August 6, 2020

Advances in Modelling the Galaxy-Halo Connection

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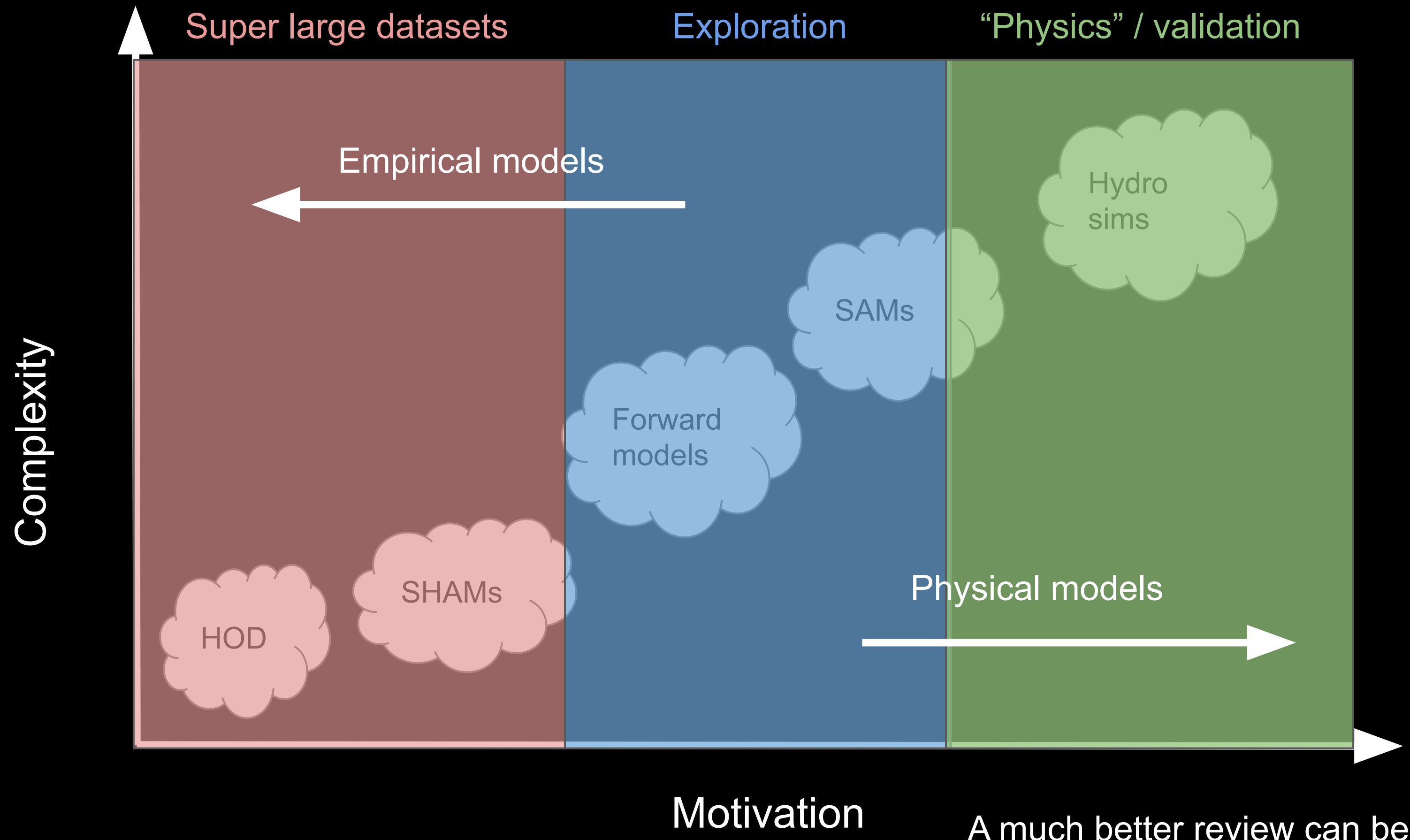
Outline

- Physical models for building the galaxy-halo connection
- The observational frontier for constraining the galaxy-halo connection
- Future directions and applications of the galaxy-halo connection



A much better review can be found in: Wechsler & Tinker 2018

Recent developments in hydro sims

- Simulations of galaxy formation are becoming **increasingly larger**, with computational volumes that are relevant to large-scale structure cosmology

  BAHAMAS (McCarthy et al. 2017); TNG-300 (Pillepich et al. 2018); SIMBA (Davé et al. 2019); Horizon Run-5 (Lee at al. 2020)

- For the largest DM haloes, there have been significant advancements in the growth and evolution of black holes, and associated **feedback processes**

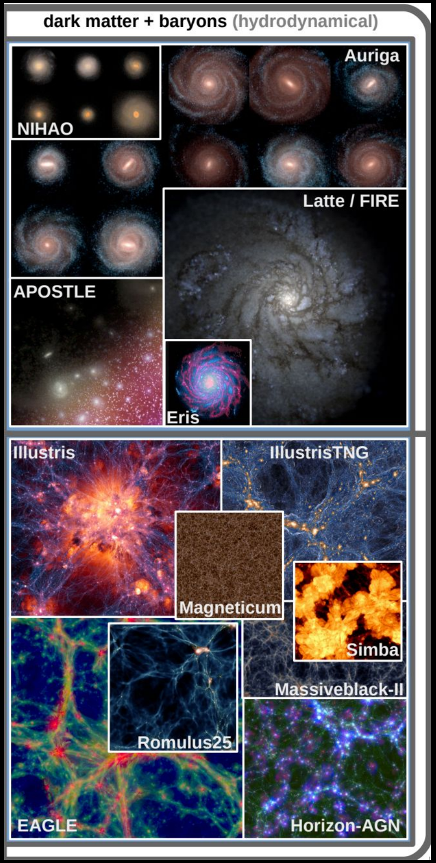
  Dubois et al. 2016; Weinberger et al. 2017; Anglés-Alcázar et al. 2017; Tremmel et al. 2017

- Much more **detailed physics** that were once considered “too exotic”: magnetic fields, cosmic rays, thermal conduction

  Kannan et al. 2016; Simpson et al. 2016; Ruszkowski et al. 2017; Marinacci et al. 2018

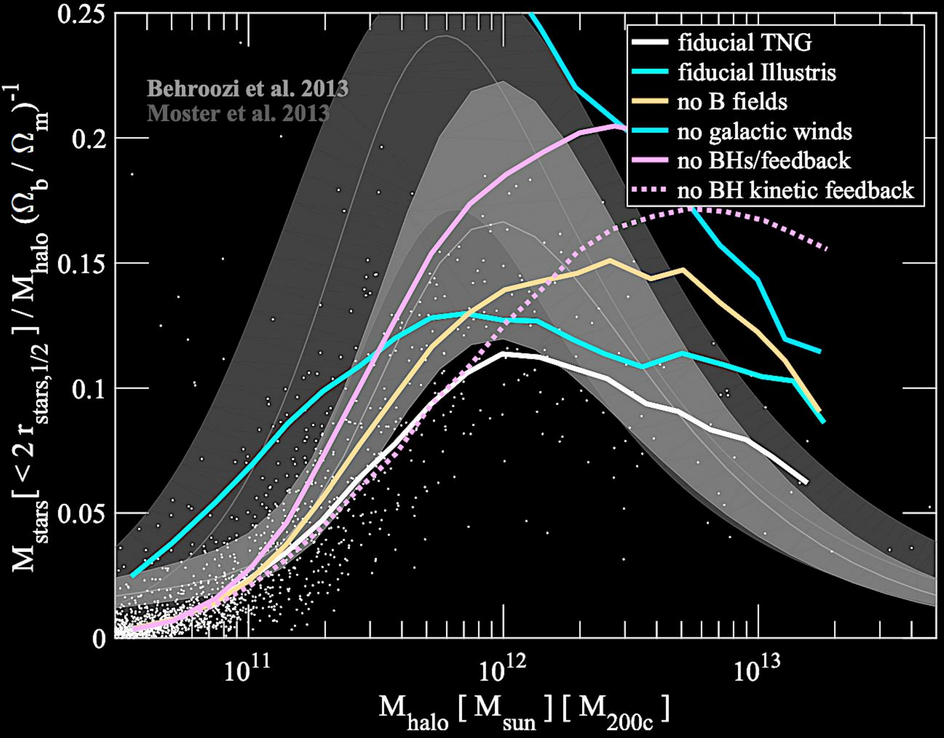
- On smaller scales, there have also been significant advancements in **modelling the multiphase ISM and star formation**: this is particularly relevant for dwarfs

  Semenov et al. 2016; Hopkins et al. 2018; Wheeler et al. 2018; Munshi et al. 2019 ; Rey et al. 2019; Marinacci et al. 2019; Agertz et al. 2020



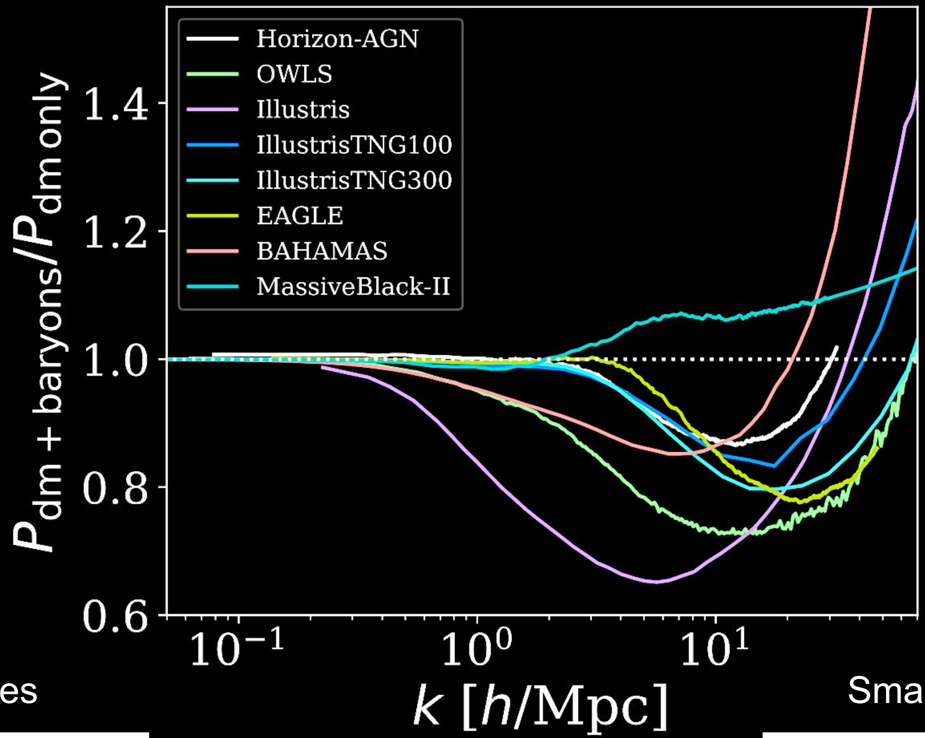
Vogelsberger et al. 2020

Feedback and the galaxy-halo connection



Pillepich et al. 2018

Feedback and the total matter distribution

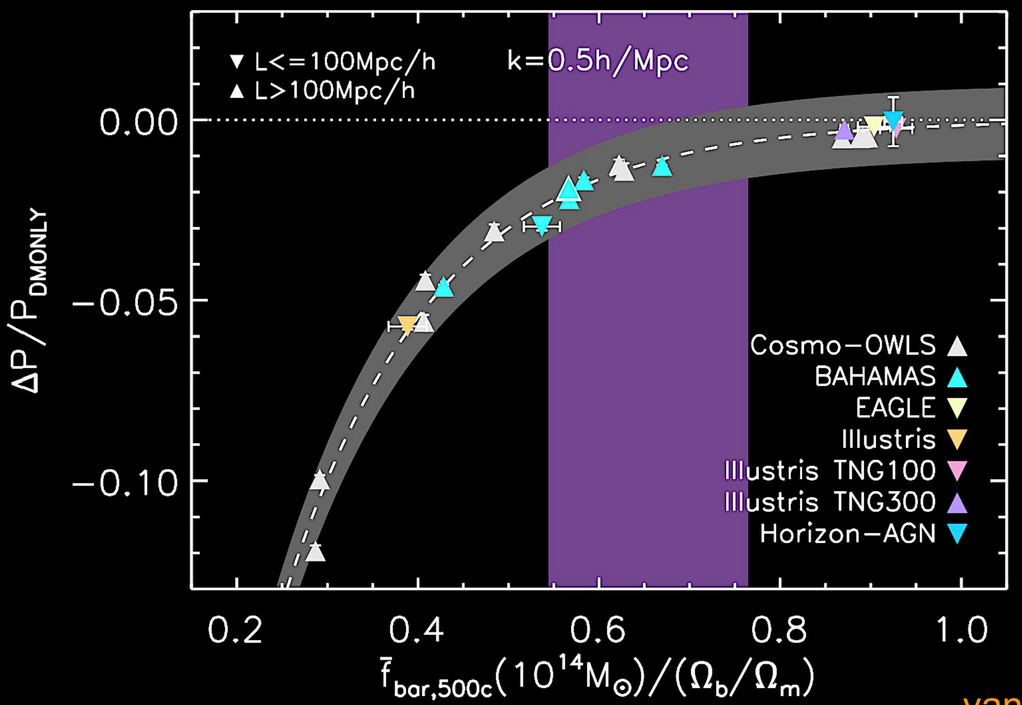


Chisari et al. 2019

Large scales

Small scales

The baryon content of groups and clusters



van Daalen et al. 2020

Recent developments in SAMs

- Application to much larger volumes than is possible with hydro (for now): **increased statistical power**

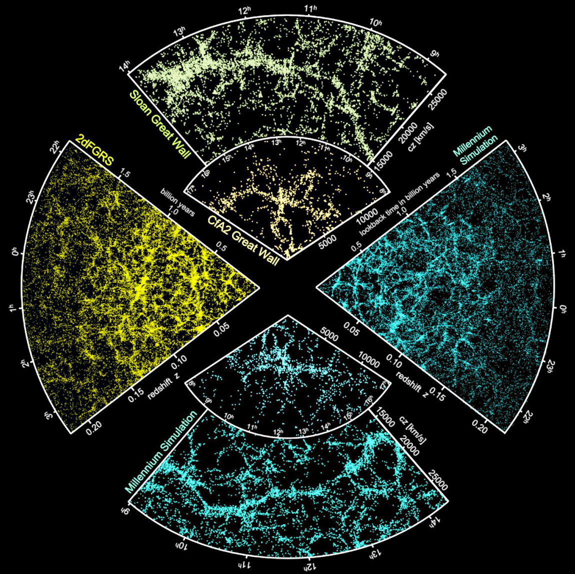
Smith et al. 2017; Cora et al. 2018; Merson et al. 2019; Baugh et al. 2019

- Newer SAMs now calibrate model parameters to a **more diverse set of observational data** (luminosity functions, quenched/star-forming fractions, clustering) which helps determine the relative importance of individual parameters

Henriques et al. 2015; van Daalen et al. 2016; Xie et al. 2017; Lagos et al. 2018

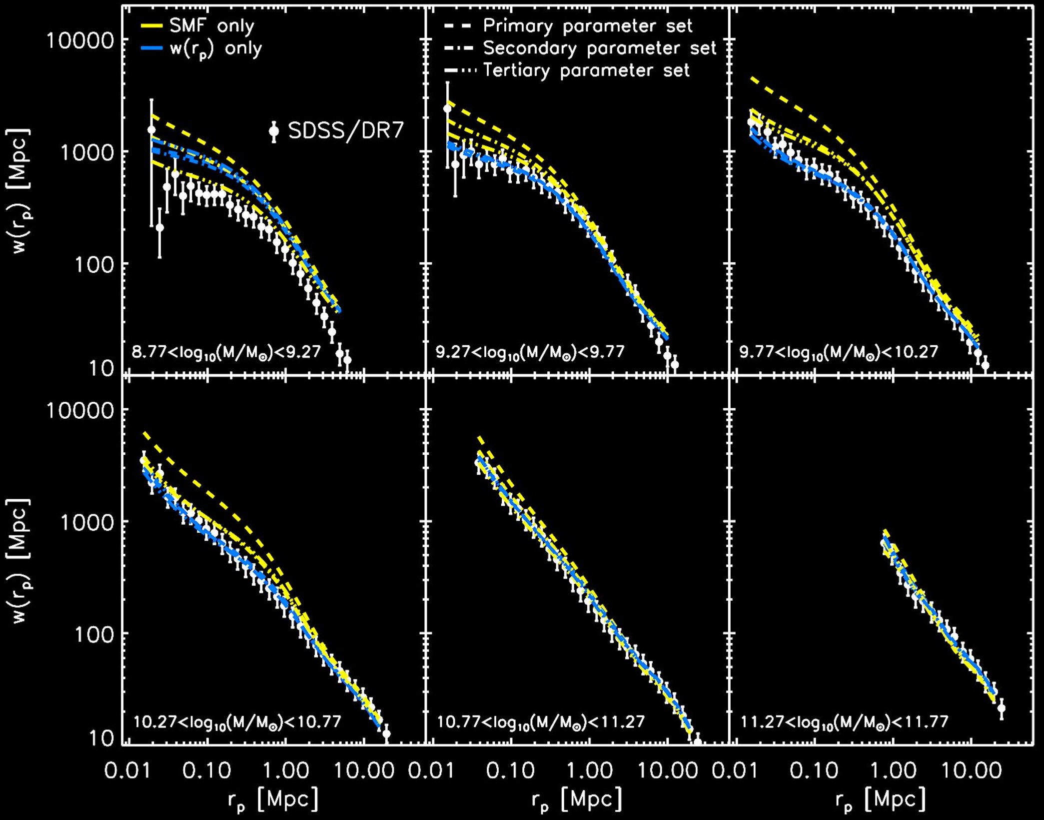
- Improved treatment of satellite galaxies through the **orphan technique** which has significant impact on one-halo clustering and the galaxy-halo connection for dwarfs

Simha & Cole 2017; Knebe et al. 2017; Pujol et al. 2017; Bose et al. 2020; Nadler et al. 2020; Carlsten et al. 2020



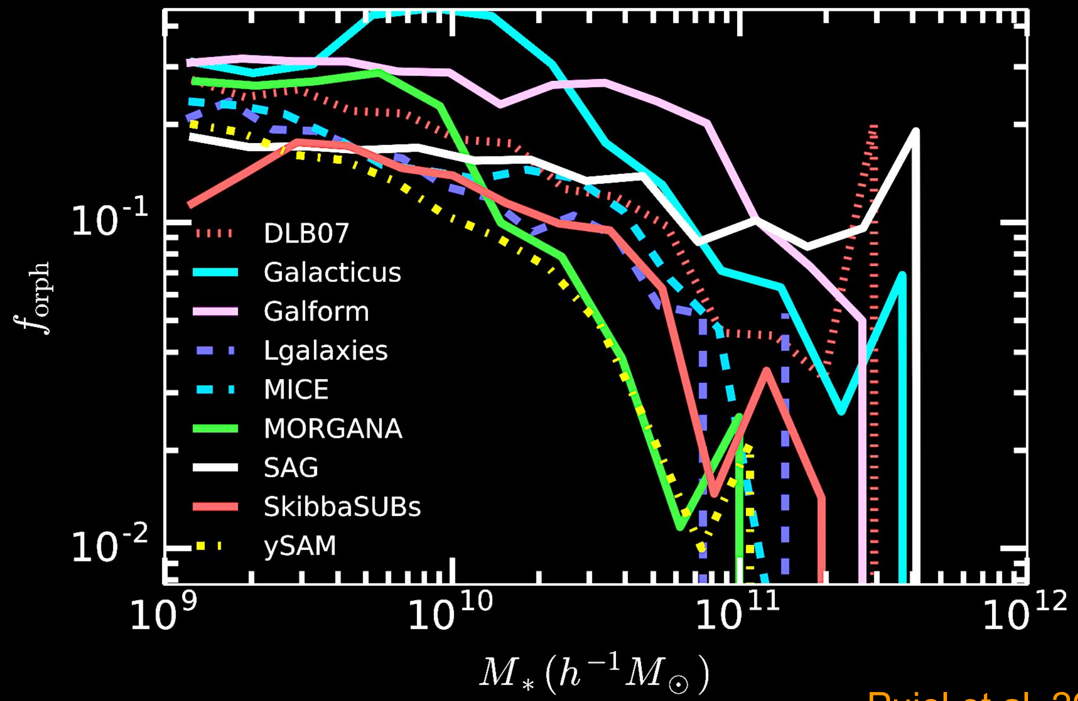
Springel et al. 2005

Clustering as a constraint on galaxy formation



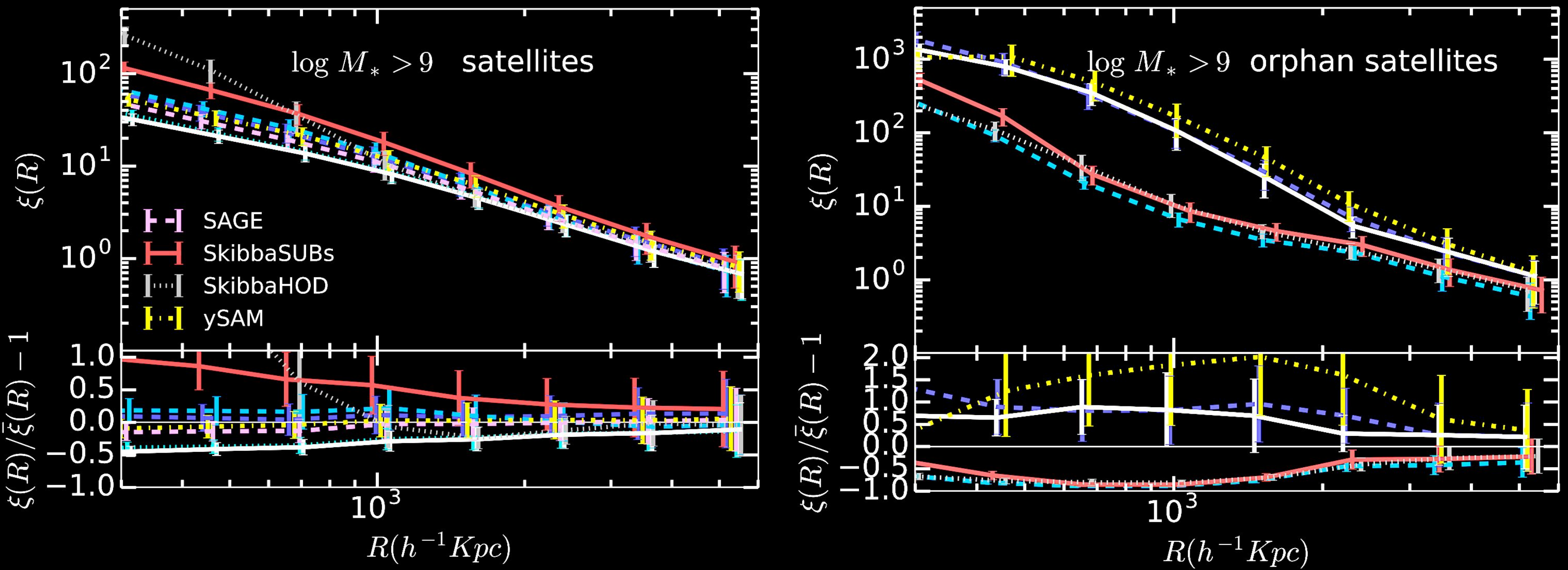
van Daalen et al. 2016
(L-Galaxies model)

The significance of orphan galaxies



Pujol et al. 2017
(nIFTy comparison project)

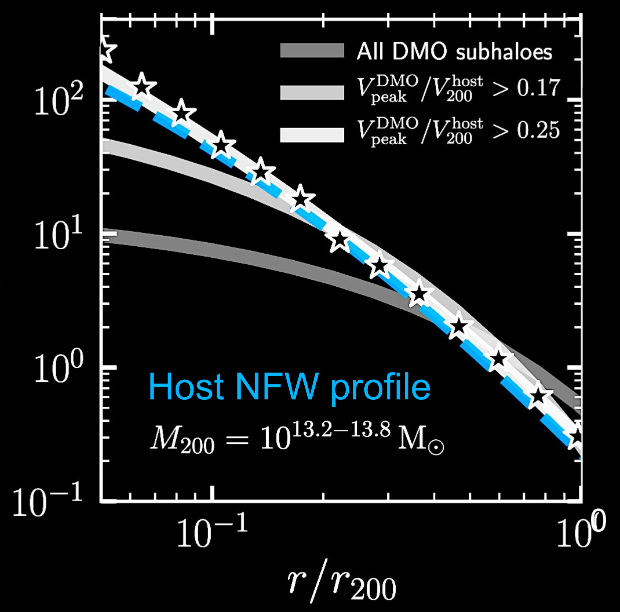
The significance of orphan galaxies



Pujol et al. 2017
(nIFTy comparison project)

Physical models provide critical validation data

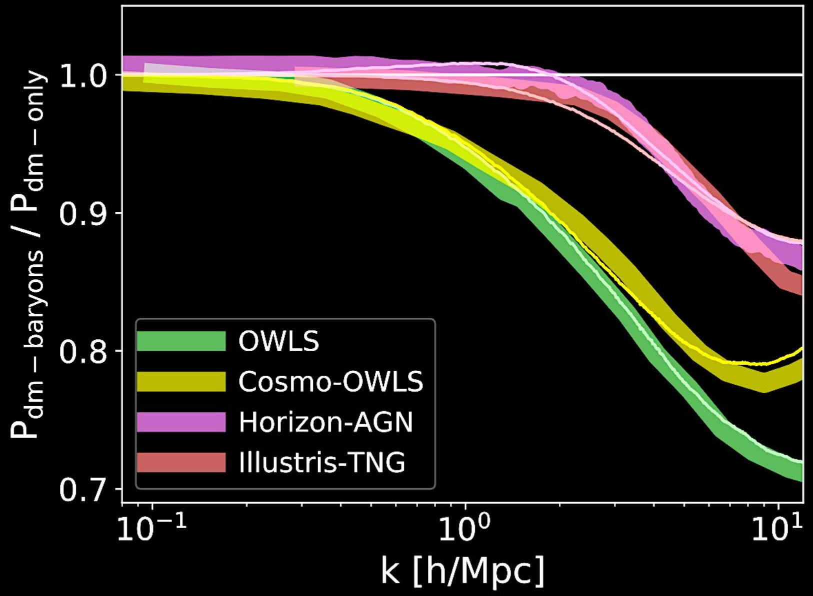
How are satellites distributed?



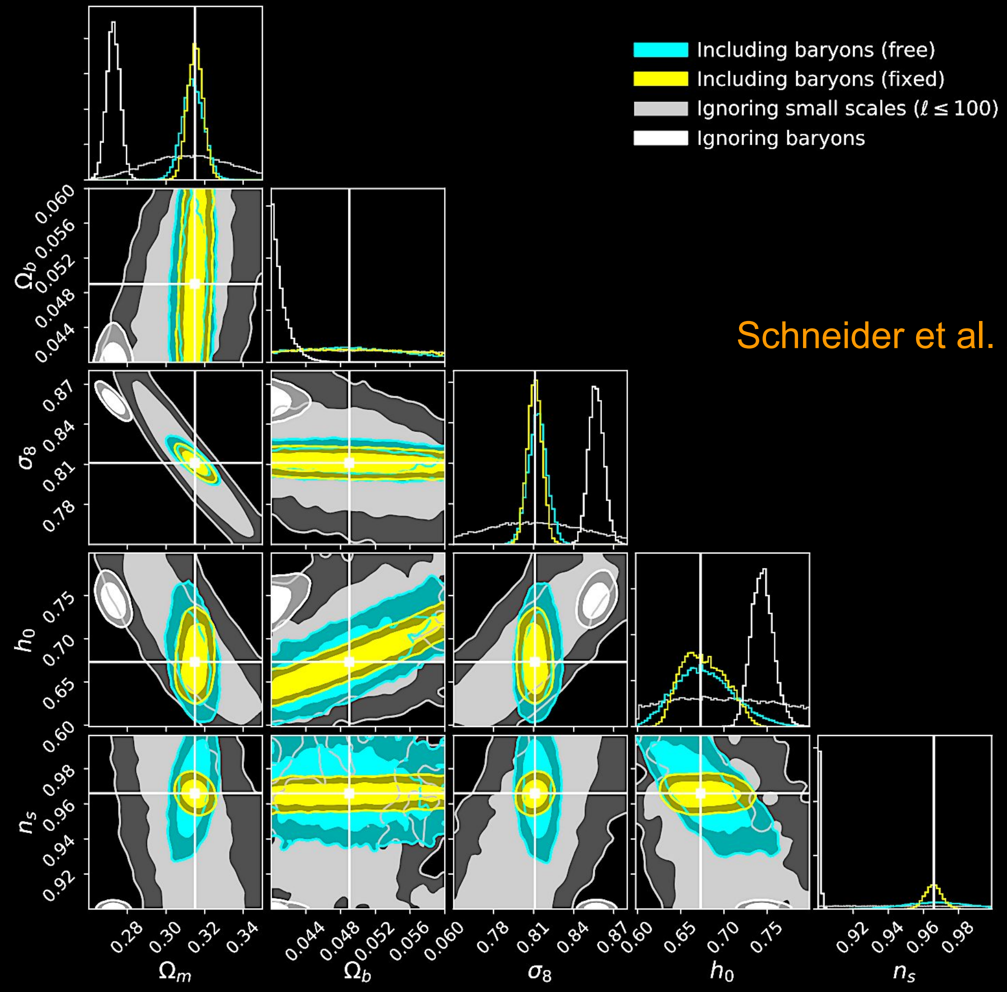
Bose et al. 2019

… and can be used to quantify/model systematics

- There is a limit to which we will be able to use hydrodynamical simulations to model the impact of baryon physics on large-scale structure (and, therefore, the extent to which this affects measurements like weak lensing and constraints on cosmological parameters)
- A compromise: develop “approximate methods” that mimic the effect of baryons on matter by calibrating against hydrodynamical simulations
- ***Baryonification***: perturb the non-linear particle distribution in the vicinity of haloes in an N-body simulations by applying displacement functions parameterised by halo profiles (Schneider & Teyssier 2015)



Chisari et al. 2019



Schneider et al. 2020

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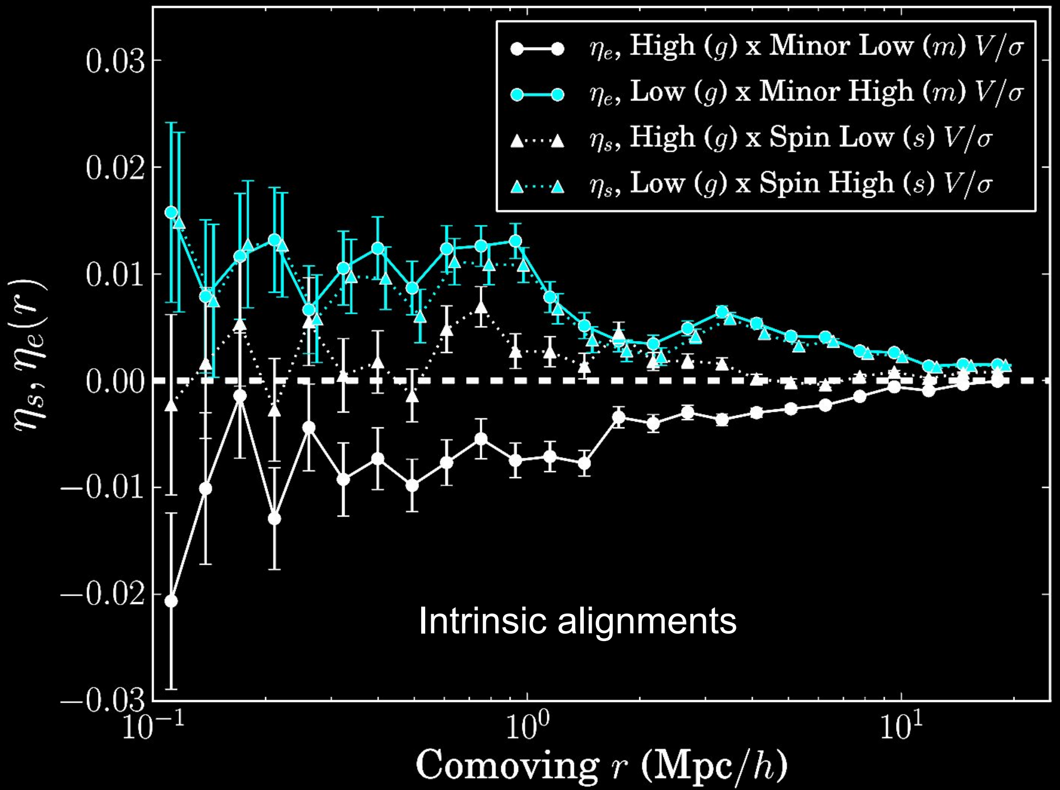


Chisari et al. 2015;
Bate et al. 2020;
Tenneti et al. 2020

Outstanding issues

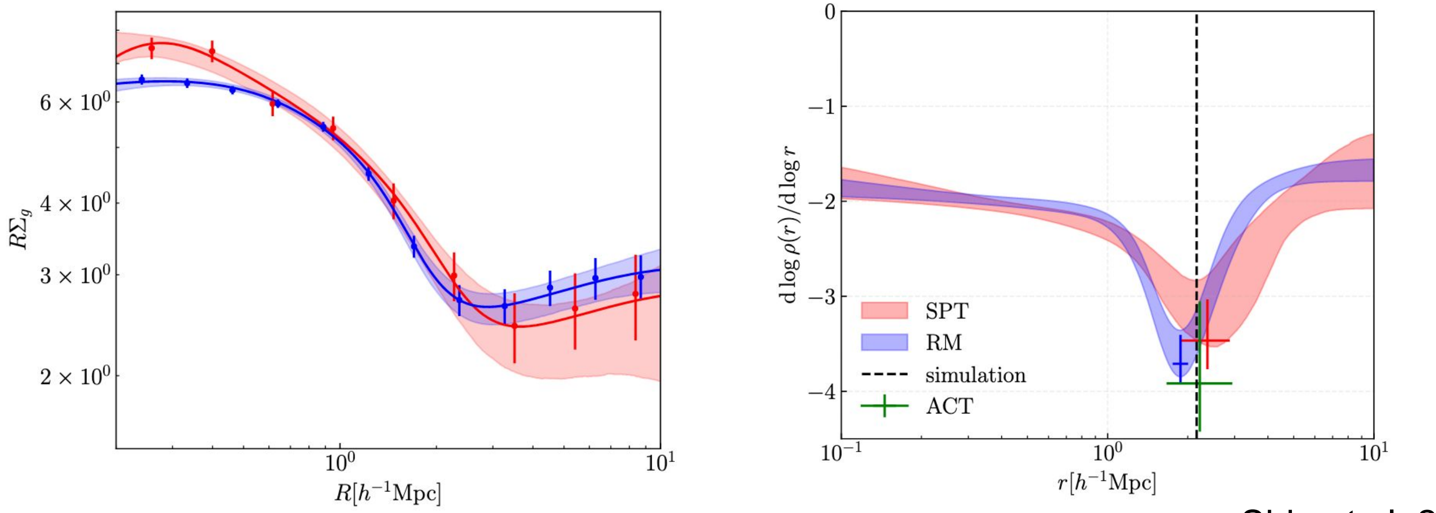
Modelling

- Better motivated black hole seeding, growth, energy coupling
- Using sequences of smaller experiments to inform “subgrid” choices
- Marginalise over all possible galaxy formation / feedback models?

Numerics

- How well converged are hydro/SAM predictions in the LSS regime?
- Are orphans being treated correctly?
- Choices in force softening, artificial disruption of substructures?
- Vagaries in the definition of halo boundaries

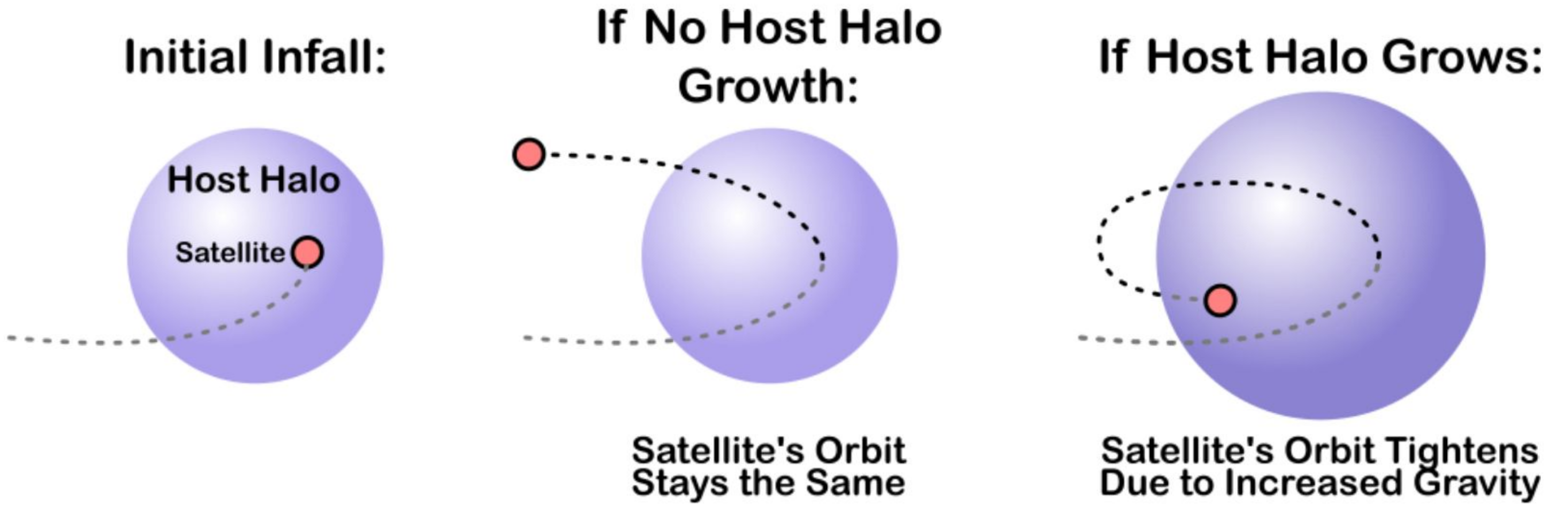
Observables: Splashback Radii



Shin et al. 2018

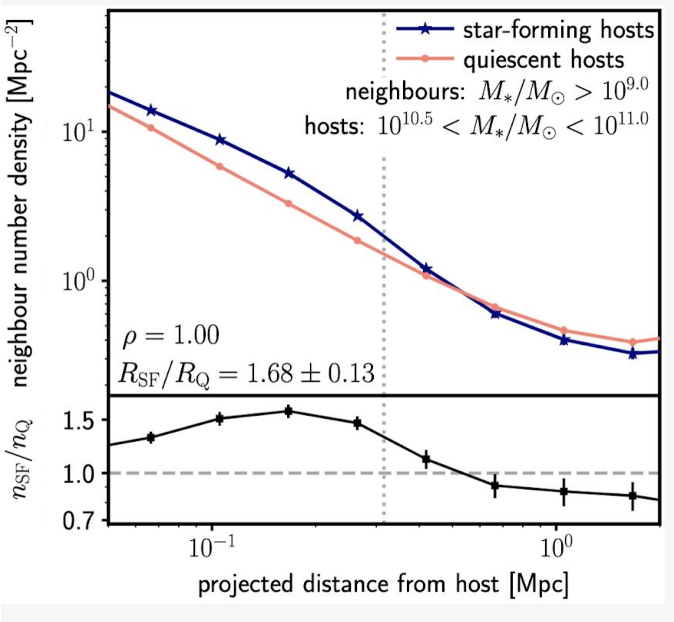
See also: Zurcher & More (2018), Murata+ (2020), Contigiani+ (2020), Xhakaj+ (2020), Adhikari+ (2018), and many more...

Observables: Splashback Radii



O'Donnell et al. (2020a+b)

Observables: Galaxy-Halo Assembly Connection



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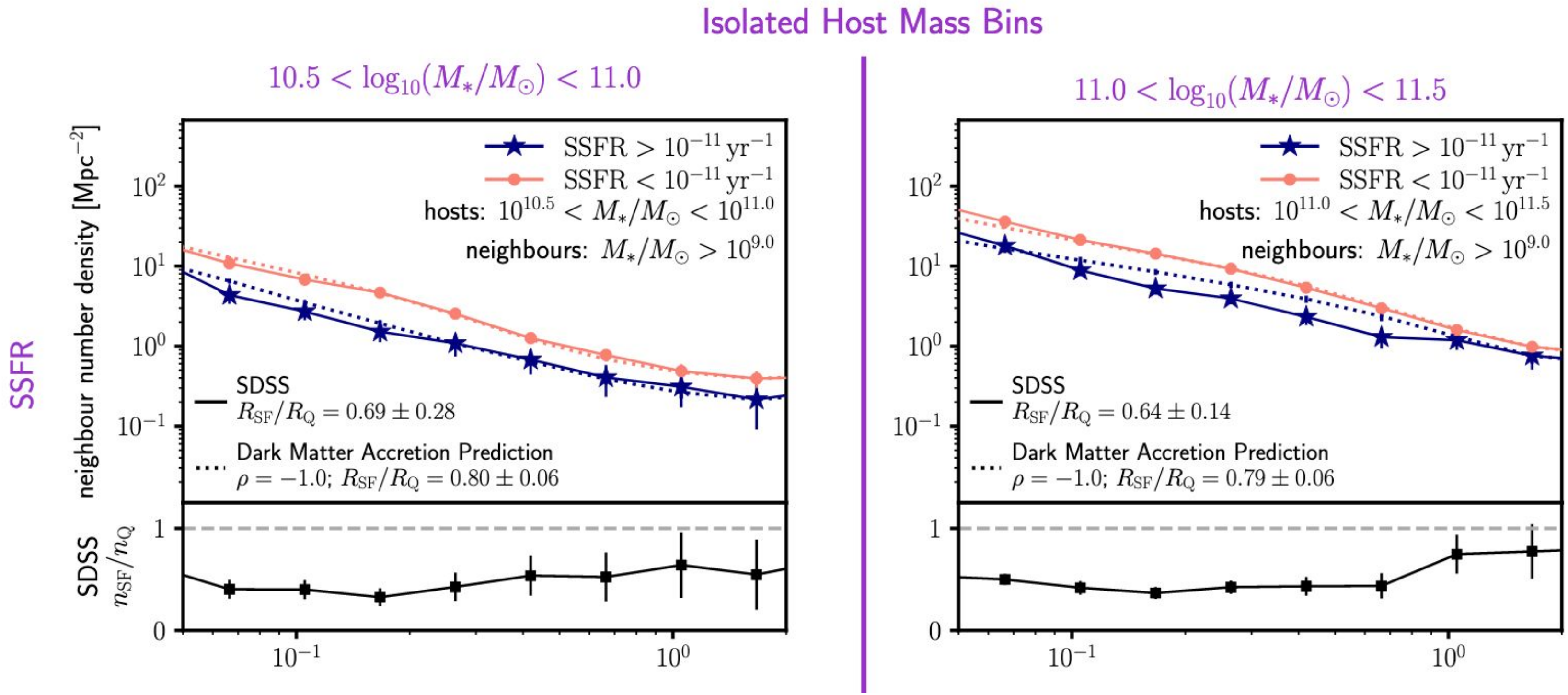

O’Donnell et al. (2020a+b)

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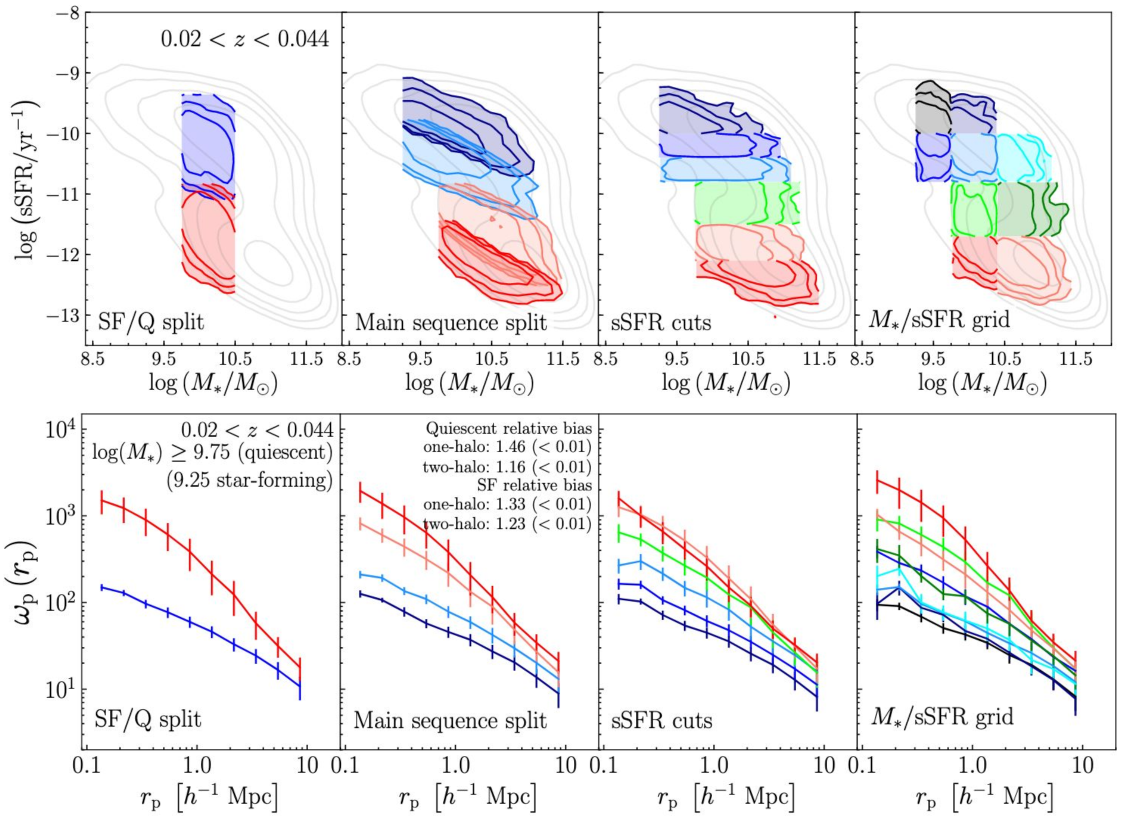
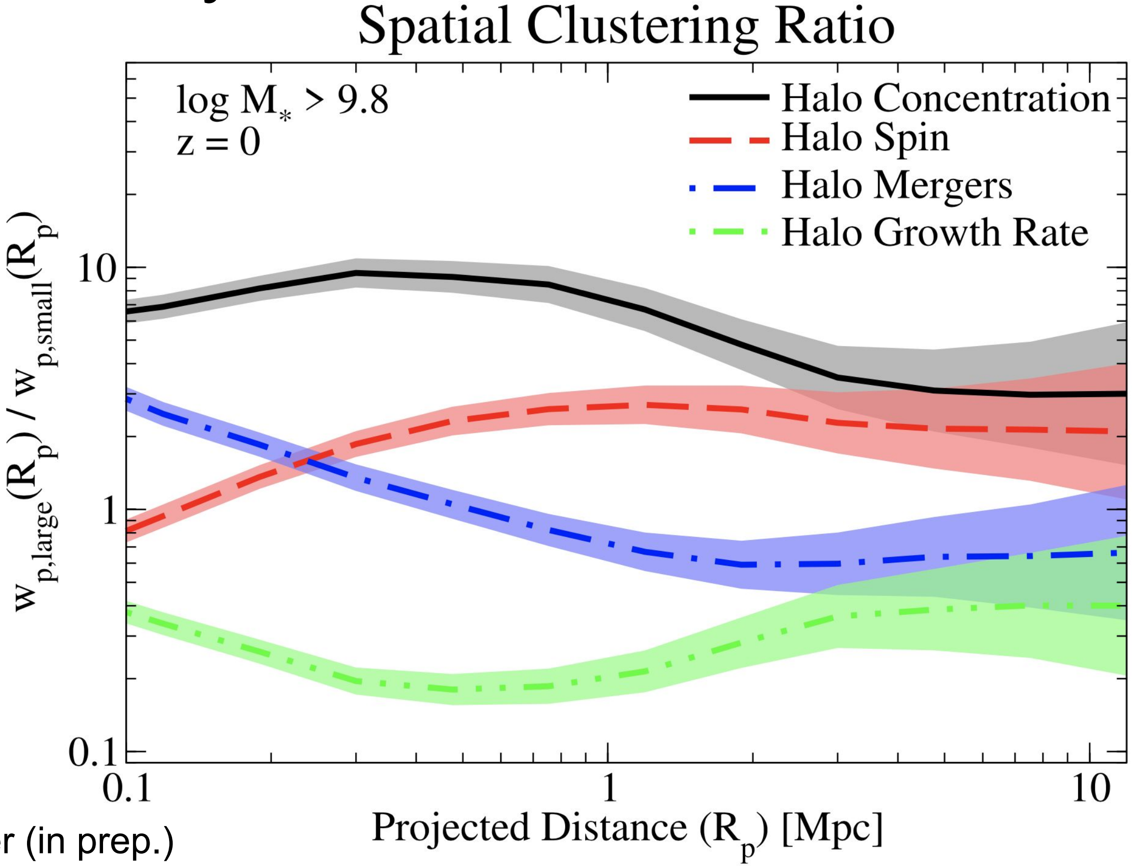


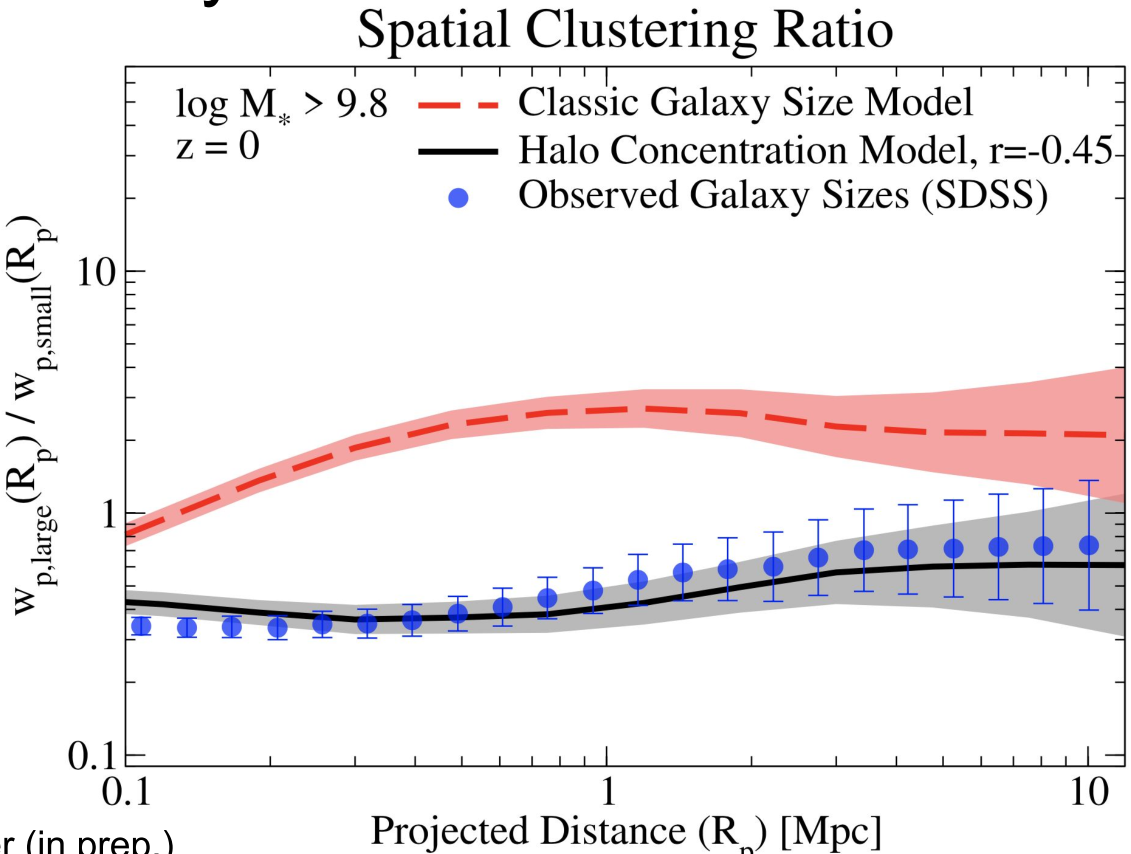
Berti+ (in prep.)

Observables: beyond halo mass & accretion rate



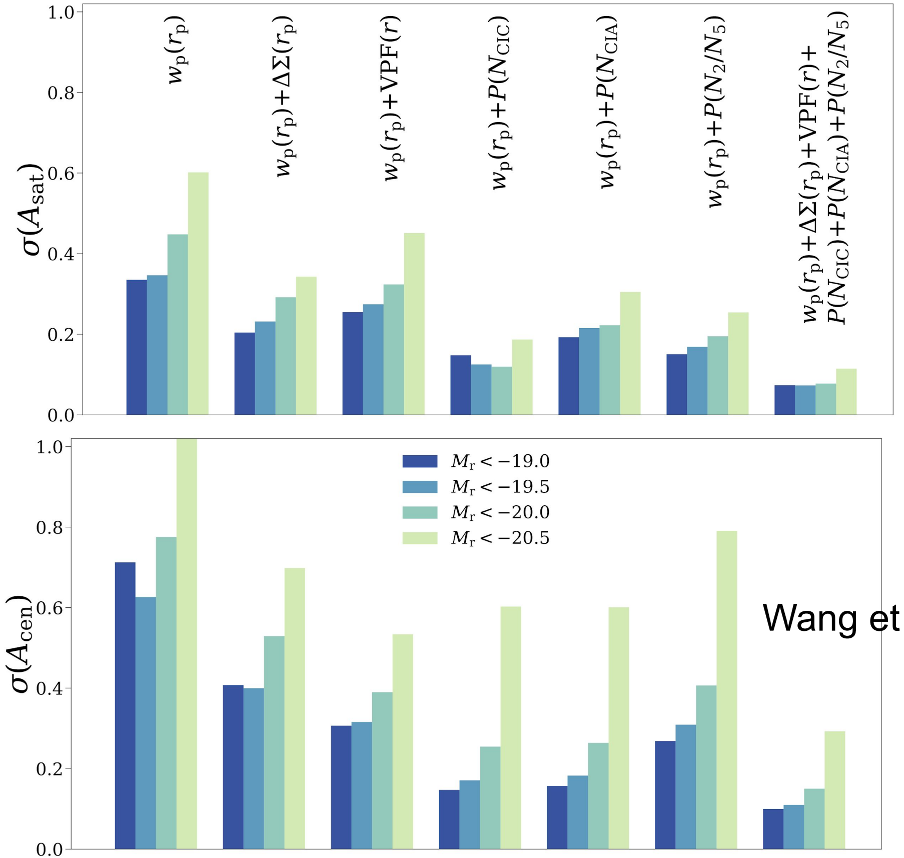
Behroozi, Hearin, Moster (in prep.)

Observables: beyond halo mass & accretion rate



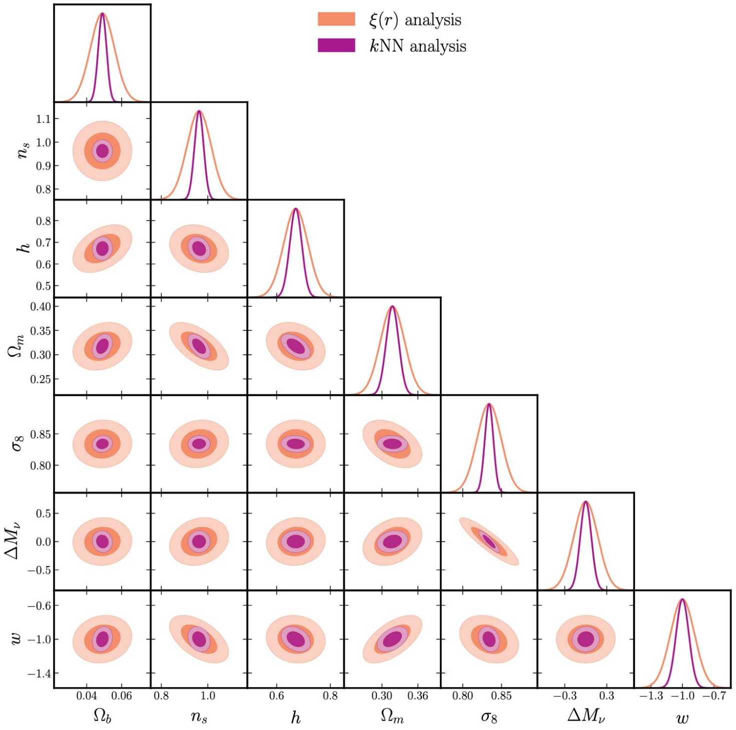
Behroozi, Hearin, Moster (in prep.)

Observables: constraints from higher-order sumstats



Wang et al. (2019)

Banerjee & Abel (2020)



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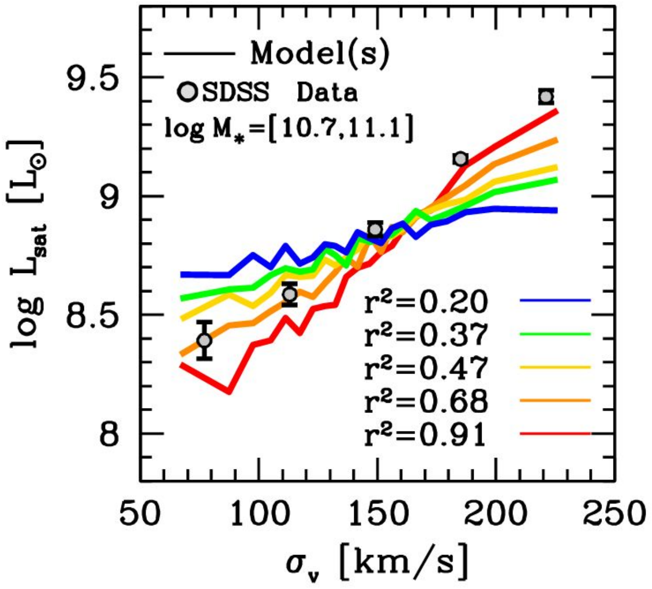
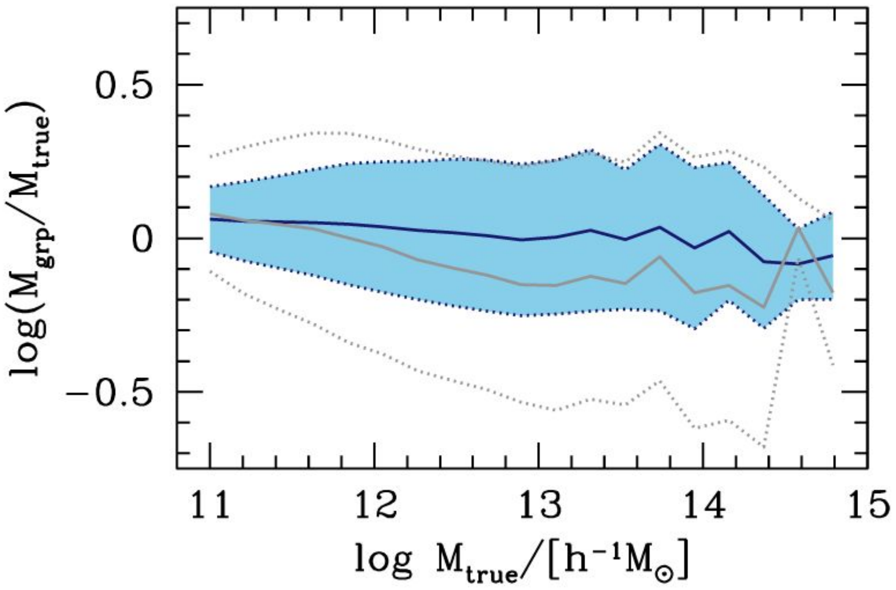


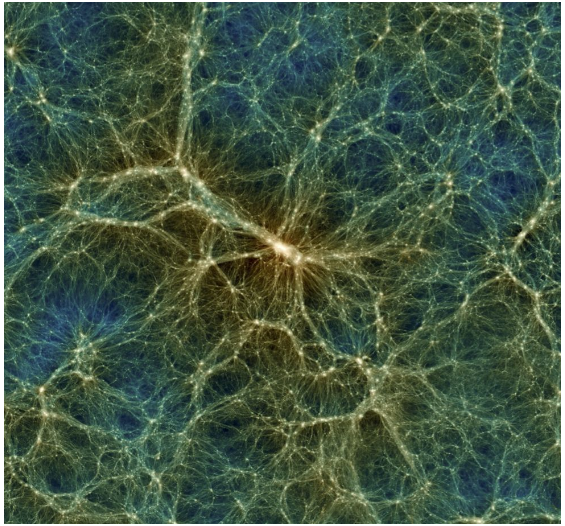


Tinker (2020)

Future Directions

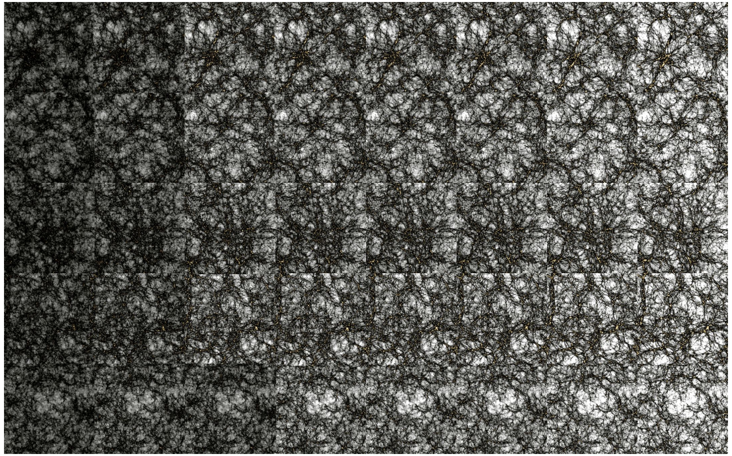
Rapidly expand landscape of cosmological N-body simulations

Extreme-scale boxes



Uchuu, Last Journey, Euclid Flagship, Farpoint

Large-volume suites



Quijote, AbacusSummit, Mira-Titan, Aemulus

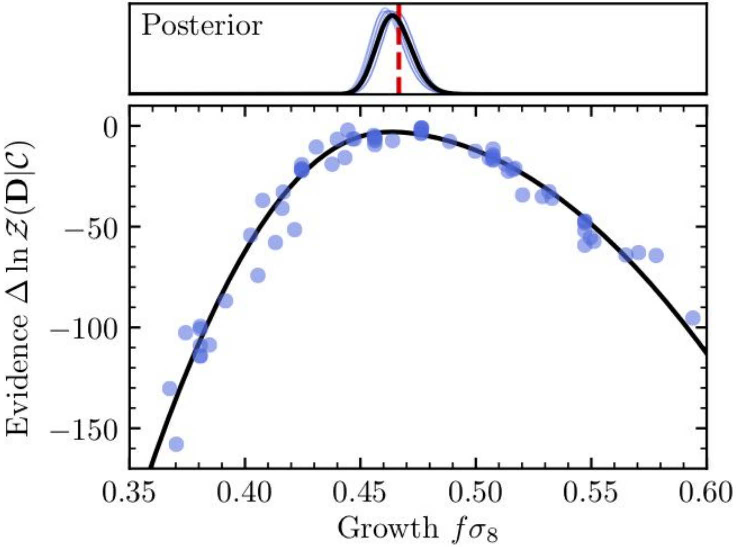
Future Directions

Increasingly realistic mocks and robust LSS-based inference

Extreme-scale mocks

(cosmoDC2, Buzzard, Mice, UniverseMachine, Skies&Universes)

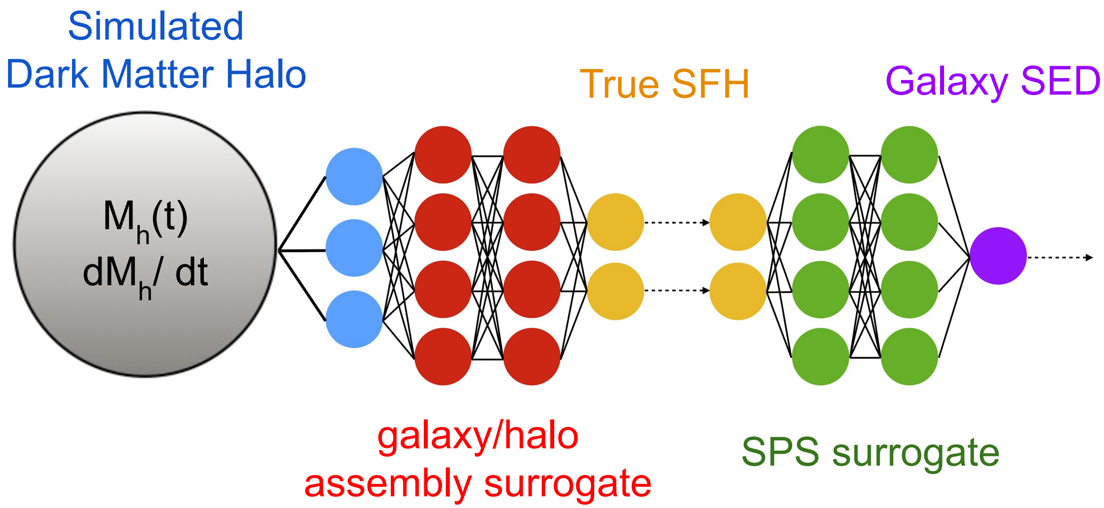
Forward Modeling Posteriors

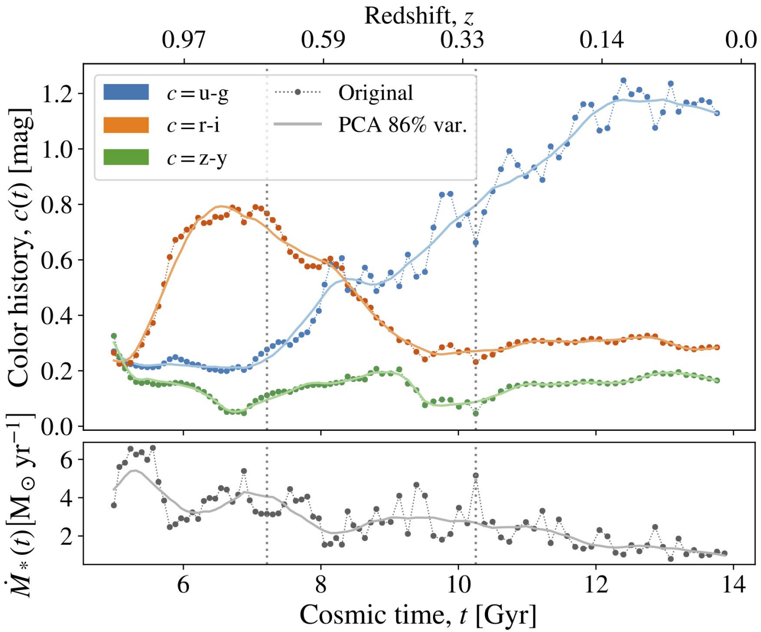


Salcedo+19, Wibking+19, Lange+19

Future Directions

AI-Accelerated Differentiable Forward Models of SEDs





Differentiable sumstat predictions with JAX, Becker, Hearin+, (in prep)
Scaling to large sims with thechopper, Villarreal & Hearin, (in prep)
See also the Differentiable Universe Initiative

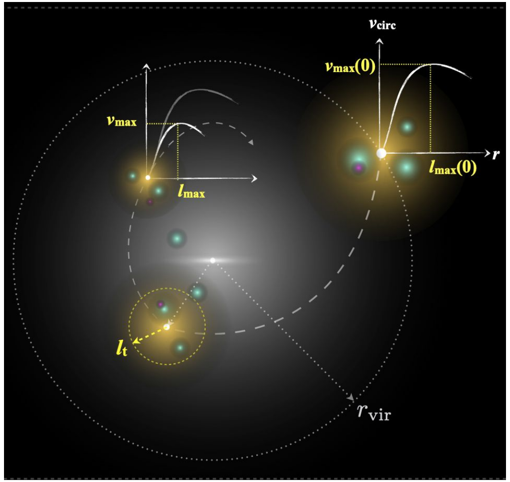
SBU, Chaves-Montero & Hearin, (in prep)
Speculator, Alsing et al. (2020)

Future Directions

New generation of subhalo orbit modeling

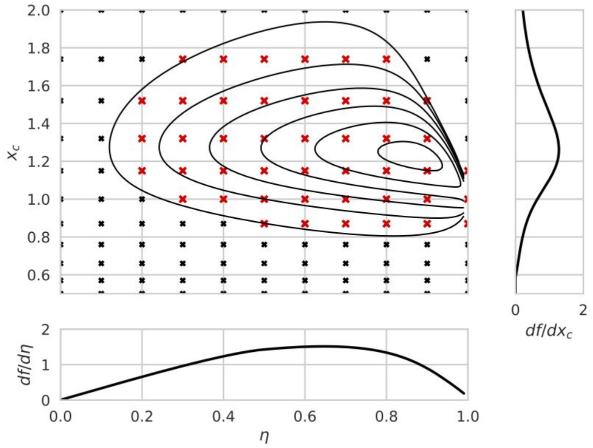
(prime target for AI acceleration!)

SatGen model for satellite orbits



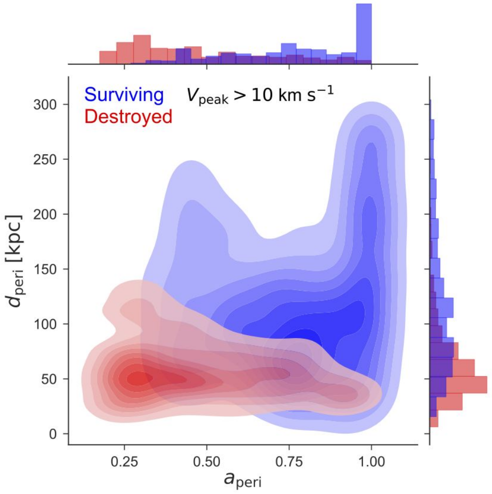
Jiang+20

DASH Library of subhalo orbits



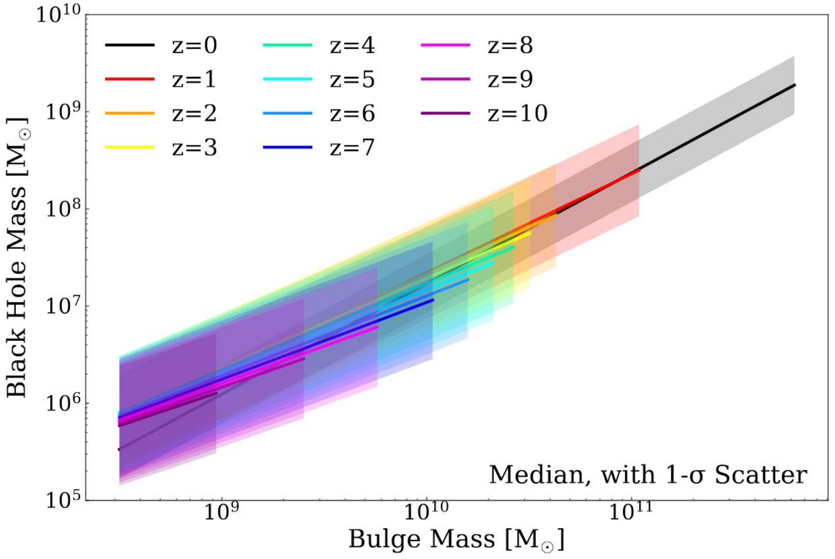
Ogiya+20

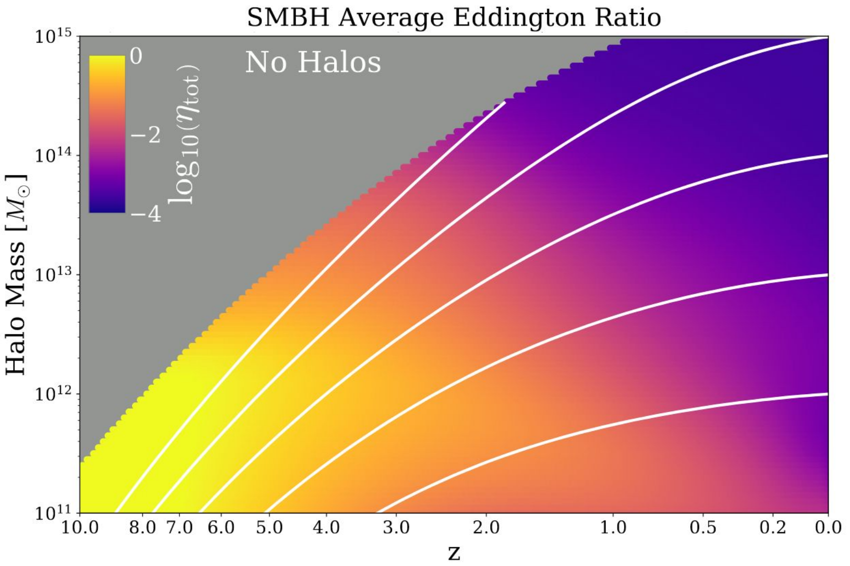
ML-based model for subhalo disruption in high-res FIRE sims



Nadler+18

Future Directions: Not Just Stellar Mass and SFR





Zhang, Behroozi+ (in prep.)

Future Directions

GalaxyNet: NN-formulation of the galaxy-halo connection

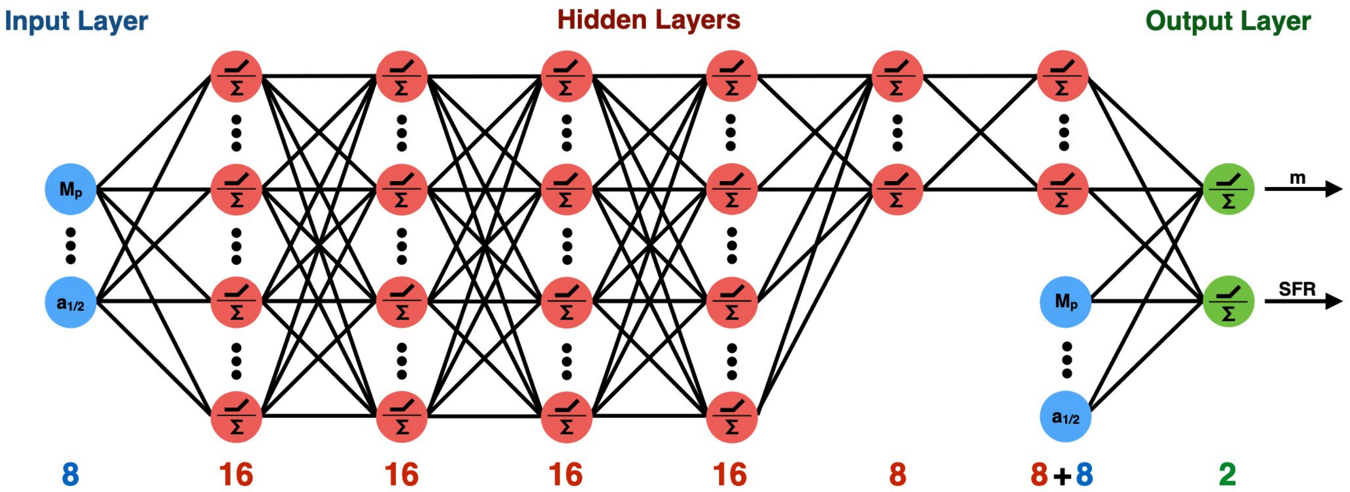


Figure 3. Architecture of the adopted wide & deep neural network (WDNN). The input layer consists of 8 features, i.e. halo properties (blue). The first 4 hidden layers consist of 16 nodes, while the last two hidden layers have 8 nodes (red). The last hidden layer is concatenated with the 8 input features. The output layer gives the two targets, i.e. galaxy properties (green). All hidden layers are densely connected. The optimal number of nodes per layer is given at the bottom.

Moster et al. (2020)