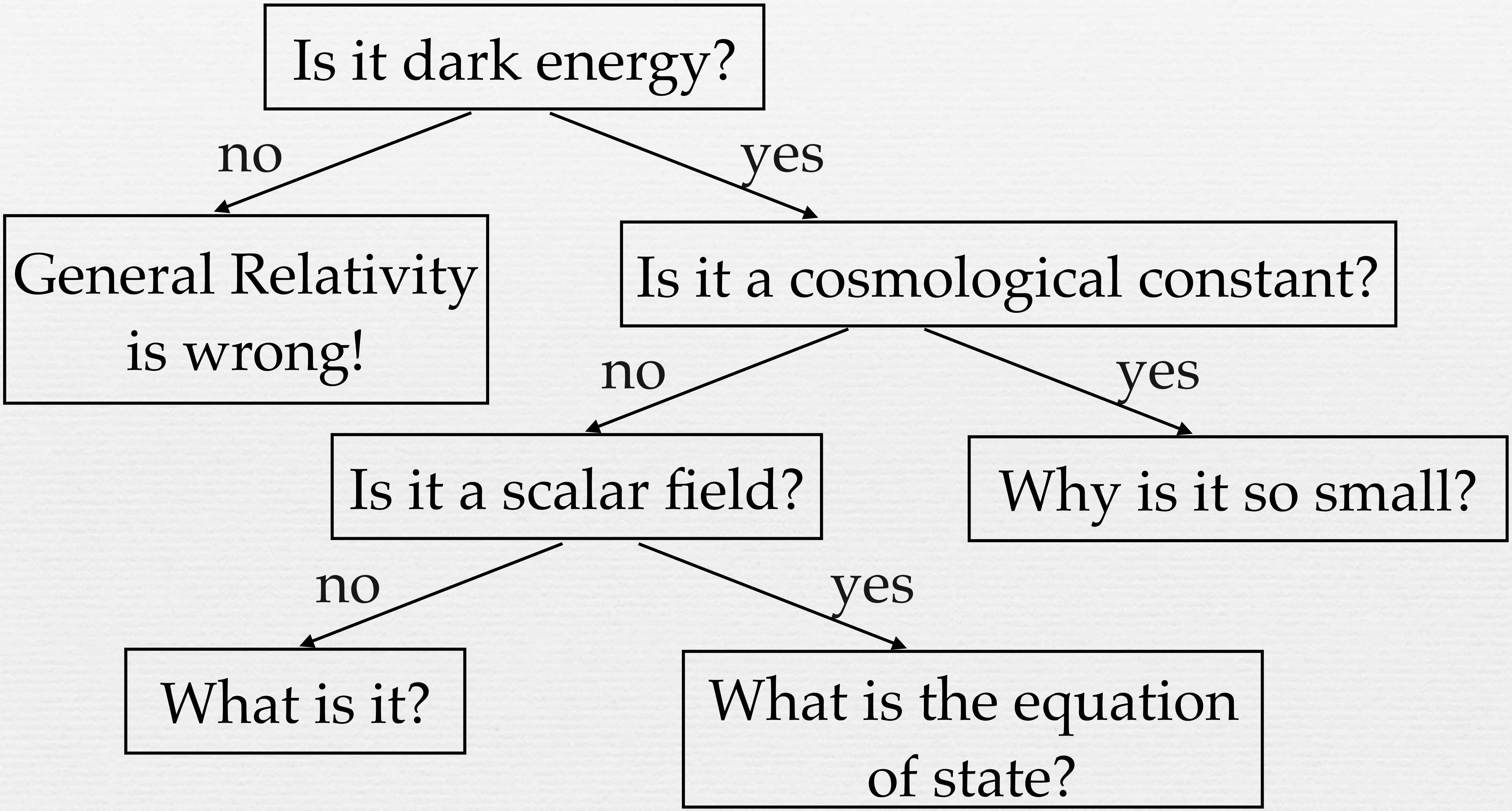
Dark matter vs. dark energy



In general, $P = w\,\rho$ (equation of state), $\rho \propto a^{-3(1+w)}$

$w = -1$: cosmological constant

What causes the cosmic acceleration?

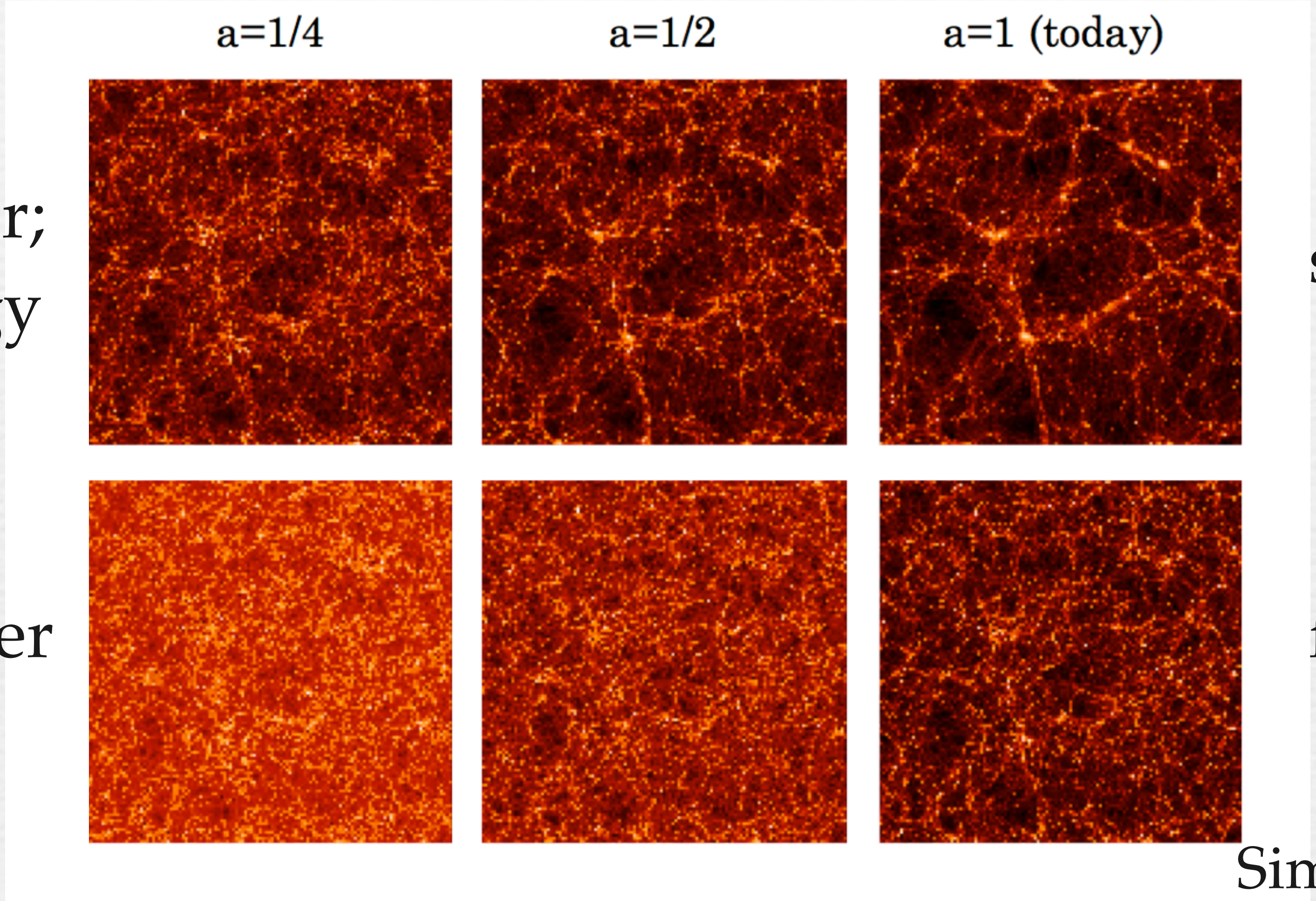


We need measurements other than the expansion rate.

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)

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

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Galaxy clusters: the highest density peaks

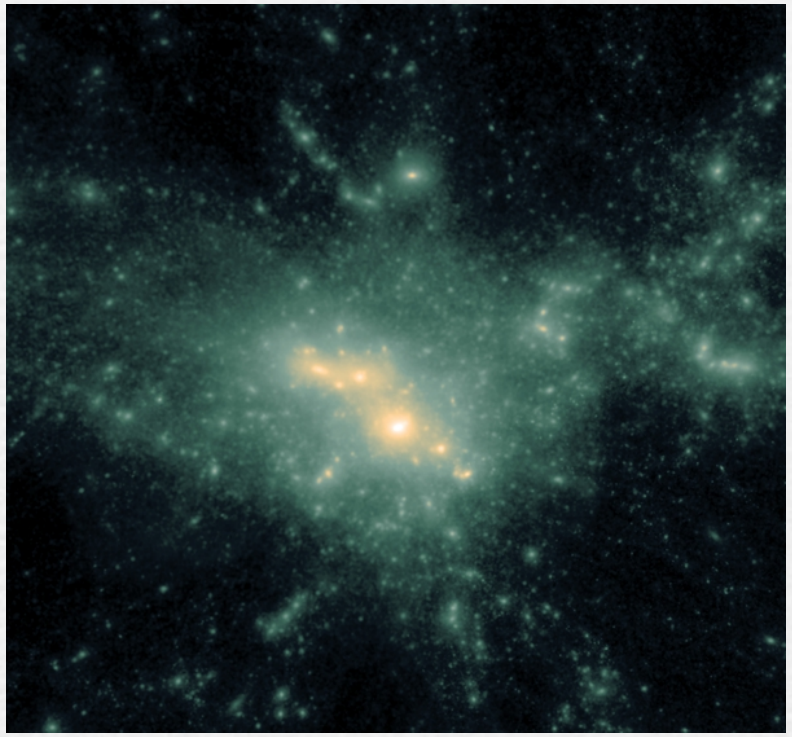
Galaxies

2%

Hot gas

10%

Dark matter halo



88%

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

Size ~ a few million parsecs (Mpc)

1 $M_\odot \approx 2\times10^{30}$ kg

1 parsec

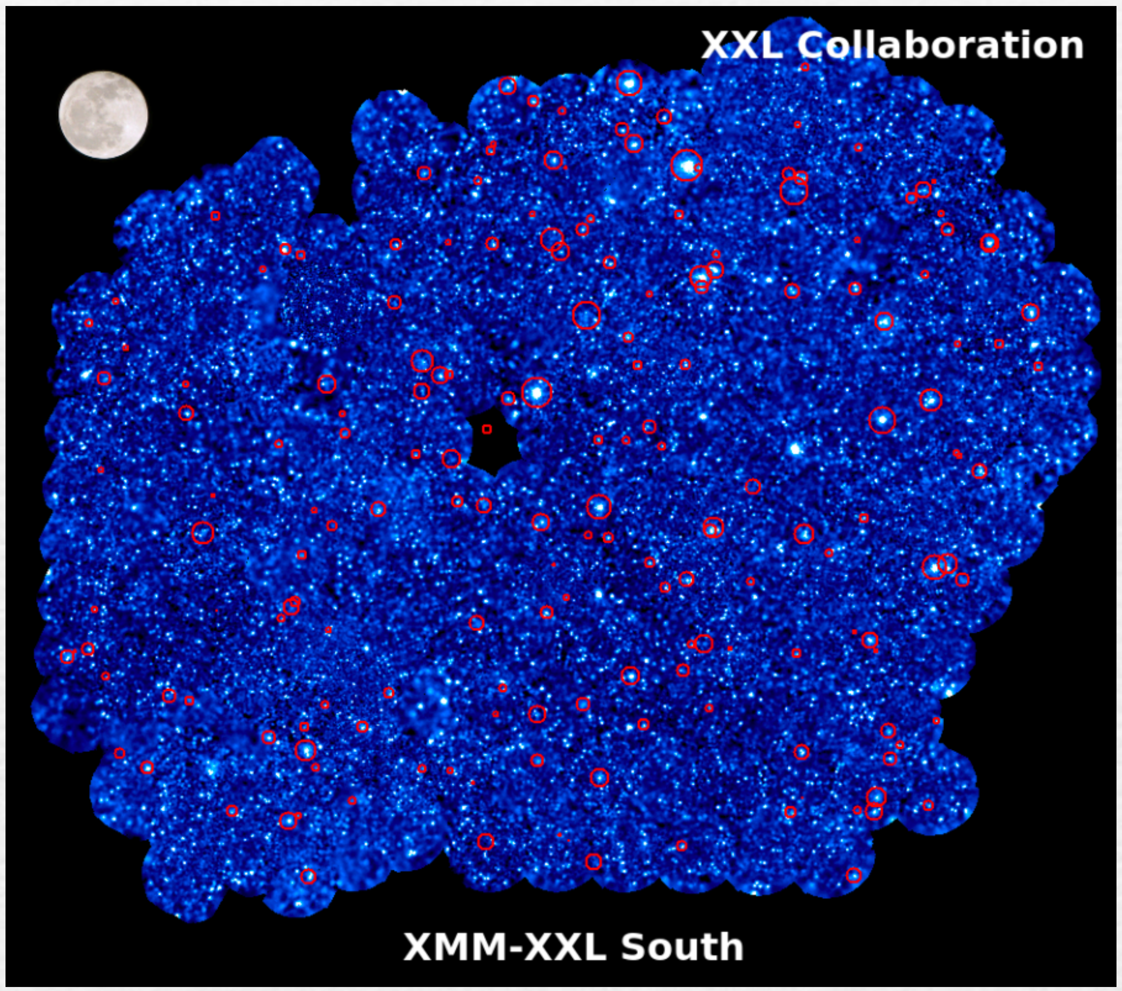
$\approx$ 3 lightyears

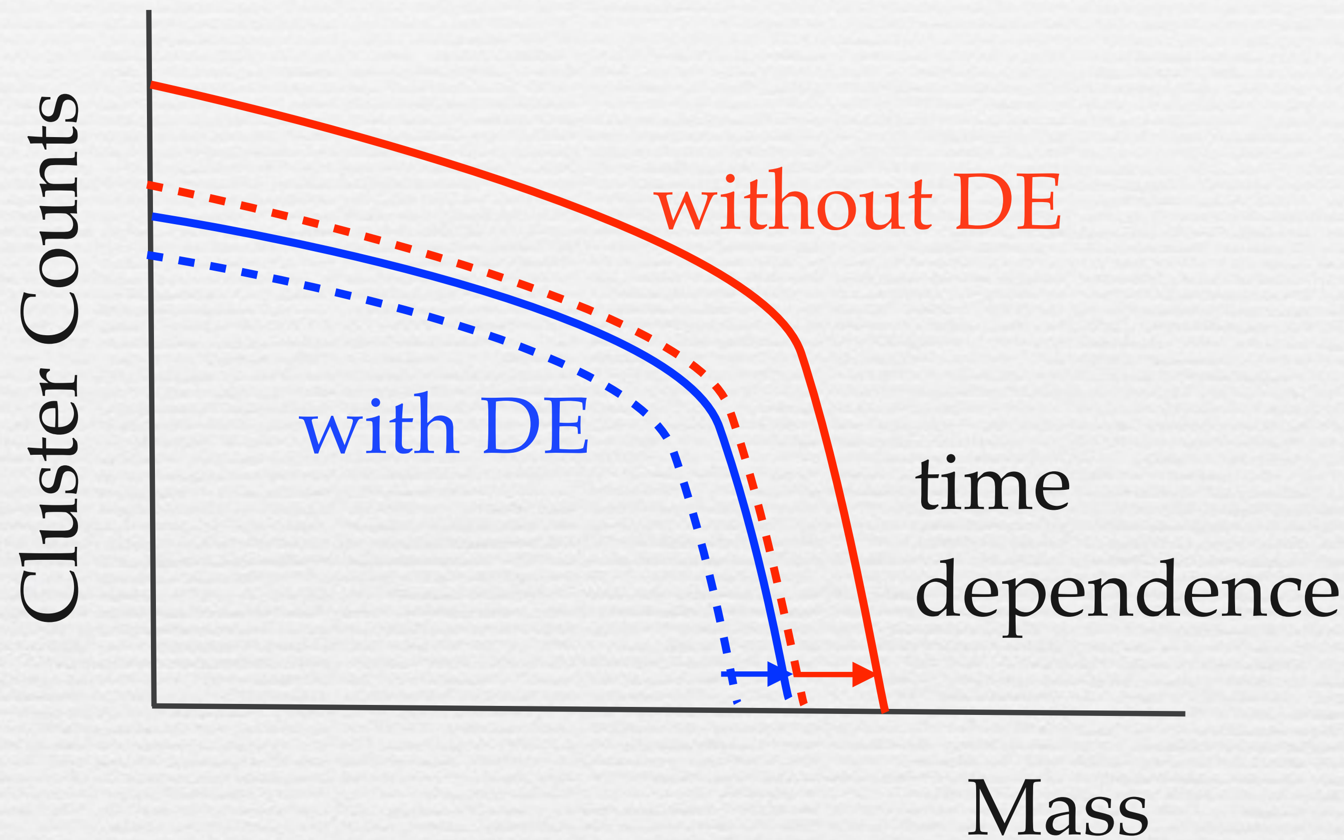
$\approx 3\times10^{16}$ m

How do galaxy clusters form?

Simulation: Heidi Wu. Visualization: Ralf Kaehler

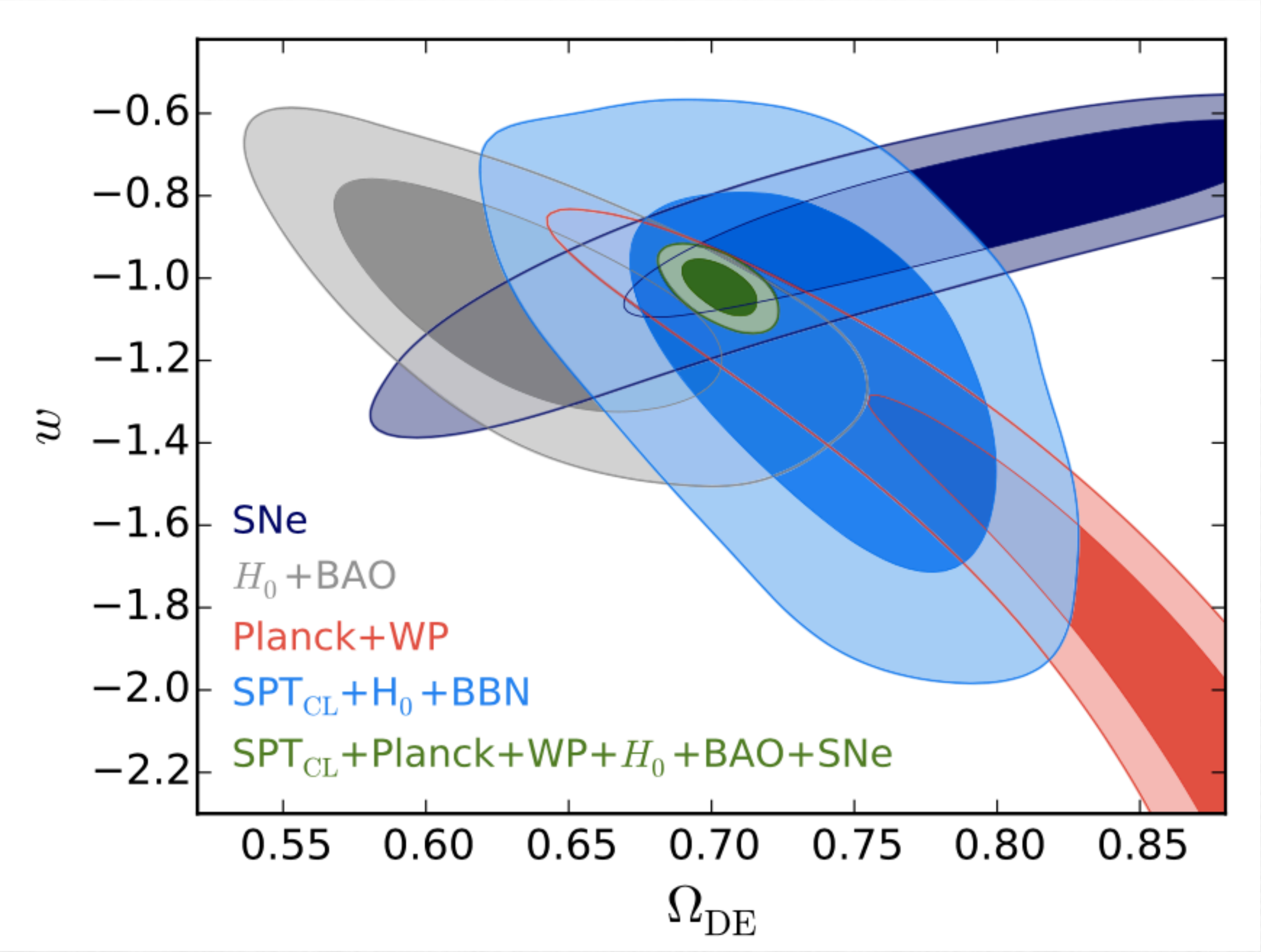
Measuring dark energy using the number counts of galaxy clusters





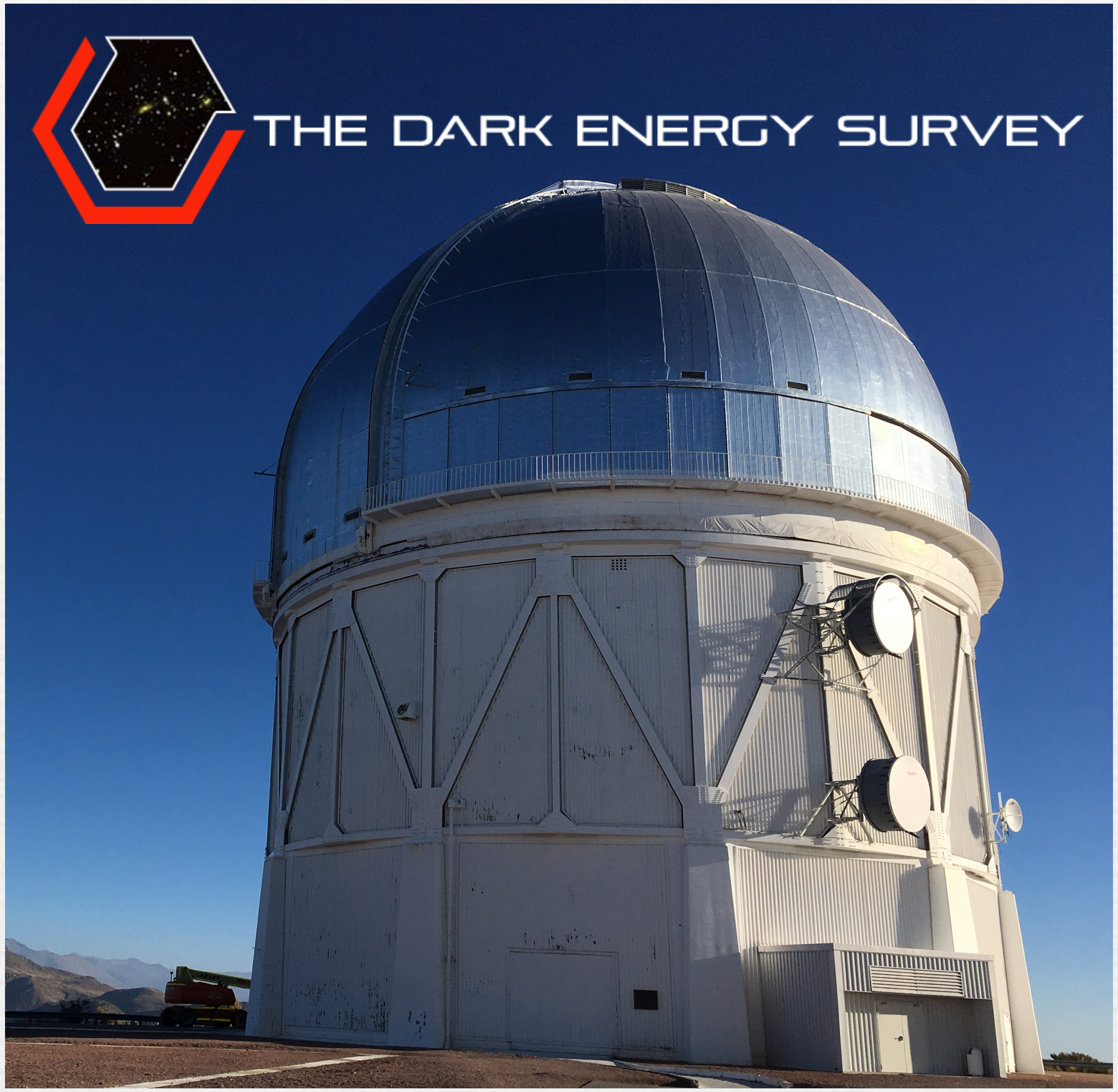
We need to infer cluster mass from observable properties.

Dark energy constraints from clusters

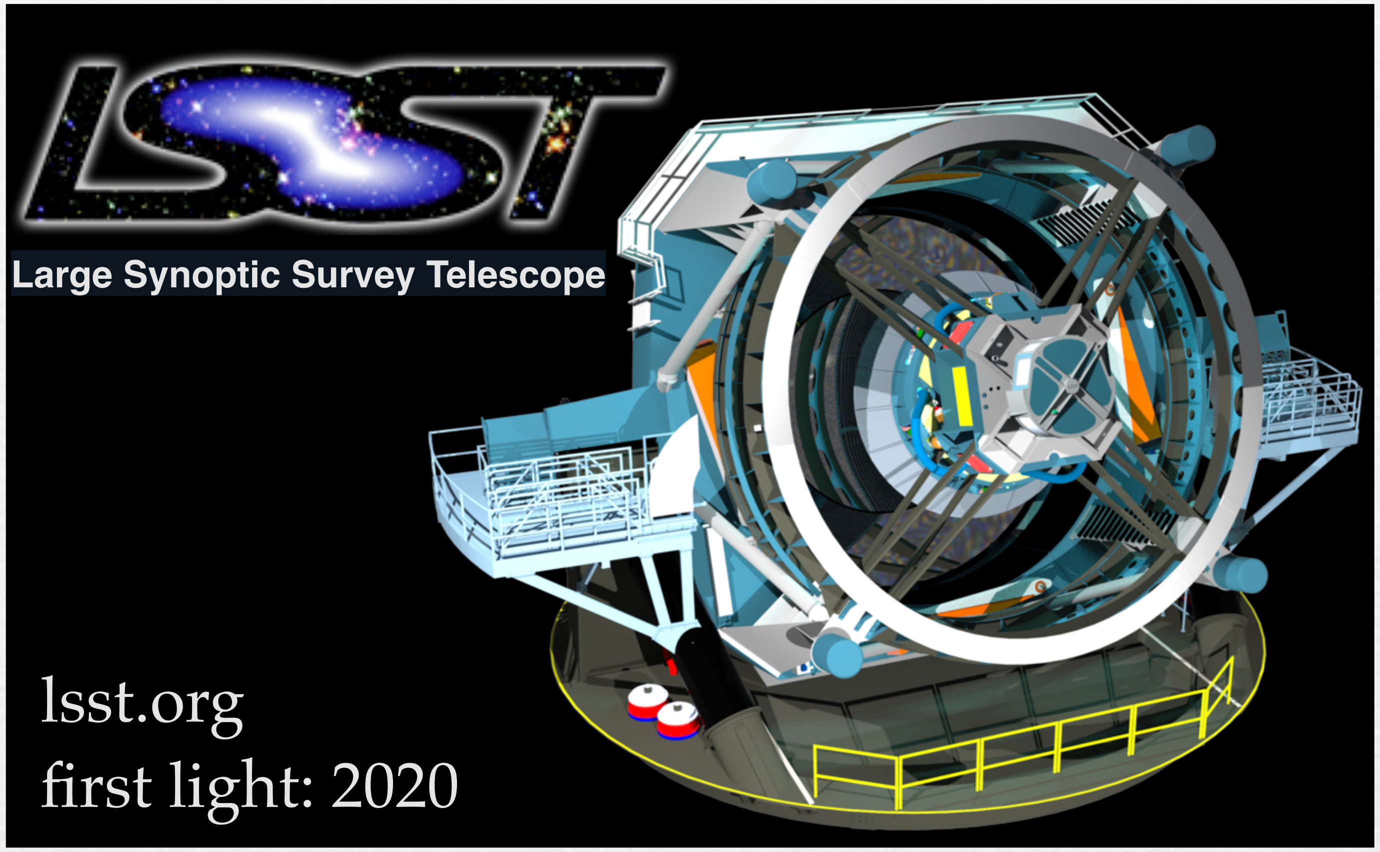


de Haan et al. (2016), South Pole Telescope

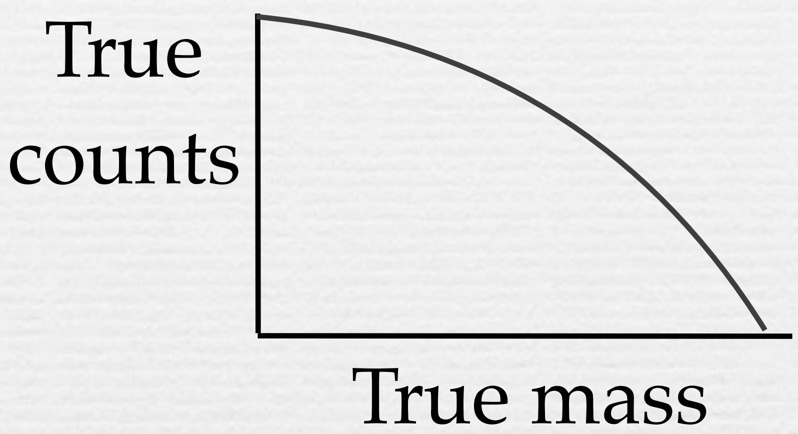
Optical surveys of galaxy clusters



2013-2019
4m Blanco Telescope in Chile
1/8 of sky, 300 million galaxies,
~200,000 clusters

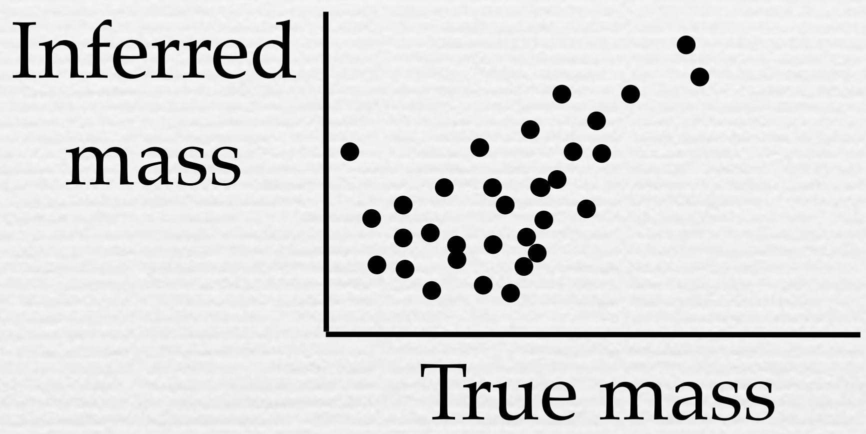


Importance of precise mass calibration



+

Scatter between mass
and observable



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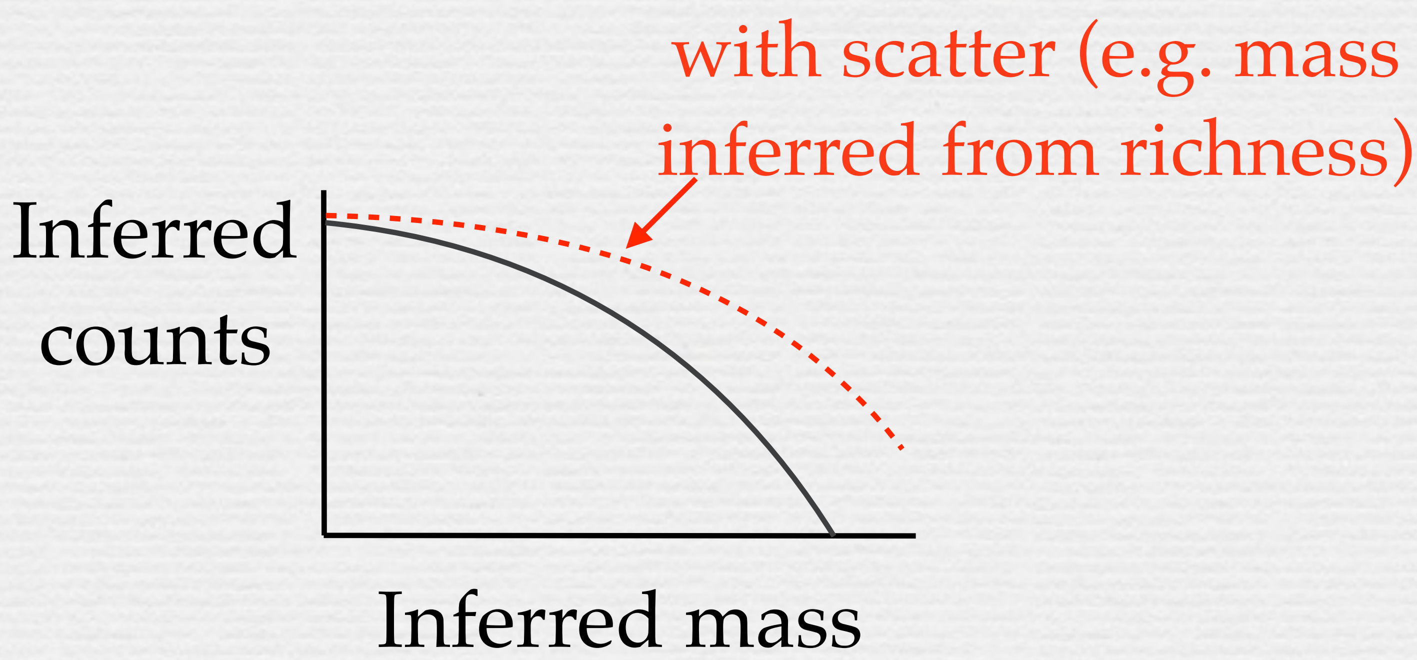


Scatter can mimic
the effect of low
dark energy!

How to measure the mass of galaxy clusters?

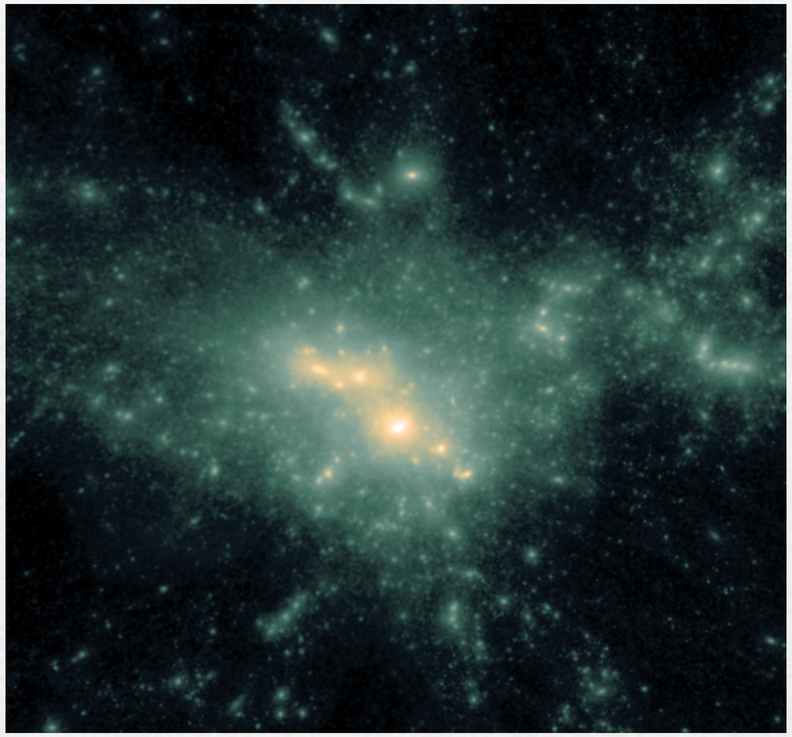
Galaxies

- Number of galaxies (richness)
- Velocity dispersion

Hot gas

- X-ray emission
- Sunyaev-Zeldovich (SZ) effect: scattering of photons of cosmic microwave background (CMB)

Dark matter halo



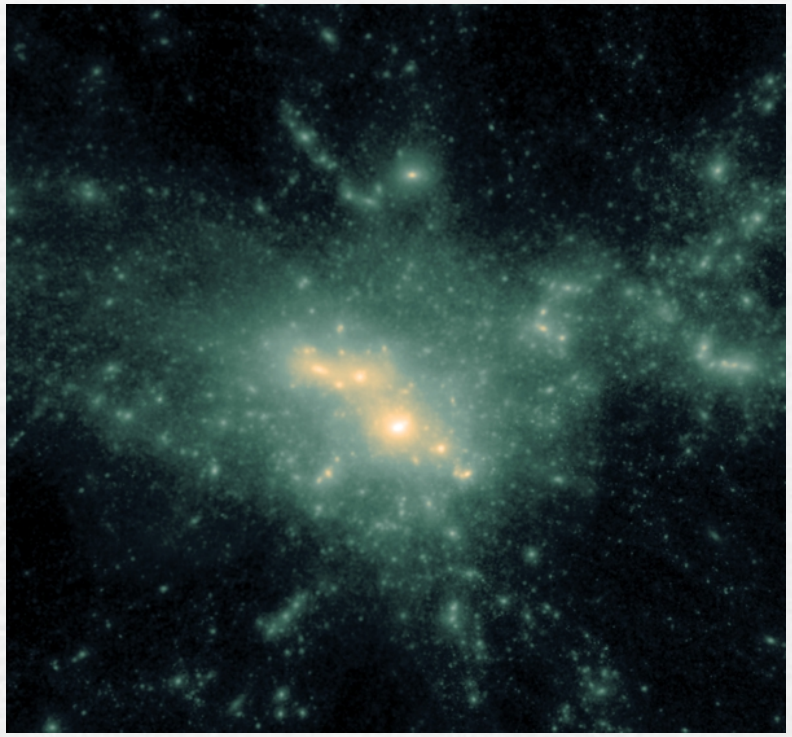
Gravitational lensing

How to measure the mass of galaxy clusters?

Galaxies

Hot gas

Dark matter halo



- Number of galaxies (richness)
- Velocity dispersion **(Wu et al. 2013)**

- X-ray emission **(Wu et al. 2015)**
- SZ effect

Gravitational lensing (this talk)

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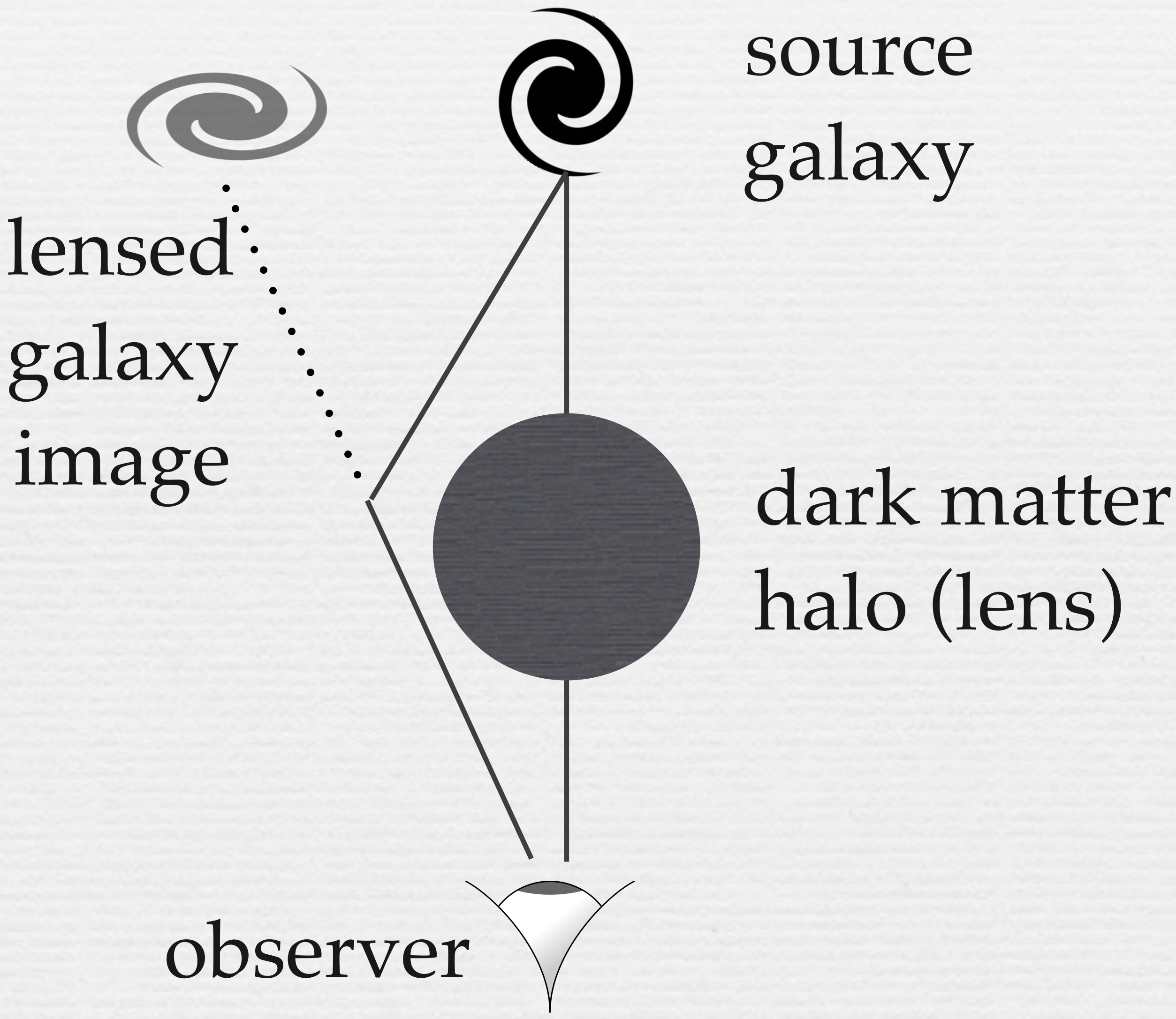
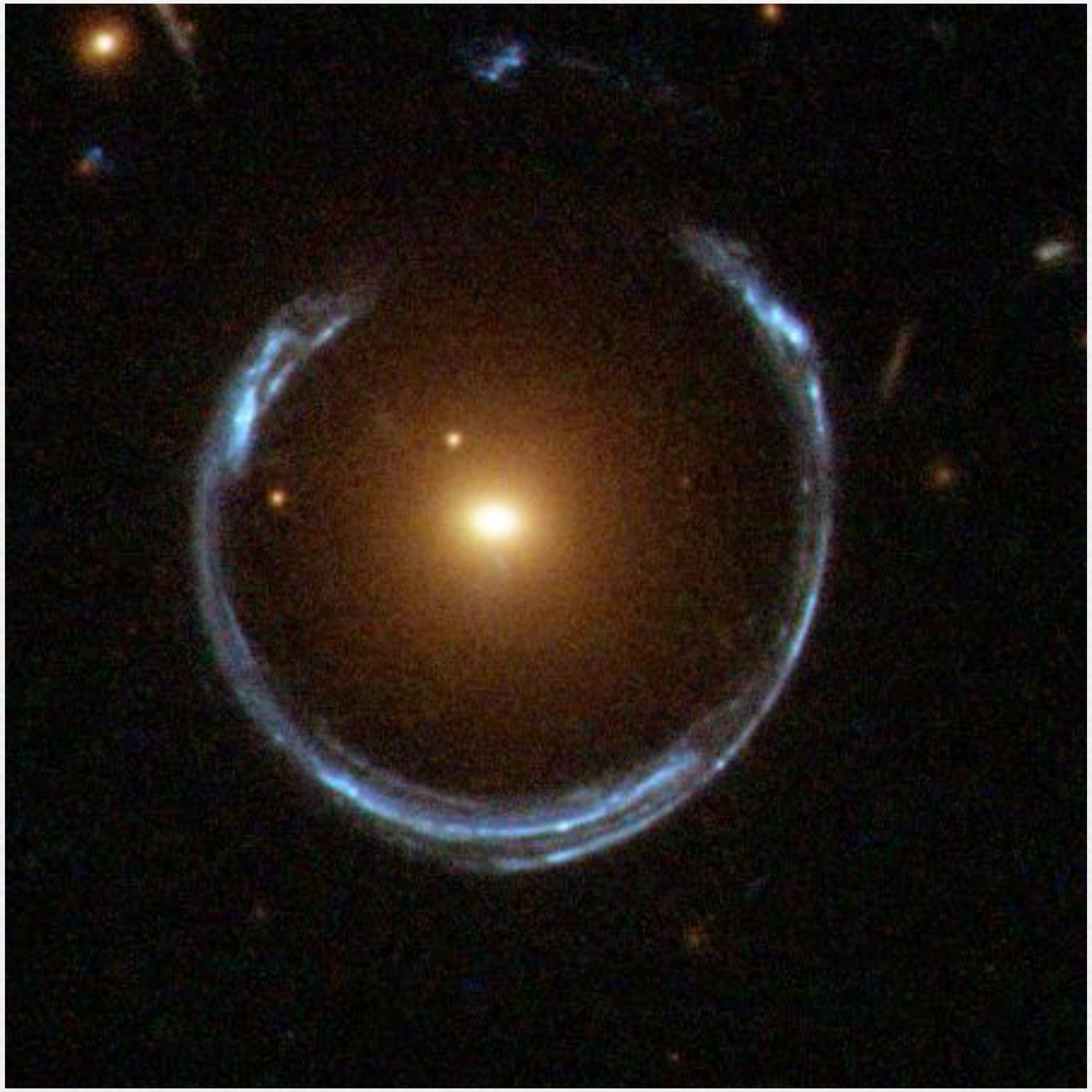
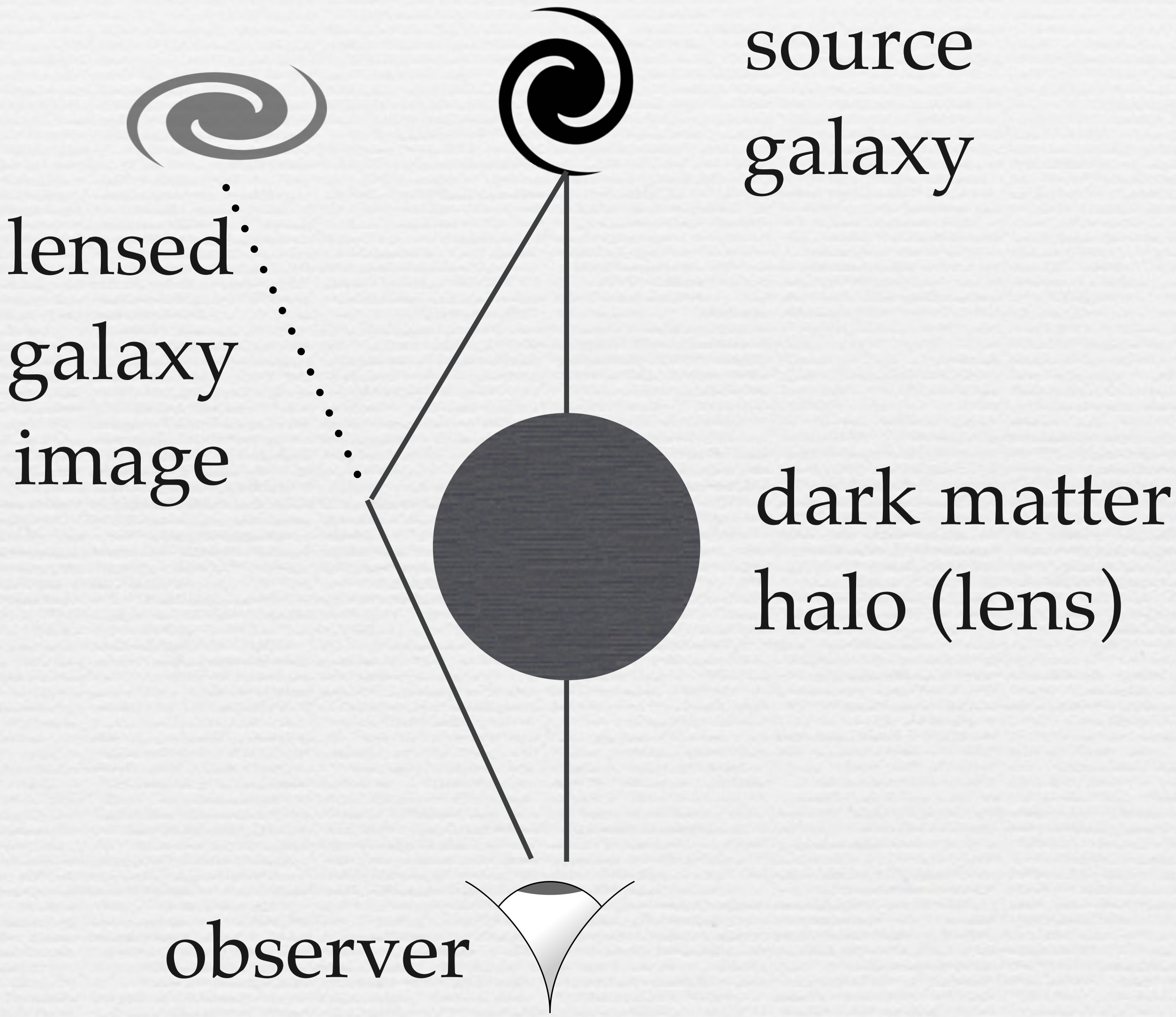
Measuring halo mass using gravitational lensing effect



Strong lensing (rare)



Measuring halo mass using gravitational lensing effect



Weak lensing (everywhere)

Inferring cluster mass from weak lensing

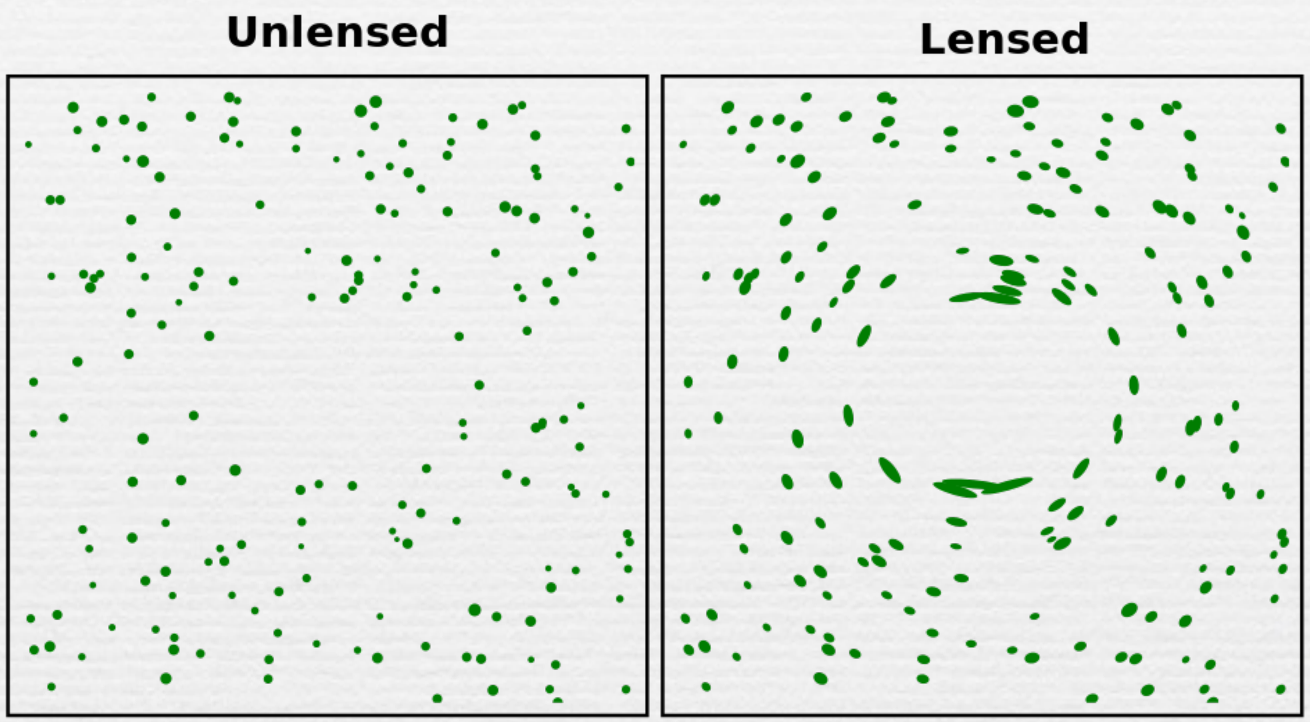
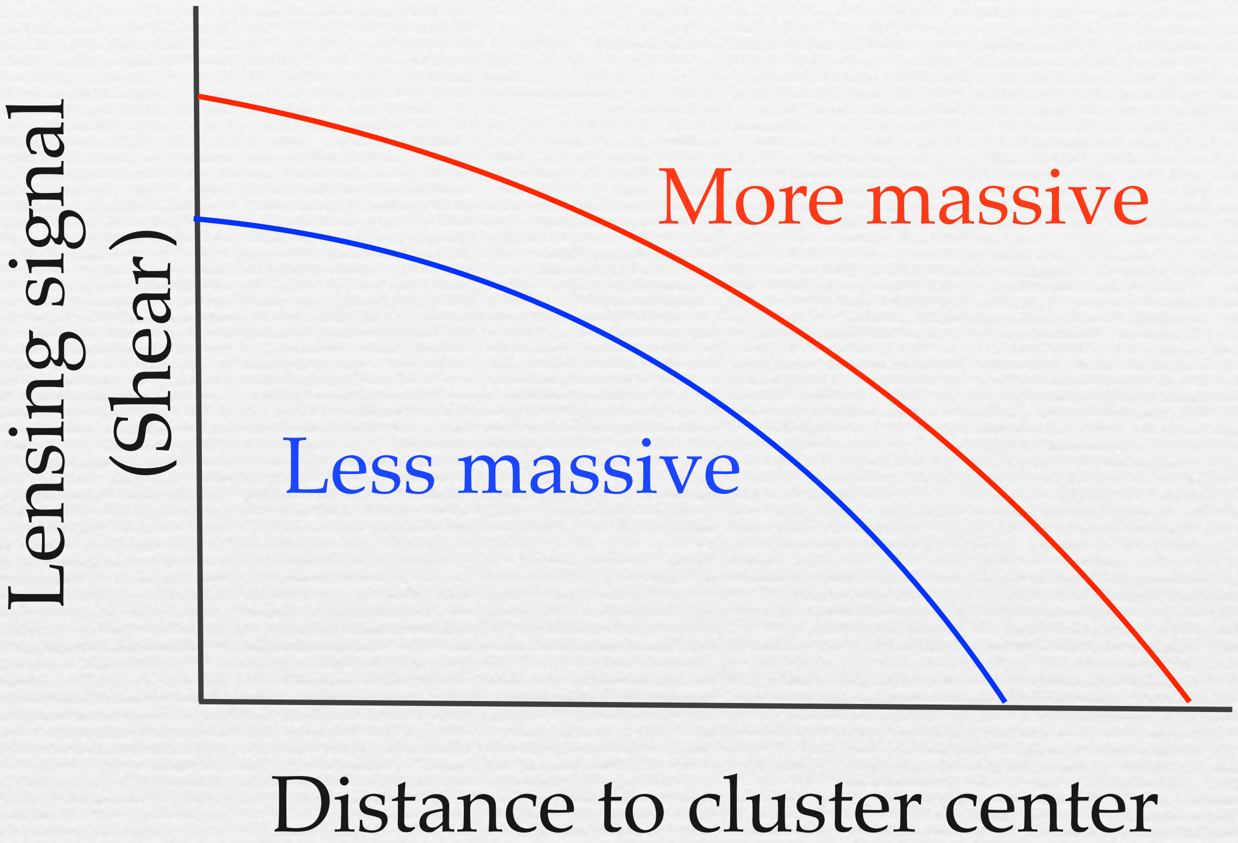


Figure from Wikipedia



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

Part I: Modeling the cluster lensing signal using simulations

in collaboration with Zhuowen Zhang, Chun-Hao To, Yuanyuan Zhang, Tom McClintock, Matteo Costanzi, Eduardo Rozo, Joe DeRose, and many others in the **Dark Energy Survey** collaboration

Buzzard Simulations

DeRose et al. (arXiv: 1901.02401)

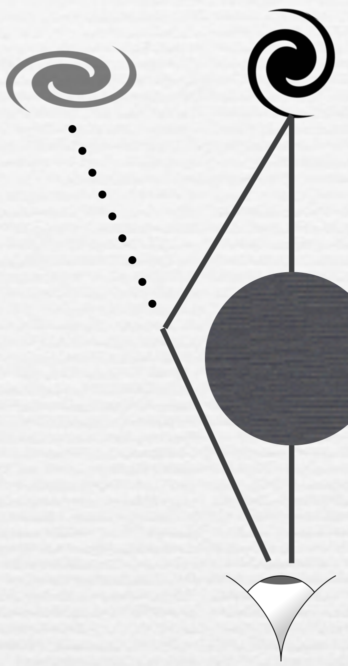
- Mock catalogs for the DES volume
- Based on dark matter N-body simulations.
- Galaxies are assigned to dark matter particles based on local density
- Recovering the observed galaxy correlation functions

redMaPPer Cluster Finder

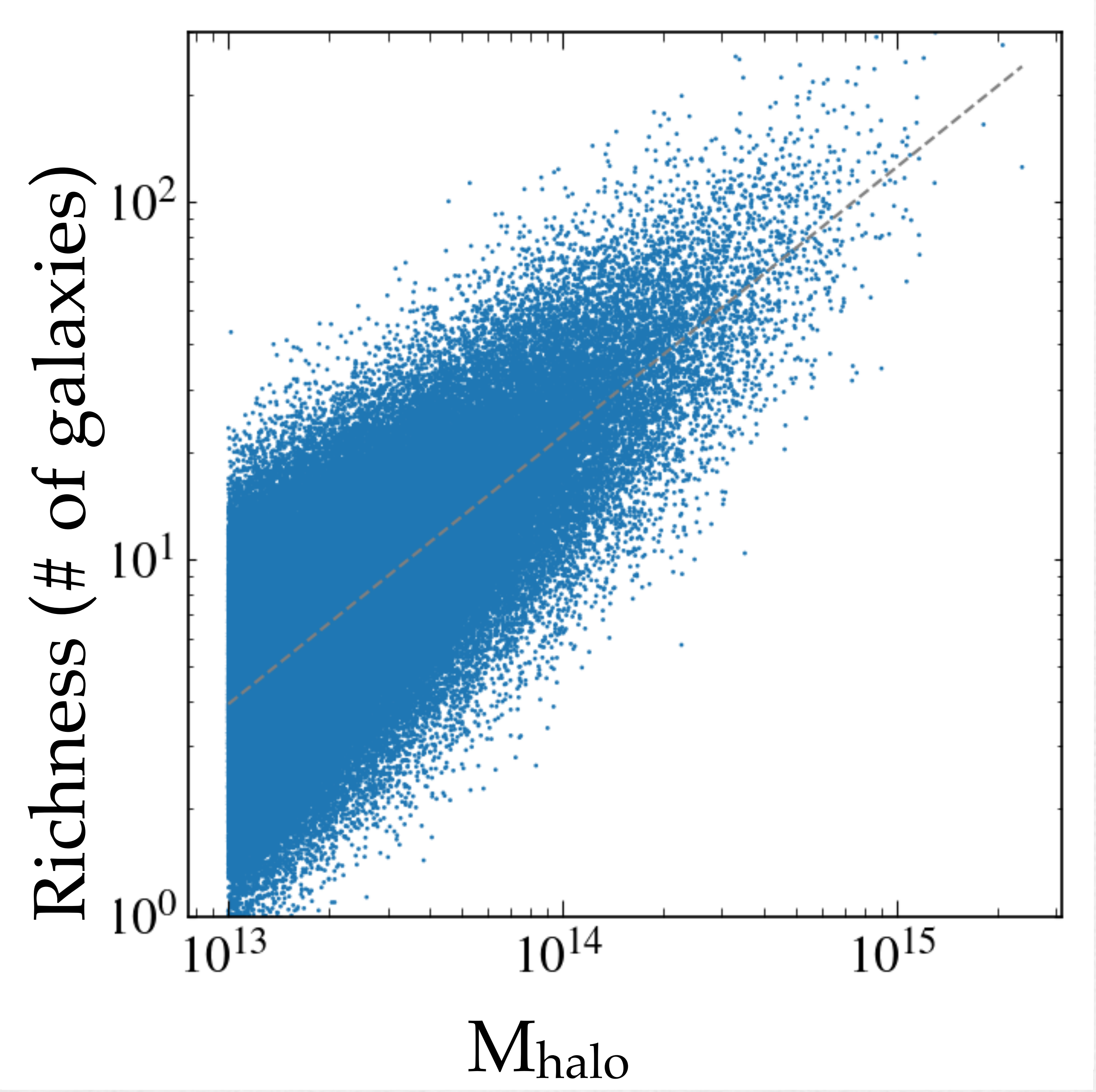
Rykoff & Rozo et al. (2014)

- Identifying clusters using red-sequence in photometric data
- Assigning cluster membership probability for each galaxy
- Richness "λ" (similar to the number of galaxies in a cluster)
- For Buzzard sims, we apply redMaPPer to the halo center (thus avoiding mis-centering effect)

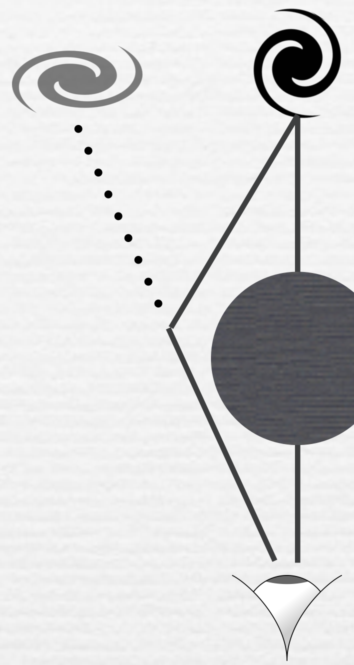
Stacking the weak lensing effect



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



Stacking the weak lensing effect



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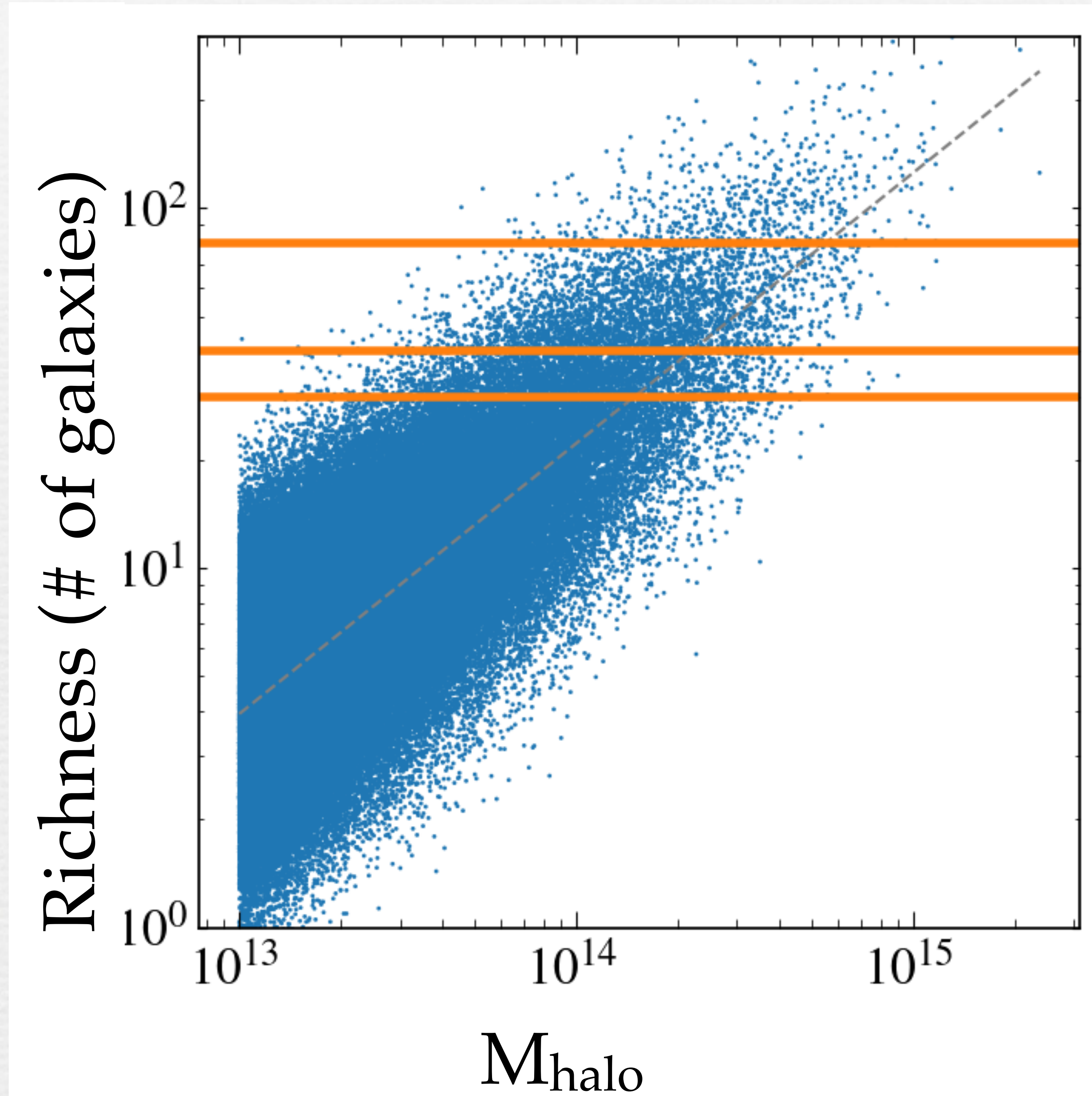

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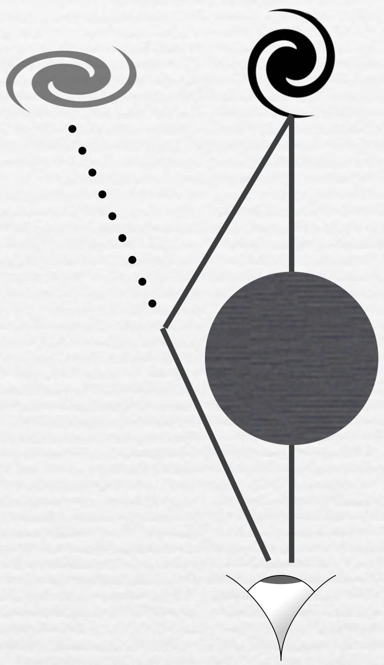

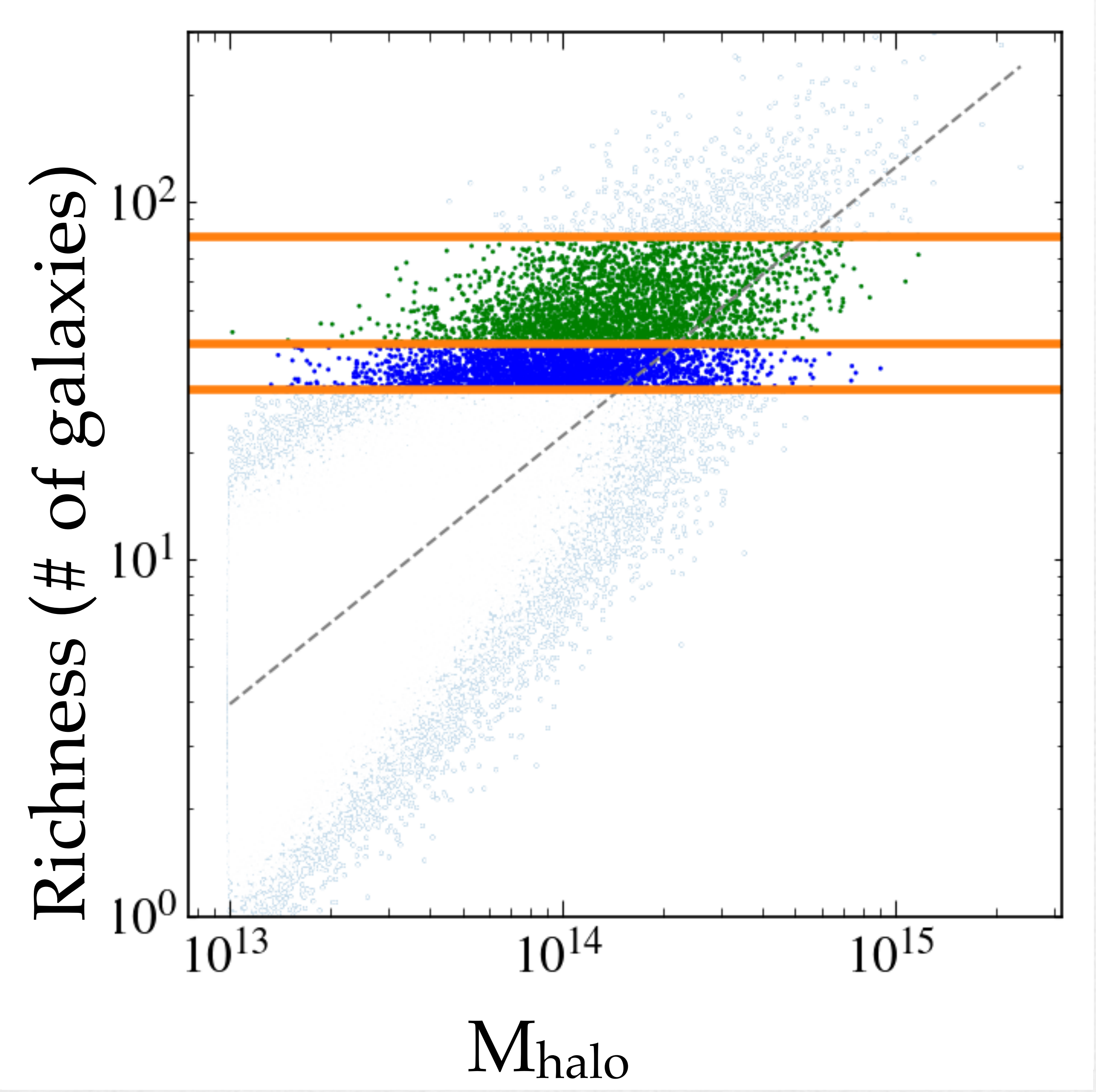

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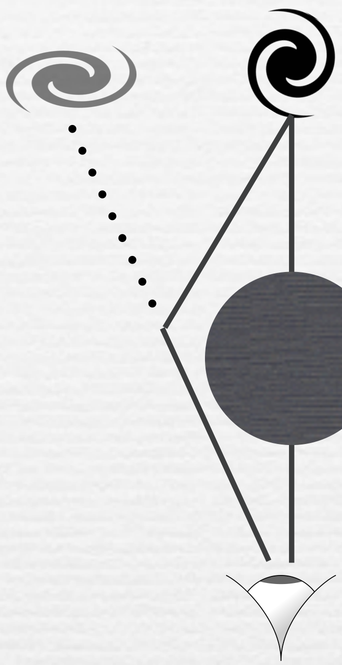
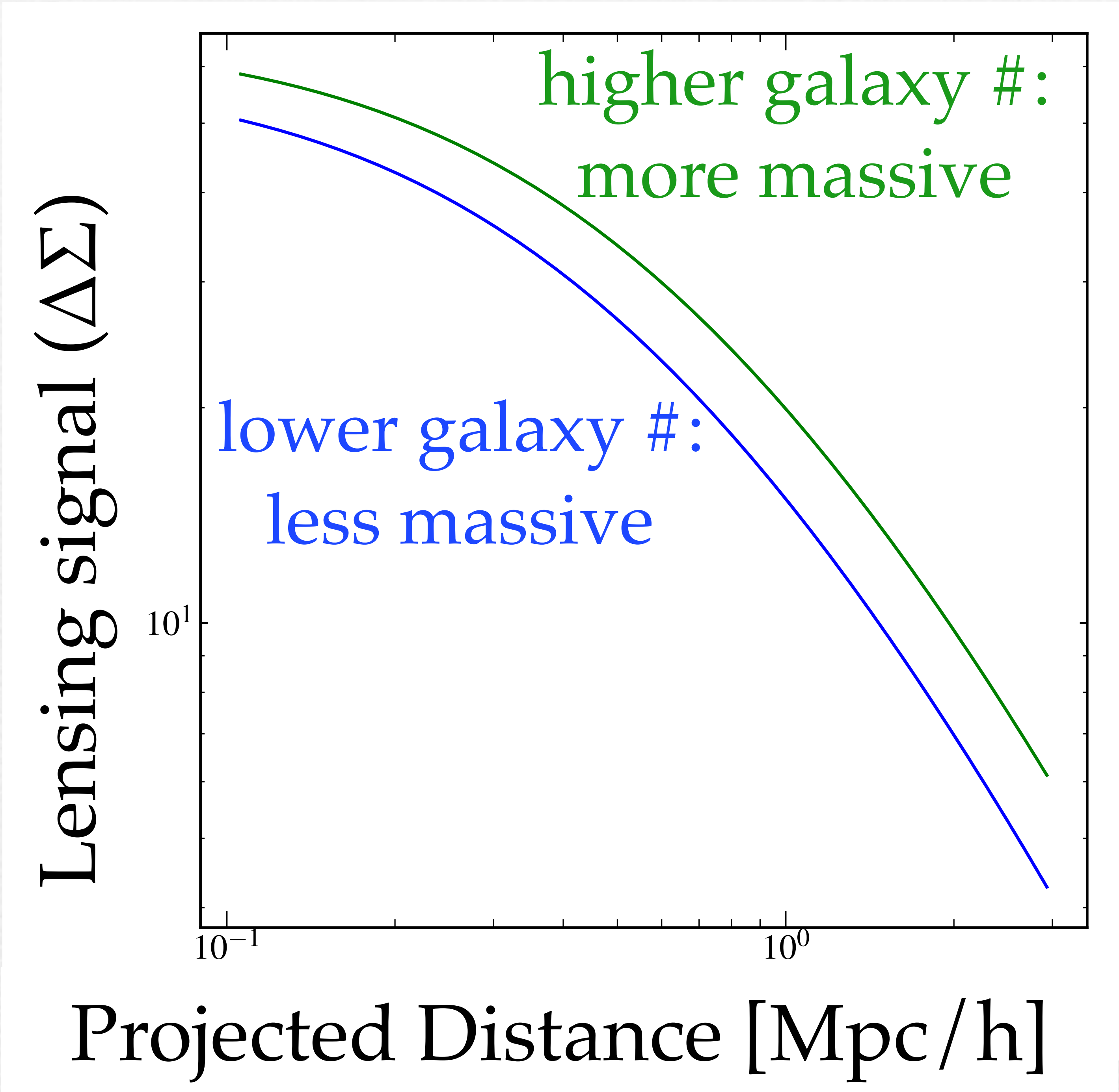
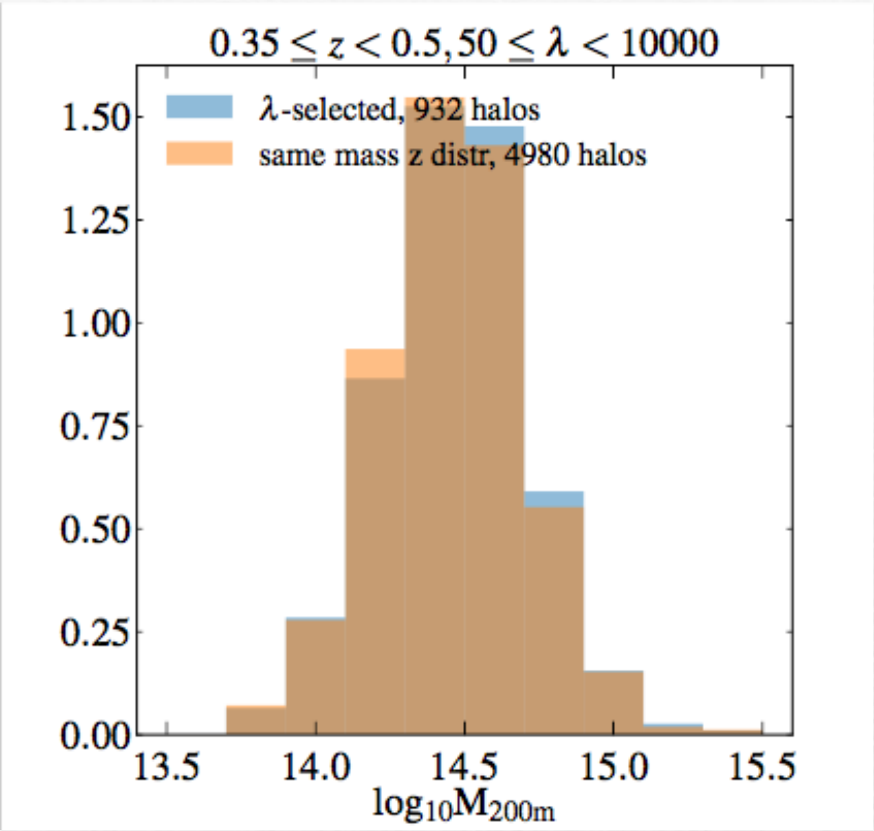
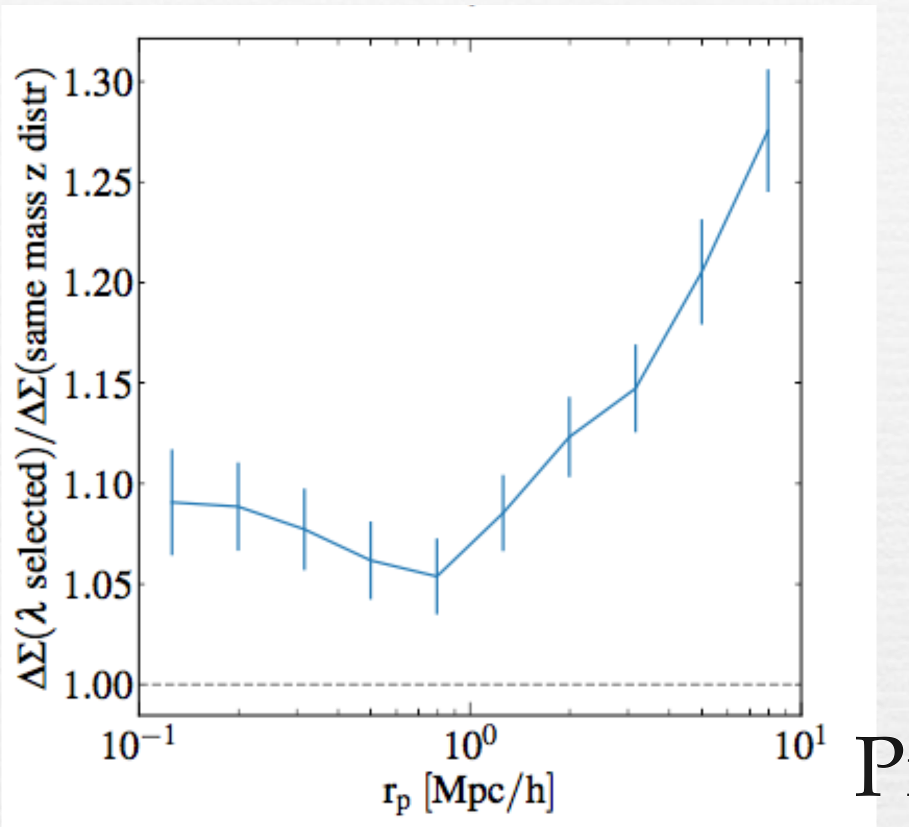


Deriving the mean mass of clusters in a richness bin from the stacked lensing



Is there a selection bias in this process?





Preliminary

Step 1: selecting clusters based on richness, calculating the PDF of the underlying halo mass

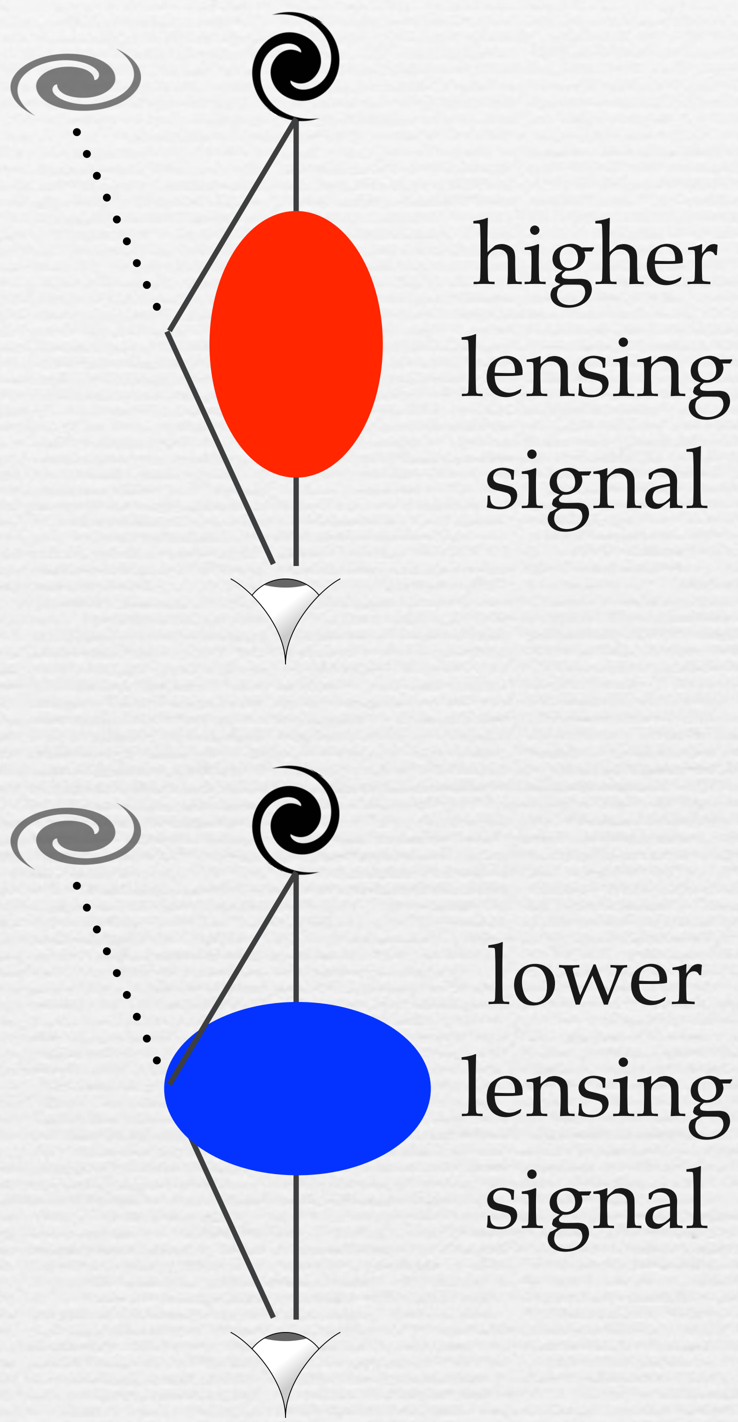
Step 2: select random halos from the entire sim to match this mass PDF

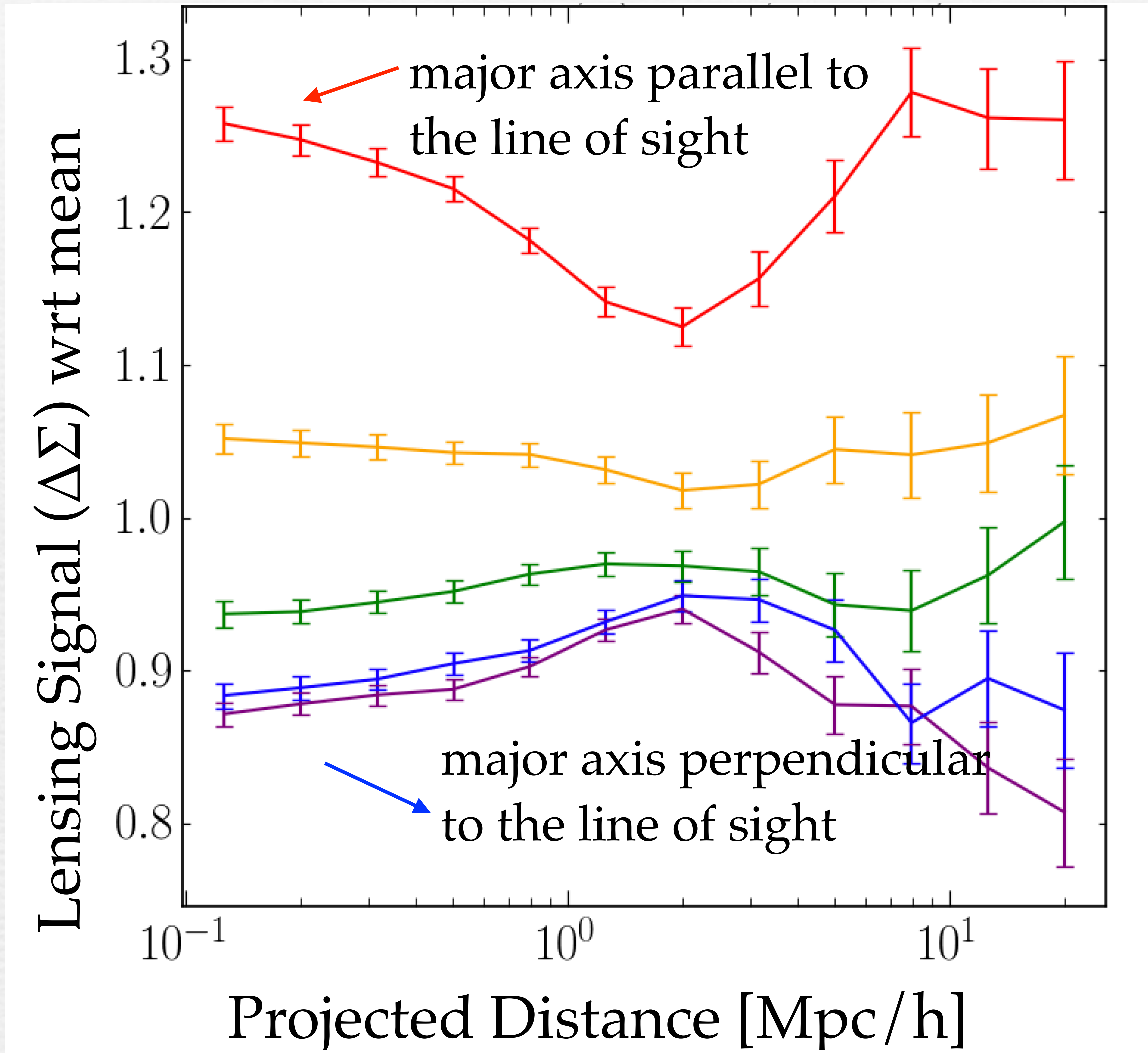
Step 3: taking the ratio of lensing signals. The ratio would be 1 if there's no selection bias. We found ~10-30% bias in lensing signal.

Systematic effect 1: Orientation Bias

Systematic effect 2: Projection Effect

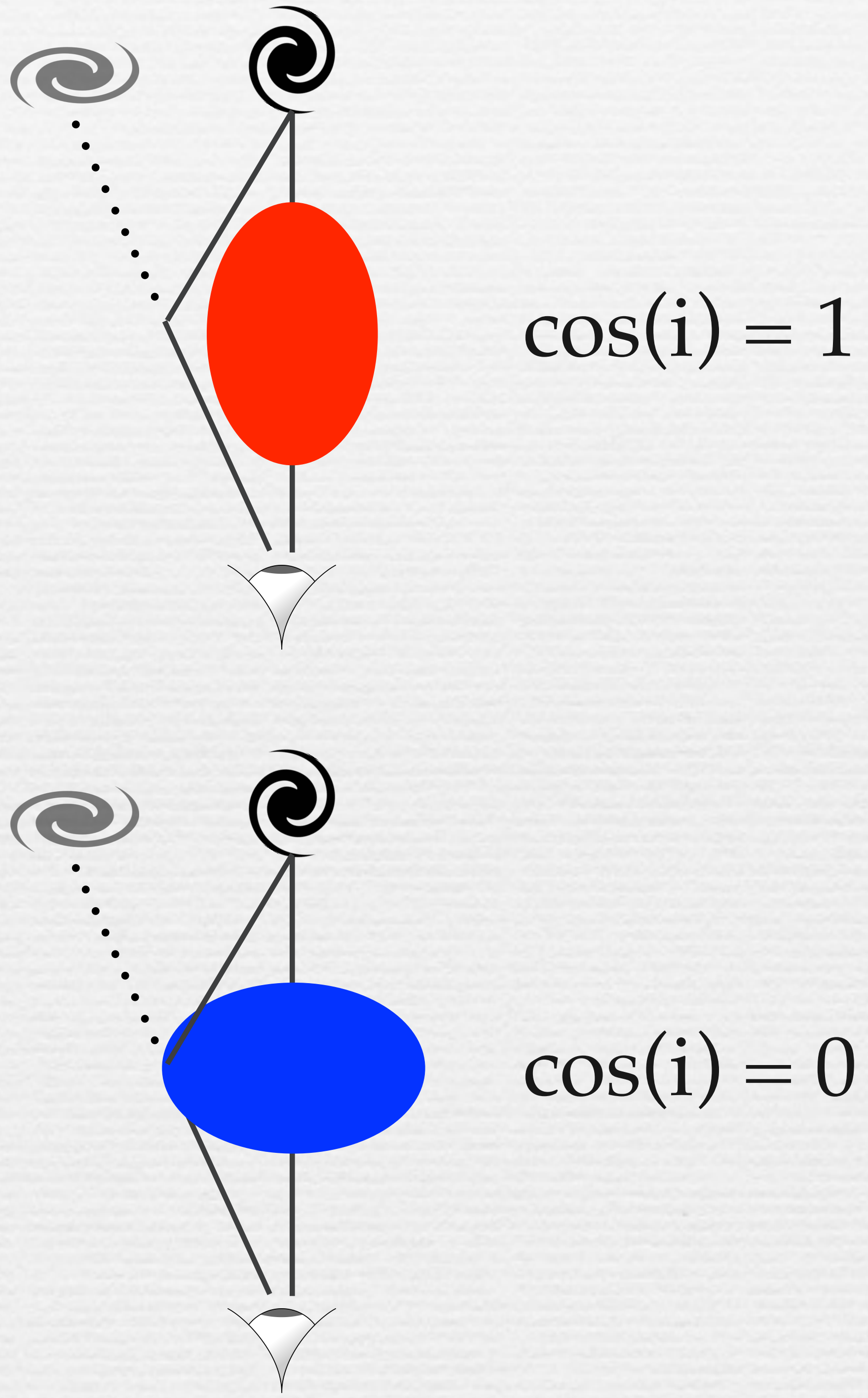
Impact of halo orientation on cluster lensing

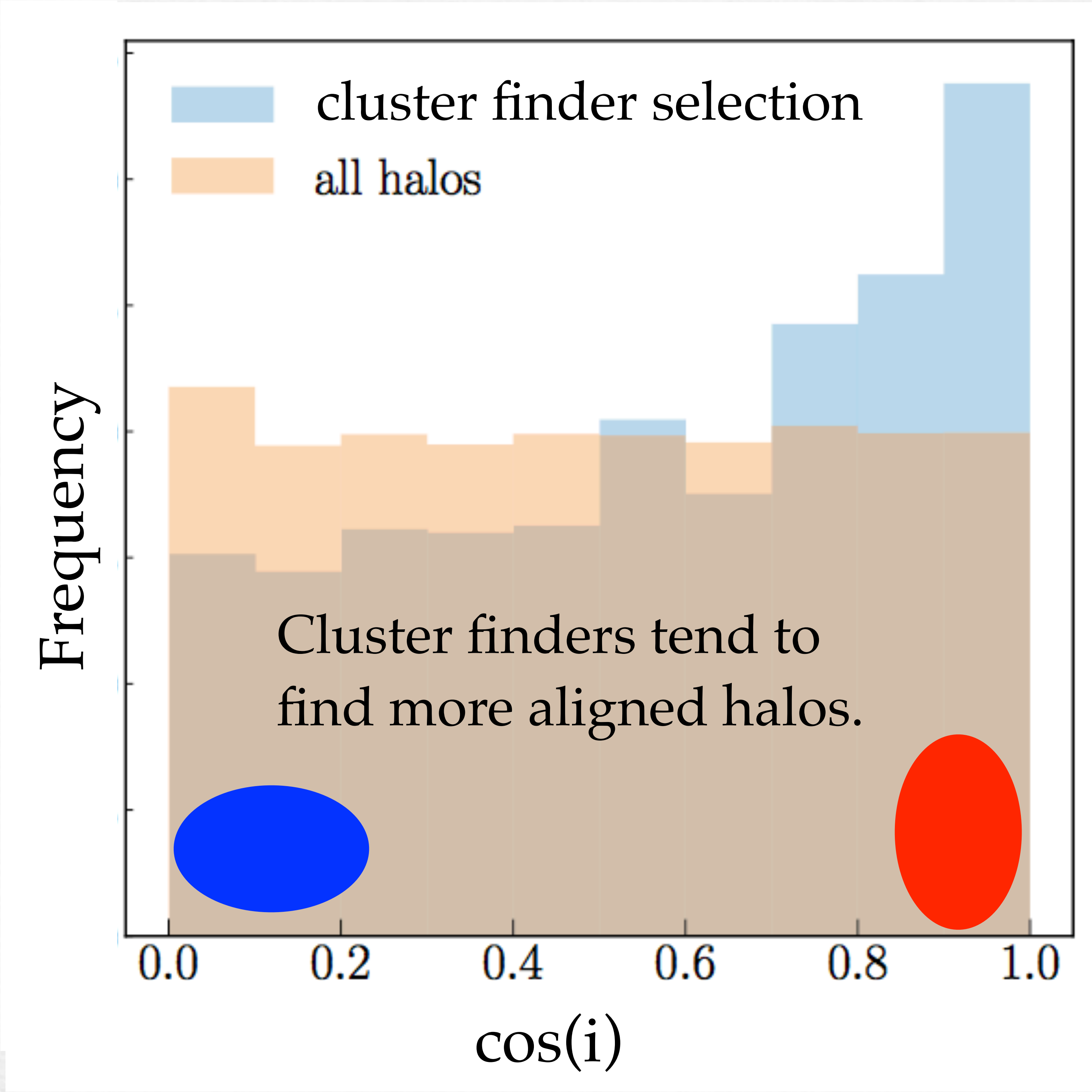




Preliminary

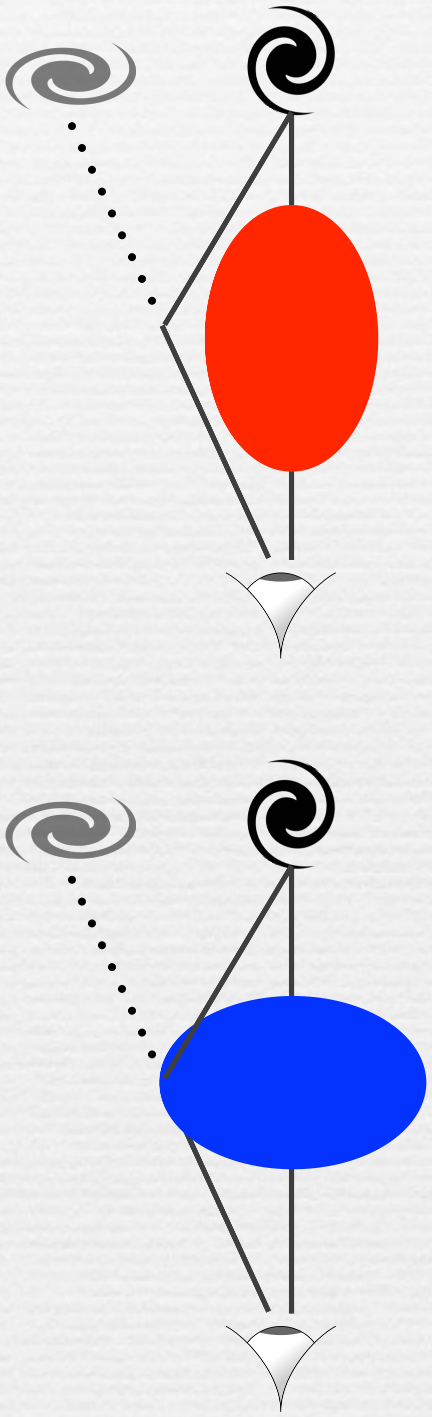
Impact of orientation on selection





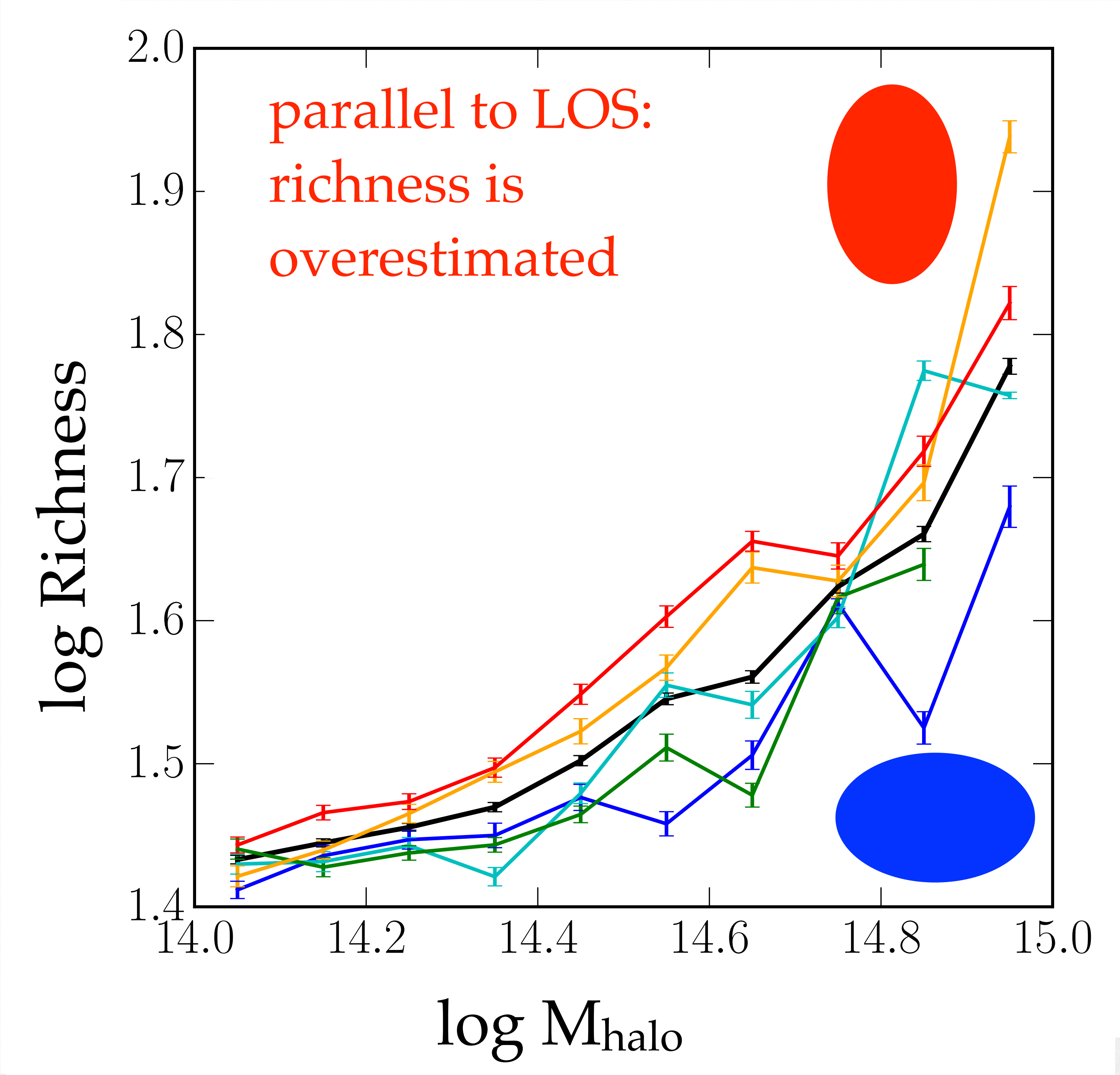
Preliminary

Impact of halo orientation on richness



over-
estimated
richness

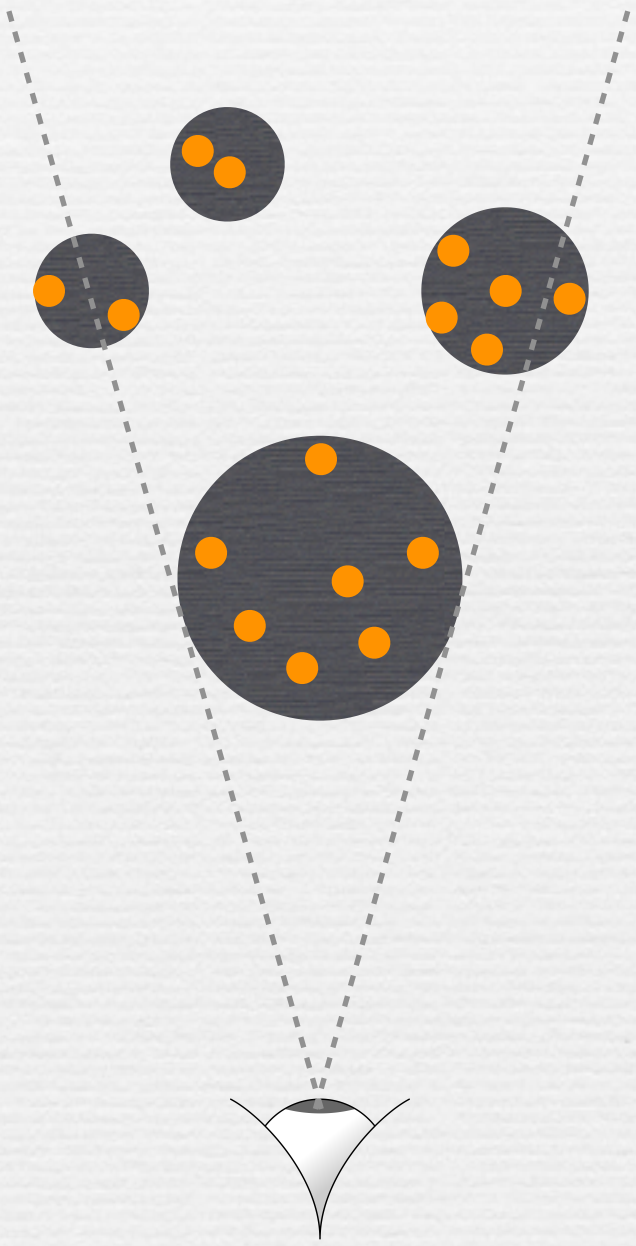
under-
estimated
richness



Preliminary

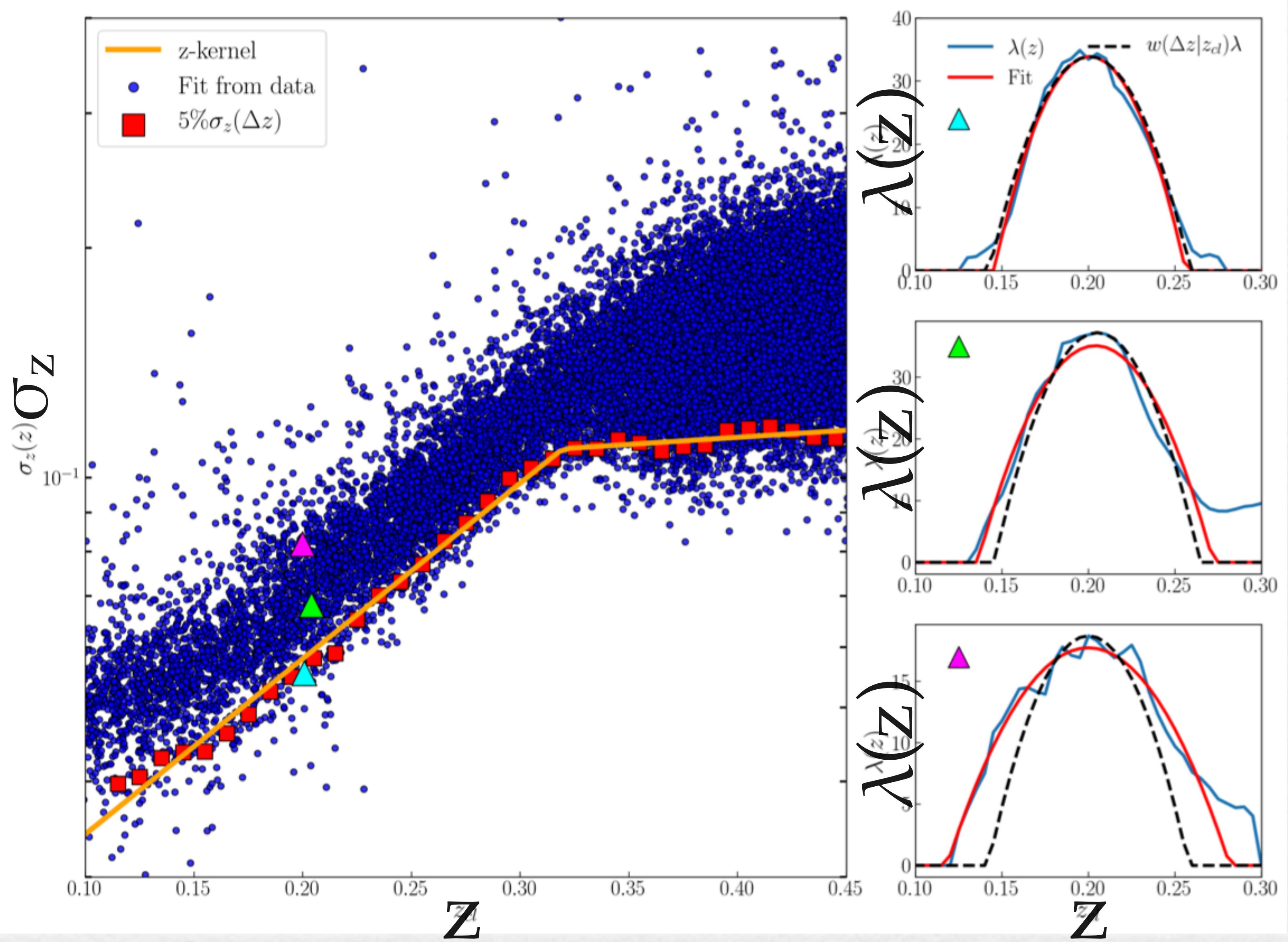
Systematic effect 2: Projection Effect

Projection effect changes observed richness



- The true number of galaxies in a cluster (true richness, or λ_{true}) has some intrinsic scatter.
- If redshift uncertainties are large, we tend to include galaxies along the line-of-sight as cluster members (observed richness, or λ_{obs}).
- Projection effect thus changes richness and adds scatter.
- Mass along the line-of-sight can also increase lensing signal.

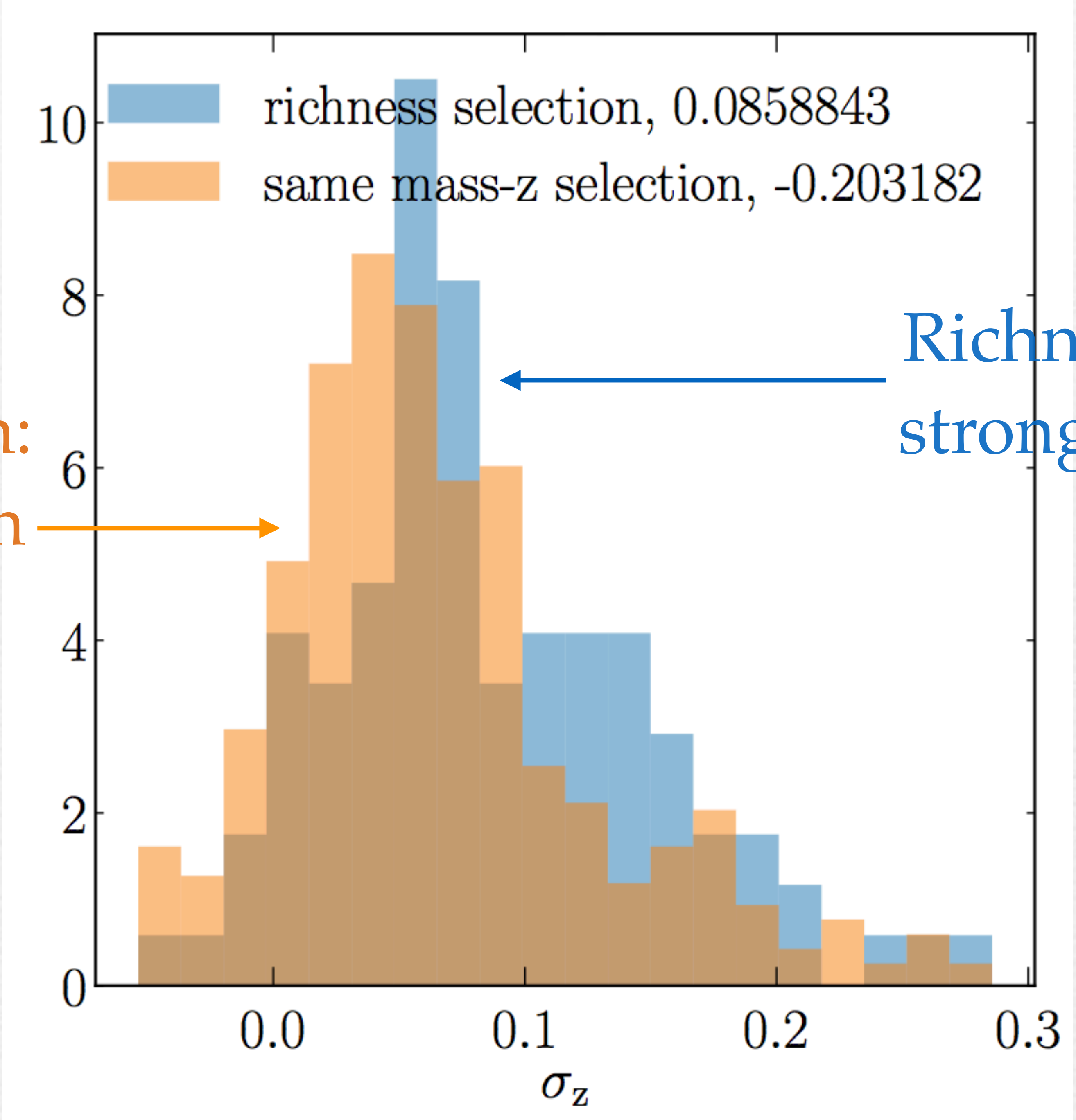
Quantifying the projection effect
(Costanzi et al. 2019)



- λ(z): measuring richness at various redshift
- Peak: contribution from galaxies in the cluster
- Wings: contribution comes from galaxies outside the cluster

The spread of λ(z) quantifies the projection effect (denoted as σ_z)

Cluster finders tend to select clusters with stronger projection effect



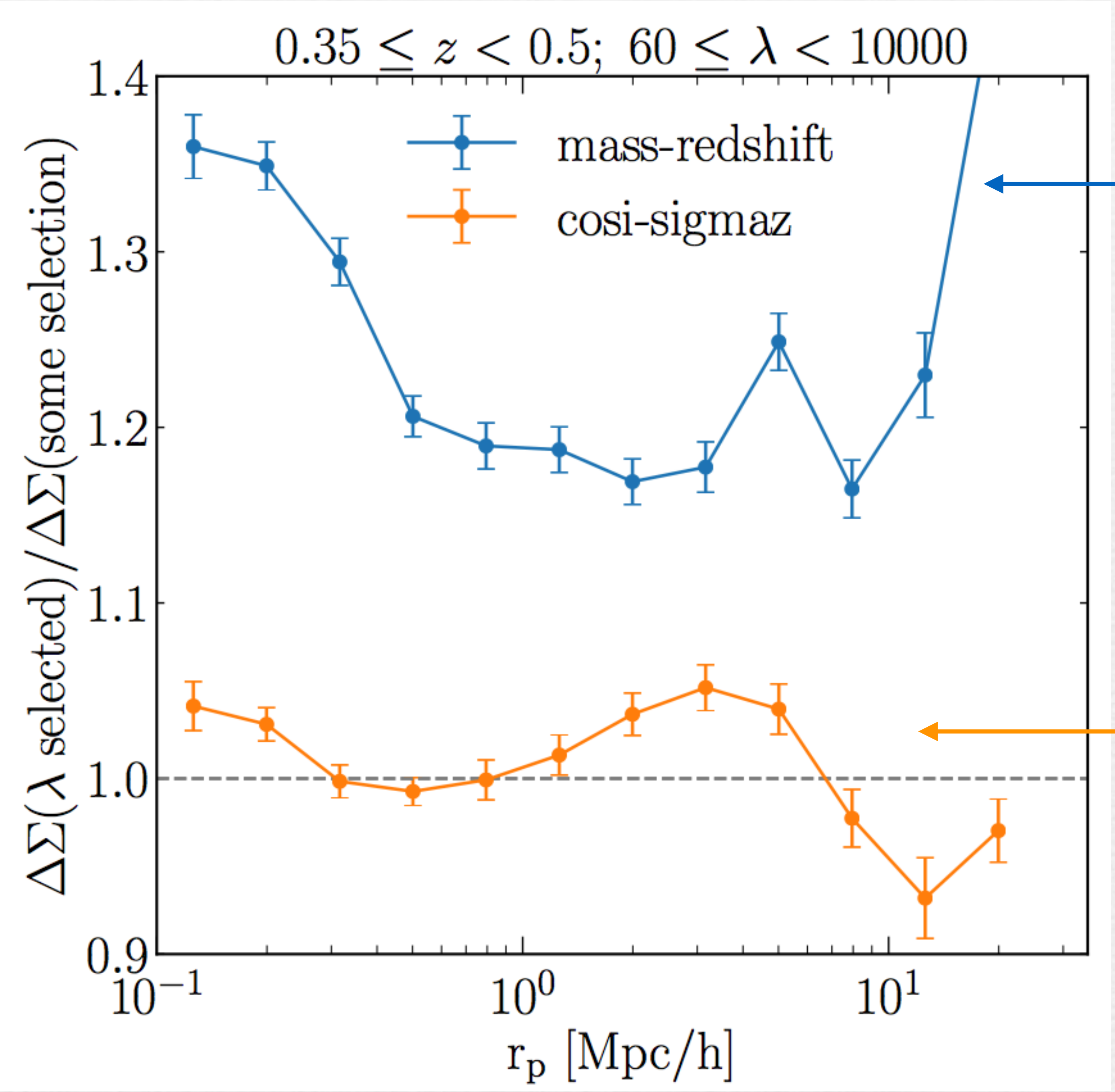
Richness selection: stronger projection

Random selection: weaker projection

stronger projection effect →

Preliminary

Orientation & projection can explain most of the lensing biases



matching mass and redshift PDF: signal biased high

matching mass, redshift, orientation, and projection: bias mostly removed

Preliminary

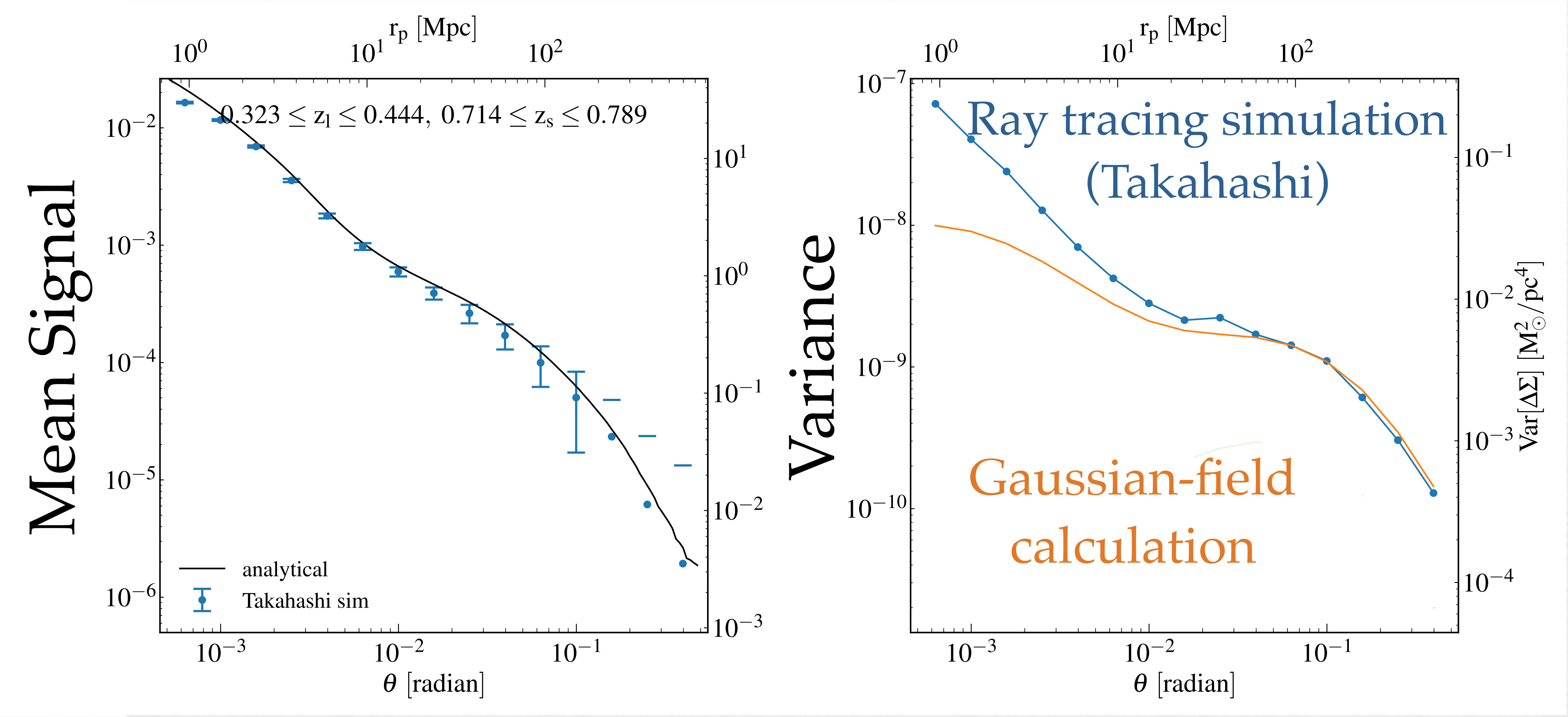
Summary of Part I: Modeling cluster lensing signals

- Stacked weak lensing signal based on richness-selected clusters can suffer from selection bias.
- Orientation bias: halos with axes parallel to line-of-sight has higher richness and stronger lensing signal.
- Projection effect: changes richness and lensing signal simultaneously.
- Taking into account these two effect removes most of the systematic errors of lensing. We are working on detailed modeling for cosmology analyses.

Part II: Modeling the covariance matrices for cluster lensing

in collaboration with Andres Salcedo, Ben Wibking, David Weinberg, and others in the **WFIRST** team

Simulations vs. Analytic Calculations



- Analytic calculations: cannot capture medium/small-scale correctly
- Ray-tracing sims: limited to > 1 Mpc, expensive to run
- We combine high-resolution N-body sims with analytic calculations, validating with ray-tracing sims.

Three major components for 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 ellipticity

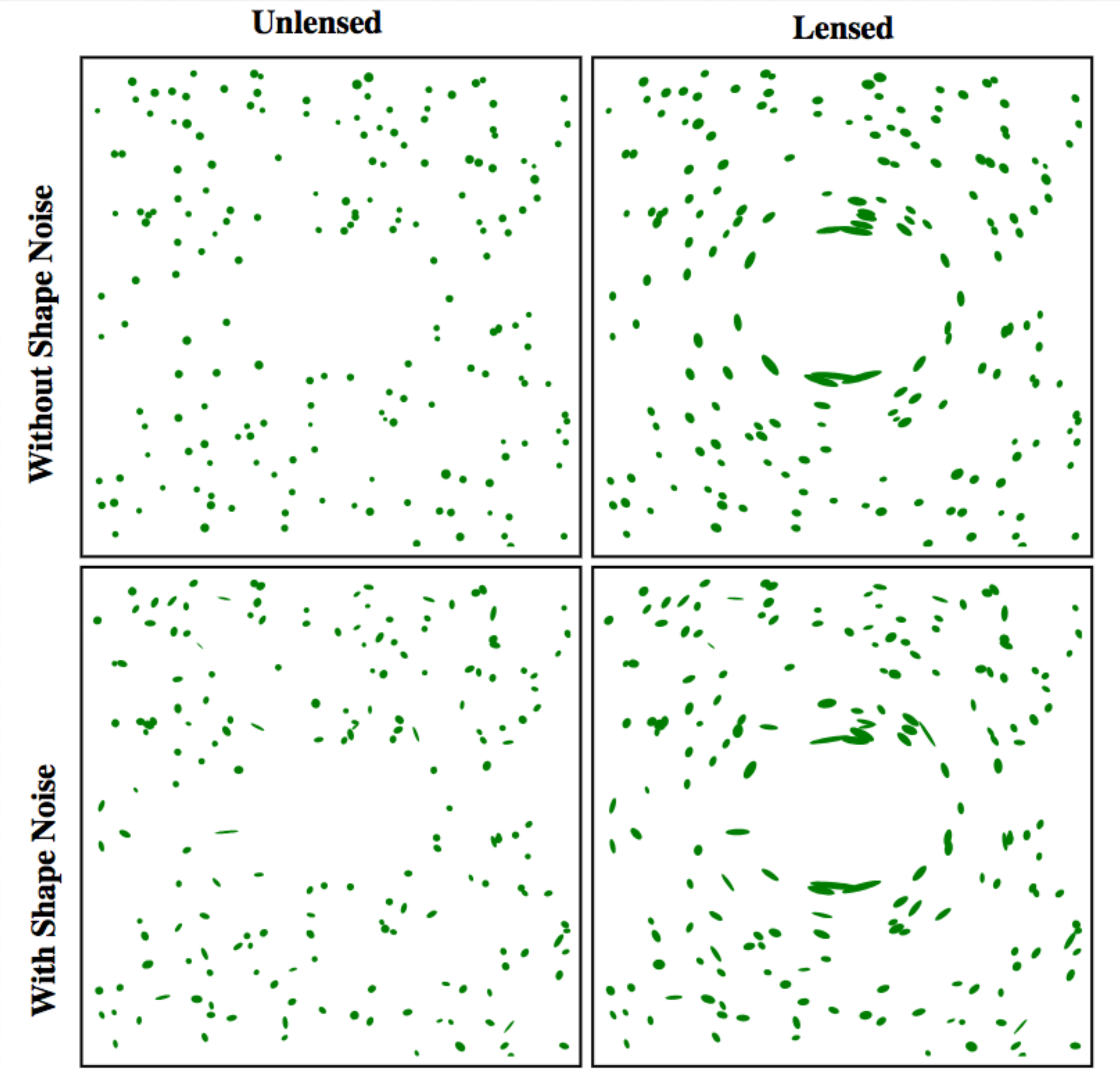
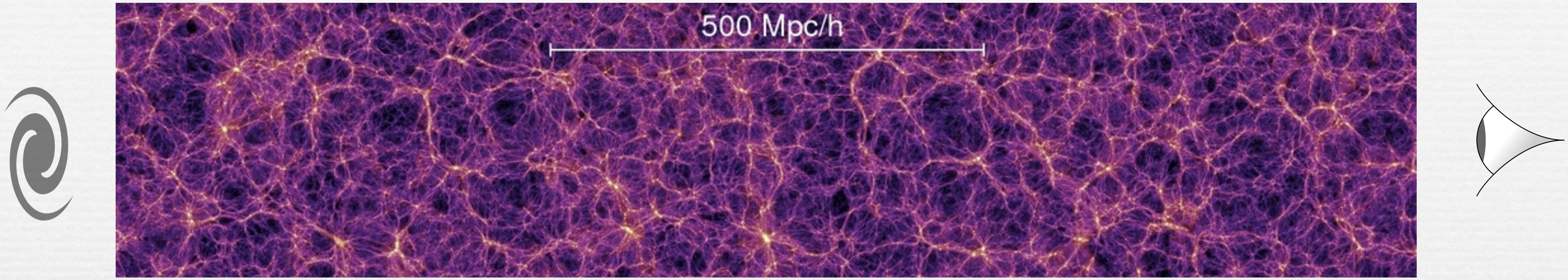


Figure from Wikipedia

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

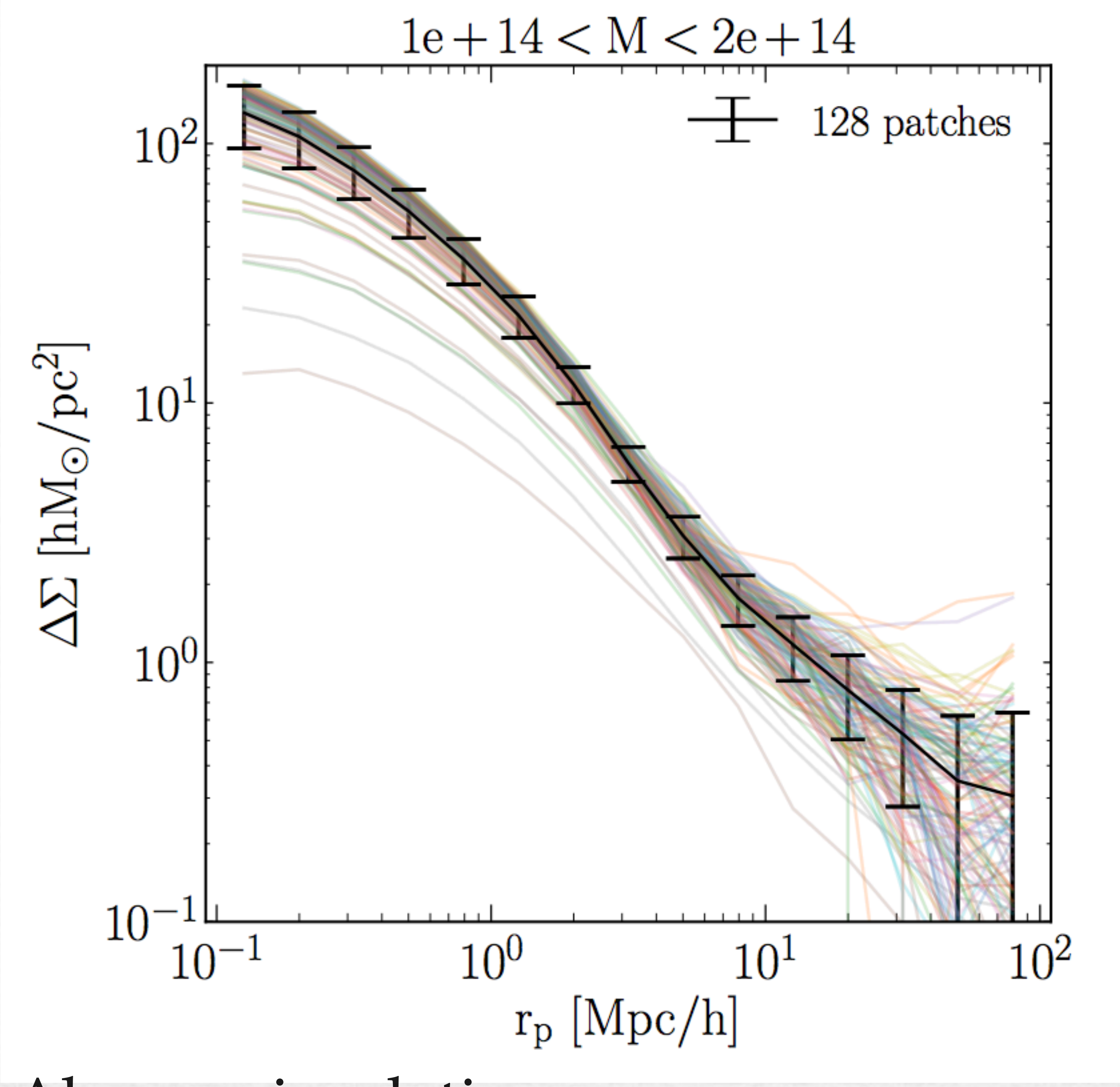
Noise from Large-Scale Structure



- All uncorrelated large-scale structures in front of source galaxies contribute to lensing noise.
- 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

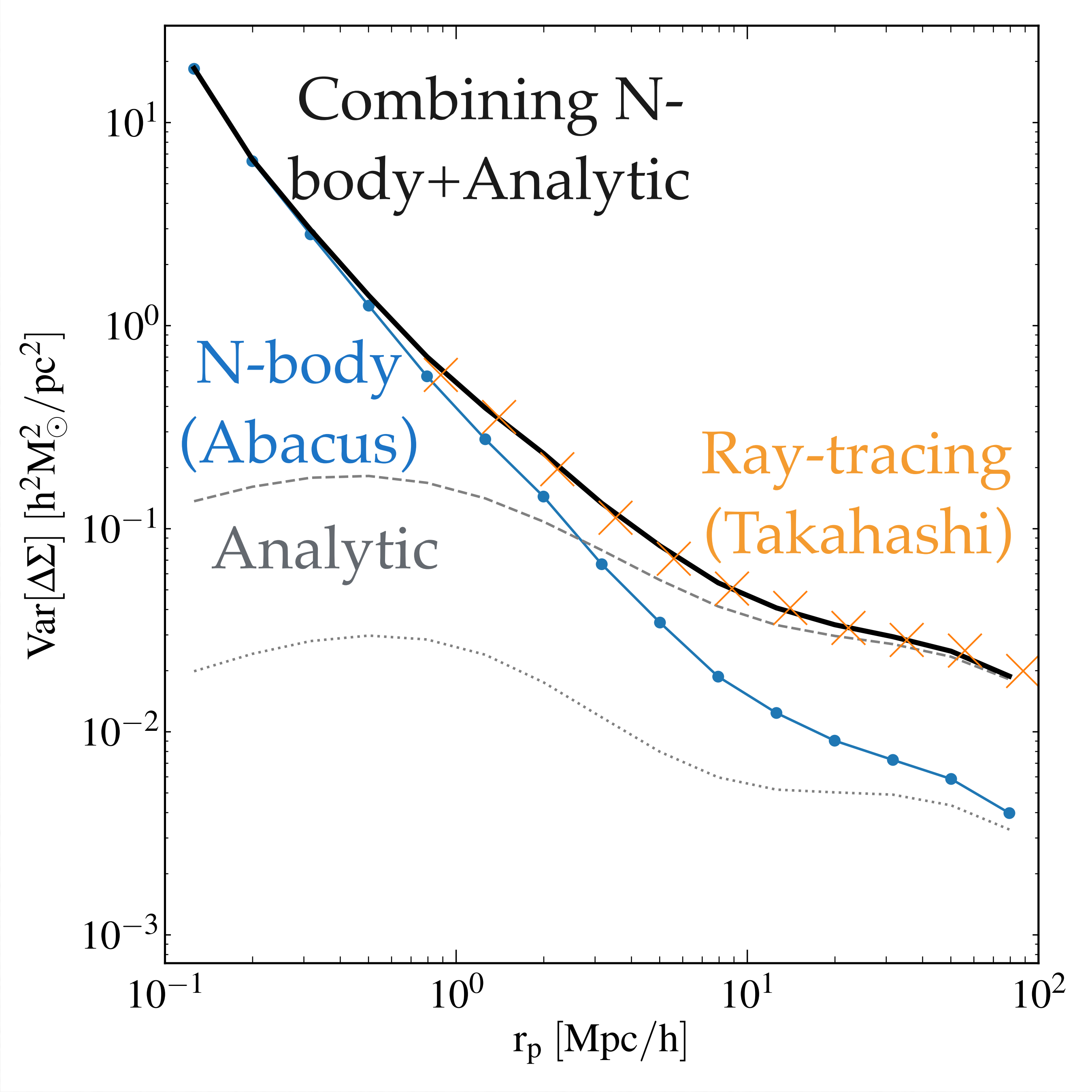
Noise from Intrinsic Variation of Halo Density Profiles



Abacus simulations

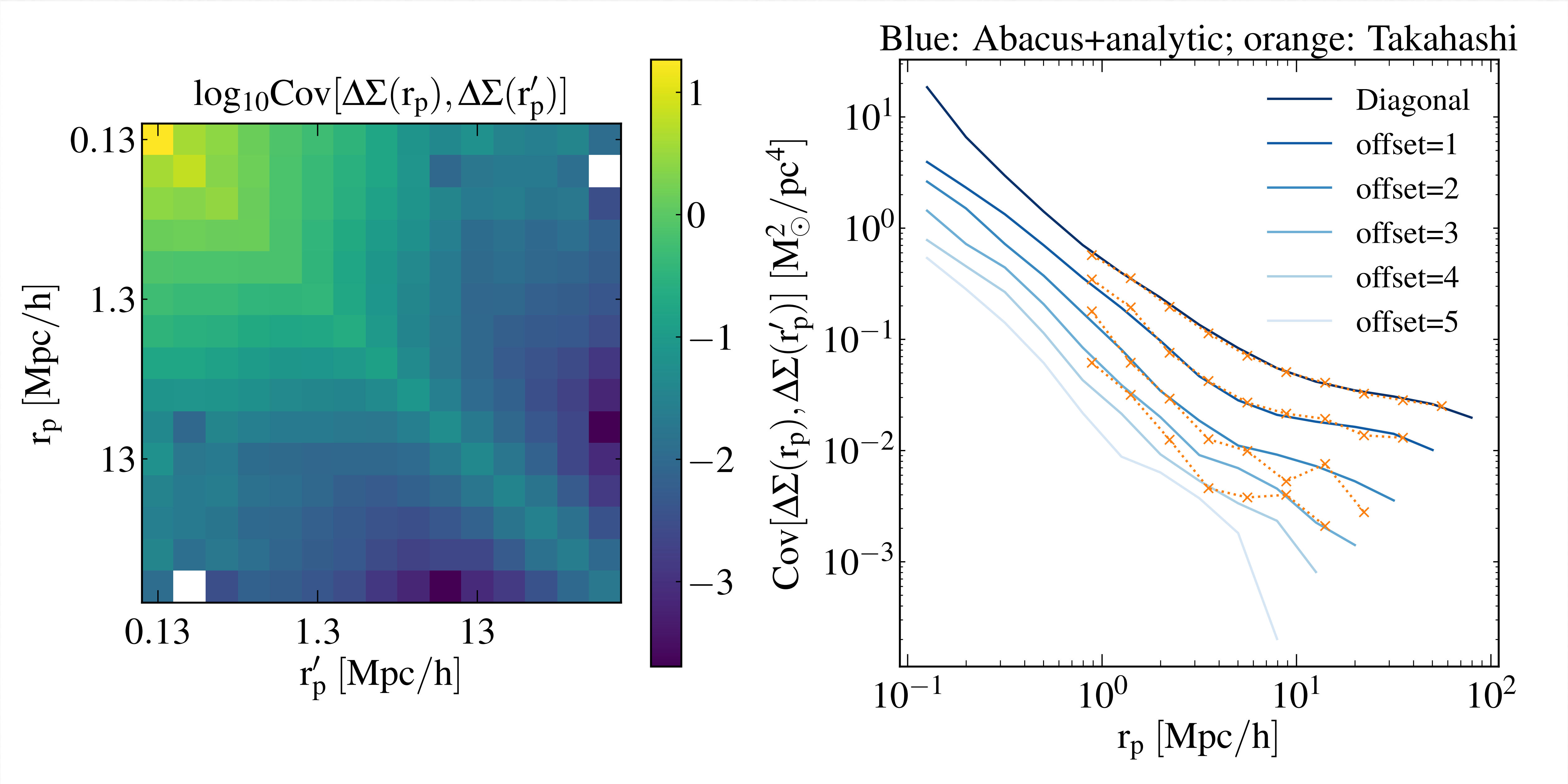
- At a given halo mass, halos have diverse projected density profiles due to different concentration, triaxial shape, etc.

Combining N-body simulations and analytical calculations



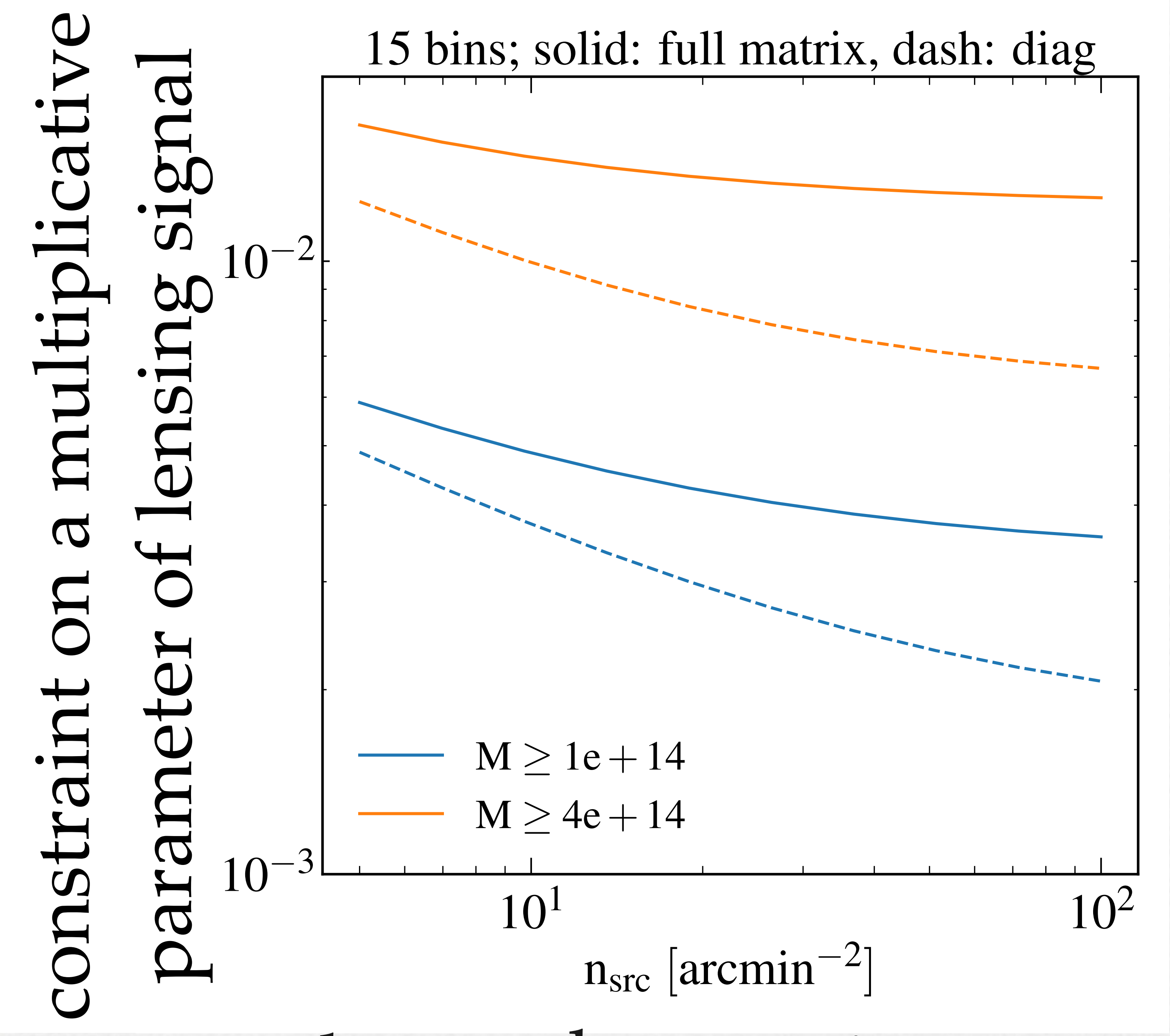
- Small scales: using halos from N-body simulations
- Large scales: analytical calculations assuming Gaussian random fields (infeasible to use N-body simulations)
- Grafting the two regimes together, validating with ray-tracing simulations

A full cluster lensing covariance matrix



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

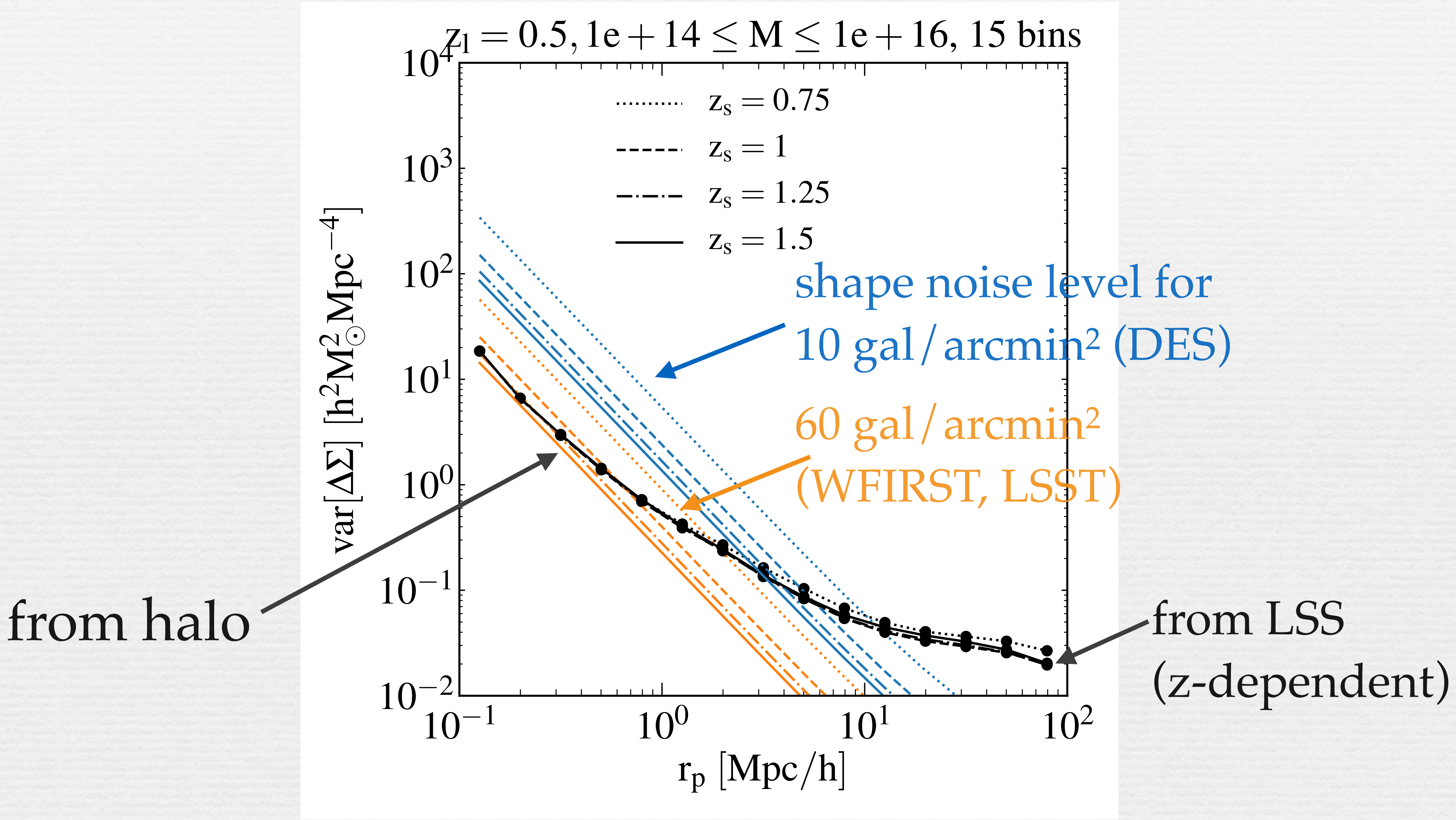
Importance of off-diagonal elements



lower shape noise →

- Ignoring the off-diagonal elements would lead to ~2x underestimation of lensing error budget
- The underestimation is worse when shape noise is low

Importance of shape noise



Summary of Part II: Cluster lensing covariance matrix

- Current cluster surveys like DES are limited by shape noise. For future cluster surveys like LSST and WFIRST, the noise will be dominated by large-scale structure and halo profile variance.
- We combine analytic calculations and high-resolution N-body simulations to calculate the covariance matrix accurately.

Summary

- The abundance of galaxy clusters is a sensitive probe of cosmic acceleration.
- Calibrating the mass-observable relation is the key for cluster cosmology.
- Optical surveys use stacked gravitational lensing to calibrate cluster mass. We use simulations to remove the systematic uncertainties.
- Upcoming optical surveys like LSST, WFIRST will achieve unprecedented precision for gravitational lensing and push our horizons further.