Dark Matter

ASTR 333/433
Spring 2024
TR 11:30am-12:45pm
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

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Homework DUE

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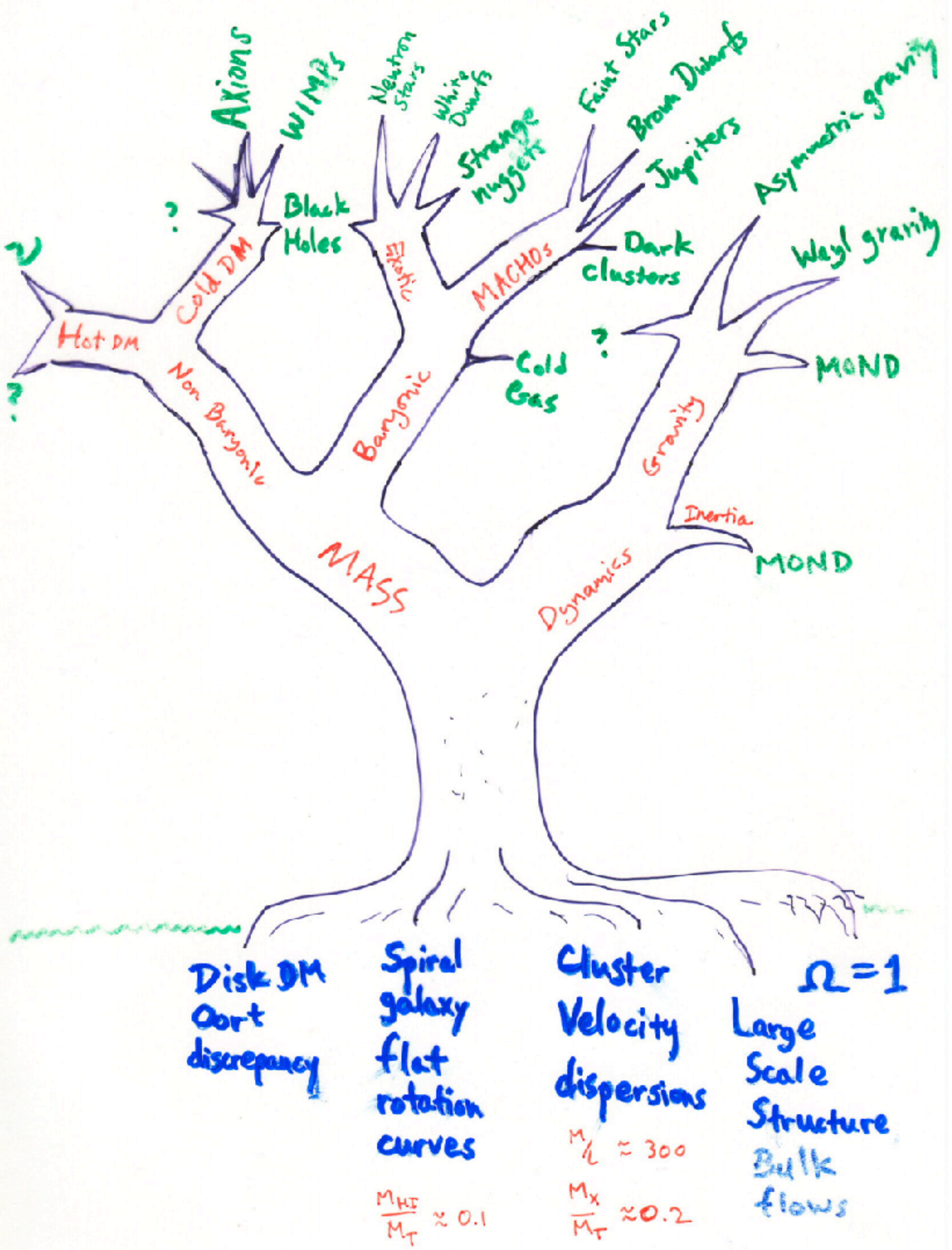


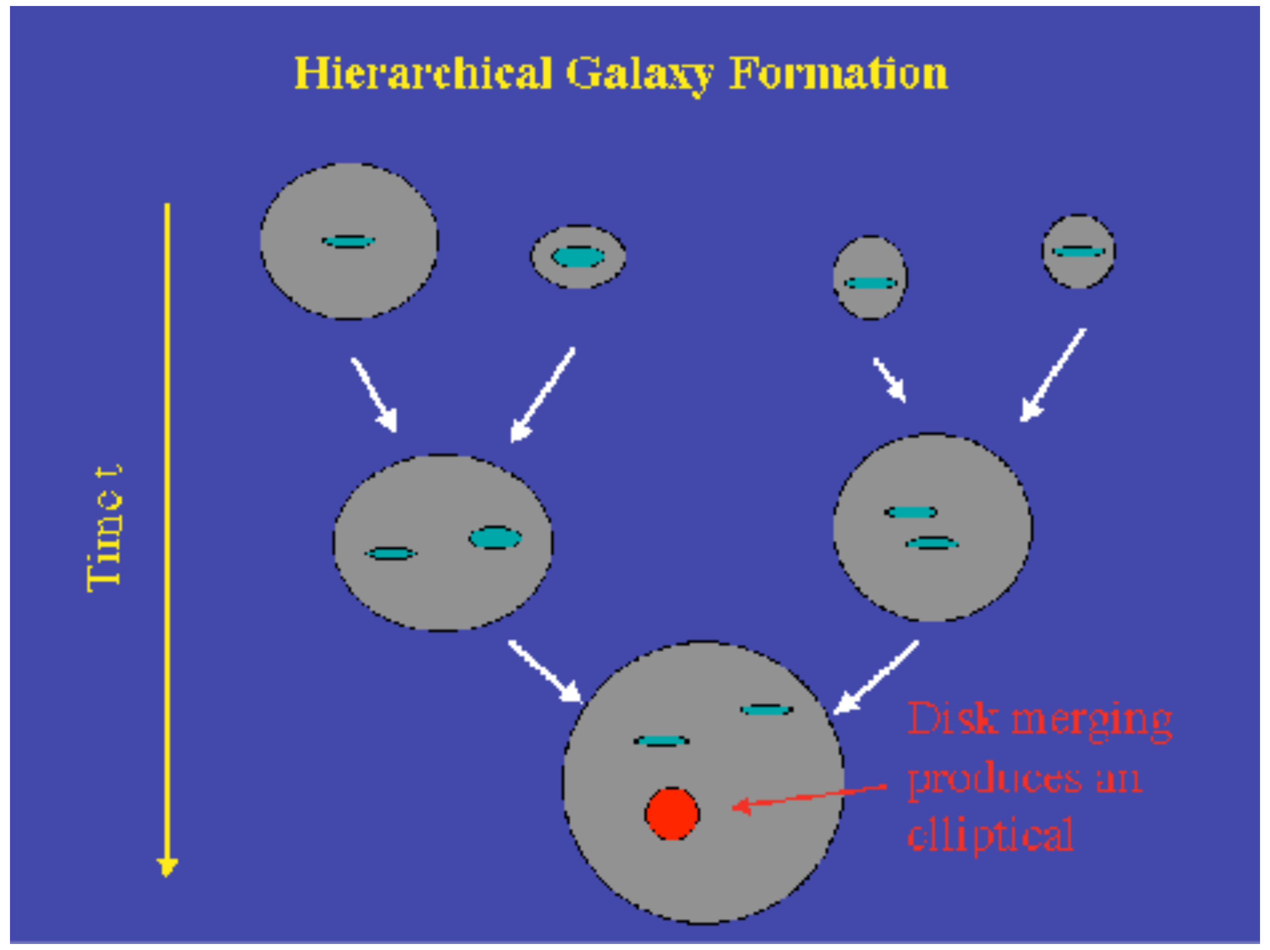
Galaxy formation with Cold Dark Matter

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**



merging fundamental to hierarchical galaxy formation, but this doesn't have to be the only way to make elliptical 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

- Fine-tuning
  - Laws of galactic rotation do not follow naturally from CDM
  - Too little scatter in TF, RAR - galaxies look like MOND
- 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)
  - overcooling/condensation problem

Generic prescription: Feedback

Gas cools, sinks to centers of DM halos - gotta happen, but how?

Condensation

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

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

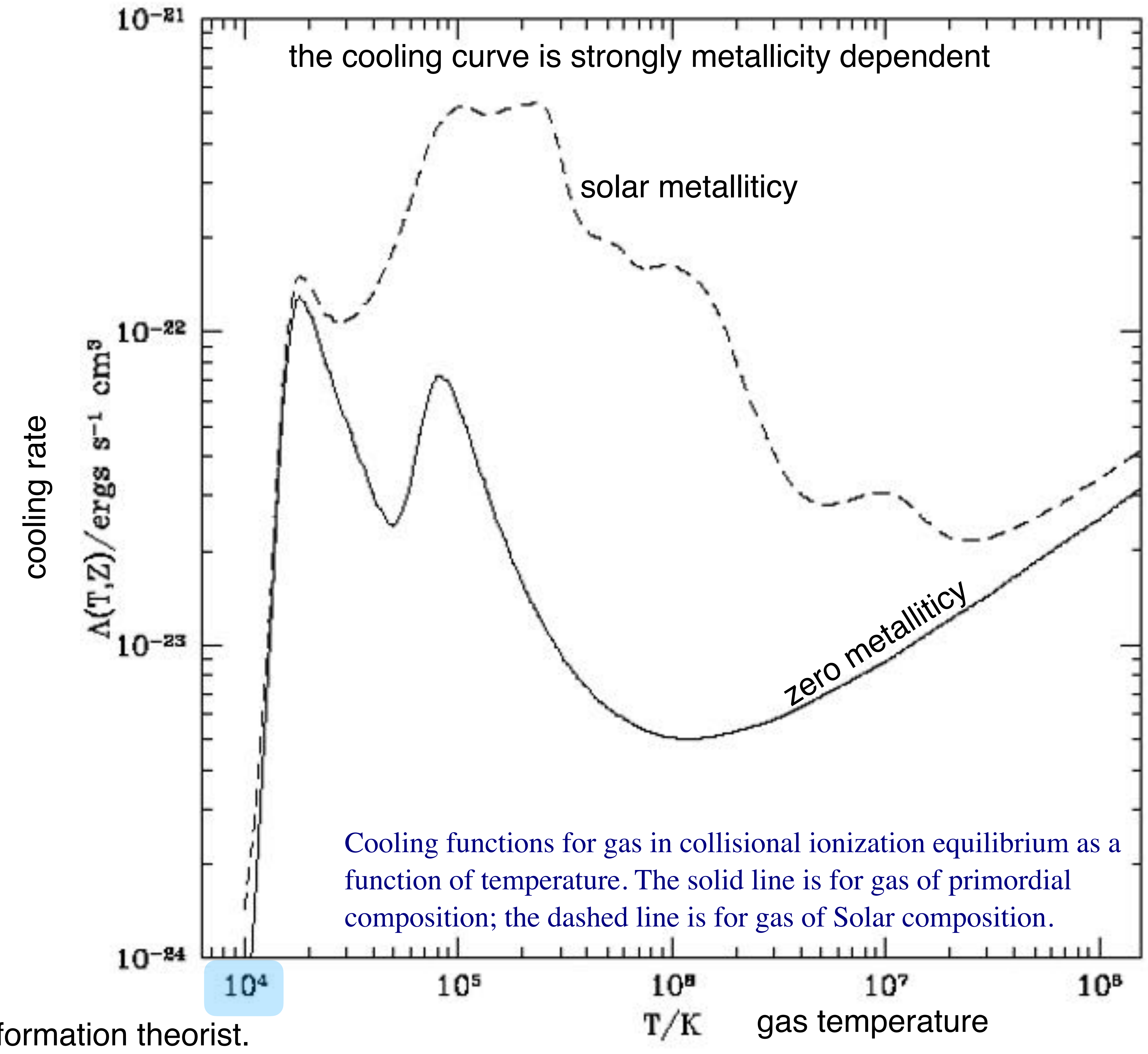
In absence of cooling, supported in hydrostatic equilibrium

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

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

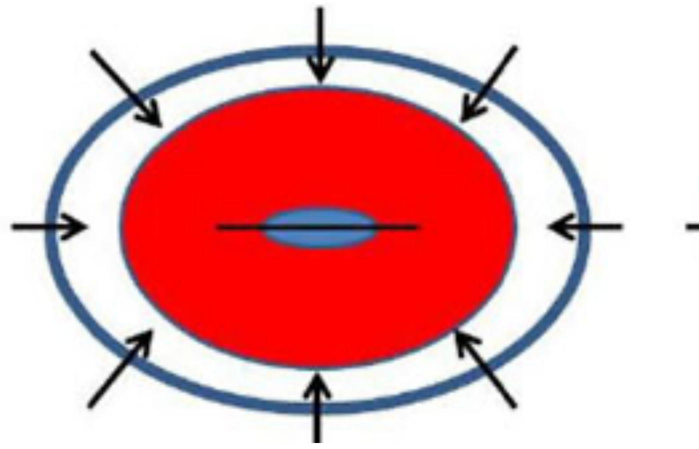
$$\mathscr{L} = n_H^2\,\Lambda(T,Z)$$

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



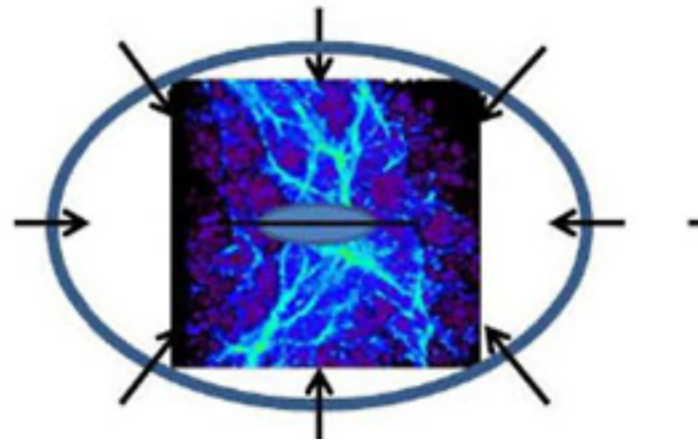
Any $T < 10^4$ K is "cold" to a galaxy formation theorist.

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



Gas cools inside out; innermost baryons form gas disk

Or maybe gas arrives in cooling flows along cosmic filaments



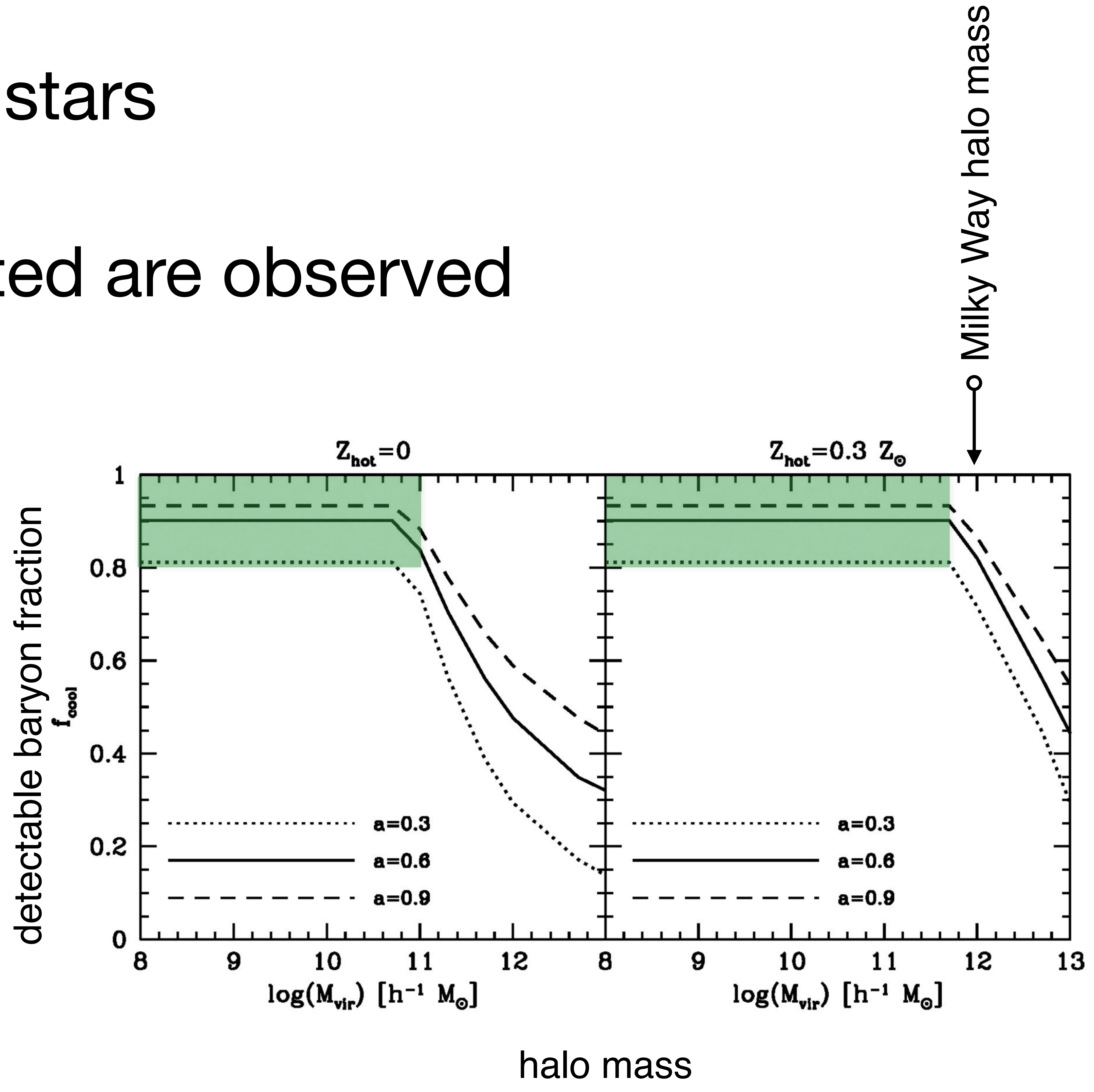
Shlosman (arXiv:1212.1463)

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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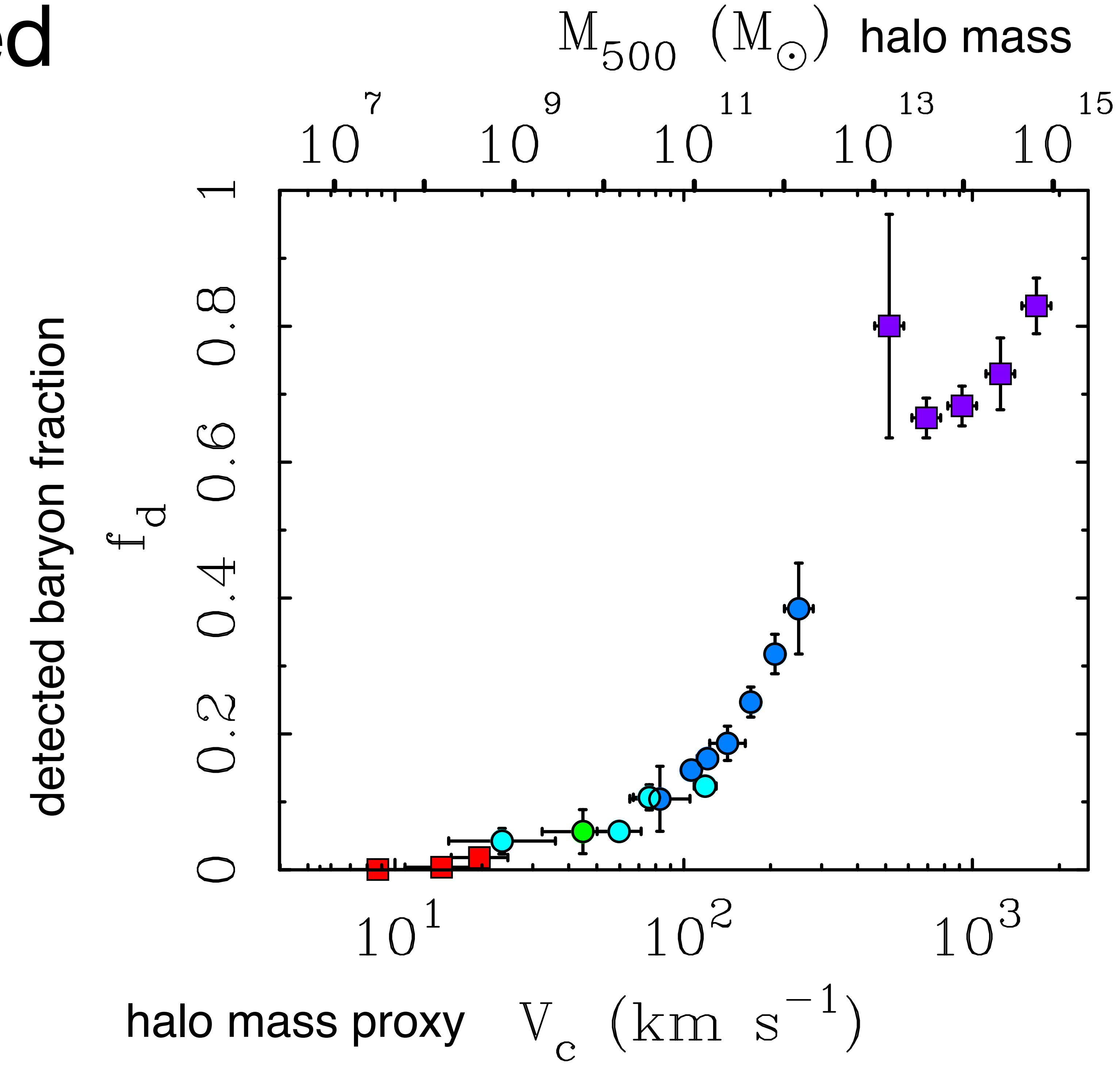
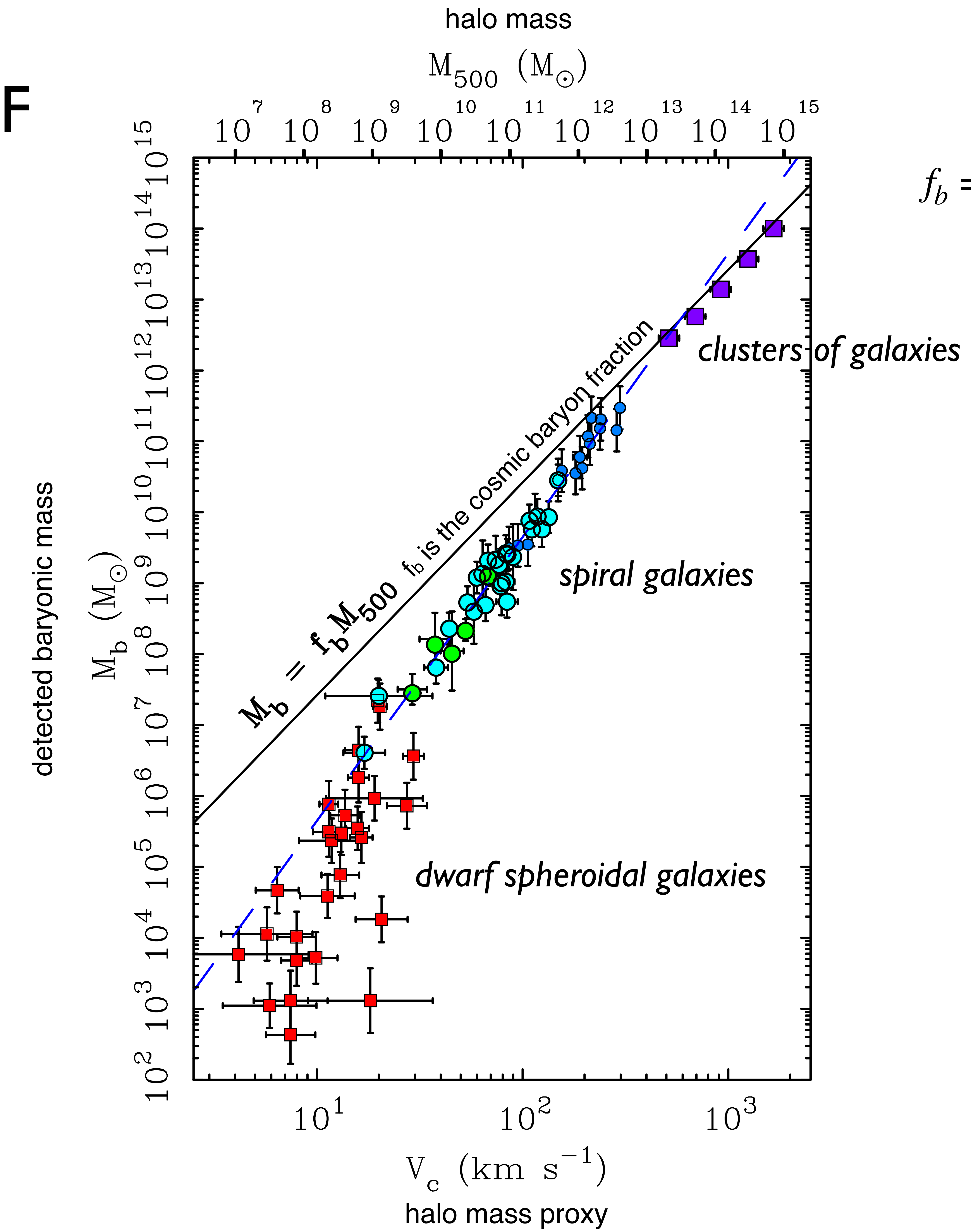


Extended TF



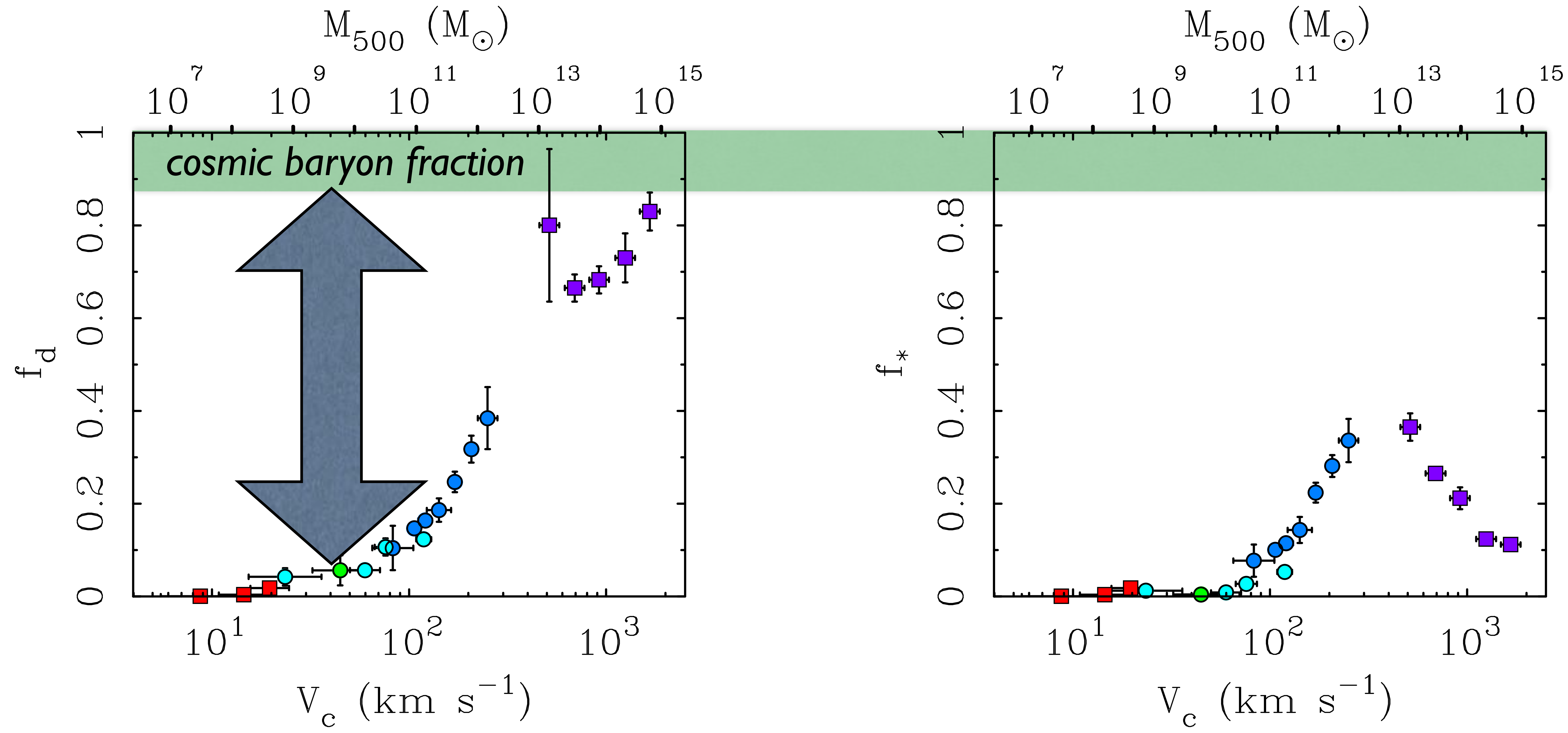
$$f_b = \frac{\Omega_b}{\Omega_m}$$

McGaugh et al. (2010)

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

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

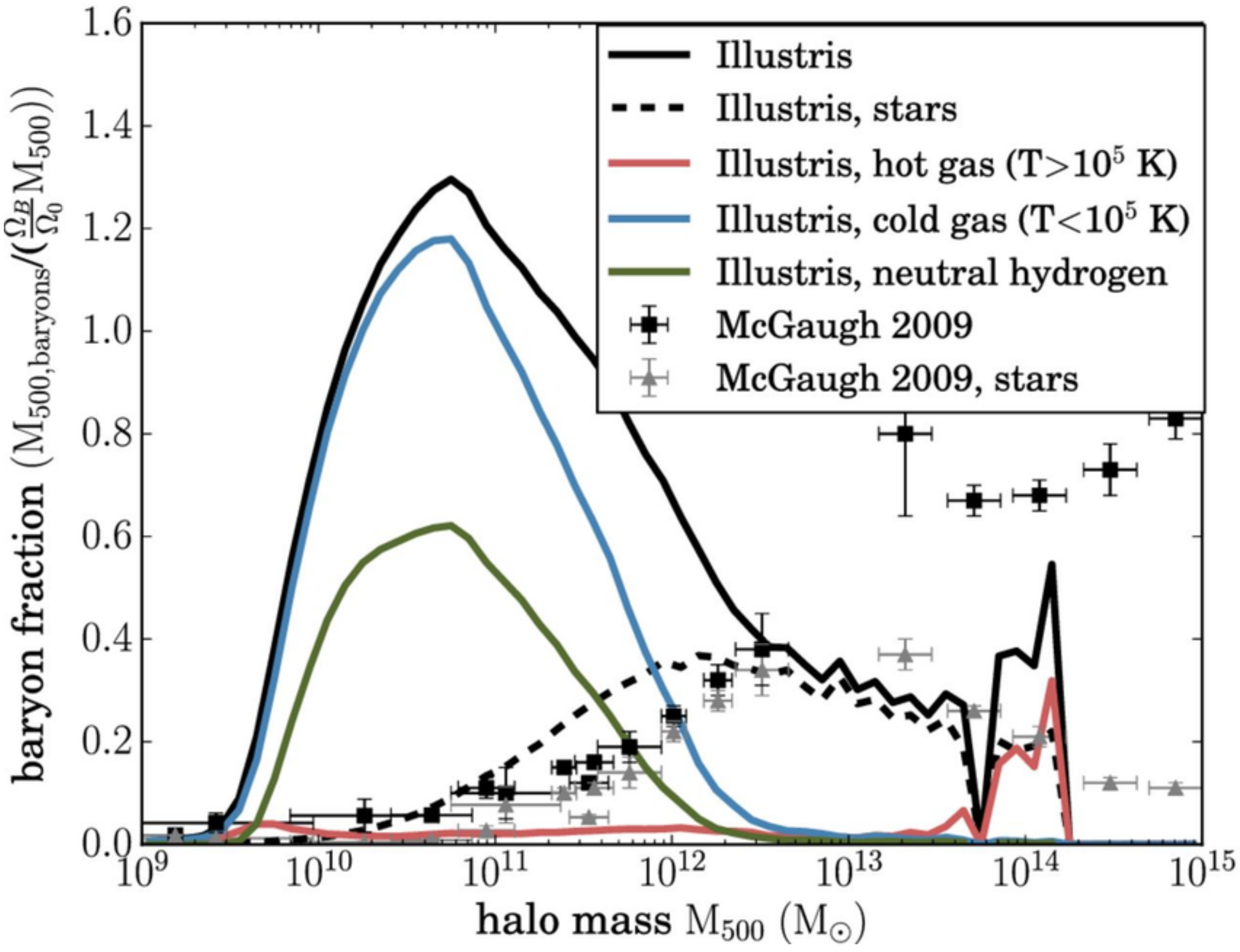
$$f_b = \frac{\Omega_b}{\Omega_m}$$



McGaugh et al. (2010)

Halo by halo missing baryon problem

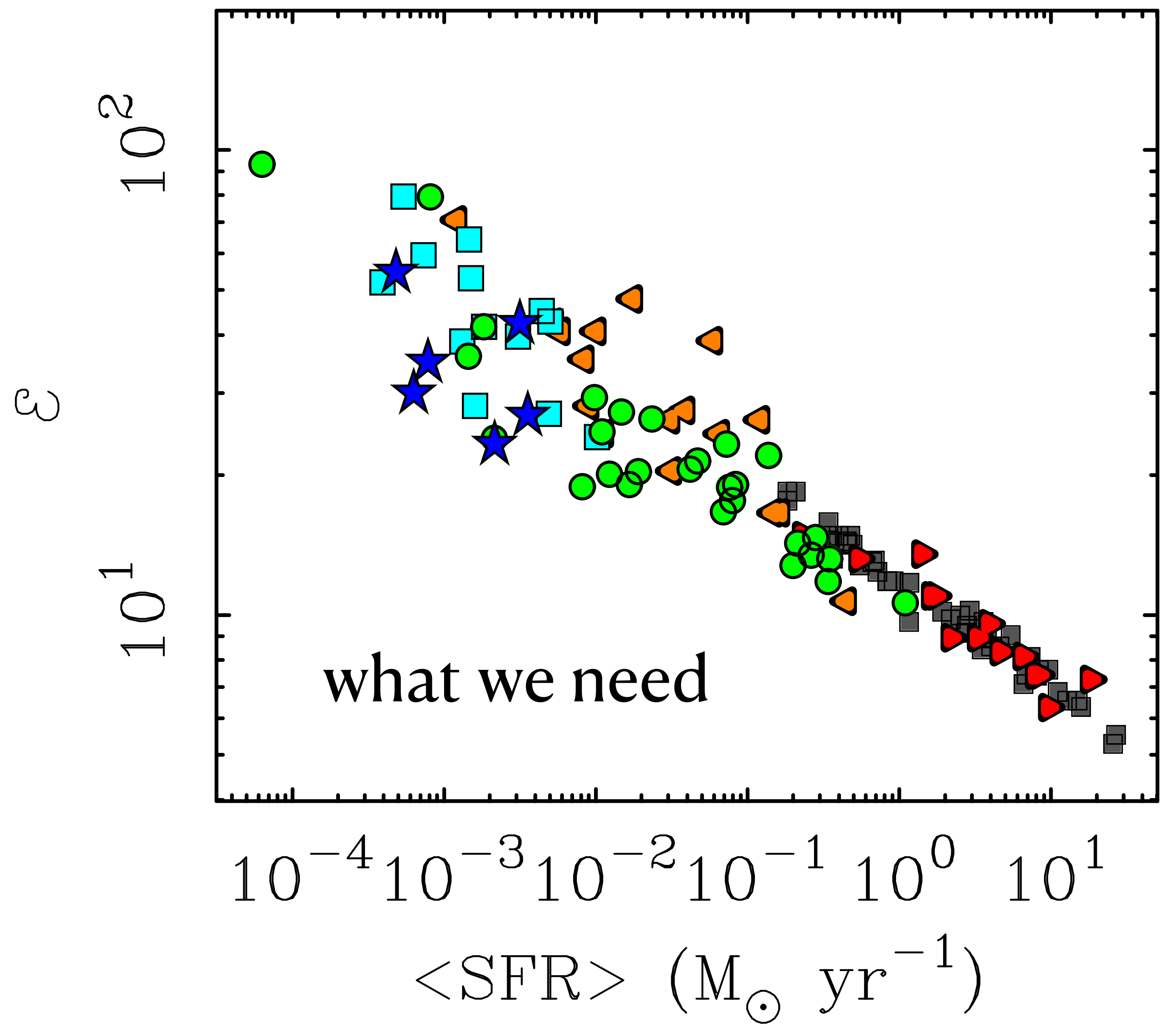
2 missing mass problems: baryonic AND non-baryonic DM



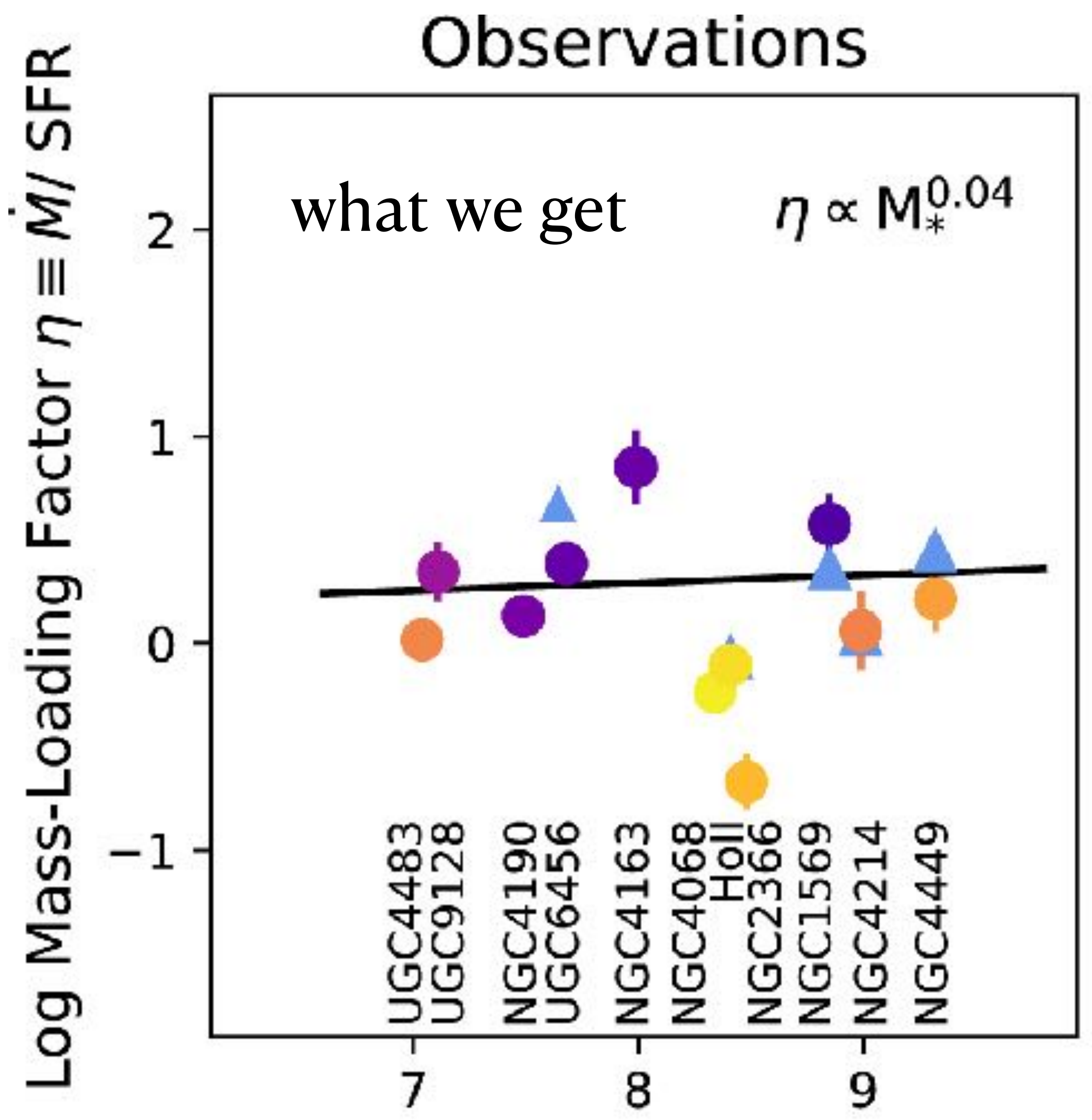
Haider, Steinhauser, Vogelsberger, & Hernquist (2015)

Feedback

invoked to explain cusp-core problem and
missing baryon/missing satellite problem



$H_0 \, M_*$ (M$_\odot$ yr^{-1})



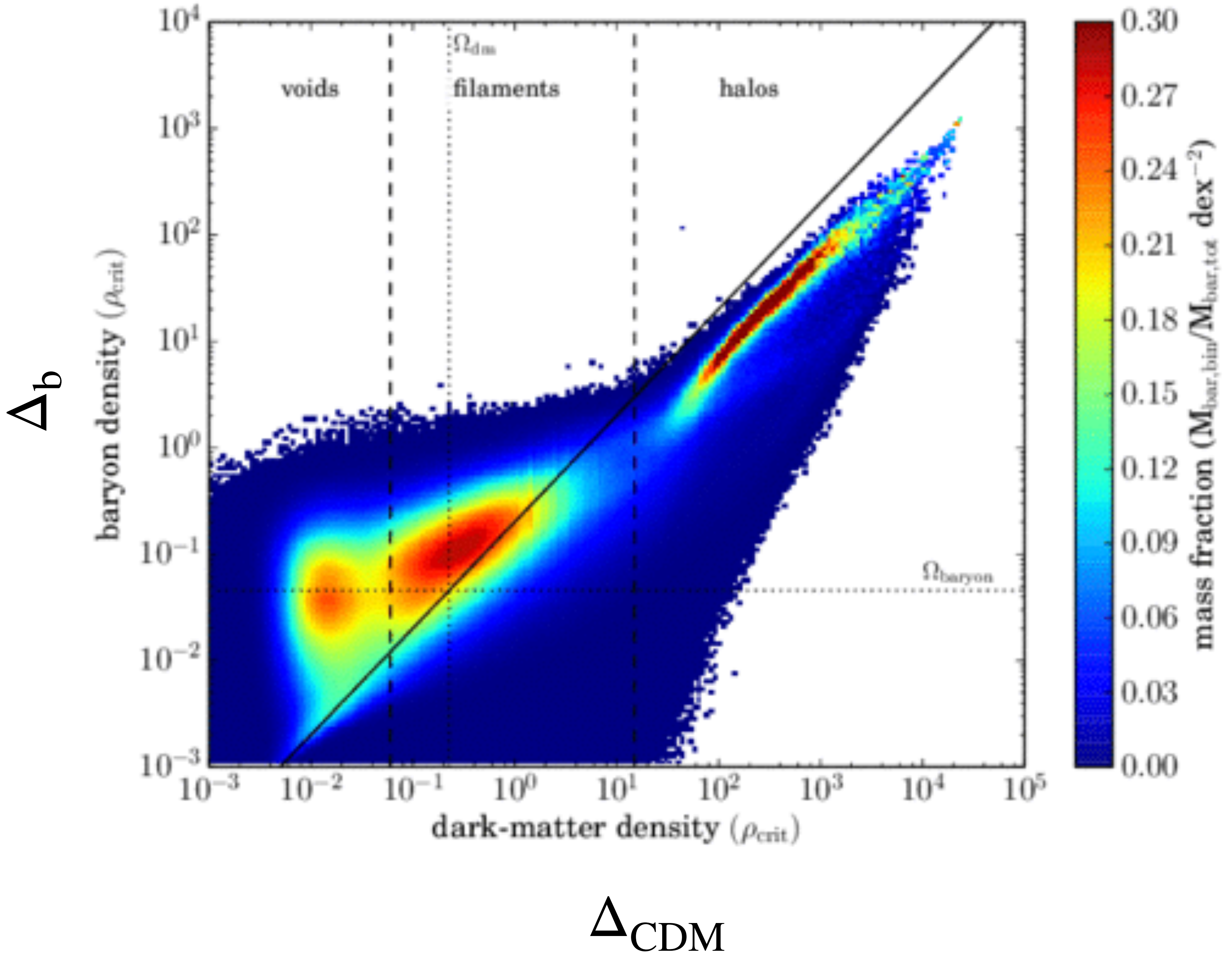
M_* (M$_\odot$)

Efficacy of feedback: $\log \varepsilon = 3 \log f_V - \log f_d$.

Basically the ratio of baryons lost to those retained.

Most baryons are missing, especially from low mass halos.

component	dark matter density region (ρ_{crit})	% of total dark matter mass	% of total baryonic mass	% of total mass	% of total volume
haloes	> 15	49.2 %	23.2 %	44.9 %	0.16 %
filaments	0.06 - 15	44.5 %	46.4 %	44.8 %	21.6 %
voids	0 - 0.06	6.4 %	30.4 %	10.4 %	78.2 %
ejected material inside voids	0 - 0.06	2.6 %	23.6 %	6.1 %	30.4 %

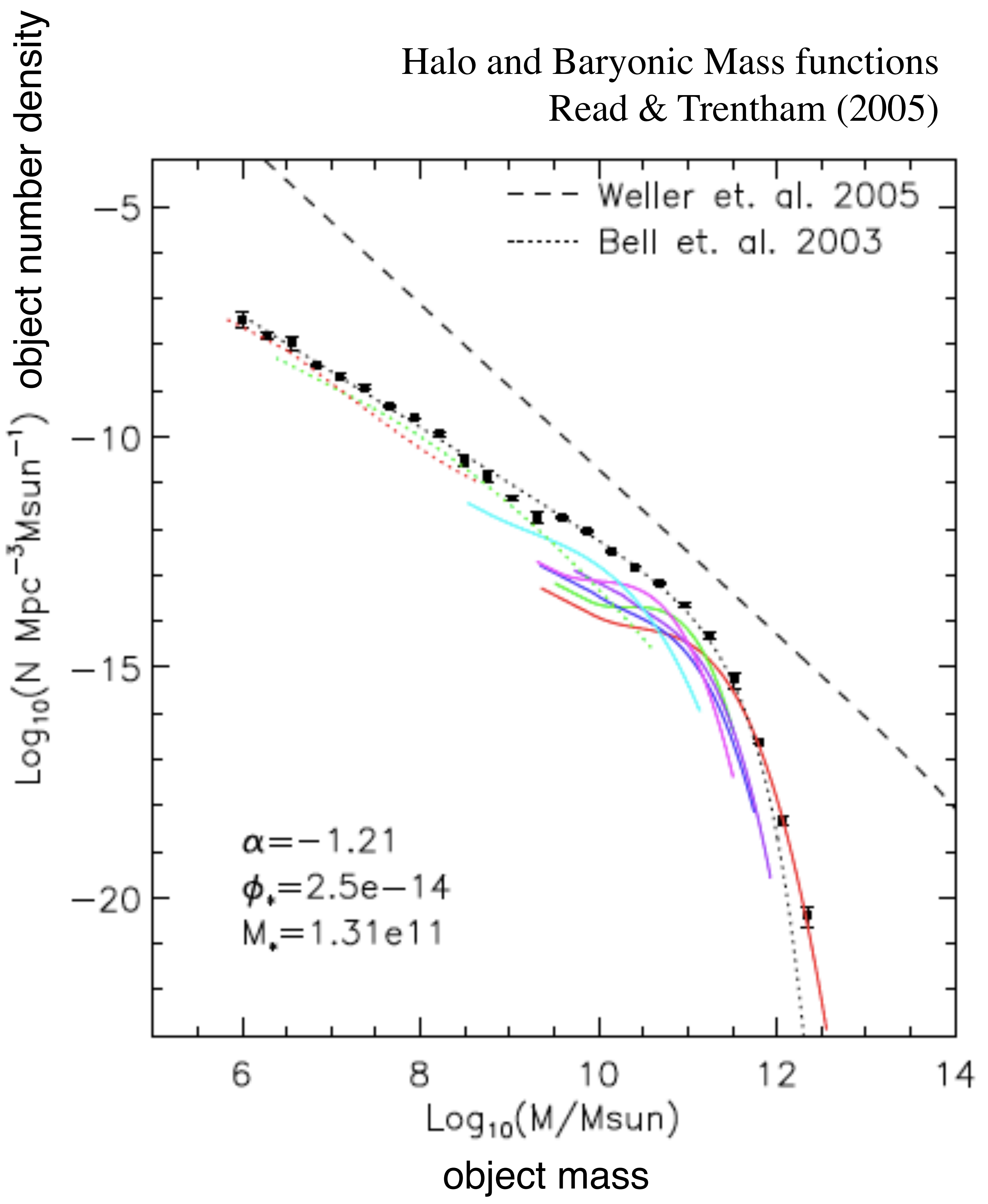


ature and metallicity maps with Fig. 3 and
that the majority of the baryons in voids i
warm to hot gas enriched by metals. Those
most likely been ejected from the haloes thr
Because the ejected material has a higher ten
the other baryons in voids, we can use the t
discriminate between baryons naturally residi
baryons which have been transported there. W
ditional 'ejected material' region in Table 2 w
as having a temperature higher than 6 × 10
to the dark matter density cut. With 23.6
baryons, this 'ejected material' region is respo
of the baryons in dark matter voids. In Fig.
region corresponding to the ejected material i
that it fills about 40 % of the voids. We shoul
that the ejected mass most likely heats some

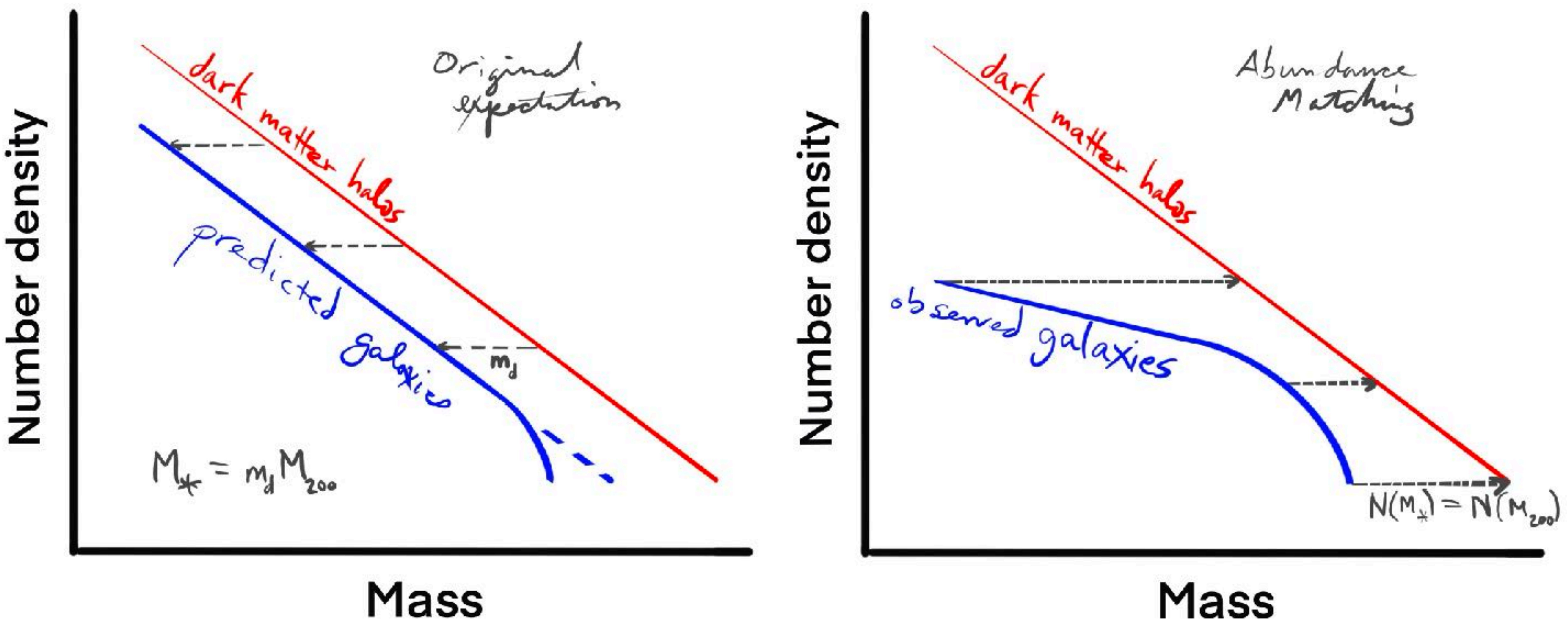
Haider, Steinhauser, Vogelsberger, & Hernquist (2015)

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



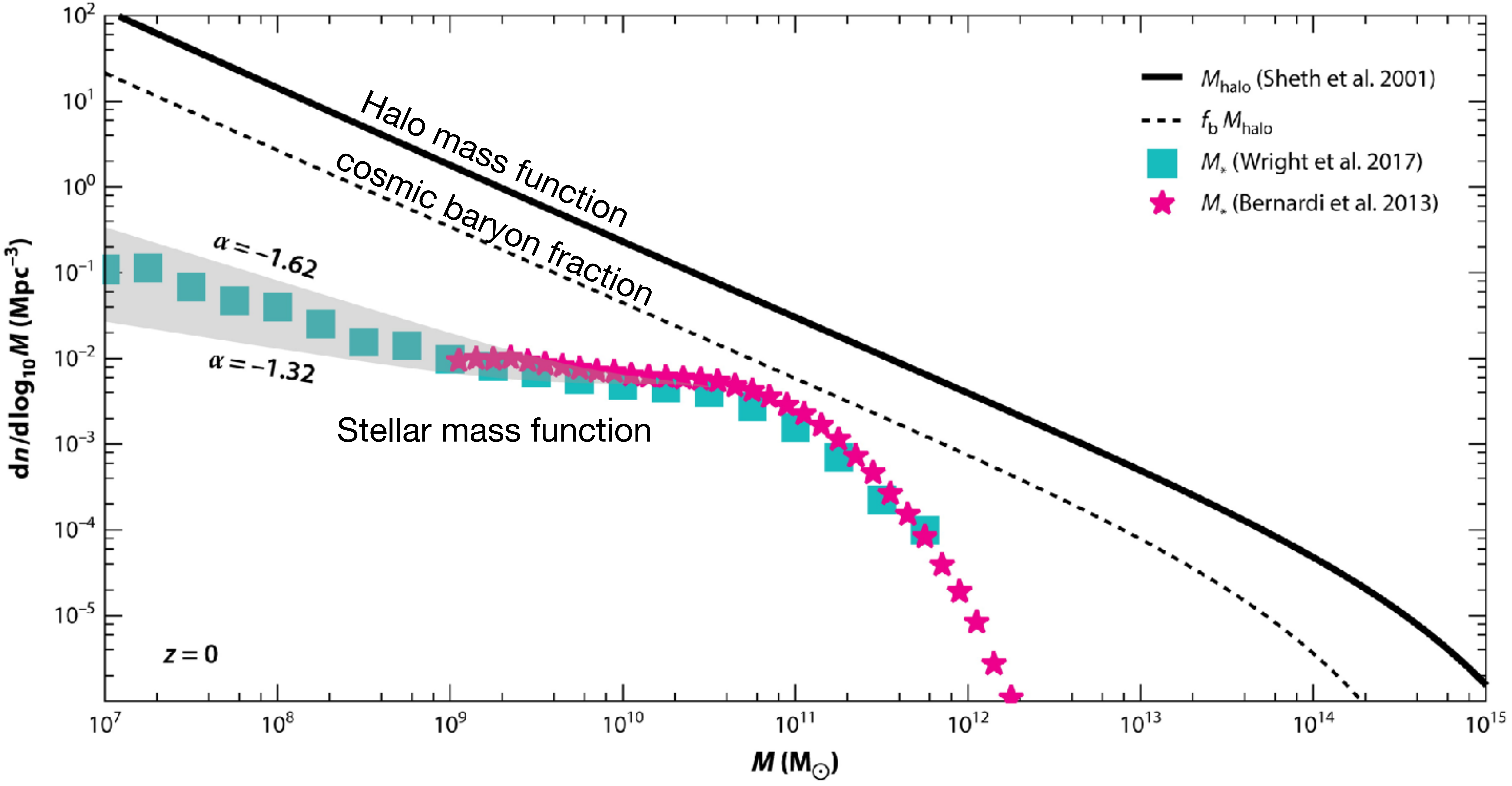
Abundance Matching



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)

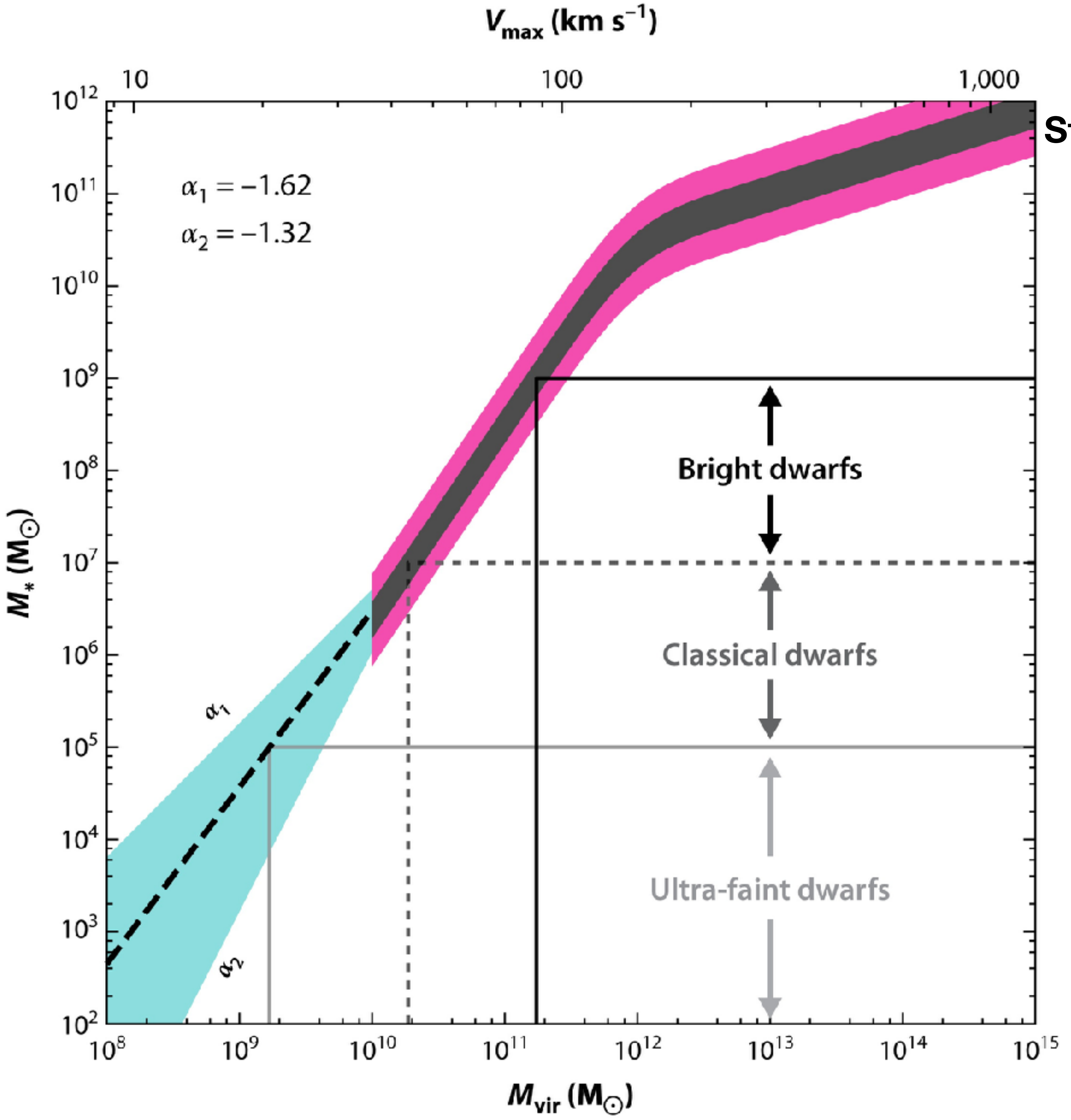


Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

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

Stellar Mass-Halo Mass Relation from Abundance Matching

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



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

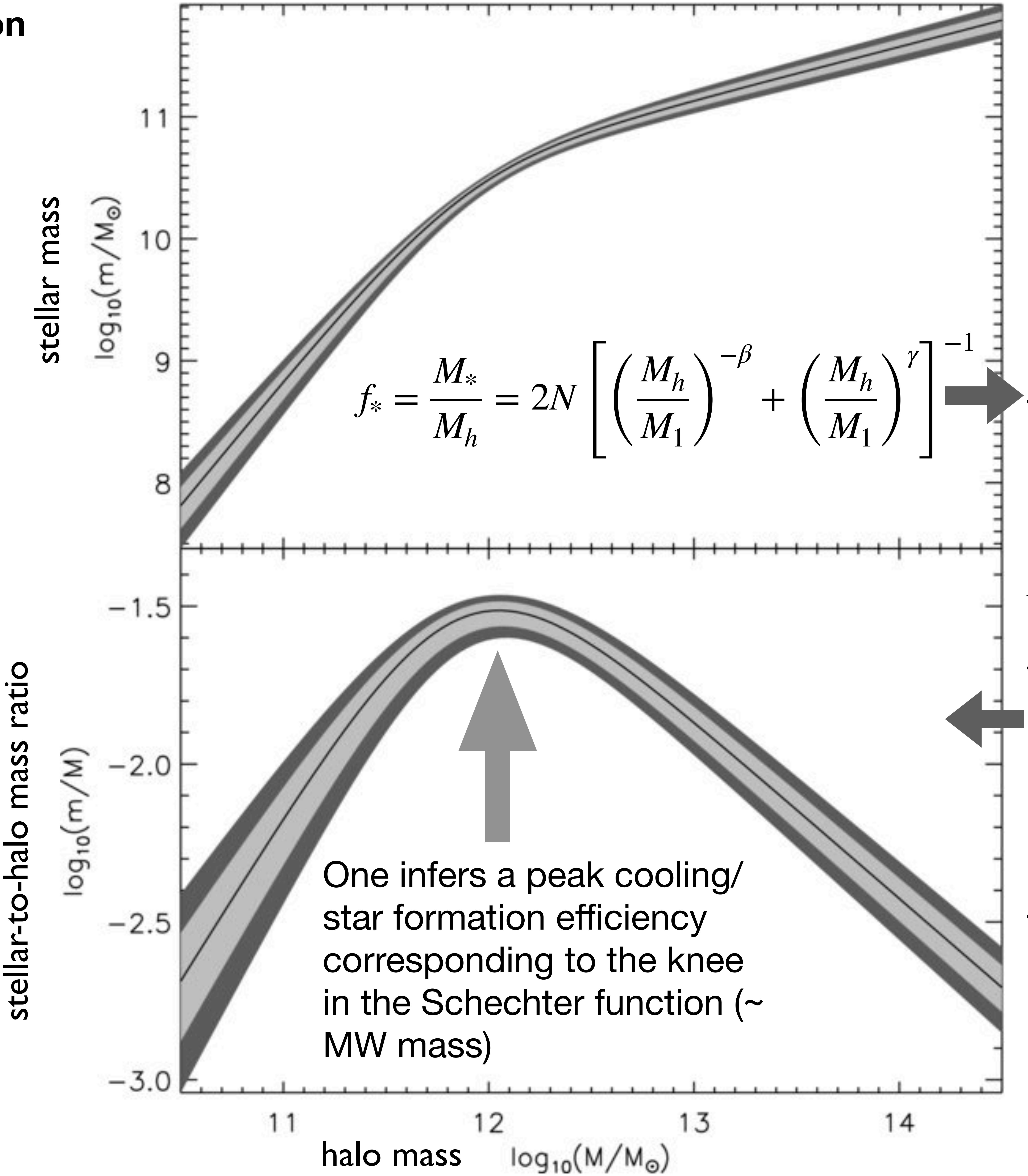
Stellar Mass-Halo Mass Relation from Abundance Matching

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.



$$f_* = \frac{M_*}{M_h} = 2N \left[\left(\frac{M_h}{M_1} \right)^{-\beta} + \left(\frac{M_h}{M_1} \right)^{\gamma} \right]^{-1}$$

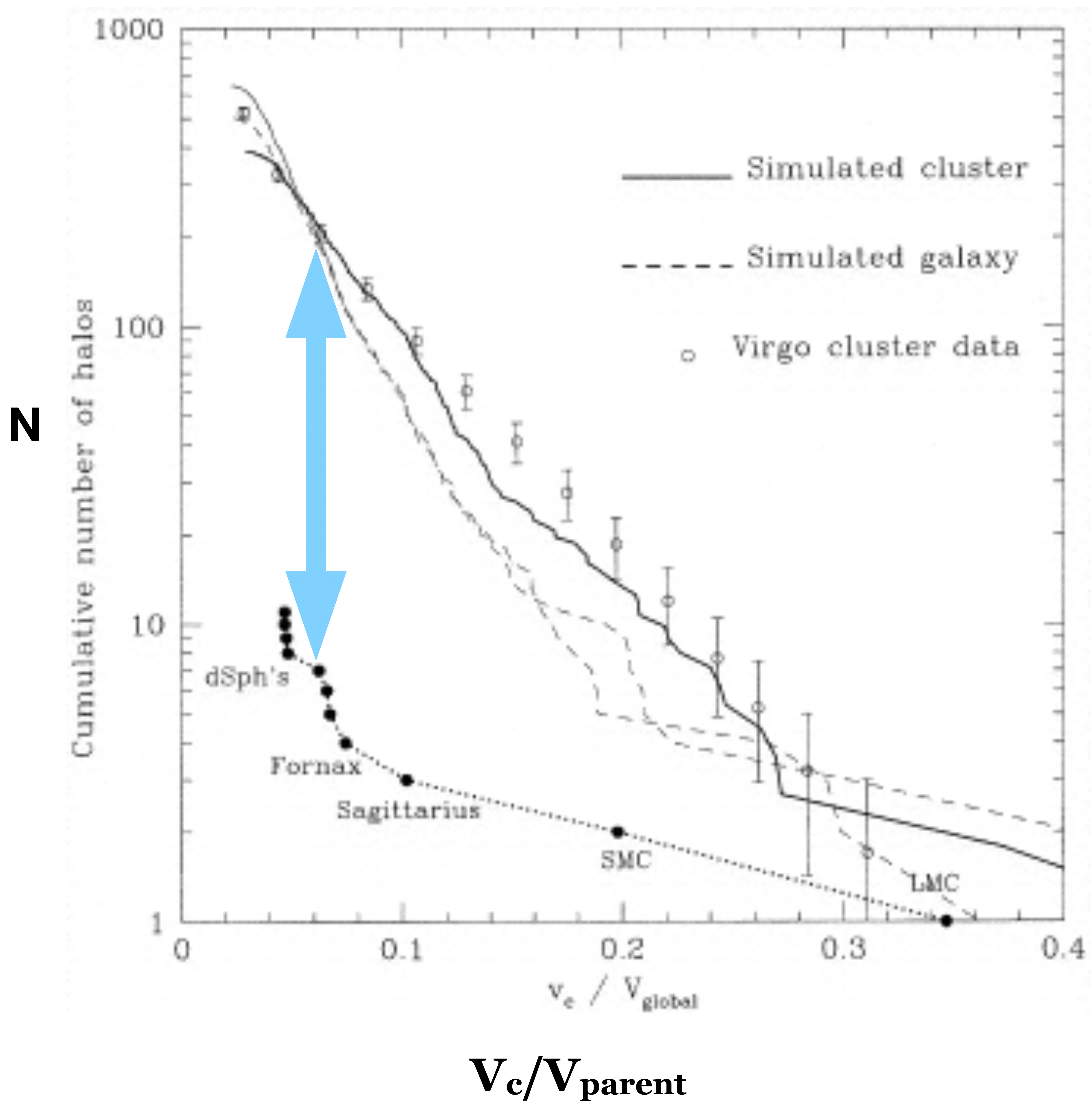
One infers a peak cooling/ star formation efficiency corresponding to the knee in the Schechter function (~ MW mass)

Common fitting function used to describe stellar mass-halo mass relation where M_1, β, γ, N are parameters to fit the shape seen at bottom. There's a bend point, a low- and high-mass slope, and a normalization. This is useful for relating the halo mass to the observable stellar mass.

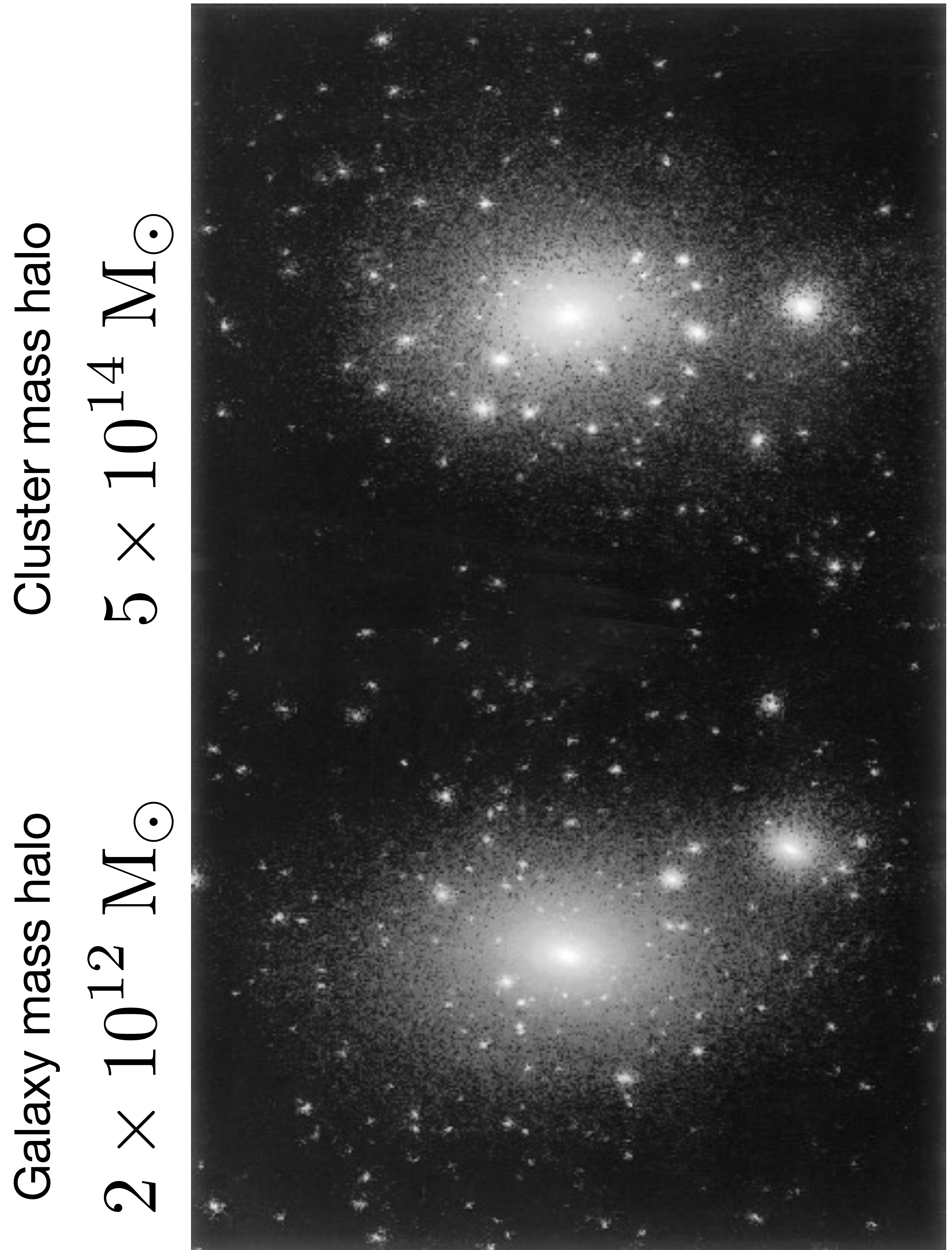
Missing Satellites

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



Dwarf spheroidals problematic for CDM in two distinct ways:

- there should be thousands of them rather than dozens
  (missing satellite problem)

- they have cored dark matter halos
  (cusp/core problem)

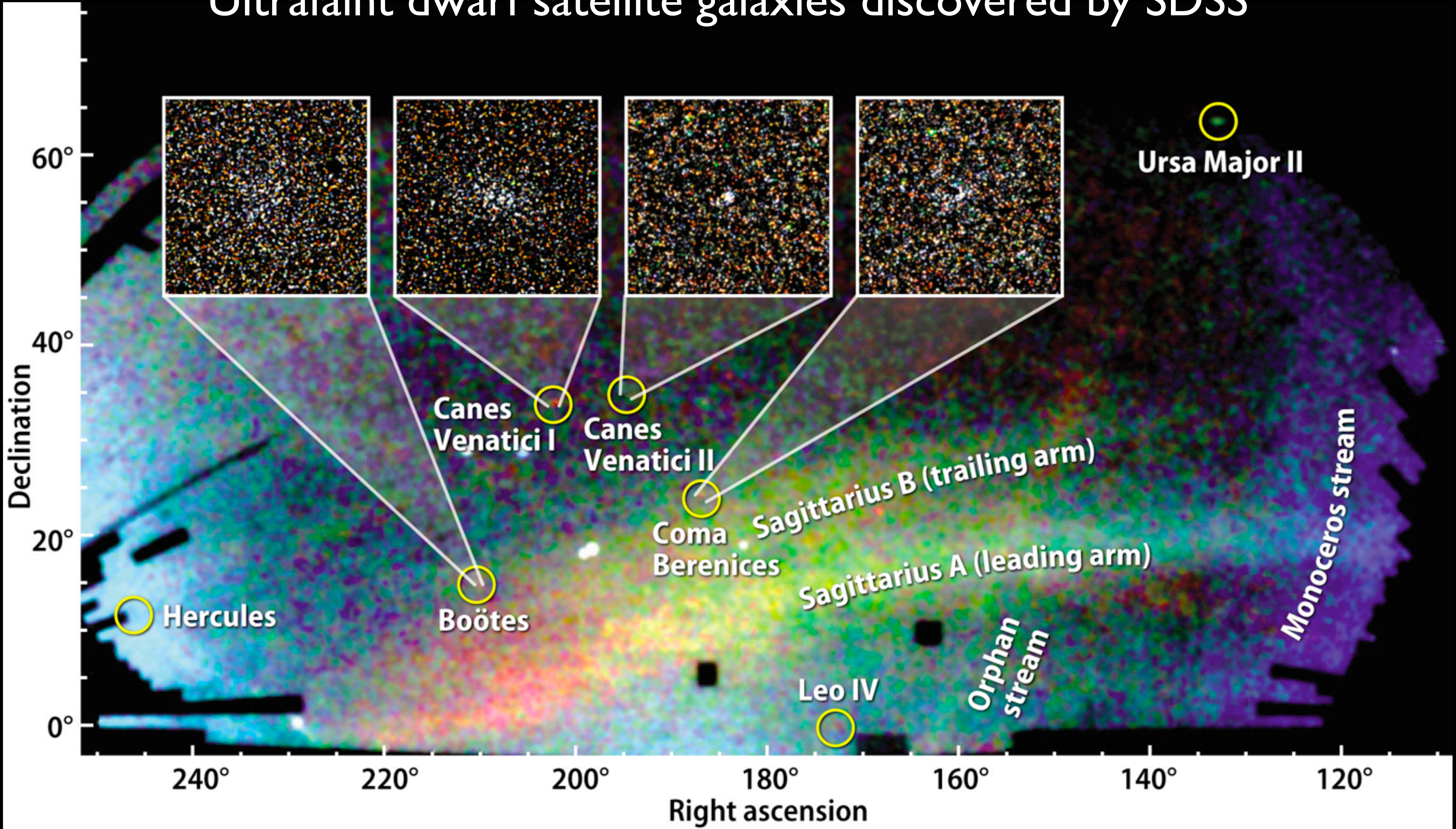
These are really just the same problems as in the field, scaled to the Local Group

The Local Group
does not look like a simulated dark matter halo

≠


KK98-250
KK98-251
~ 70 kpc

Ultrafaint dwarf satellite galaxies discovered by SDSS



Milky Way Missing satellites - solved?