Dwarf Galaxies: The Extremes of Galaxy Formation

Advanced Cosmology Course

Adi Zolotov

OUTLINE

- What is a dwarf galaxy?
- What are some of their properties?
- A brief detour to discuss stellar halos
- A challenge to the CDM model?
  - Reionization & Missing Satellites Problem
  - Feedback & the Cusp/Core problem

WHAT IS A DWARF GALAXY?

- Least massive and least luminous galaxies known
- Low-Luminosity: 10^3-10^8 $L_\odot$
- Low-Mass: 10^5-$10^{10} M_\odot$
- Low surface brightness: hard to find!
- Most of the known dwarfs are in the Local Volume for this reason
- So, why are they important?

DWARF GALAXIES: IN CDM CONTEXT

- In the CDM context, first galaxies to form are low mass galaxies (aka, dwarfs)
- Galaxies grow hierarchically -> dwarf remnants in stellar halo of MW and M31
- DM-only movie: DM sim

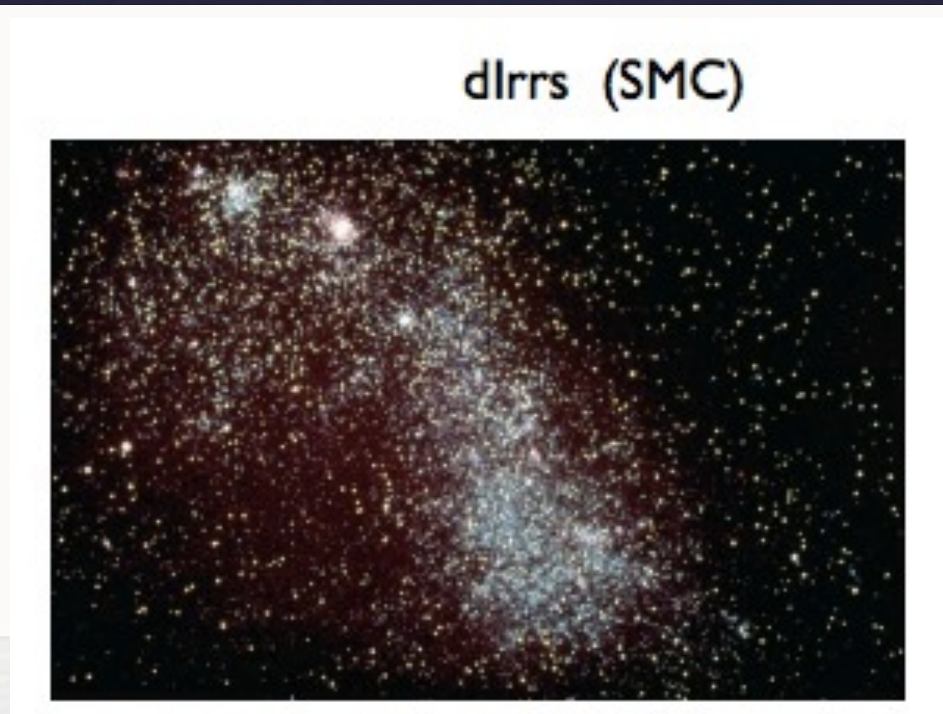
WHY ARE DWARFS IMPORTANT?

- Majority of the galaxies in the Universe are dwarf galaxies
- Dwarf galaxies are remnants of galaxy formation process
- Dwarf galaxies are currently being “eaten” by larger galaxies
- Dwarf galaxies are relatively simple systems (didn’t undergo mergers; very faint -> little complex baryonic physics?) -> Can be used to test DM predictions!

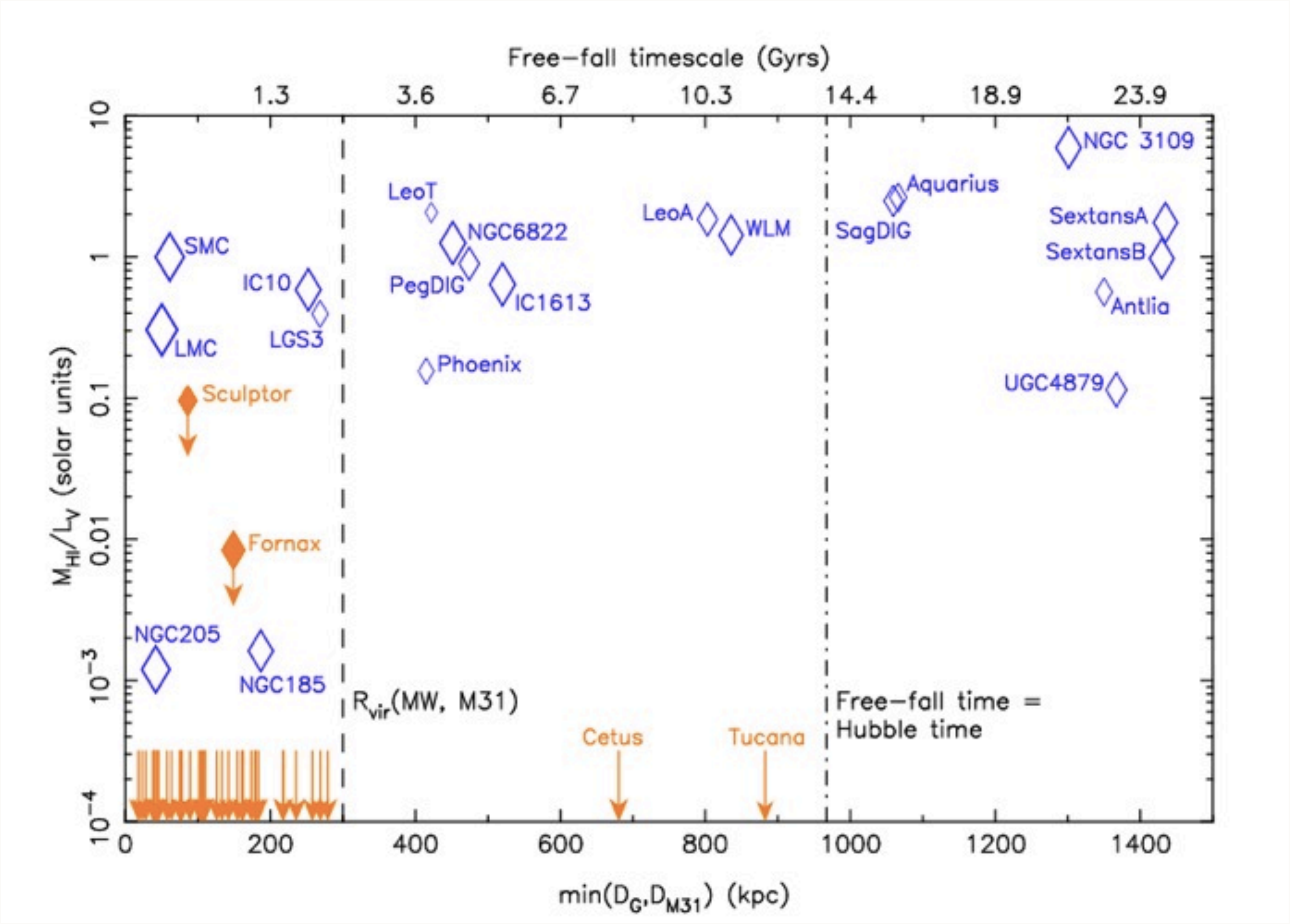
DIFFERENT FLAVORS OF DWARFS

- Dwarf ellipticals (dE): Gas poor, old stellar populations, mostly around M31
- Dwarf spheroidal (dSph): gas-poor, diffuse systems, low-luminosity end, only found as satellites
- Dwarf Irregulars (dIrr): gas-rich, ongoing star formation, found in all environments, rotationally supported
- Is there an evolutionary connection between dE, dIrr and dSph?

DIFFERENT MORPHOLOGIES



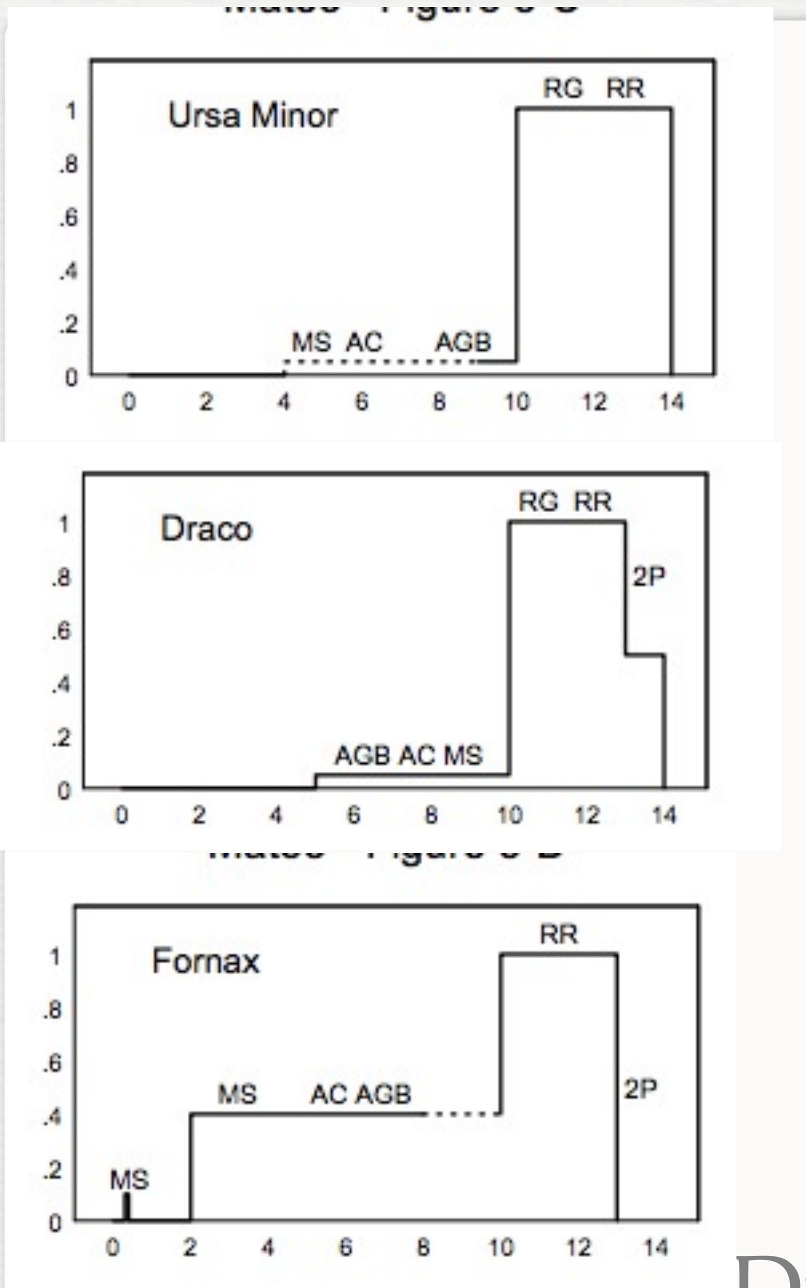
POSITION-MORPHOLOGY RELATION



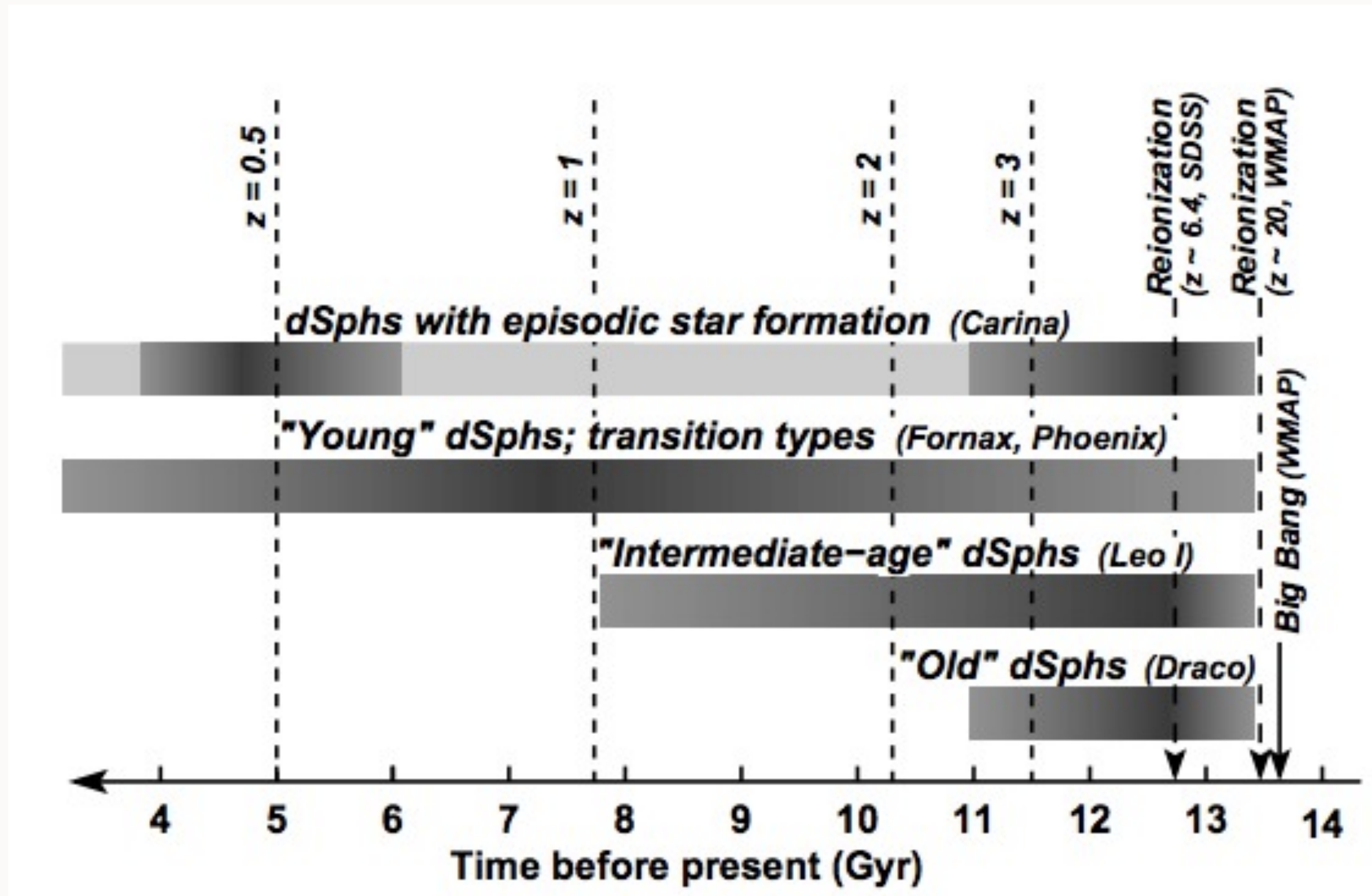
FOCUS ON MW AND M31 SATELLITES

- Why? Because despite being the faintest galaxies (and hence, hardest to observe), they are our nearest neighbors
- We can study them in great detail by resolving their stellar populations

STELLAR POPULATIONS



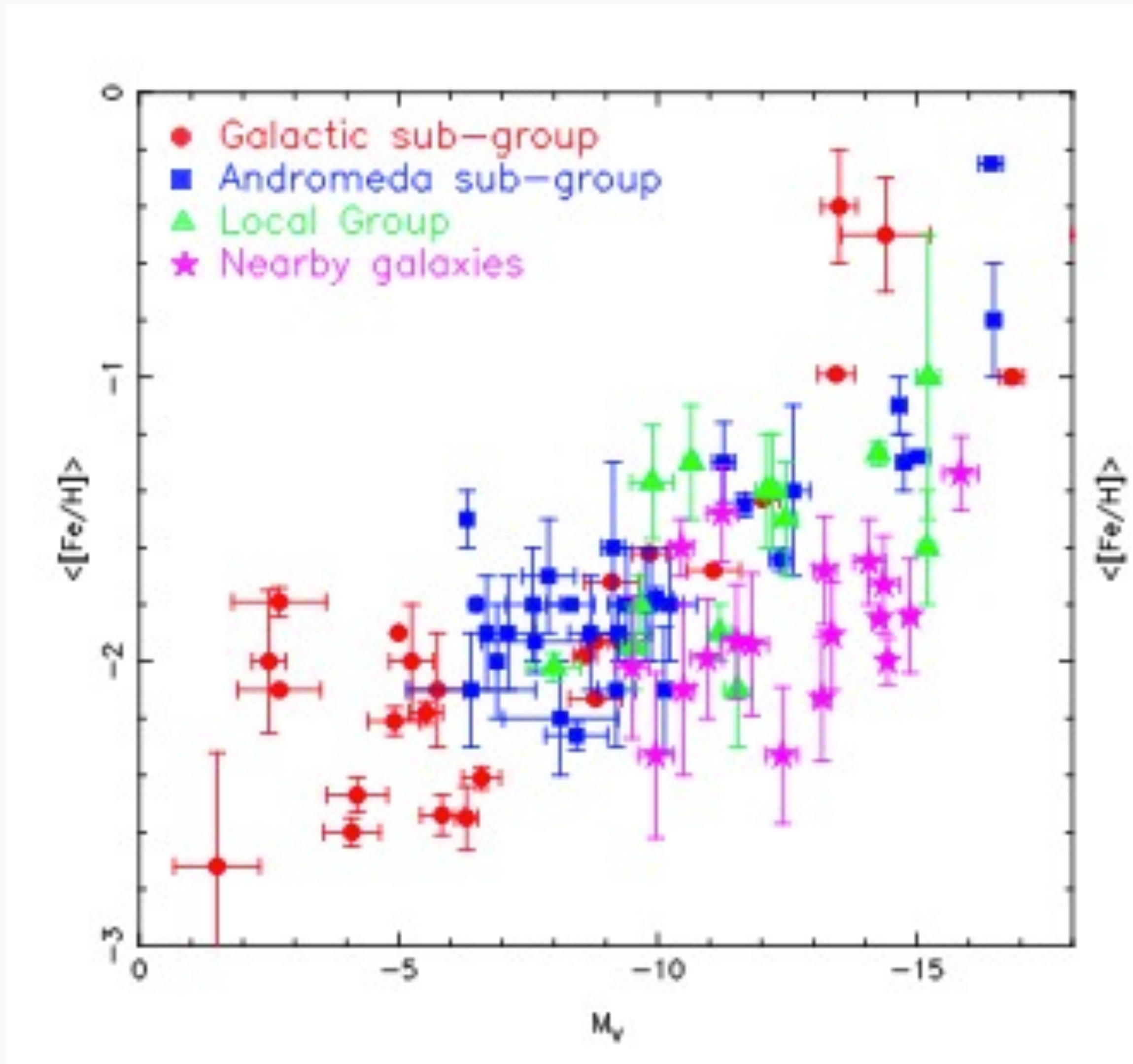
AGE



Grebel 2005

Dwarfs contain stars as old as Universe

MASS-METALLICITY RELATION

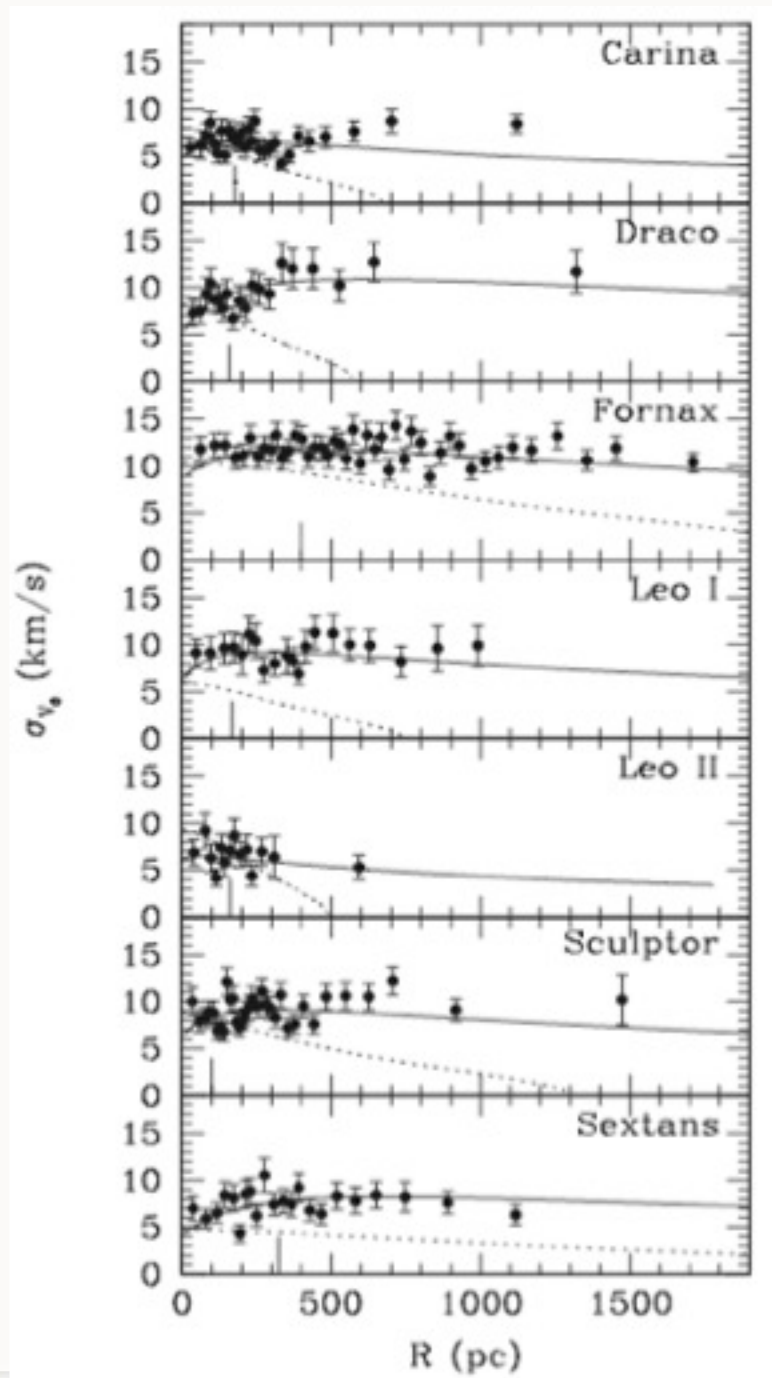


McConnachie 2012

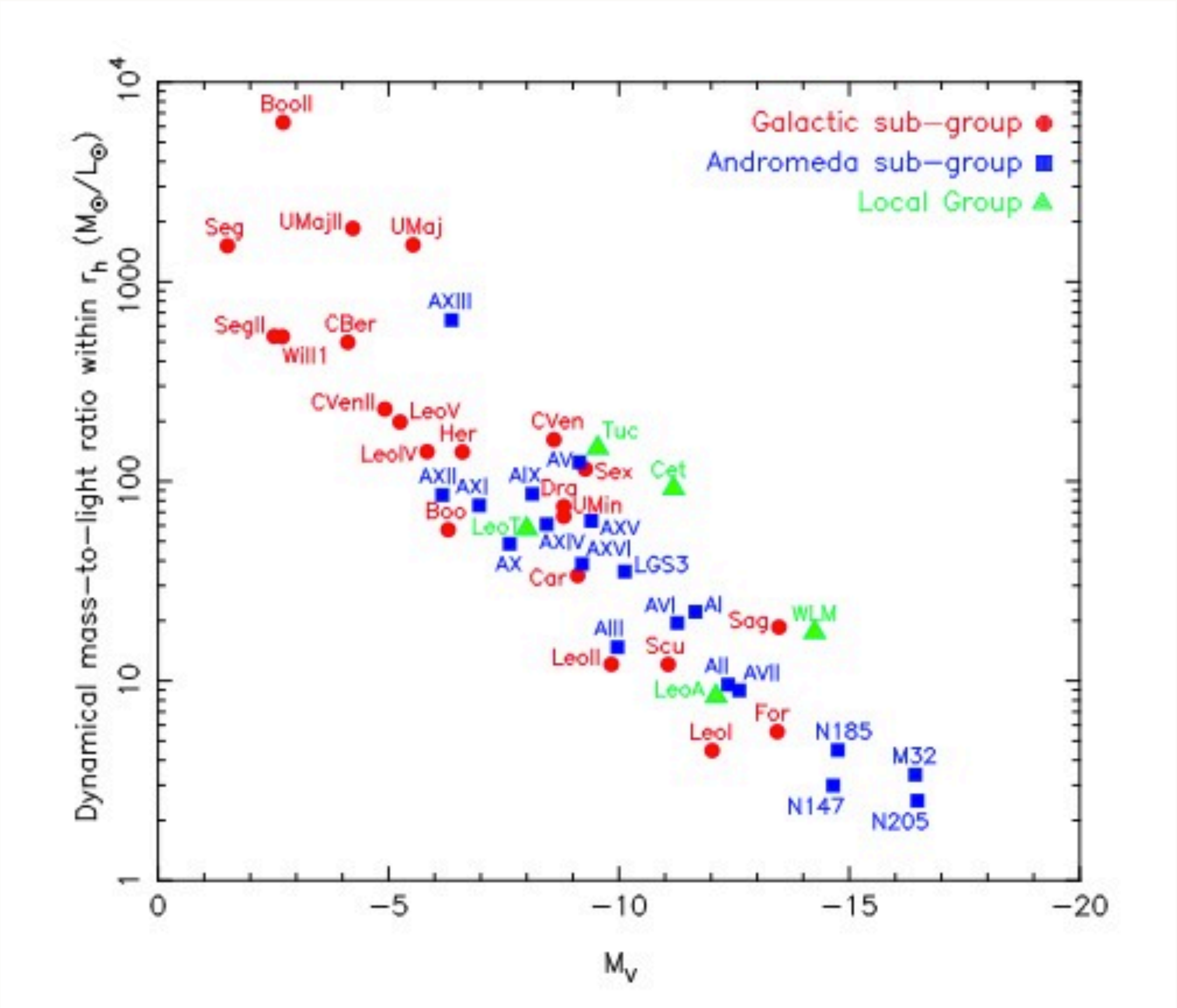
STELLAR KINEMATICS

From Jean's equation

$$M_{dyn} \sim 2\,\sigma^2\, r\, /\, G$$



DARK MATTER DOMINATED!



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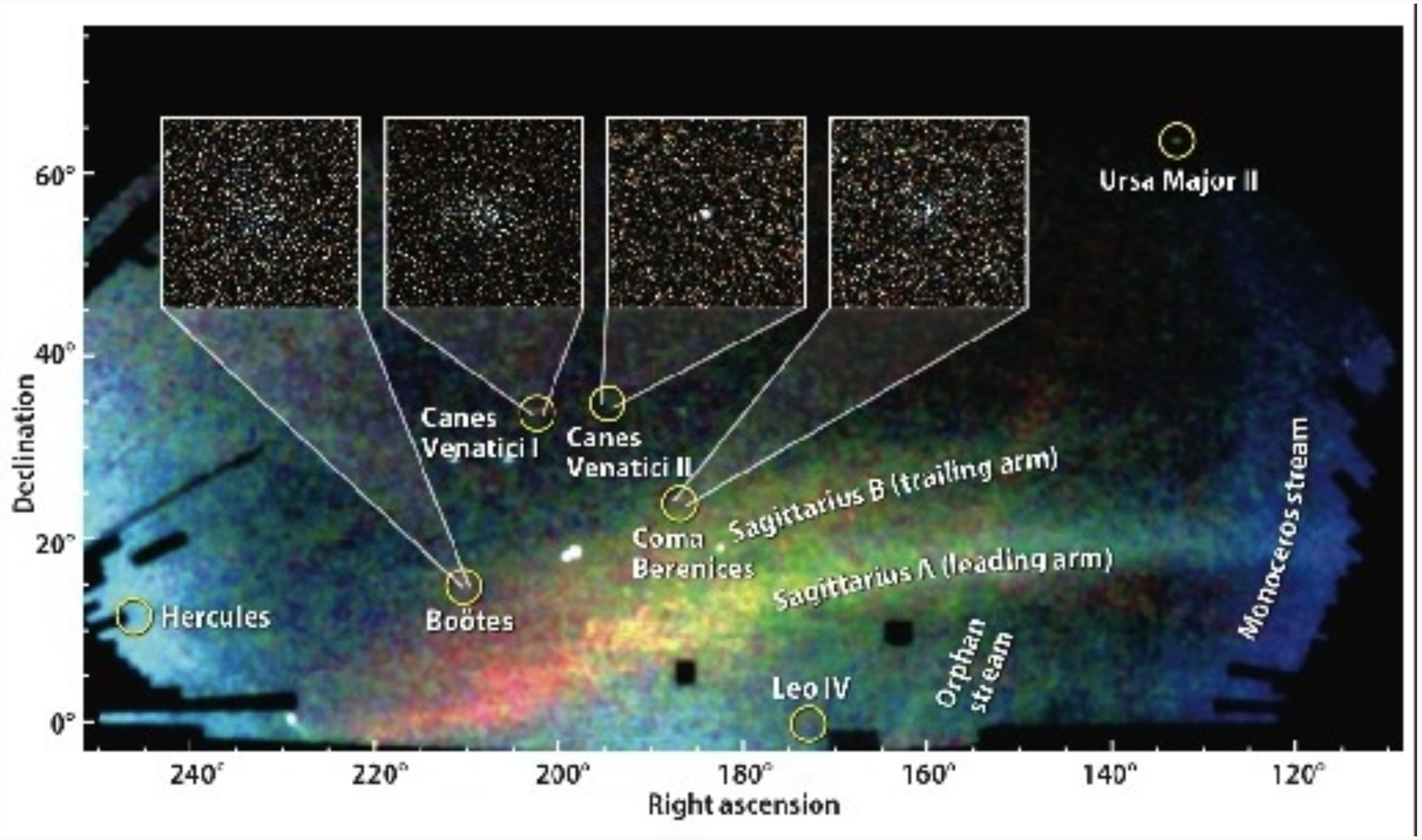
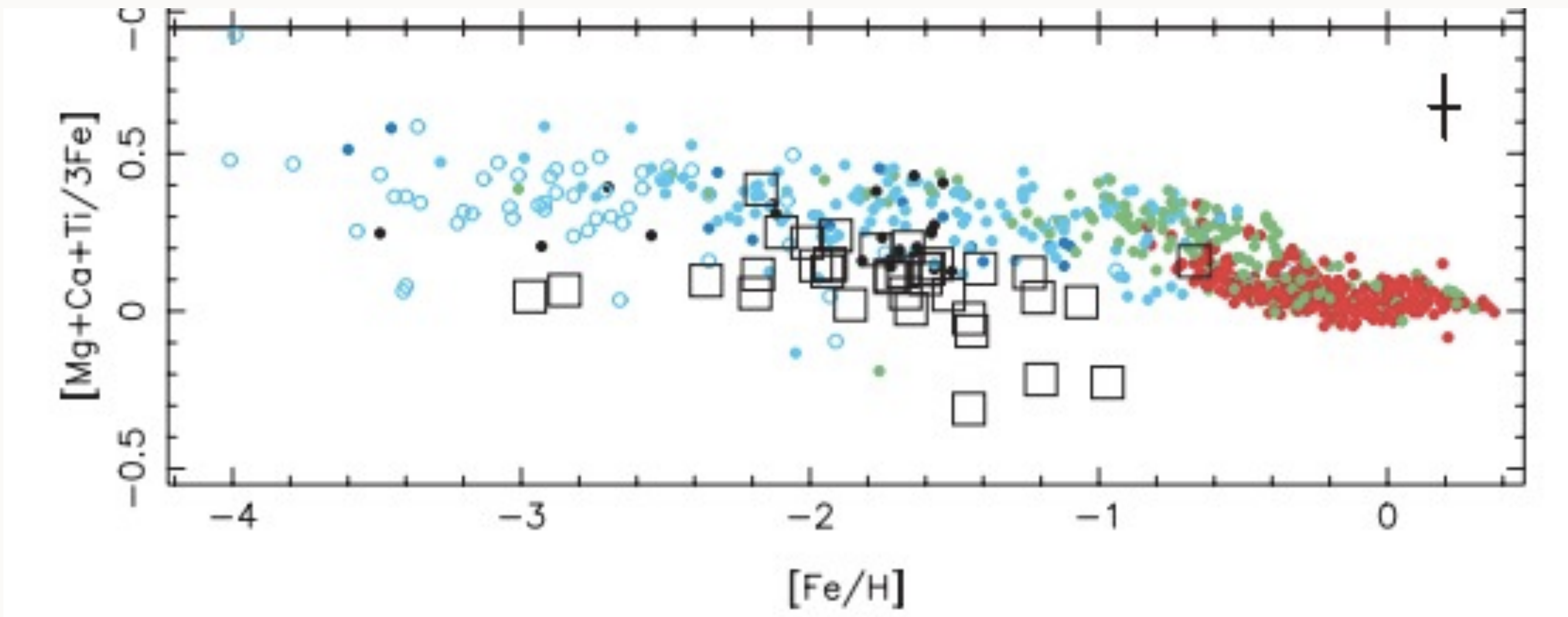
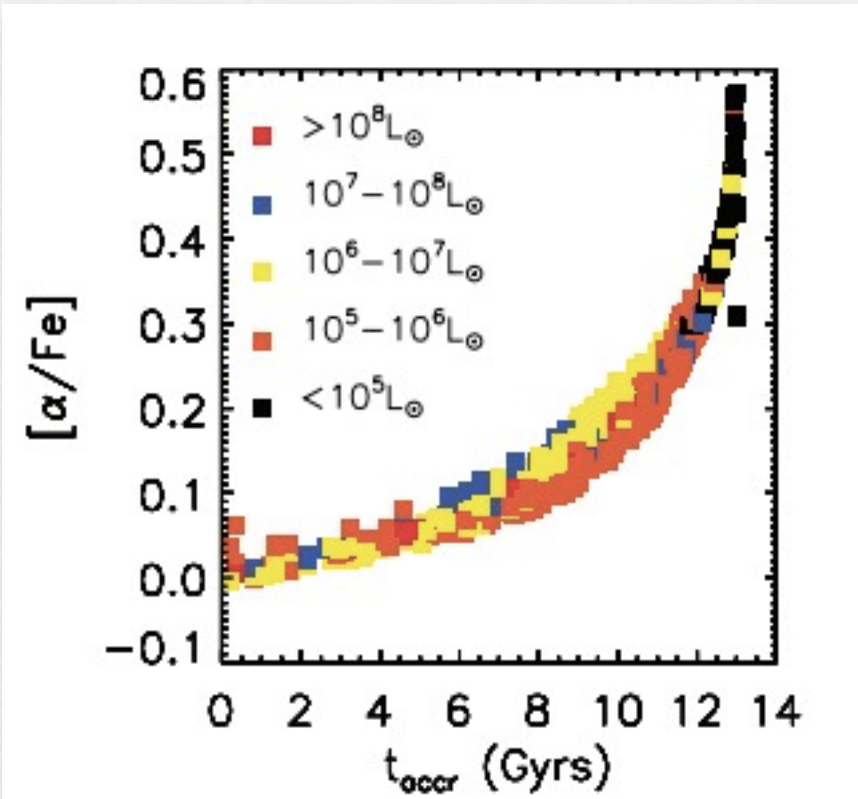
CAN YOU BUILD A STELLAR HALO FROM DWARFS?



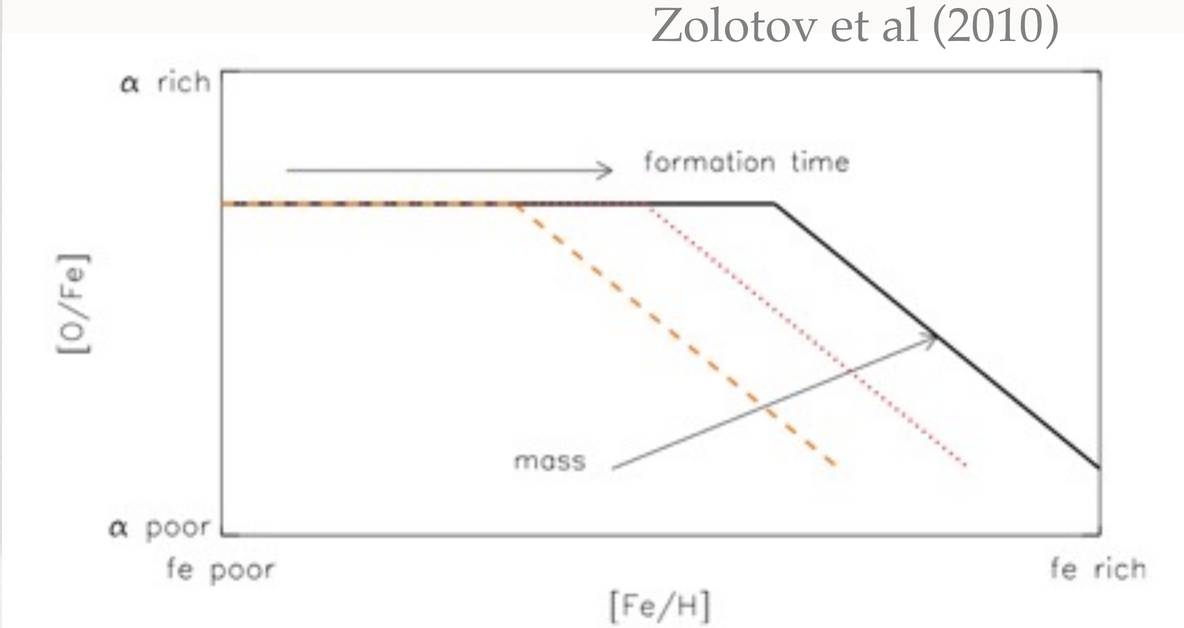
STELLAR METALLICITY & THE PUZZLE OF THE HALO

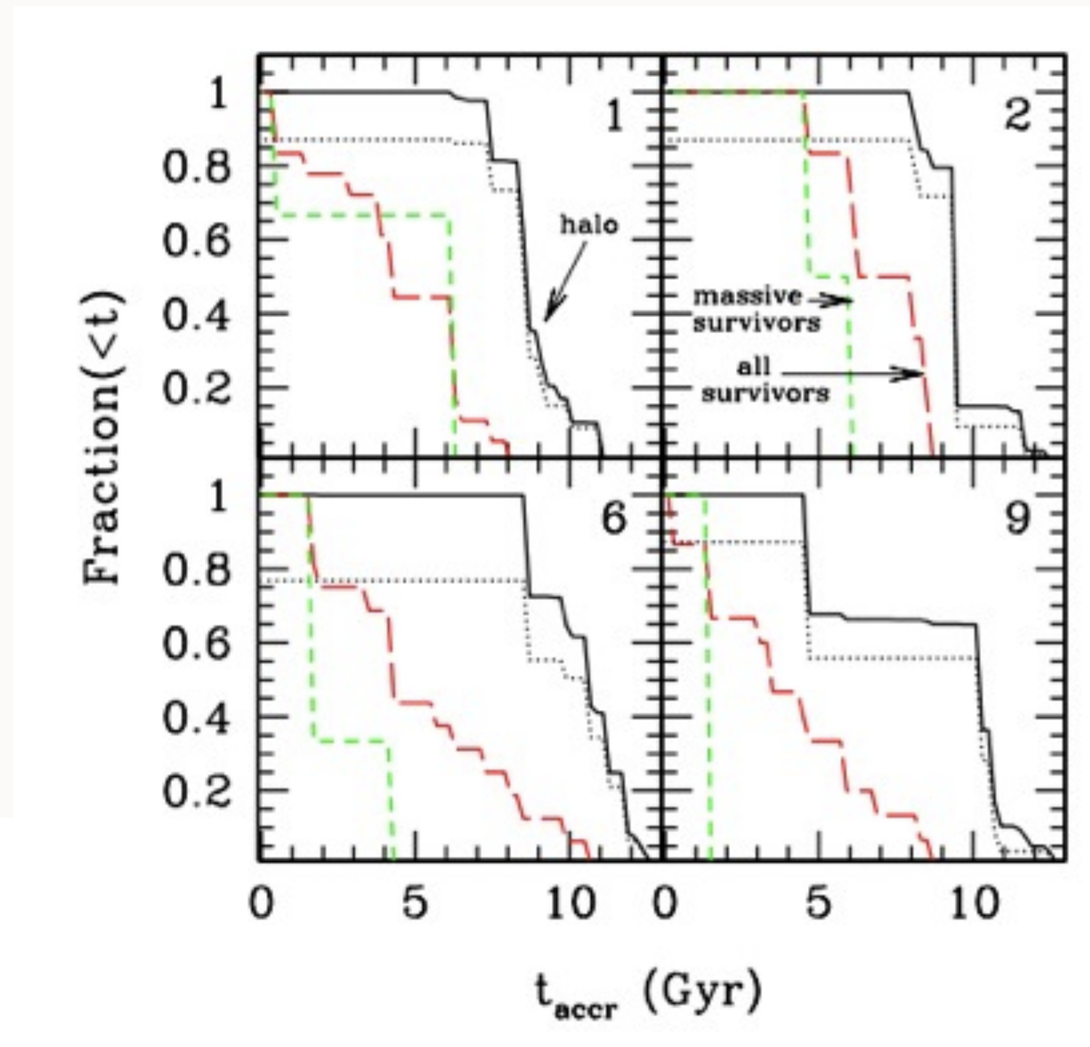


Venn et al (2004)



Zolotov et al (2010)





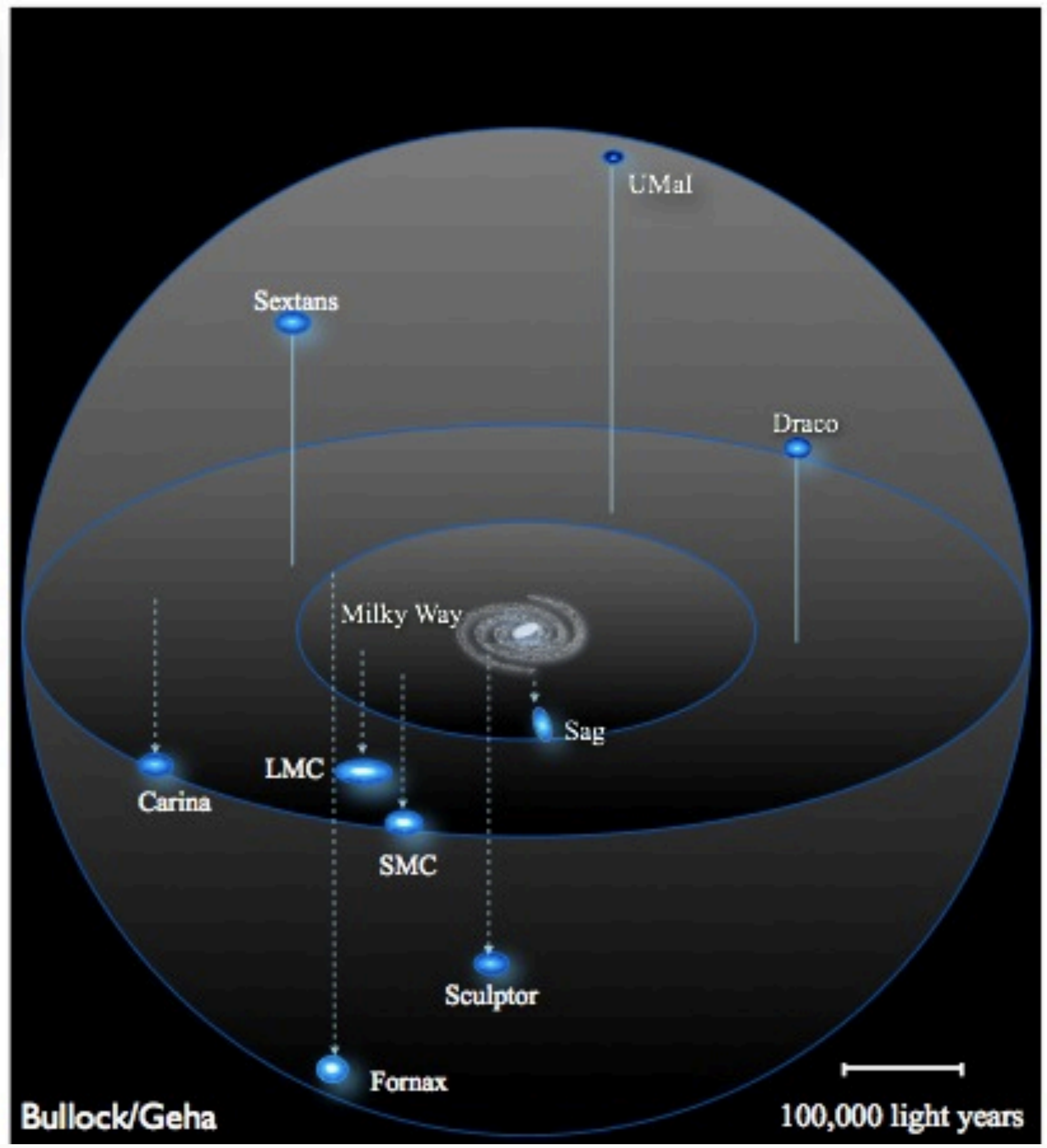
Johnston et al. (2008)

MEET THE NEIGHBORS: THE MILKY WAY SATELLITES

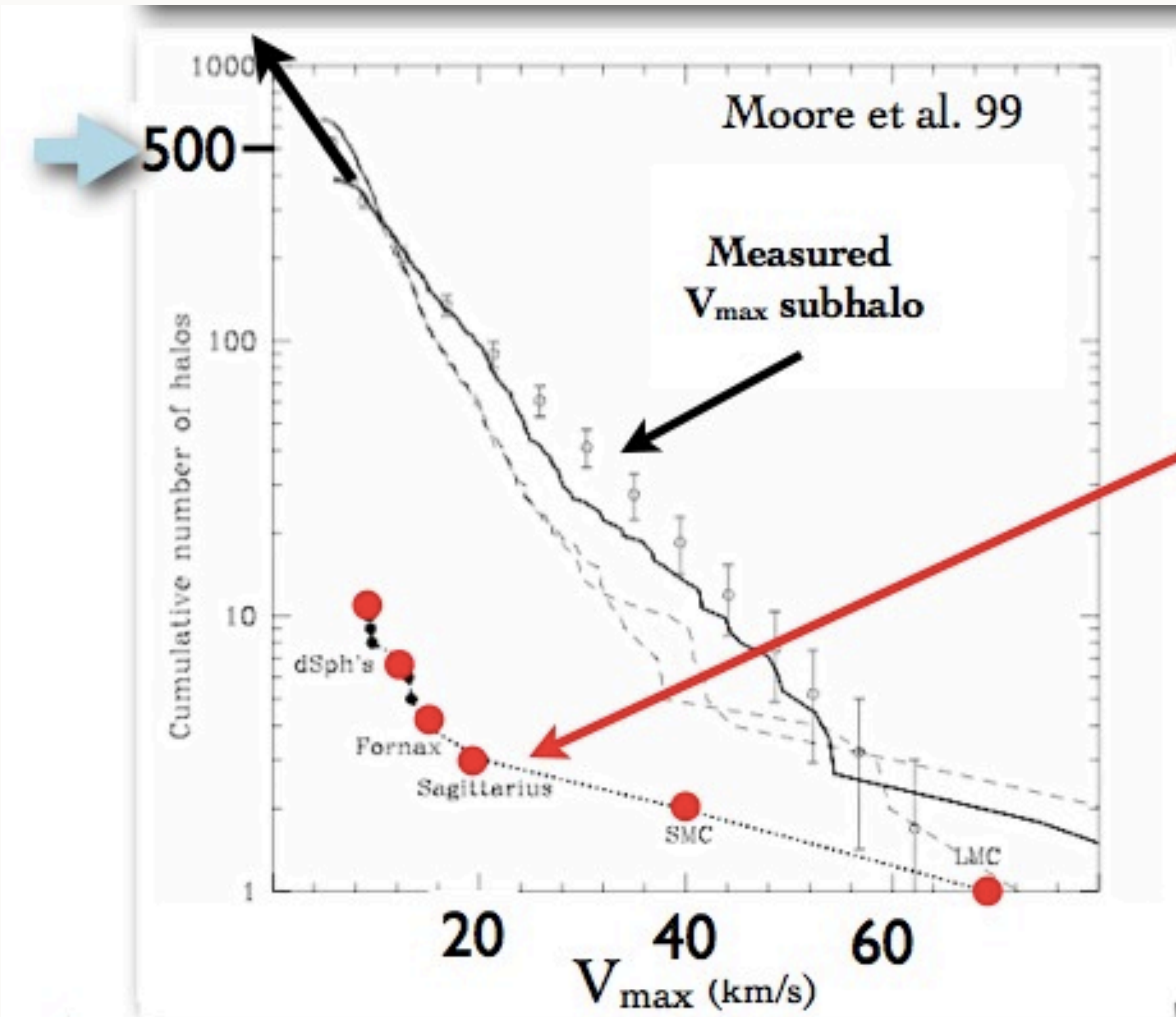
Milky Way circa 2004

11 Dwarf Satellites

Name	Year Discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994



A SERIOUS PROBLEM FOR CDM

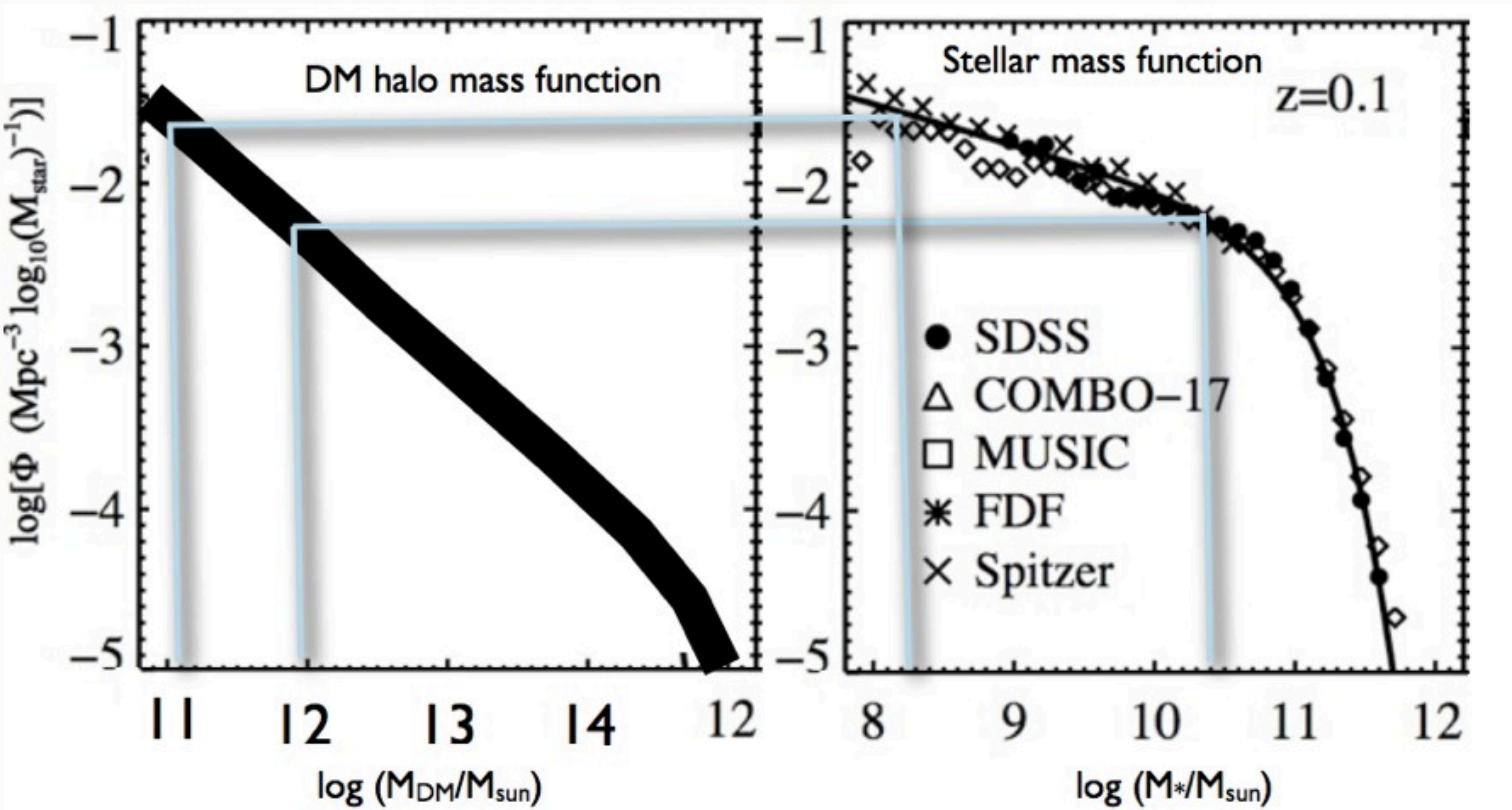


Also:
Klypin et al. 99

classical
MW satellites

$$V_{max} = \max\left(\frac{Gm(<r)}{r}\right)^{1/2}$$

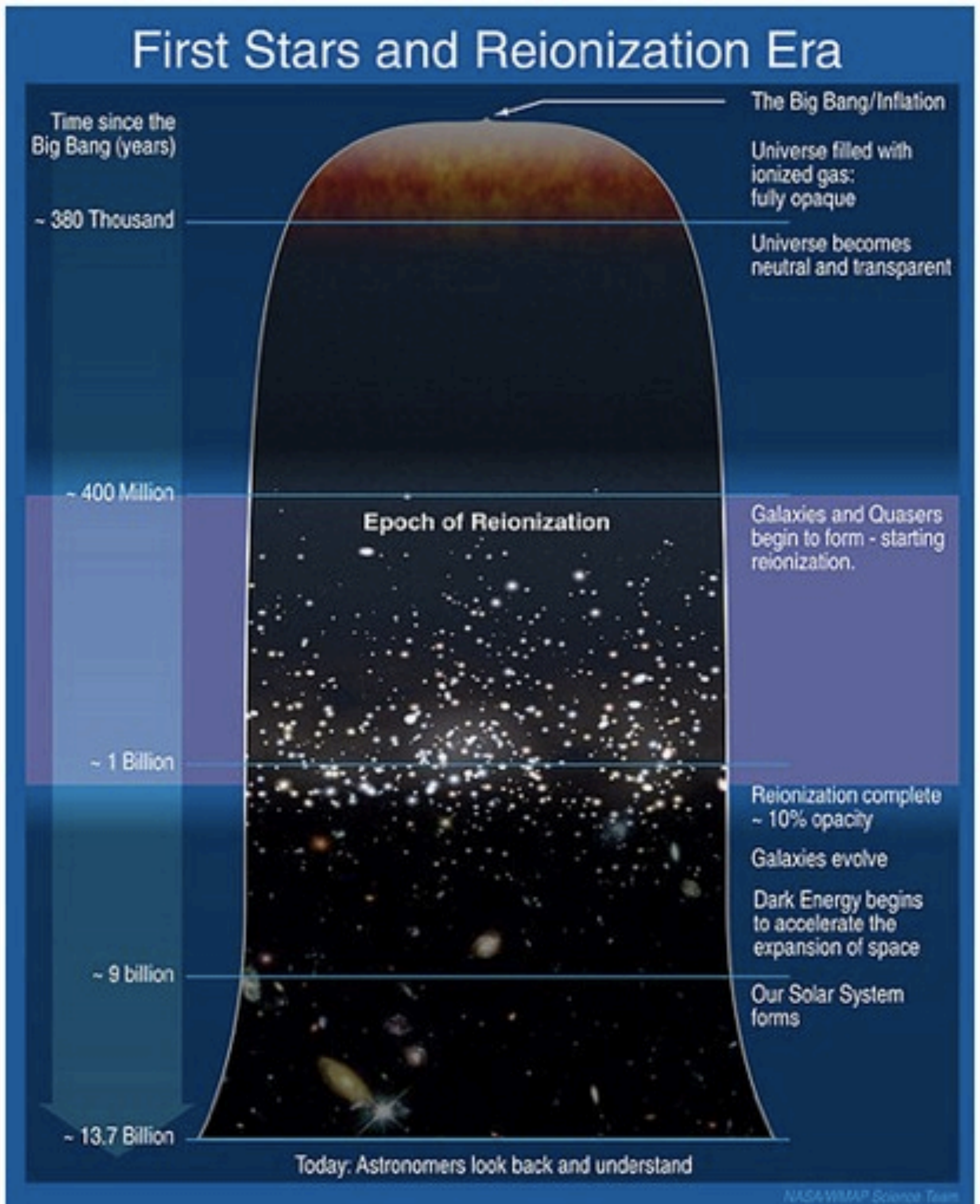
GALAXY FORMATION (IN)EFFICIENCY



Galaxy formation is highly inefficient at small scales!

- why are low mass galaxies inefficient at making stars?! reionization & feedback

REIONIZATION



recombination of protons & electrons
-> neutral Hydrogen (z~1000)

At some point, galaxies and stars start to ionize neutral Hydrogen ($6 < z < 20$)

WHAT CAUSED THE IONIZING BACKGROUND?

- To ionize neutral hydrogen, an energy larger than 13.6 eV is required, which corresponds to photons with a wavelength of 91.2 nm -> UV radiation
- Quasars emit a lot of light above this threshold, but may not have been abundant at high redshift.
- Population III (massive, low-metallicity) stars that went supernovae also emit a lot of light above this threshold.

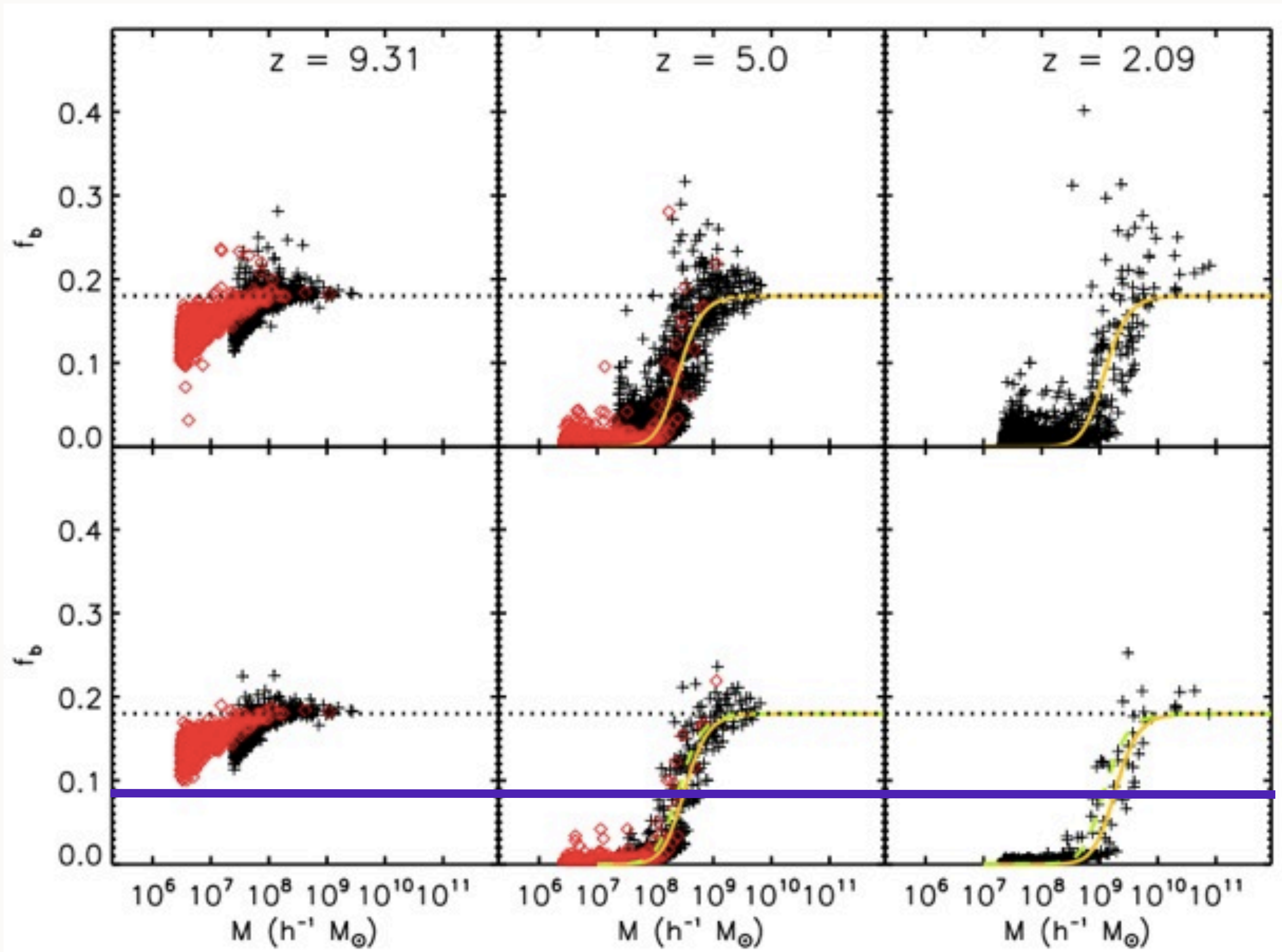
CHARACTERISTIC SCALE FOR DARK HALOS

- UV radiation from stars and quasars photoheats the gas in small halos -> gas escapes shallow potential well.
- From virial theory, we know that: $$T_{\rm vir} = \frac{1}{2}\frac{\mu m_{\rm p}}{k_{\rm B}} V_{\rm c}^2$$
- Gas gets too hot to be confined by galaxy's potential well at virial temperatures of ~ 10^4 K -> Vmax ~ tens km/s. (gas does not get hot enough to cool by atomic processes)
- Mc = characteristic mass, below which galaxies are strongly effected by UV background.

- Before reionization, the baryon fraction in a galaxy is $f_b \equiv M_b / M_{tot}$, $\langle f_b \rangle \equiv$ Omega_b/Omega_m ~ 0.18
- After reionization f_b drops sharply for galaxies below a characteristic mass $M_c(z)$, halos with $M < M_c(z)$ have too shallow potential wells to hold onto their gas.
- M_c defined where $f_b < \langle f_b \rangle / 2$

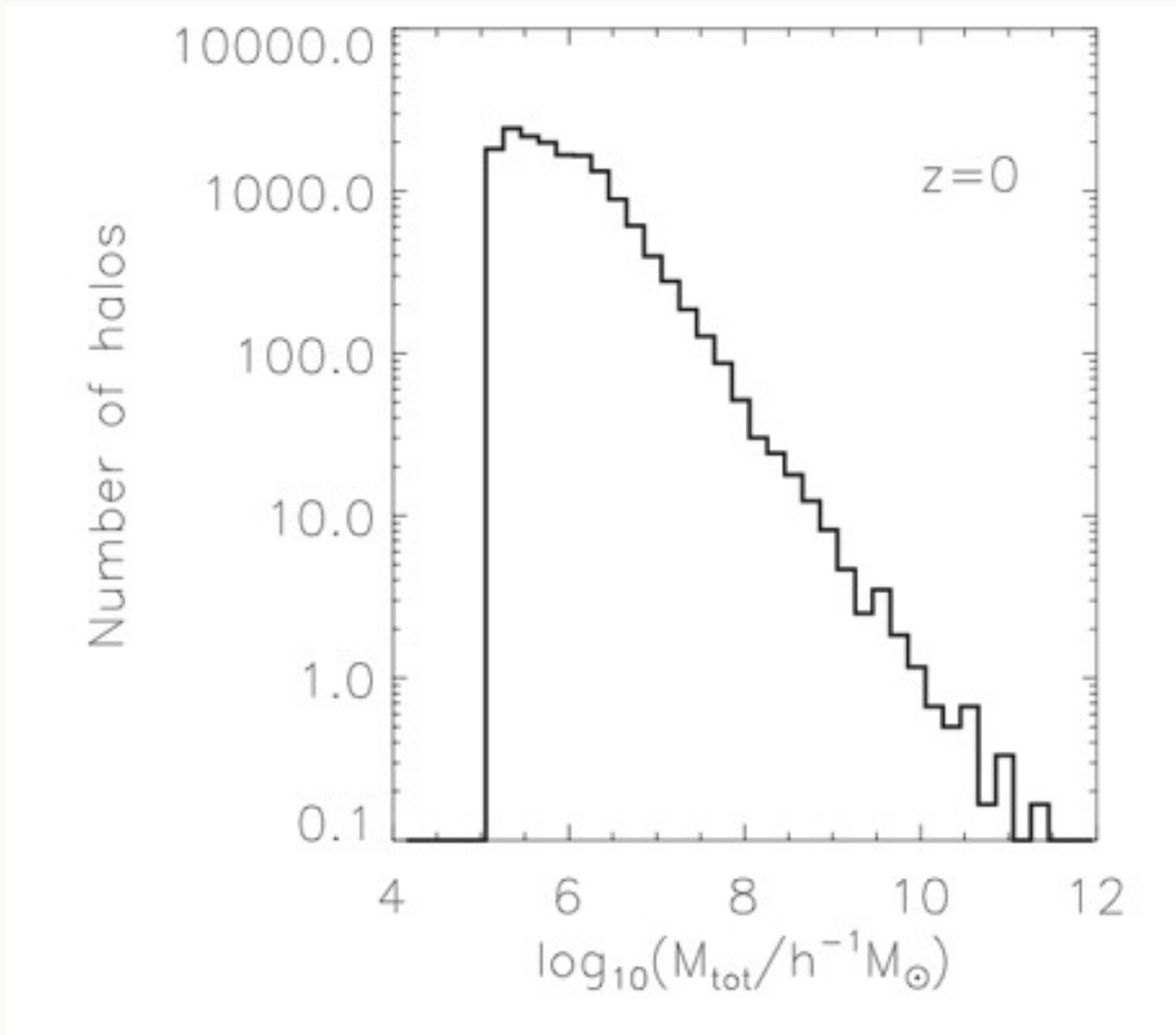
.

CHARACTERISTIC MASS



Okamoto et al (2008)

LET'S APPLY THIS TO SUBHALOS



The following treatment is based on Koposov et al. (2009)

MODELS TO POPULATE DM HALOS WITH STARS

- Model 1:

$$M_* = f_* \times M_{\rm sat}.$$

$$F_* \equiv \frac{f_*}{\Omega_b/\Omega_m} = 6.25 f_*.$$

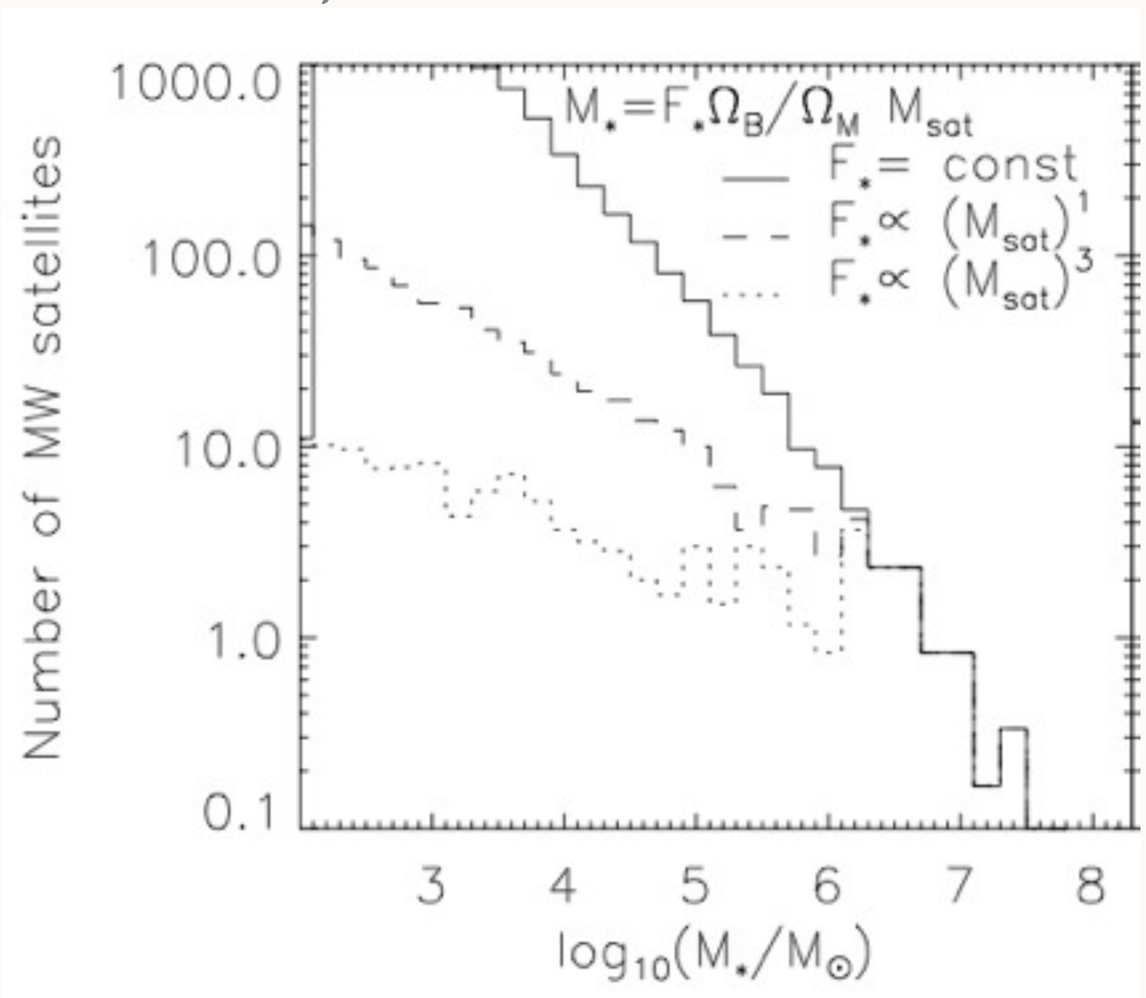
- f_* (stellar fraction in halos) ~ 10^{-4}- 10^{-2} from kinematic observations of dSph (M/L ~ a few - 1000)
- from abundance matching of field dwarfs, f_* ~ $10^{-3.6}$ -> F_* ~ 10^{-3}
- Assume to be the same at all halo masses
- Model 1B: SF efficiency declines at lower M -> Stellar fraction is power law below M_0
- M_0 ~ 10^{10}, vary alpha

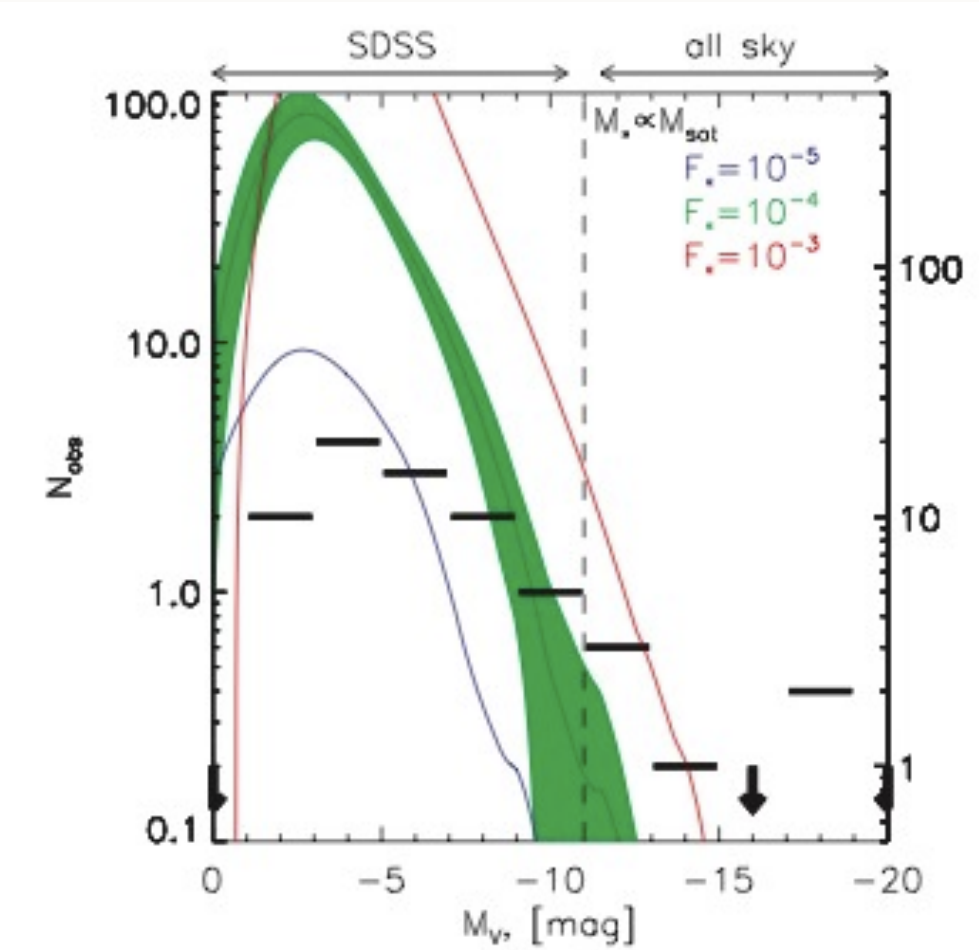
$$M_* = f_* \times \mathtt{min}\left(\left(\frac{M_{\rm sat}}{M_0}\right)^{\alpha}, 1\right) \times M_{\rm sat}.$$

Friday, May 16, 14

MODEL 1

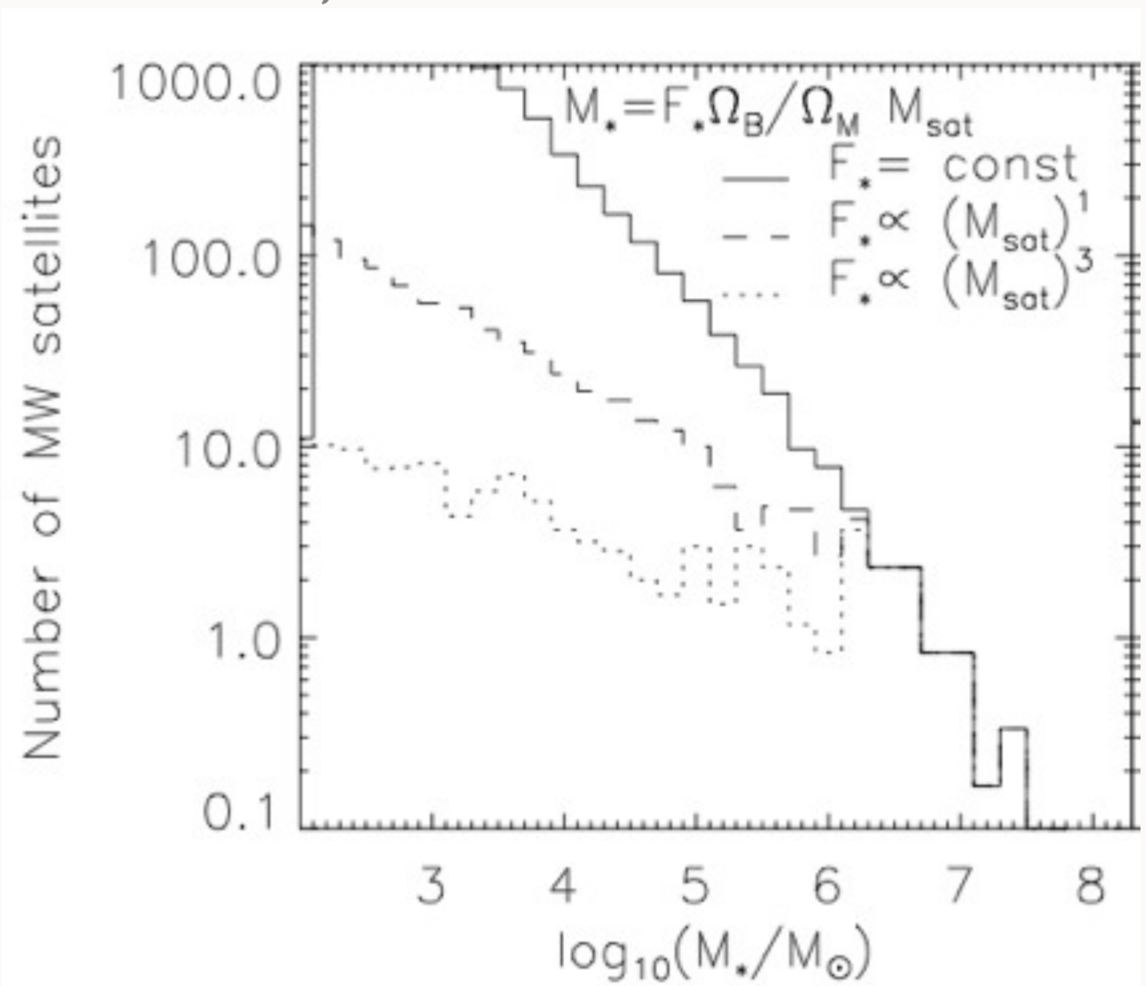
Model 1A, $F_* = 10^{-3}$

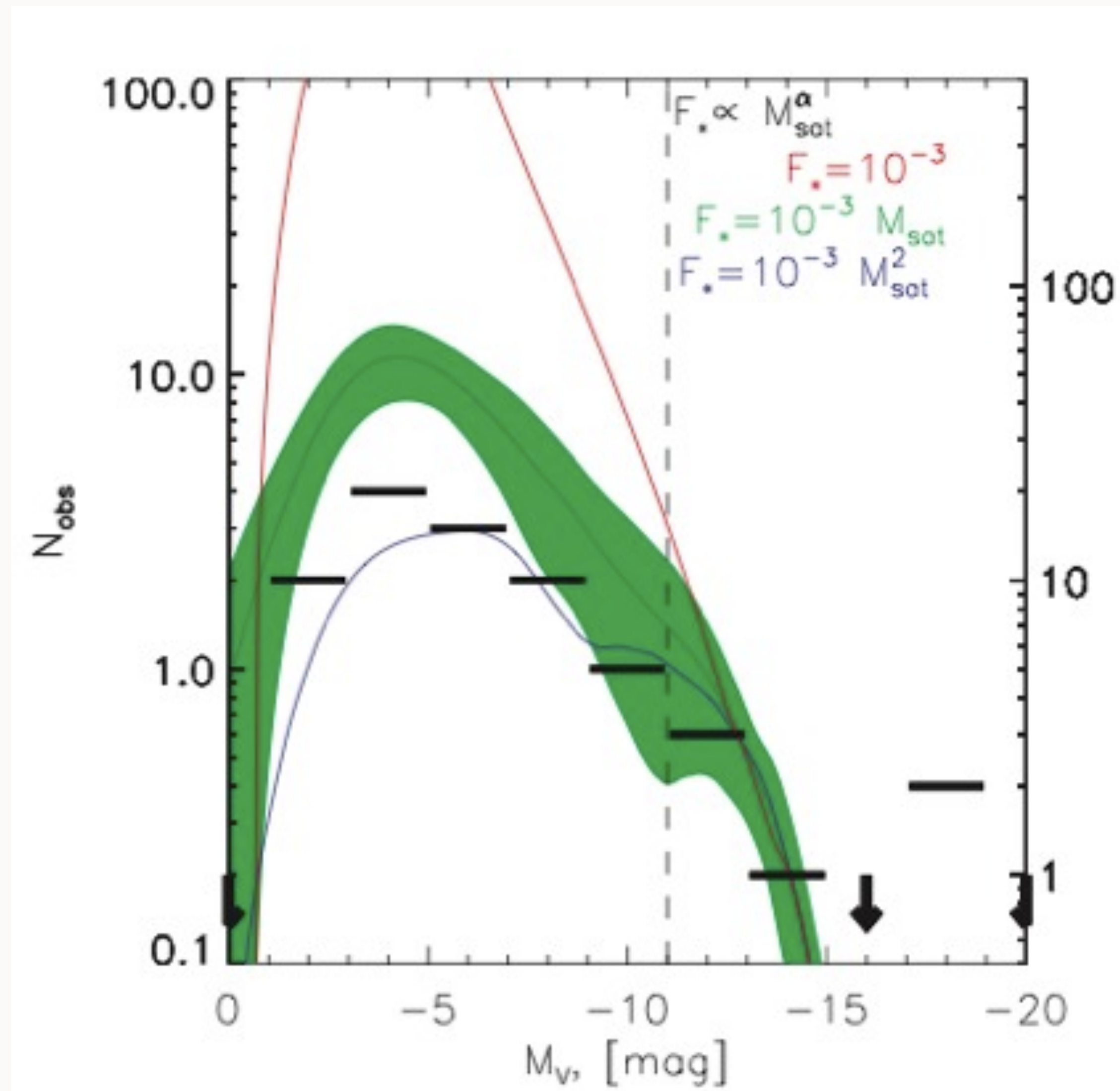




MODEL 1

Model 1A, $F_* = 10^{-3}$



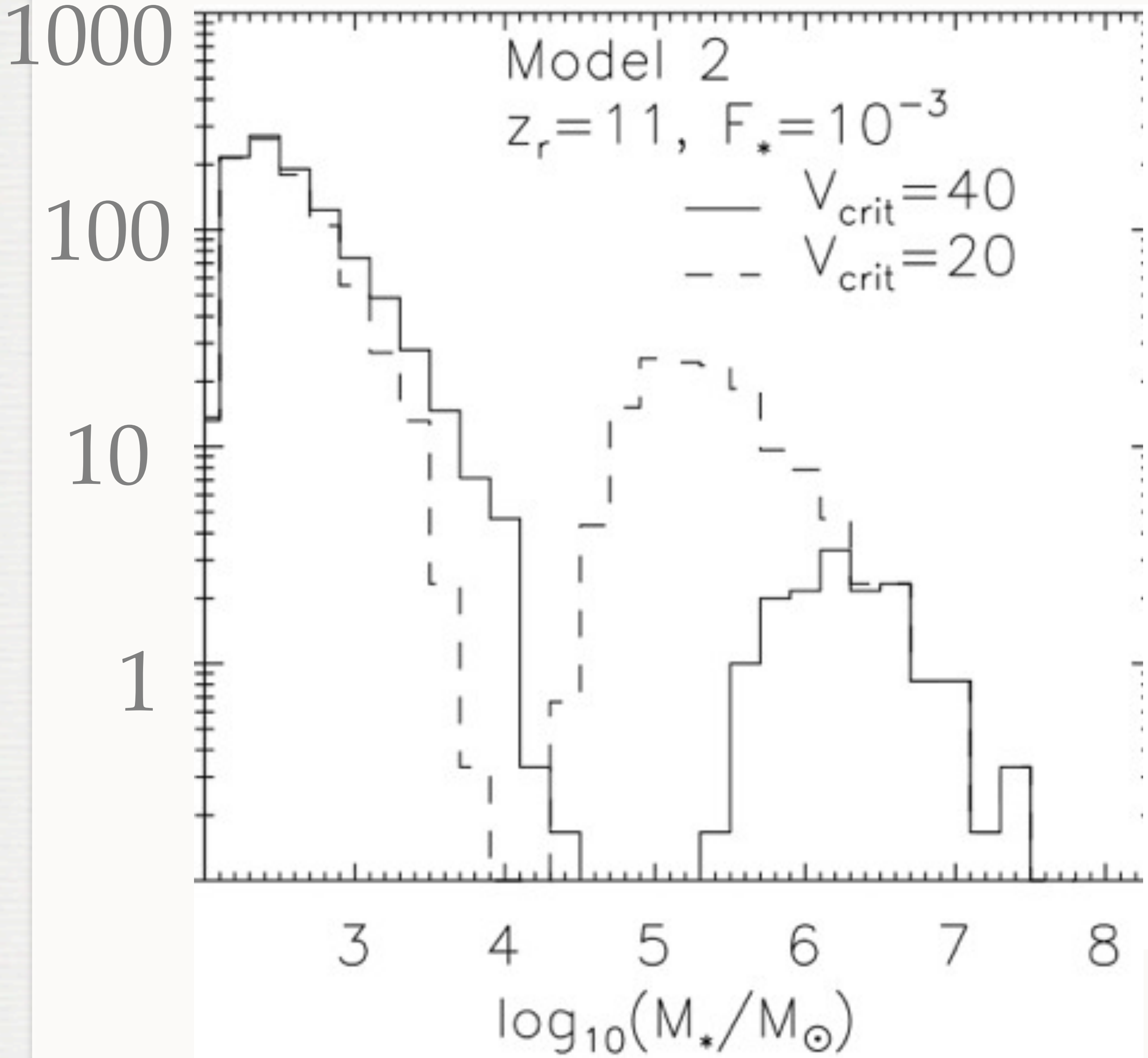


MODEL 2: INCLUDE REIONIZATION

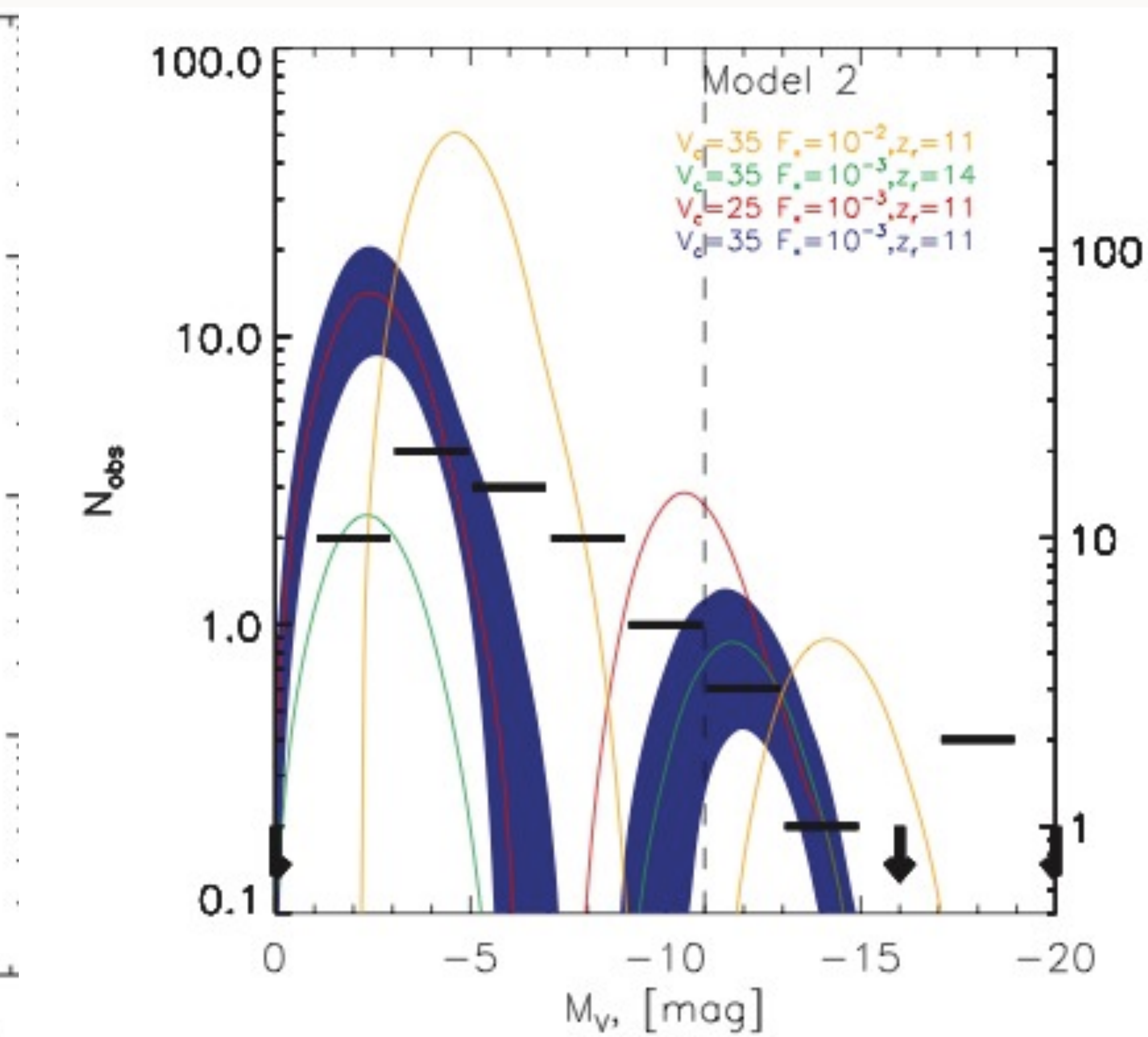
$$M_* = f_* \times M_{\text{sat}} \text{if } V_{\text{circ}}(z_{\text{sat}}) > V_{\text{crit}}$$
$$f_* \times M_{\text{rei}} \text{if } V_{\text{circ}}(z_{\text{sat}}) < V_{\text{crit}}.$$

- Model 2:
- stellar mass before reionization: $M_* = f_* \times M_{\text{rei}}$
- Bimodal: low-mass dwarfs in which all stars formed before reionization and the high- mass dwarfs that exceeded the critical velocity threshold before becoming satellites, $V_{circ}(z_{sat}) > V_{crit}$

MODEL 2



1000
100
10
1
Model 2
$z_r=11,\ F_*=10^{-3}$
$V_{crit}=40$
$V_{crit}=20$
3 4 5 6 7 8
$\log_{10}(M_*/M_\odot)$

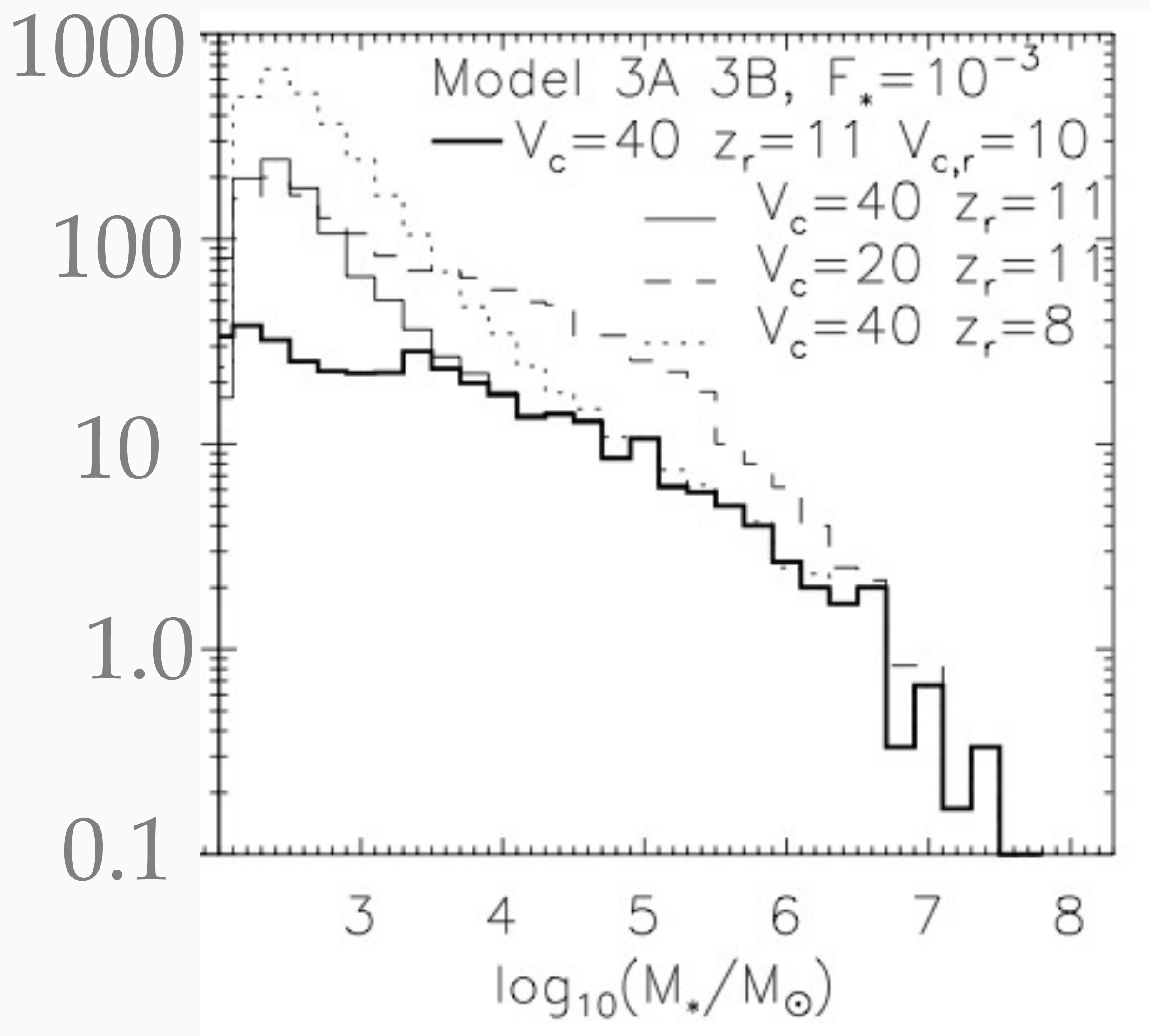


Model 2
$V_c=35\ F_*=10^{-2}, z_r=11$
$V_c=35\ F_*=10^{-3}, z_r=14$
$V_c=25\ F_*=10^{-3}, z_r=11$
$V_c=35\ F_*=10^{-3}, z_r=11$
100.0
10.0
1.0
0.1
N_{obs}
100
10
1
0 −5 −10 −15 −20
M_V, [mag]

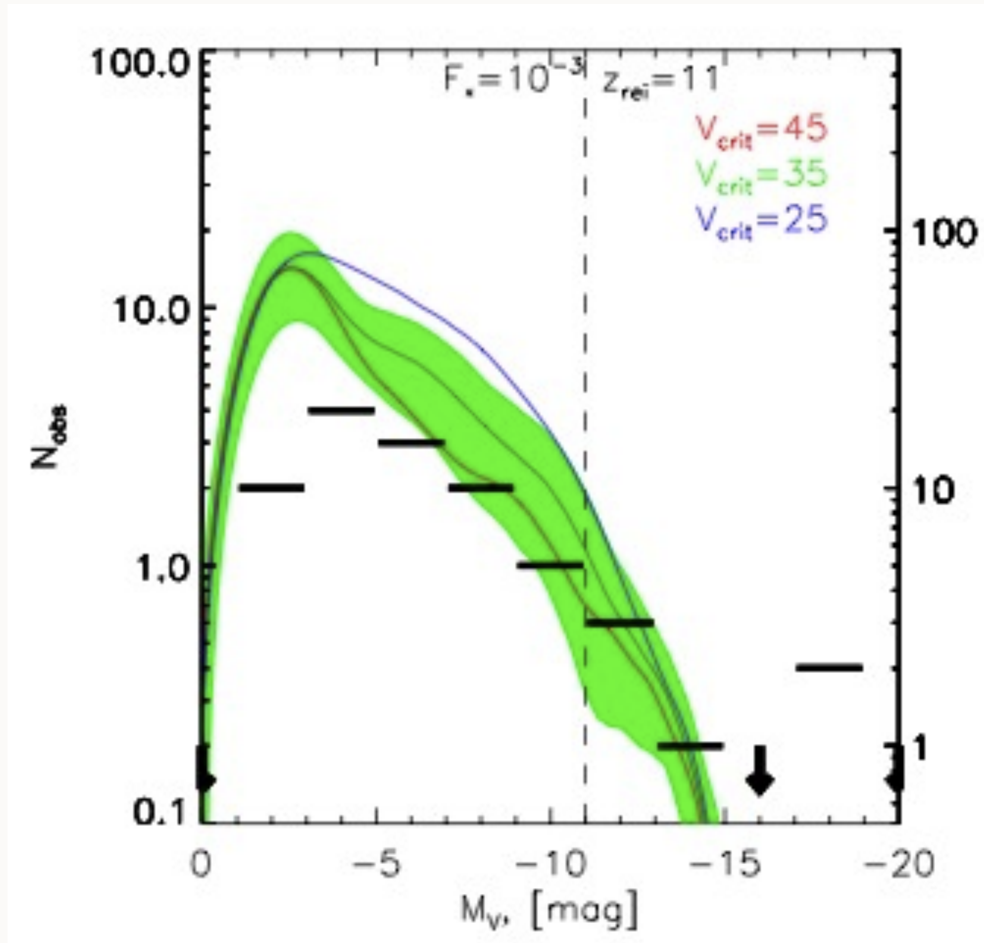
MODEL 3

- Model 3A: $$M_* = \frac{f_* \times (M_{\rm sat} - M_{\rm rei})}{(1 + 0.26\,(V_{\rm crit}/V_{\rm circ}(z_{\rm sat}))^3)^3} + f_* \times M_{\rm rei}.$$
- M* strongly suppressed below Vcrit ~ 30 km/s
- The assumption that all halos can form stars before zrei may not be justified because in halos with virial temperature Tvir<10^4 K (Vcirc < 10 km s^{-1}) the gas does not get hot enough to cool by atomic processes
- Model 3B: Eliminate stellar mass in pre-reionization halos below a critical threshold Vcrit,r ~ 10 km s^{-1}
- $$M_* = \frac{f_* \times M_{\rm sat}}{(1 + 0.26\,(V_{\rm crit}/V_{\rm circ}(z_{\rm sat}))^3)^3},$$

MODEL 3

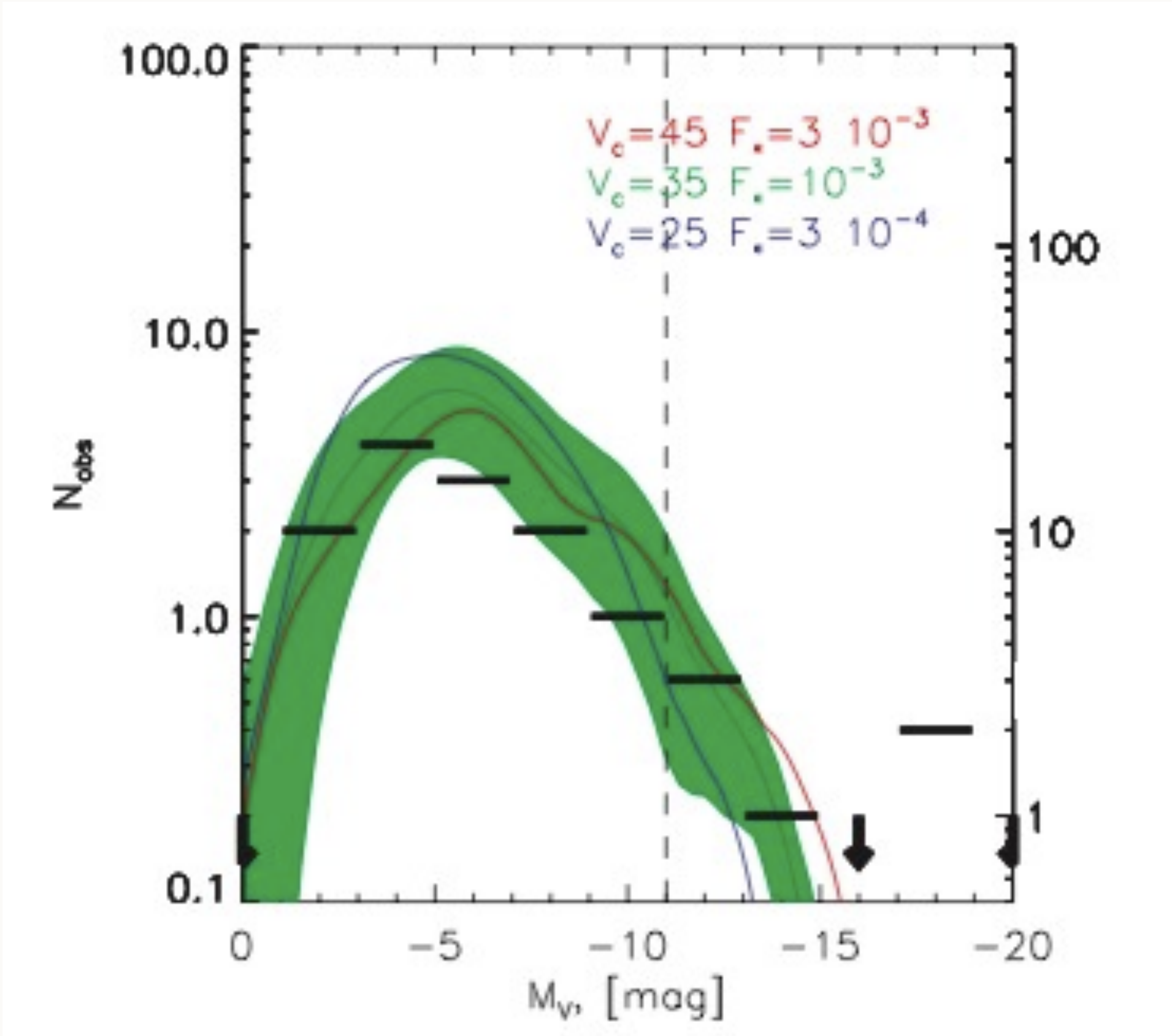


Model 3A 3B, $F_*=10^{-3}$
$V_c=40$ $z_r=11$ $V_{c,r}=10$
$V_c=40$ $z_r=11$
$V_c=20$ $z_r=11$
$V_c=40$ $z_r=8$
1000
100
10
1.0
0.1
3
4
5
6
7
8
$\log_{10}(M_*/M_\odot)$



$F_*=10^{-3}$
$z_{rei}=11$
$V_{crit}=45$
$V_{crit}=35$
$V_{crit}=25$
100.0
10.0
1.0
0.1
N_{obs}
100
10
1
0
−5
−10
−15
−20
M_V, [mag]

MODEL 3B



100.0
10.0
1.0
0.1
N_{obs}
V_c=45 F_*=3 10^{-3}
V_c=35 F_*=10^{-3}
V_c=25 F_*=3 10^{-4}
100
10
1
0
−5
−10
−15
−20
M_V, [mag]

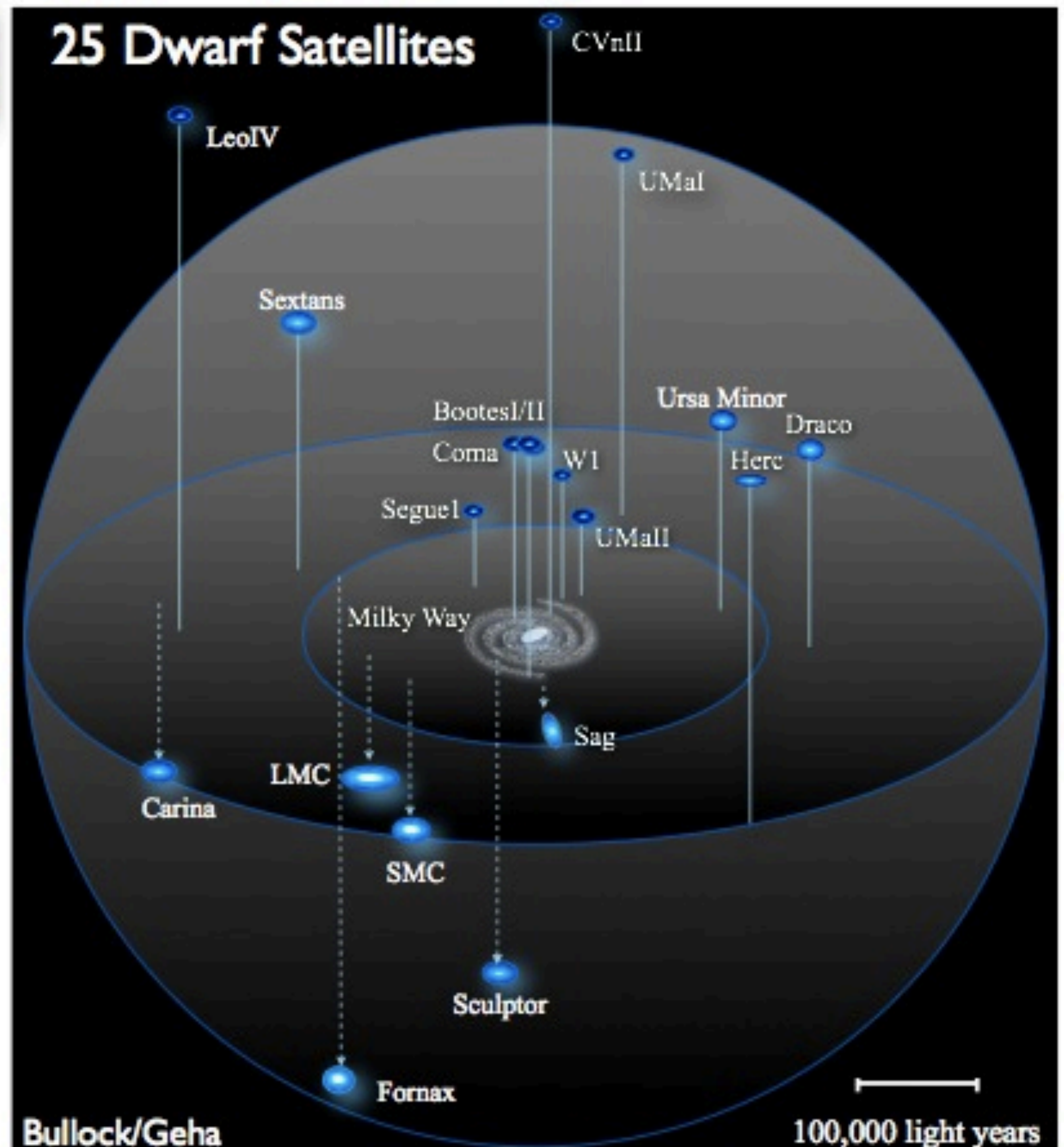
WHAT HAVE WE LEARNED FROM THIS?

- What works: A model in which the photoionizing background suppresses gas accretion onto halos with $V_{circ}(z_{sat}) < V_{crit} \approx 35$ km s^{-1} with the smooth mass-dependent suppression suggested by numerical simulations
- star formation in halos before reionization must be extremely inefficient to avoid producing too many satellites in the range $0 < M_V < -6$.
- Inefficient molecular cooling (and/or stellar feedback) drastically reduces the efficiency of star formation in pre-reionization halos below the hydrogen atomic line cooling threshold $V_{crit,r} \approx 10$ km s^{-1}
- For the values $V_{crit} = 25$–35 km s^{-1} favored by numerical simulations, F_* must be $< 10^{-3}$, so even subhalos above the V_{crit} threshold have star formation efficiency far lower than the values $F_* \approx 0.1$–0.4 found for bright galaxies
- Models with constant M_*/M_{sat} predict far too many faint satellites relative to bright satellites.

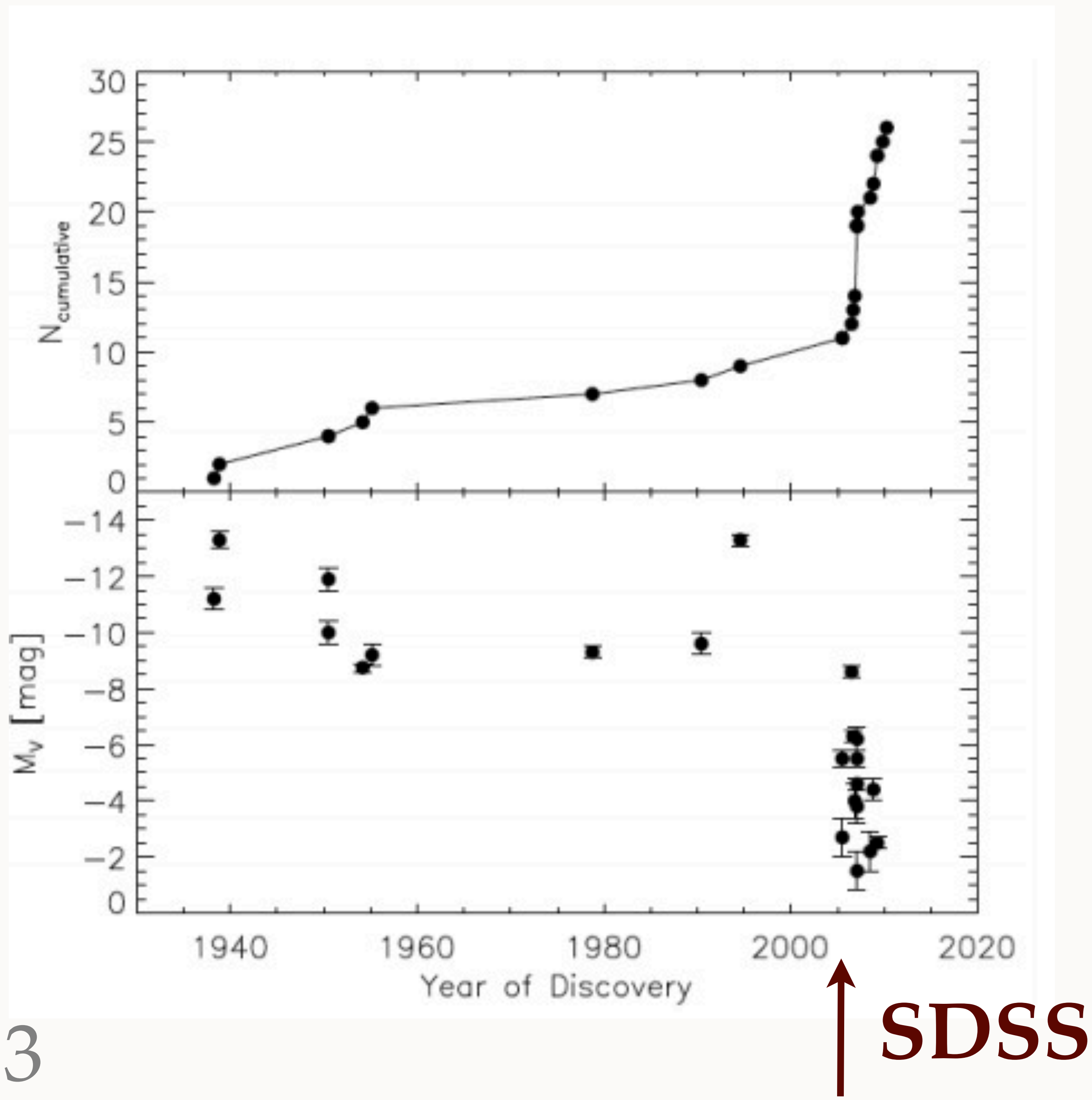
MW SATELLITES IN THE ERA OF SDSS

Milky Way circa 2009

Name	Year Discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994
Ursa Major I	2005
Willman I	2005
Ursa Major II	2006
Bootes	2006
Canes Venatici I	2006
Canes Venatici II	2006
Coma	2006
Segue I	2006
Leo IV	2006
Hercules	2006
Leo T	2007
Bootes II	2007
Leo V	2008
Segue II	2009

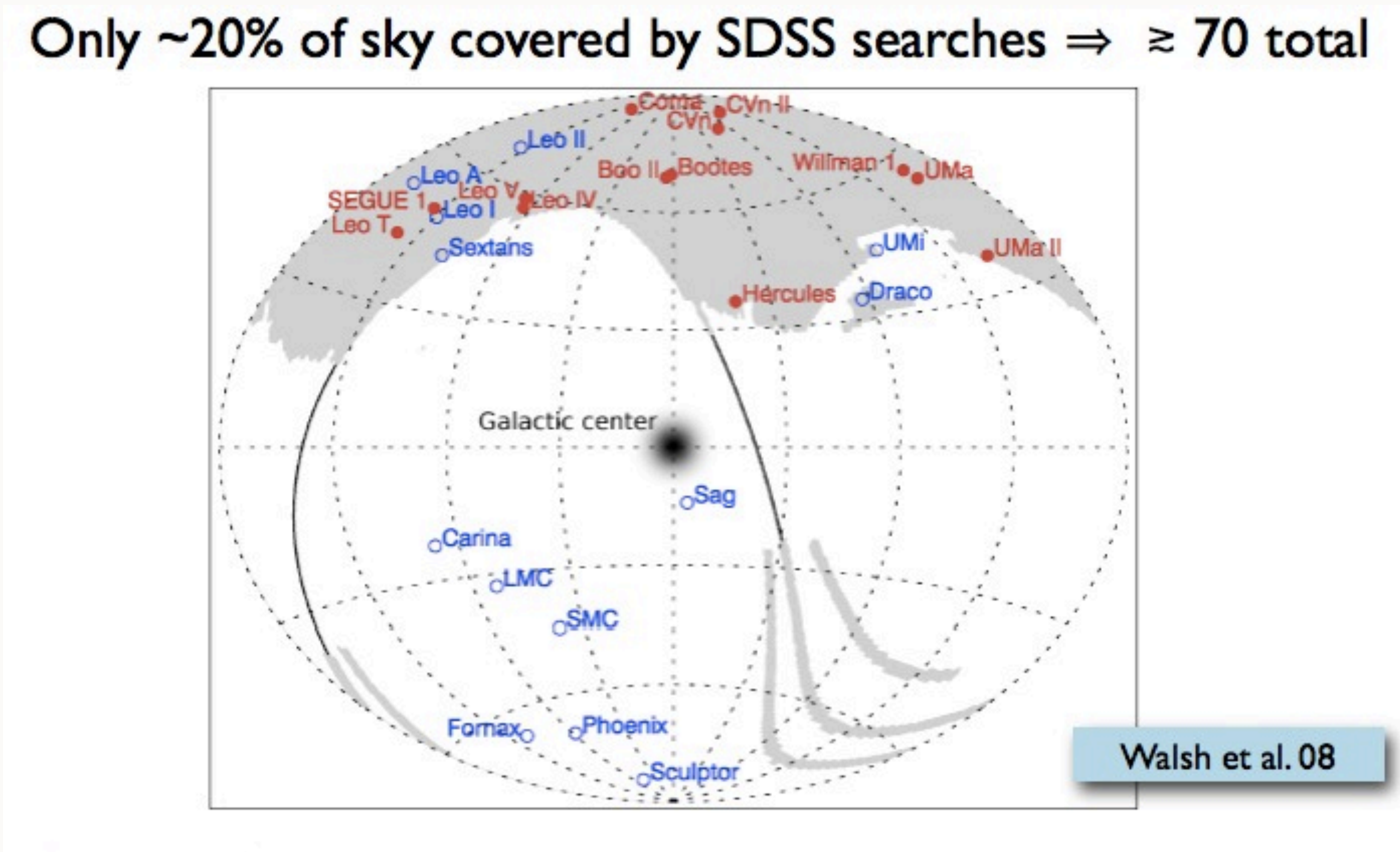


DISCOVERING NEW SATELLITES



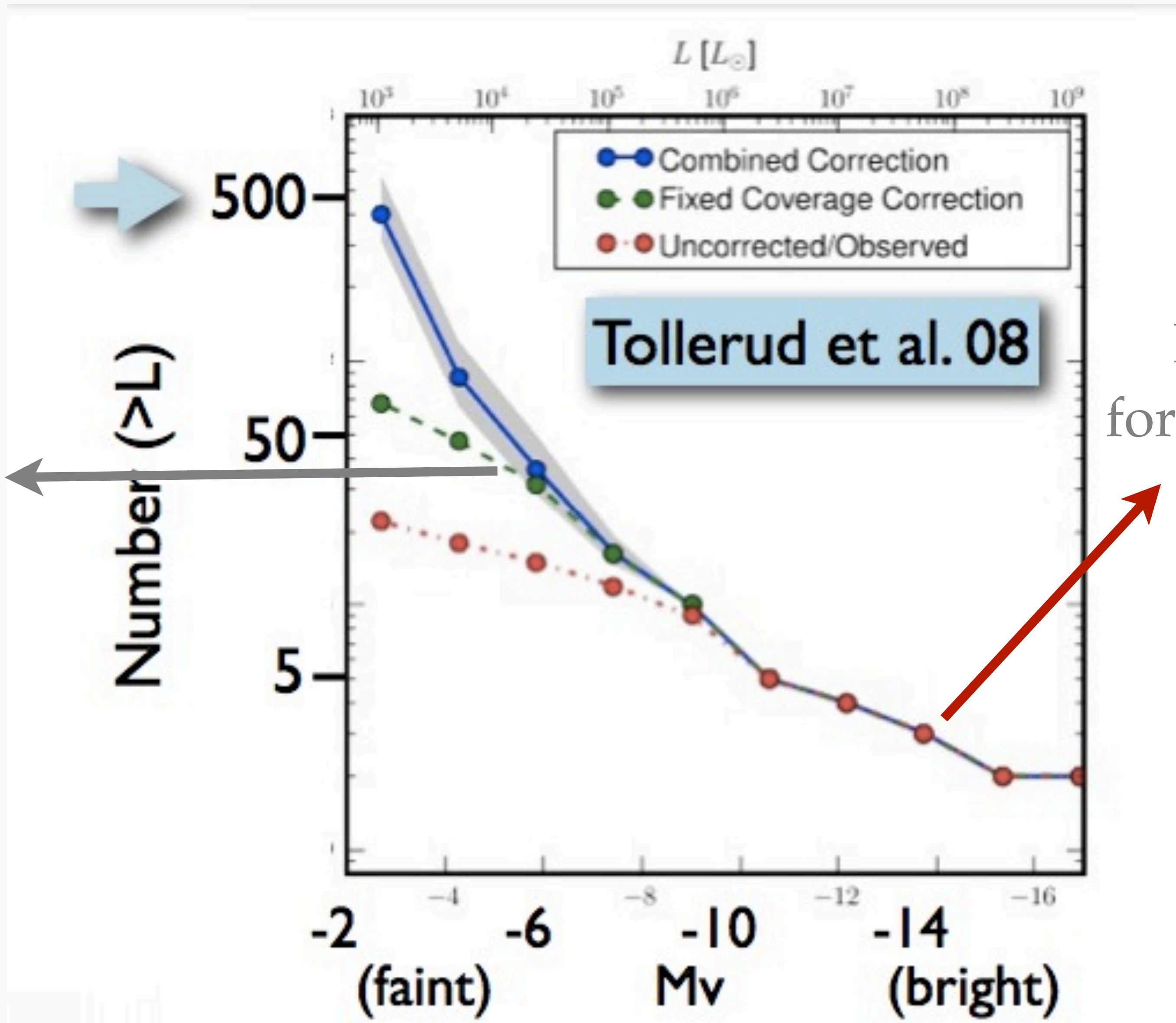
Walker 2013

OBSERVATIONAL INCOMPLETENESS



12 x 5 = 60 +10 classical = 70 satellites

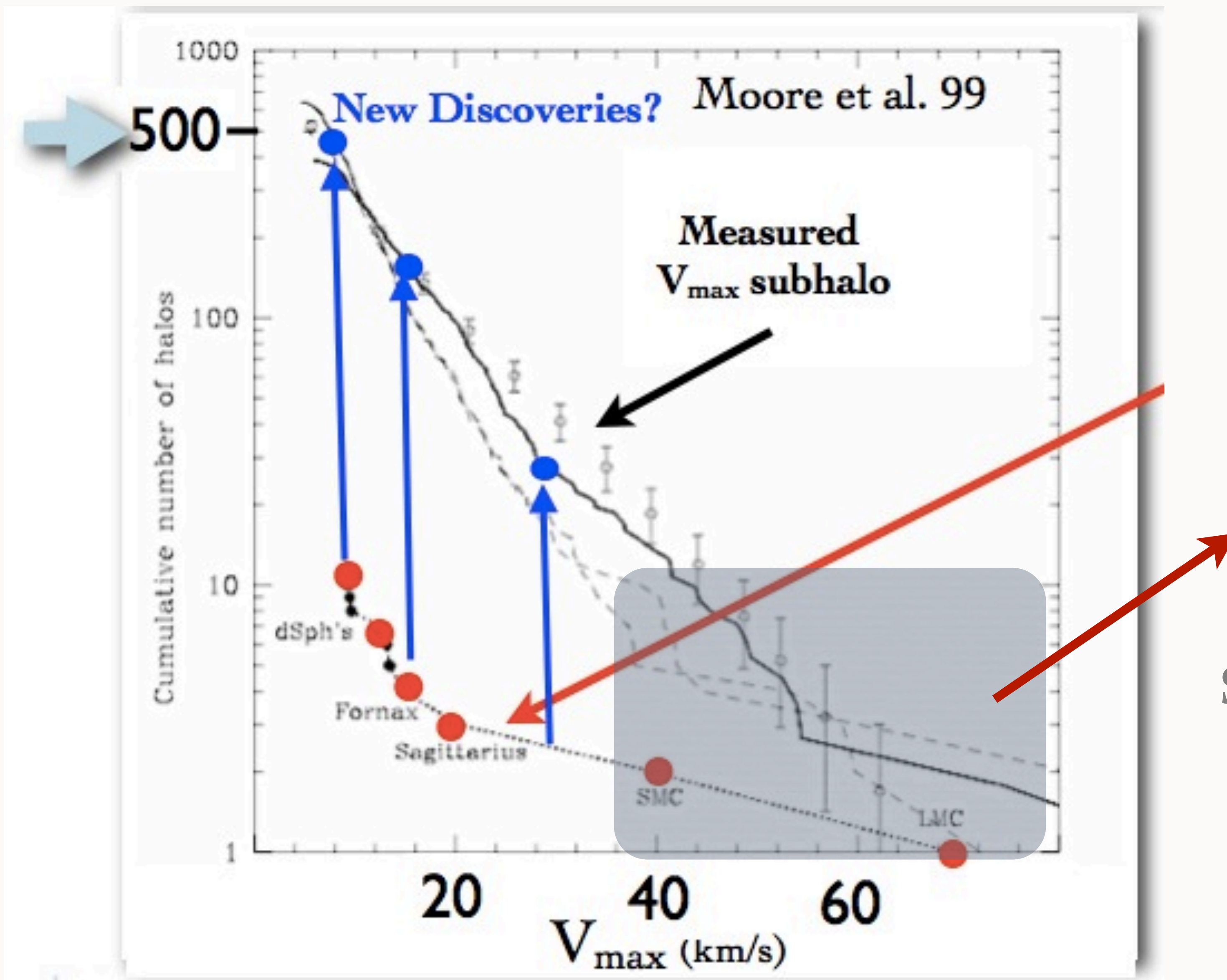
MAGNITUDE CORRECTION



only complete in inner ~ 50 kpc

No correction for classical dwarfs

MISSING SATELLITES?



still missing!

WHAT HAVEN'T WE LEARNED

- Note, there is nothing about these results that necessarily picks out photoionization as the suppression mechanism in low-mass subhalos!
- What about the more massive halos that Koposov et al. ignored?

SUPERNOVAE FEEDBACK

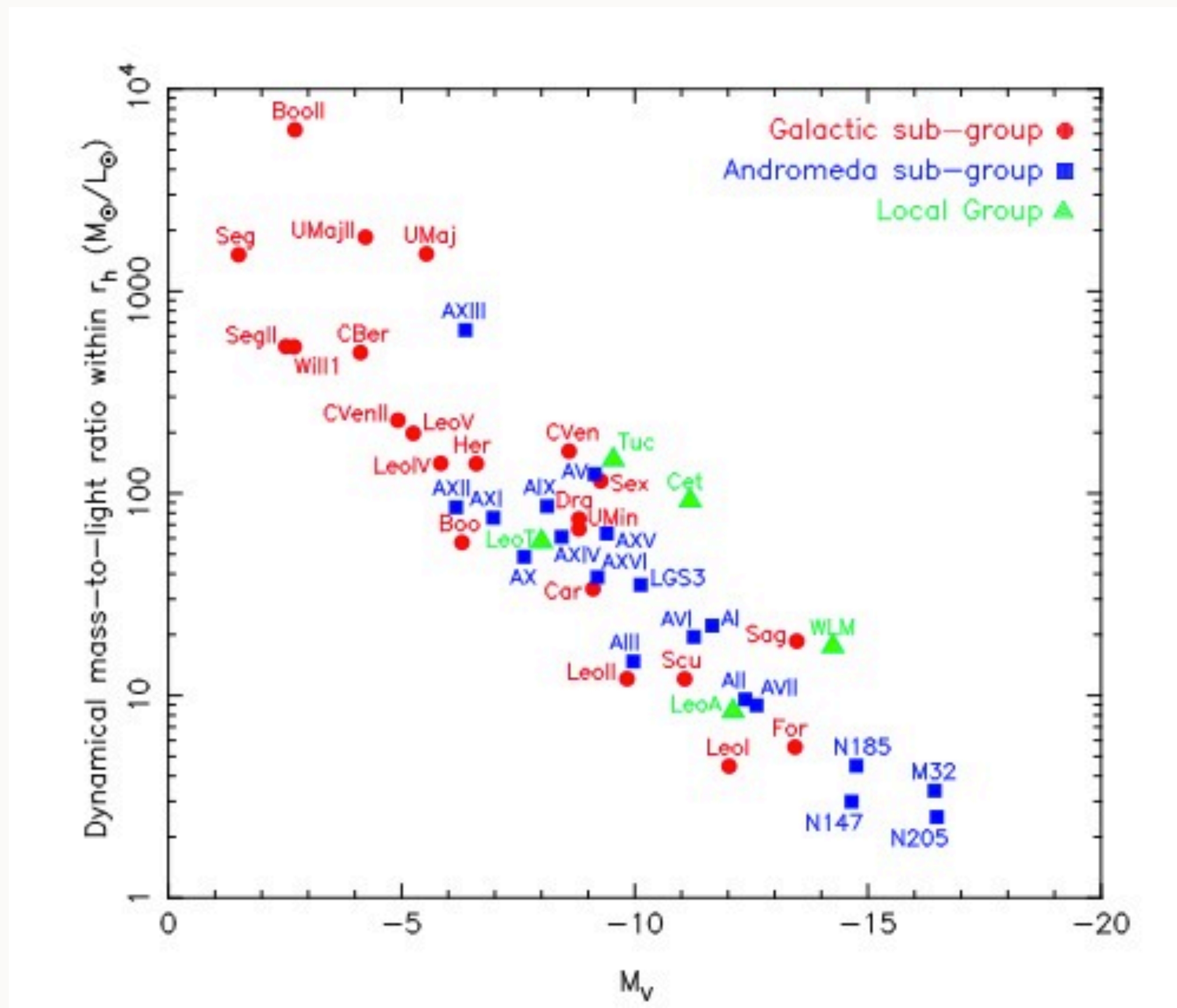
- When massive stars explode, they deposit a lot of energy into the ISM ($E \sim 10^{51}$ ergs/SN)
- The ISM heats up, and large under-pressurized bubbles form -> outflows!
- These outflows are particularly effective at removing gas from low-mass halos because of low $V_{esc} \sim 40$ km/s
- Dekel & Silk (1986)

$$\dot{M}_{out} = \dot{M}_{\star}(t) \frac{2\epsilon E_{SN+winds}}{V_{esc}^2}.$$

DARK MATTER DOMINATED!

From Jean's equation

$$M_{dyn} \sim 2\,\sigma^2\, r\, /\, G$$

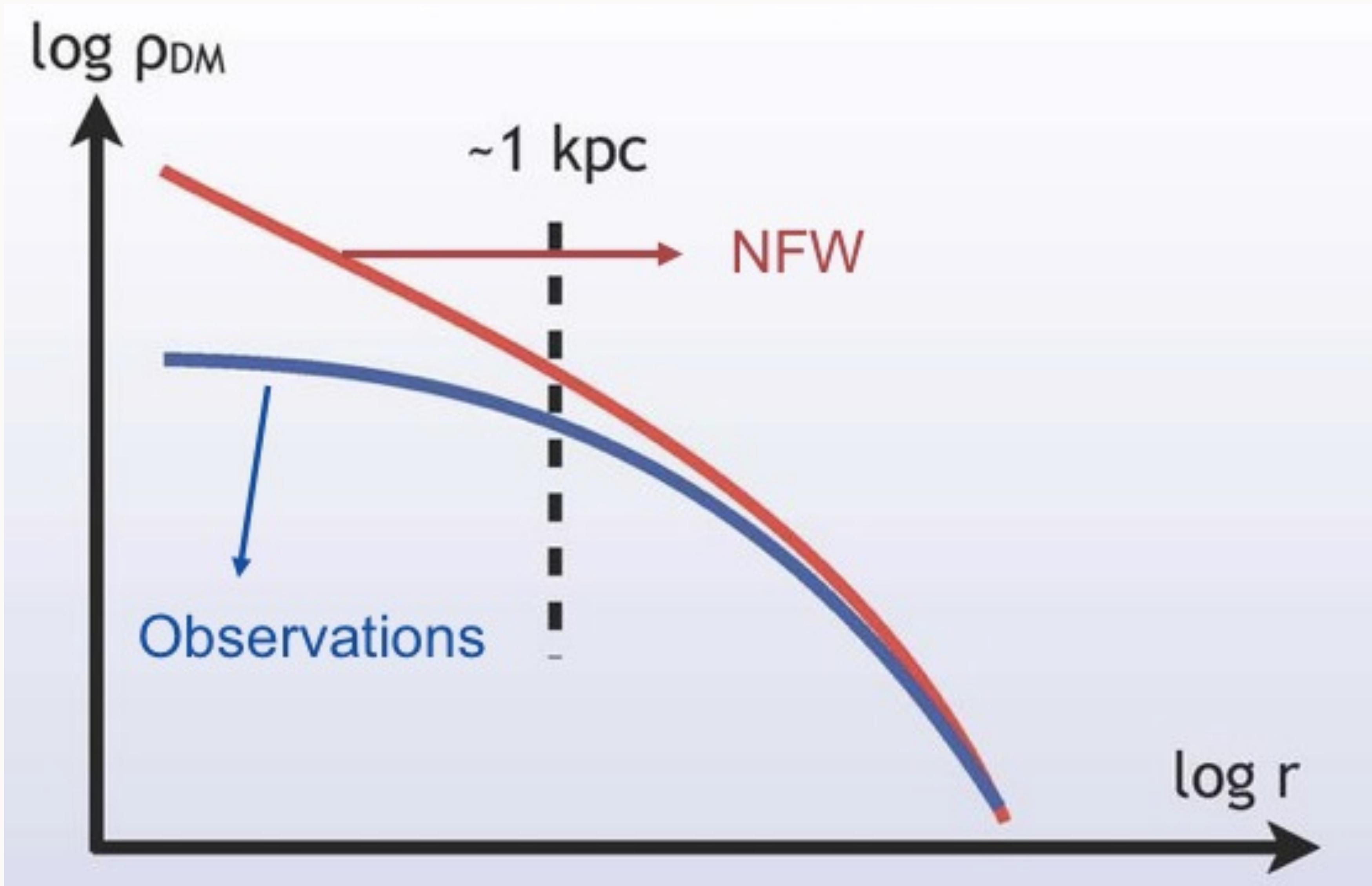


McConnachie 2012

THE SMALL SCALE CRISIS OF CDM

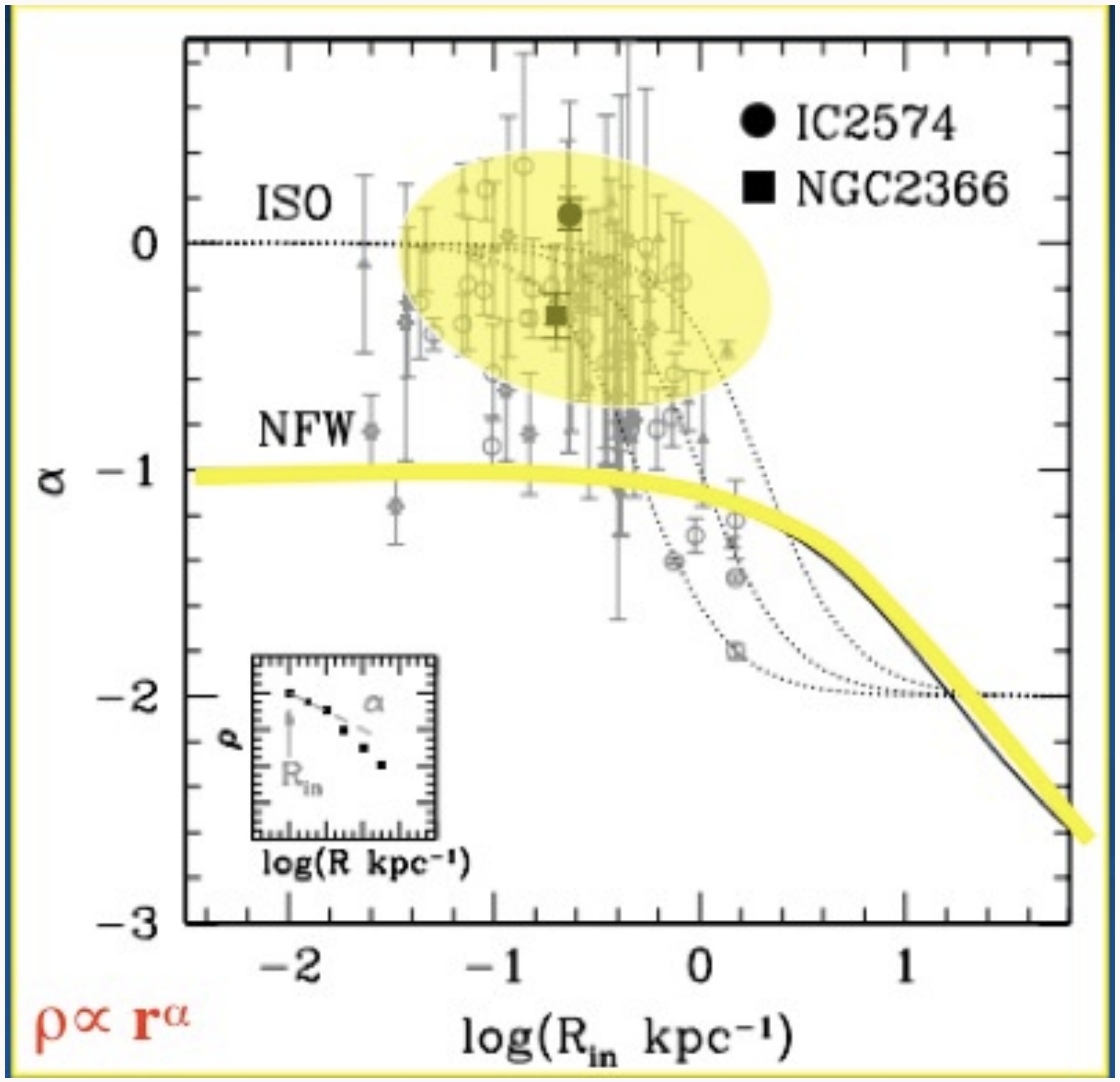
1. cusp/core problem
2. missing satellites problem
3. too-big-to-fail problem

CUSP/CORE PROBLEM

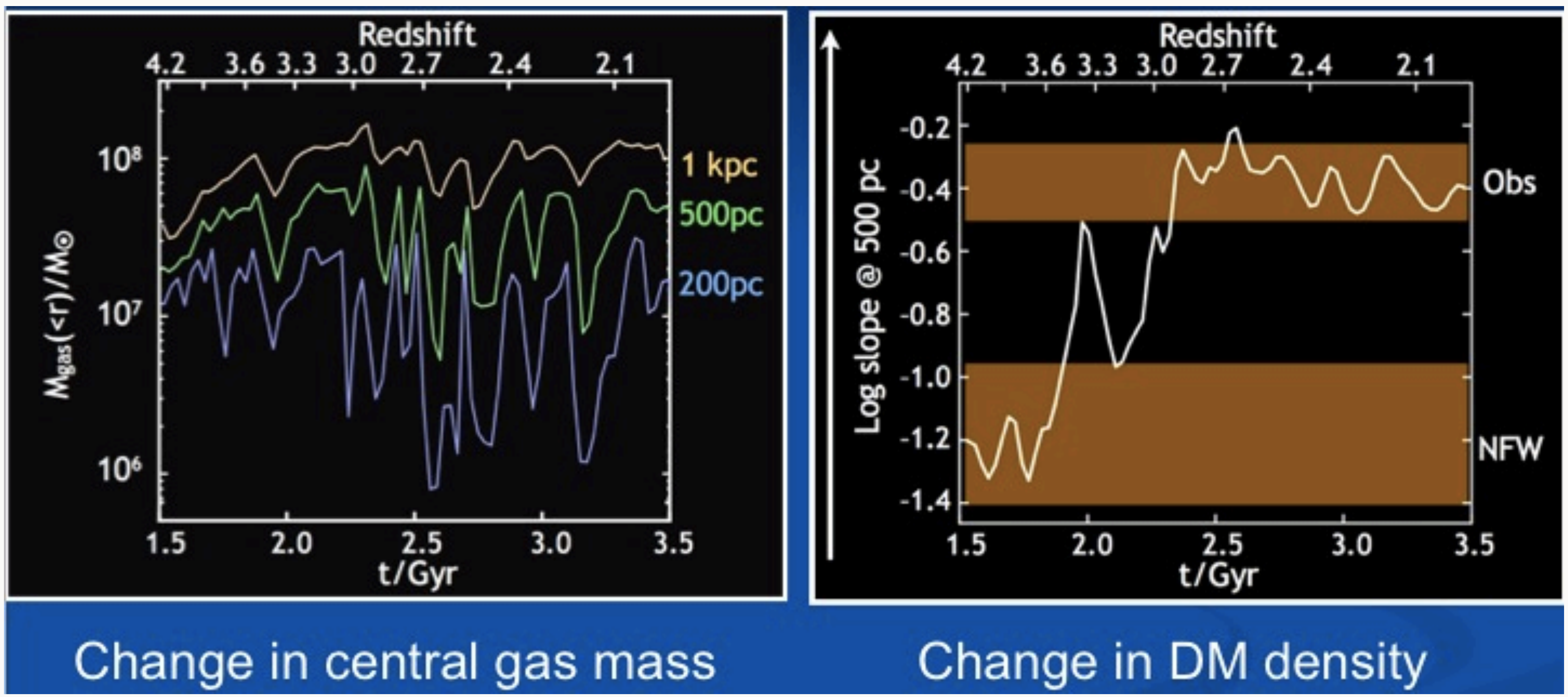


$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_{\rm c}}{(r/r_{\rm s})(1 + r/r_{\rm s})^2},$$

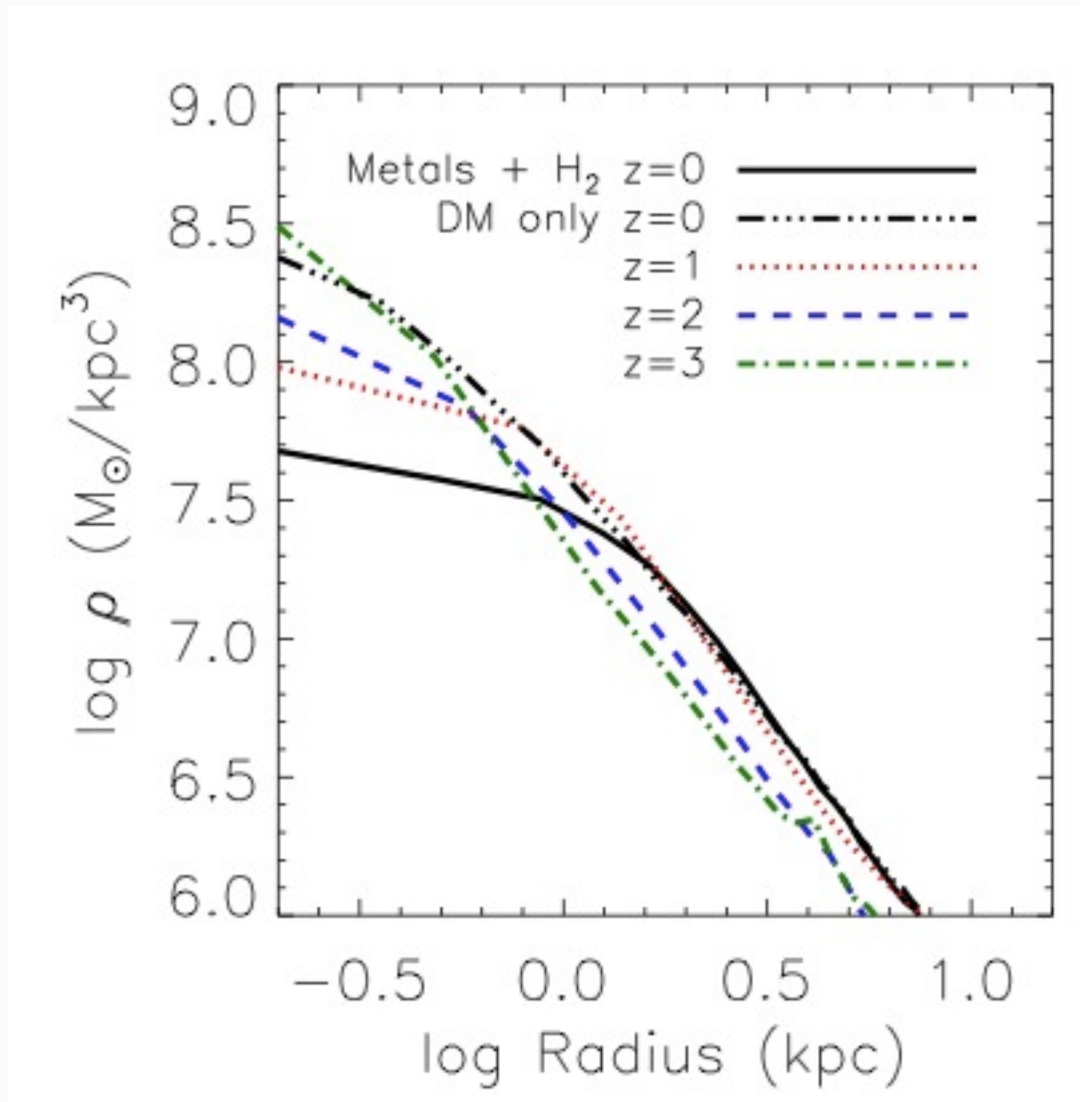
CUSP/CORE PROBLEM



SUPERNOVAE FEEDBACK AS A SOLUTION?

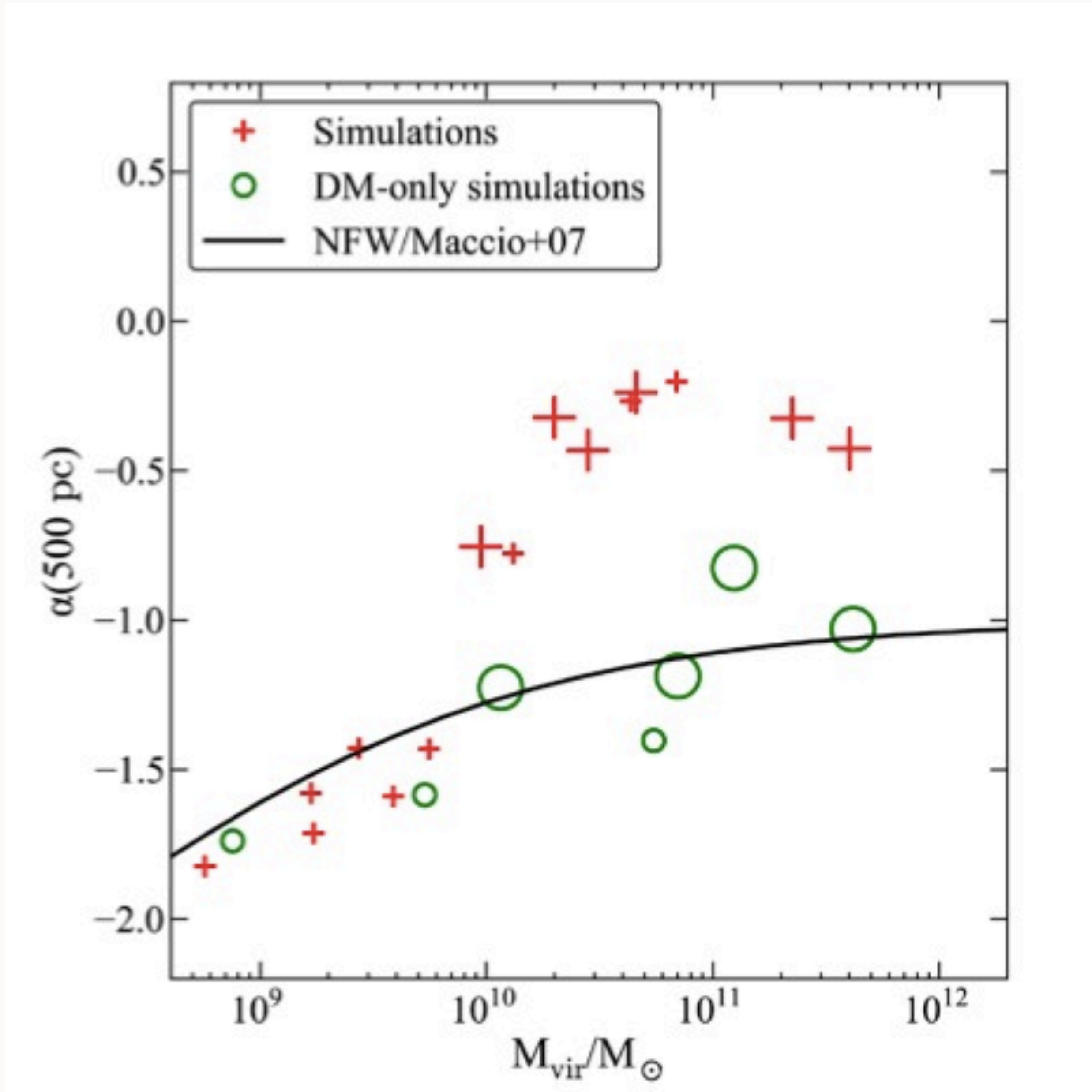


Pontzen & Governato 2012



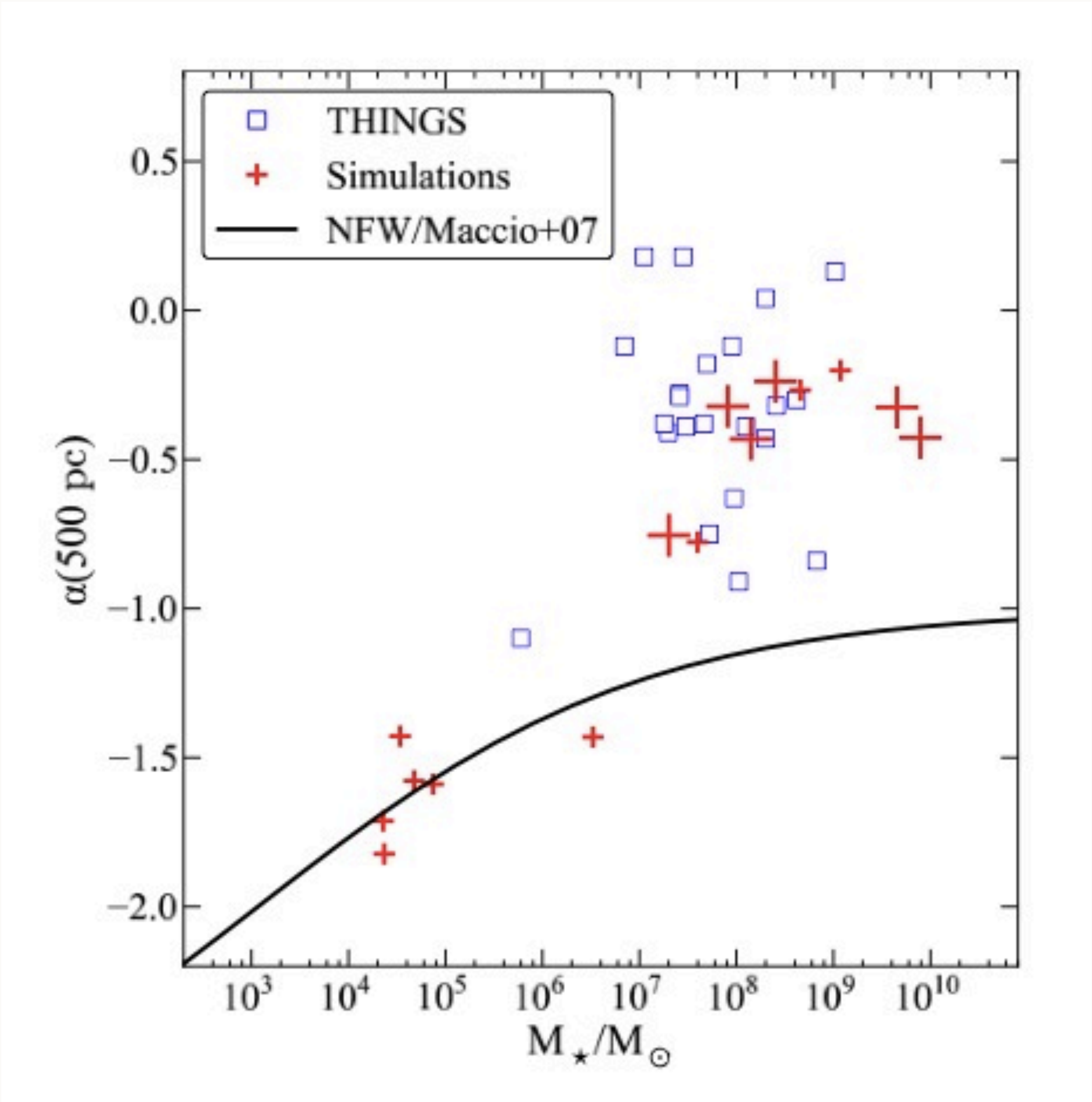
Governato et al. (2012)

MASS DEPENDENCE OF CORE FORMATION

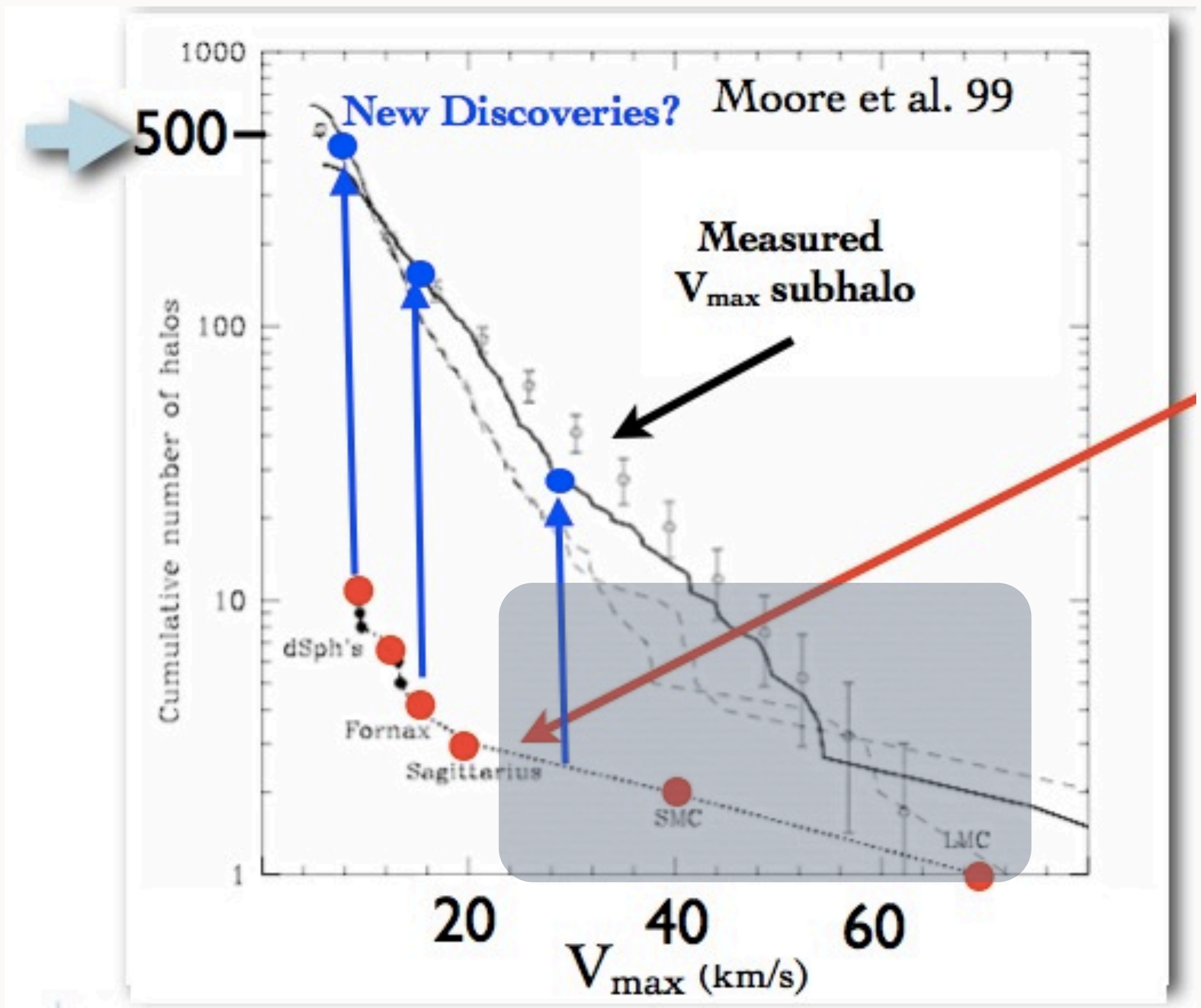


Governato et al. (2012)

CORE FORMATION: THEORY VS OBSERVATIONS

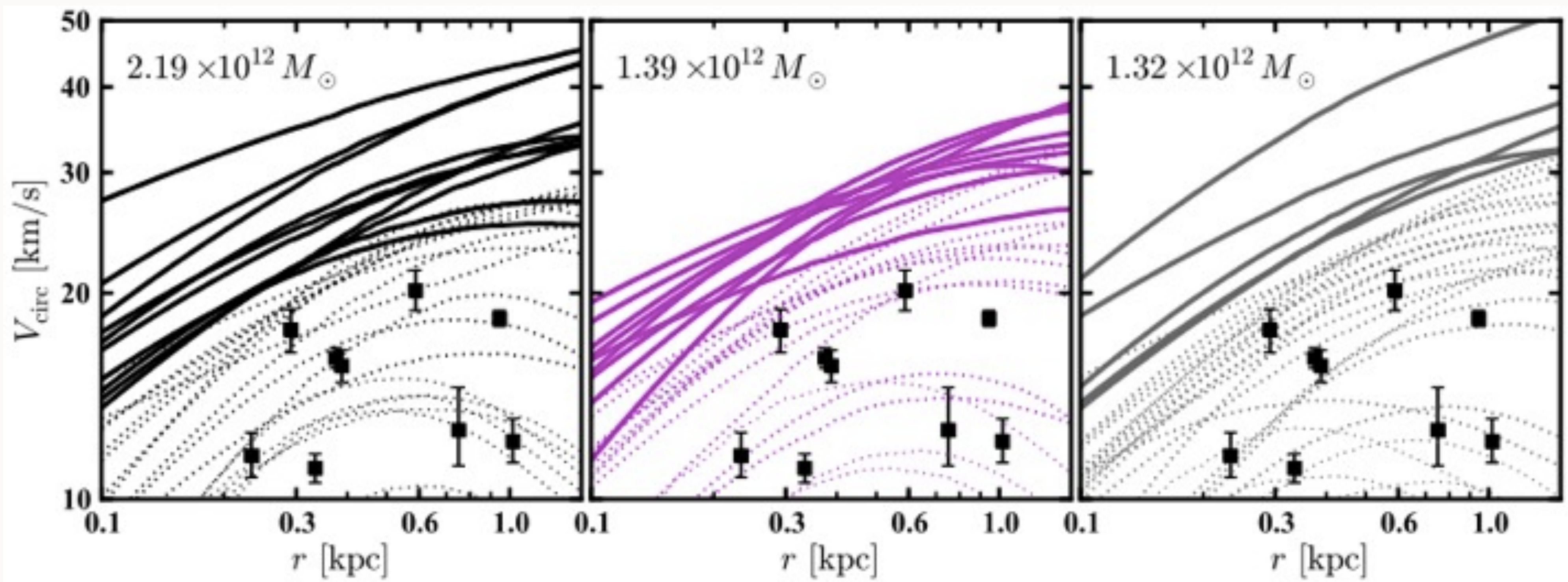


MISSING SATELLITES?



still missing!

MISSING SATELLITES PROBLEM: REVISITED

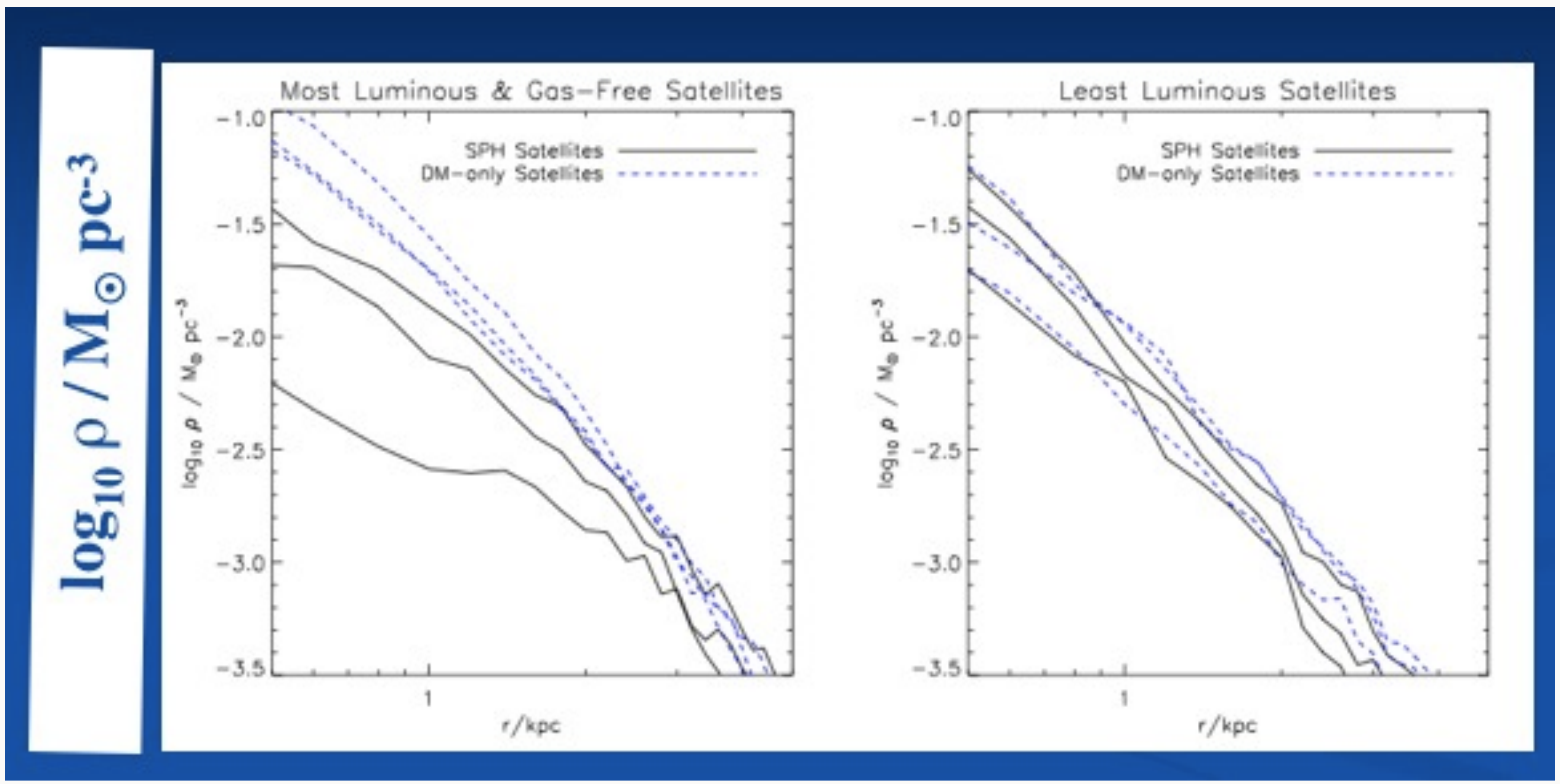


Boylan-Kolchin et al. (2011)

POSSIBLE SOLUTIONS

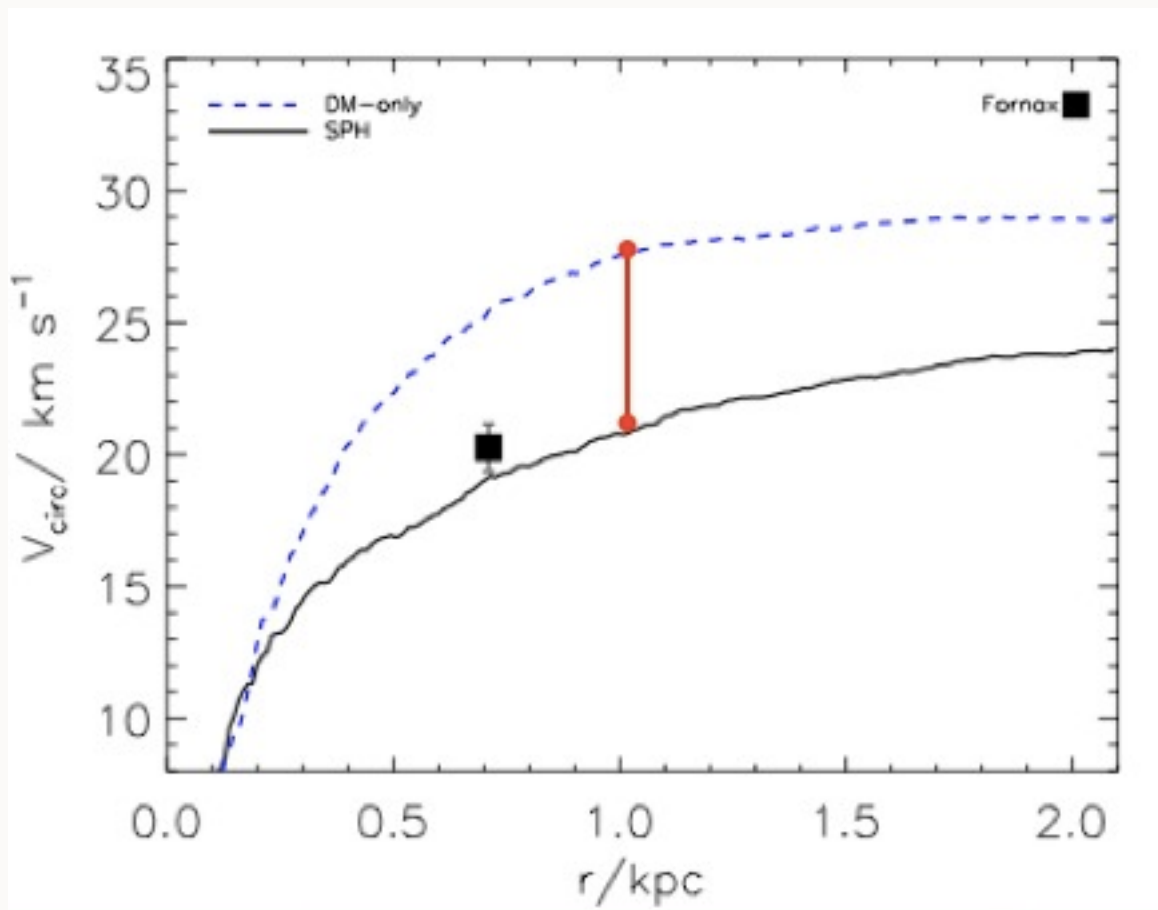
1. Supernova feedback
2. Lower MW mass
3. CDM is wrong

SUPERNOVAE FEEDBACK



Zolotov et al (2012)

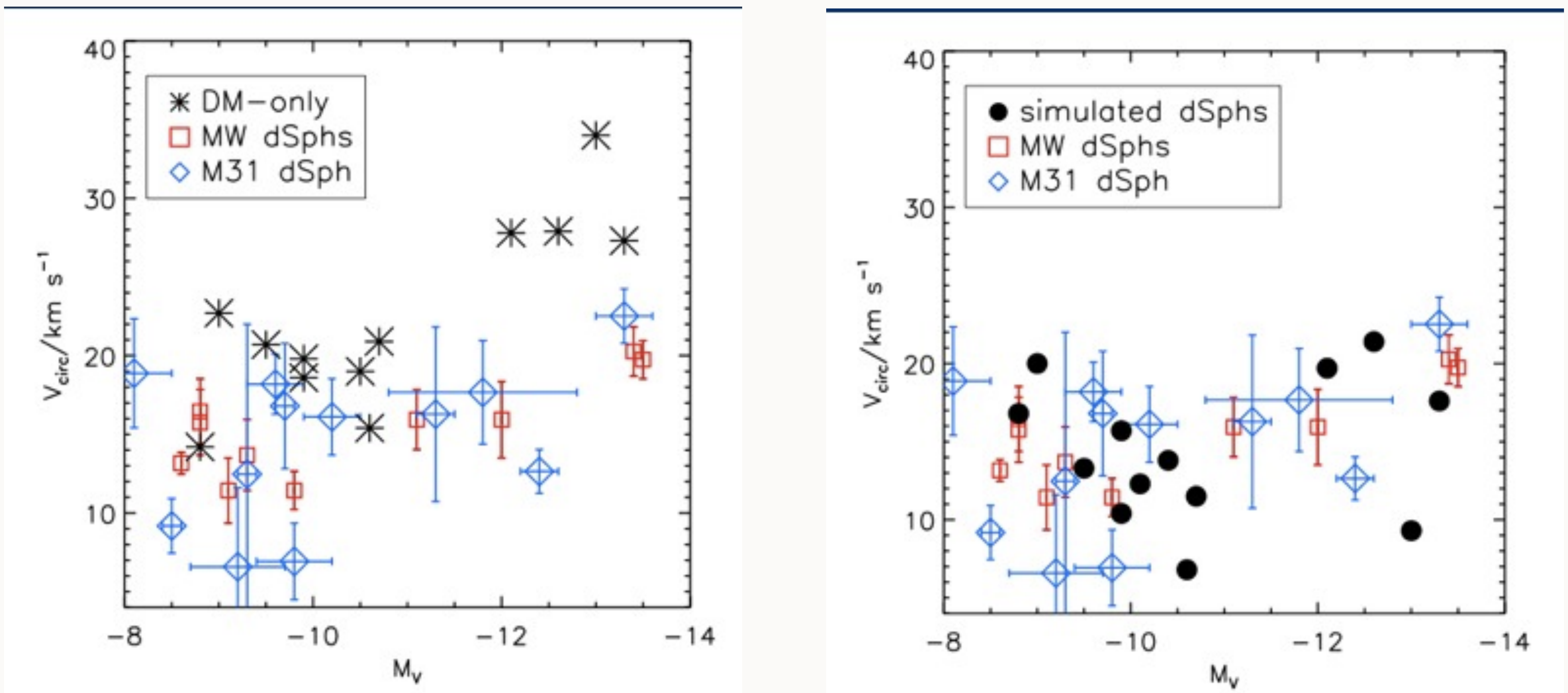
SUPERNOVAE FEEDBACK



Zolotov et al (2012)

Friday, May 16, 14

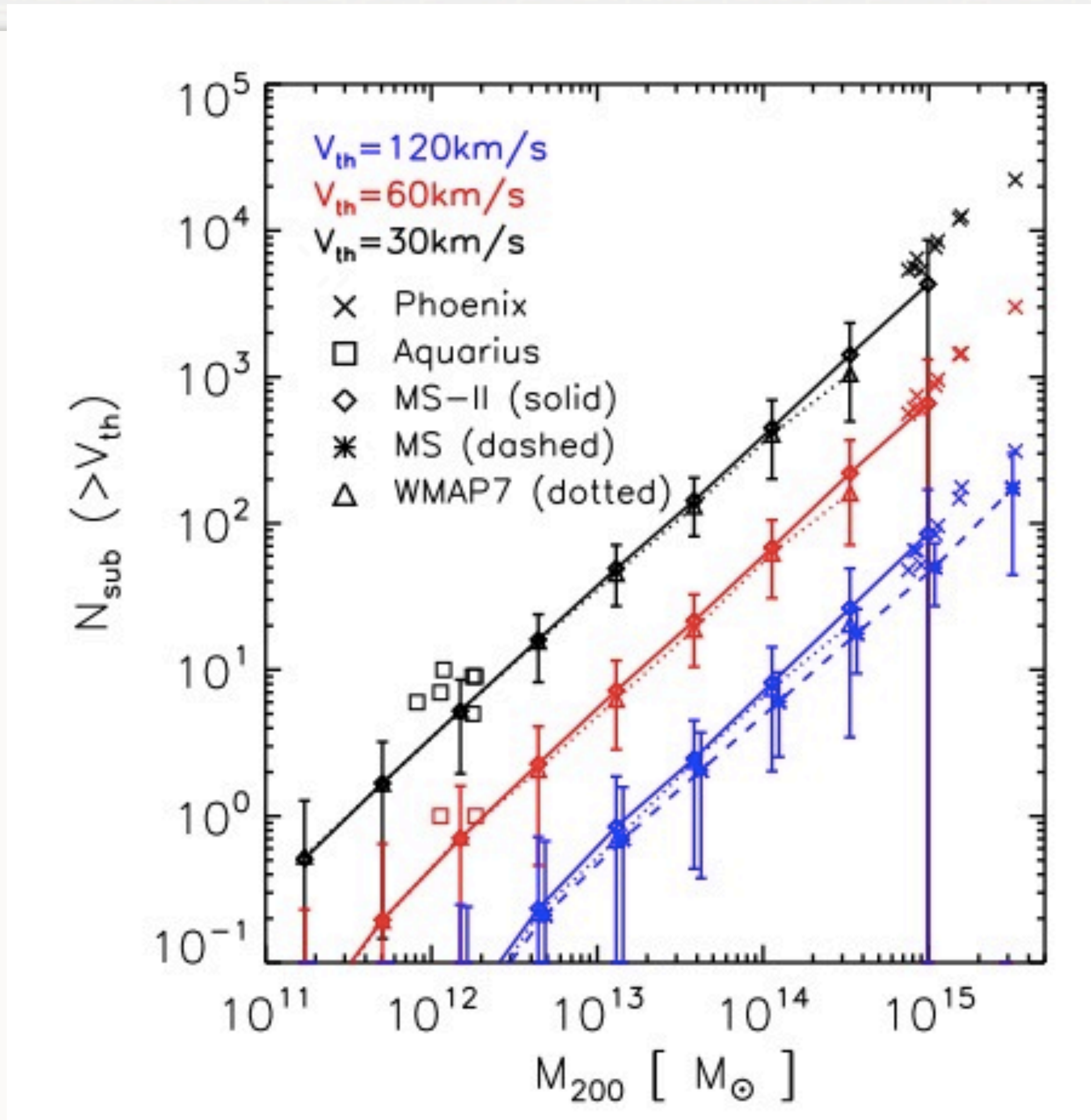
SUPERNOVAE FEEDBACK



Zolotov et al (2012)

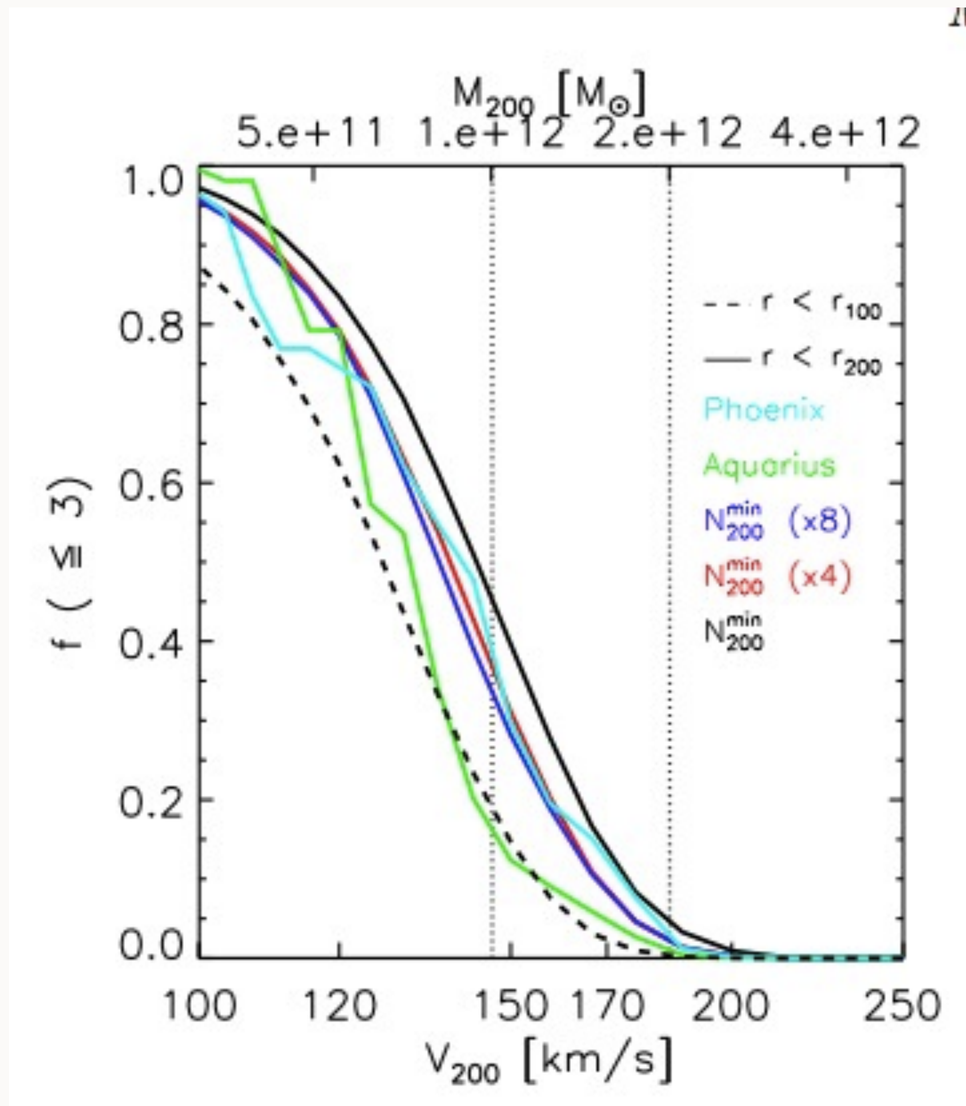
MW'S HALO MASS

Wang et al (2012)

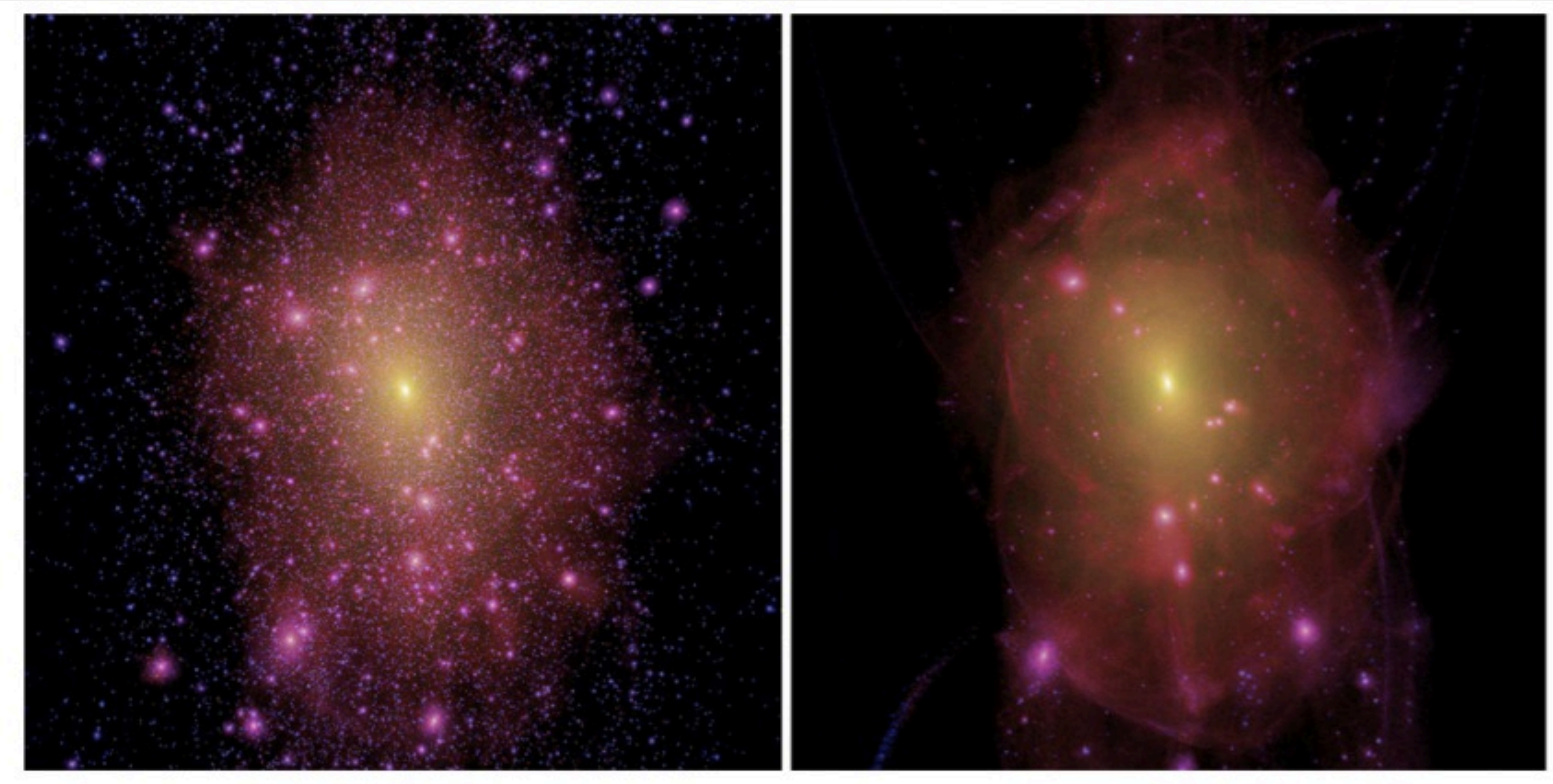


The number of subhalos depends ~ linearly on halo mass and increases strongly with decreasing velocity threshold

N_{SAT} DEPENDENCE ON MW MASS



WDM VS CDM



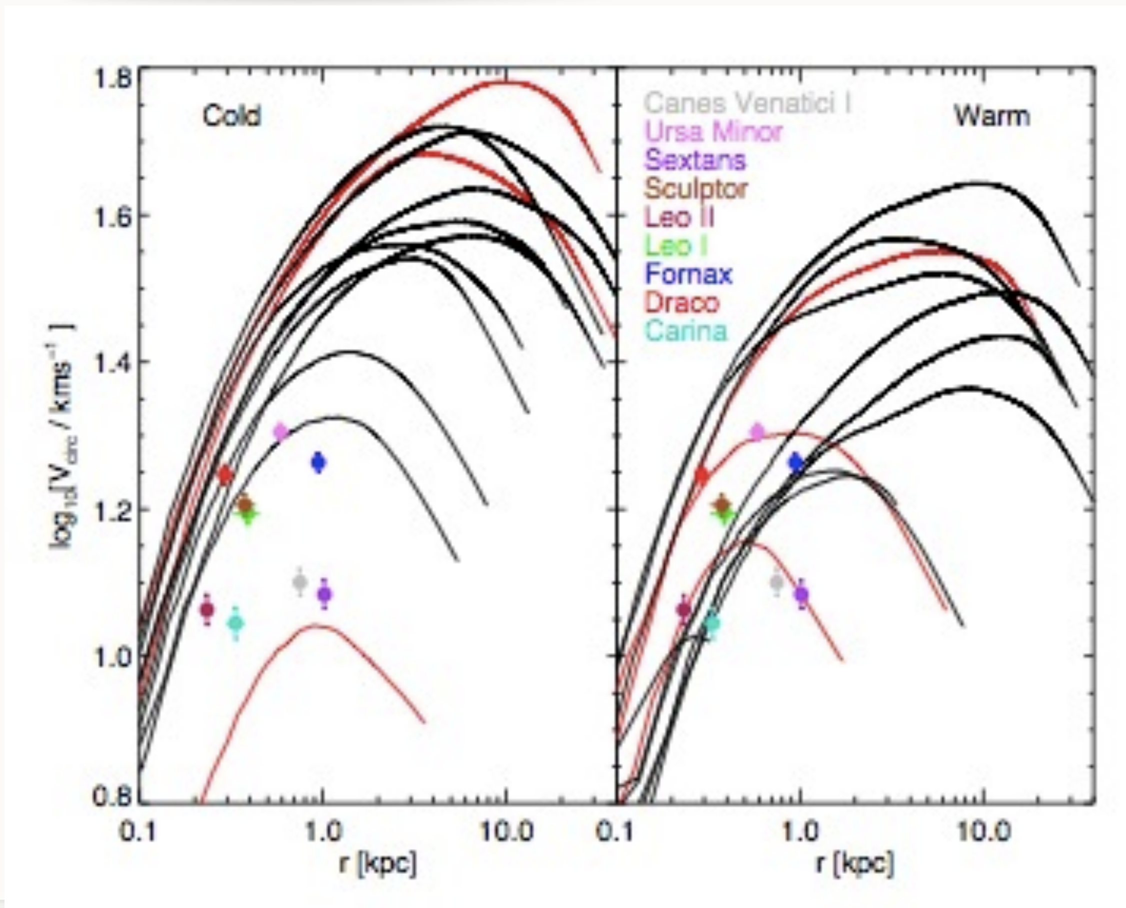
Lovell et al. (2012)

WDM: suppress galaxy formation below 10^{10} M

WDM VS CDM

- WDM particle[...]er free-streaming length than CDM pa[...]ress the formation of small galaxies

how far the particles could move due to random motions in the early universe, before they slowed down due to the expansion of the Universe



- Dwarf galaxies are the lowest-luminosity, lowest-mass galaxies known.
- New dwarfs are still being discovered.
- Dwarf galaxies were first galaxies to form, and were/are accreted by large galaxies, like the MW
- Today's surviving dwarfs aren't necessarily the building blocks of stellar halos of MW galaxies
- Dwarfs pose a challenge to the CDM model