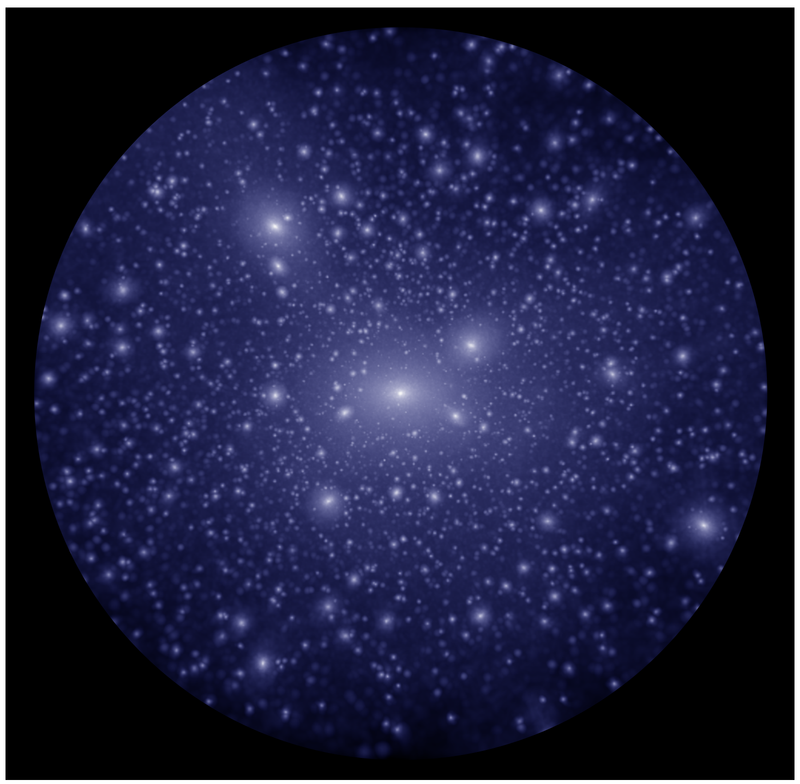
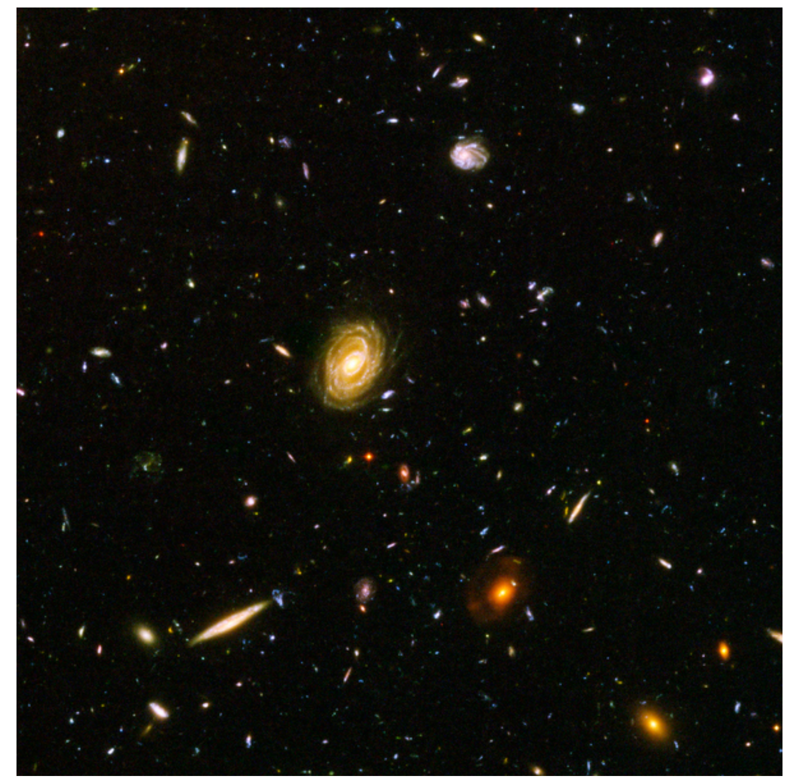
Dark Matter and Galaxies





Aseem Paranjape

Joint Astro & Particle Physics meeting, IISER Pune, 25 February 2018

Basic Questions

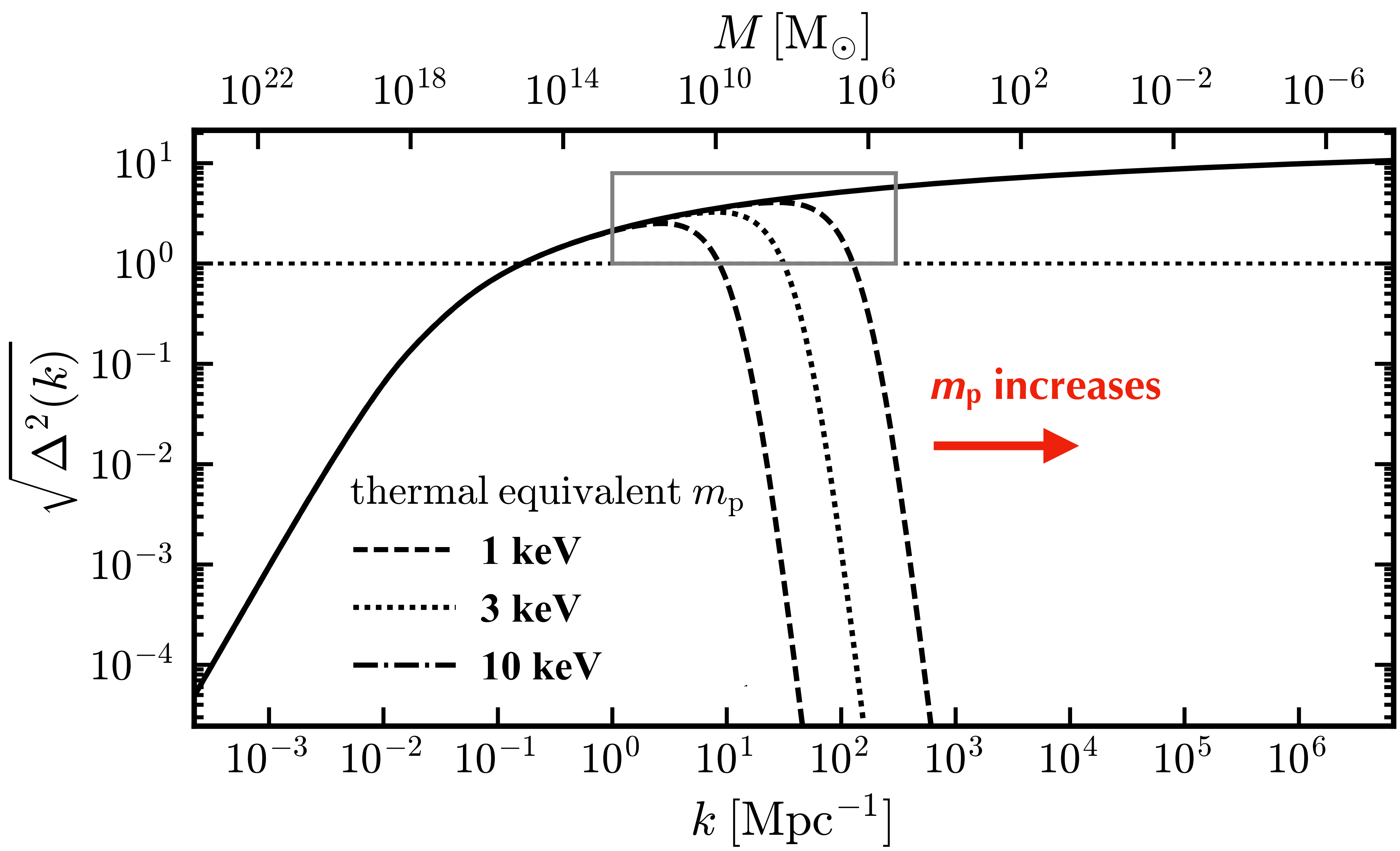
- What do extra-Galactic observations say about the nature of dark matter?
  - What are the predictions (and limitations) of simulations of non-standard DM models?
  - What is the role of astrophysical (`baryonic') feedback processes?
  - What is the current status of constraints from astrophysical observations?

Outline

- Vocabulary
- DM-galaxy connection and problems
- Simulations and their limitations
- Summary

Dark Matter Vocabulary

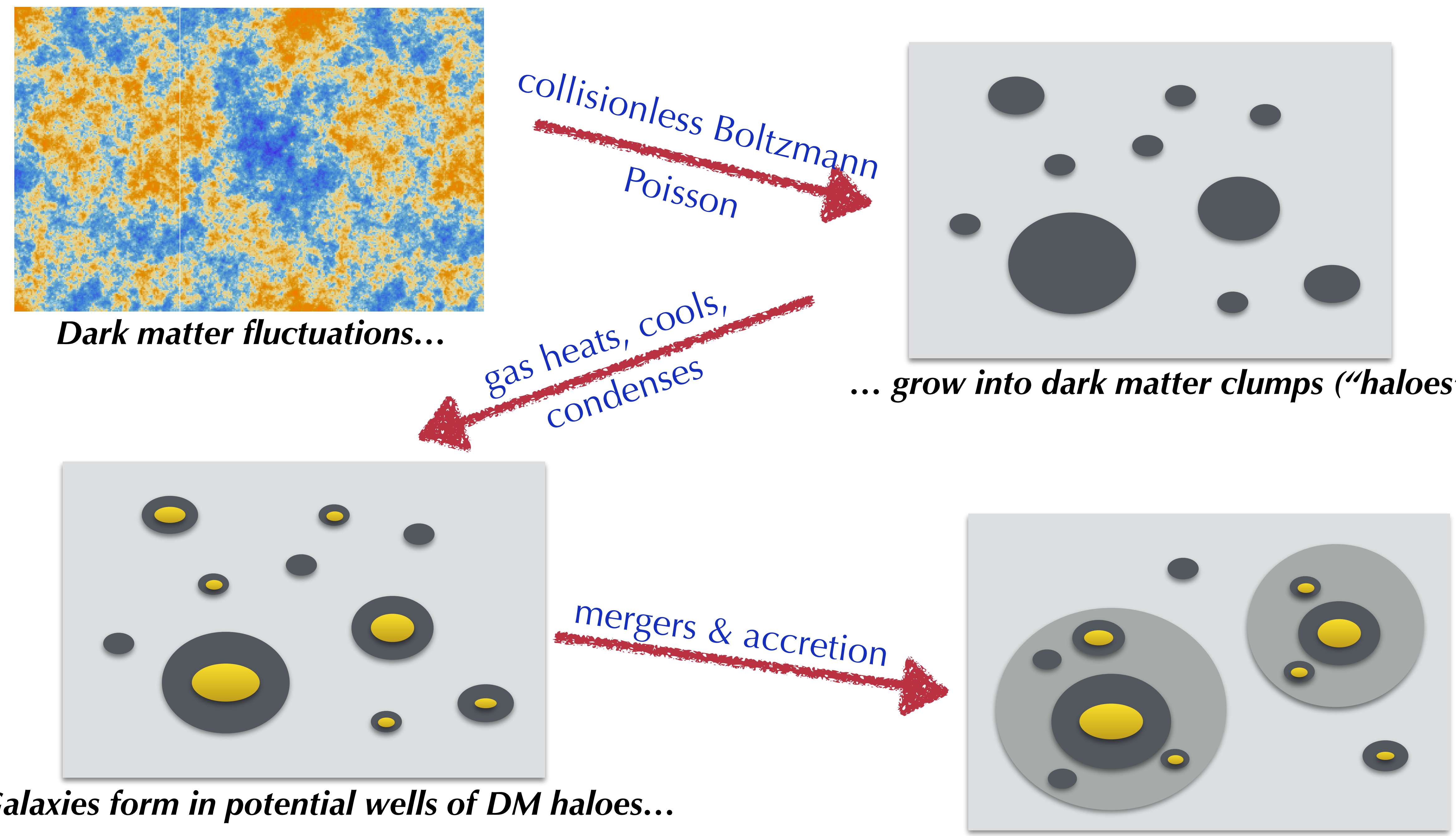
Linear perturbation theory



Bullock & Boylan-Kolchin (ARAA 2017, ***arXiv:1707.04256****)* ➡ [will be used throughout talk]

Dark Matter Vocabulary

Hierarchical structure formation



Dark matter fluctuations…

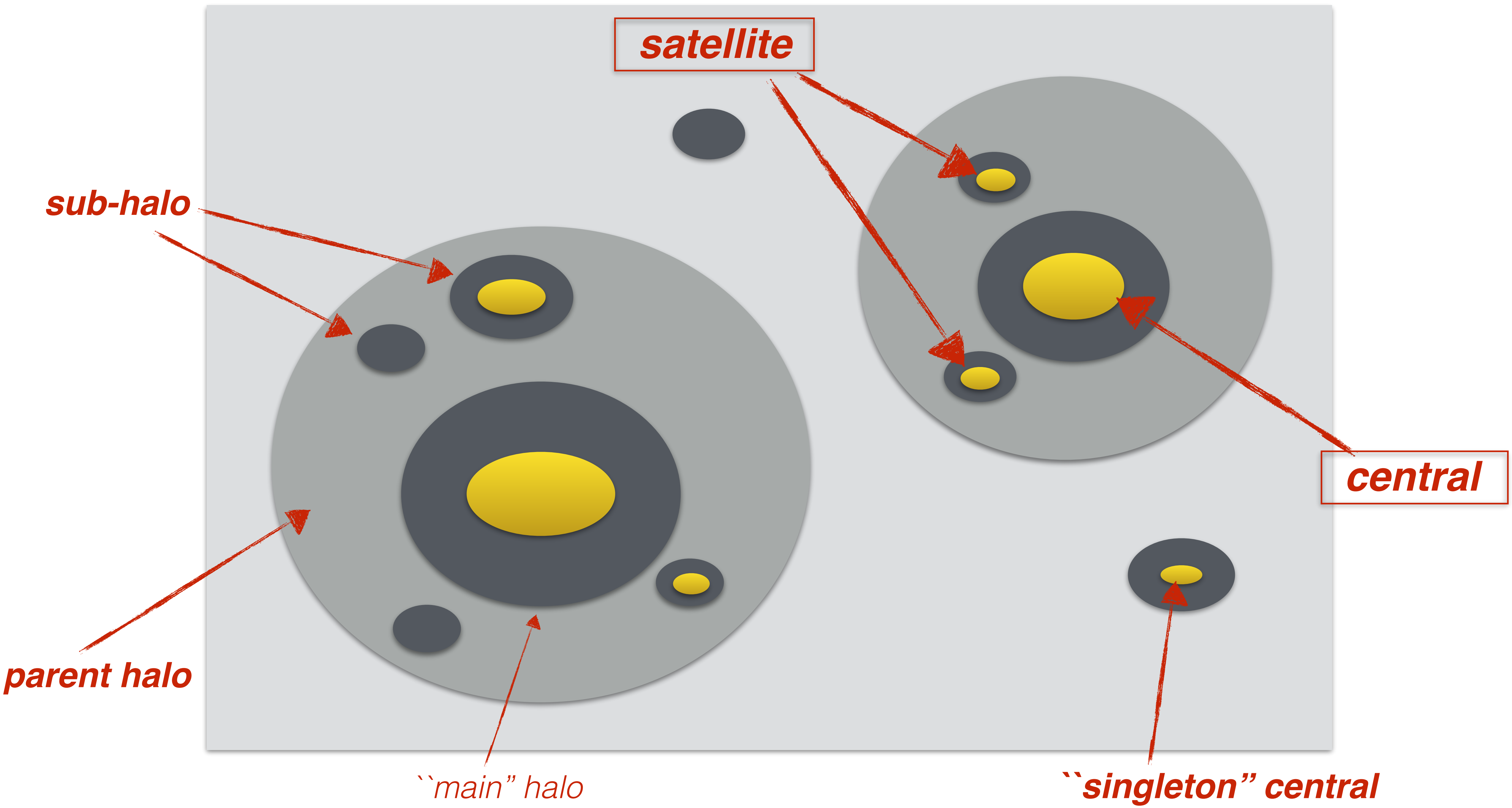
… grow into dark matter clumps ("haloes")

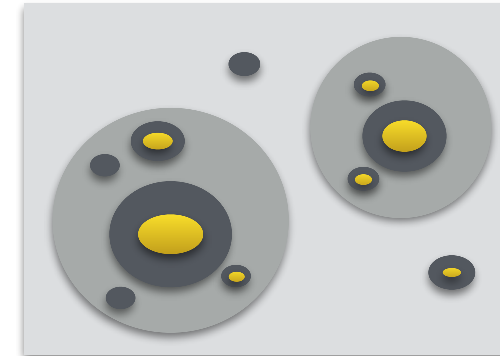
Galaxies form in potential wells of DM haloes…

… and form groups as haloes grow and merge

Dark Matter Vocabulary

Non-linear regime

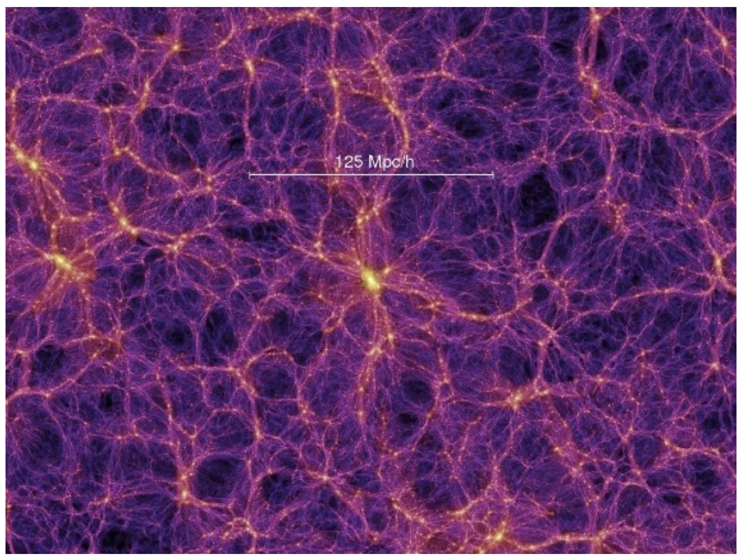




Dark Matter Vocabulary

Non-linear regime

Cosmic web



$$M_{\rm vir} = \frac{4\,\pi}{3}\,R^3_{\rm vir}\,\Delta\,\rho_{\rm m}$$

$$\Delta \sim 300$$

$$V_{\rm vir} \equiv \sqrt{\frac{G M_{\rm vir}}{R_{\rm vir}}}$$

$V_{\rm max}$ = max. circ vel over halo profile

Galaxy Clusters:

$M_{\rm vir} \approx 10^{15}\,M_\odot$

$V_{\rm vir} \approx 1000\,{\rm km\,s^{-1}}$

Milky Way:

$M_{\rm vir} \approx 10^{12}\,M_\odot$

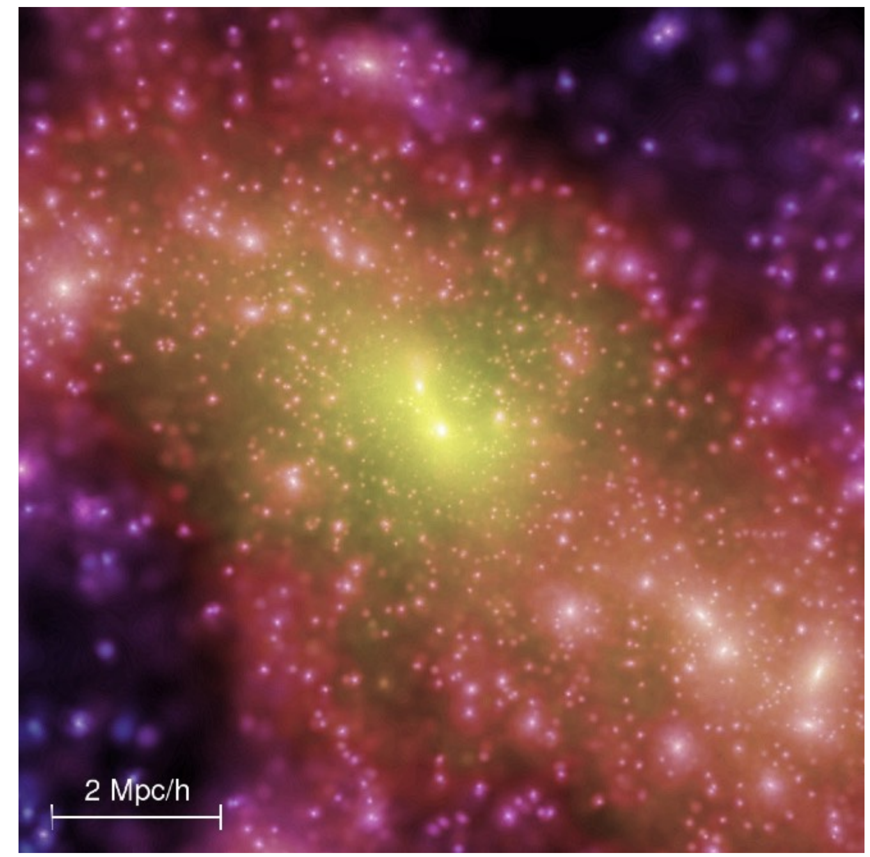
$V_{\rm vir} \approx 100\,{\rm km\,s^{-1}}$

Smallest Dwarfs:

$M_{\rm vir} \approx 10^{9}\,M_\odot$

$V_{\rm vir} \approx 10\,{\rm km\,s^{-1}}$

Halo and substructure



$$M_l = \frac{4\,\pi}{3}\,r_l^3\,\rho_{\rm m} = \frac{\Omega_{\rm m}\,H_0^2}{2\,G}\,r_l^3$$

$$= 1.71 \times 10^{11}\,M_\odot \left(\frac{\Omega_{\rm m}}{0.3}\right)\left(\frac{h}{0.7}\right)^2\left(\frac{r_l}{1\,{\rm Mpc}}\right)^3$$

$$R_{\rm vir} = 0.15\left(\frac{\Delta}{300}\right)^{-1/3} r_l$$

Dark Matter Vocabulary

"Small" scales

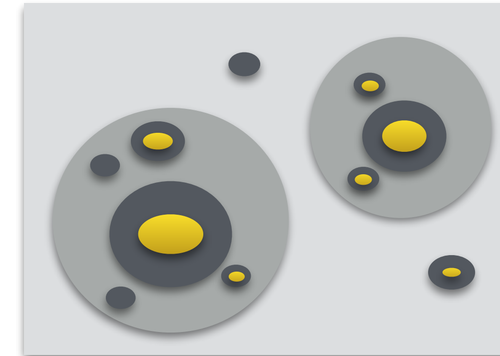
$$M \approx 10^{11}\, M_{\odot}$$

$$\leftrightarrow k \approx 3\,\mathrm{Mpc}^{-1} \leftrightarrow r_l \approx 1\,\mathrm{Mpc}$$

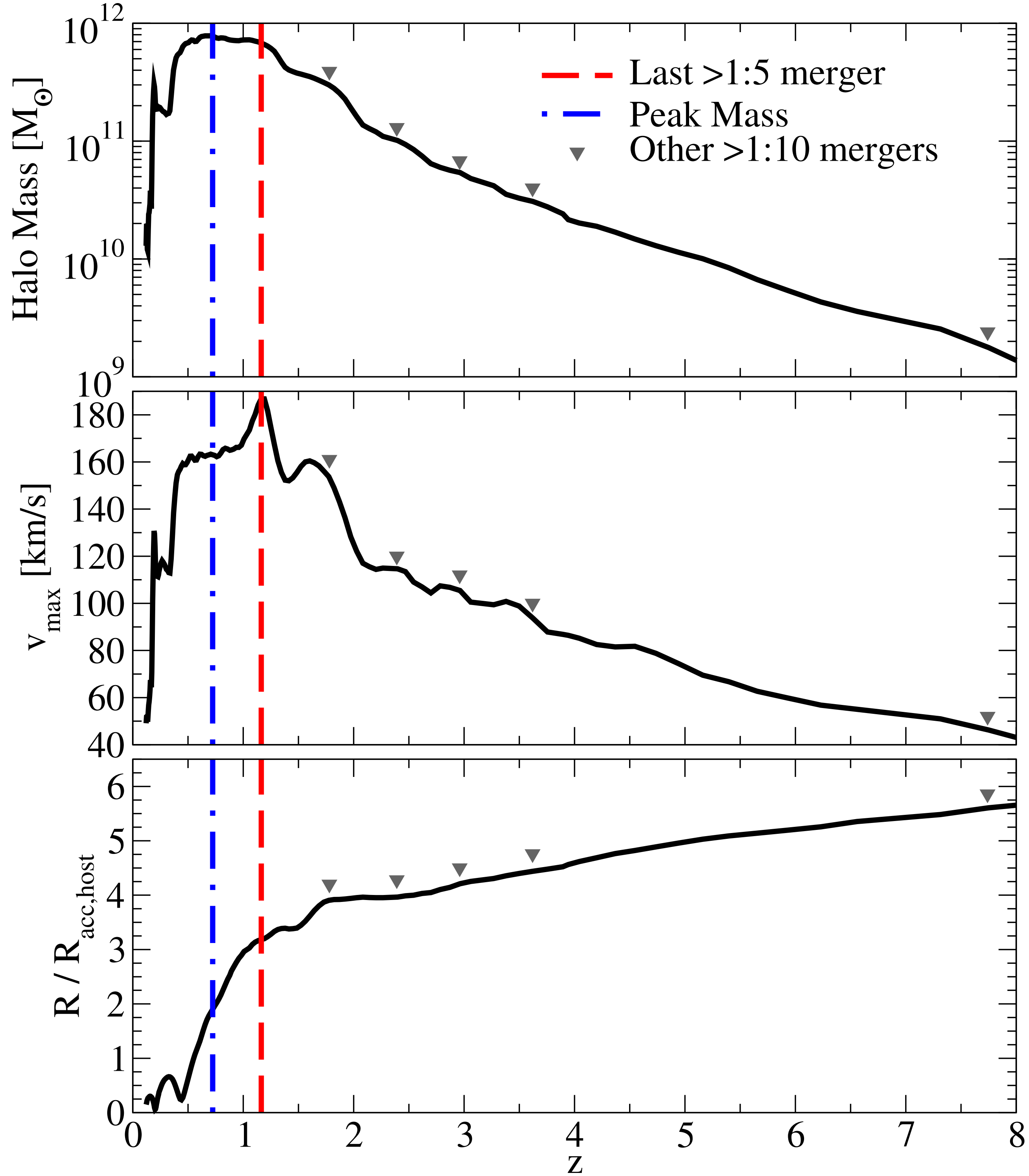
$$\leftrightarrow R_{\rm vir} \approx 150\,\mathrm{kpc} \leftrightarrow V_{\rm vir} \approx 50\,\mathrm{km\,s}^{-1}$$

$$\leftrightarrow V_{\rm max} \simeq 1.2\,V_{\rm vir} \simeq 60\,\mathrm{km\,s}^{-1}$$

Dark Matter Vocabulary



Satellite-specific nomenclature



***M*$_{peak}$** → maximum virial mass over accretion history

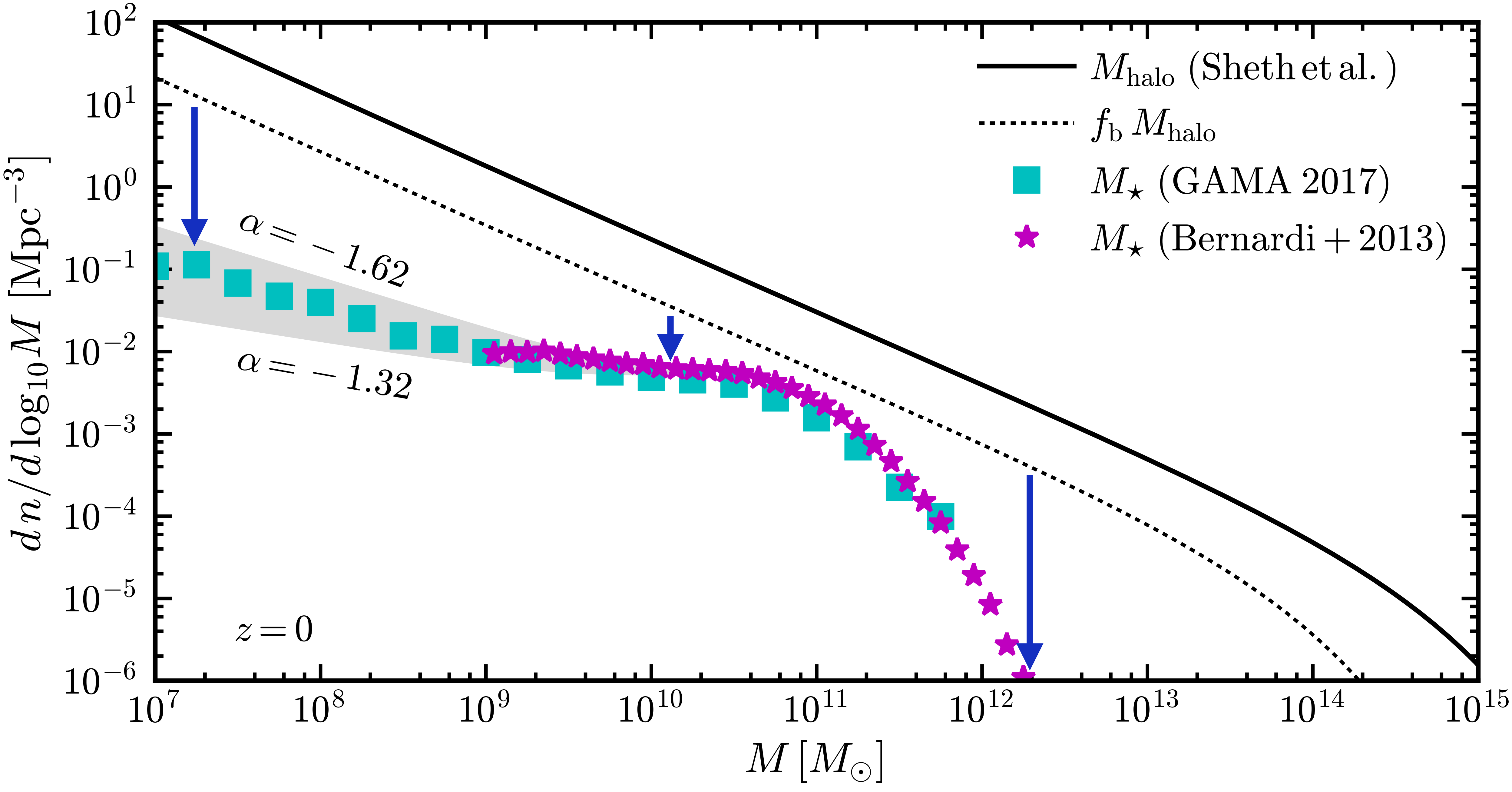
***V*$_{peak}$** → maximum V_{max} over accretion history

Both occur well outside virial radius of eventual host.

Behroozi+ (2014)

Dark Matter — Galaxy connection

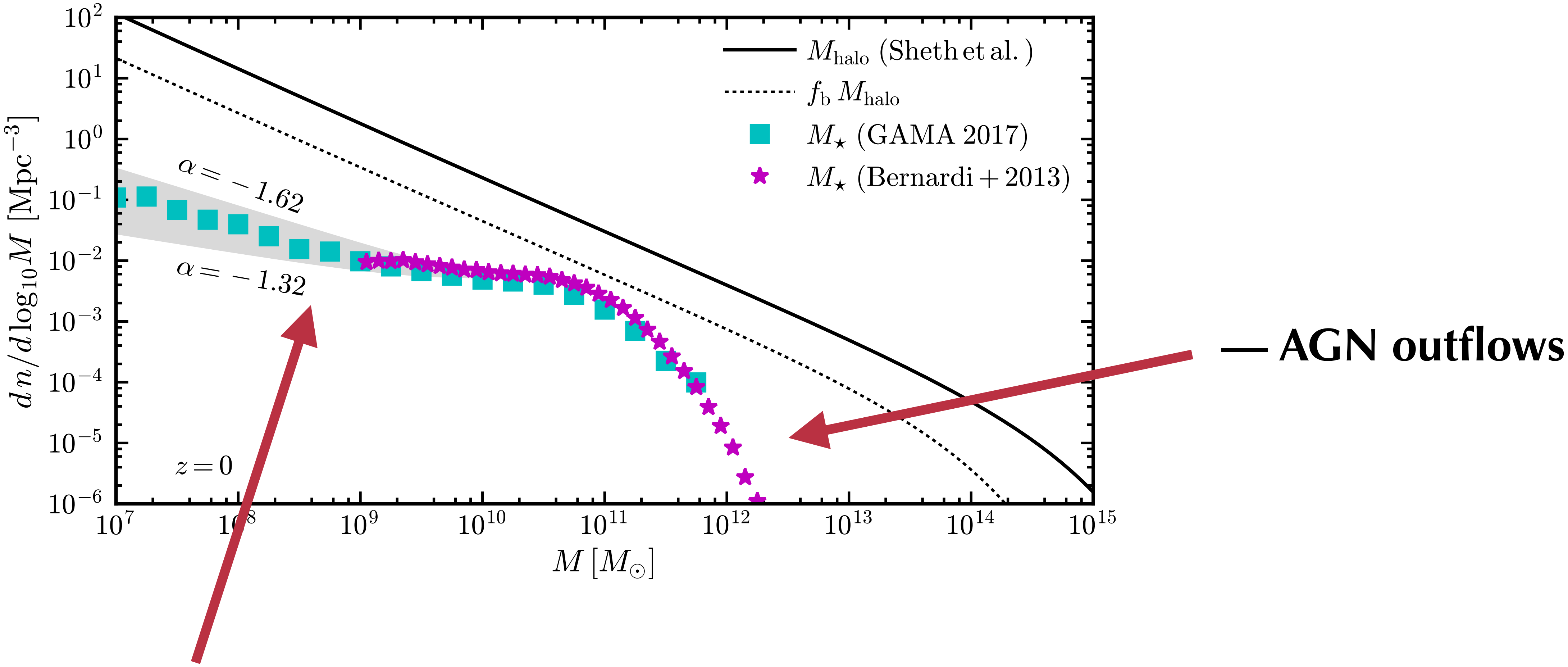
0. Scale-dependent star formation efficiency



Dark Matter — Galaxy connection

0. Scale-dependent star formation efficiency

Astrophysical mechanisms that inhibit star formation are mass-dependent.

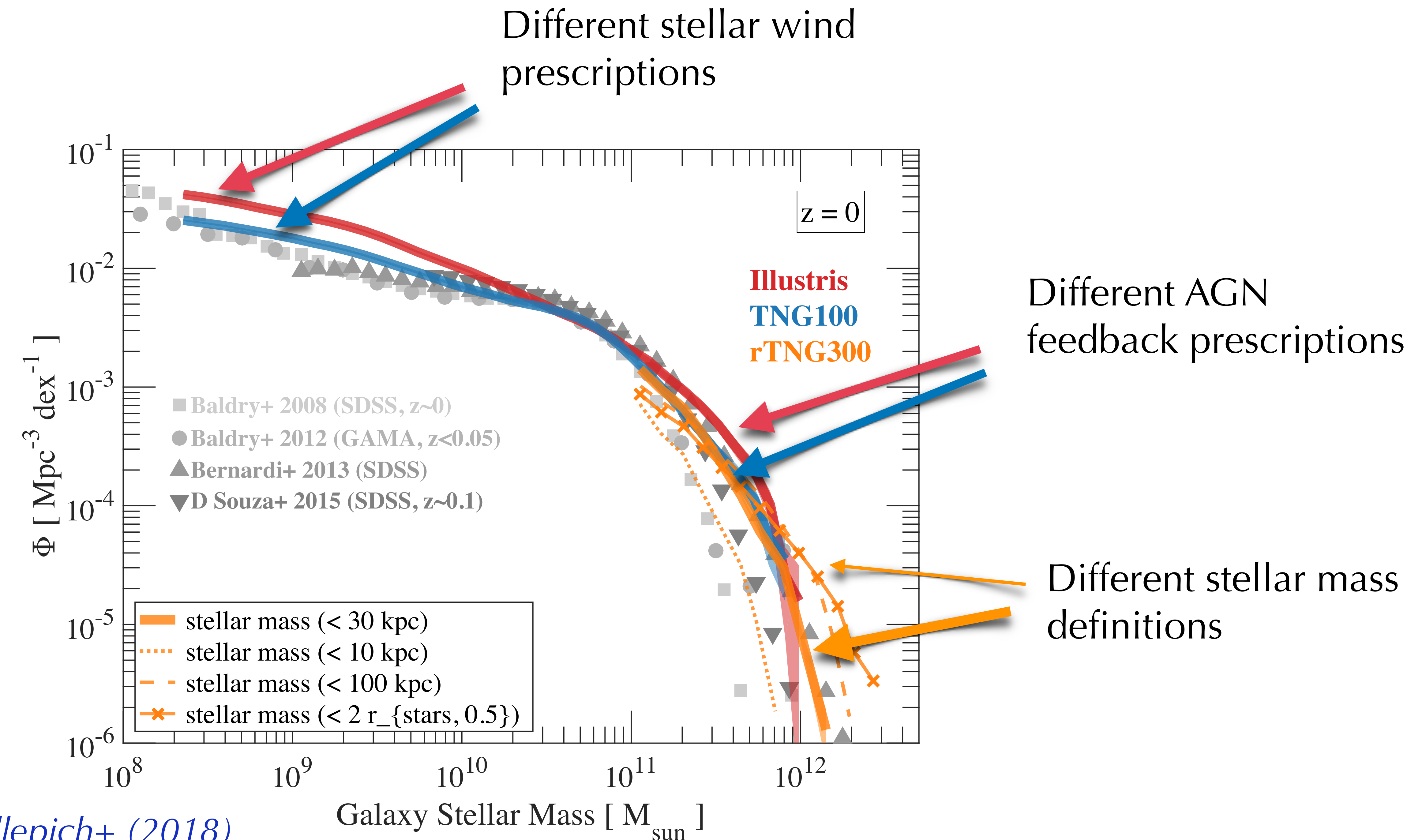


— SNe, stellar outflows
— Reionisation
— Satellite-specific processes

Simulating these is hard due to both large uncertainties and high dynamic range

Dark Matter — Galaxy connection

0. Scale-dependent star formation efficiency

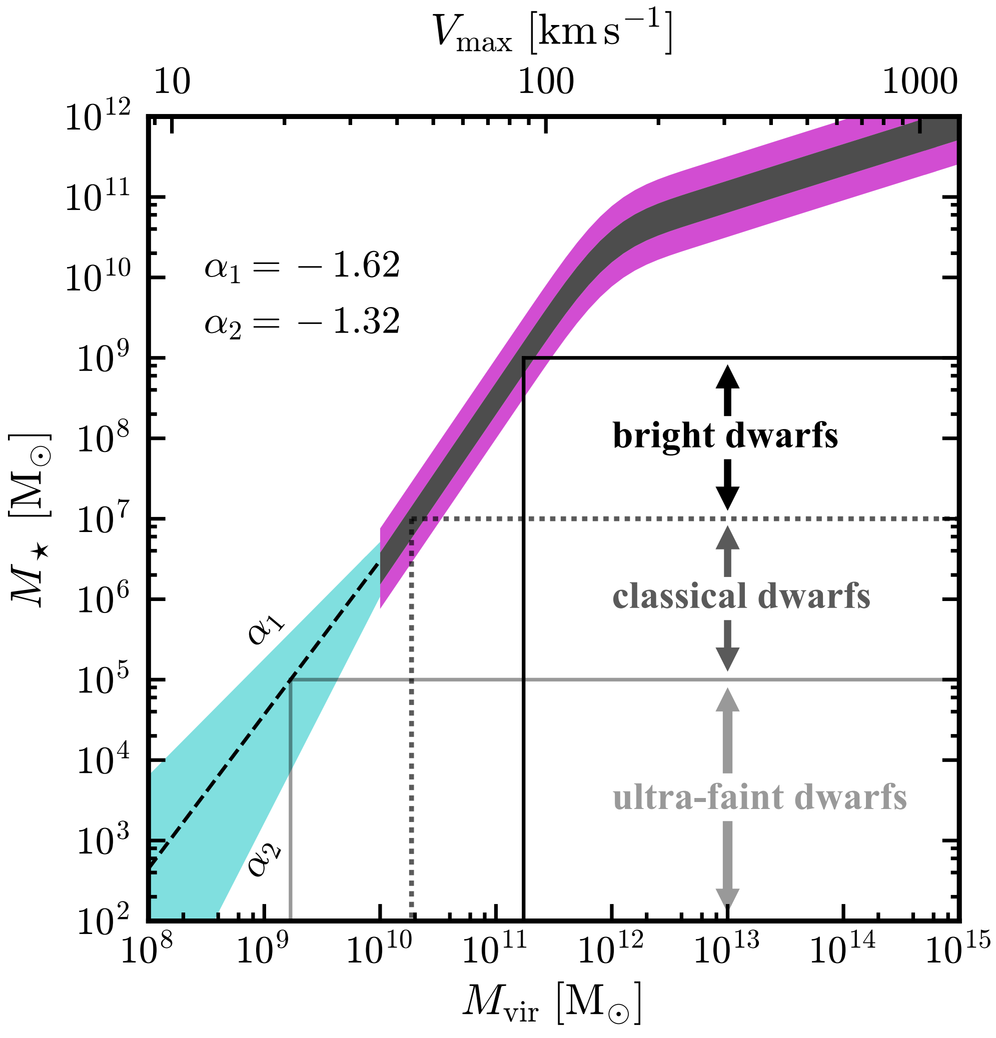


Pillepich+ (2018)

Dark Matter — Galaxy connection

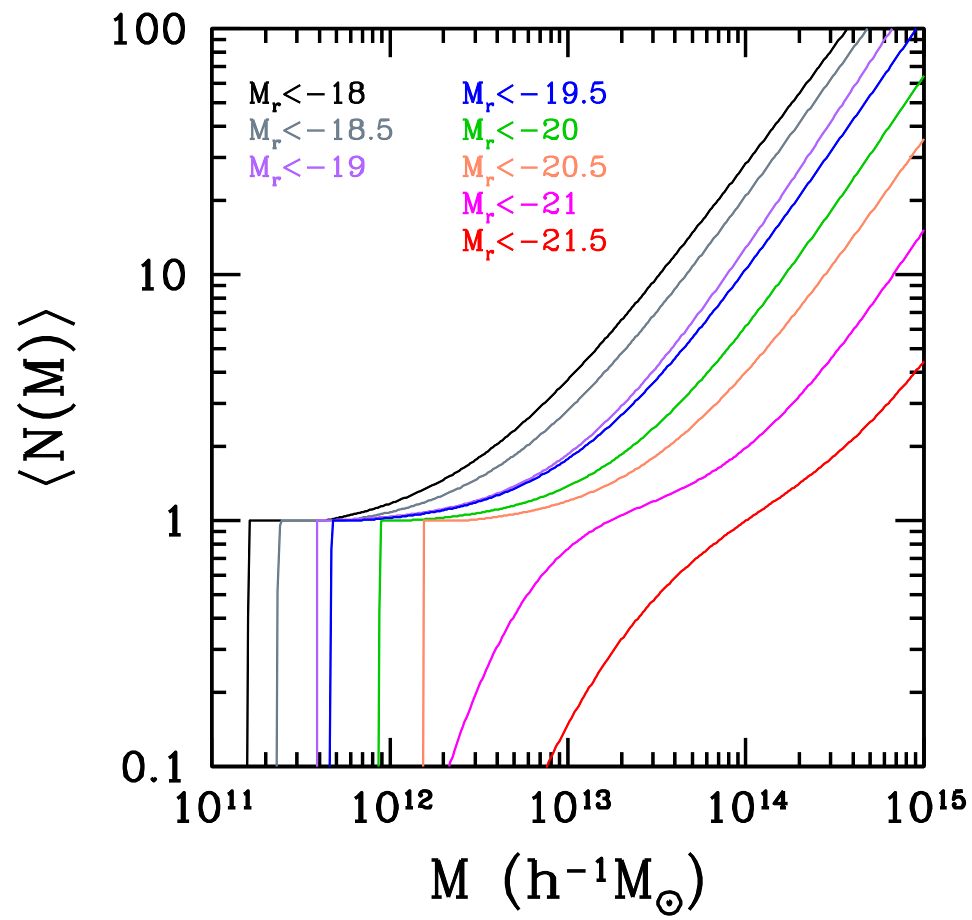
0. Scale-dependent star formation efficiency

Statistical approach: assume galaxy formation physics depends on only few properties of host halo. **Match *observed*** galaxy abundances (and clustering).
— simplest model: ***only mass of host halo matters***



Abundance matching

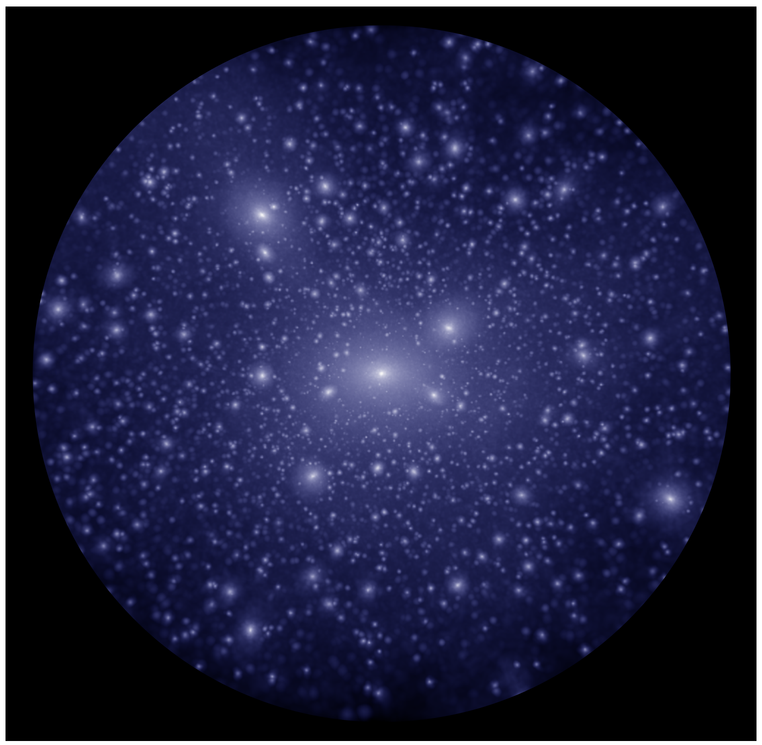
Guo+ (2015)

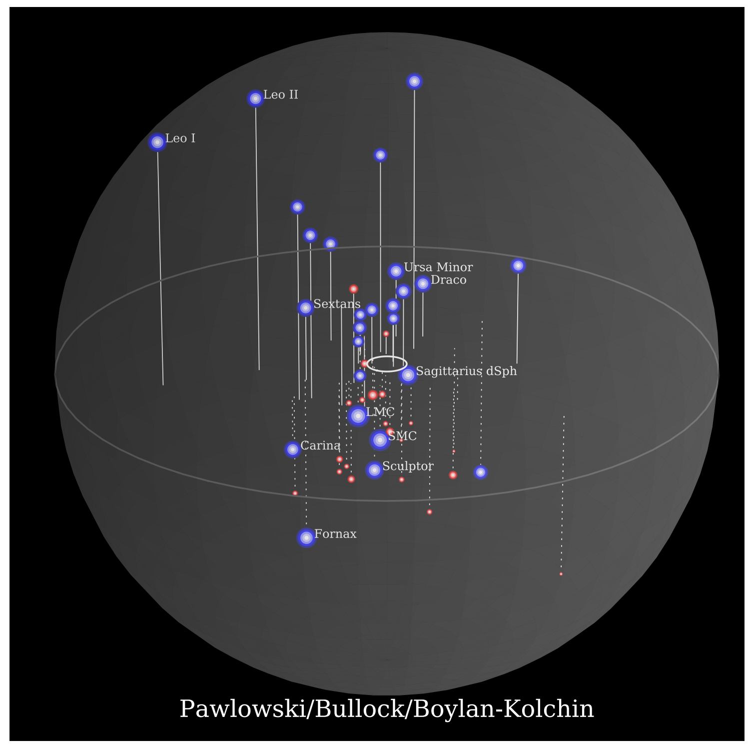


Halo Occupation Distribution (HOD)

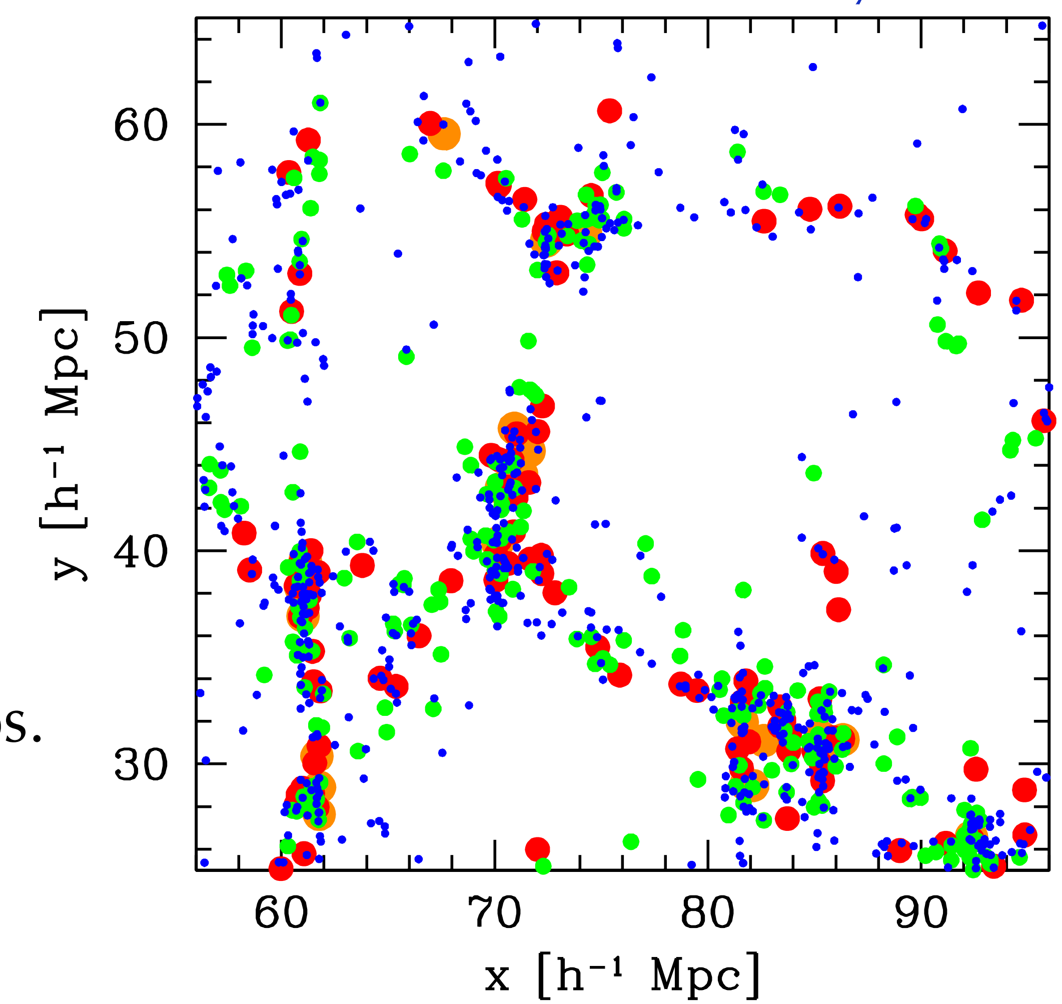
Dark Matter — Galaxy connection

1. Missing satellites / Void phenomenon





Tinker & Conroy (2008)



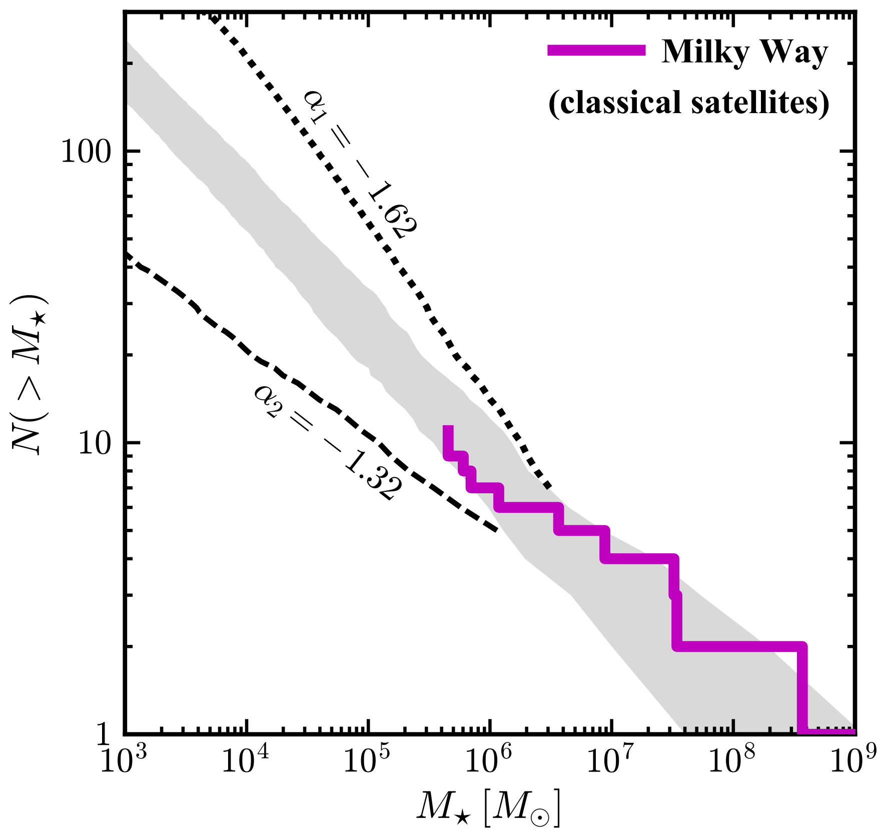
Many subhalos (~$10^8 M_{sun}$) expected in MW-sized halos.
Many small (~$10^{9\text{-}10} M_{sun}$) halos expected in voids.

Where are the corresponding dwarf galaxies?

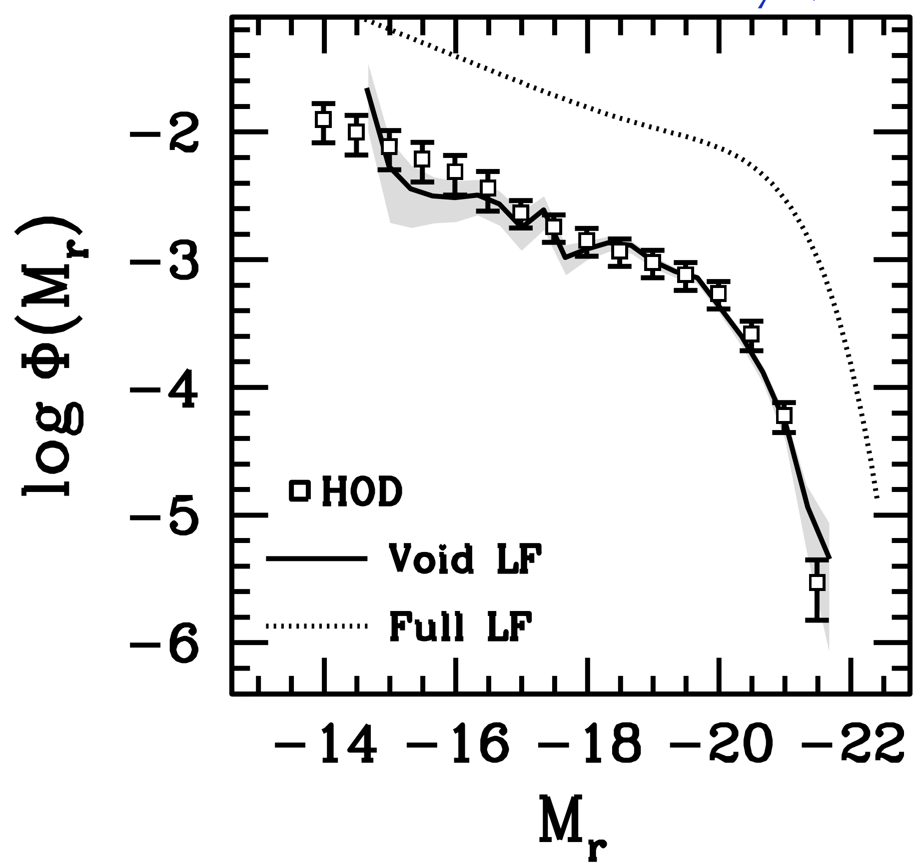
If *N*(halo mass | environment) is large, why is *N*(light | environment) small?

Dark Matter — Galaxy connection

1. Missing satellites / Void phenomenon



Tinker & Conroy (2008)



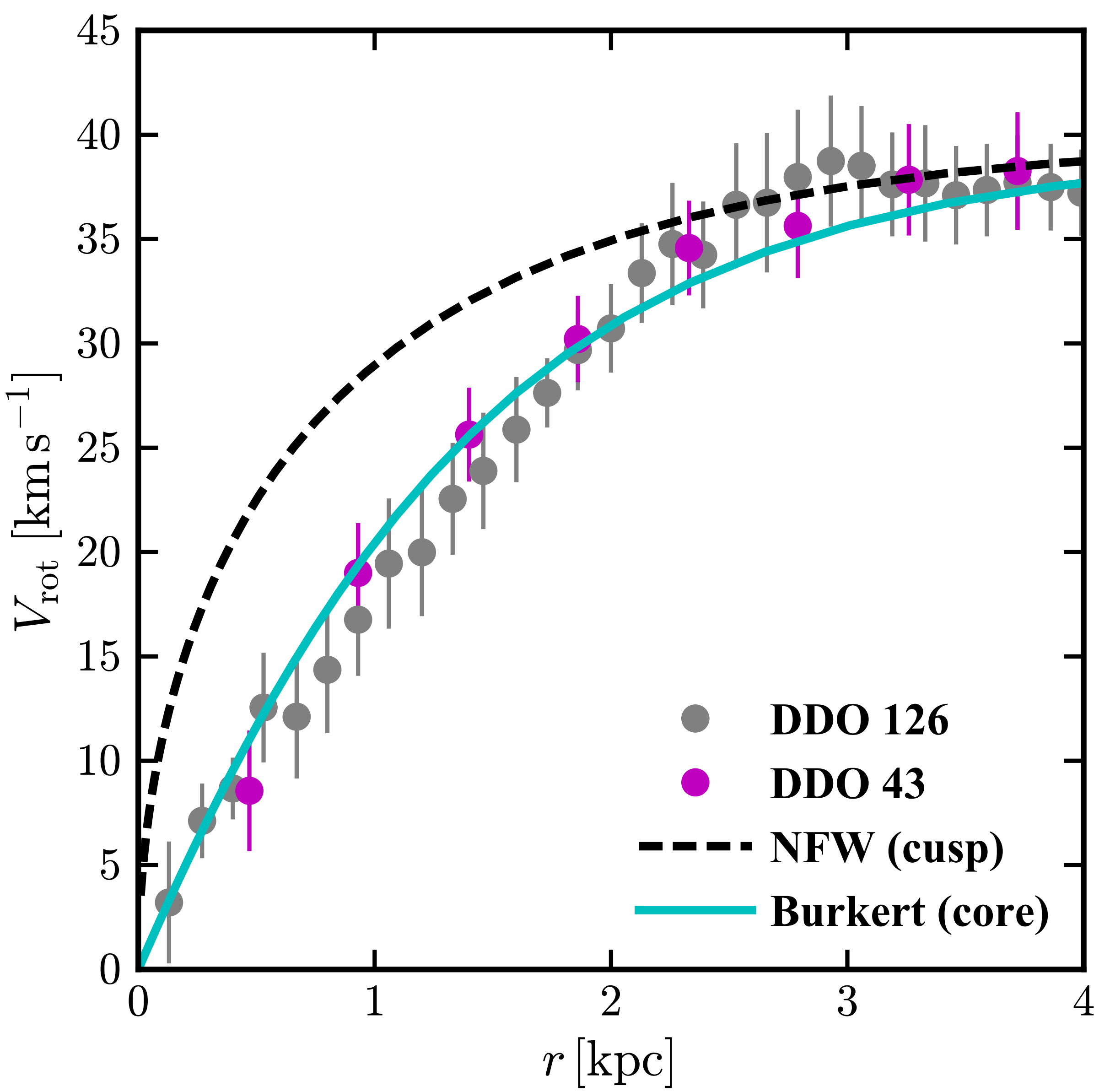
Explanation within CDM statistical framework that _matches observed luminosity function_:
Because observed (M/L) becomes very large for faint galaxies in *any* environment.

Simple mass-only model says:
Galaxy environment is `inherited' from host. Together with large M/L (originating from baryonic feedback), explains both `missing' satellites and void phenomenon.

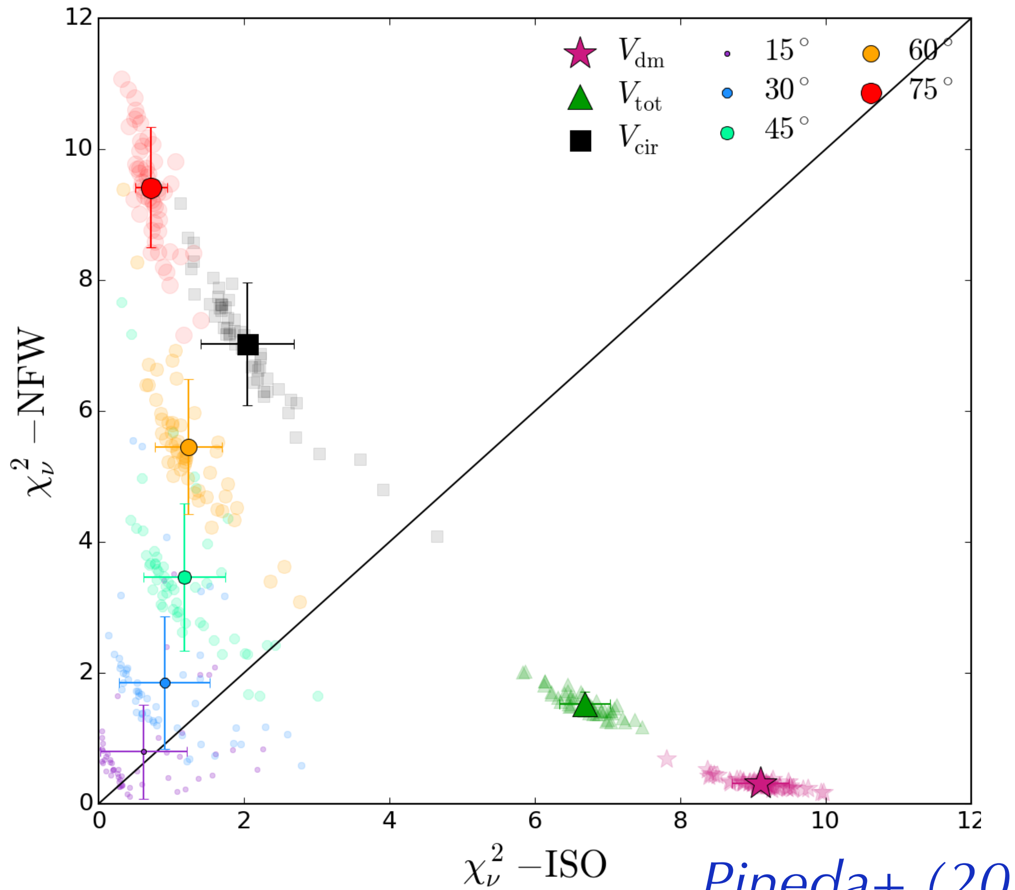
Dark Matter — Galaxy connection

2. Core vs Cusp

Inner regions of low mass, DM-dominated galaxies are less dense and less cuspy than CDM-only predictions.



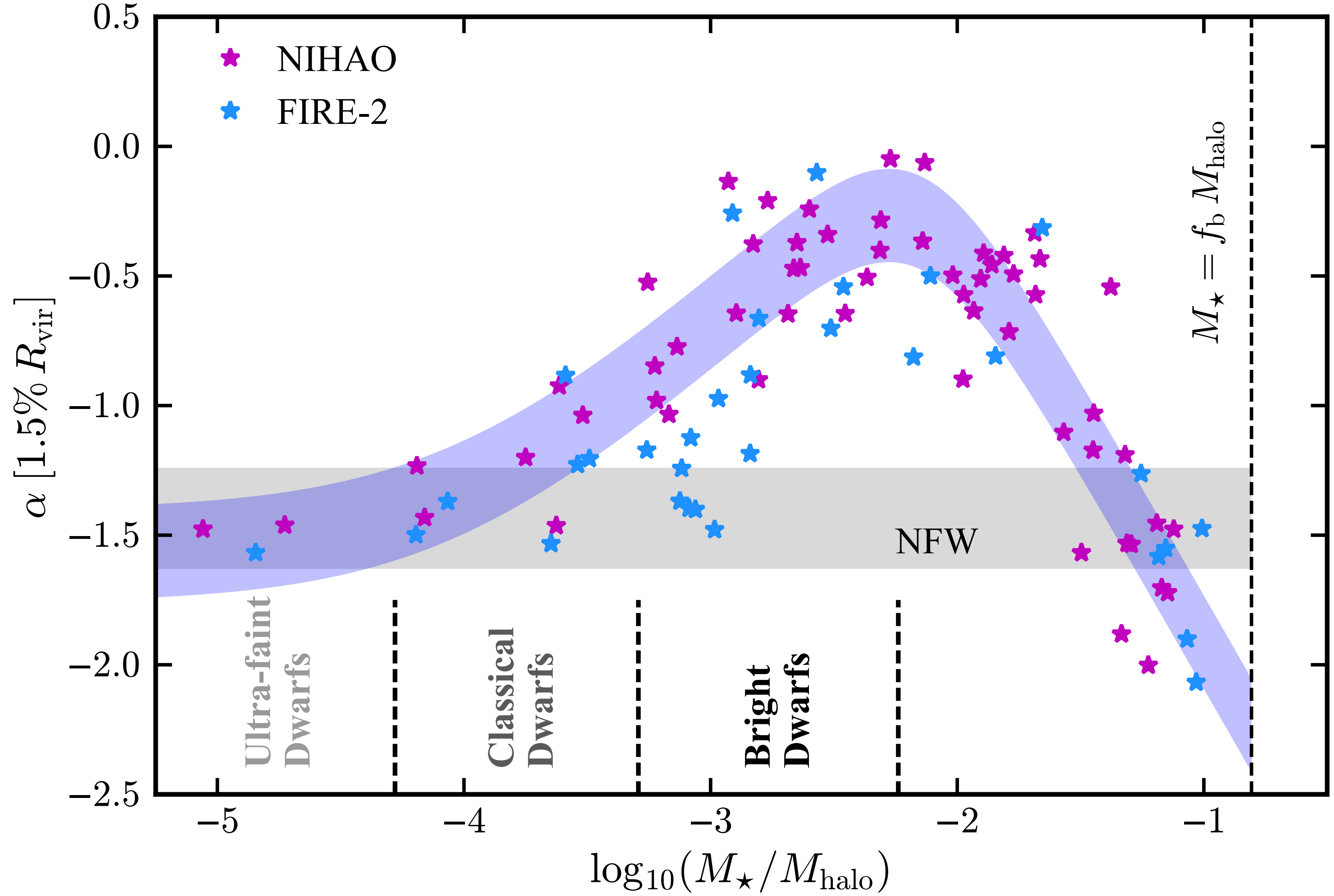
Inferences drawn from rotation curve fitting / velocity dispersion modelling.
See, e.g., Pineda+ (2017) and Genina+ (2018) for ***caveats*** *reg systematics.*



Pineda+ (2017)

Dark Matter — Galaxy connection

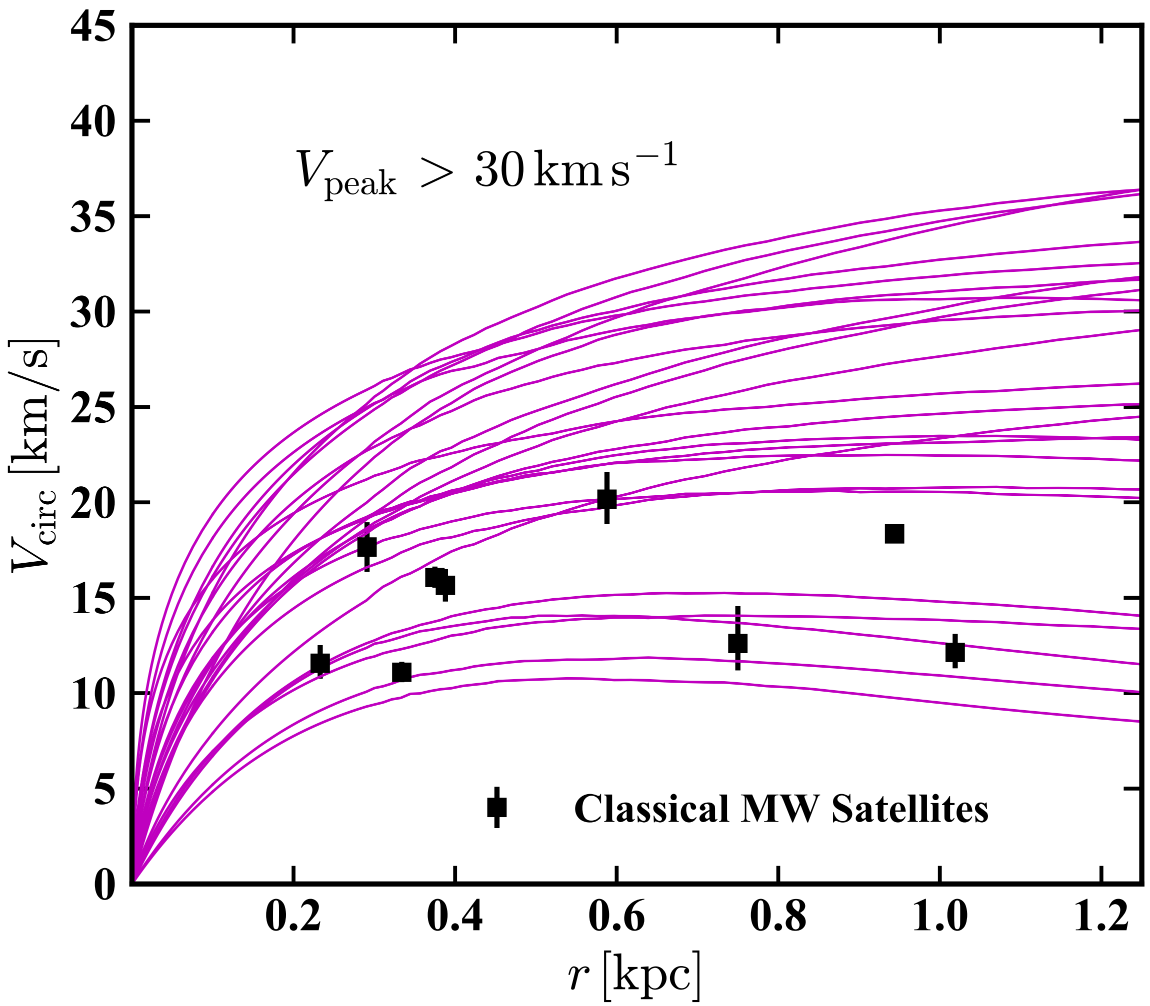
2. Core vs Cusp

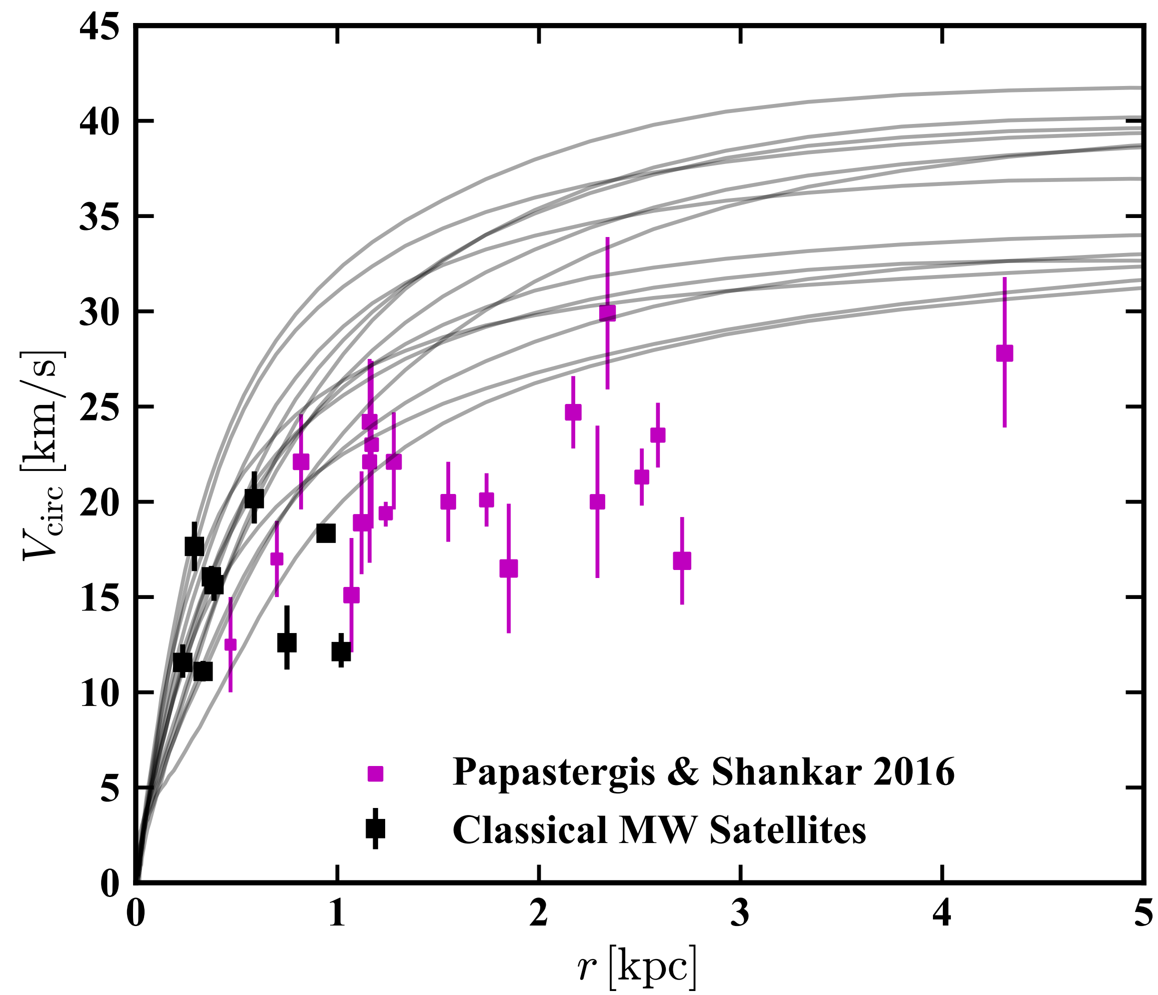


If observational systematics are under control and numerical star-formation / feedback prescriptions can be trusted for low-mass systems, then cusp-core problem is not solved by baryonic feedback for $\log(M_*/M_{halo})$ <~ -4.

Dark Matter — Galaxy connection

3. "Too big to fail"





Why would galaxies fail to form in the most massive subhalos, yet form in dark matter satellites of lower mass?

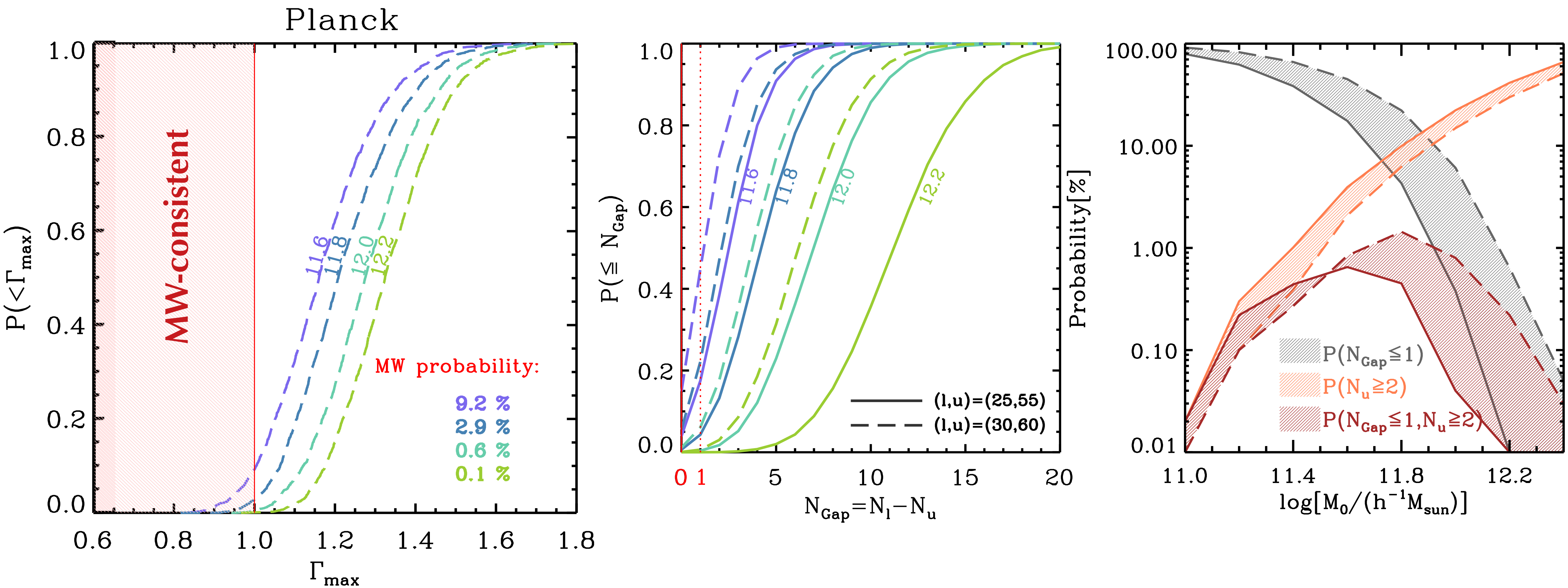
Dark Matter — Galaxy connection

3. "Too big to fail"

Caveats: *(Jiang & van den Bosch 2015)*

— multiple formulations with different severity
— each suffers from look-elsewhere and/or ignores observational systematics
— severity depends on statistic used, *sample size of simulation suite*, assumed MW mass and cosmological parameters

Authors' new formulation gives **MW-consistency of 1.4%** for subhalos with $\boldsymbol{V_{max}}$ **> 15km/s**.



Dark Matter — Galaxy connection

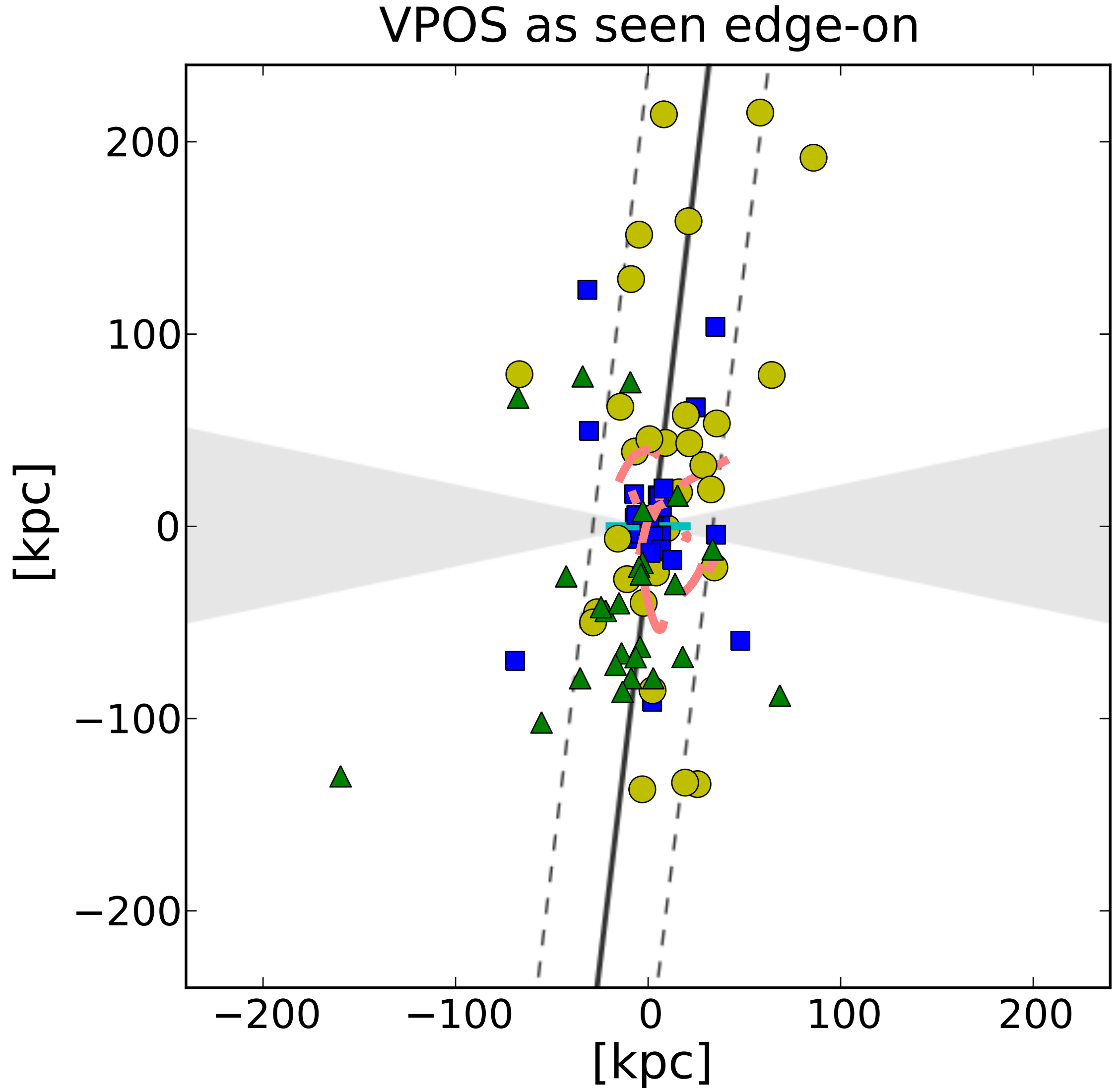
3. "Too big to fail"

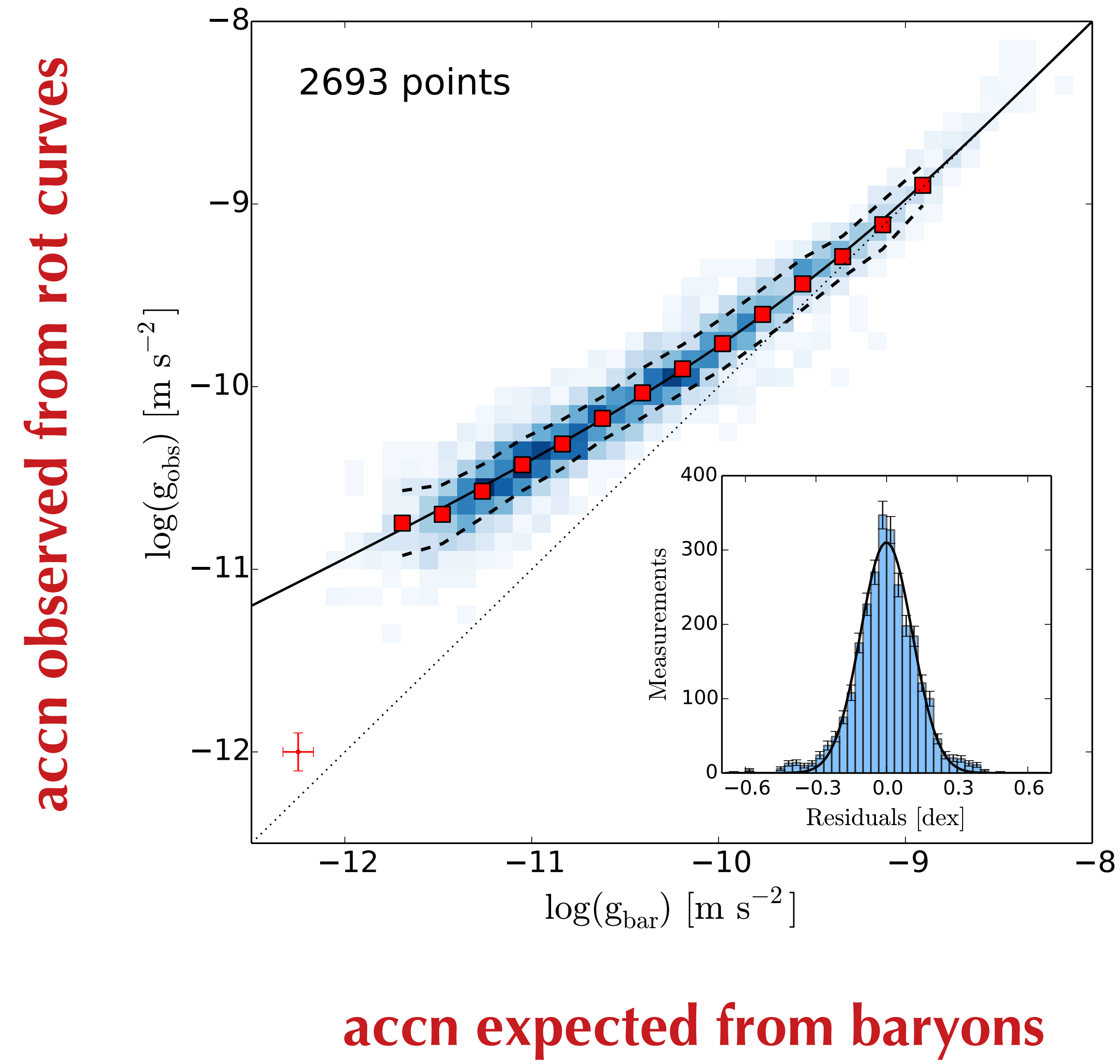
Potential solutions within CDM:

- For $M_* >\sim 10^6\ M_{sun}$, existence of baryon-induced cores could explain low densities.
- For $M_* <\sim 10^6\ M_{sun}$, satellite-specific mechanisms could be important (tidal stripping, disk shocking, ram-pressure stripping) between 1-2 $R_{vir,host}$.
- Above not relevant for isolated field dwarfs, but see previous for potential issues with connecting observed rotation curves to gravitational potential.

Dark Matter — Galaxy connection

4. Planes and lines

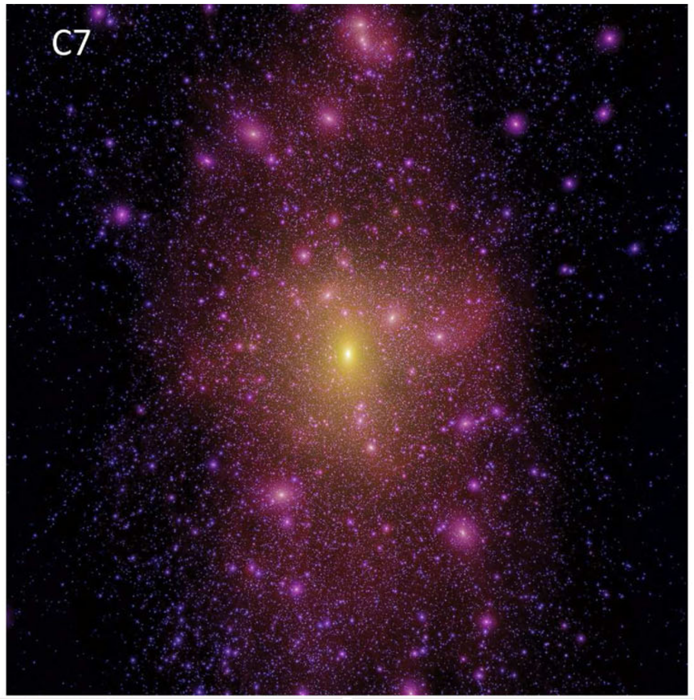




Plane of satellites

Radial acceleration relation

Simulations: CDM



Numerical techniques

***Goal*:**

Solve collisionless Boltzmann eqn with cold ICs

***Approach*:**

N-body technique

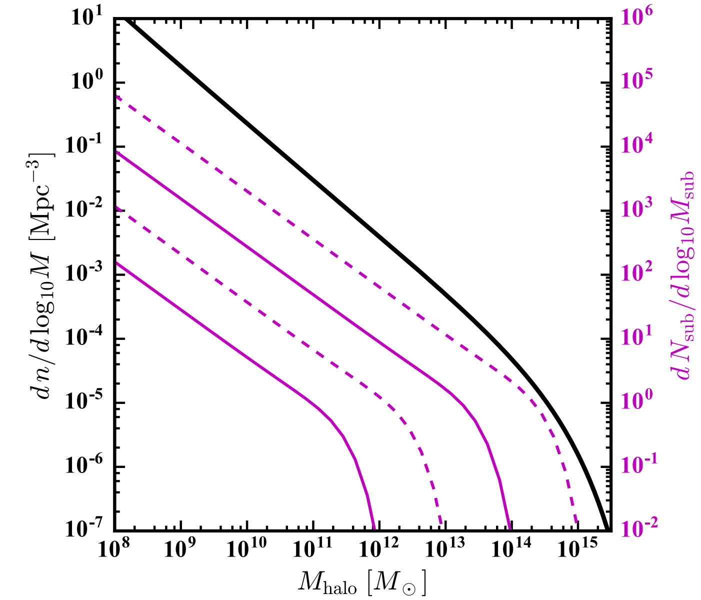
- Sample phase space distribution function with mass tracers (`particles') and follow their positions and velocities (Newton's law augmented by Poisson equation).
- Avoid small scale 2-body effects through `force softening' (Newton's law with a core radius).
- Code efficiency + accuracy increases by combining Fourier techniques on particle mesh (PM) for large scale forces with direct calculations for small scale forces.
- Test for convergence of various statistics with $N_{\rm part}$, softening scale, PM grid size, etc.

***Typical application*:**

Periodic cubic box in comoving coordinates.

Simulations: CDM

Products

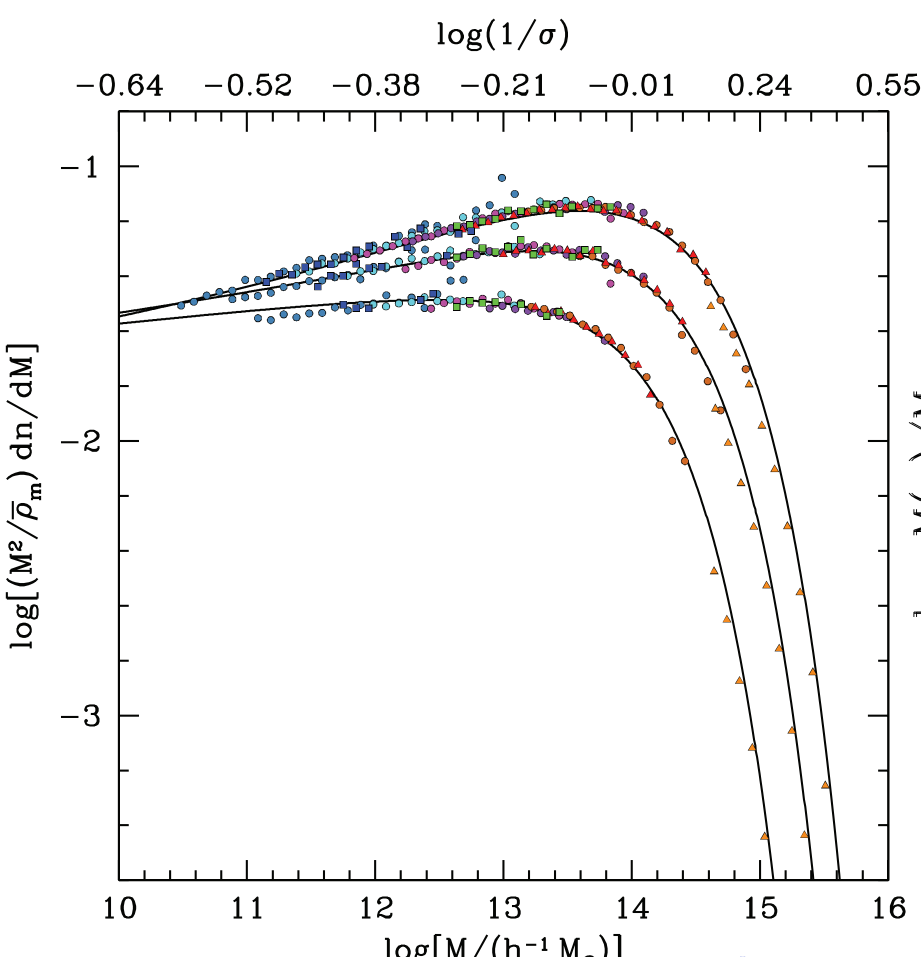


***Post-processing*:**

Identify halos, substructure, merger tree.

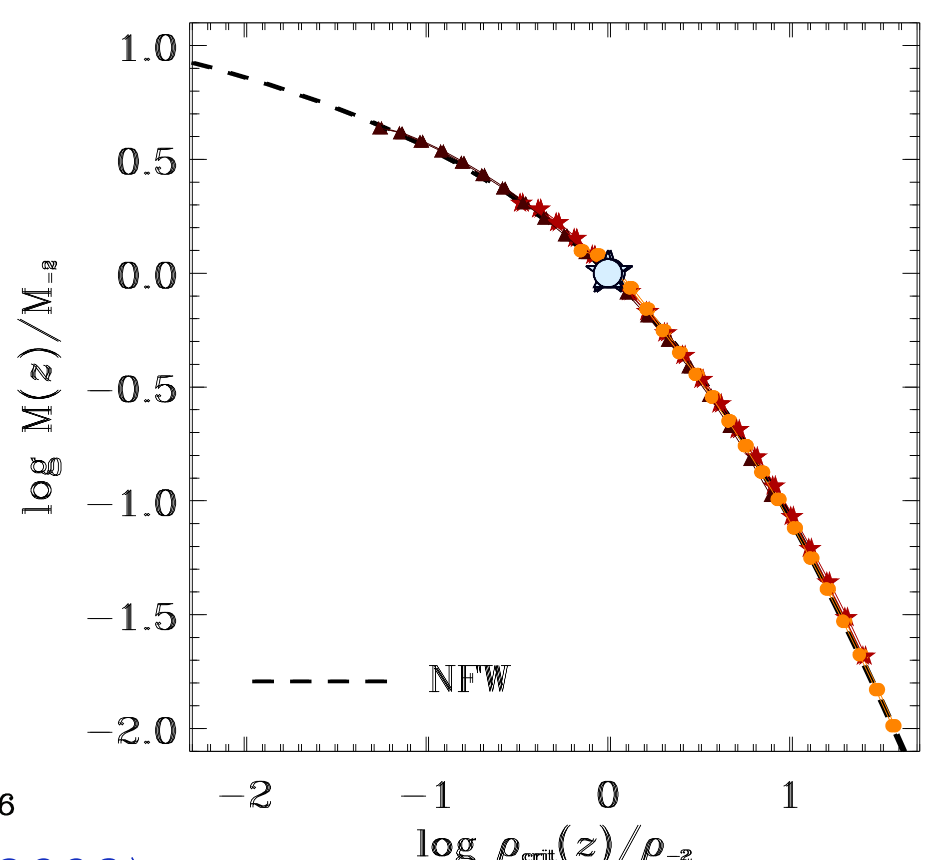
***Predictions*:**

Halo + subhalo mass functions, accretion history, clustering (halos/DM).

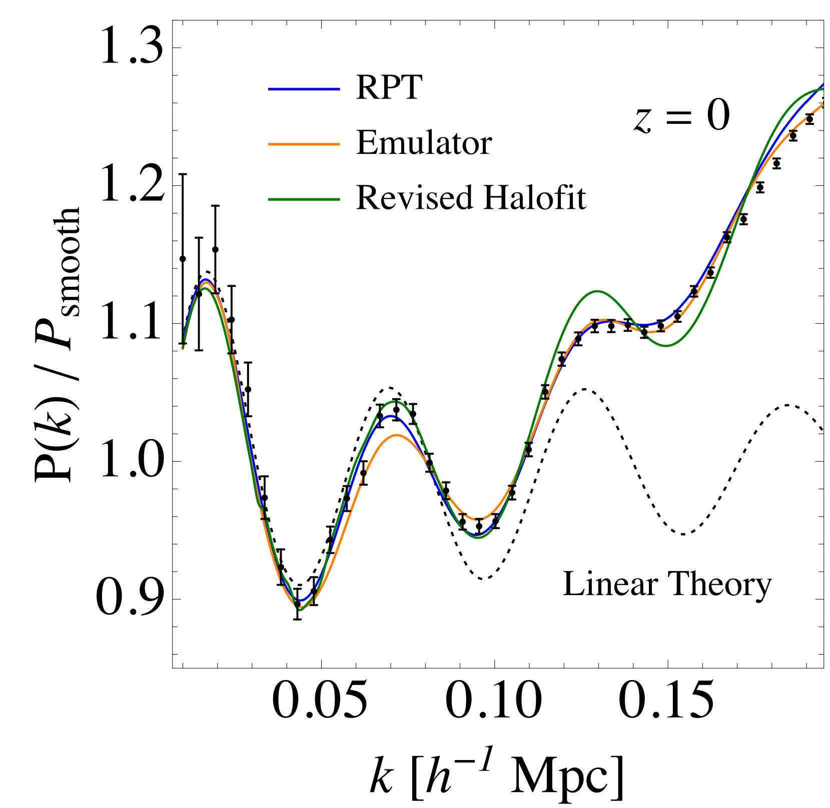


Tinker+ (2008)

Ludlow+ (2016)

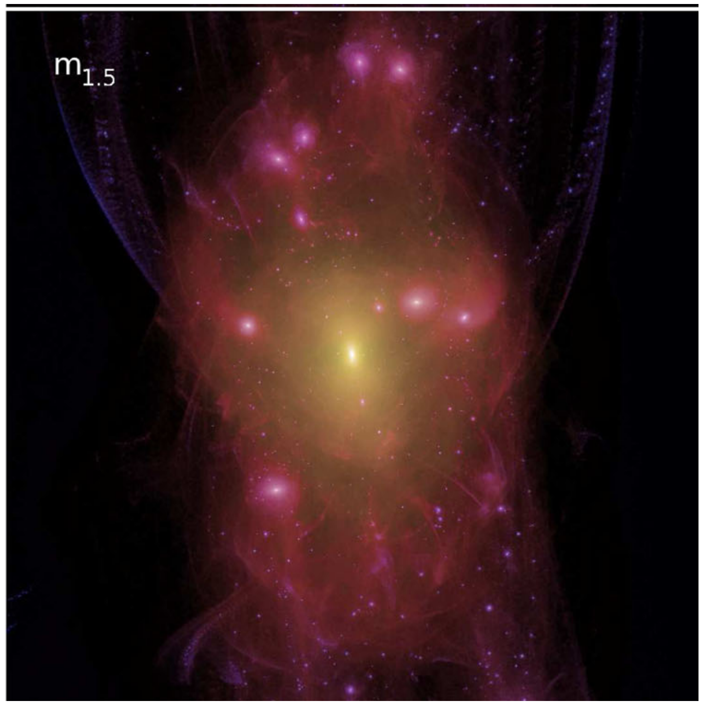


Fosalba+ (2015)



Simulations: beyond CDM

Numerical issues

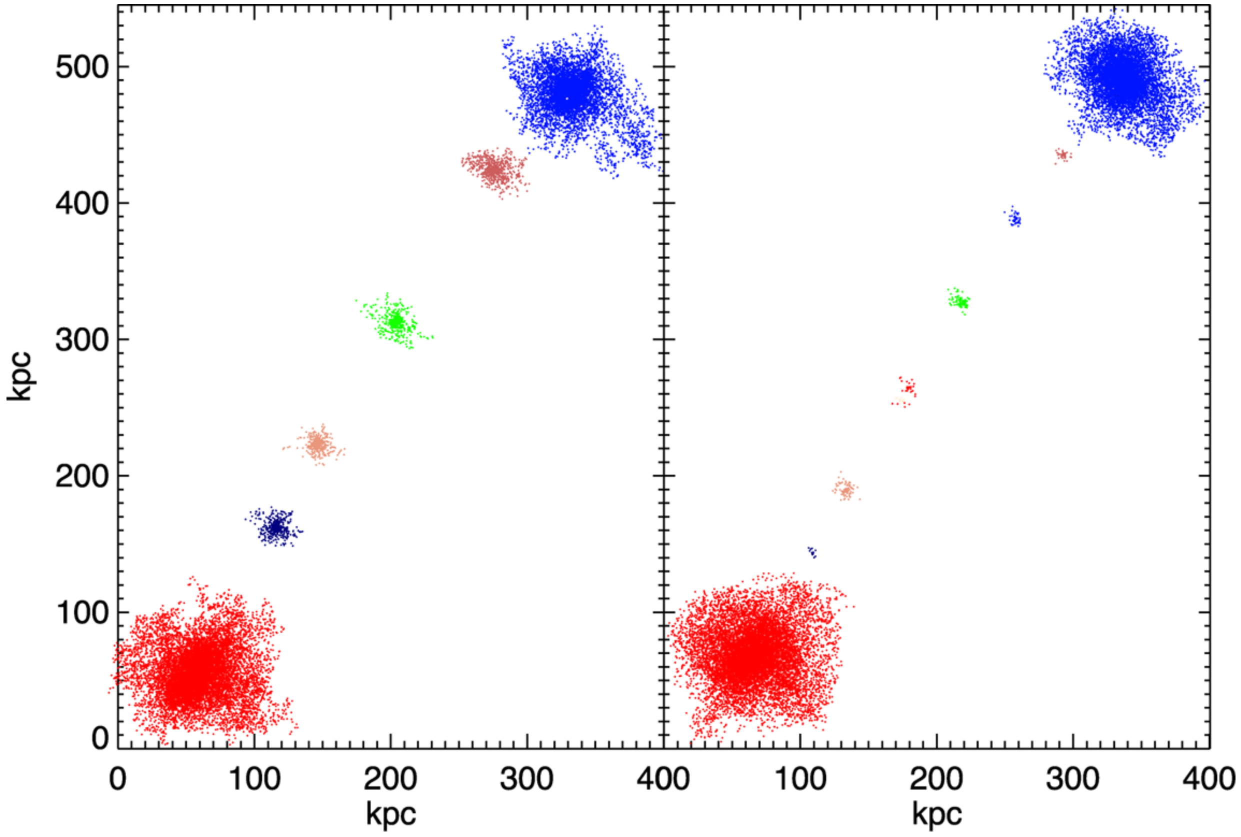


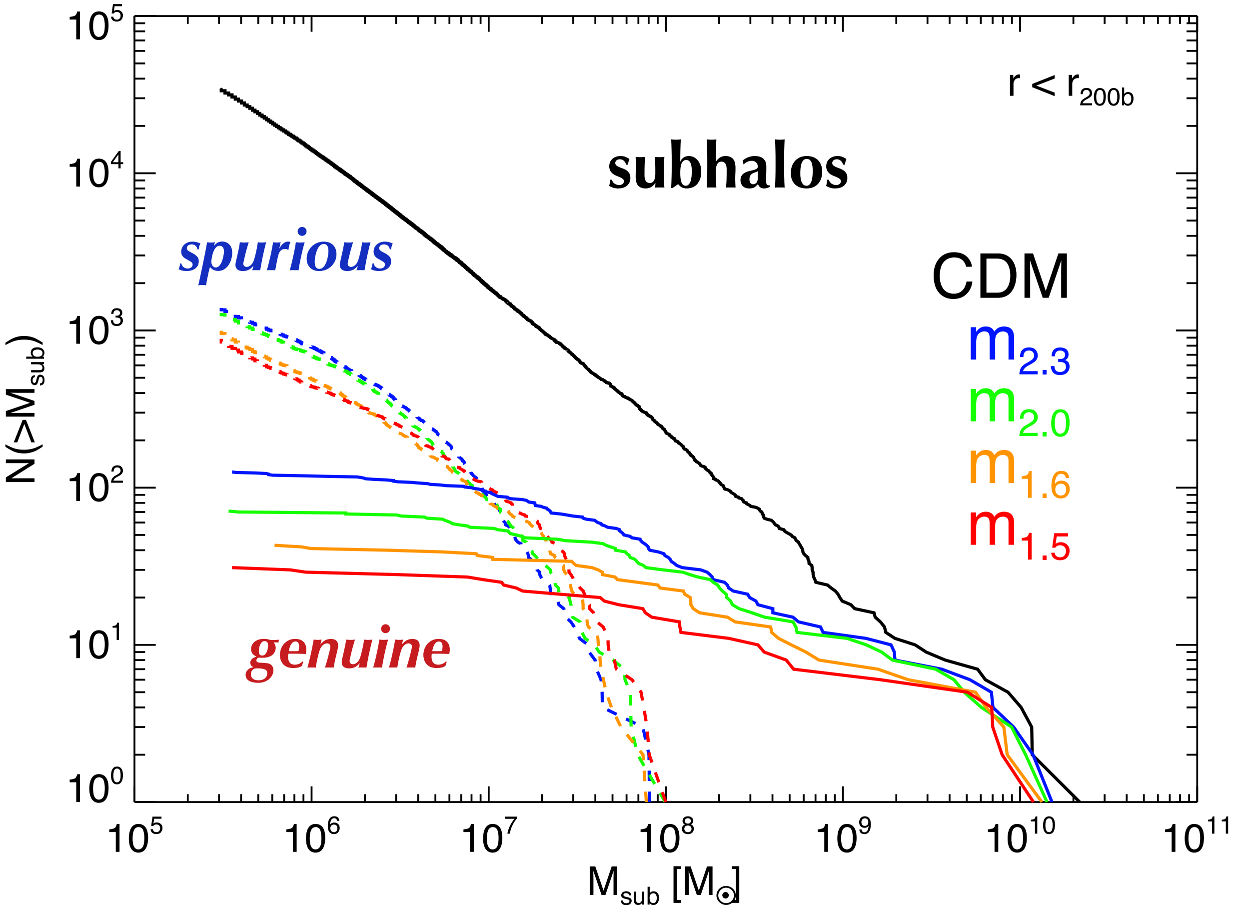
***Case study*:**
Warm DM (same as CDM but with cutoff in initial power spectrum)

- Ignore thermal dispersion at z <~ 100 (where simulation ICs are usually set.) *[[not good for neutrinos!]]*
- So just replace IC file and run N-body code!! *[[wouldn't work for SIDM / ALP]]*

***Problem*:**
discretisation noise → spurious perturbations (which gravitate) → ***spurious halos!***

Lovell+ (2014)





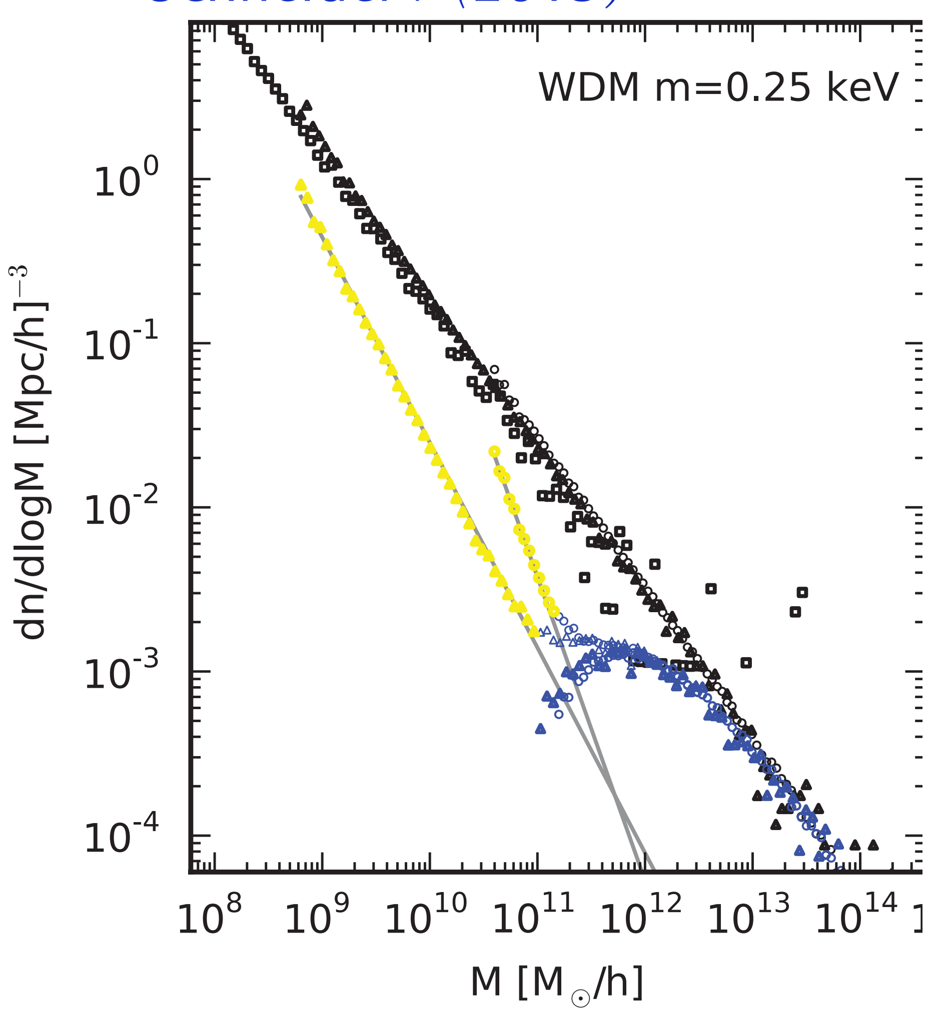
Simulations: beyond CDM

Numerical issues

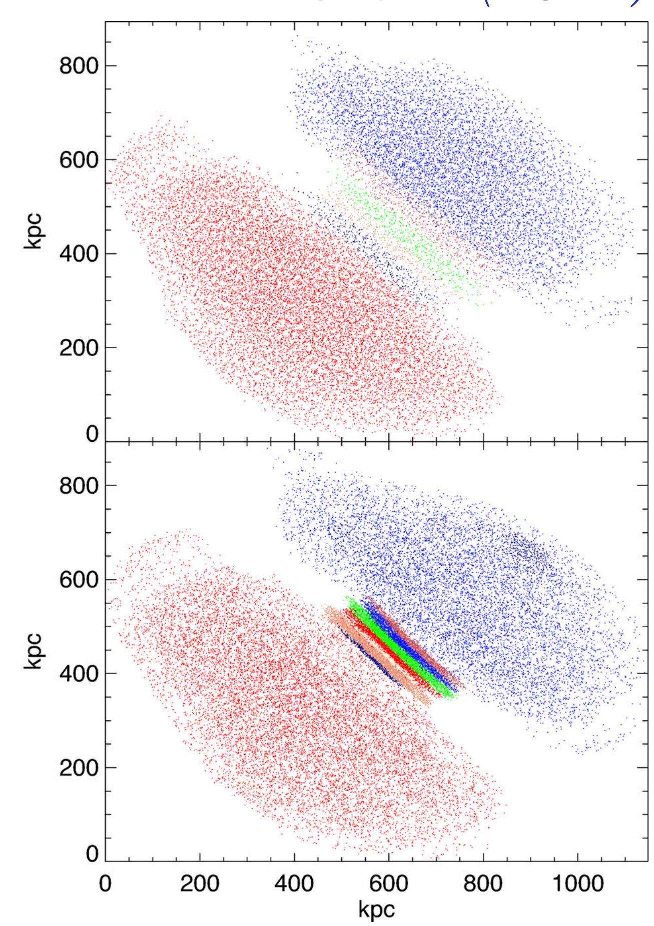
Solutions:

- statistical (limited use).
- clean up catalogs object-by-object (better than statistical).
- move to phase-space interpolation techniques (currently expensive)

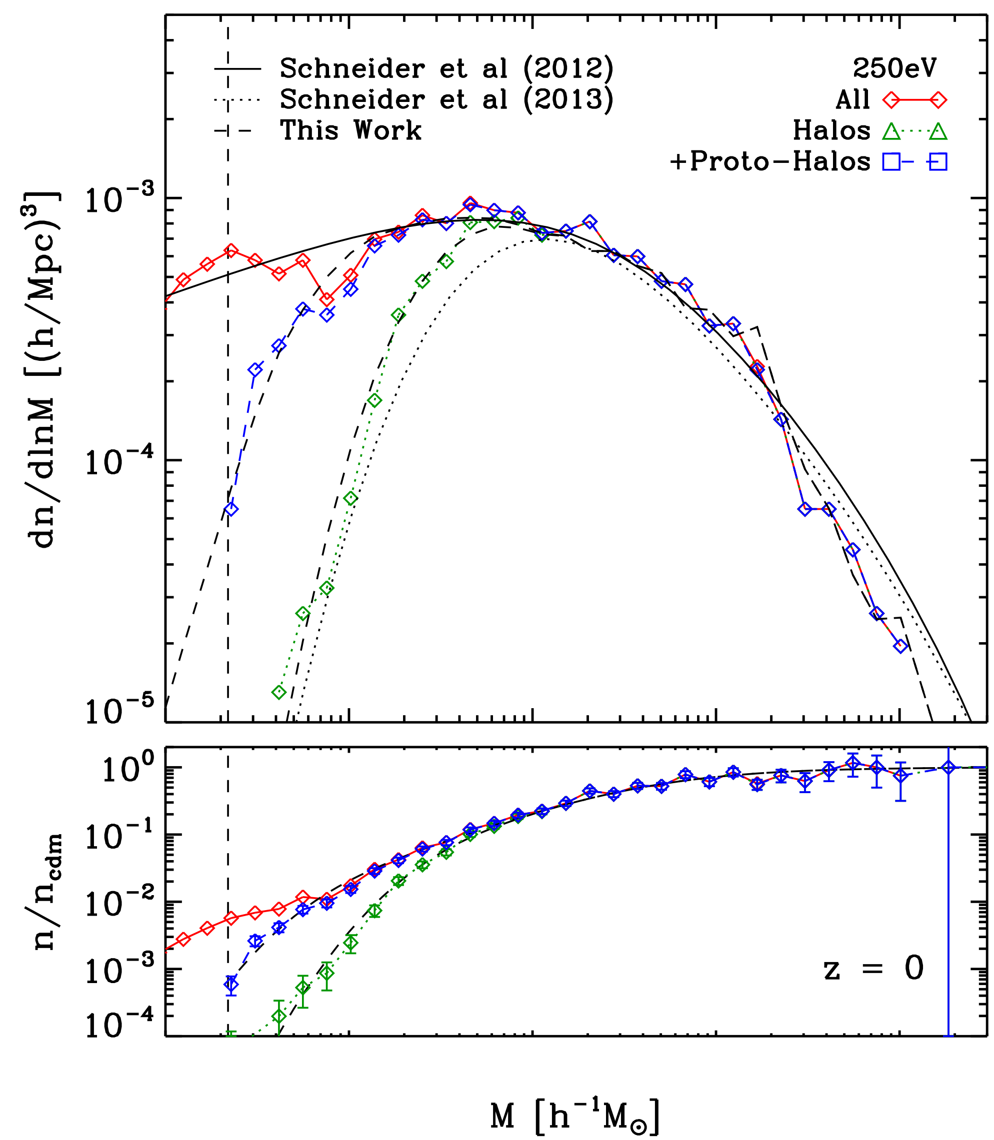
Schneider+ (2013)



Lovell+ (2014)



Angulo+ (2013)



Summary

- Galaxy-DM connection has many interesting “features”. Most (*all?*) of these can be understood using CDM within the uncertainties of astrophysical modelling.
- Simulations of CDM have a long history and make robust predictions. Simulations of nonCDM are relatively recent and are getting there.
- Caveats are everywhere!