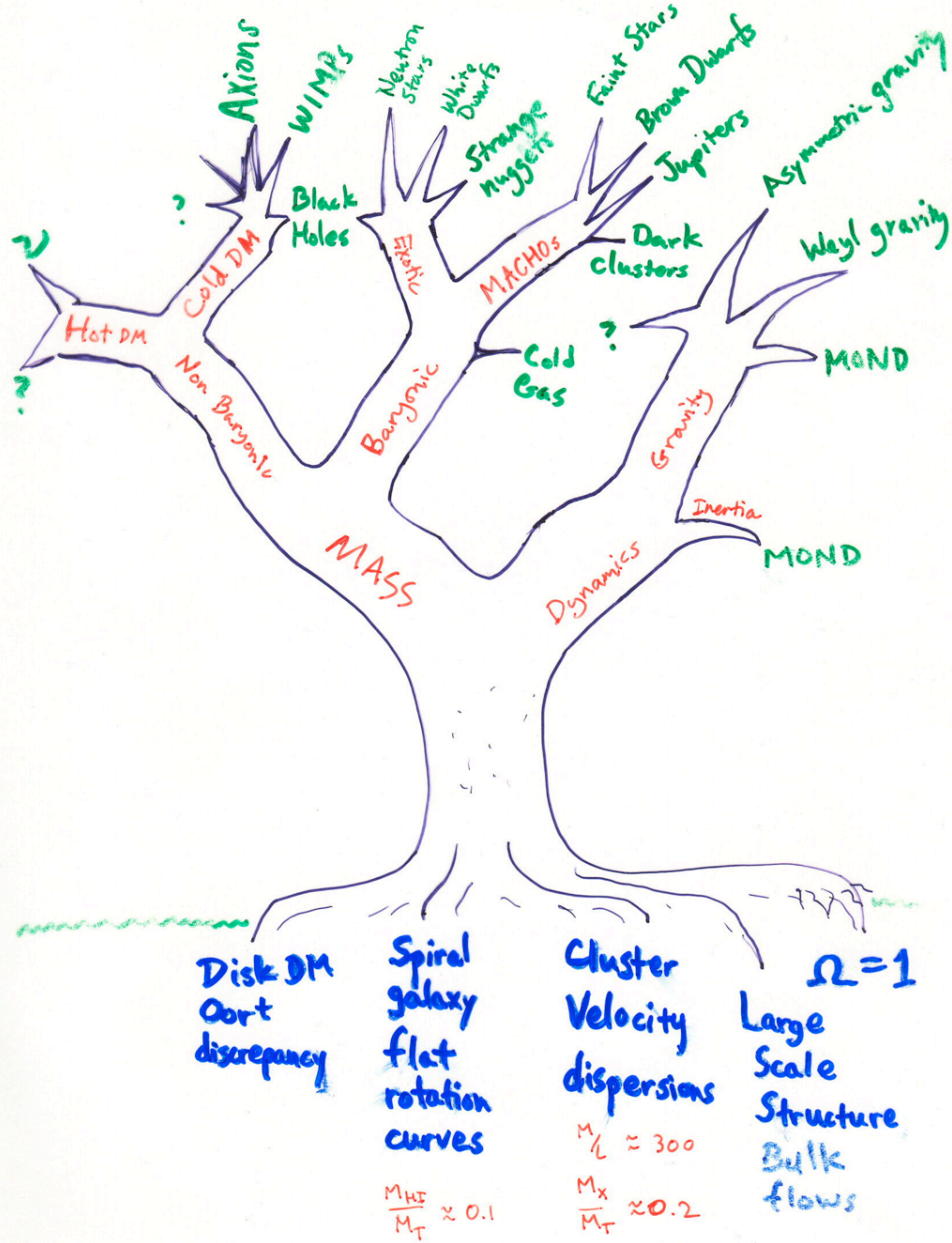
Dark Matter

ASTR 333/433

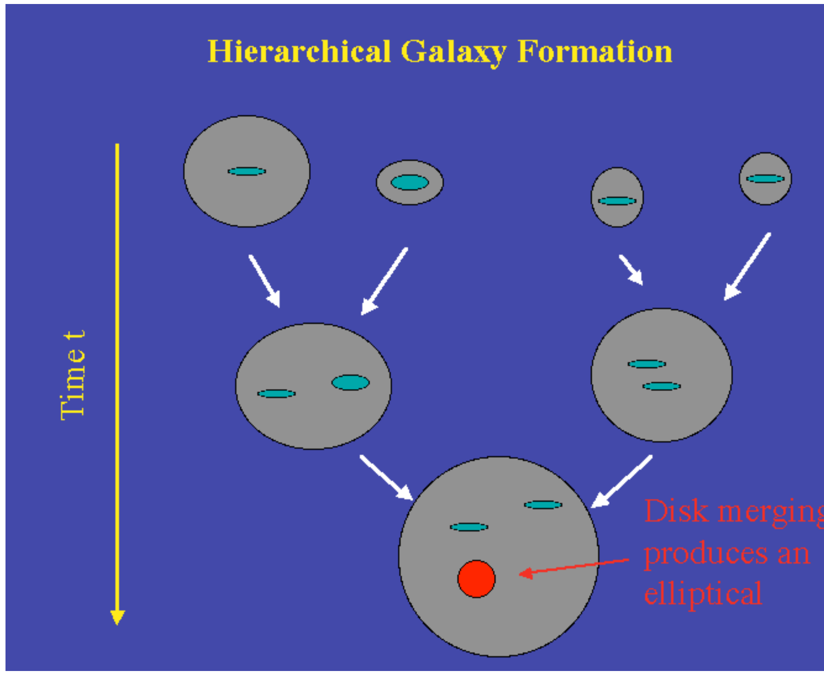
TODAY

Galaxy Formation

A few problems



Galaxy formation with Cold Dark Matter



CDM first, then baryons — hierarchical

1. **Dark matter halos form**; **merge** into ever larger masses
2. **Baryons fall in** to the potential wells of DM halos
3. **Gas cools, sinks** to centers of DM halos
   - Halos compressed by sinking baryons
   - gas forms rotating disks at centers of DM halos
4. **Stars form** in disks
   - *Feedback* heats gas, dissuading further gas accretion

     invoked to fix various problems
5. Mergers transform some disks into ellipticals
   - star formation truncated
6. Renewed gas accretion may re-form disks around ellipticals
   - thus becoming the bulges of S0s and early type spirals
7. Merging lessens; more gradual accretion of dark matter and gas may continue
8. **Galaxies**

Fundamental elements in **bold**; other details subject to revision.
"Feedback / baryonic physics" is an auxiliary hypothesis invoked to save the phenomena

Generic CDM problems

- Too much mass at small radii
  - Cusp-core problem (esp. in dwarfs)
  - Massive bulges too common
- Missing Satellites / Satellite Planes / Too Big to Fail
  - too few satellites around bright galaxies
    - phase space wrong
  - mass function problem in the field (not just satellites)

Generic prescription: Feedback

Condensation

Gas falling into a DM halo shock heats to the virial temperature

$$T_{vir} = \frac{2}{3}\frac{GM_{vir}}{R_{vir}}\frac{\mu m_H}{k_B}$$

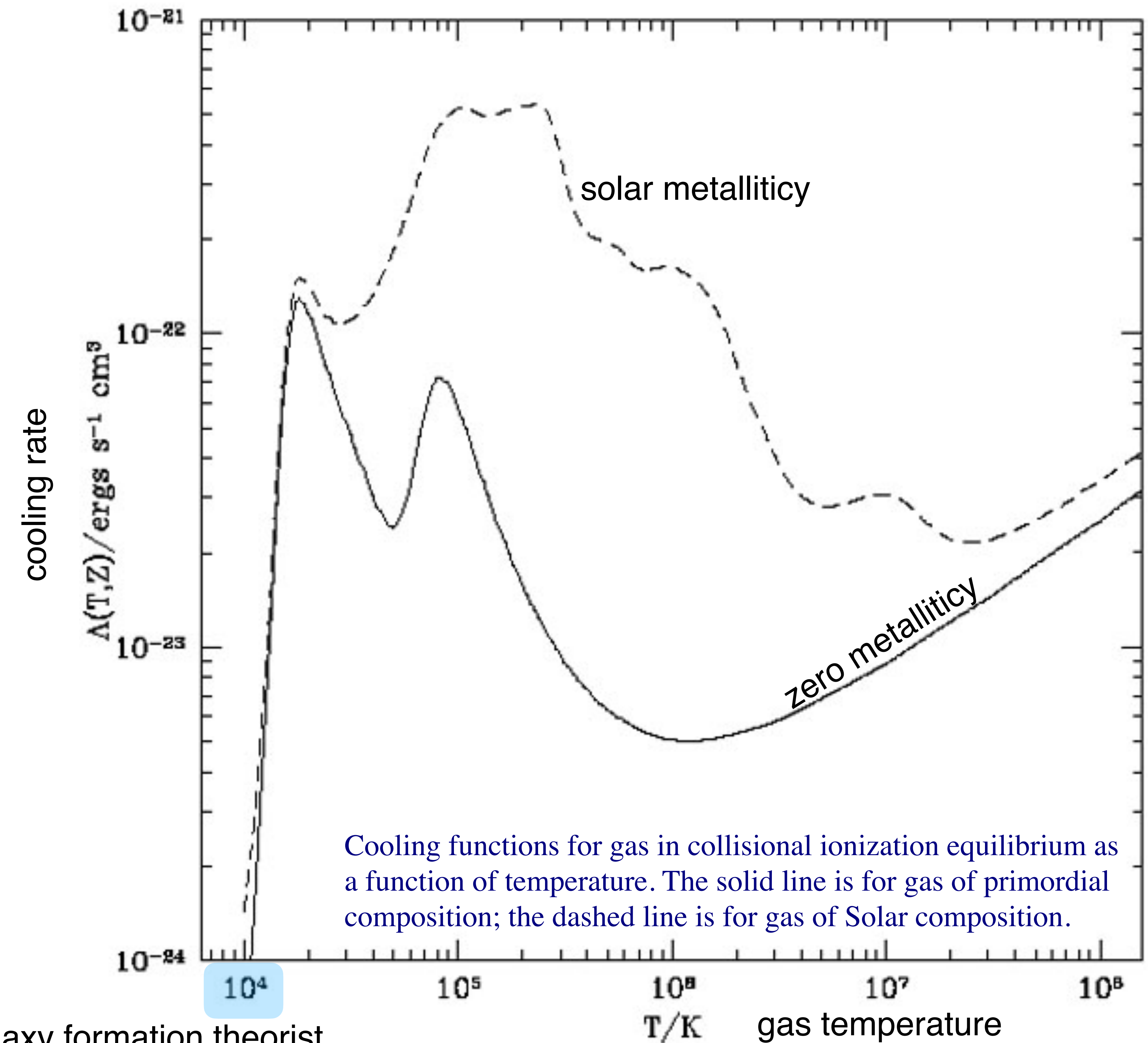
In absence of cooling, supported in hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{GM(r)}{r^2}\rho(r)$$

Gas cools inside out at a rate that depends on density and metallicity

$$\mathscr{L} = n_H^2\,\Lambda(T,Z)$$

Even a small amount of heavy elements provide a lot of emission lines that enhance the cooling rate.



Cooling functions for gas in collisional ionization equilibrium as a function of temperature. The solid line is for gas of primordial composition; the dashed line is for gas of Solar composition.

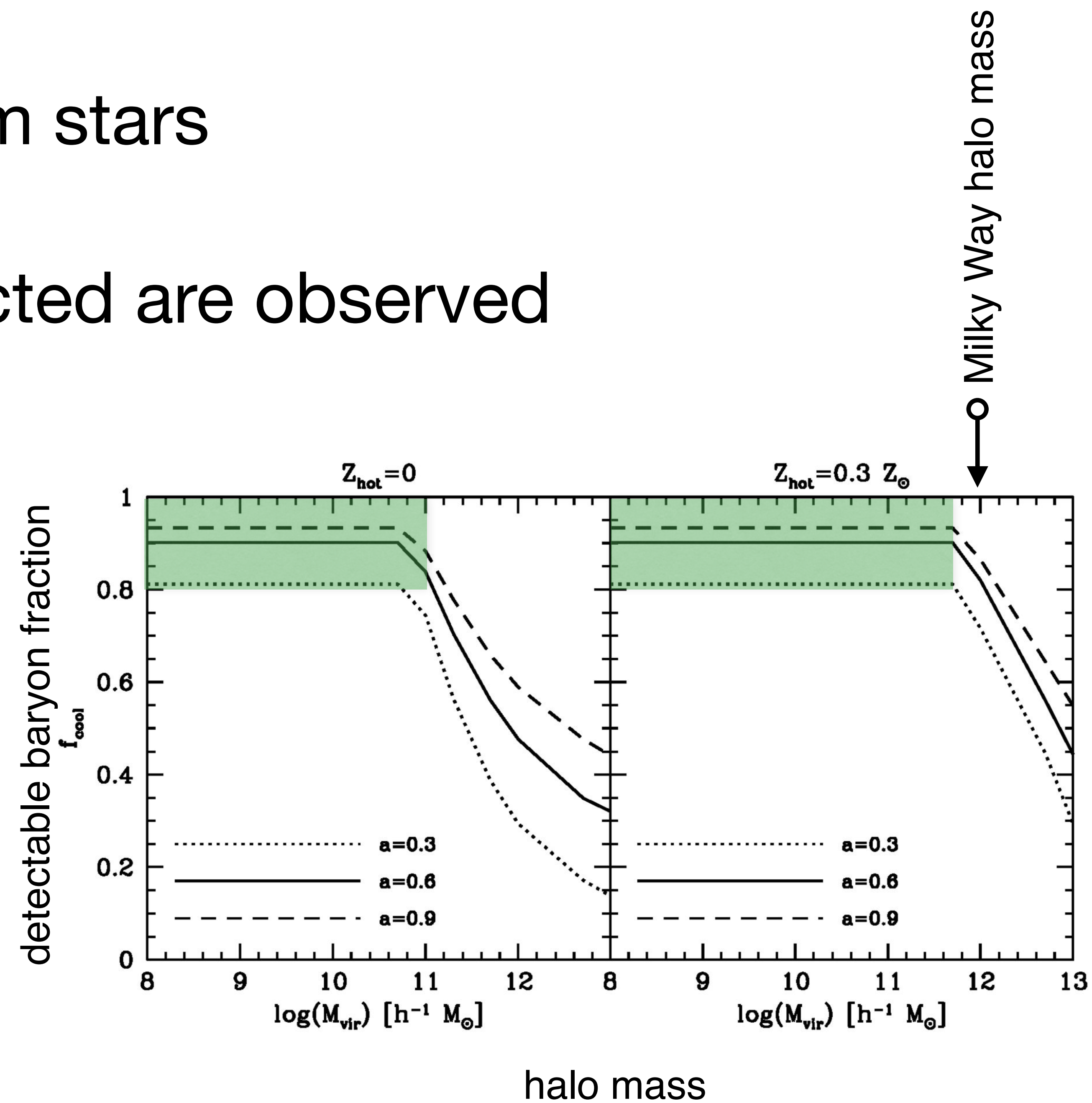
Any $T < 10^4$ K is “cold” to a galaxy formation theorist.

Condensation problem

- Baryons in low (galaxy) mass halos have time to cool
  - Should condense & form stars
- Fewer baryons than expected are observed

The fraction, f_{cool}, of baryonic mass inside the virial radius that has cooled and settled in present-day discs as function of the present-day virial mass. (van den Bosch 2001)

Nearly all baryons in galaxies have time to cool; should result in the baryon fraction on each halo being close to the cosmic baryon fraction (16%) and the galaxy luminosity function paralleling the halo mass function.



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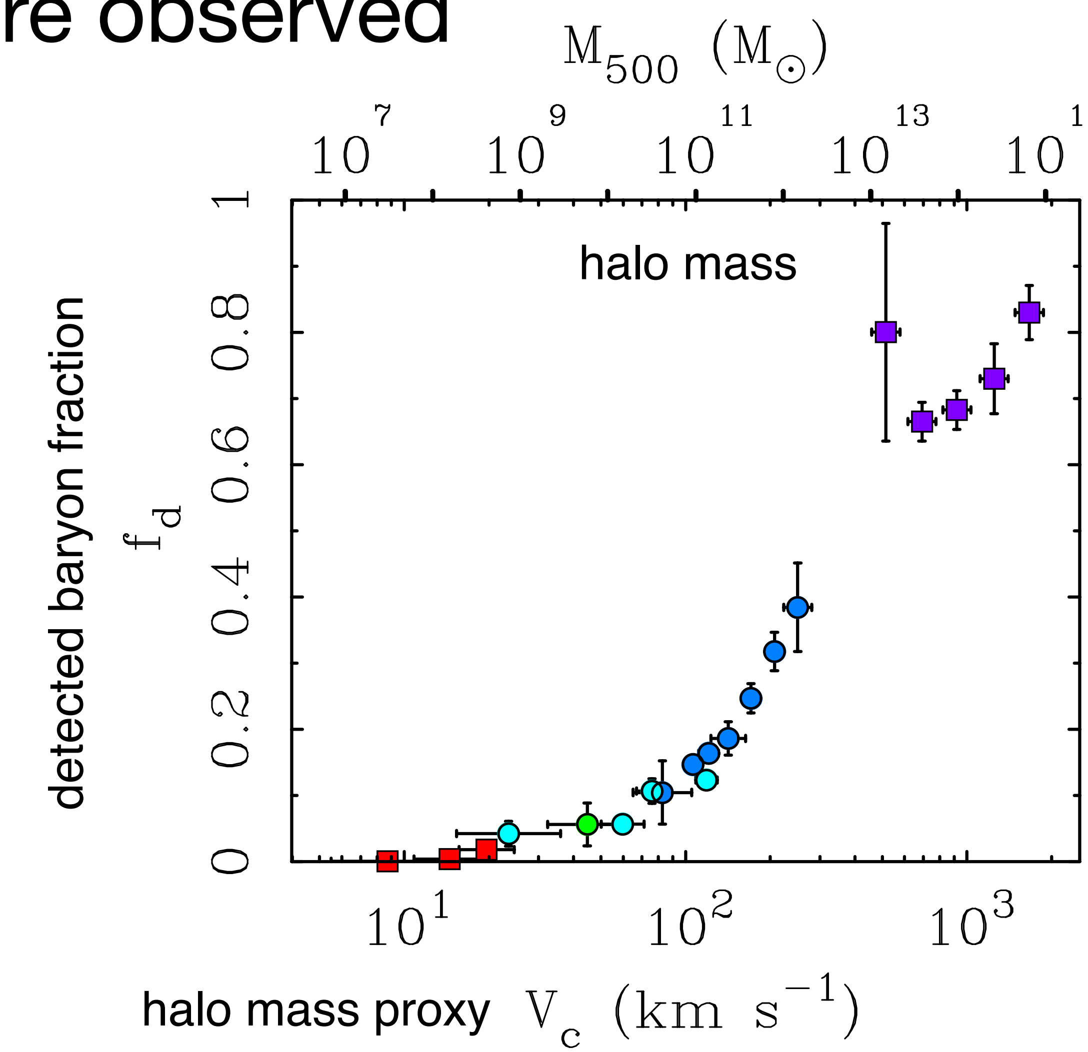
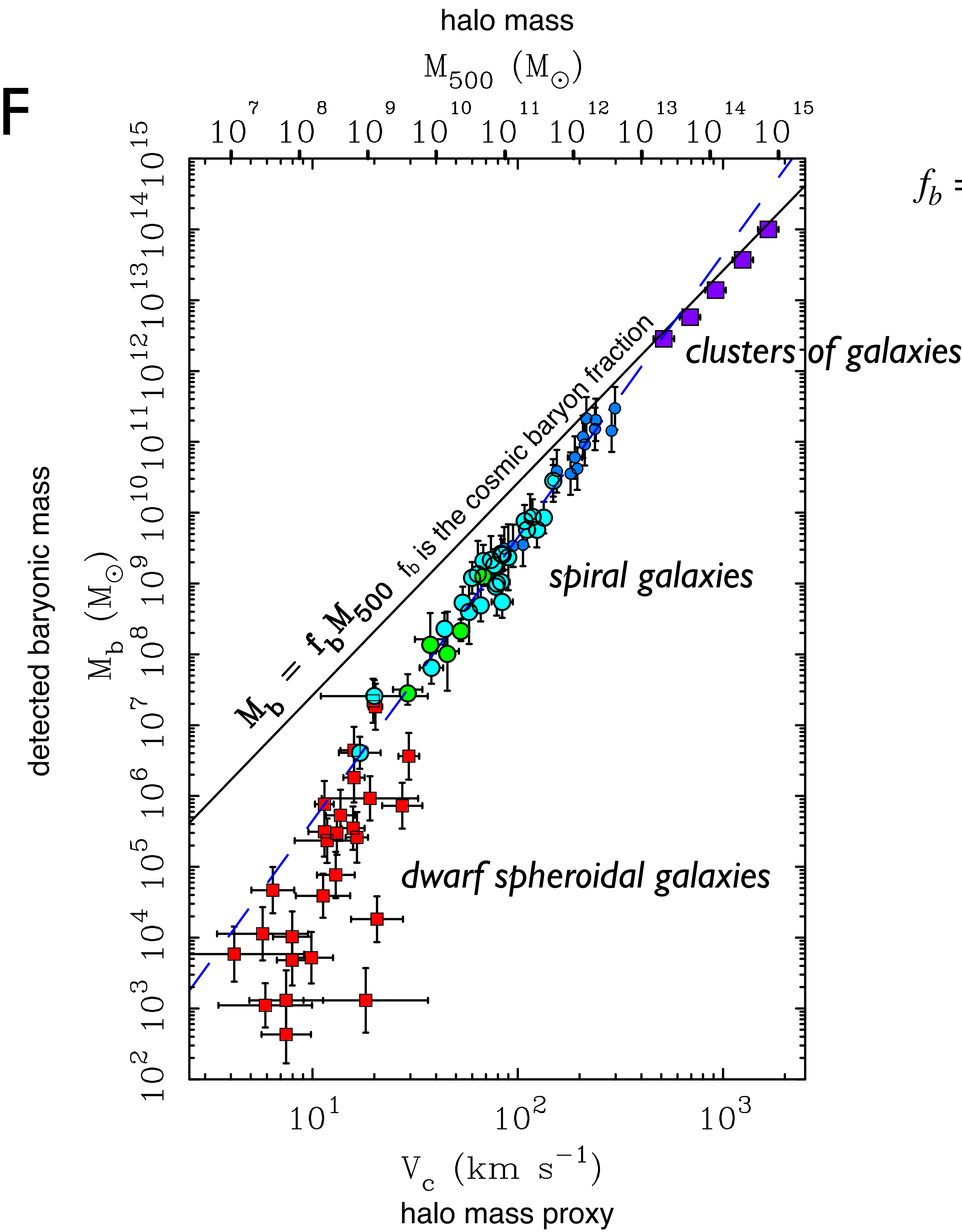


Extended TF

$$f_b = \frac{\Omega_b}{\Omega_m}$$

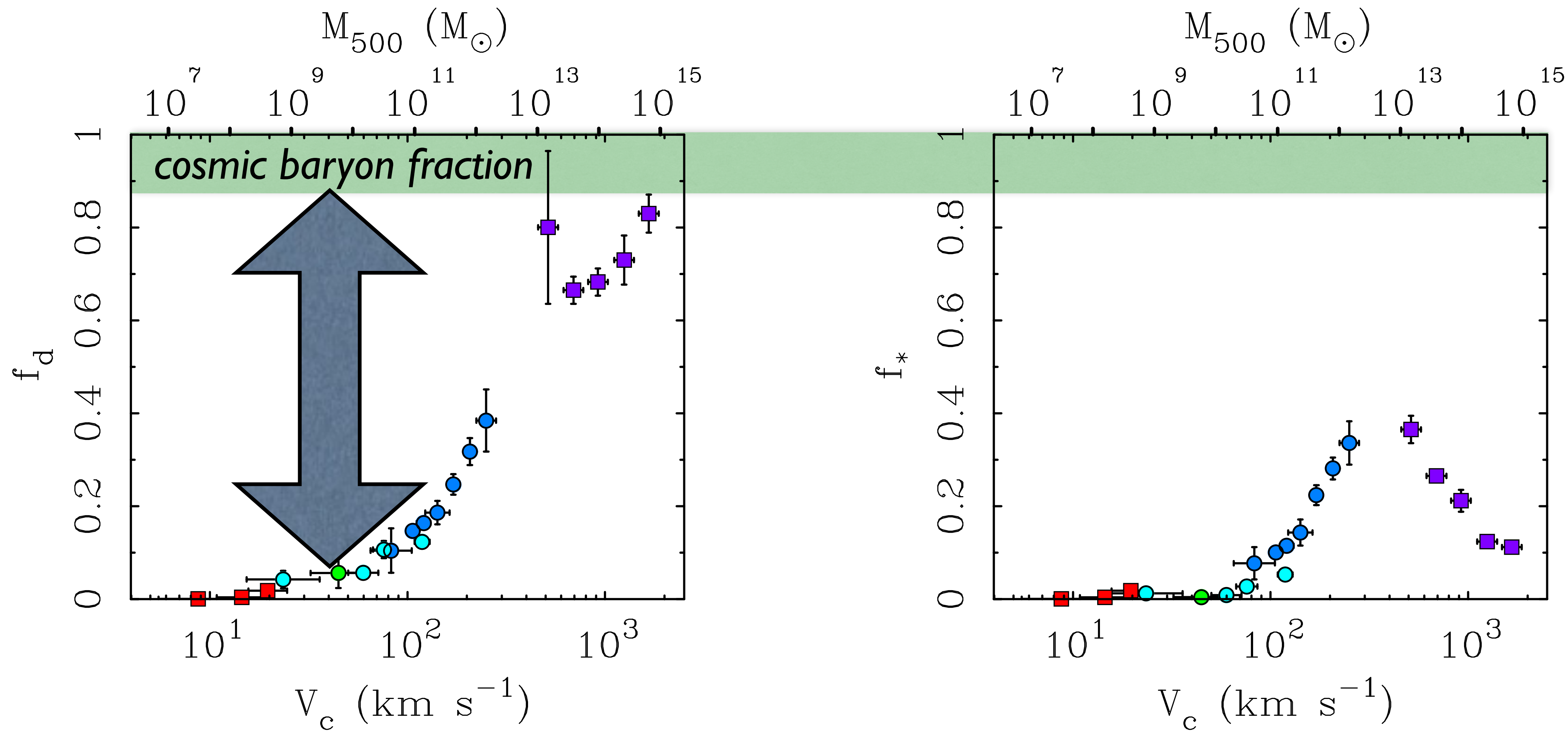


McGaugh et al. (2010)

$$f_d = \frac{M_b}{f_b M_{500}}$$

$$f_* = \frac{M_*}{f_b M_{500}}$$

$$f_b = \frac{\Omega_b}{\Omega_m}$$



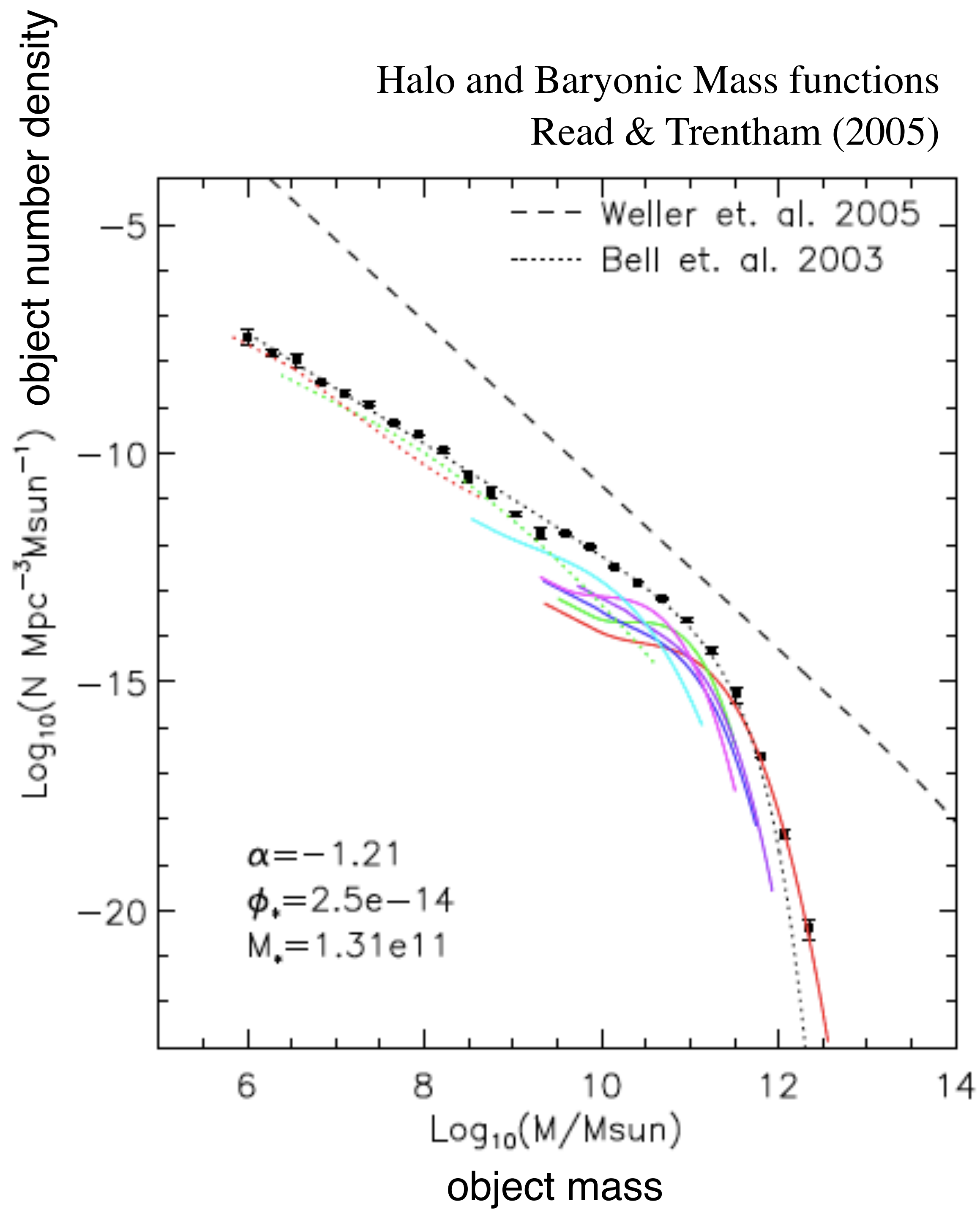
McGaugh et al. (2010)

Halo by halo missing baryon problem

2 missing mass problems: baryonic AND non-baryonic DM

Condensation problem

- Galaxy luminosity function should descend from the halo mass function
  - predicted: steep power law
  - observed: Schechter fcn with shallow faint end slope
- Fewer galaxies than expected are observed



Baryonic Mass Function
(Read & Trentham 2005)

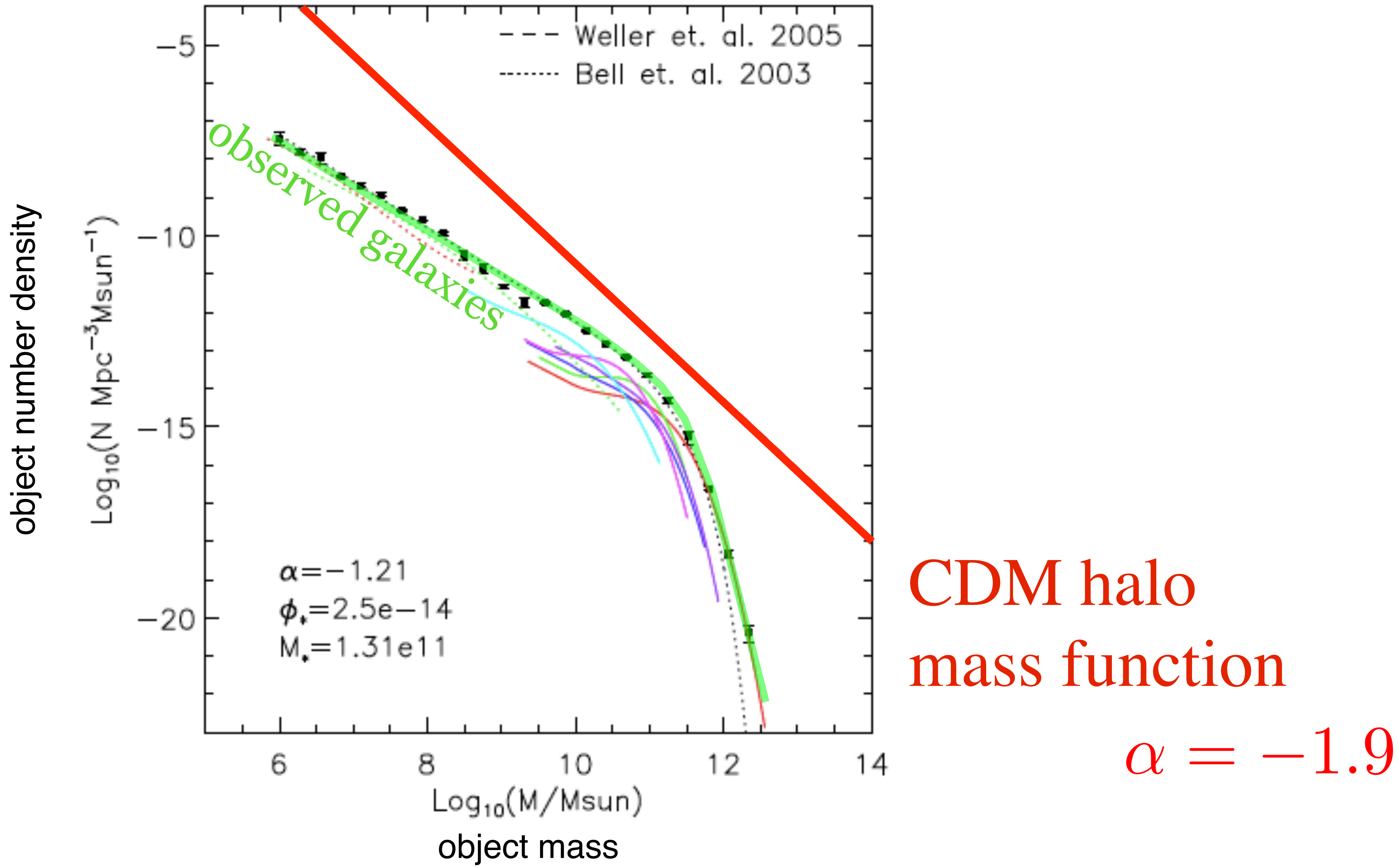
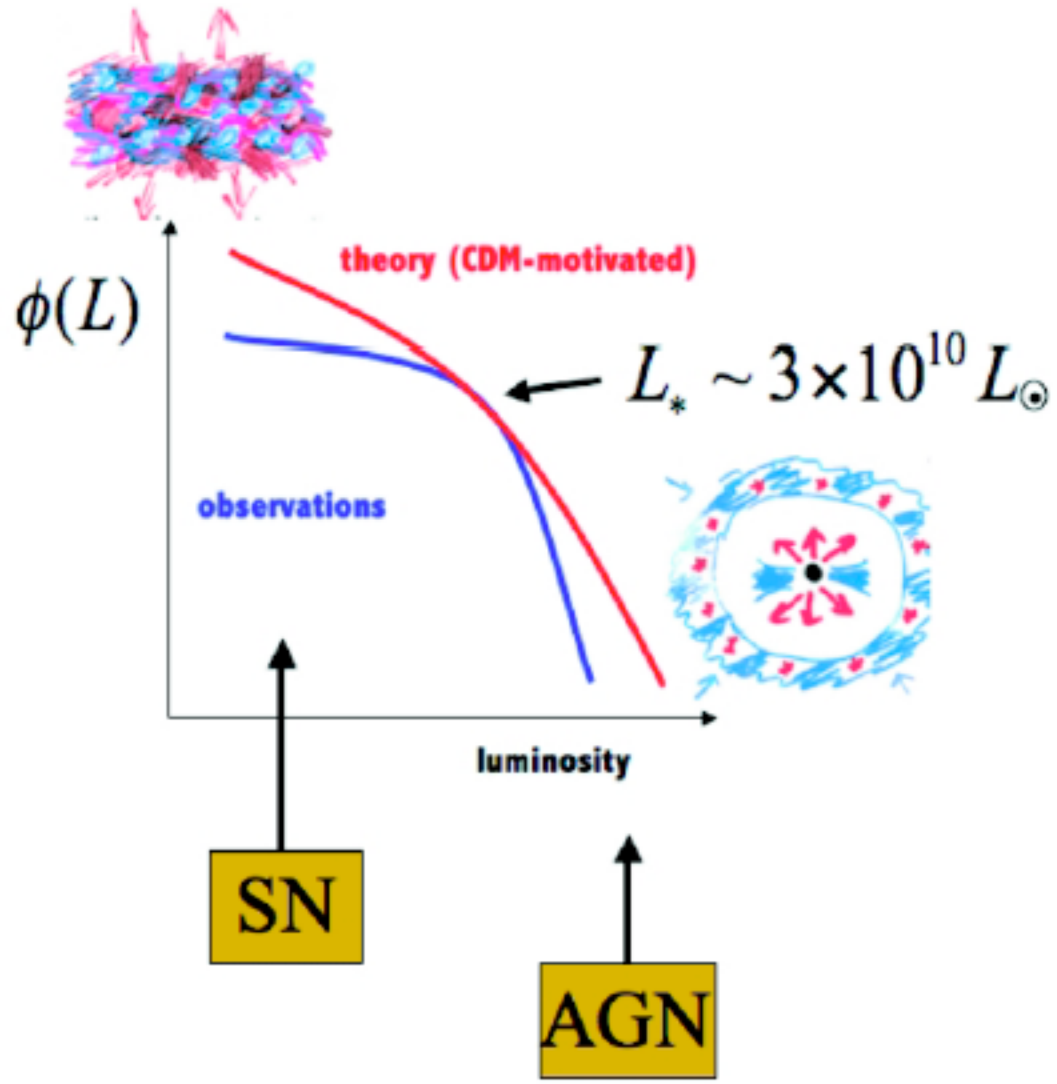


Figure 4. The field galaxy baryonic mass function. The data points are for all galaxies, while the lines show spine fits by Hubble Type. The lines are as in Figure 2. The CDM mass spectrum from the numerical simulations of Weller et al. (2004) is also shown. Overlaid are parameters for a Schechter fit to the total mass function.

Feedback

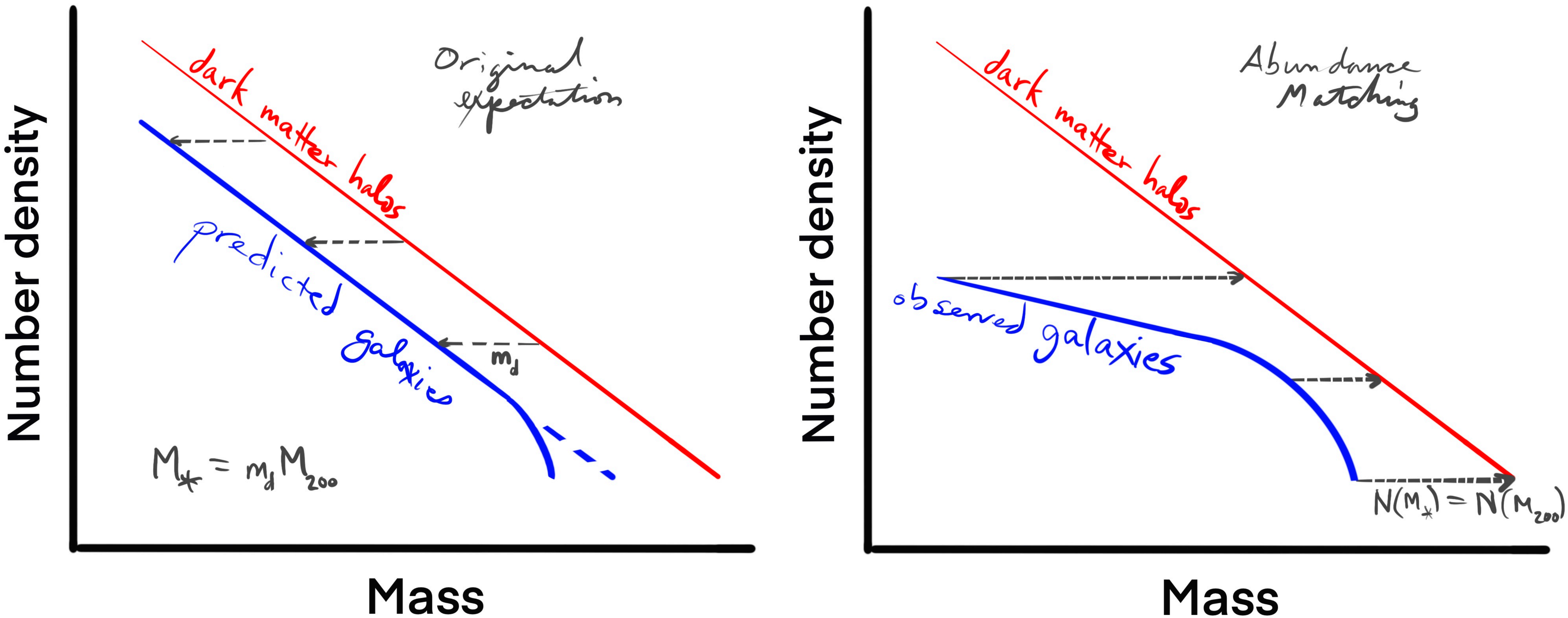
See notes for example feedback scheme (Dutton)



Basic idea: SN affect low mass halos

Energy from supernovae and other sources (e.g., stellar winds, radiation pressure) heats the surrounding gas, preventing it from cooling as expected, altering the shape of the galaxy luminosity function from the predicted halo mass function.

Abundance Matching

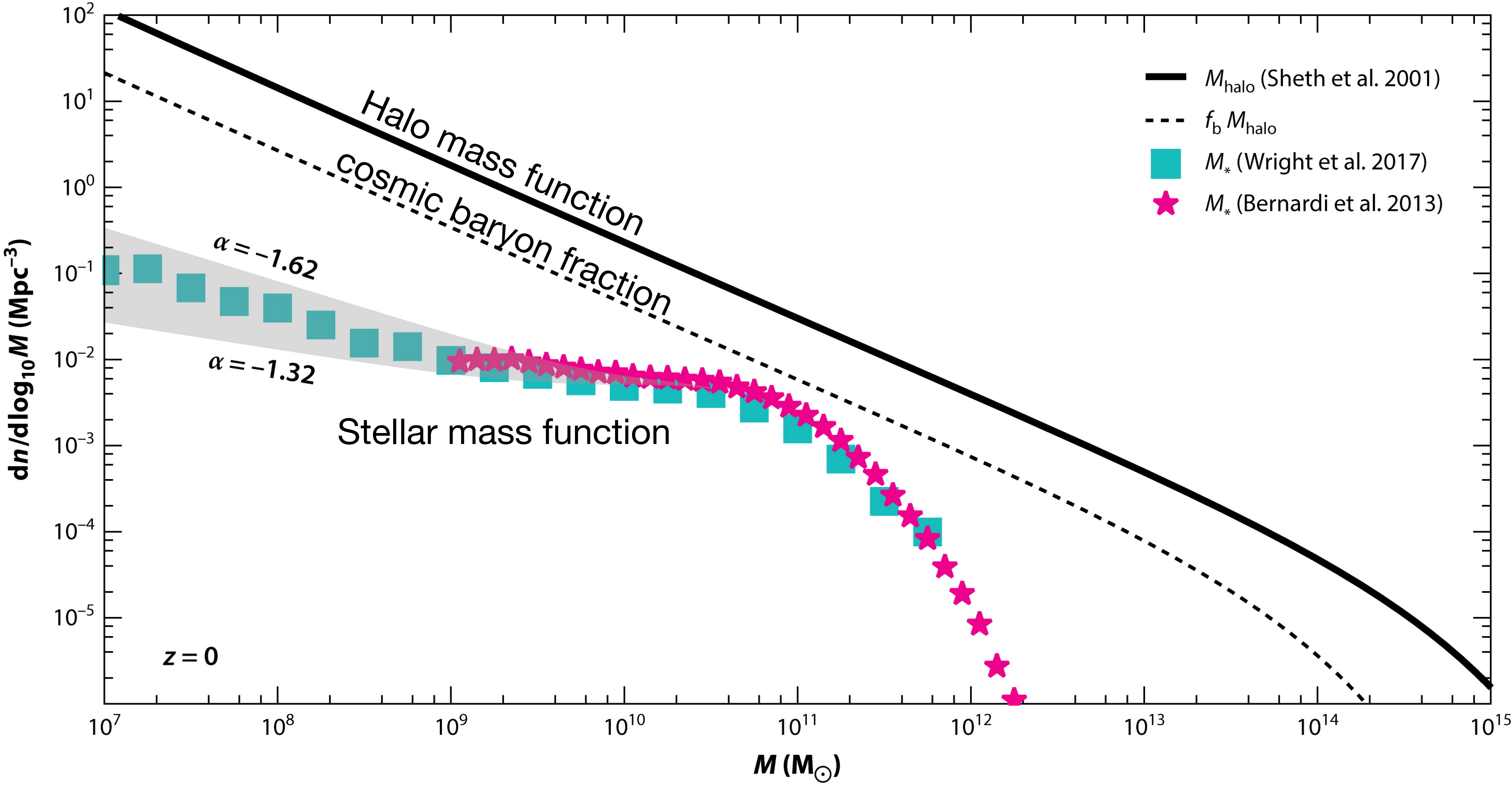


There is no predictive theory for the effects of feedback, so simply match the observed number density of galaxies to the predicted number density of dark matter halos.

$$f_* = \frac{M_*}{M_{200}}$$ varies with M_*

Halo and stellar mass function

(Bullock & Boylan-Kolchin)

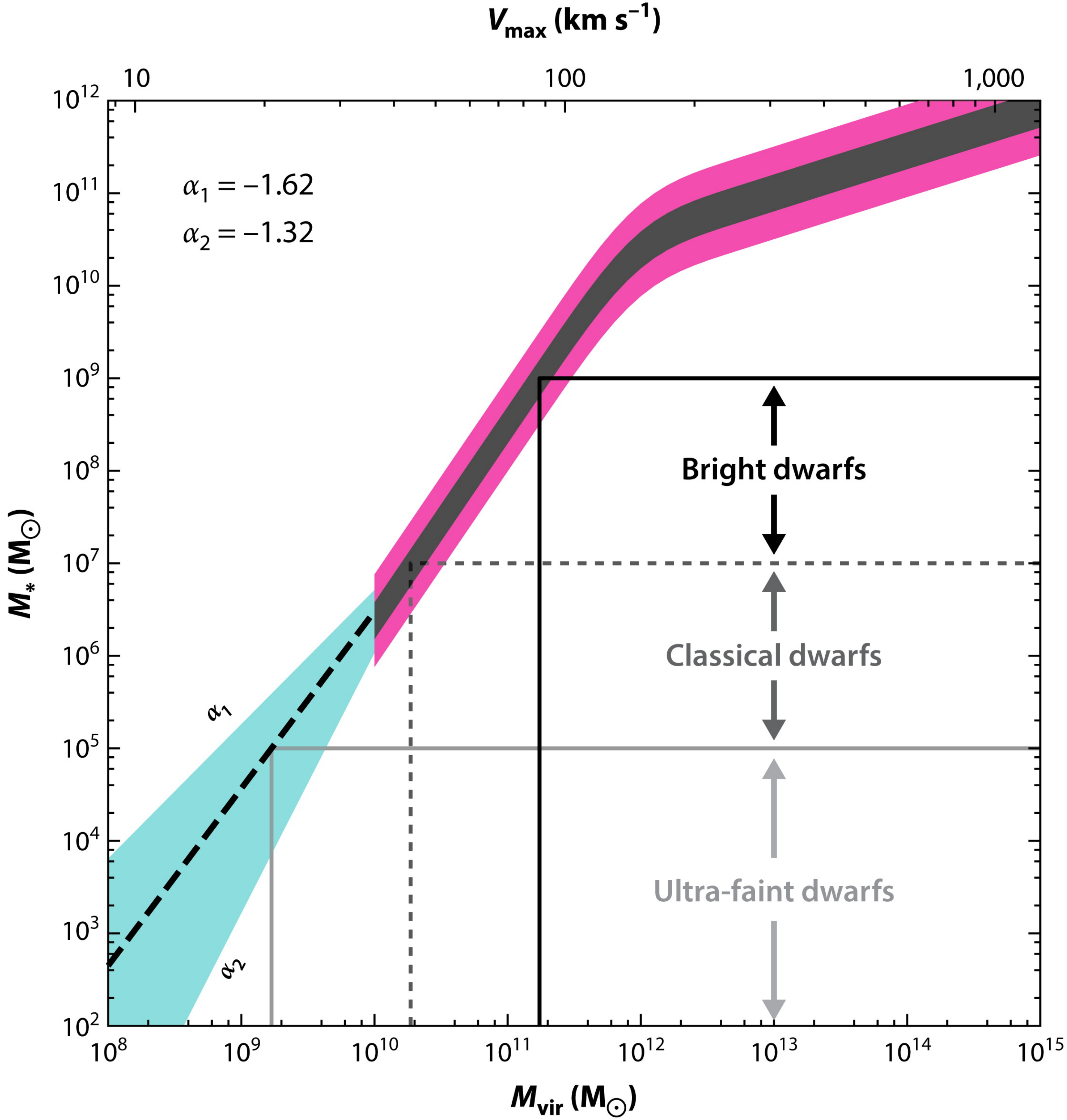


Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

$$f_* = \frac{M_*}{M_{200}} \quad \text{varies with } M_*$$

Abundance Matching

(Behroozi; by way of Bullock & Boylan-Kolchin)



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Abundance Matching

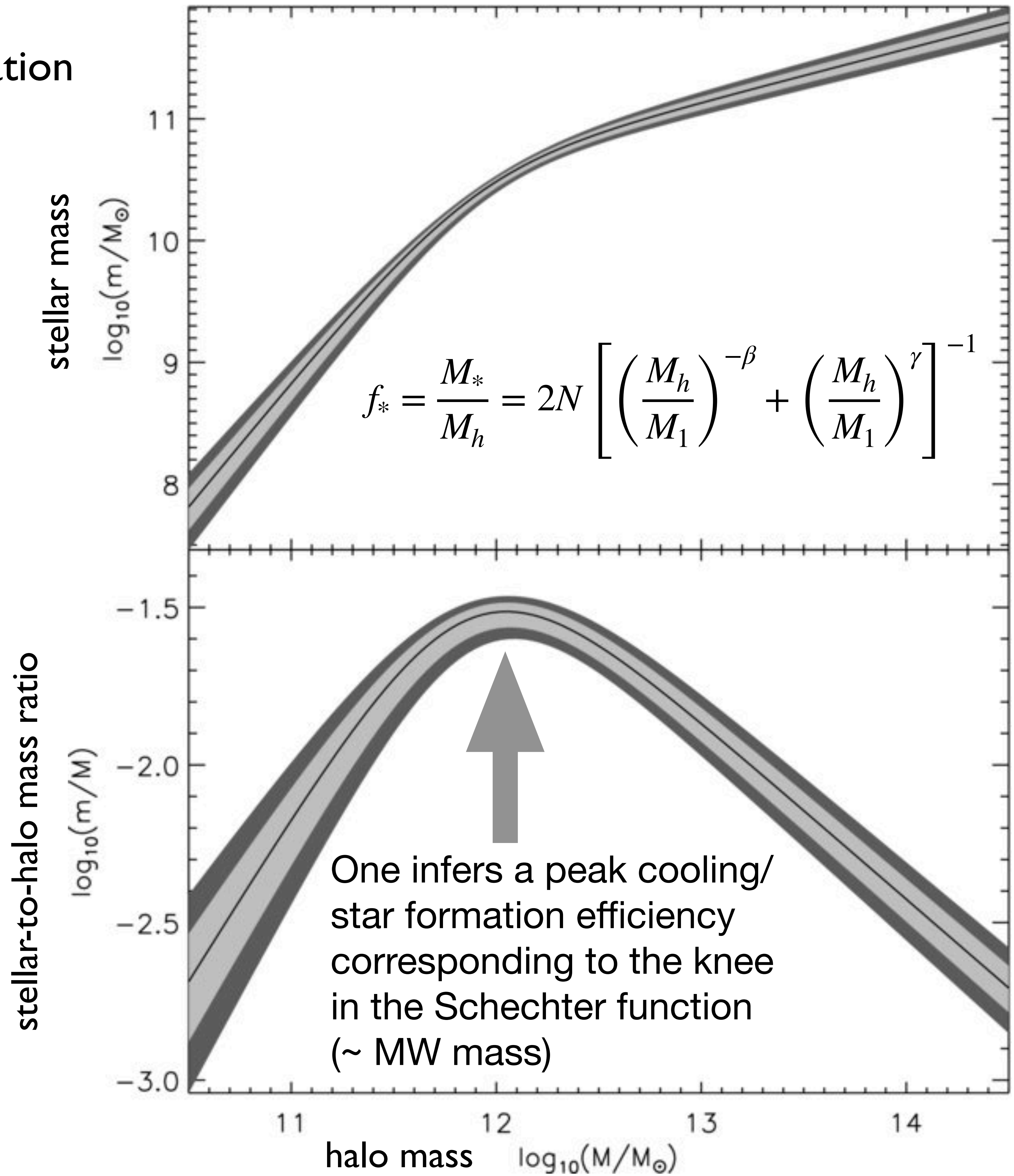
Stellar mass-Halo mass relation

Behroozi et al (2013)
Moster et al (2013)
Kravstov et al (2019)

From "abundance matching"

Match the number density of simulated dark matter halos to that observed for galaxies as a fcn of mass

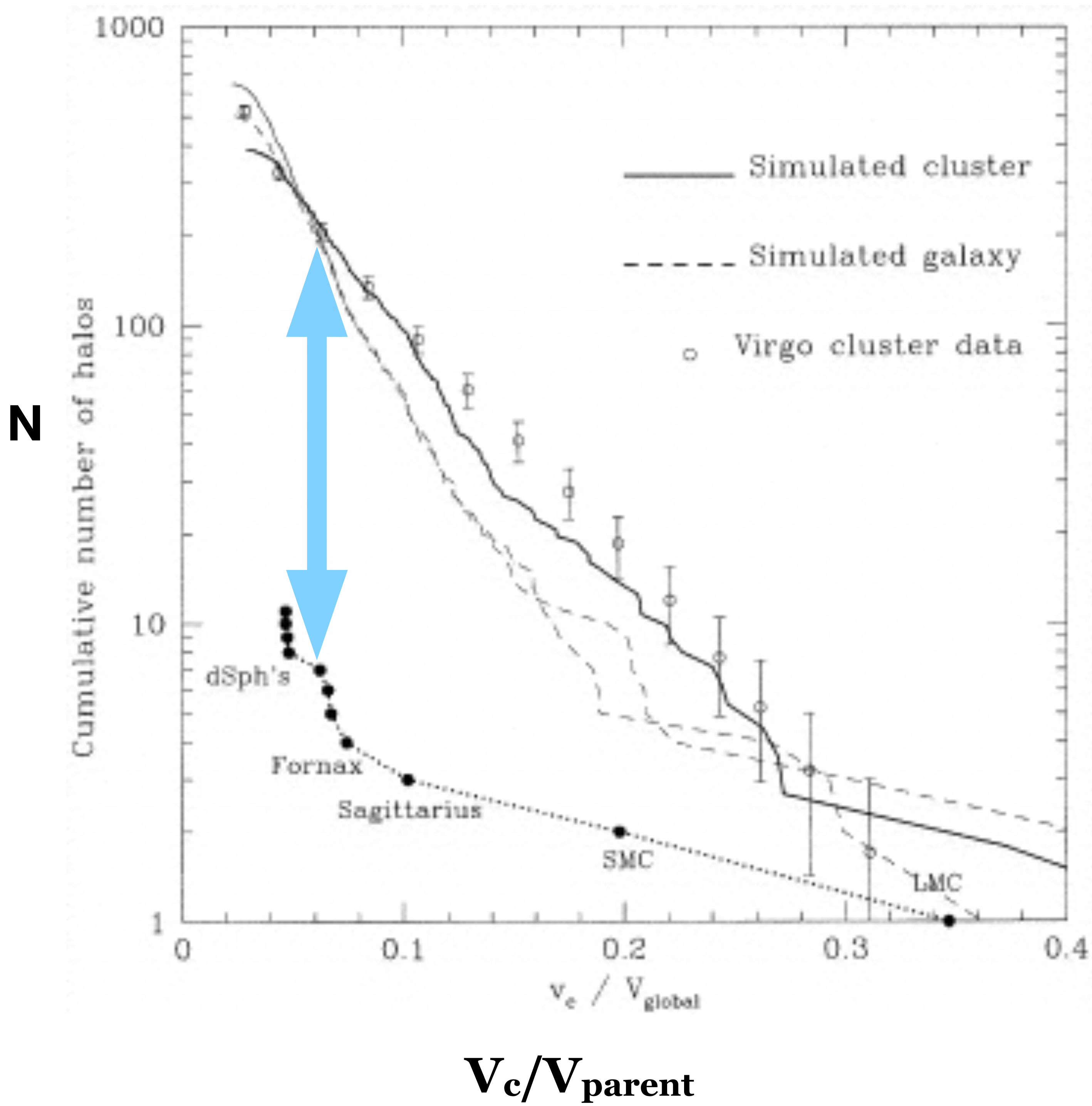
Note that a large range in stellar mass gets wedged into a narrow range in halo mass.



Missing Satellites

e.g., Moore et al. (1999); Klypin et al. (1999)

Same problem as with the field luminosity function:
Too few faint things. Can extend to much lower mass locally.



CDM is scale free