Today's Challenges in Cluster Cosmology

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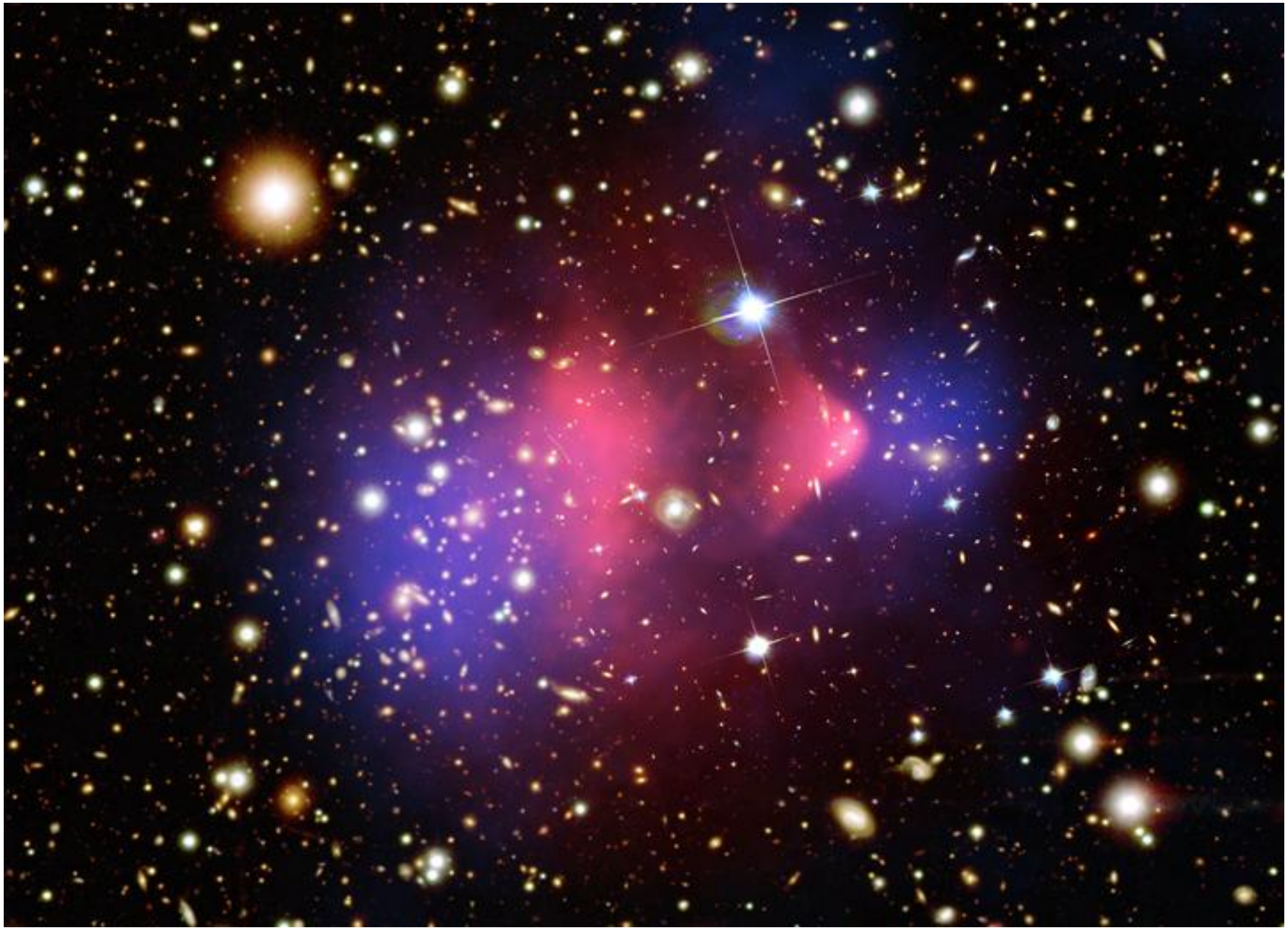
Galaxy Clusters as Cosmological Probes



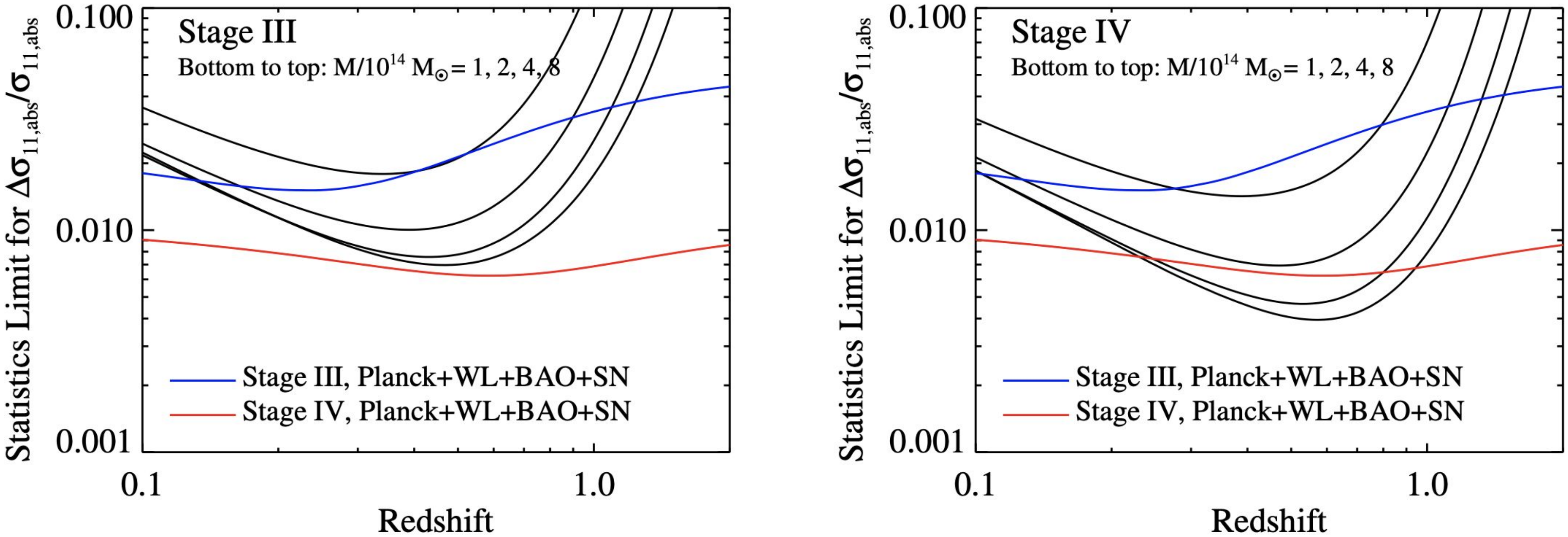
X-ray: NASA/CXC/CfA/ M. Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

Long history of helping us prove important things...

Galaxy Clusters as Cosmological Probes

- **Clusters make great cosmological probes!**
- **Sensitive to background cosmology**
  - Background evolution controls the evolution of the volume element
  - Impacts both the current number density as well as the relative evolution of number density over cosmic history
- **Sensitive to perturbations**
  - σ_8: variance ("clumpiness") of density perturbations
  - Clusters form from the highest density peaks in the initial density field
  - Higher $\sigma_8 \rightarrow$ more high-density peaks $\rightarrow$ more clusters

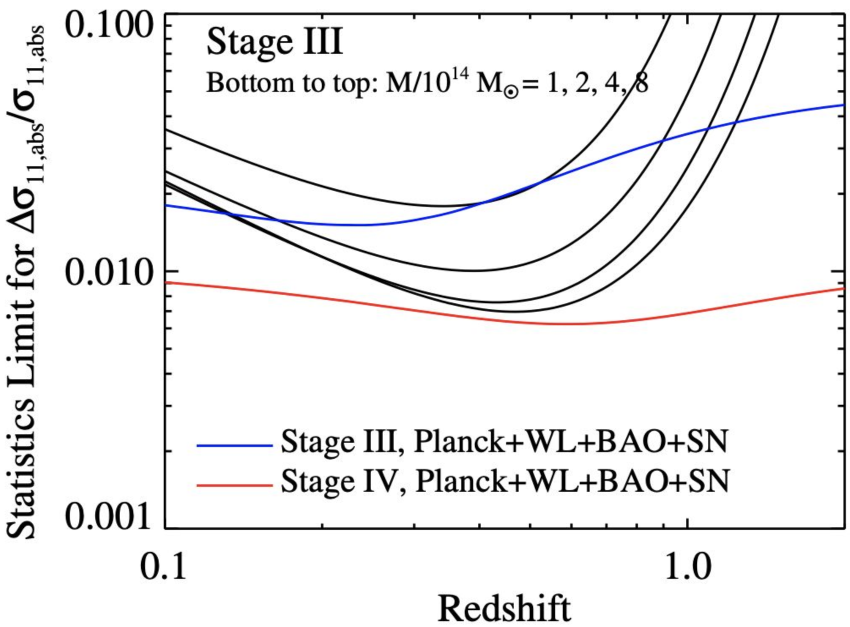
The "Promise"

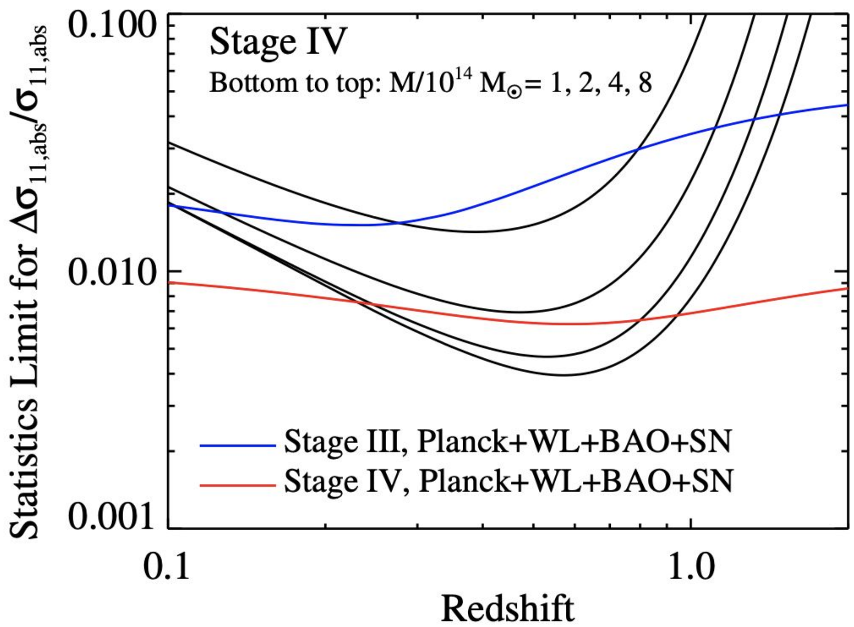


Snowmass '13, Huterer et al.

" We see that galaxy clusters are statistically competitive with and often better than probes

The "Promise"





Snowmass '13, Huterer et al.

" We see that galaxy clusters are statistically competitive with and often better than probes

[...] the cosmological utility of cluster samples is always limited by our ability to estimate the corresponding cluster masses."

Mass Calibration and Proxies

- **Cluster masses are indirectly determined through proxies**
- **Clusters are truly “multi-messenger” objects**
  - X-ray brightness (L_x)
  - SZ effect signal (Y_{SZ})
  - Optical richness (λ)
- **Proxy ↔ Survey type**
- **Optical richness?**
  - Roughly, the “number of galaxies virially bound within the cluster”
  - More technically, the sum of membership probabilities (pmem) of galaxies associated with a given cluster center

Optical Clusters

- **Operates based on photometric galaxy surveys**
- **Upsides**
  - Relatively easy to identify uniformly and completely
  - Relatively easy to obtain large sample sizes
  - Self-consistent mass calibration becomes possible via lensing masses
- **Downsides**
  - Photometry (and photometric redshifts) is inherently noisy;
    much of the line-of-sight information is lost
  - Results are highly dependent on the cluster finder algorithm

Cosmology with Optical Clusters

1. **Observe galaxies**

2. **Find clusters**
   a. Identify overdensities of red galaxies (good tracers of halos)
   b. Iteratively determine clusters and members, respectively defined by the cluster centers and the membership probabilities
   c. Obtain a sample of clusters with assigned richnesses

3. **Combine cluster observables in (λ, z) bins**
   a. Abundance: literally the number count of clusters in bin
   b. Lensing: the stacked lensing signal centering around clusters
   c. Clustering: can be both cluster auto and cluster-galaxy cross

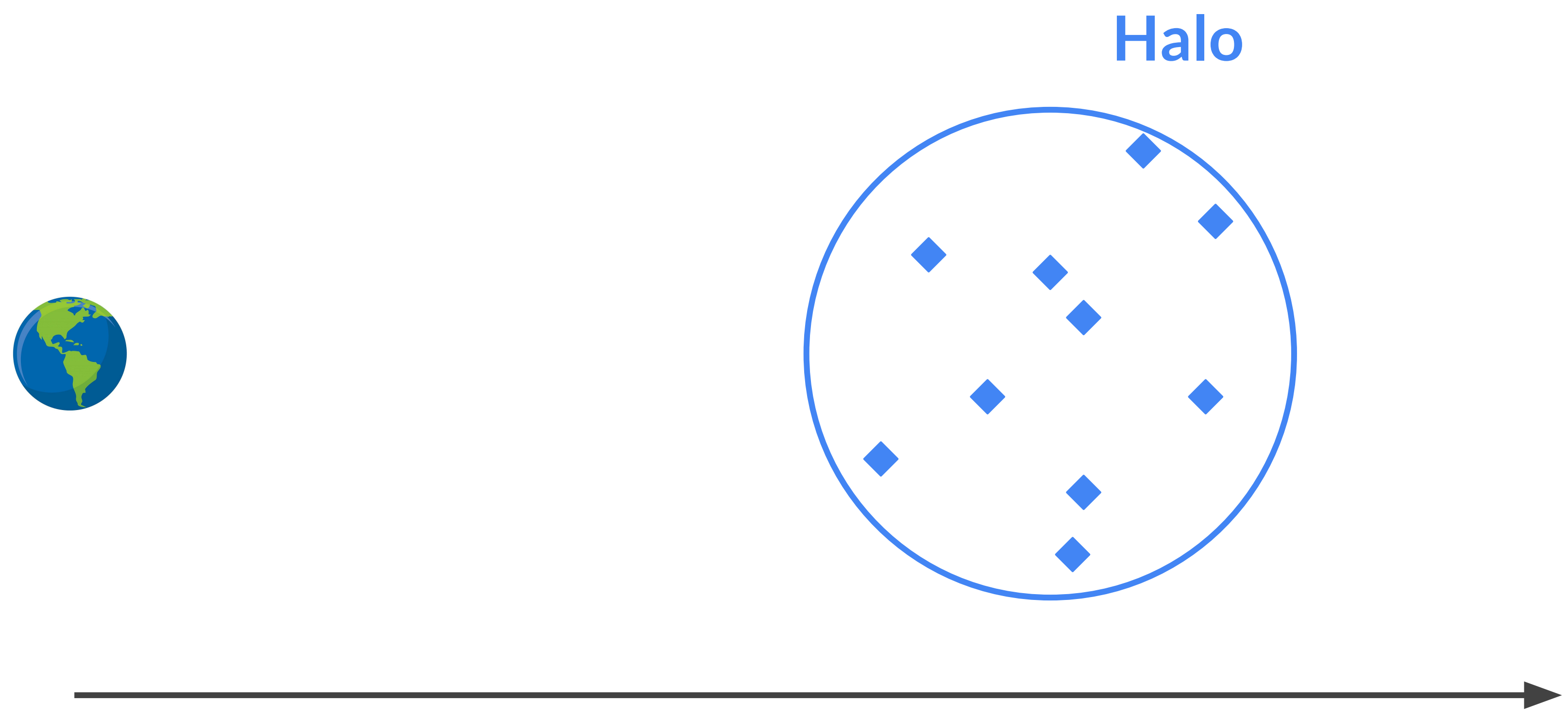
4. **Get cosmology!**

Common-Wisdom Systematics

- **Member dilution**
  - Cluster members can be misidentified as background (source) galaxies; dilutes the lensing signal around clusters
  - Solved via “boost factors”
- **Off-centering**
  - The assigned center of a cluster, by definition a galaxy, can be offset from the true center of the cluster halo
  - Also dilutes the lensing signal; subdominant and solved via modeling
- **Halo Triaxiality**
  - Dark matter halos are actually triaxial rather than spherical; theoretical systematics can arise if spherical models are used
  - Proved from simulations to be subdominant

Projection Effects

- **The line-of-sight issue**



Projection Effects

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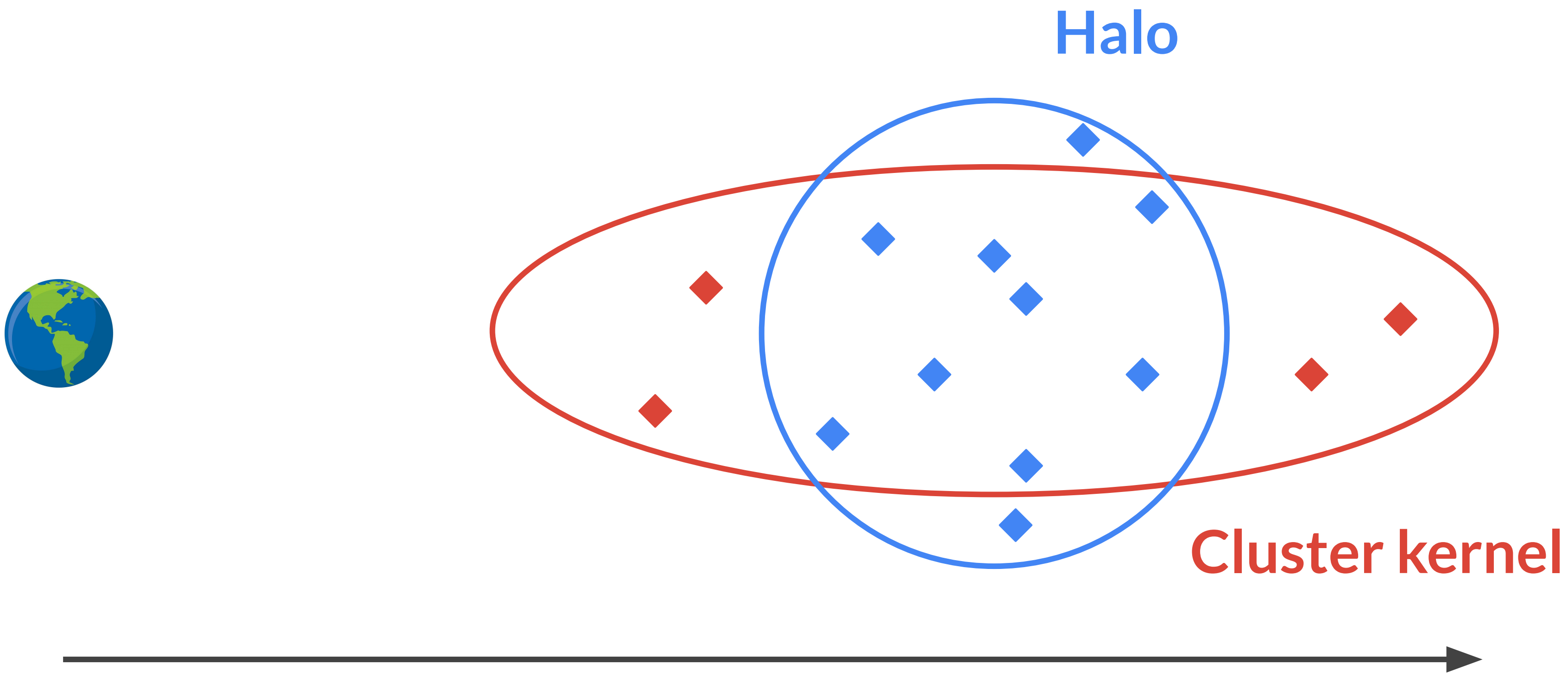

Projection Effects

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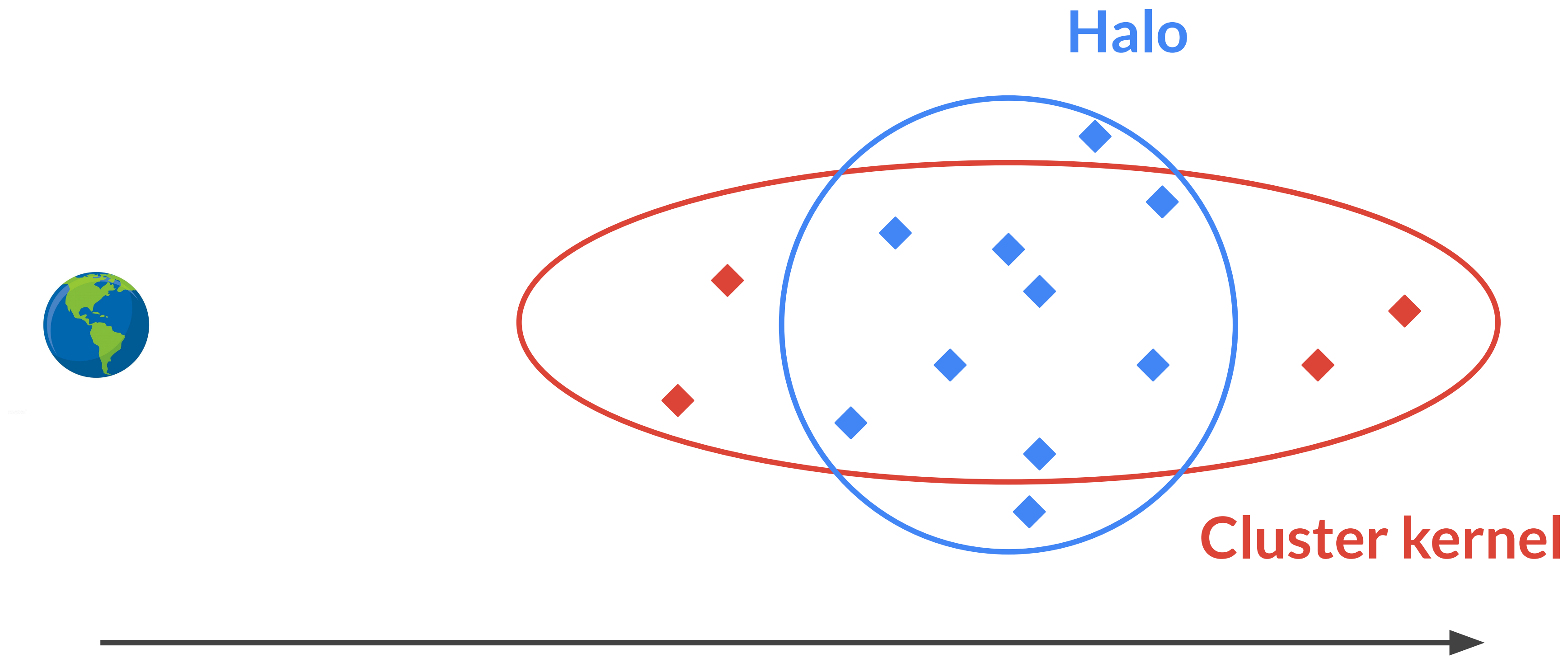
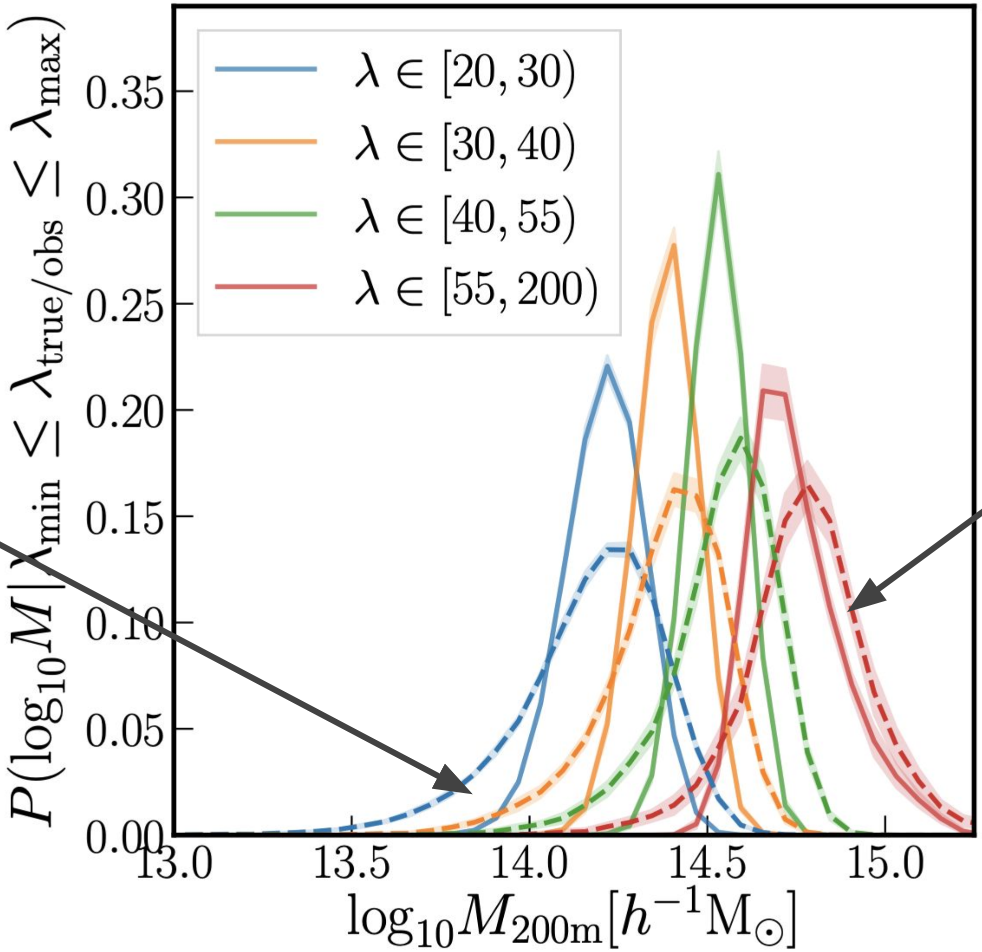


Interlopers contaminate the true richness

Projection Effects: Impact on Richnesses



Projection tail

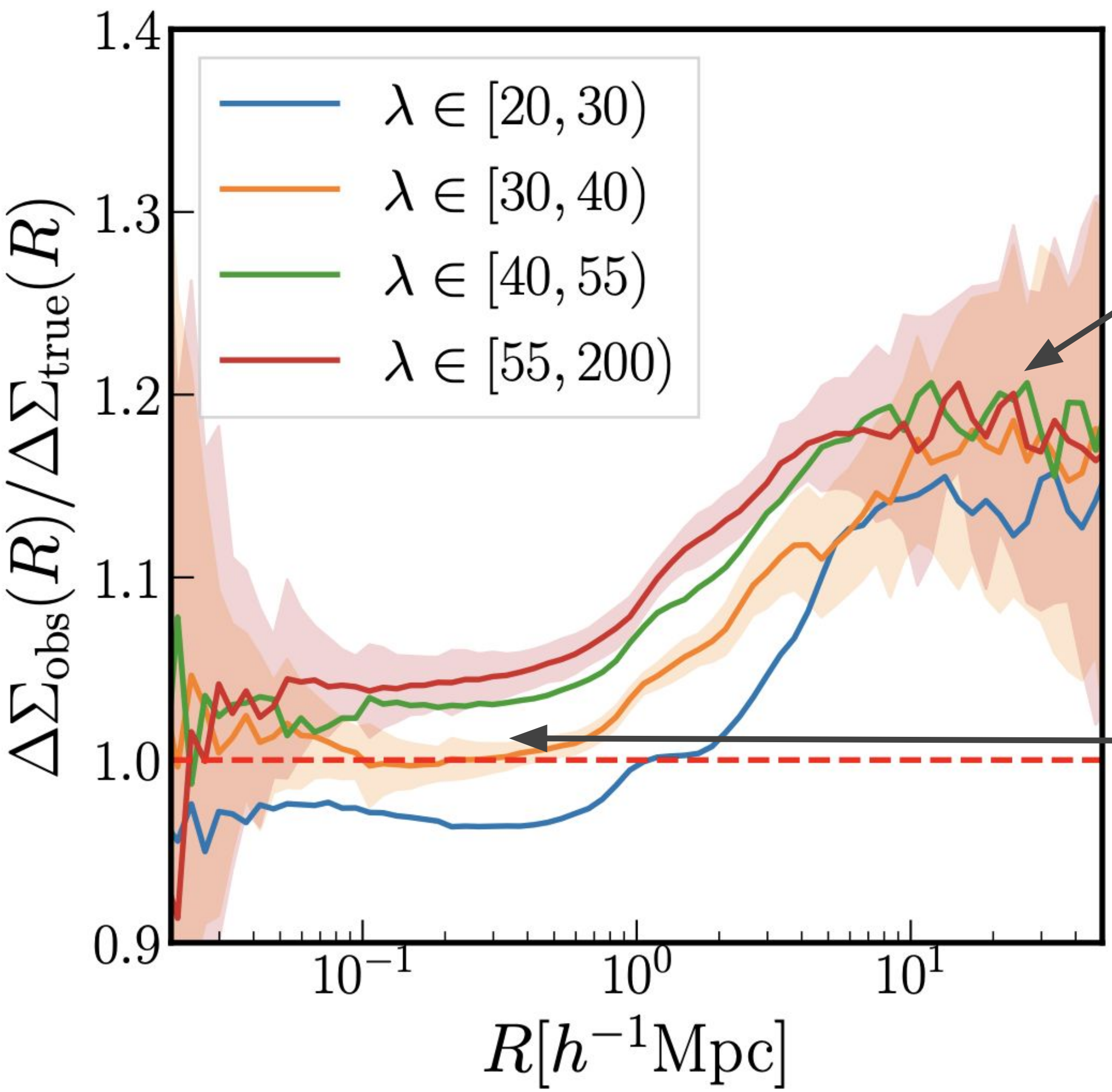
Radial filter tail

Sunayama, YP, Takada et al. (2020)

Projection Effects: Impact beyond Richnesses

- **Is richness mis-estimation the end of the story?**
  - If so can be solved via a more flexible richness-mass relation
- **How can we find out?**
  - Create a mock cluster catalog by running a mock cluster finder algorithm on N-body simulations
  - Compare the "observed" signals against emulator predictions, *assuming the true underlying cluster mass information*
- **Side note: emulators give you a happy life**
  - Fully nonlinear yet isotropic predictions for various halo statistics
  - Significantly reduces theoretical systematics

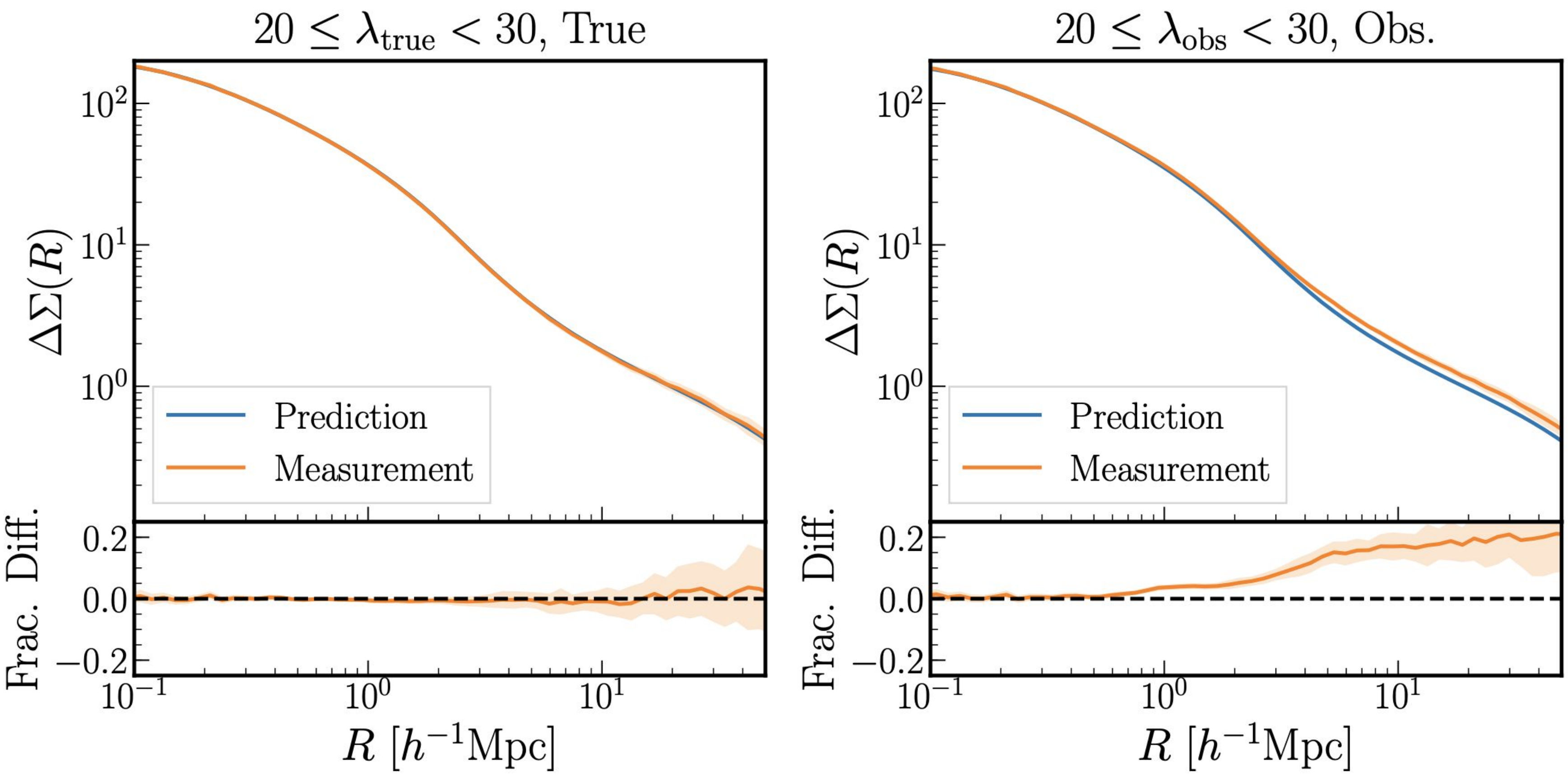
A Disconnect in the Halo Model



Large-scale signal (2-halo regime) is consistently boosted

Small-scale signal (1-halo regime) follows the underlying mass distribution

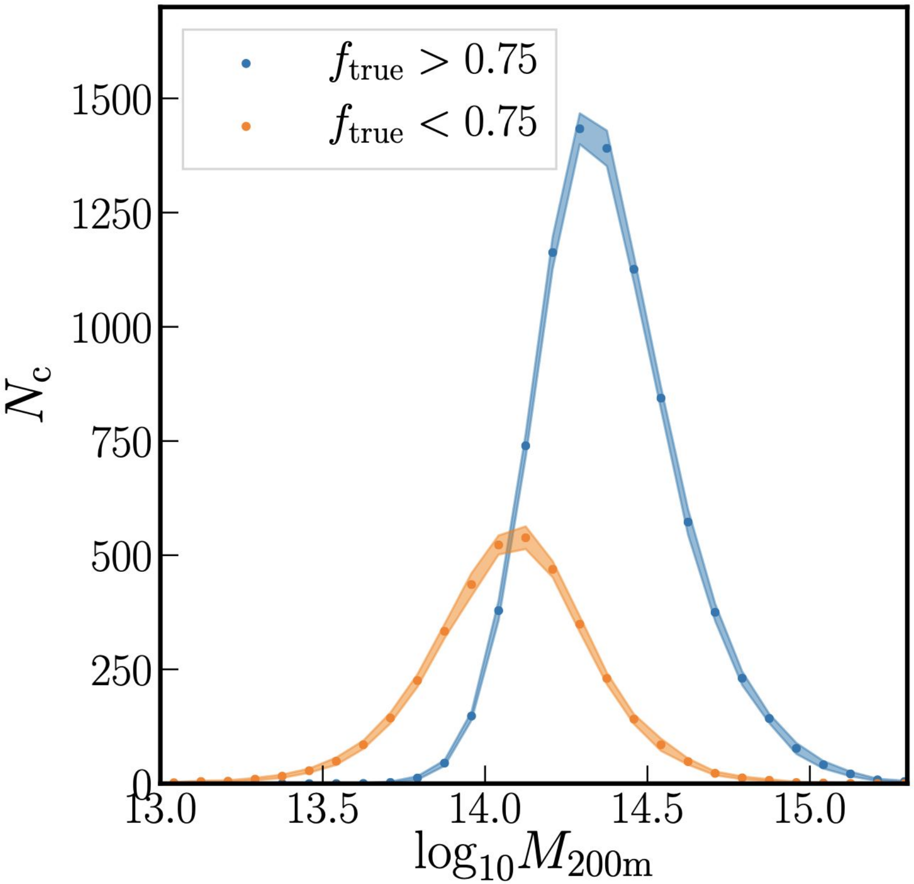
Unexpected Large-Scale Boosts



Observed clusters show a clear large-scale boost in lensing!

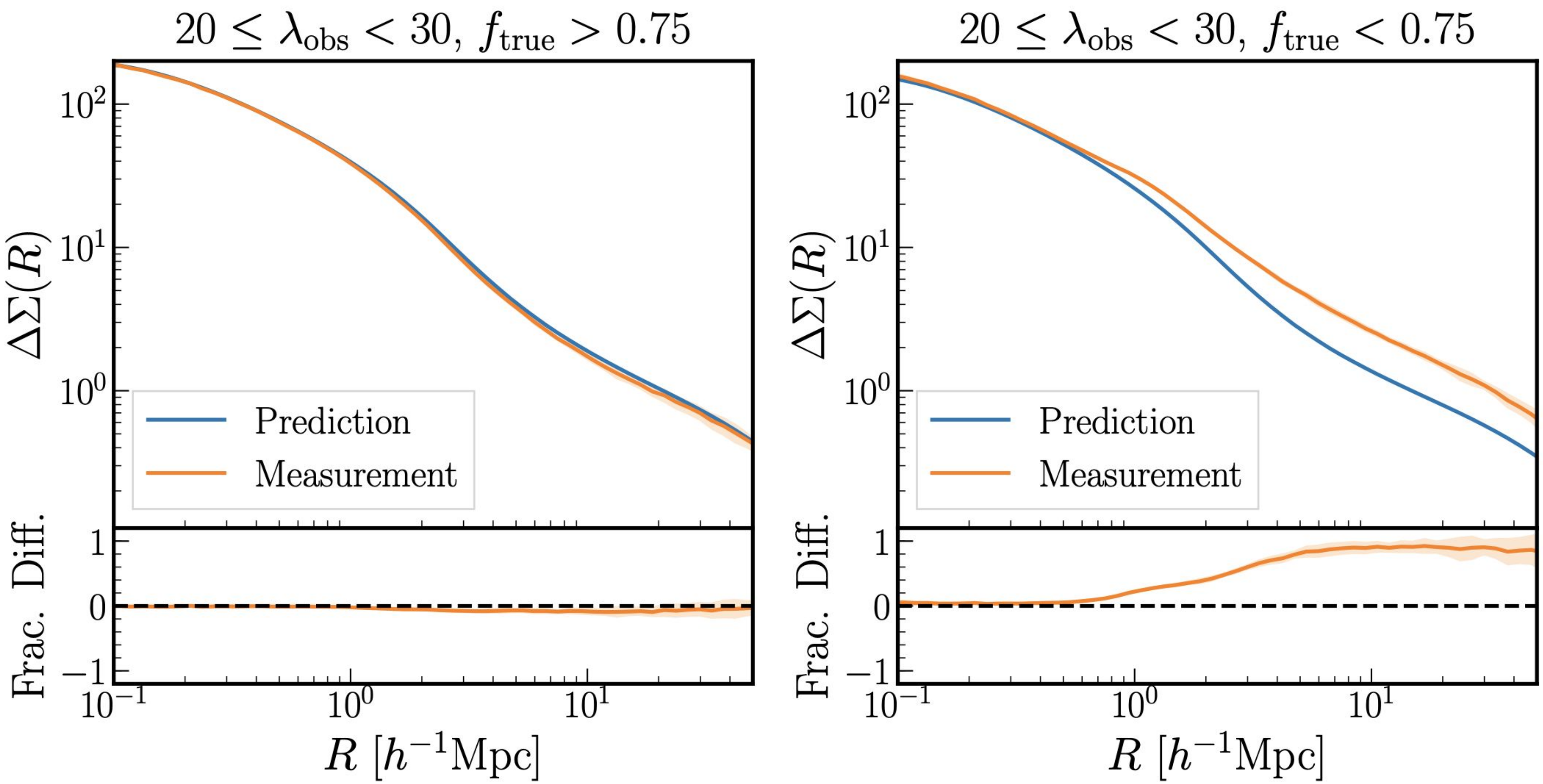
Culprits

$$f_{\text{true}} = \frac{\lambda_{\text{primary}}}{\lambda_{\text{obs}}}$$



Split into subsamples based on a proxy, f_{true}

Unexpected Large-Scale Boosts Explained

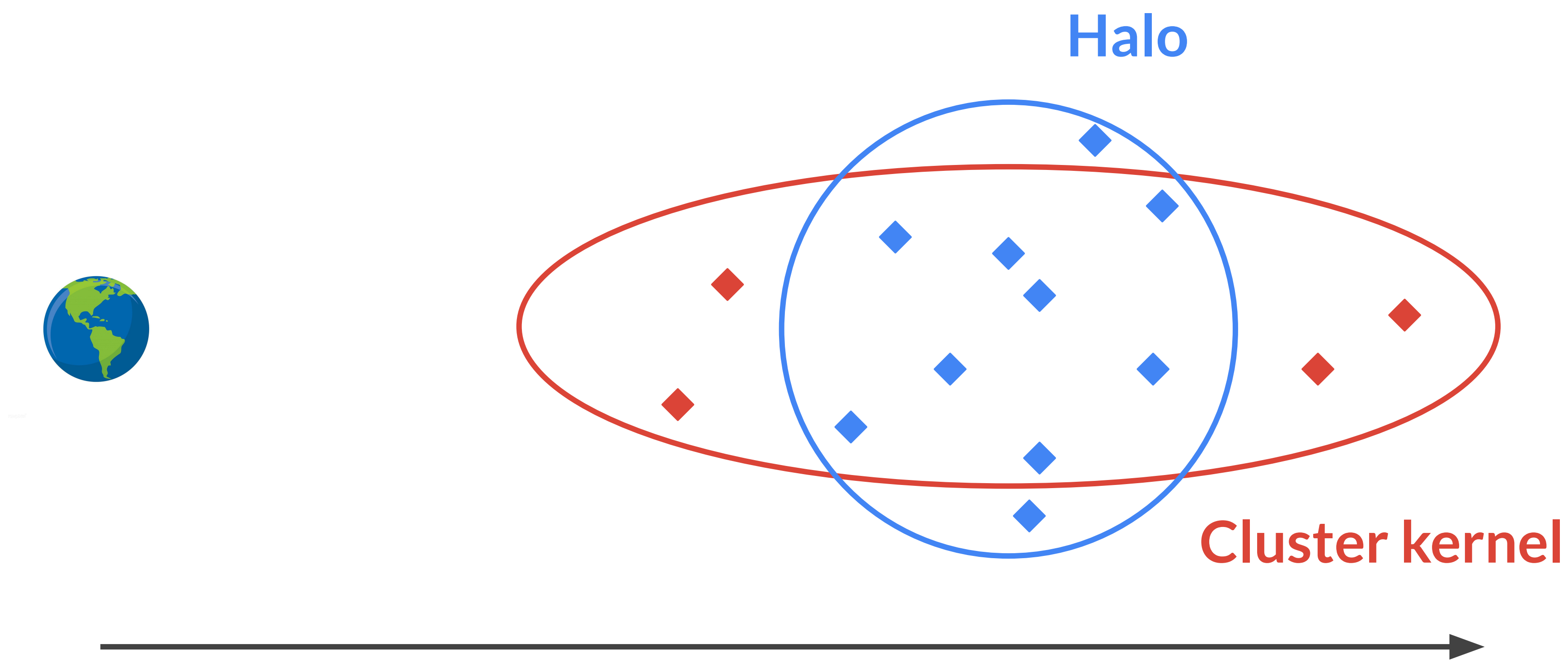


The boost originates from "contaminated" clusters!

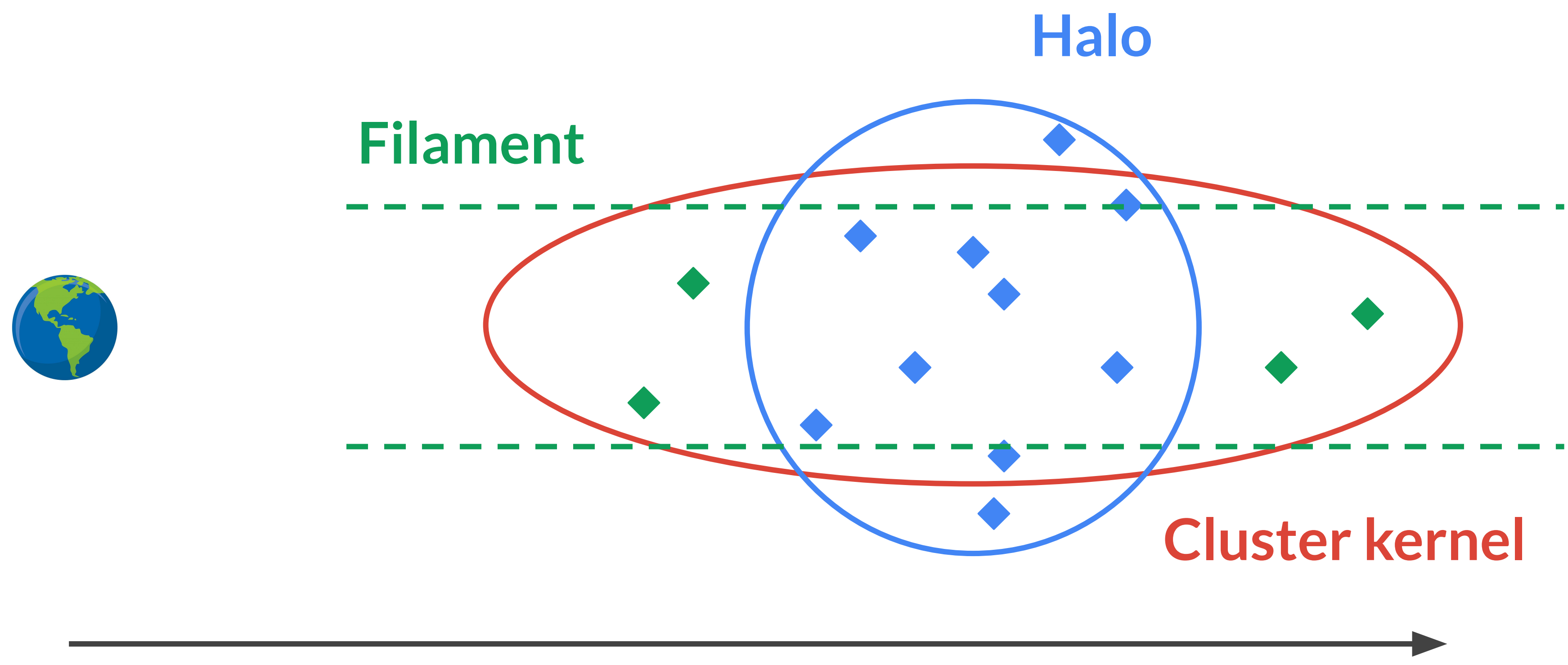
Interpretations

- **What we found out**
  - Optically identified clusters show an unexplained large-scale boost in their lensing (and clustering) signals
  - The boost originates from a minority of clusters in a given sample with high degrees of interloper contamination along the line-of-sight
- **What we can postulate**
  - Contaminated clusters are embedded within aligned filaments
  - Aligned filaments introduce anistropies in the geometry, inducing the large-scale boosts

Interpreting Projection Effects



Interpreting Projection Effects



Cluster kernels naturally prefer aligned filaments that modify lensing/clustering signals

Interpreting Projection Effects

- **What we found out**
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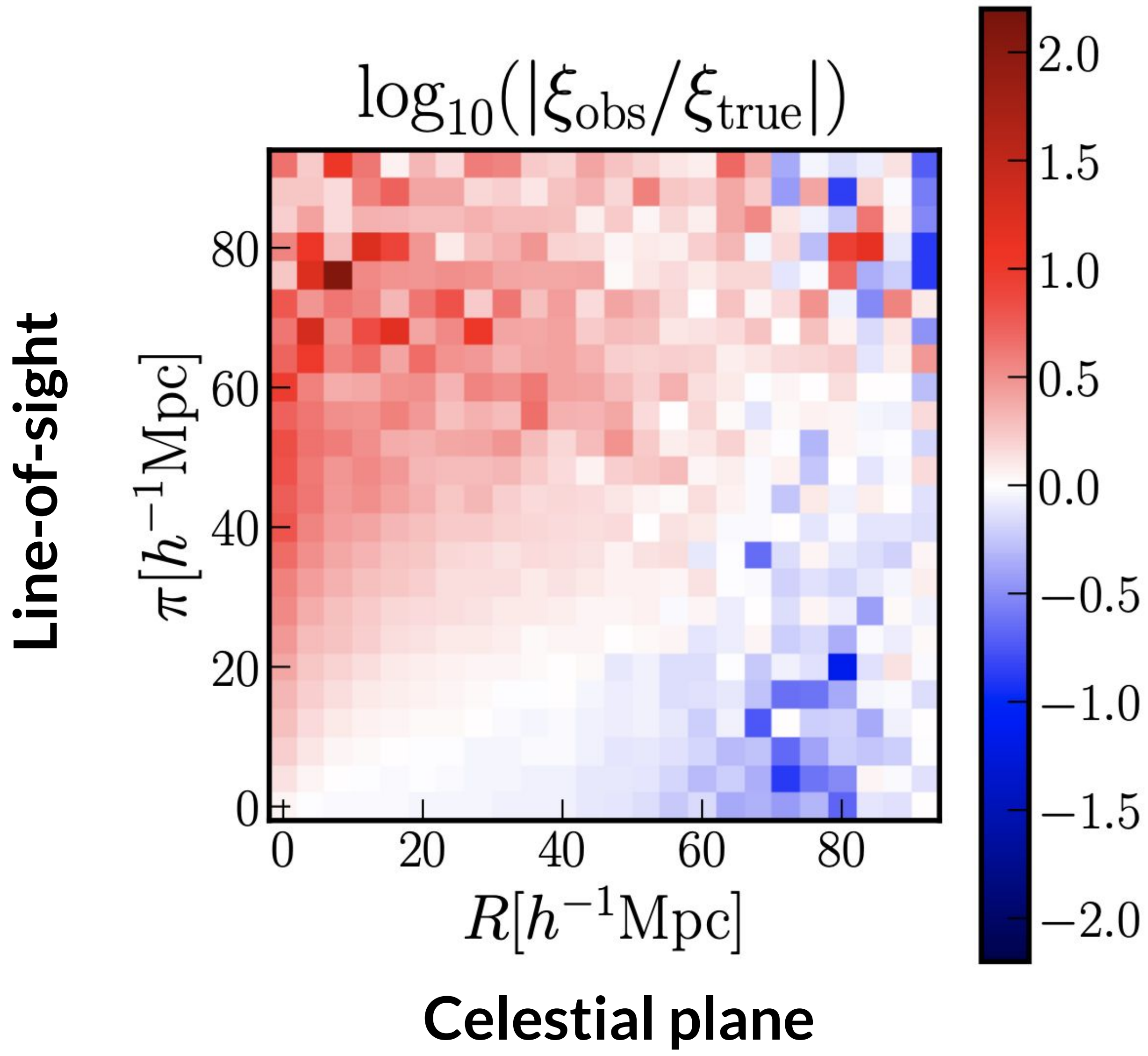
  - The boost originates from a minority of clusters in a given sample with high degrees of interloper contamination along the line-of-sight
- **What we can postulate**
  - Contaminated clusters are embedded within aligned filaments
  - Aligned filaments introduce anistropy in the geometry, inducing the large-scale boosts
- **The story checks out against previous studies, as well as our own measurements!**

Interpreting Projection Effects



Modeling Projection Effects

- **Empirical approach**
  - The shape of the boost is simple; model it with a fitting function and marginalize over the parameters
  - Simple approach, probably works as soon as functional form is fixed
  - Less restrictive, greater loss of cosmological information
- **Physical approach**
  - We know the origin of the boosts; model the anistropic matter distribution and derive the form of the boosts
  - Elegant but more complicated, naive attempts are proving to be suboptimal in producing the boost profiles
  - More restrictive, minimizes loss of cosmological information
- **One way or another, solvable...**

But...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THE EMPIRE STRIKES BACK
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DAVID PROWSE · KENNY BAKER · PETER MAYHEW · FRANK OZ
Directed by IRVIN KERSHNER Produced by GARY KURTZ
Screenplay by LEIGH BRACKETT and LAWRENCE KASDAN Story by GEORGE LUCAS
Executive Producer GEORGE LUCAS Music by JOHN WILLIAMS
SOUNDTRACK ON RSO RECORDS & TAPES
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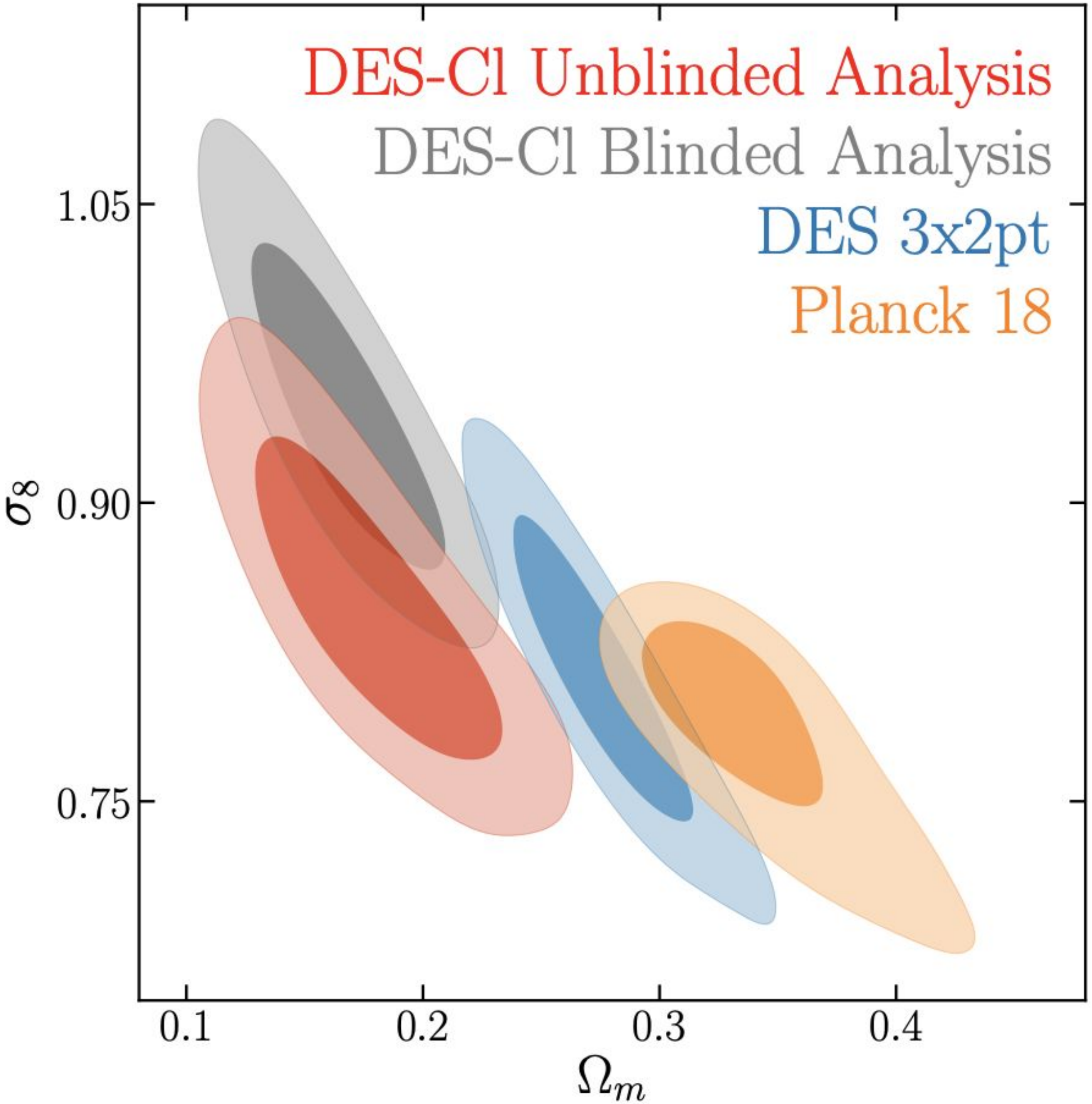
Recent Developments



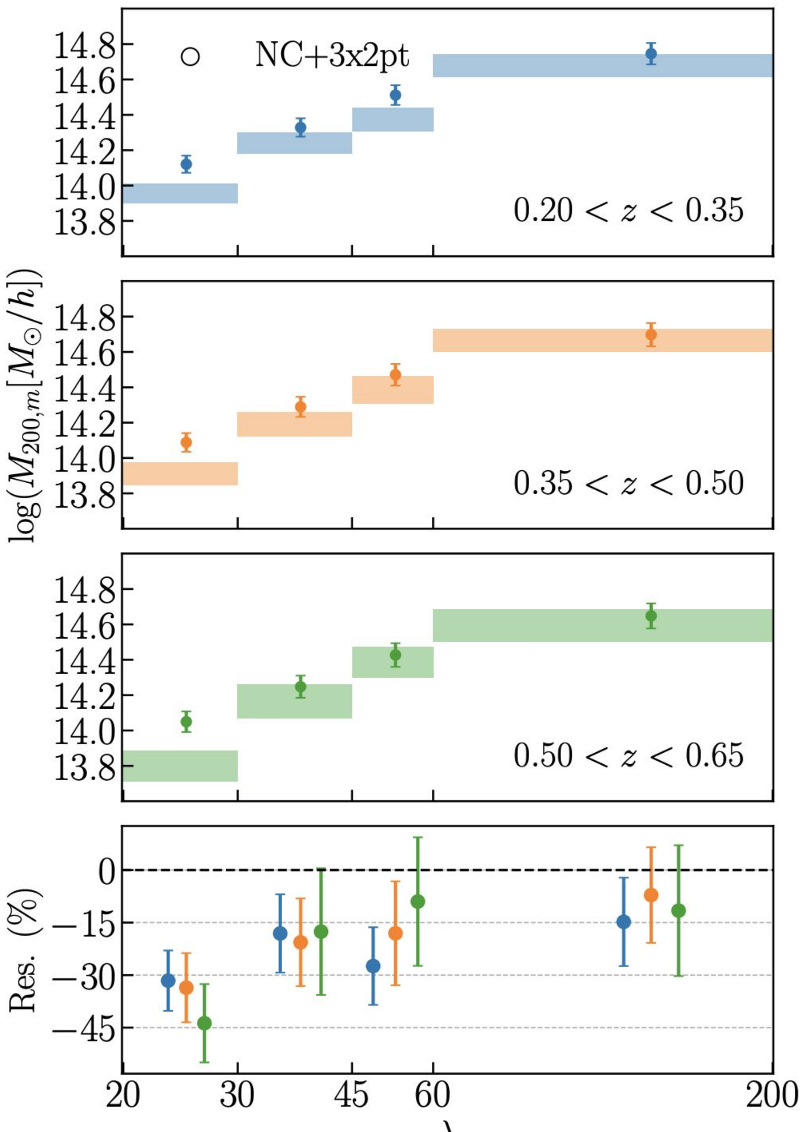
DES Collaboration (2020)

(w/ projection effect boost modeling)

(w/o projection effect boost modeling)

?!?

Opposite Signs



DES Collaboration (2020)

- Bands: real data
- Points: predictions based only on NC, assuming the DES Y1 cosmology
- Comparison suggests that lensing masses are *underestimated!*
- Could suggest another selection effect completely different from projection effects!

Where to?

- **Concerning projection effects**
  - Community is in agreement on the impact and the origin
  - Systematics modeling for projection effects will soon become default for cluster cosmology analyses
- **Concerning the "new" selection effect**
  - Community has little idea about where this is coming from
  - Rough consensus is to look at as much multi-wavelength data on low-richness clusters as possible to figure out the origin
  - Suggests that most attempts to date at using lensing masses, at least to some degree, are biased
- **Optical clusters remain untamed for now**

Avenues

- **Spectroscopic Data**
  - Direct confirmation of the aligned filaments scenario via detecting dense samples of spectroscopic galaxies in cluster regions
  - Building proxies for the degree of projection effects via cross-correlations of clusters and spectroscopic galaxies
- **SZ Data**
  - Complementing optical cluster catalogs with SZ-based selections
  - In combination with X-ray, quantifying the degree of projection effects by exploiting the different line-of-sight integrals
- **Optical clusters will not remain untamed for long**