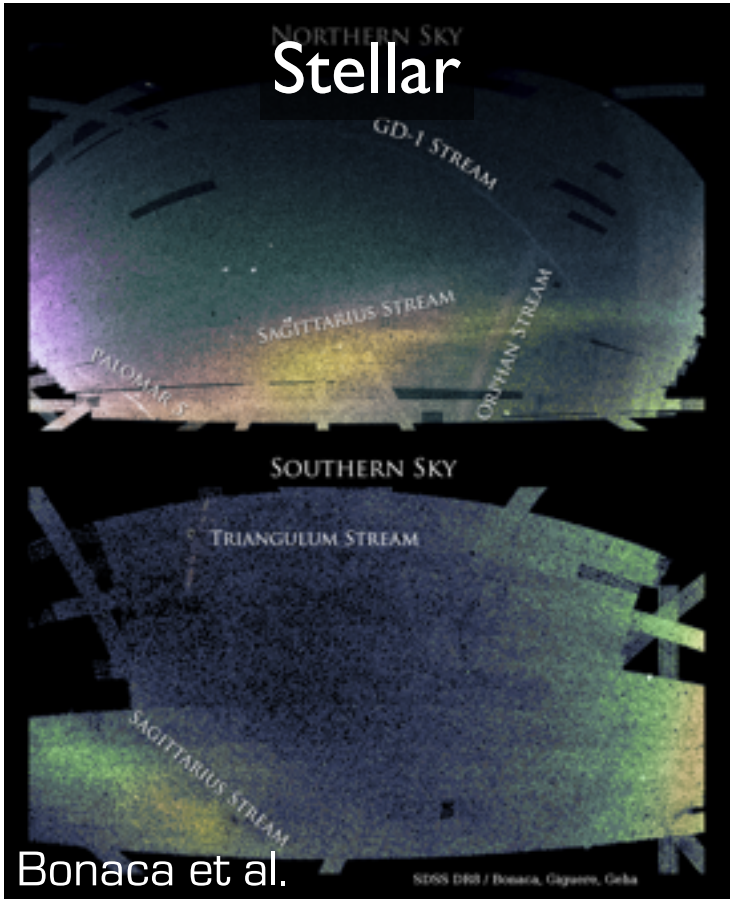
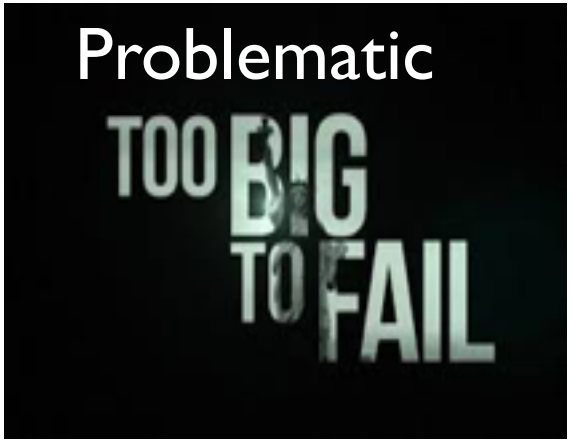
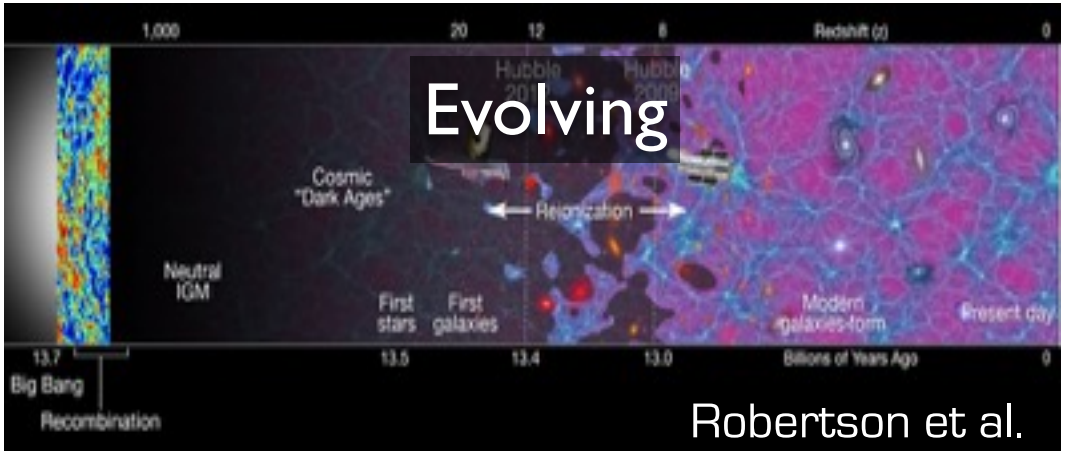
The Milky Way's Halo



Bonaca et al.





Robertson et al.

The Milky Way's Stellar Halo

What's it origin?

Shredded stuff [Searle & Zinn 1978]

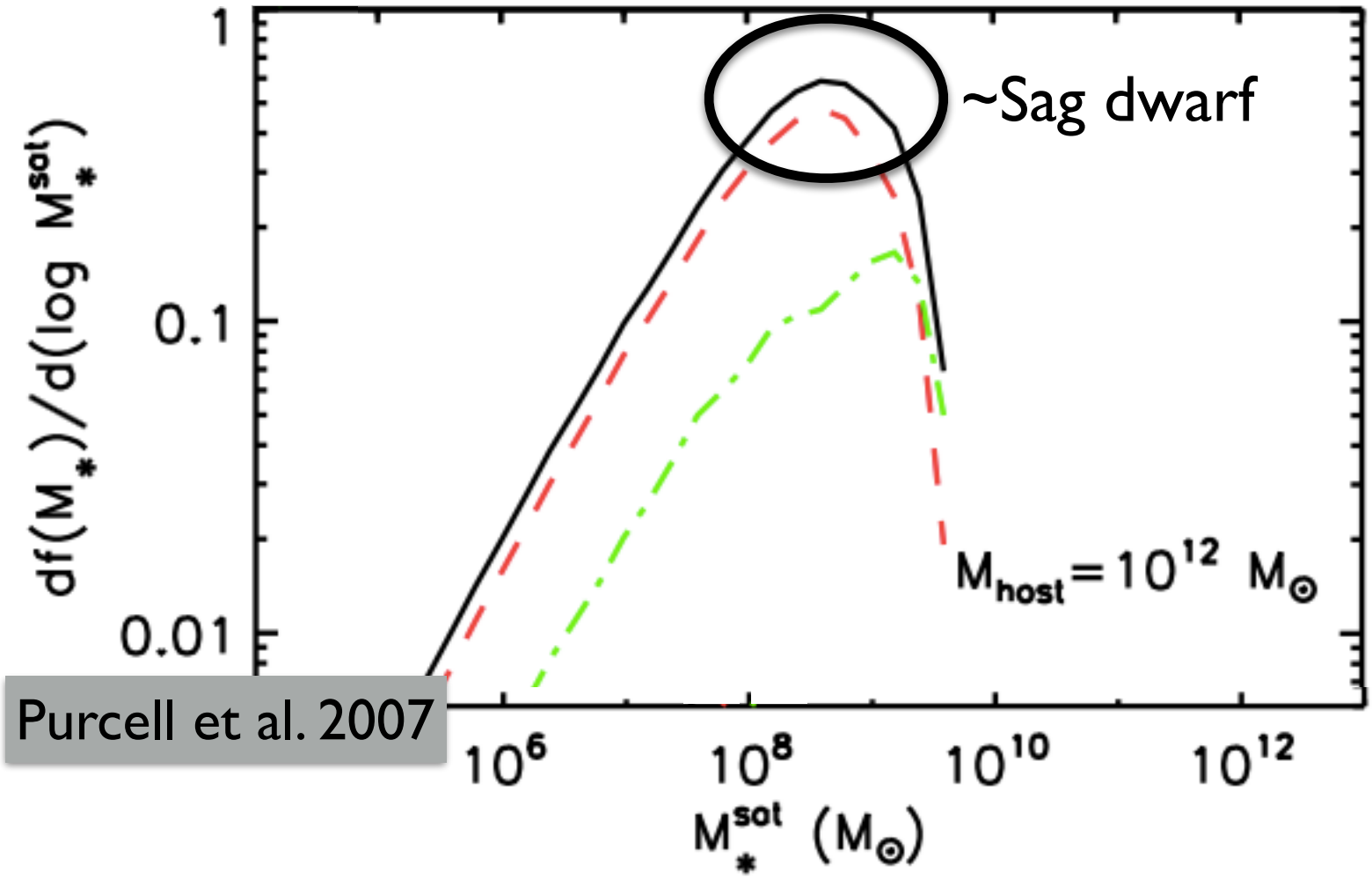
- massive dwarfs (>10^6 M_{sun}) [e.g. JSB & Johnston 2005]
- ultrafaint dwarfs (< 10^4 M_{sun}) [e.g. Frebel et al. 2010]
- globular clusters? [e.g. Carretta et al. 2010]

In situ [ELS 1962; Zolotov + 2009]

- heated disk stars [e.g. Purcell + 2009]
- infalling/stripped gas [Cooper et al. 2015]

Dual halo: inner vs. outer [e.g. Corollo et al. 2007]

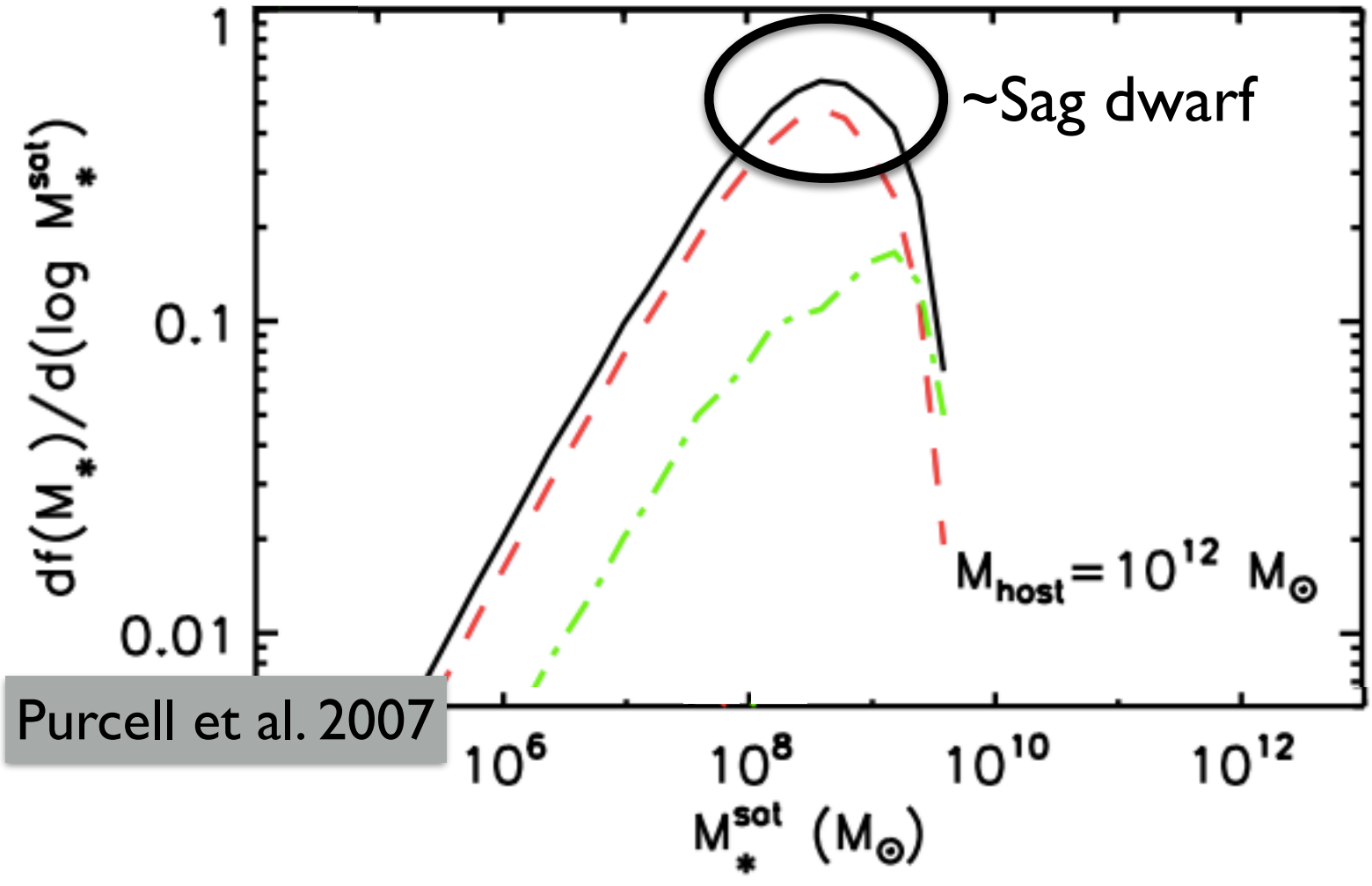
CDM-based models: Massive dwarfs build outer halo



Purcell et al. 2007

see: JSB, Kravtsov, &Weinberg 01; JSB & Johnston 05; Cooper et al. 2010

CDM-based models: Massive dwarfs build outer halo



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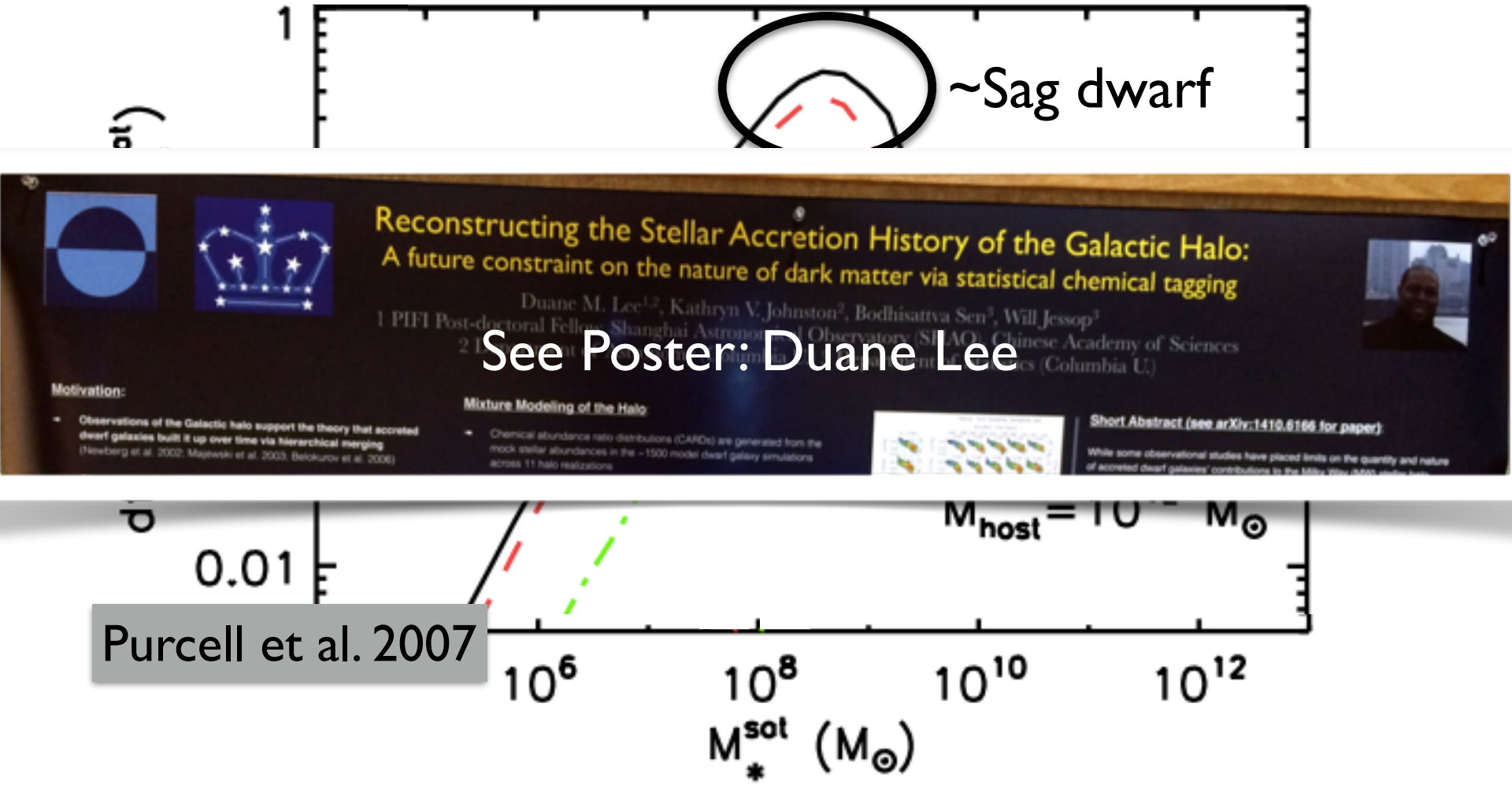
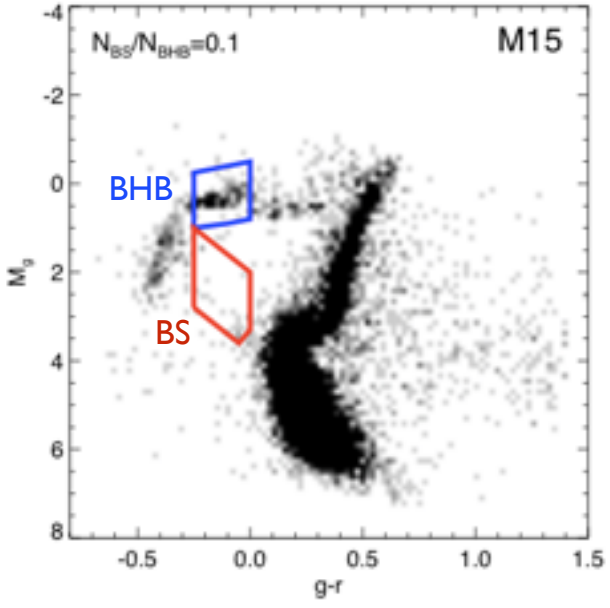
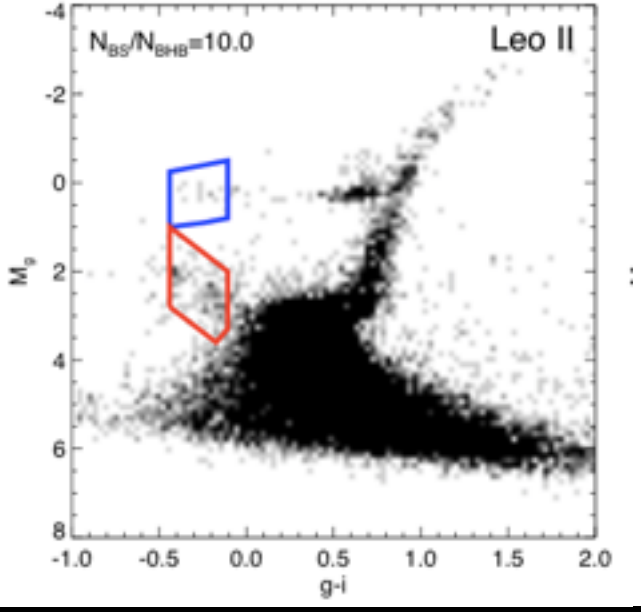
CDM-based models: Massive dwarfs build outer halo

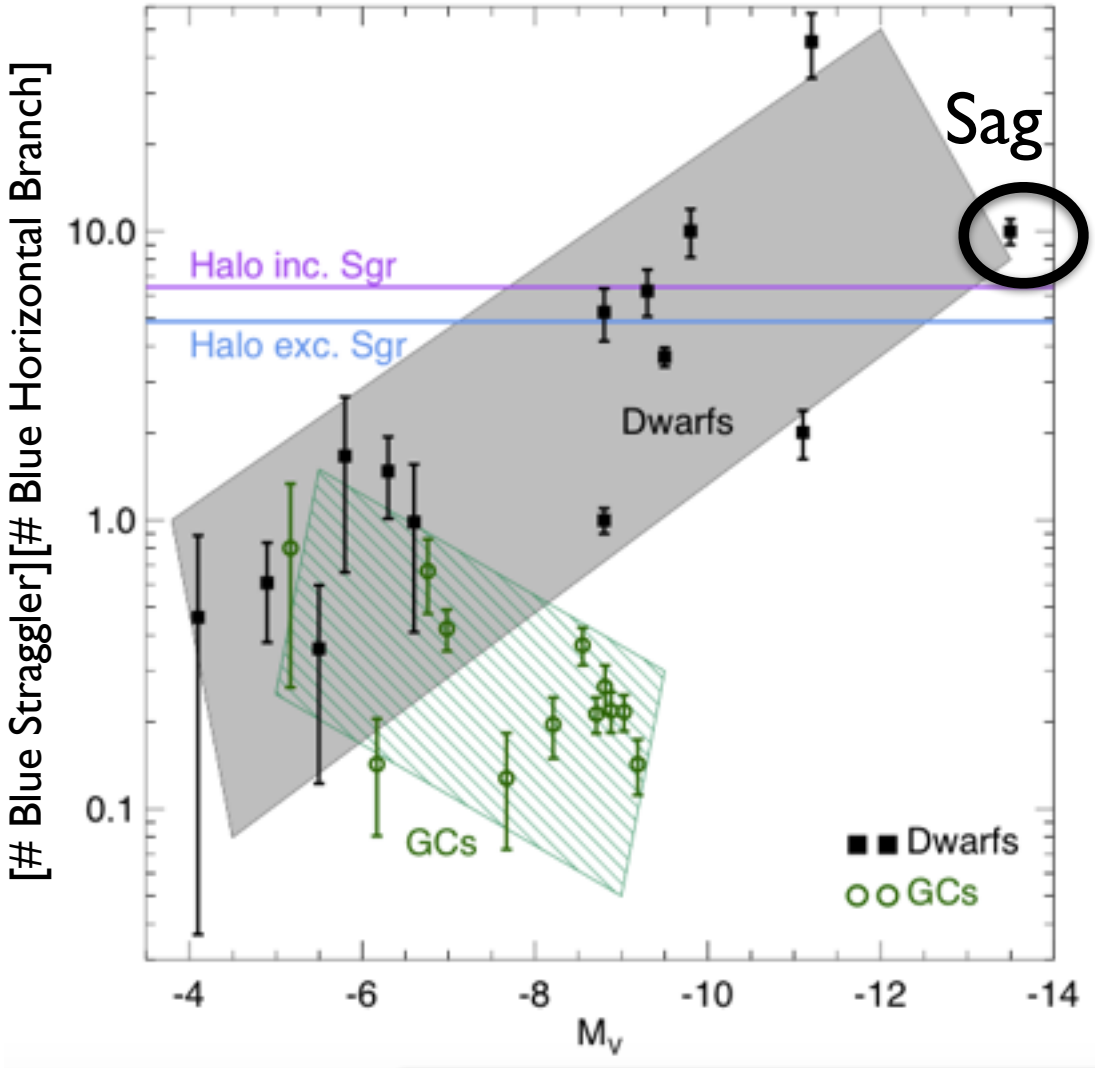


see: JSB, Kravtsov, &Weinberg 01; JSB & Johnston 05; Cooper et al. 2010

BS-to-BHB ratio in (outer) stellar halo=> mostly built by massive dwarfs







Deason, Belokurov, & Weisz 2015

The Milky Way's Dark Halo

Mass at large radius?

Hard via stellar halo tracers even if assume spherical symmetry

$$M(r) = \frac{r\,\sigma_r^2}{G}\,(\gamma_\star + \gamma_\sigma - 2\beta)$$

log slope tracer profile

log slope vel. disp. profile

vel. anisotropy

The Milky Way's Dark Halo

Mass at large radius?

Hard via stellar halo tracers even if assume spherical symmetry

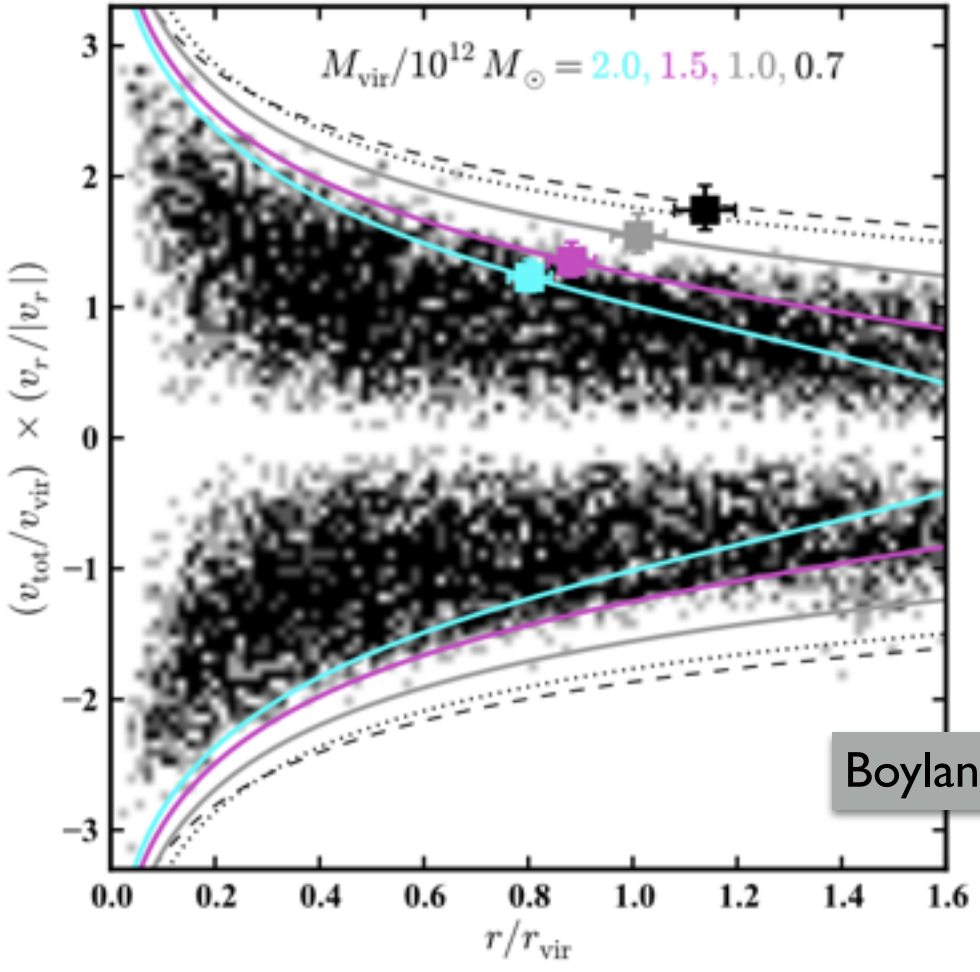
$$M(r) = \frac{r\,\sigma_r^2}{G}\left(\gamma_\star + \gamma_\sigma - 2\beta\right)$$

log slope tracer profile

log slope vel. disp. profile

vel. anisotropy

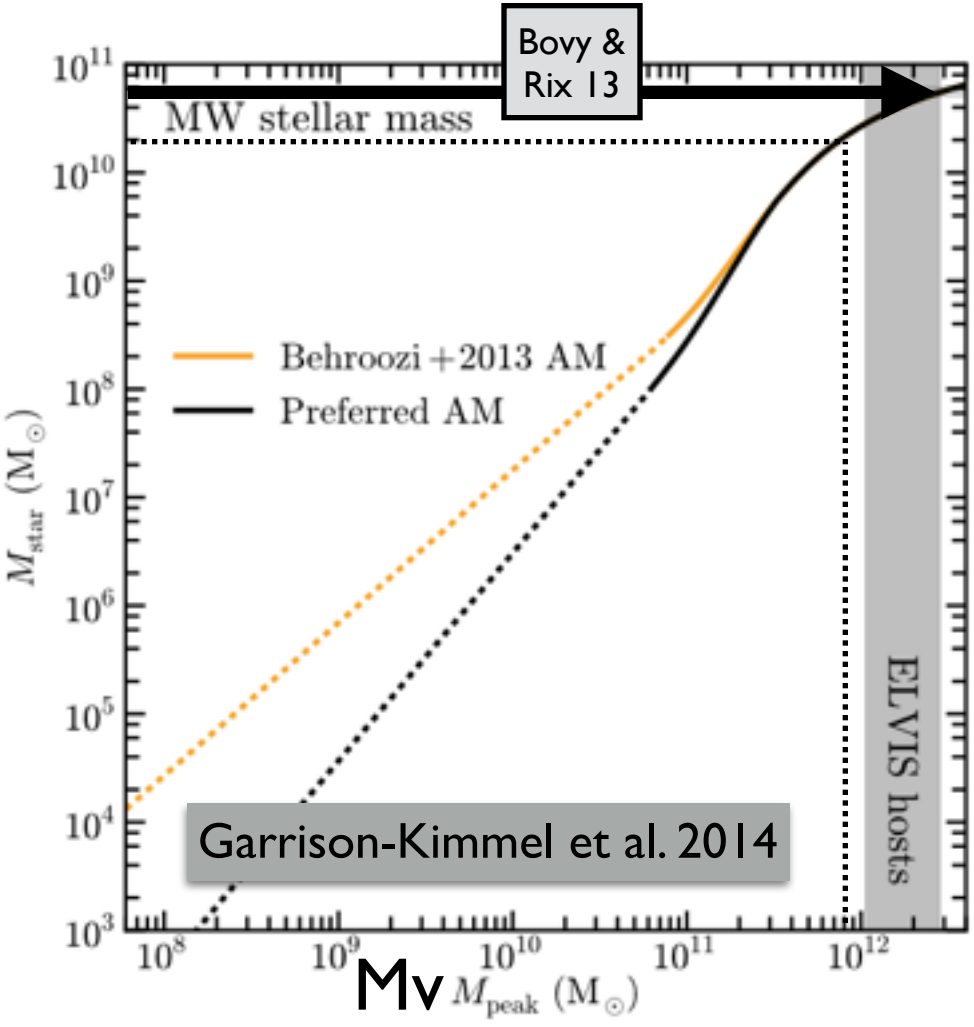
Existence of a few energetic satellites (leo I, LMC) suggest massive MW dark matter halo



Leo I
vs.
Aquarius
halos

Boylan-Kolchin et al. 2013

Low-mass MW DM halo (Mv = 8.e12 M_{sun}) would imply MW is unusually efficient converting baryons to stars



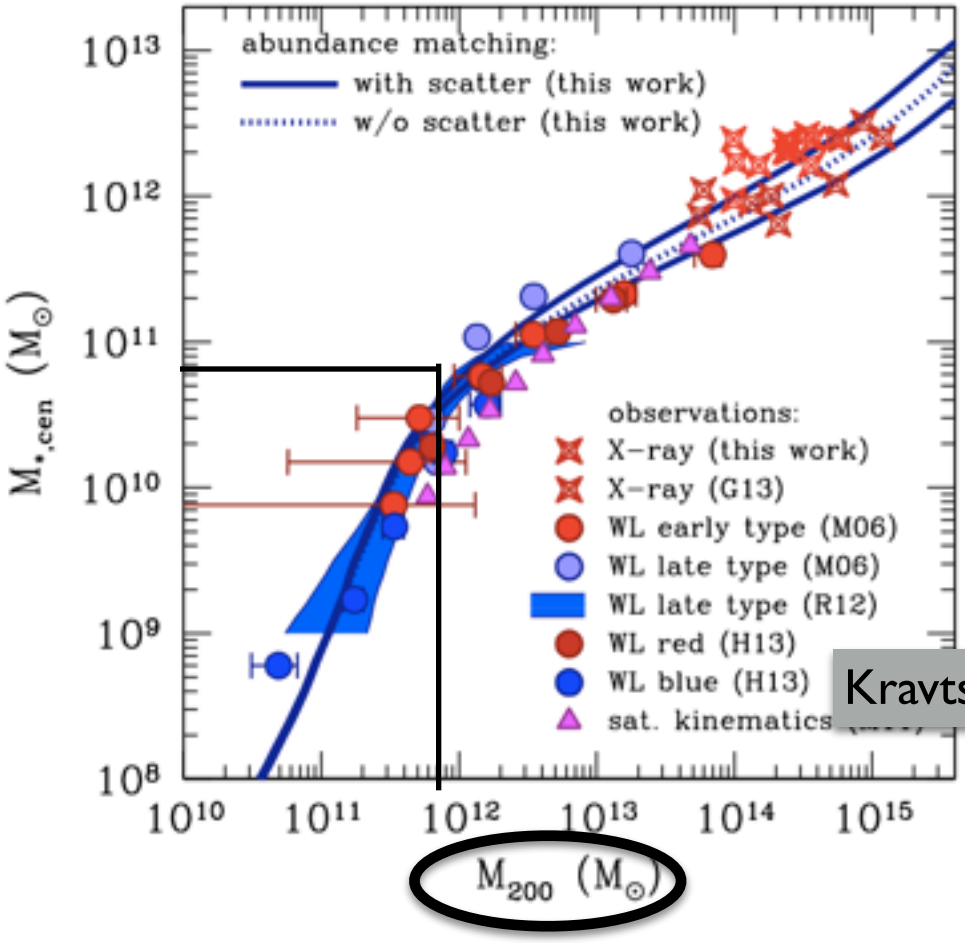
<u>Abundance matching:</u>

Mv = 2.5e12 M_{sun}

for

M_{star} = 6.e10 M_{sun}

Low-mass MW DM halo (Mv = 8.e12 M_{sun}) would imply MW is unusually efficient converting baryons to stars



Kravtsov et al. 2014

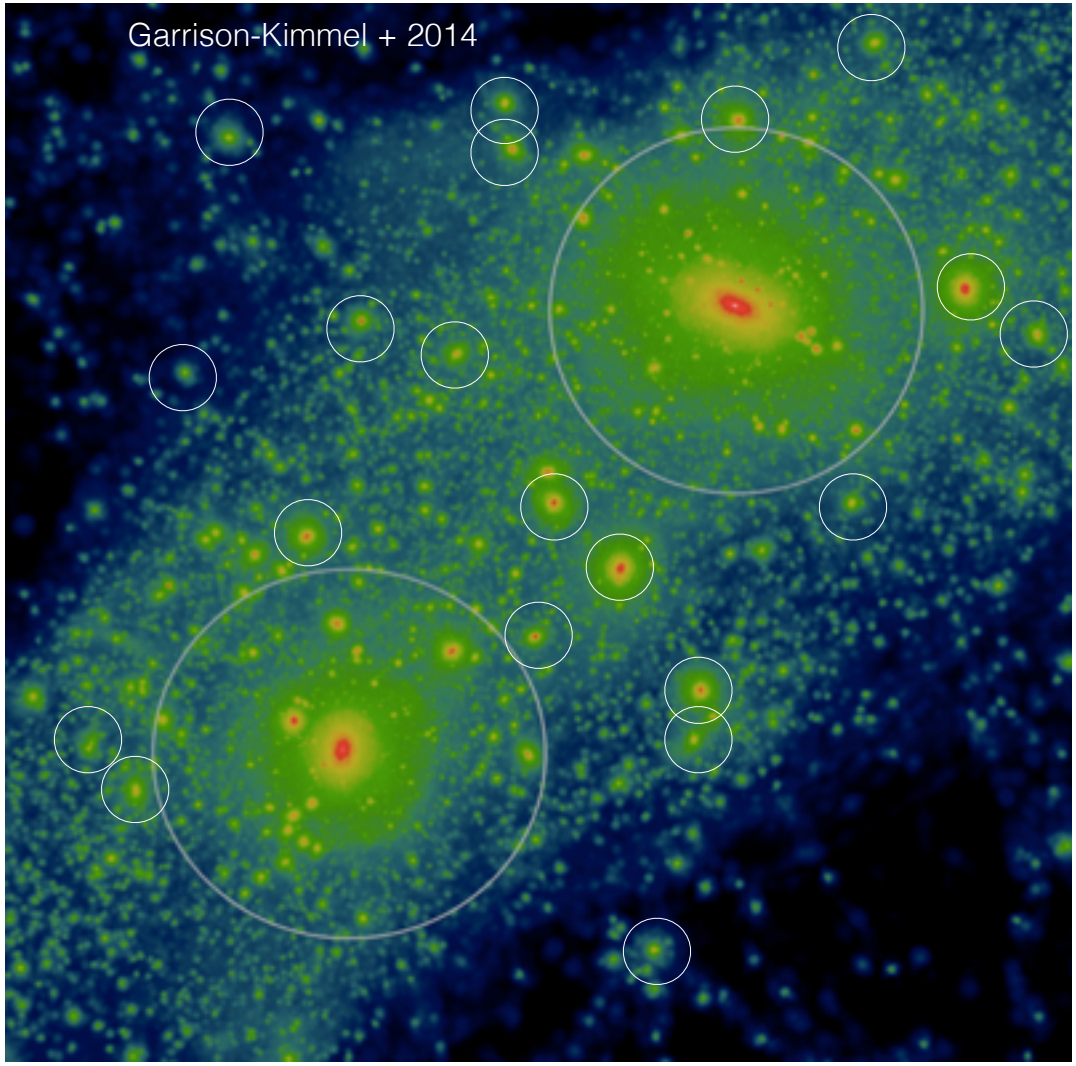
<u>Abundance matching:</u>

Mv = 2.5e12 M_{sun}

for

M_{star} = 6.e10 M_{sun}

Skinny Milky Way Doesn't Solve Too Big to Fail



Missing dense halos everywhere

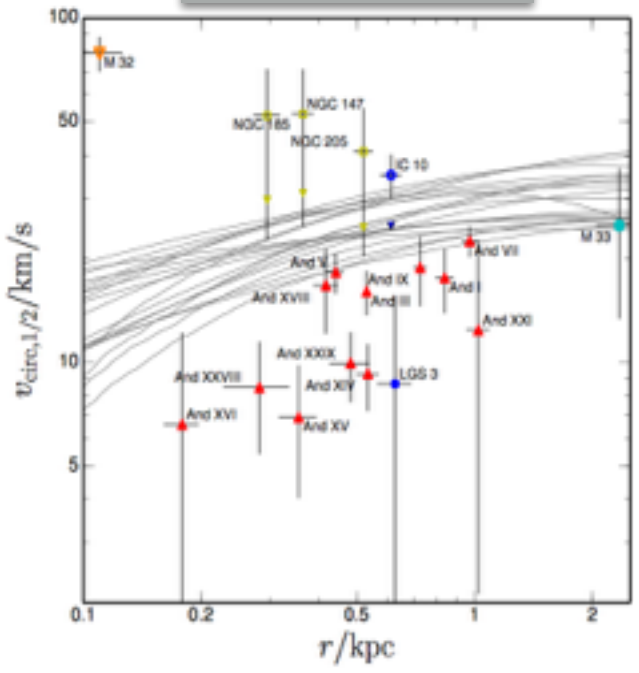
Appears to be a problem well beyond MW viral radius:
- satellites of M31
- Outer Local Gp (~ 1 Mpc)
- In the field

Kirby+2013

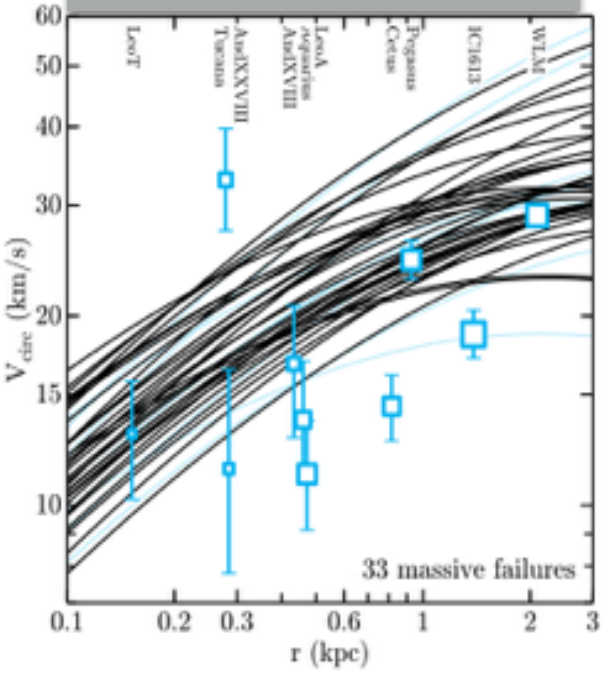
Klypin+2014; Ferrero+ 2012

Skinny Milky Way Doesn't Solve Too Big to Fail

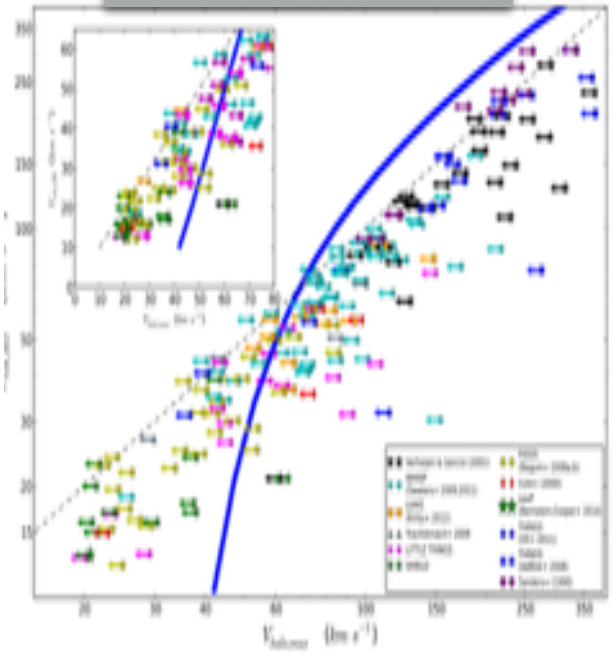
Tollerud + 2014



Garrison-Kimmel+2014

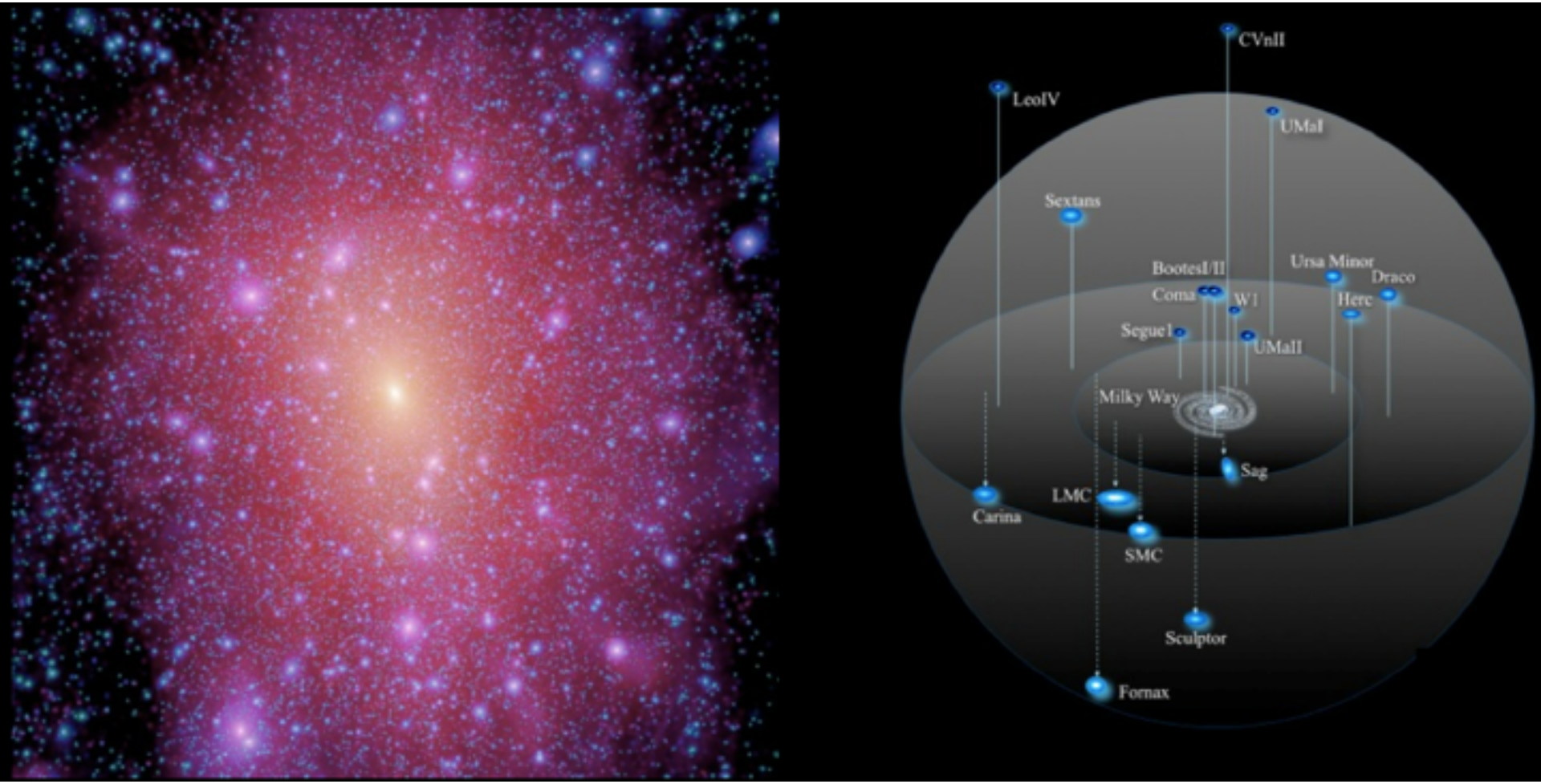


Papastergis + 2014



☍ IN ANDROMEDA ☌ IN THE OUTER LOCAL GROUP ⌂ IN THE FIELD

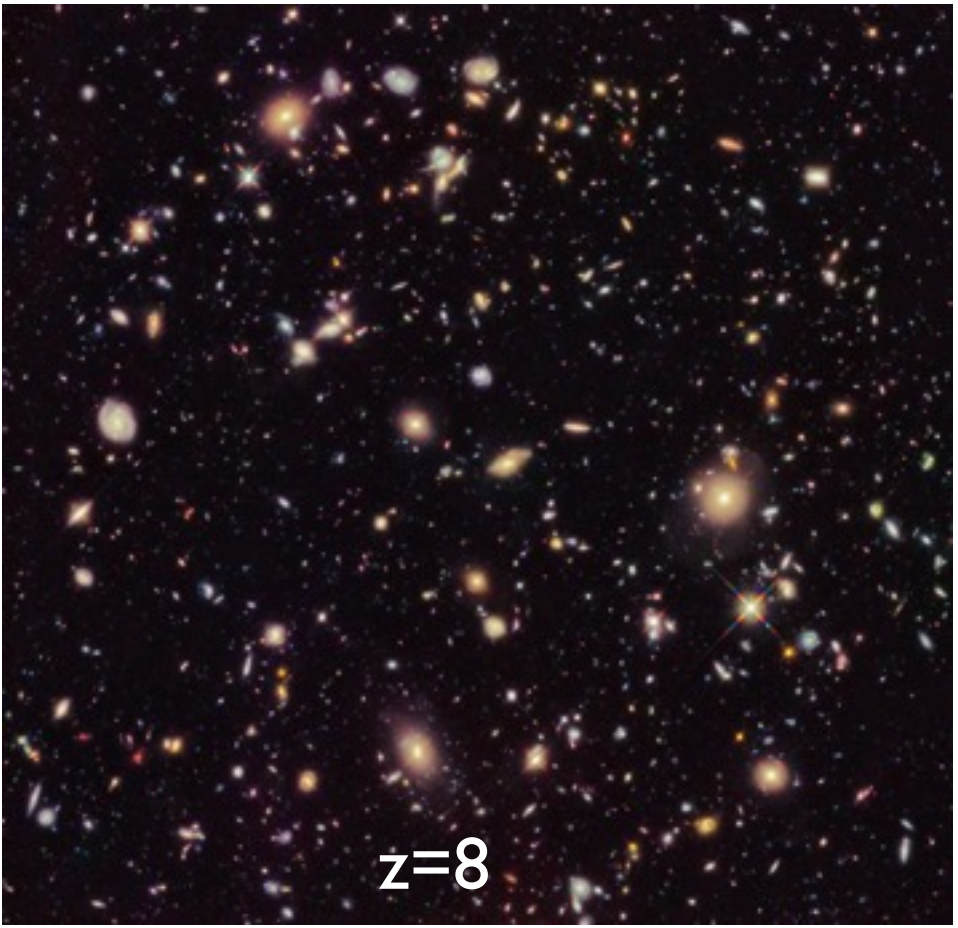
Small halos at z=0: **must** lack stars



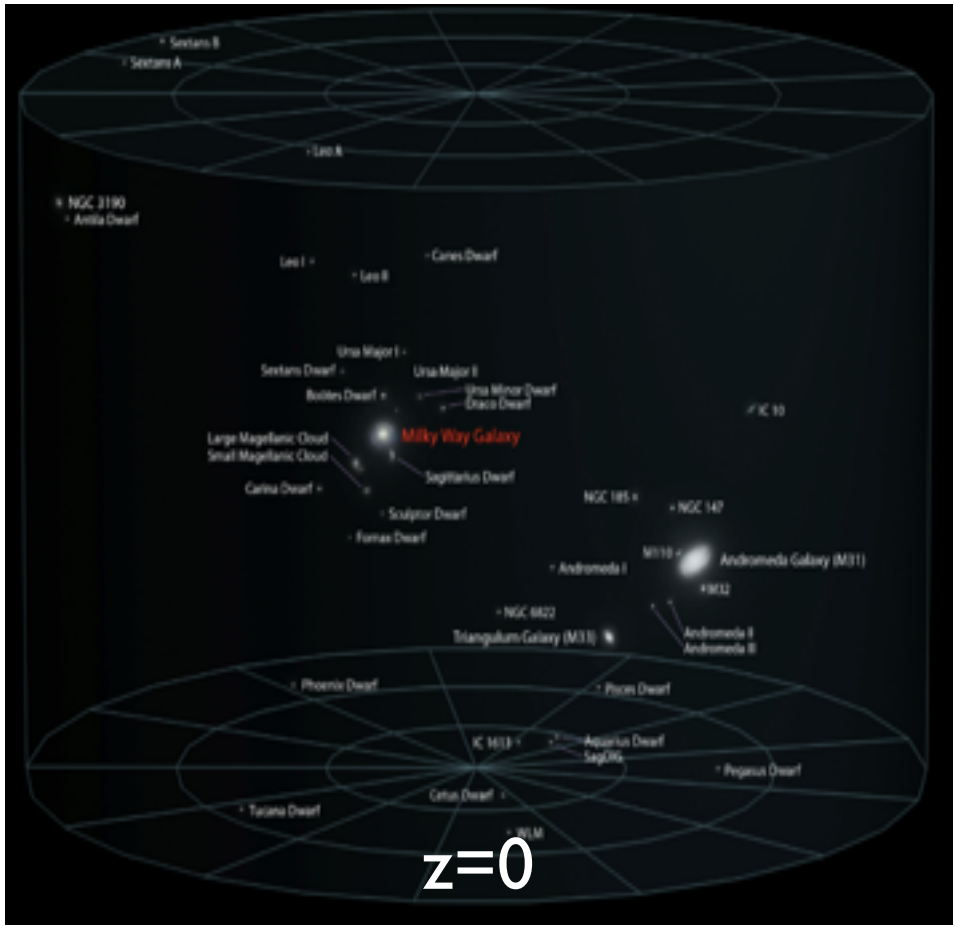
Missing Satellites, Too Big to Fail, etc. (Klypin, Moore, Boylan-Kolchin…)

Conventional wisdom at high-z is very different..

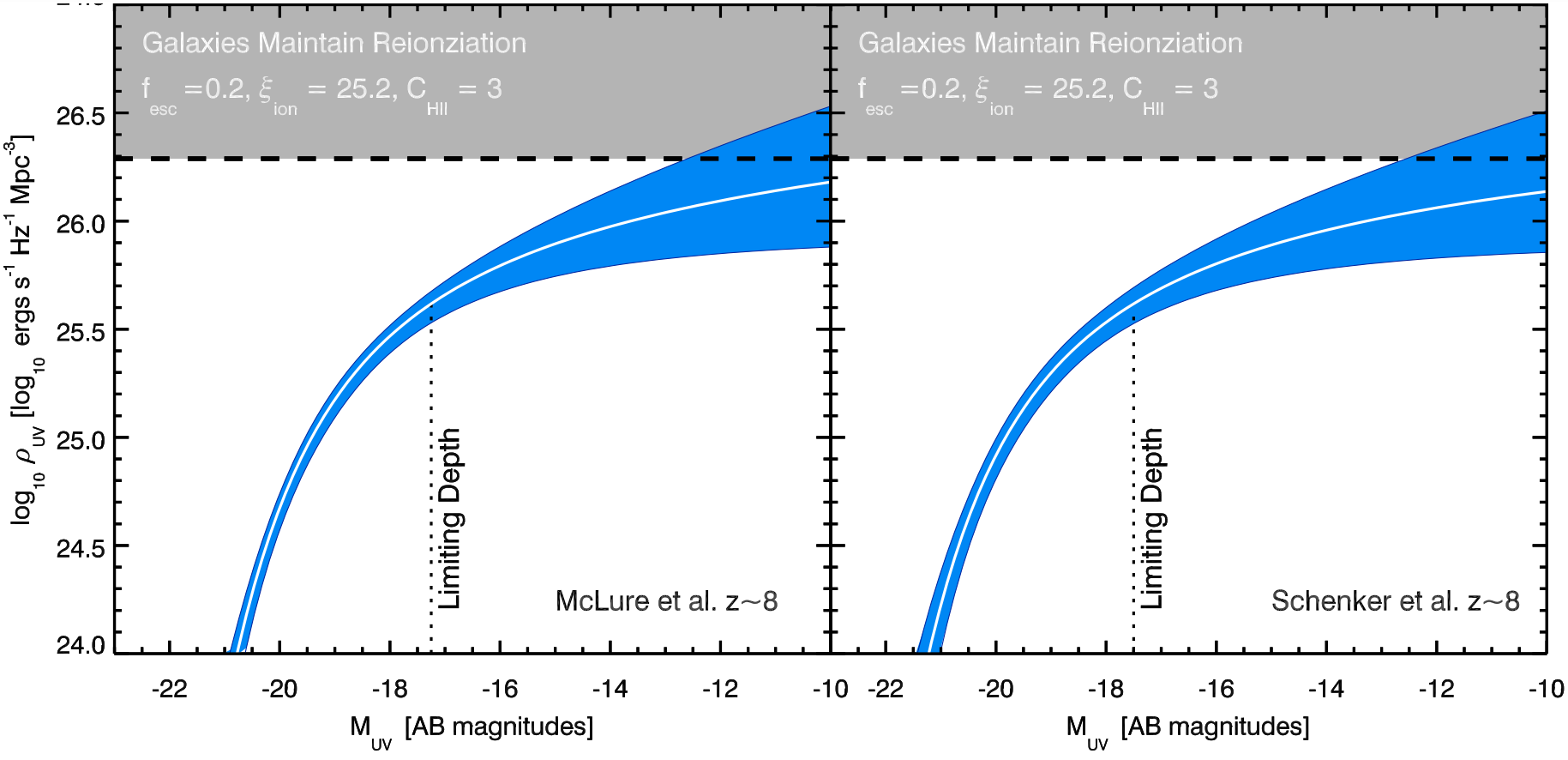
Deep Field



Near Field

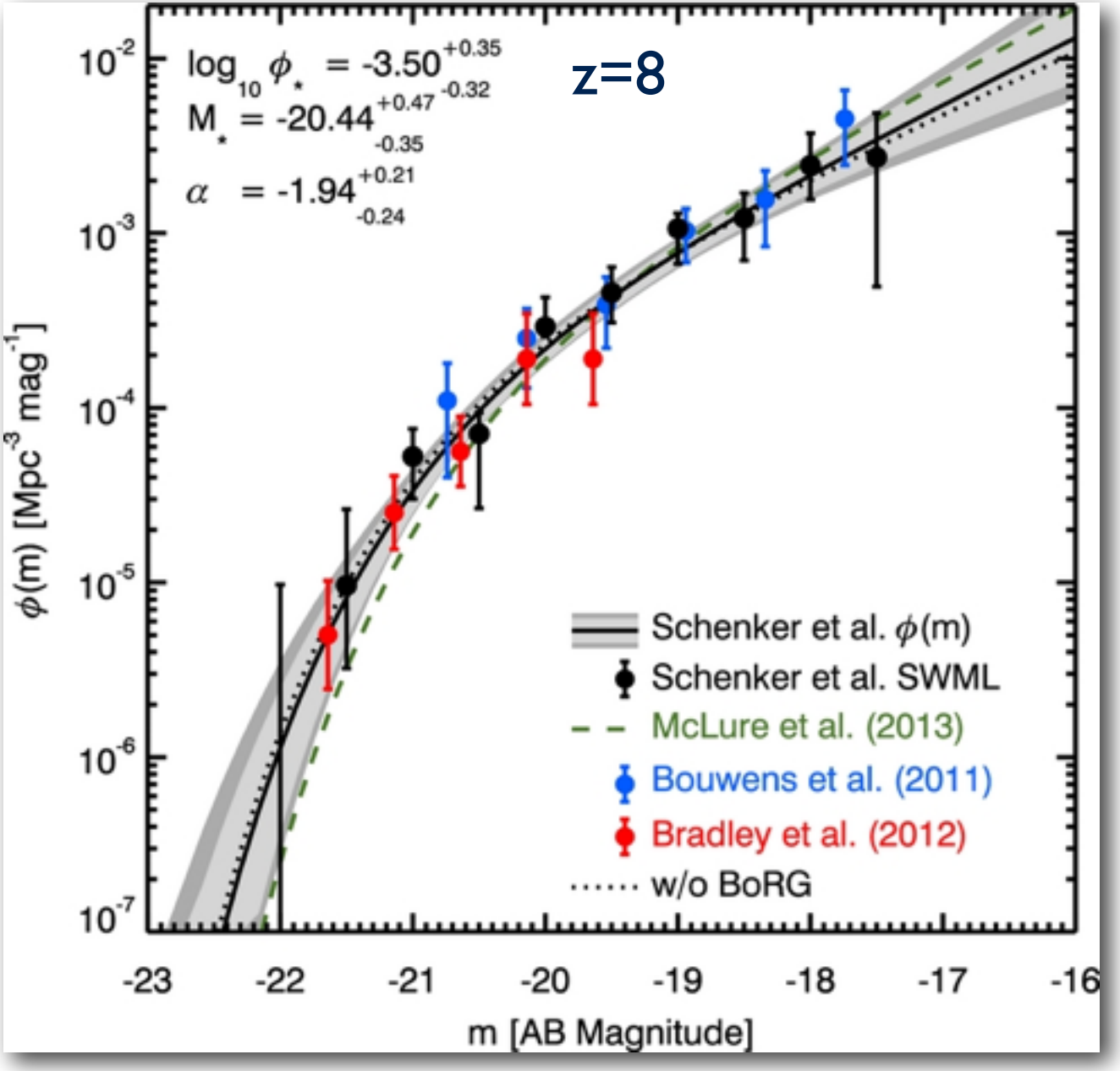


Faint galaxies (M_{uv} ~ -10) drive reionization?



Robertson et al. 2013

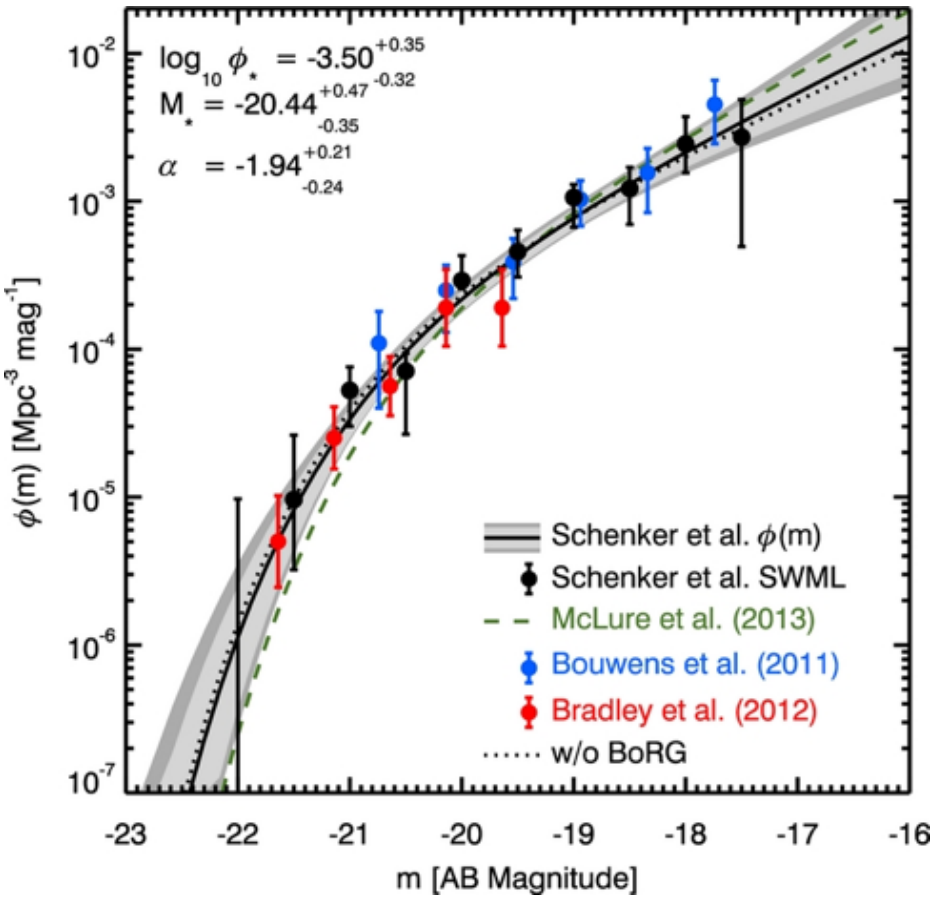
Also: Finkelstein et al. 2012, Kuhlen & Faucer-Giguere 2012

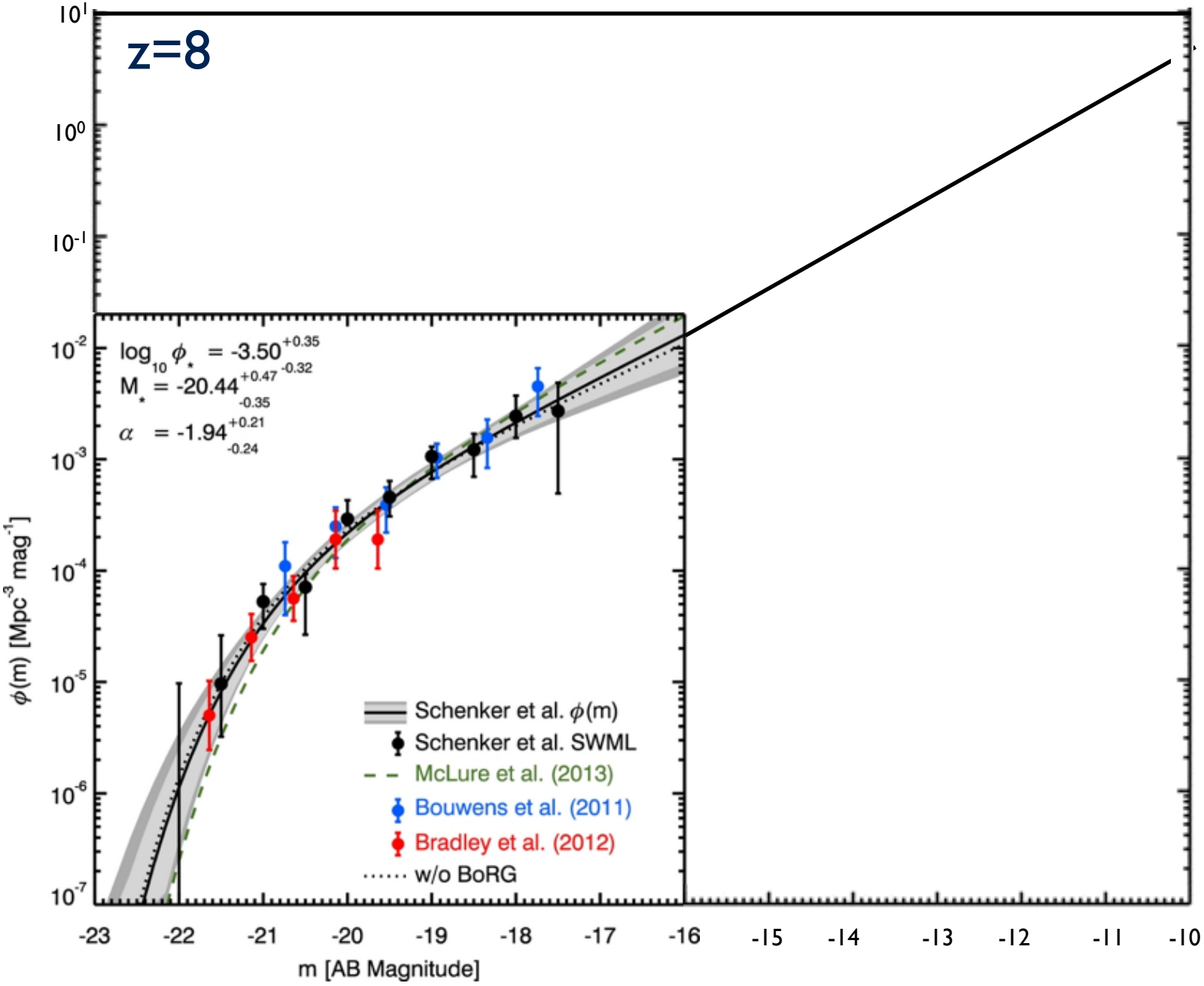


Also:

Oesch et al. 2013;
Illingworth et al. 2013;
Bouwens et al. 2014;

z=8


$\log_{10}\phi_* = -3.50^{+0.35}_{-0.32}$
$M_* = -20.44^{+0.47}_{-0.35}$
$\alpha = -1.94^{+0.21}_{-0.24}$
Schenker et al. ϕ(m)
Schenker et al. SWML
McLure et al. (2013)
Bouwens et al. (2011)
Bradley et al. (2012)
w/o BoRG
ϕ(m) [Mpc^{-3} mag^{-1}]
m [AB Magnitude]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
-23
-22
-21
-20
-19
-18
-17
-16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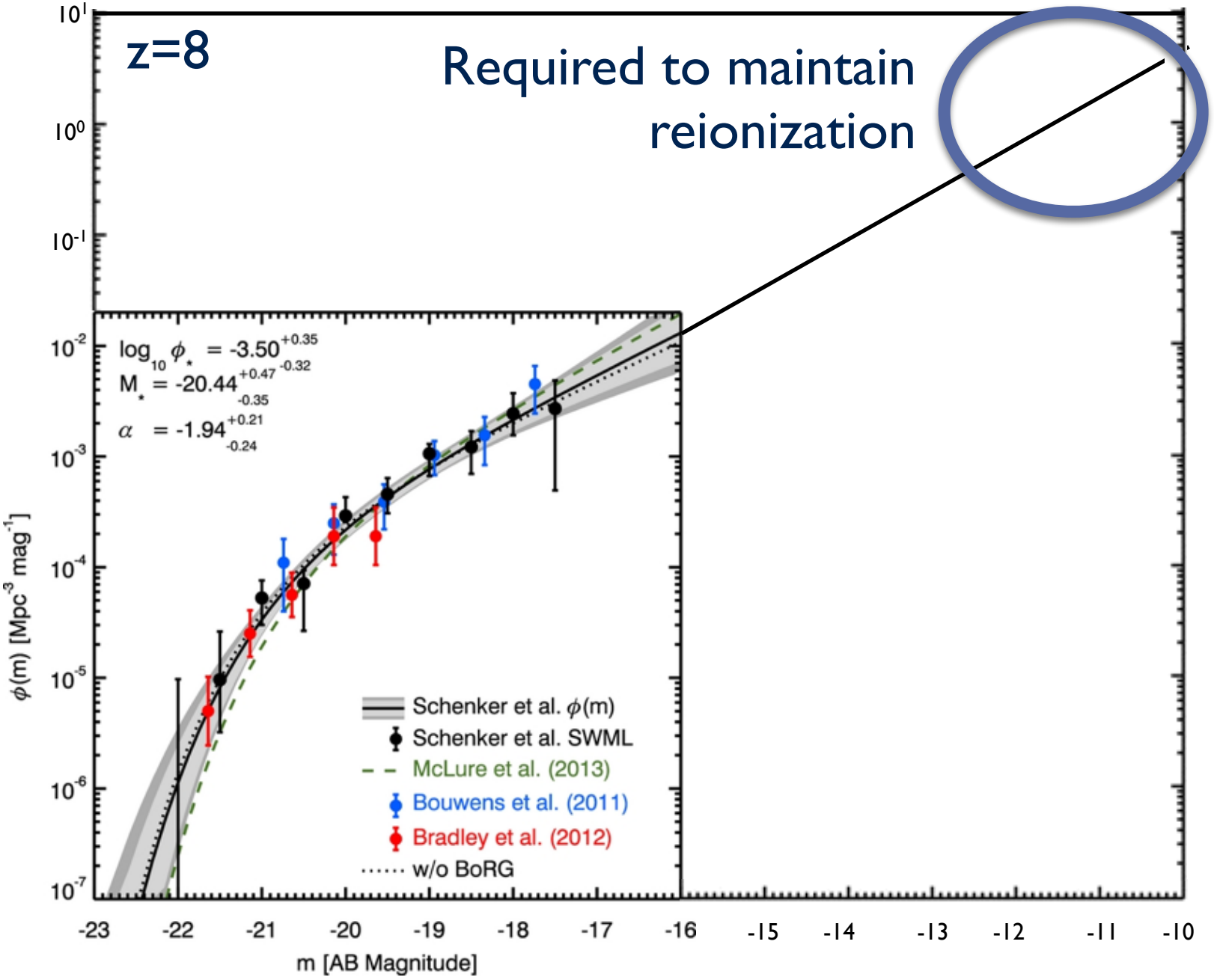
w/o BoRG
ϕ(m) [Mpc^{-3} mag^{-1}]
m [AB Magnitude]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
-23
-22
-21
-20
-19
-18
-17
-16
-15
-14
-13
-12
-11
-10


z=8
Required to maintain reionization
$\log_{10}\phi_* = -3.50^{+0.35}_{-0.32}$
$M_* = -20.44^{+0.47}_{-0.35}$
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Schenker et al. ϕ(m)
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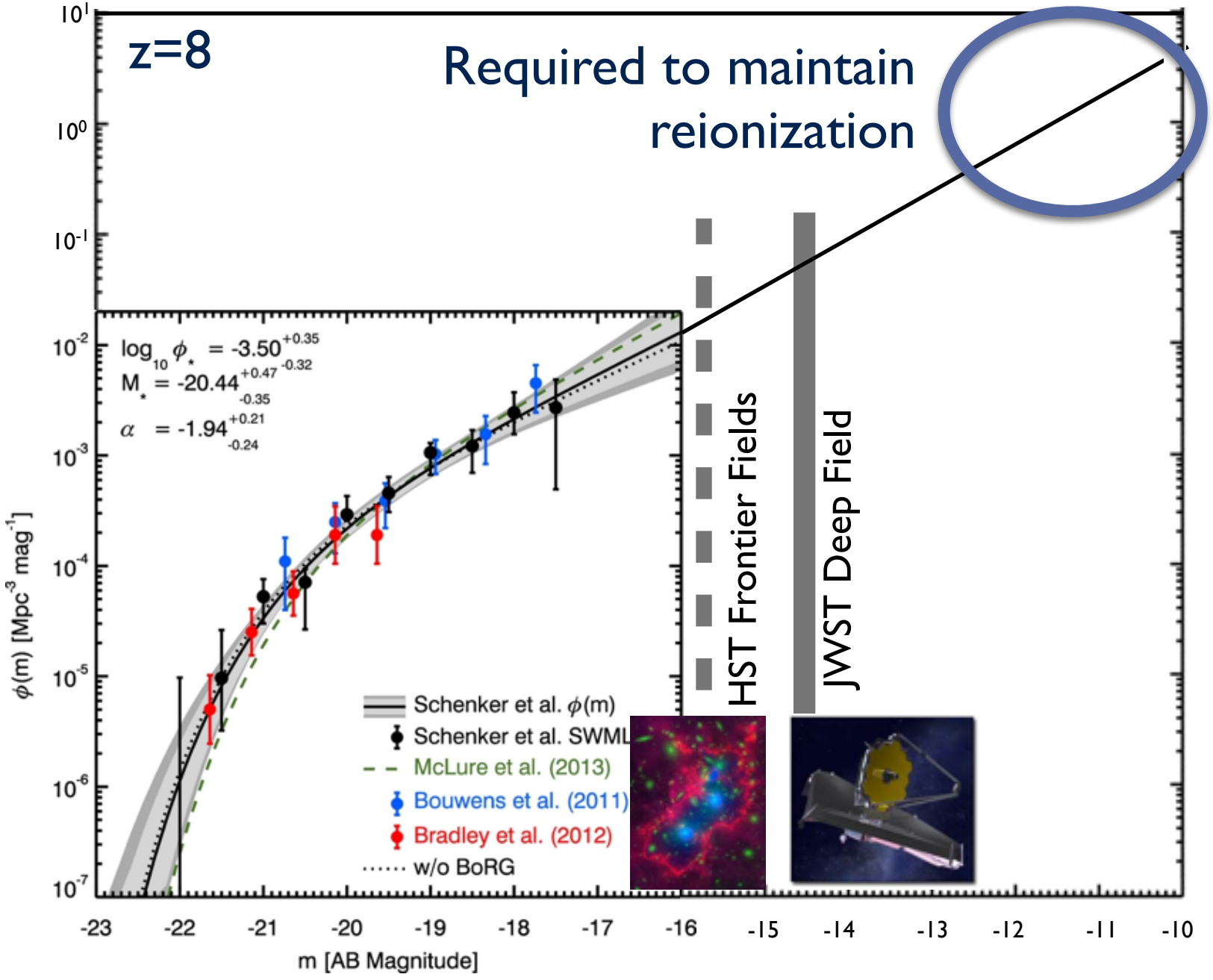
ϕ(m) [Mpc^{-3} mag^{-1}]
m [AB Magnitude]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
-23
-22
-21
-20
-19
-18
-17
-16
-15
-14
-13
-12
-11
-10


z=8
Required to maintain reionization
HST Frontier Fields
JWST Deep Field
$\log_{10}\phi_* = -3.50^{+0.35}_{-0.32}$
$M_* = -20.44^{+0.47}_{-0.35}$
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Schenker et al. ϕ(m)
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w/o BoRG
ϕ(m) [Mpc^{-3} mag^{-1}]
m [AB Magnitude]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
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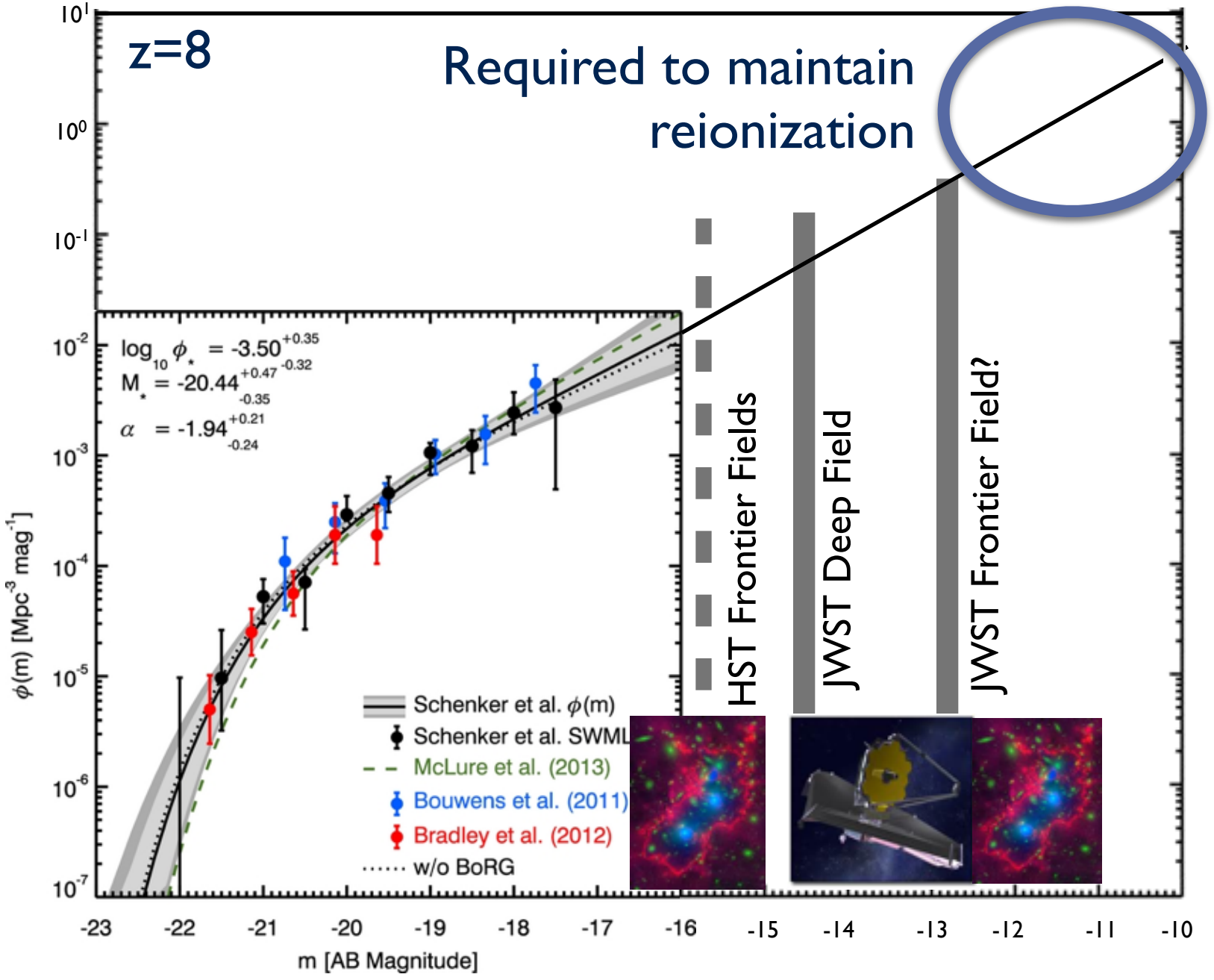
-12
-11
-10


z=8
Required to maintain reionization
HST Frontier Fields
JWST Deep Field
JWST Frontier Field?
$\log_{10}\phi_* = -3.50^{+0.35}_{-0.32}$
$M_* = -20.44^{+0.47}_{-0.35}$
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w/o BoRG
ϕ(m) [Mpc^{-3} mag^{-1}]
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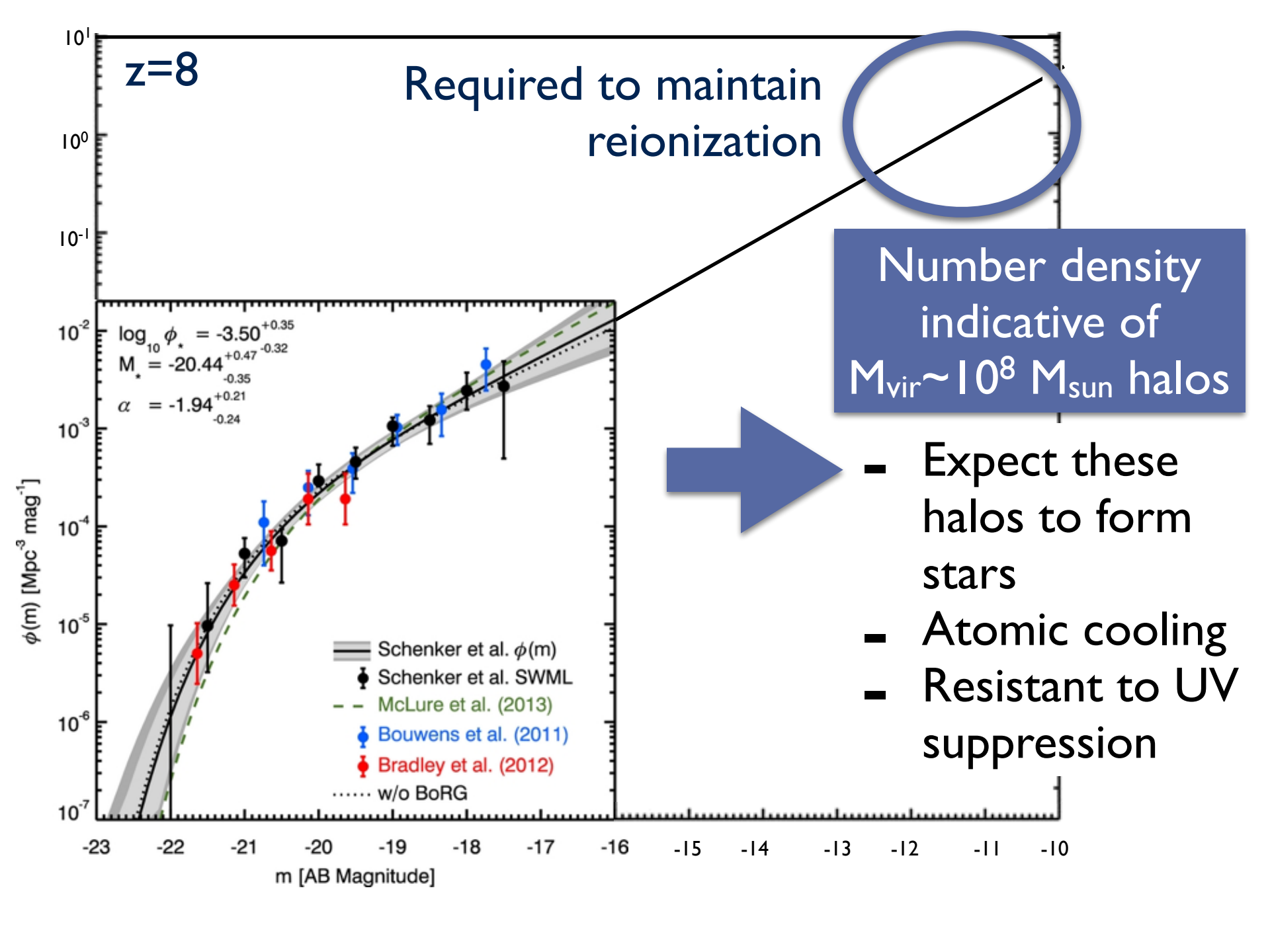
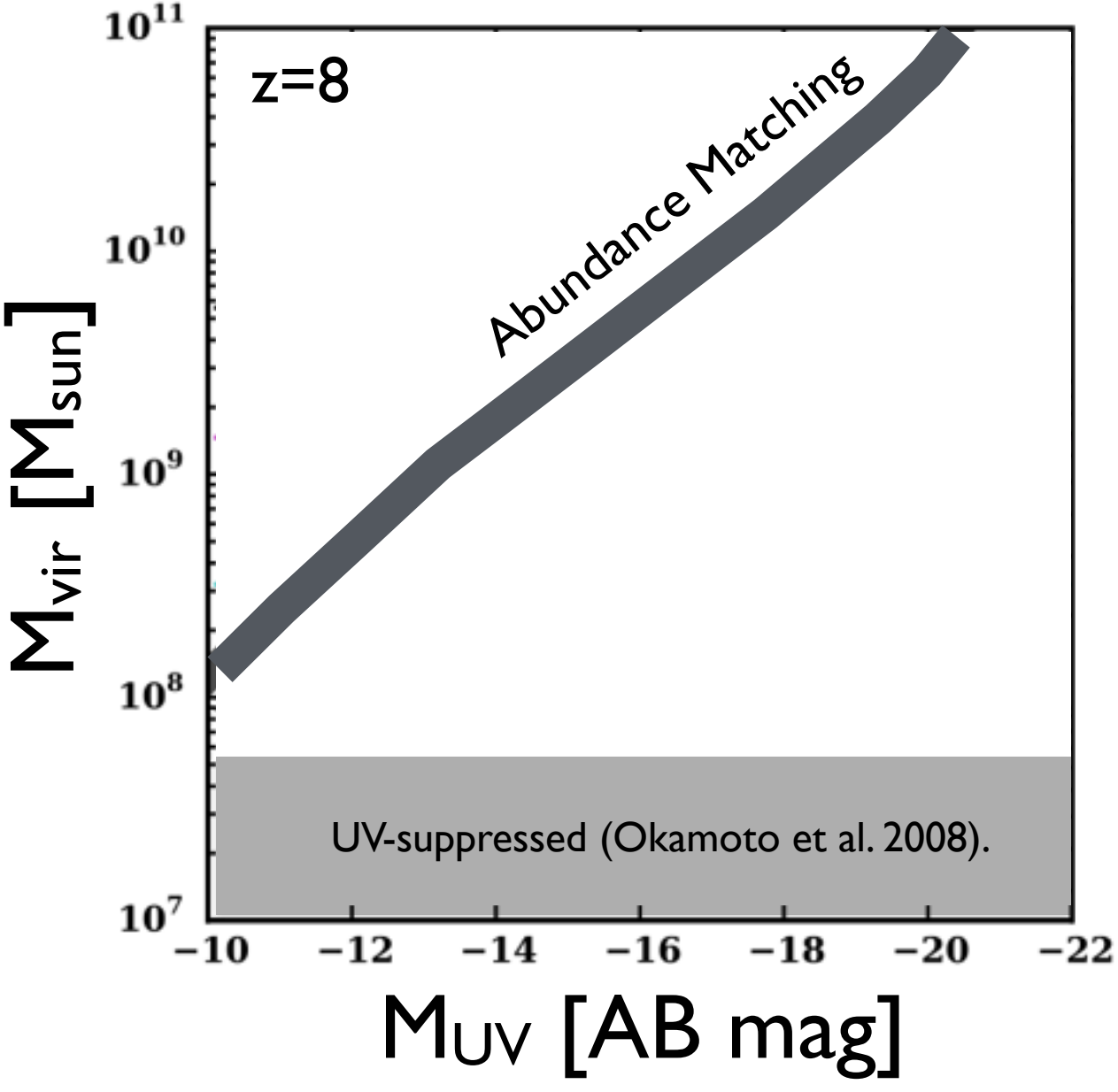
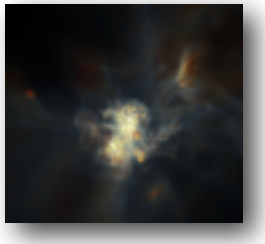
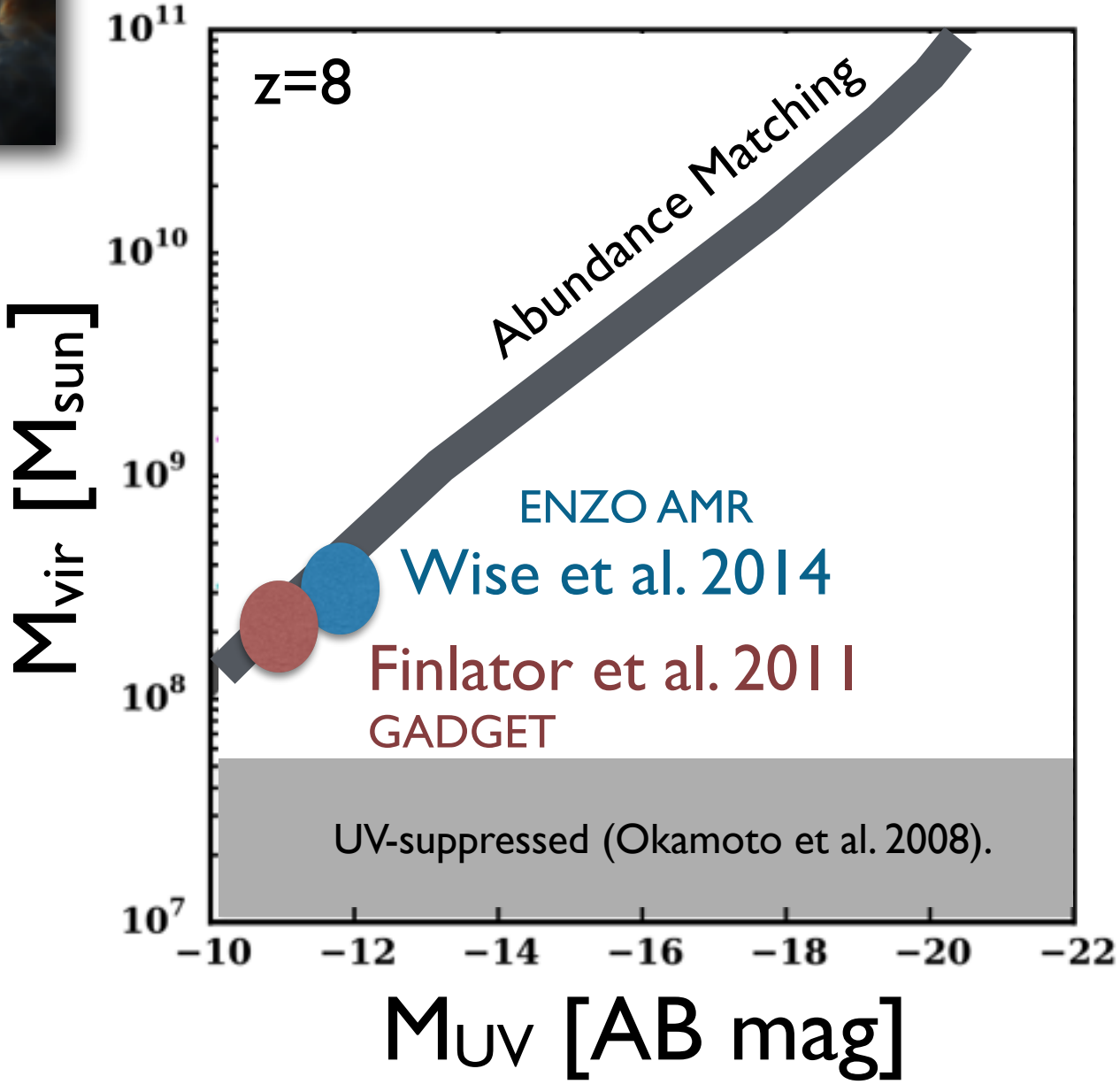
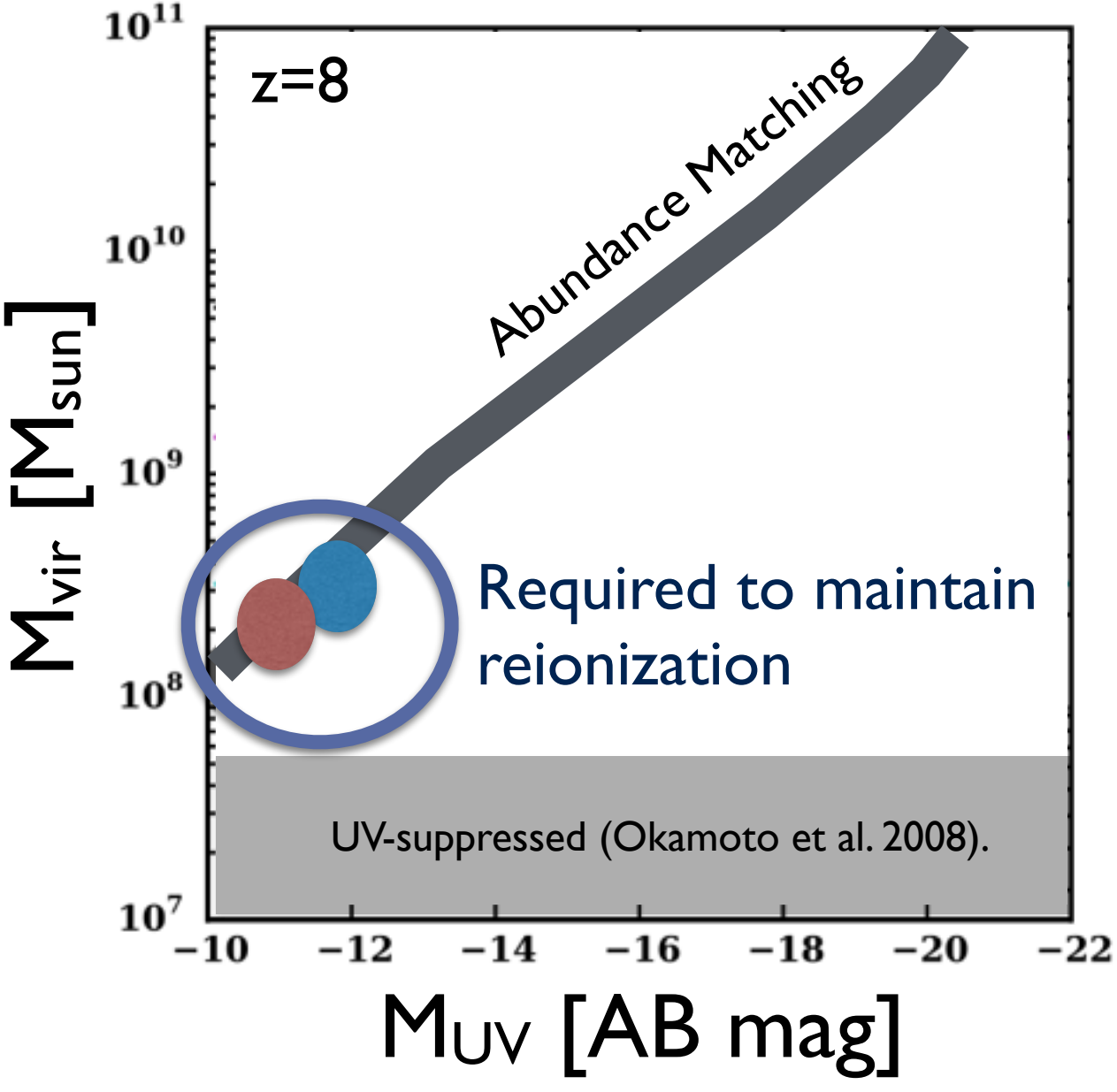
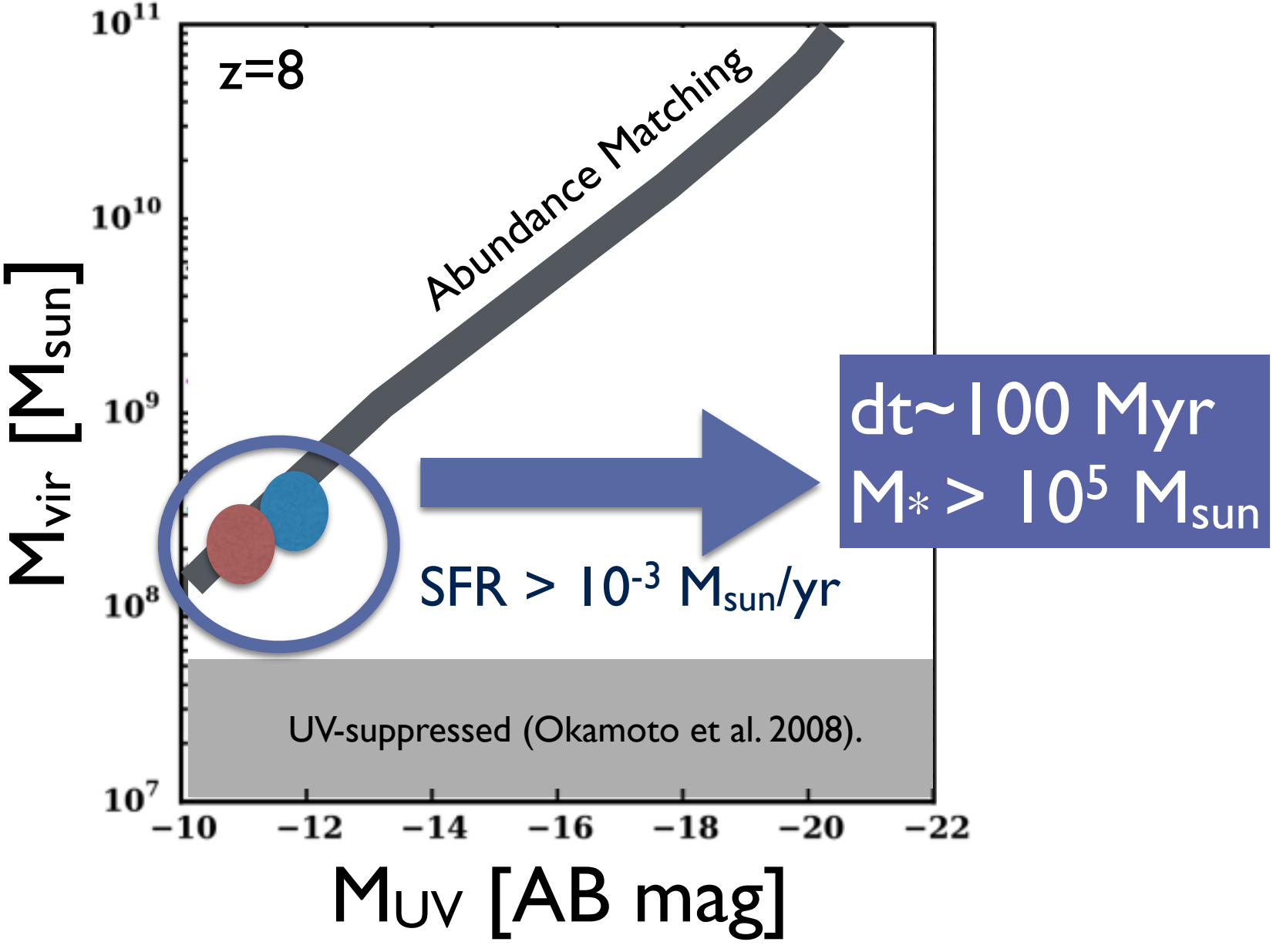

z=8
Required to maintain reionization
Number density indicative of $M_{vir} \sim 10^8 M_{sun}$ halos
- Expect these halos to form stars
- Atomic cooling
- Resistant to UV suppression
$\log_{10}\phi_* = -3.50^{+0.35}_{-0.32}$
$M_* = -20.44^{+0.47}_{-0.35}$
$\alpha = -1.94^{+0.21}_{-0.24}$
Schenker et al. ϕ(m)
Schenker et al. SWML
McLure et al. (2013)
Bouwens et al. (2011)
Bradley et al. (2012)
w/o BoRG
ϕ(m) [Mpc^{-3} mag^{-1}]
m [AB Magnitude]


z=8
Abundance Matching
UV-suppressed (Okamoto et al. 2008).
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
−10
−12
−14
−16
−18
−20
−22
M_{vir} [M_{sun}]
M_{UV} [AB mag]

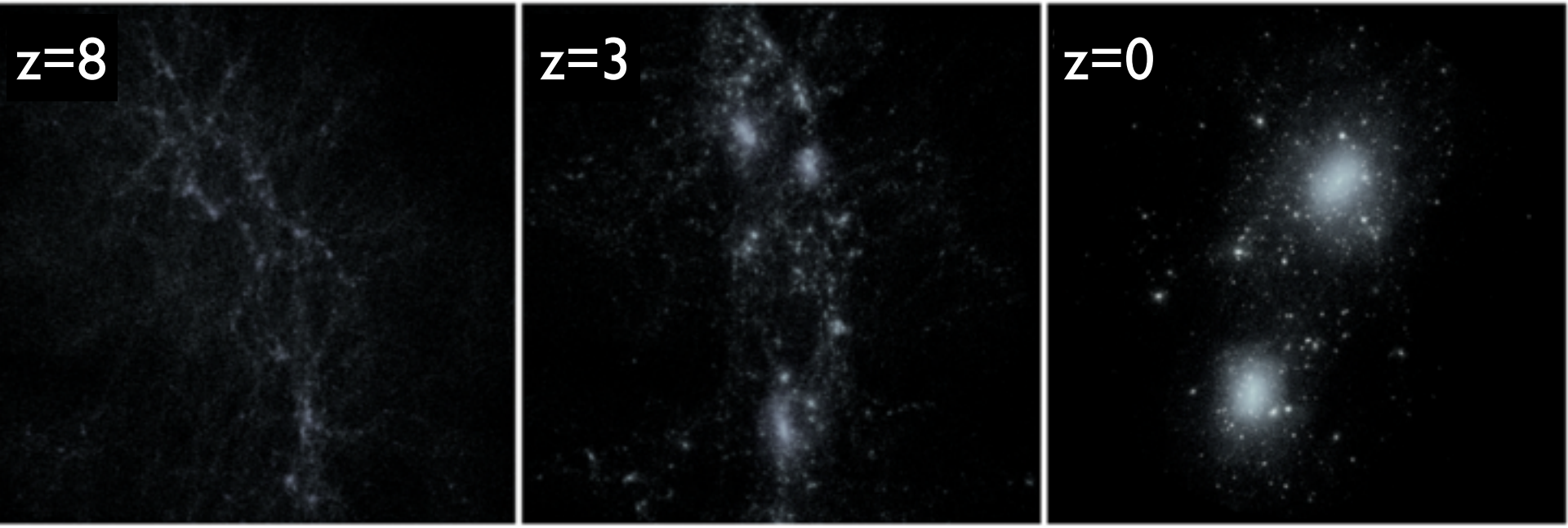



z=8
Abundance Matching
ENZO AMR
Wise et al. 2014
Finlator et al. 2011
GADGET
UV-suppressed (Okamoto et al. 2008).
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
M_{vir} [M_{sun}]
−10
−12
−14
−16
−18
−20
−22
M_{UV} [AB mag]


z=8
Abundance Matching
Required to maintain reionization
UV-suppressed (Okamoto et al. 2008).
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
M_{vir} [M_{sun}]
−10
−12
−14
−16
−18
−20
−22
M_{UV} [AB mag]


z=8
Abundance Matching
dt~100 Myr
M* > 10^5 M_sun
SFR > 10^-3 M_sun/yr
UV-suppressed (Okamoto et al. 2008).
M_vir [M_sun]
M_UV [AB mag]
10^11
10^10
10^9
10^8
10^7
−10
−12
−14
−16
−18
−20
−22

Connecting Galaxies Over 13.5 Billion Years



ID systems with $M_v > 10^8 M_{sun}$

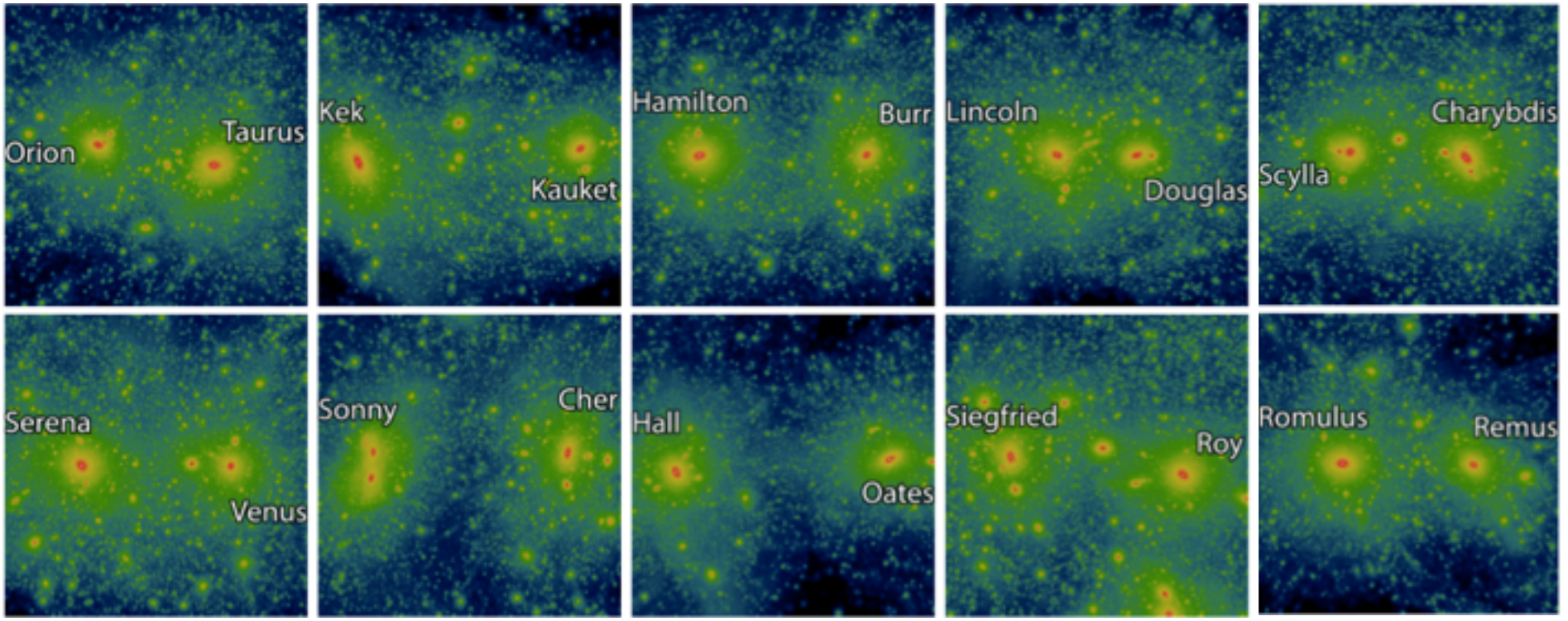
Bound progenitors at z=8

ELVIS

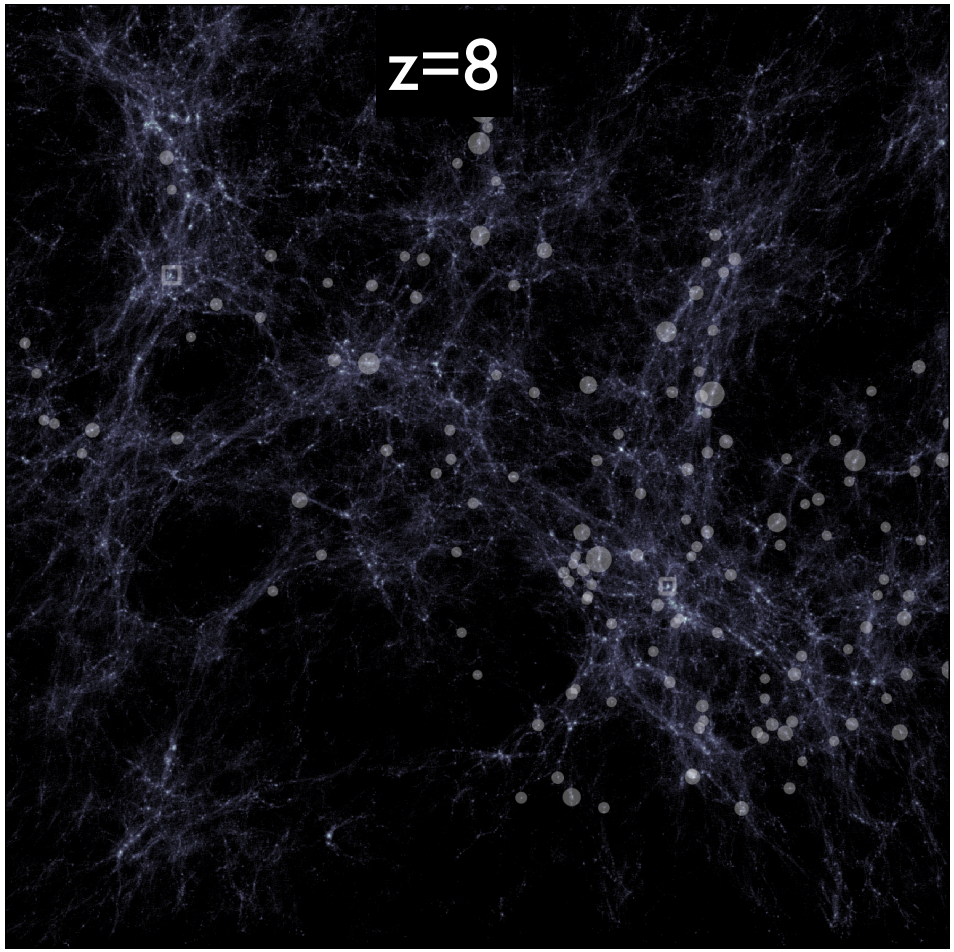
[Exploring the Local Volume In Simulations]

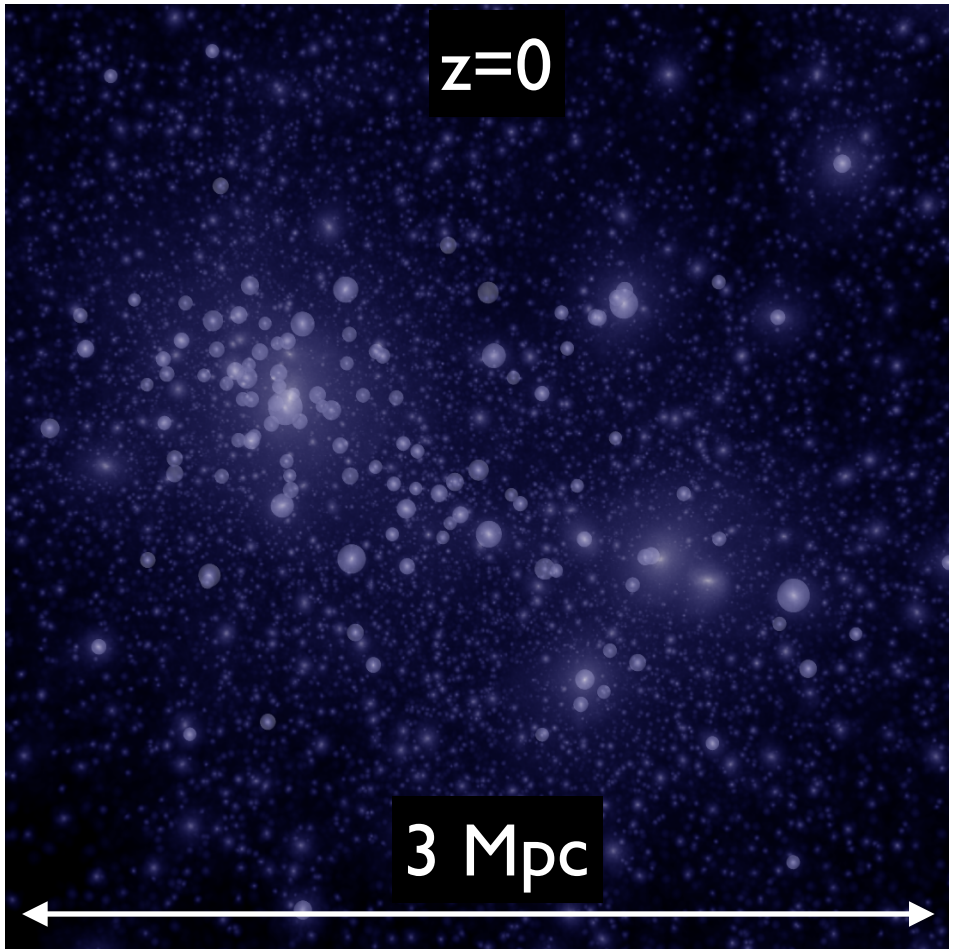
Garrison-Kimmel, Boylan-Kolchin, JSB
(2014, MNRAS)

http://localgroup.ps.uci.edu/elvis/



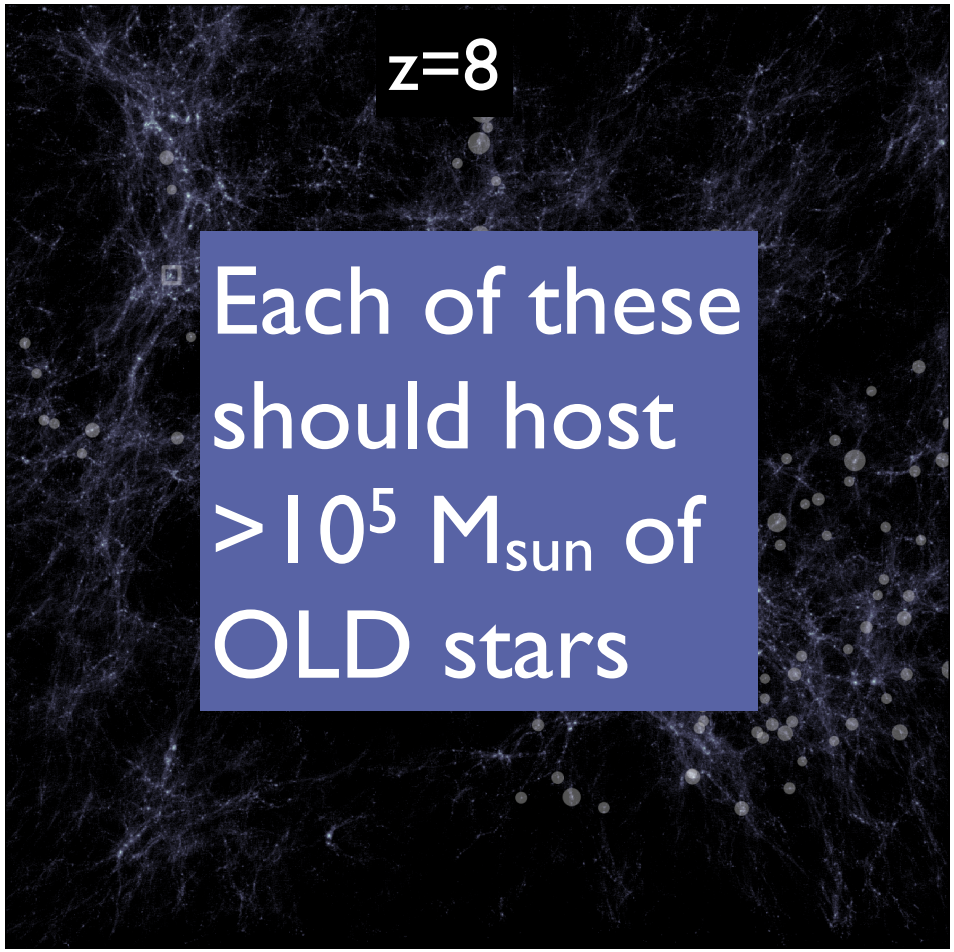
Descendants of Reionization in the Local Group

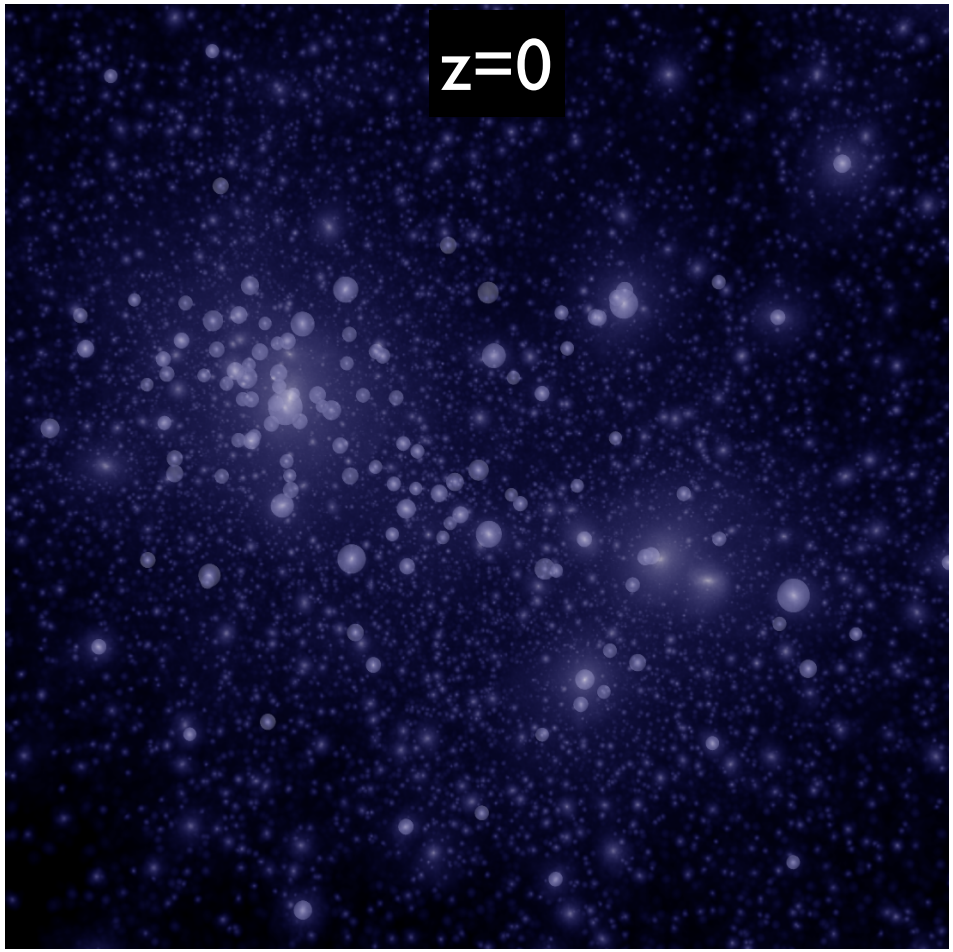




~170 bound descendants of halos atomic cooling halos z=8

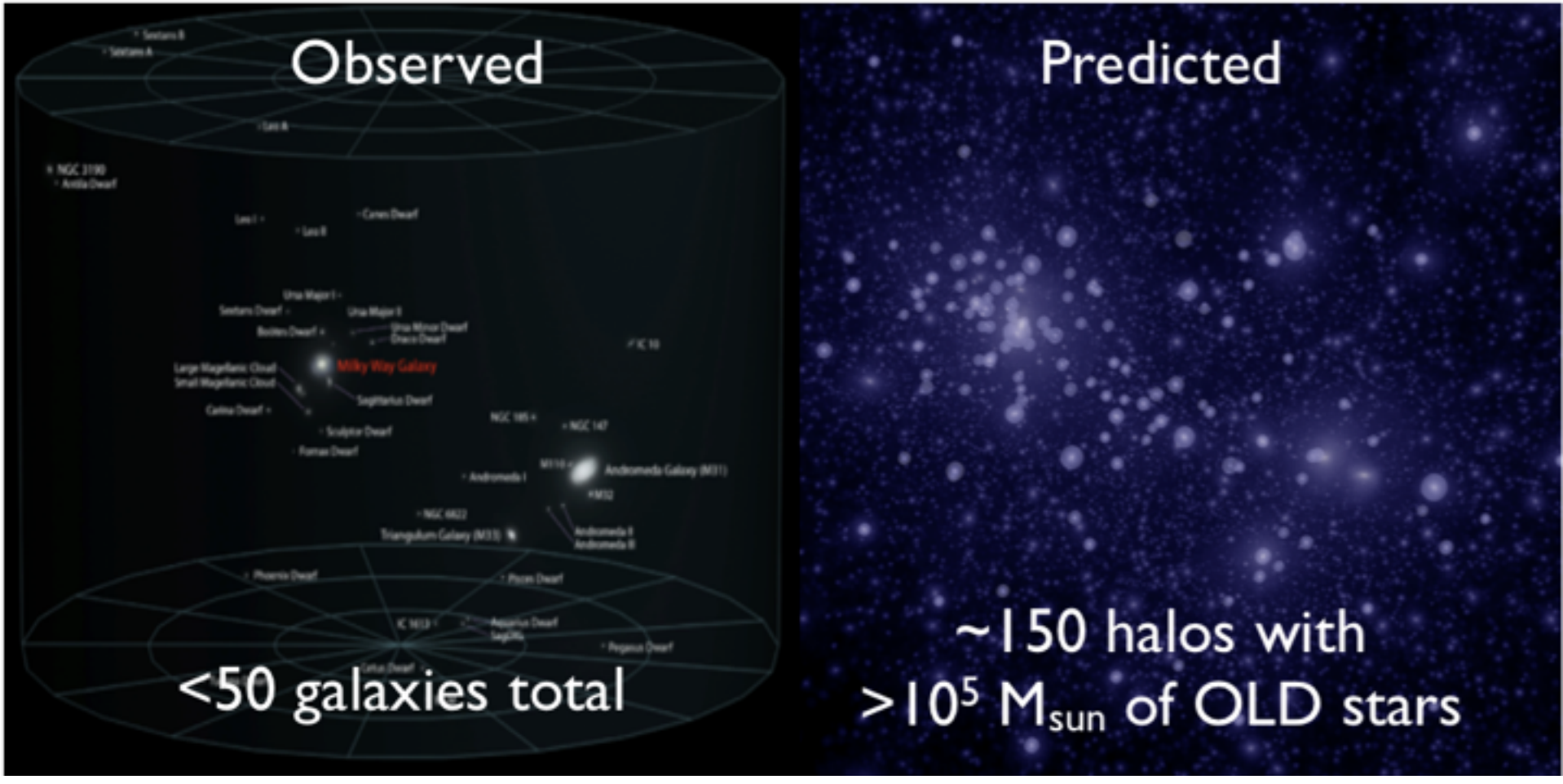
Descendants of Reionization in the Local Group



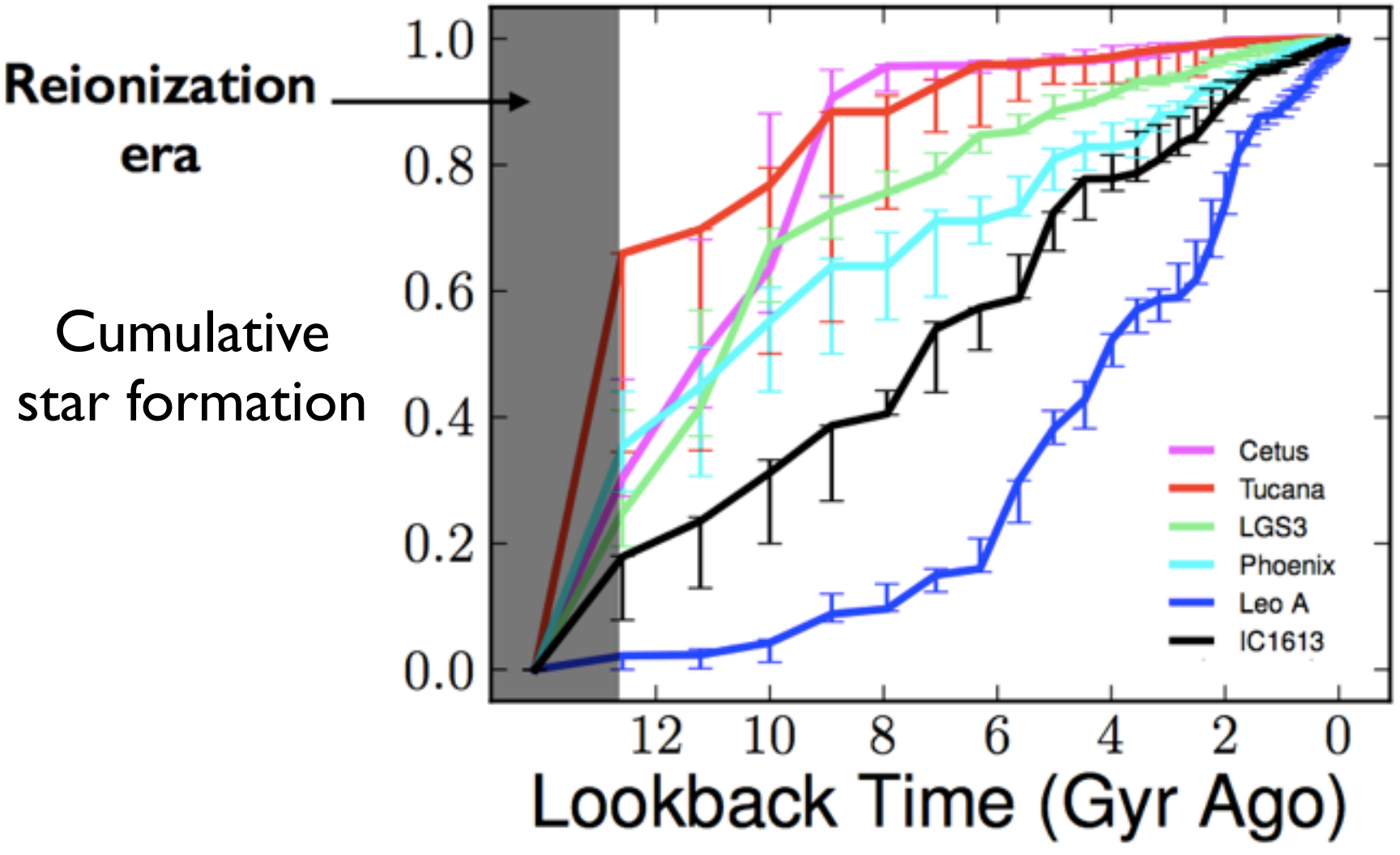


~170 bound descendants of halos atomic cooling halos z=8

Descendants of Reionization in the Local Group

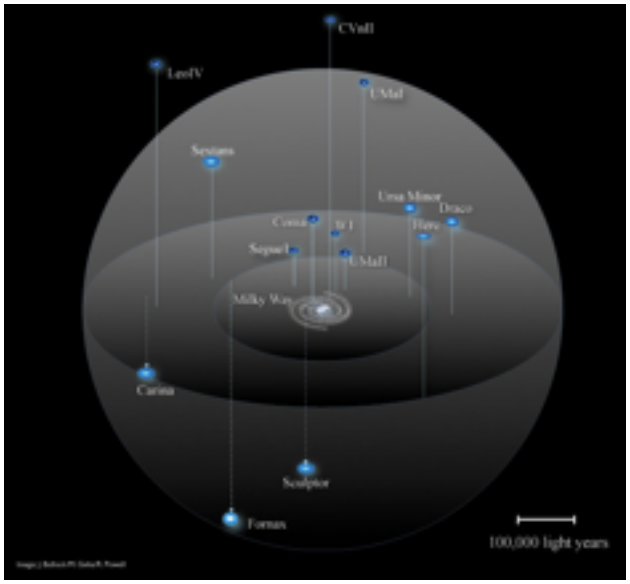


Local Group Dwarf Star Formation Histories



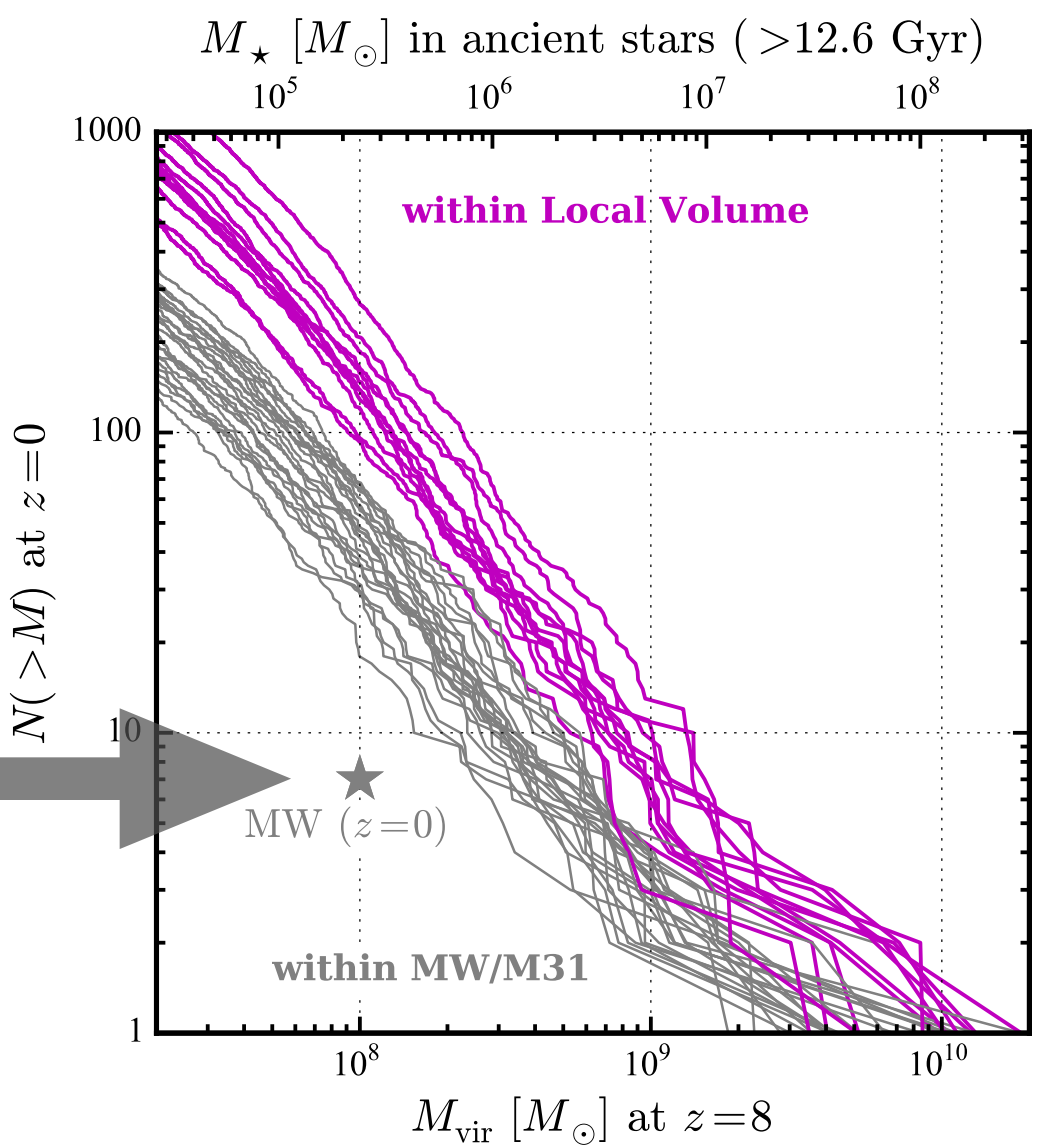
Skillman et al. 2014 (ACS LCID project); Weisz et al. 2014

Where are the “first light” halos?



MW has only 7 satellites with $>2.10^5 M_{sun}$ in ancient stars

Weisz et al. 2014



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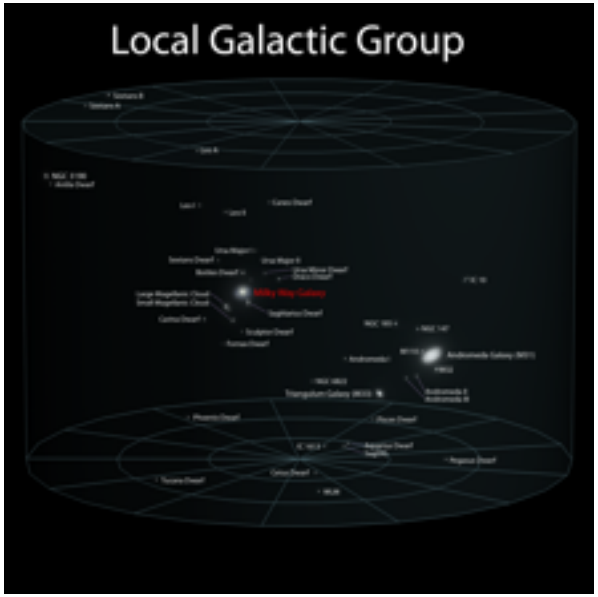
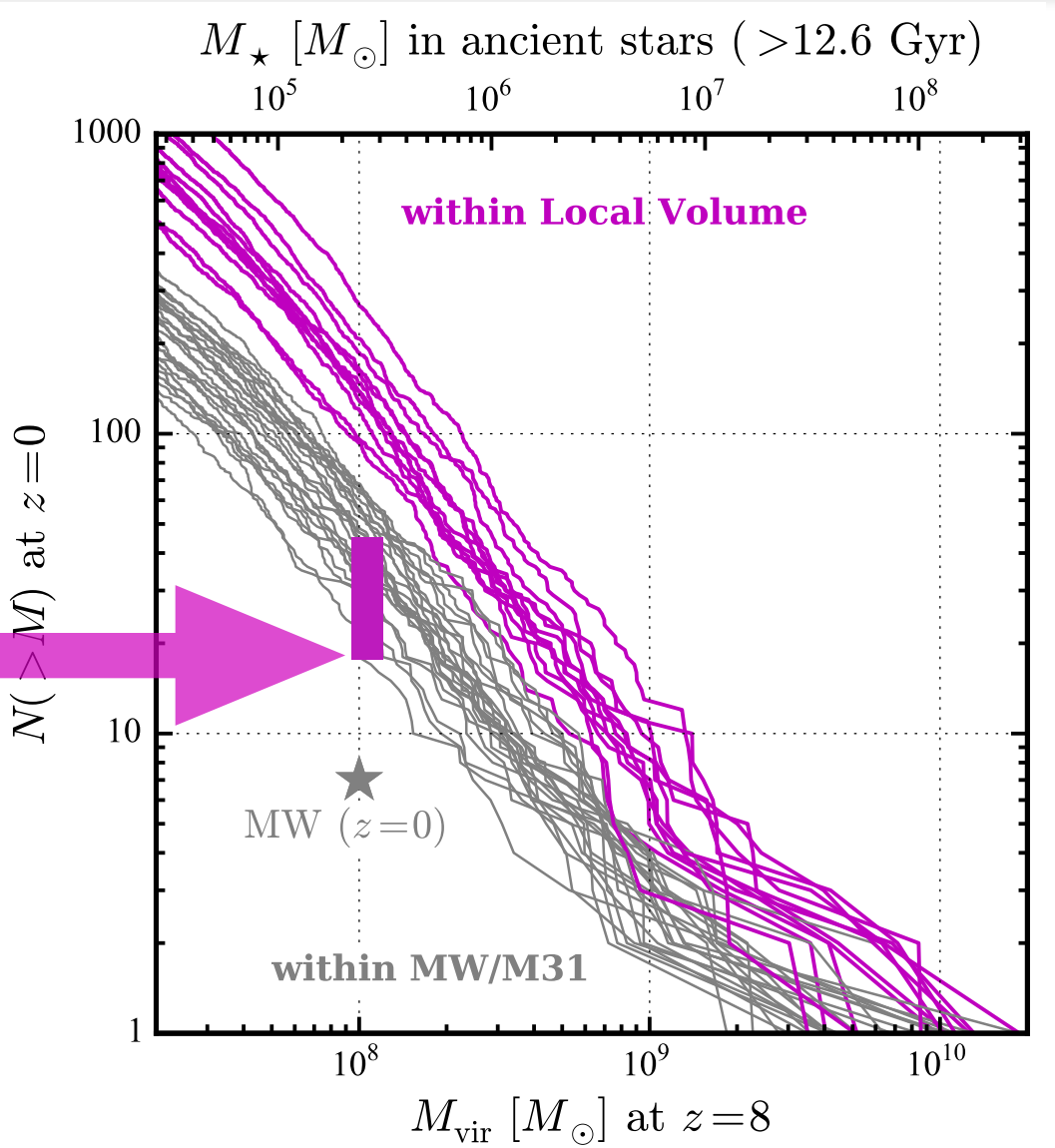
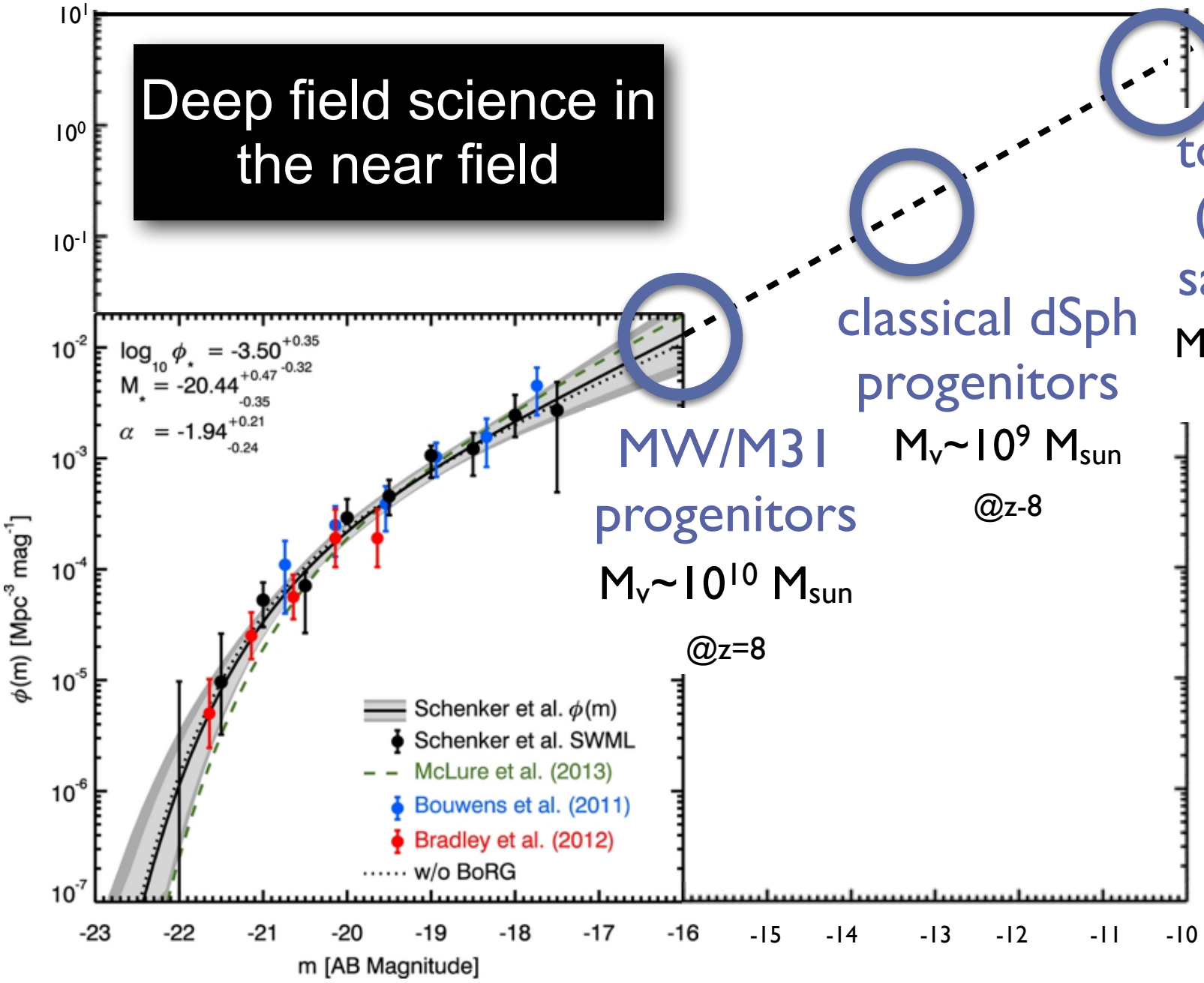


Local group has ~30 galaxies w/ > 2.10^5 M_{sun} of ancient stars

Weisz et al. 2014



Deep field science in the near field



z=8

too many (missing satellites)

$M_v \sim 10^8\ M_{sun}$

@z=8

classical dSph progenitors

$M_v \sim 10^9\ M_{sun}$

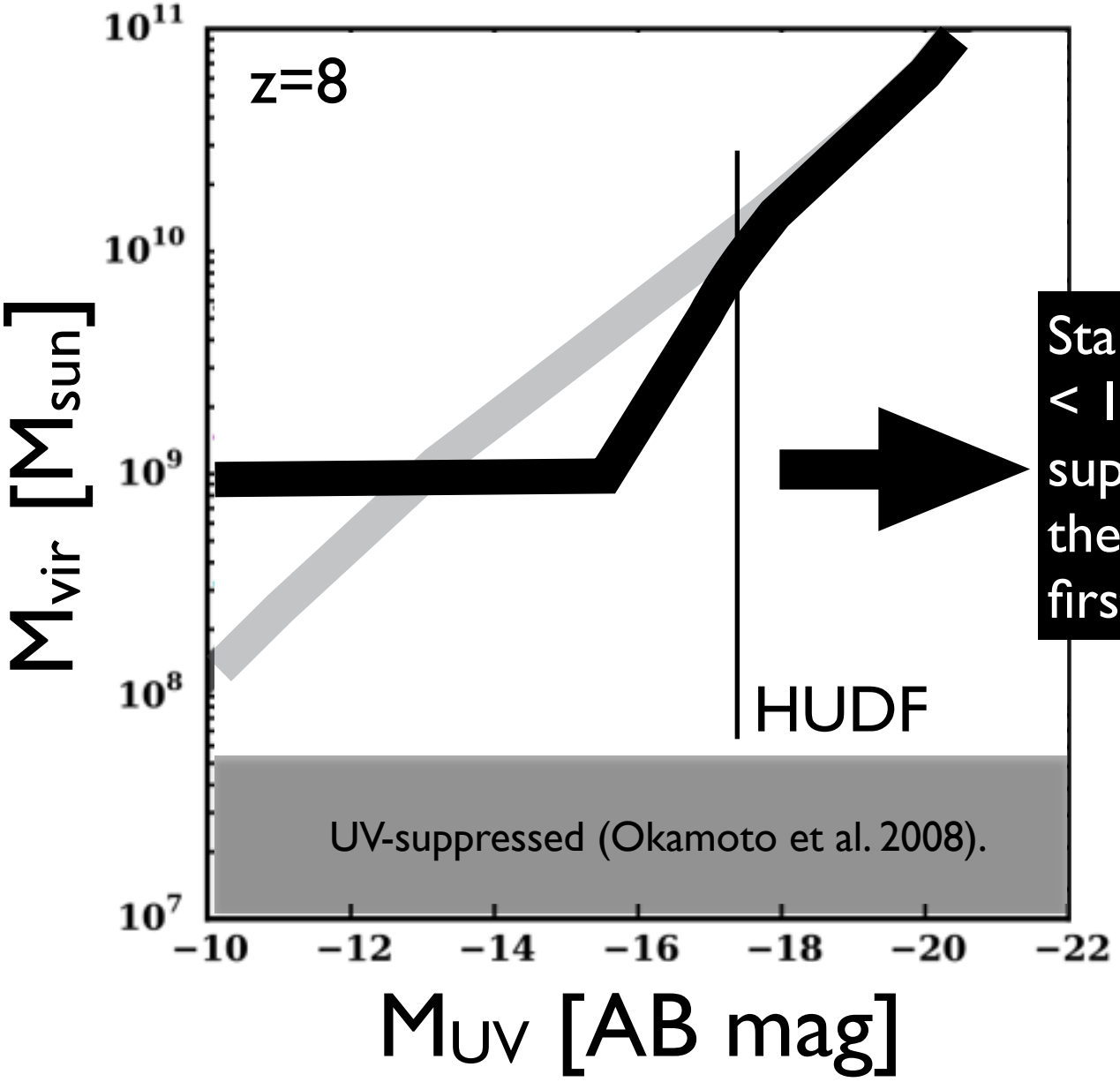
@z-8

MW/M31 progenitors

$M_v \sim 10^{10}\ M_{sun}$

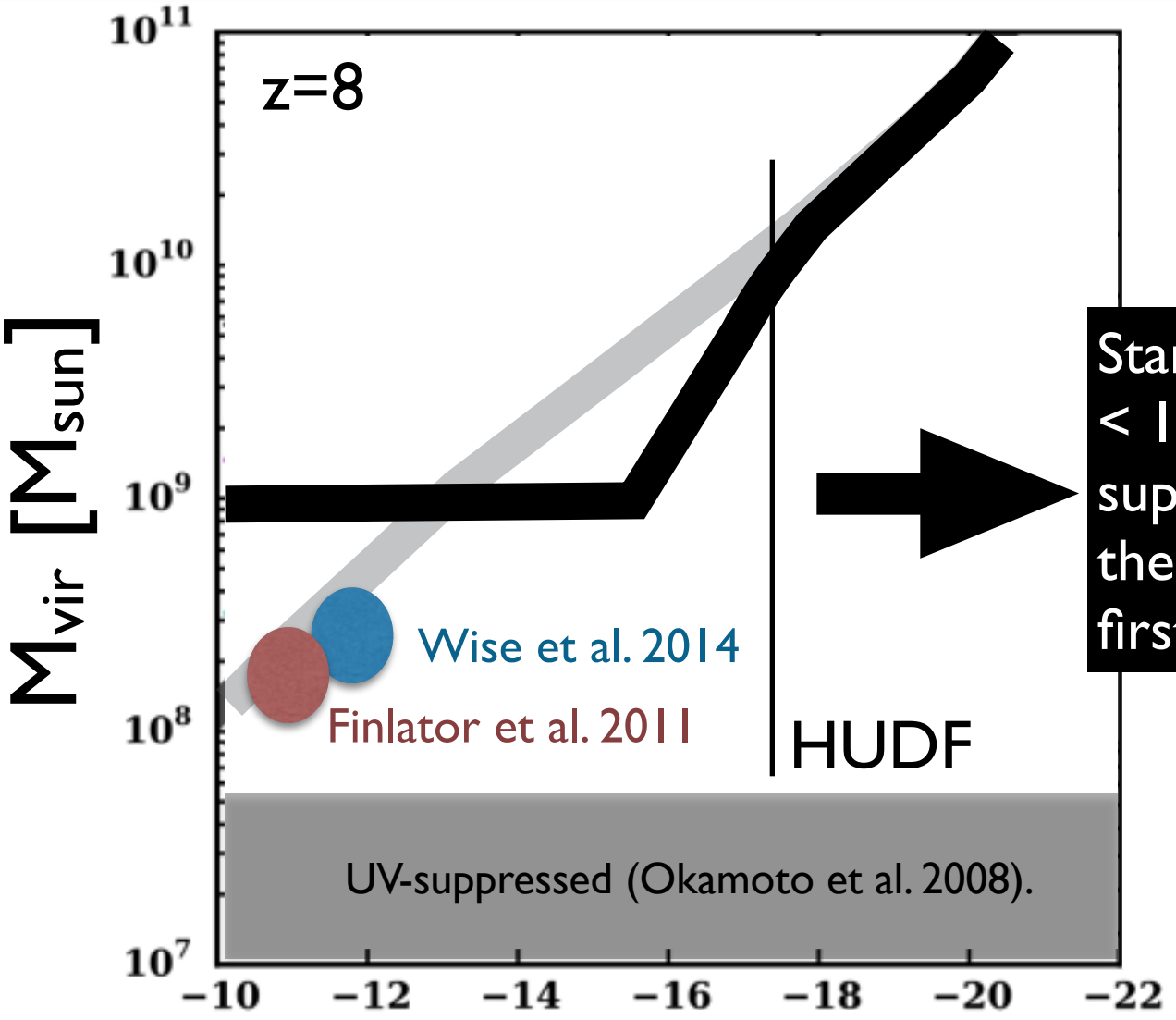
@z=8

How could we evade this bound?



Star formation in $< 10^9$ M_{sun} halos suppressed at the epoch of first light.

How could we evade this bound?

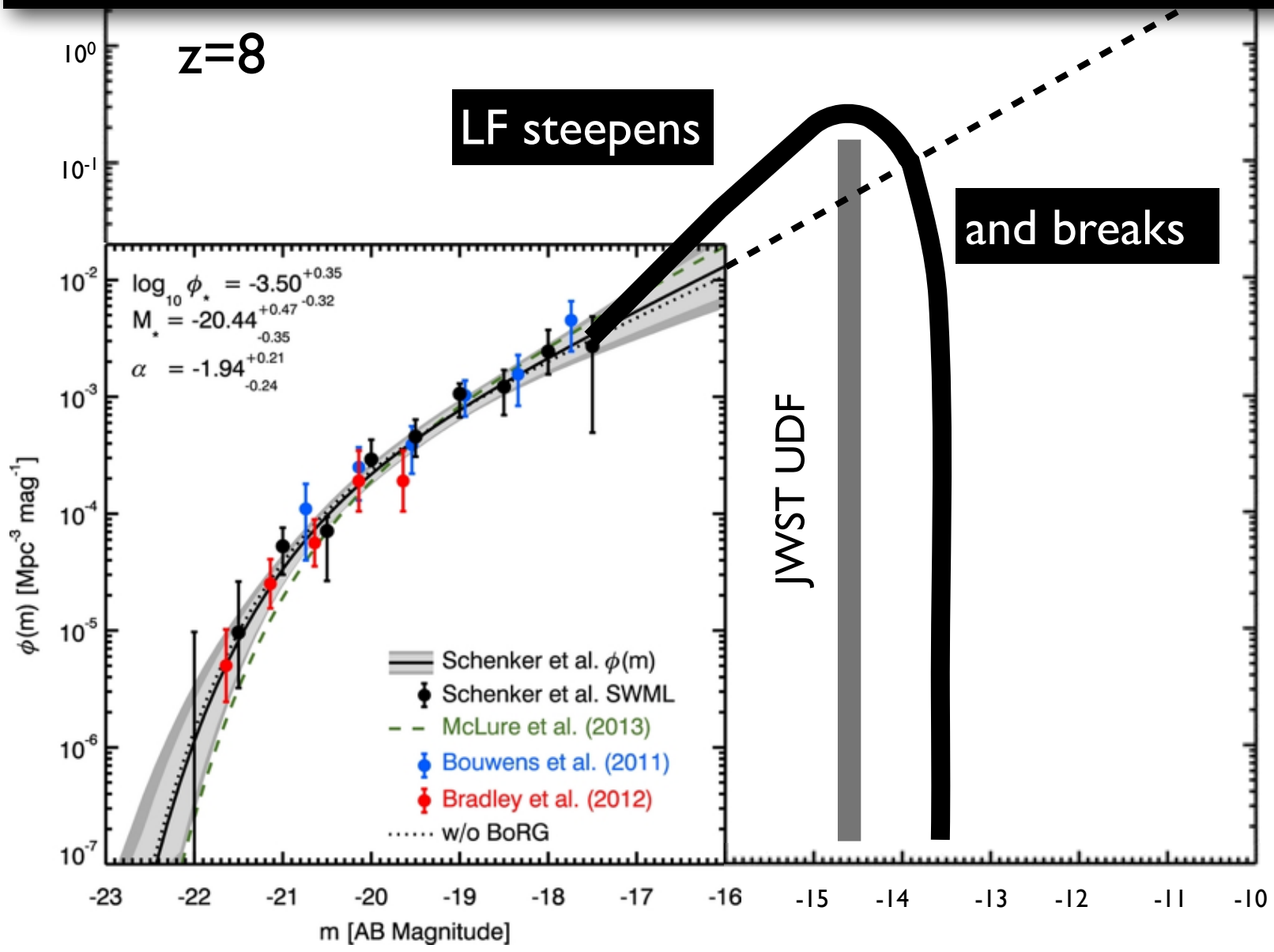


Star formation in $< 10^9$ M_{sun} halos suppressed at the epoch of first light.

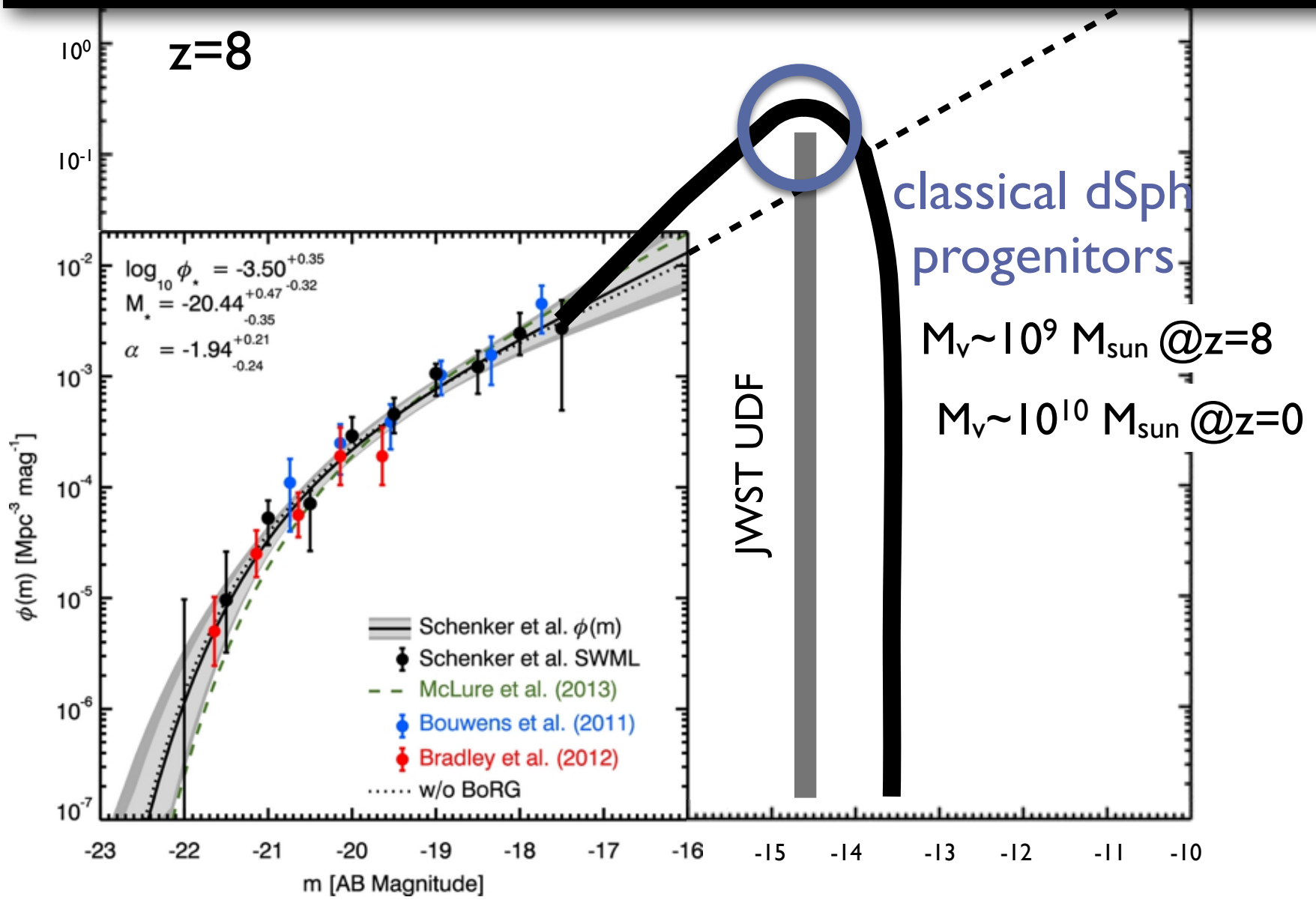
WHY?

- The most sophisticated simulations to date don't see this…

How could we evade this bound?



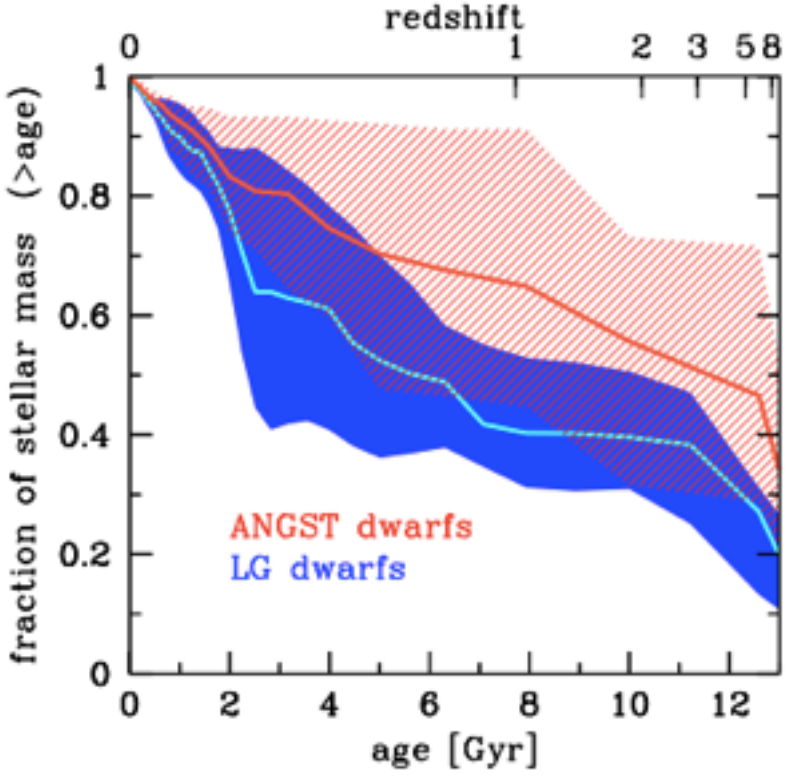
How could we evade this bound?

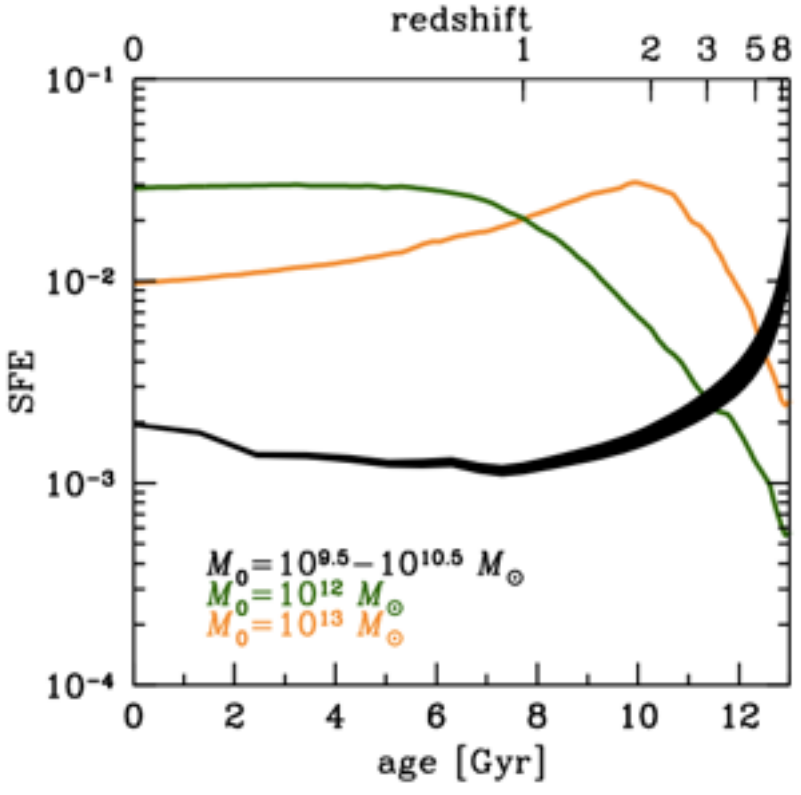


REVERSAL OF FORTUNE: INCREASED STAR FORMATION EFFICIENCIES IN THE EARLY HISTORIES OF DWARF GALAXIES?

PIERO MADAU[1], DANIEL R. WEISZ[1,2,3], AND CHARLIE CONROY[1]

ApJL, in press

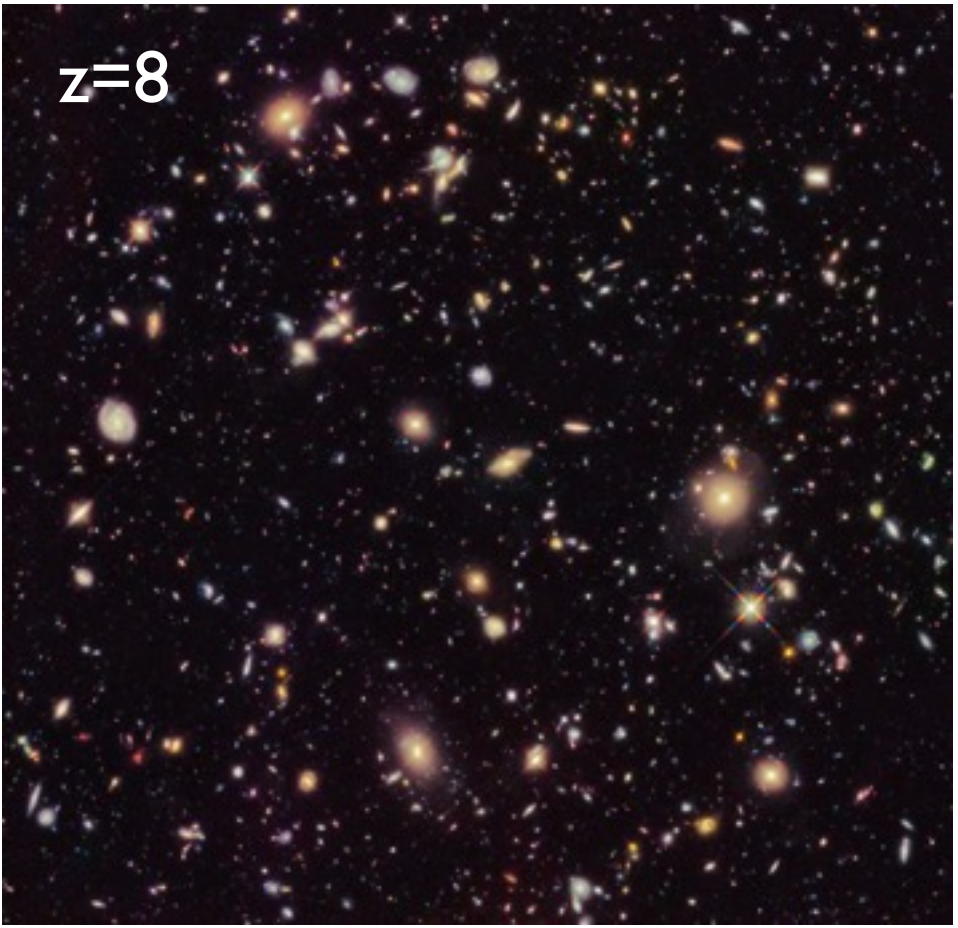


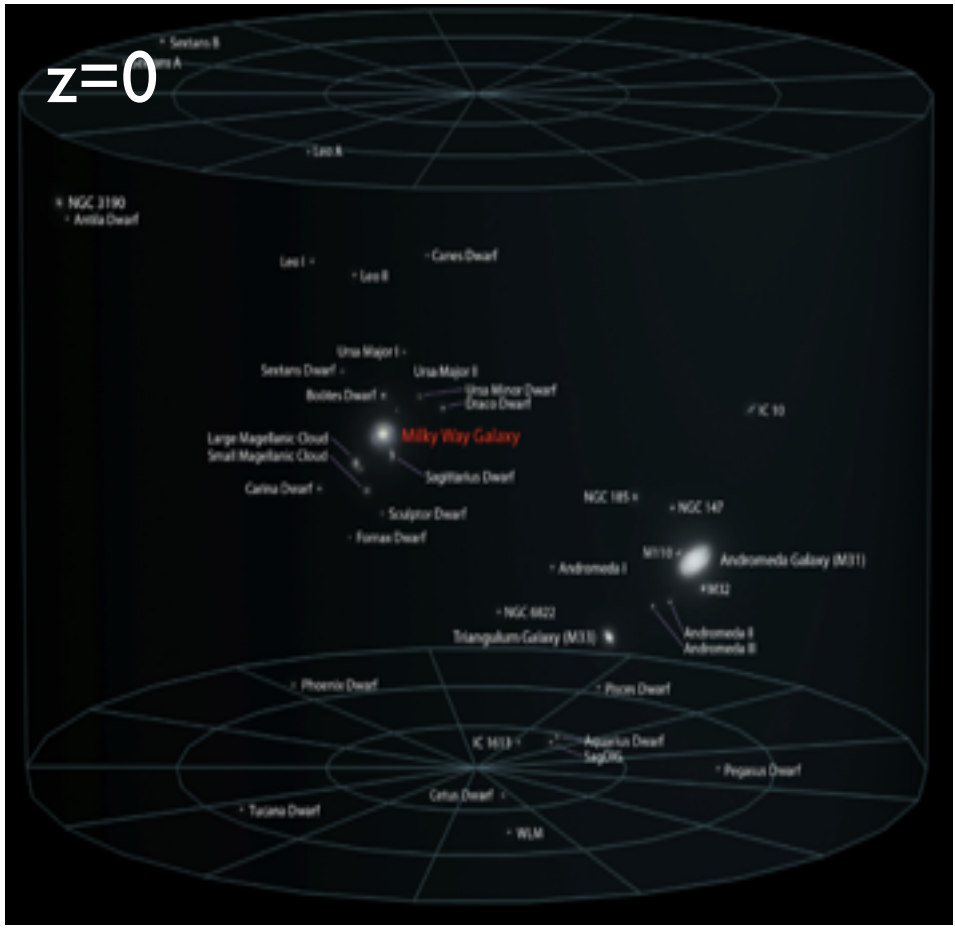


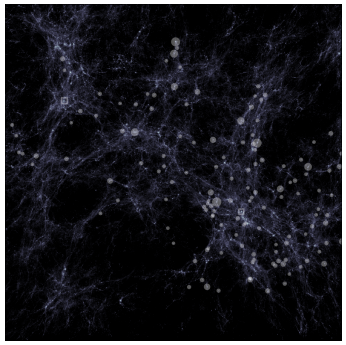
A basic tension for small halos (M_{dm} ~10^8 M_{sun})

Lots of star formation

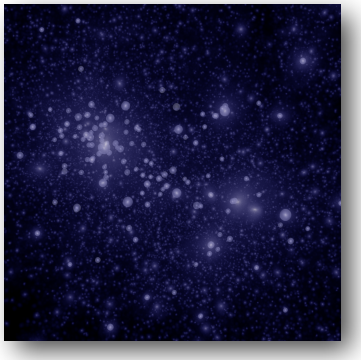
Very few stars







Summary



- The Local Group should have ~150 bound descendants of z~8 atomic cooling halos (M_v~10^8 M_{sun} at z~8)

- Local galaxy counts strongly suggest that these small halos (M_v~10^8 M_{sun}) are NOT forming stars significantly at z~8 and do **not** contribute significantly to reionization.

→ Need to shut off galaxy formation in M_v<~$10^9 M_{sun}$ halos at z~8. HOW?

→ Are progenitors of Local dSphs major contributors to reionization?