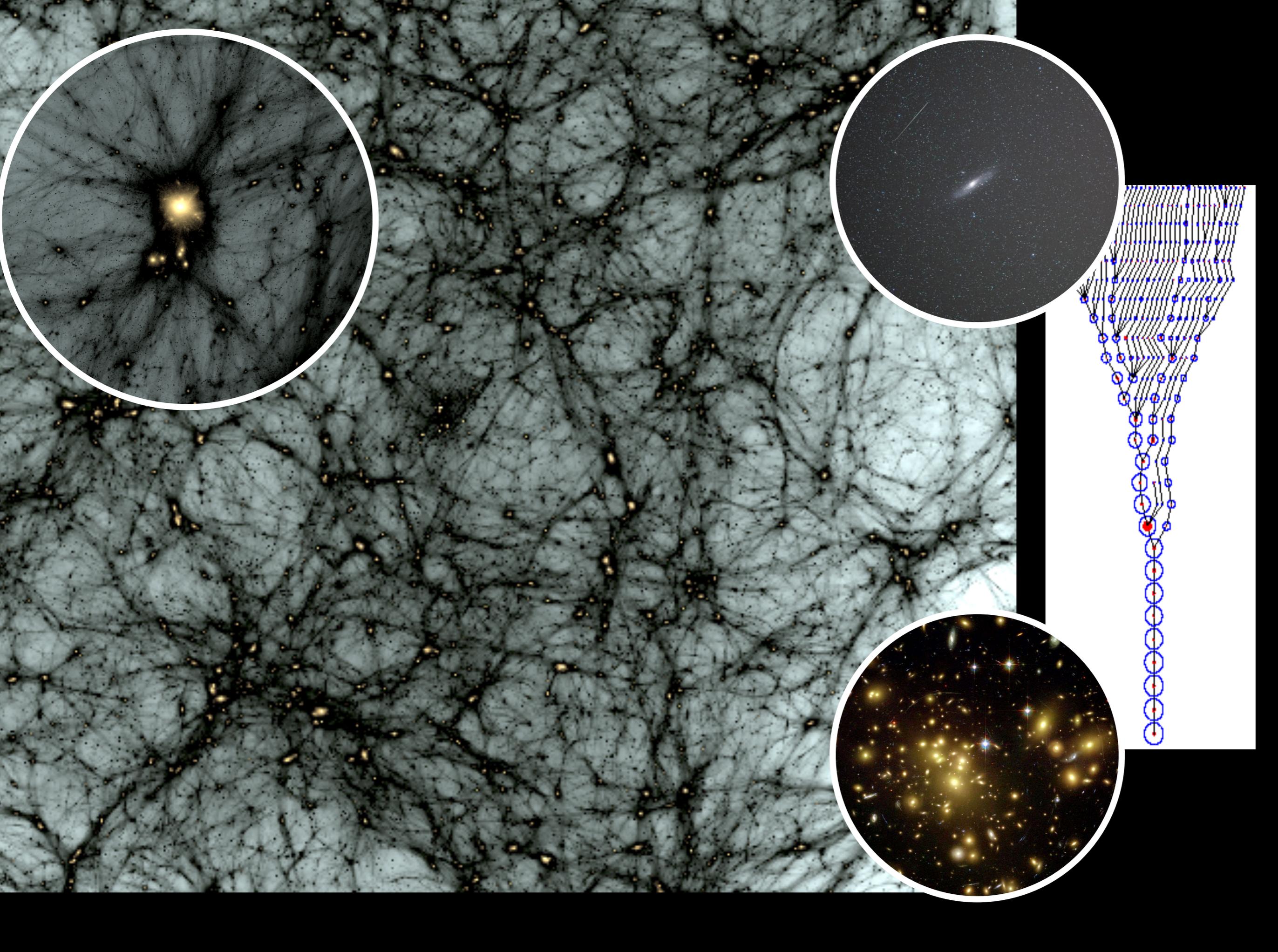


Connecting galaxies and dark matter halos: methods, insights, and challenges



Risa Wechsler
KIPAC @ Stanford/SLAC

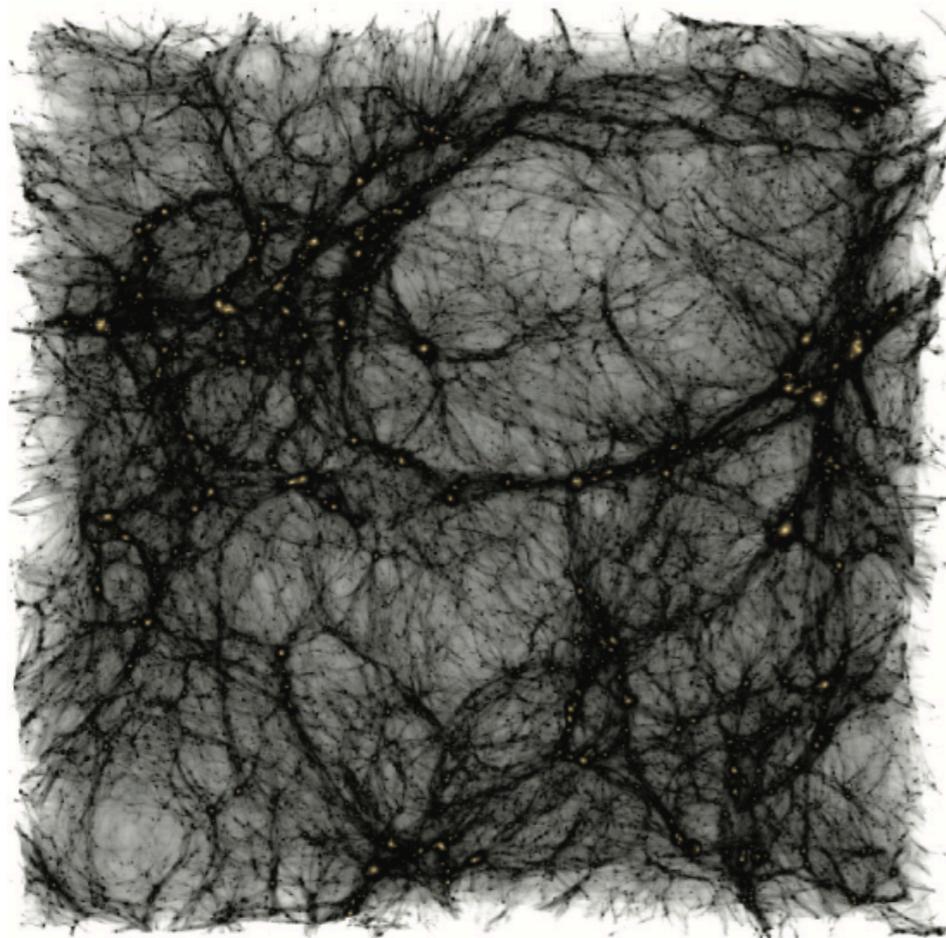
KICC 10th Anniversary Symposium
September 17, 2019



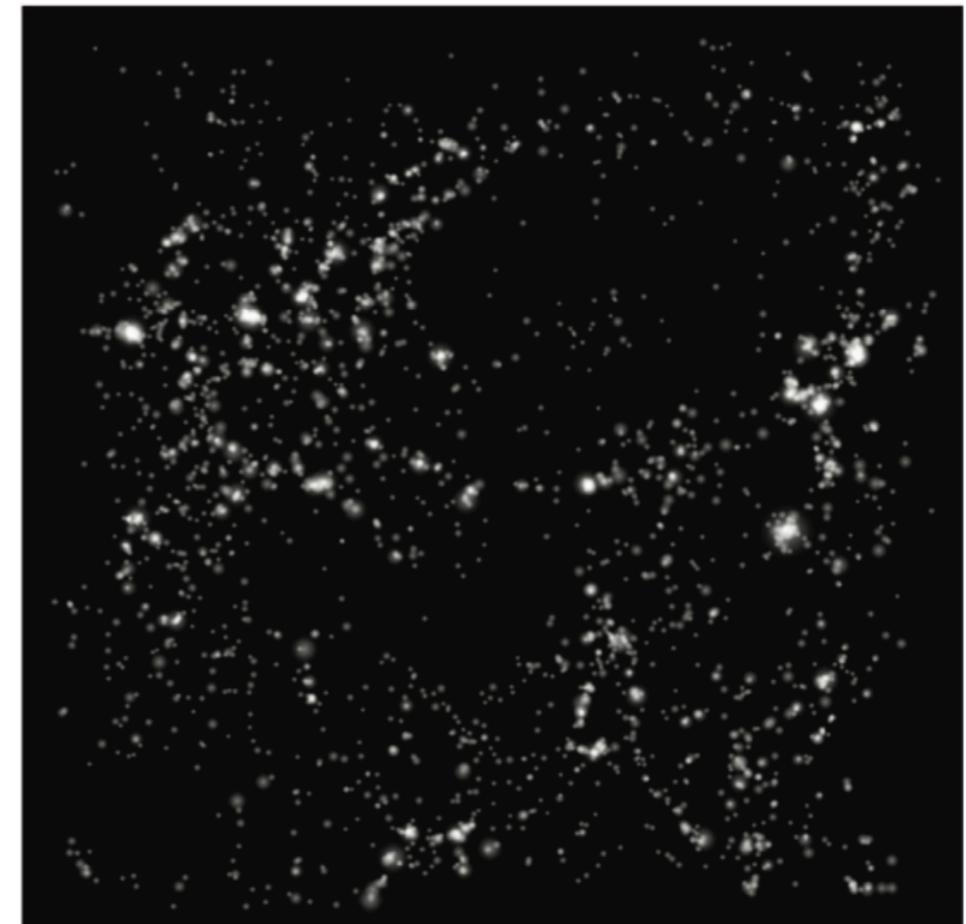
What are models of the galaxy-halo connection good for?

- Parameterize the galaxy-halo connection; marginalize over it to constrain cosmological parameters
- Model the galaxy-halo connection to make realistic realizations of large surveys
- Constrain the parameters (and parameterization) of a galaxy-halo model to understand galaxy formation physics
- Parameterize the galaxy-halo connection; marginalize over it to constrain dark matter physics

Approaches to
modeling the galaxy-
halo connection



Galaxy-halo connection



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

Subhalo abundance matching

Number of galaxies/halos



Galaxy / halo mass

Galaxy stellar mass

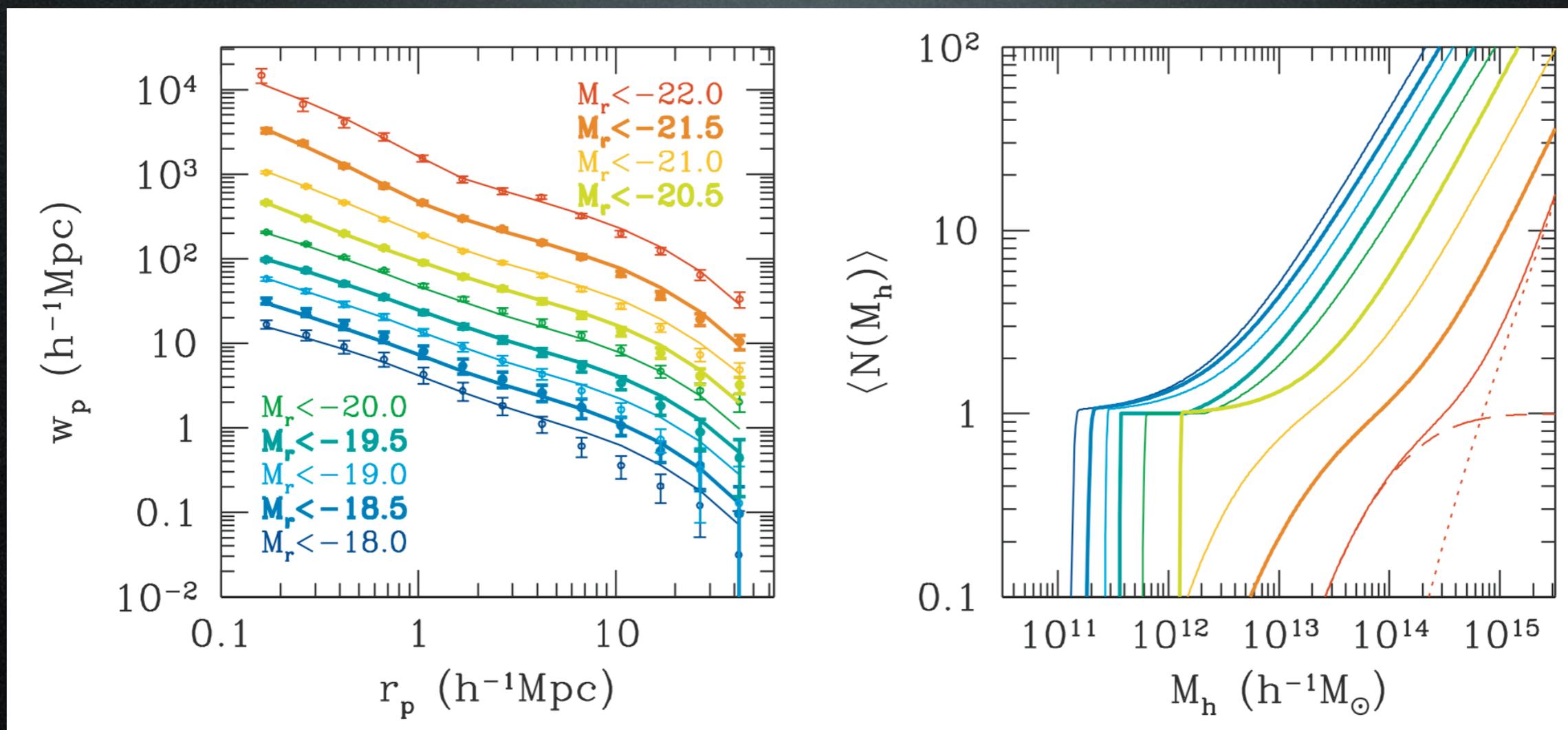


halo mass

Vale & Ostriker 2004; Kravtsov, Berlind, RW et al 2004; Tatistomi et al 2004;
Conroy, RW, Kravtsov 2006; Behroozi et al 2010; Moster et al 2013;
Behroozi et al 2013; Reddick et al 2014; Lehmann et al 2017

Recent models parameterize scatter and concentration dependence of galaxy properties

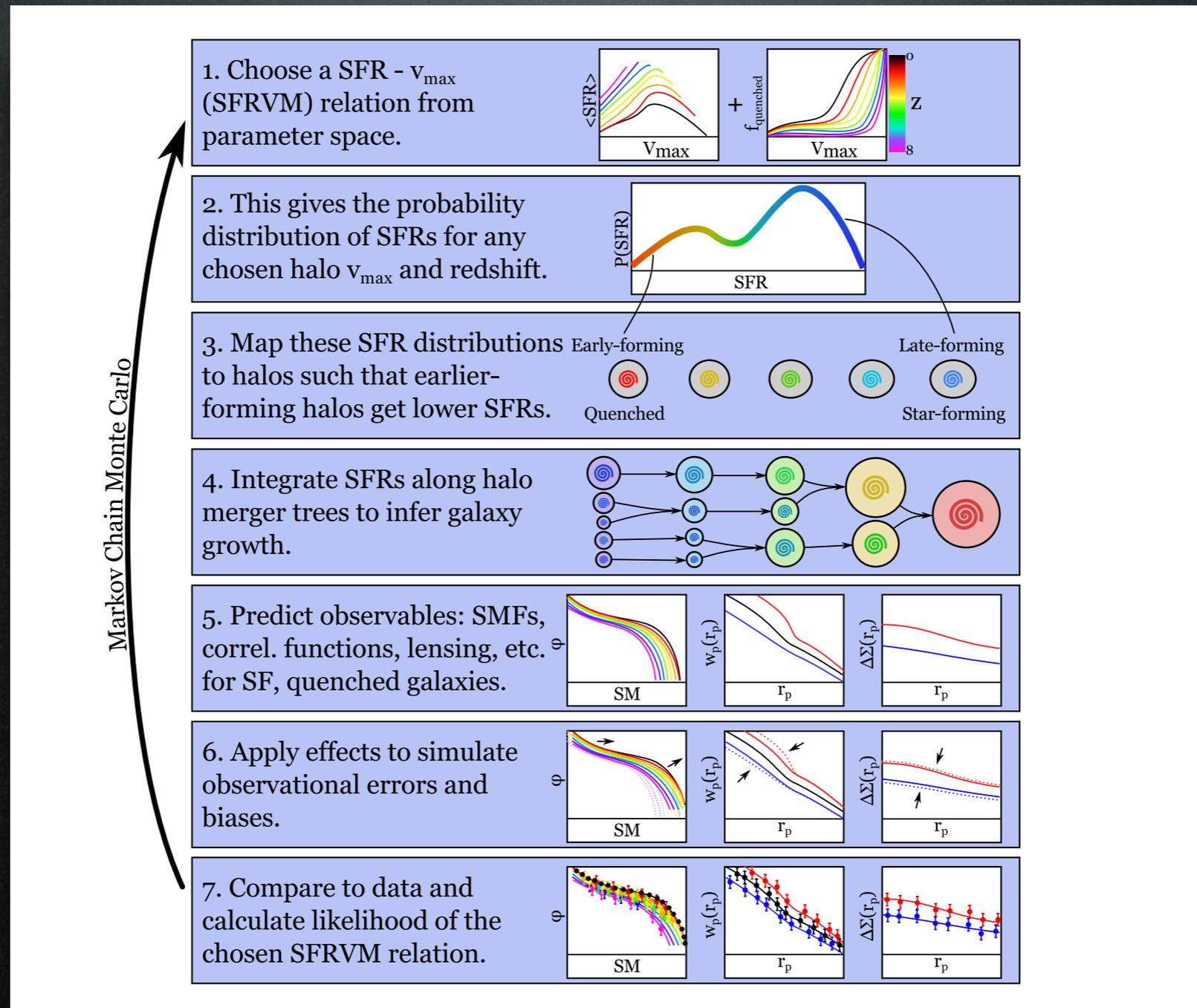
Constraining the halo occupation with galaxy clustering



Zehavi et al 2011

Can also use group & cluster statistics, galaxy-galaxy lensing, velocities in groups & clusters, counts in cells, void statistics...

Combine observations with halo statistics and growth

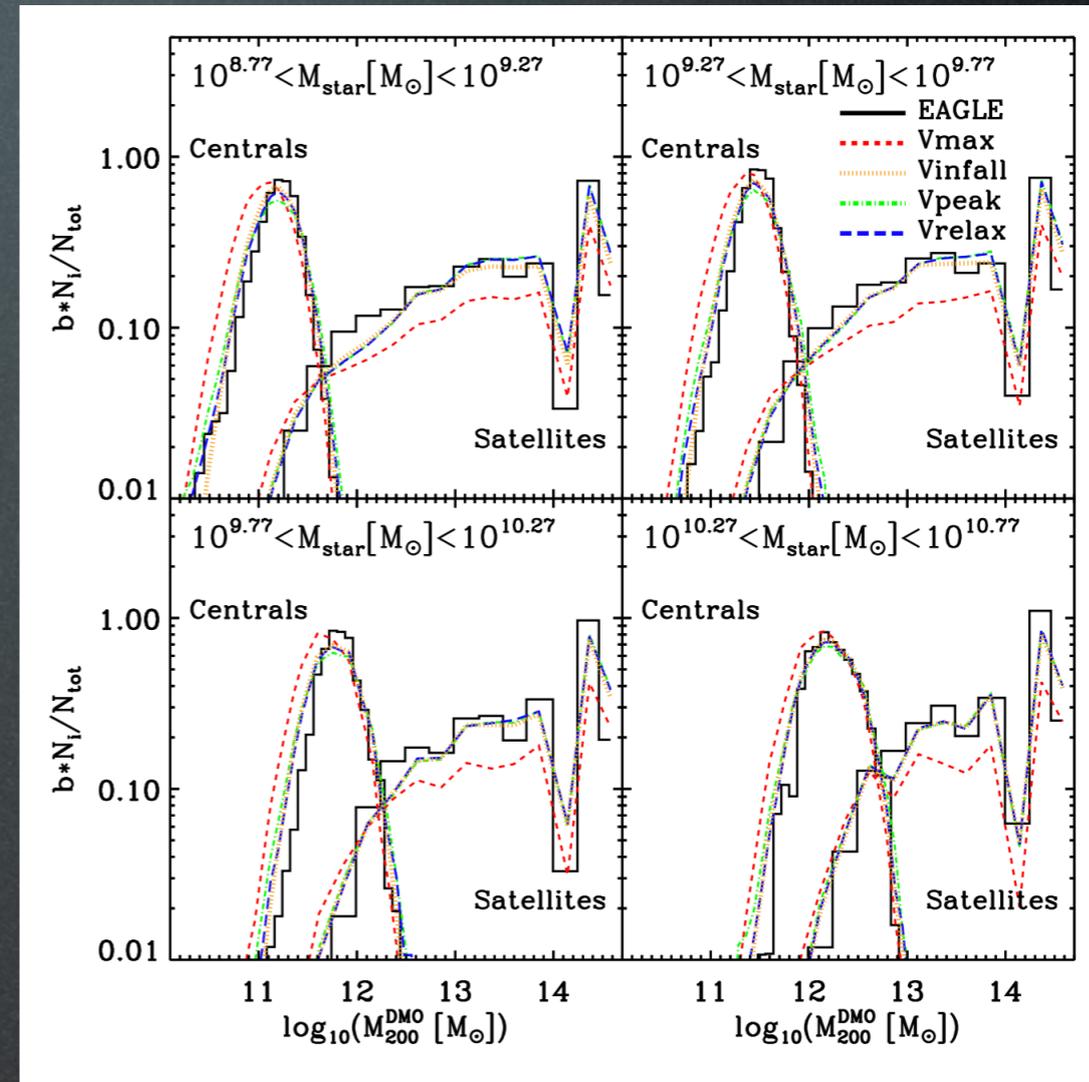
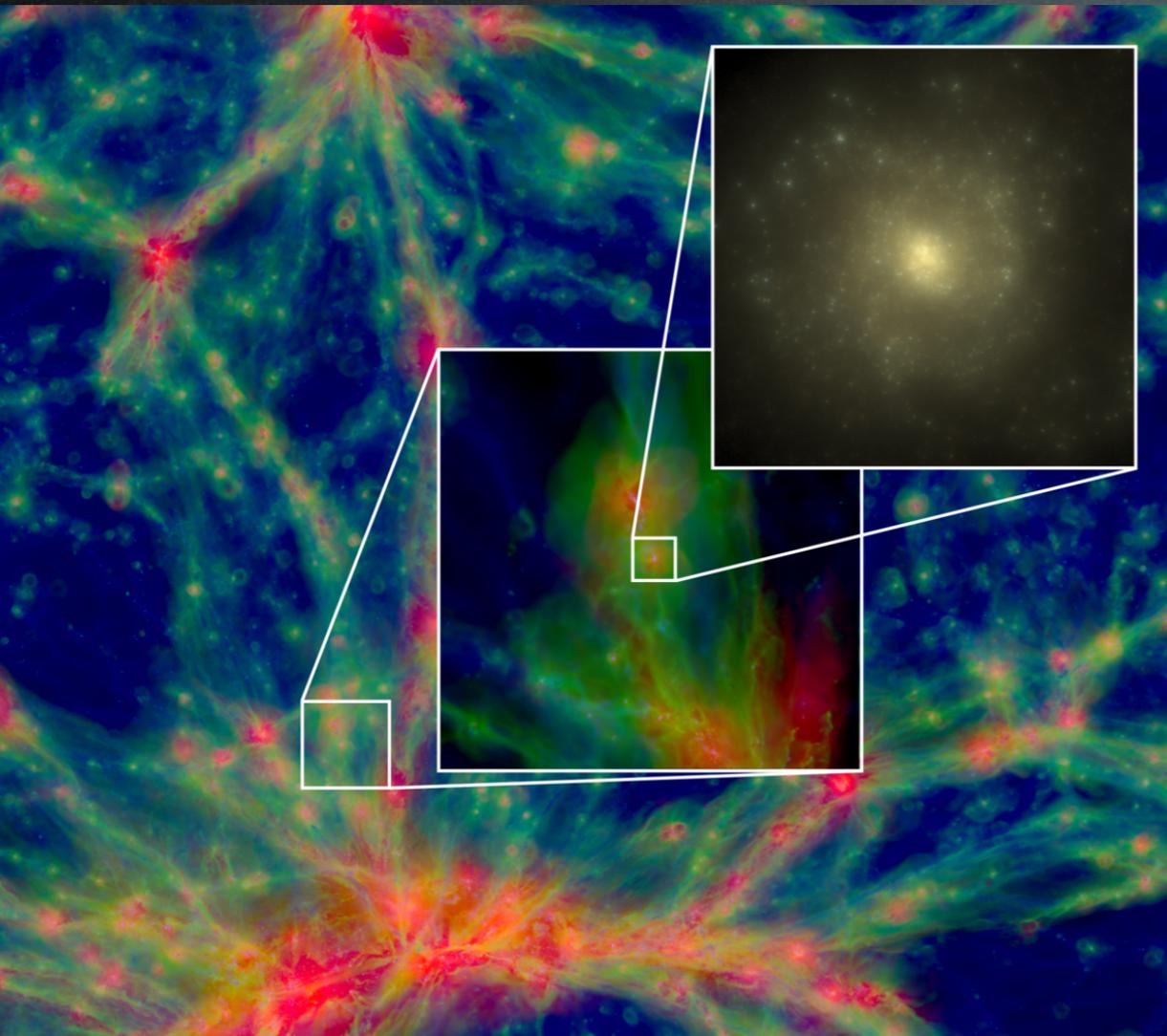


Behroozi, RW, Hearin & Conroy 2019

(see also Becker 2015; Rodriguez-Puebla et al 2016; Chon 2017; Moster et al 2018)

Based on framework first explored in Conroy & Wechsler 2009
parameterized SFR(mass accretion rate)... constrain with SMF, SFR, clustering.

Hydrodynamical simulations



Chavez-Montaro et al 2016; Eagle simulations

Best understanding of the physics

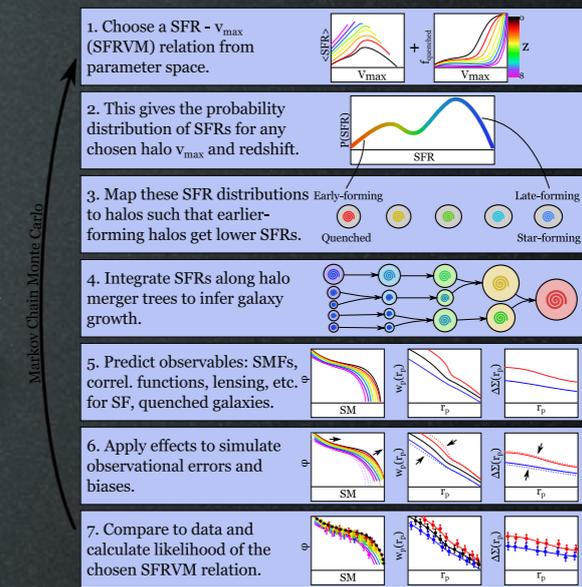
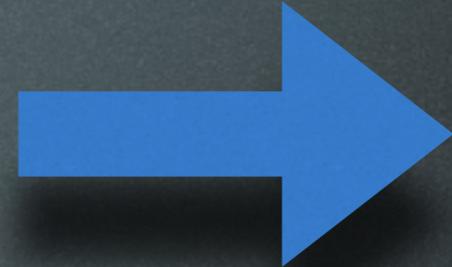
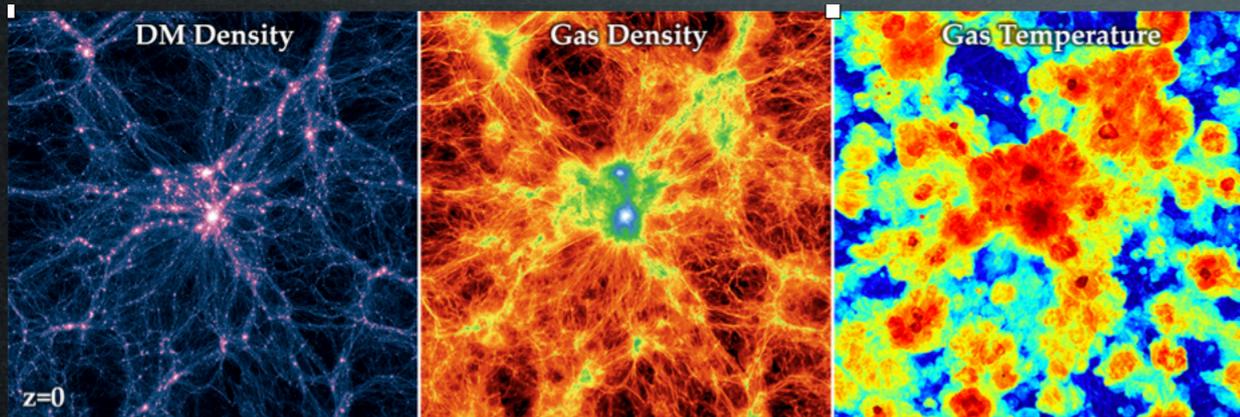
Can test key assumptions in parametric models

Expensive; hard to explore parameter space

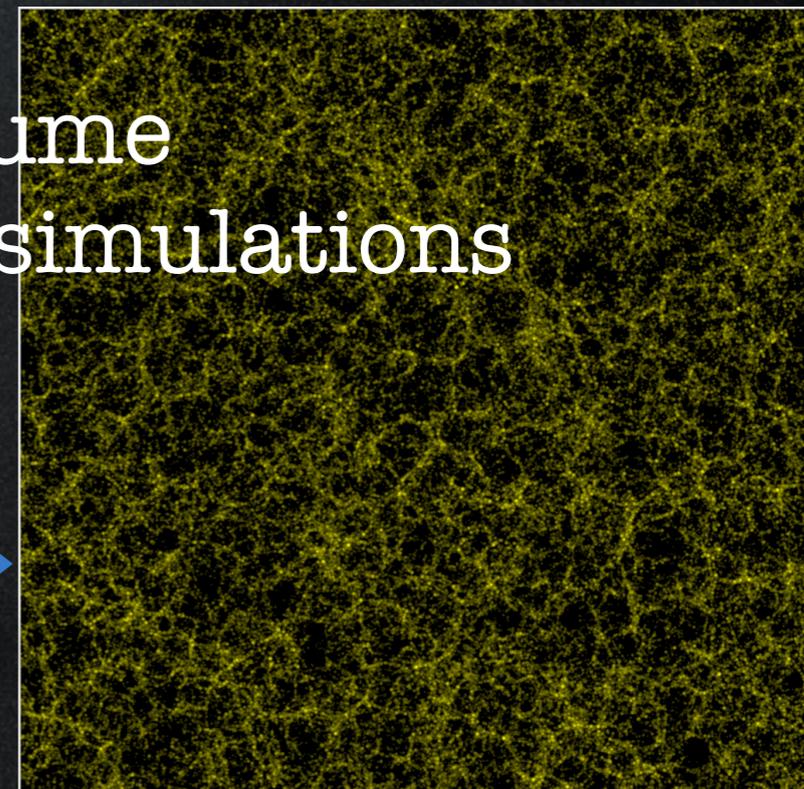
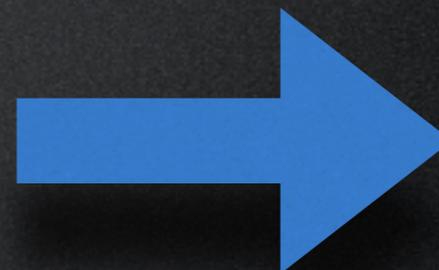
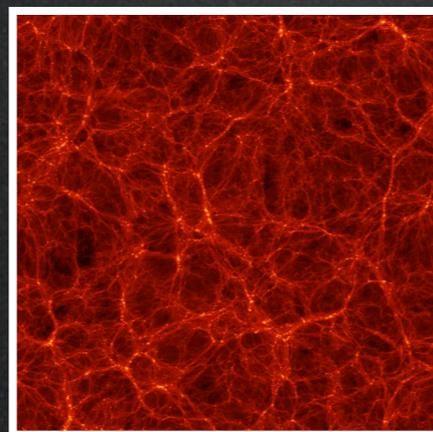
Interplay between physical and empirical modeling approaches AND interplay between high fidelity and inexpensive approaches is essential.

- Current hydro simulations are not accurate, flexible, or fast enough to be used for direct modeling of full galaxy surveys.
- Current empirical models are missing key correlations and some important galaxy properties; need to test them with more physical models.
- Galaxies probably do all live in dark matter halos! But those halos are not always properly resolved in dark matter simulations; can be modified or destroyed by baryons...

Interplay between approaches



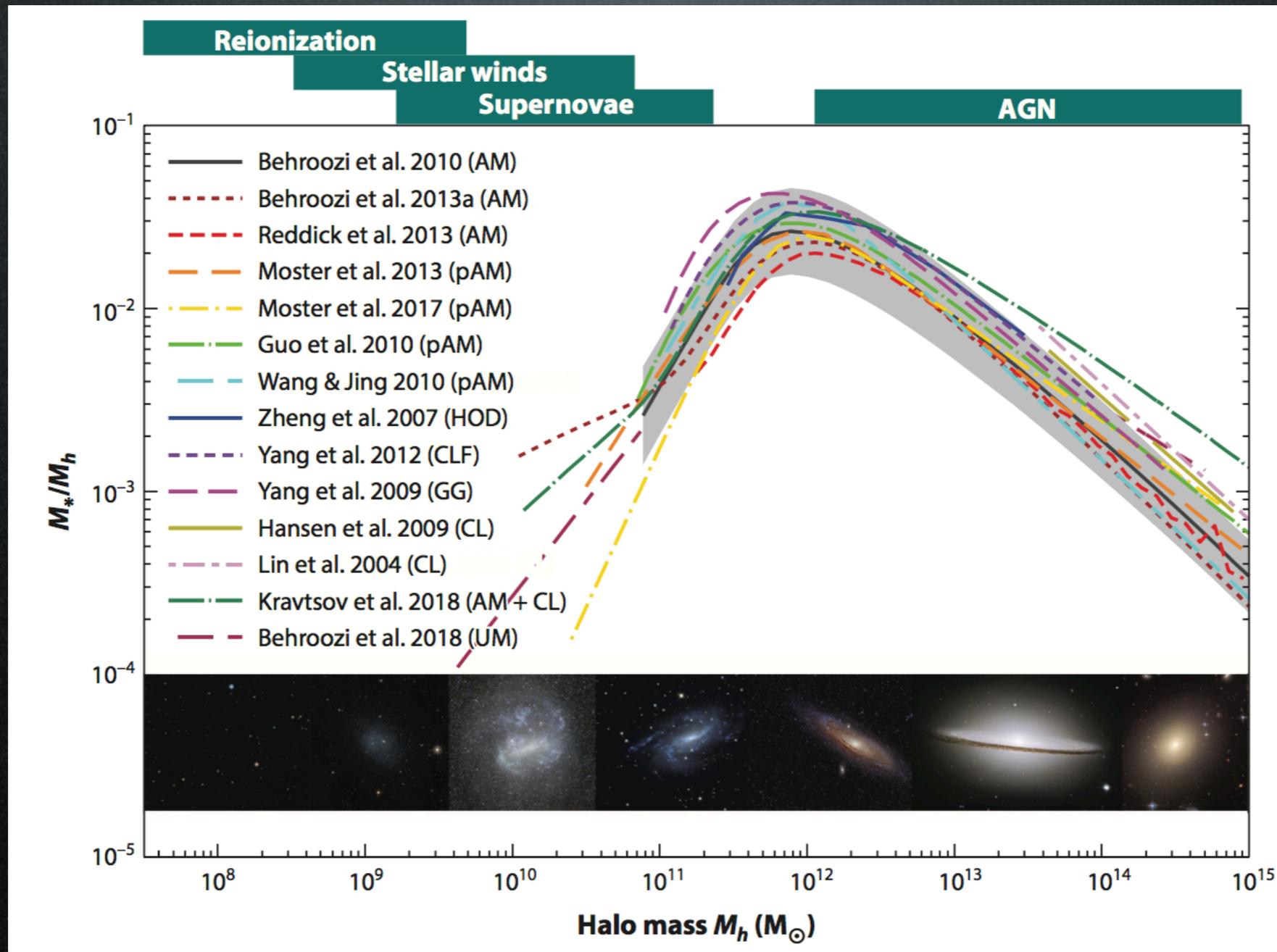
- Test simple parameterizations against best hydro simulations and semi-analytic models
- Test sensitive systematics on best models possible
- Train models on high-fidelity small volume simulations and apply to large volume simulations



What have we learned
about the galaxy-halo
connection?

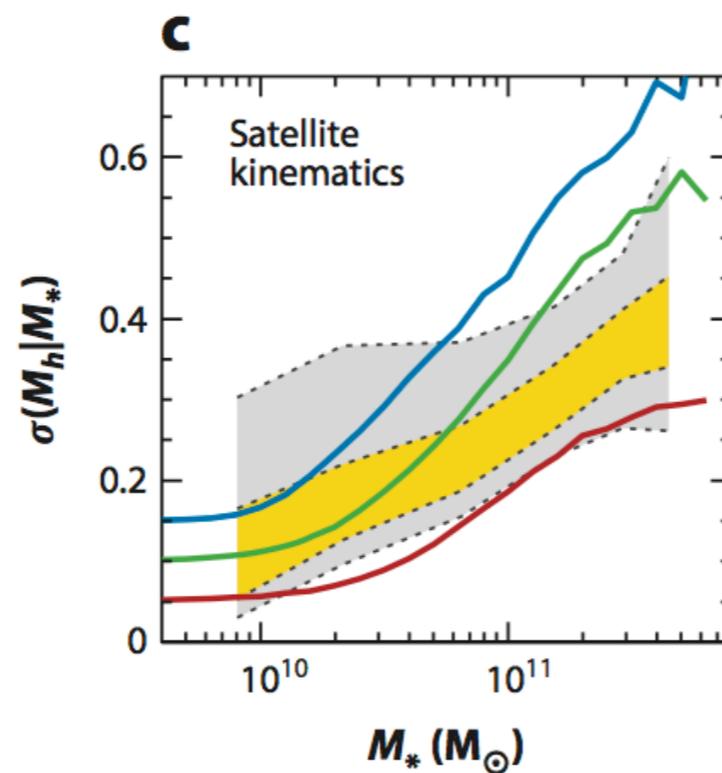
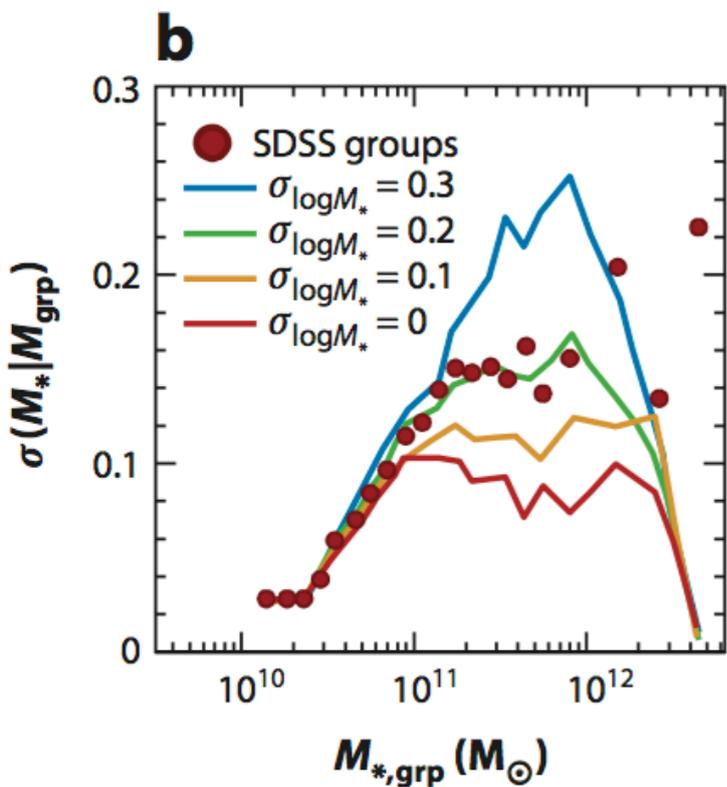
Galaxy formation is inefficient; feedback is important.

fraction of mass in stars



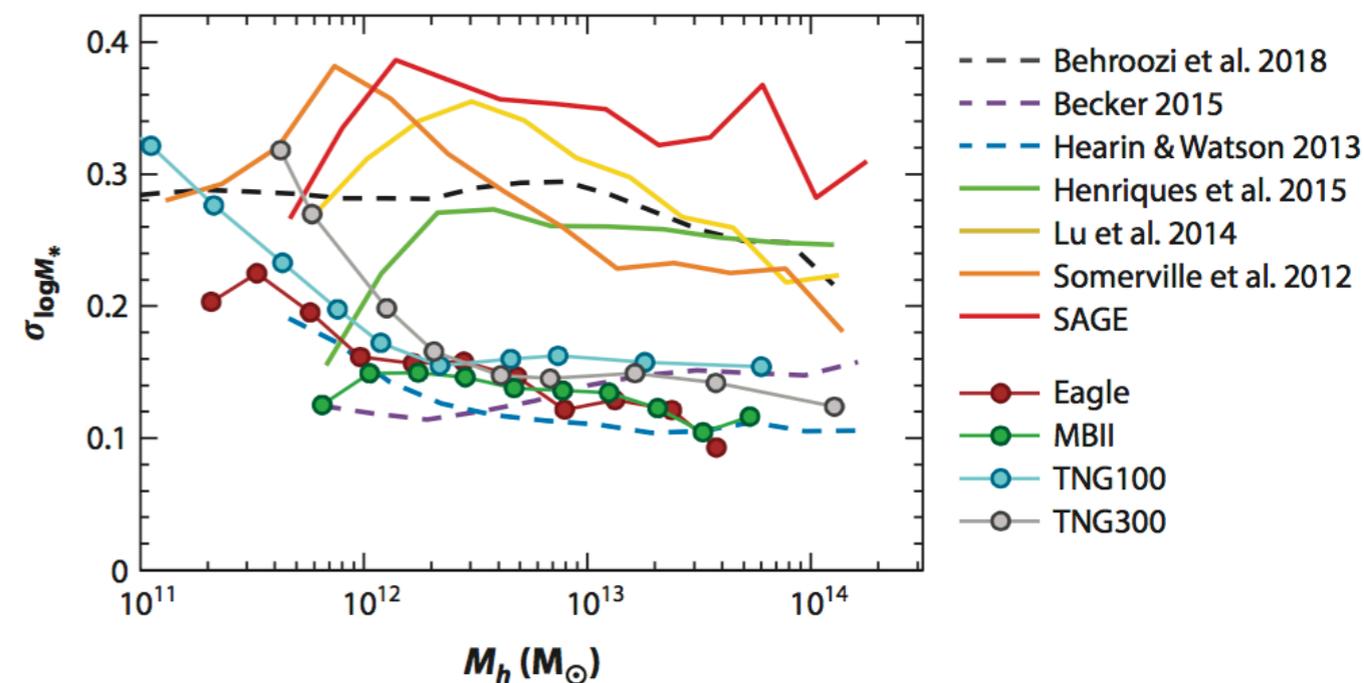
halo mass

Galaxy masses are tightly connected to the masses of their dark matter halos

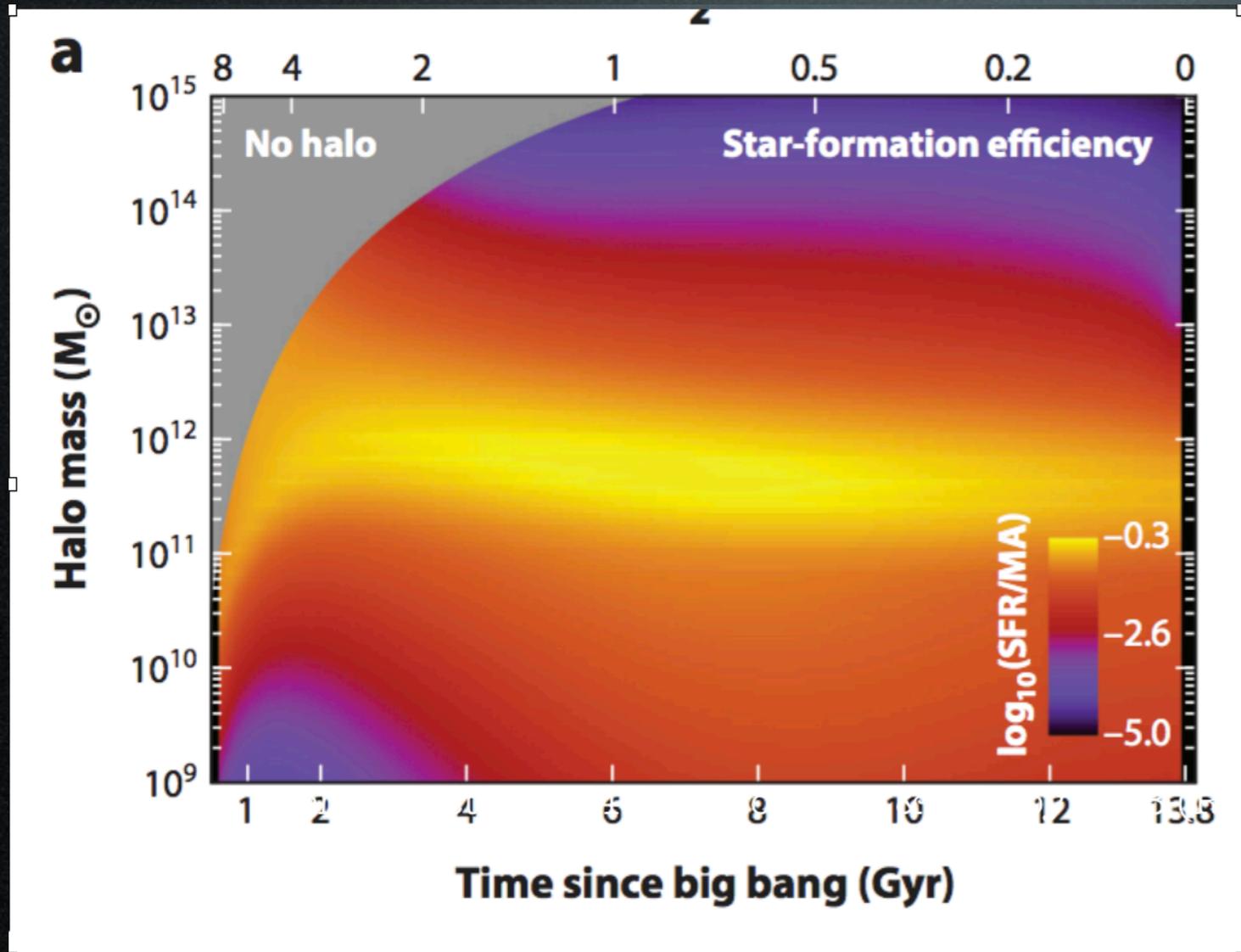


Scatter in stellar mass at a given halo mass is small. ~ 0.2 dex at high mass; probably still < 0.3 dex at small mass

Scatter is larger in current semi-analytic models than in current hydrodynamical simulations...



Most stars in the Universe form in a small range of halo mass, around the mass of the Milky Way



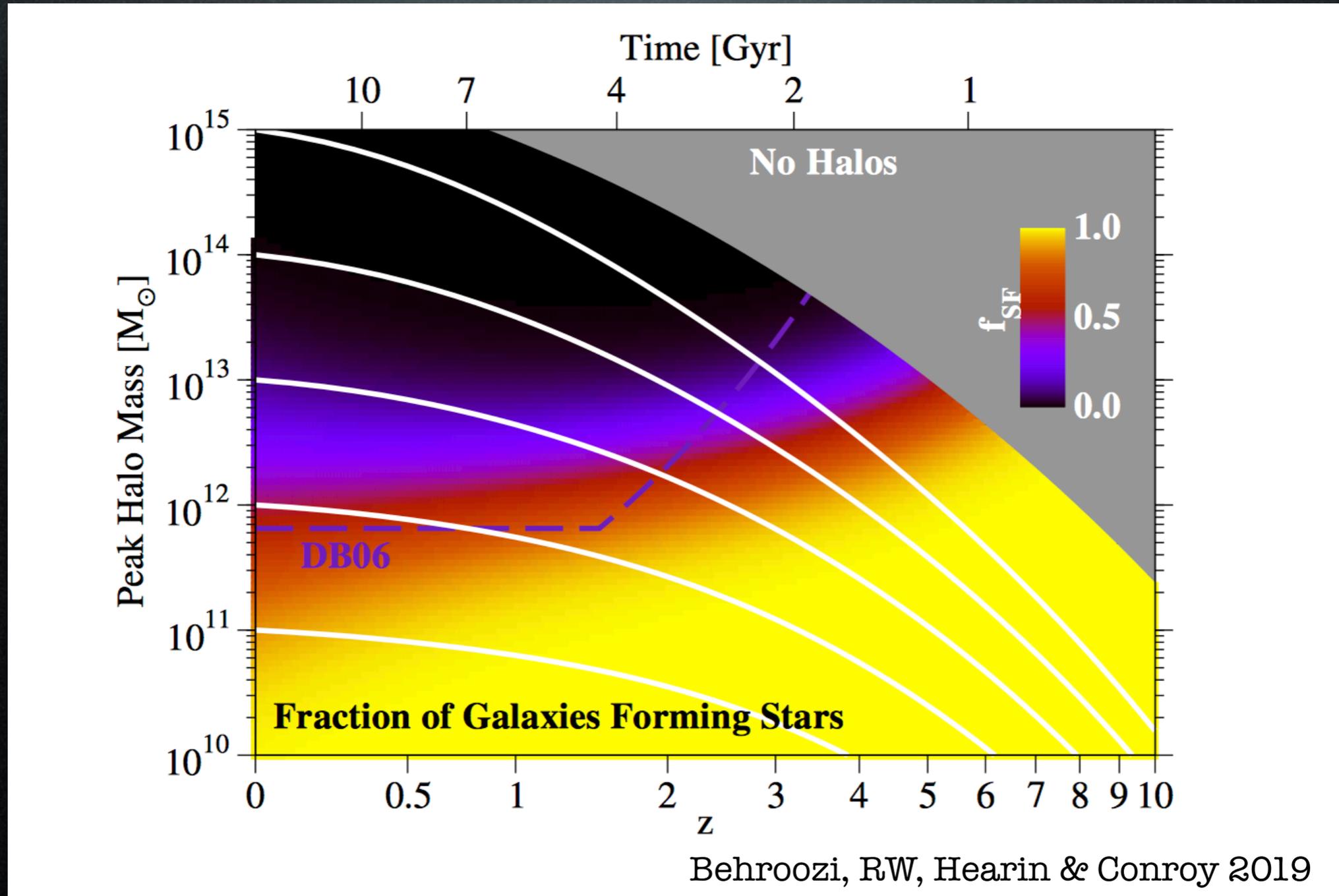
- Efficiency of forming stars given incoming gas is roughly constant over 10 billion years.
- Decline in star formation rate due primarily to decline in mass accretion onto halos

Behroozi, Conroy & RW 2014; Behroozi, RW, Hearin & Conroy 2019; RW & Tinker, ARAA 2018

massive galaxies: start forming early, peaked at $z \sim 2-4$, then quenched. halo growth continues after galaxy growth slows.

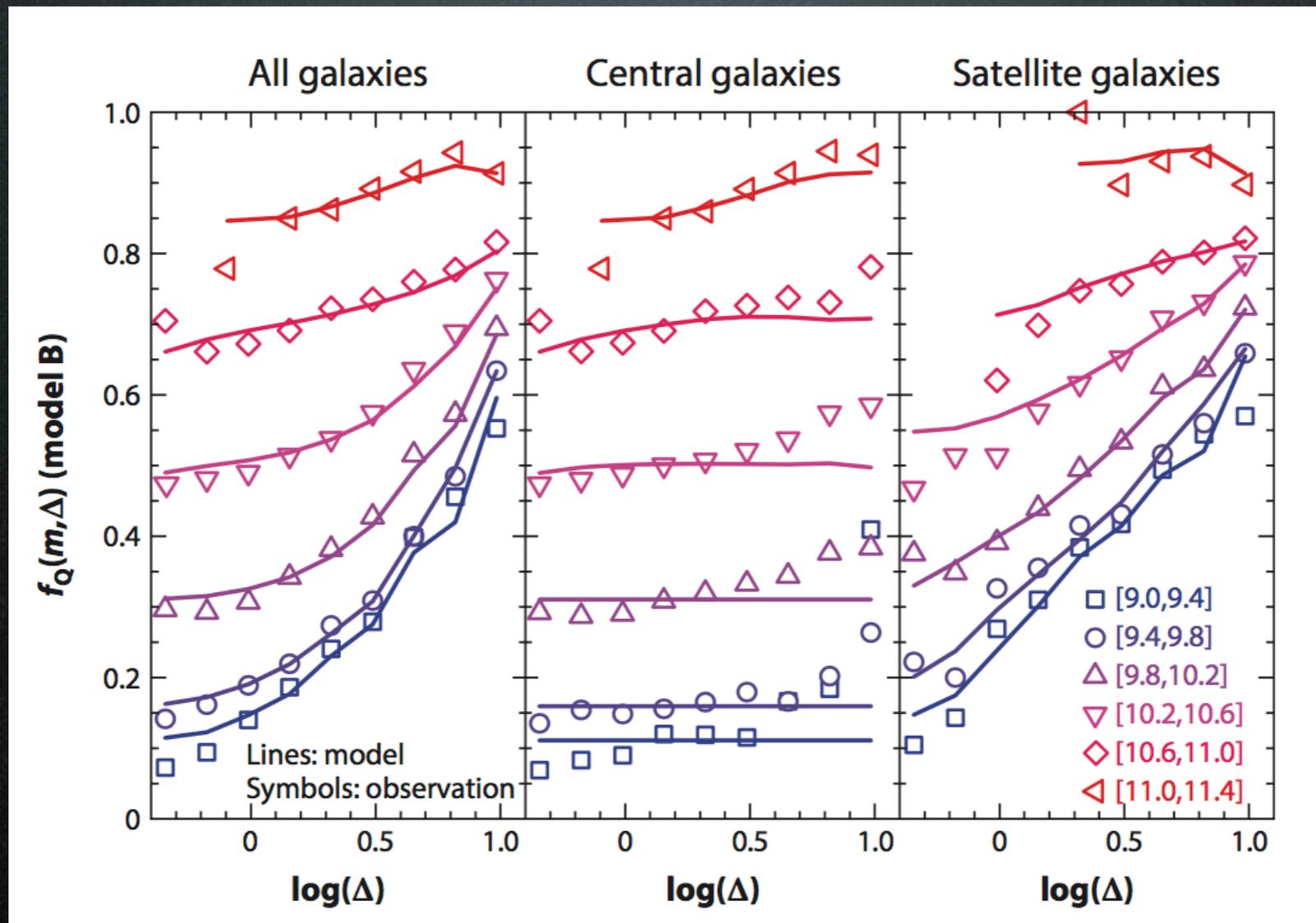
low mass galaxies: extended star formation histories, start later and continue longer at a low rate.

Quenched fraction is a strong function of mass



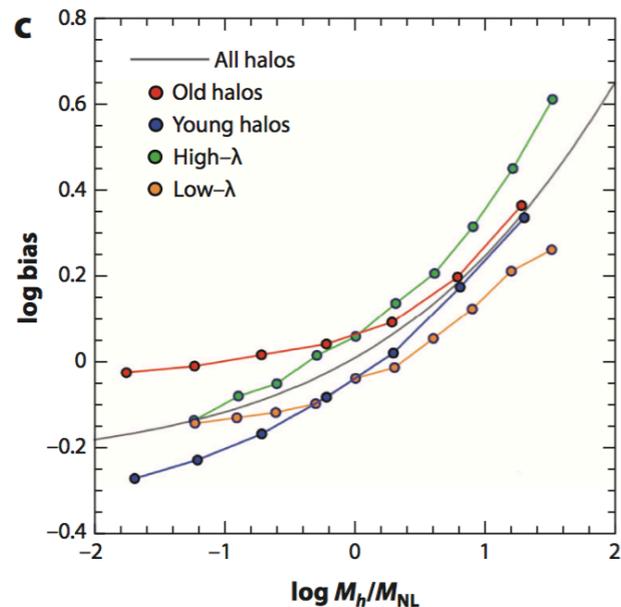
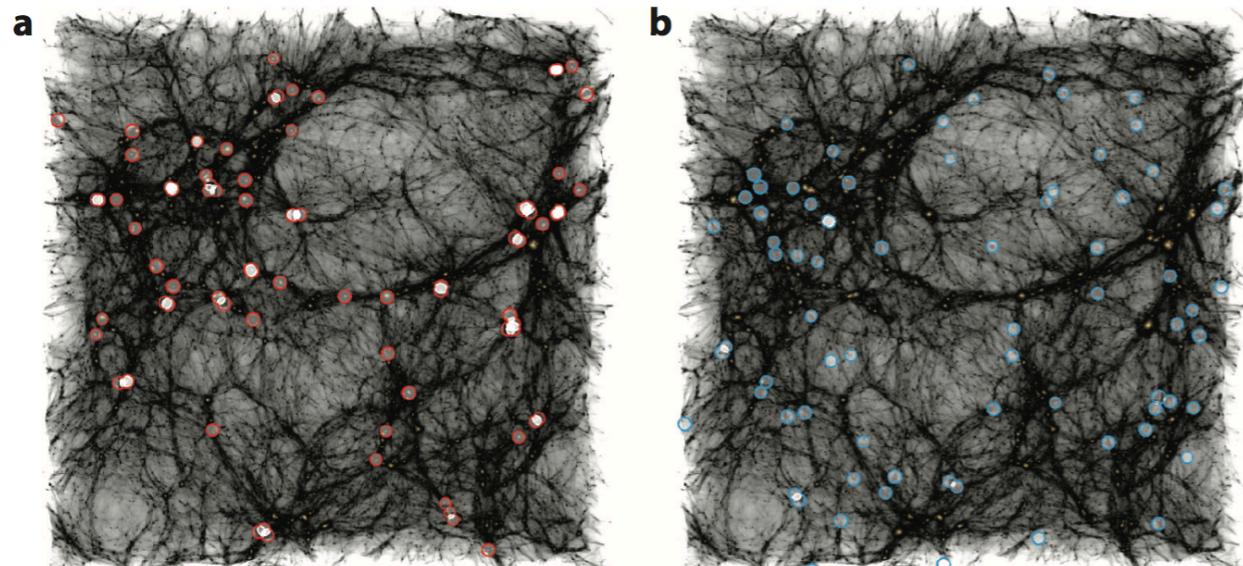
fraction of galaxies that are quenched increases rapidly with time at a fixed number density, but is not a strong function of time at fixed halo mass

Quenched fraction changes with environment and central / satellite identity

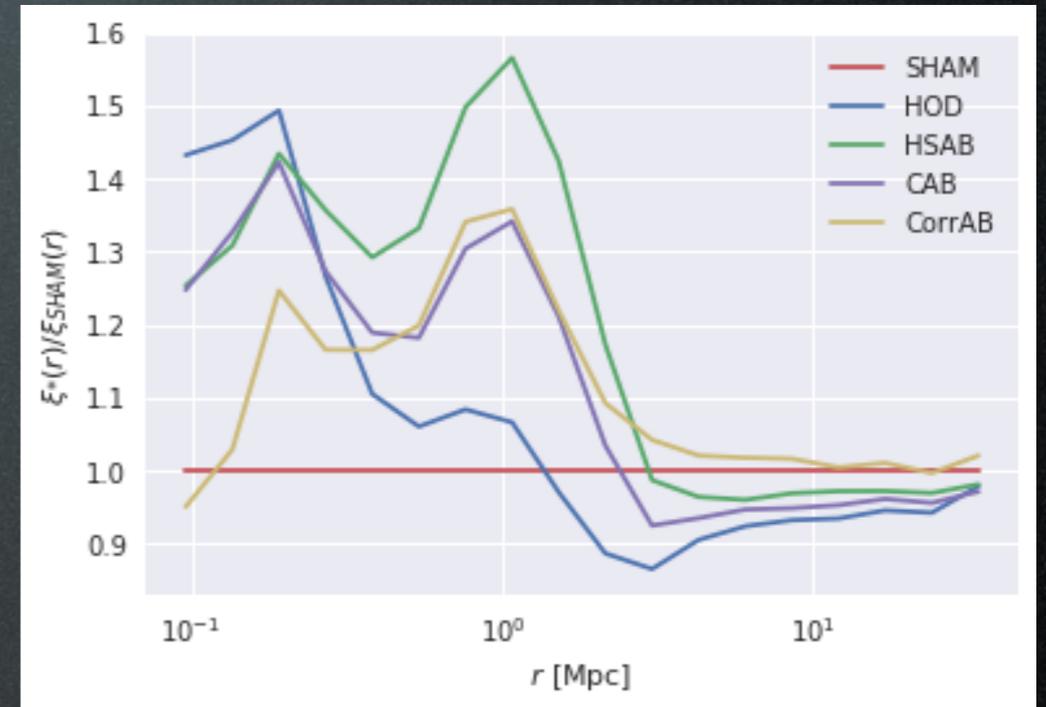


But this can mostly be explained by quenching that is just a function of halo mass and how long something has been a satellite...

Halo mass is not enough (Assembly bias)



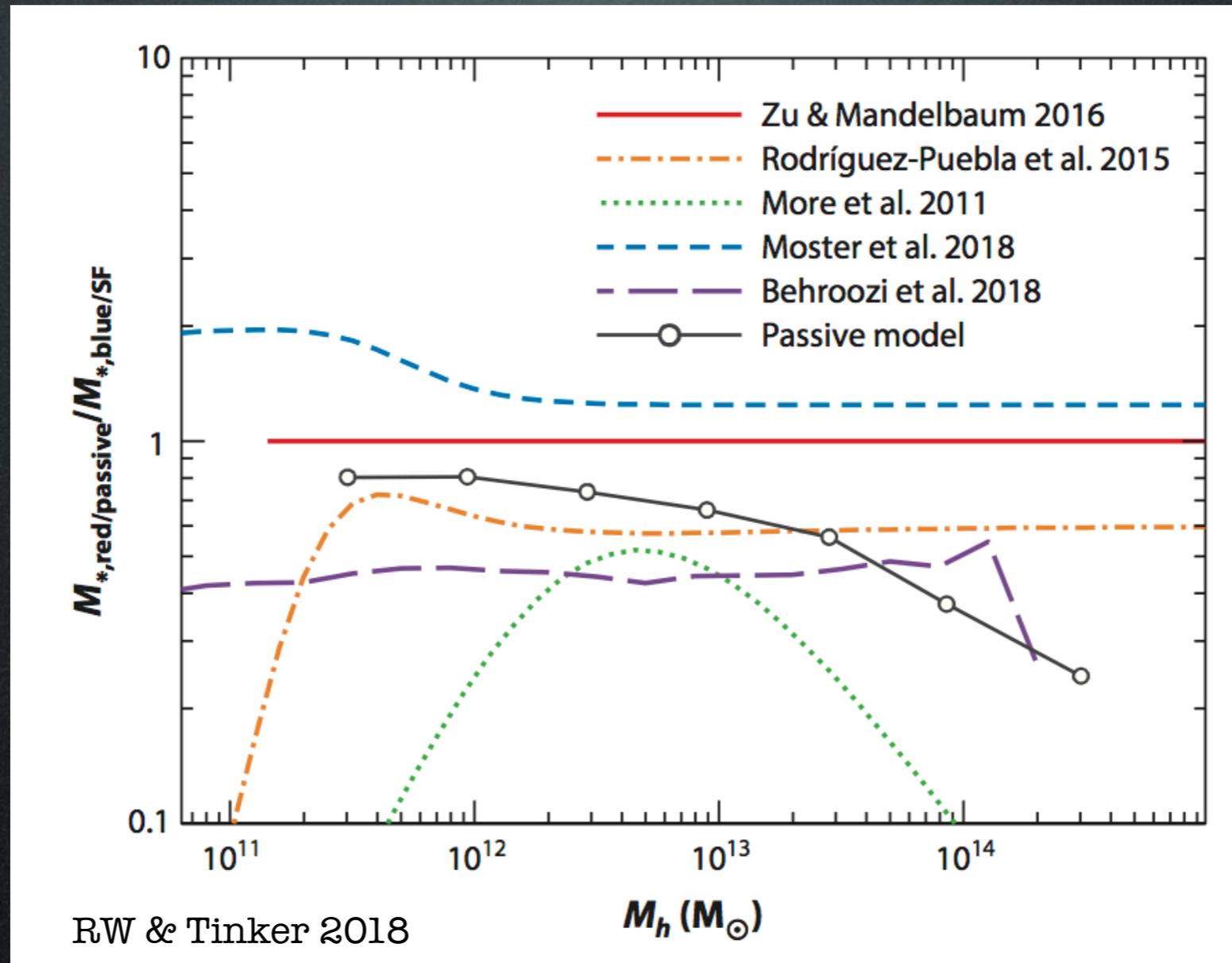
McLaughlin et al in prep



Fitting for assembly bias is not straightforward, and may increasingly matter in cosmological modeling...

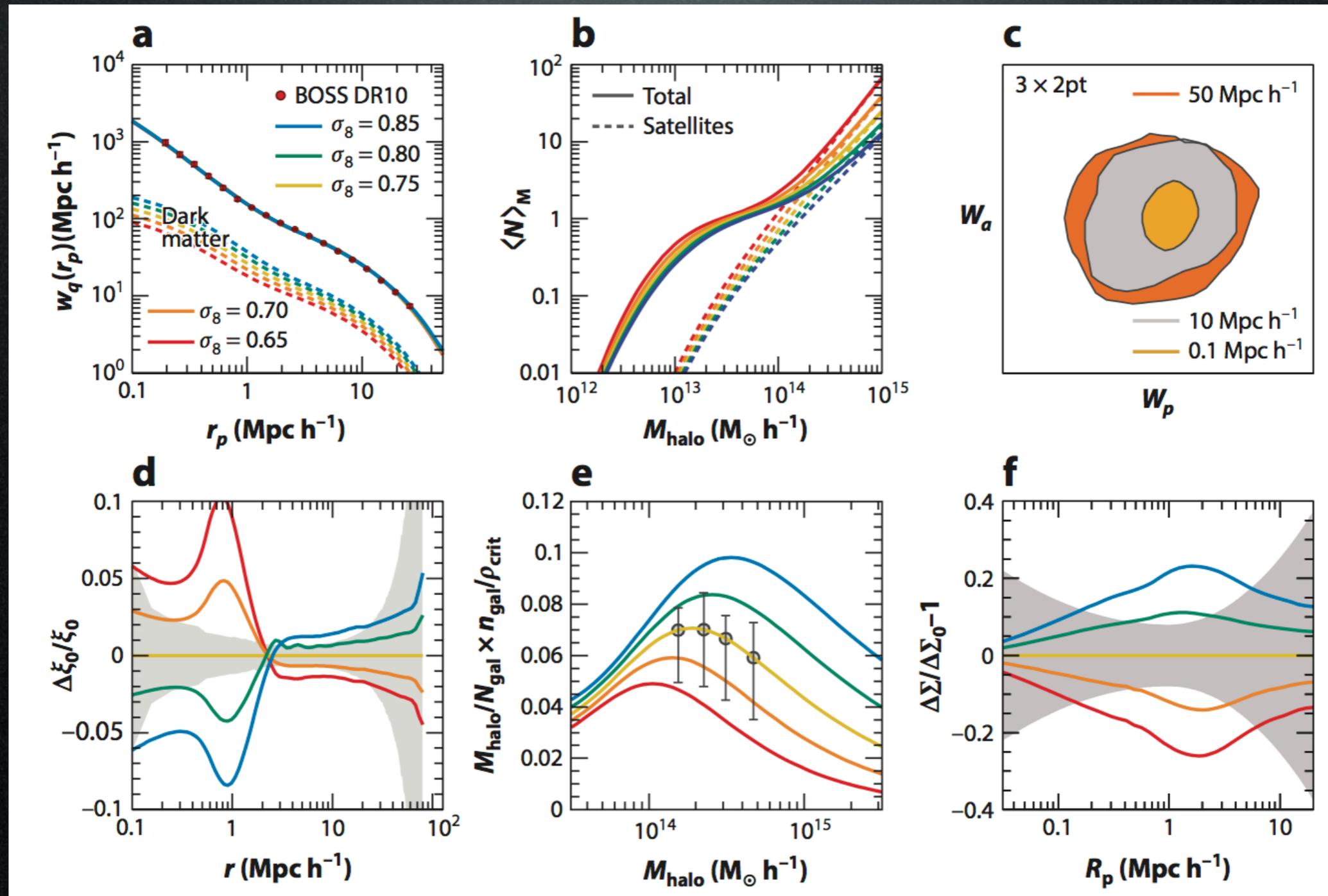
Wechsler 2001; Gao et al 2005; Wechsler et al 2006;
 Gao et al 2007; Croton et al 2007; Dalal et al 2008;
 Zentner et al 2014; Mao et al 2018;
 Mansfield & Kravtsov 2019
 many more...Plot from Wechsler & Tinker 2018;

Still uncertainty in some basics!

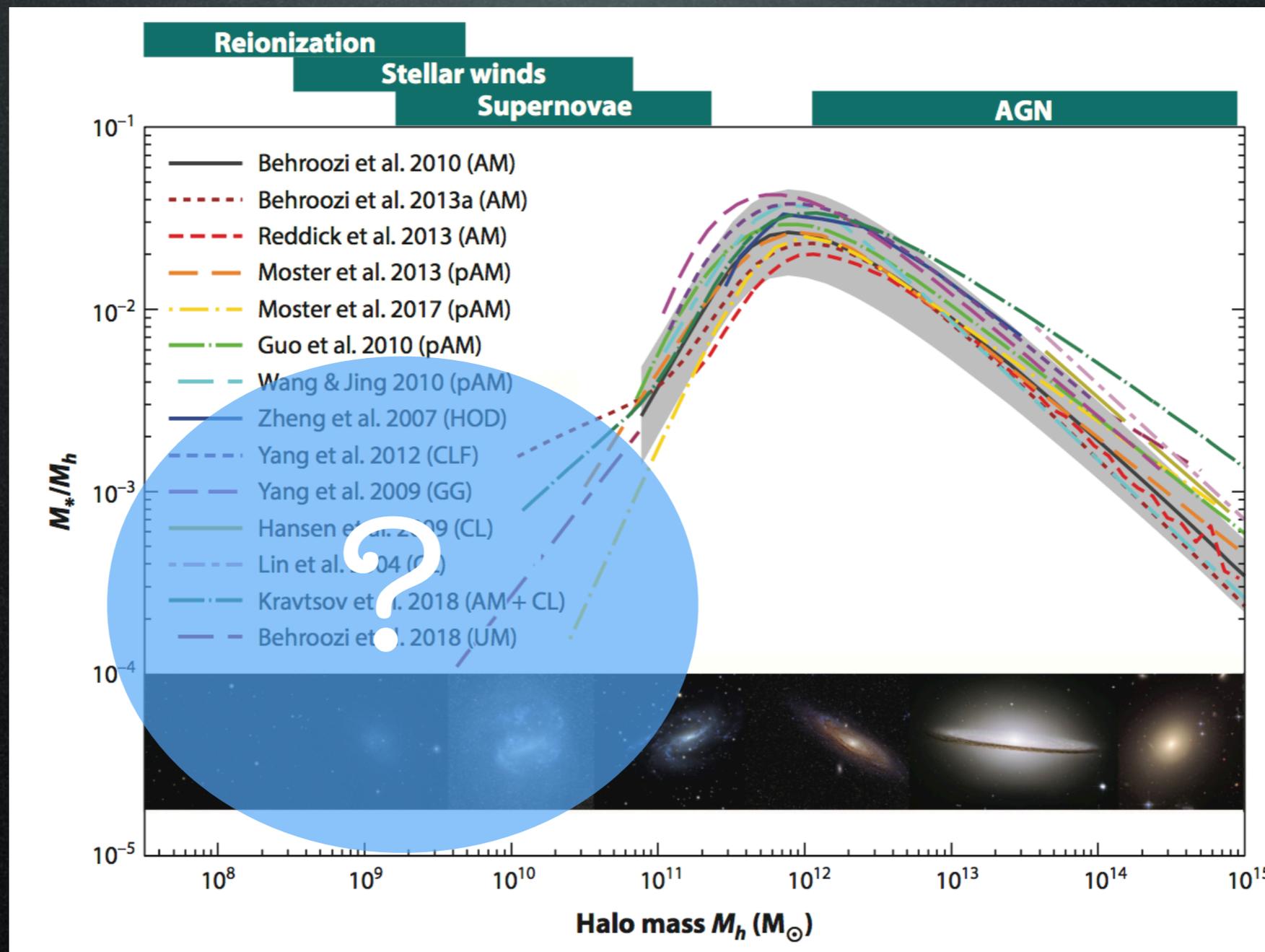


At a given halo mass,
are red or blue galaxies more massive?

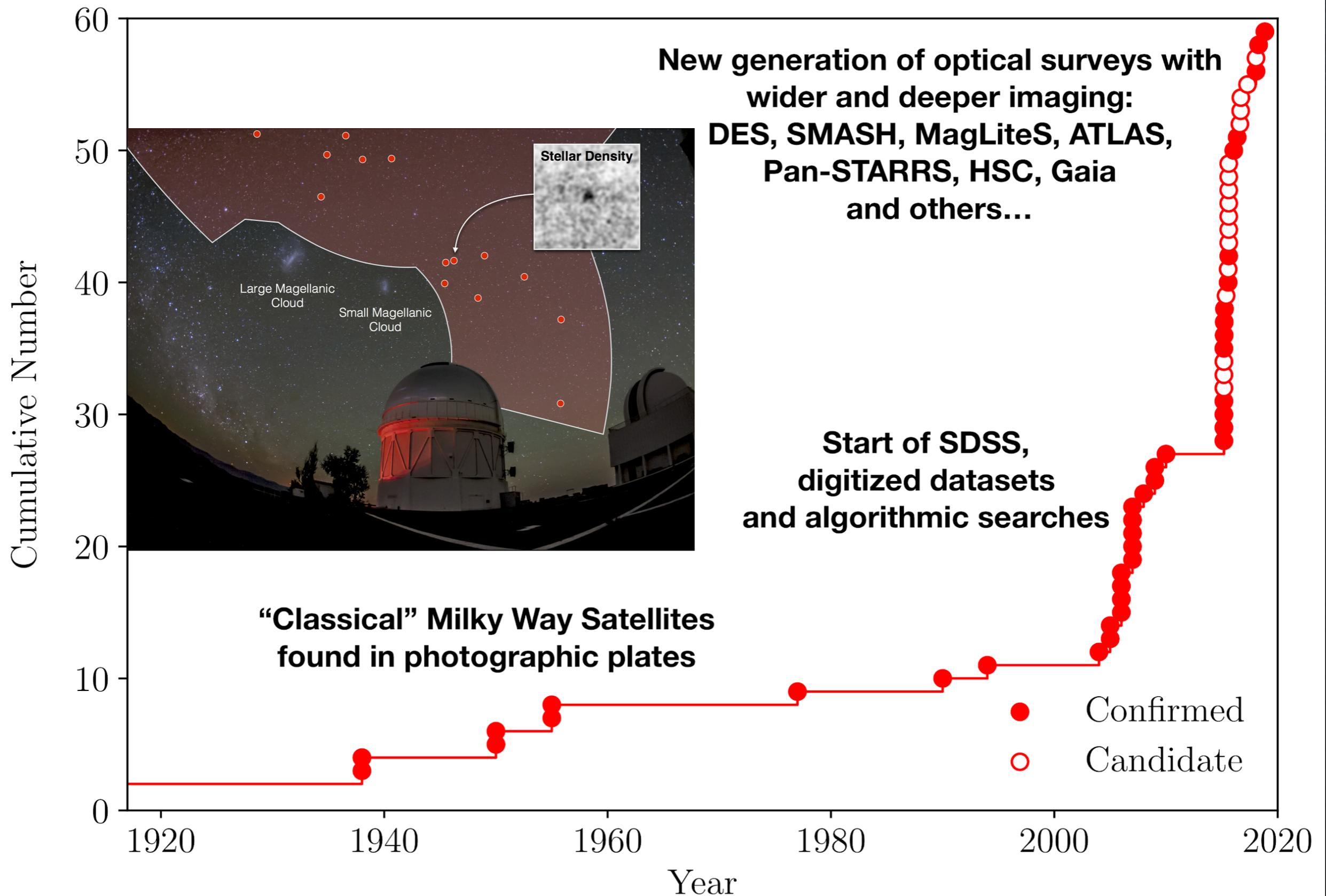
Modeling small scales can be very powerful...requires joint fitting of cosmology and halo occupation parameters



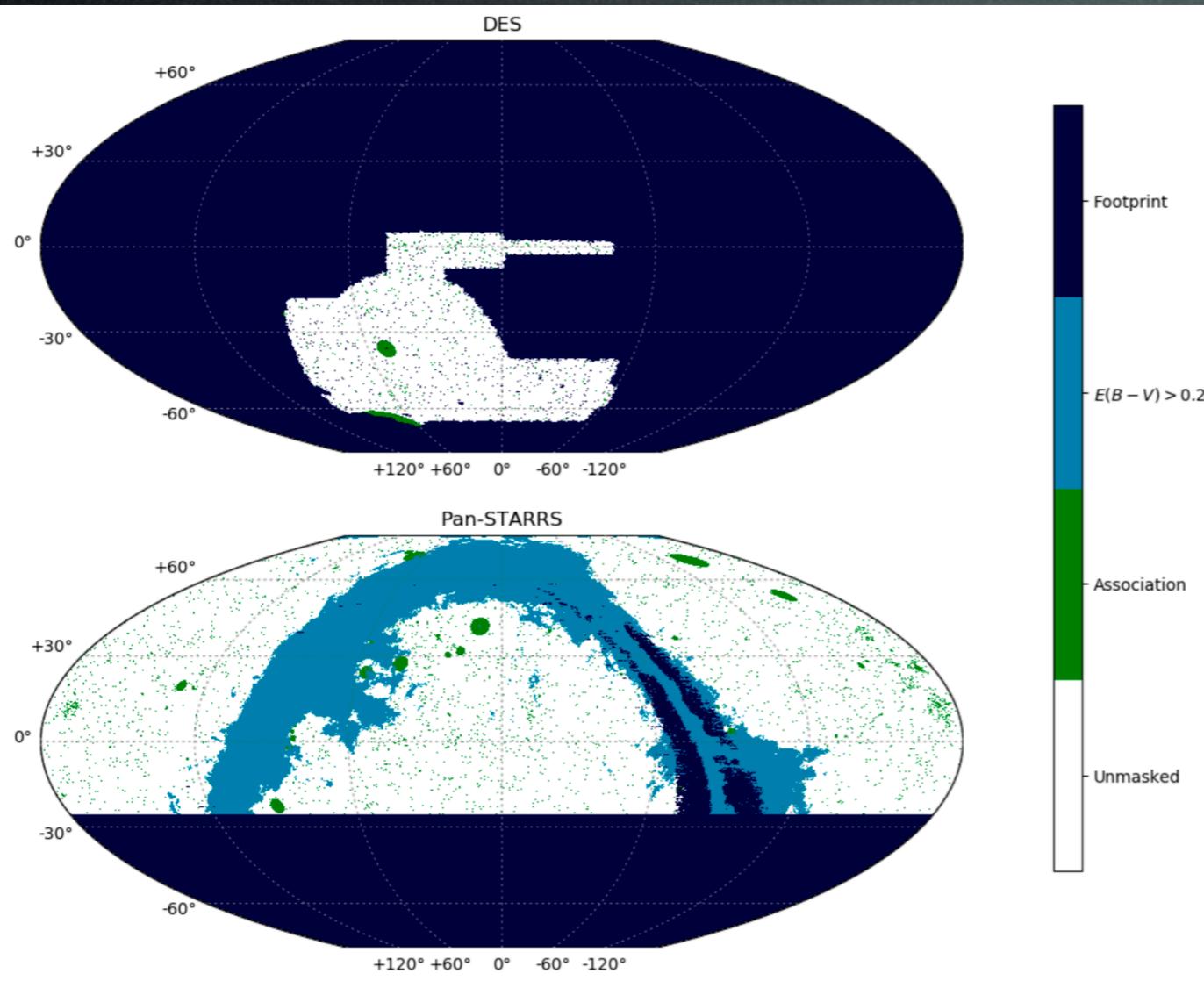
Galaxy-halo connection at the smallest masses



Discoveries in the Milky Way



New search of 3/4 of the sky using DES + PanSTARRS

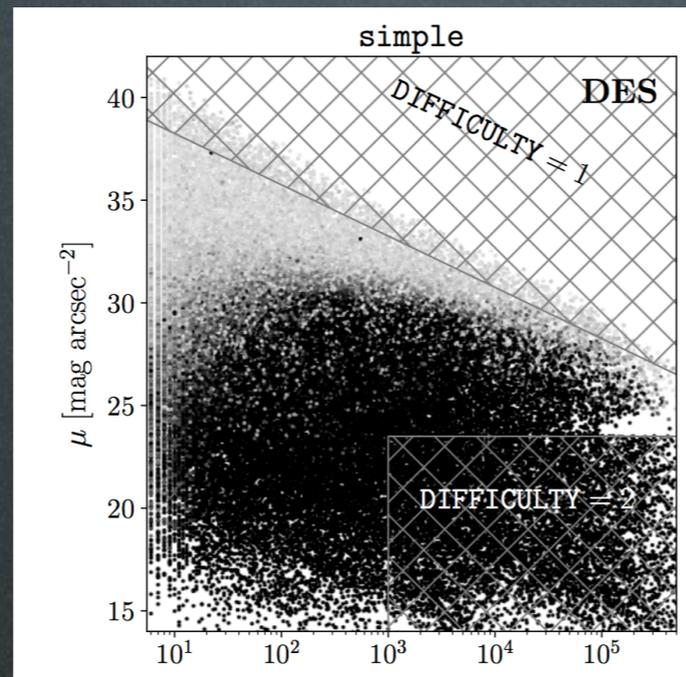


- Automated search using two independent algorithms
- Majority of statistically significant “hot spots” are concentrated in problematic regions of the survey (e.g., high dust extinction, bright stars and galaxies).
- Apply a geometric mask based on reddening maps and external catalogs.
- Recover vast majority of known satellites with an automated pipeline; **no new satellites detected**

17/19 known sats in DES footprint
21/31 known sats in PanSTARRS footprint
9 known sats outside these footprints

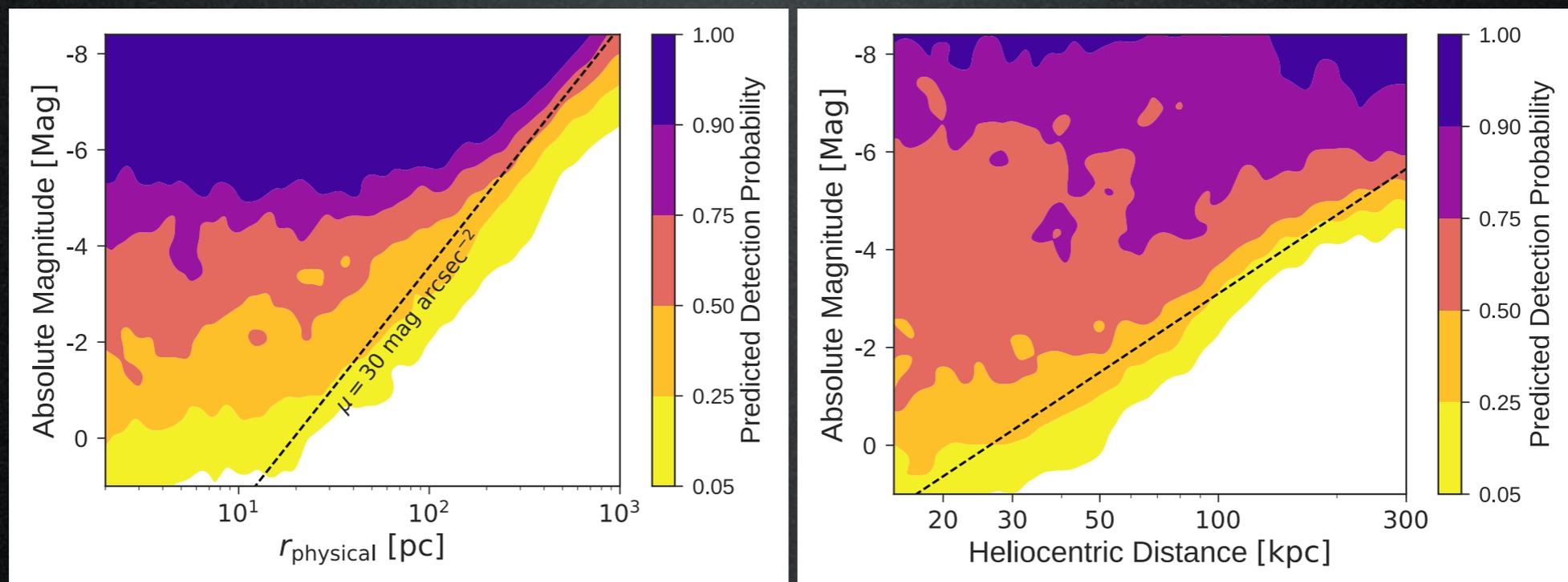
Observational Selection Function

Run two satellite search algorithms on stellar populations injected into survey data

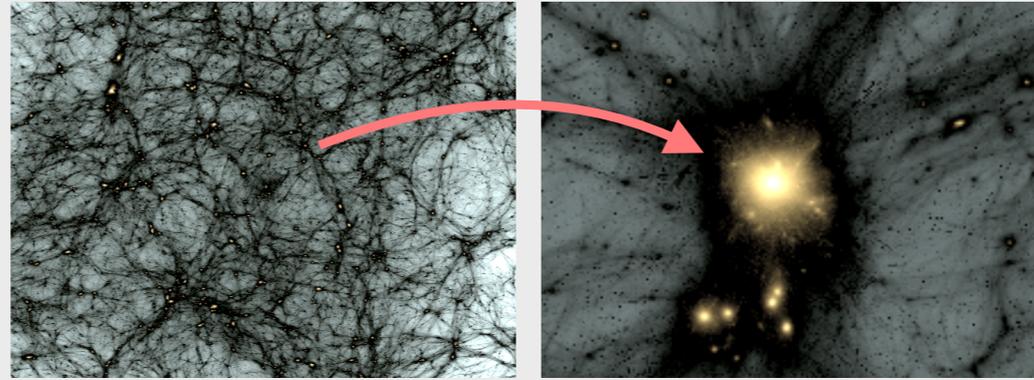


Number of bright stars and surface brightness are the most important properties.

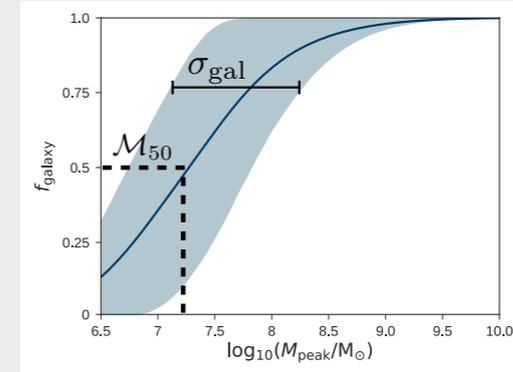
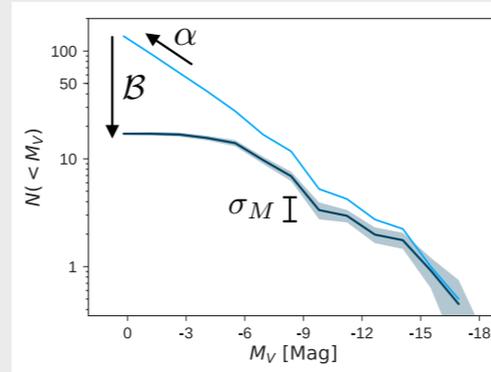
→ Project detection probability in physical parameter space



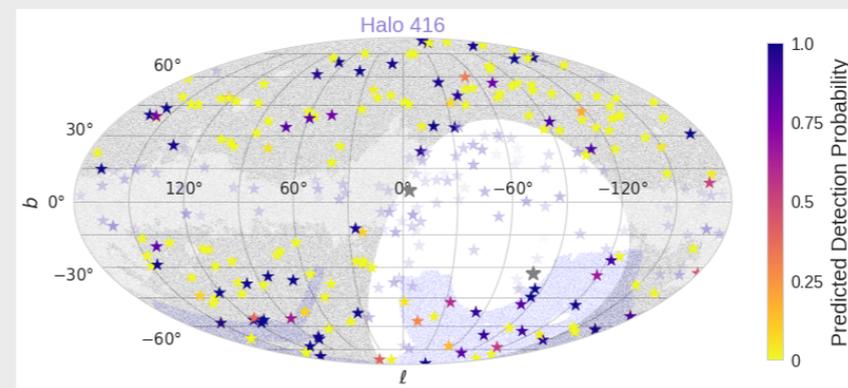
1. Resimulate Milky Way-like halos from large cosmological volume.



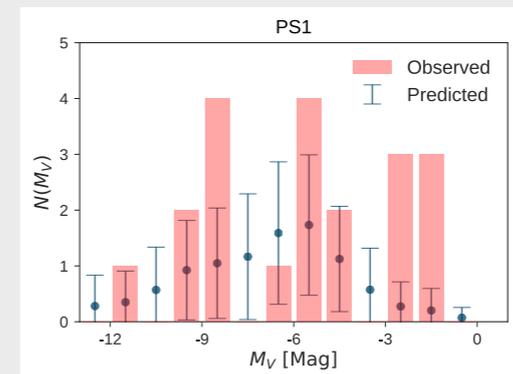
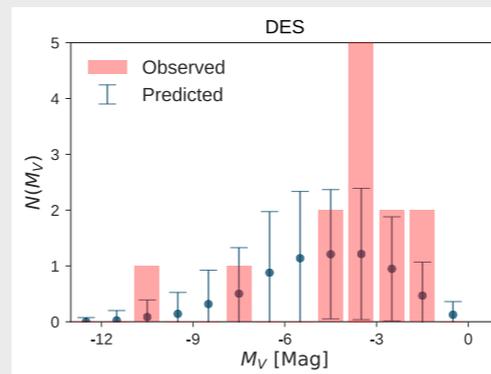
2. Paint satellite galaxies onto subhalos using galaxy-halo model.



3. Apply observational selection effects based on imaging data.

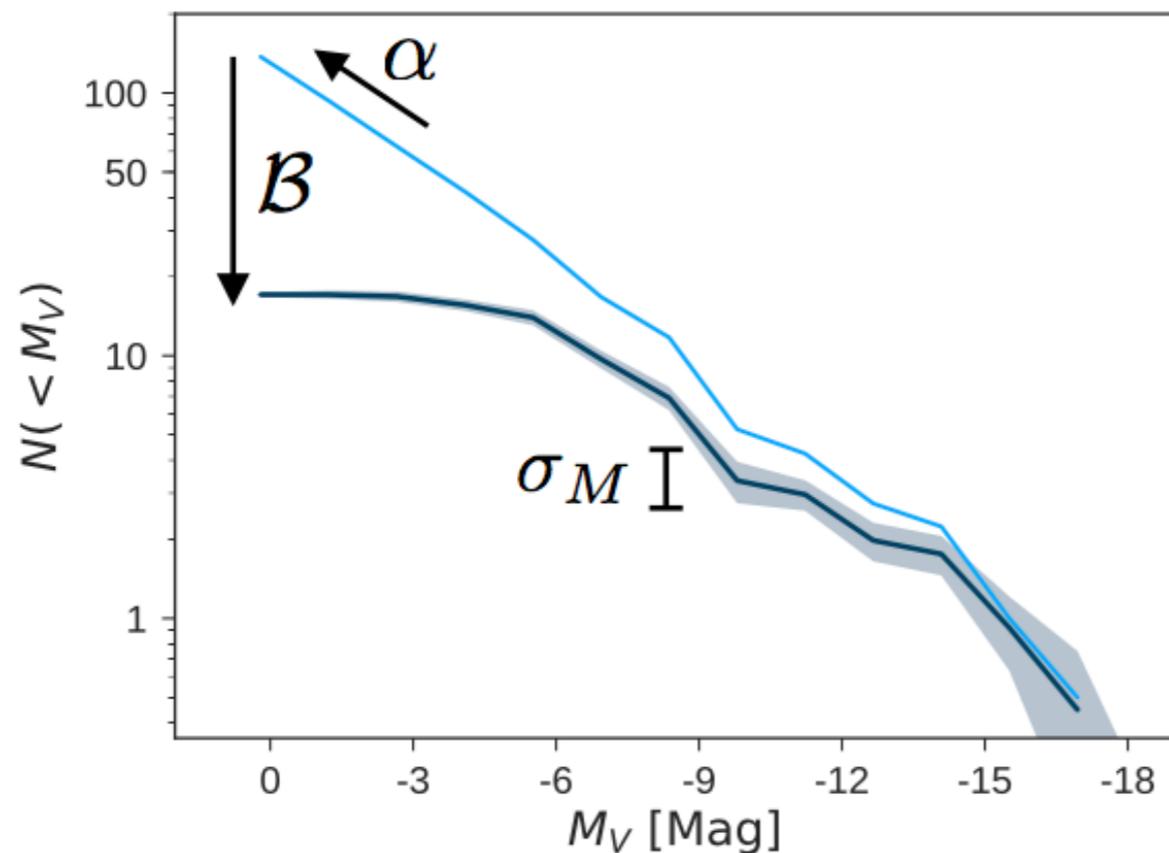


4. Calculate likelihood of observed satellites given galaxy-halo connection parameters.

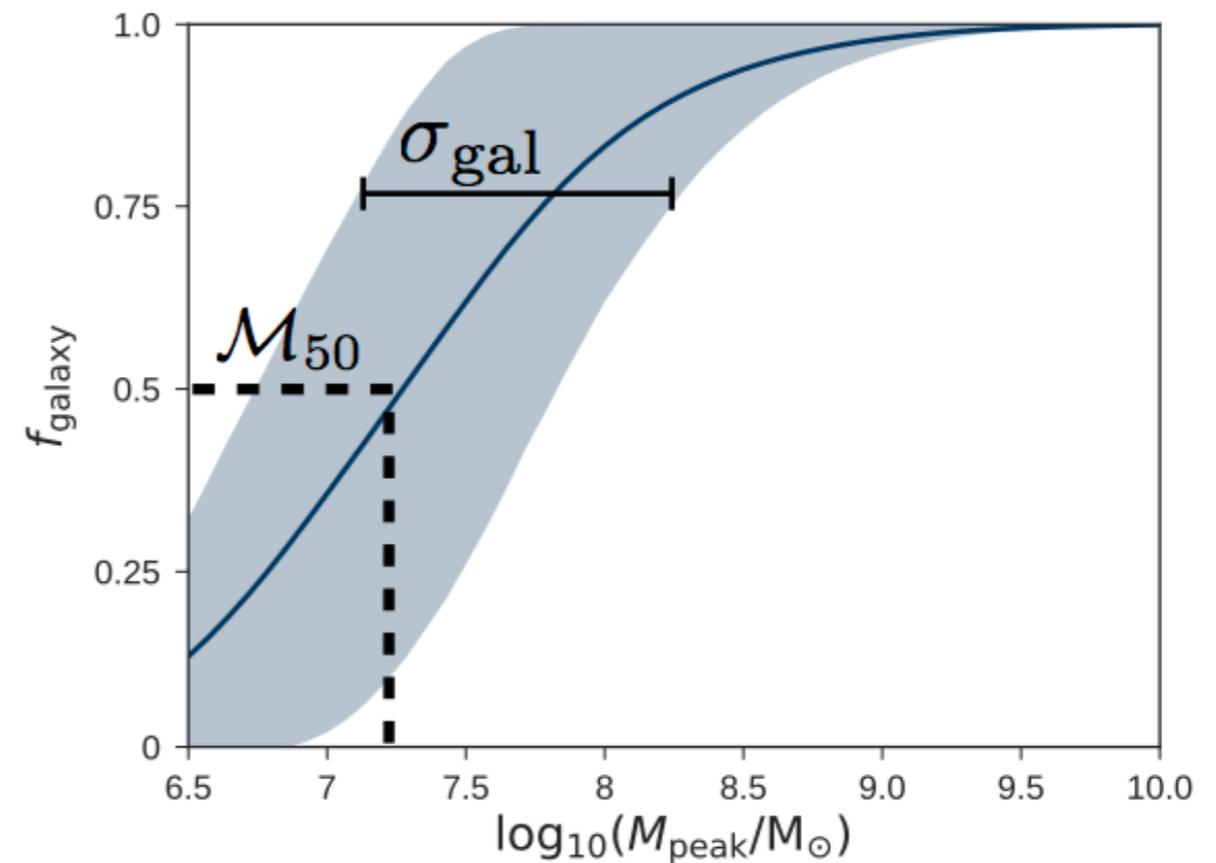


Satellite Galaxy-Subhalo Model

Satellite counts



Galaxy occupation

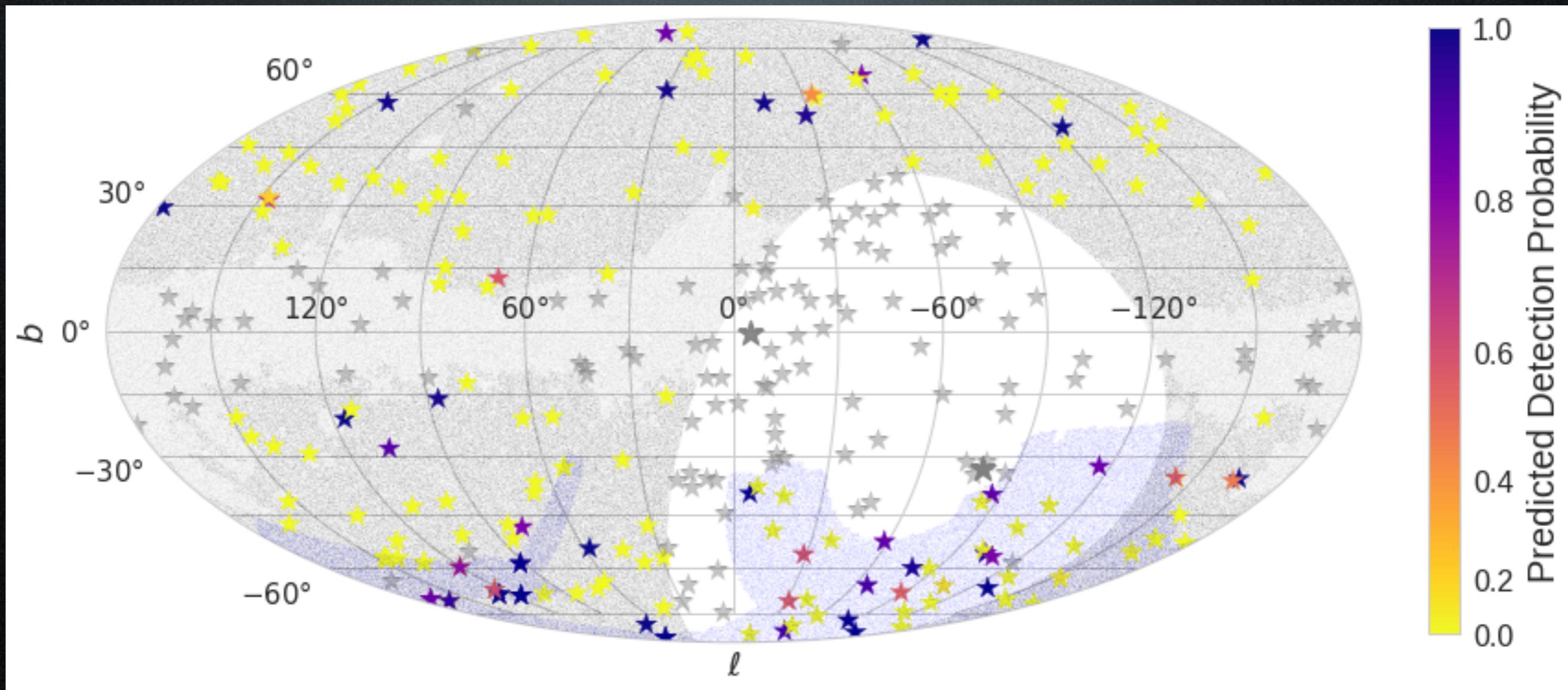


Here “galaxy” means anything brighter than $M_V=0$

Nadler, RW & the DES MW Working group in prep

See also Nadler et al 2019 for model details

Feed model through observational selection function

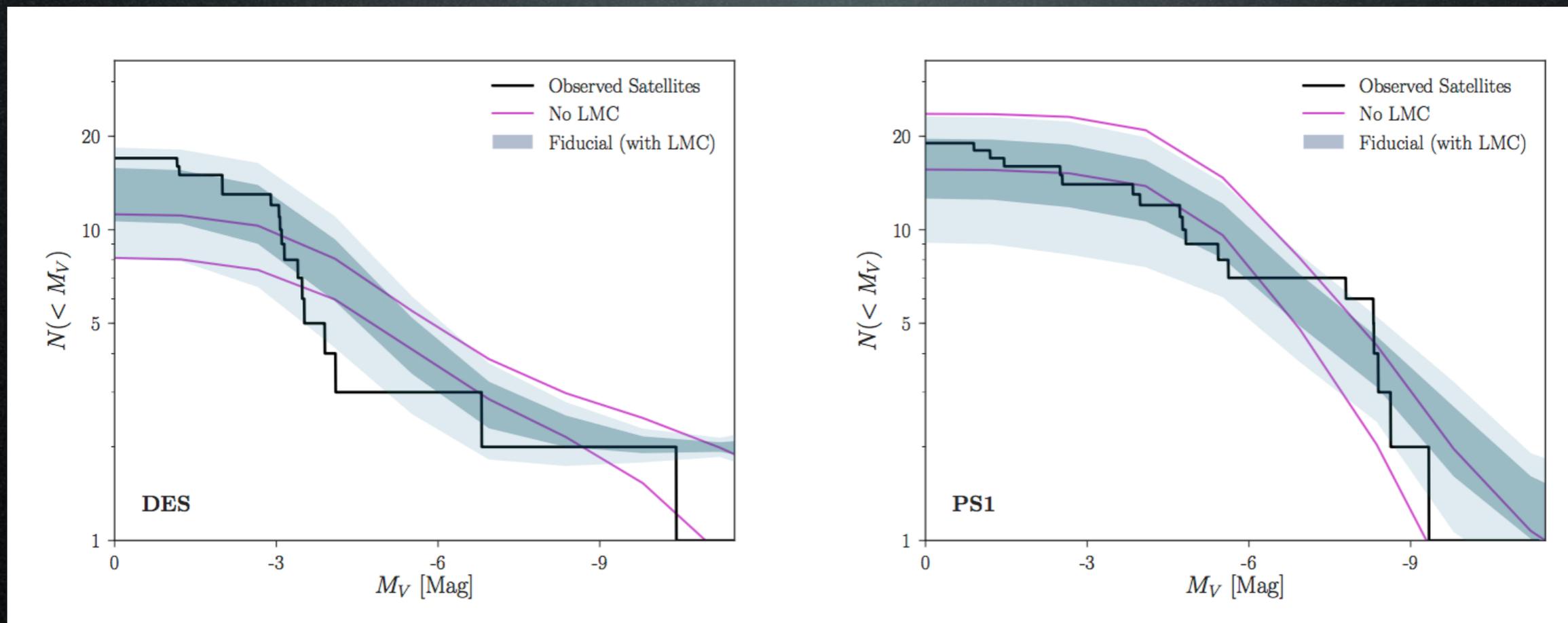


Selection function from DES + PanSTARRS

Presence of the LMC?

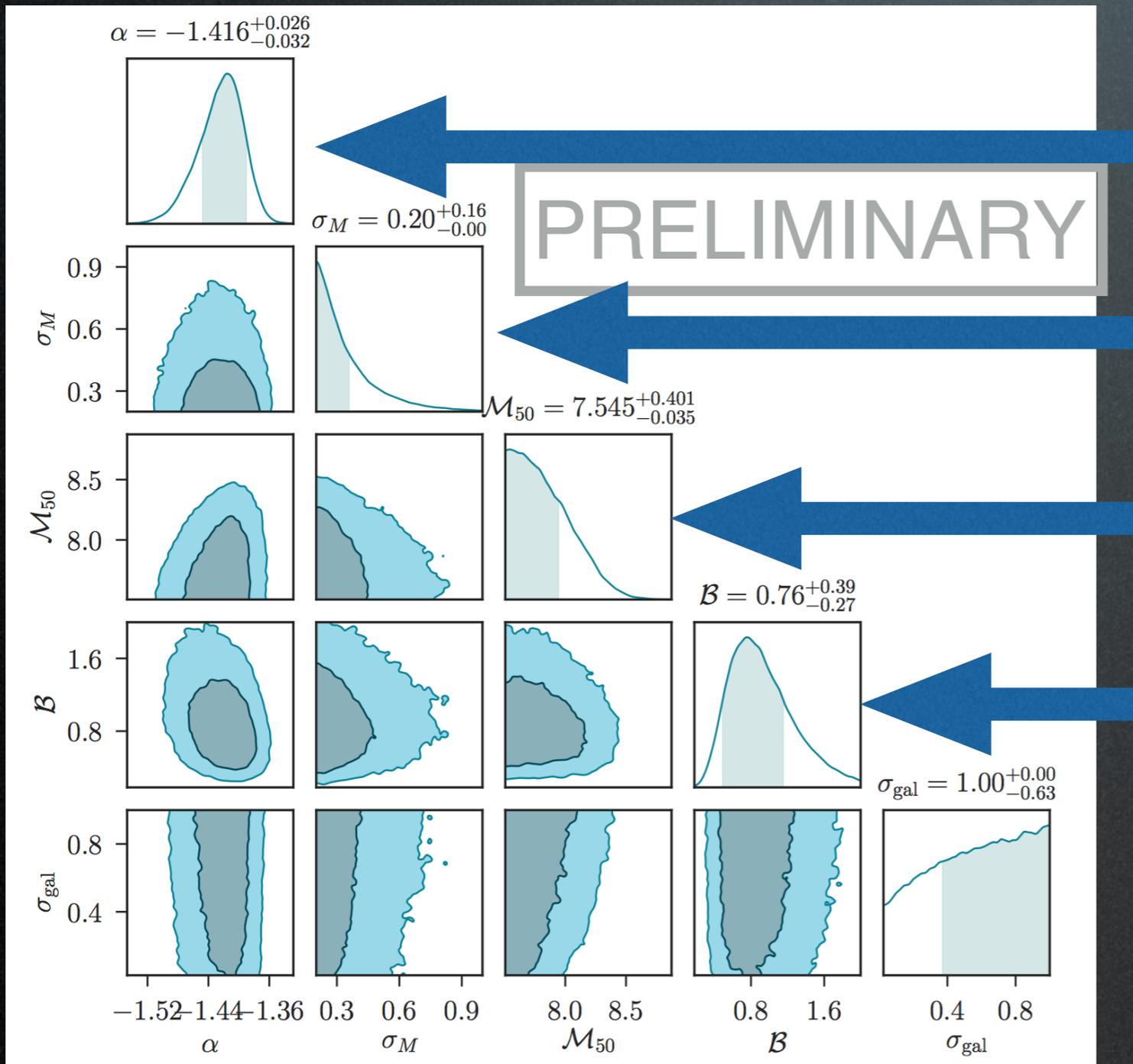
- Does the LMC matter for understanding the luminosity of MW satellites and the halos they inhabit?
- Here we consider two samples:
 - “LMC analogs”: two best fits to LMC.
 - ≥ 1 subhalos with $v_{\text{peak}} > 55$ km/s, $30 \text{ kpc} < d < 70 \text{ kpc}$
 - Accreted within 2 Gyr
 - “No LMC”: 4 hosts with same c distribution, no LMC

Observed satellite counts of DES vs. PanSTARRS



- Very difficult to explain anisotropy between DES and PS1 without LMC-associated satellites
- Predict 8 ± 2 (out of 39) observed DES (6) + PS1 (2) satellites to be LMC-associated.

Luminosity Function and Minimum Halo Mass



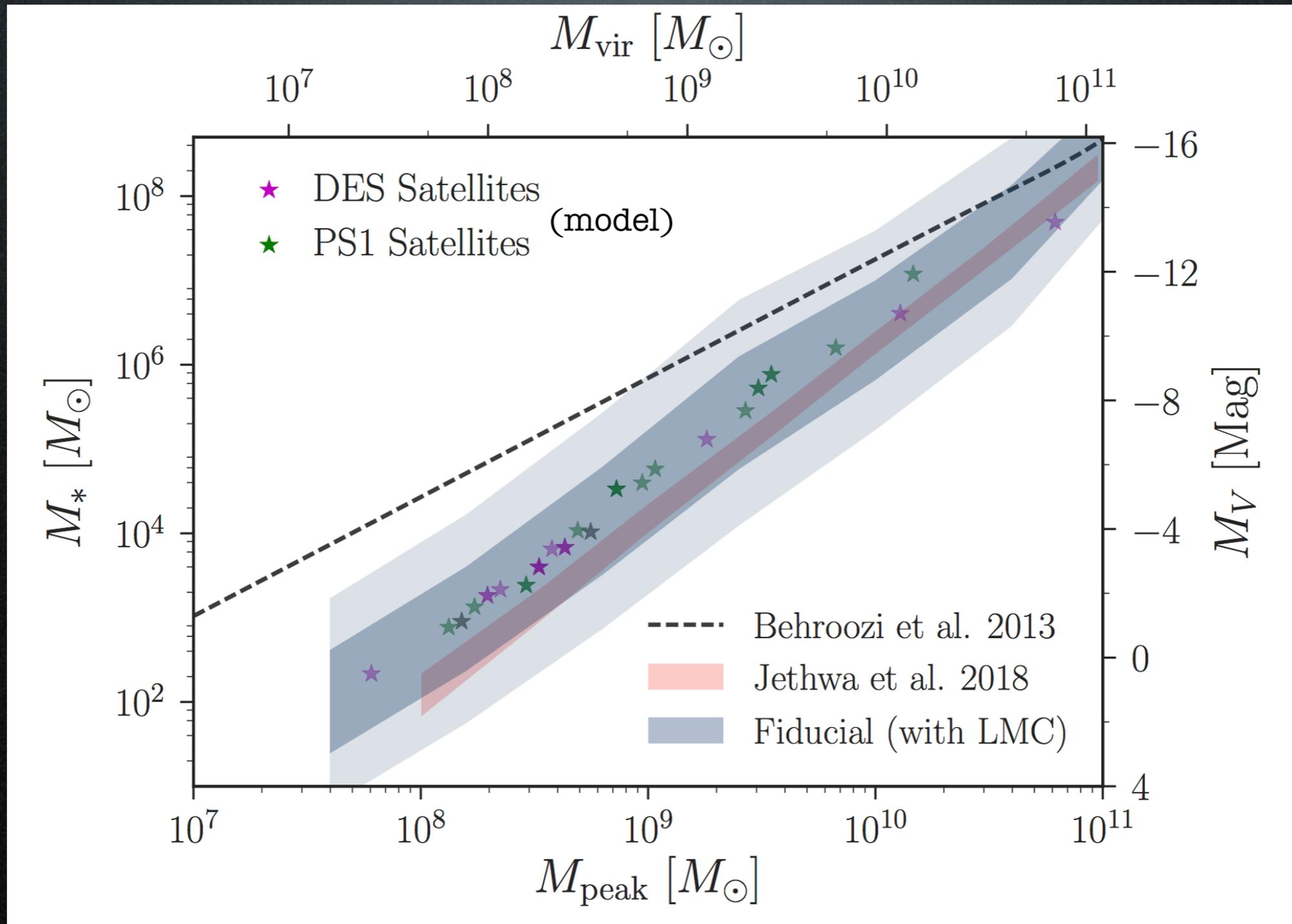
Faint end slope: consistent with global LF

Galaxy-halo scatter: consistent with massive systems

M_{50} , mass at which 50% of halos are occupied: 95% upper limit = $2 \times 10^8 M_{\text{sun}}$

Impact of baryons: no impact ruled out, consistent w destruction tuned to FIRE simulations

Galaxy-halo connection

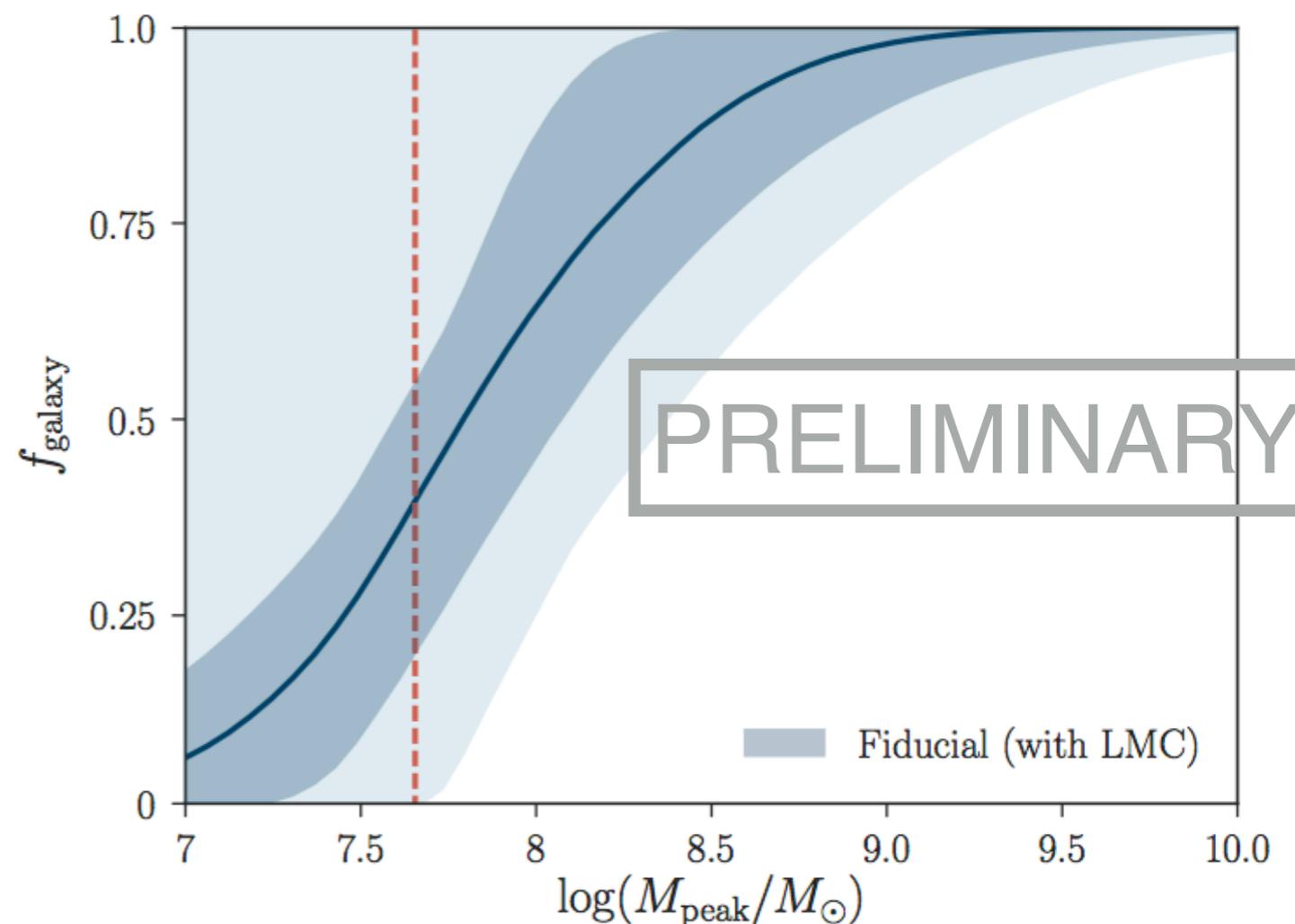


What is the smallest mass that can form a galaxy?

“galaxy” defined as $Mv < 0$

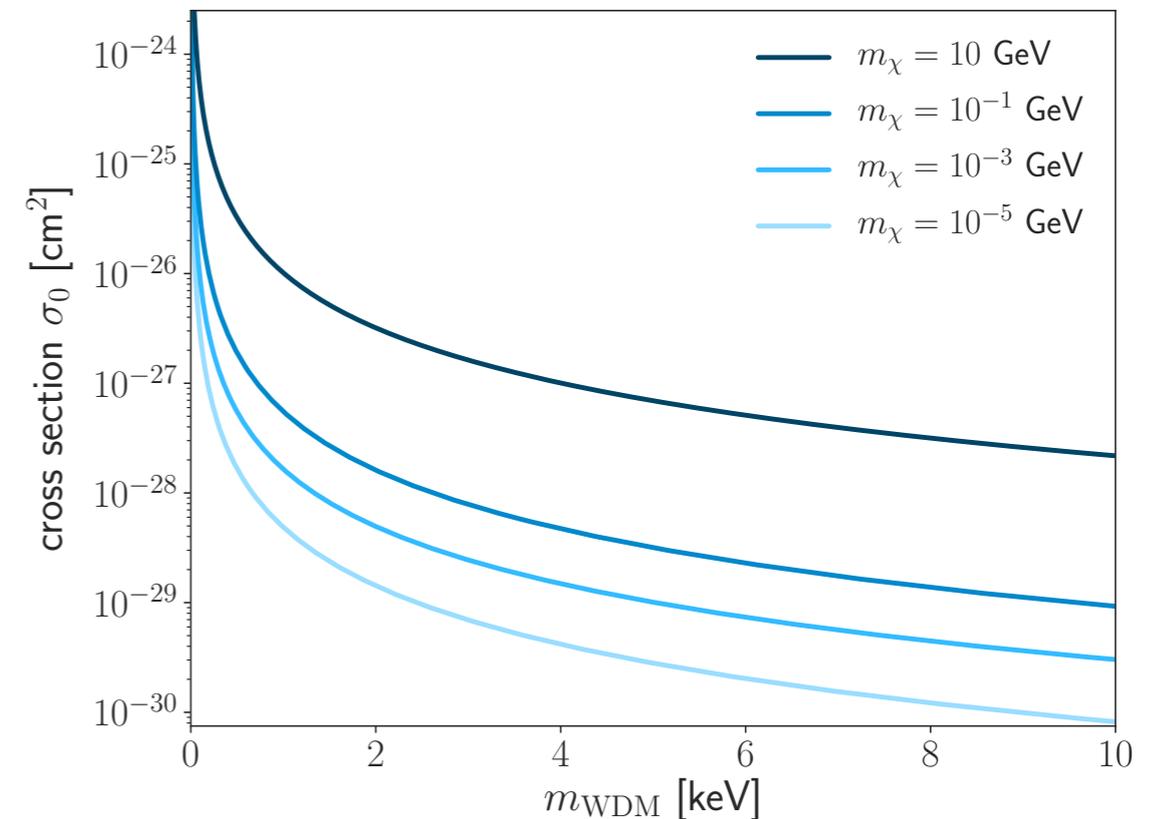
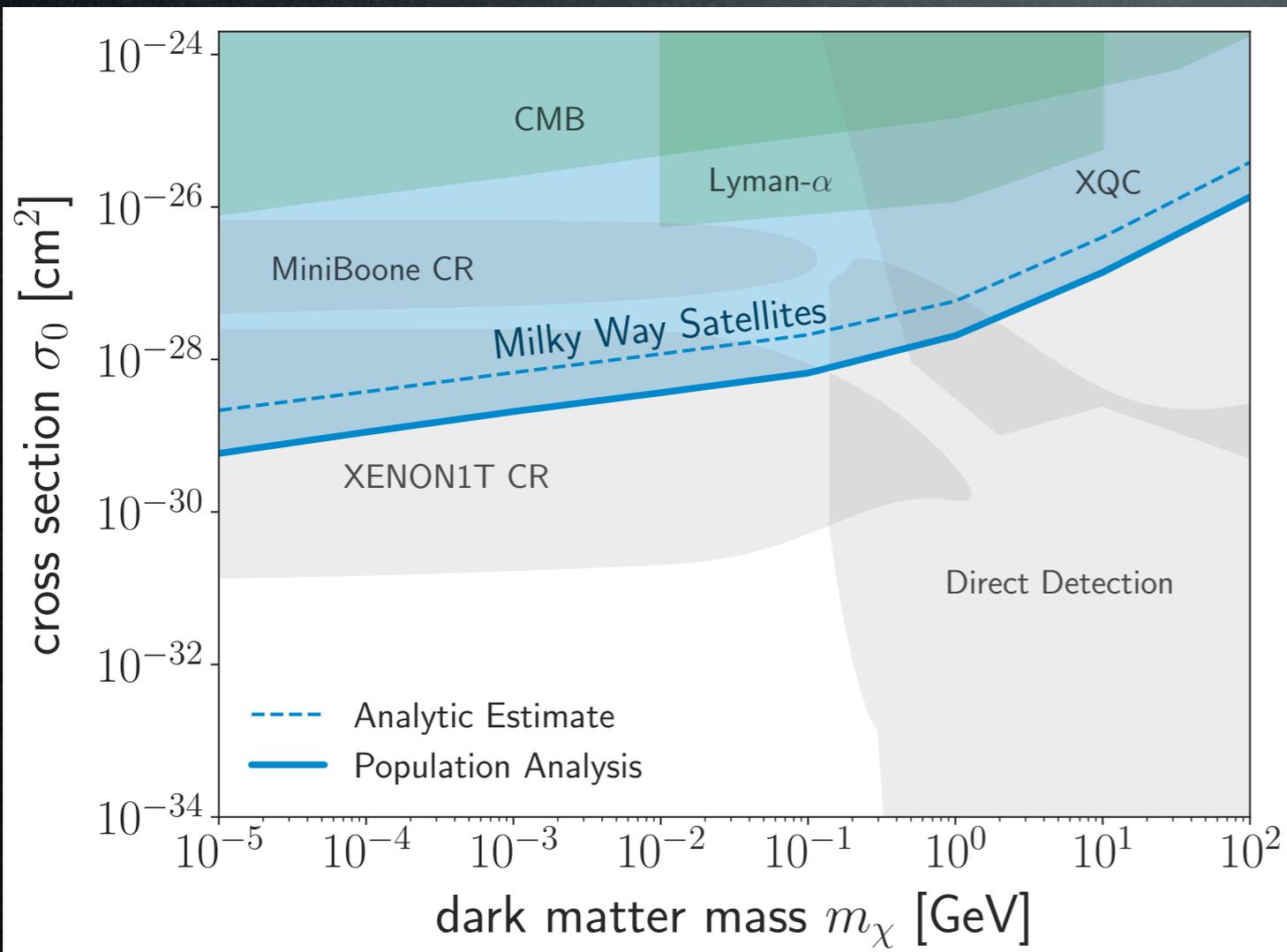
$$f_{\text{gal}} = \frac{1}{2} \left(1 + \text{erf} \left(\frac{M_{\text{peak}} - M_{50}}{\sqrt{2}\sigma} \right) \right)$$

M_{50} , mass at which 50% of halos are occupied = few $\times 10^7$ (95% upper limit = $2 \times 10^8 M_{\text{sun}}$)



What does this tell us
about dark matter?

DM-Baryon Scattering Constraints



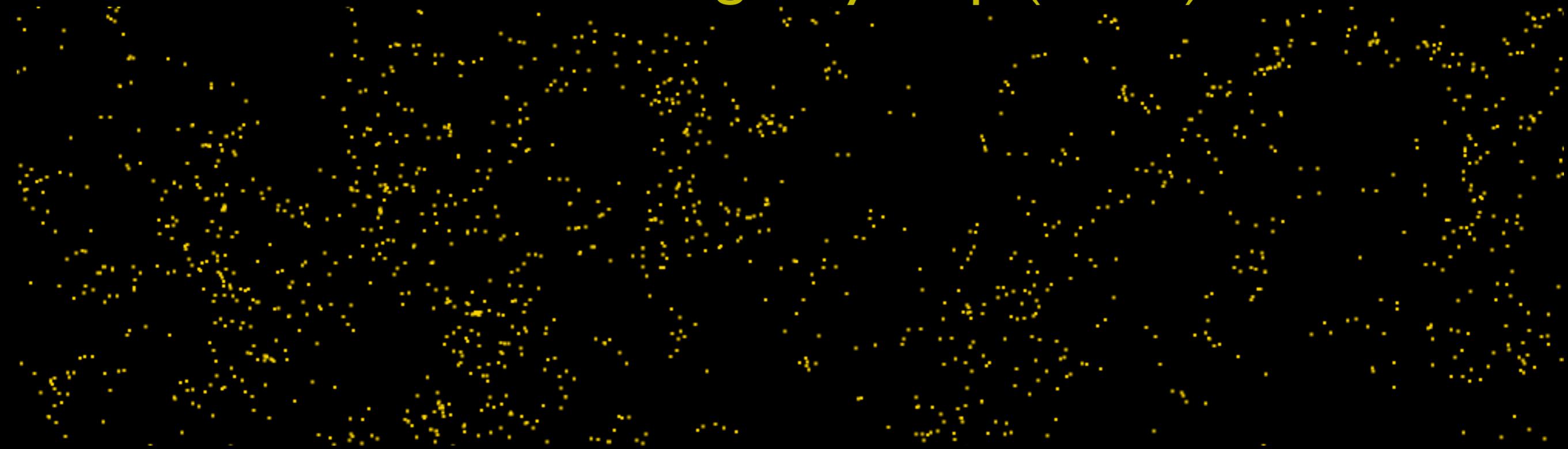
$m_{\text{WDM}} > 3.3$ keV (95% C.L.)

Nadler, Gluscevic, Boddy, Wechsler 2019

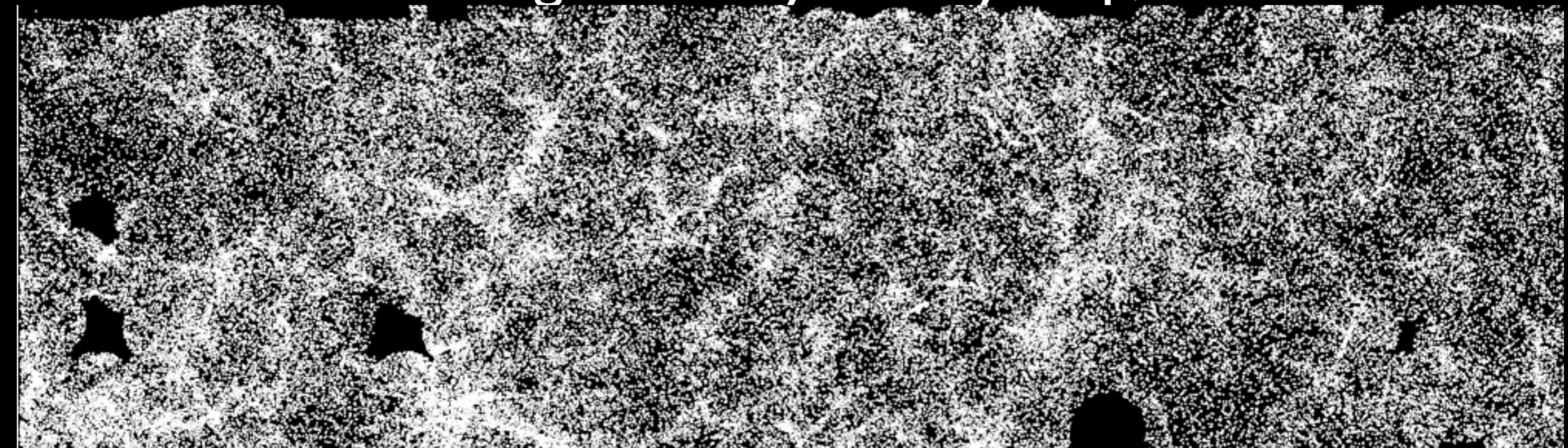
Dark matter-baryon interaction constrained by factor of 1000 more constraining than previous cosmological analysis, using SDSS + classical satellites only. Preliminary estimate for new analysis: constraints will improve by \sim factor of two in cross-section; $m_{\text{WDM}} > 4\text{keV}$

Lots of progress to be
made soon...

Our current galaxy map ($z \sim 0.3$)



DESI Bright Galaxy Survey map, $z \sim 0.3$



Things you should know about how galaxies and halos are connected:

- Galaxy formation is inefficient: efficiency of turning gas into stars peaks at 20–30% of the baryon fraction in halos of $10^{12} M_{\odot}$, significantly lower for higher- & lower-mass halos.
- Stellar masses of central galaxies are a strong function of DM halo mass below $10^{12} M_{\odot}$, scaling like $M_* \sim M^{2-3}$, and a weaker function above this pivot point, $M_* \sim M^{1/3}$.
- The scatter in galaxy stellar mass or luminosity at fixed halo mass (before halos are stripped by a larger system) has a scatter of less than 0.2 dex for objects above $10^{12} M_{\odot}$; this likely increases at lower halo mass but by no more than a factor of two.
- For most of the Universe's history from $z \sim 8-0$, the bulk of all star formation occurs in galaxies that live in a narrow range of halo mass around $10^{12} M_{\odot}$.
- Most galaxies at any stellar mass are the central galaxies in their own dark matter halo; the fraction of satellite galaxies at a given galaxy stellar mass declines from $\sim 30\%$ at low mass to $\sim 5\%$ at high mass.
- Most trends of galaxy properties with large-scale environment are well explained by the fact that the halo mass function and average halo properties vary with environment, combined with a galaxy–halo connection that is mostly independent of environment.
- Halo mass is the dominant determinant of the state of the galaxy occupying it, but there is statistically significant evidence that some galaxy properties are influenced by other halo properties and that this manifests in galaxy clustering properties (assembly bias).