On the Cosmological Interpretation of Non-Linear Scales in BOSS and Beyond

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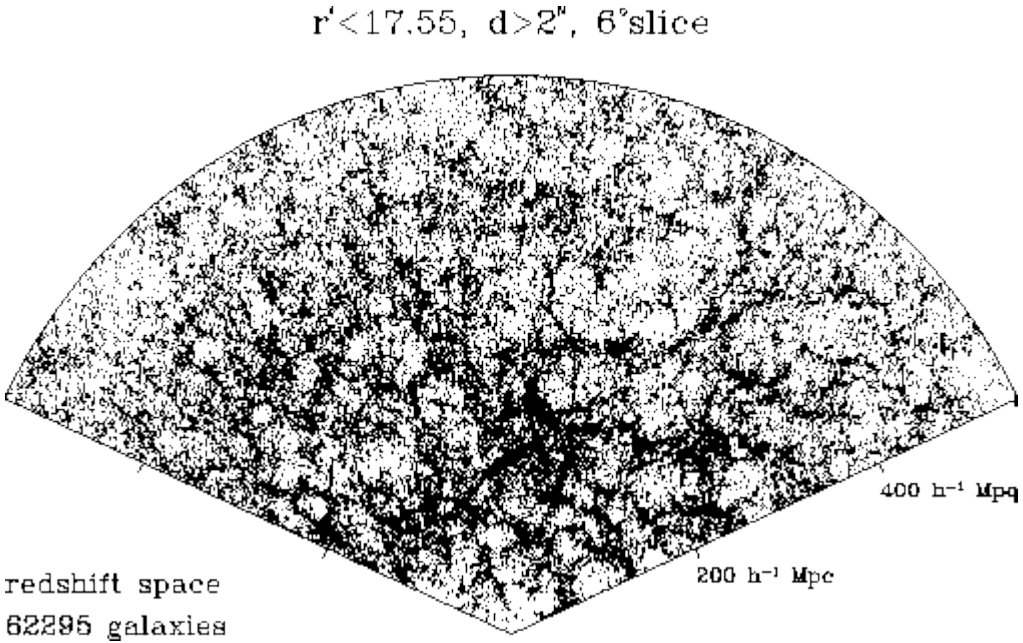
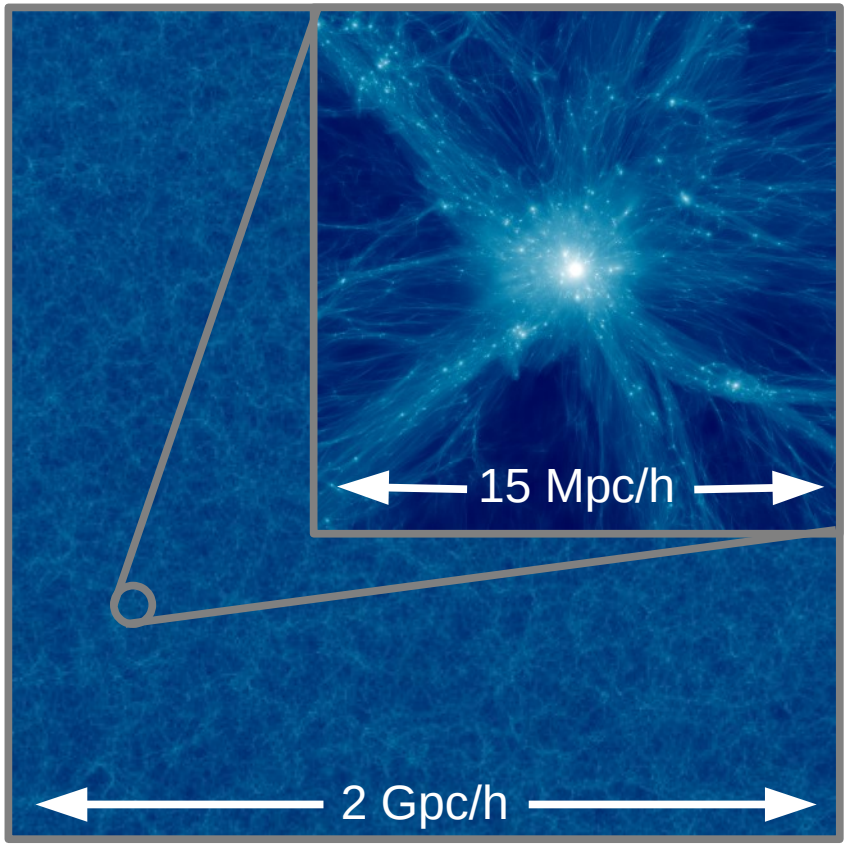
Different Scales in Large-Scale Structure



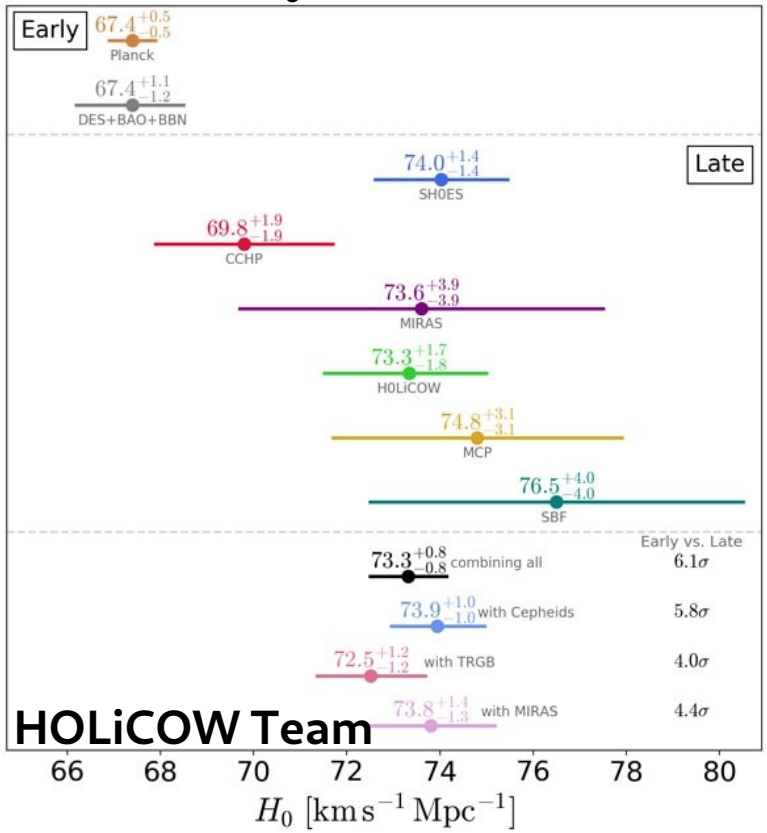


Non-Linear Scales: A Skeptic's View

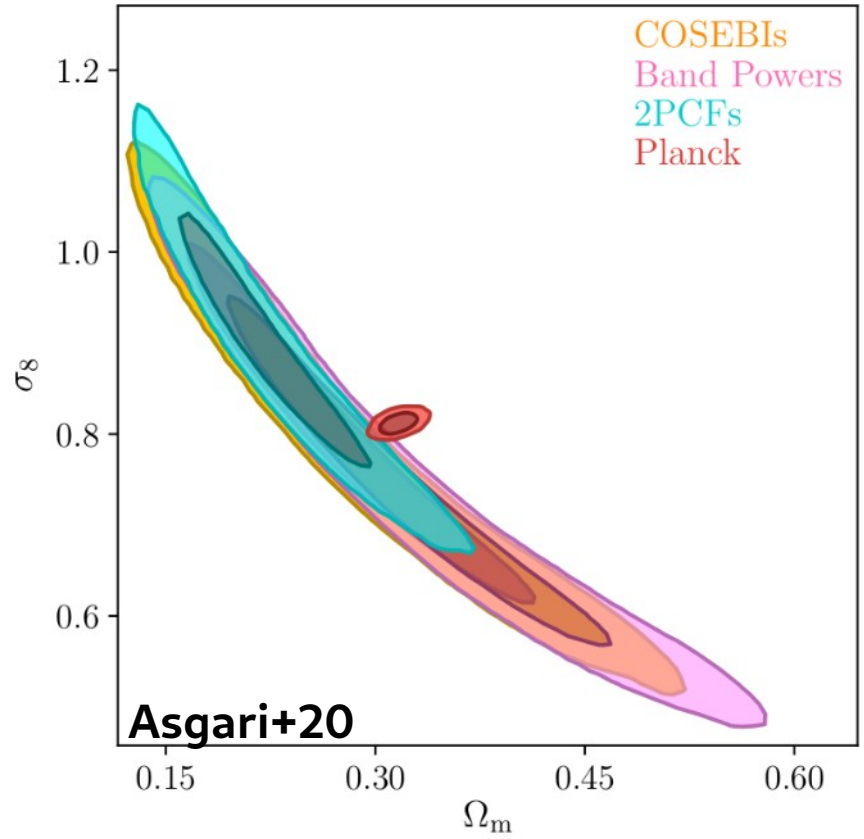
"The skeptic's [...] suggestion was that precision measurements of cosmological parameters should perhaps be left to clean probes such as baryon acoustic oscillation experiments or CMB experiments [...], while small scale structure probes [...] are excellent tools for discovery [...]. It highlighted the importance of demonstrating the resilience of small scale probes to uncertainties in galaxy formation physics."

Discovery Space: Cosmological Tensions

H_0 Tension

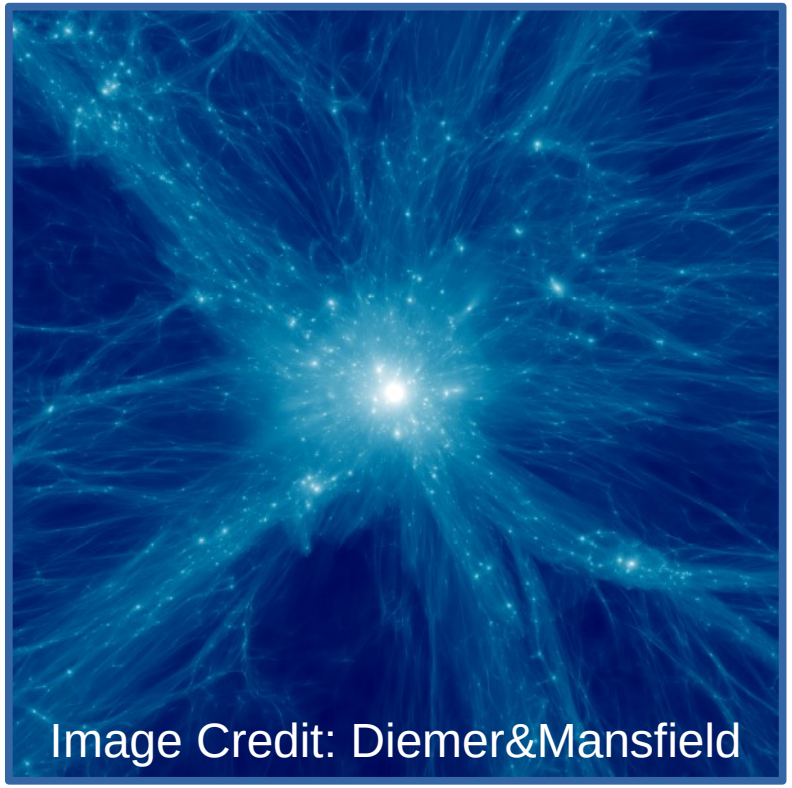


S_8 Tension



Outline

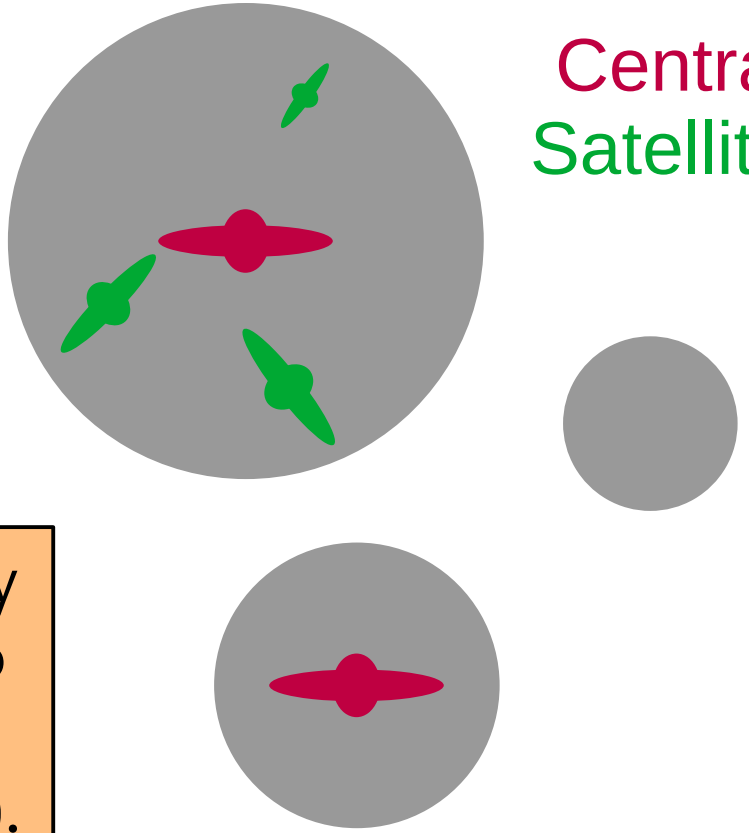
- Introduction to Non-Linear Scales
- Recent Advancements in Modeling
- Growth-Rate Constraints from RSDs in BOSS LOWZ
- Lensing is Low: A cosmological Tension?
- Future Directions: Combined Probes, DESI and more



Advancements in Modeling

Background: The Halo Model

- Dark matter collapses into dark matter halos
- Galaxies live (only) in dark matter halos



The statistical properties of the galaxy field arise from properties of the halo distribution (cosmology) and how galaxies occupy halos (galaxy physics).

Evolution of Modeling Non-Linear Scales

Analytic Halo Model

$$\xi_{mm}(r) + n_h(M_h) + b_h(M_h) + c(M_h) + \ldots + N_g(M_h)$$

↓

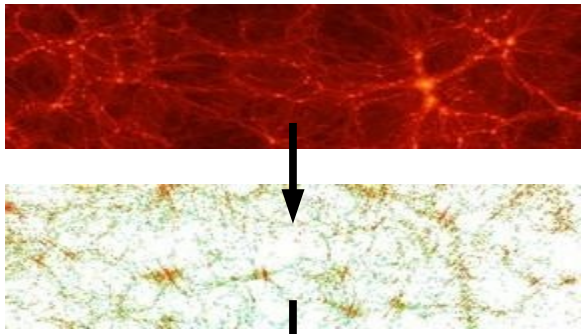
Observables

✘ Accuracy

✘ Assembly Bias

~ Cosmology

Mock Population



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Observables

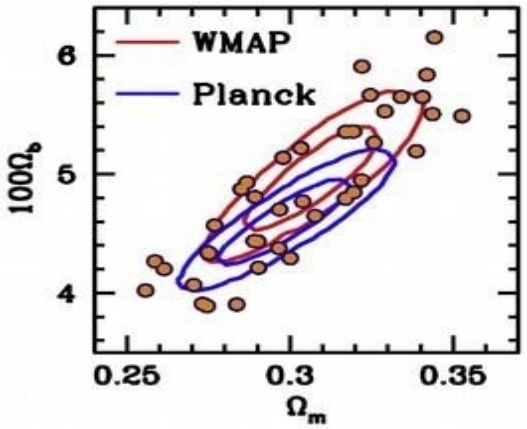
✔ Accuracy

✔ Assembly Bias

✘ Cosmology

Multi-Cosmology Mock Population

DeRose+ 19

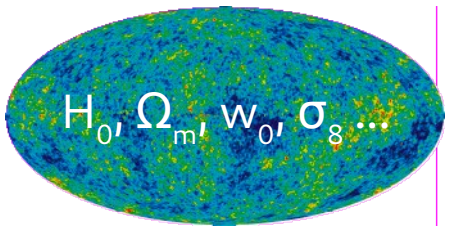


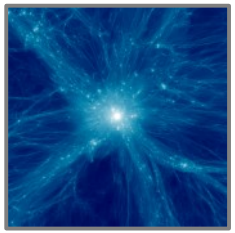
✔ Accuracy

✔ Assembly Bias

✔ Cosmology

The Naive Approach





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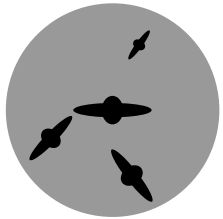

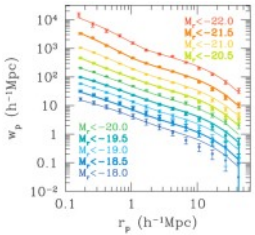

$L(\text{Model}_1)$

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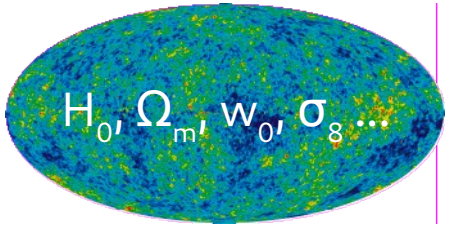

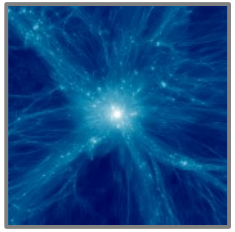

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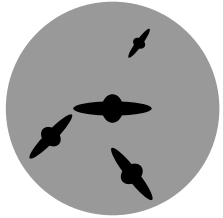
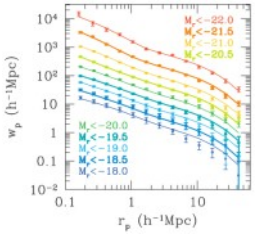
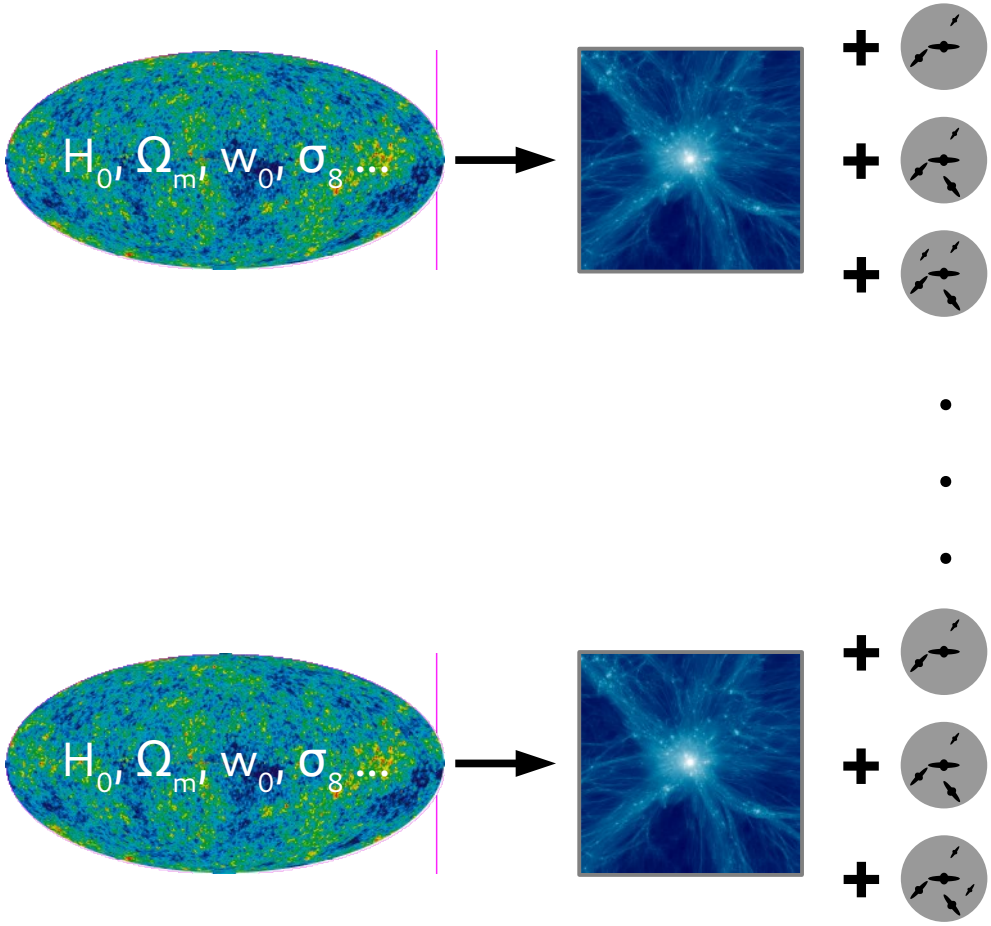
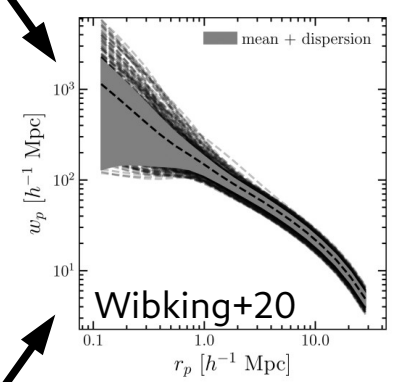




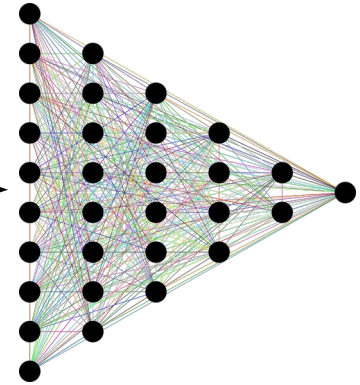
$L(\text{Model}_{1000000})$

Emulator or Surrogate Modeling

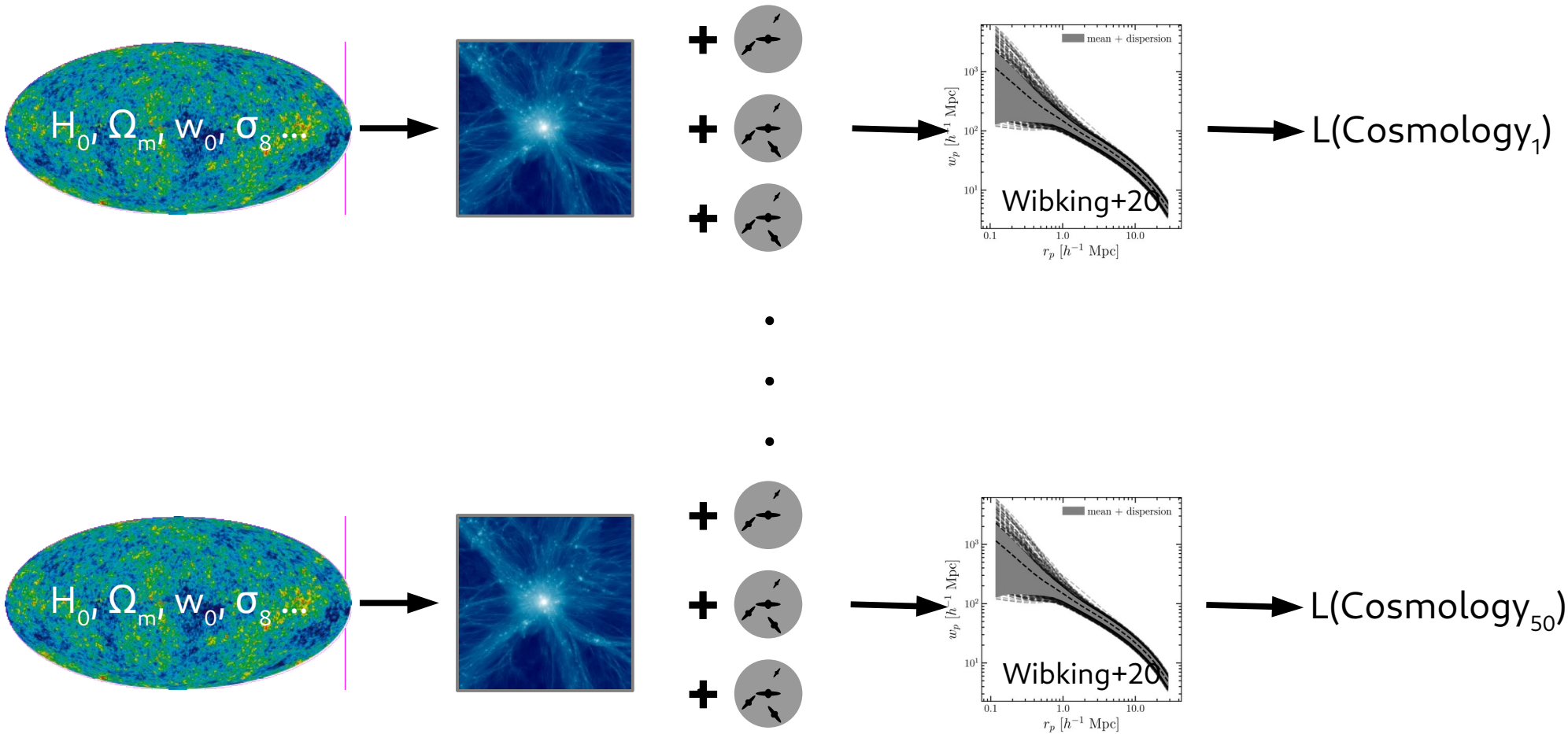




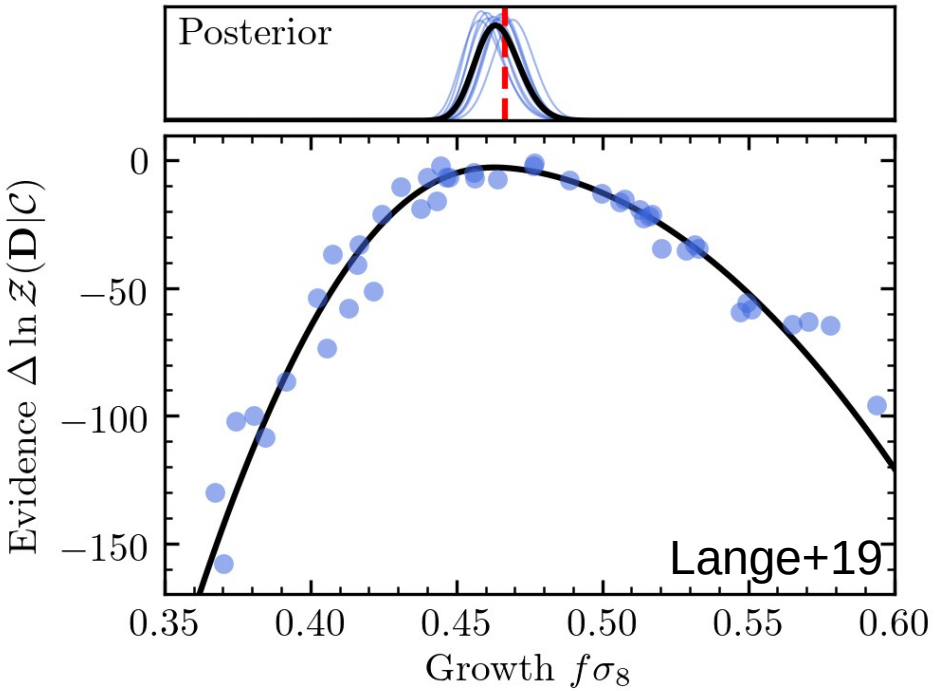
Machine Learning

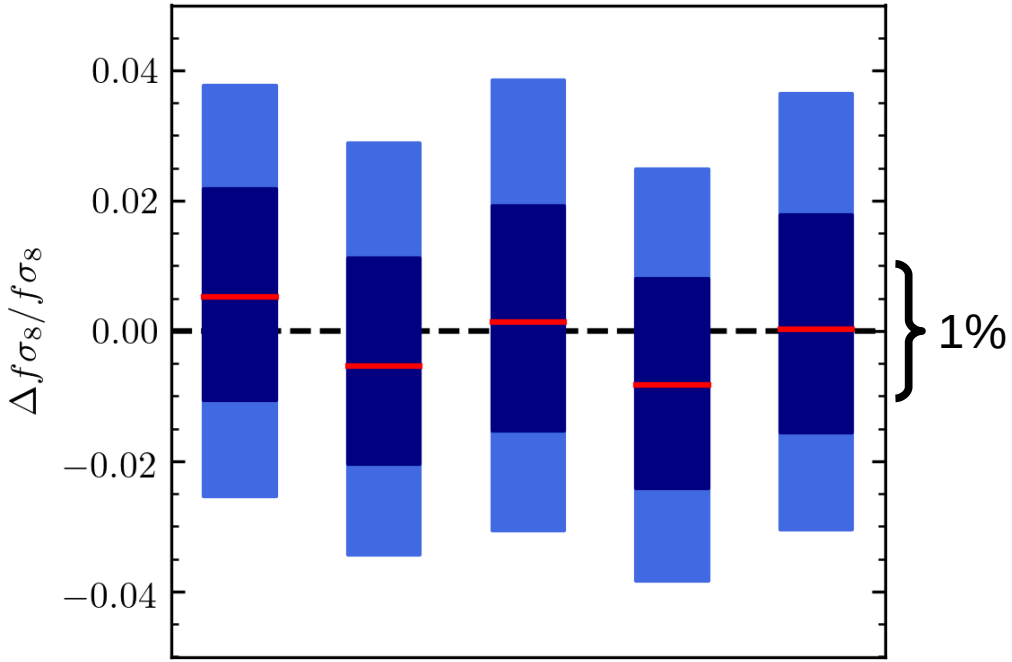


Cosmological Evidence Approach



Application to Mock Data

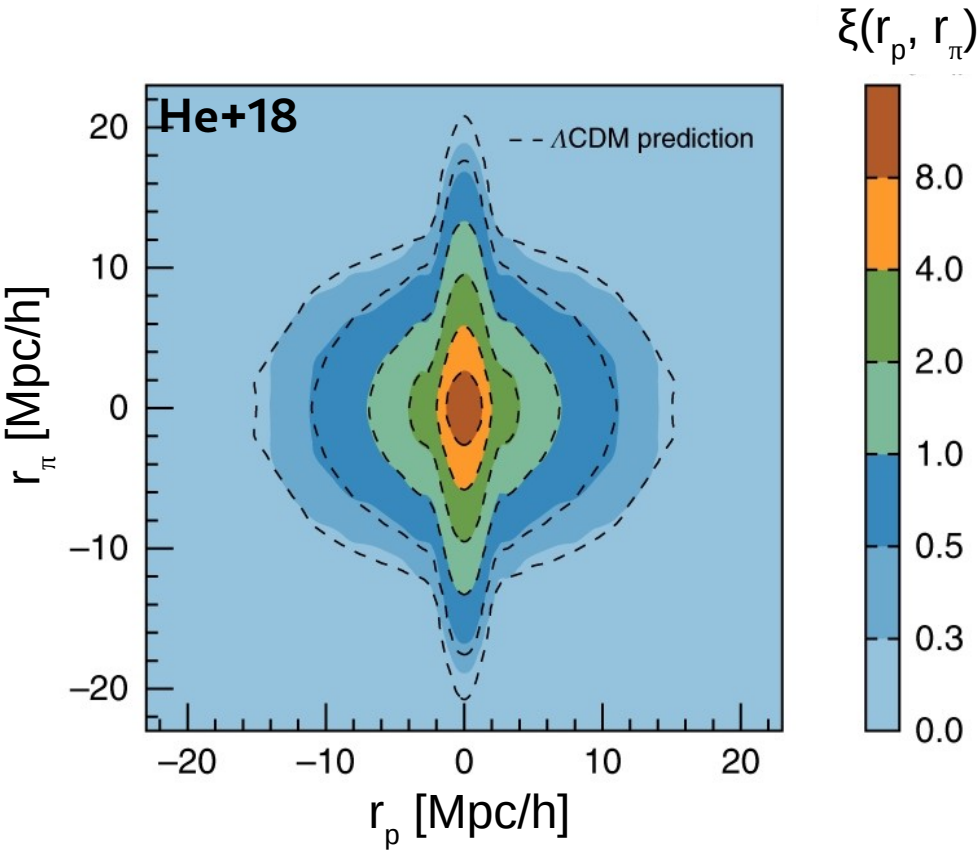




Our new approach allows for more complex galaxy models while reducing modeling uncertainties by a factor of a few.

Growth Rate Constraints from Non-Linear Anisotropic Clustering

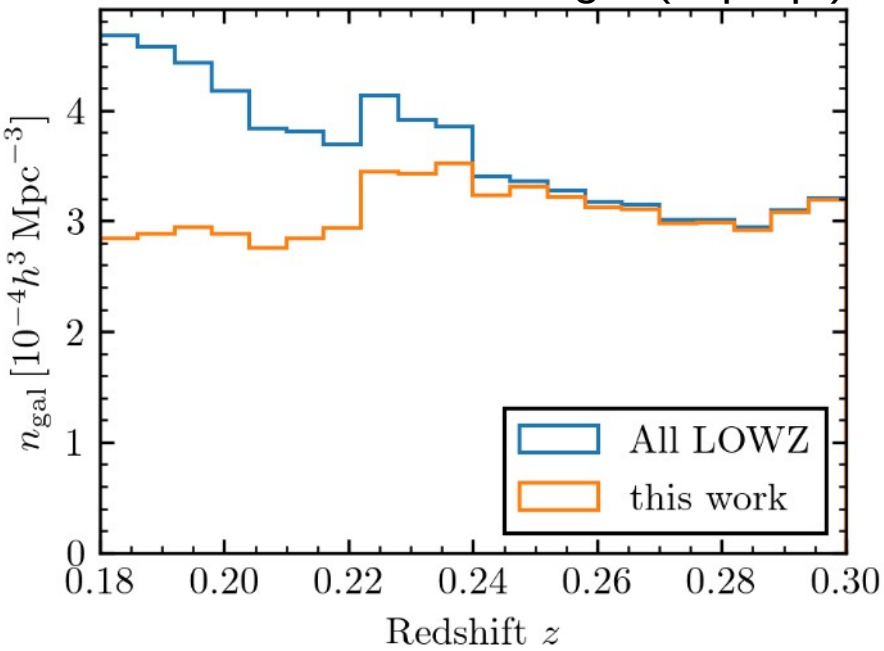
Redshift-Space Distortions (RSDs)



- small r_p: virialized motions of satellites (Fingers of God effect)
- medium to large r_p: coherent infall motions (Kaiser effect)
- Kaiser effect can be used to infer structure growth rate (and test gravity)

BOSS LOWZ Samples

Lange+(in prep.)



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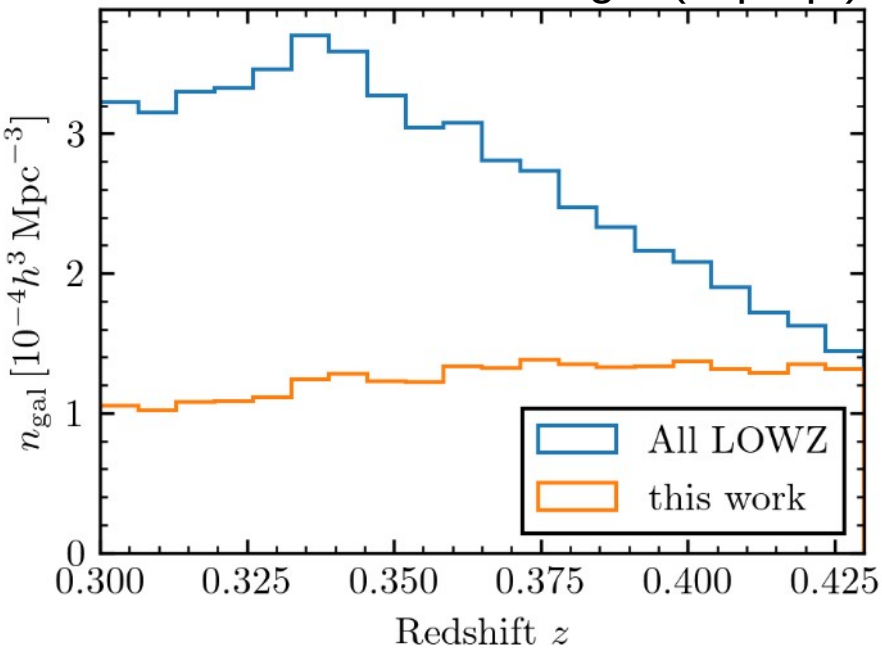


Number of Galaxies: 2 x ~70,000 = 140,000 (~14% of BOSS)

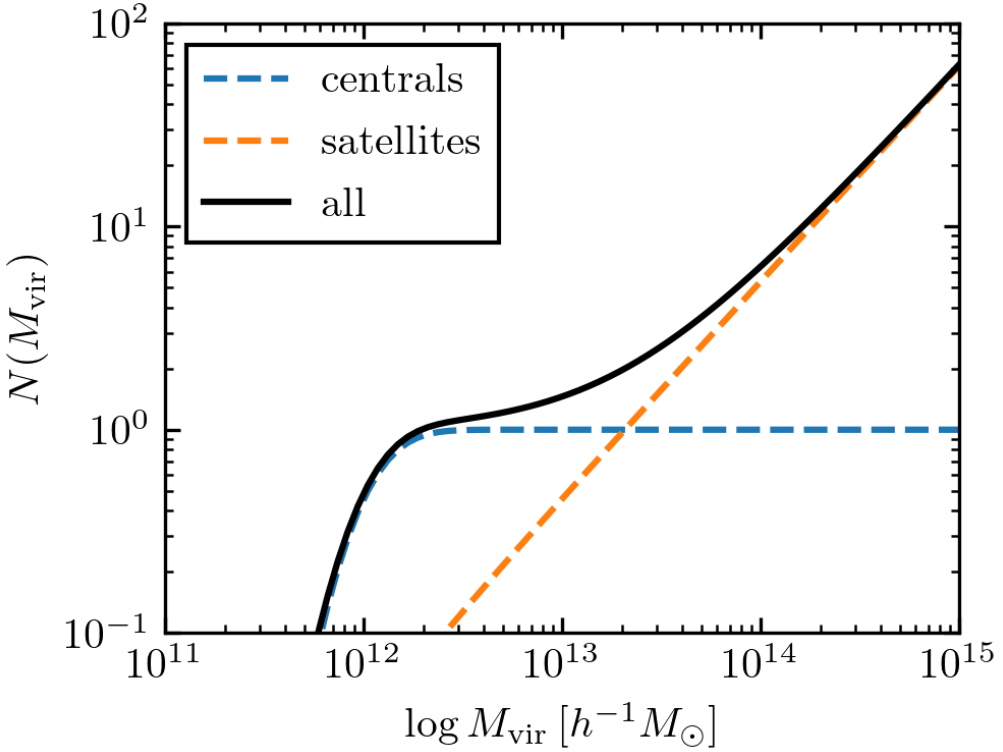
Galaxy-Halo Connection Model

Halo Occupation Distribution

- standard HOD parametrization:
  M_{min}, M_1, M_0, σ_{logM}, α
- central incompleteness f_Γ

$$\langle N_{\rm cen}|M\rangle = \frac{f_\Gamma}{2}\left(1+{\rm erf}\left[\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right]\right)$$

$$\langle N_{\rm sat}|M\rangle = \left(\frac{M-M_0}{M_1}\right)^{\alpha}$$



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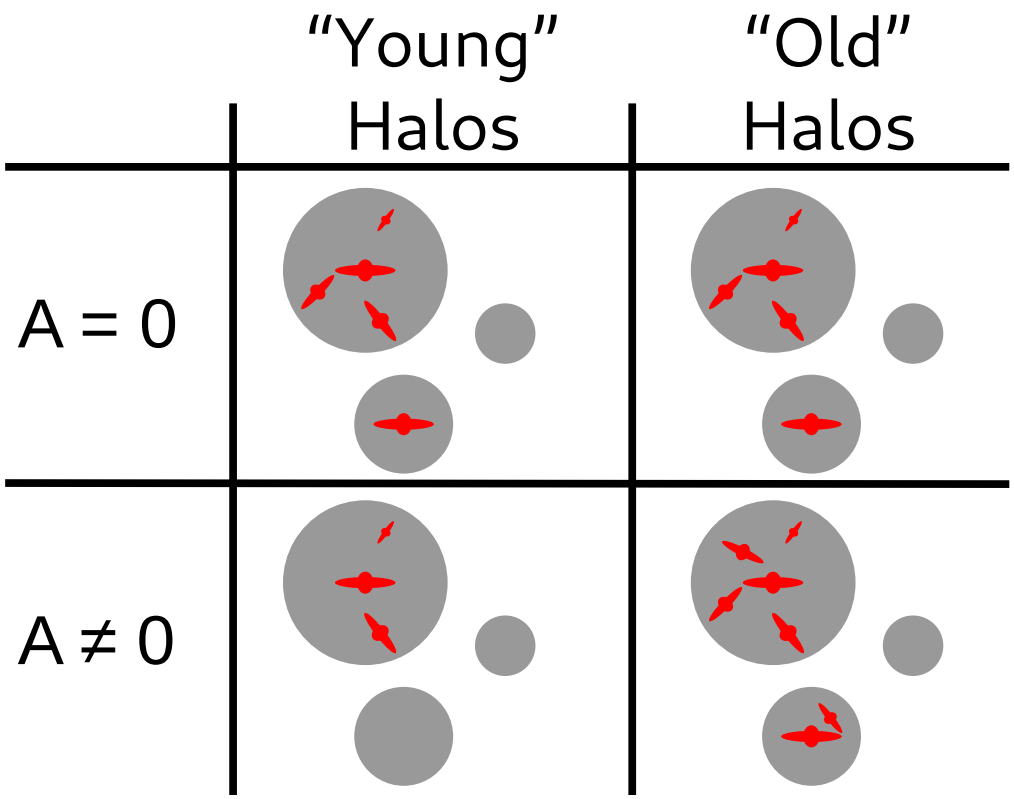
- galaxy assembly bias via decorated HOD (Hearin et al., 2016): A_{cen}, A_{sat}



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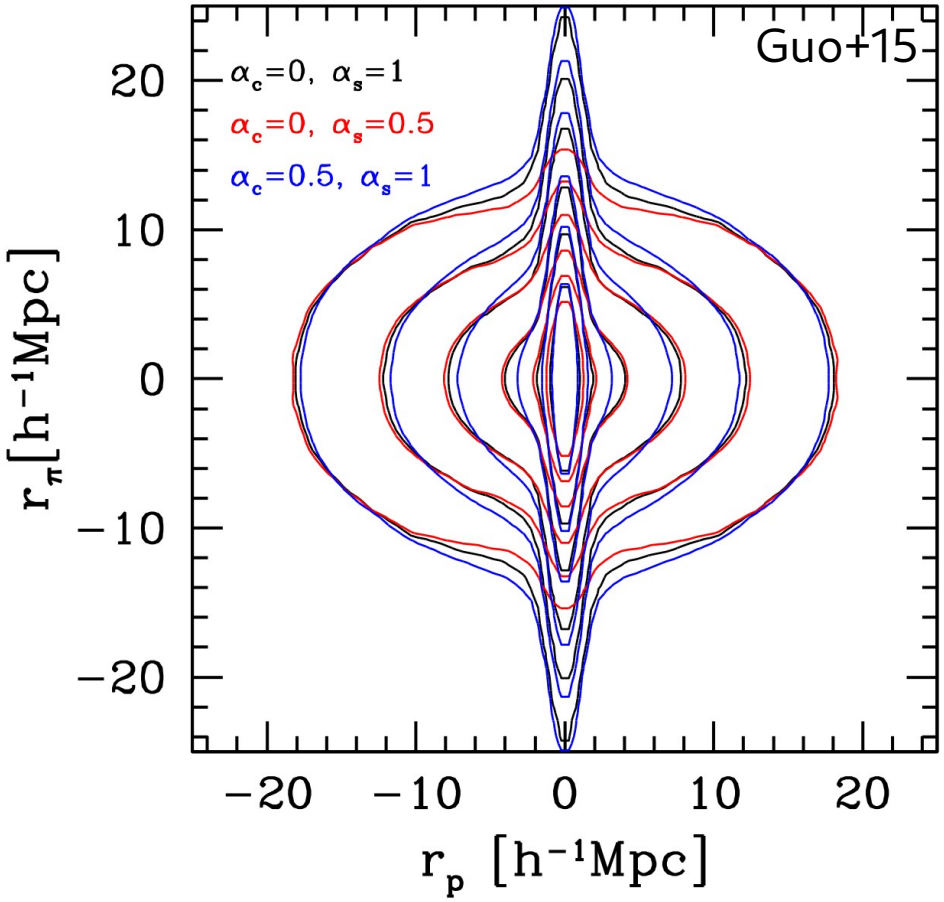

Velocity and Spatial Bias

- satellites follow analytical NFW profile, concentration can vary wrt dark matter: $c_{sat} / c_{dm} = \eta$
- satellite velocity dispersion calculated from Jeans equation
- additional central and satellite velocity bias: α_c, α_s

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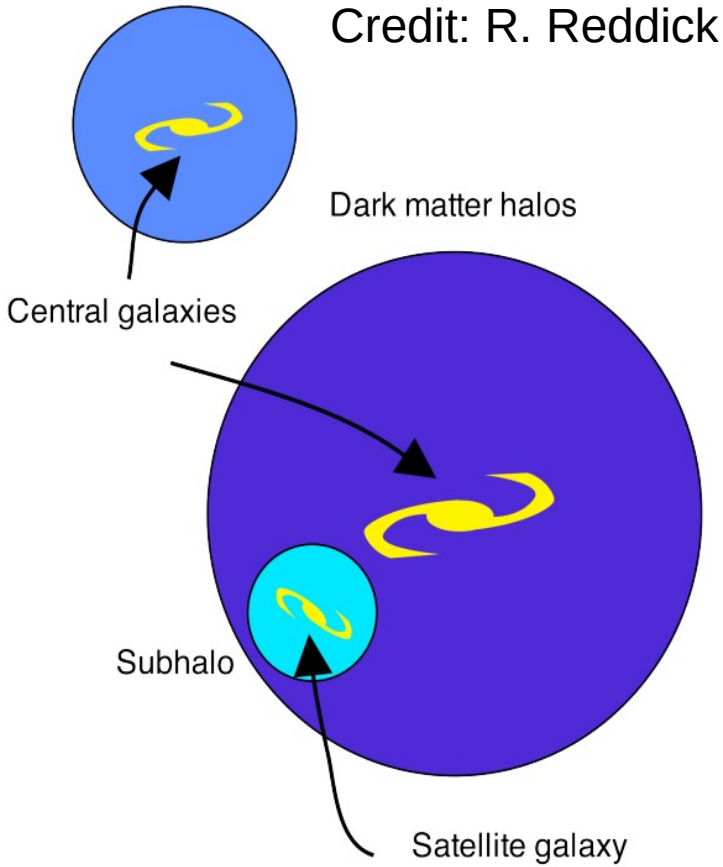
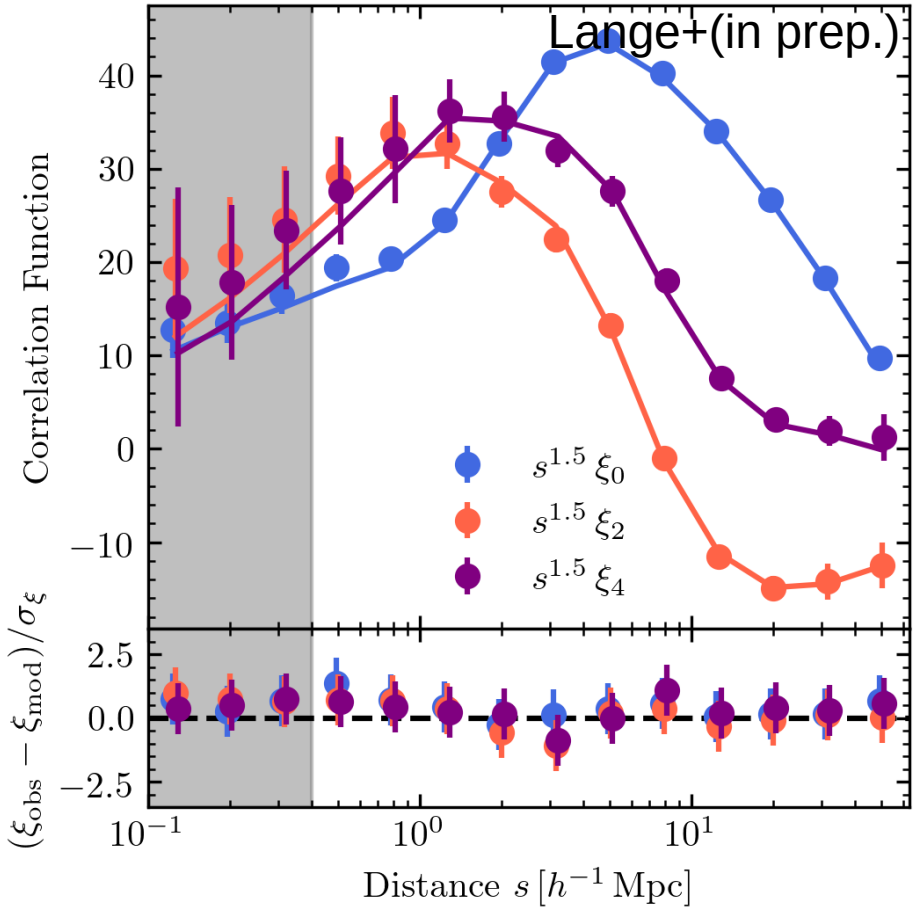
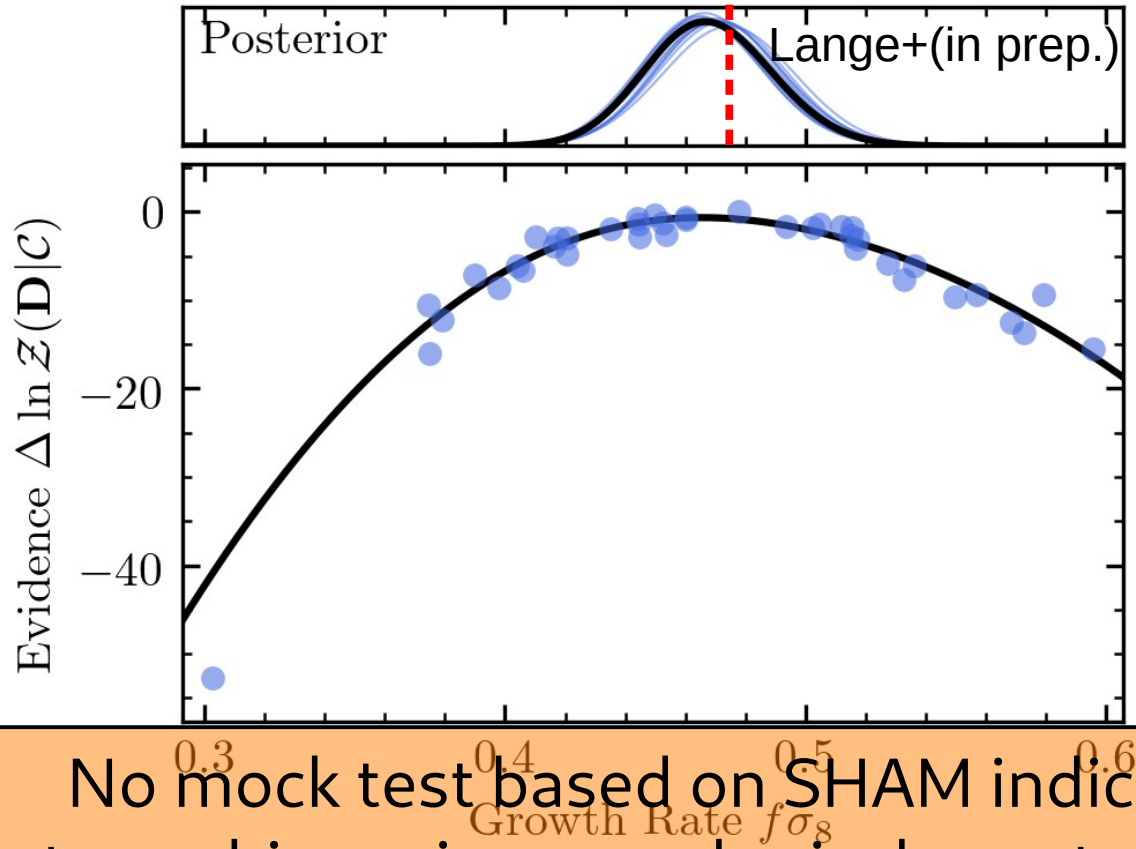
Mock Tests with SubHalo Abundance Matching





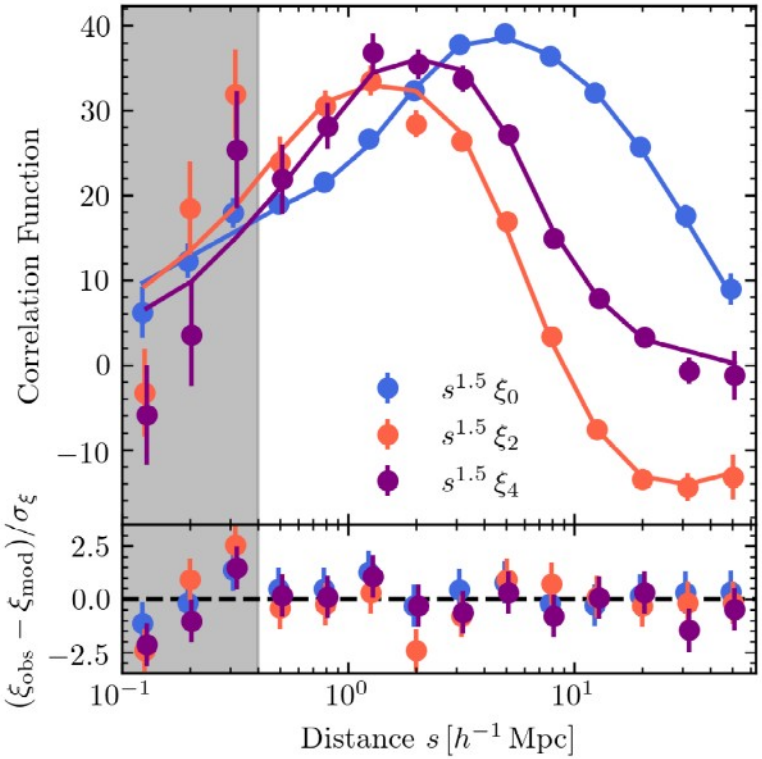
Mock Cosmology Recovery



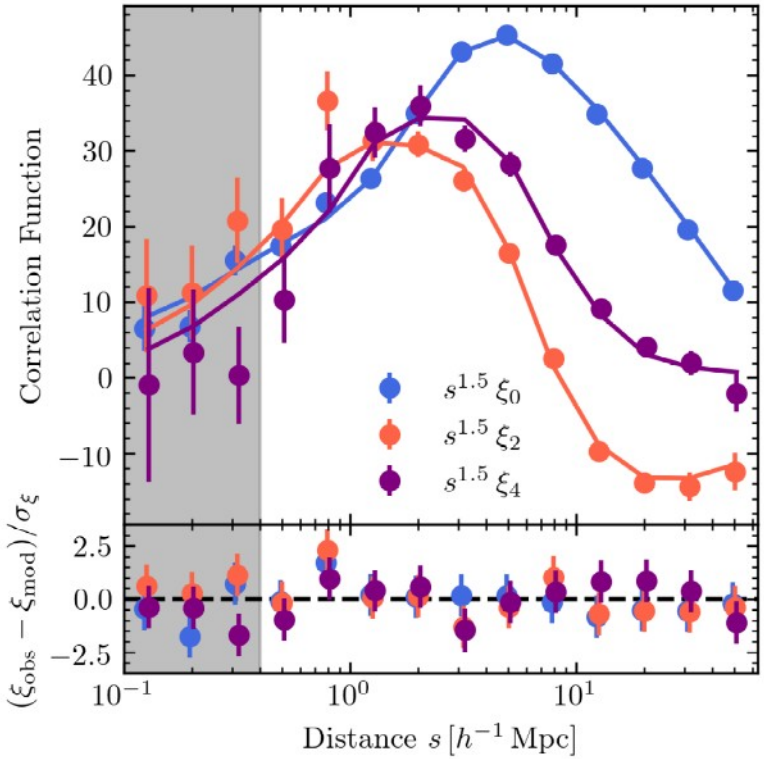
No mock test based on SHAM indicate strong biases in cosmological constraints.

Application to BOSS Data

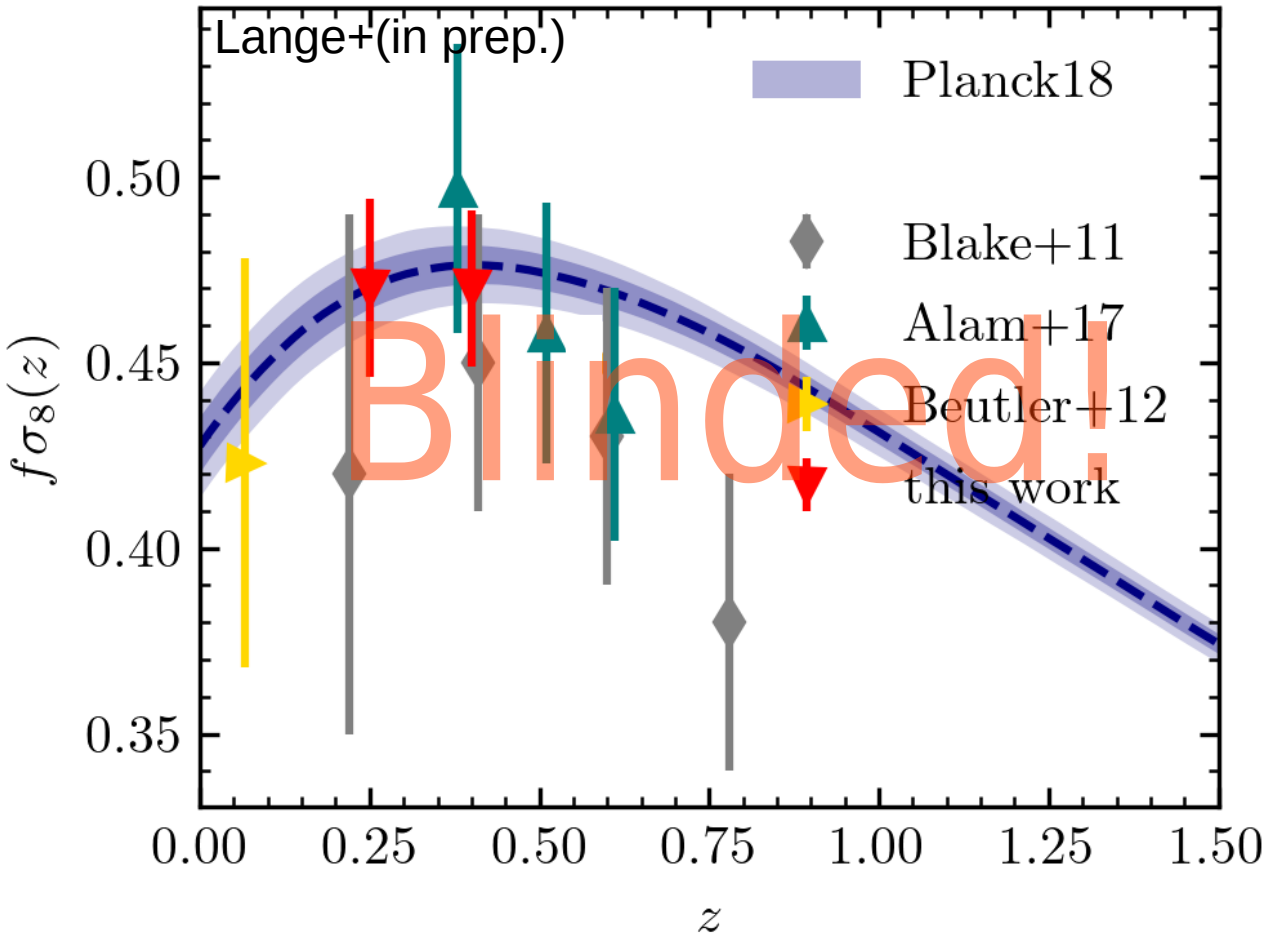
z ~ 0.25



z ~ 0.45



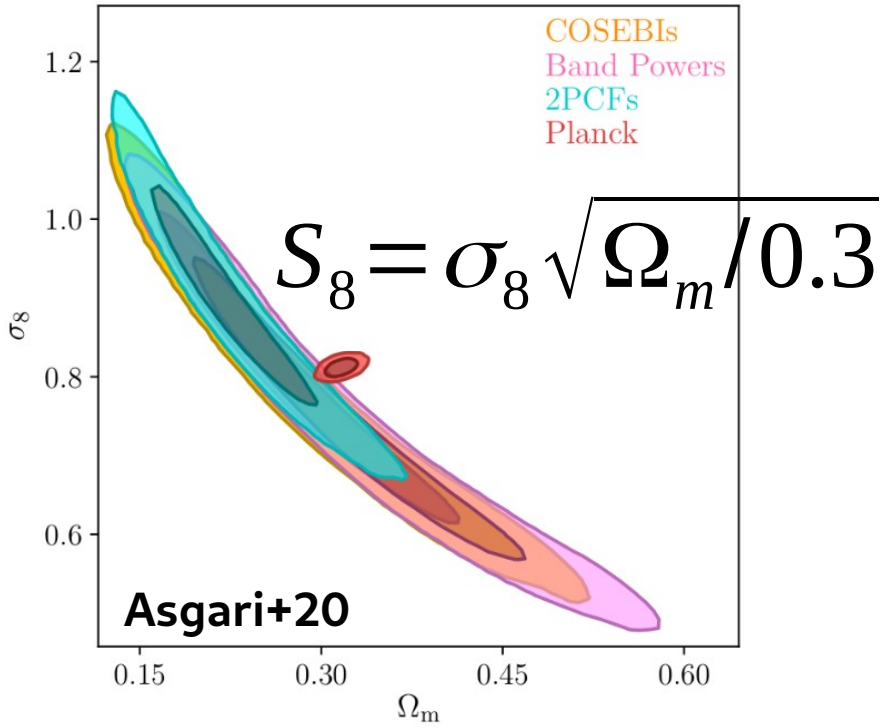
Growth Rate Constraints

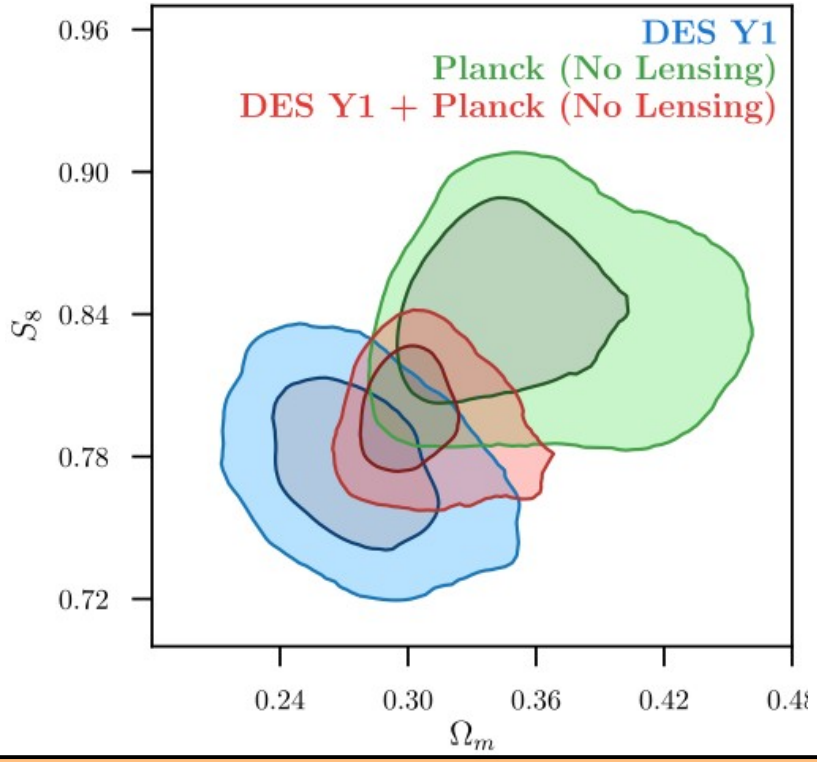


Using non-linear scales, we get more stringent constraints than previous on large scales while only ~using 15% of BOSS.

Lensing is Low:
A cosmological Tension?

S_8 Tension: A Problem for ΛCDM?



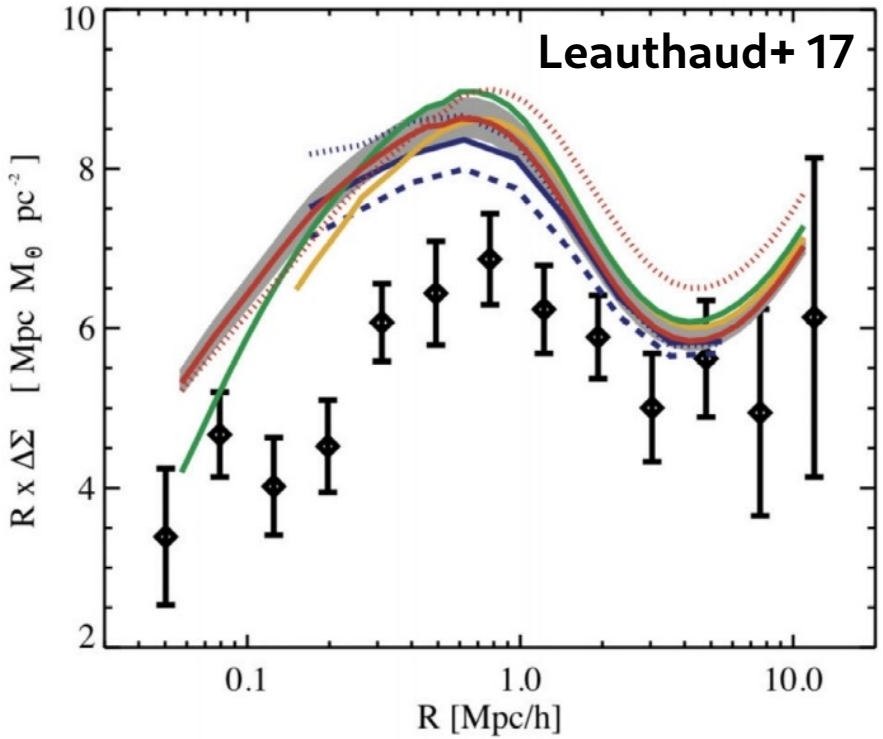


Universe appears to have less structure than predicted by CMB+ΛCDM. However, this finding is not statistically conclusive on large scales.

S_8 Tension Manifestation: Lensing appears Low

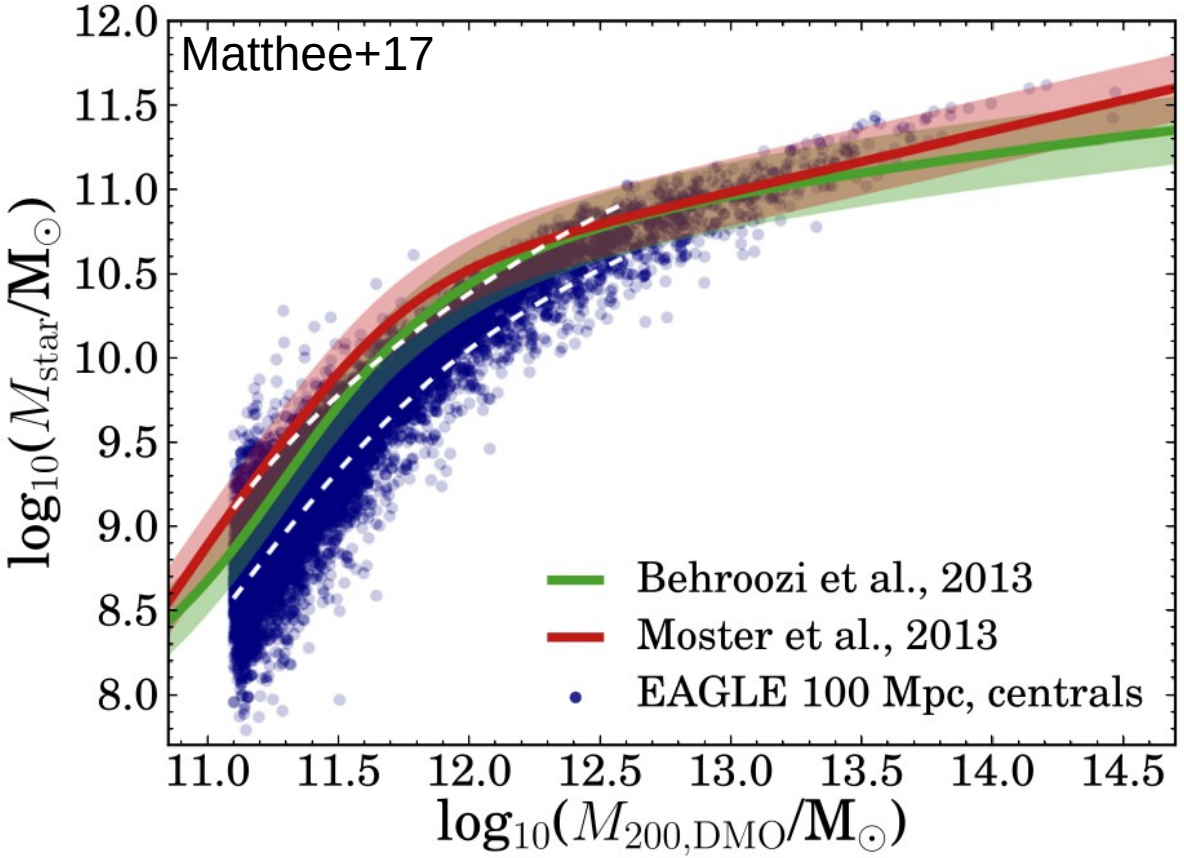
Galaxy-Galaxy Lensing

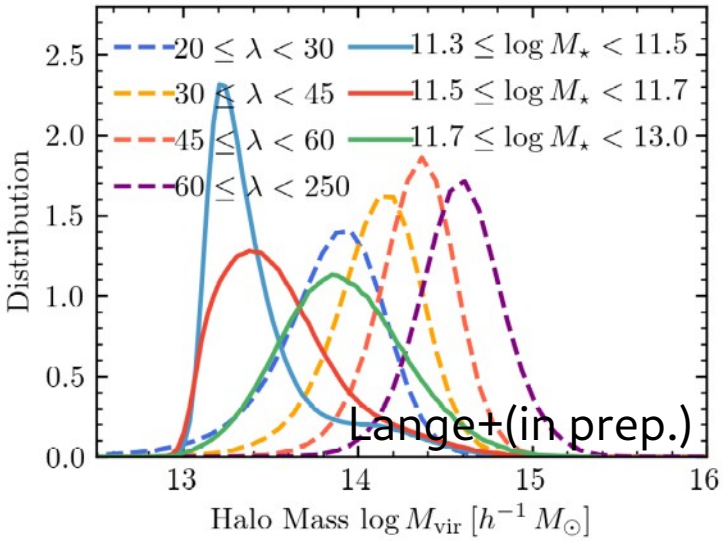
$$\Delta\Sigma(r) = \overline{\Sigma}(<r) - \overline{\Sigma}(r)$$



Galaxy clustering + CMB+ΛCDM makes precise predictions for lensing. Predictions do not agree with observations.

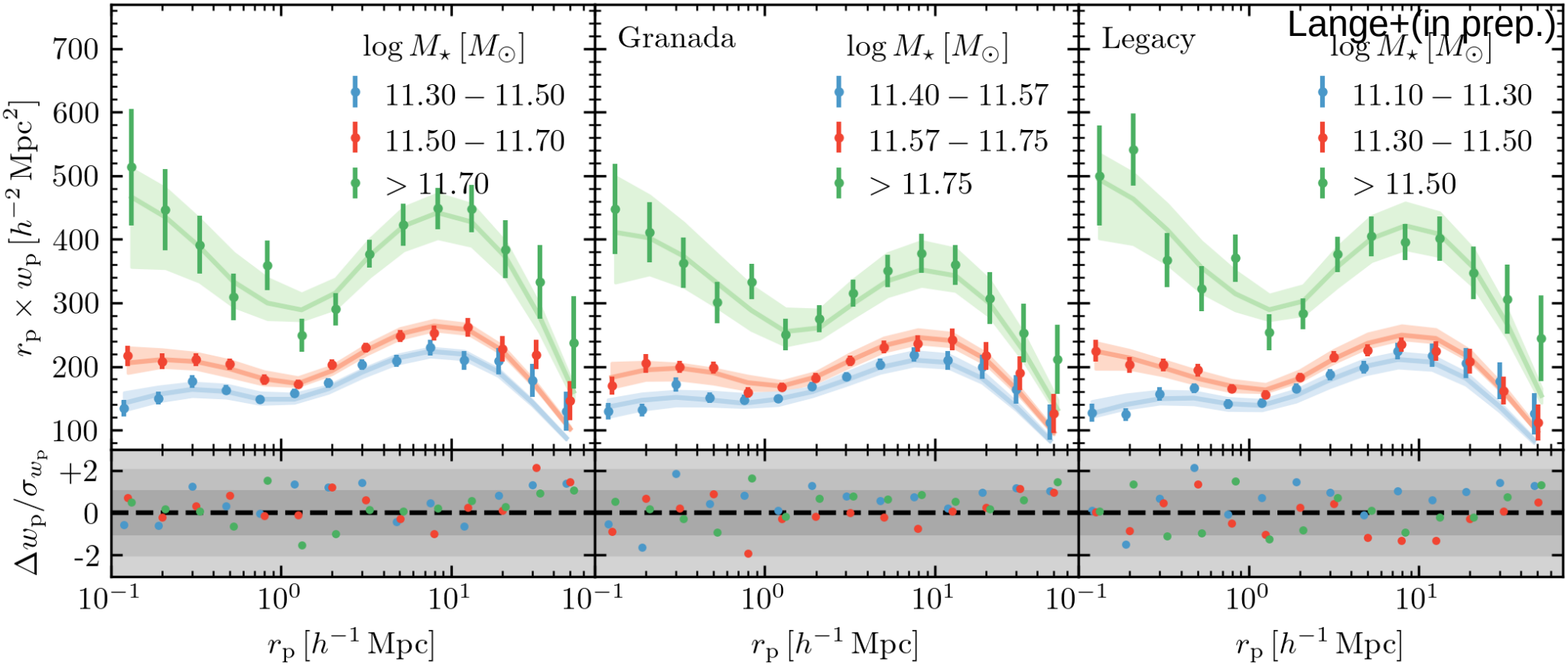
Analyzing Lensing-is-Low with LOWZ

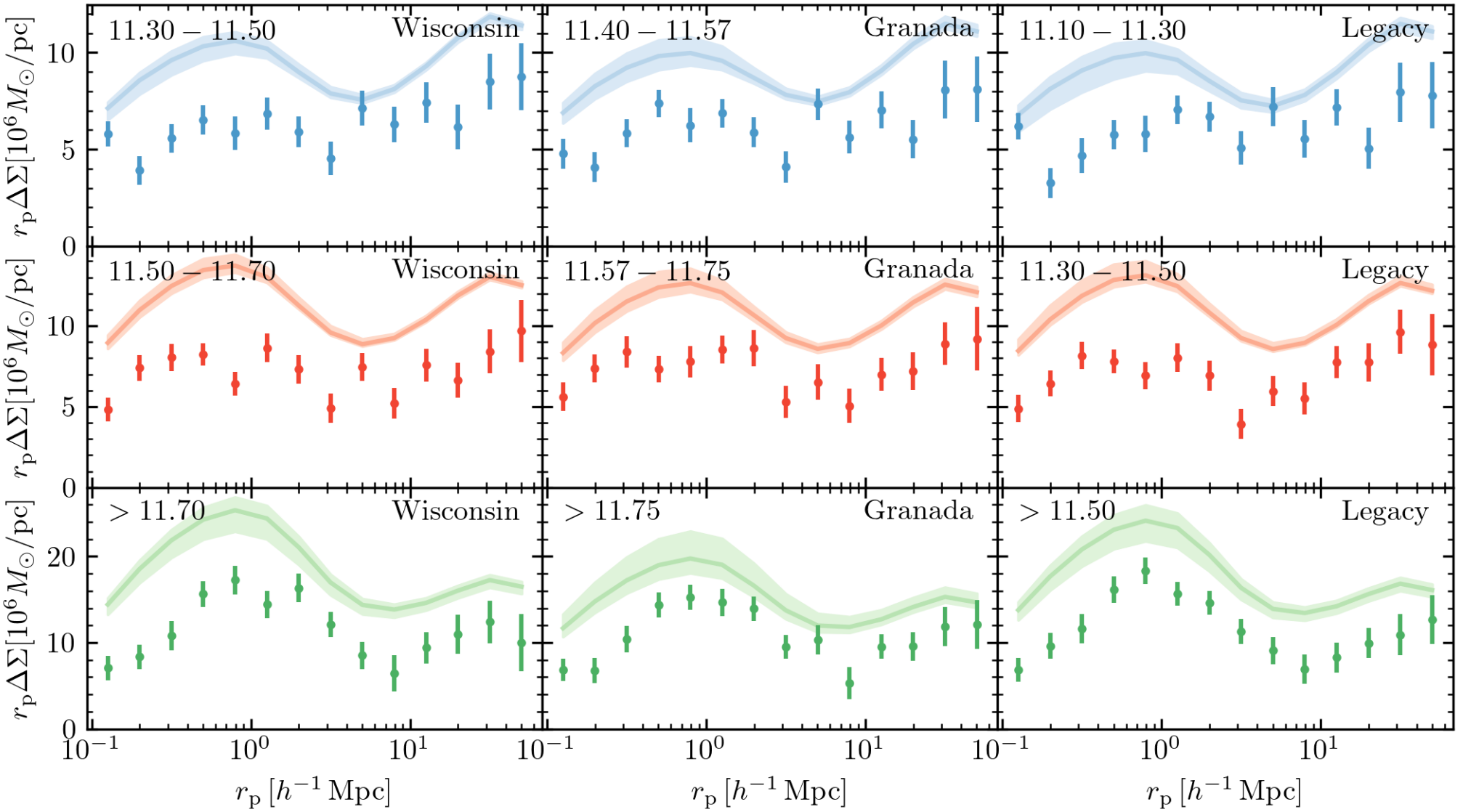




We use stellar mass as a proxy for halo mass.

Mass-Dependent Clustering




11.30 – 11.50
Wisconsin
11.40 – 11.57
Granada
11.10 – 11.30
Legacy
11.50 – 11.70
Wisconsin
11.57 – 11.75
Granada
11.30 – 11.50
Legacy
> 11.70
Wisconsin
> 11.75
Granada
> 11.50
Legacy
$r_{\rm p}\Delta\Sigma[10^6 M_\odot/{\rm pc}]$
$r_{\rm p}\Delta\Sigma[10^6 M_\odot/{\rm pc}]$
$r_{\rm p}\Delta\Sigma[10^6 M_\odot/{\rm pc}]$
0
5
10
0
5
10
0
10
20
10^{-1}
10^{0}
10^{1}
$r_{\rm p}\,[h^{-1}\,{\rm Mpc}]$
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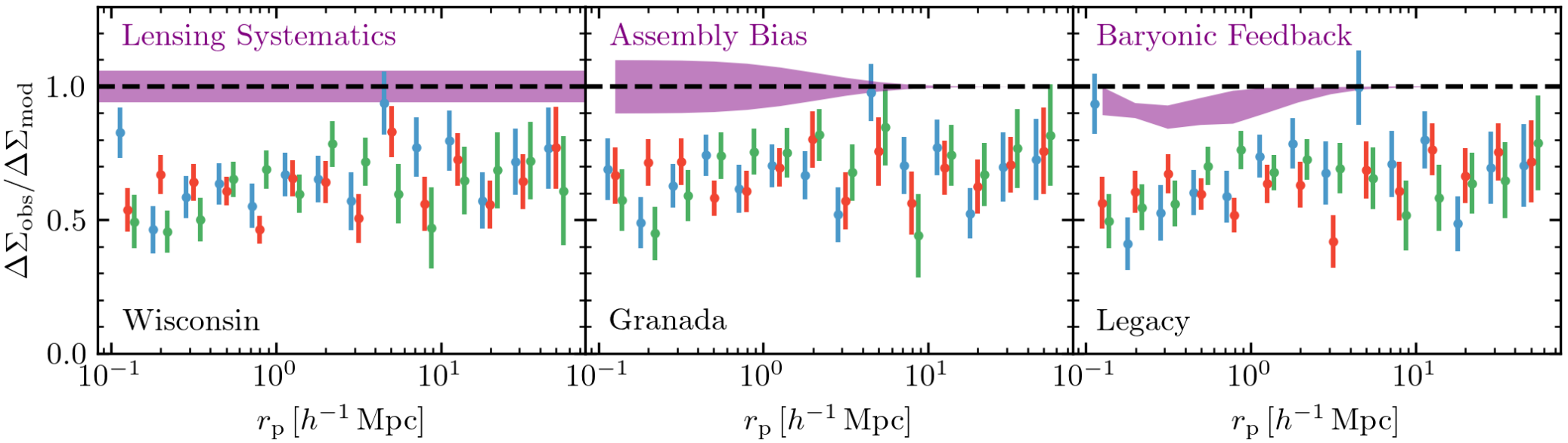
$r_{\rm p}\,[h^{-1}\,{\rm Mpc}]$

Mass and Radial Scale Dependence

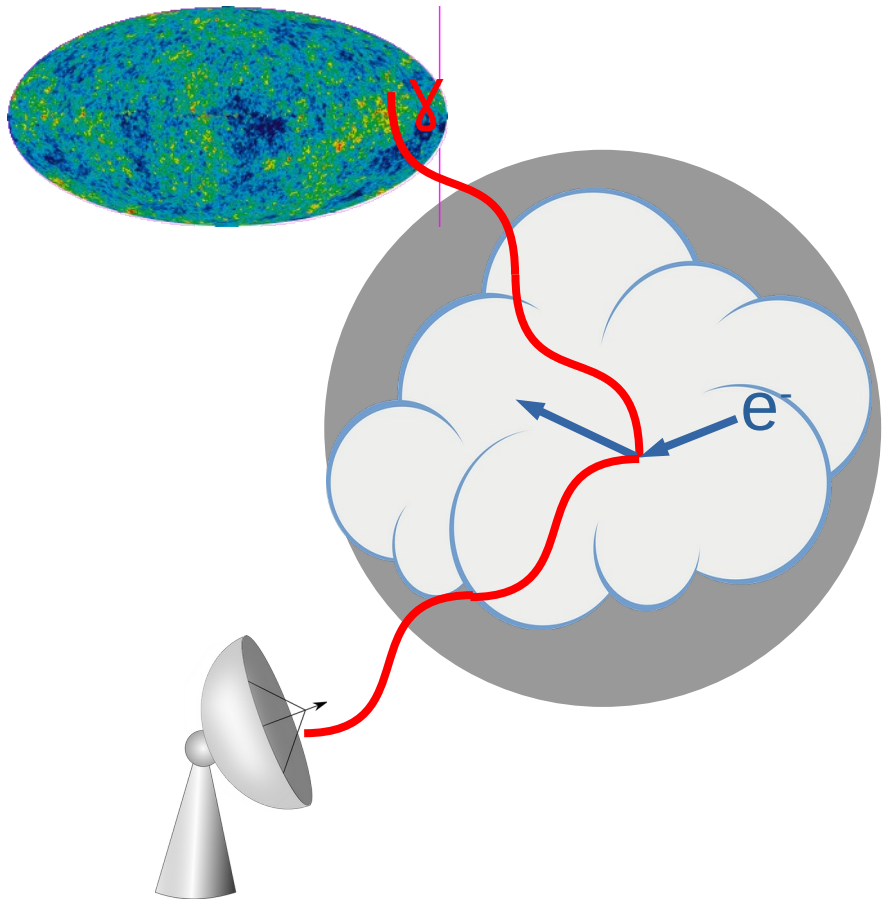
Lange+(in prep.)

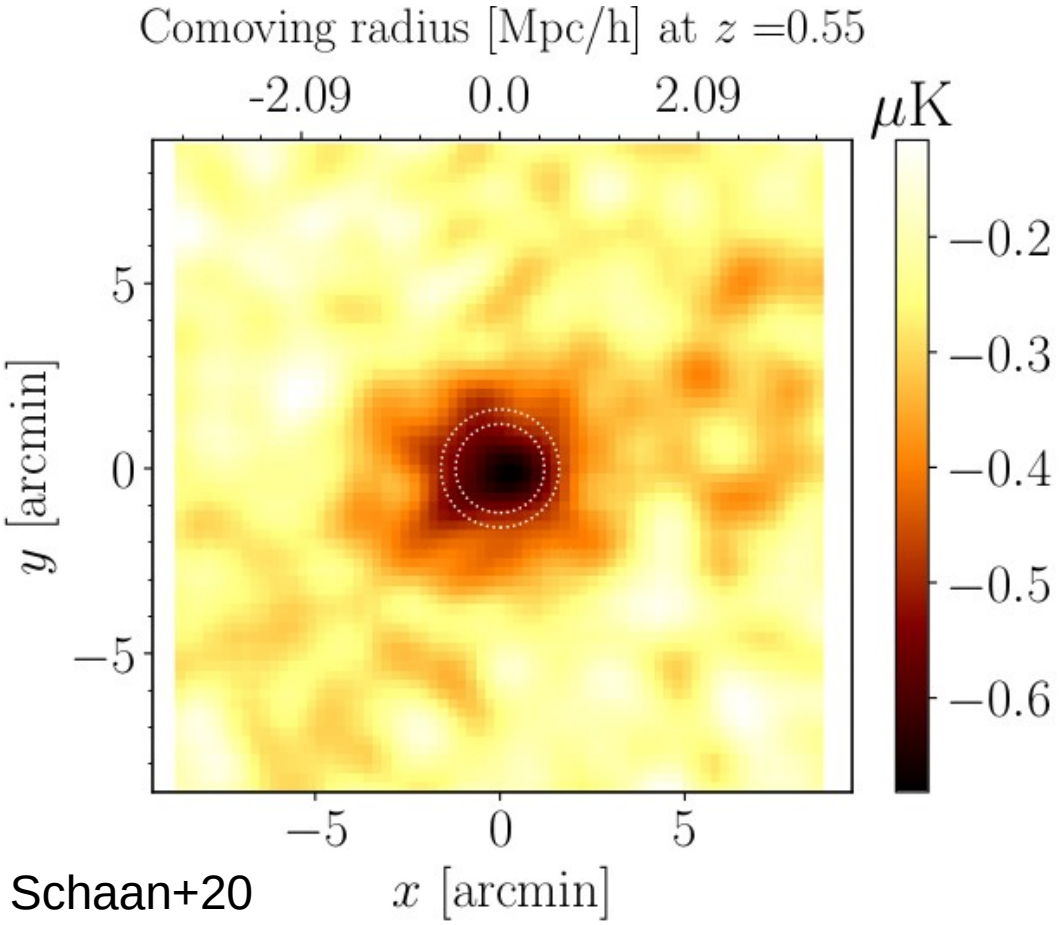


We find the measured lensing amplitude to be consistently low on all scales and for all masses. Difficult to explain by modeling or observational systematics.

Future Directions: Combined Probes, DESI and more

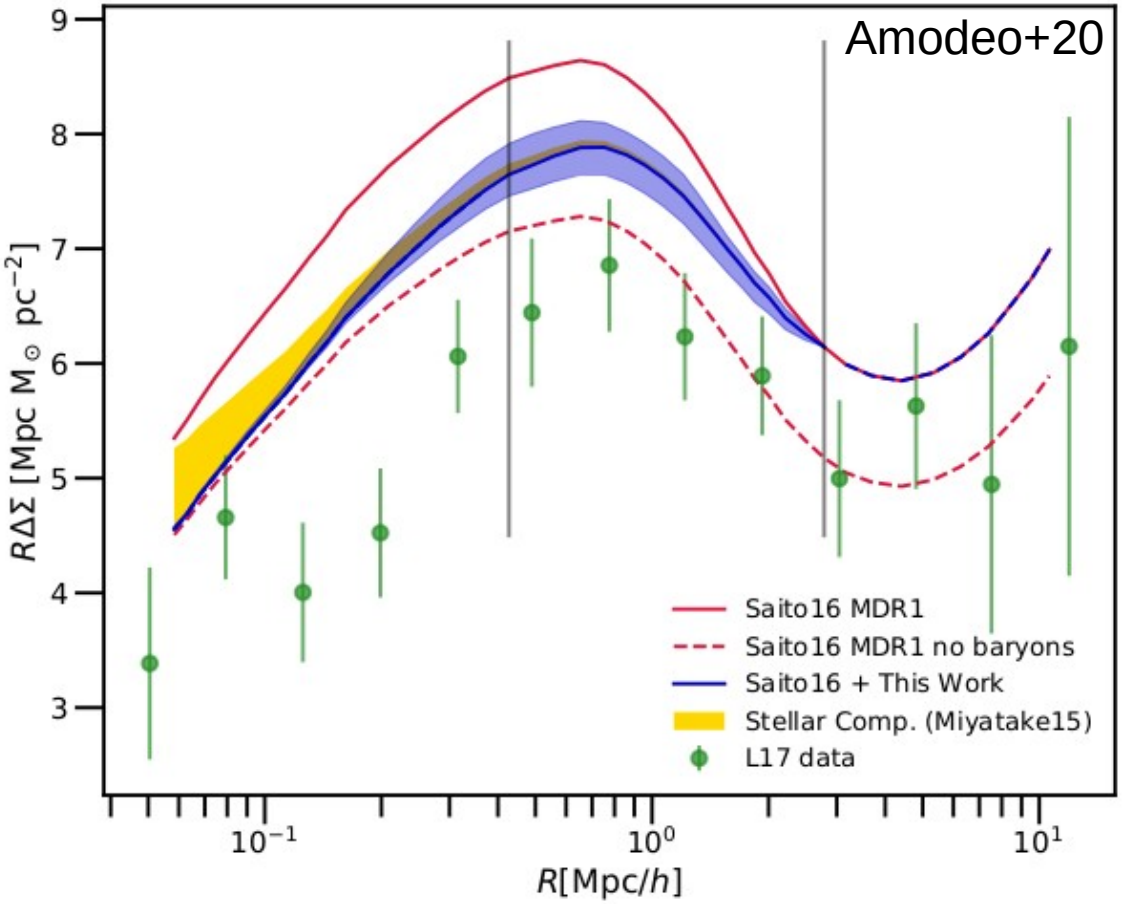
Constraints on Gas Dynamics from SZ



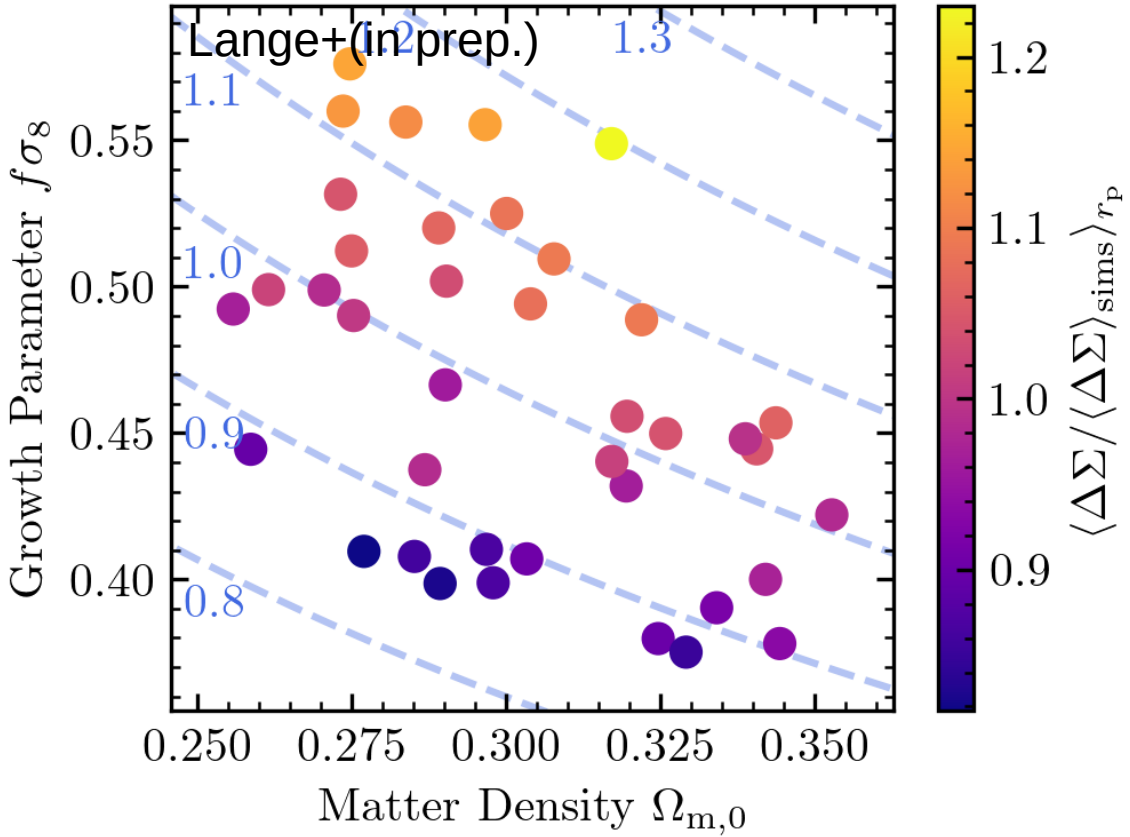


Schaan+20

SZ Tightly Constrains Baryonic Feedback



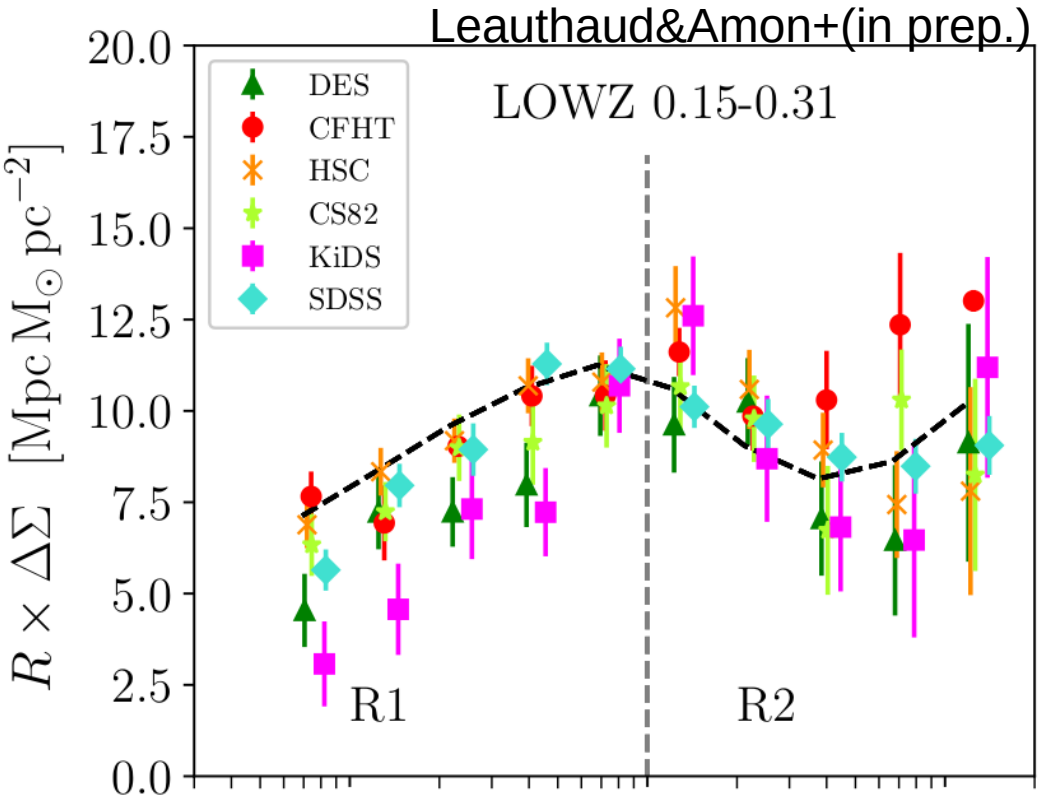
Putting it all Together



Small-Scale RSD+Lensing+SZ

- Cosmology, breaking Ω_m-σ_8 degeneracy
- Baryonic feedback, including impact on shear
- General Relativity
- Galaxy-Halo Connection

Galaxy-Galaxy Lensing in DESI

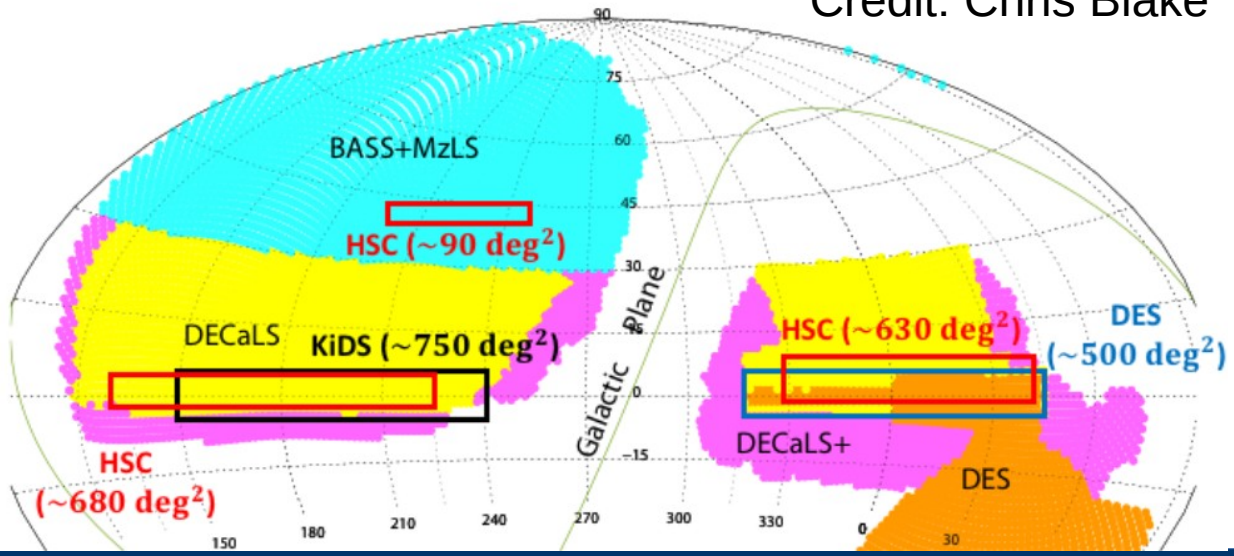


- $\Delta\Sigma$ physical quantity → same for different imaging surveys → empirical tests for lensing systematics
- Tests with BOSS compatible with no unknown systematics

Galaxy-Galaxy Lensing in DESI

- DESI will have more overlap, HSC/DES/KiDS more data → factor few better S/N
- Framework for unified lensing analysis
- C3 lensing mock challenge

Credit: Chris Blake



Summary

- We're in a new stage of fully simulation-based analysis of non-linear scales.
- Coming soon: High-precision growth rate constraints from BOSS LOWZ (Lange in prep.) and BOSS CMASS (Aemulus in prep.).
- Non-linear scales support idea that S_8 tension is a genuine cosmological tension. Future work could distinguish between σ_8 vs. Ω_m tension.
- Combined analysis of SZ+RSD+Lensing will probe baryonic feedback, gravity, cosmology and galaxy physics.
- For DESI, we will have higher S/N and more robust lensing measurements. Cosmological constraints from non-linear scales will be further tested.