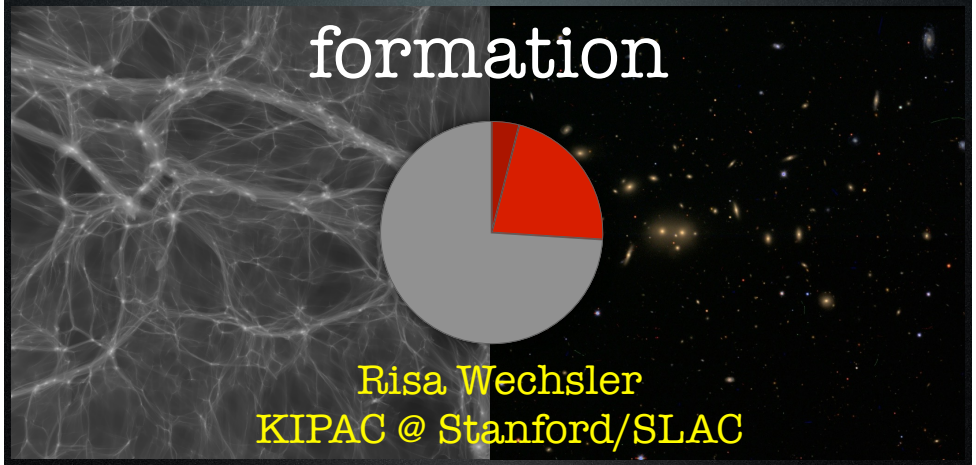
Modeling galaxies and non-linear structure formation



Risa Wechsler
KIPAC @ Stanford/SLAC

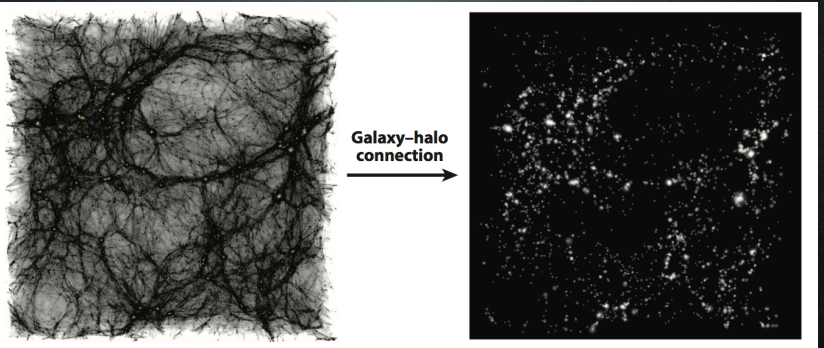
BCCP Lensing
January 14, 2019

★The current and upcoming era of cosmological surveys requires precise modeling of galaxies in the non-linear regime.

- Our measurements will be systematics dominated (most are already)... There is no way around this!

★Need to model non-linear structure formation AND the galaxy-halo connection (preferably together)

- What do we know about the galaxy-halo connection already?
- What do we need to know about the galaxy-halo connection to do cosmology with lensing, and how can we measure it?
- How do we make predictions; how do we test our models and pipelines?



Approaches to modeling the galaxy–halo connection

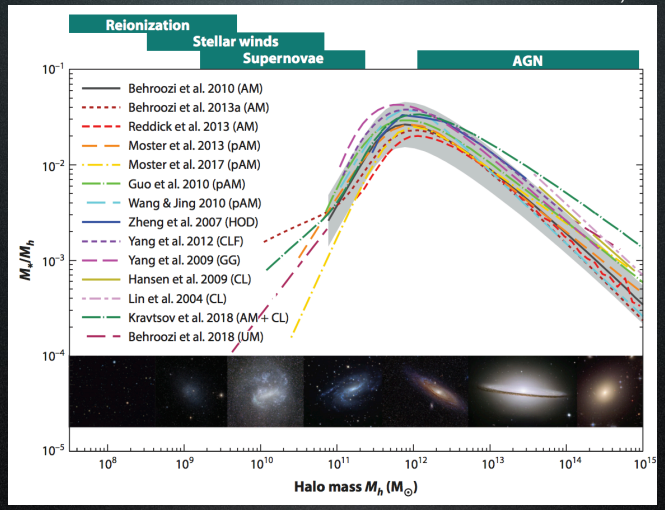
← Physical models				Empirical models →
Hydrodynamical simulations	**Semianalytic models**	**Empirical forward modeling**	**Subhalo abundance modeling**	**Halo occupation models**
Simulate halos and gas; star formation and feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos and subhalos) plus assumptions about galaxy–(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

RW & Tinker, ARAA 2018

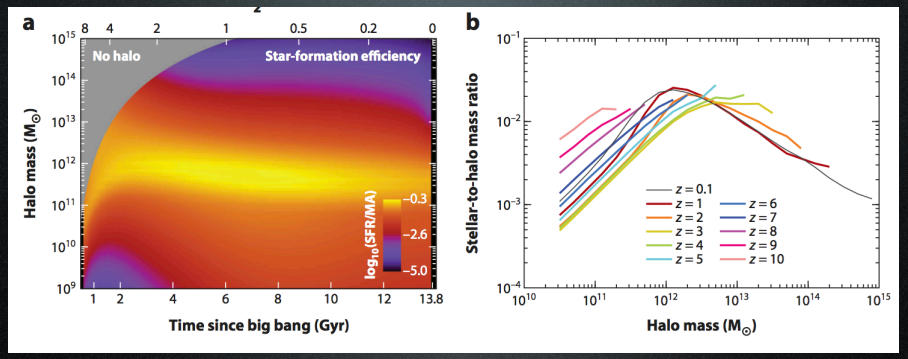
The complexities of the galaxy-halo connection

- Lensing masses for galaxy clusters depend on projection, orientation, photometric redshifts...
- Intrinsic alignments for a galaxy sample likely depend on red/quenched fraction and satellite fraction...
- The connection between galaxy-galaxy clustering and galaxy-galaxy lensing for a given sample can depend on assembly bias...

RW & Tinker, ARAA 2018

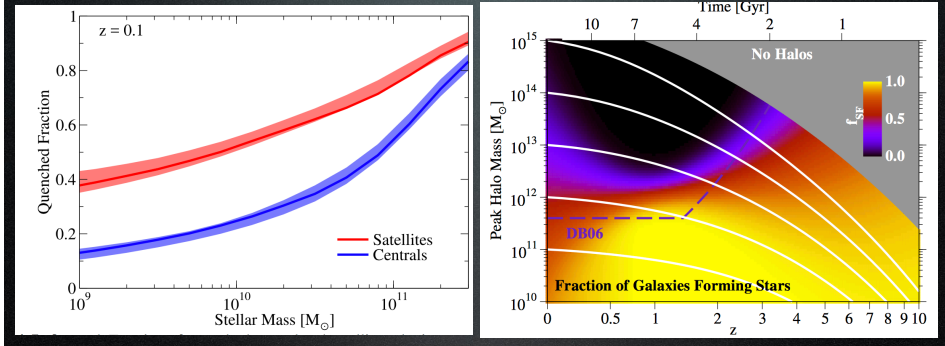


Galaxy formation is inefficient
Galaxy formation peaks in halos ~ 1e12
Lensing is in good agreement with other techniques



Behroozi et al 2014; Behroozi, RW & Conroy 2018 (RW & Tinker, ARAA 2018)

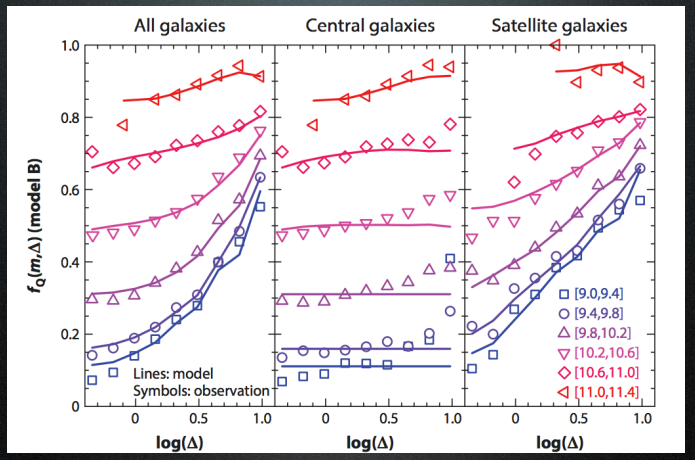
Star formation most efficient in halos of ~1e12
Little evolution with redshift...
But only tested with lensing at low redshift



Behroozi, RW et al 2018

Galaxy quenching is a function of stellar mass, centrals vs satellites, redshift

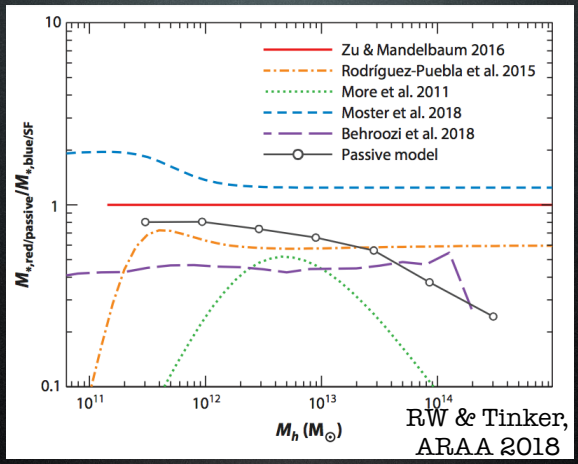
Halos matter



Wang et al 2018 (RW & Tinker, ARAA 2018)

Most environmental trends are driven by (a) halo mass and (b) central vs satellites.

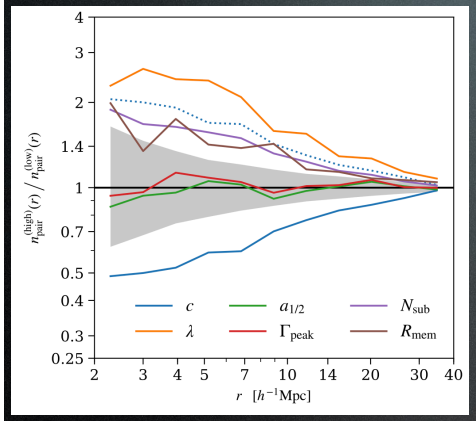
Still many questions about secondary effects



RW & Tinker, ARAA 2018

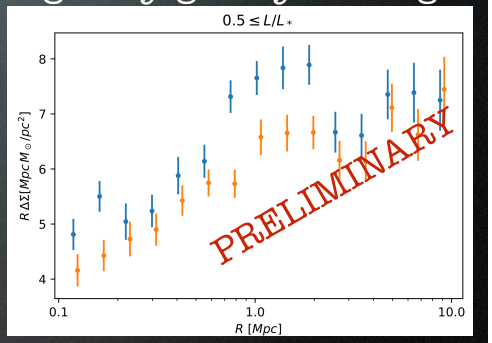
Various models / inference not yet agreeing on basics of red vs. blue galaxy-halo connection

Assembly bias is tricky



Mao, Zentner & Wechsler 2018

Size dependence of galaxy-galaxy lensing



Kokron in prep

Different halo properties impact clustering differently. Galaxy formation not yet well understood to predict robustly.

Two example uses of simulations:

I: The mock as the test —

Systematics estimation and marginalization

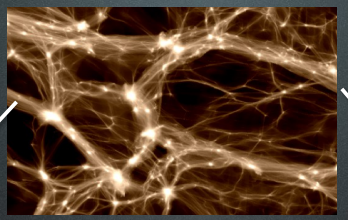
Pipeline and algorithm development

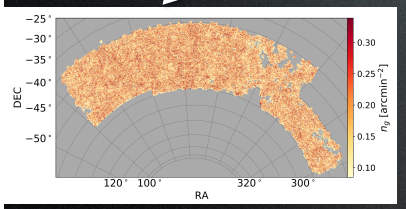
Case study: end-to-end validation of DES Y1 3x2 point cosmology analysis using simulated skies

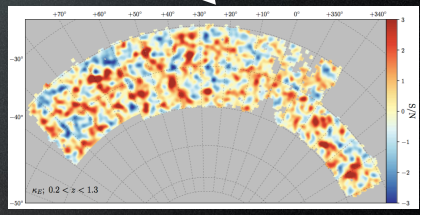
II: The mock as the model —

AEMULUS Project: Accurate predictions for non-linear and complex observables

DES Year 1 Cosmology Analysis: 3x2pt







galaxies x galaxies: **angular clustering**

Elvin-Poole+2017

galaxies x lensing: **galaxy-galaxy lensing**

Prat, Sanchez+2017

lensing x lensing: **cosmic shear**

Troxel+2017

Pipeline testing

★ Is my full pipeline accurate enough for the precision of my measurements?

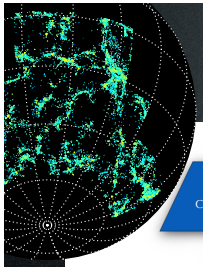
- Robust to assumptions about the galaxy model (including e.g. bias, photo-z's) or underlying cosmological model?

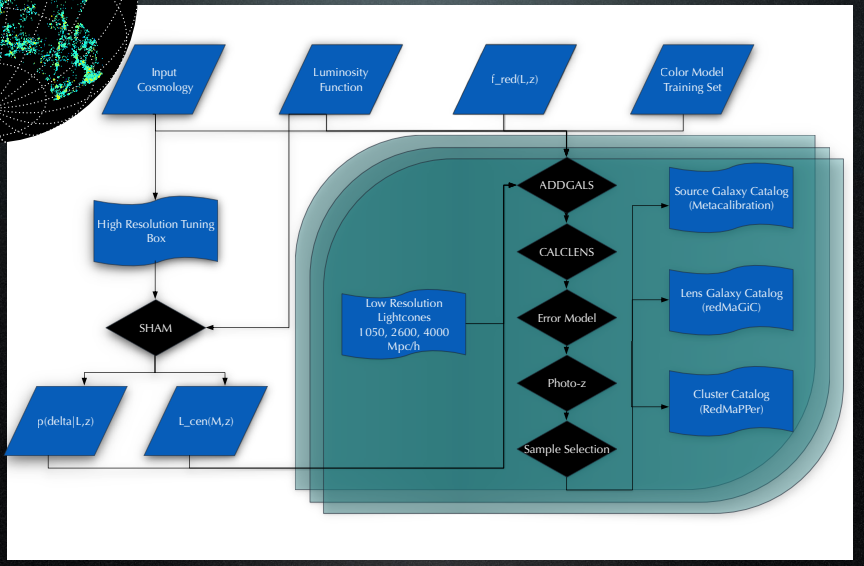
★ Requirements:

- Model all of the relevant survey observables (e.g. cluttering, lensing, clusters, photometric redshifts, other aspects of the density field)
- Many times survey volume —> lightweight

DES Mock catalogs

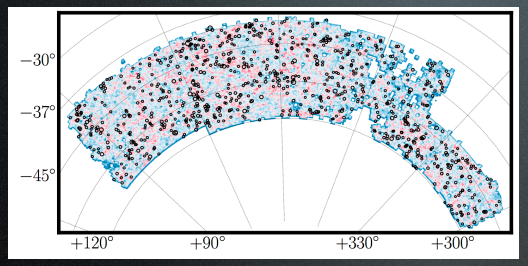
DeRose, RW, Becker et al (arXiv:1901.02401)

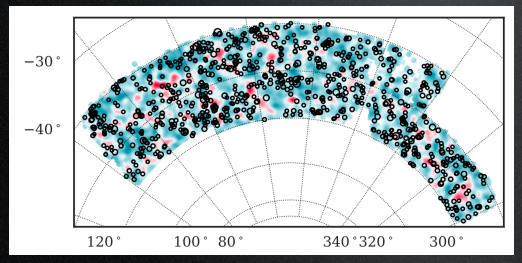




18 mock DES Y1s produced for co-analysis with DES data

DES Mock catalogs

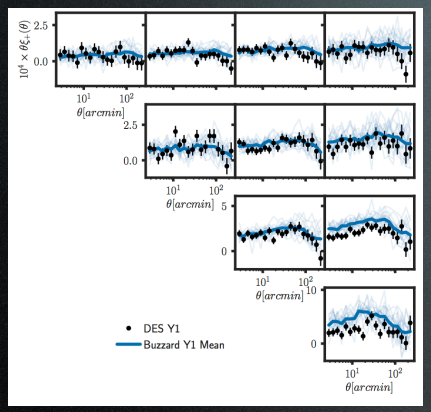




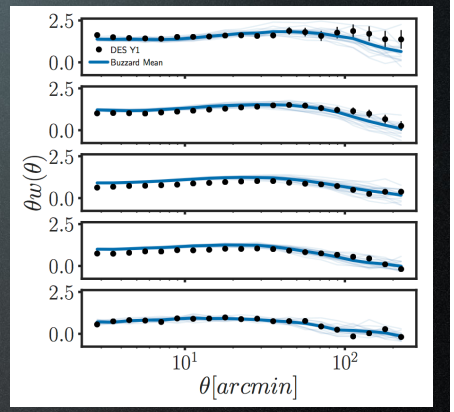
DeRose, RW, Becker et al 2019

—> 18 realizations of the DES Y1 footprint, with galaxy catalogs, shear, redmagic galaxy catalogs redmapper cluster catalogs, cluster lensing profiles, photometric redshifts, CMB lensing

3x2pt measurements



Shear
in data and sim

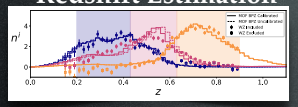


Galaxy clustering
in data and sim

DeRose, RW et al 2019

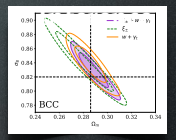
Allows for a diversity of uses (examples from DES Y1 analyses)

Redshift Estimation



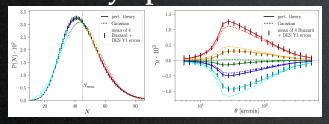
Gatti, Vielzeuf et al.
Hoyle et al.

3x2pt Parameter



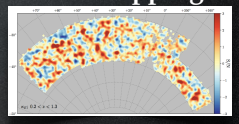
MacCrann, DeRose, RW et al. 2018

Density Split Statistics



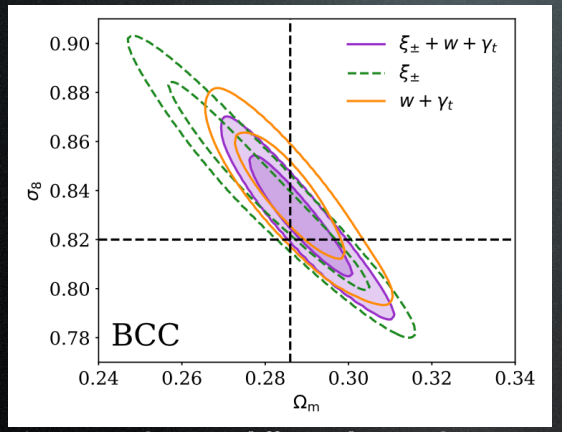
Gruen et al 2018; Friedrich et al. 2018

Mass Mapping



Chang et al. 2018

3x2pt end-to-end pipeline testing



Agreement between different data combinations

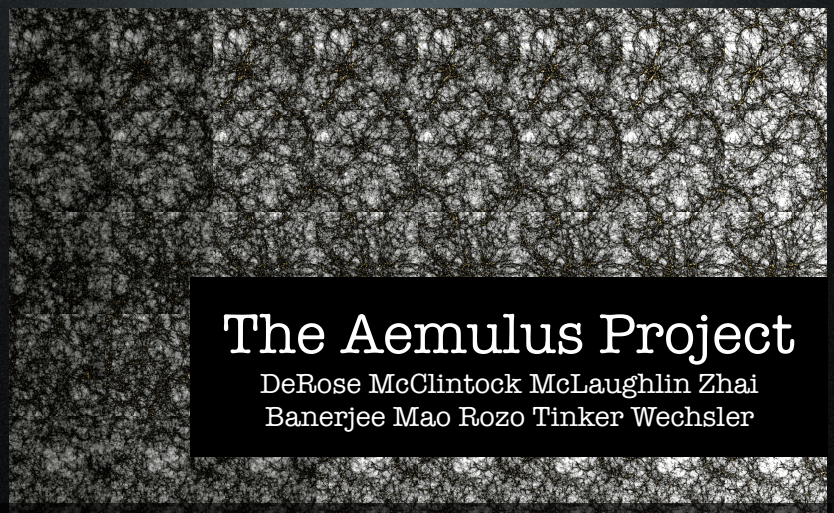
McCrann, DeRose, RW et al 2018

Compare the full analysis on simulated data before looking at real data.

Constrained possible bias to < 1sigma.

Requires volume significantly larger than survey volume.

II: The Mock as the Model



The Aemulus Project

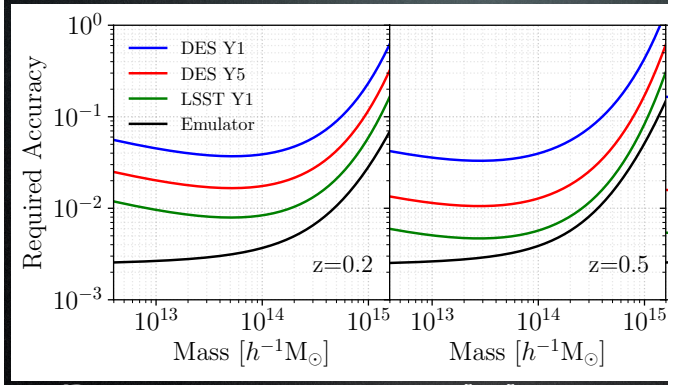
DeRose McClintock McLaughlin Zhai
Banerjee Mao Rozo Tinker Wechsler

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

The Aemulus Project

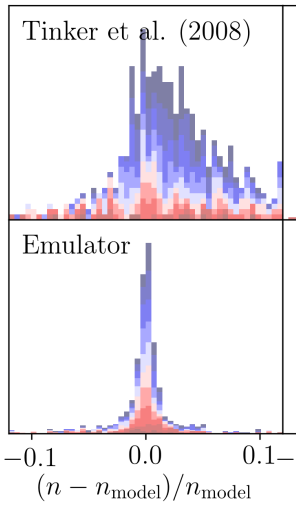
- Goal: Precision emulation of statistics of dark matter halos and galaxies (and their cross-correlations).
- Methods:
  - Suites of high-resolution N-body simulations spanning currently-allowed cosmological space.
  - Interpolate statistics within this space using Gaussian Process algorithms.
- Philosophy: Build problem-specific emulators, as lightweight and close to the data as possible.
- Results so far: percent-level estimates of the halo mass function and redshift-space galaxy clustering.
- Work in progress: galaxy clustering, galaxy-galaxy lensing, galaxy-mass correlations, including cosmology, HOD, assembly bias.

Aemulus II: Halo Mass Function



Percent precision needed in LSST era. New result is sufficient for DES and LSST Y1

Aemulus II: McClintock et al, arXiv:1804.05866



See also RSD results in Zhai et al 2018

Aemulus future:

- Work in progress/near future:
  - Galaxy bias and cluster mass profiles in the cluster regime
  - Joint predictions for galaxy clustering and galaxy-galaxy lensing as a function of cosmology and assembly bias
  - Use of higher resolution simulations that can model halo histories; including neutrino mass
  - Modeling additional observables, e.g. void statistics, cluster lensing profiles.

See also work at Argonne, IPMU, OSU

Examples for the near future:

- DES (and LSST) Cluster modeling
  - Challenging interplay between systematics which depend on the galaxy-halo connection (e.g. projection effects; orientation bias, photometric redshifts). Need to test full pipelines on simulated datasets with key systematics.
- DESI clustering + HSC & DES lensing
  - What range of scales and galaxy-halo models can we predict robustly? Need to develop precise emulators, show they are flexible to possible galaxy formation prescriptions.

Summary

- Accurate simulations and realistic and flexible galaxy modeling are essential to extracting cosmology from the next generation surveys
  - Many of the systematics we care about in these surveys depend on details of the galaxy population / galaxy-halo connection.
  - Have learned a lot about the basics of the galaxy-halo connection over the past decade (e.g. mass and redshift dependence of quenching, satellite fraction). The dependence of clustering on secondary properties of halos and galaxies is still uncertain and important.
  - Modest resolution simulations, with realistic galaxy populations, allow one to do tens of realizations of full survey volumes; essential for high precision tests of joint probes.
  - Structure formation observables can be predicted directly from suites of simulations using efficient parameter space sampling and an emulator. Potentially makes it possible to jointly solve for cosmological parameters and the galaxy-halo connection.

★ Efficiency, effectiveness, and achieved accuracy of the community's simulation / mock / galaxy modeling strategy may be the determining factor in how powerful next generation surveys are.