Probing Cosmic Acceleration with Galaxy Clusters

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The Ohio State University

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

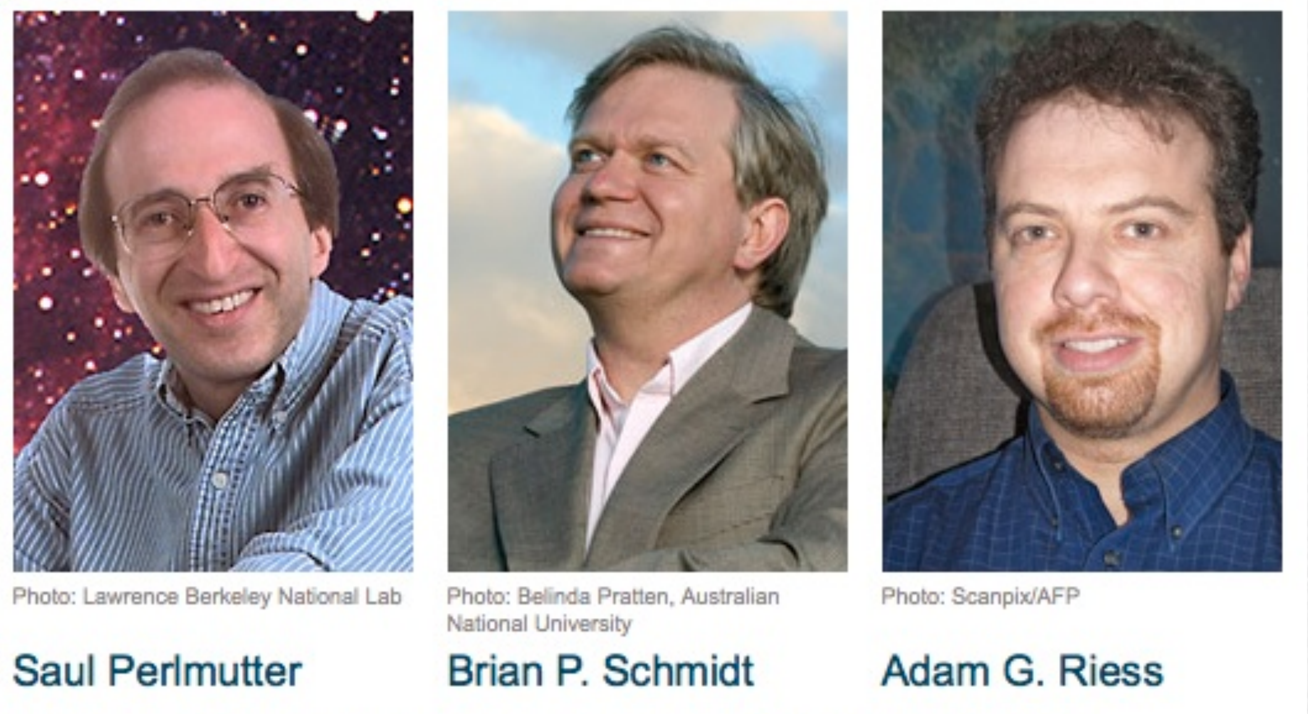


Photo: Lawrence Berkeley National Lab

Saul Perlmutter

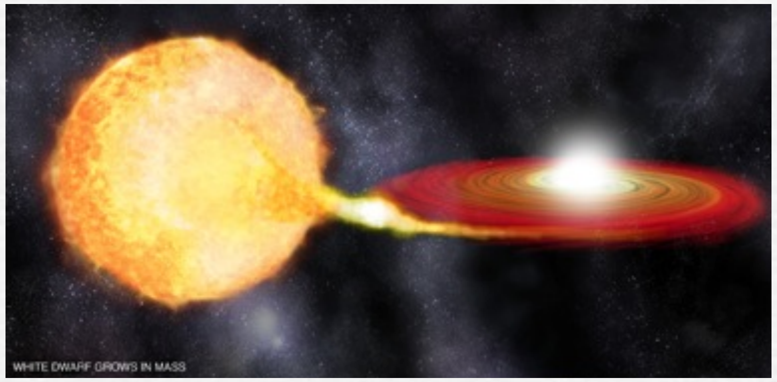
Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Scanpix/AFP

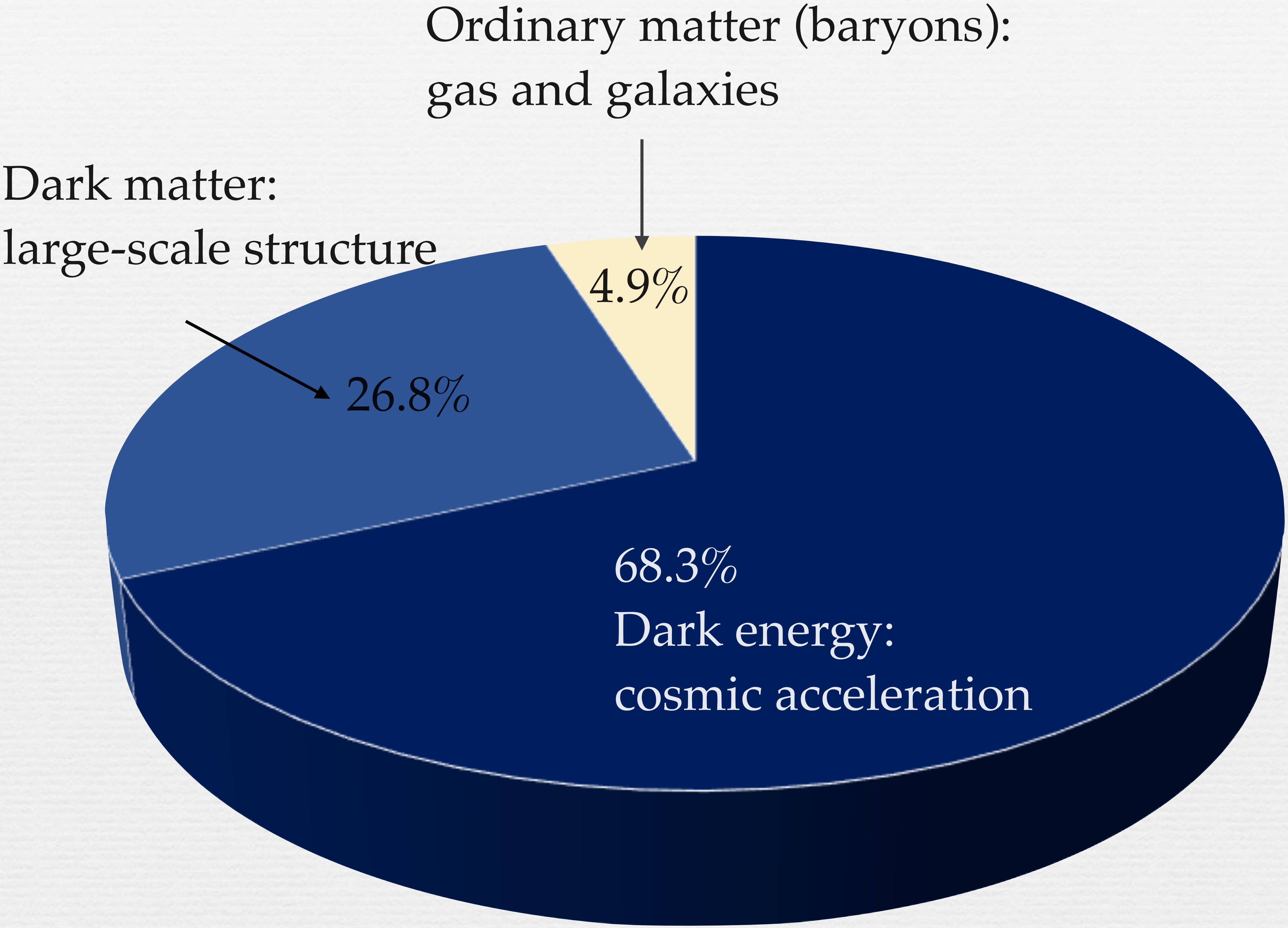
Adam G. Riess

2011 Nobel Prize in Physics



hubblesite.org

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

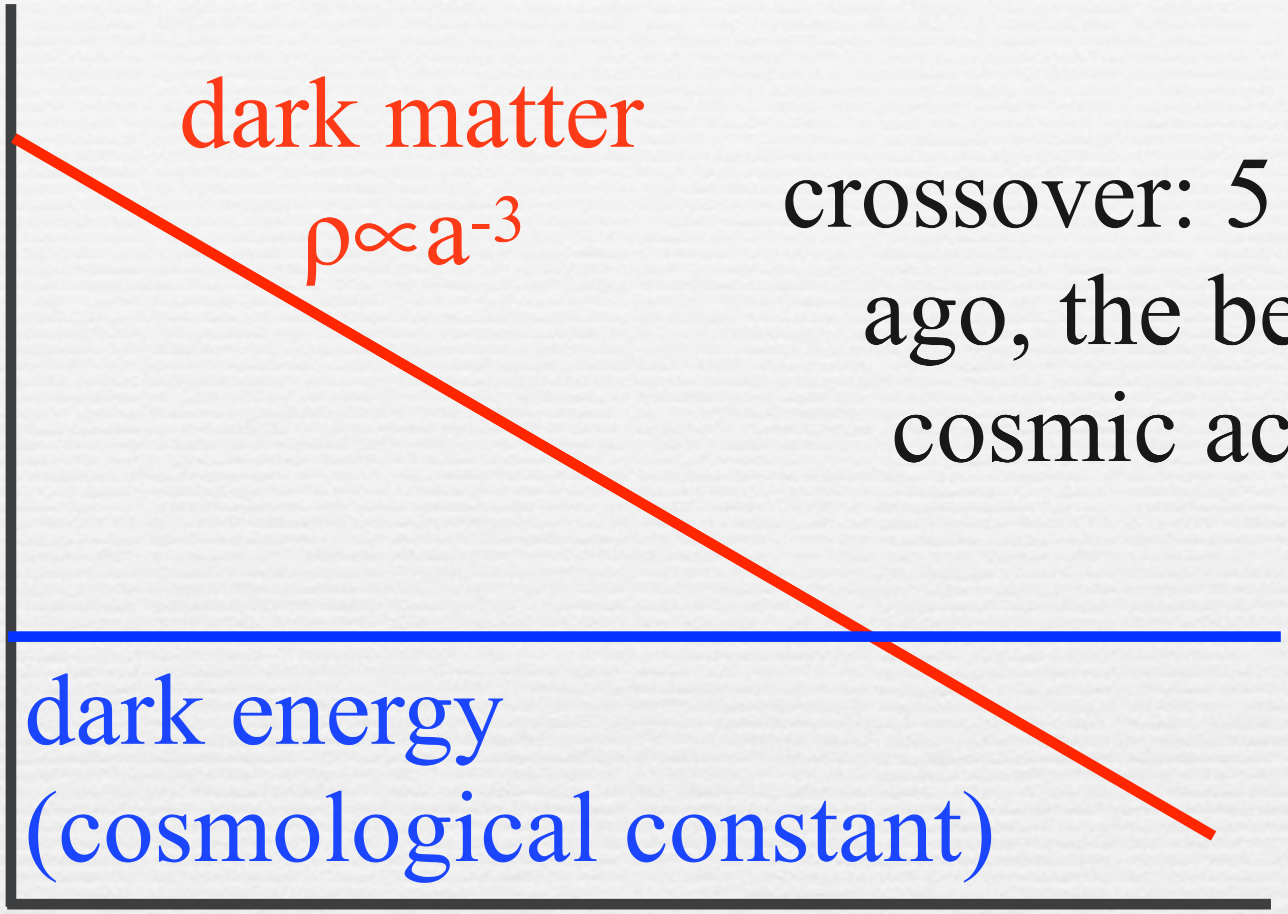
4.9%

Dark matter:
large-scale structure

26.8%

68.3%
Dark energy:
cosmic acceleration

Dark matter vs. dark energy



log ρ
(density)

dark matter
$\rho \propto a^{-3}$

crossover: 5 billion years ago, the beginning of cosmic acceleration

dark energy
(cosmological constant)

log a (scale factor)

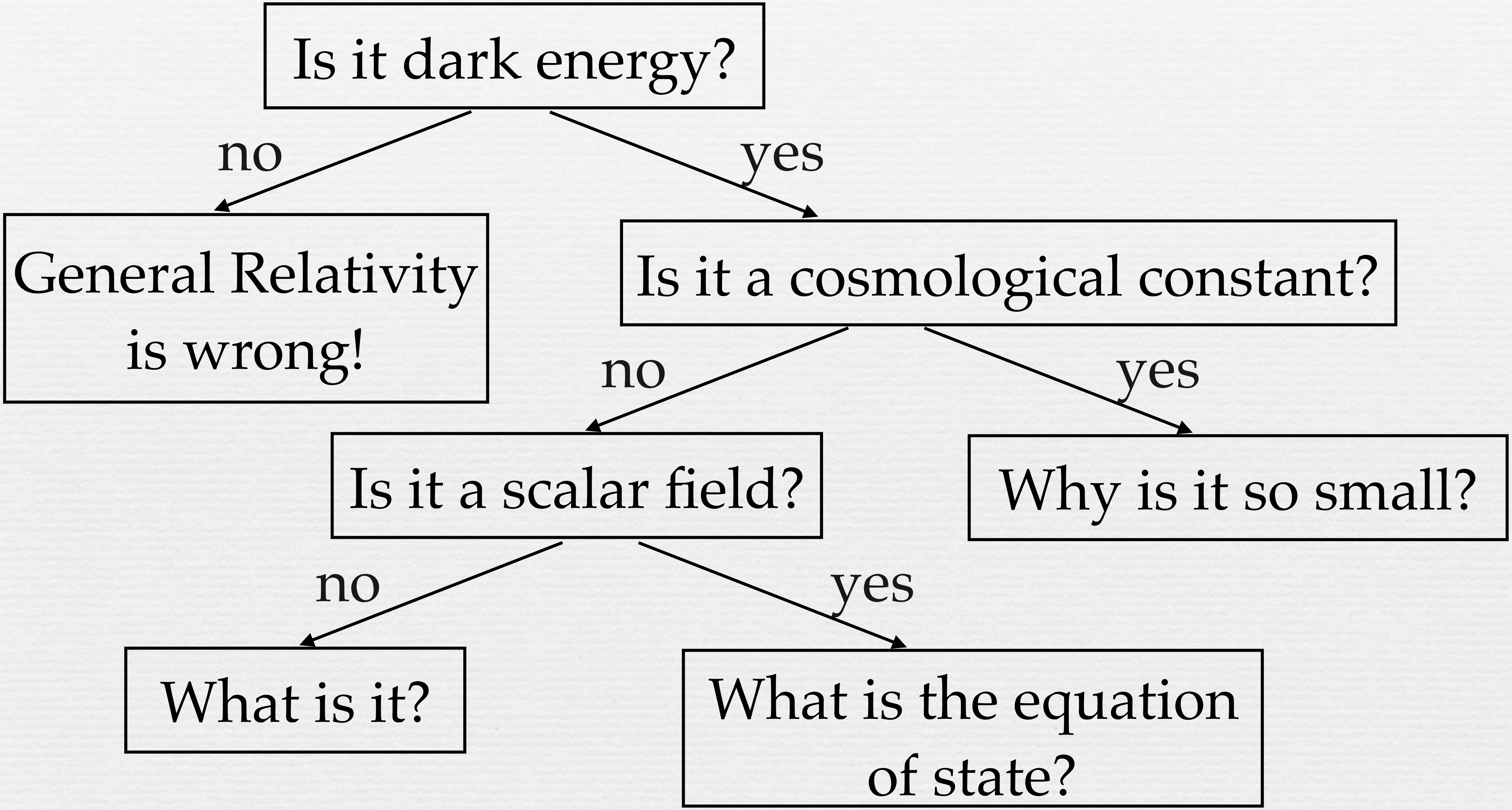
early Universe

today

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

$w = -1$: cosmological constant

What causes the cosmic acceleration?



Is it dark energy?

no

General Relativity is wrong!

yes

Is it a cosmological constant?

no

Is it a scalar field?

no

What is it?

yes

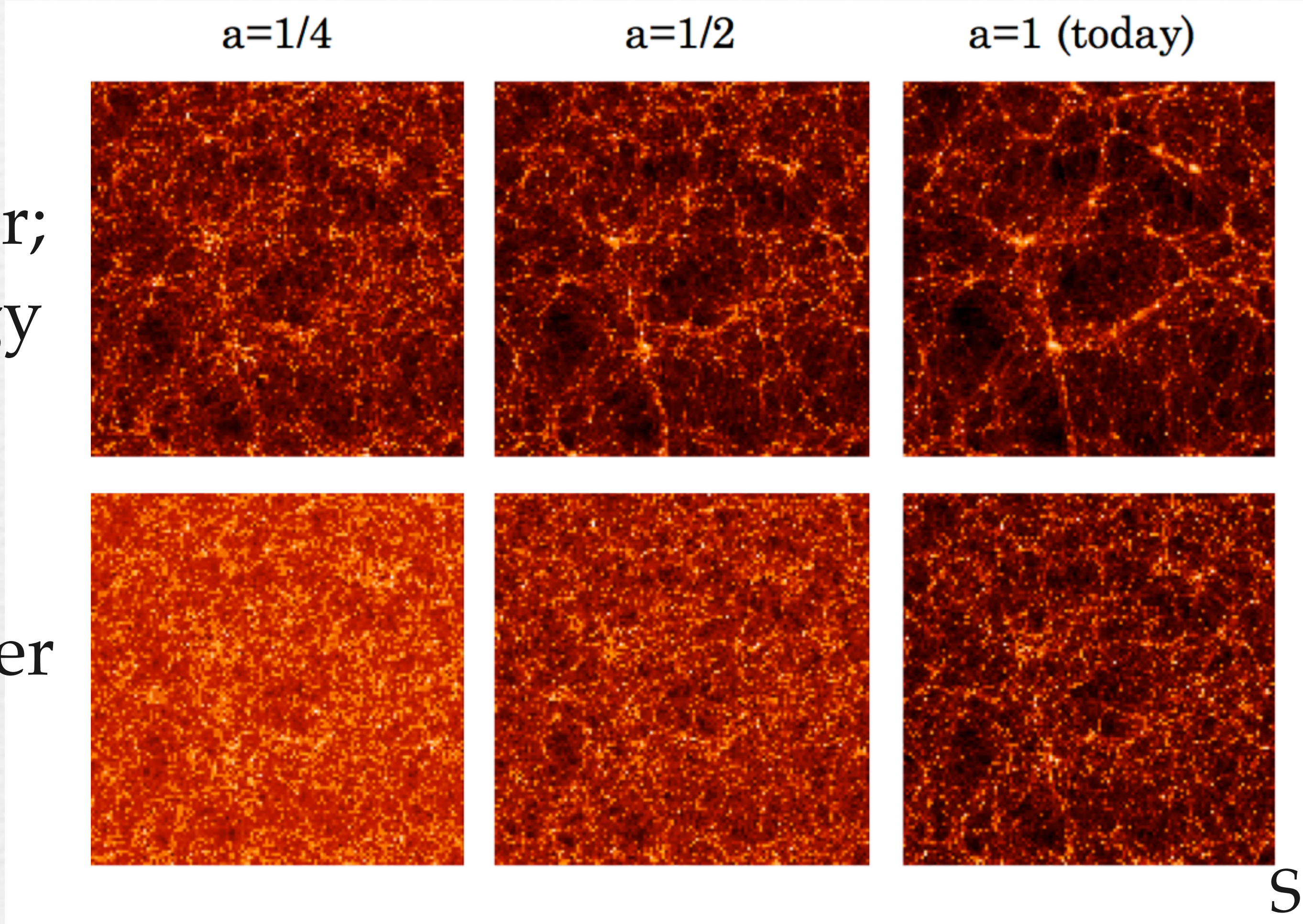
What is the equation of state?

yes

Why is it so small?

We need measurements other than the expansion rate.

Dark energy slows down the growth of large-scale structure



30% dark matter;
70% dark energy

slower evolution

100% dark matter

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

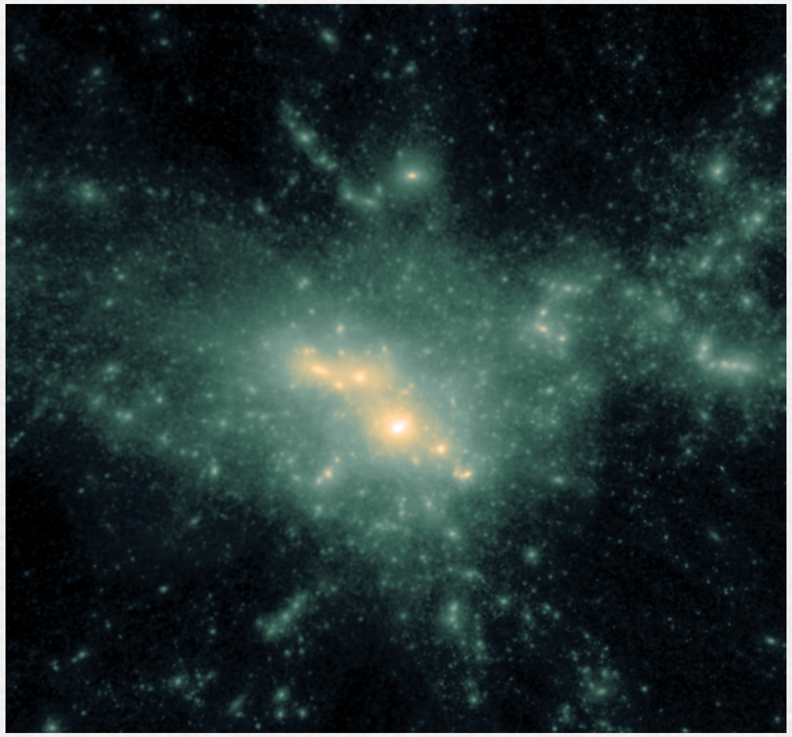
Galaxies

2%

Hot gas

10%

Dark matter halo



88%

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

Size ~ a few million parsecs (Mpc)

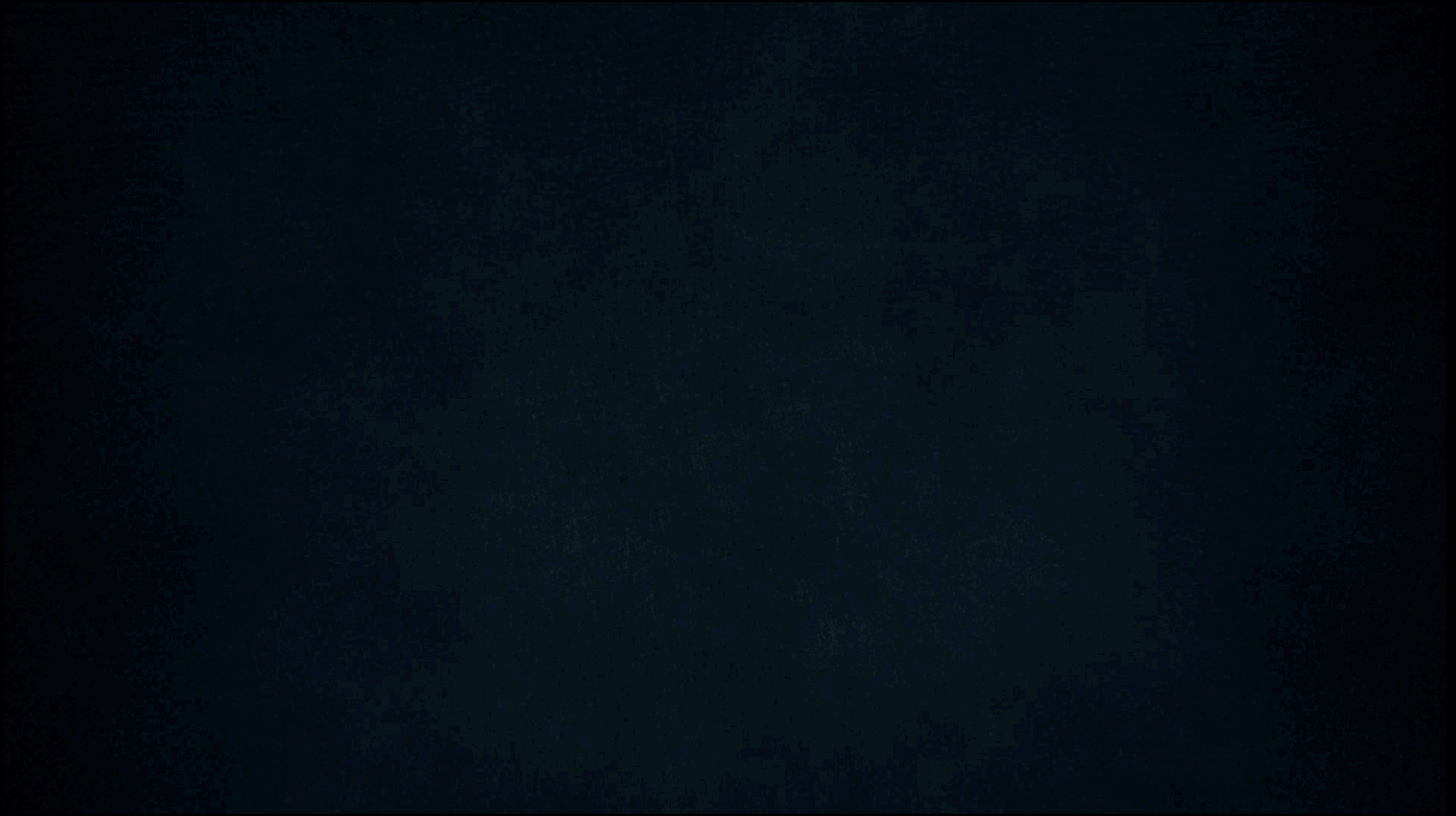
$1\ M_\odot \approx 2\times10^{30}$ kg

1 parsec

≈ 3 lightyears

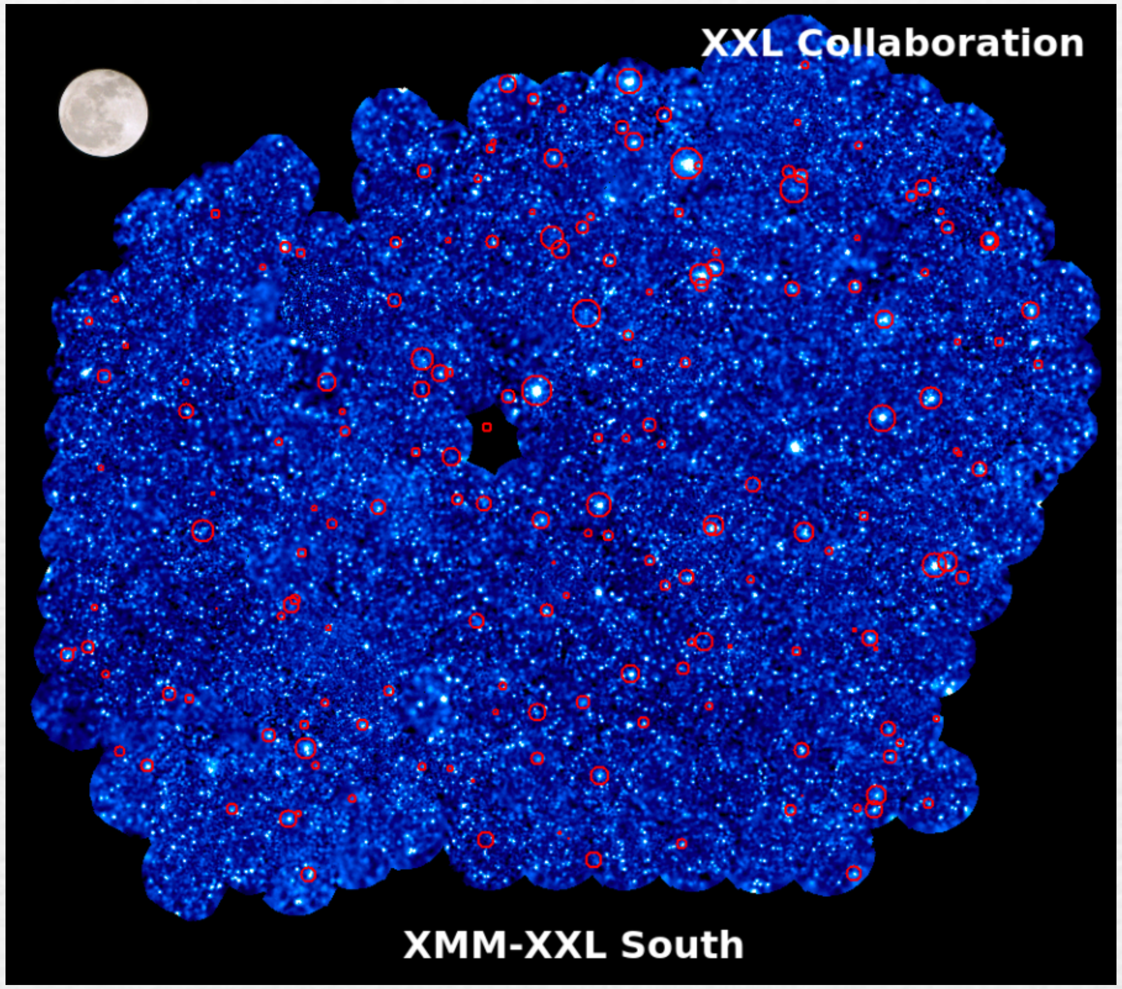
$\approx 3\times10^{16}$ m

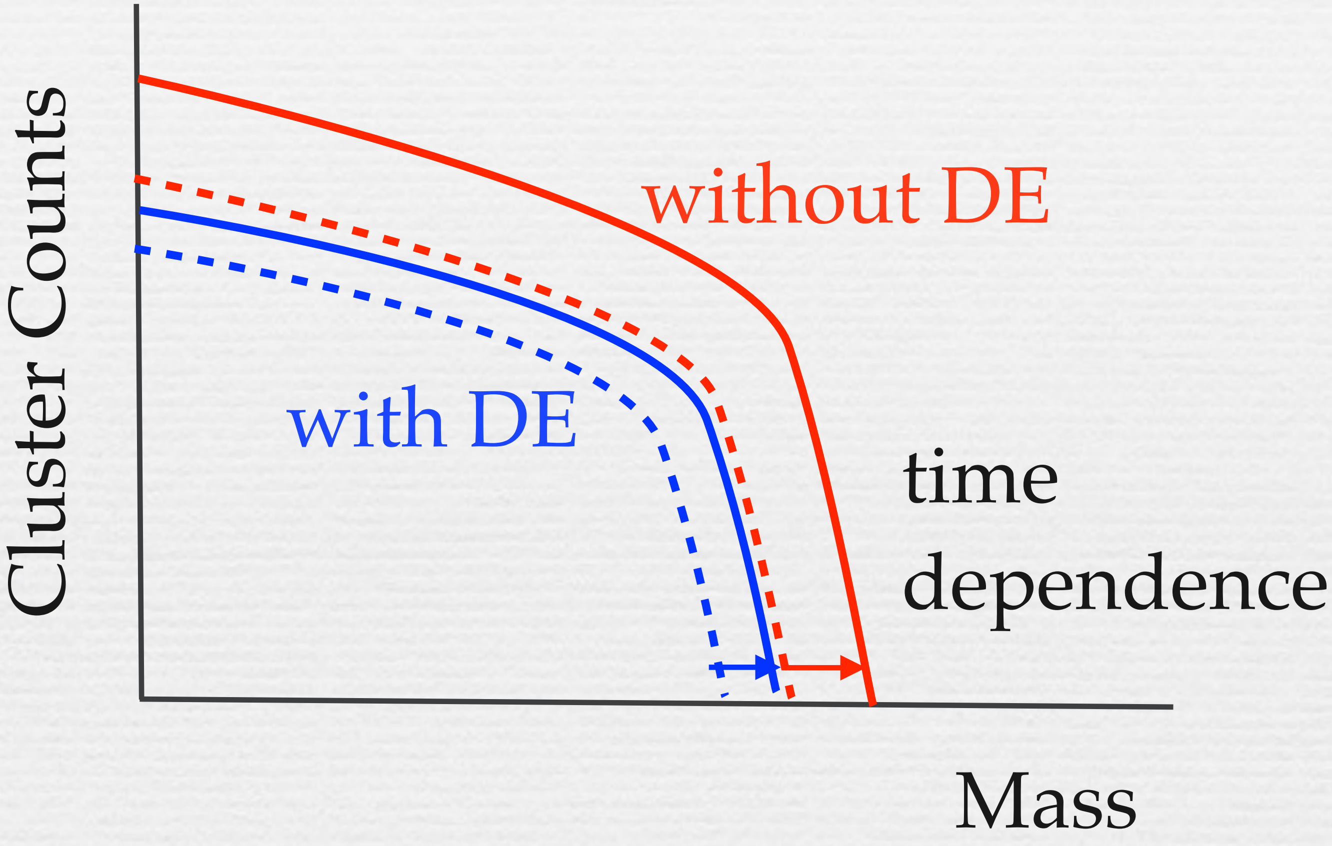
How do galaxy clusters form?



Simulation: Heidi Wu. Visualization: Ralf Kaehler

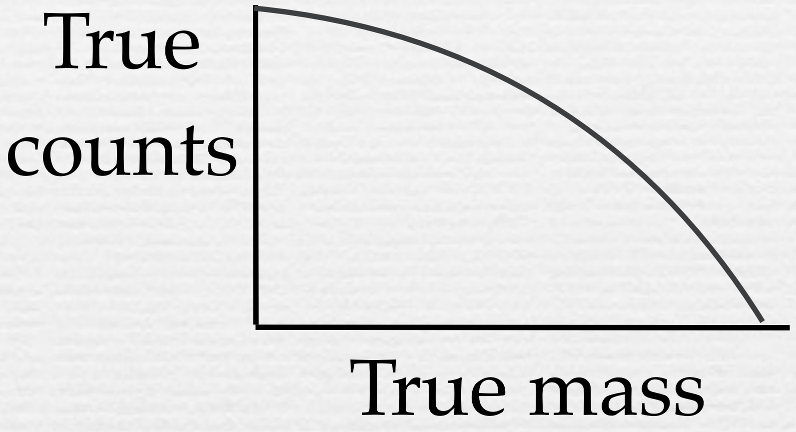
Measuring dark energy using the number counts of galaxy clusters





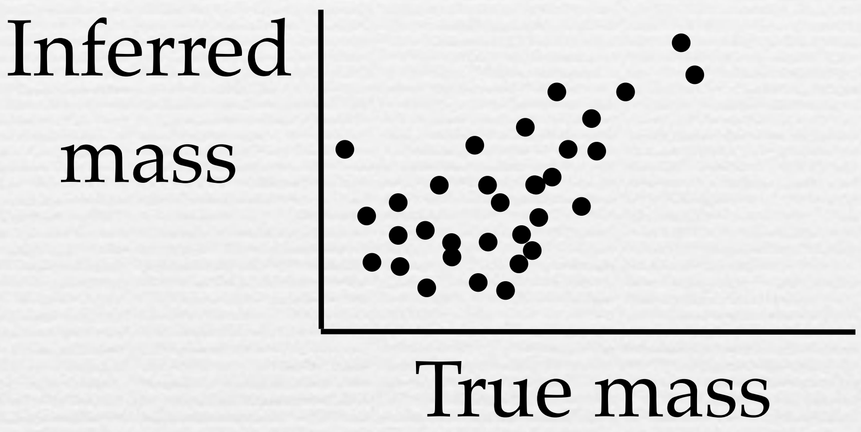
We need to infer cluster mass from observable properties.

Importance of precise mass calibration



+

Scatter between mass and observable



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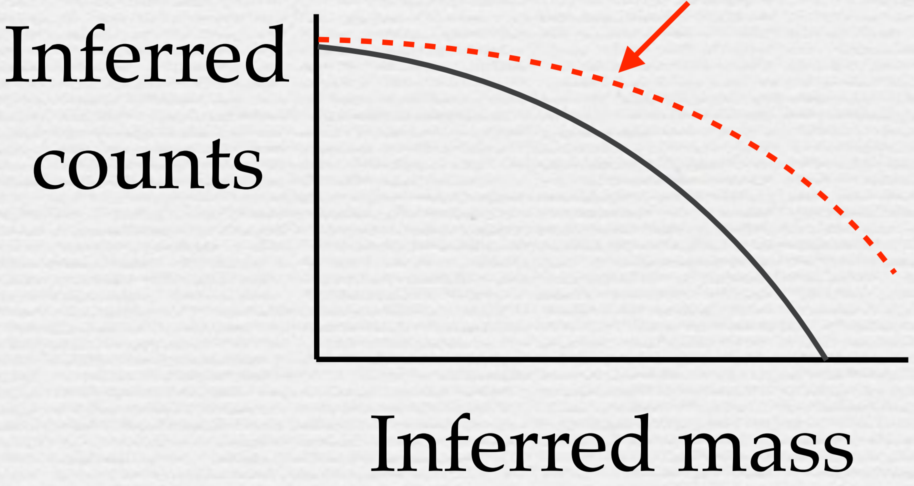


with scatter (e.g. mass inferred from richness)

Scatter can mimic the effect of low dark energy!

How to measure the mass of galaxy clusters?

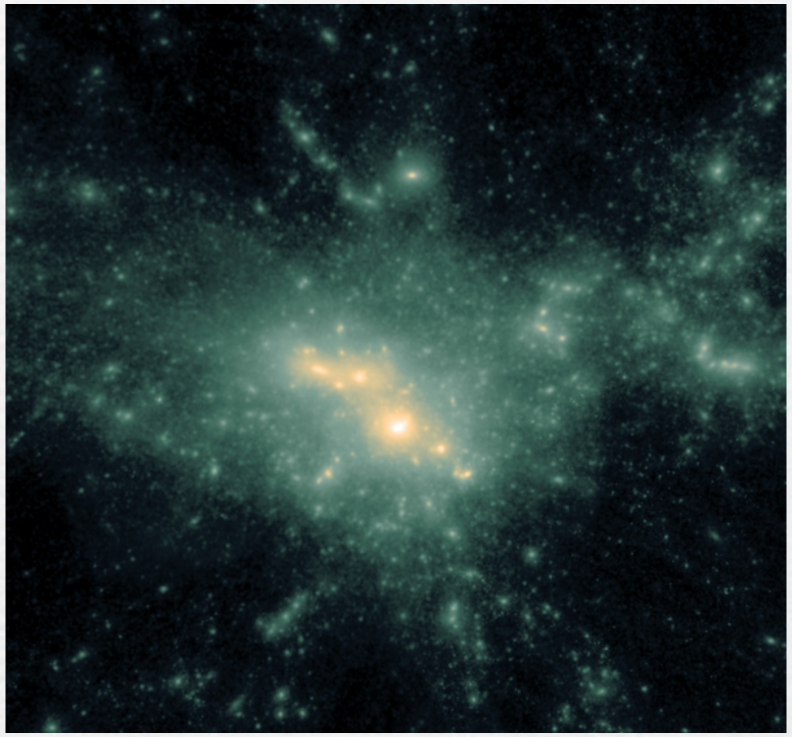
Galaxies

- 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



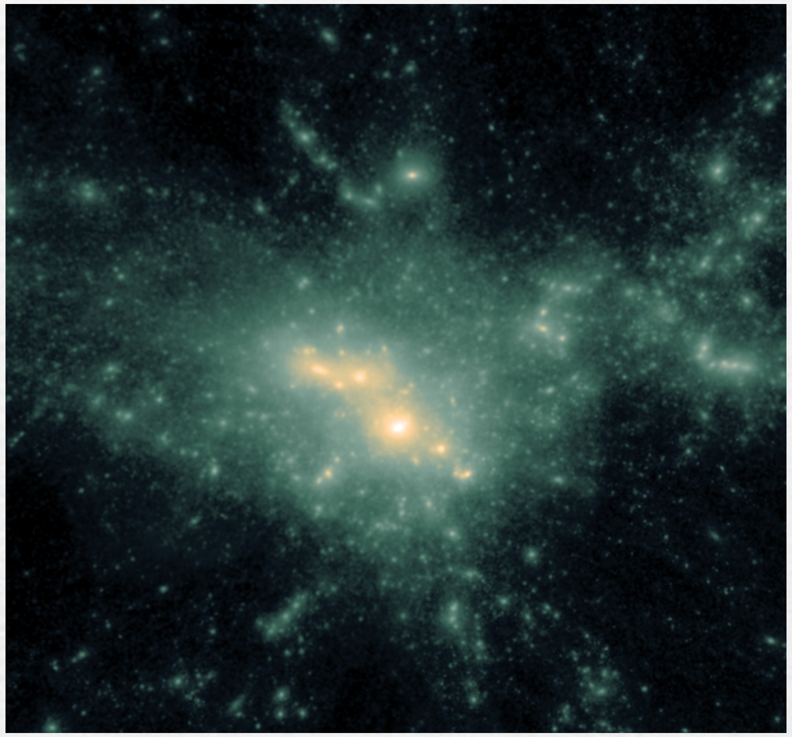
Gravitational lensing

How to measure the mass of galaxy clusters?

Galaxies

Hot gas

Dark matter halo

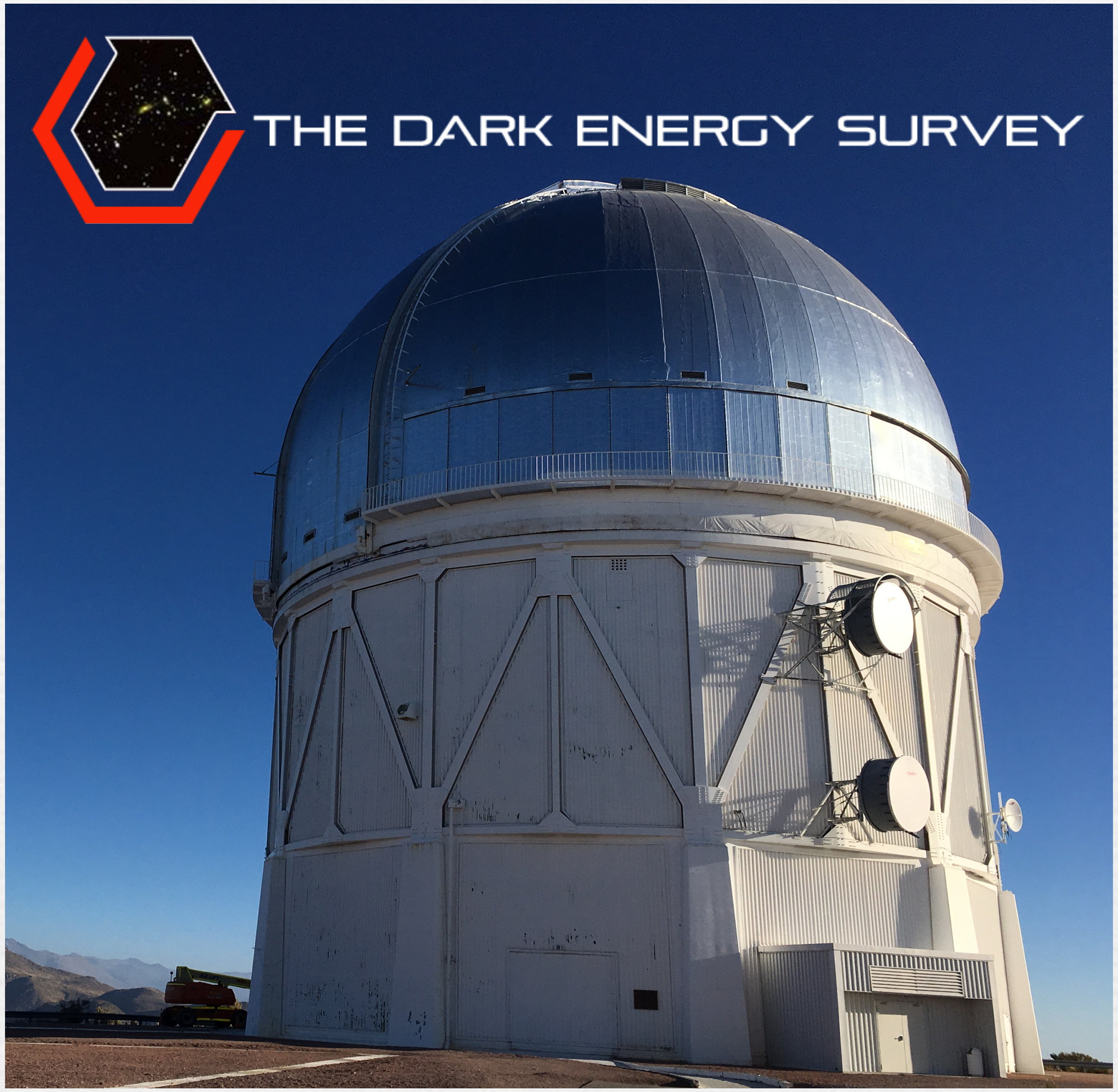


- Number of galaxies (richness)
- Velocity dispersion **(Wu et al. 2013)**

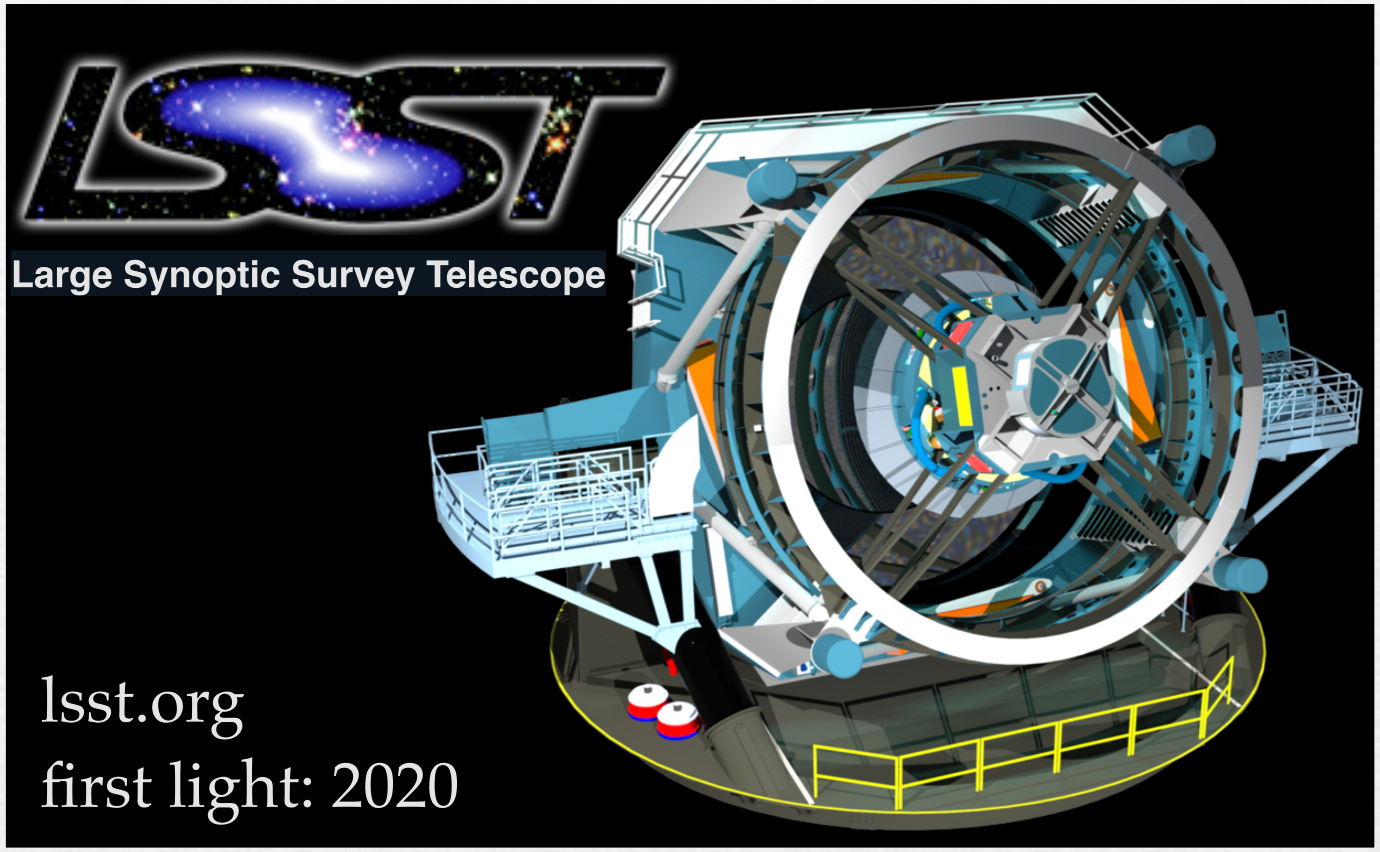
- X-ray emission **(Wu et al. 2015)**
- SZ effect

Gravitational lensing (this talk)

Optical surveys of galaxy clusters



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



lsst.org
first light: 2020

wfirst.gsfc.nasa.gov
launch: mid-2020s

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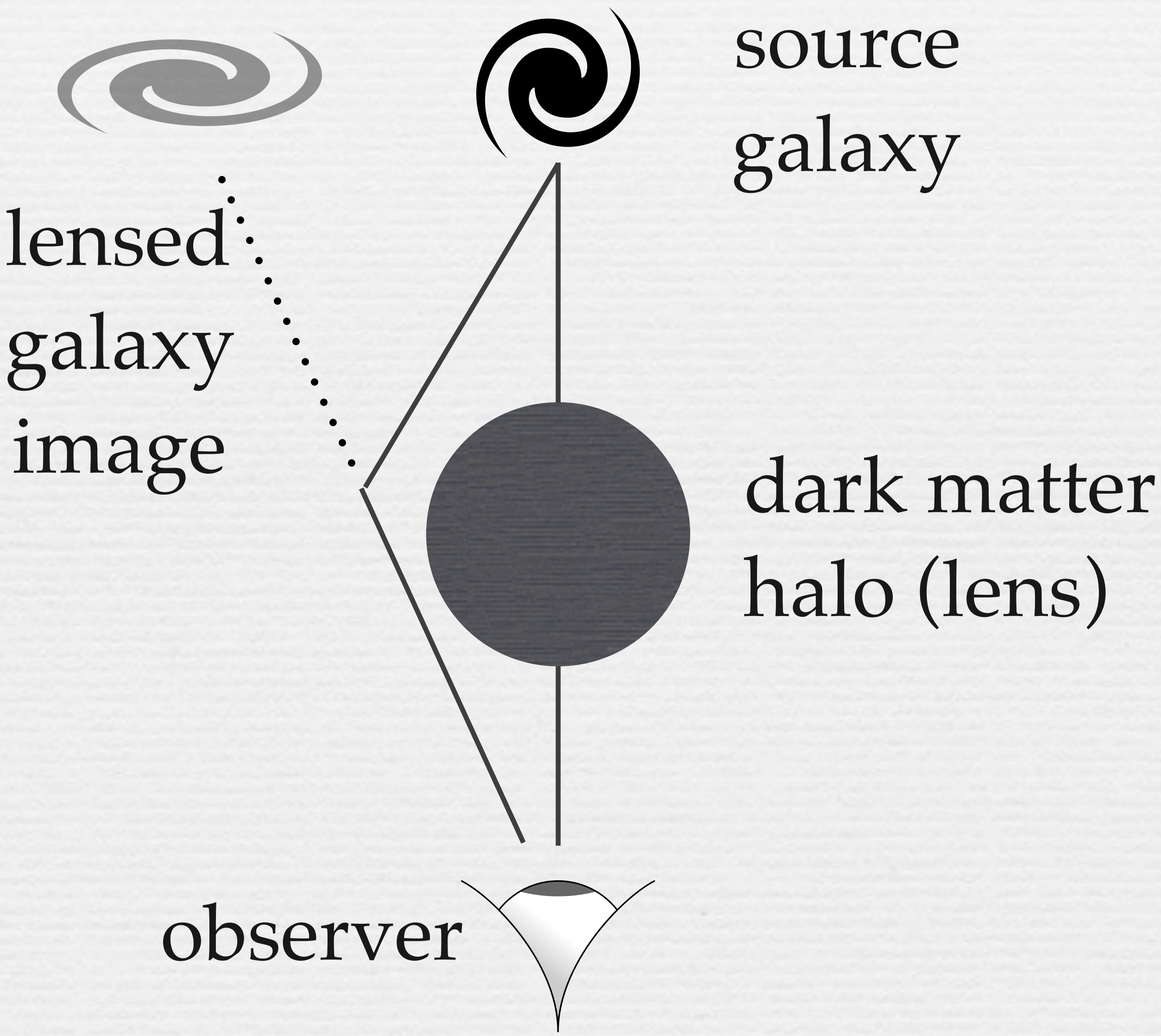
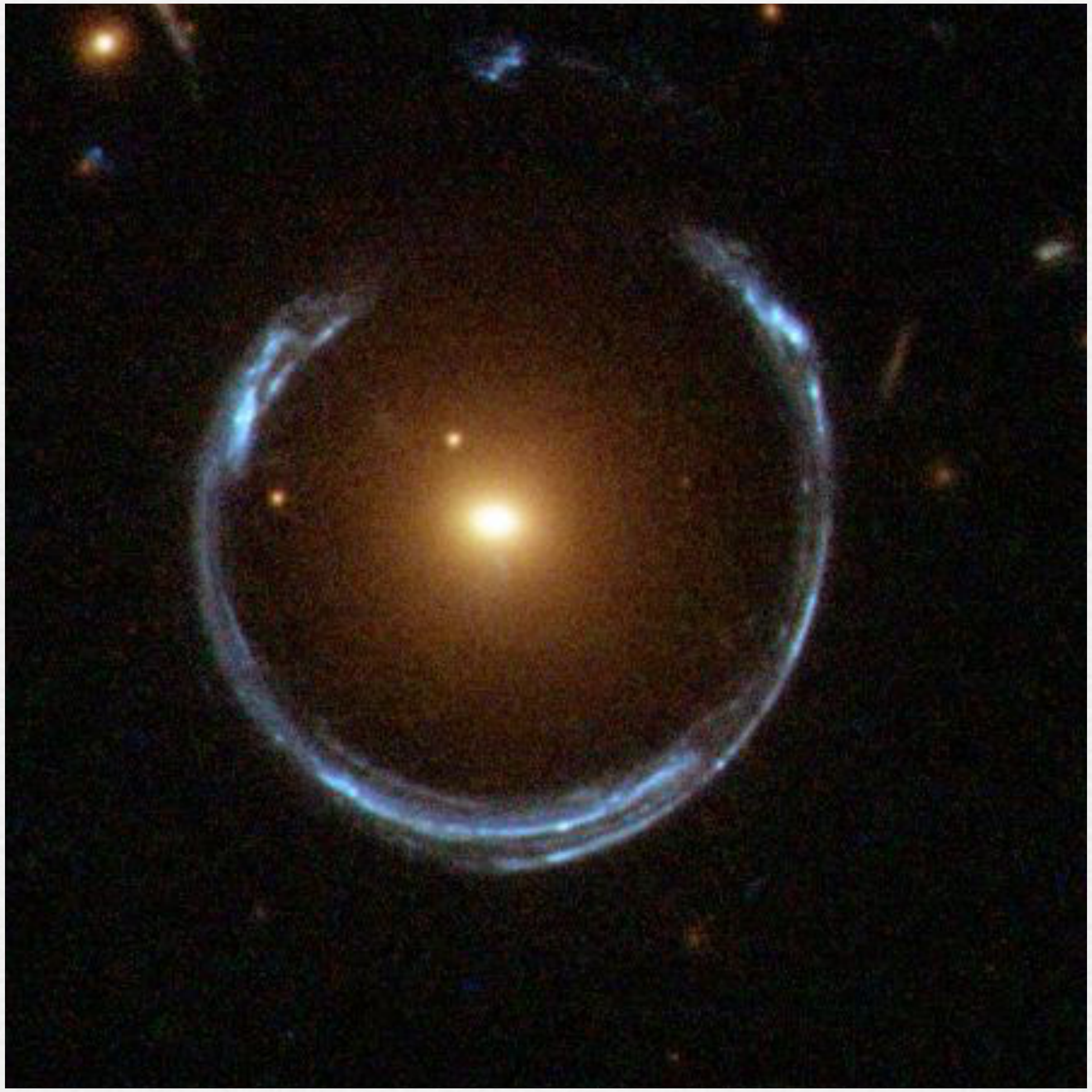
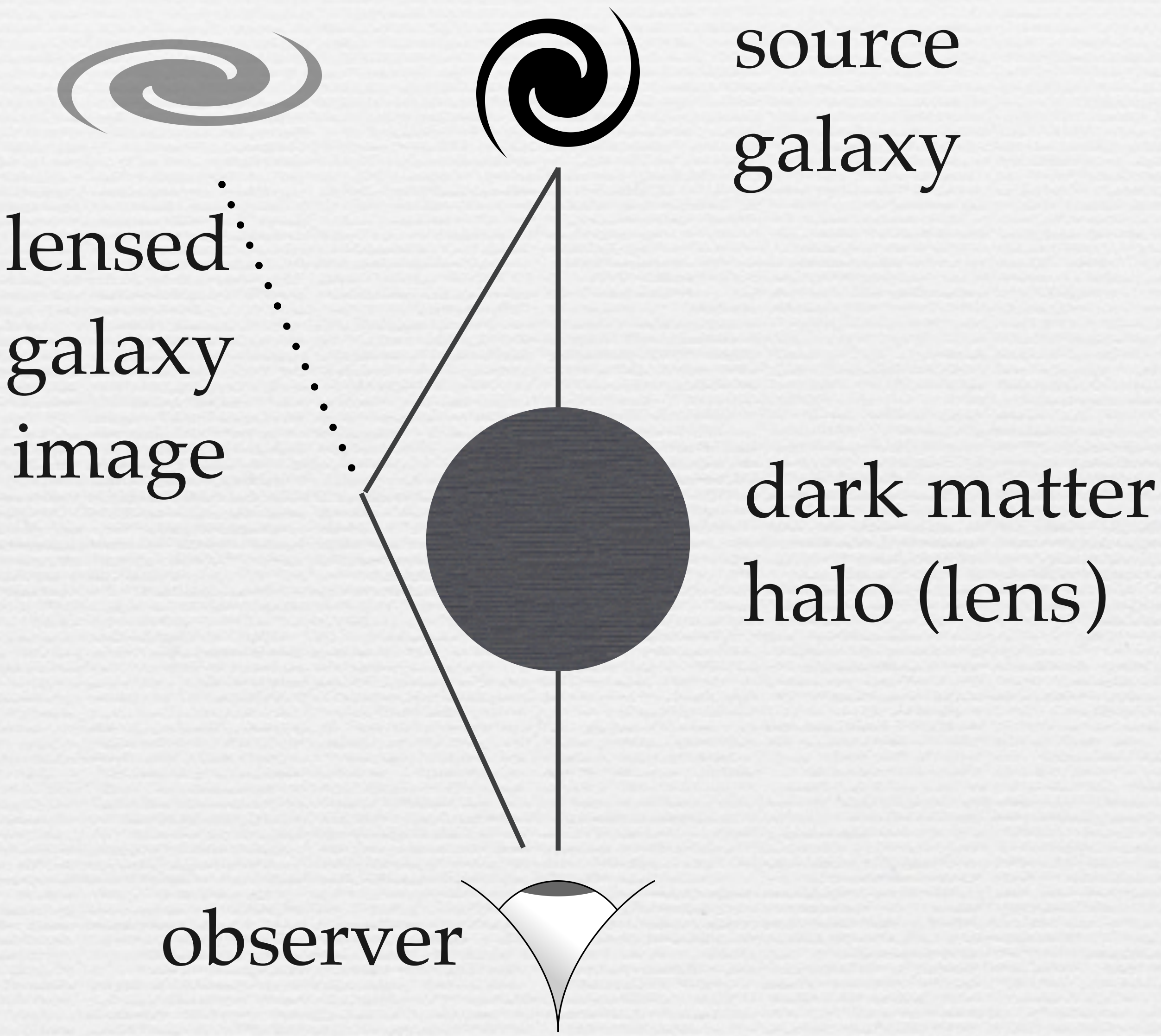
Measuring halo mass using gravitational lensing effect



Strong lensing (rare)



Measuring halo mass using gravitational lensing effect



source
galaxy

lensed
galaxy
image

dark matter
halo (lens)

observer

Weak lensing (everywhere)

Inferring cluster mass from weak lensing

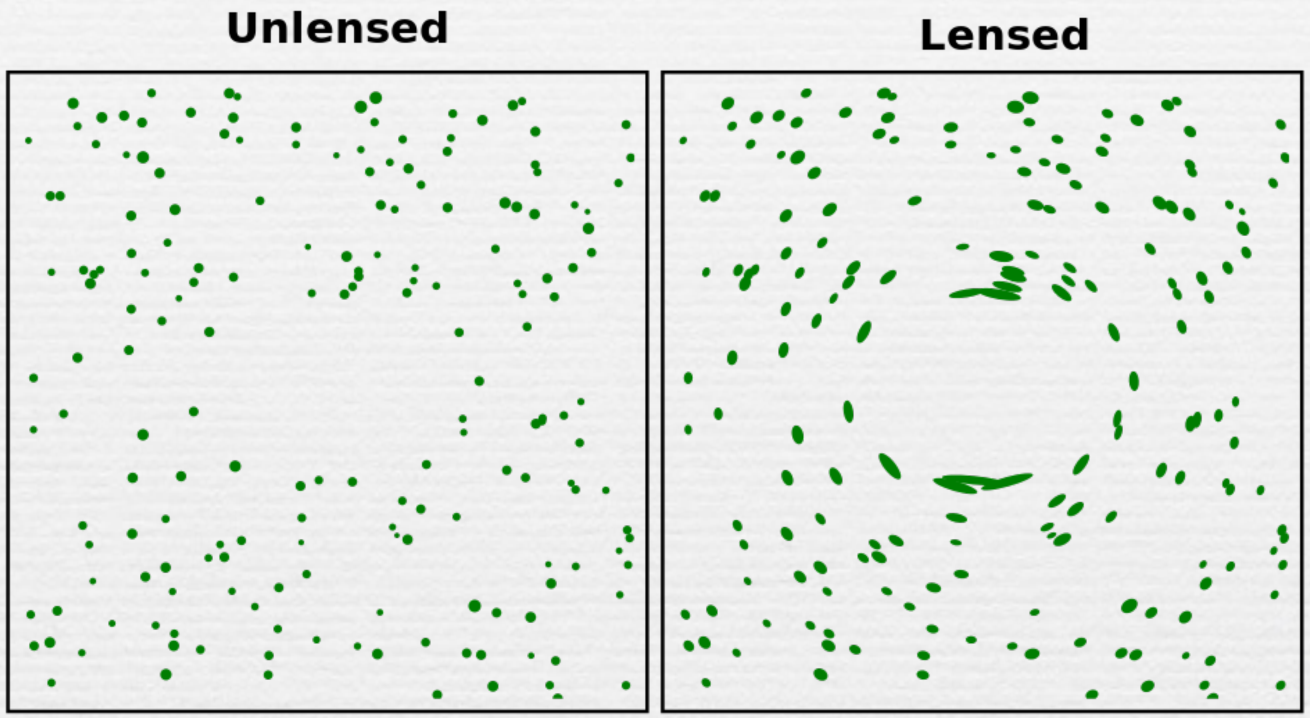
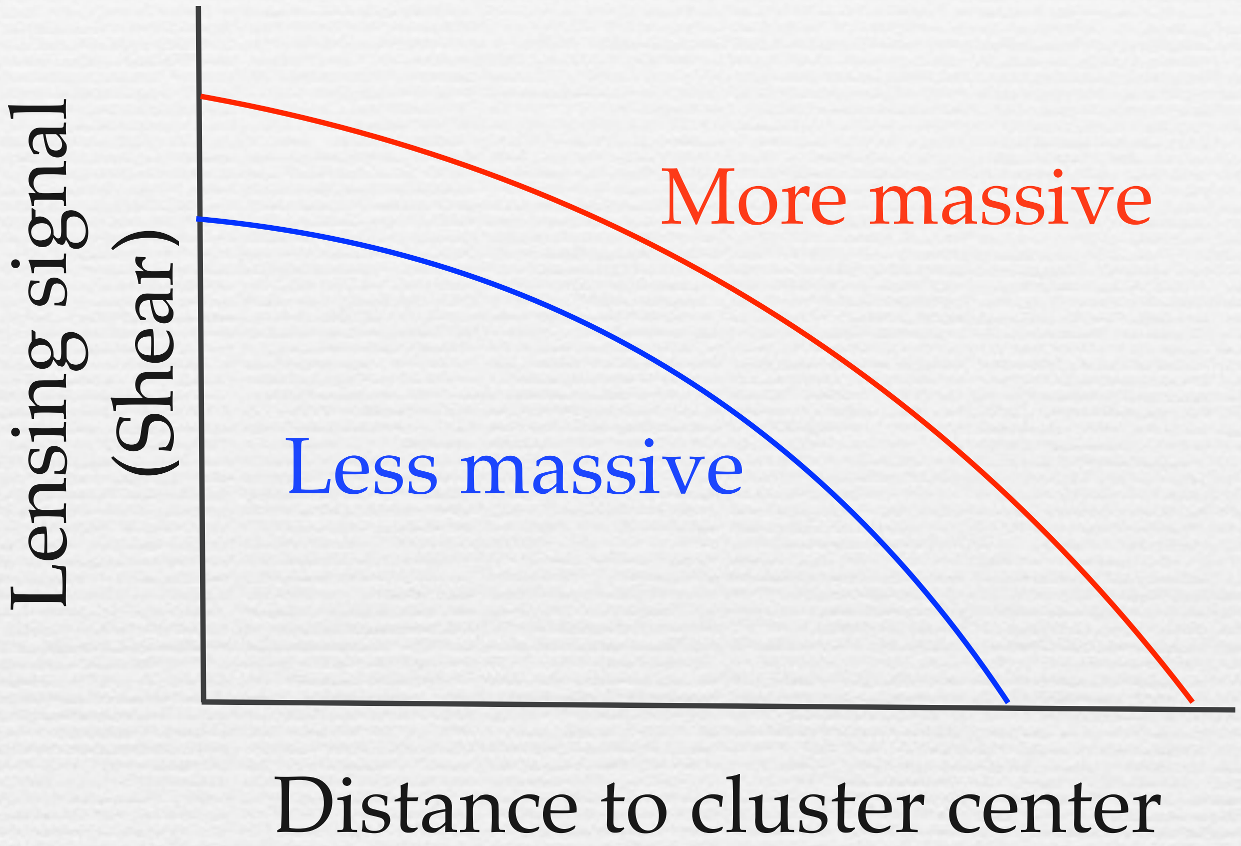


Figure from Wikipedia



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)

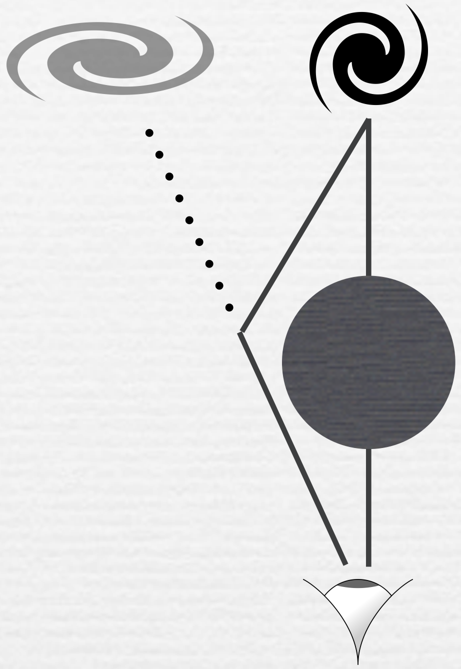
- Mock catalogs for the DES volume (several Gpc^3)
- Based on dark matter N-body simulations
- Galaxies are assigned to dark matter particles based on local density
- Recovering the observed galaxy correlation functions

redMaPPer Cluster Finder

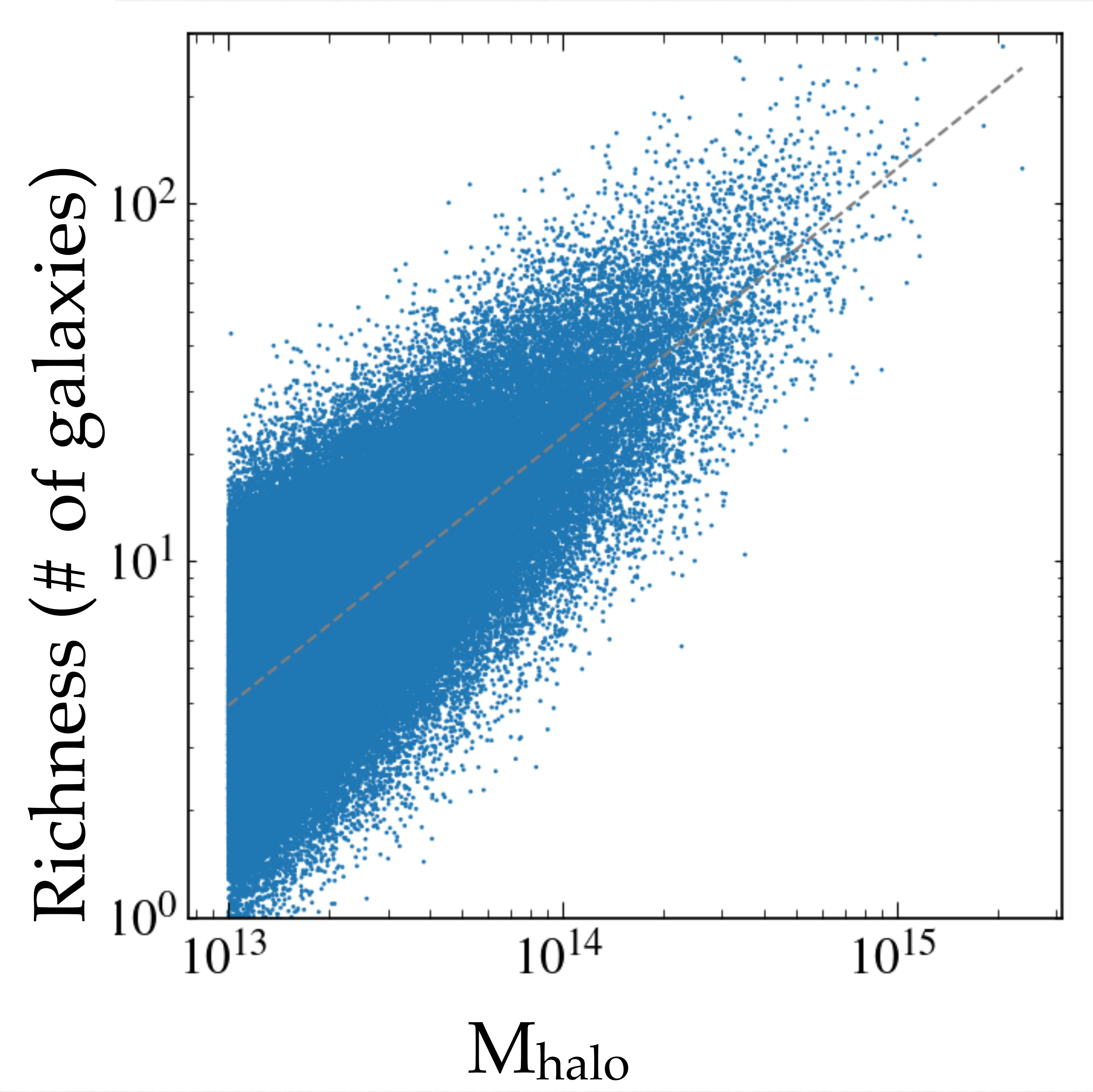
Rykoff & Rozo et al. (2014)

- Identifying clusters using red-sequence in photometric data
- Assigning a 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)



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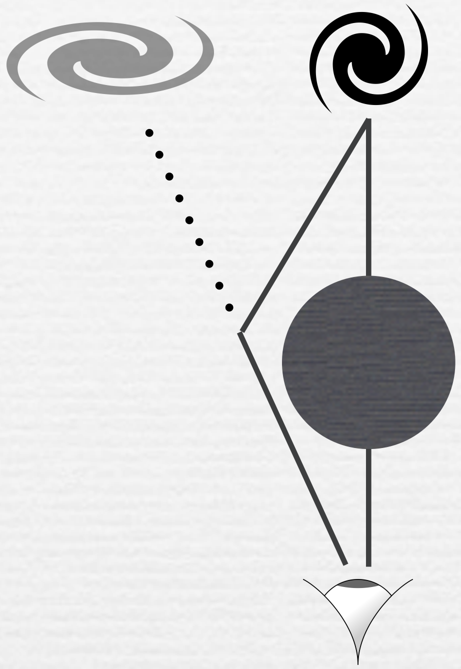

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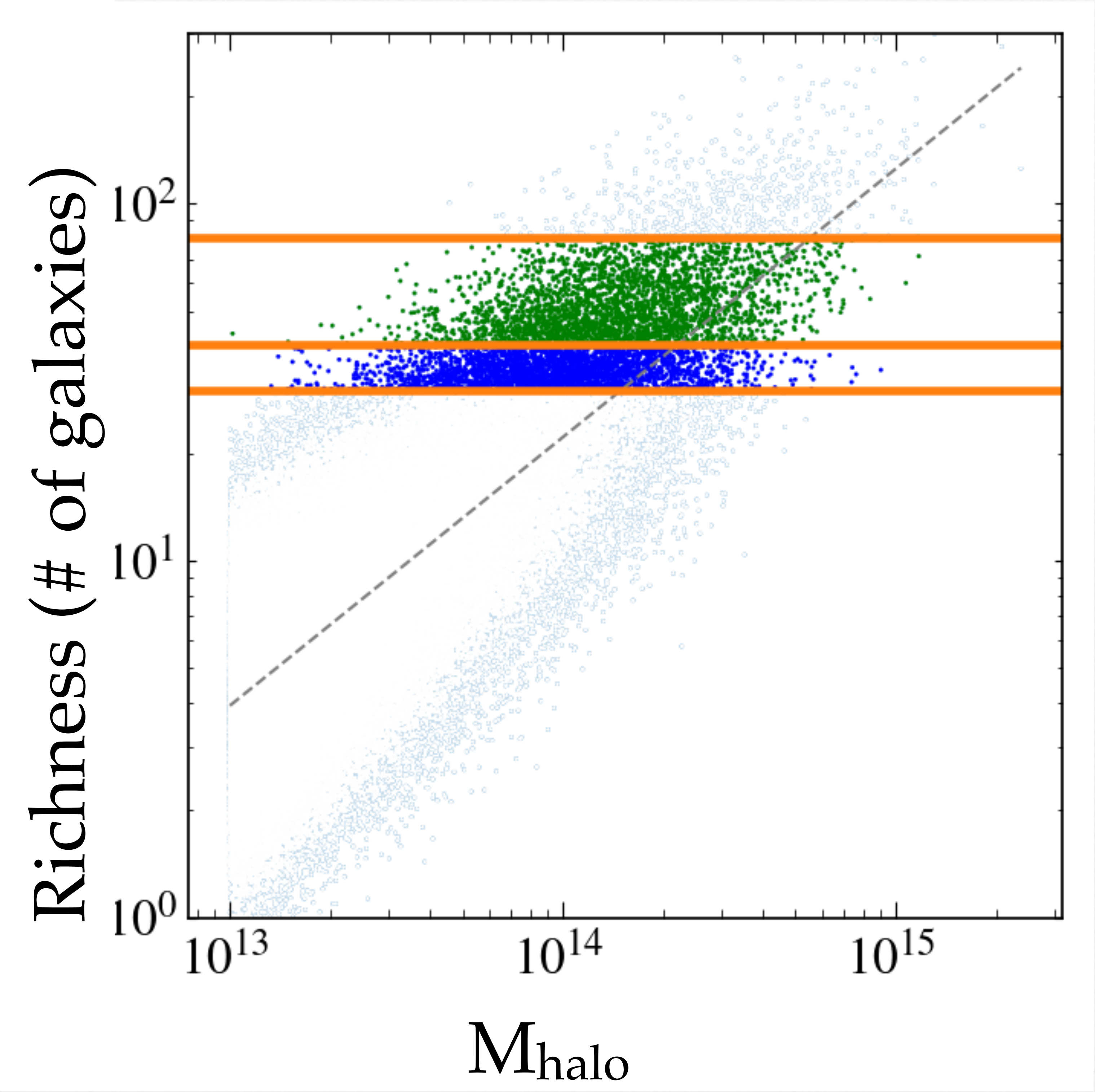
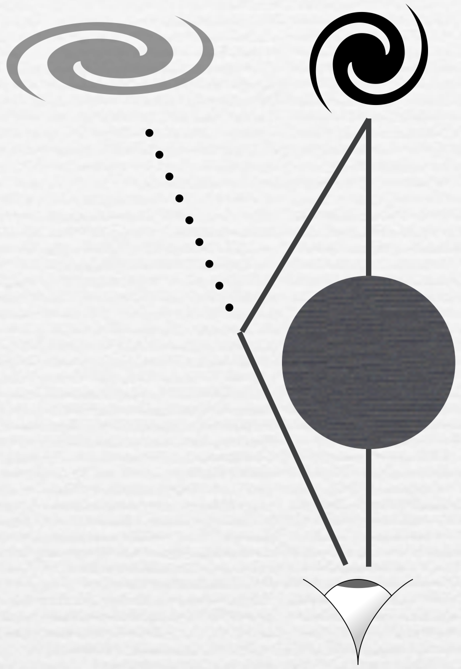
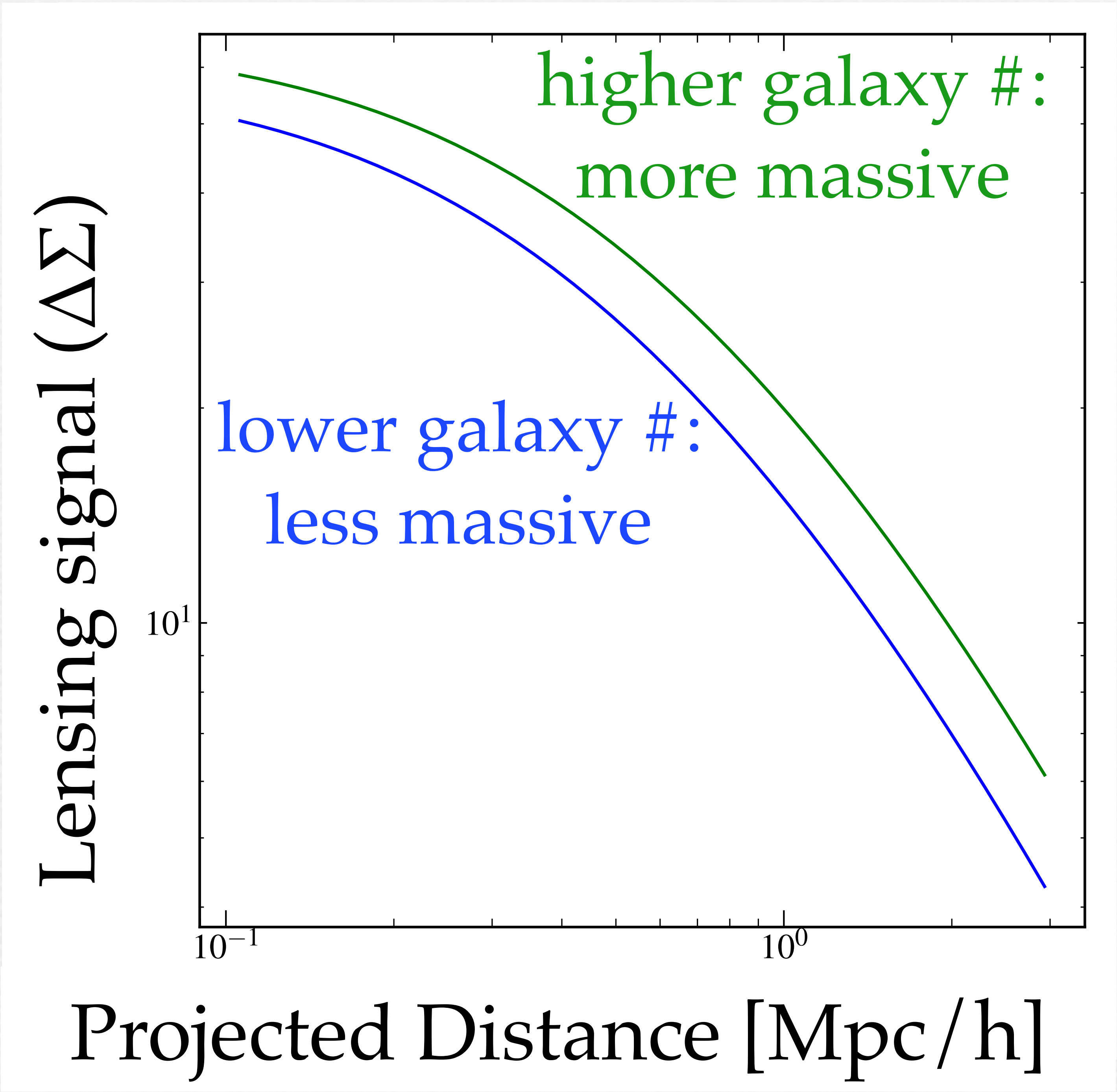


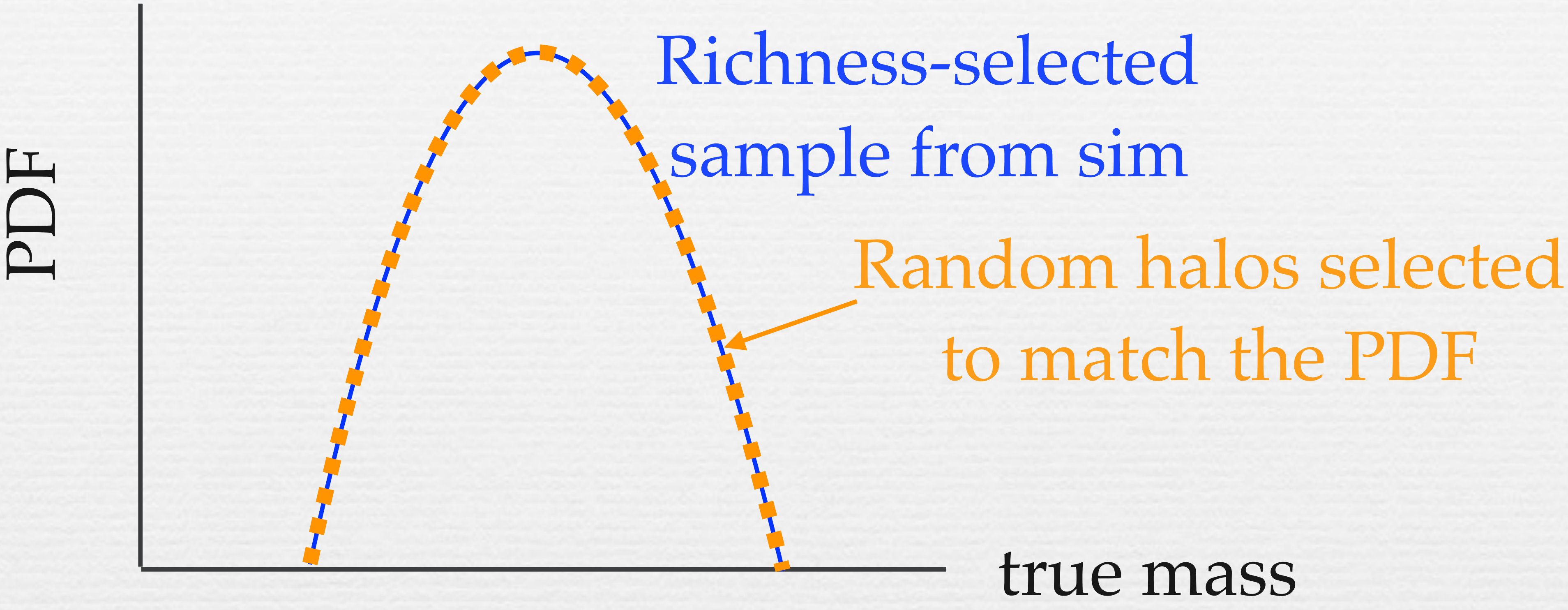
Stacking the weak lensing effect



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



Is there a selection bias in this process?



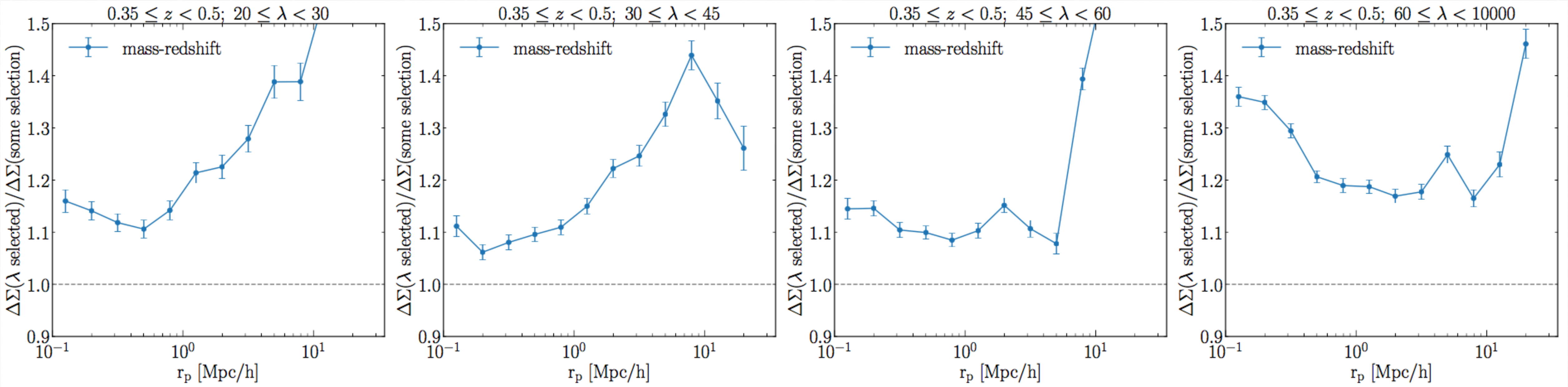
Step 1: selecting clusters based on richness, calculating the PDF of the underlying halo mass

Step 2: selecting 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 is no selection bias.

Is there a selection bias in this process?



higher richness ⟶

- We find a ~10-40% bias in lensing signal.
- Richness selected clusters tend to have higher lensing signals than halos of the same mass.
- If we do not correct for it, the weak lensing mass would be biased high.

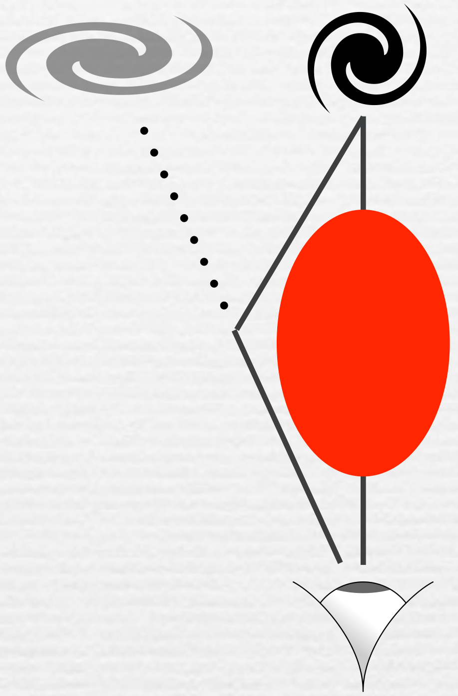
Preliminary

What is causing this systematic bias?

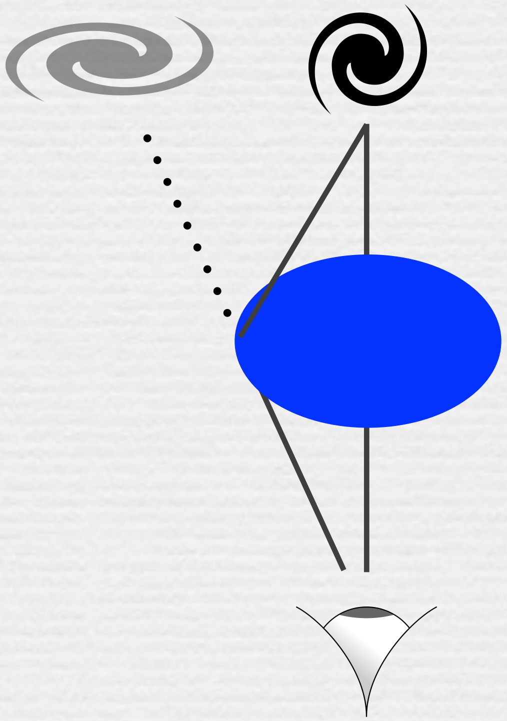
Systematic effect 1: Orientation Bias

Systematic effect 2: Projection Effect

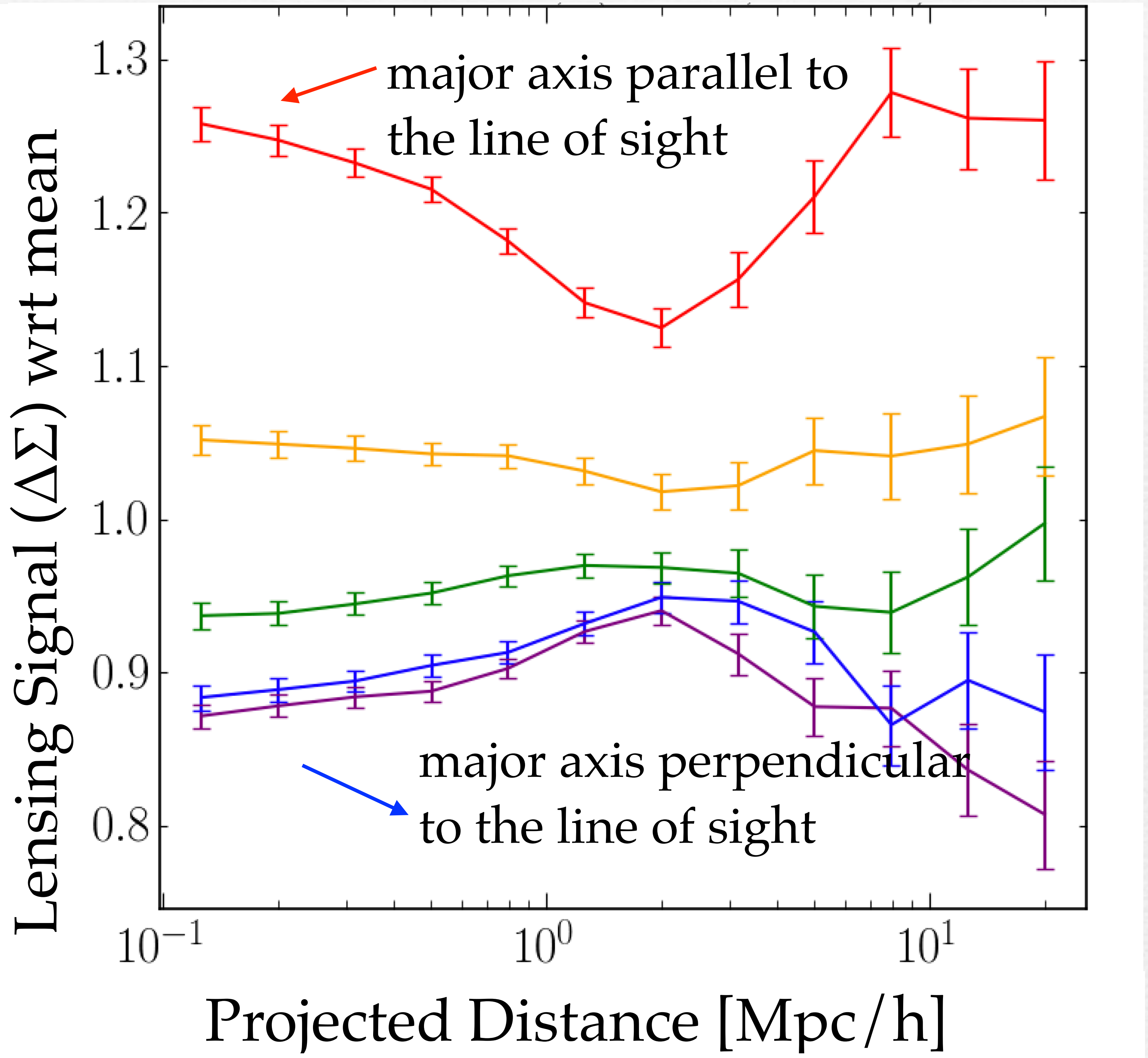
Impact of halo orientation on cluster lensing



higher lensing signal

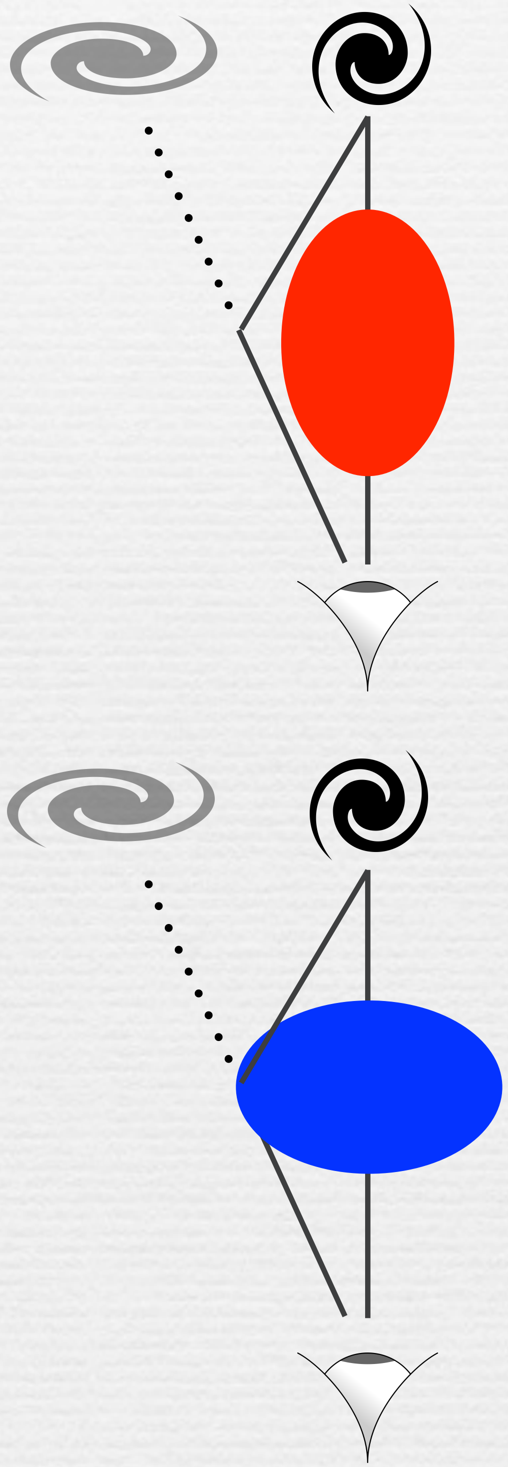


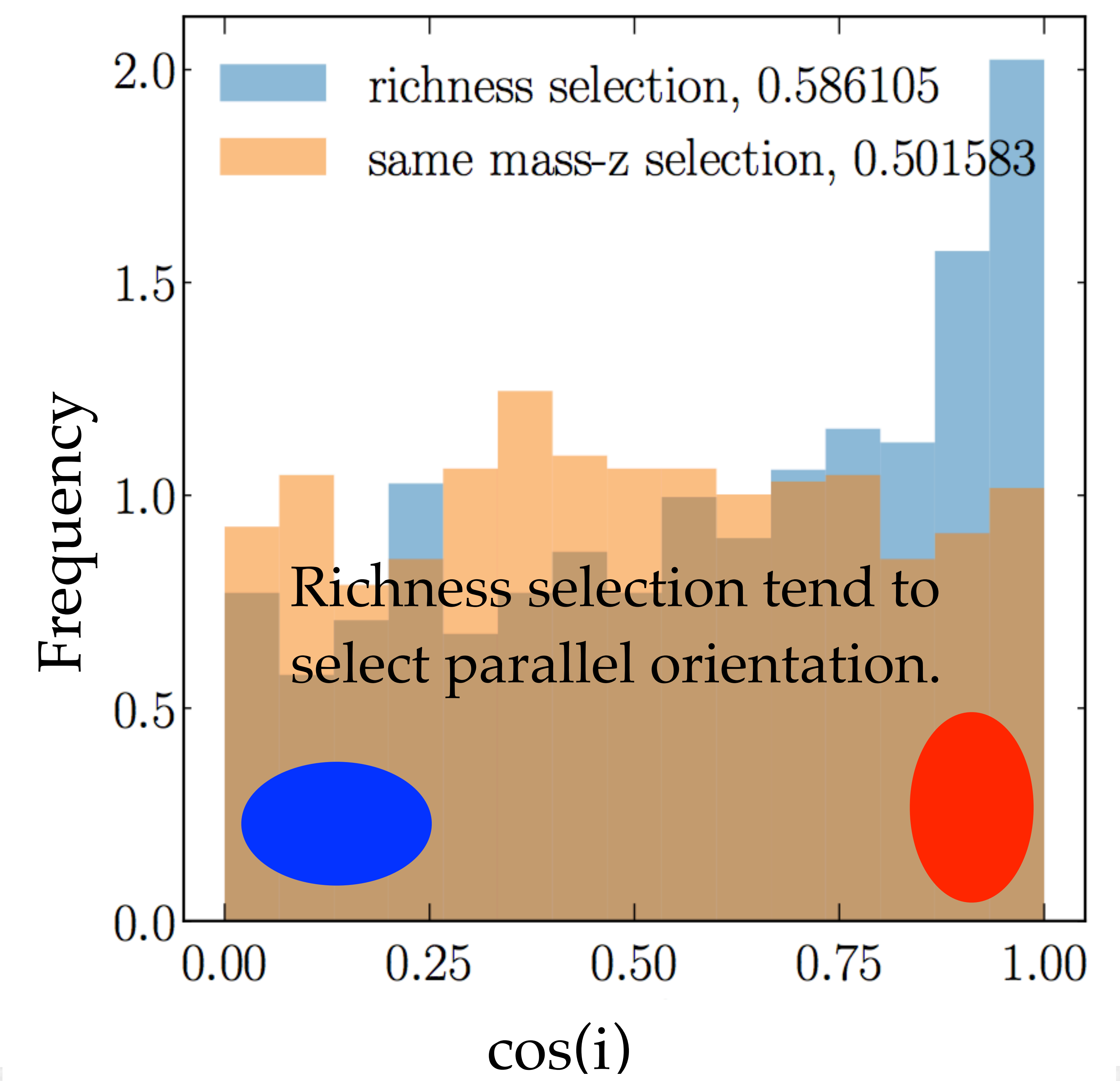
lower lensing signal



Preliminary

Impact of orientation on selection

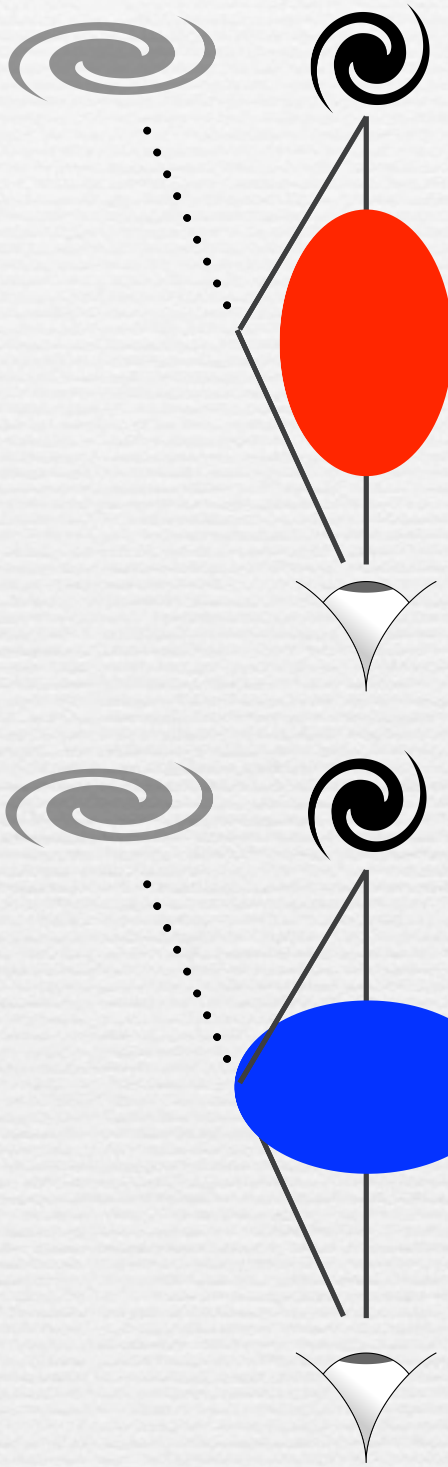




Richness selection tend to select parallel orientation.

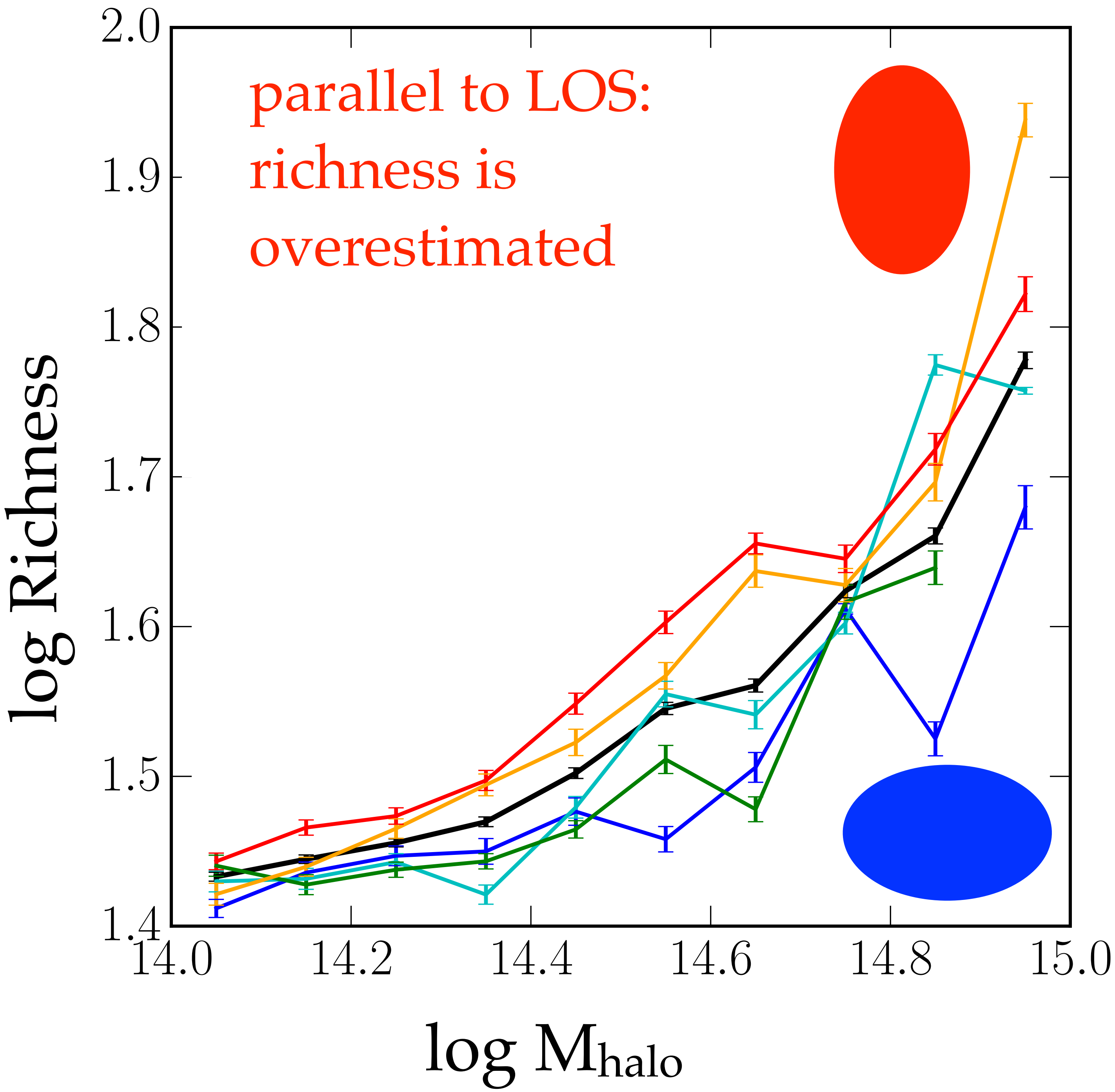
Preliminary

Impact of halo orientation on richness



over-estimated richness

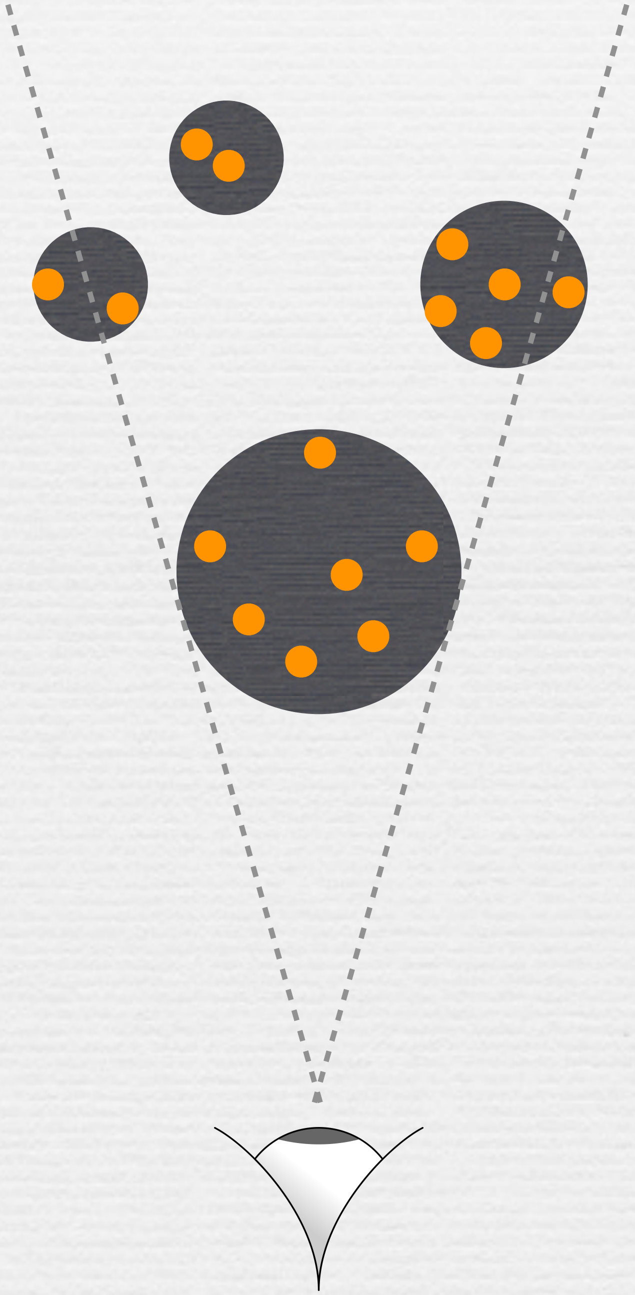
under-estimated richness



Preliminary

Systematic effect 2: Projection Effect

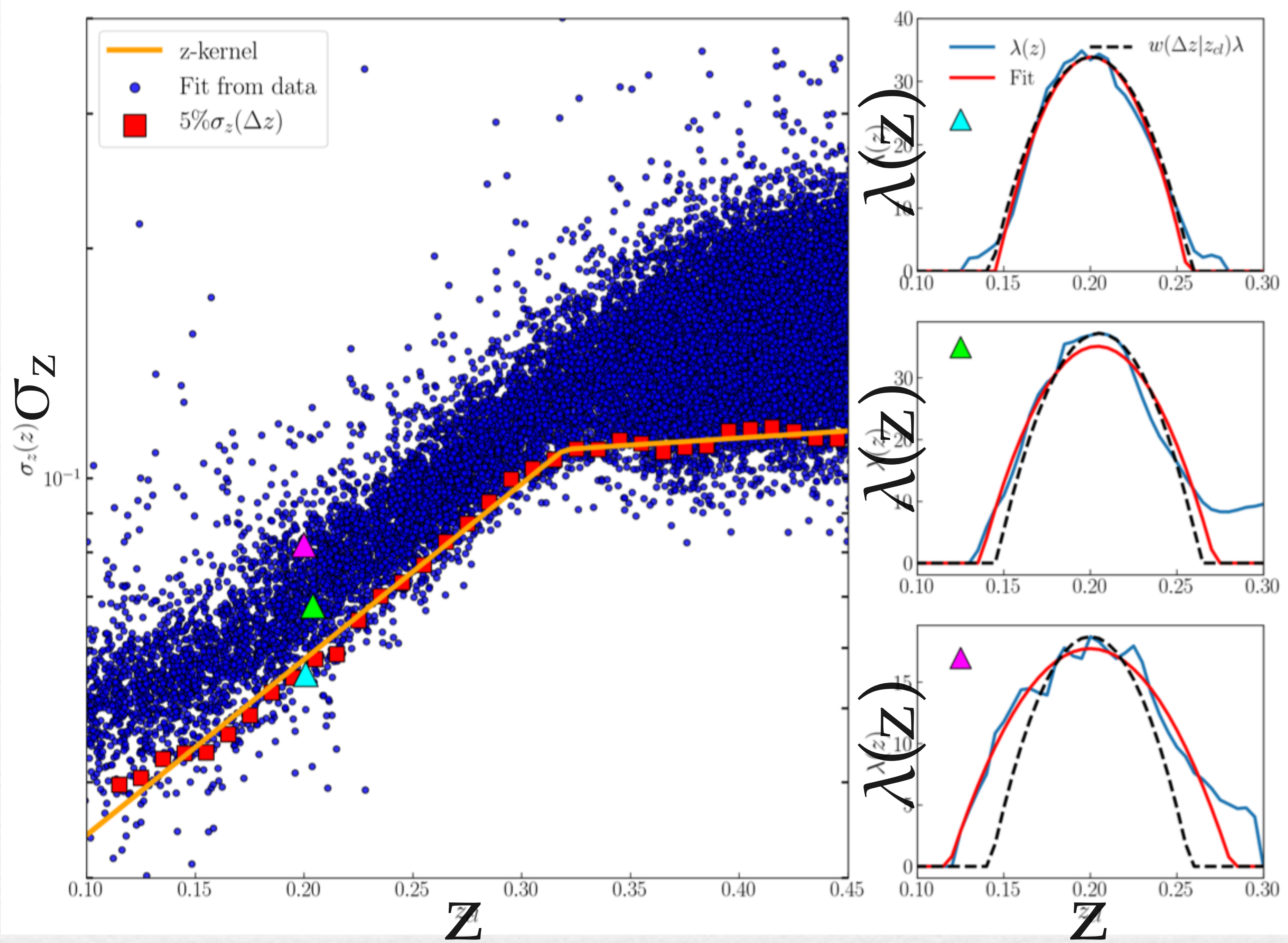
Projection effect changes observed richness



- Projection effect changes richness and adds scatter.
- Mass along the line-of-sight can also increase lensing signal.

Quantifying the projection effect

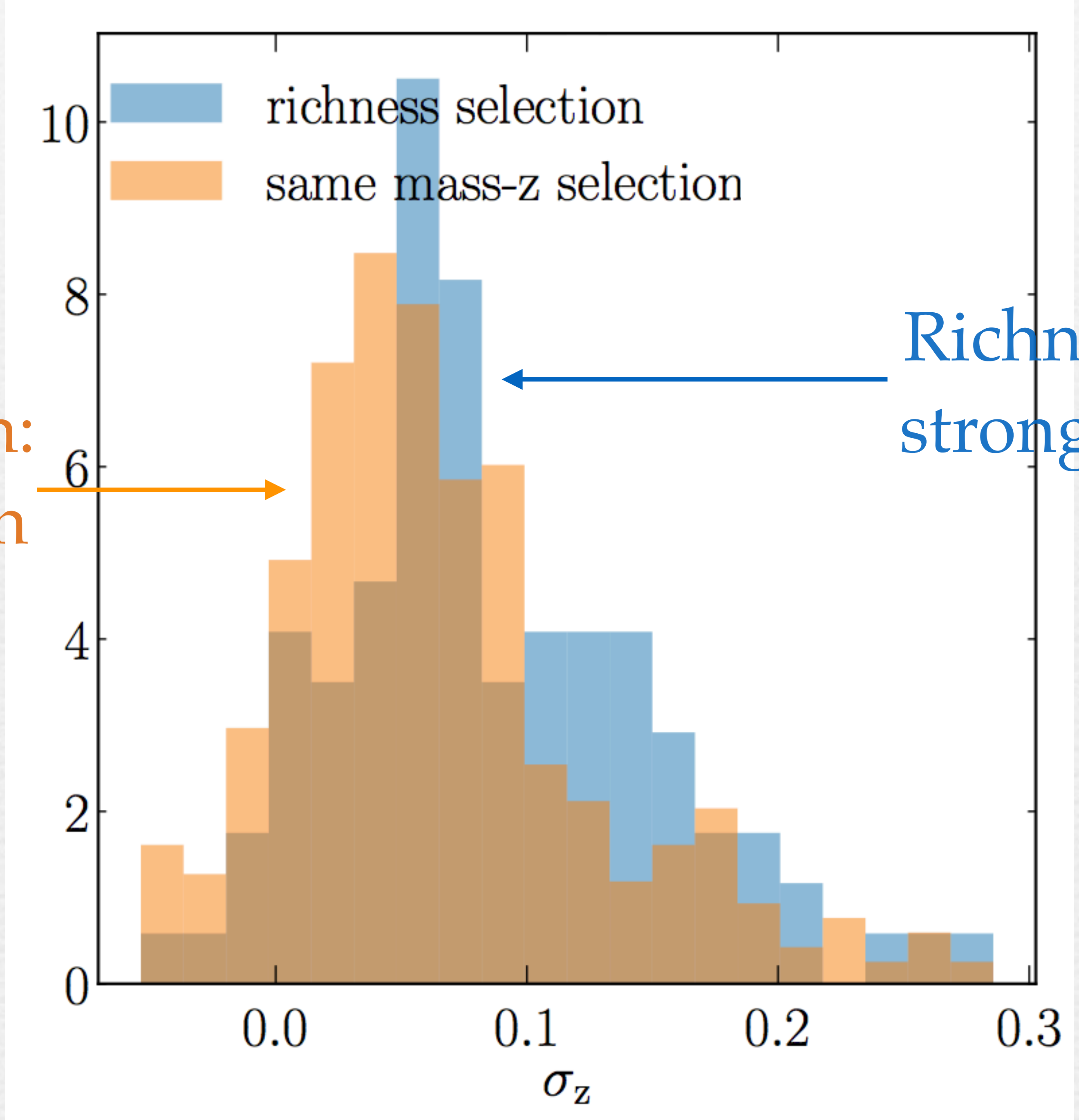
(Costanzi et al. 2019)



- 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



Random selection:
weaker projection

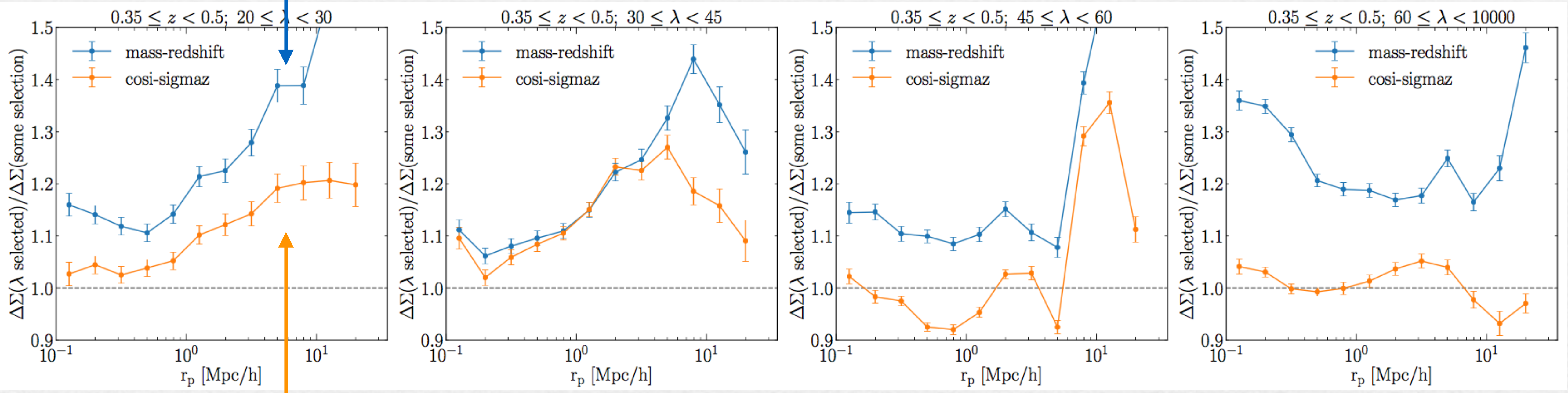
Richness selection:
stronger projection

stronger projection effect →

Preliminary

Orientation & projection can explain part of the lensing biases

matching mass and redshift PDF: signal biased high



higher richness →

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

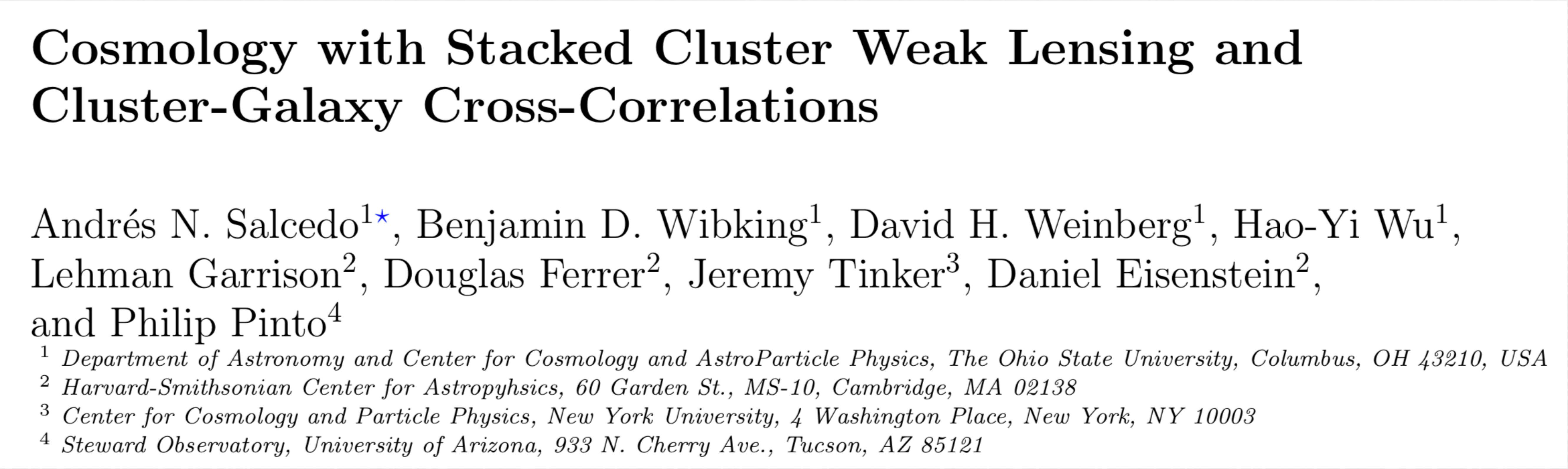
Preliminary

Summary of Part I: Modeling cluster lensing signals

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

Sorry I missed the Journal Club…

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



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

Andrés N. Salcedo[1⋆], Benjamin D. Wibking[1], David H. Weinberg[1], Hao-Yi Wu[1], Lehman Garrison[2], Douglas Ferrer[2], Jeremy Tinker[3], Daniel Eisenstein[2], and Philip Pinto[4]

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[3] *Center for Cosmology and Particle Physics, New York University, 4 Washington Place, New York, NY 10003*
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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

$$w_{p,cg} \propto b_c b_g \sigma_8^2,$$

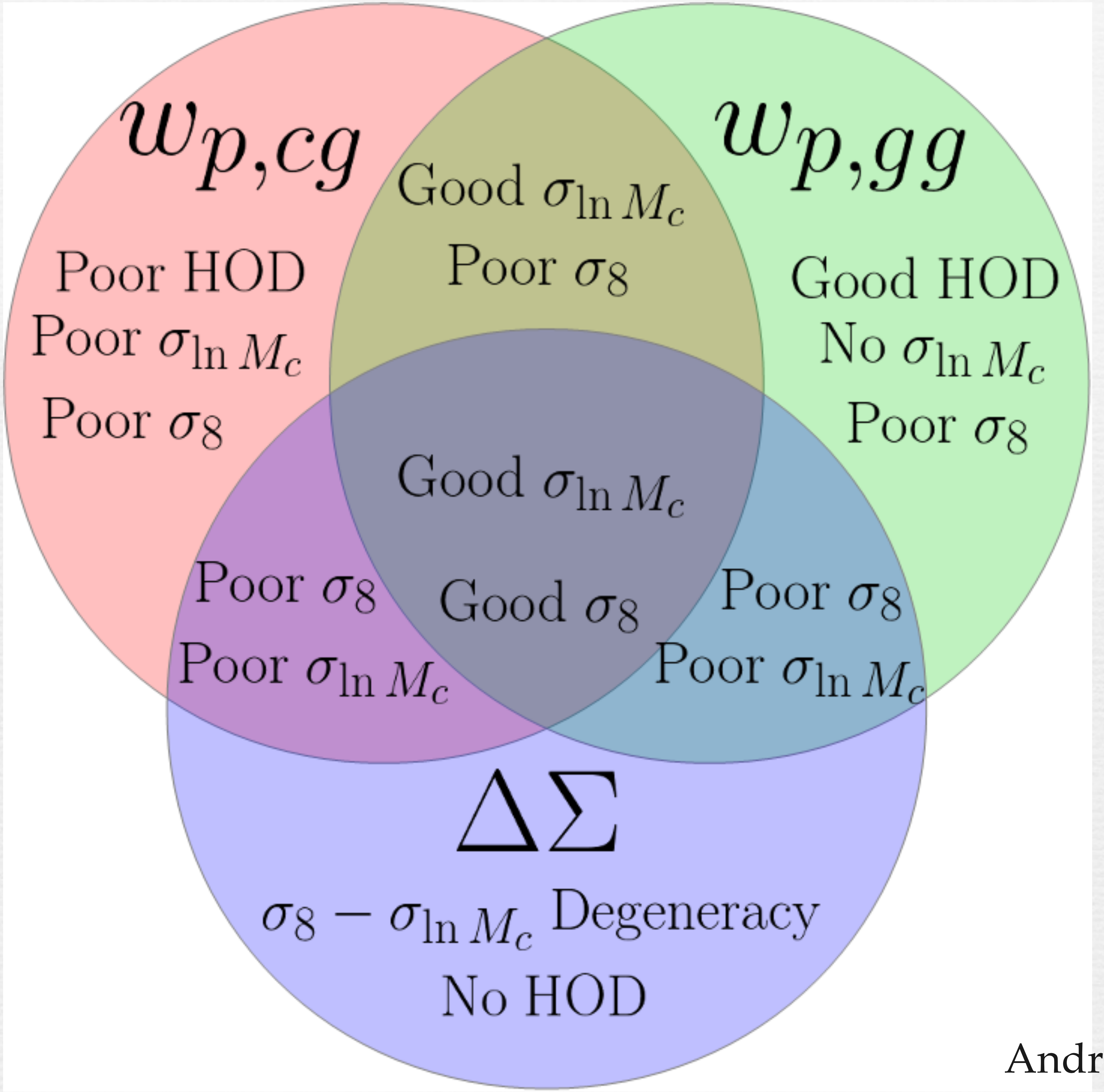
Galaxy auto correlation

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

3 unknowns, 3 observables

Constraining nuisance parameters

Cluster lensing	observable-halo relation
Cluster galaxy cross correlation	both
Galaxy auto correlation	galaxy-halo connection



$w_{p,cg}$

Poor HOD
Poor $\sigma_{\ln M_c}$
Poor σ_8

Good $\sigma_{\ln M_c}$
Poor σ_8

$w_{p,gg}$

Good HOD
No $\sigma_{\ln M_c}$
Poor σ_8

Good $\sigma_{\ln M_c}$
Good σ_8

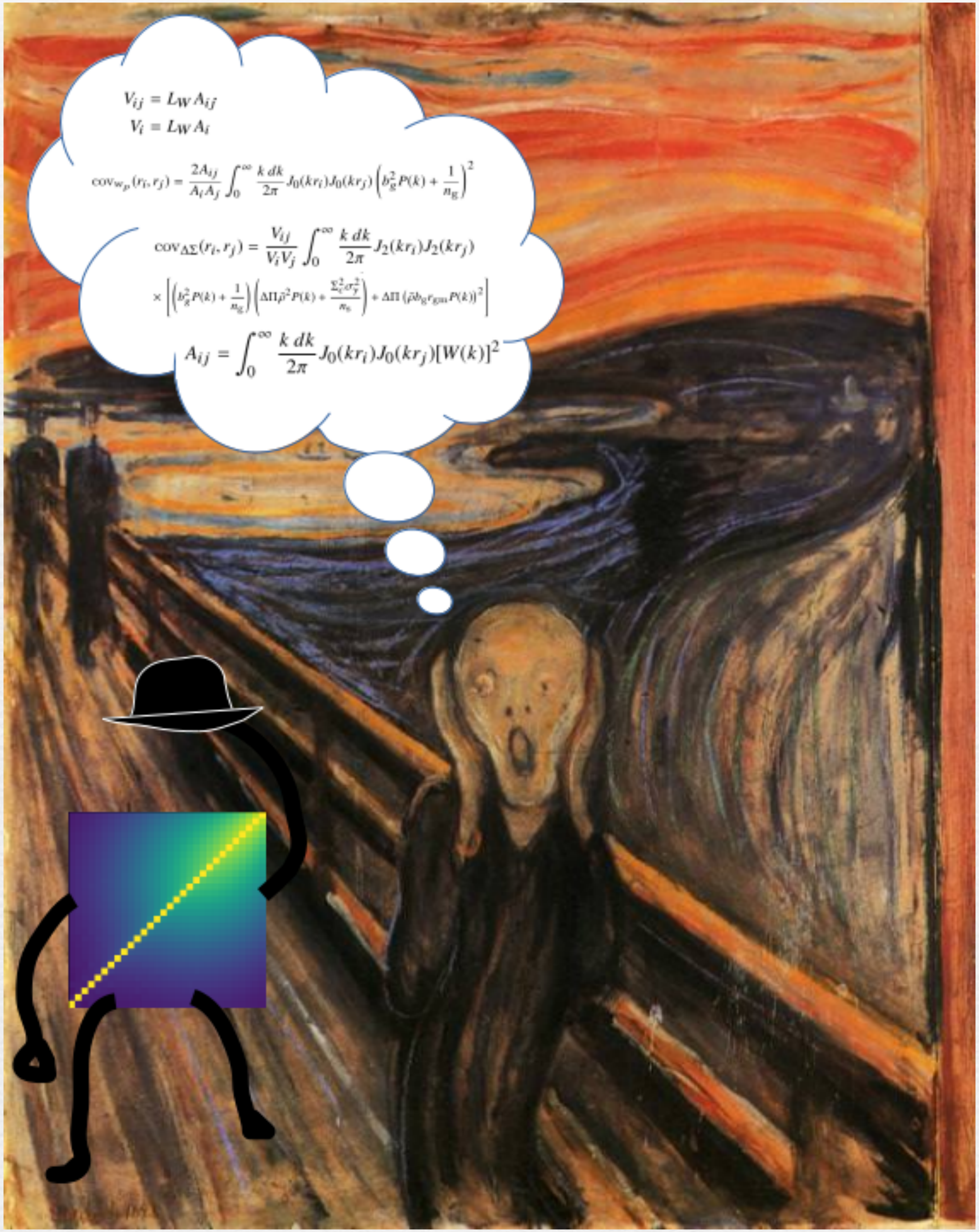
Poor σ_8
Poor $\sigma_{\ln M_c}$

Poor σ_8
Poor $\sigma_{\ln M_c}$

$\Delta\Sigma$

$\sigma_8 - \sigma_{\ln M_c}$ Degeneracy
No HOD

Andres Salcedo



$$V_{ij} = L_W A_{ij}$$

$$V_i = L_W A_i$$

$$\mathrm{cov}_{w_p}(r_i, r_j) = \frac{2A_{ij}}{A_i A_j} \int_0^\infty \frac{k\,dk}{2\pi} J_0(kr_i) J_0(kr_j) \left(b_g^2 P(k) + \frac{1}{n_g} \right)^2$$

$$\mathrm{cov}_{\Delta\Sigma}(r_i, r_j) = \frac{V_{ij}}{V_i V_j} \int_0^\infty \frac{k\,dk}{2\pi} J_2(kr_i) J_2(kr_j) \times \left[\left(b_g^2 P(k) + \frac{1}{n_g} \right) \left(\Delta\Pi \bar{\rho}^2 P(k) + \frac{\Sigma_c^2 \sigma_\gamma^2}{n_s} \right) + \Delta\Pi \left(\bar{\rho} b_g r_{gm} P(k) \right)^2 \right]$$

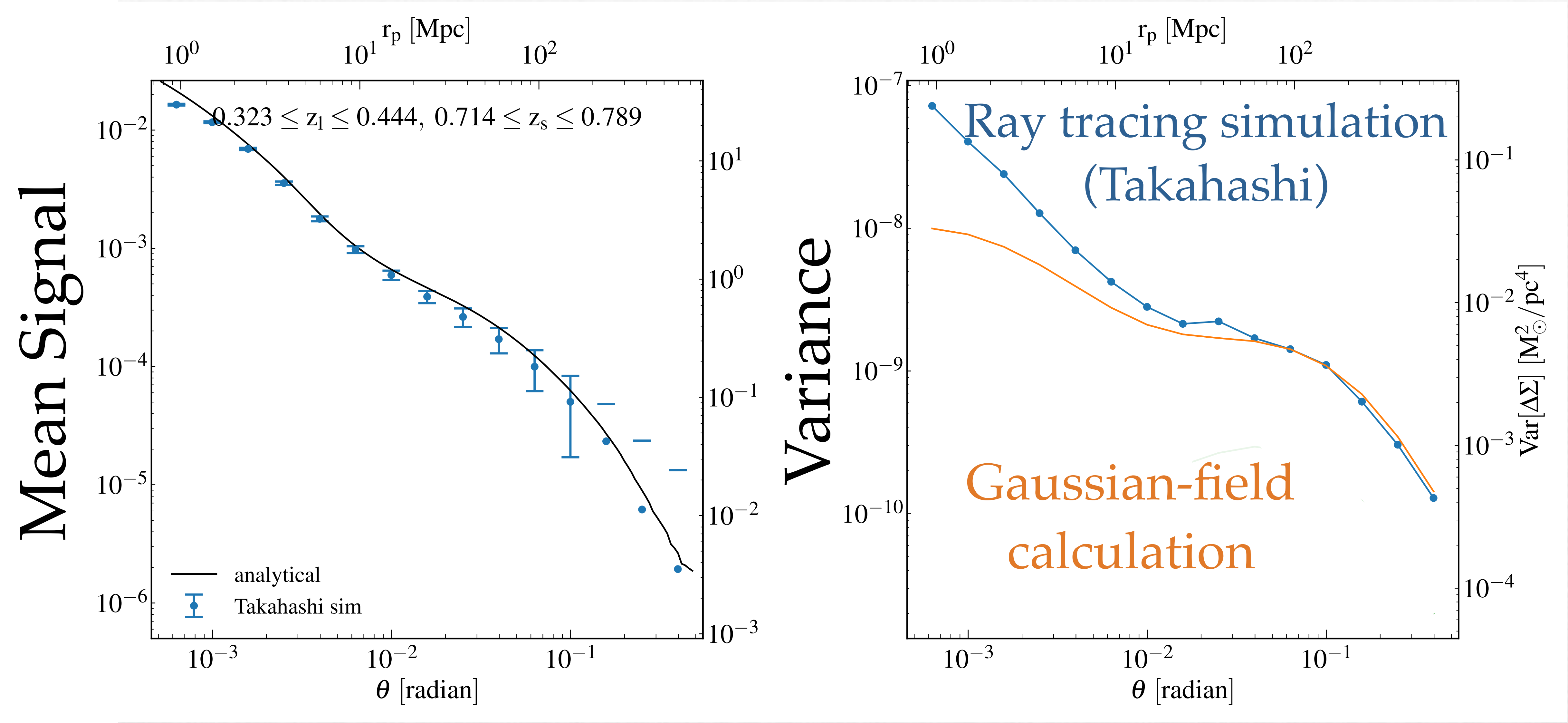
$$A_{ij} = \int_0^\infty \frac{k\,dk}{2\pi} J_0(kr_i) J_0(kr_j) [W(k)]^2$$

Andres Salcedo

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. 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 analytic calculations, validating with ray-tracing sims.

Three major components for cluster lensing covariance matrices

1. Shape noise (~$1/N_{gal}$)
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

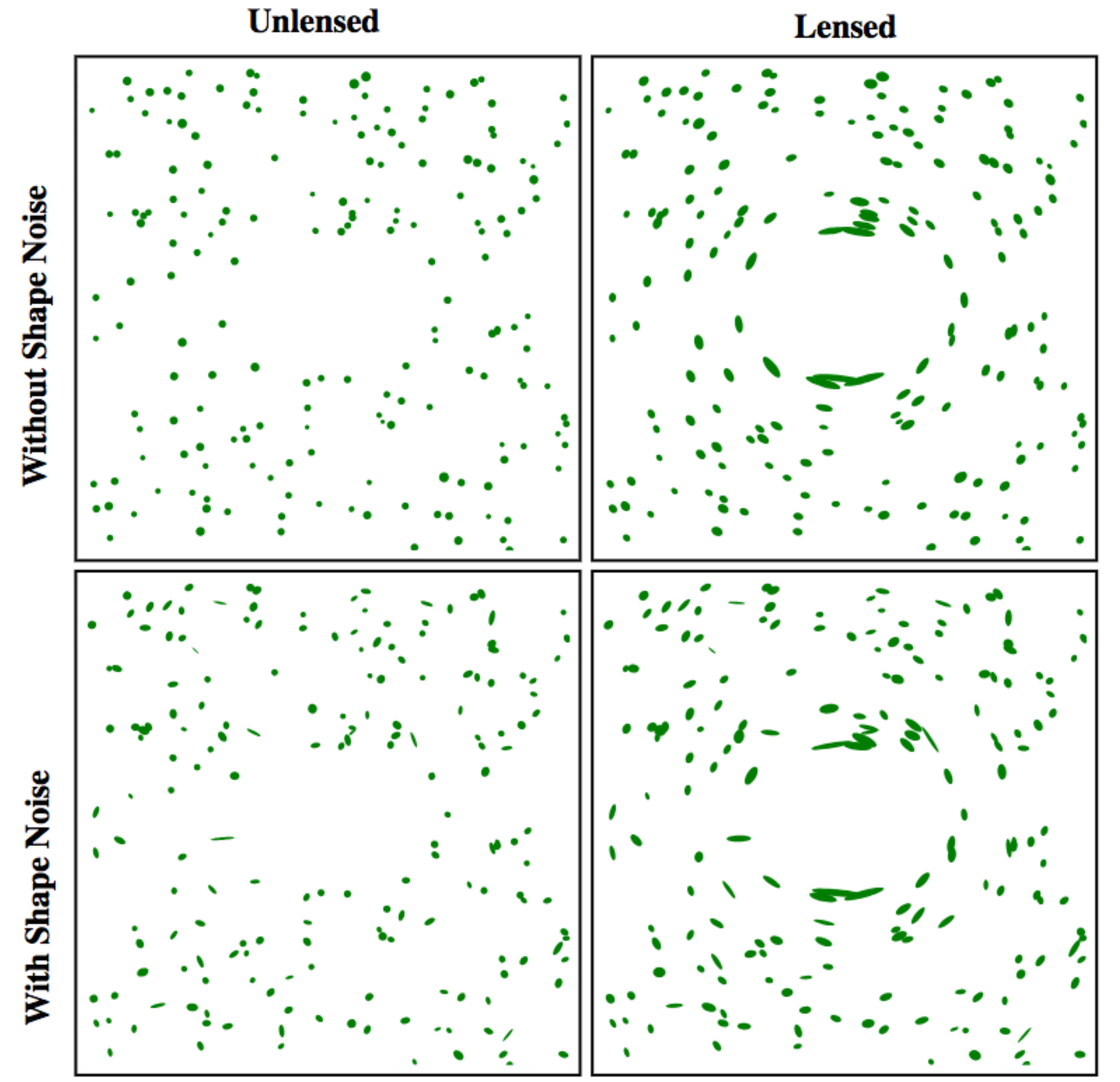
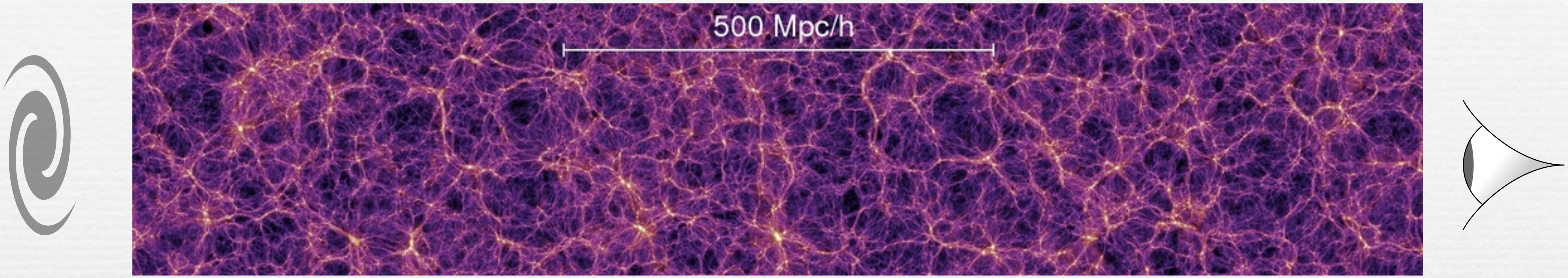


Figure from Wikipedia

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

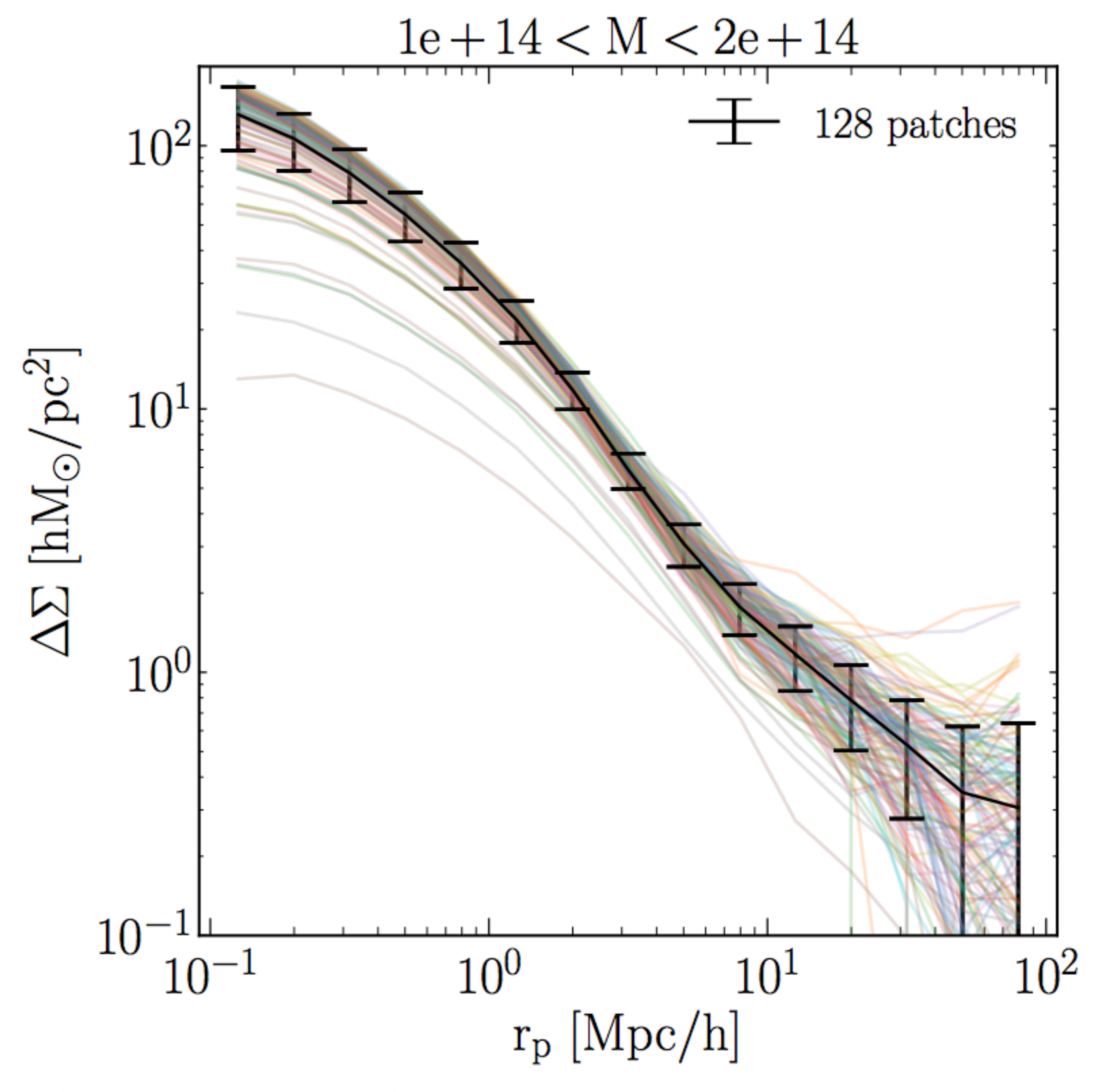
Noise from Large-Scale Structure



- 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

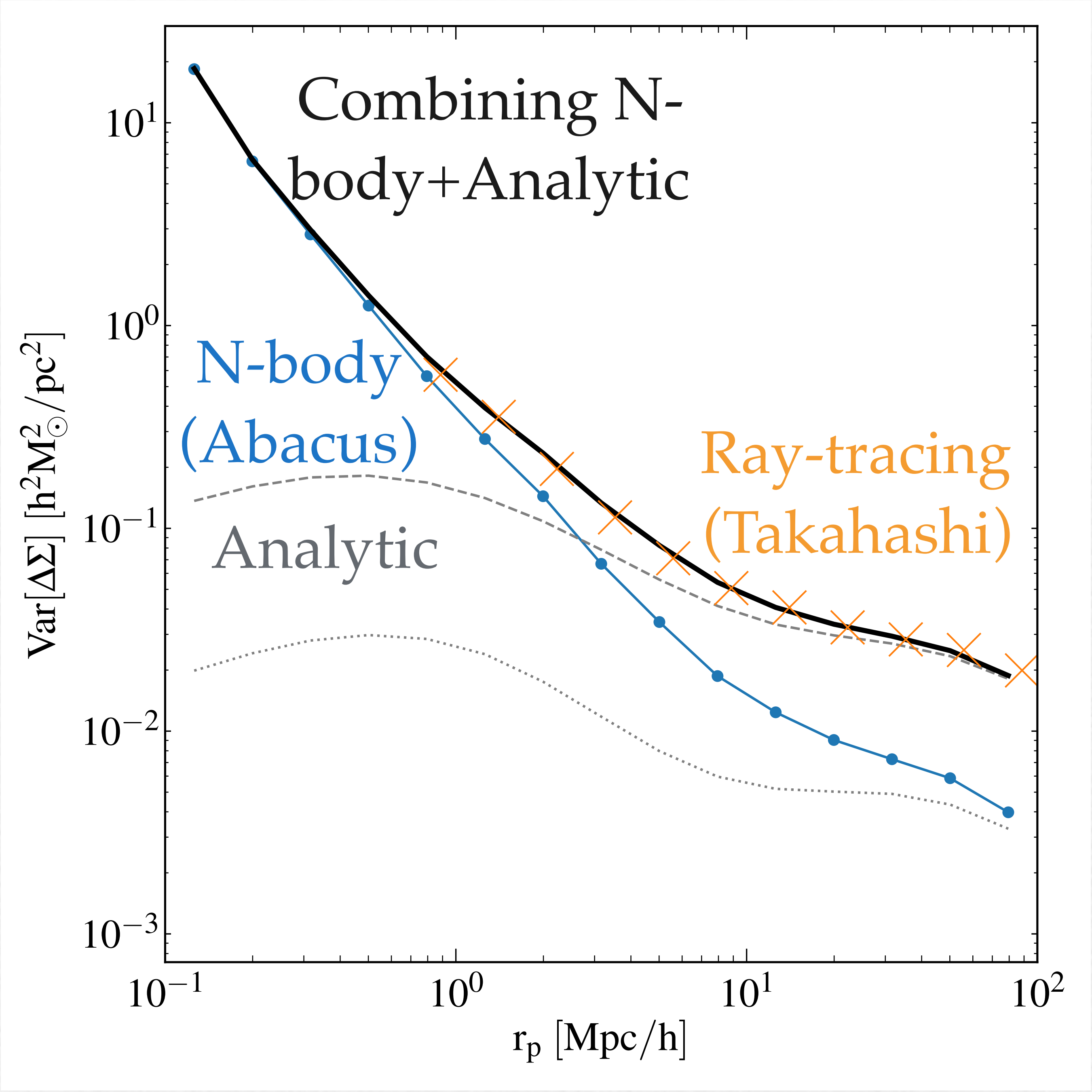
Noise from Intrinsic Variation of Halo Density Profiles



Abacus simulations

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

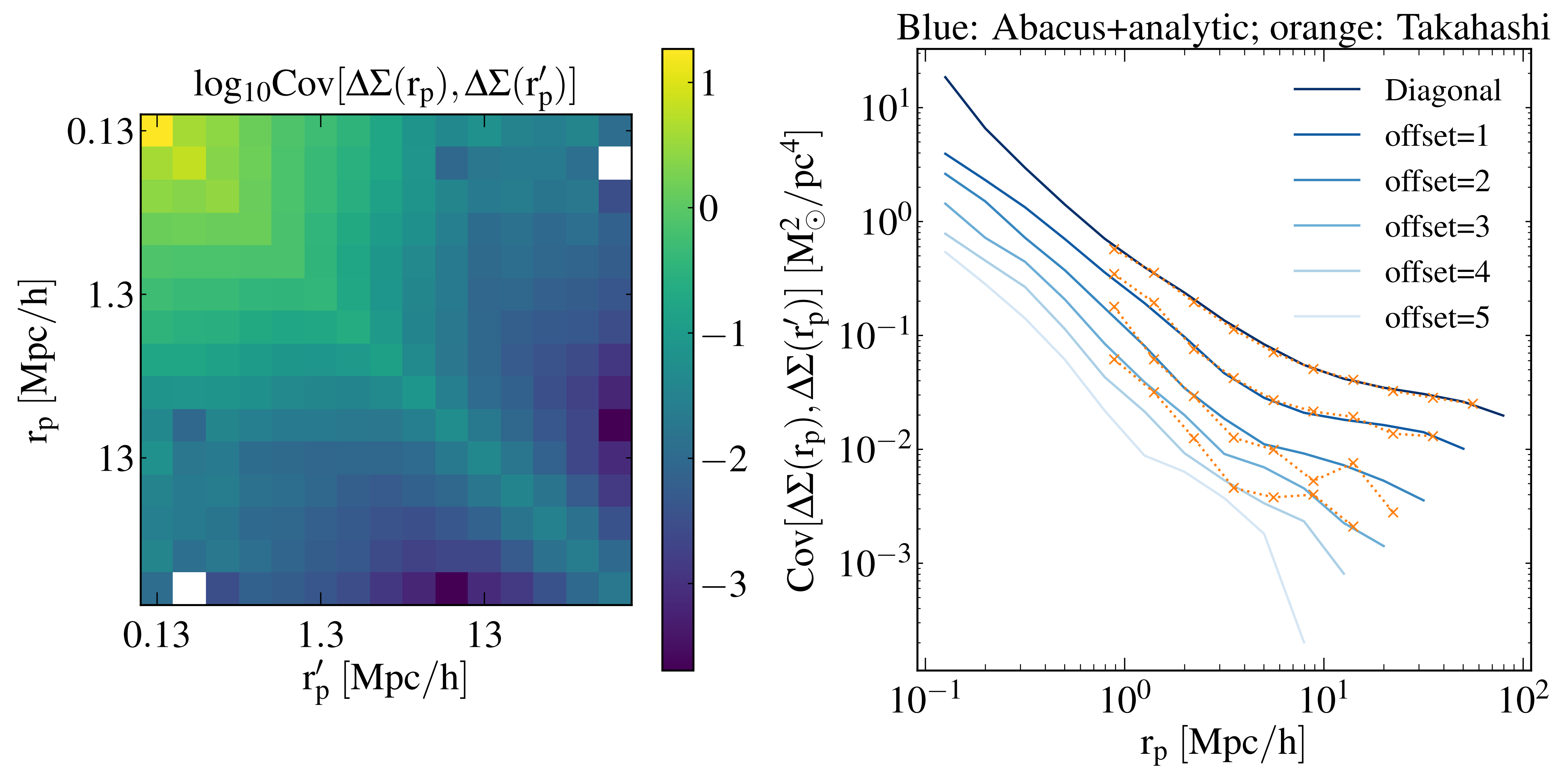
Combining N-body simulations and analytical calculations



- 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

Wu et al. (2019 in prep)

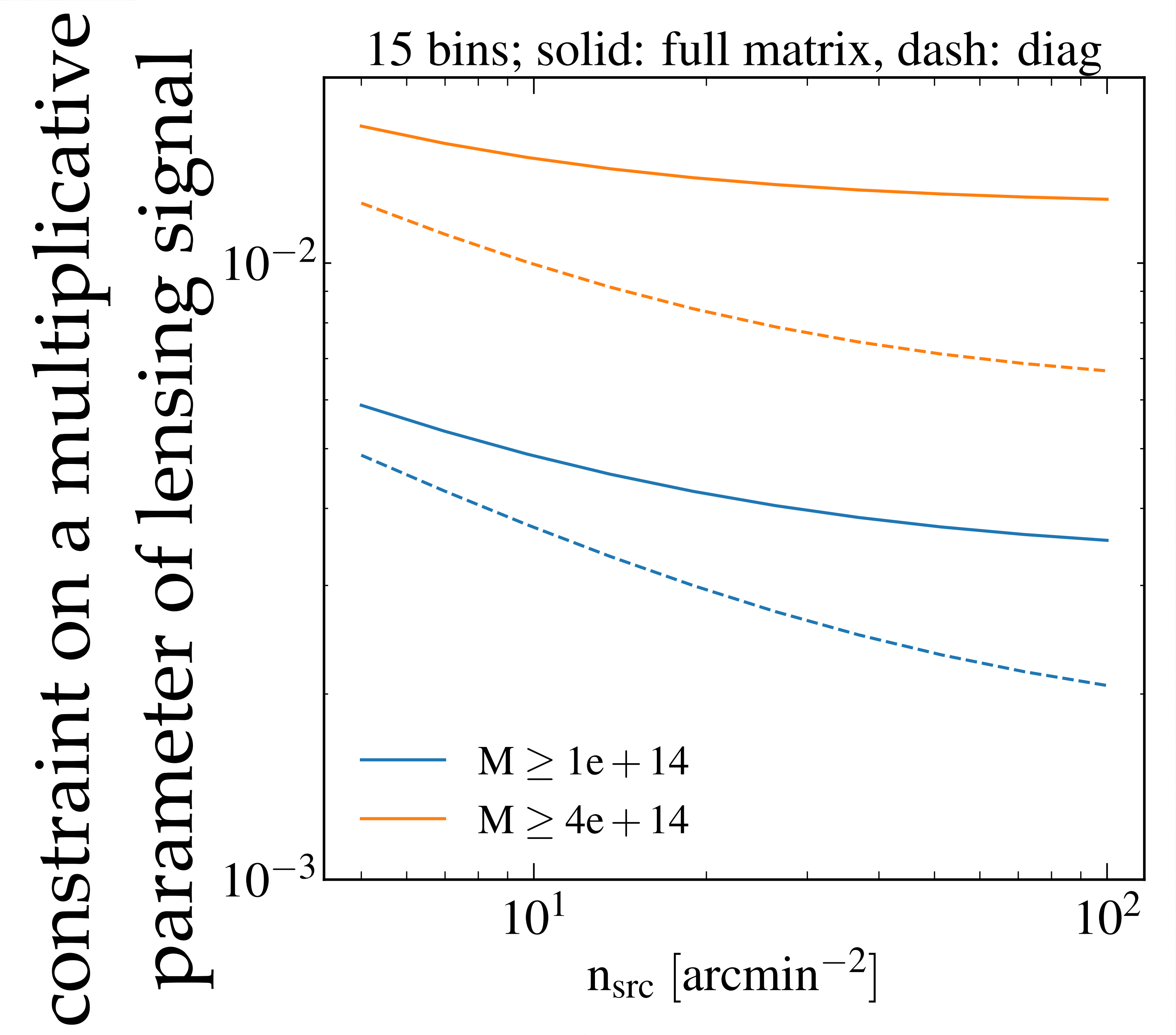
A full cluster lensing covariance matrix



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

Wu et al. (2019 in prep)

Importance of off-diagonal elements

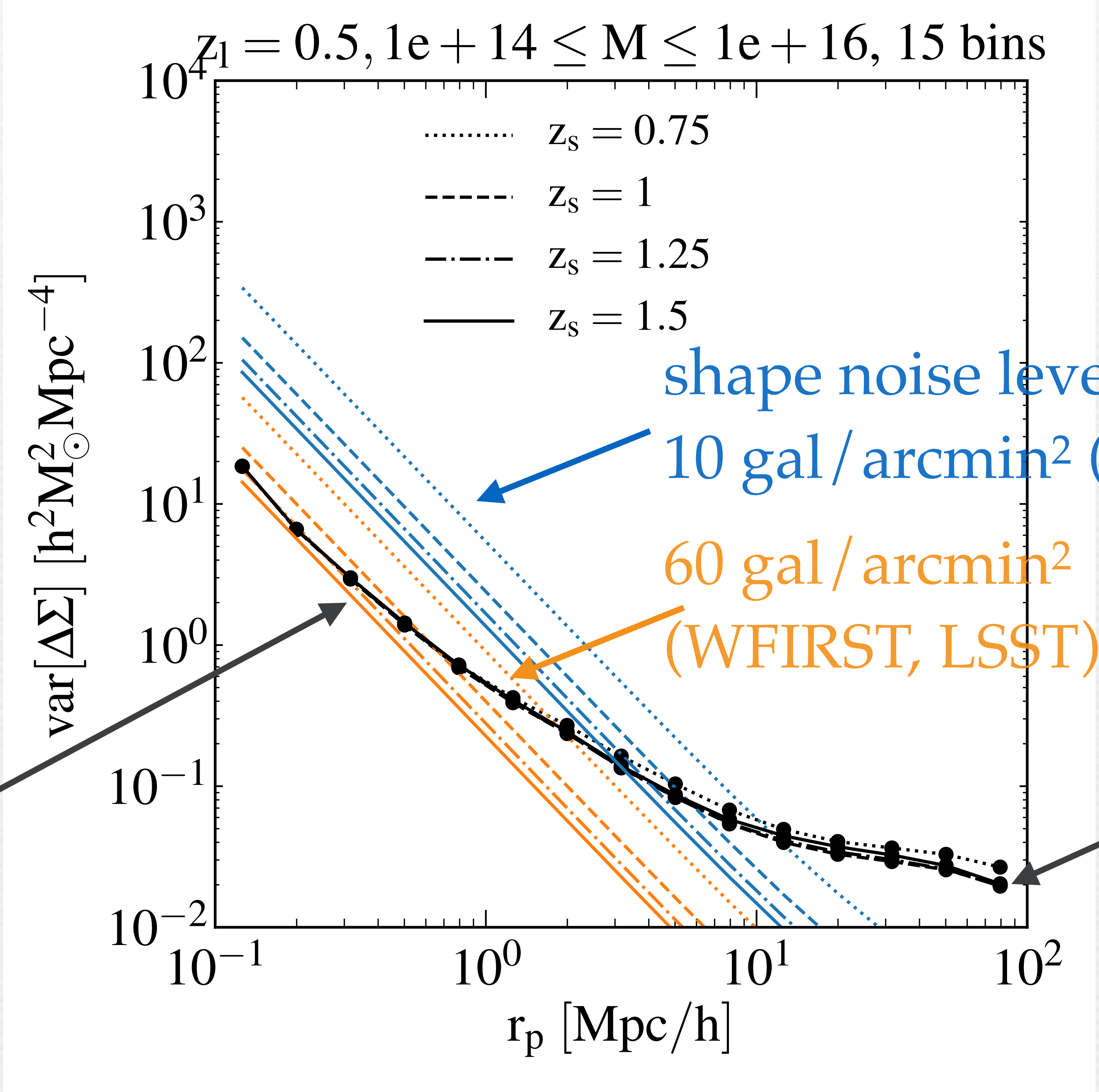


lower shape noise →

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

Wu et al. (2019 in prep)

Importance of shape noise vs. density fluctuations



shape noise level for
10 gal/arcmin² (DES)

60 gal/arcmin²
(WFIRST, LSST)

from halo

from LSS
(depends on
source redshift)

Wu et al. (2019 in prep)

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 analytical calculations and high-resolution N-body simulations to calculate the covariance matrix accurately.

Summary

- The abundance of galaxy clusters is a sensitive probe of growth of structure and cosmic acceleration.
- Calibrating the mass-observable relation is the key for using cluster to constrain cosmic acceleration.
- Optical surveys use stacked gravitational lensing to calibrate cluster mass. Simulations help us calibrate the lensing systematic biases.
- Upcoming optical surveys like LSST, WFIRST will achieve unprecedented precision for gravitational lensing and push our horizons further.