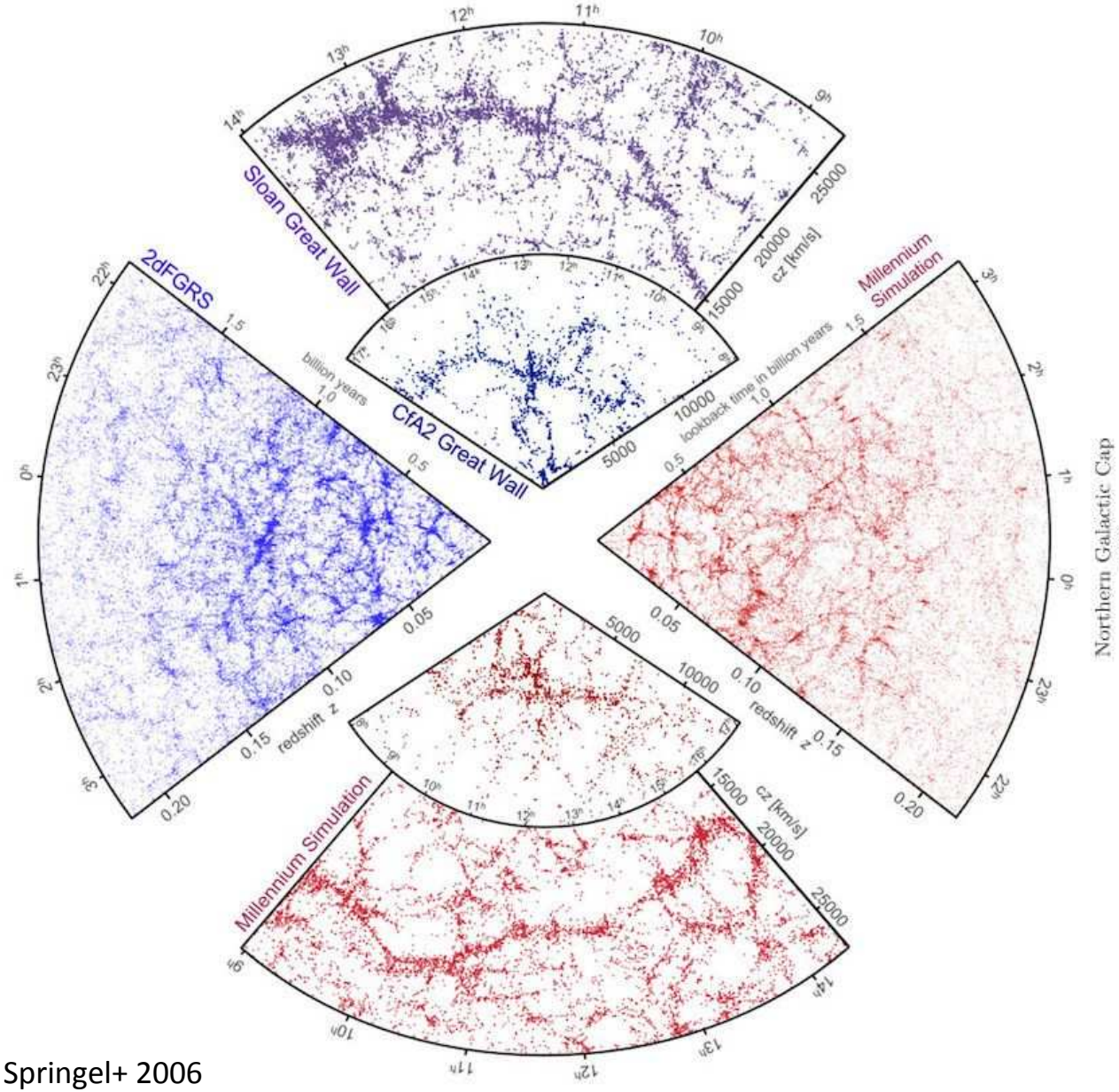
The Genesis "Mocks" (& SURFS "Mocks")

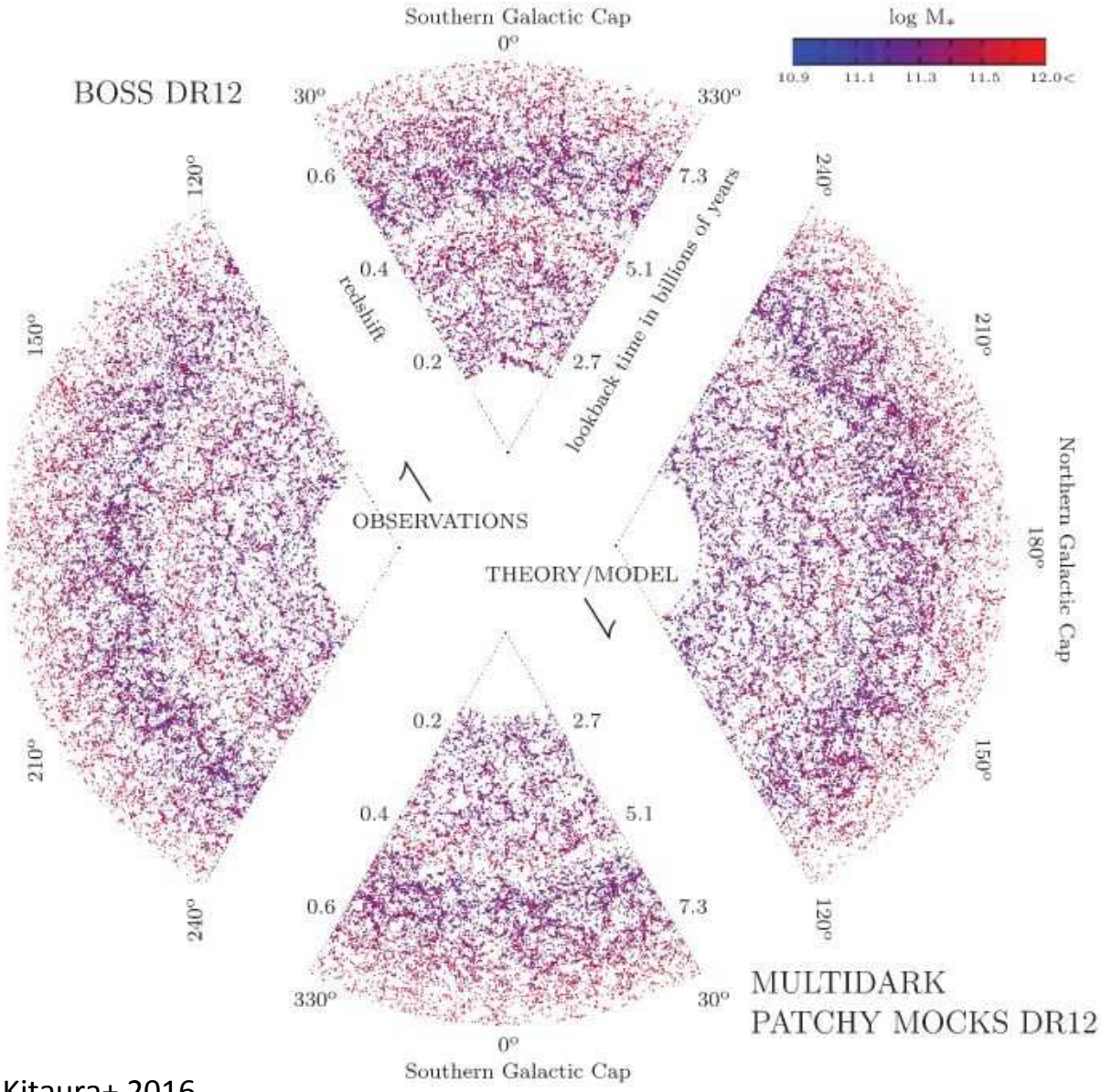
Pascal Elahi

THE UNIVERSITY OF WESTERN AUSTRALIA

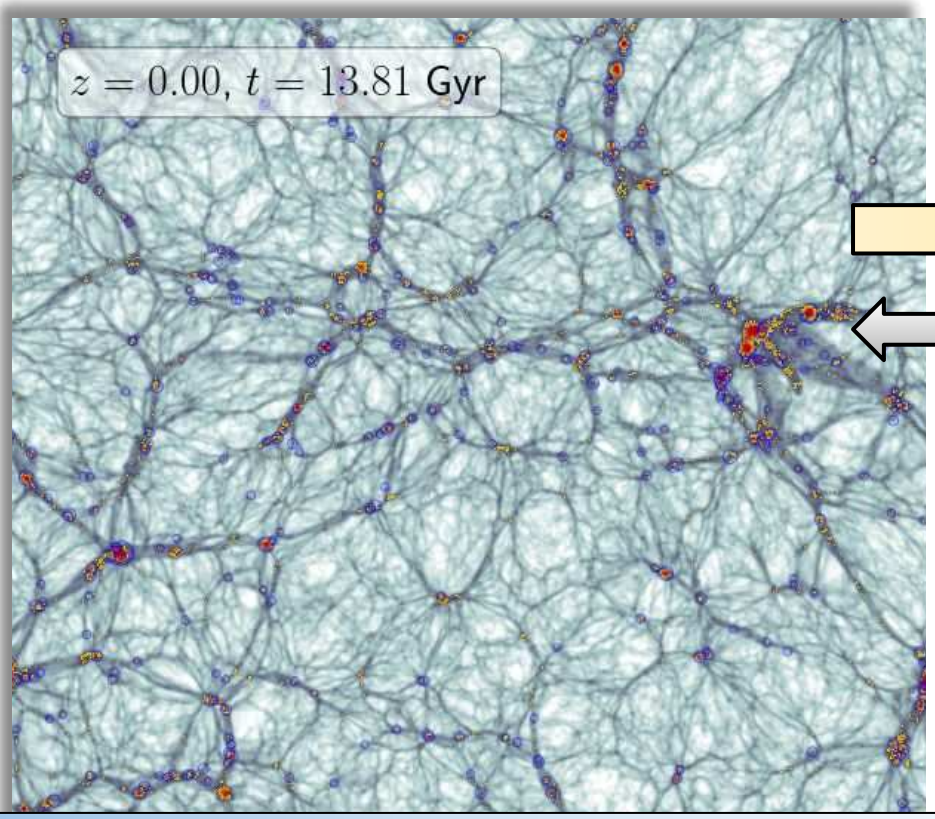
Rhys Poulton, Garima Chauhan, Matias Bravo, Jacob Seller, Madeline Marshall, Yisheng Qiu, Pipit Triani, Claudia Lagos, Adam Stevens, Chris, Power, Aaron Robotham, Danail Obreschkow, Manodeep Sinha, Darren Croton, Simon Mutch



Springel+ 2006

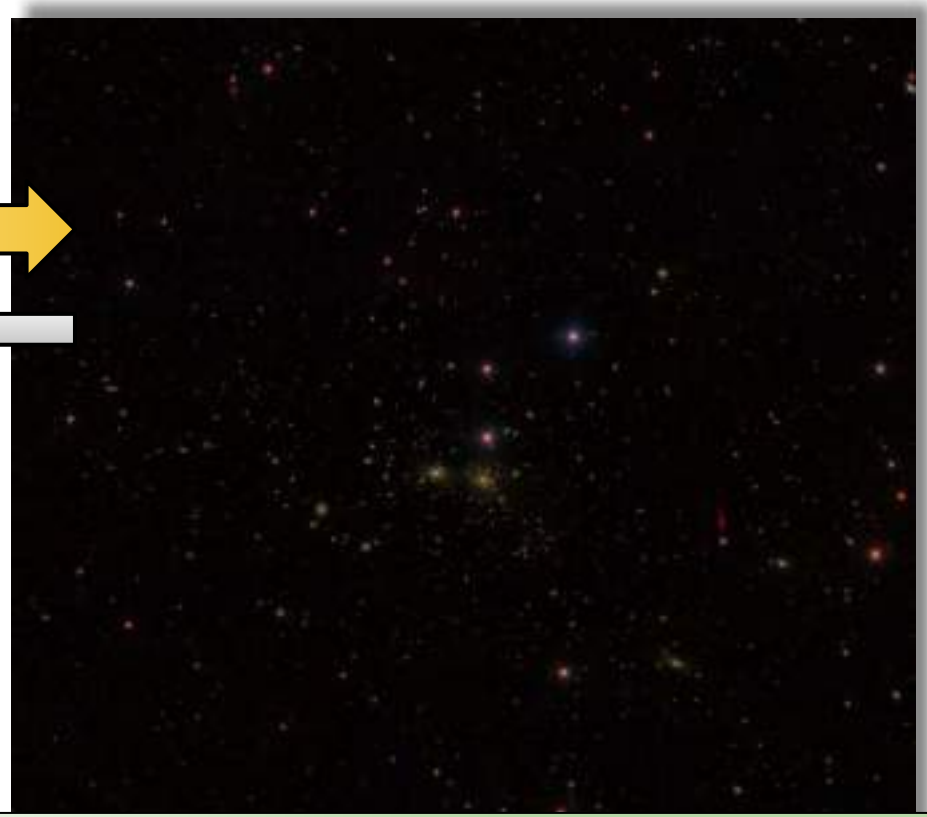


Kitaura+ 2016



Connecting Dark Matter Halos To Galaxies

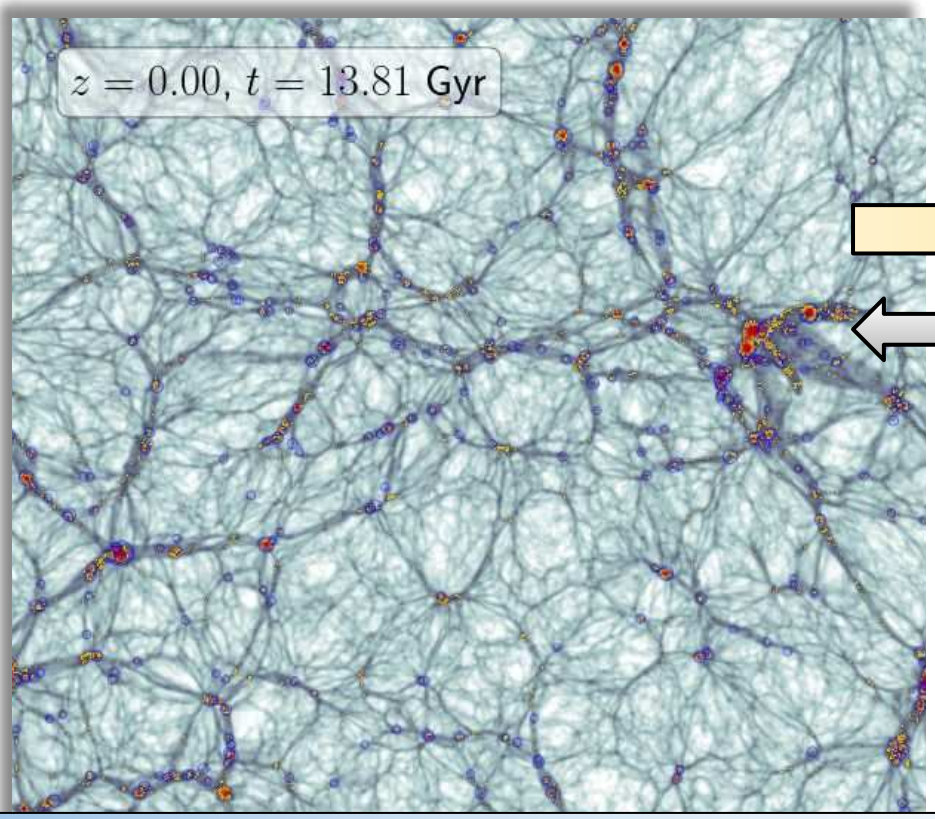
galaxies reside in halos



Physical, Computationally Expensive, Small Volumes

Empirical/Approximative, Quick, Large (Gpc) Volumes

Hydrodynamical simulations	Semianalytic Models (SAM)	Abundance Matching, Halo Occupation Models	Approximative N-body + Halo Occupation Models
Model gravity, hydro forces, subgrid star formation feedback prescriptions	Model gravity, follow halo evolution and use galaxy scale subgrid prescriptions	N-Body (Sub)Halo distribution + assumptions of (sub)halo to galaxy mapping	Mapping of density to halo + assumptions of halo to galaxy mapping.



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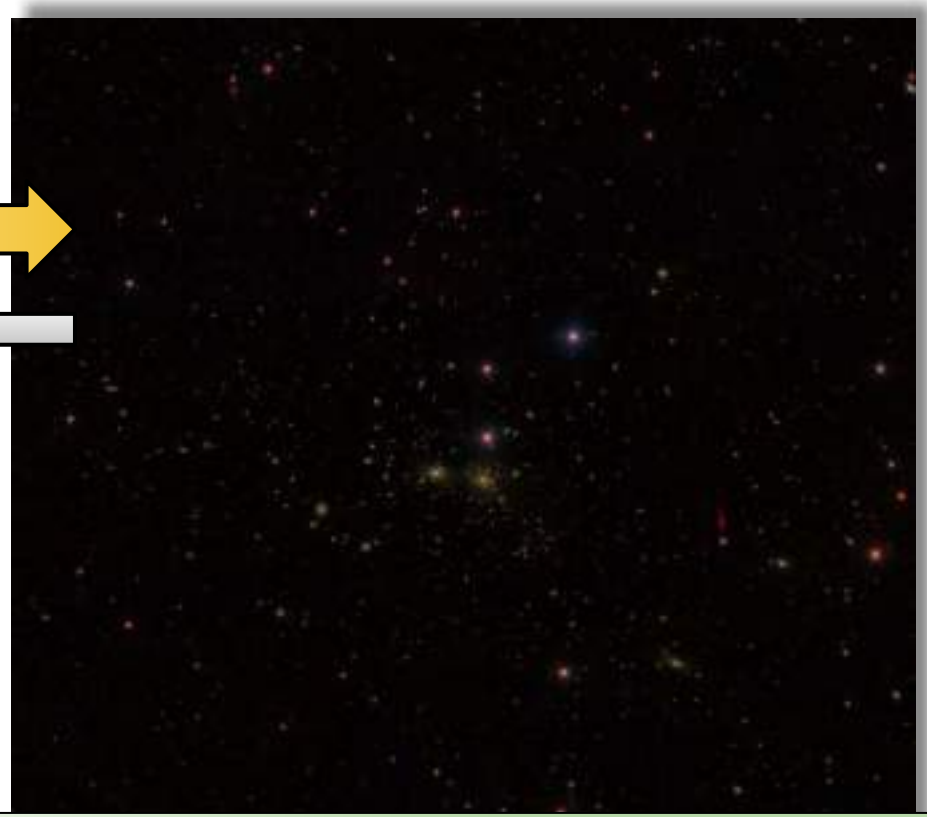

Physical, Computationally Expensive, Small Volumes ← → **Empirical/Approximative, Quick, Large (Gpc) Volumes**

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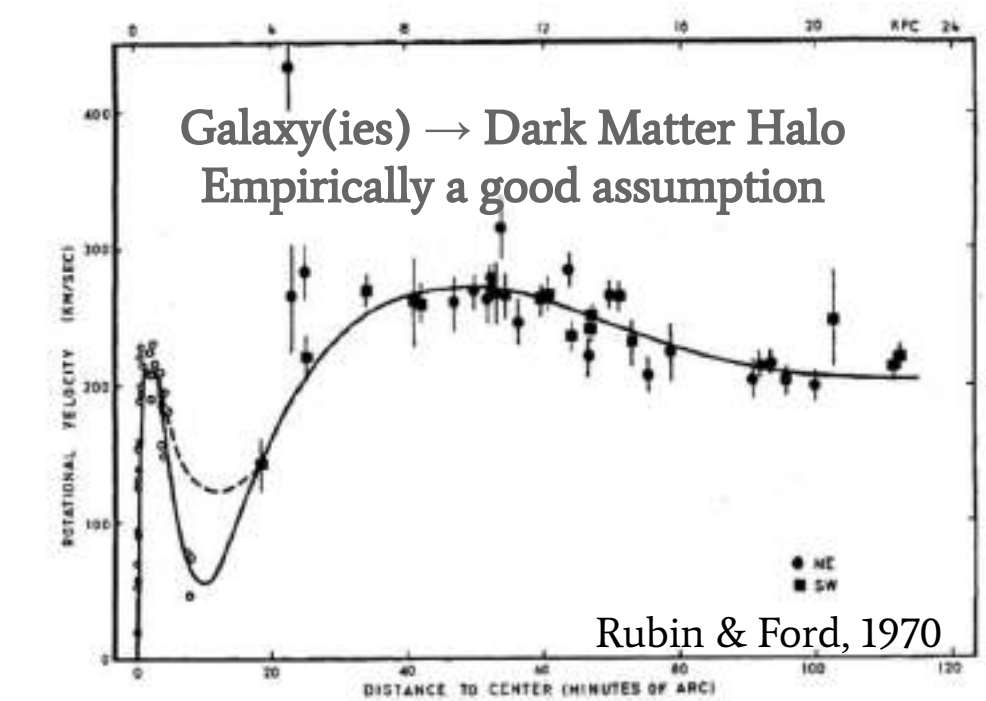
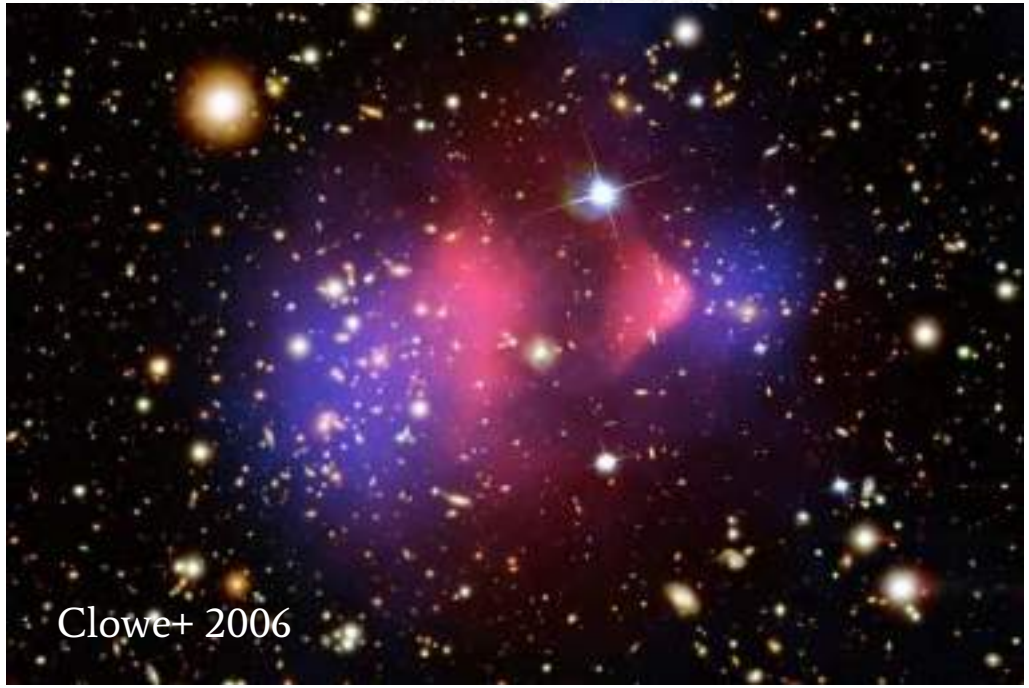

Galaxy(ies) → Dark Matter Halo
Empirically a good assumption
ROTATIONAL VELOCITY (KM/SEC)
DISTANCE TO CENTER (MINUTES OF ARC)
KPC
NE
SW
Rubin & Ford, 1970


But maybe not always true
NGC1052-DF2
van Dokkum+ 2018

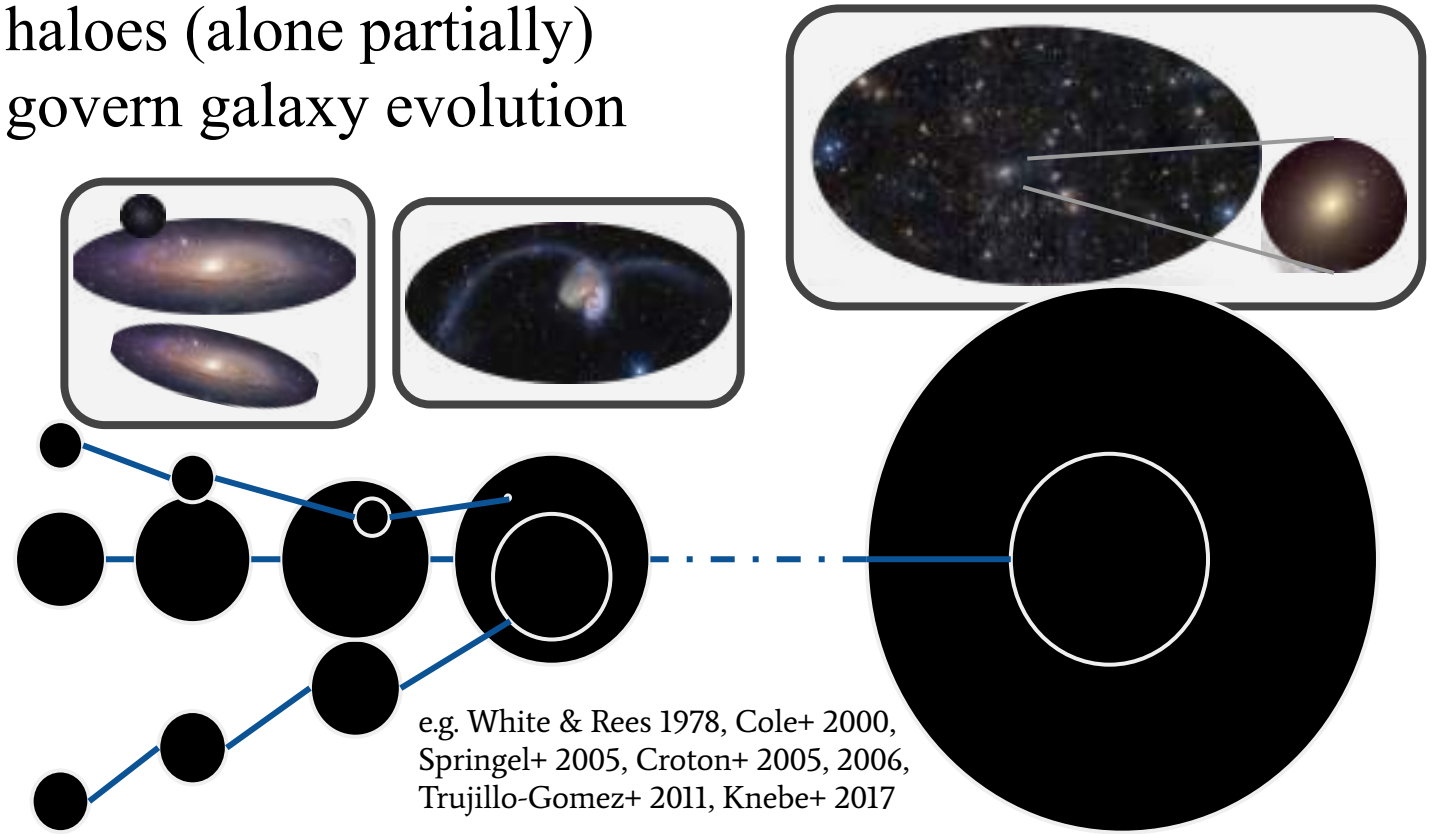

Clowe+ 2006


2537
2239
1968
1790
1452
NGC1052-DF4
van Dokkum+ 2019

Synthetic Galaxies with SAMs

ASTRO 3D

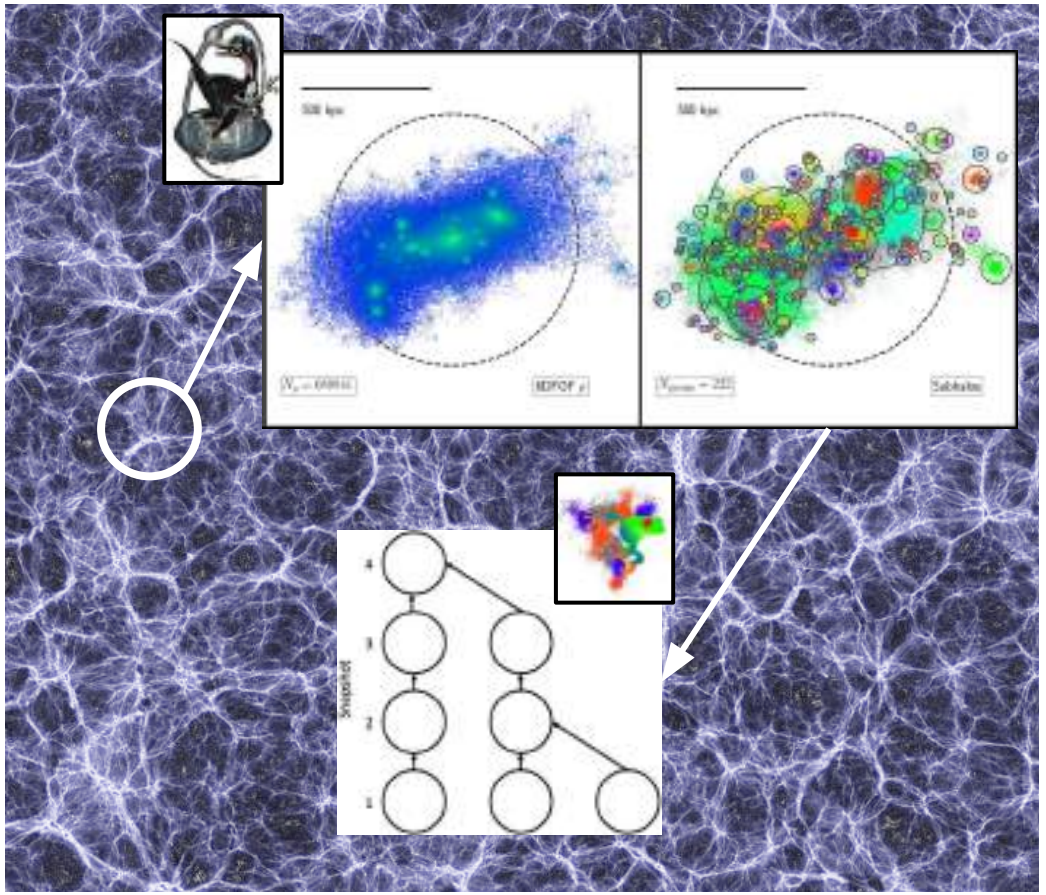
Underlying assumption is haloes (alone partially) govern galaxy evolution



e.g. White & Rees 1978, Cole+ 2000, Springel+ 2005, Croton+ 2005, 2006, Trujillo-Gomez+ 2011, Knebe+ 2017

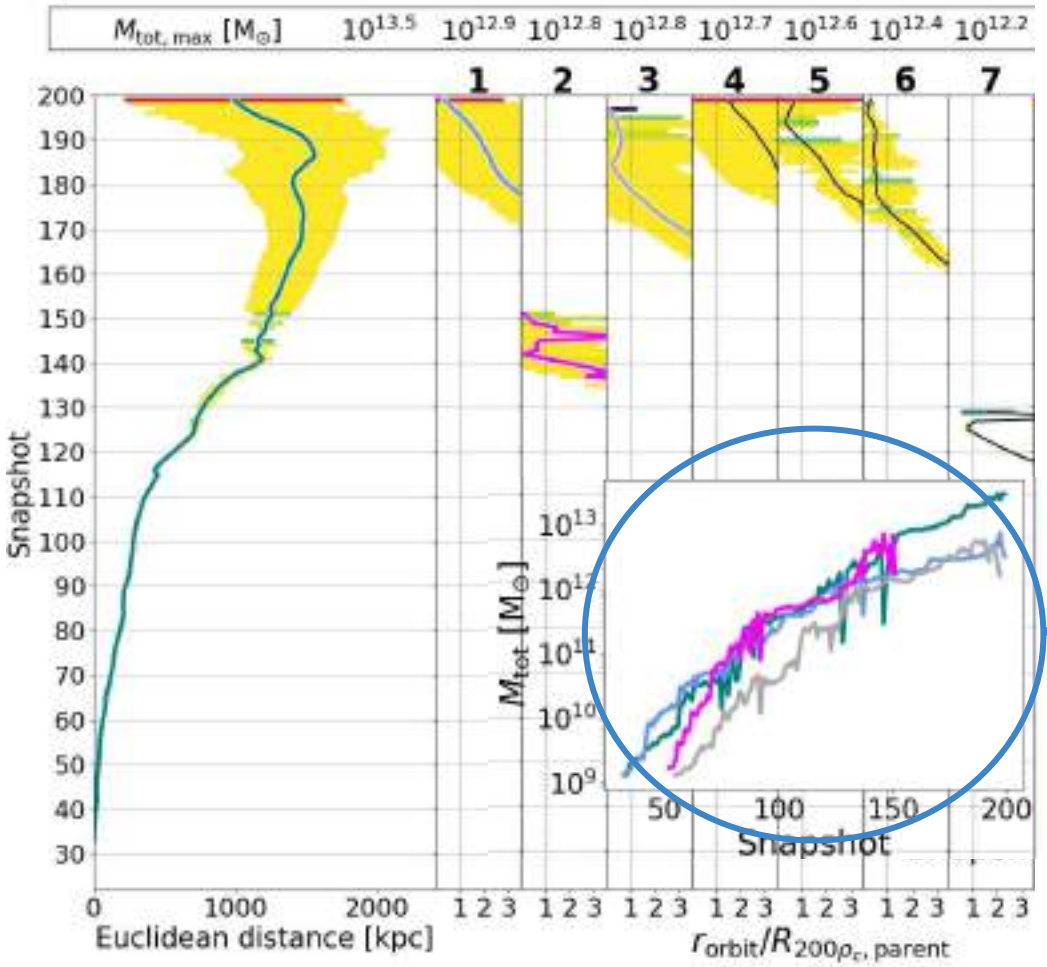
Includes secondary halo bias but not cosmic web influence on baryons

N-body simulations
+ Halo Finder (`VELOCIraptor`, Elahi+ 2019)
+ Tree Builder (`TreeFrog`, Elahi+ 2019)
= Halo merger tree inputs



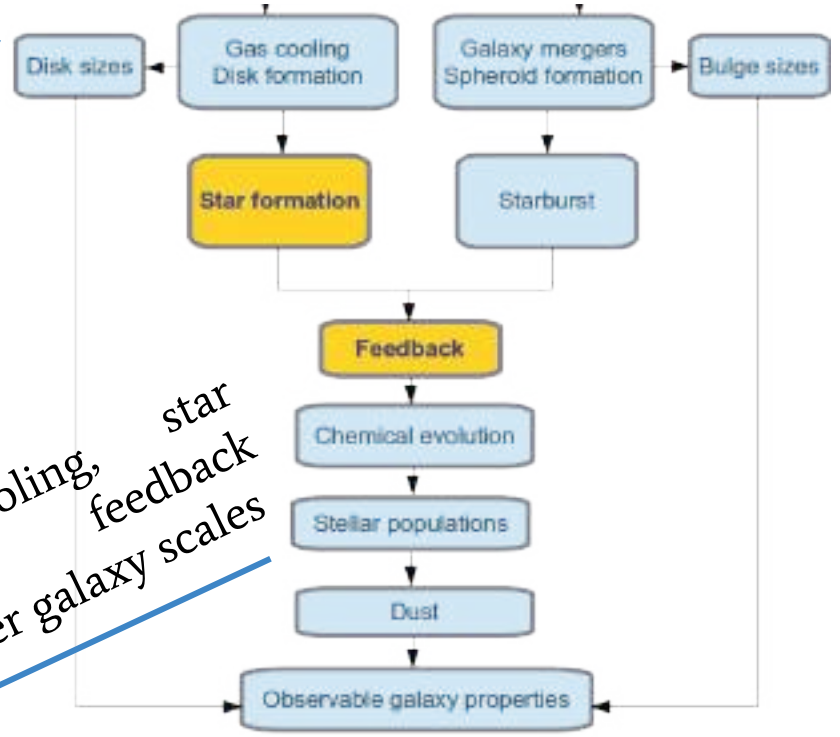
Synthetic Galaxies with SAMs

ASTRO 3D



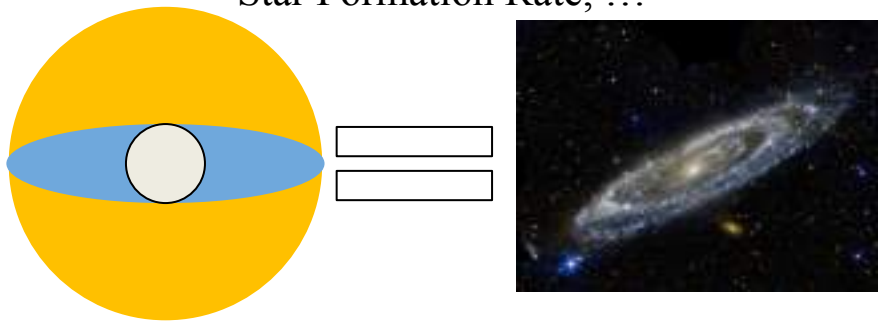
Couple the DM mass (angular momentum) flow into a (sub)halo to baryons

Describe cooling, star formation, feedback averaged over galaxy scales



Galaxy "Particle"

Gas & Stellar Mass (in Bulge, Disk, etc),
Star Formation Rate, …



Current N-body Simulations

ASTRO 3D

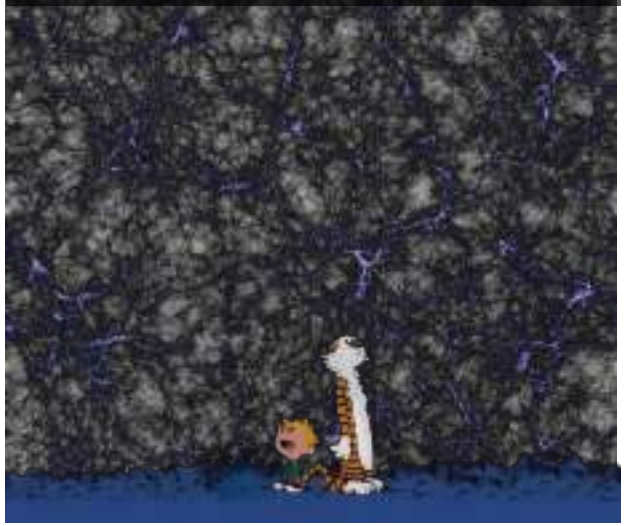
Box length [Mpc/h]	Particle Number	Halo mass resolution (20 particles) [$M_\odot$/h]	Min z	Comments
40	512^3	1.2e9	0	• Small volume test bed, moderate resolution • HI content
210	1024^3 1536^3 **6144^3**	2.2e10 6.6e9 **1.0e8**	0 0 -	• Moderate volume, variety of resolutions, ~200 Myr cadence • Galaxies down to dwarfs, HI content
35	**2650^3**	**5.9e6**	**5 (2)**	• **High mass resolution, high cadence (~ Myr) trees.** • **Epoch of reionisation (EOR)†, high-z**
105	**2048^3**	**3.4e8**	**0)**	• **Moderate resolution, full redshift range, ~200 Myr cadence** • **EOR to present day†**
500	1024^3 2160^3 4320^3	3.0e+11 3.2e+10 4.0e+9	0 0 -	• Large scale structure and environmental studies • Large volume galaxy surveys

SURFS (ICRAR/UWA), **GENESIS (ASTRO 3D/UWA)**
Planck Cosmology

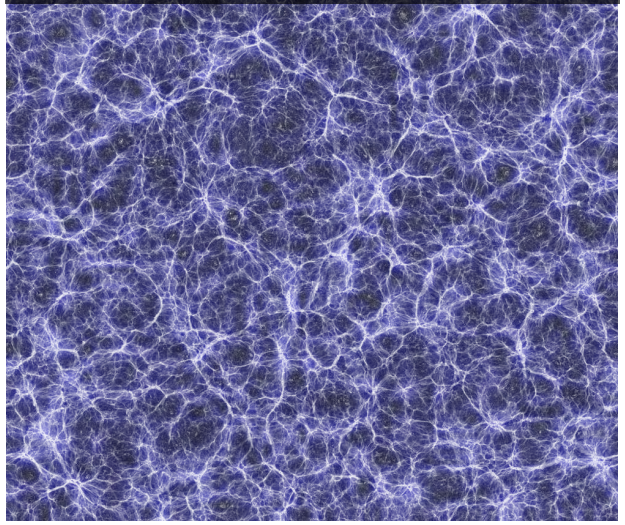
Credit: All simulations run by **Chris Power** and **Pascal Elahi** (ICRAR / UWA).

†Ideal EOR mock survey is ~300 - 500 Mpc resolving 10^6 solar mass halos i.e., a 21600^3 simulation (***not feasible***)

L_{box}=35 Mpc/h, High z

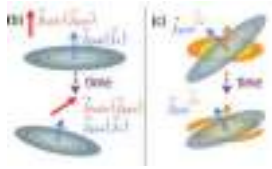


L_{box}=500 Mpc/h, z=0



Current SAMs

ASTRO 3D

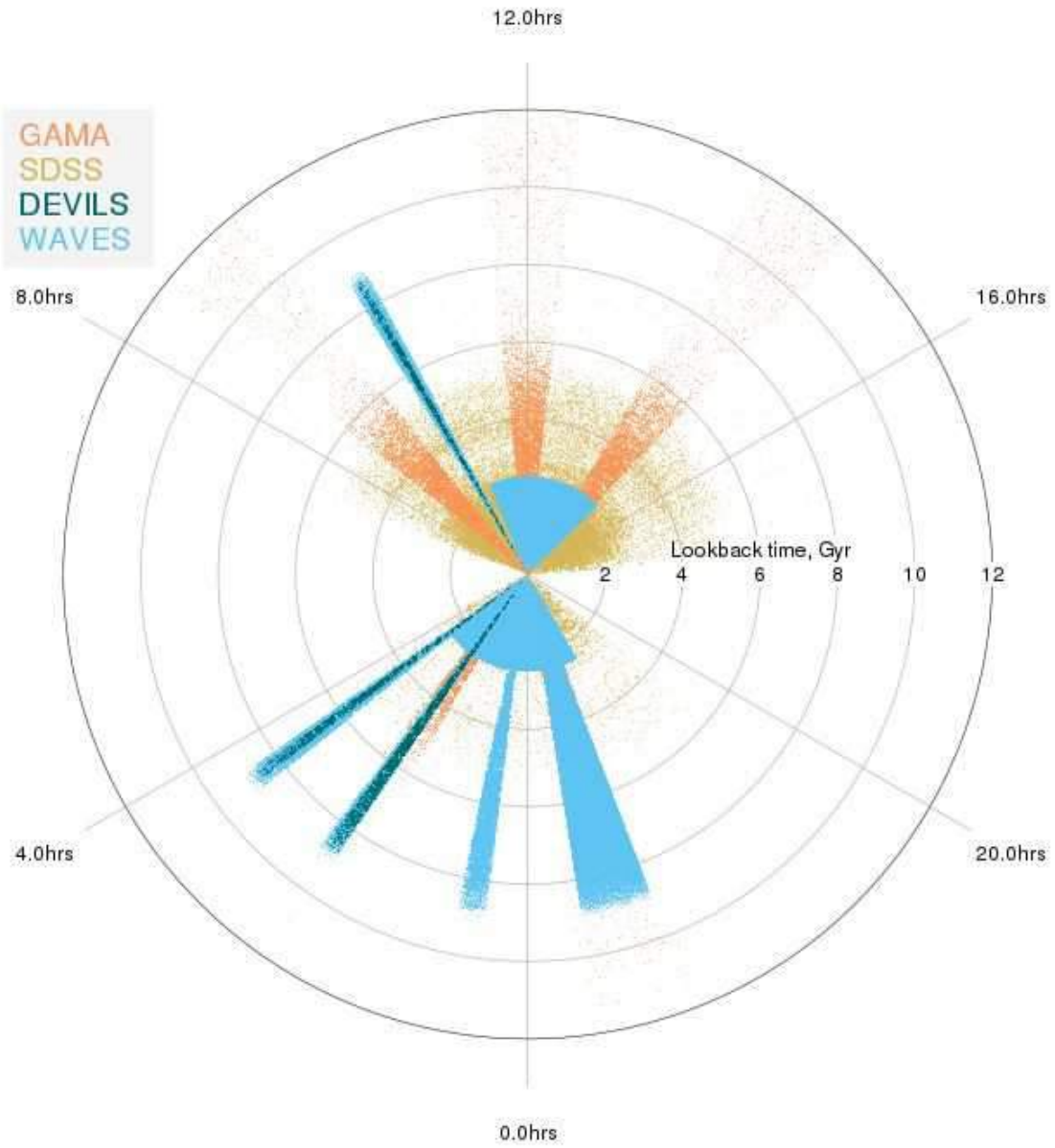
SAM Name	Description	Comments
SAGE (Croton+ 2016)	• Open source, C, MPI • Includes several models for gas cooling; star formation; active galactic nuclei, stellar & photo-ionization feedback • Fast	**Several branches focusing on range of specific physics** (EOR, SED integration, etc)
DARK SAGE (Stevens+ 	• Open source, C, MPI • Based on SAGE. • Includes rigorous treatment of angular momentum evolution of disks (using annuli)	**Improved disk treatment** can give more realistic HI masses, line profiles.
MERAXES (Mutch+ 2016) 	• C, CUDA+MPI • Integration of 21cmFAST, semi-numerical reionization algorithm • Couples galaxy growth to reionization temporally & spatially. • Automated calibration (MCMC, Emulation)	**Coupled reionisation** used to explore high-z galaxies and EOR in small volume, high mass resolution simulations. Does require density+velocity fields + halo merger tree (forests).
SHARK (Lagos+ 2018) 	• Open source, C++11, OpenMP • Modular, allowing easy model exploration • Includes several models for gas cooling; star formation; active galactic nuclei & stellar feedback • Automated calibration (Particle Swarm)	**Several mocks using SURFS simulations** produced using SEDs from PROSPECT (Robotham+, in prep), lightcones form STINGRAY (Obreschkow+, in prep)

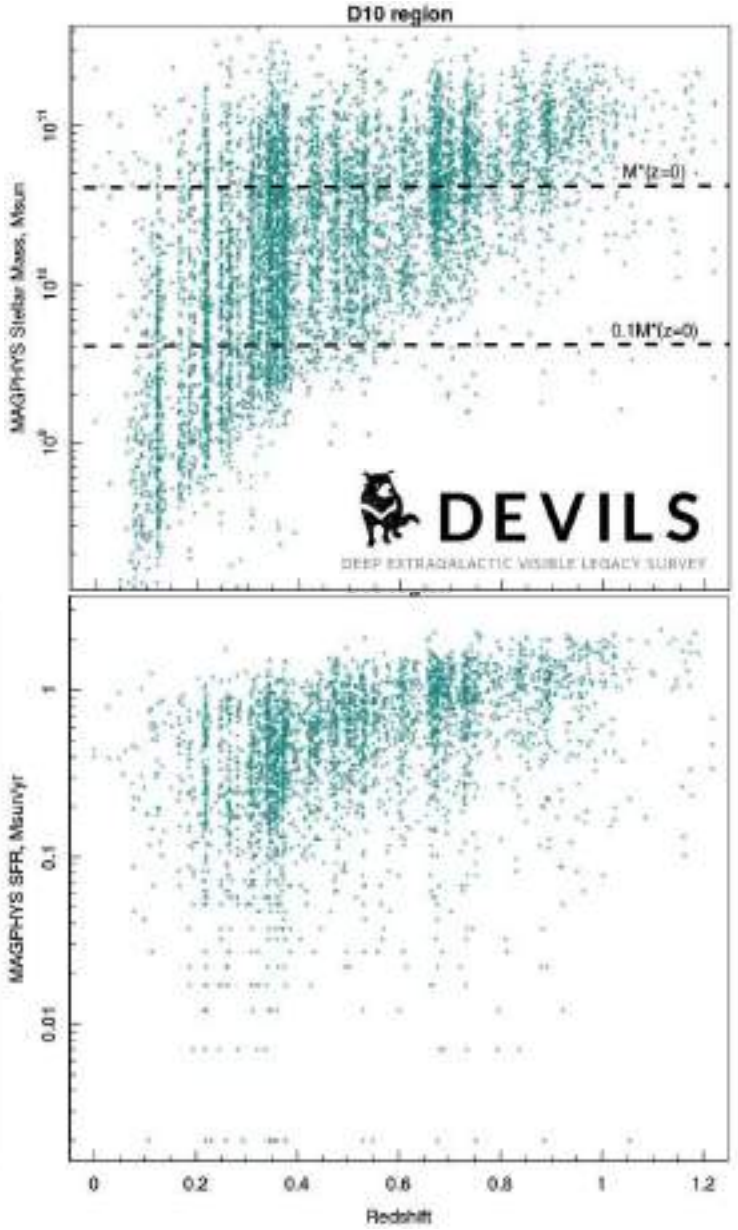
Sample of Current Mocks

ASTRO 3D

Survey Name	Description	Goals & Comments
GAMA 	• Spectroscopic survey of ~300,000 galaxies down to r < 19.8 mag over ~286 deg2 (Driver+ 2011, Liske+ 2015, Baldry+2018) • Completed	**Goal:** Measure dark matter halo mass function to 10^{12} $M_{\odot}$, probe star formation efficiency, and merger rates • Builds on existing data in multiple bands. • High completeness means high fidelity group catalogues.
DEVILS 	• Spectroscopic survey designed to identify groups 10^{13} $M_{\odot}$ to z =0.7 by selecting Y < 21.2 • Running, ECD 2020	**Goal:** examine multi-scale environment (groups) on galaxy evolution (star formation) at z > 0.3. • Builds on existing data in multiple bands • Deep survey
WAVES 	• Spectroscopic survey of 2 million galaxies • Will sample fields with multi-wavelength observations (overlapping proposed LSST fields) • ESD 2022	**Goal:** probe galaxy evolution over the last 8 Gyr down to stellar masses of 10^{6} $M_{\odot}$ (and halo masses of 10^{10} $M_{\odot}$). • Builds on existing data in multiple bands, has overlap with upcoming LSST • Deep fields and large area fields
AFALFA 	• Blind HI survey using Arecibo probing ~20000 galaxies out to 200 Mpc • Completed.	**Goal:** measure HI in nearby universe, characterising the HI mass function, and the extent & origin of HI disks. • Blind HI survey, high galactic latitudes • Largest number of HI sources (31000, 22000 with optical counterpart)
WALLABY	• Blind HI survey possibly finding ~0.5 million HI detections • ESD ? Hopefully soon.	**Goal:** measure HI to greater depth, measuring HI in ~0.5 million galaxies out to z=0.25. • Blind(er) HI survey using SKA pathfinder covering ⅔ of the sky • Initial early science data taken

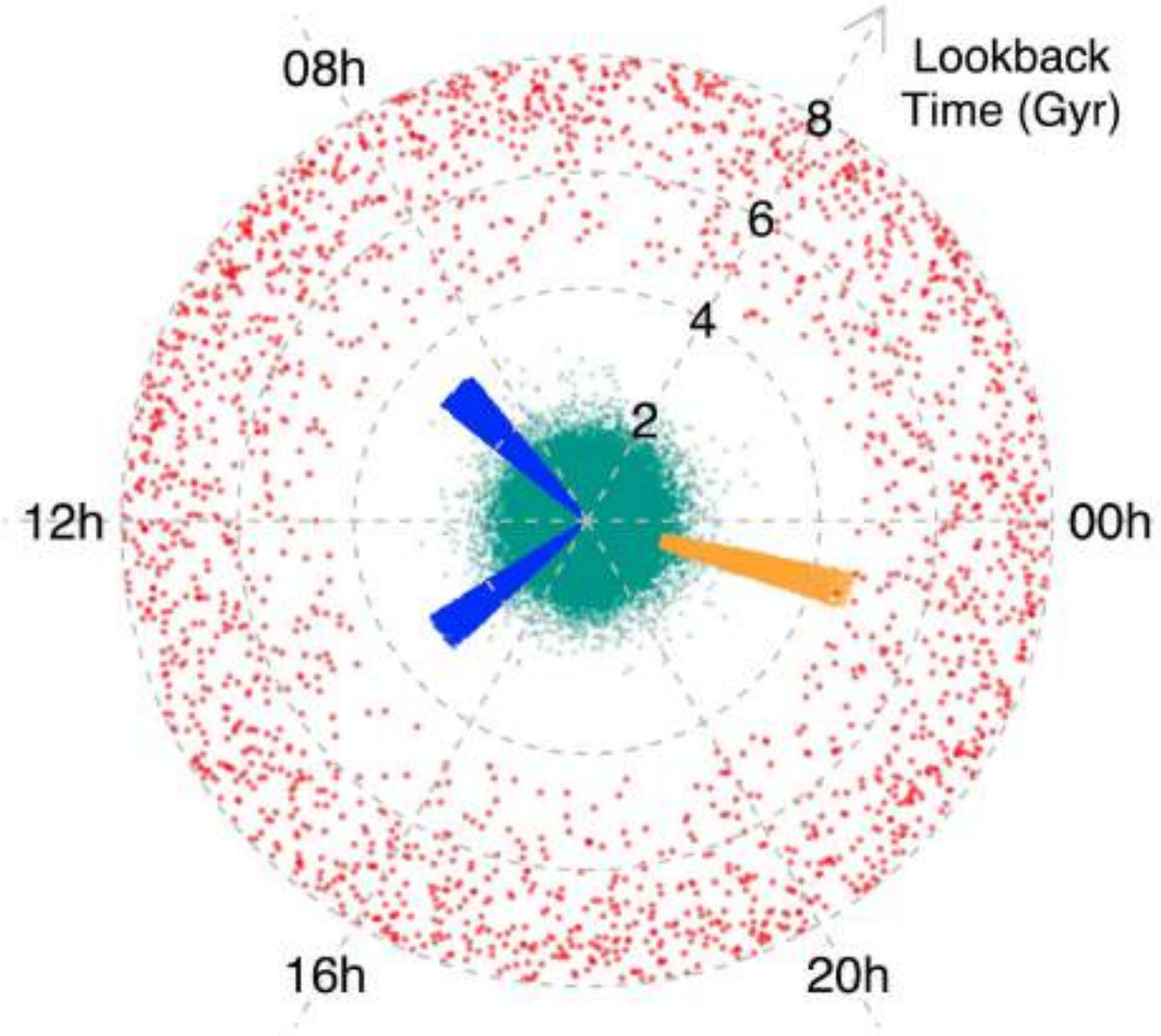
(Optical) Galaxy Mocks

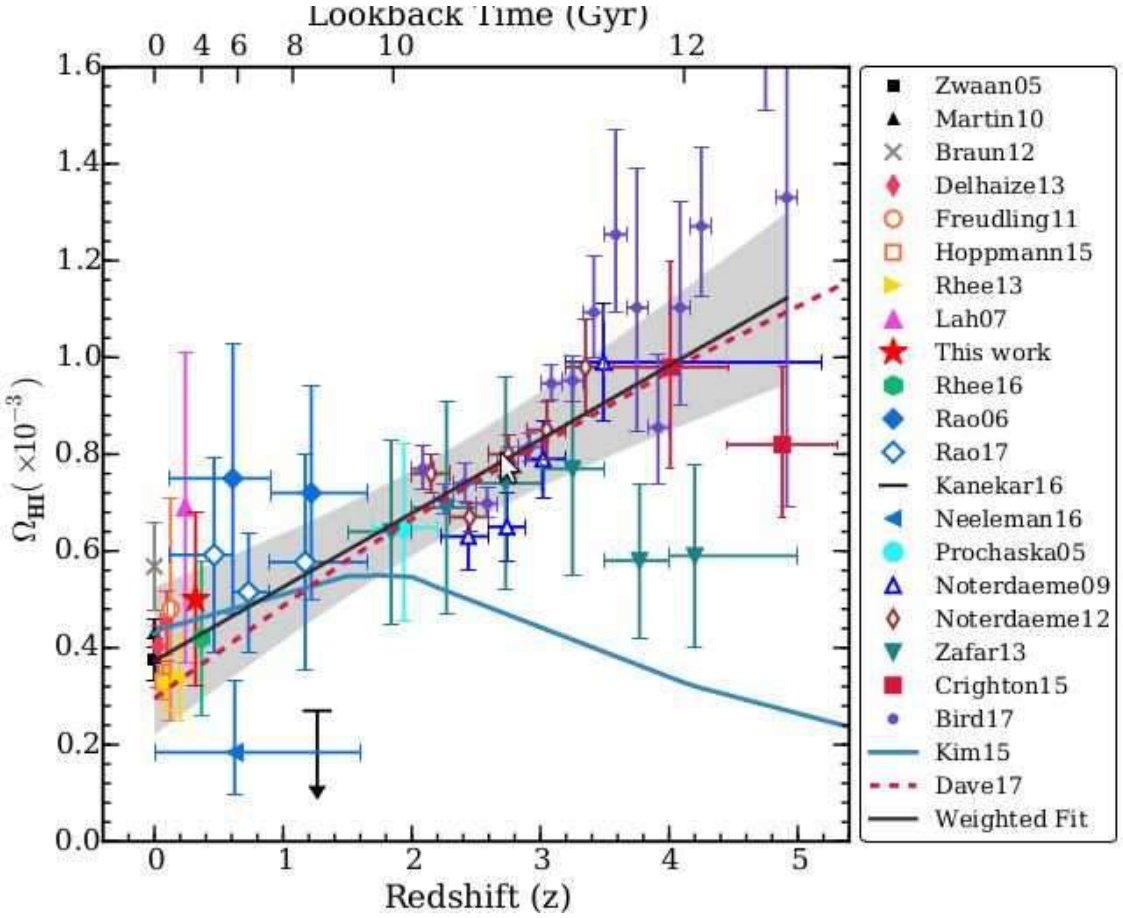




(HI) Galaxy Mocks

ASTRO 3D



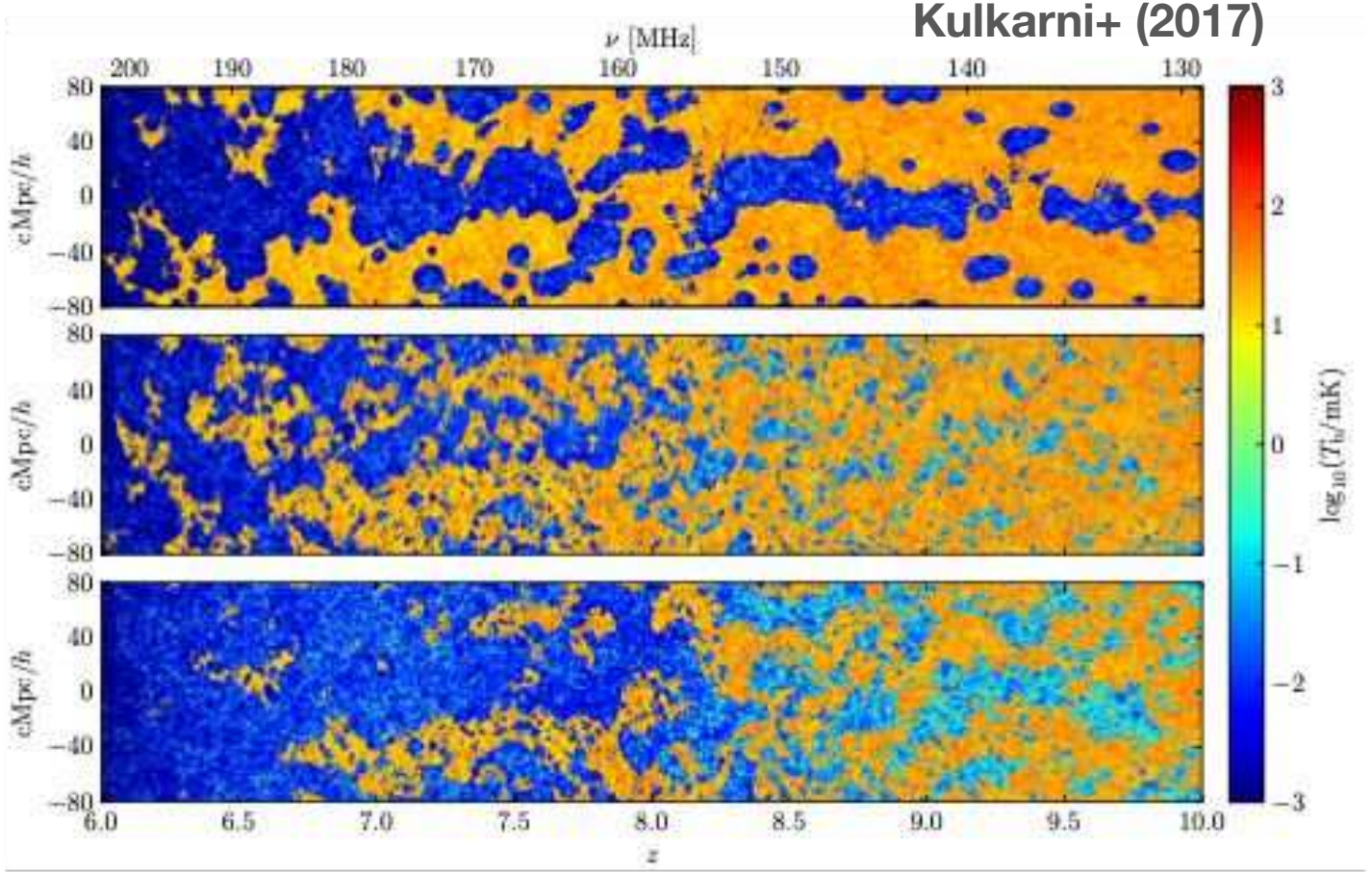


(21 cm) EOR Mocks

ASTRO 3D

- More to mocks than galaxies.
- Feedback physics leaves imprint on Epoch of Reionisation
- Ongoing/upcoming radio telescopes probing HI content + EOR

Kulkarni+ (2017)



LOFAR

SKA
SQUARE KILOMETRE ARRAY

Simulations

ASTRO 3D

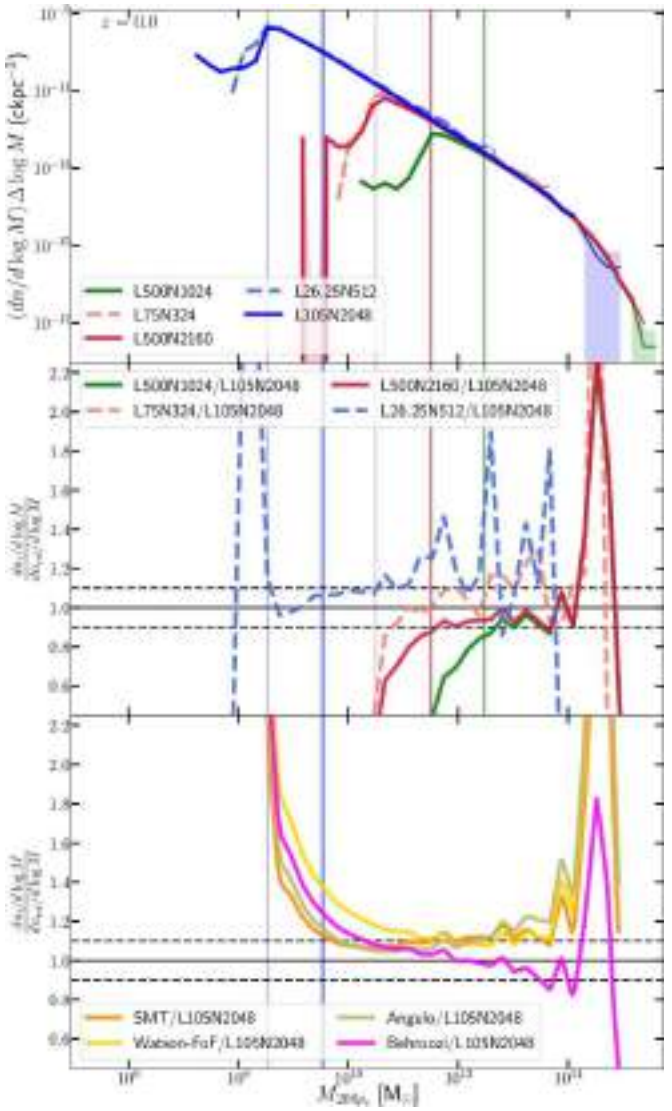
GENESIS (Elahi+, in prep) & SURFS (Elahi+ 2018) simulations span several volumes, mass resolutions but all have high cadence trees.

- Tests convergence over wide mass range, quantify effect of missing large-scale power
- High cadence halo merger trees means welled sampled orbits & halo evolution during EOR
- Accretion histories from higher res sim can be used as input accretion history for newly formed halos in lower res sim

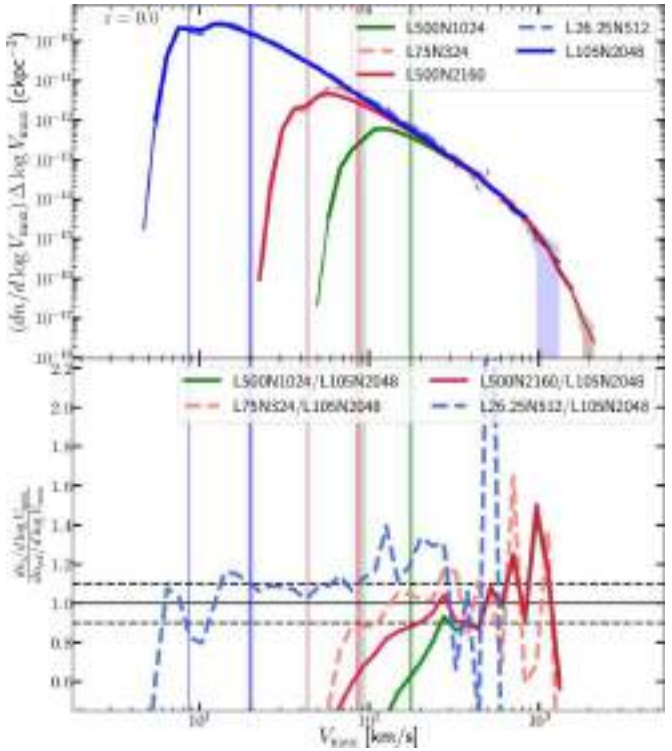
We find:

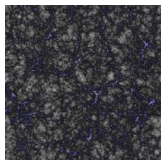
- Convergence in mass mass functions at ~40 particles, velocities & accretion at ~ 200 particles

Mass Functions

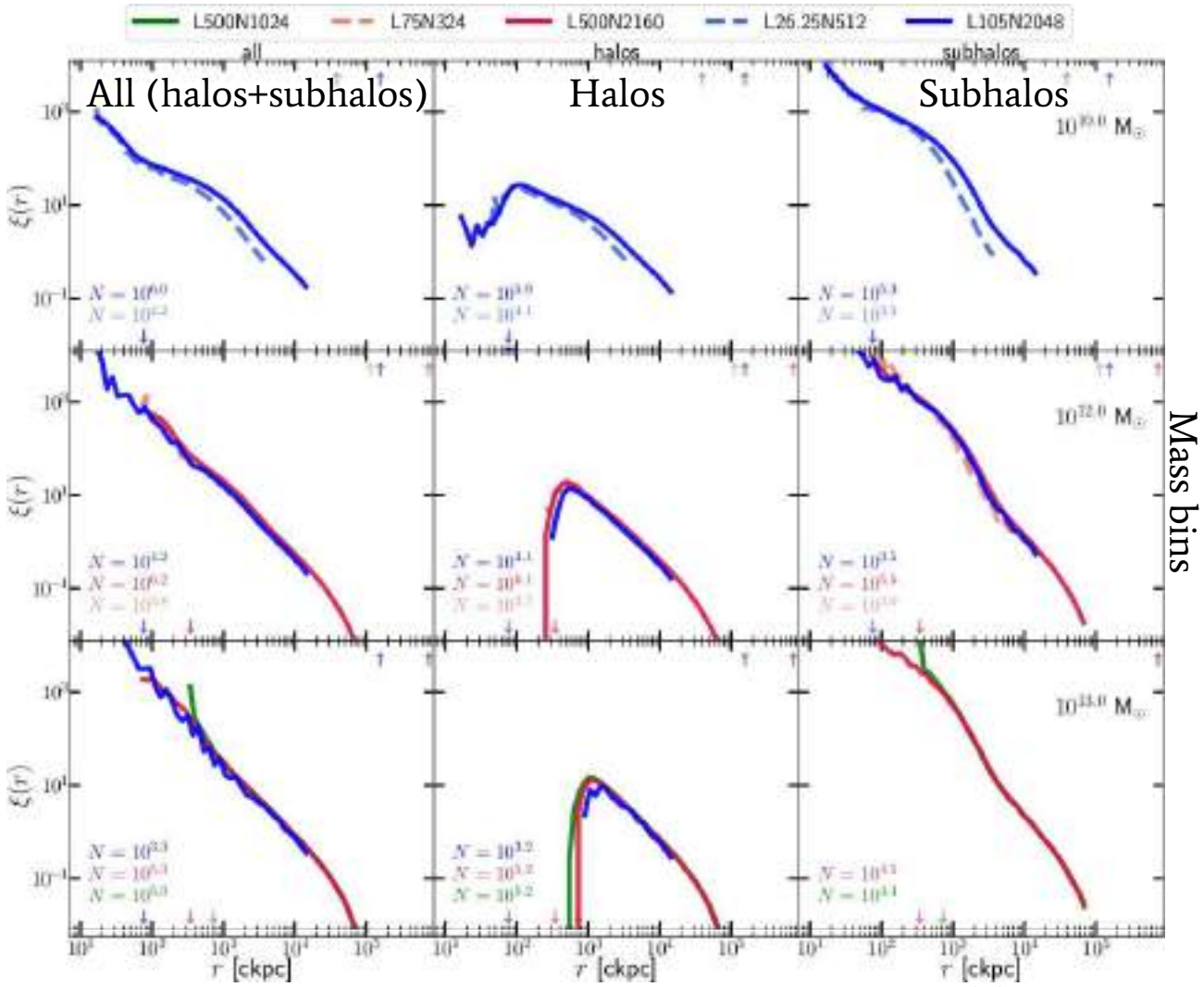


Velocity Function





Simulations

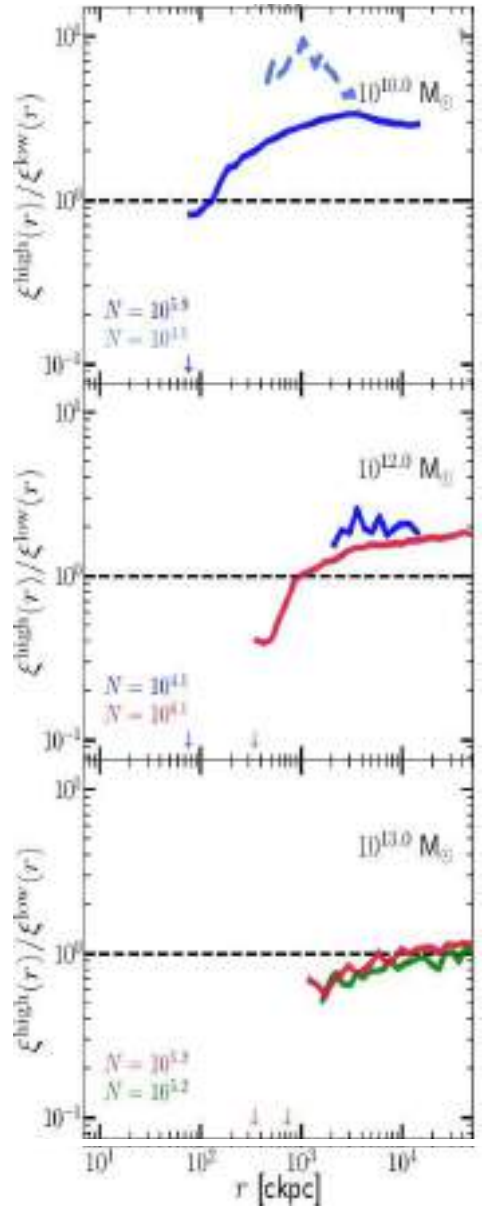


Correlation Function

Elahi+, in prep

[left]
Correlation function of halos agrees in different sims (modulo large-scale power)

[right]
Large-scale power has larger effect on secondary halo bias (aka assembly bias, [e.g., Mao+ 2018, Contreras+ 2019])
Here showing correlation of greater than average concentration of halos / less than average concentrated halos, which is typically < 1 for large halos.

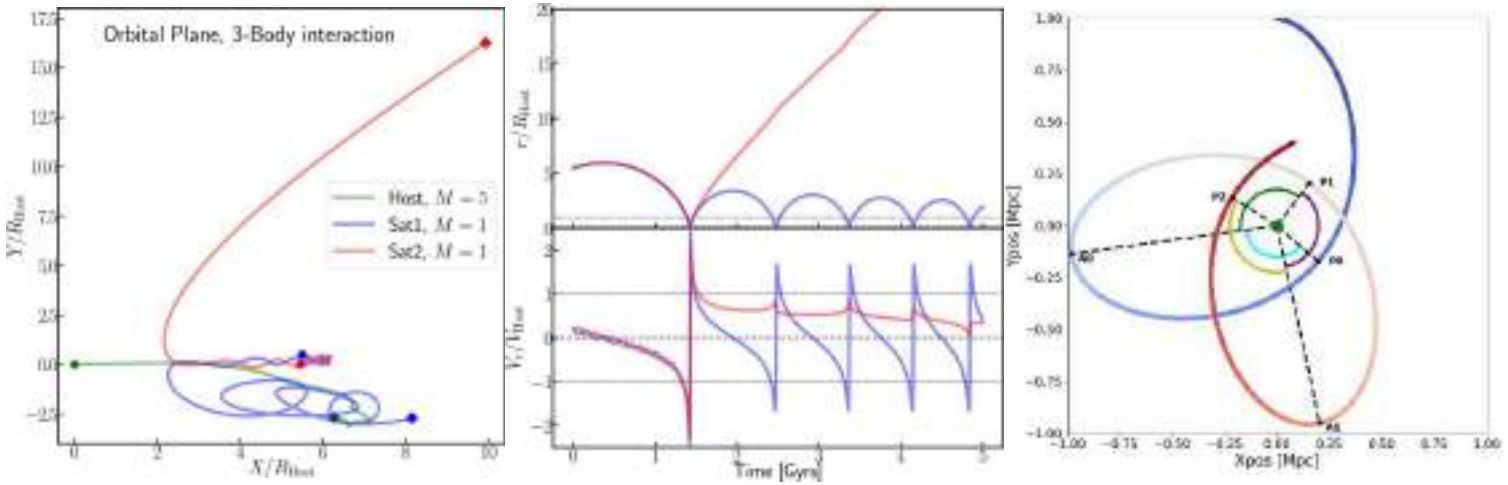


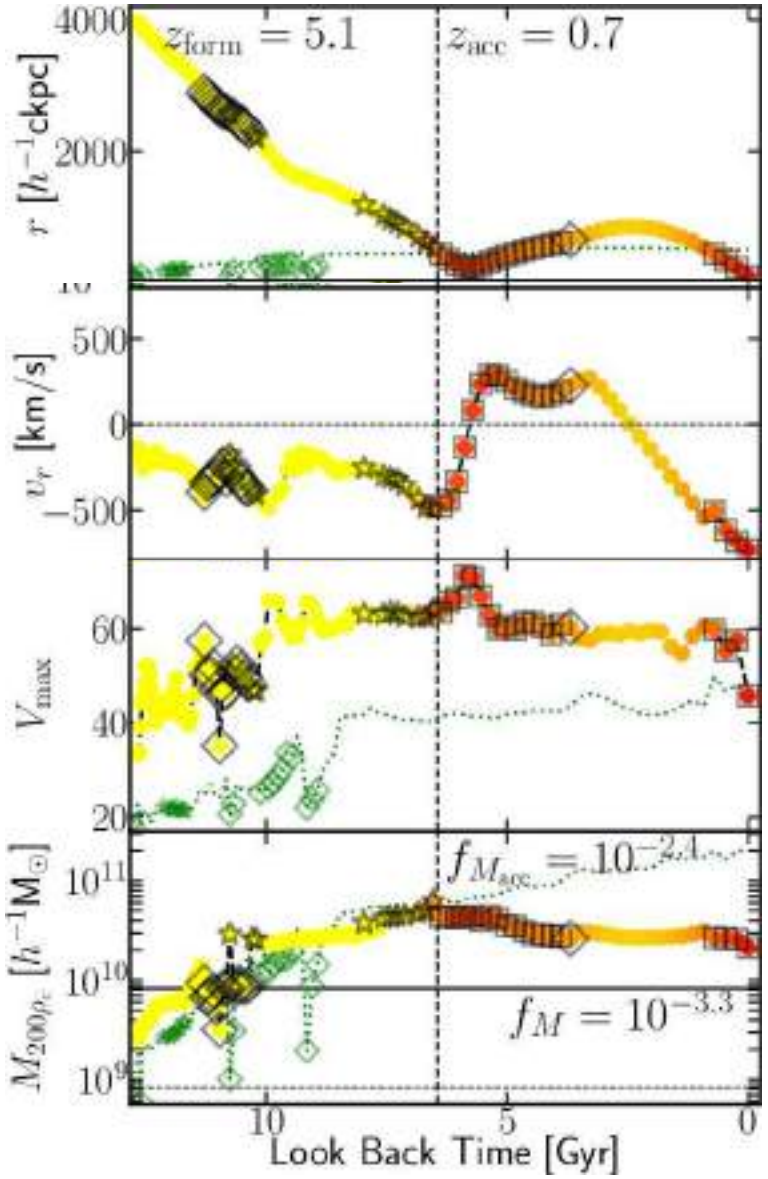
Correlation Function

Subhalos, Orbits & Mergers

With high quality trees can study evolution of orbiting subhalos using `OrbWeaver` (**Poulton**, PJE+, in prep), follow the evolution till object mergers

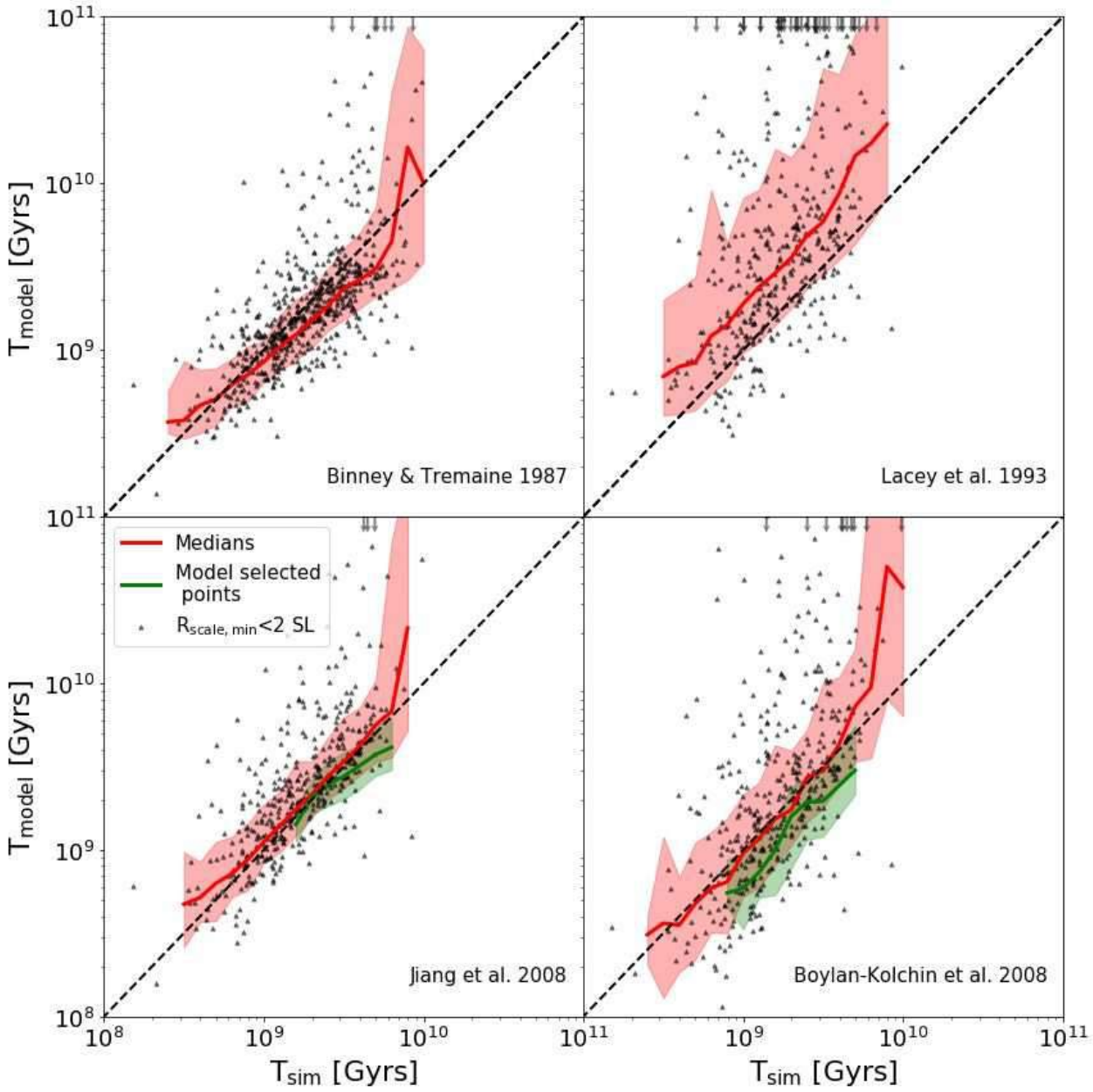
- Measure mass loss rates, dynamical friction, merger timescales
- Couple orbit catalog to examine splashback galaxies, how mass should be added to central (bulge, diffuse component)



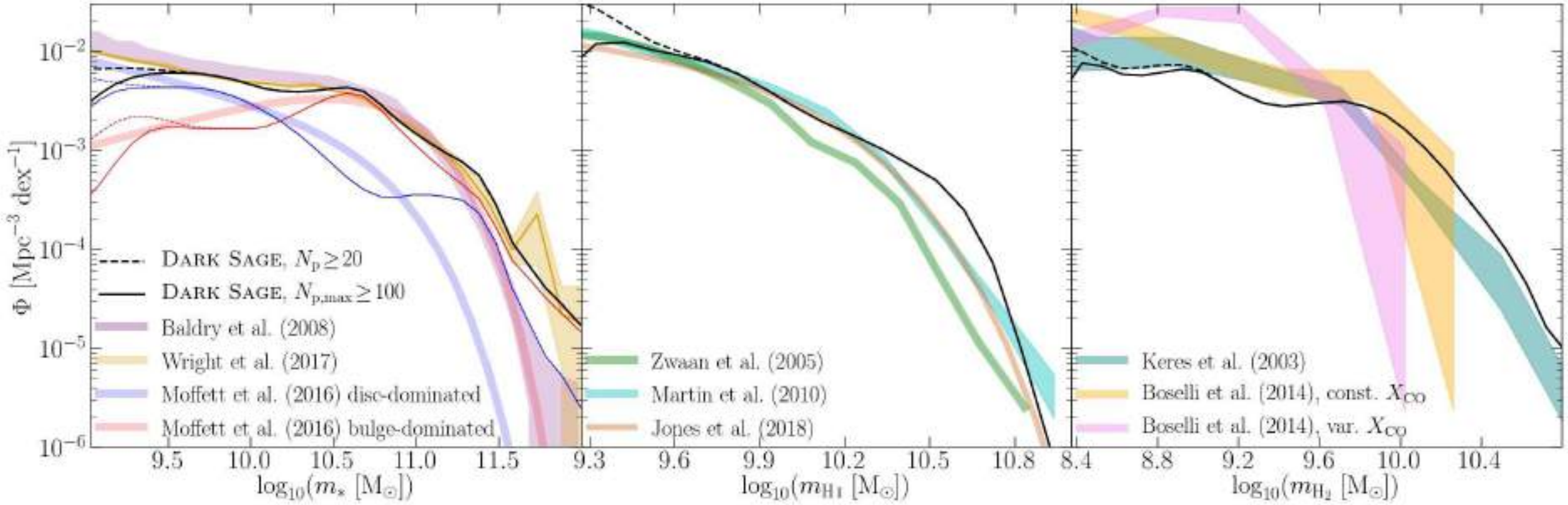


Subhalos, Orbits & Mergers

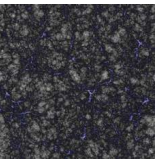
- **Poulton**+, in prep finds commonly used merger time scales work well for objects with large mass accretions (minor to major mergers)
- Smaller objects experience tidal mass loss so merger time scales overestimate lifespan.

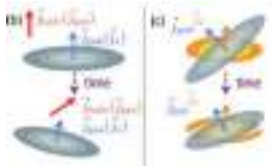


Initial SAM Without Full Calibration

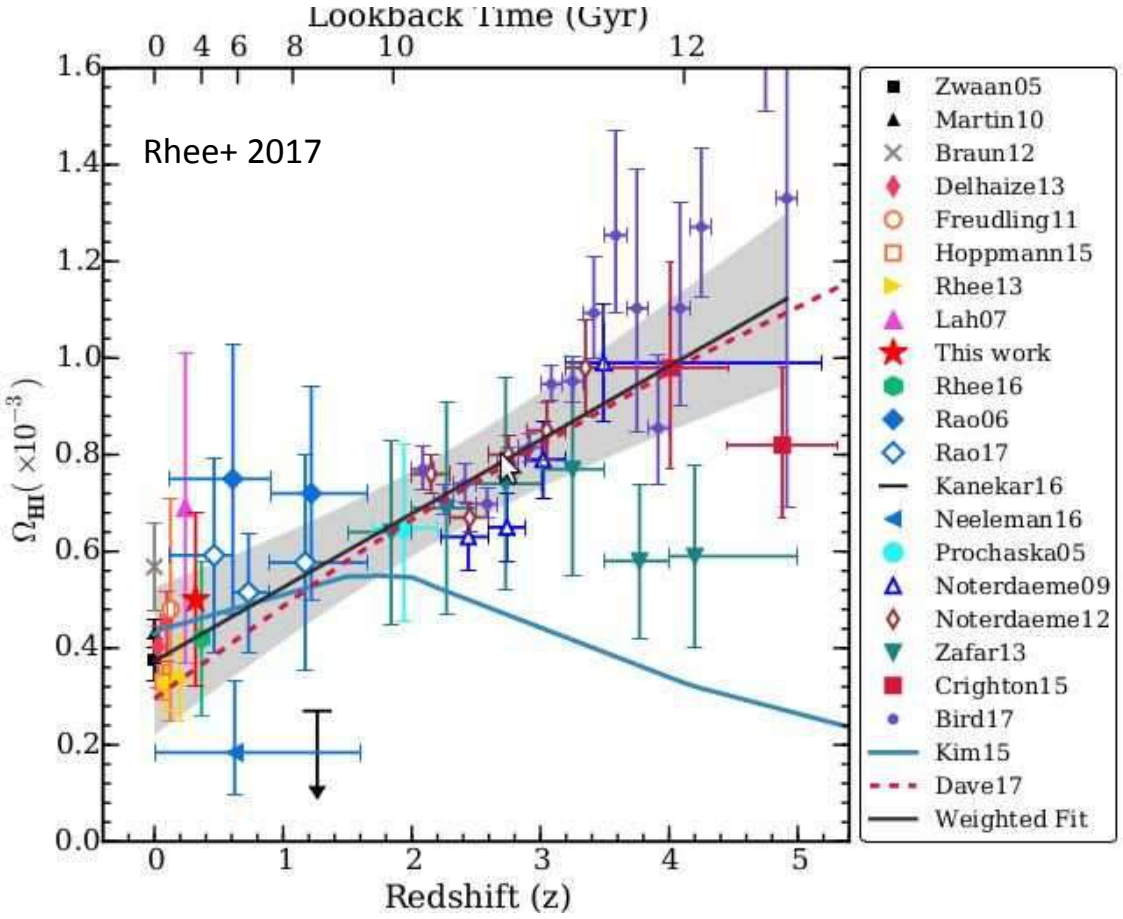


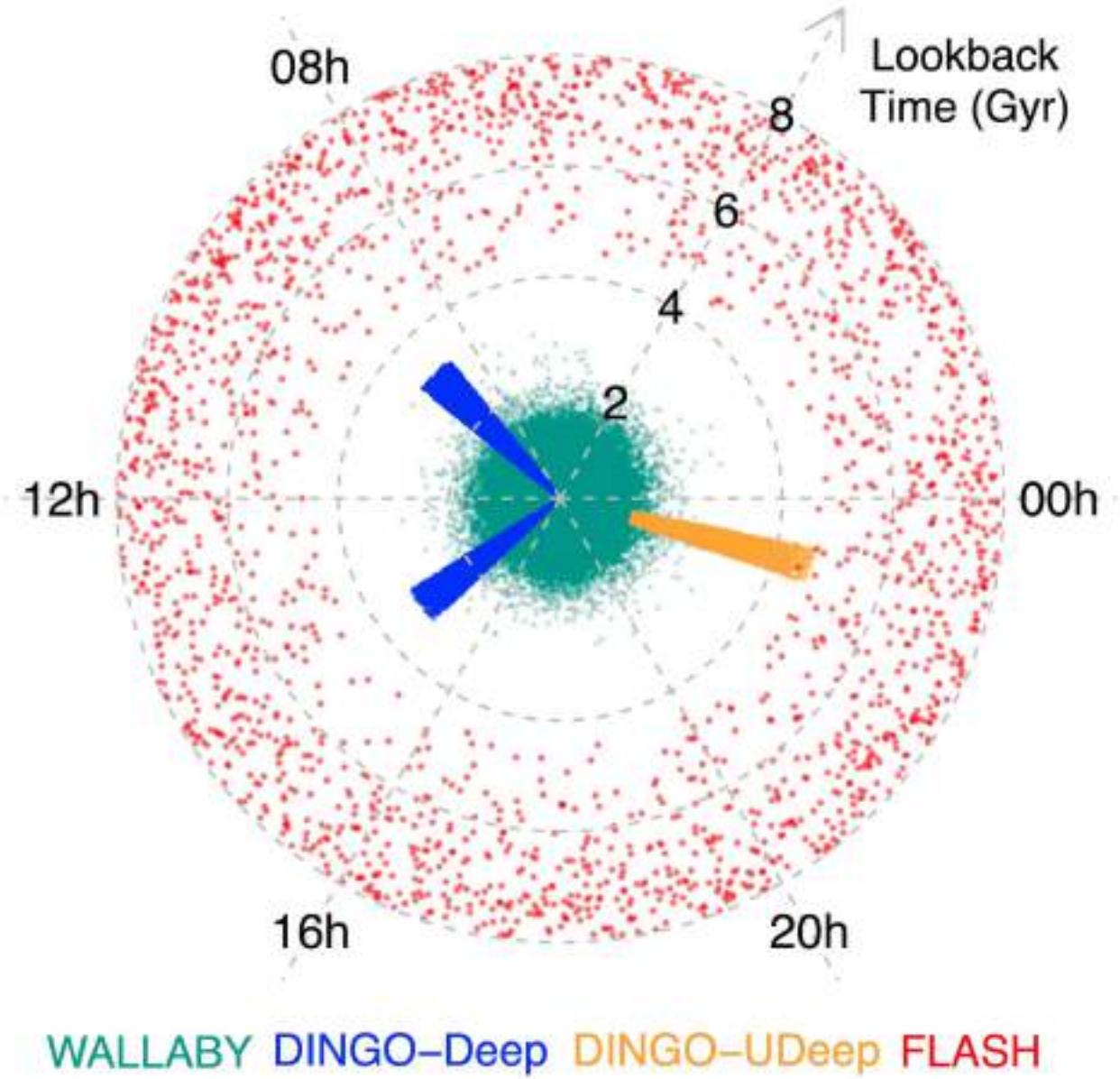
Using smaller calibration volumes with same cadence/mass resolution in halo merger trees, we can quickly calibrate (here done with χ^2-by-eye), get results for larger volumes (shown here). Tools available to fully calibrate (MCMC, Particle Swarm, Emulation)





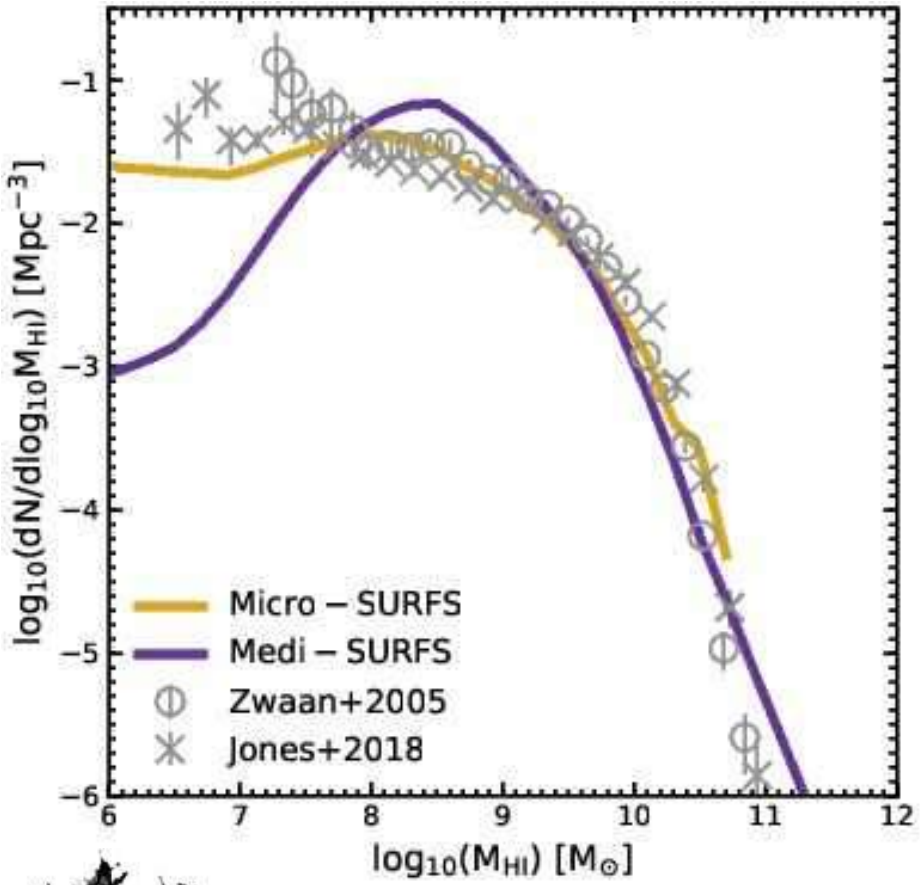
(HI) Galaxy Mocks

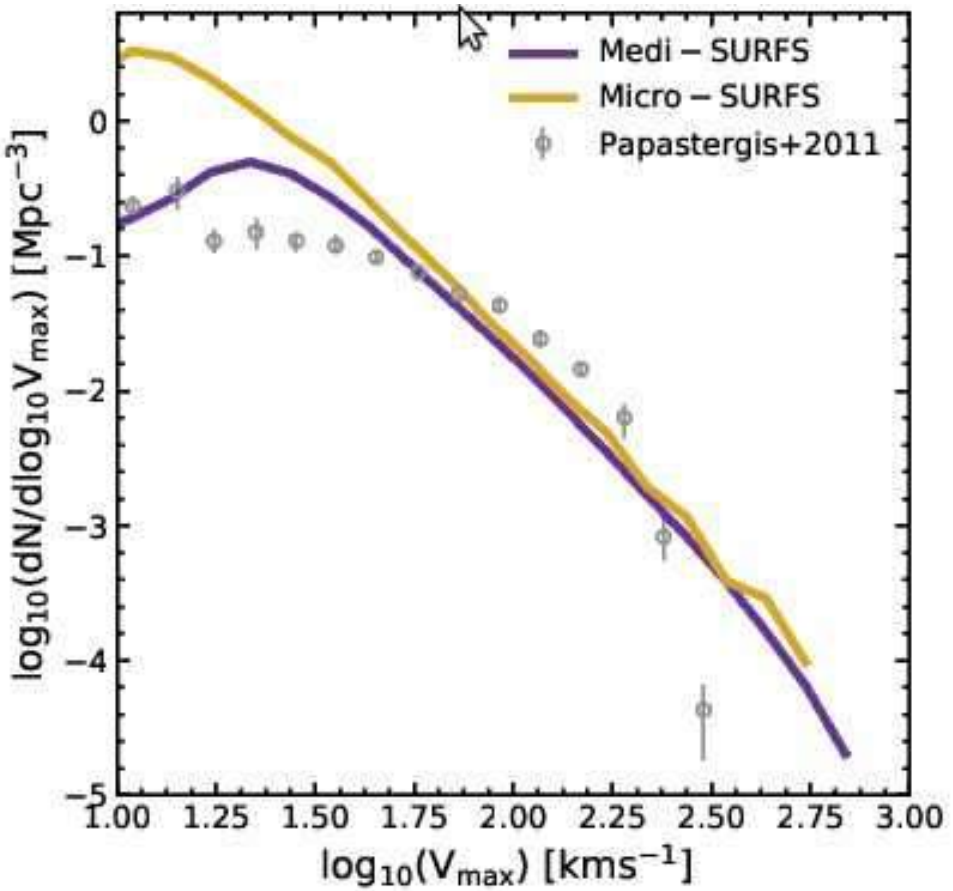




Synthetic HI content

HI galaxy observations seem to be at odds with predictions, specifically the velocity distribution.
Suggestions of non-circular motions from hydro sims (e.g. Oman+ 2015, Maccio+ 2016, Brooks+ 2017)



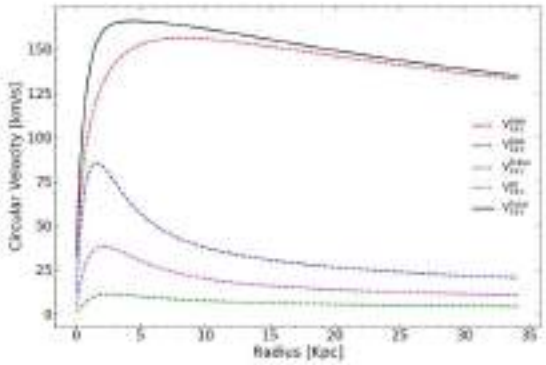


NBody+VR+TF+SHARK HI galaxies compared to ALFALFA

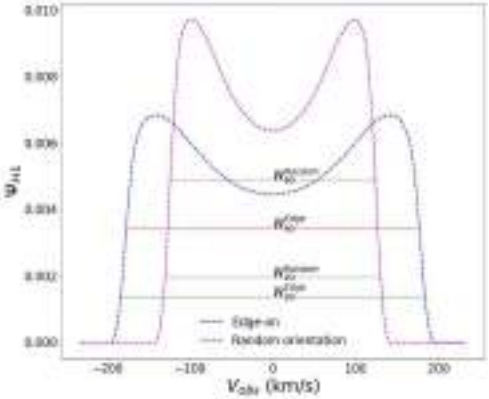
Synthetic HI content

ASTRO 3D

Circular Velocity Profile



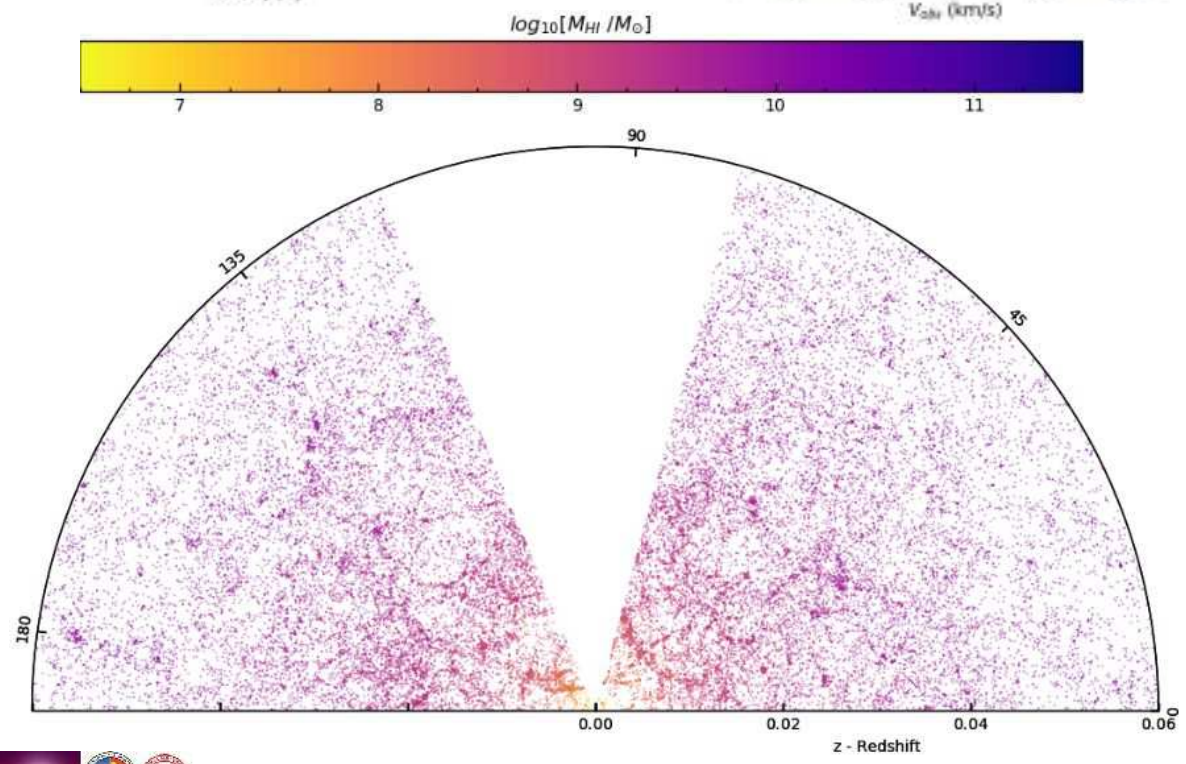
Observed HI Profile



Chauhan, PJE+, in prep, produced ALFALFA mock using

- SURFS simulations (N-Body+VR+TF),
- SAM (SHARK) + HI line profile construction
- Lightcone (STINGRAY) & ALFALFA selection function

Like-for-like comparisons between sims and obs critical for interpretation.

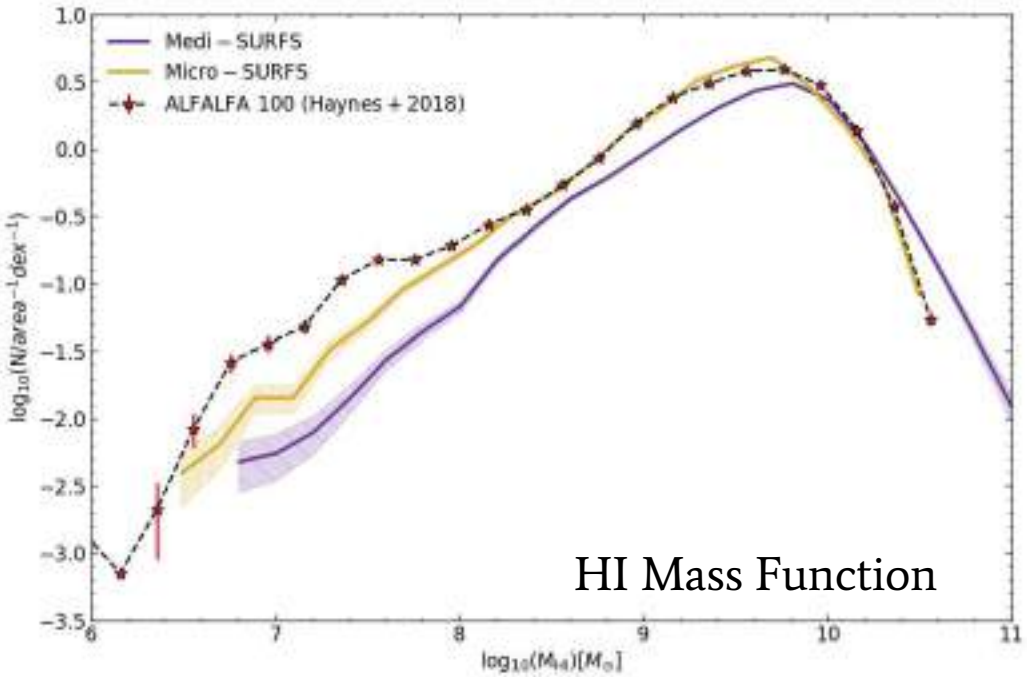


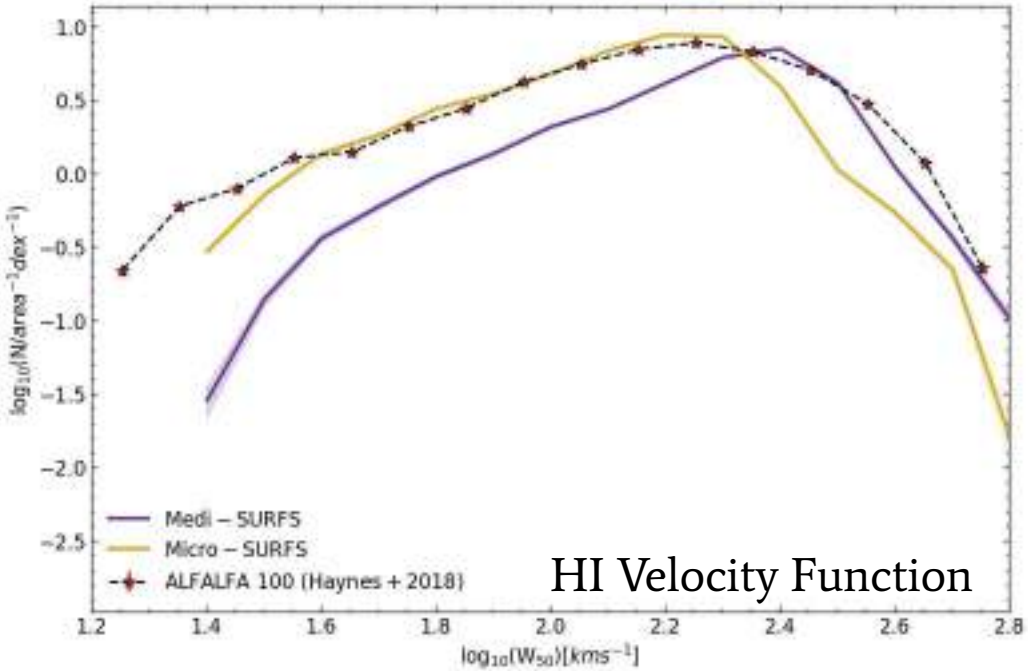
SHARK

ALFALFA

Synthetic HI content

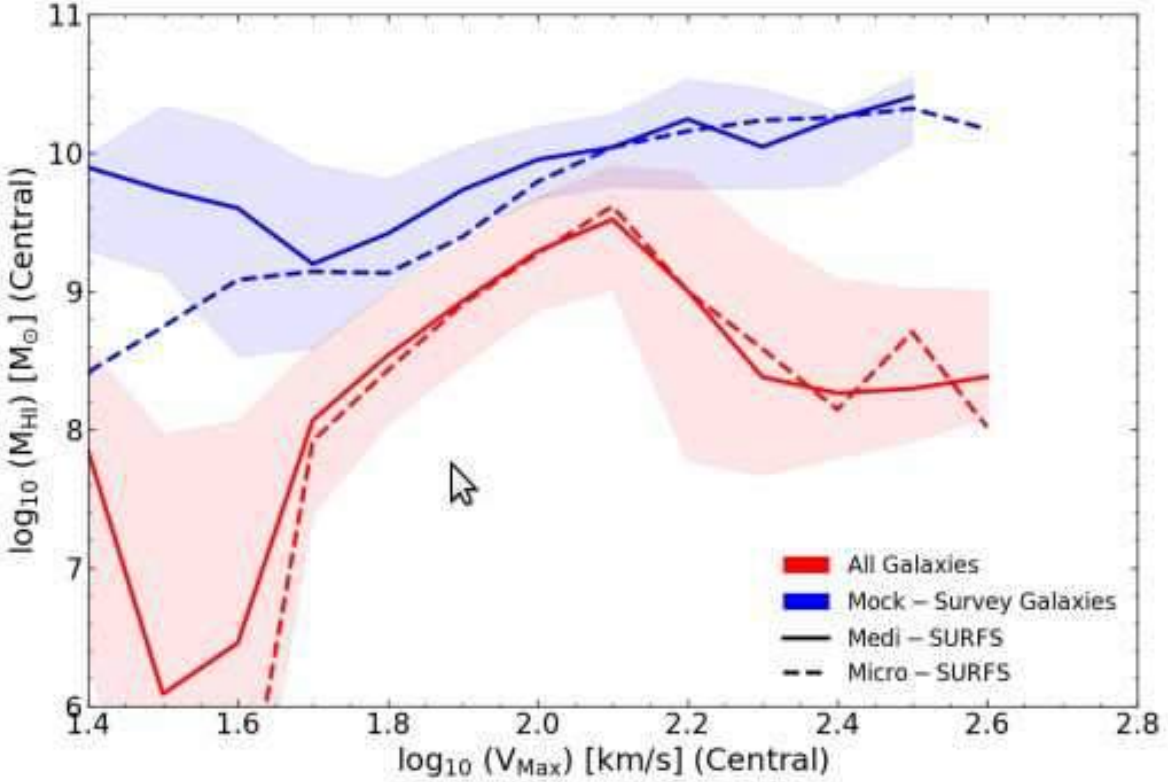
- Large discrepancies in Velocity Function (> 10) if comparing ALFALFA to DM halos V_{max}
- SAMs can (roughly) match HI mass function but will not reproduce observed VF
- Only S/N+HI ALFALFA selection on simulated line profiles reproduces observed HI VF
- Does not require corrections from non-circular motions, *only like-for-like comparison*

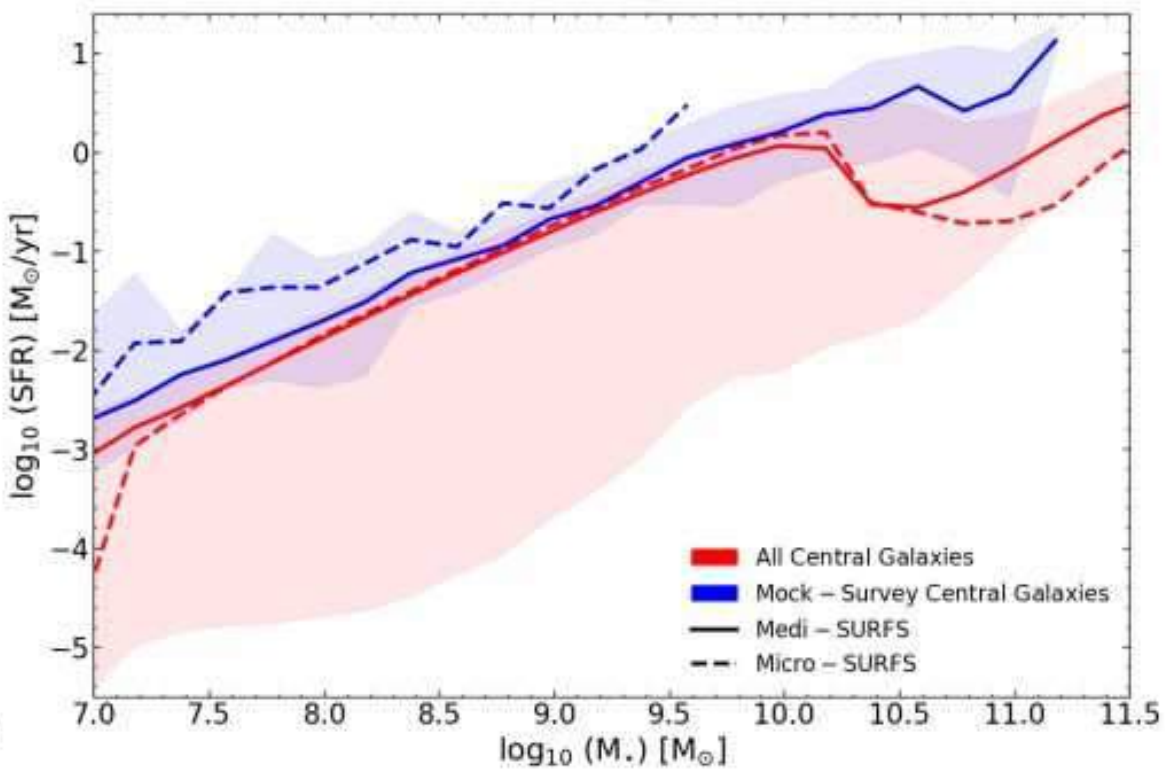




Synthetic HI content

Observed galaxies are a biased sample, with the bias varying with mass.



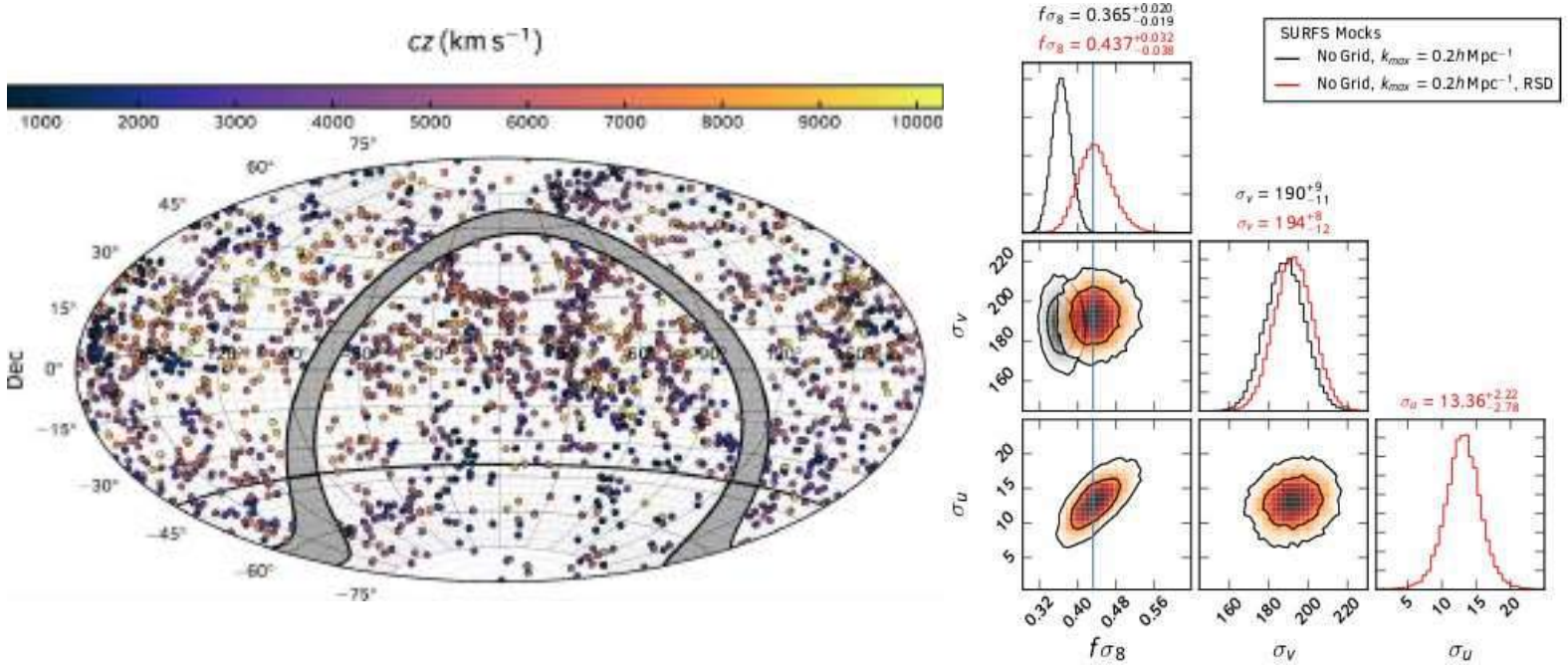


AM/HOD Cosmology

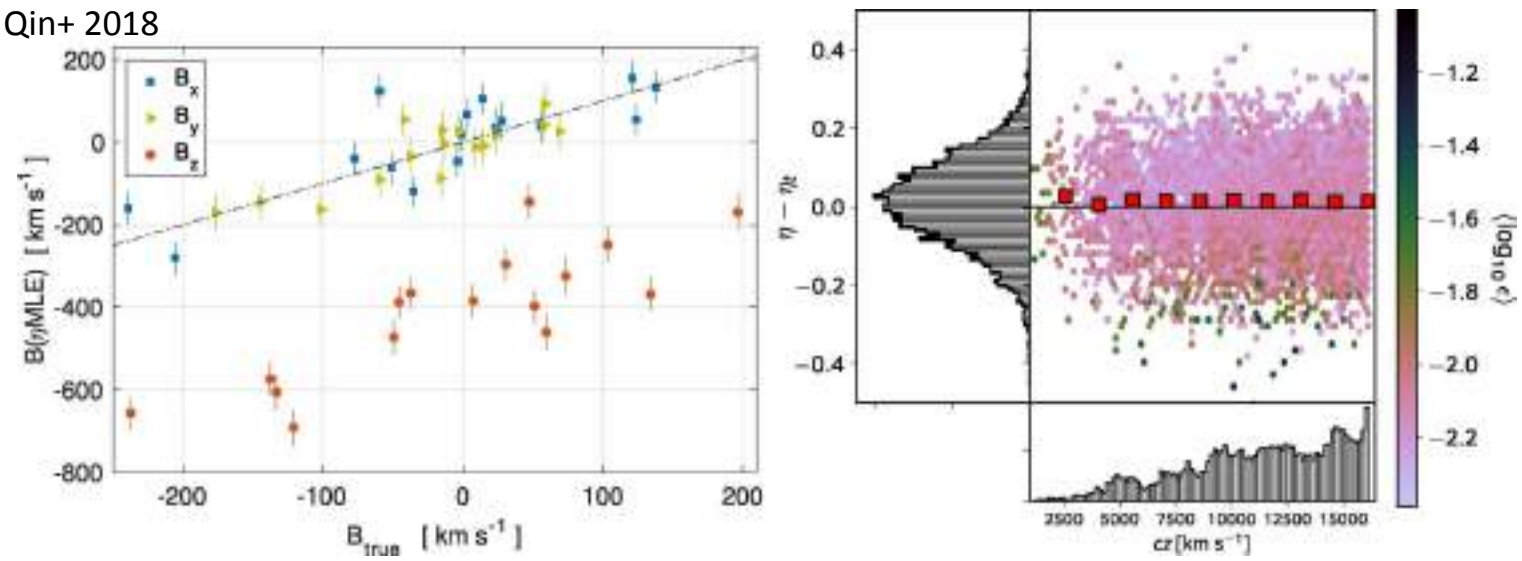
Large volume SURFS simulations (N-Body+VR & PICOLA+VR) containing halos populated with galaxies using Subhalo Abundance Matching (SHAM) [Howlett, PJE+ 2017; Qin+ 2018, 2019] to match optical (central(ish)) galaxy survey for cosmology

Upcoming surveys will use HI selected galaxies whose bias is different.

Howlett+ 2017



Qin+ 2018



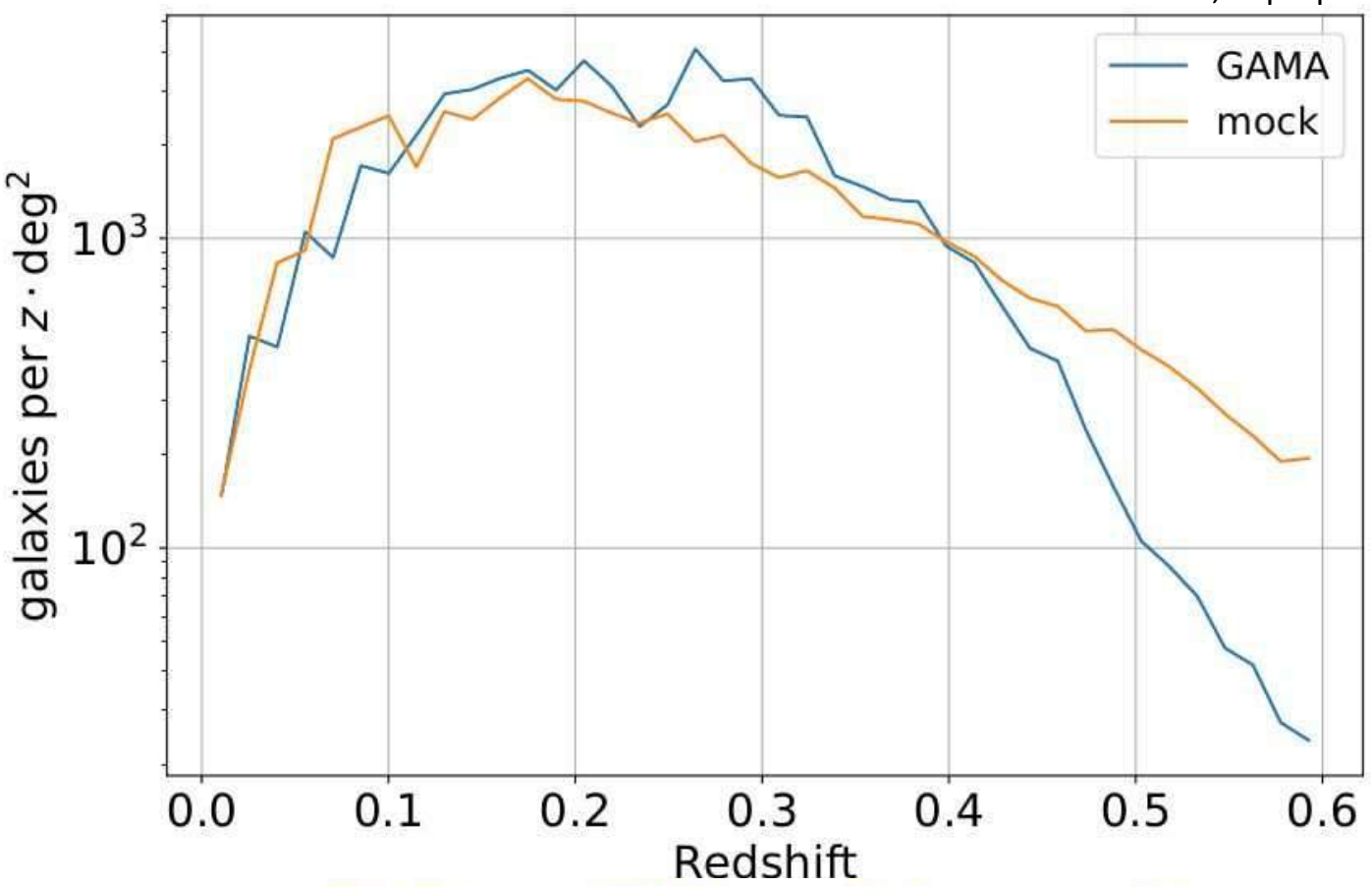
Upcoming Developments …

ASTRO 3D

- Large (~0.5x10^{12} particles) N-Body simulations using `SWIFT+VELOCIraptor` (Elahi, Schaller, Willis) . `SWIFT` is next gen Hydro code, + `VR` on the fly halo finding
  - Sims will probing galaxy distribution to ~10^8 $M_\odot$ with multiple SAMs, SEDs, lightcones
  - EOR power spectrum predictions using coupled reionisation+galaxy formation
- Zoom hydrodynamical simulations with variety of subgrid physics
  - explore stellar feedback in low mass galaxies
  - explore EOR
- Large volume approximate simulations (Howlett, Elahi) using PICOLA+VR+ HODs/CLFs/SHAM for fast, low gravitational accuracy (no halo substructure) mocks
  - Cosmological probes, covariance, etc
  - Tailored mocks to produce appropriate sites of galaxy formation (i.e., dark matter physics, modified gravity)

Things to consider

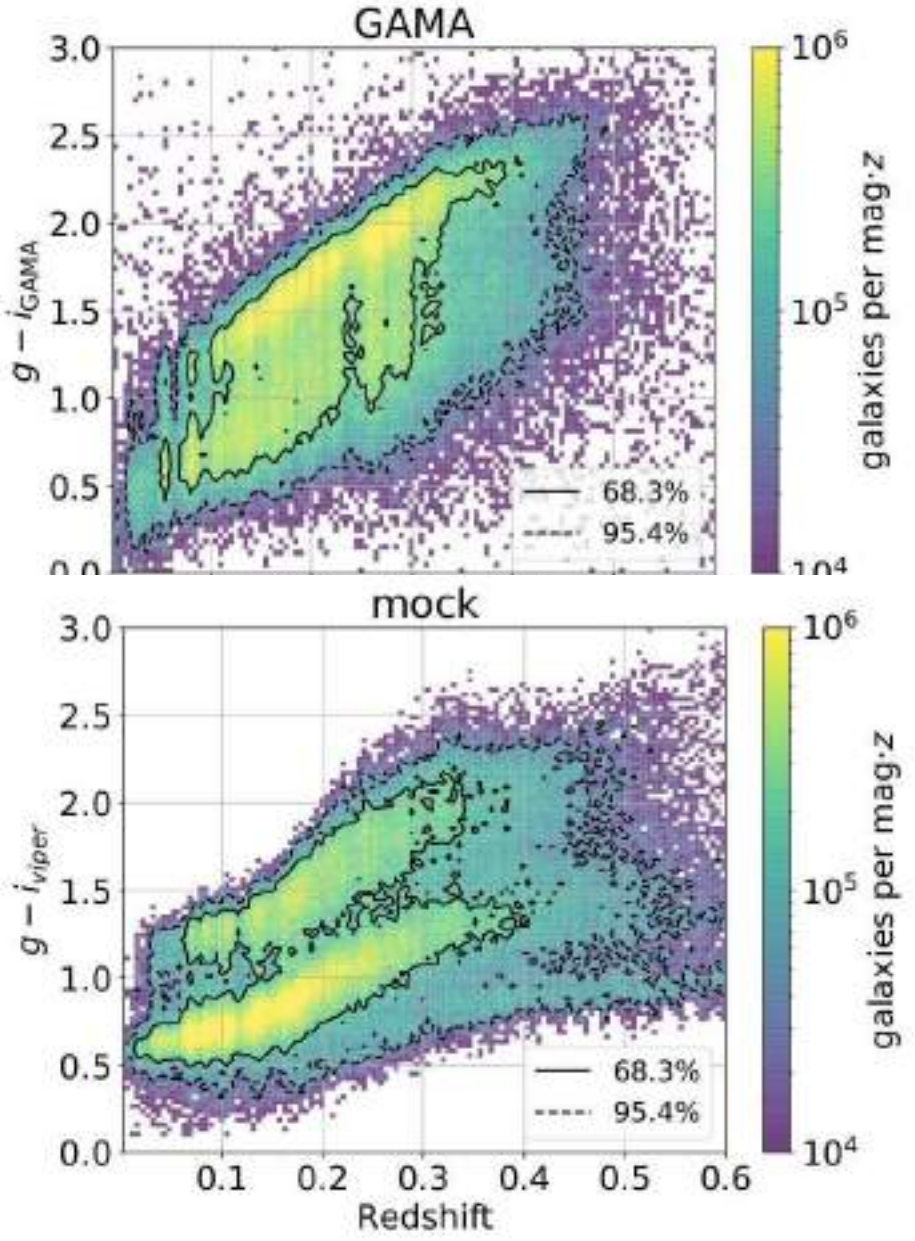
Bravos+, in prep



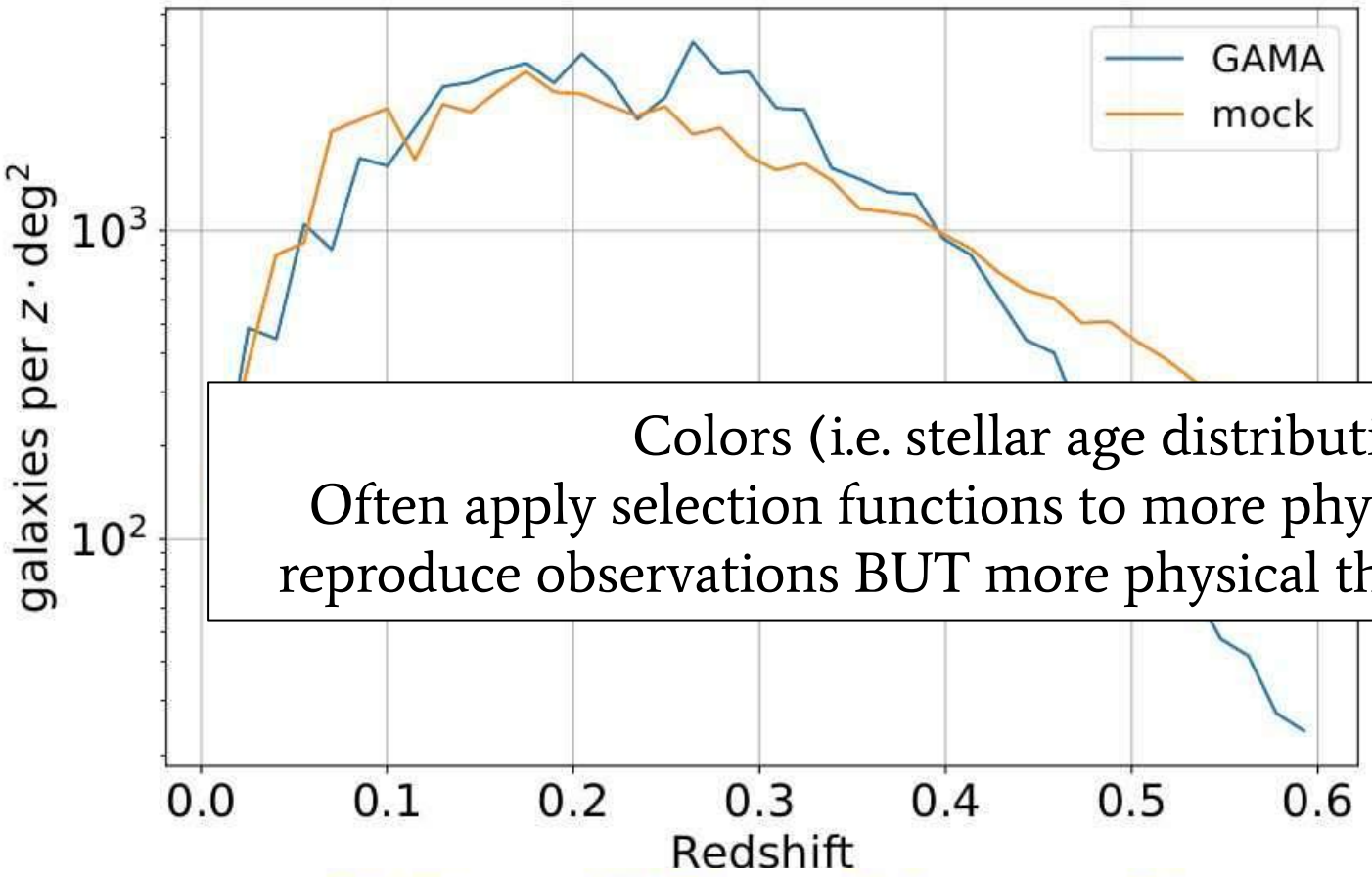
Mao+ 2018, DESCQA

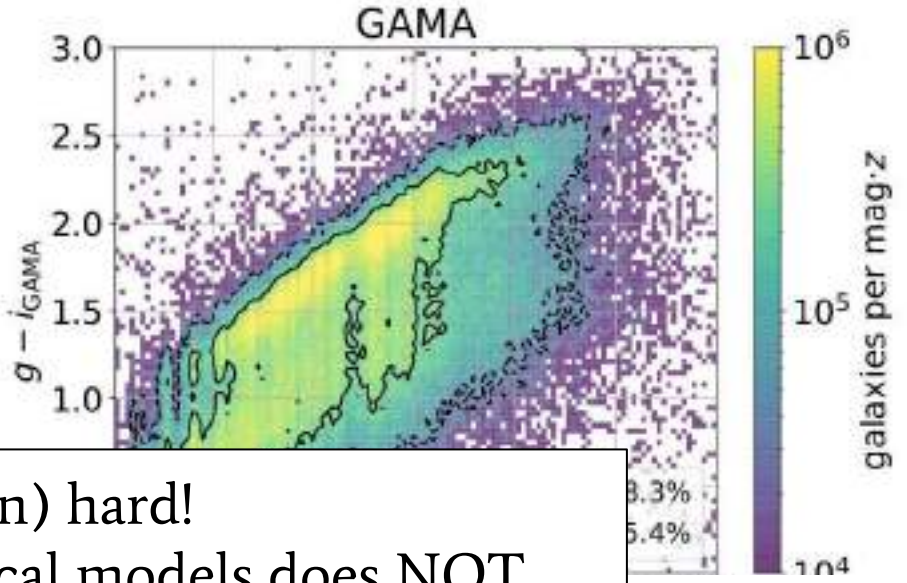
	CAM_LiWhite	CAM_MBII	Galacticus	MBII
Color_SDSS	FAILED 0.0158	FAILED 0.0172	FAILED 0.0717	FAILED 0.0494

SAG	SHAM_LiWhite	SHAM_MBII	iHOD
FAILED 0.0703	FAILED 0.0461	FAILED 0.0445	FAILED 0.0373

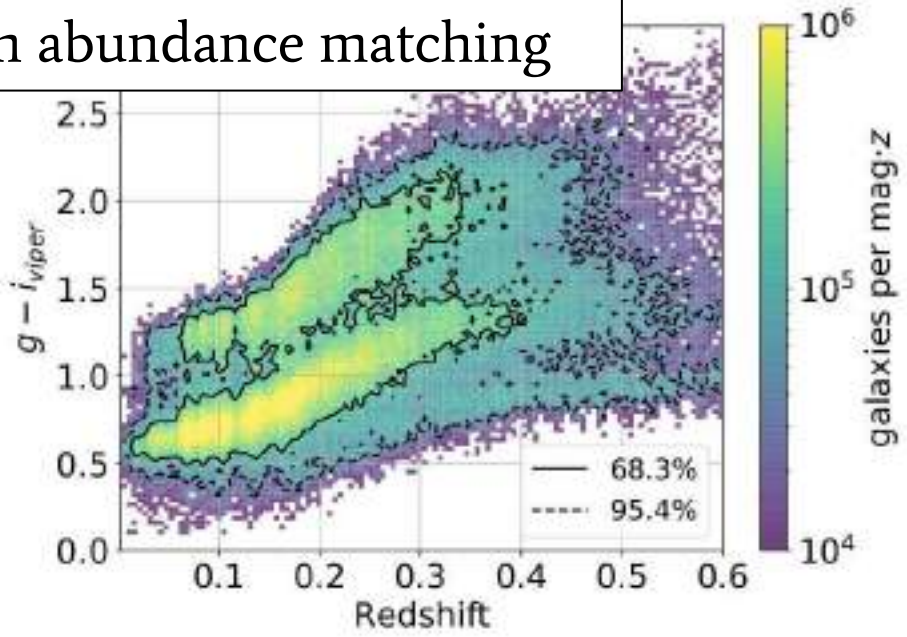


Things to consider





Colors (i.e. stellar age distribution) hard!
Often apply selection functions to more physical models does NOT reproduce observations BUT more physical than abundance matching



	CAM_LiWhite	CAM_MBII	Galacticus	MBII
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