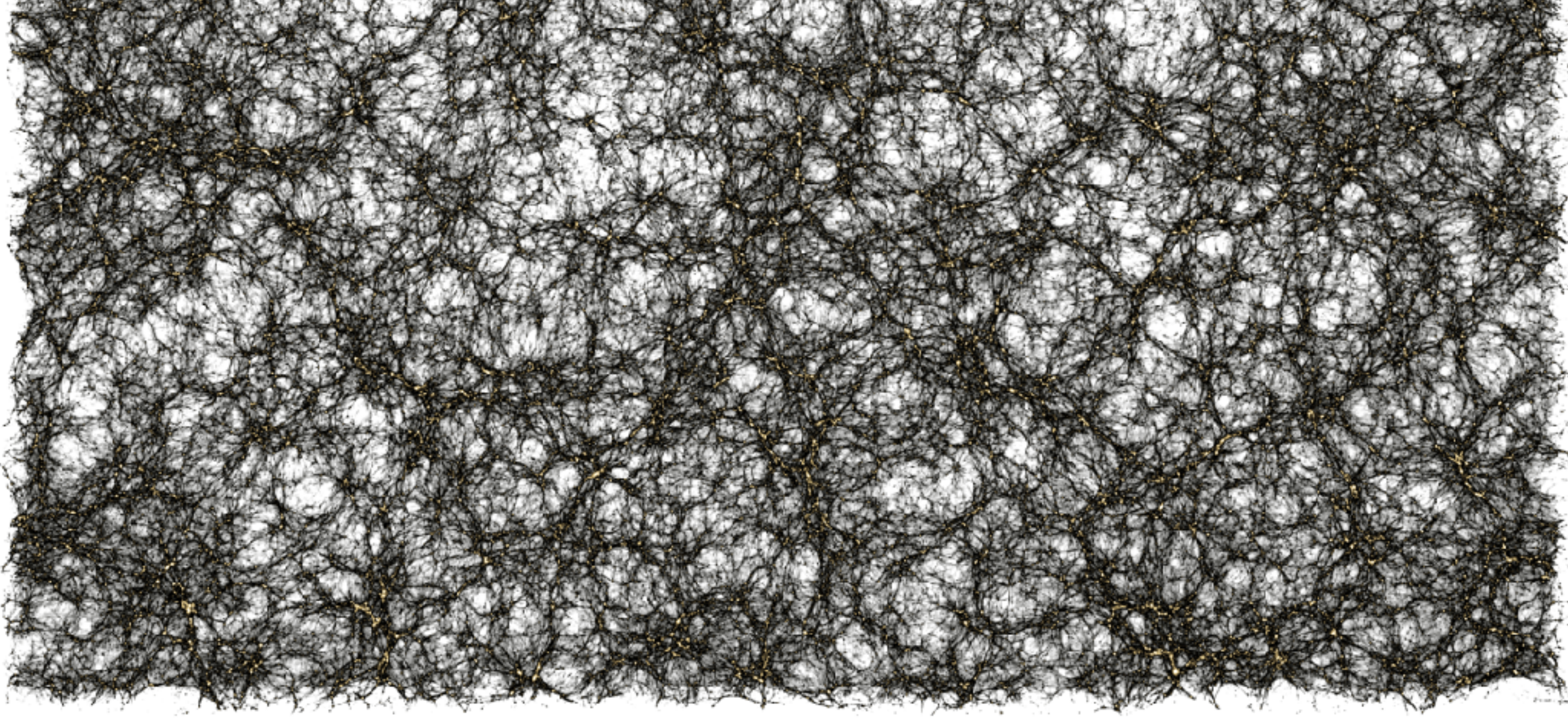


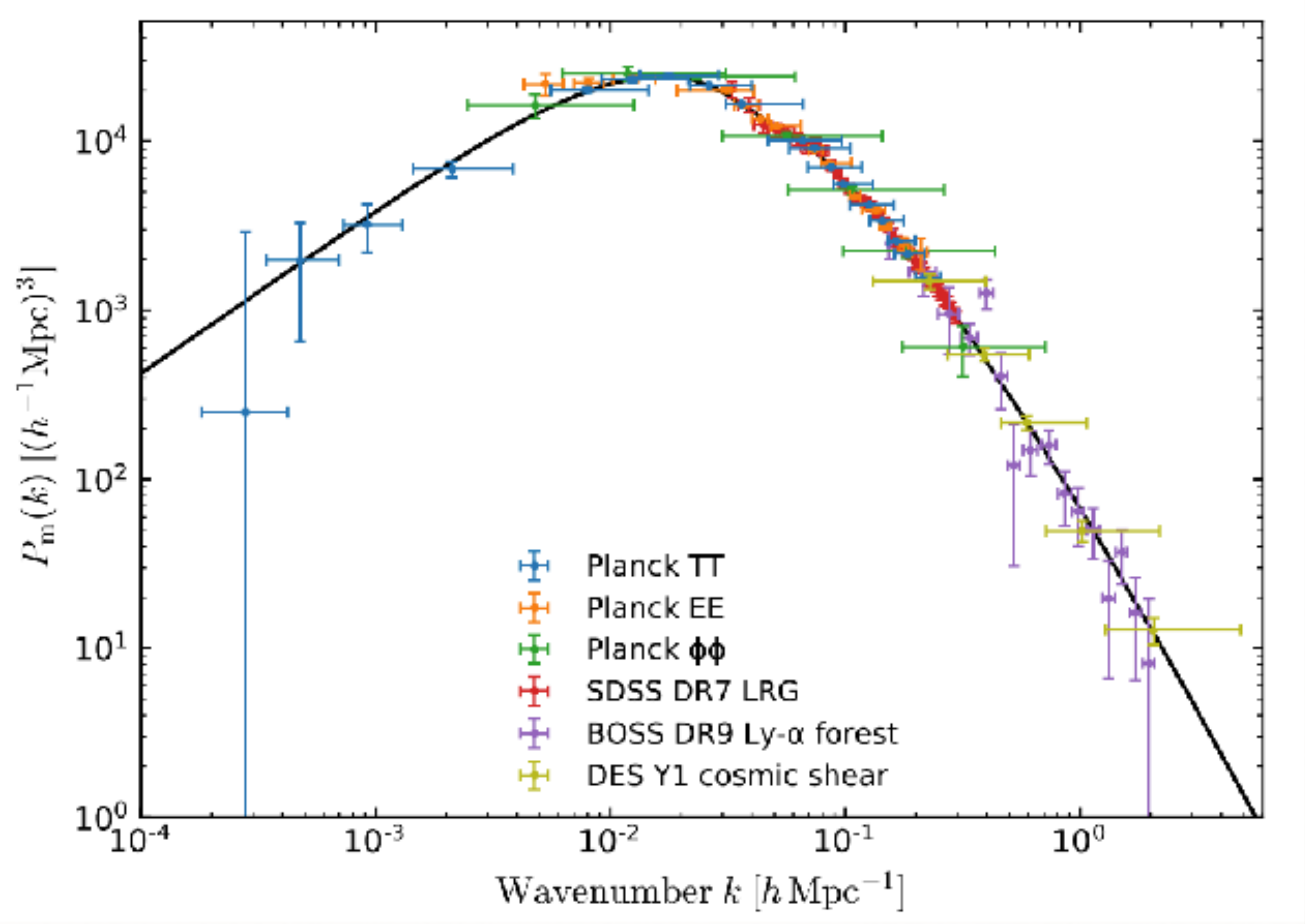
Modeling the Non-Linear Universe using Cosmological Simulations

Joe DeRose

9/4/18 — UC Berkeley

The Standard Model of Cosmology

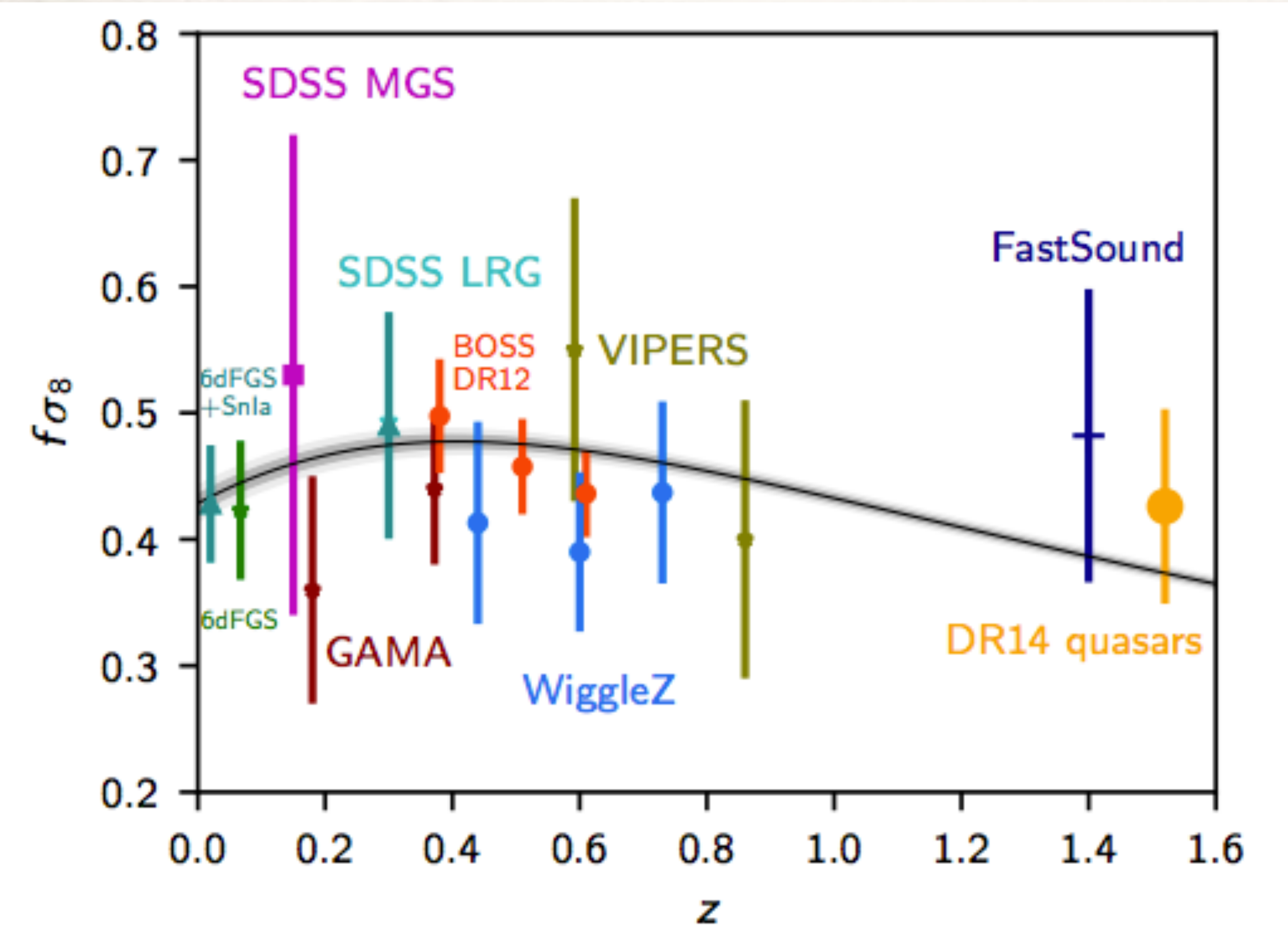
Planck Collaboration 2018



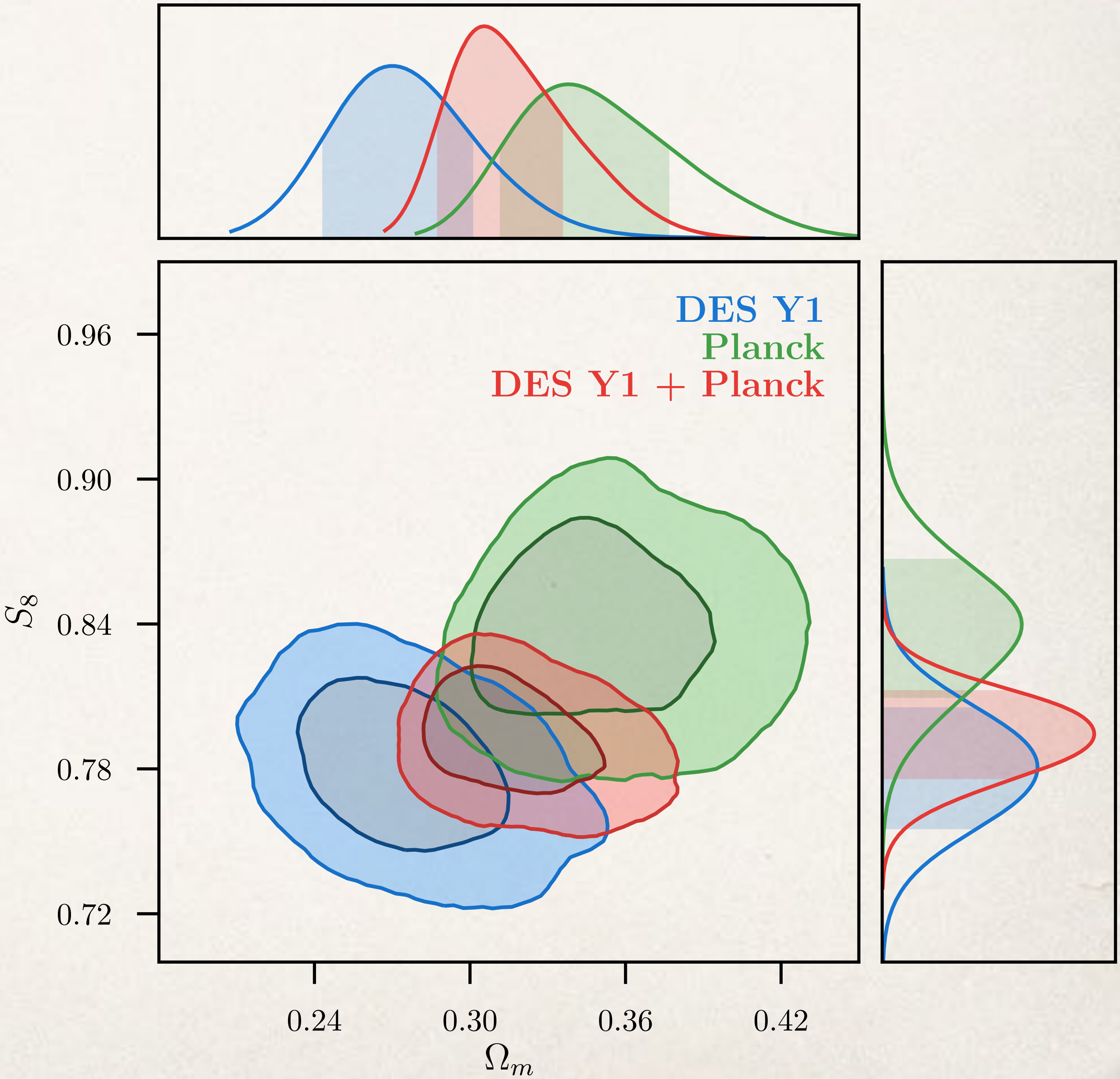
ΛCDM explains current observations to exquisite precision

Late-time Universe Tests

Planck Collaboration 2018

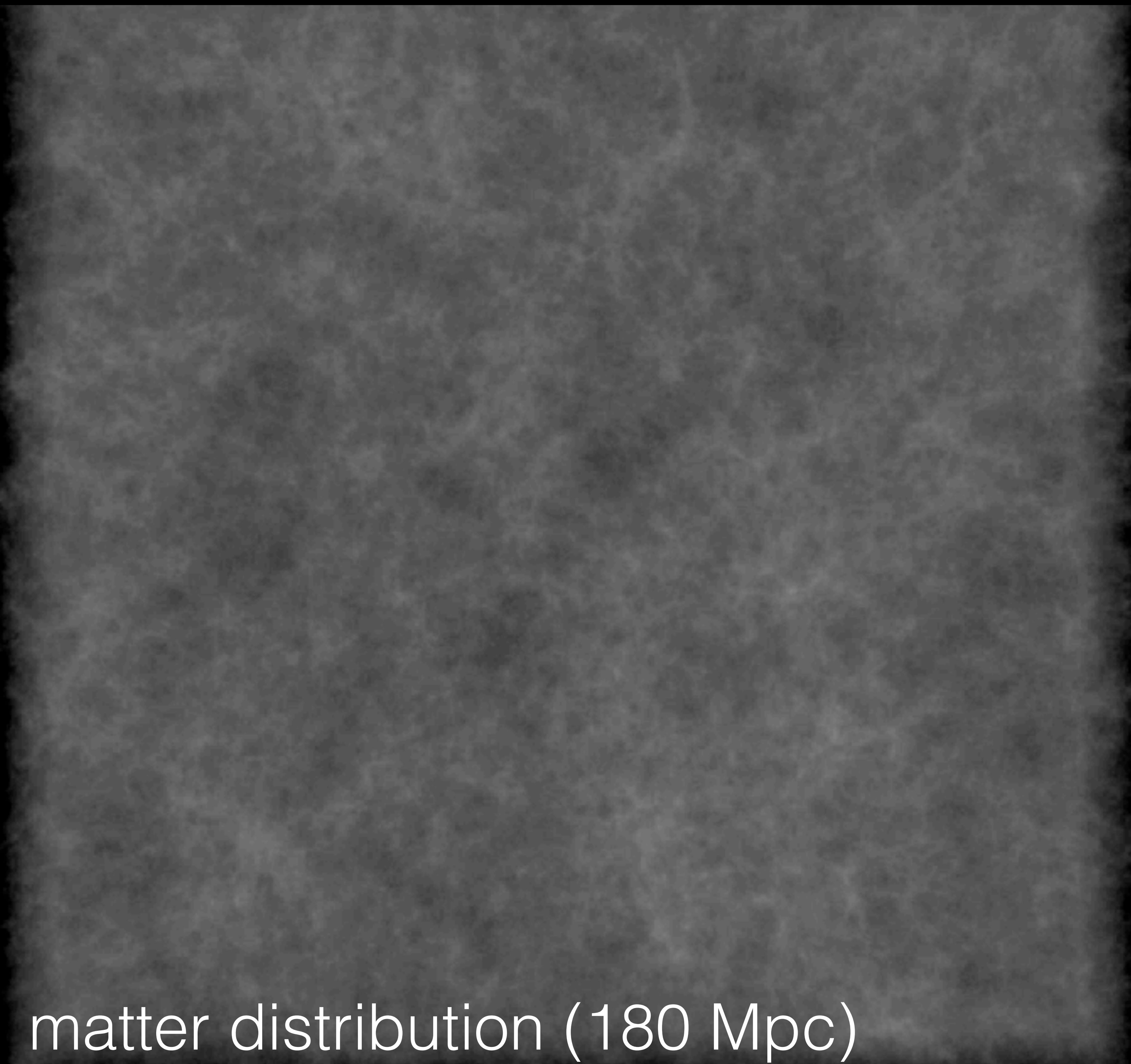


DES Collaboration 2018



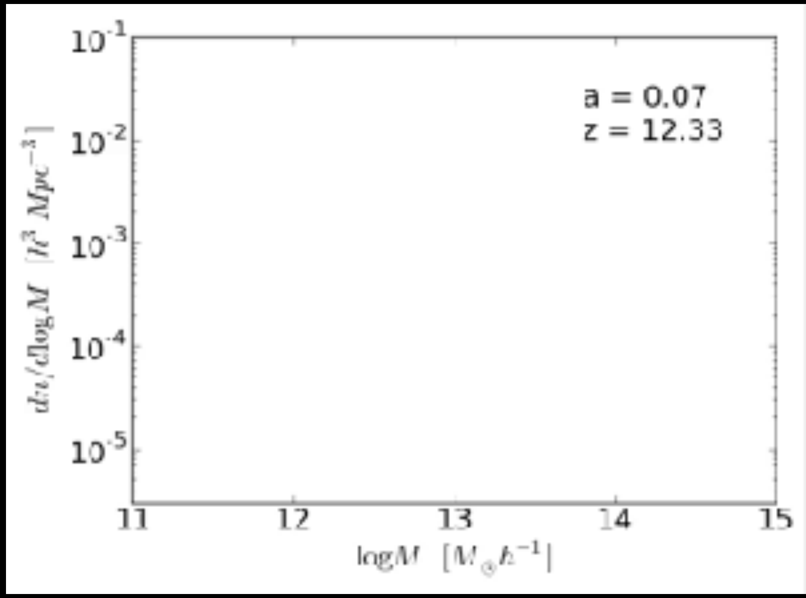
Stage III and Stage IV galaxy surveys will put it to the test

How does structure form?

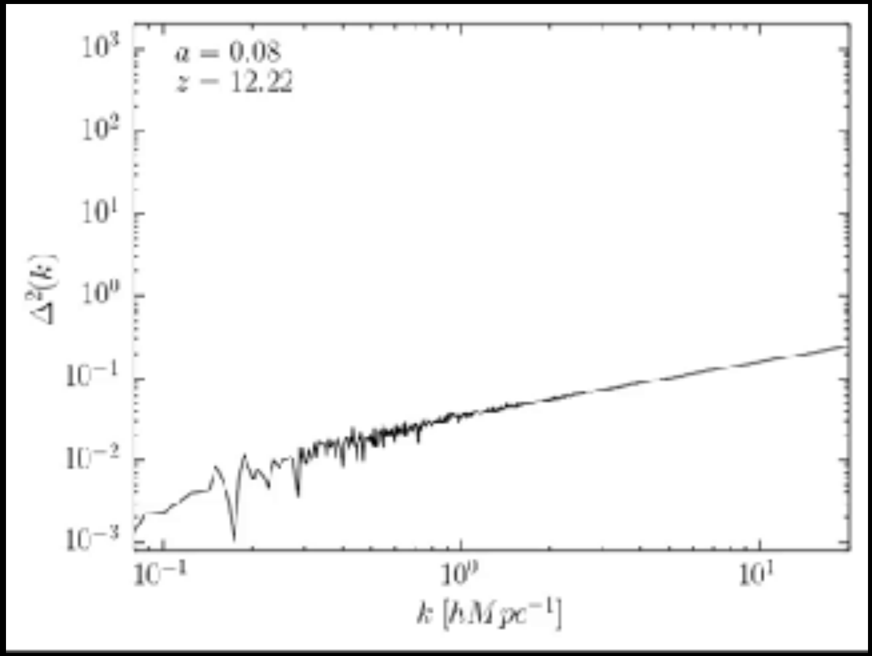


example statistics:

halo mass function



matter power spectrum



movie, simulation, statistics: Matt Becker, Ralf Kaehler, Yao-Yuan Mao, Rachel Reddick, Risa Wechsler (Stanford/SLAC)

Role of Cosmological Simulations in Modern Surveys

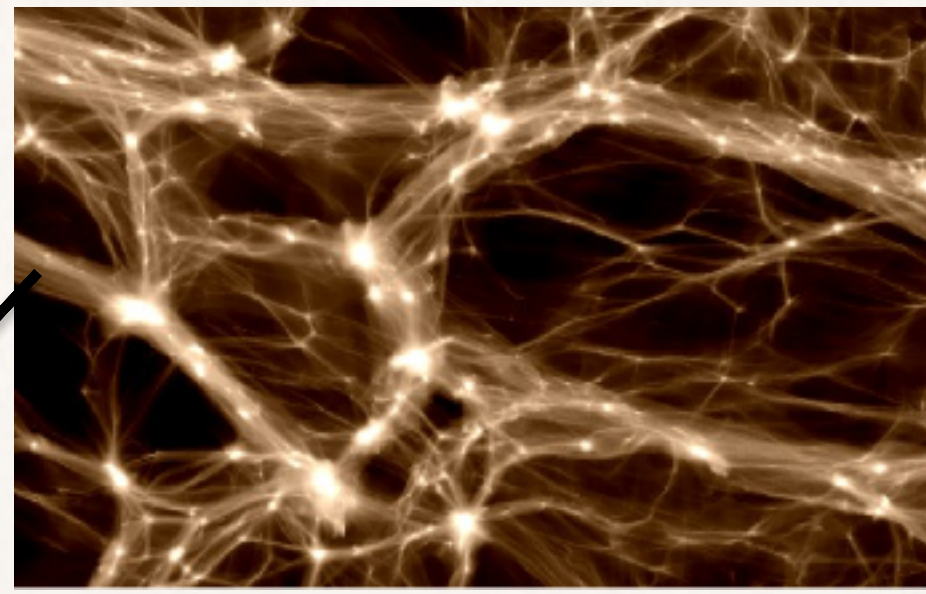
- **Part I**: The Mock as the Test
  - Systematics estimation and marginalization
  - Pipeline and algorithm development
  - Case study - the Dark Energy Survey

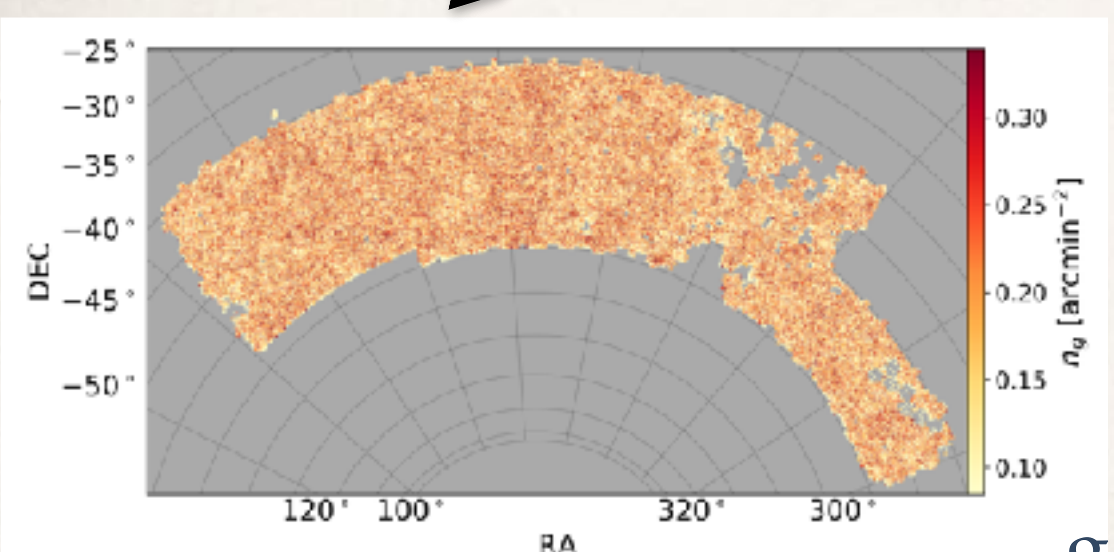
- **Part II**: The Mock as the Model
  - Accurate predictions for non-linear and highly complex observables
  - Covariances (not in this talk)

The Dark Energy Survey

- Imaging survey of the southern sky
  - ~5000 sq. degrees
  - 4m Blanco Telescope on Cerro Tololo, Chile
  - 5 bands: *grizy*
- Done taking 5 years of data, results published for first year (Y1) and working on analyzing first 3 years (Y3)

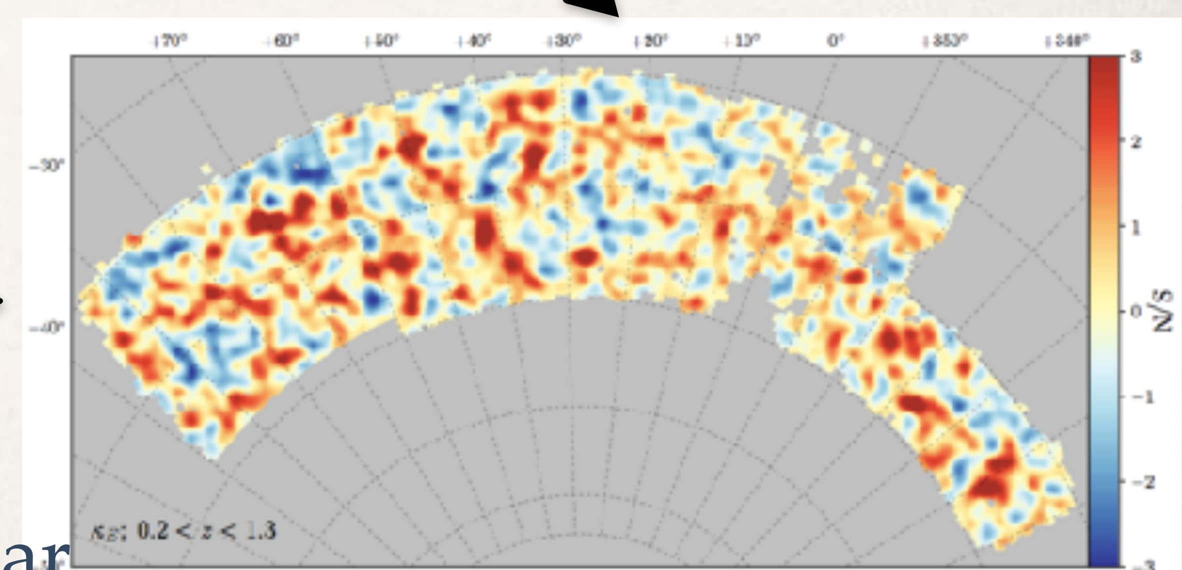
DES Year 1 Cosmology: 3x2pt





galaxies x galaxies
angular clustering

galaxies x shear
galaxy-galaxy lensing

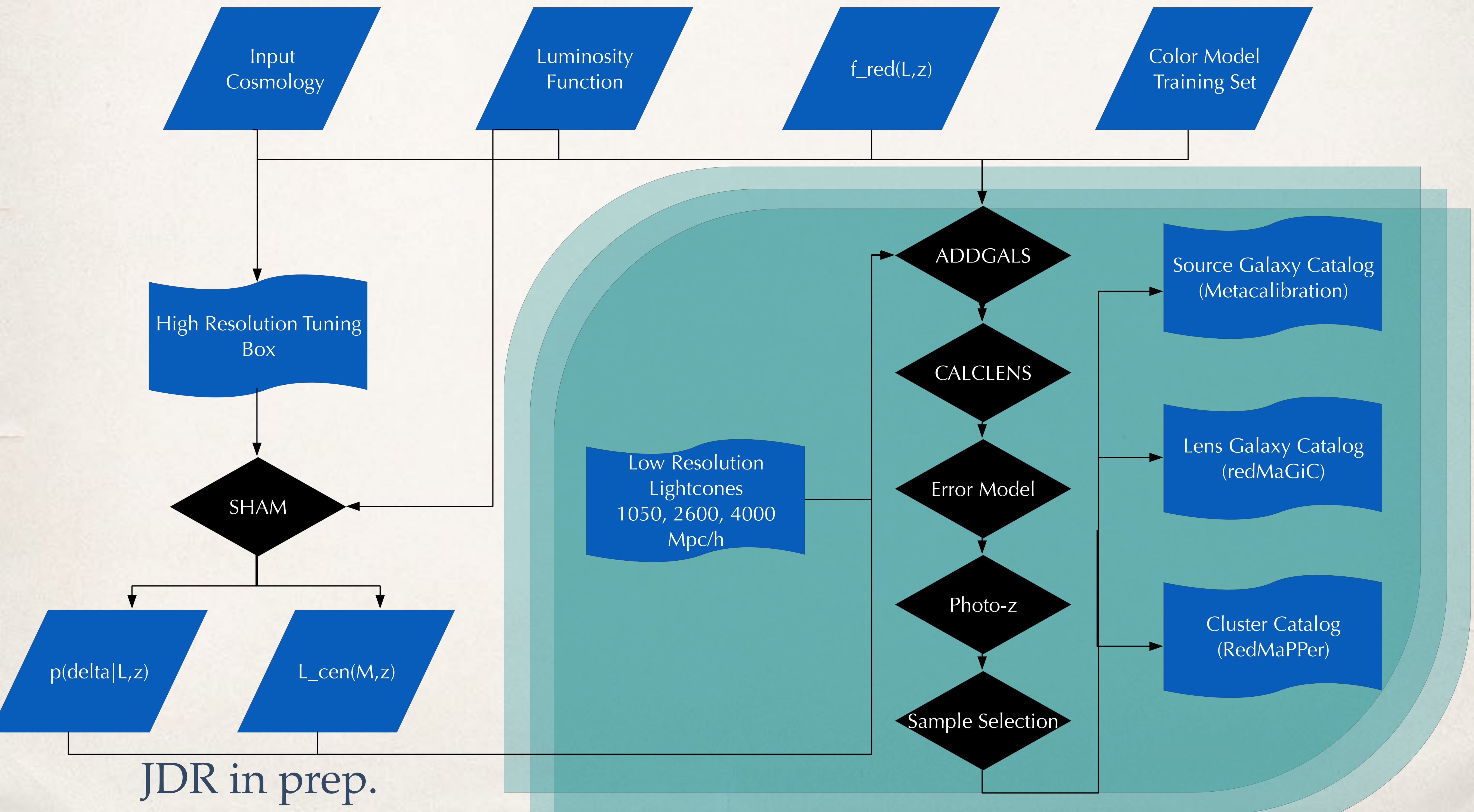


lensing x lensing
cosmic shear

Pipeline Testing

- Is my pipeline accurate enough for the statistical precision of my data?
  - Robustness to modeling assumptions
    - galaxy bias, photo-zs, intrinsic alignments, baryons, shear calibration, etc.
  - Blind challenges: can I recover a range of possible cosmologies
- Requirements
  - Models all probes accurately (e.g. clustering and lensing)
  - Many times the volume of the survey (must be inexpensive)
  - Variety of galaxy models at each cosmology

Our Solution: The Buzzard Flock

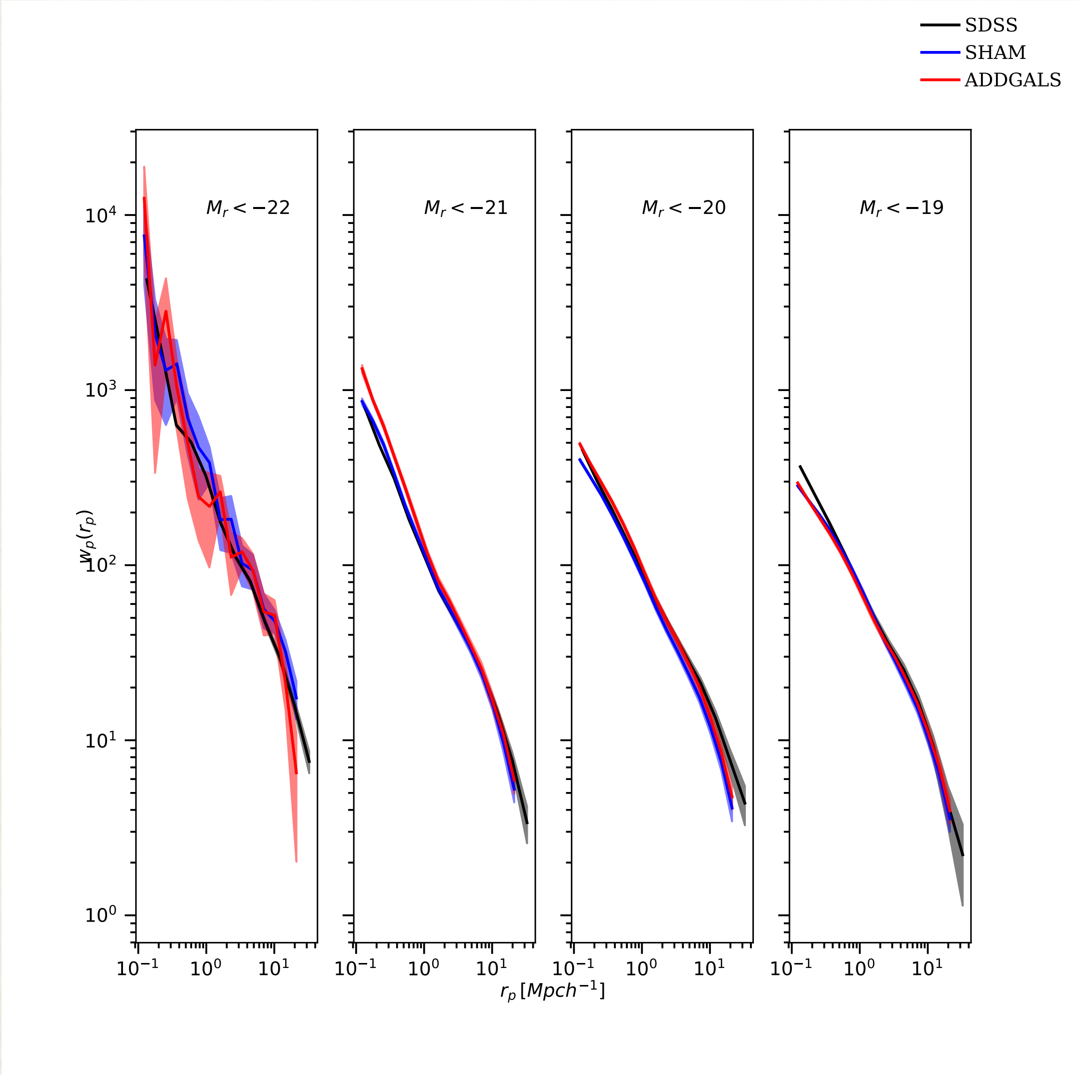


JDR in prep.

ADDGALS

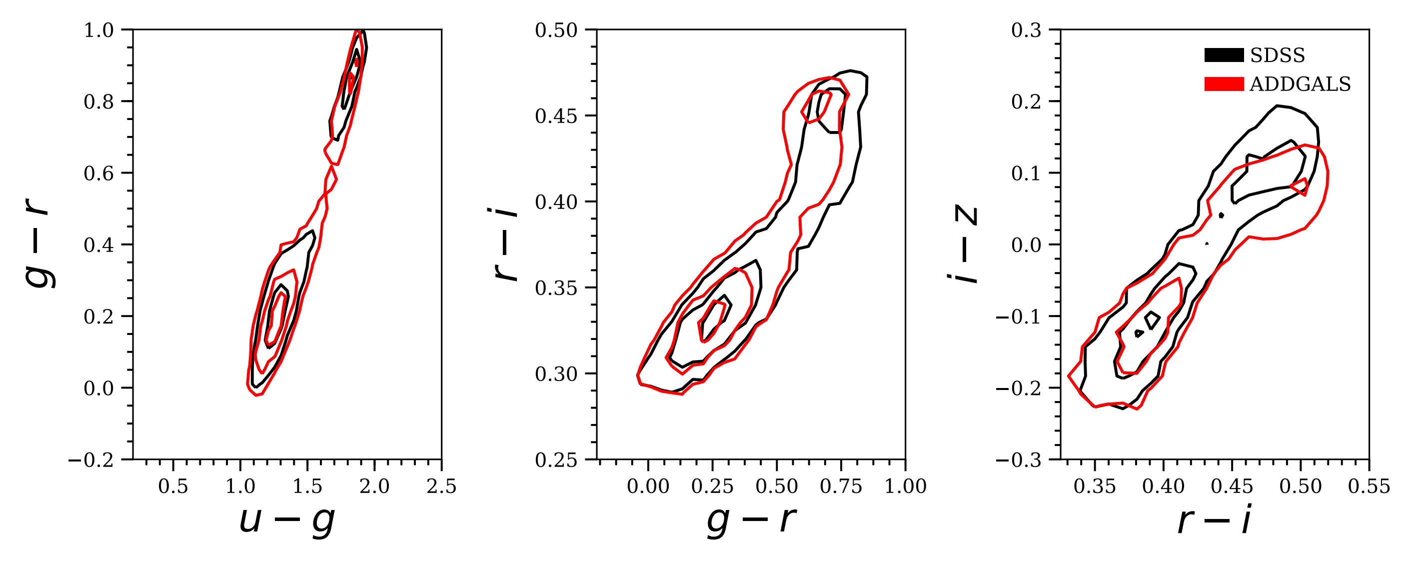
Adding Density Determined Galaxies to Lightcone Simulations

- Assign galaxies to particles in lightcone with using $p(\delta \mid L, z)$ tuned from Abundance Matching



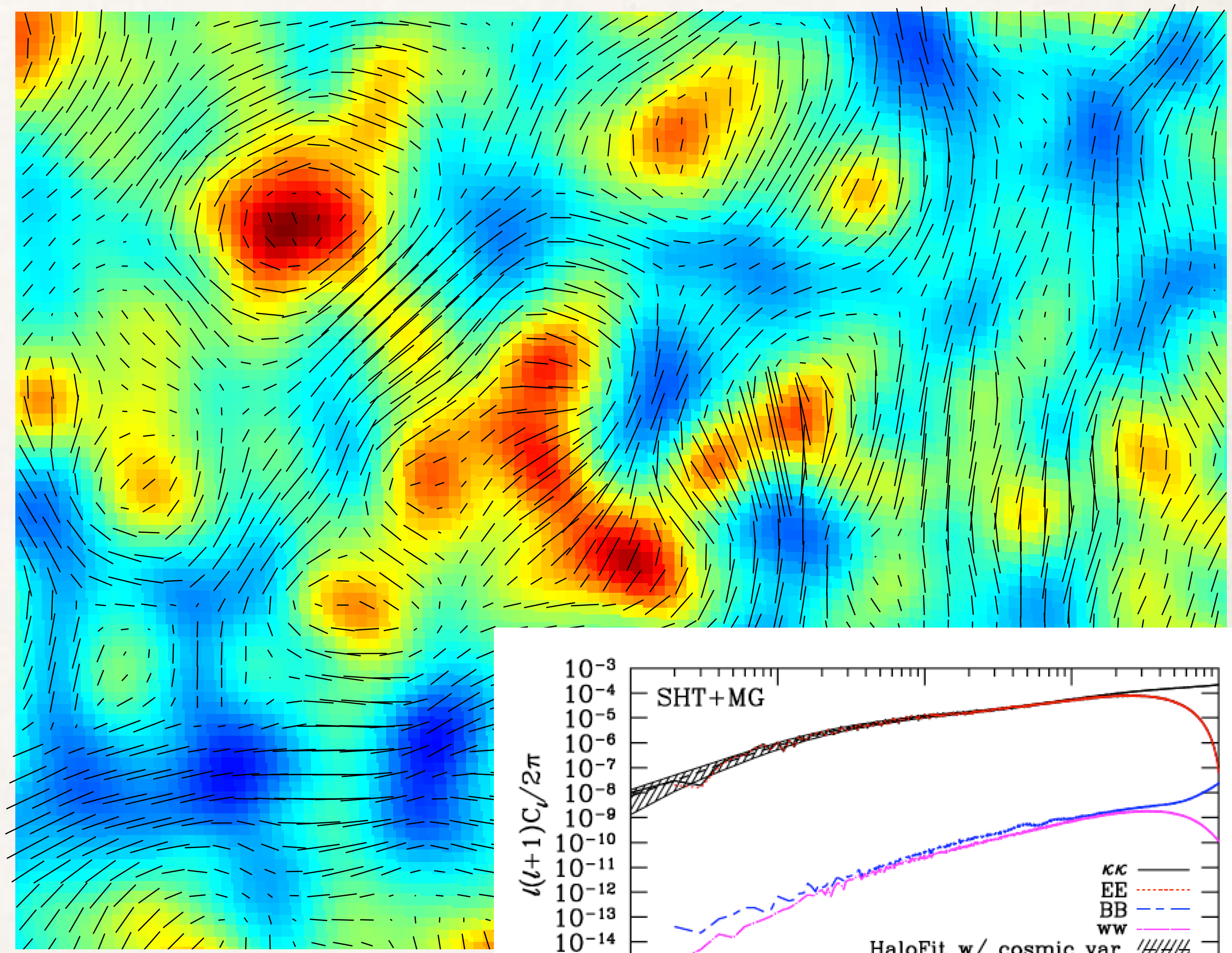
Wechsler, JDR in prep.

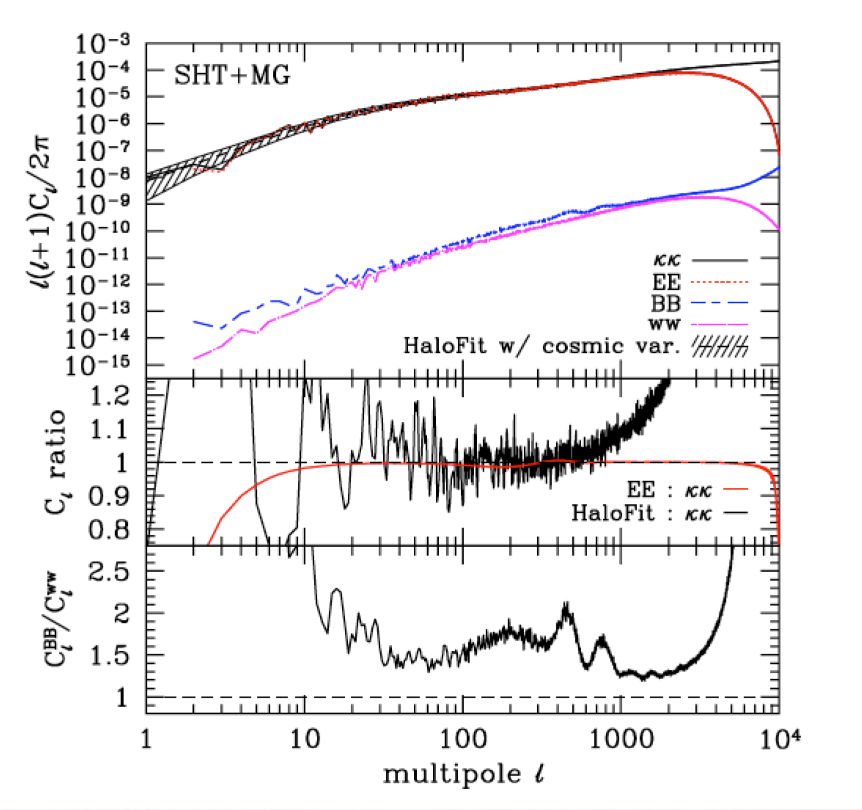
Colors assigned using SED-density relation in SDSS



CALCLENS

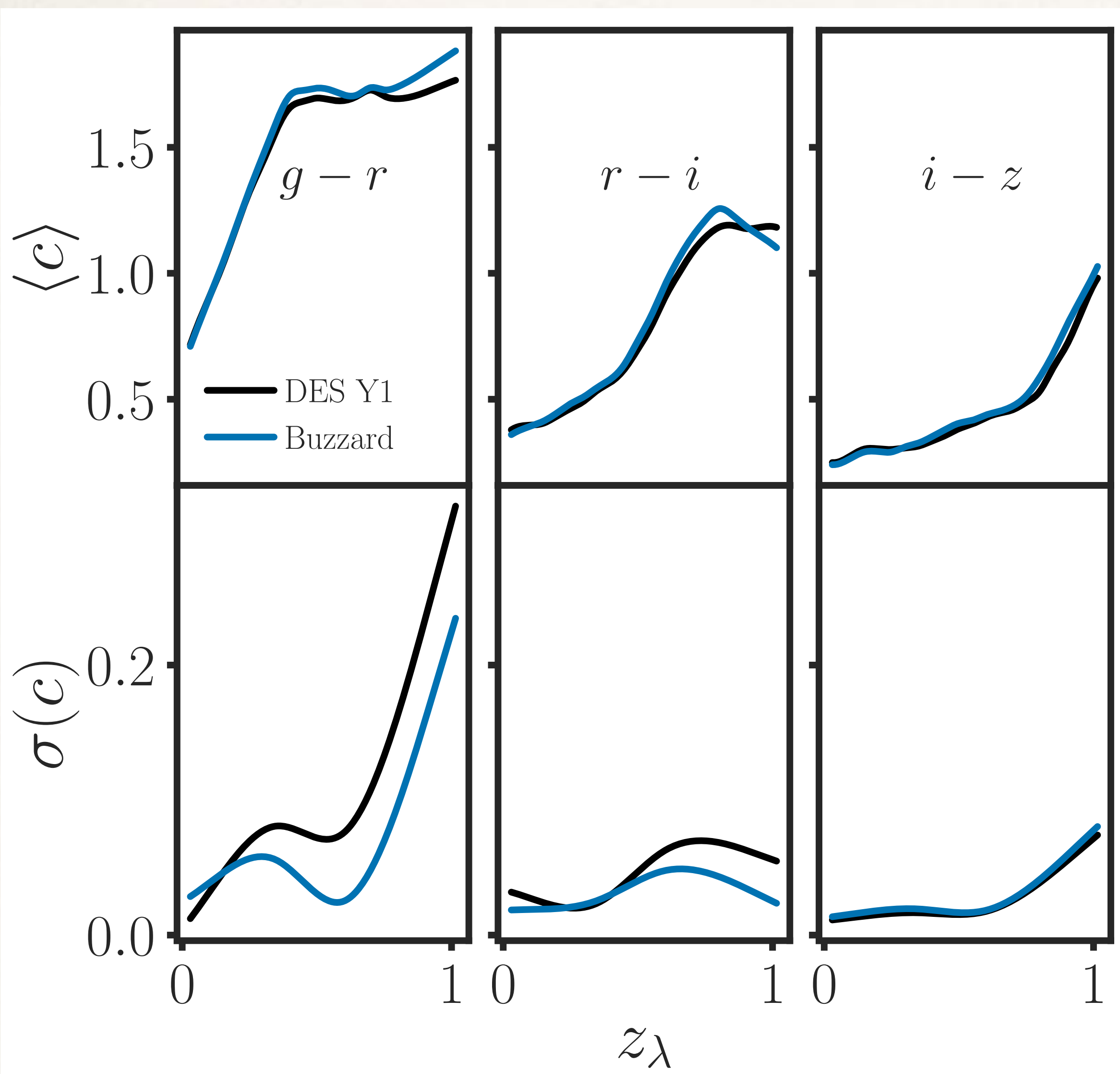
- Ray-tracing on nside=8192 healpix grid
- Spherical harmonic transform Poisson solver
- Calculates shear, convergence for all galaxies

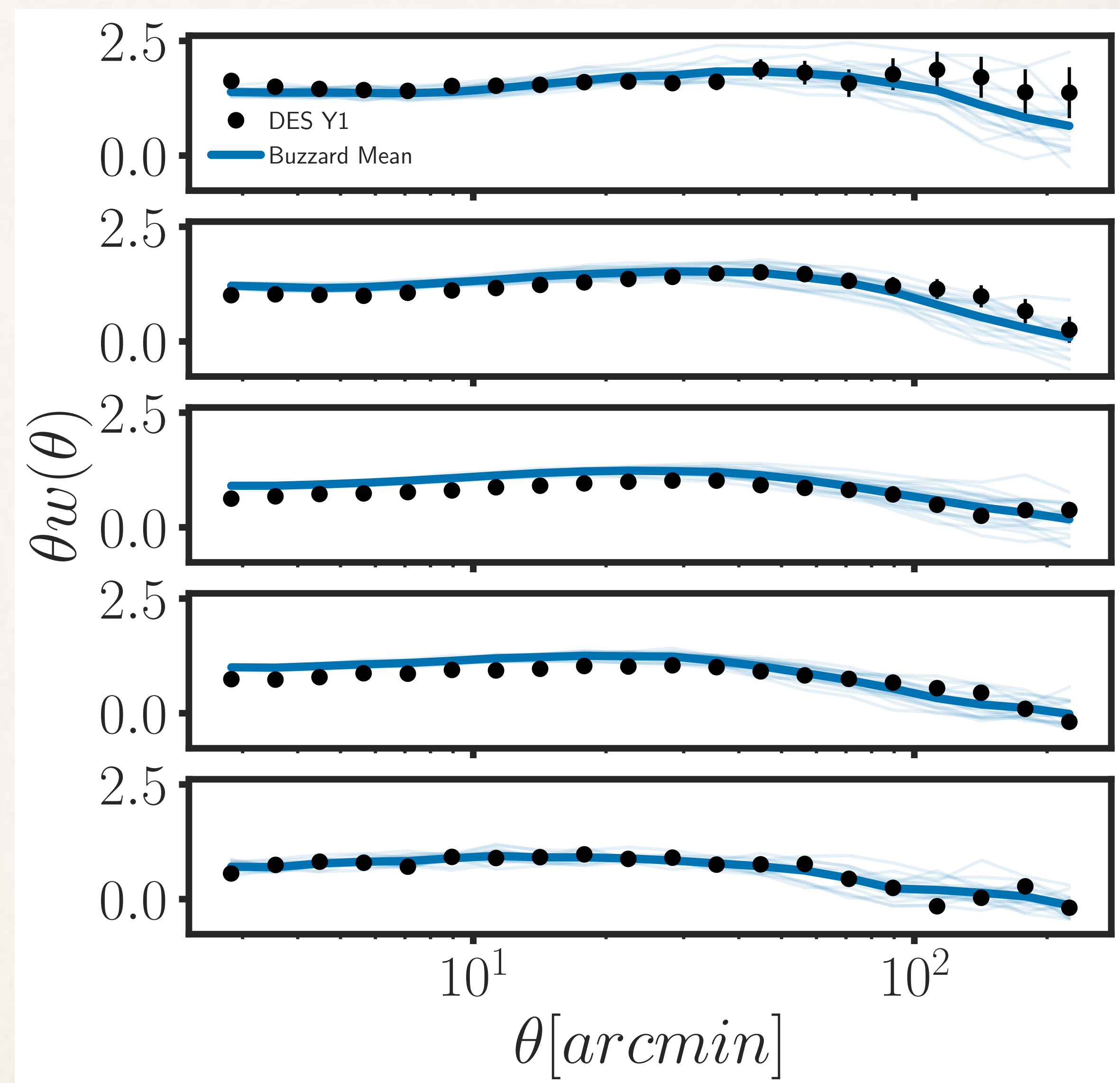




Becker 2013

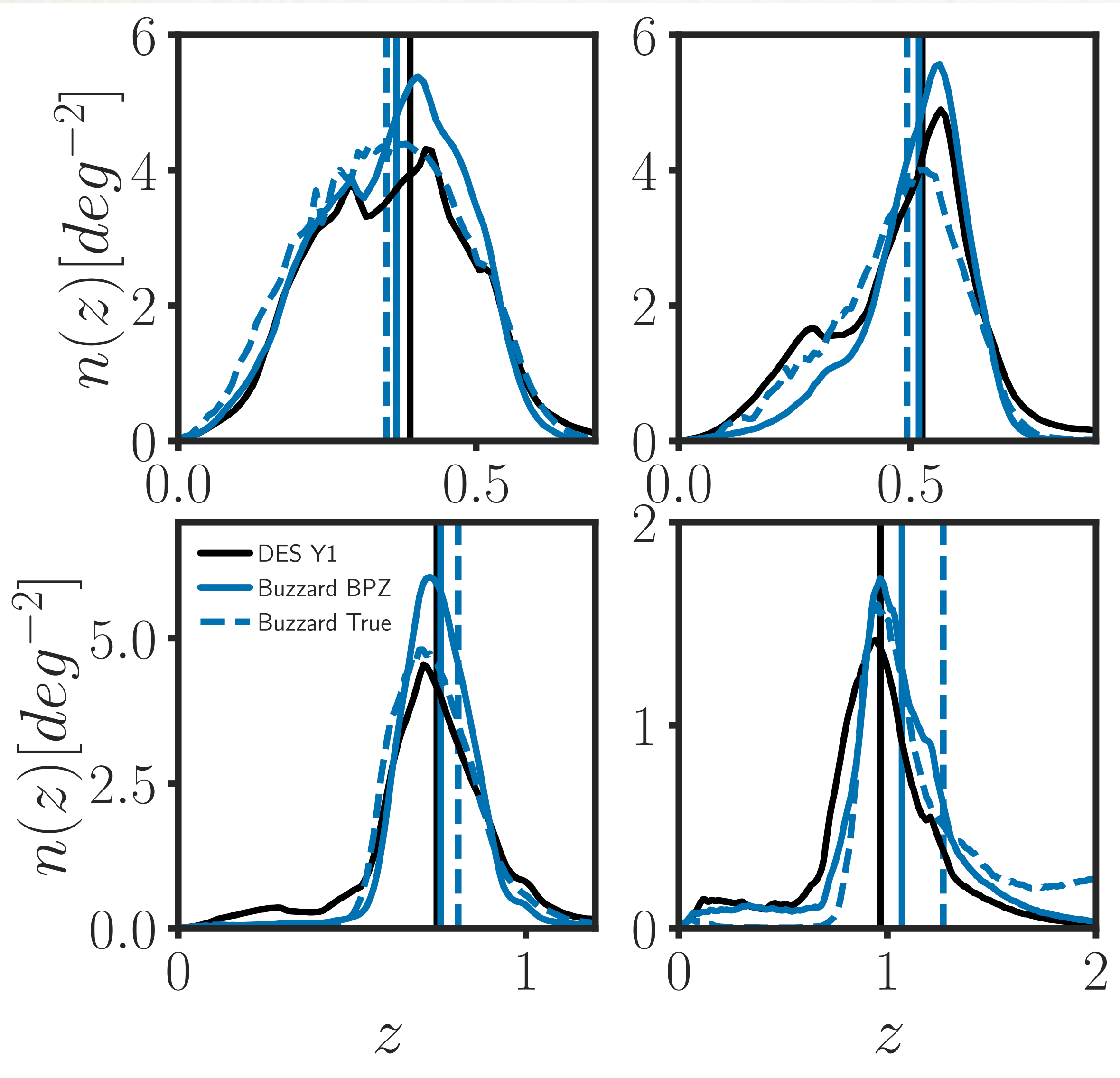
Realistic Observables: Lens Galaxies

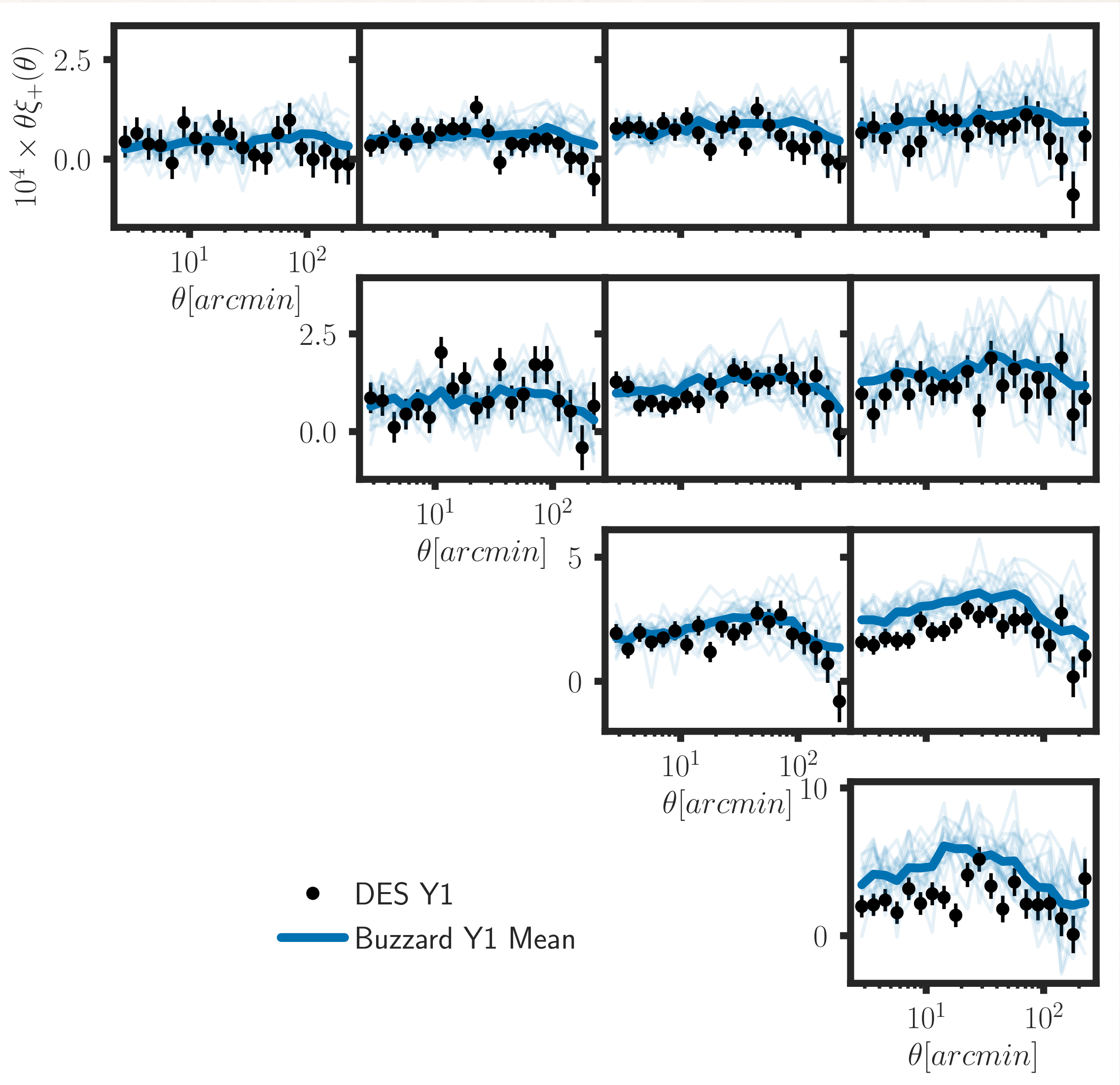




Robust red-sequence allows high fidelity redMaGiC sample selection

Realistic Observables: Source Galaxies

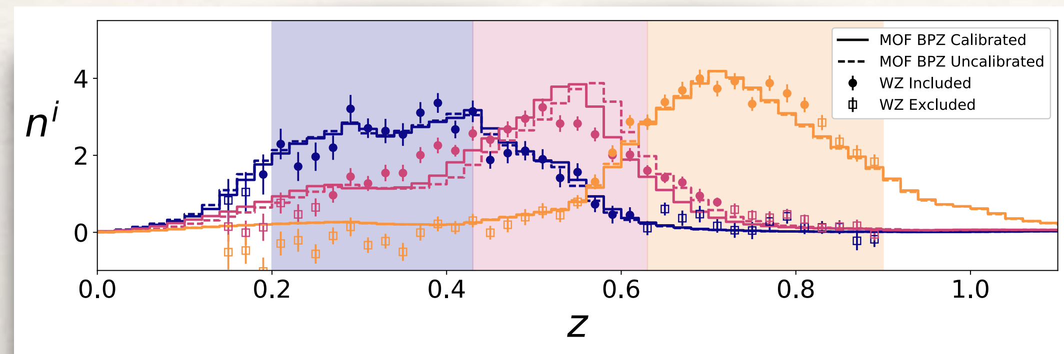




Metacalibration like sample selected with similar S/N properties as data.

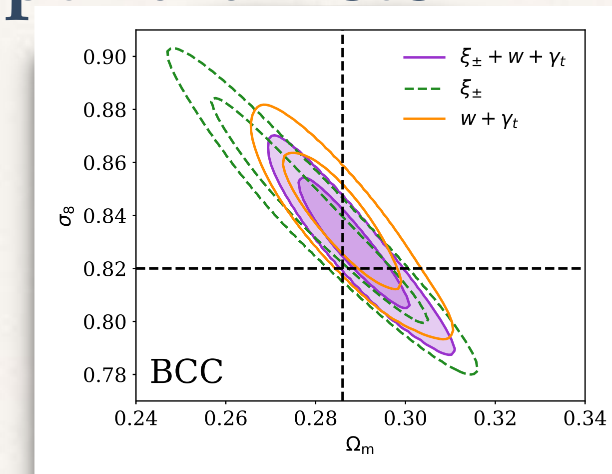
Buzzard sims used in a 11/14 of "DES Y1 Results"

Redshift Estimation



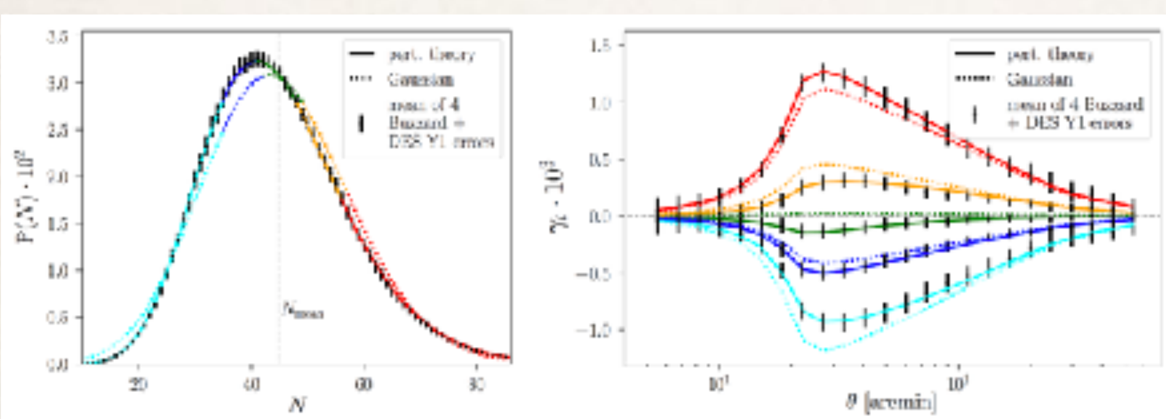
Gatti, Vielzeuf et al.
Hoyle et al.

3x2pt Parameter Inference



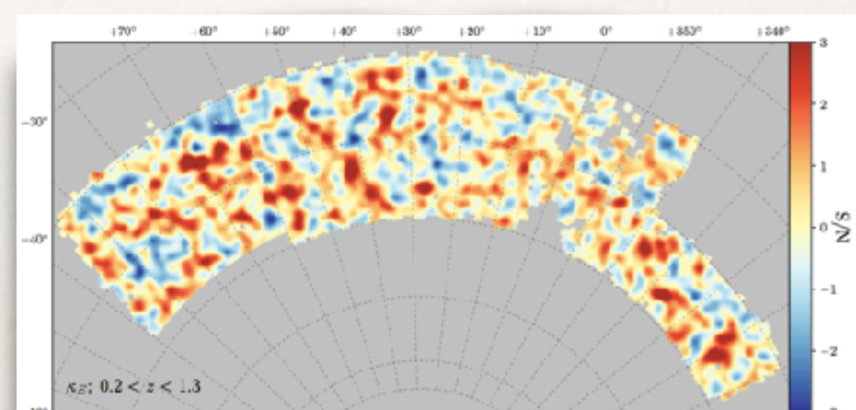
MacCrann, JDR et al. 2018

Density Split Statistics



Gruen, Friedrich, Krause, JDR et al.
Friedrich, Gruen, JDR, Krause et al.

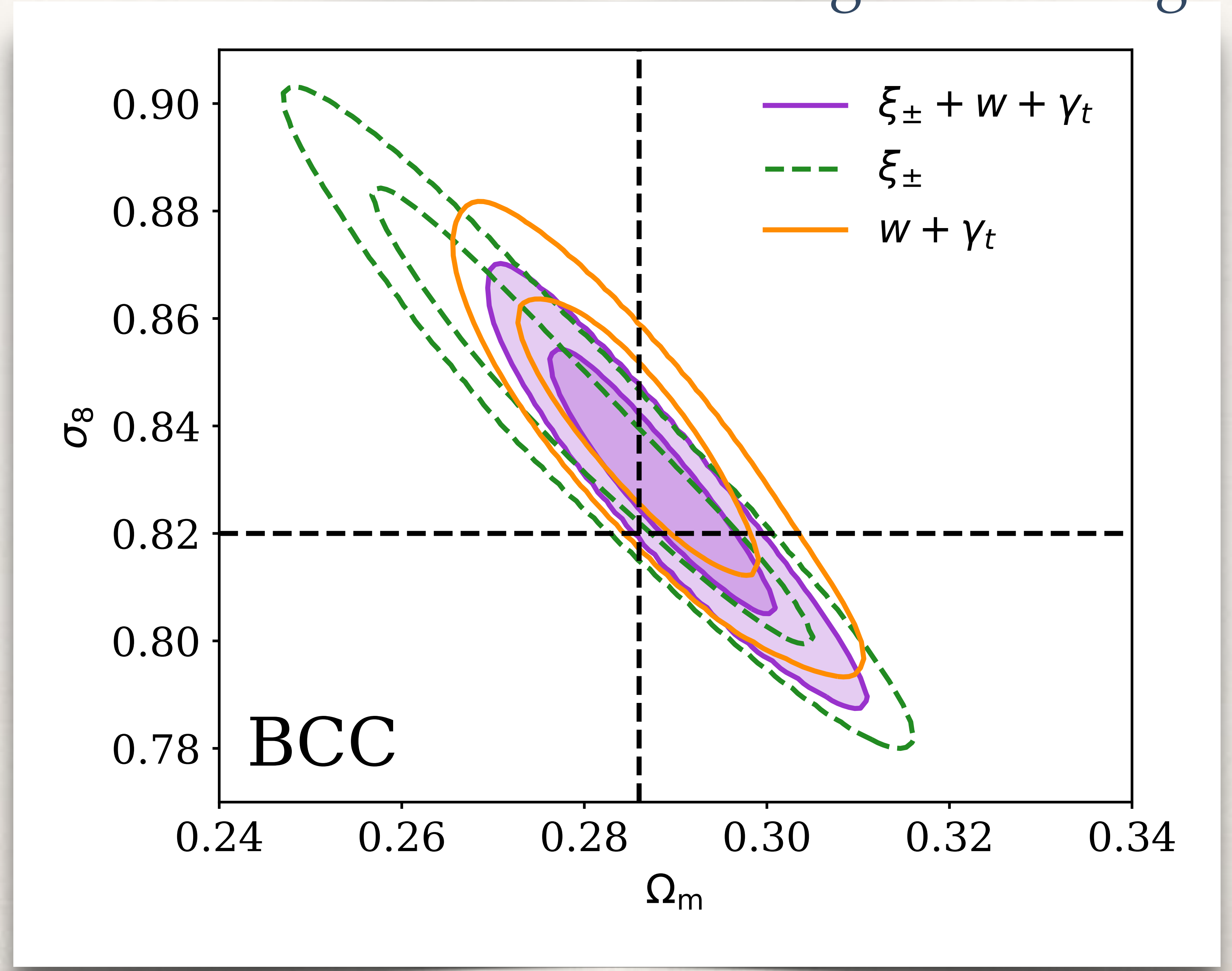
Mass Mapping



Chang et al. 2018

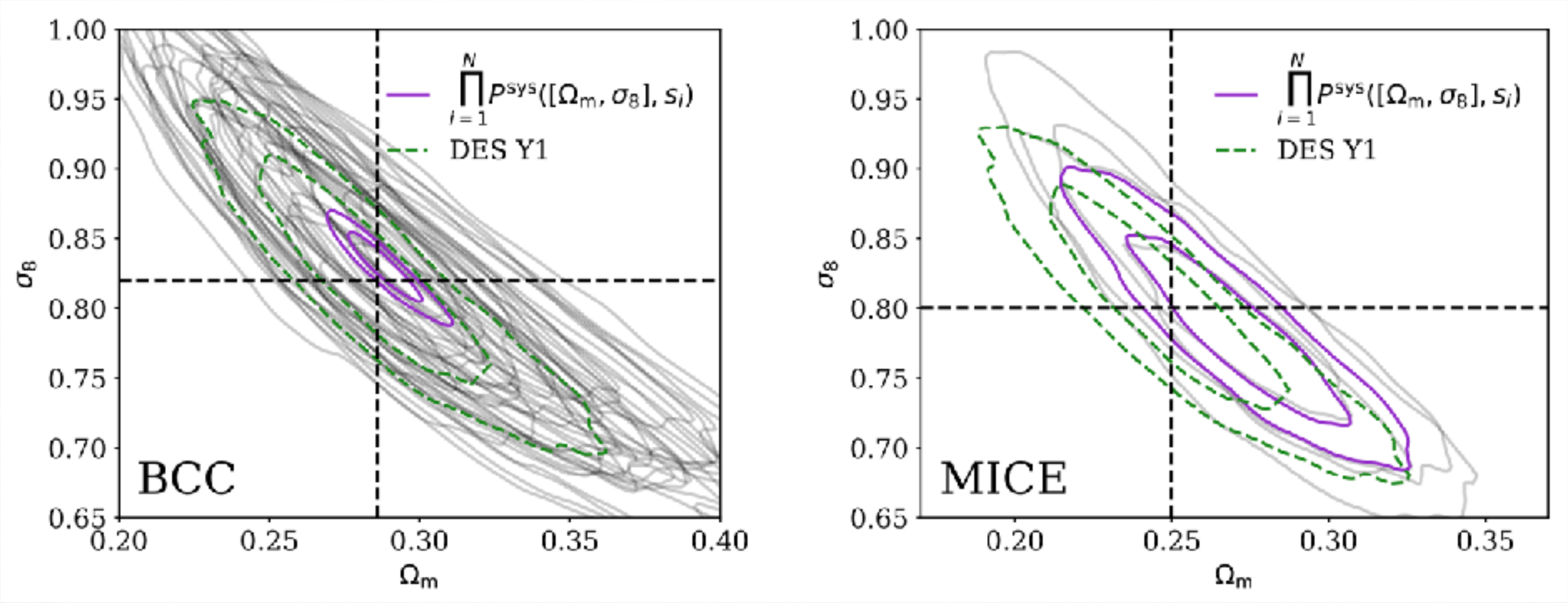
Highlight: Validating the 3x2pt Pipeline

Constrained biases on inference to <1 sigma with high confidence



MacCrann, JDR et al. 2018

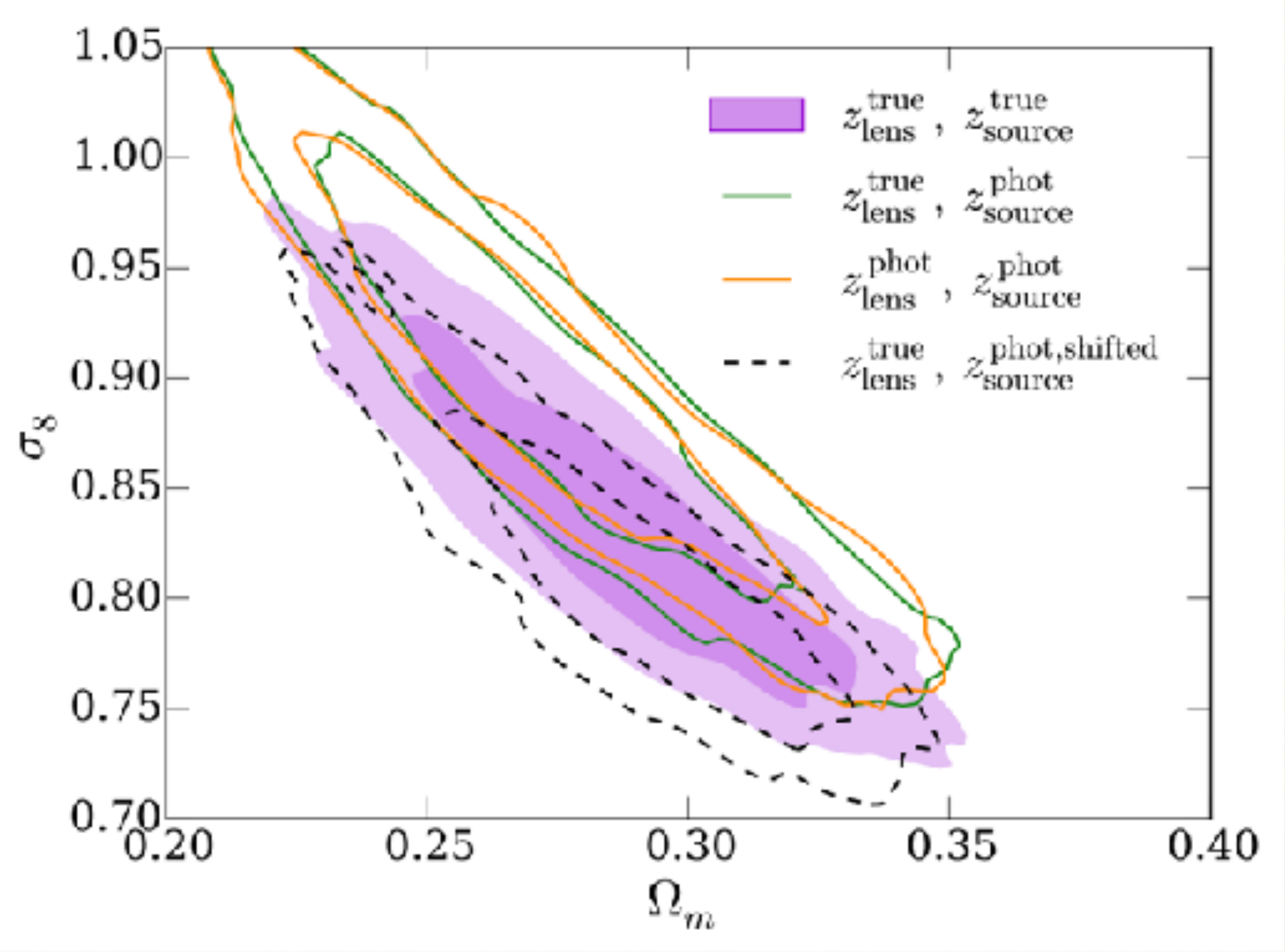
Highlight: Validating the 3x2pt Pipeline



Results corroborated from an independent simulation.

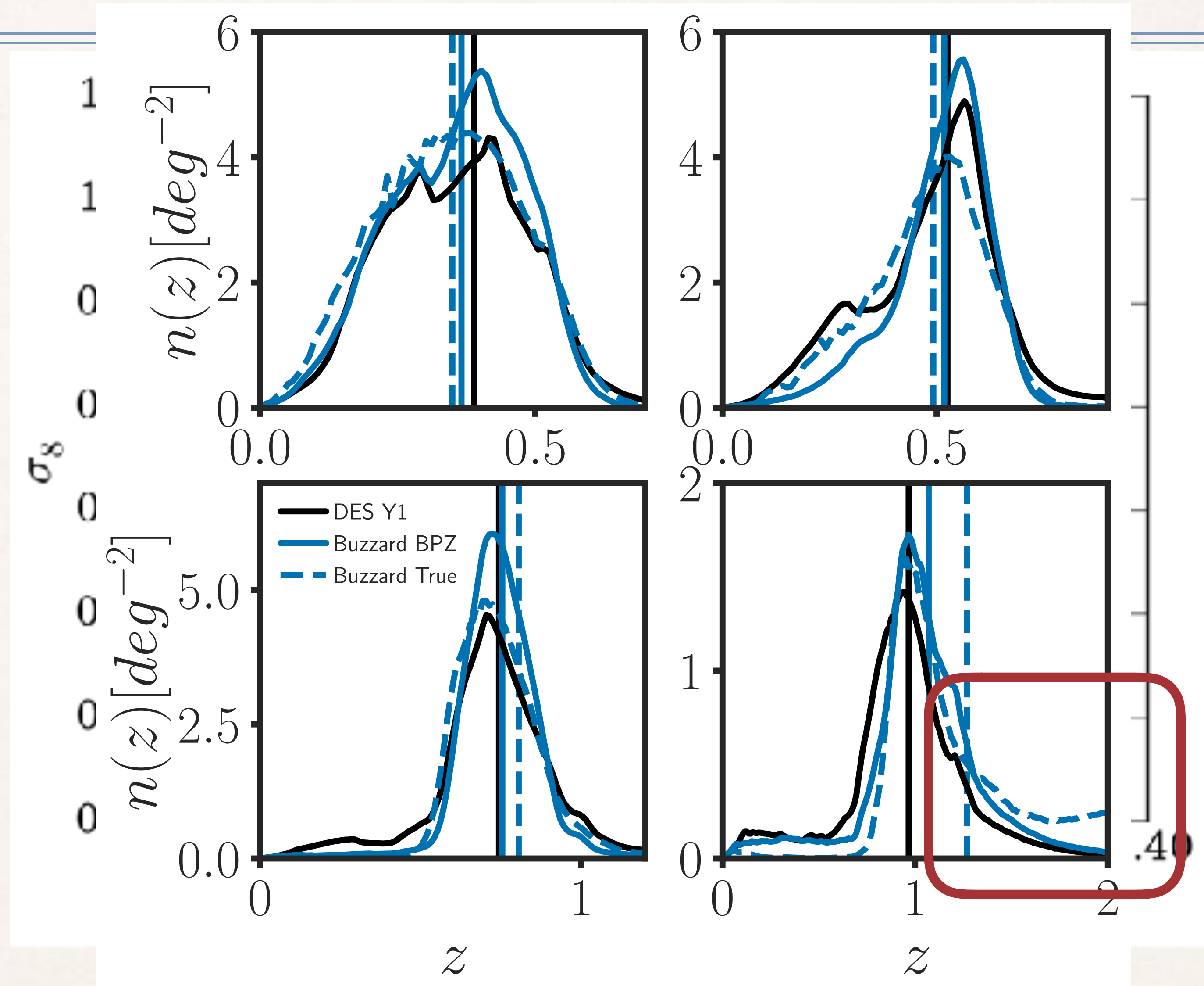
MacCrann, JDR et al.

Modeling Photo-zs



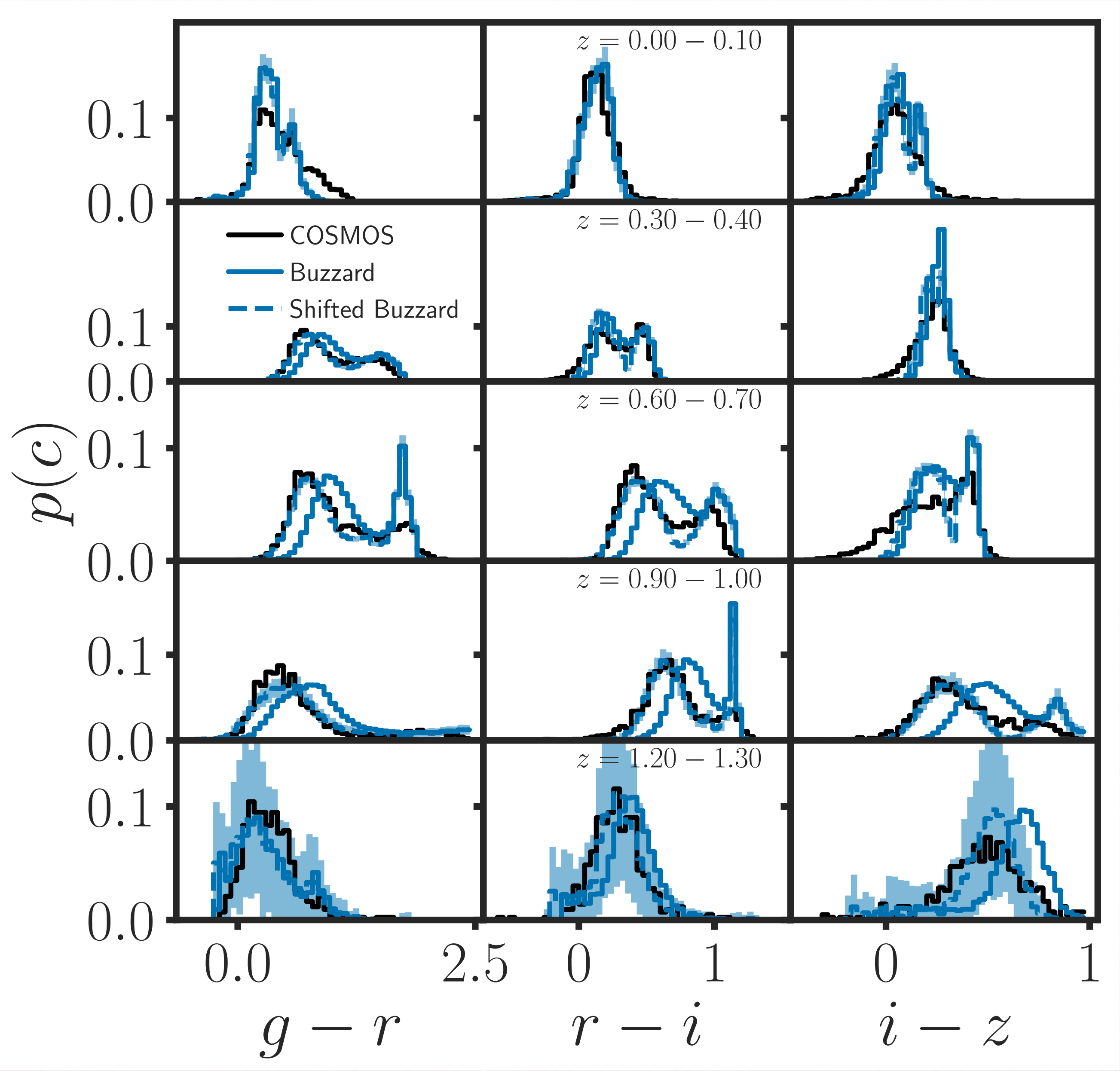
We weren't quite able to draw conclusions about photo-z marginalization

Modeling Photo-zs



We weren't quite able to draw conclusions about photo-z marginalization

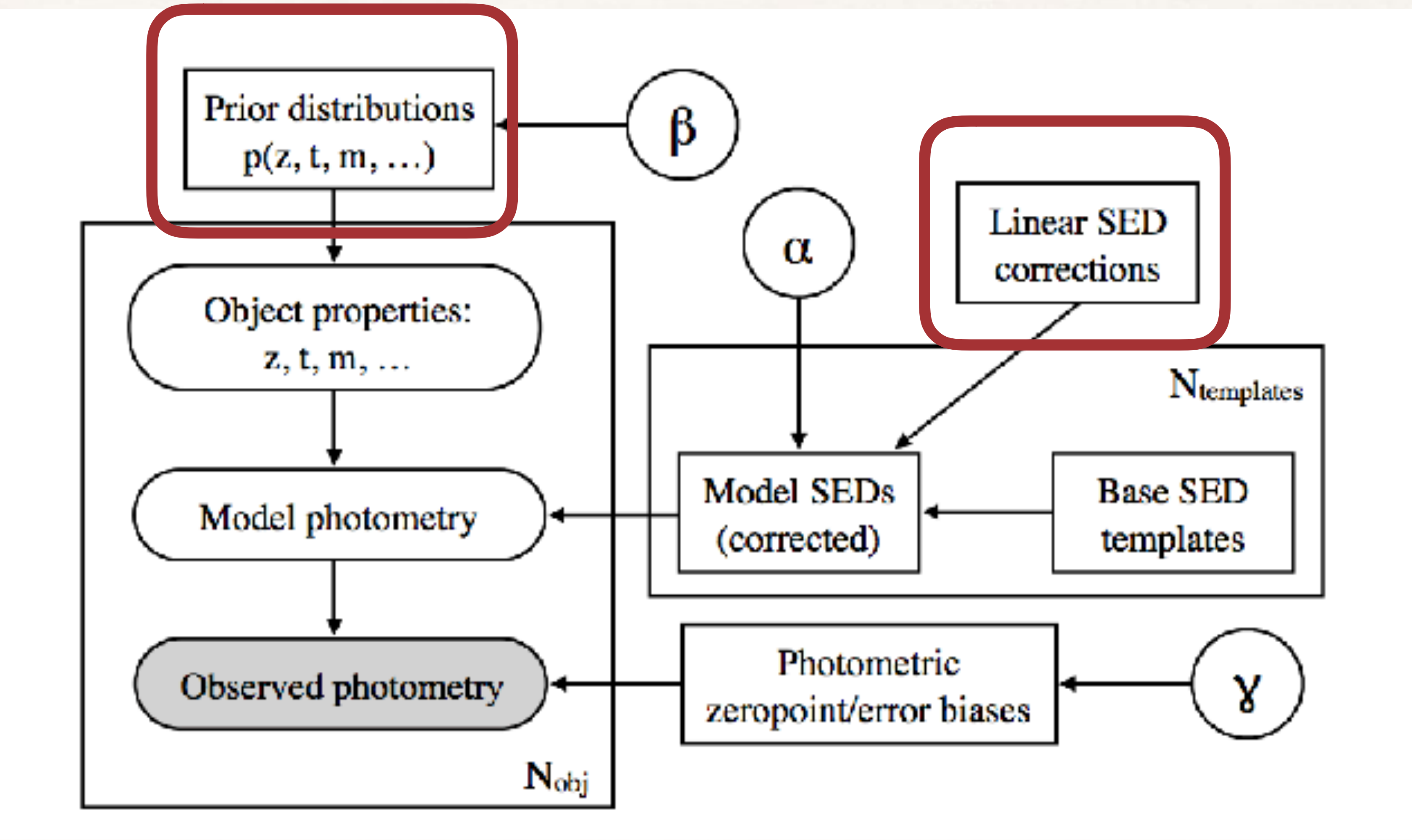
SED Modeling



Compared to cosmos, simulations are off by a shift in the mean color of the blue-sequence, broadening of red-sequence

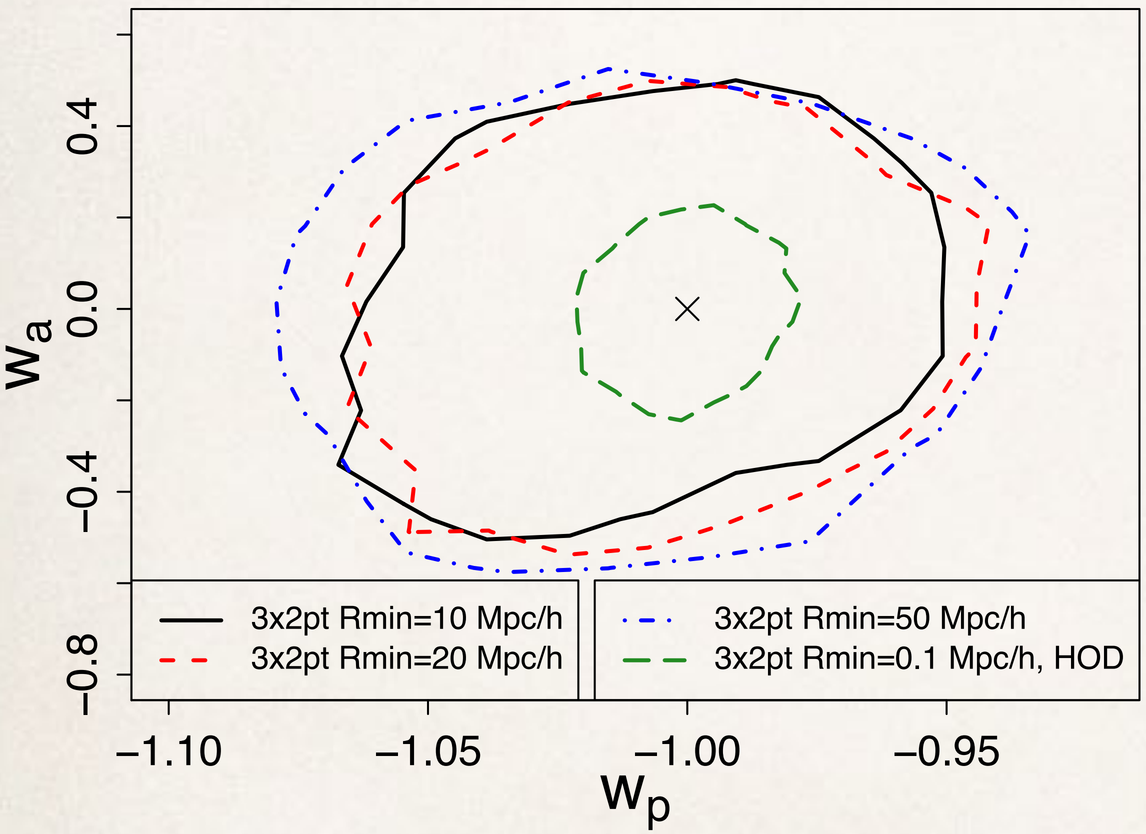
SED Modeling

Leistedt, Hogg, Wechsler & JDR 2018

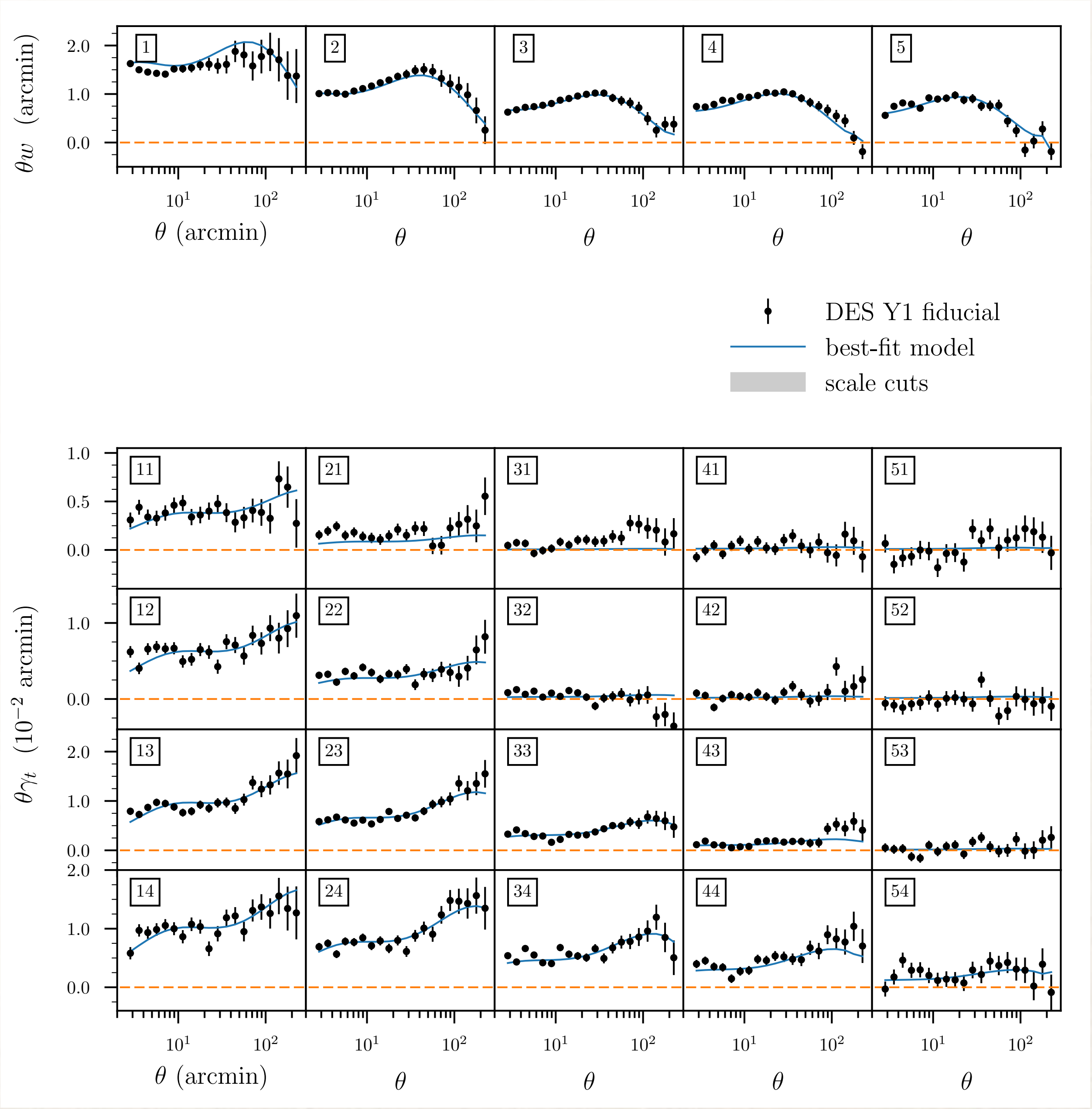


Can fit for SED template corrections, population statistics simultaneously!
Apply to sims to recover more realistic colors.

Pushing to Smaller Scales



Krause & Eifler 2016



Perturbative Bias Modeling

How much extra constraining power is actually available at small scales?

Y3 approach: Perturbative Bias Models

Schematically:

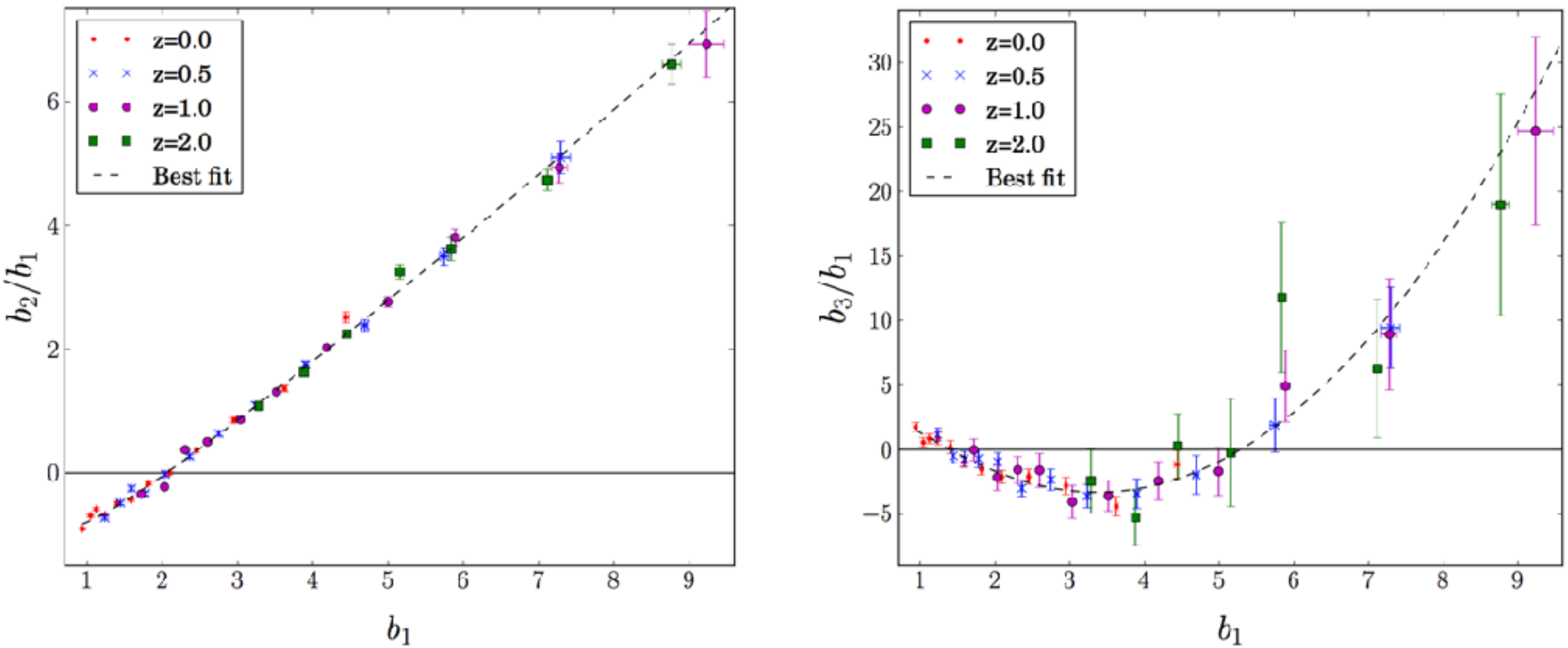
$$\delta_g(\boldsymbol{x},\tau) = \sum_O b_O(\tau) O(\boldsymbol{x},\tau)$$

Benefits - “complete” description of bias allowed by symmetries of GR

Work with Shivam Pandey, Jonathan Blazek, Niall MacCrann, Bhuv Jain

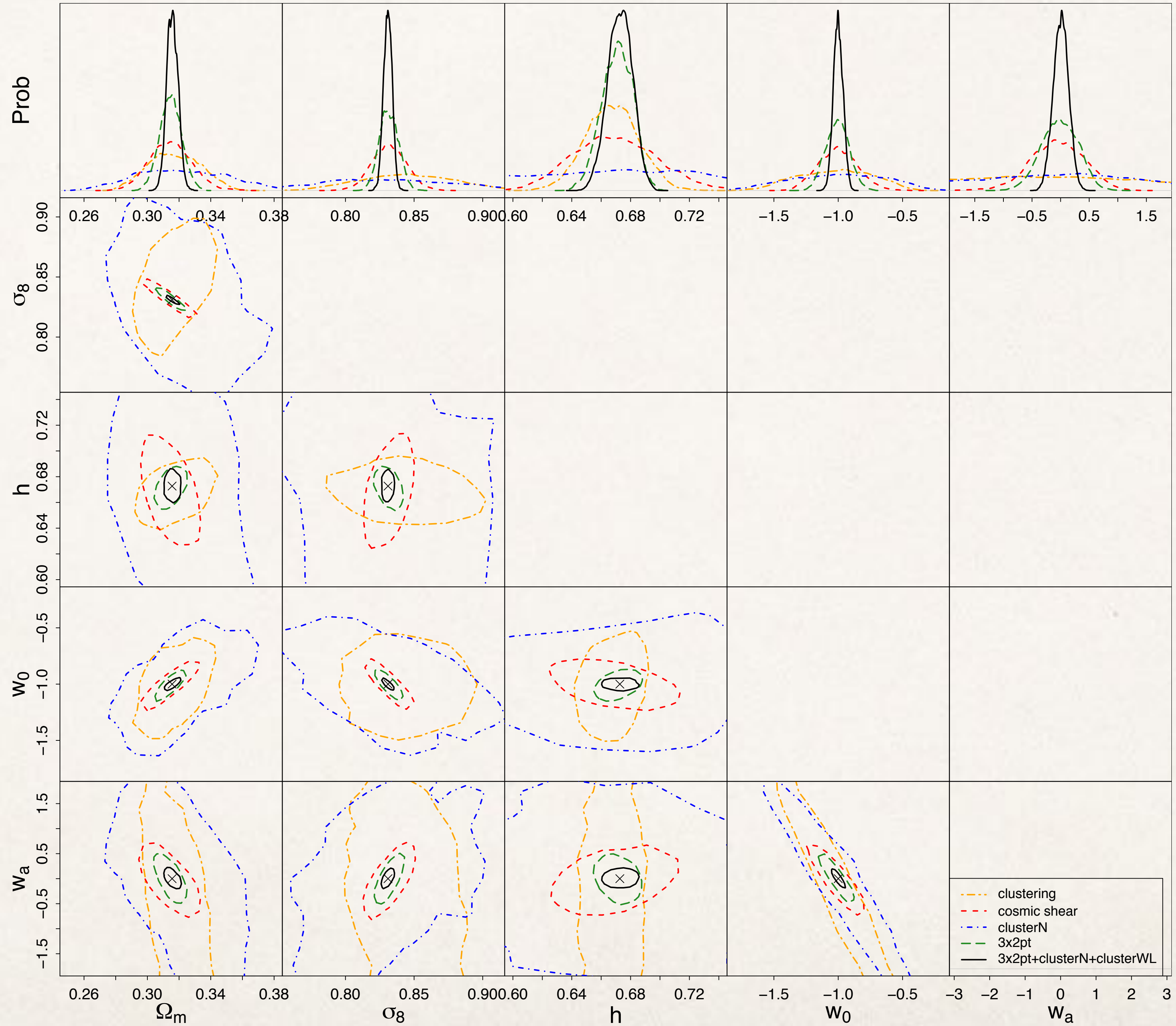
Choosing Bias Model Priors

Lazeyras et al. 2016



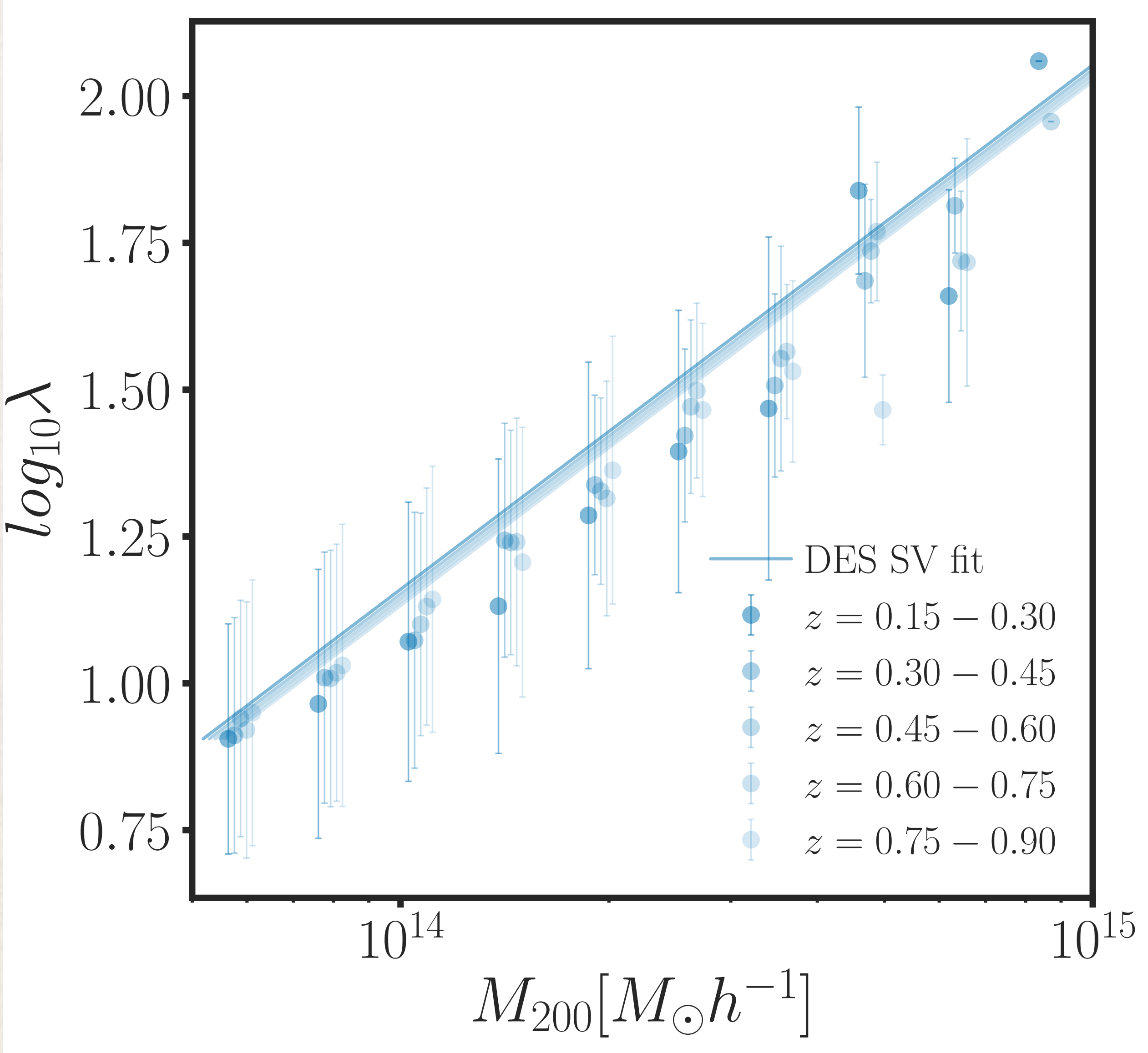
Well known relations exist between bias parameters for halos.
Investigating whether these hold up for galaxies.

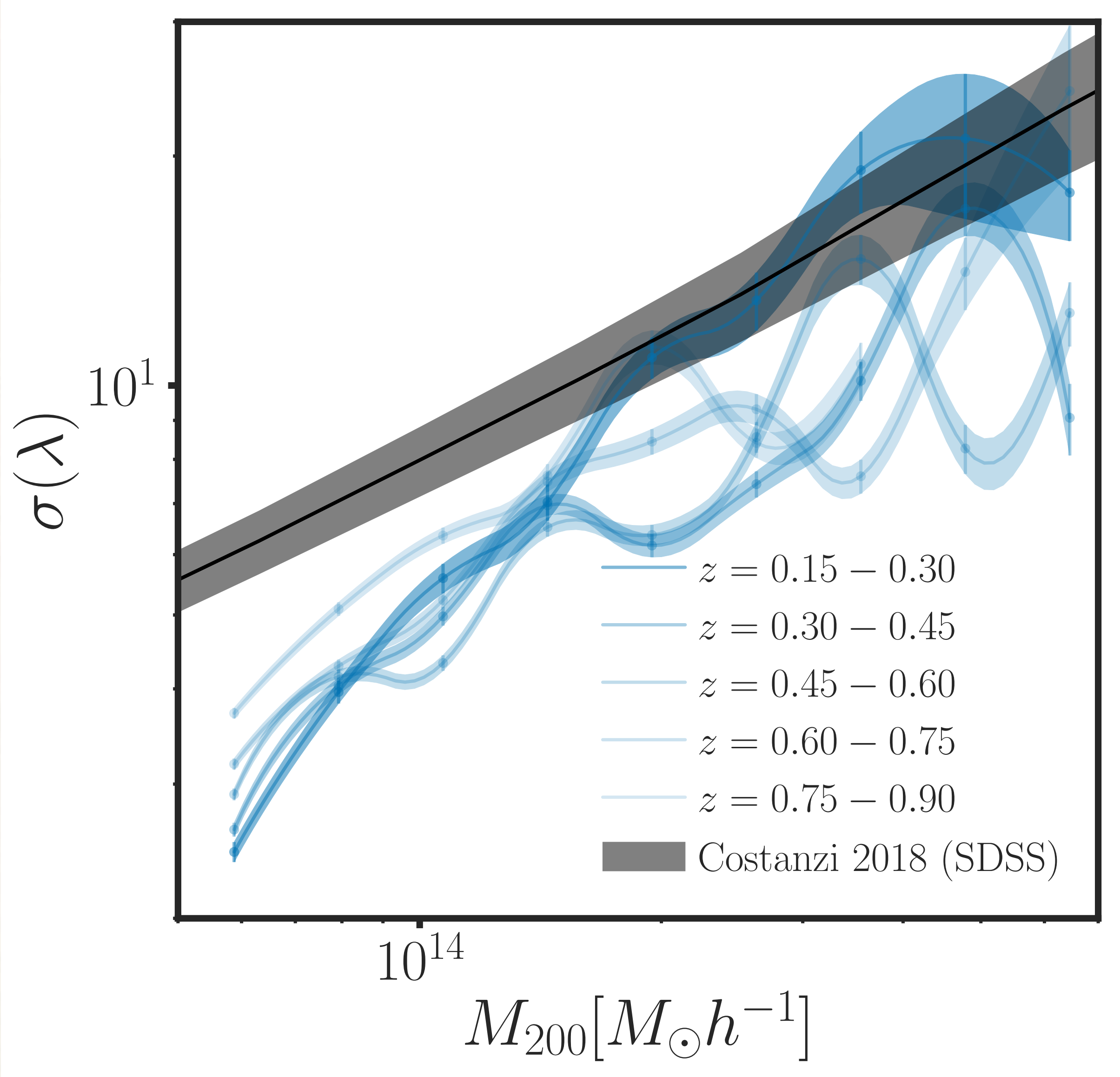
Taking Joint Probes to the Next Level



Krause & Eifler 2016

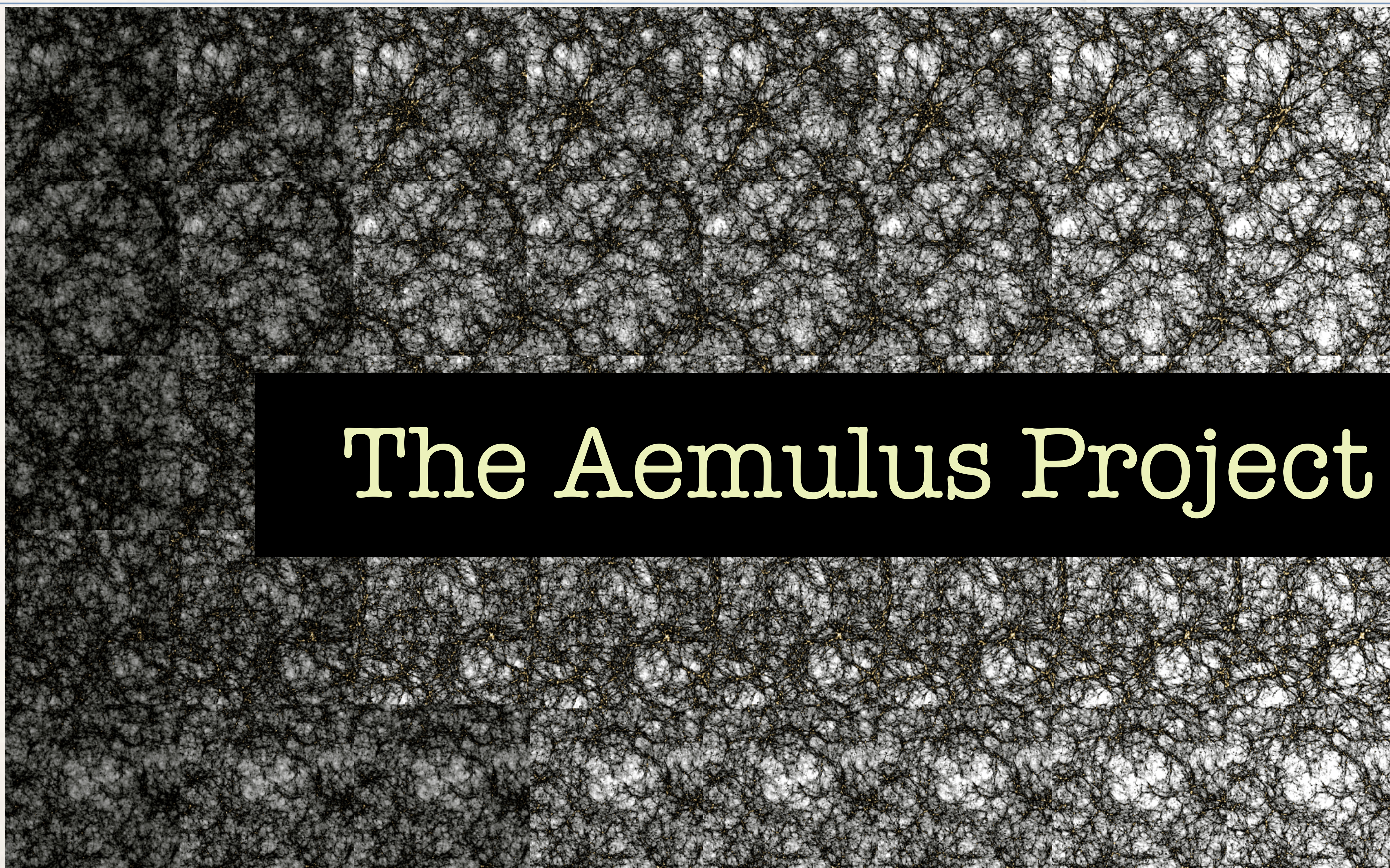
Full joint analysis validation on simulations forthcoming





Buzzard sims now have robust cluster observables, which we are using to perform similar validations for Y3 3x2pt + cluster cosmology analyses

Part II: Mock as the Model



/ˈae̯.mu.lus/, [ˈae̯.mʊ.ɫʊs] : (Latin) Striving to equal or exceed.

The Aemulus Project

- Goals: Precision emulation of statistics of dark matter halos and galaxies
- Methods:
  - Suites of high resolution N-body simulations spanning currently-allowed cosmological space.
  - Interpolating statistics within cosmological + galaxy-halo connection models using Gaussian Processes
- Results in percent-level estimates of the halo mass function and redshift-space galaxy clustering.

Aemulus Project: People

Risa Wechsler (Stanford/KIPAC)

Jeremy Tinker (NYU/CCPP)

Eduardo Rozo (Arizona)

Tom McClintock (Brookhaven)

Sean McLaughlin (Stanford)

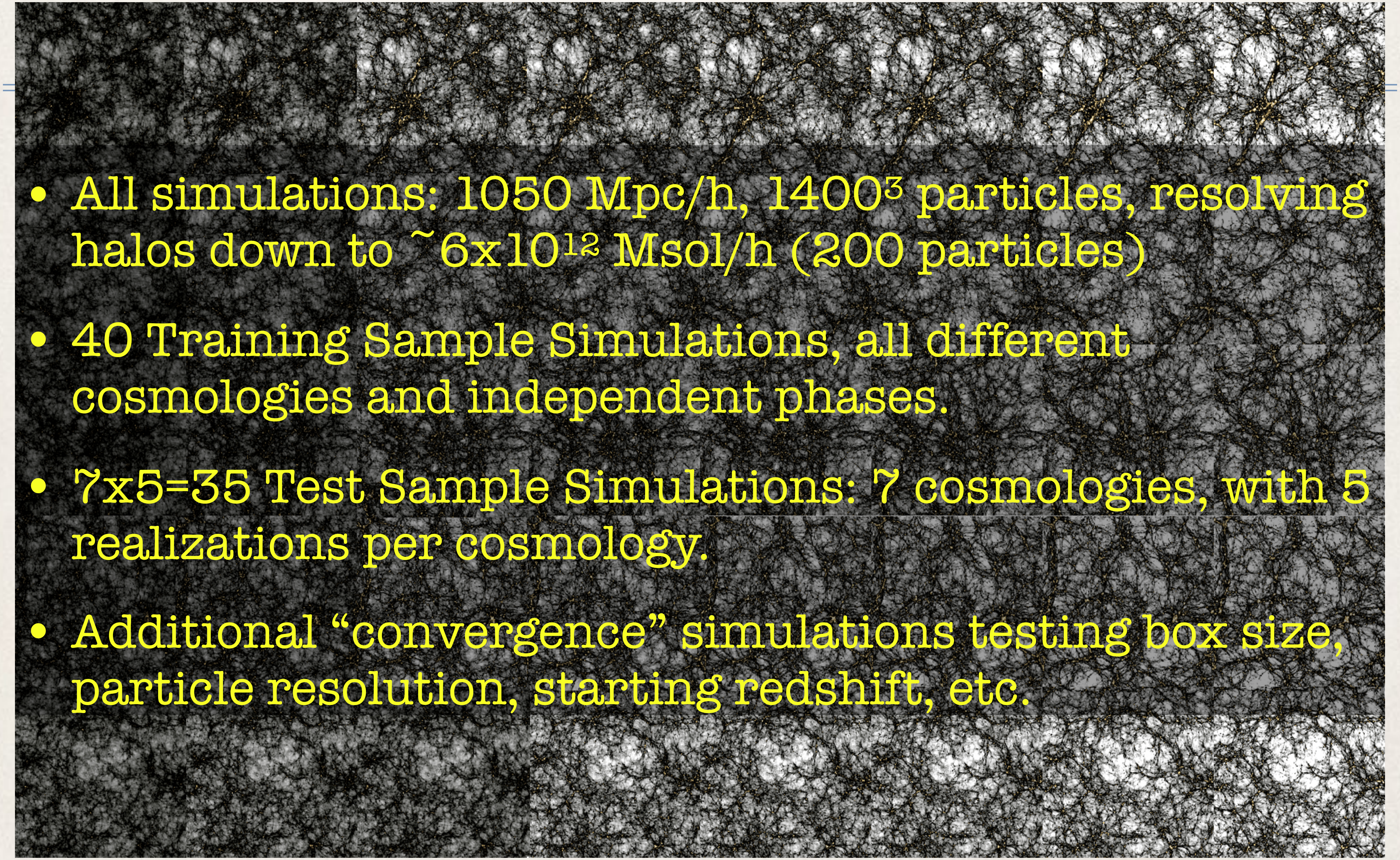
Zhongxu Zhai (Caltech)

JDR Matt Becker (Argonne), Yao-Yuan Mao (PITT-PACC)

First Set of Aemulus Papers:

- Aemulus I - JDR, Wechsler et al.
  - Parameter Space and Convergence Testing
- Aemulus II: Tom McClintock, Rozo et al.
  - Emulation the Halo Mass Function
- Aemulus III: Zhongxu Zhai, Tinker et al.
  - Emulating Galaxy RSD Clustering

Suite of 75+ Simulations

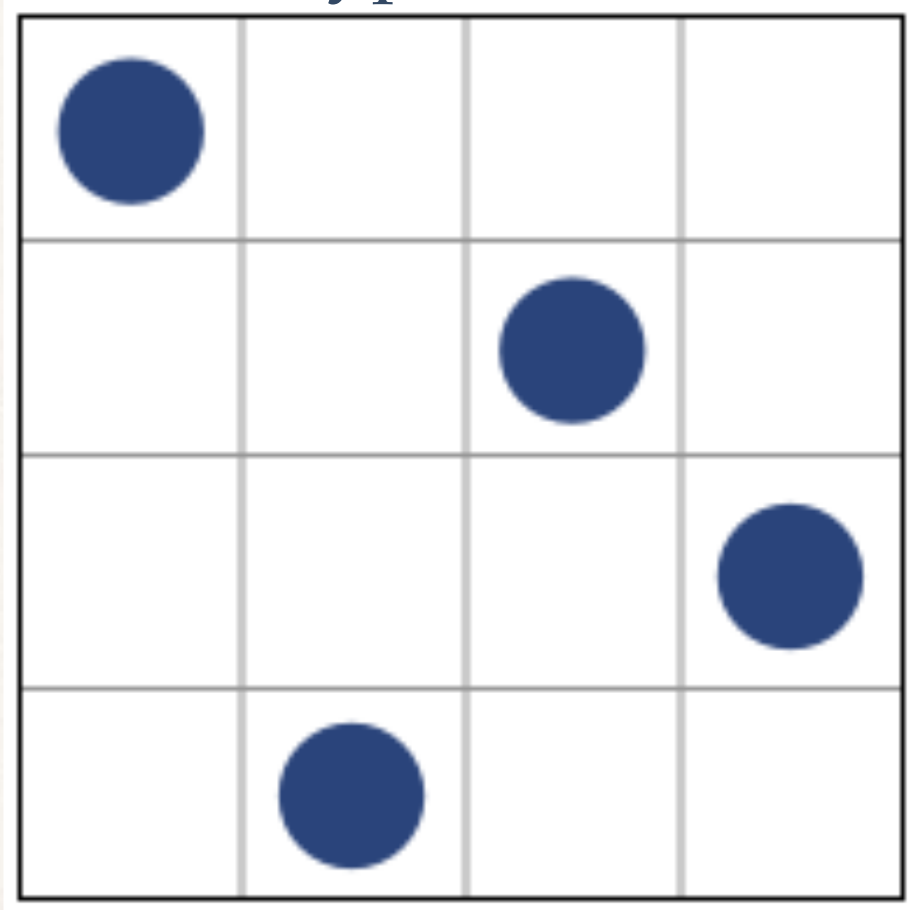


- All simulations: 1050 Mpc/h, 1400^3 particles, resolving halos down to ~6×10^{12} Msol/h (200 particles)
- 40 Training Sample Simulations, all different cosmologies and independent phases.
- 7x5=35 Test Sample Simulations: 7 cosmologies, with 5 realizations per cosmology.
- Additional “convergence” simulations testing box size, particle resolution, starting redshift, etc.

Sampling the Cosmological Parameter Space

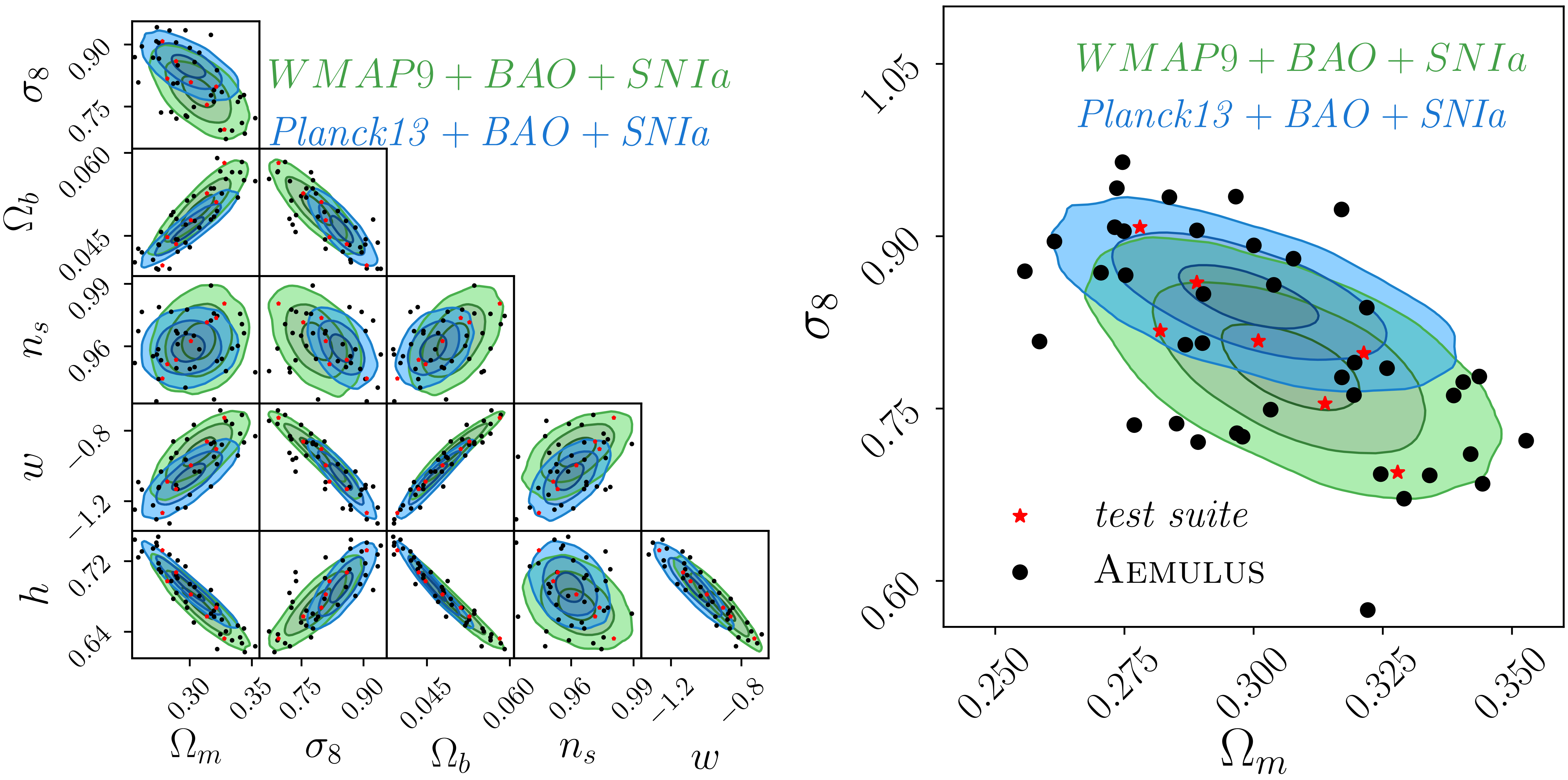
- 7 Parameter wCDM
- Sampling using a latin hypercube method based on Coyote Universe strategy (Heitmann et al. 2009)
- LH: Think of N-dimensional chessboard filled with M rooks that are unable to attack one another

N=2, M=4
“hypercube”



Aemulus I: JDR et al, arXiv:1804.05865

Sampling the Cosmological Parameter Space



Convergence Testing

Convergence Tests:

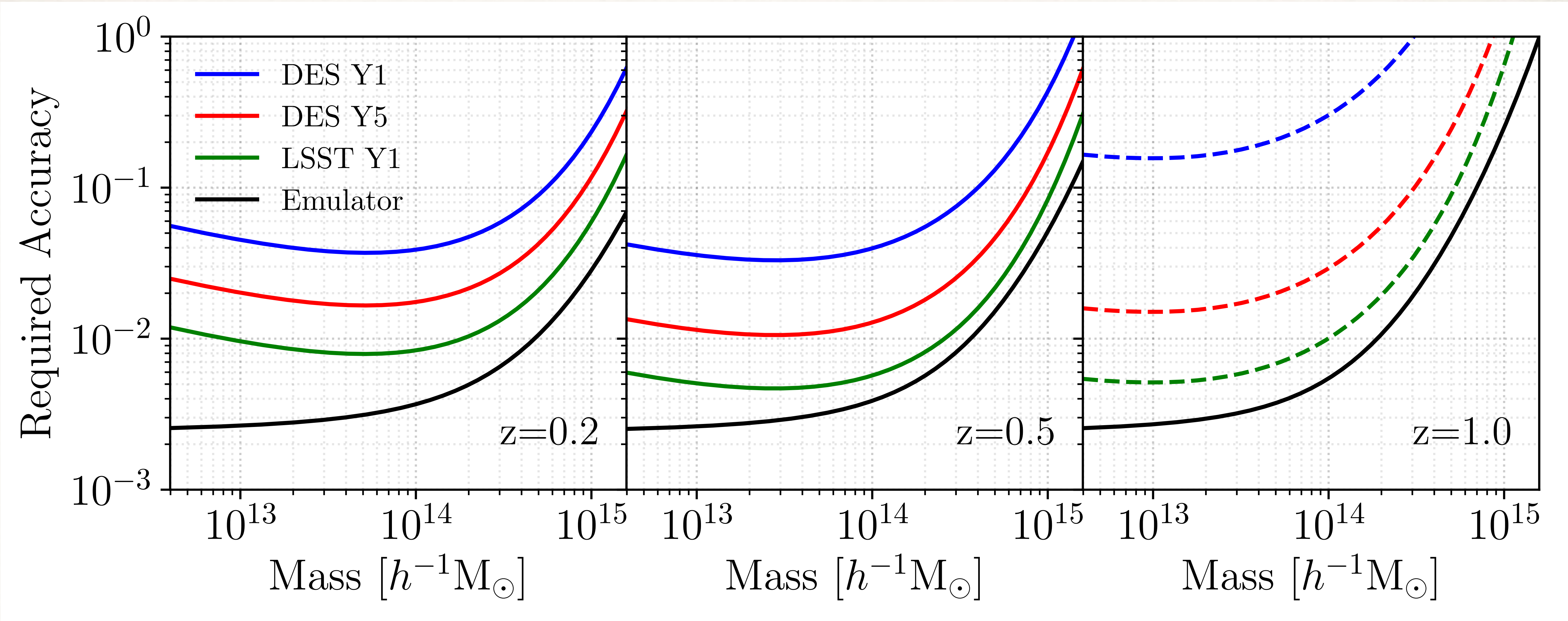
- Starting redshift
- Force Resolution
- Force Error Tolerance
- Maximum Time Step
- Particle Loading
- Finite Box Effects

Statistics Tested

- Halo Mass Function
- Halo Clustering
- Galaxy Clustering (LRG HOD)
- Matter Clustering
    - Correlation Function
    - Power Spectrum

Aemulus I: JDR et al, arXiv:1804.05865

Emulating the Halo Mass Function

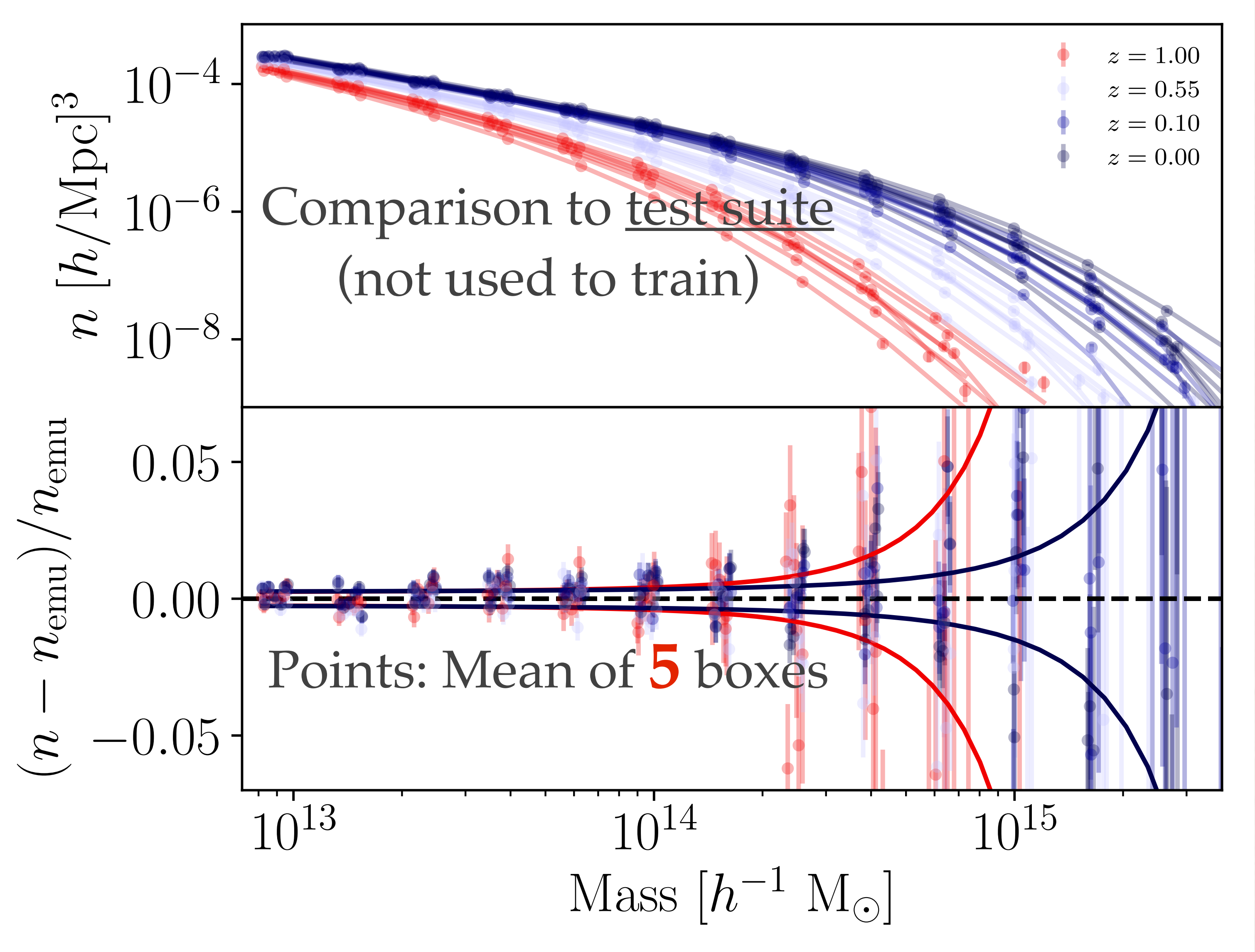


This suite of simulations has the resolution to robustly model cluster/LRG mass halos. Results in mass function emulators that are accurate enough for DES Y5 and LSST Y1

Mass Function: Methods

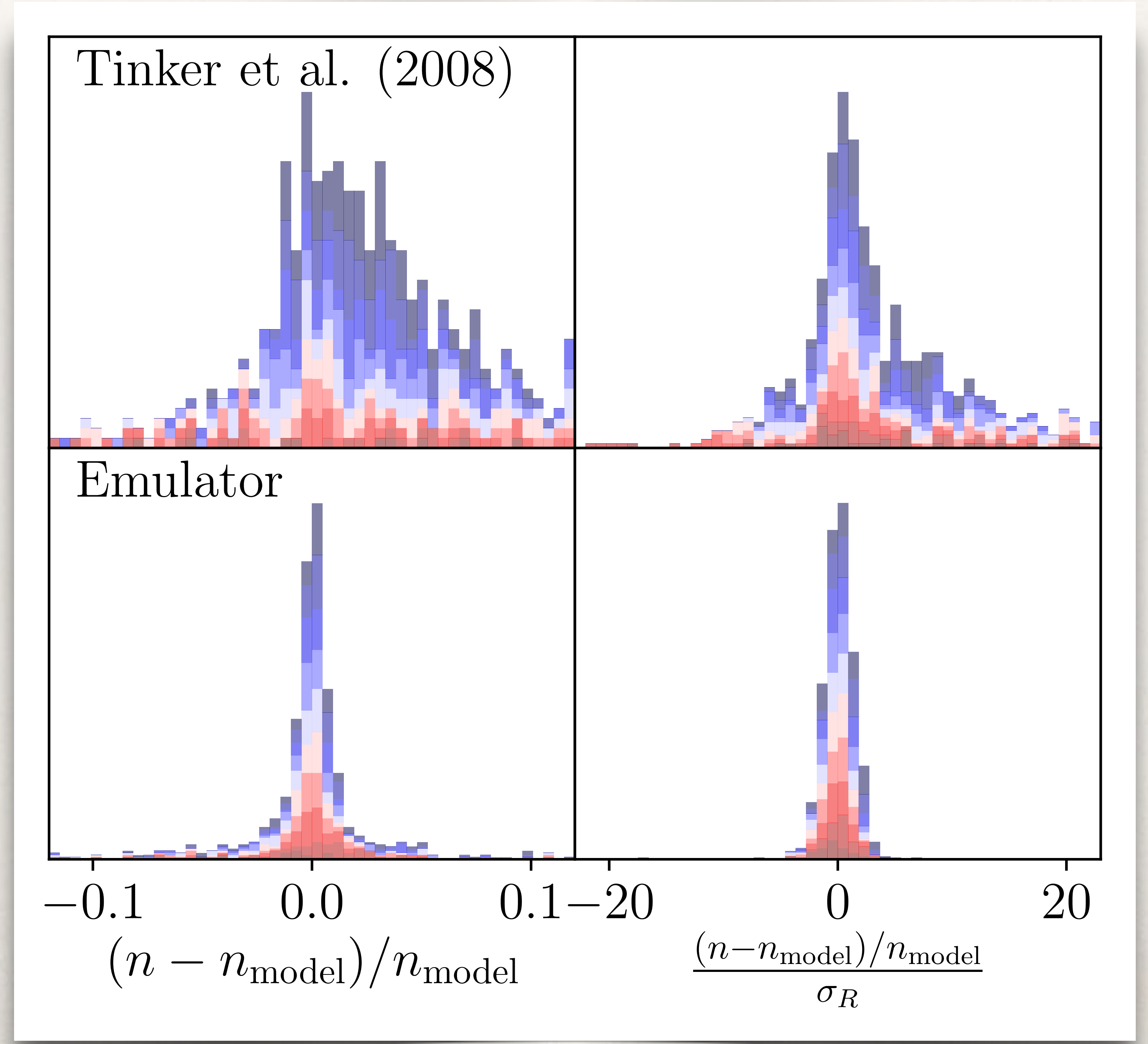
$$G(\sigma) = B\left[\left(\frac{\sigma}{e}\right)^{-d} + \sigma^{-f}\right]\exp(-g/\sigma^2)$$

- Tinker+08 fitting functions yields good fits to n(M)
- Emulate linear fit parameters as function of cosmology.



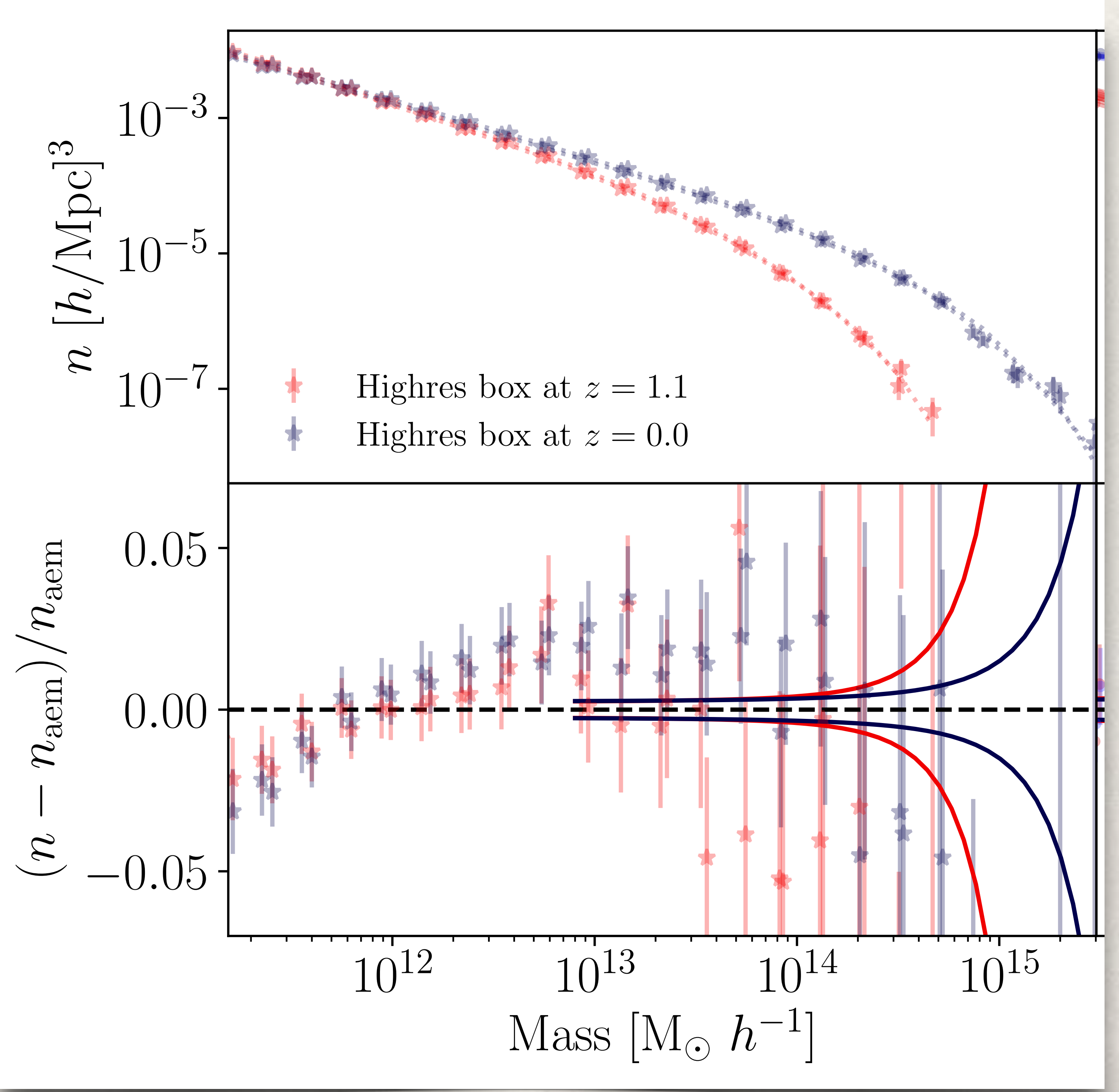
Aemulus II: McClintock et al, arXiv: 1804.05867

New State of the Art

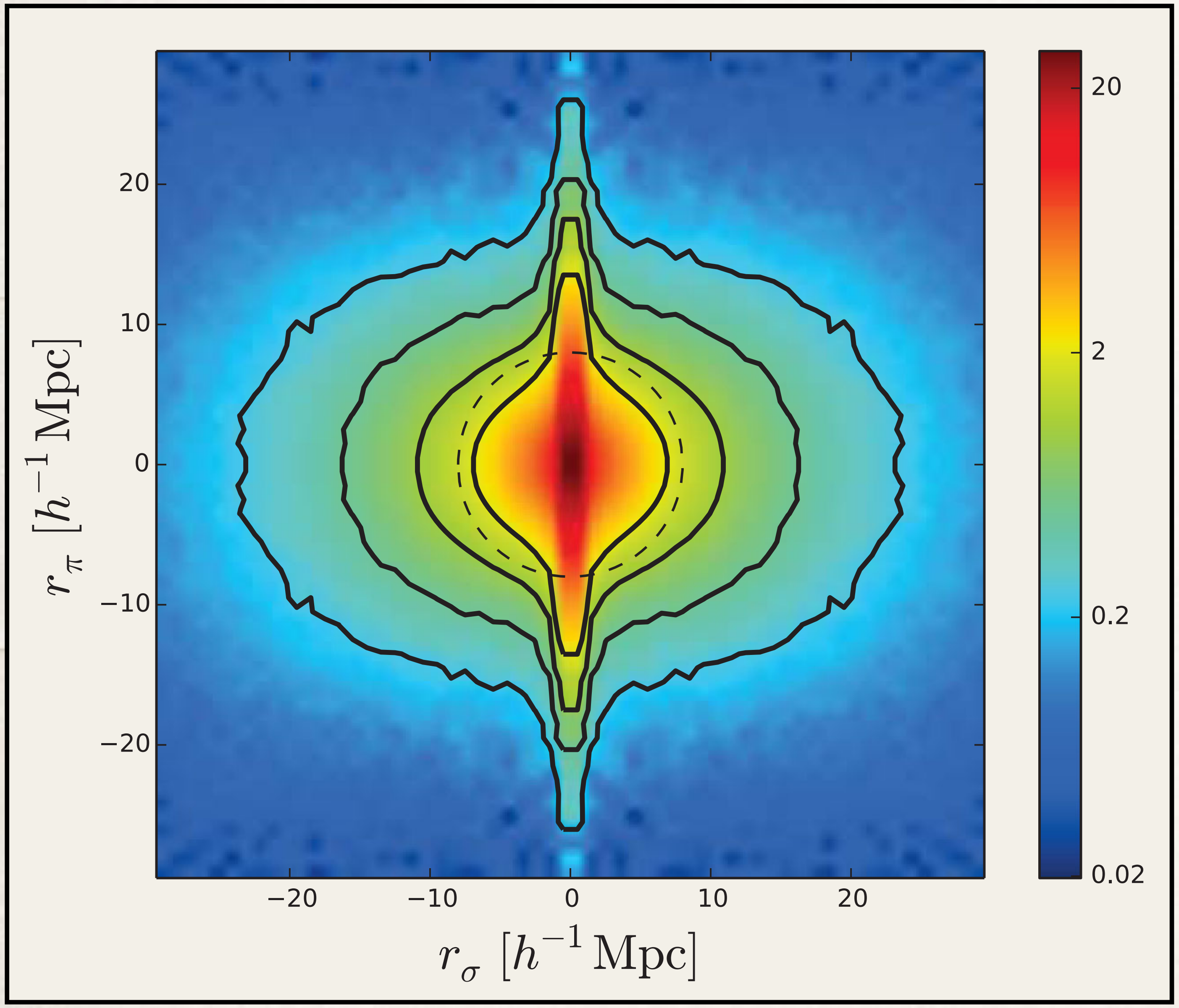


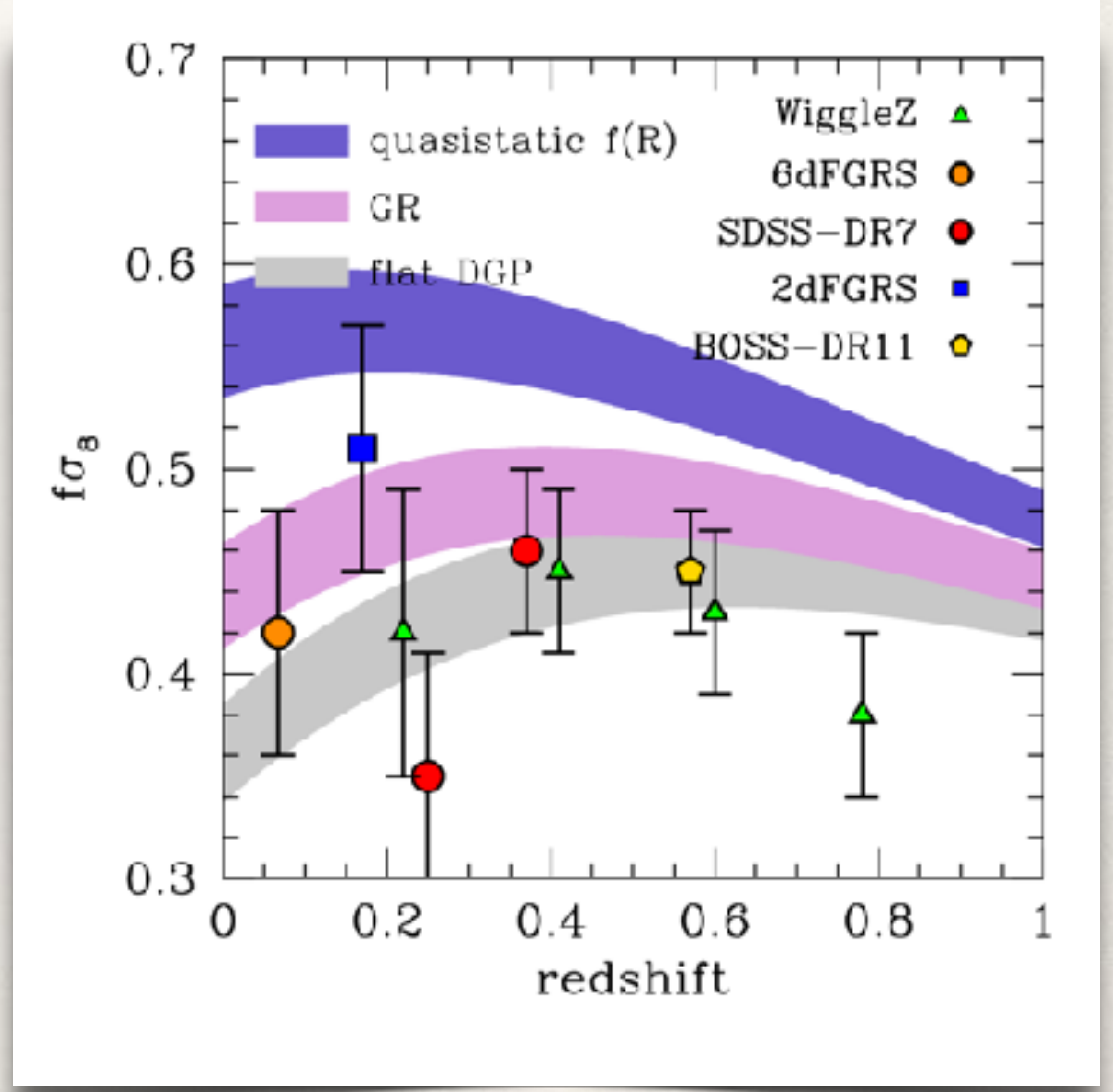
Low Mass Halo Modeling

- Emulating Tinker parameters allows for easy extrapolation to low mass.
- Compare to high-res sims which are **part of the next phase of the project**
- Results good to ~2% down to 10^{11} M_{sol}/h out to z=1.



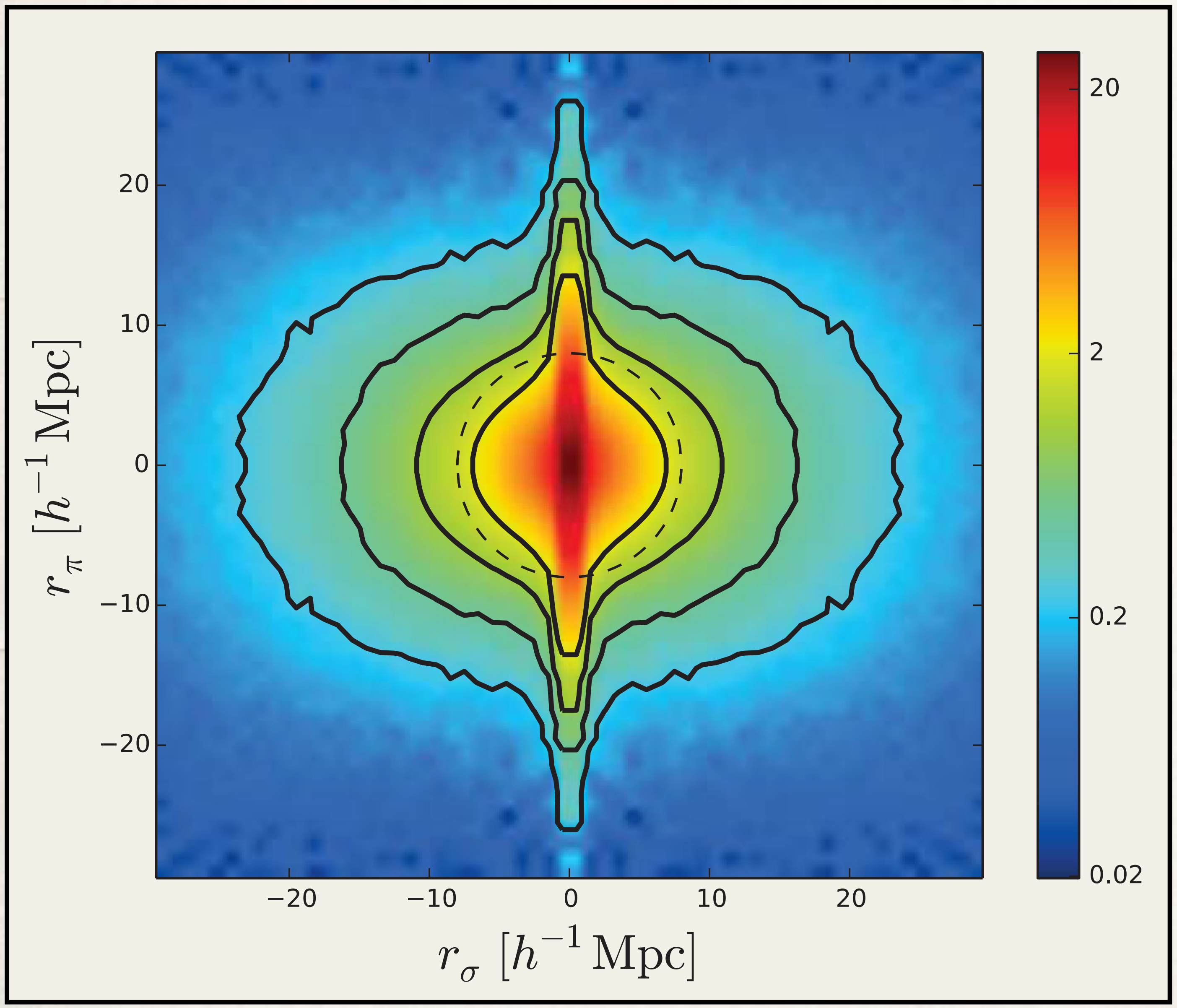
Aemulus III: Non-Linear RSD

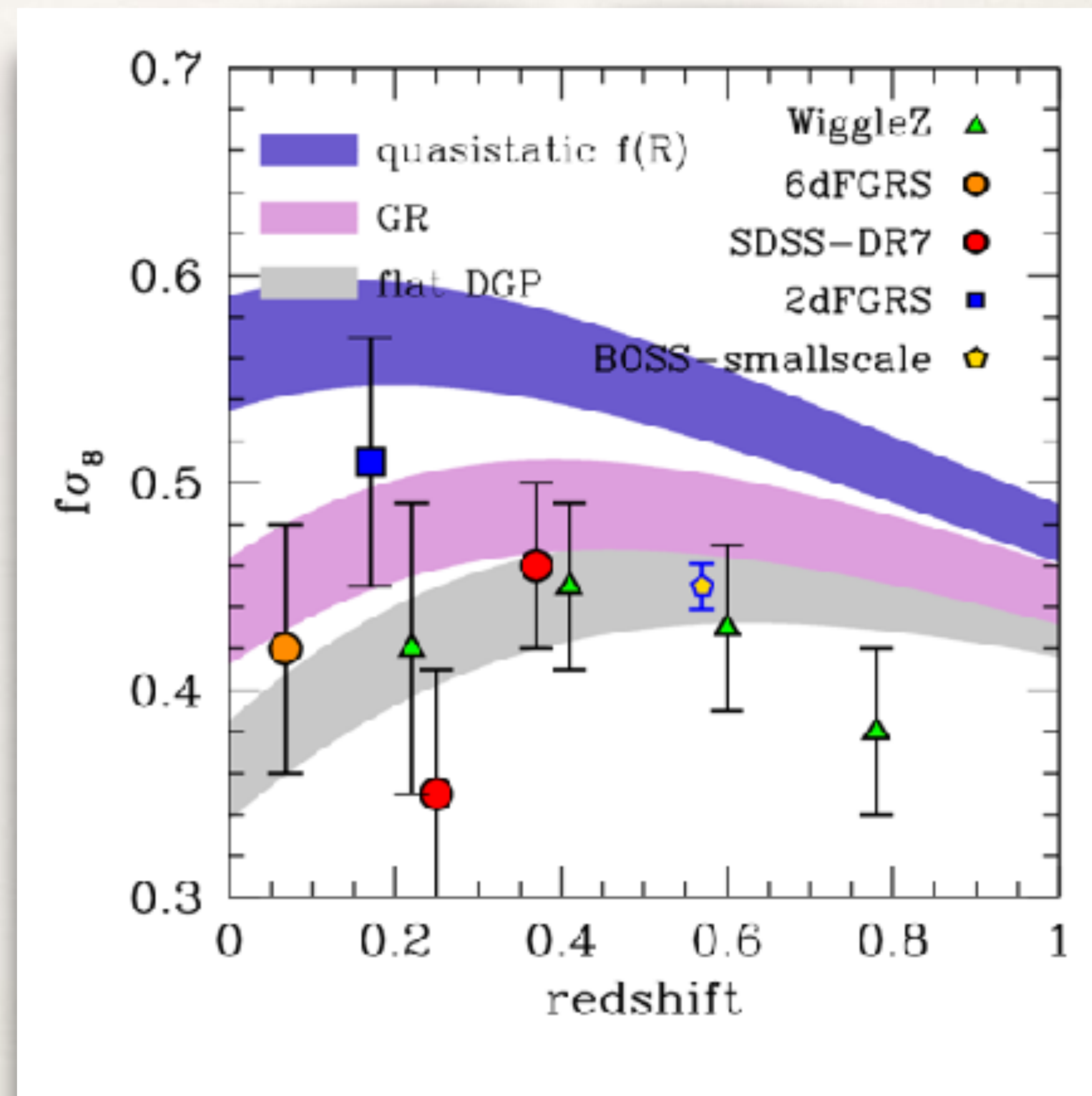




Reid et al. 2014 pilot analysis: 4x better constraints than fiducial large scale analysis.

Aemulus III: Non-Linear RSD

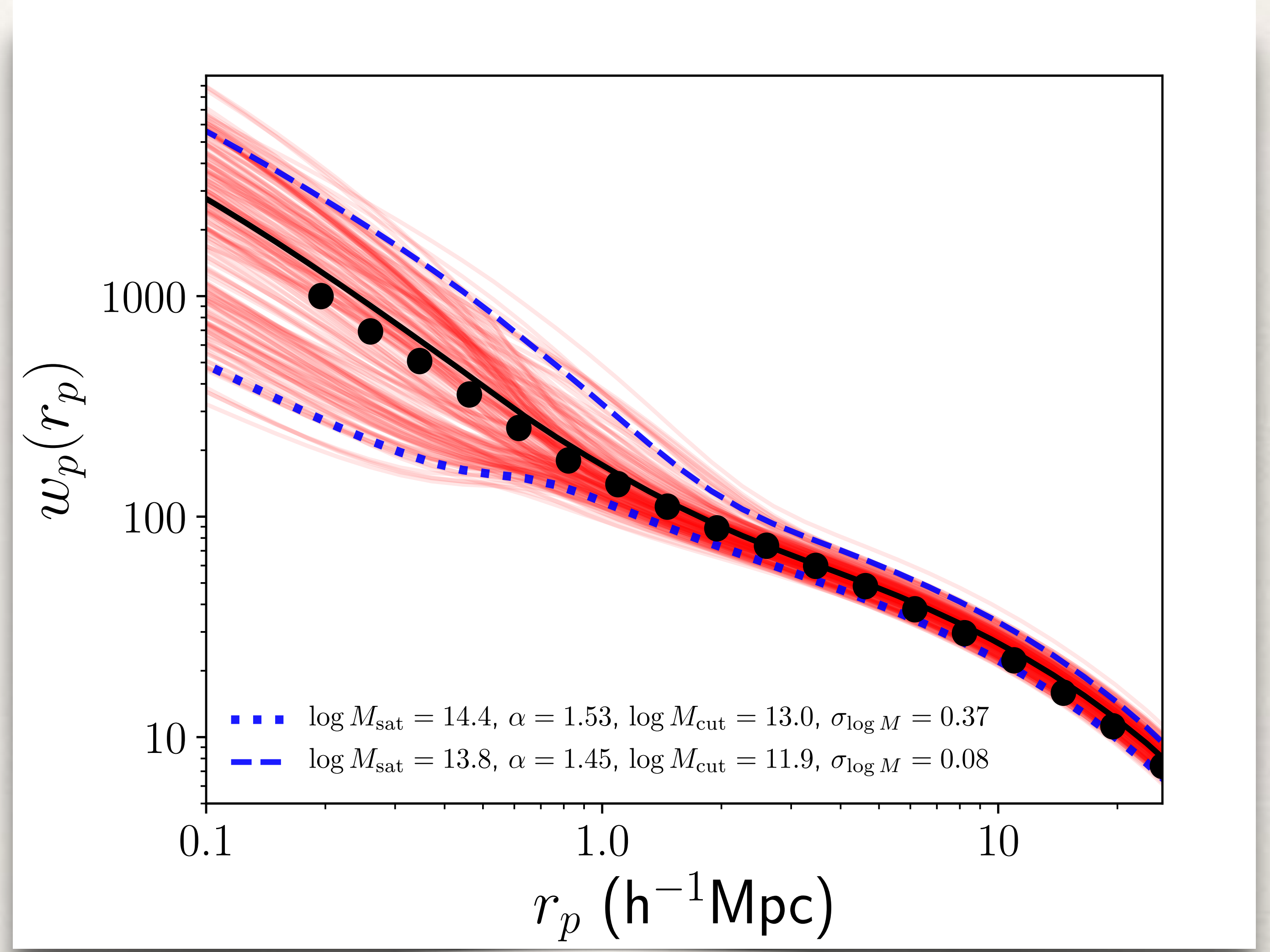




Reid et al. 2014 pilot analysis: but… fixed cosmology

Aemulus III: Non-Linear RSD

- Focusing on CMASS again. Asking:
  - How much constraining power available at small scales.
  - What statistics does it come from?



Random sample of training points for $w_p(r_p)$. Circles are BOSS DR10 data for comparison.

Aemulus III: Zhai et al, arXiv:1804.05867

Parameter Space

Aemulus III: Emulation of the Galaxy Correlation Function

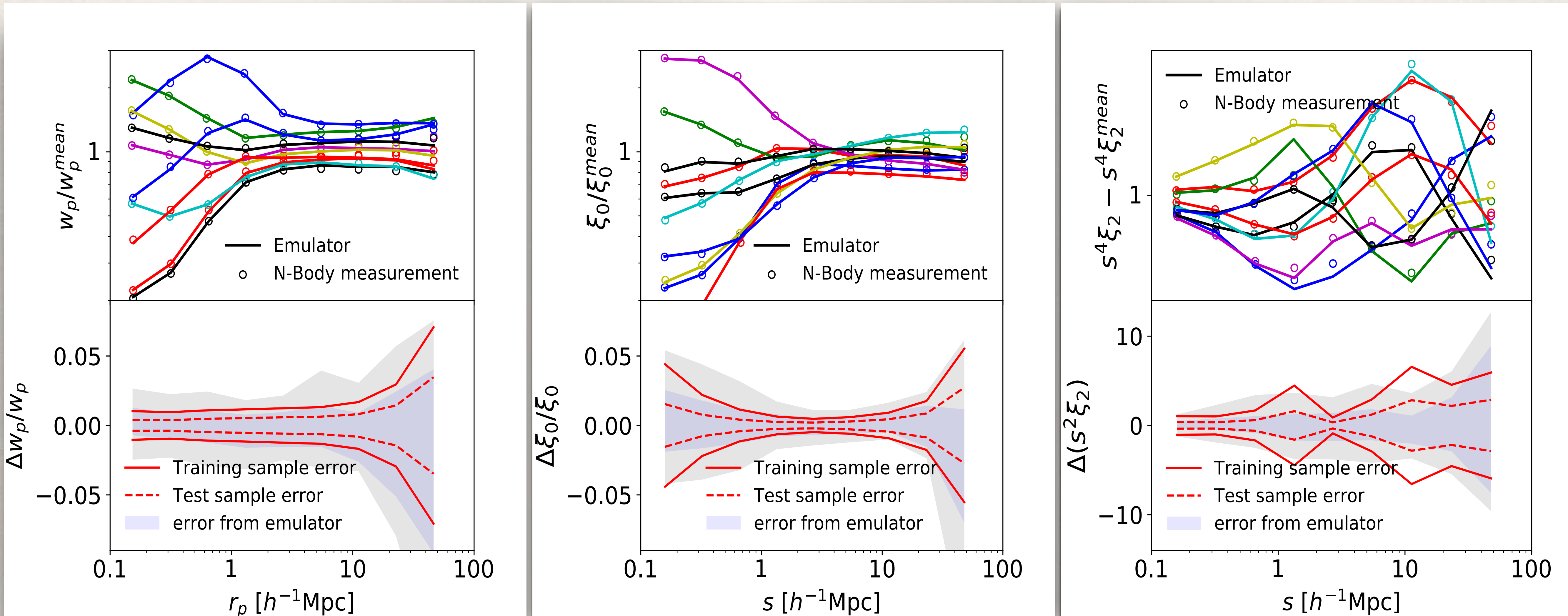
	Parameter	Meaning	Range
Cosmology	Ω_m	The matter energy density	[0.255, 0.353]
	Ω_b	The baryon energy density	[0.039, 0.062]
	σ_8	The amplitude of matter fluctuations on 8 h^{-1}Mpc scales.	[0.575, 0.964]
	h	The dimensionless Hubble constant	[0.612, 0.748]
	n_s	The spectral index of the primordial power spectrum	[0.928, 0.997]
	$w^{\dagger}$	The dark energy equation of state	[-1.40, -0.57]
	$N_{\mathrm{eff}}{}^{\dagger}$	The number of relativistic species	[2.62, 4.28]
	$\gamma_f{}^{\dagger}$	The Amplitude of halo velocity field relative to wCDM+GR	[0.5, 1.5]
HOD	$\log M_{\mathrm{sat}}$	The typical mass scale for halos to host one satellite	[13.8, 14.5]
	α	The power-law index for the mass dependence of the number of satellites	[0.2, 1.8]
	$\log M_{\mathrm{cut}}$	The mass cut-off scale for the satellite occupatioin function	[10.0, 13.7]
	$\sigma_{\log M}$	The scatter of halo mass at fixed galaxy luminosity	[0.05, 0.6]
	$\eta_{\mathrm{con}}{}^{\dagger}$	The halo concentration parameter	[0.2, 2.0]
	$\eta_{vc}{}^{\dagger}$	The velocity bias for central galaxies	[0.0, 0.7]
	$\eta_{vs}{}^{\dagger}$	The velocity bias for satellite galaxies	[0.2, 2.0]

$$\gamma_f = \frac{f}{f_{\mathrm{GR}}}$$

Υ_f scales the motion of the halos relative to that in the simulation. Thus, it is equivalent to scaling f:

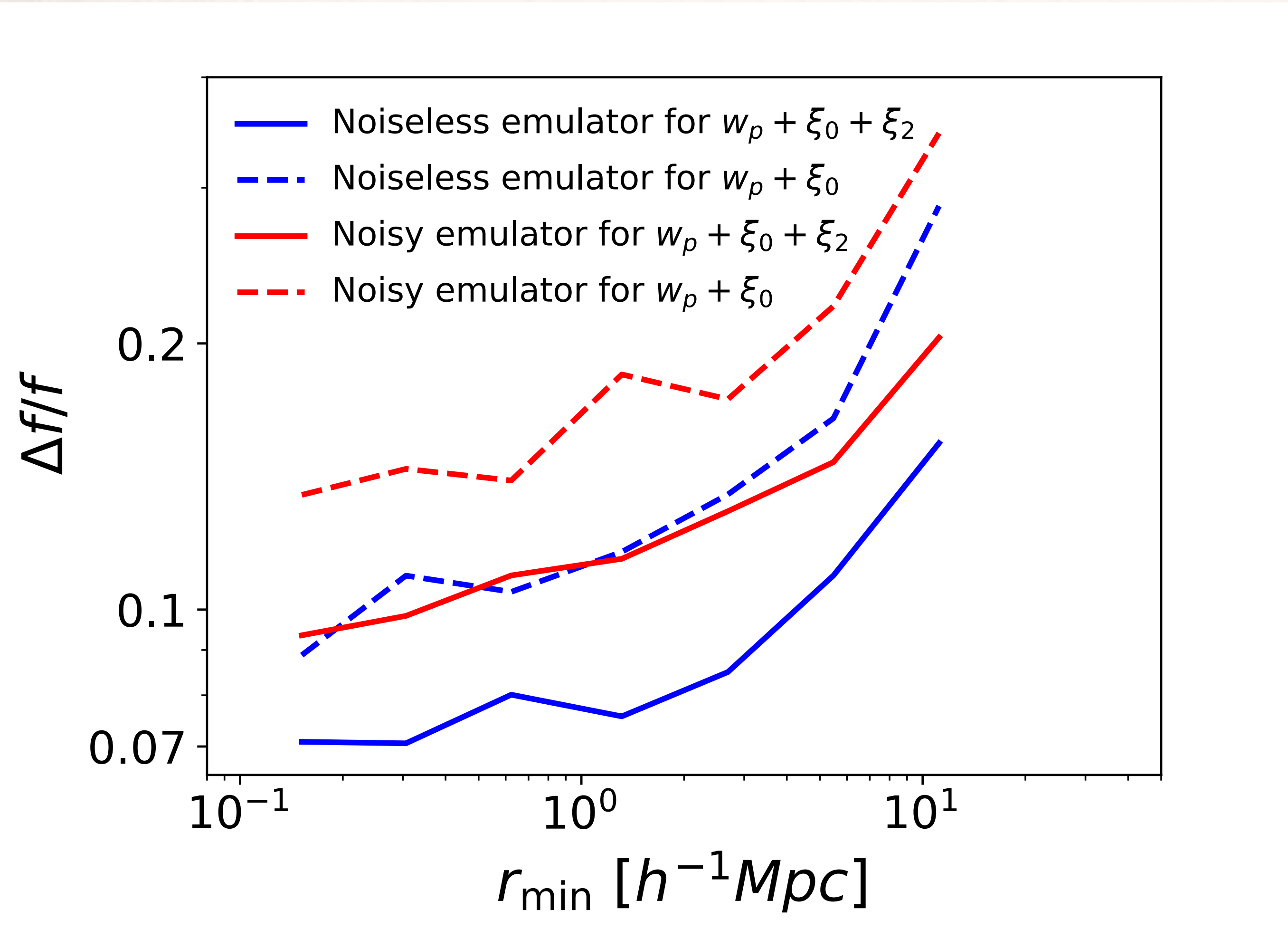
$$f_{\mathrm{GR}} = \frac{d\ln D}{d\ln a}$$

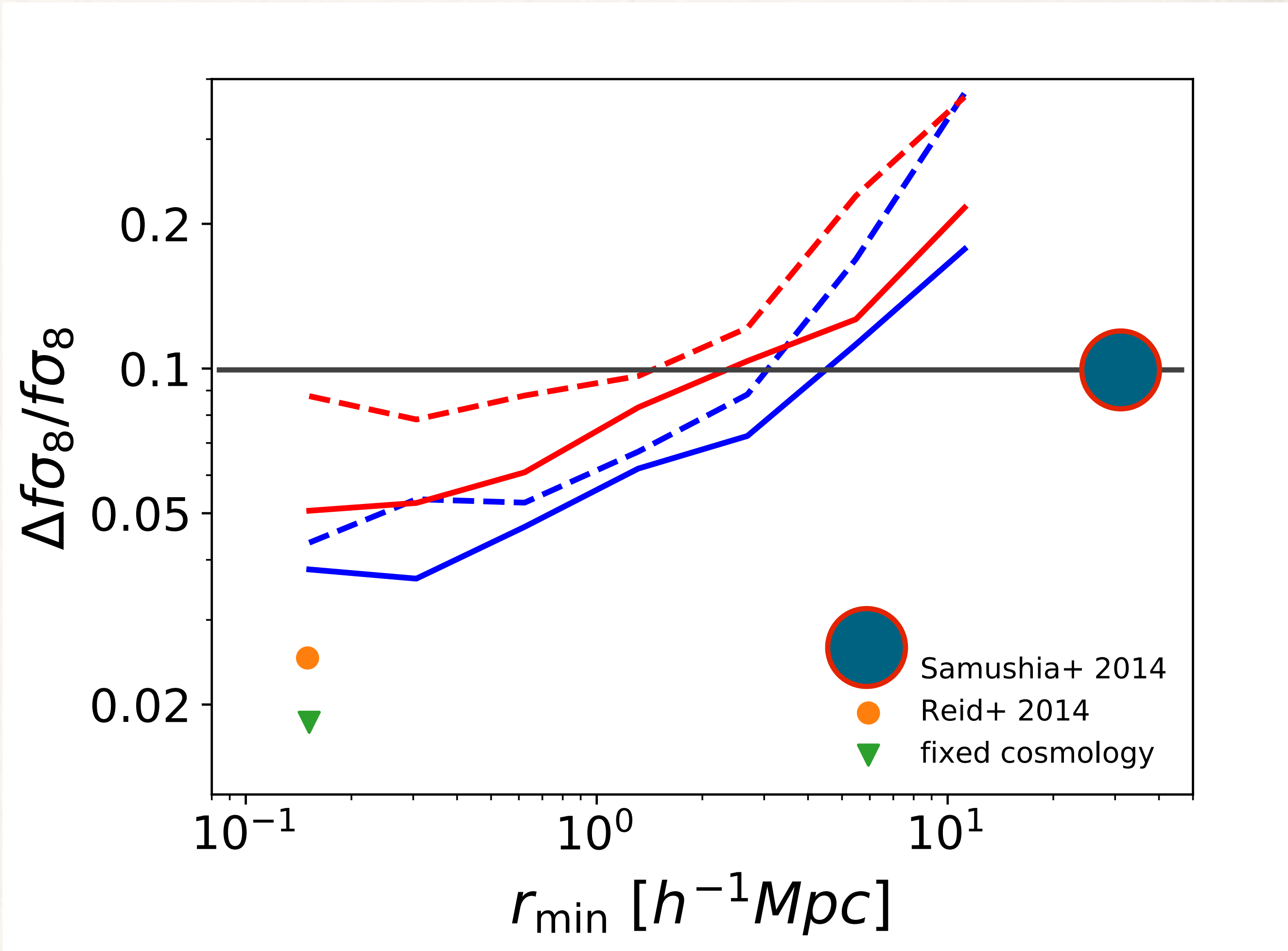
Emulator Accuracy



Emulator better than sample variance of training boxes!

BOSS-like Projections





Non-linear analysis: 2x better than large-scale analysis
Constraints improve monotonically w/ scale
~Half of constraint comes from quadrupole

A Community Resource

- Github Project Page:
  - https://aemulusproject.github.io
- Repo for all software including user friendly halo mass function emulator
- All data, including halo catalogs and snapshots will be made available once papers are accepted (very soon!)

The Future

Phase I Simulations:

- Apply methods of McClintock et. al to halo bias
- Apply RSD model (+extensions) to measurements of non-linear RSD in BOSS
- Detection (?) of assembly bias in massive galaxy samples

Phase II Simulations:

- High resolution suite: L=400 Mpc/h, $N_p=2048^3$ (nearly done!)
  - Good for DESI ELGs, BGS, g-g lensing, redMaGiC
- Simulations w/ expanded parameter space and neutrinos
- Clustering statistics using abundance matching models

Summary

- Realistic suite of simulated galaxy surveys are essential for validating systematics models and many other facets of DES
    - Volume important, but also need realism so still a place for more expensive/diverse models
- Simulations can be used as precision models for non-linear observables
    - Lots of work to be done including more physics e.g. neutrinos, baryonic effects