Making multi-wavelength, multi-redshift predictions for Cross-Survey Cosmological Analyses

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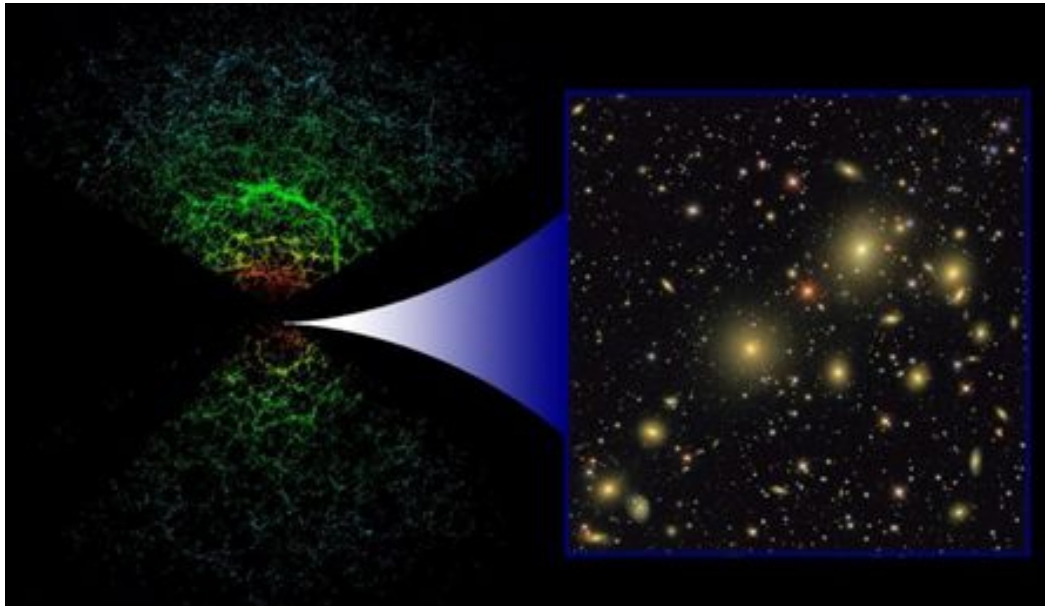
The next decade of cosmology

- The next generation of cosmological surveys will allow us to potentially explore the observational signatures of physics beyond the standard model
- Wealth of information contained in:
  - **Higher-order** clustering statistics
  - Clustering measurements in the **nonlinear** regime
  - **Multi-redshift** constraints
  - **Cross-survey** analyses

How do we take advantage of new constraining power?

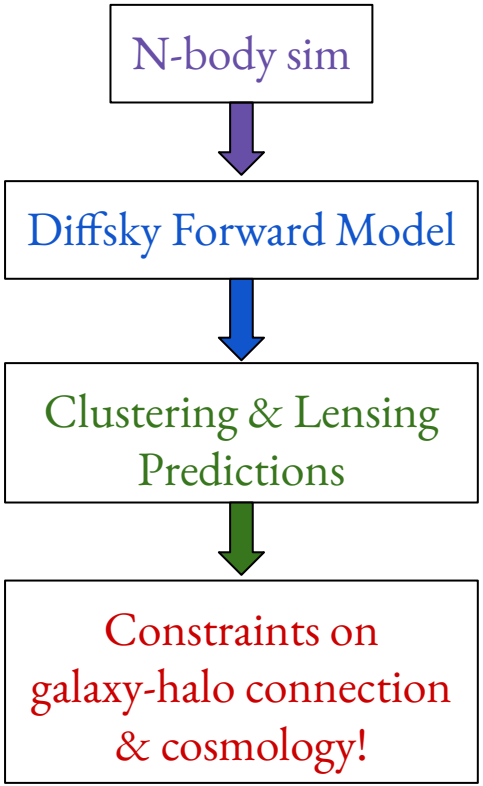
We need:

- A flexible model of the galaxy-halo connection that is accurate on small-scales
- The ability to model systematics in a physically meaningful and sufficiently complex way
- A framework that allows us to make multi-tracer, multi-z predictions *simultaneously*



A New Forward Model of the Galaxy-Halo Connection

- Goal: to develop a new generation of galaxy–halo models
  - Suitable for multi-z, multi-λ predictions
  - Based on simple physical assumptions
- Approach:
  - Reformulate predictions to be fully probabilistic & differentiable
  - Leverage good scaling of JAX on multi-GPU supercomputers
- Long-term goal: a full-scale, multi-redshift, multi-tracer, cross-survey cosmological analysis (including cross-correlations)



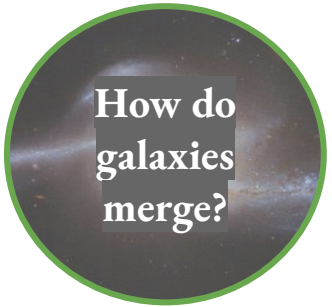
Differentiable **sky** predictions

Diffmah
(Hearin et al. 2021)

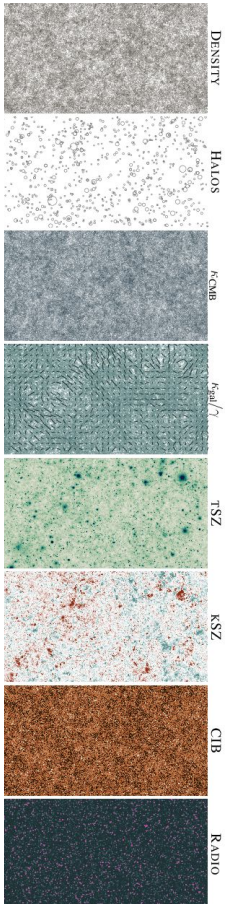
Diffstar
(Alarcon et al. 2023)

DSPS
(Hearin et al. 2023)

Diffmerge
(Beltz-Mohrmann et al. in prep.)



Multi-λ predictions

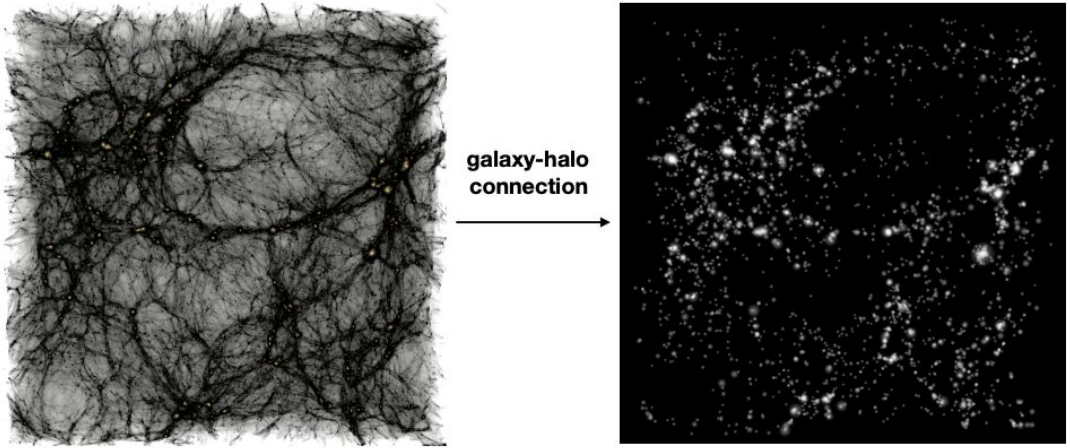


*All model parameters have physical interpretations. We seek the minimum interpretable parametric flexibility required to accurately capture the data.

Image credit: Millennium XXL simulation, NASA, ESA, Yuuki Omori/Agora simulation
Slide credit: Alex Alarcon

What makes Diffsky different?

- Empirical forward model
- Has the flexibility and multi-λ predictive power of a semi-analytic model (but no ODEs governing transfer of energy)
- Faster speed due to AI/ML techniques and good scaling of JAX on GPUs
- Model parameters have physical interpretations
- Can validate using hydro simulations & SAMs



Approaches to modeling the galaxy-halo connection

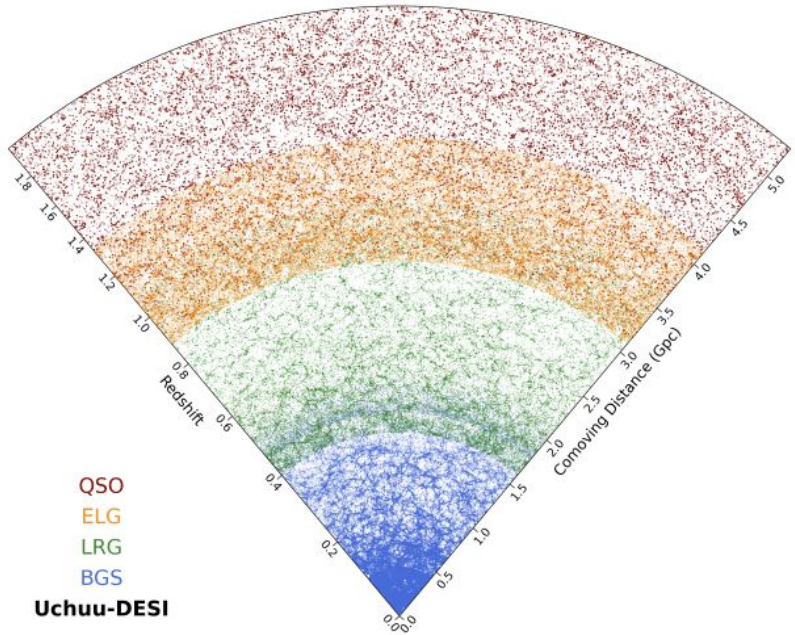
physical models ← → empirical models

Hydrodynamical Simulations	Semi-analytic Models	Empirical Forward Modeling	Subhalo Abundance Modeling	Halo Occupation Models
Simulate halos & gas; Star formation & 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 & subhalos) plus assumptions about galaxy—(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

Wechsler & Tinker 2018

Model capability

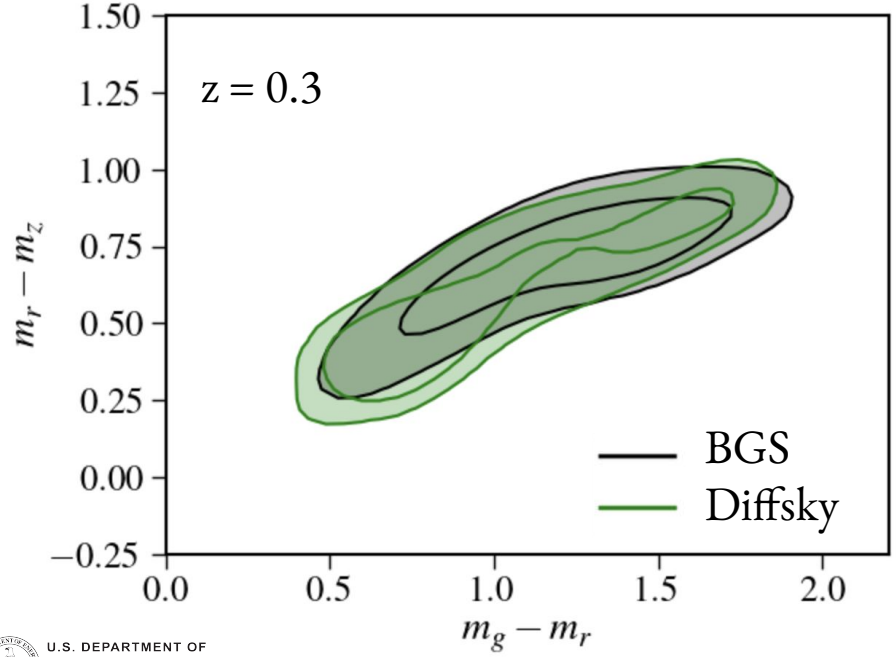
- New capability to fit data:
  - Multi-redshift, multi-wavelength, multi-tracer predictions
- Ideal for cross-survey analyses
- Allows for modeling systematics in a physically meaningful and sufficiently complex way
- We can provide validation data for other pipelines to test robustness (i.e. through mock challenges)
- We can populate simulations with different cosmologies (e.g. Abacus) to make mock galaxy catalogs

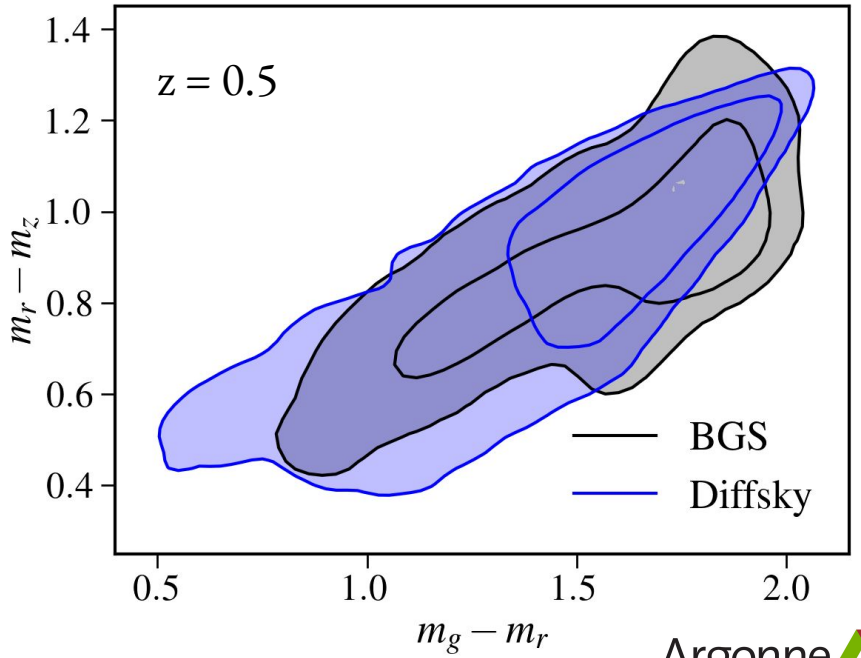


Prada et al. 2023

Fitting the model to DESI data

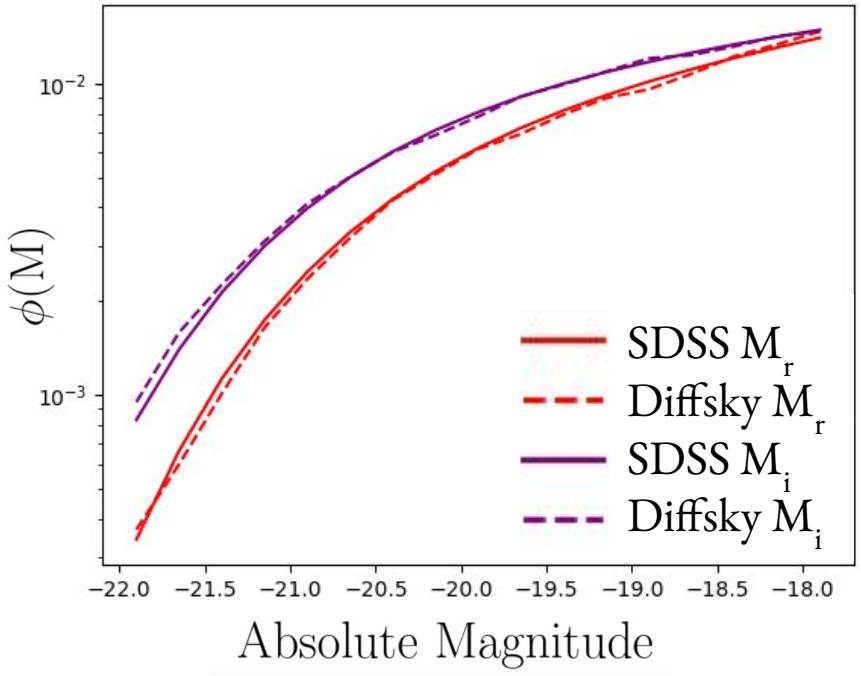
- Good agreement with BGS colors, number densities and satellite fractions at z=0.3 & z=0.5
- Also good agreement with LRG number densities and satellite fractions at z=0.5 & z=0.8



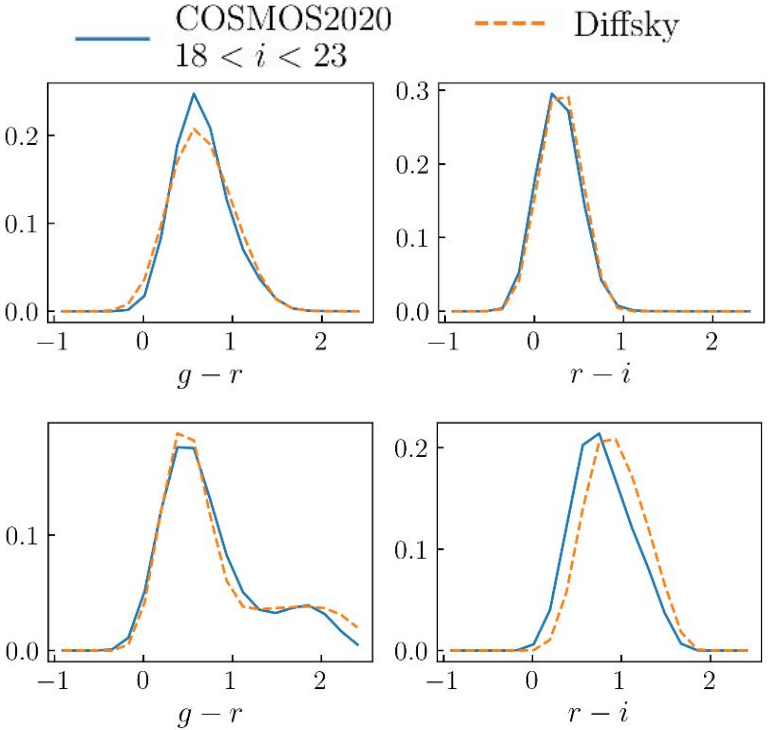


Fitting the model to SDSS & COSMOS

SDSS Main Galaxy Sample
Luminosity Functions

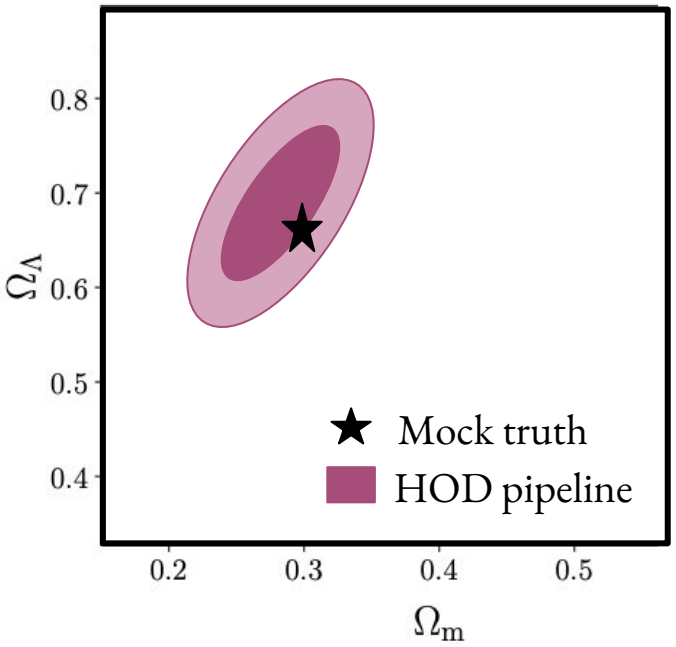


COSMOS2020 Color PDFs



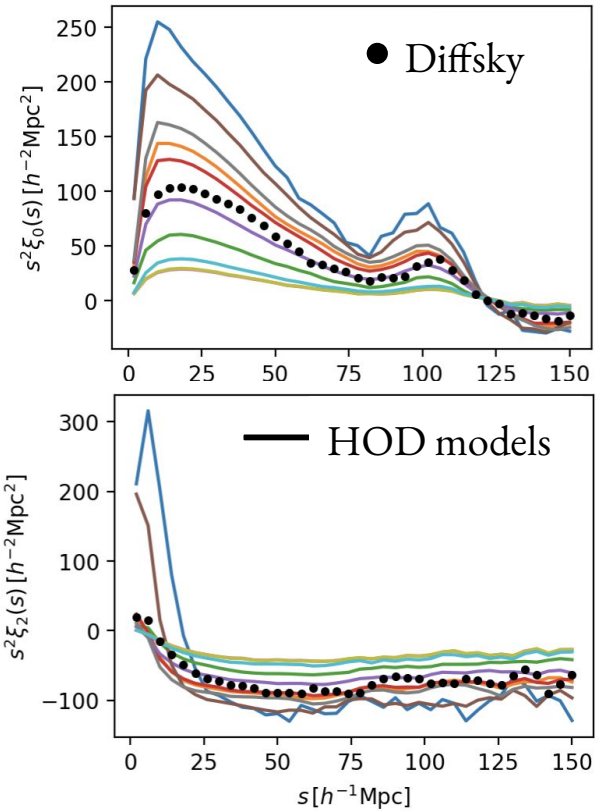
Mock validation tests

- Mock galaxy catalogs created with our pipeline are ideal for robust validation tests (i.e. mock challenges) for other pipelines that rely on traditional models of the galaxy-halo connection (e.g. HOD, CLF, EFT)
- These mock challenges represent a growing trend in the field to validate cosmological analyses, especially for non-linear and higher order statistics
    - Currently leading the DESI Emulator Mock Challenge
    - See also comparable work from the Beyond-2pt Collaboration (arXiv:2405.02252)

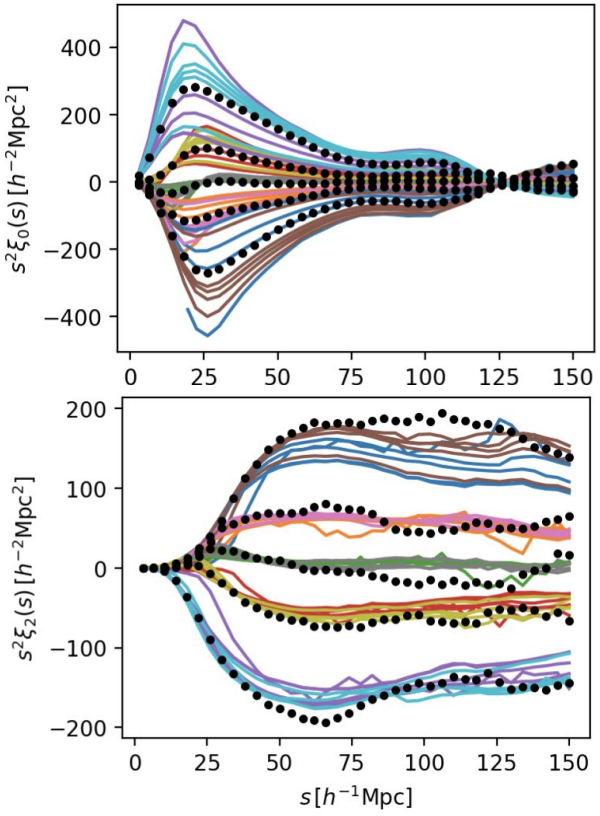


DESI Emulator Mock Challenge: Alternative Clustering Methods

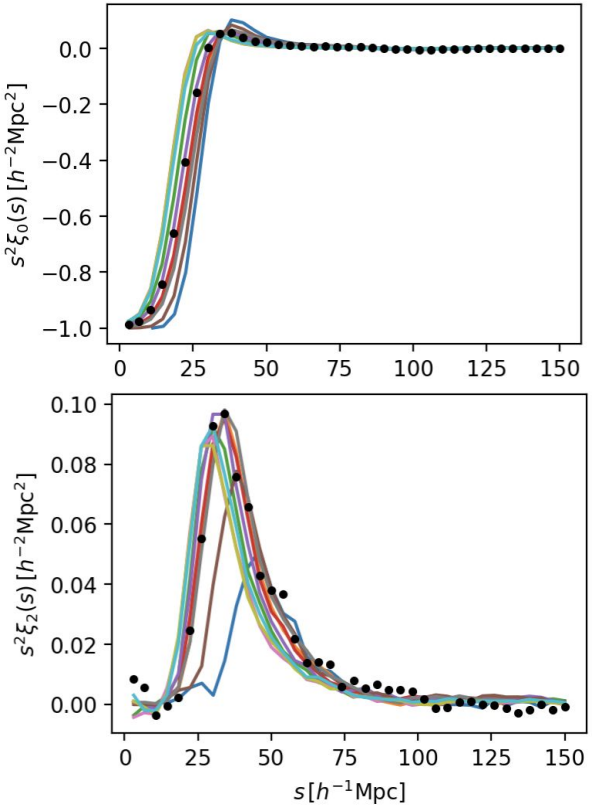
Correlation Functions



Density Split



Void Galaxy Cross Correlation



DESI Alternative Clustering Measurements Topical Group
(Enrique Paillas, Carolina Cuesta, Tristan Fraser, et al.)

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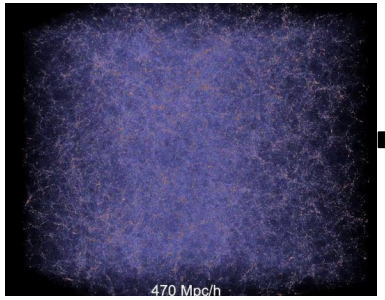
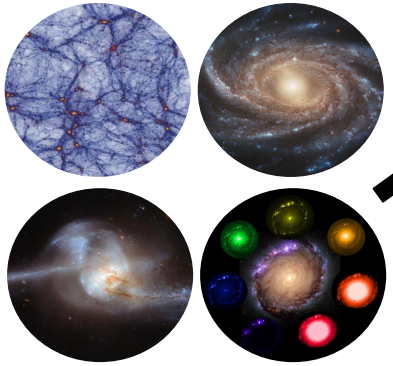
Future cosmology analysis

We plan to perform our own **full-scale, multi-redshift, multi-tracer, cross-survey cosmological analysis** (including cross-correlations) with the diffsky pipeline.

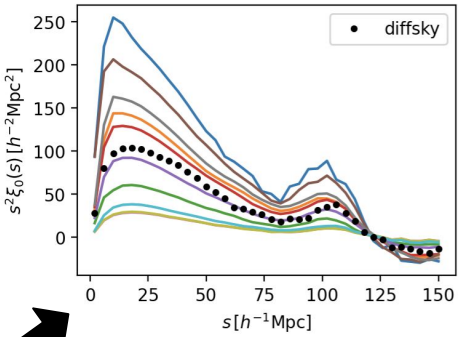


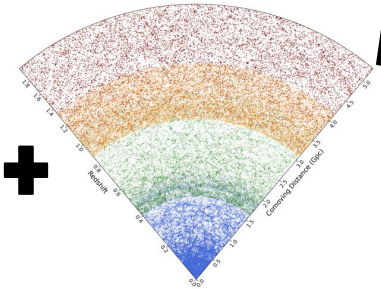
N-body simulation



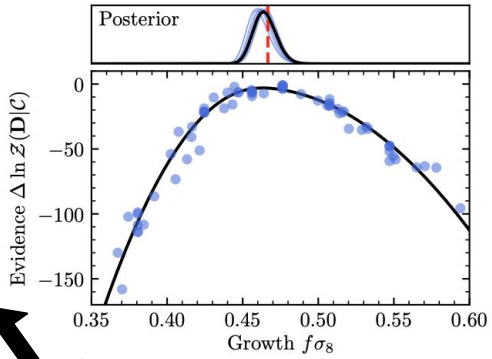
Diffsky Pipeline

Measurements + Data





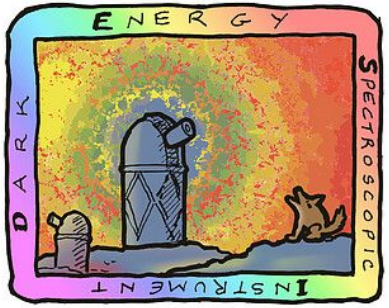
Constraints!



Cosmological Evidence Modeling (Lange et al. 2019)

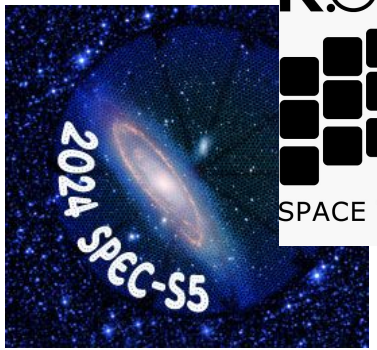
Goals for Future Surveys

- Generate detailed mocks
  - Support wide variety of $0 < z < 5$ science
  - Multi-wavelength mocks with joint modeling for LSST, DESI, Roman, Spec-S5
  - Survey-scale volumes with high-res N-body merger trees
- Joint constraints on cosmology + galaxy-halo connection
  - Simulation-based predictions for nonlinear-regime
  - Targeting w(z) with clustering and lensing of magnitude-limited samples between $0 < z < 1$



LSST DESC
Dark Energy Science Collaboration

NANCY GRACE ROMAN SPACE TELESCOPE



Thank you!
Questions?

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In collaboration with:


Andrew Hearin


Alex Alarcon


Matt Becker


Alan Pearl


Enia Xhakaj


Georgios Zacharegkas

If this sounds interesting, our team at Argonne is hiring a new postdoc to work on DiffStuff! Contact ahearin@anl.gov for more information!

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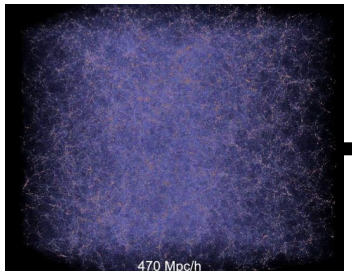
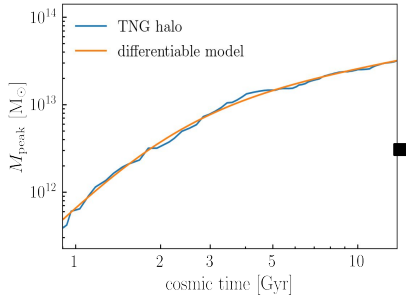
Diffsky Pipeline

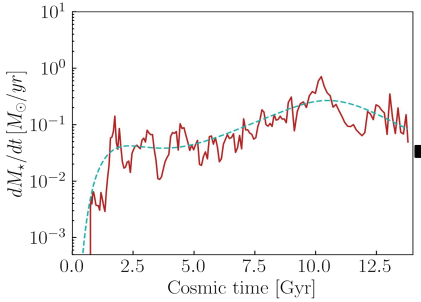
N-body simulation



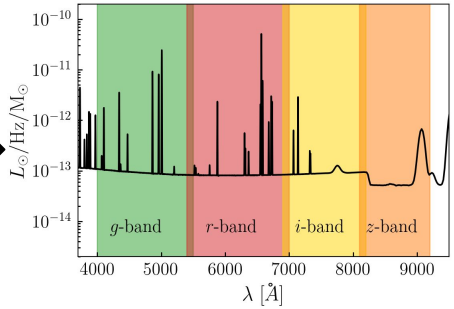
Diffmah:
Hearin et al. 2021

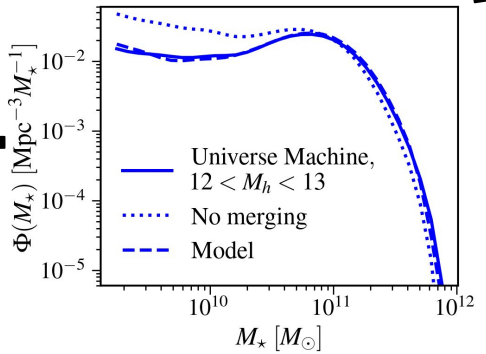


Diffstar:
Alarcon et al. 2023

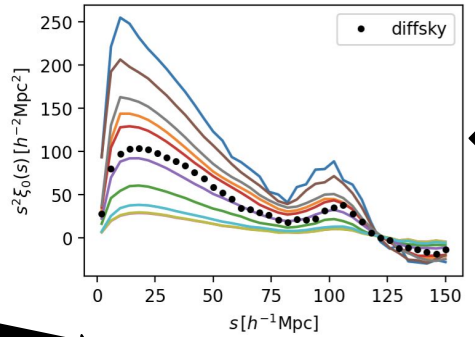


DSPS:
Hearin et al. 2023

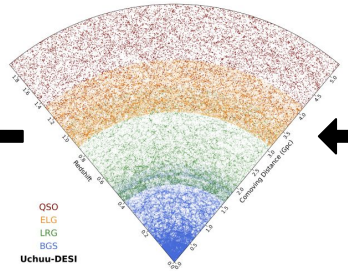




Diffmerge:
BM et al. in prep.

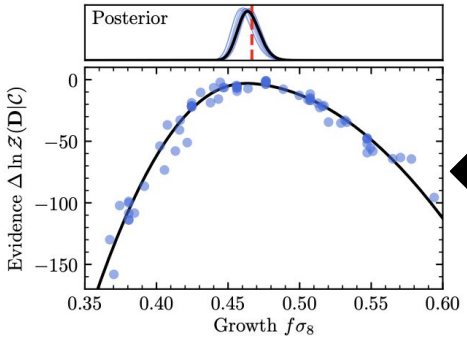


Measurements



Data

HMC



Cosmological Evidence
Modeling (Lange et al. 2019)