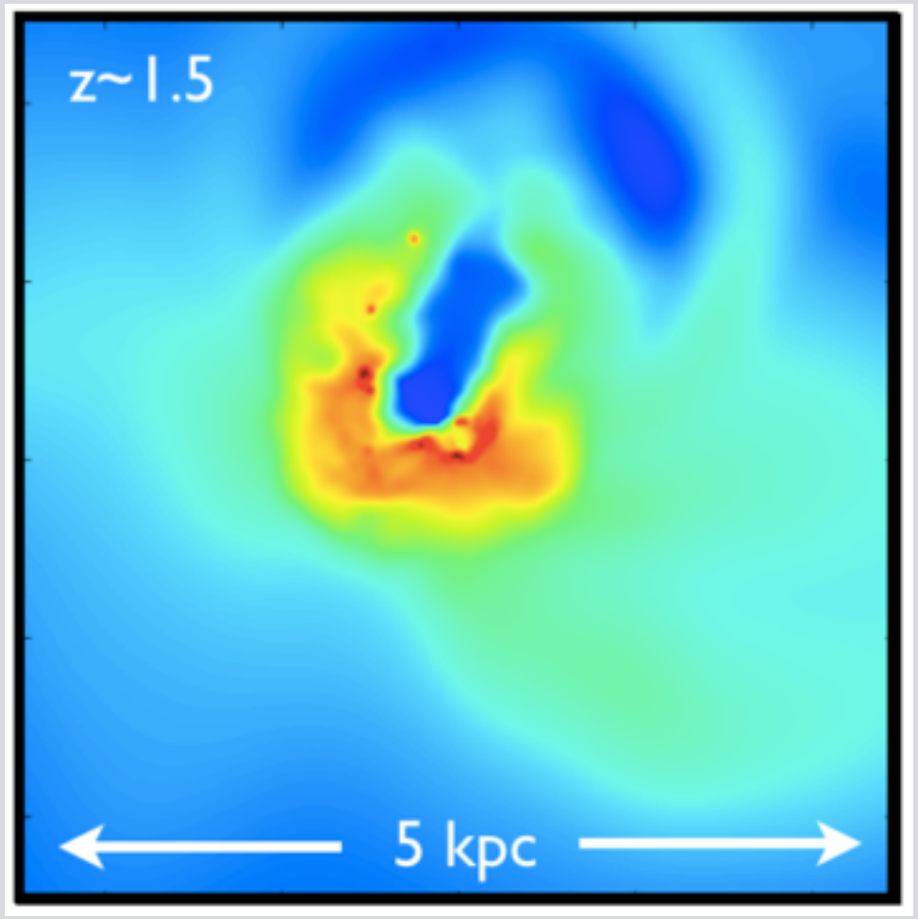
FORGED IN FIRE

CUSPS & CORES IN SMALL DWARF GALAXIES

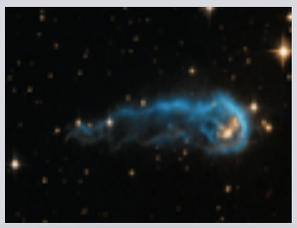


JAMES BULLOCK
UC Irvine

FIRE (Feedback In Realistic Environments)

HOPKINS, KERES, OÑORBE, FAUCHER-GIGUERE, QUATAERT, MURRAY, BULLOCK

Radiation pressure



Stellar winds

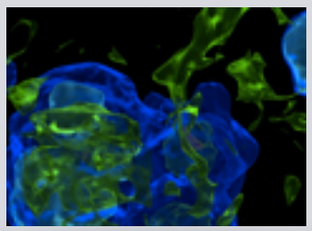
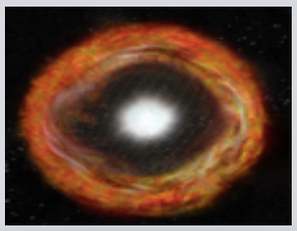
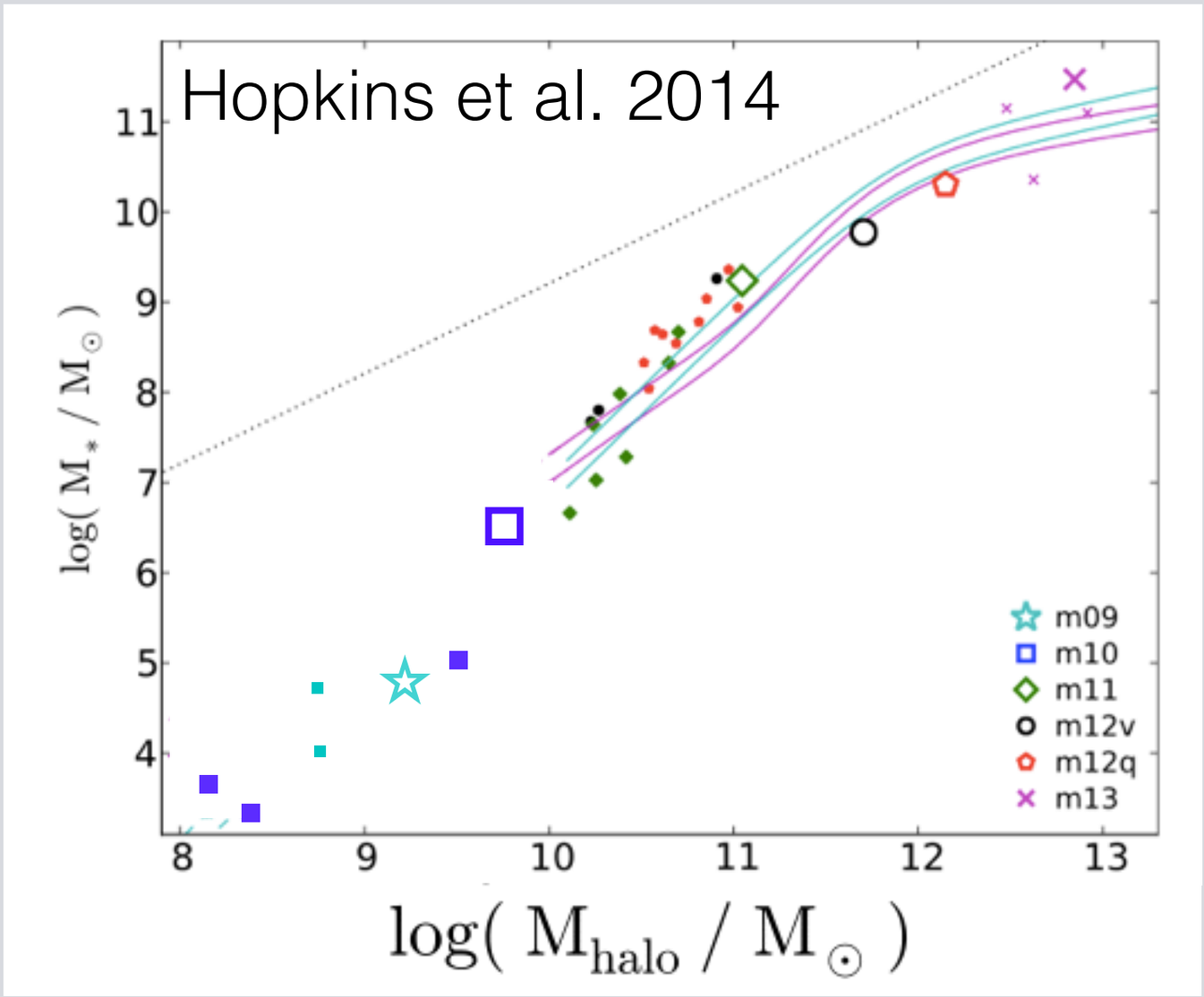


Photo-Ionization



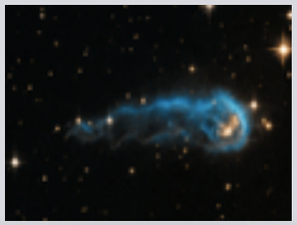
Supernovae: Impart energy & momentum directly into local SPH particles, never turn off cooling.



FIRE (Feedback In Realistic Environments)

HOPKINS, KERES, OÑORBE, FAUCHER-GIGUERE, QUATAERT, MURRAY, BULLOCK

Radiation pressure



Stellar winds

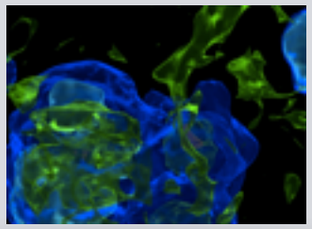
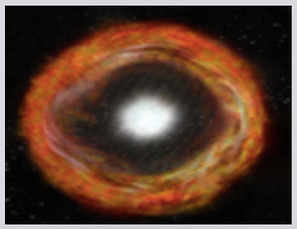


Photo-Ionization



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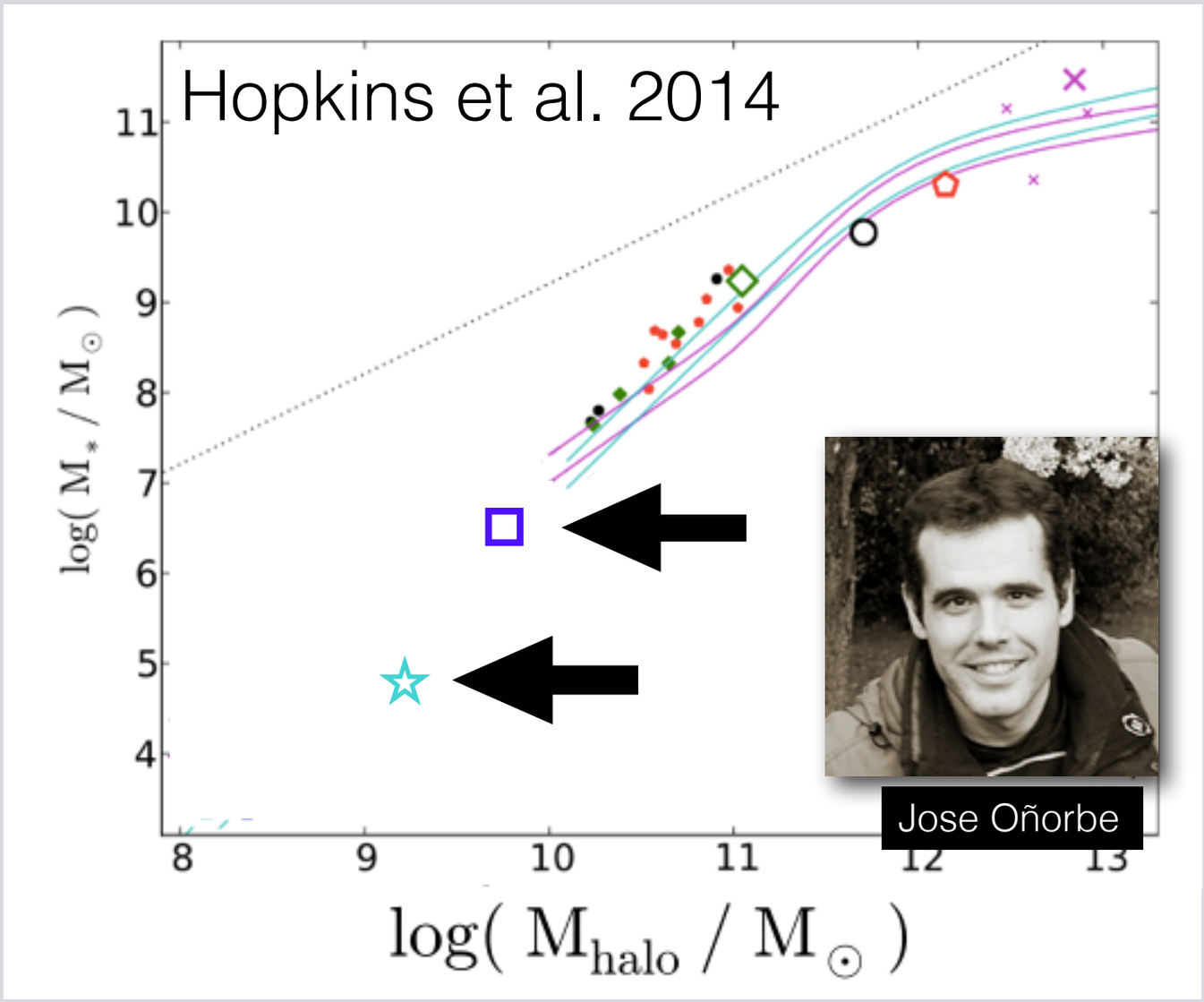
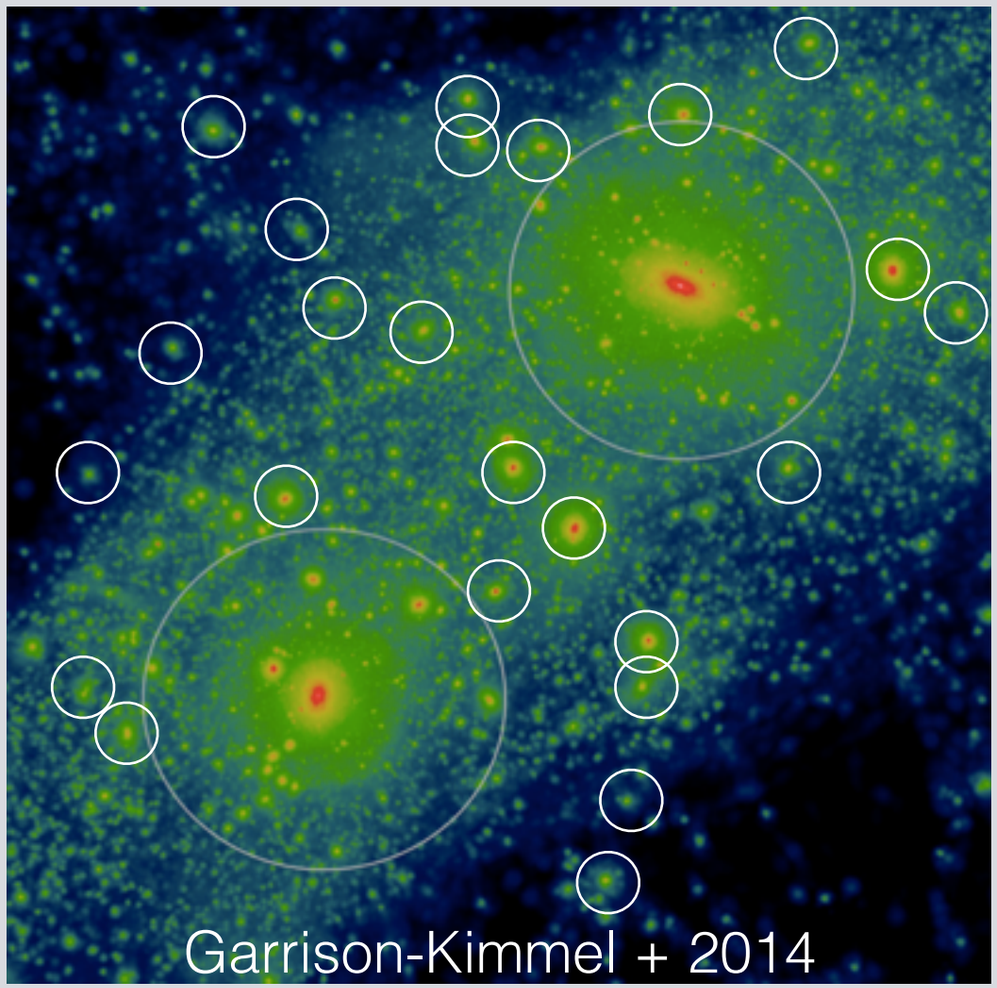


$$M_{HALO} = 10^{10}\ M_{\odot}$$

WHERE THINGS GET INTERESTING

$M_{HALO} = 10^{10}\ M_\odot$

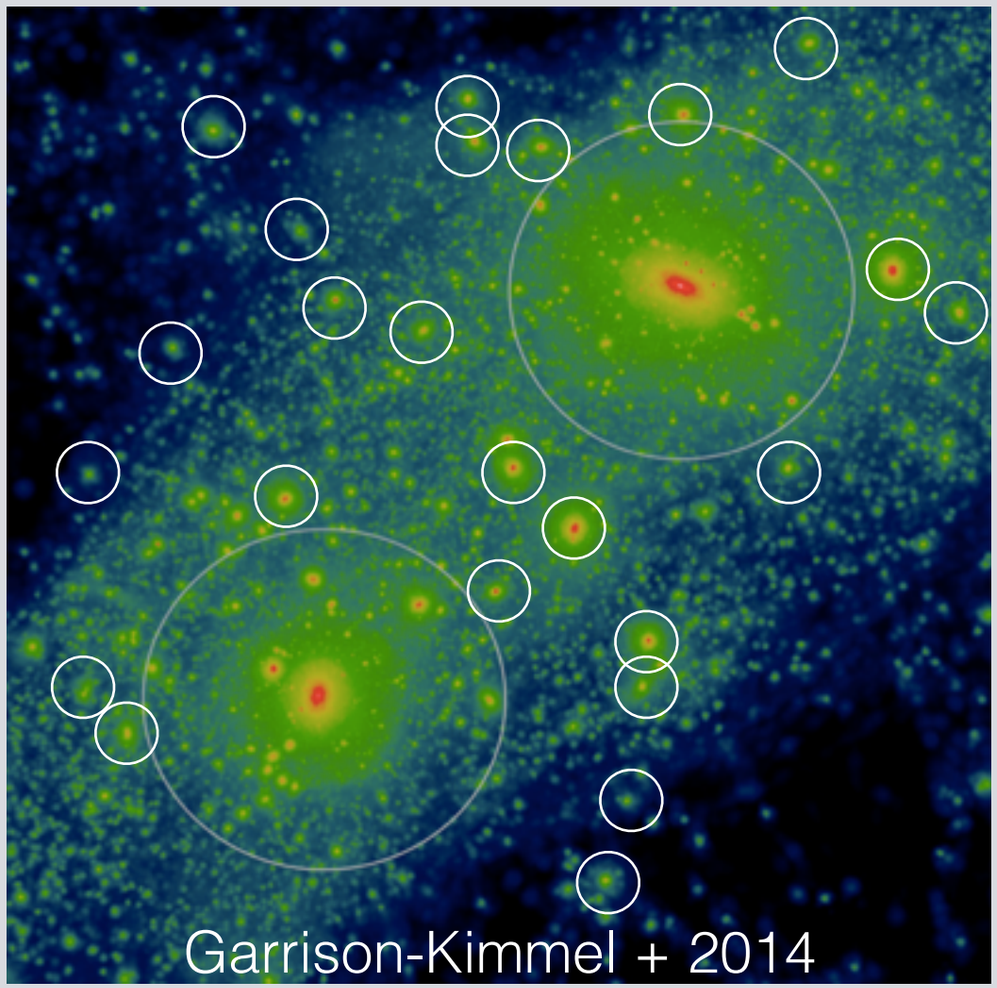
WHERE THINGS GET INTERESTING



Small enough to be abundant

$M_{HALO} = 10^{10}\ M_\odot$

WHERE THINGS GET INTERESTING



Garrison-Kimmel + 2014

Expect 10-20 within ~3Mpc of LG
[excluding subhalos of M31 or MW]

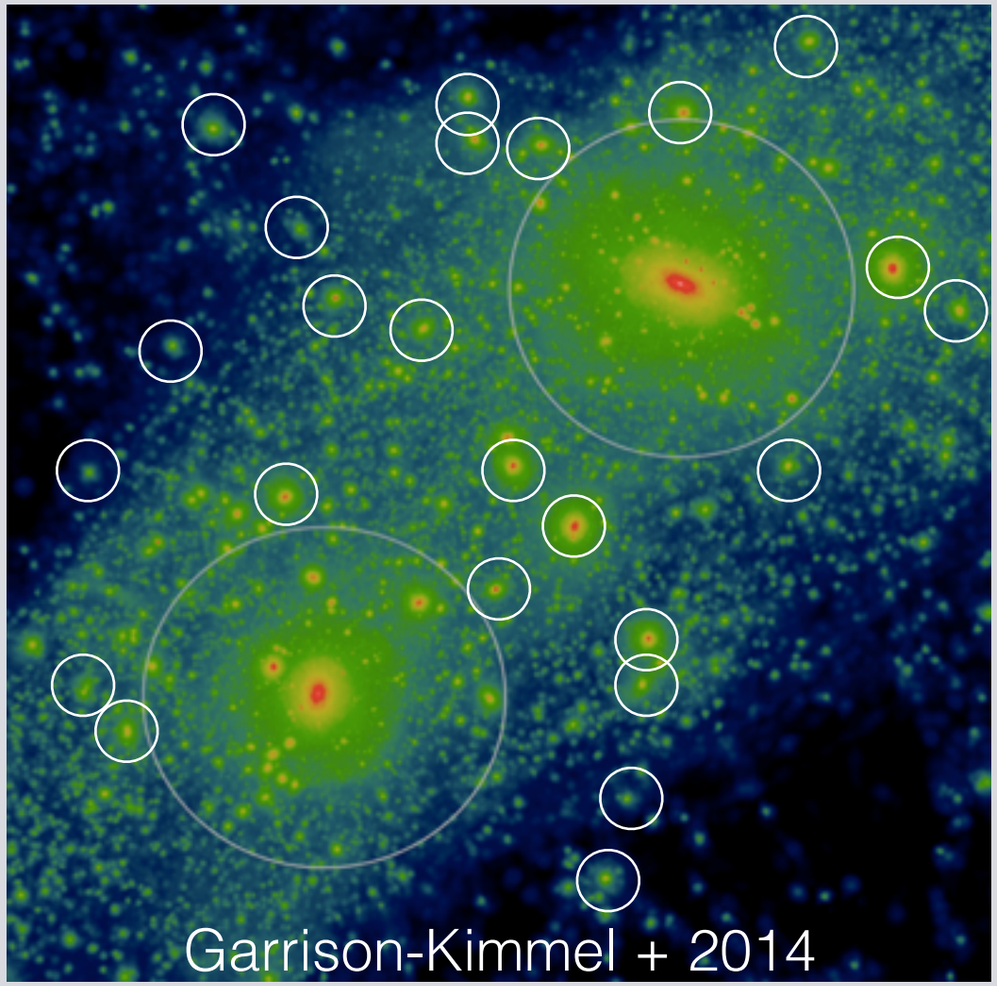
4 galaxies with $M_\star > 10^7\ M_\odot$ in this volume.

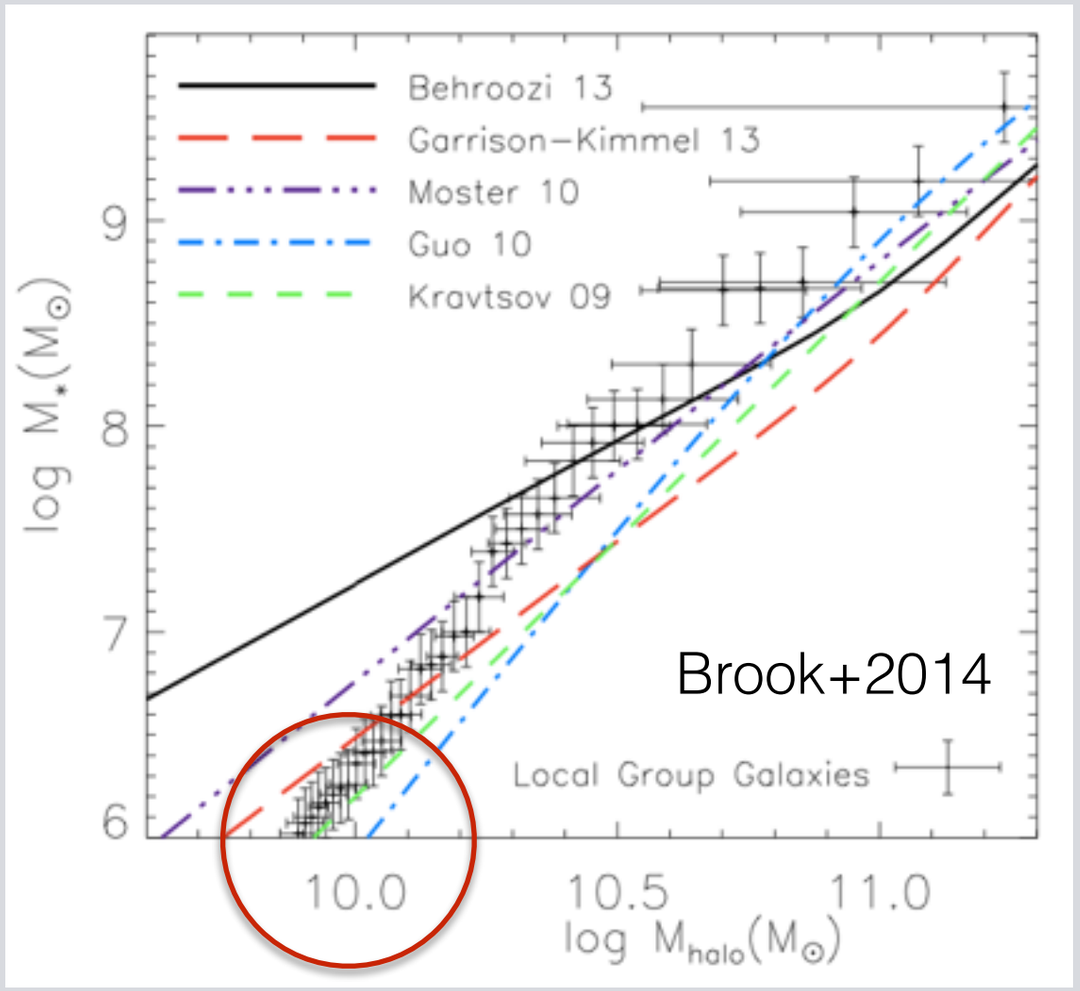
10 galaxies with $M_\star > 10^6\ M_\odot$ in this volume.

Small enough to be abundant

$M_{HALO} = 10^{10}\ M_\odot$

WHERE THINGS GET INTERESTING



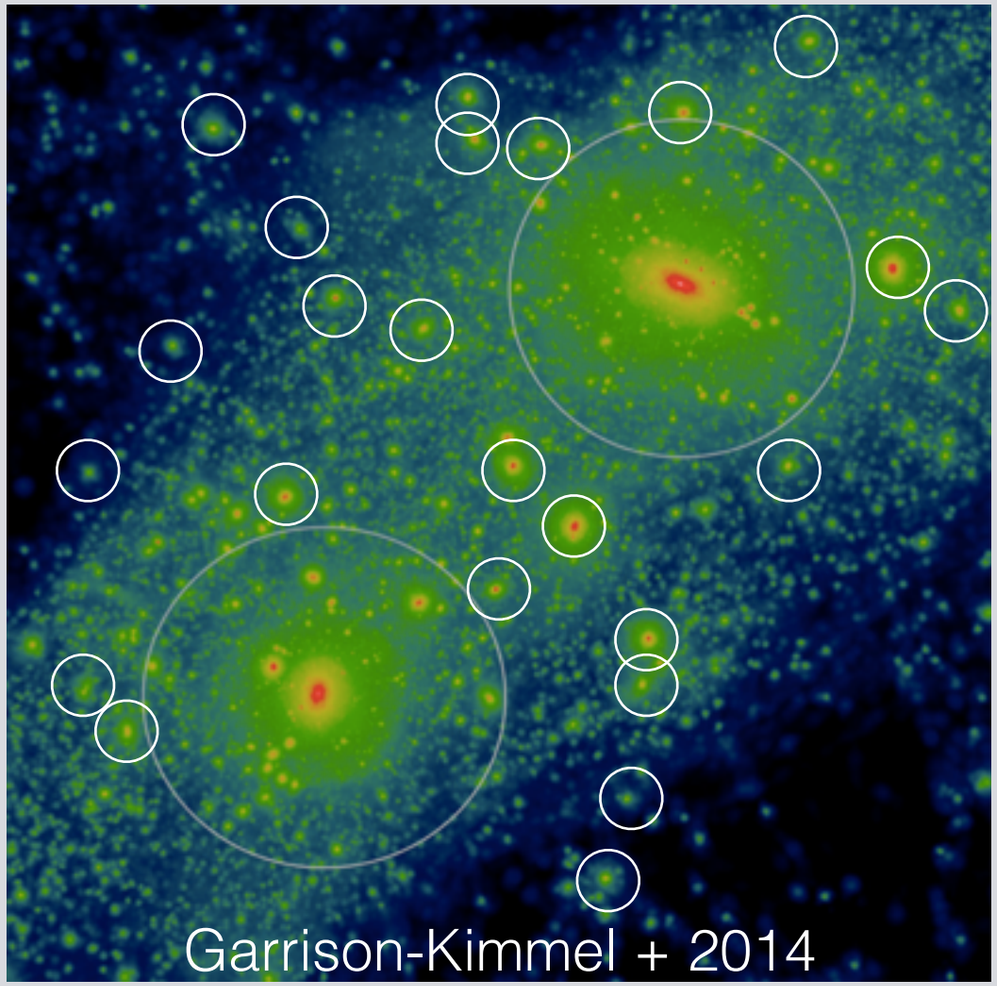


Small enough to be abundant

$M_{HALO}=10^{10}M_\odot \Leftrightarrow M_\star \sim 10^6\ M_\odot$

$M_{HALO} = 10^{10}\ M_\odot$

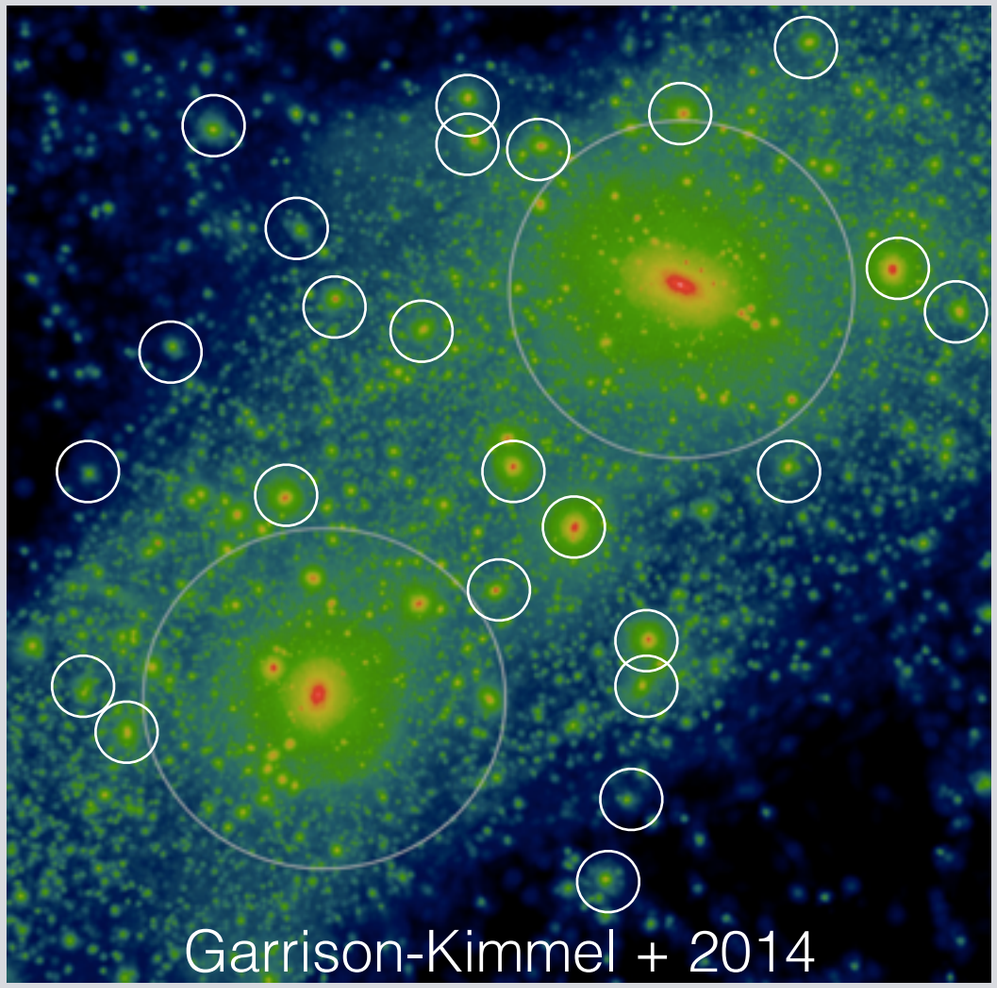
WHERE THINGS GET INTERESTING

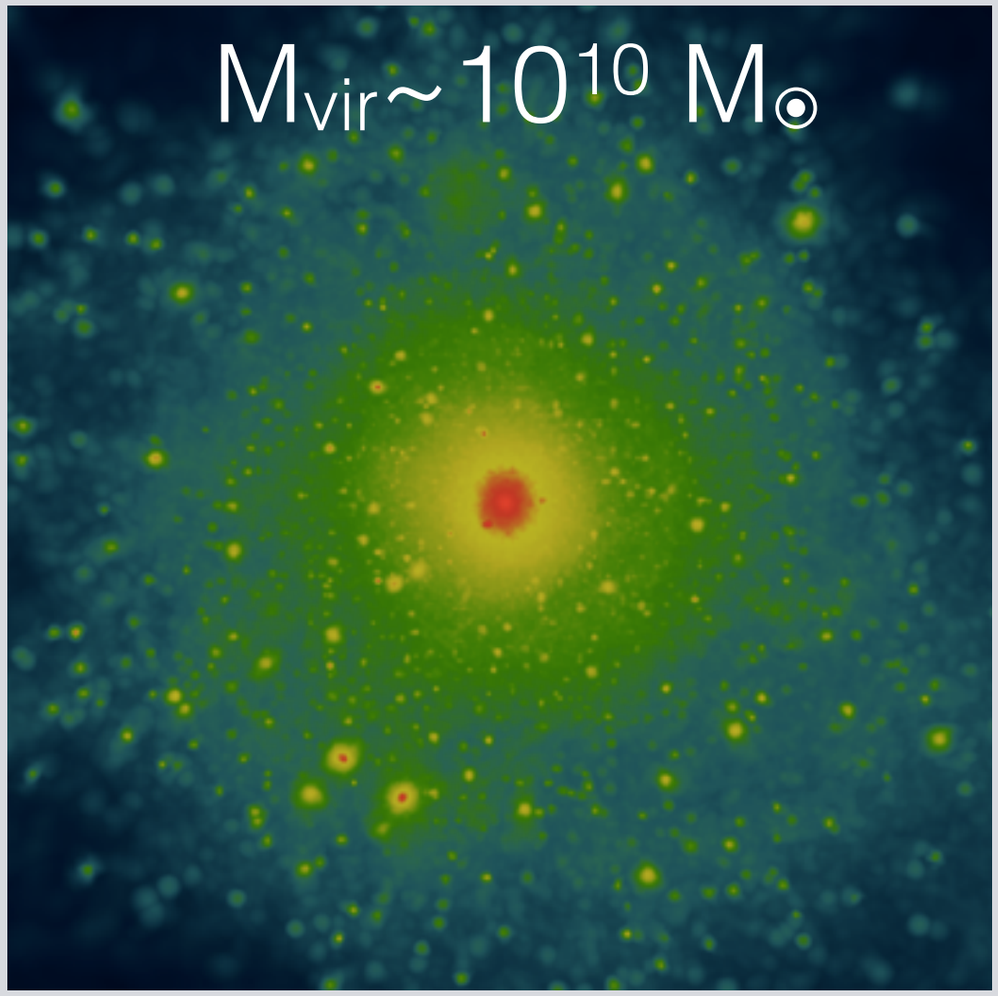


Small enough to be abundant
($M_\star \sim 10^6\ M_\odot$)

$M_{HALO} = 10^{10}\ M_\odot$

WHERE THINGS GET INTERESTING



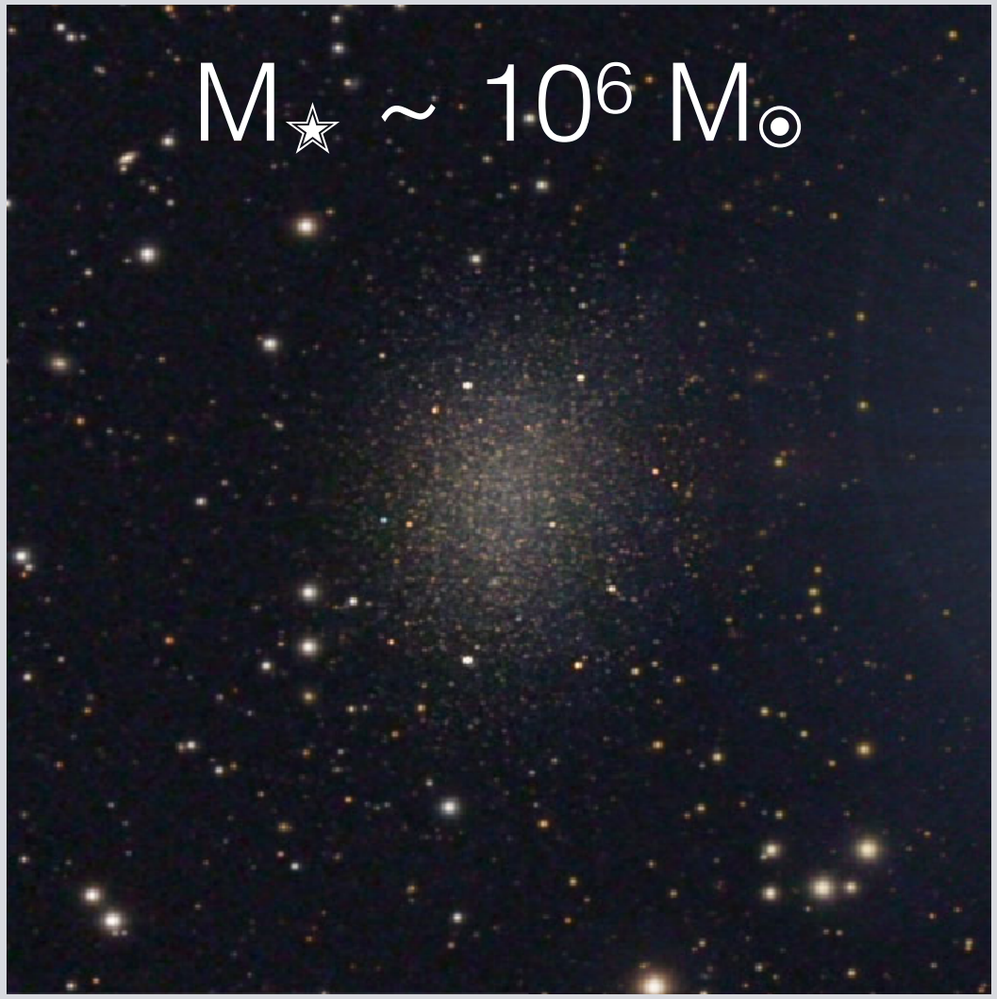


Small enough to be abundant
($M_\star \sim 10^6\ M_\odot$)

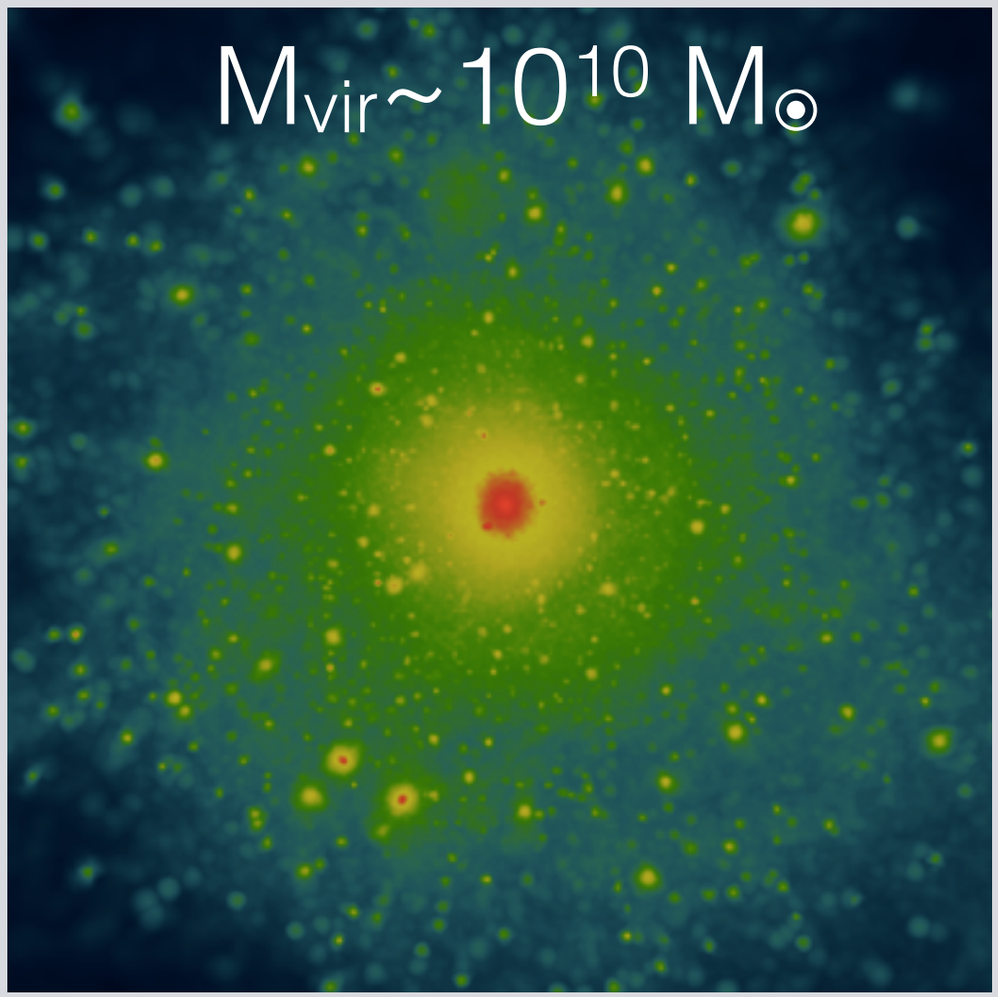
Big Enough to be dense
$V_{MAX} = 40$ km/s

$M_{HALO} = 10^{10}\ M_\odot$

WHERE THINGS GET INTERESTING



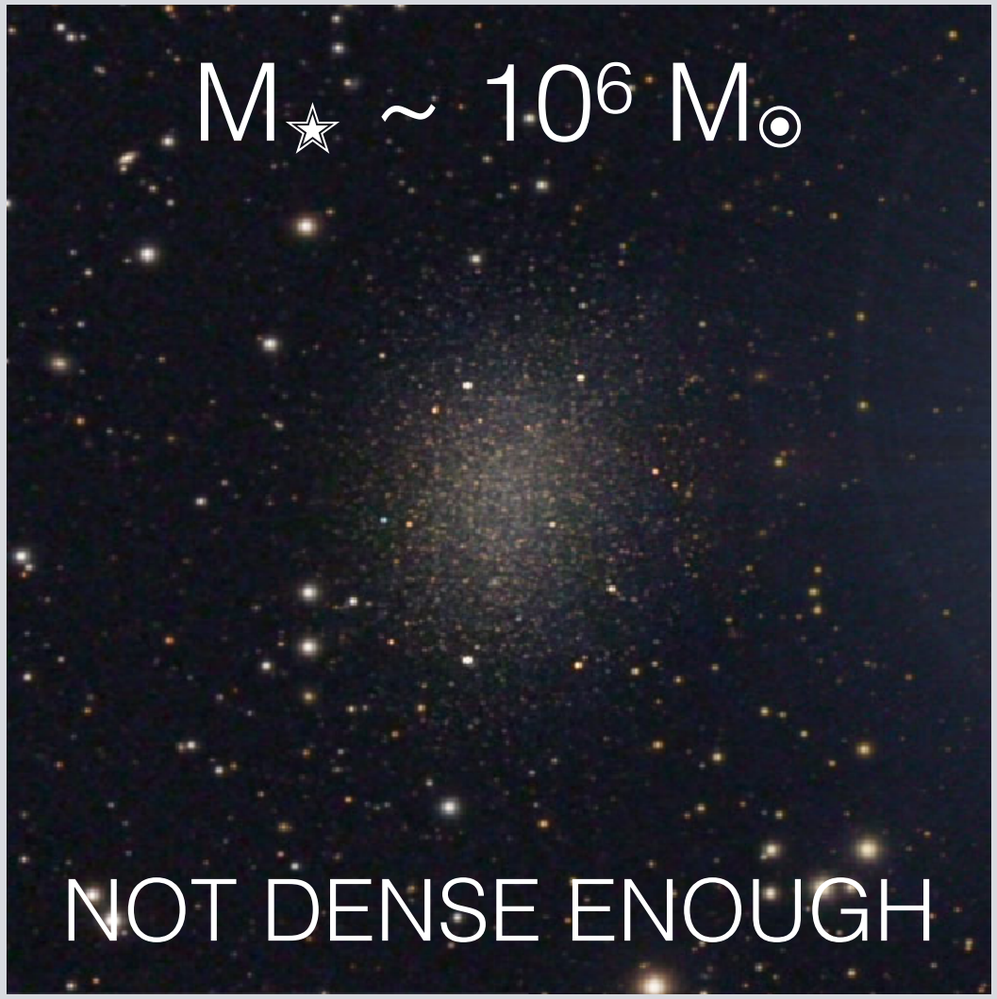
$\Longleftrightarrow$



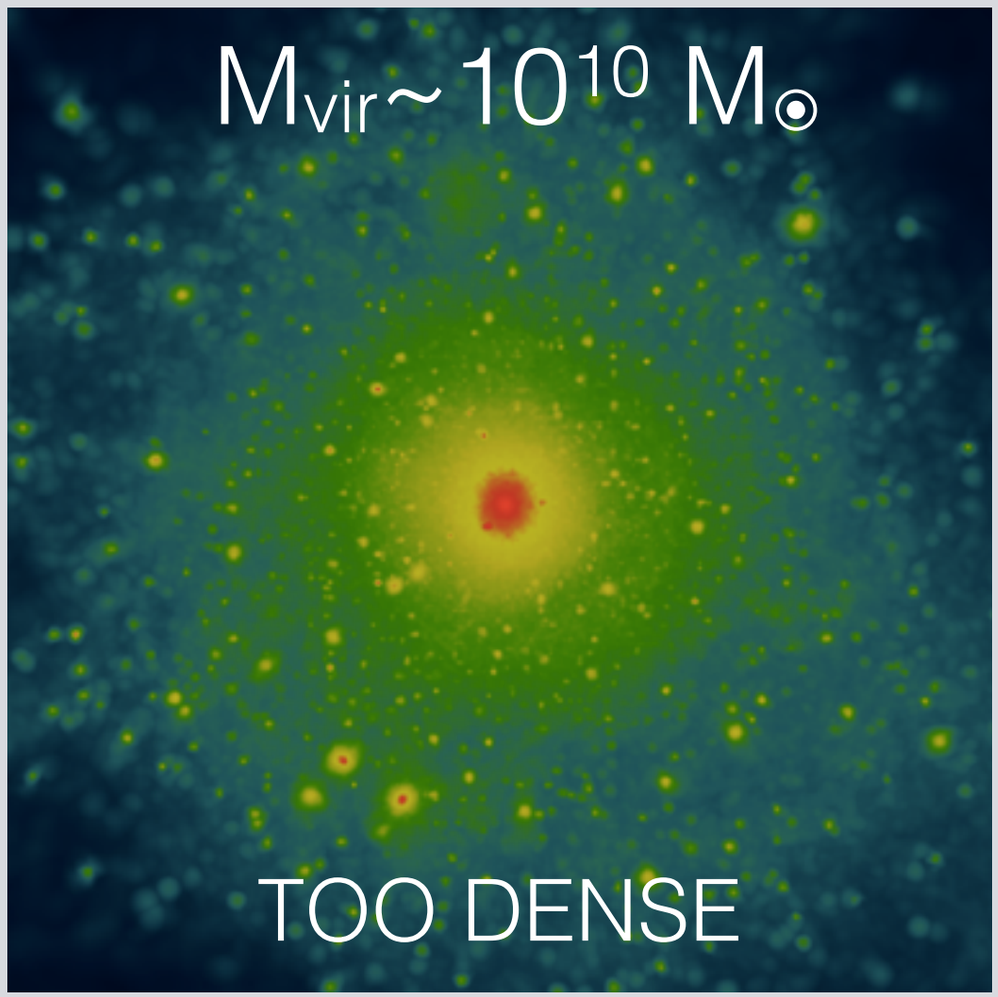
Massive enough that they should always form stars
(Too Big to Fail)

$M_{HALO} = 10^{10}\ M_\odot$

WHERE THINGS GET INTERESTING



$\Longleftrightarrow$



Massive enough that they should always form stars
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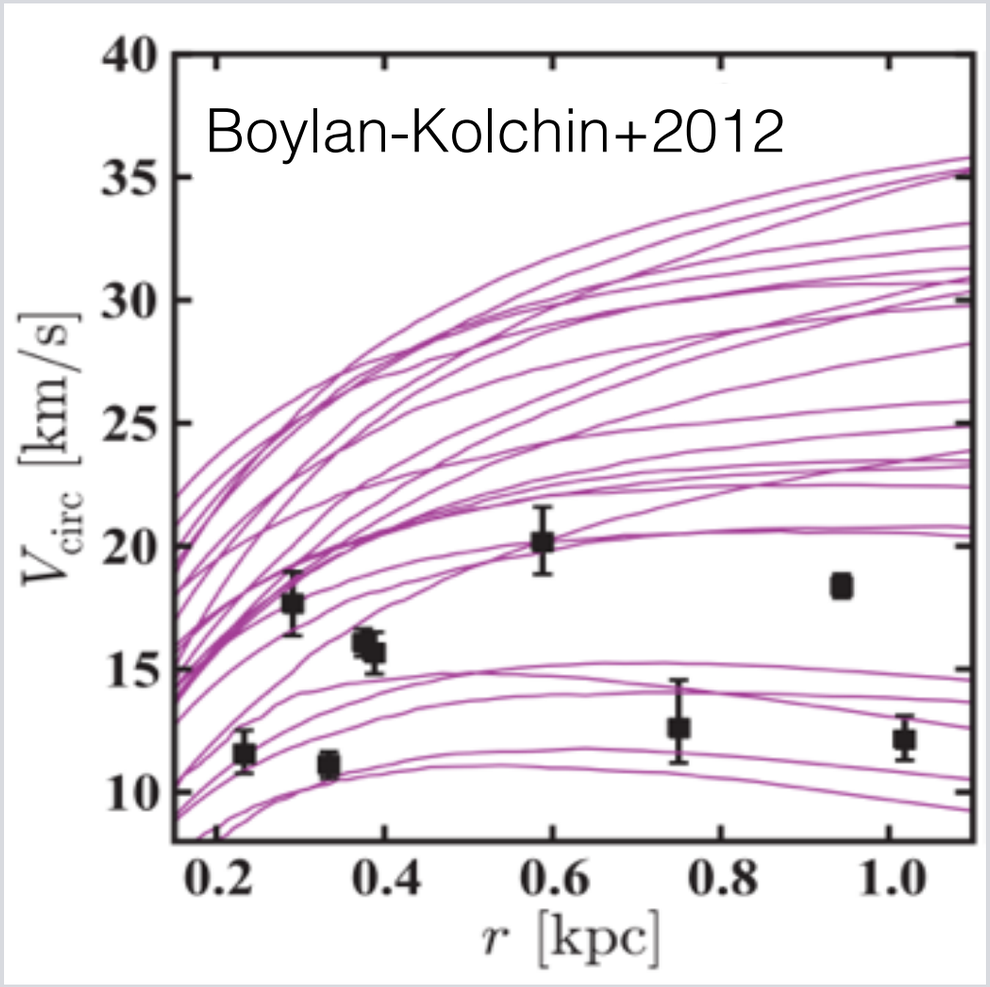
TOO BIG TO FAIL?

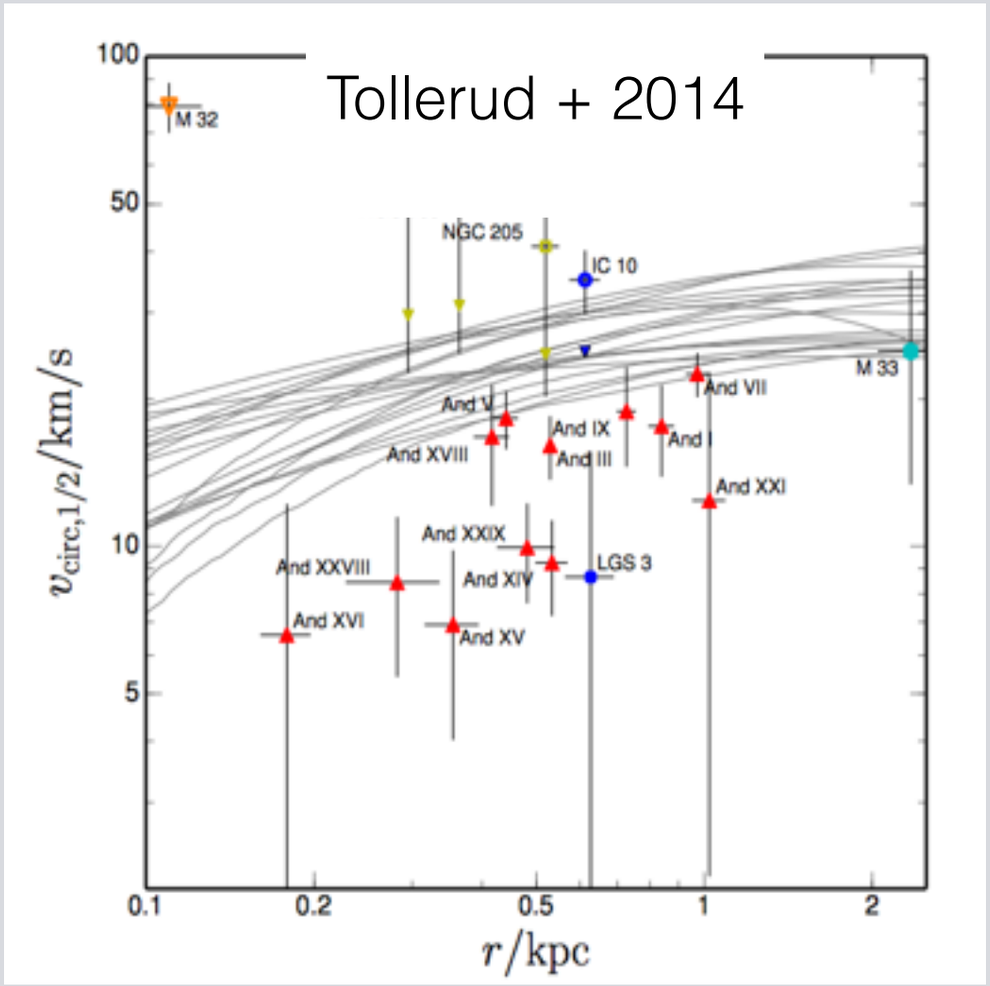
V_{MAX} ~ 40 km/s



↗ IN THE MILKY WAY

TOO BIG TO FAIL?

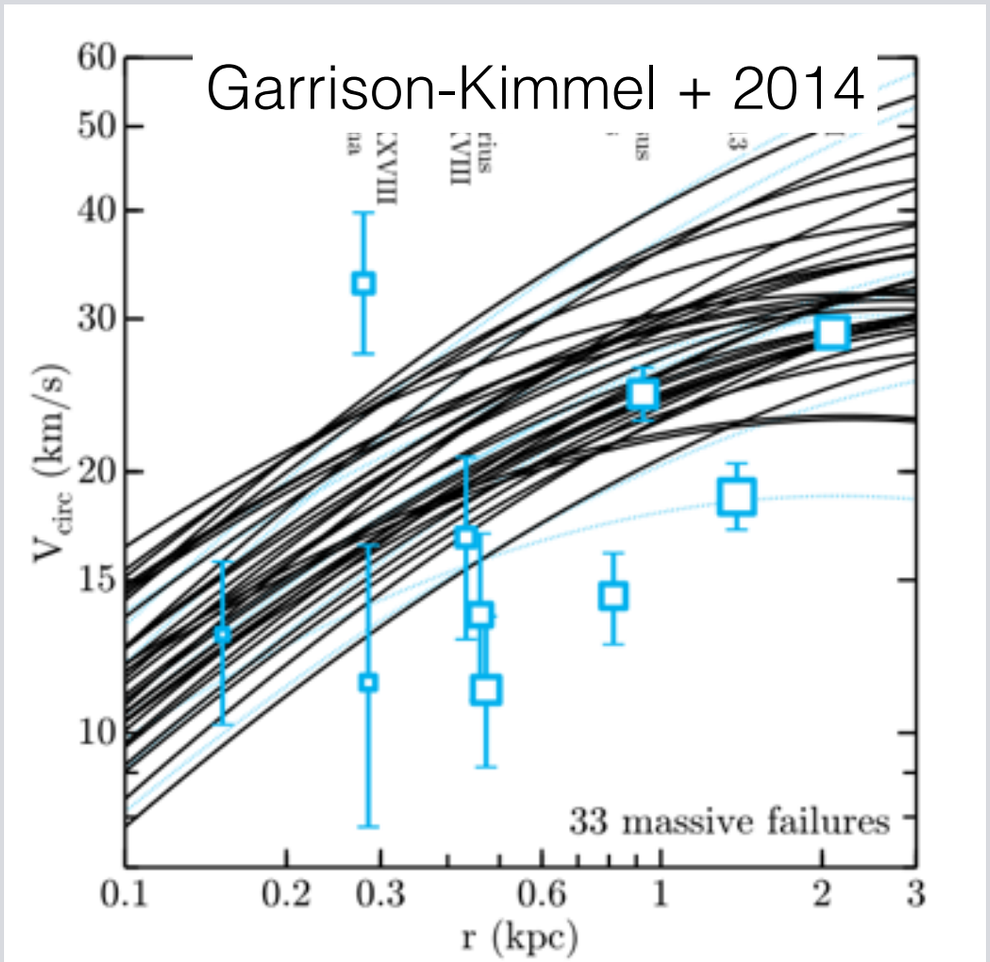
V_{MAX} ~ 40 km/s



☍ IN ANDROMEDA

TOO BIG TO FAIL?

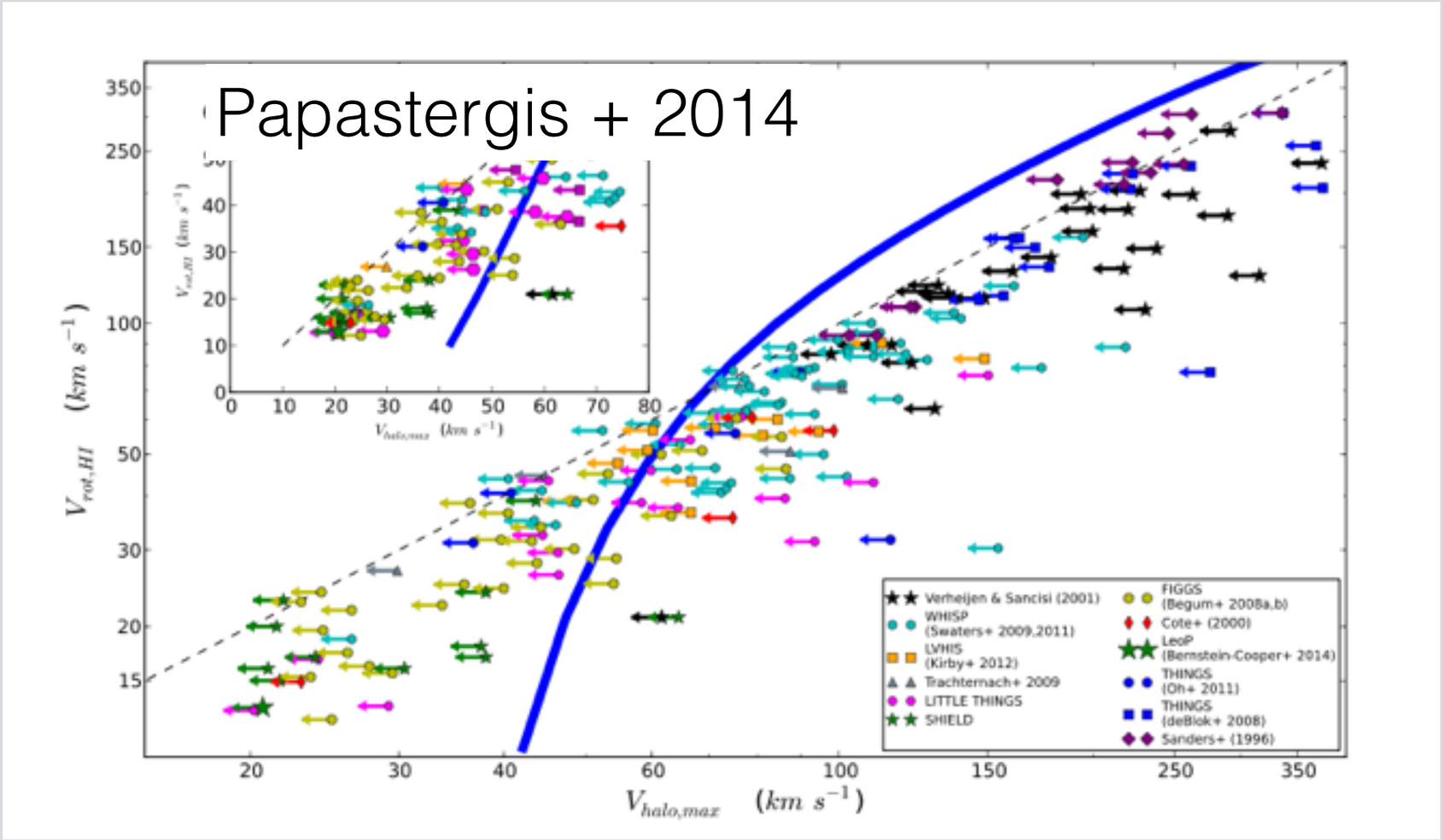
V_{MAX} ~ 40 km/s



IN THE OUTER LOCAL GROUP

TOO BIG TO FAIL?

V_{MAX} ~ 40 km/s

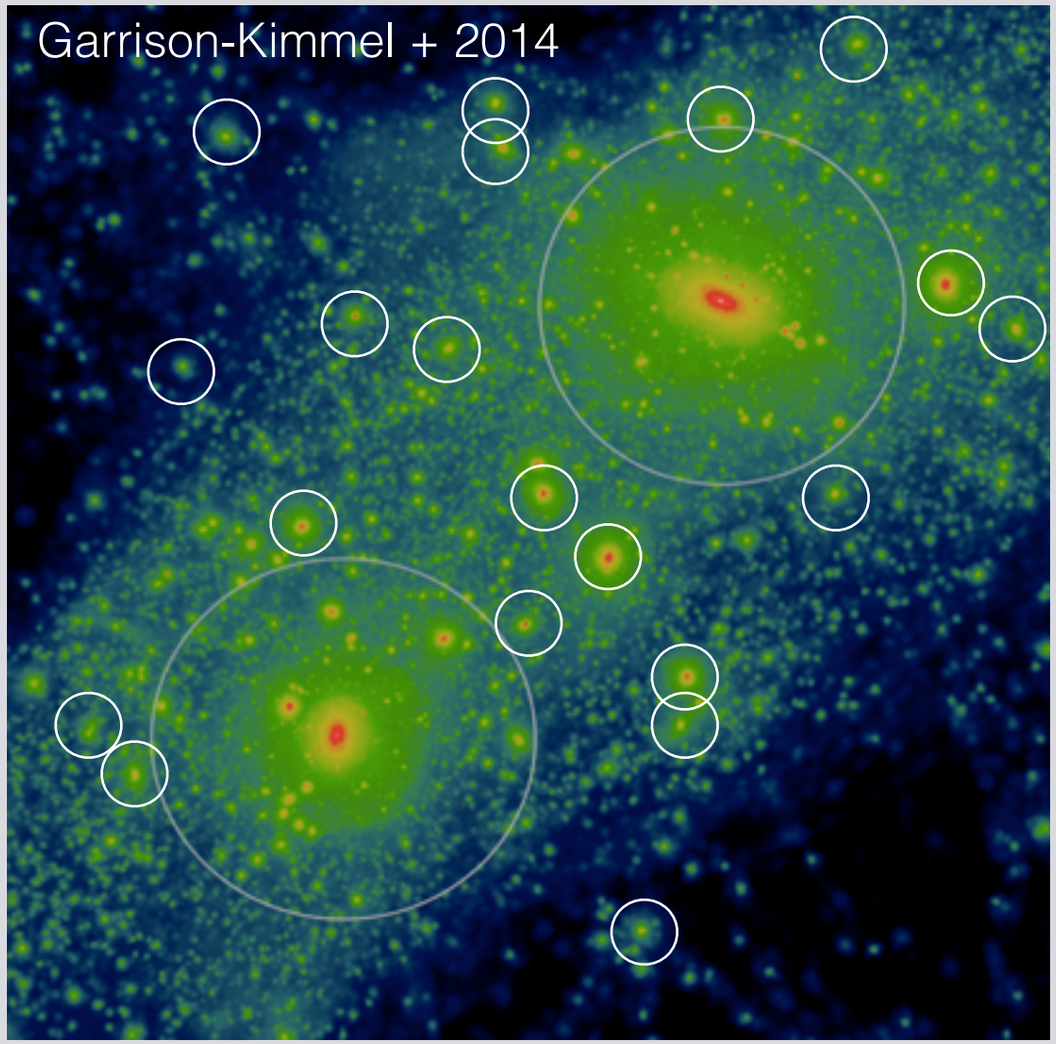


⬠ IN THE FIELD

ALSO: Klypin+2014; Ferrero+ 2012

TOO BIG TO FAIL?

V_{MAX} ~ 40 km/s

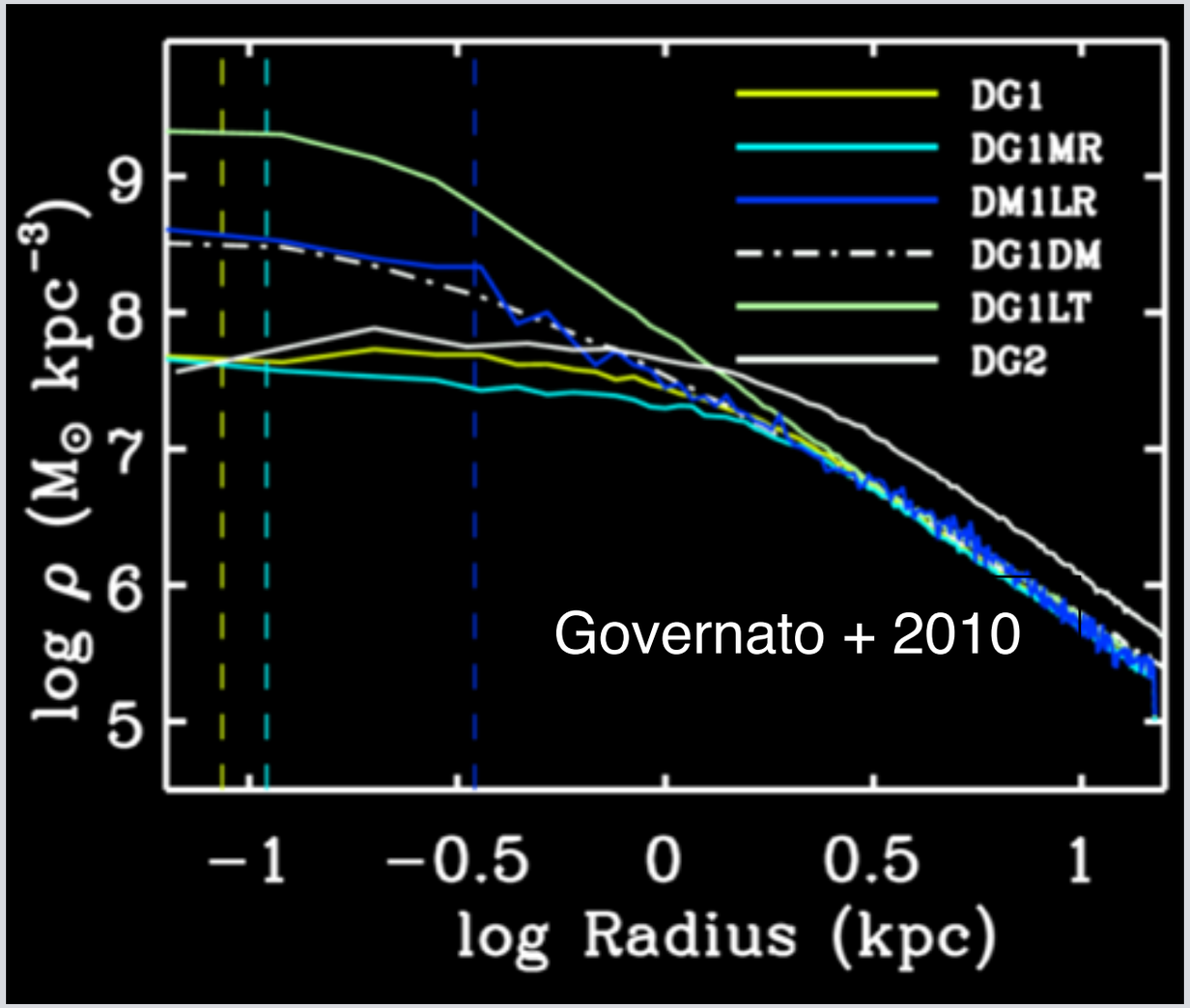


Past suggestions:
- Environment
- Statistical flukes
- Milky Way mass

All of these are unsatisfying in the face of growing ubiquity of the problem

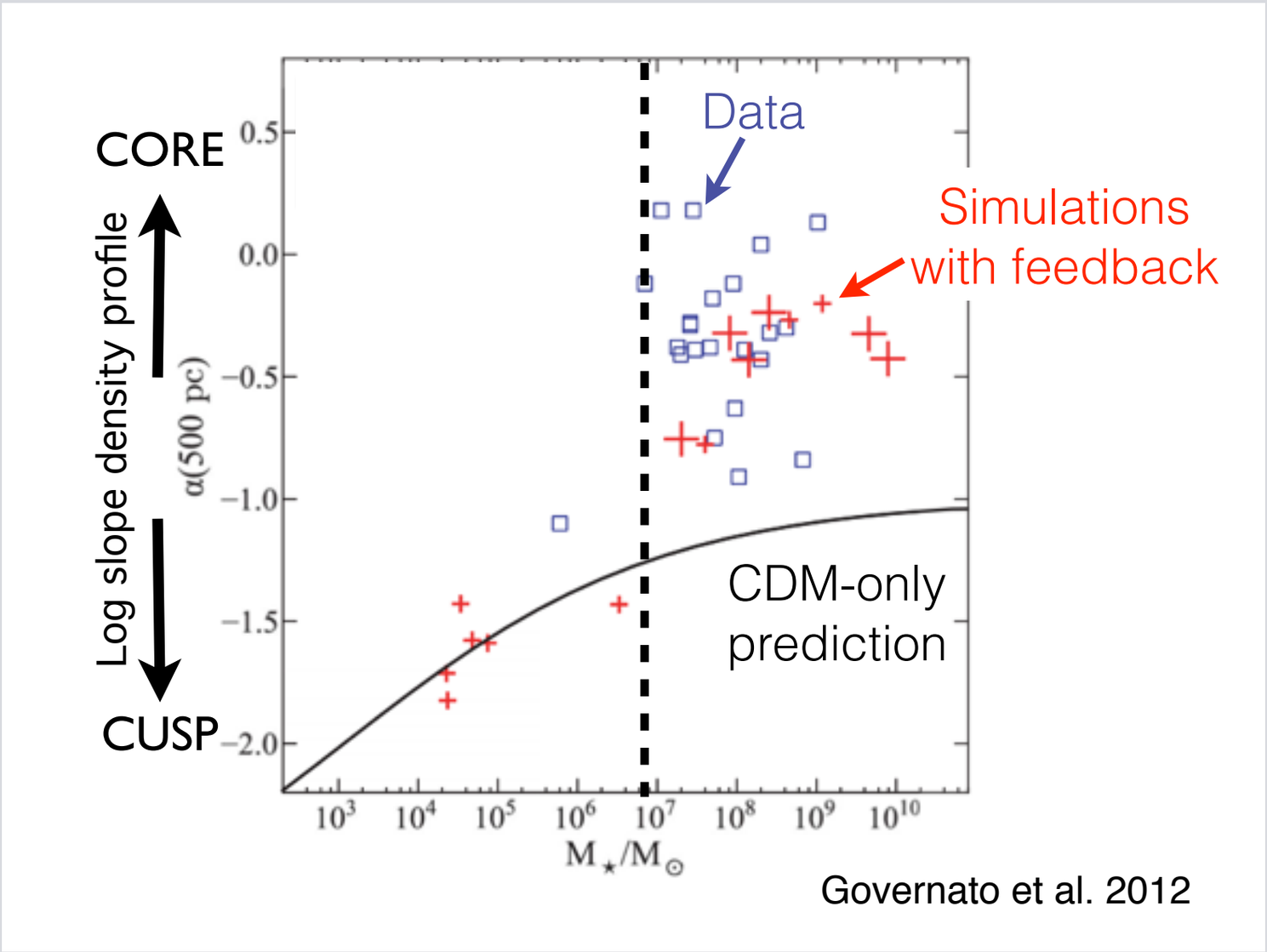
WHAT ABOUT FEEDBACK?

NAVARRO ET AL. 1996



WHAT ABOUT FEEDBACK?

CAN $M_\star \sim 10^6\ M_\odot$ GALAXIES DO IT?



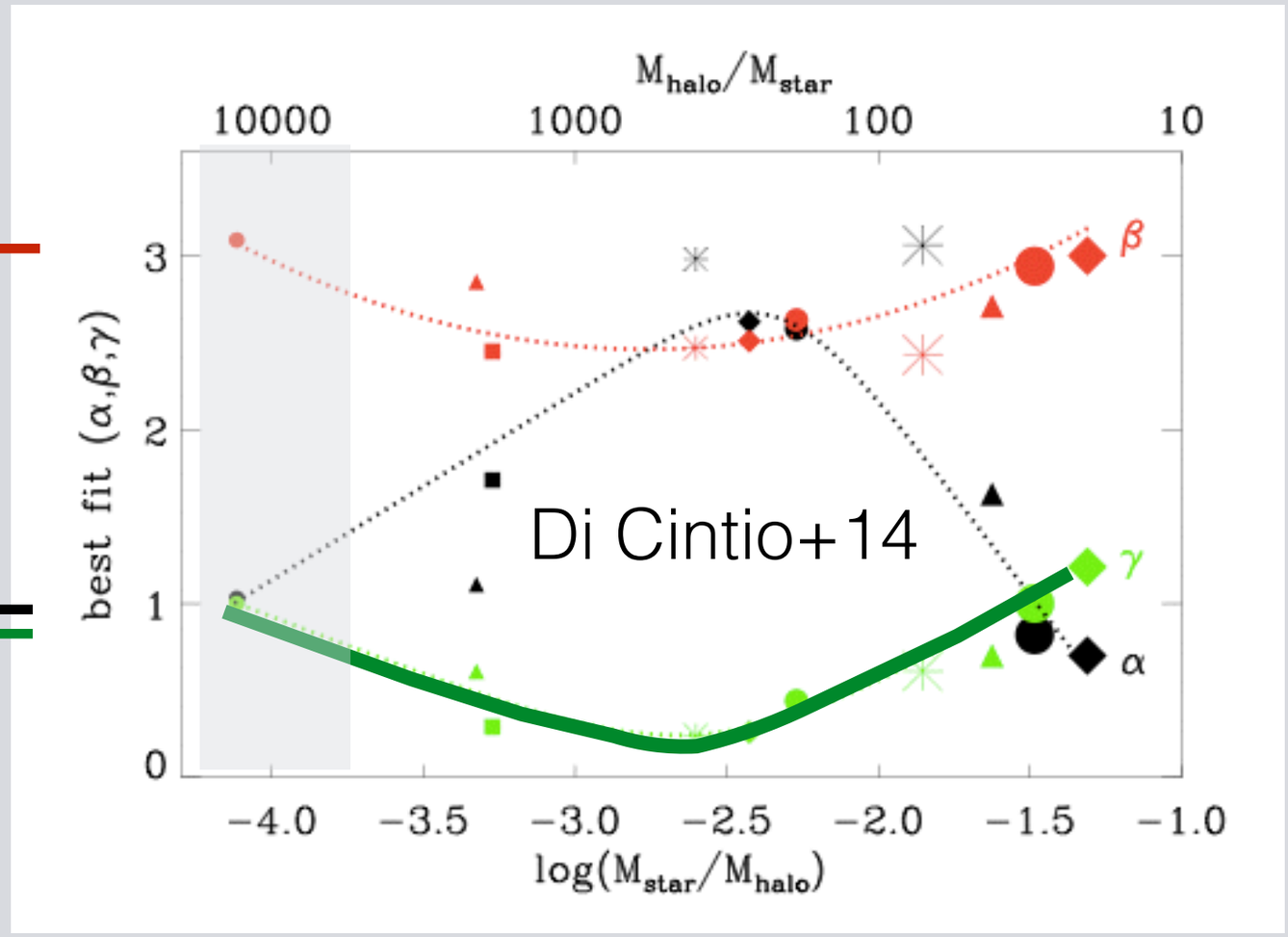
Governato et al. 2012

Penarrubia+2012; Garrison-Kimmel+2013

WHAT ABOUT FEEDBACK?

CAN $M_\star \sim 10^6\ M_\odot$ GALAXIES DO IT?

NFW values



Penarrubia+2012; Garrison-Kimmel+2013

Jose Oñorbe

DWARF GALAXIES ON FIRE

OÑORBE, BOYLAN-KOLCHIN, JSB, HOPKINS, KERES

m_{dm} ~ 1000 $M_\odot$

m_{gas} ~ 250 $M_\odot$

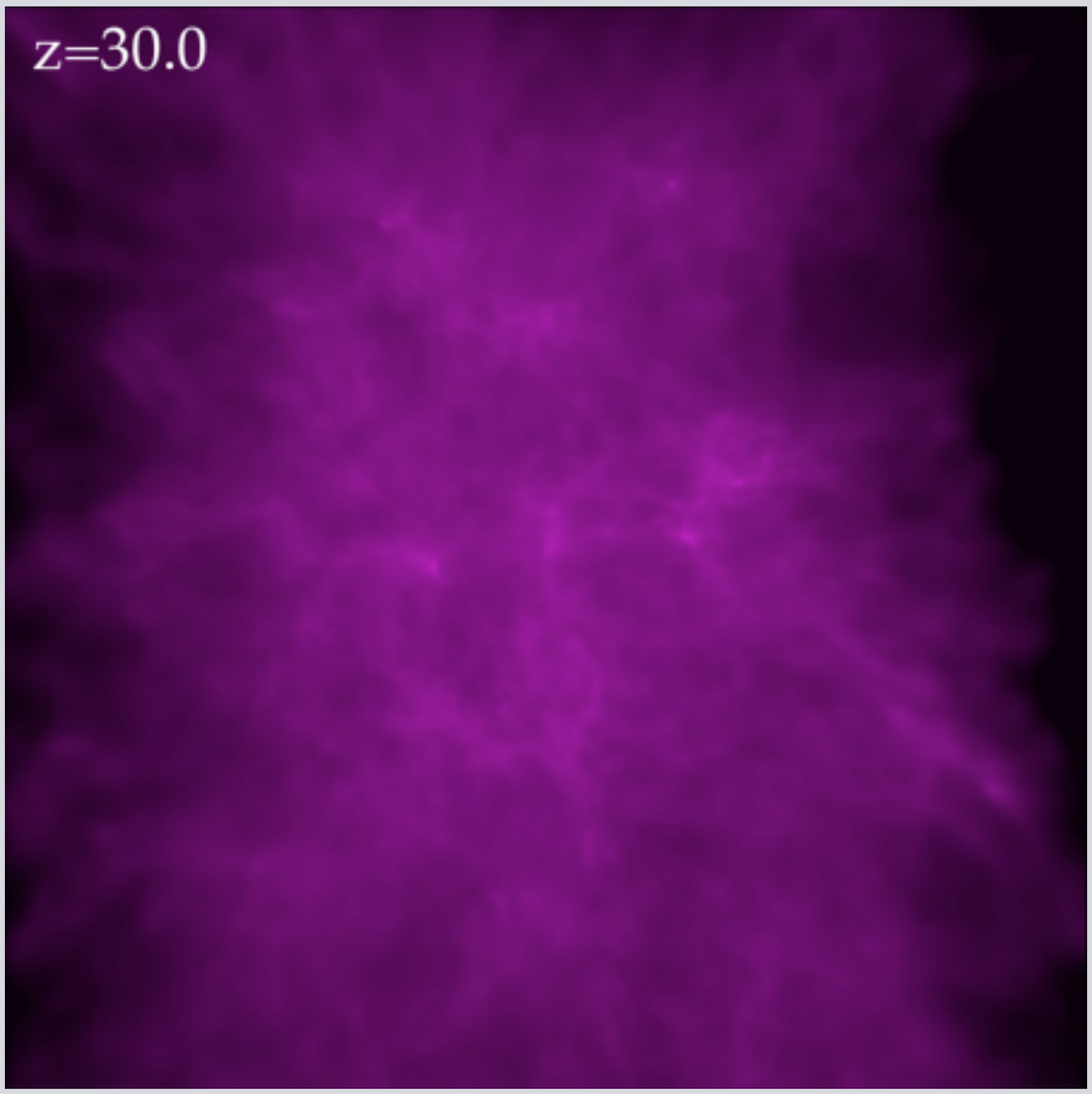
f_{res} ~ 25pc

<u>3 Dwarf Runs</u>:

- $M_{HALO}=10^{10}$ $M_\odot$
- Identical ICs
- Small changes to subgrid energy injection method
- $M_\star \sim 10^6$ $M_\odot$

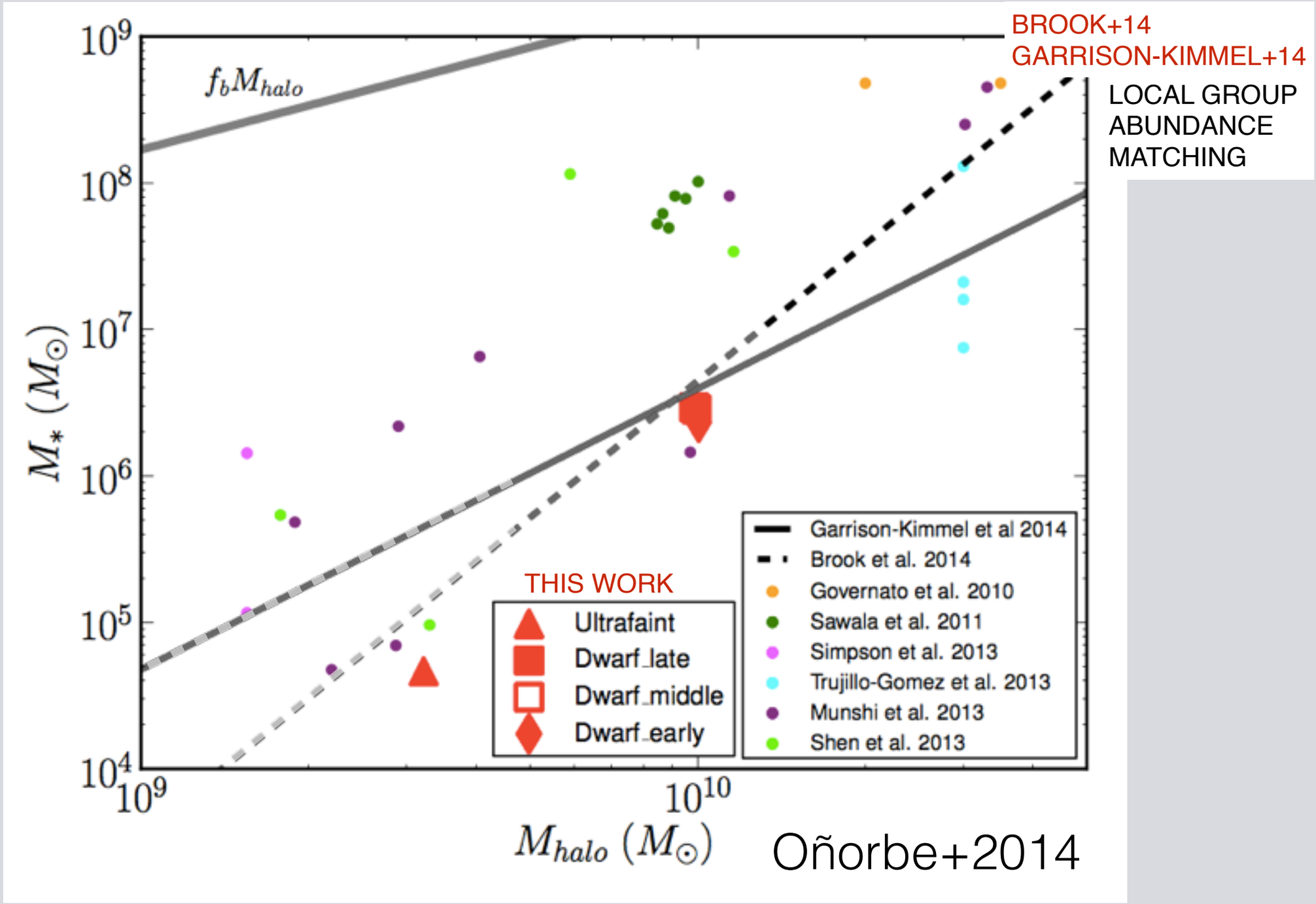
1 <u>Ultrafaint Dwarf Run</u>:

- $M_{HALO}=3.10^9$ $M_\odot$
- $M_\star \sim 10^4$ $M_\odot$



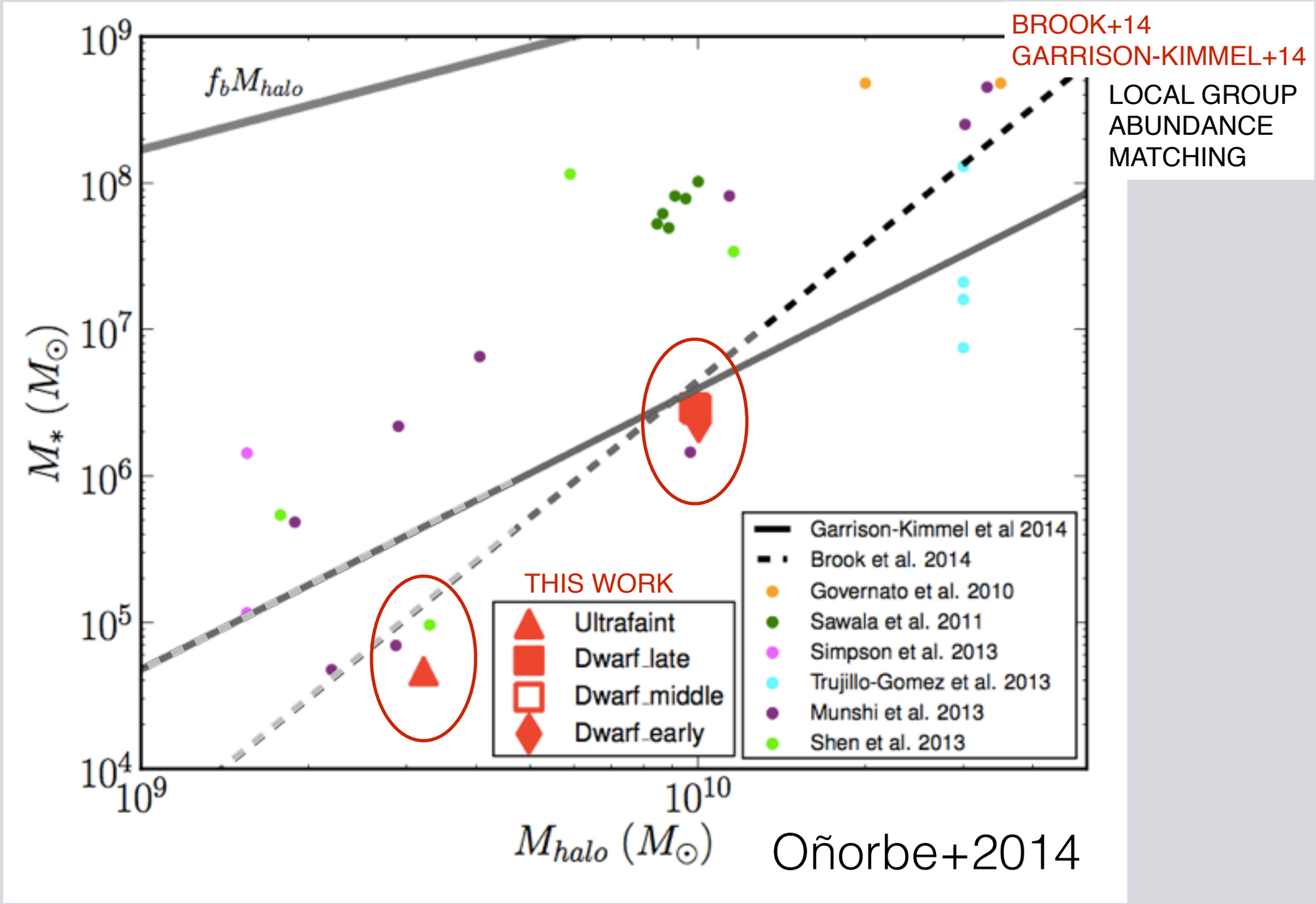
HOPKINS

$M_\star$ vs. M_{HALO}



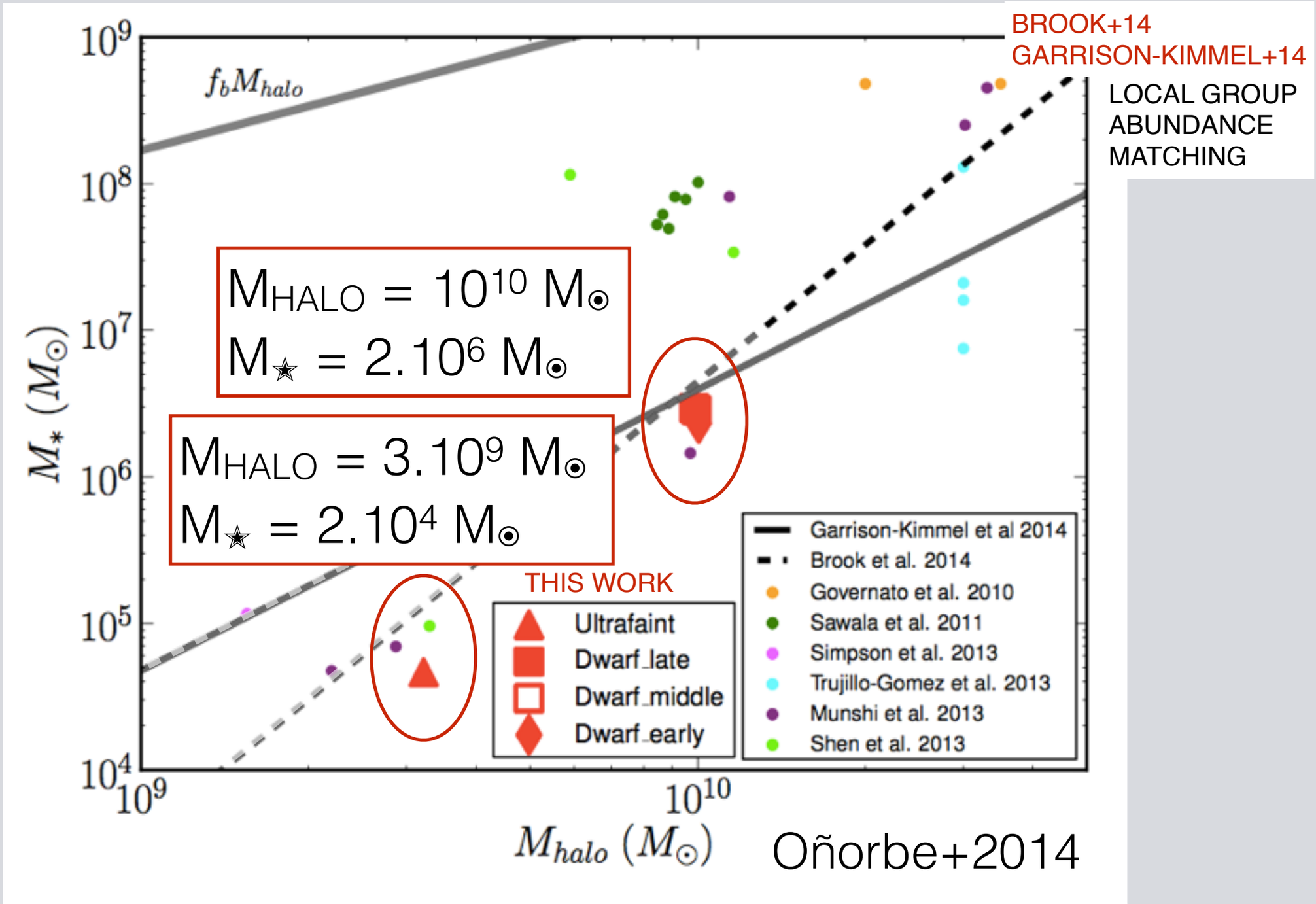
Oñorbe+2014

$M_\star$ vs. M_{HALO}



Oñorbe+2014

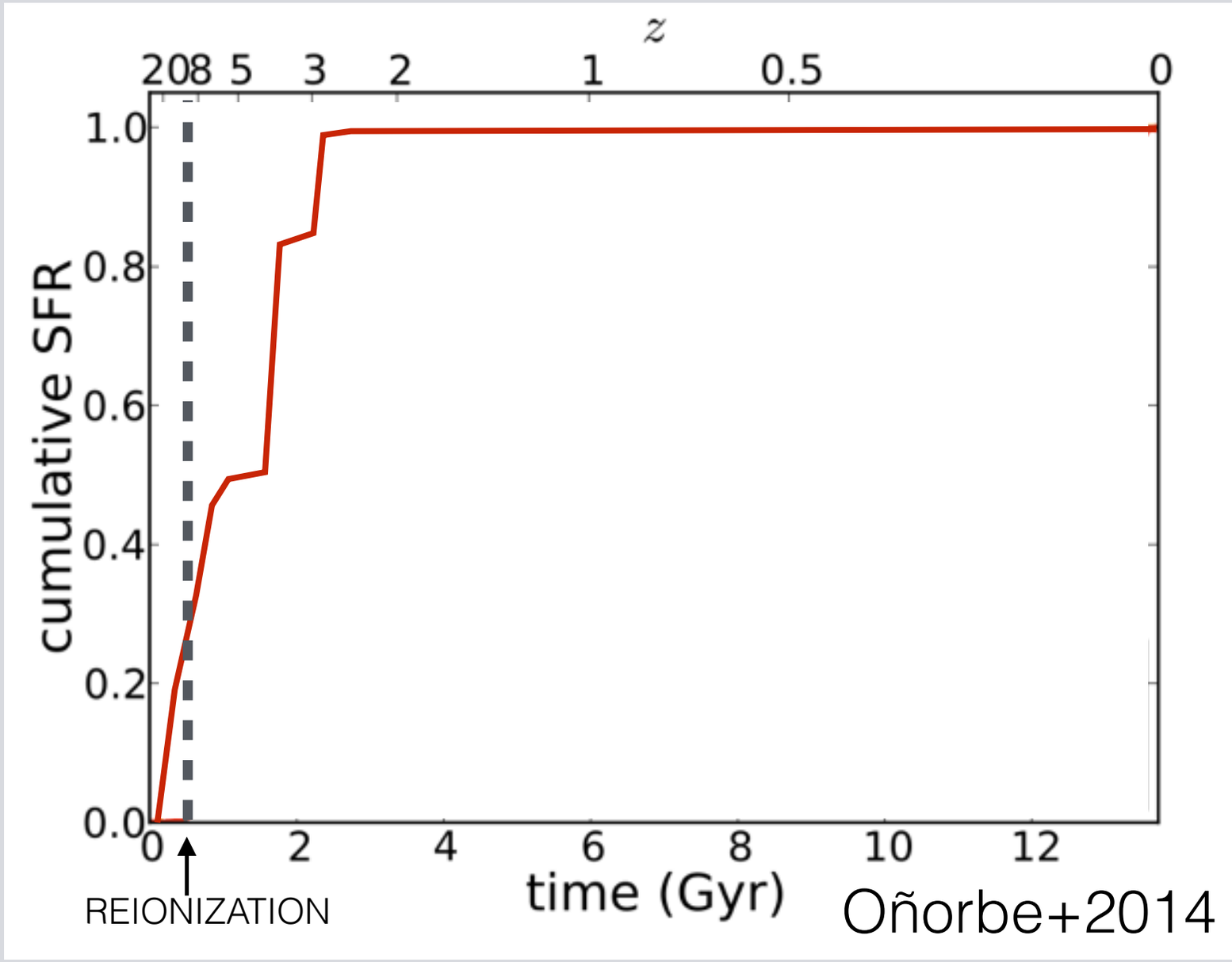
$M_\star$ vs. M_{HALO}



Oñorbe+2014

ULTRA-FAINT SFH

$M_{HALO}=3.10^9\ M_\odot$ $M_\star=2.10^4\ M_\odot$



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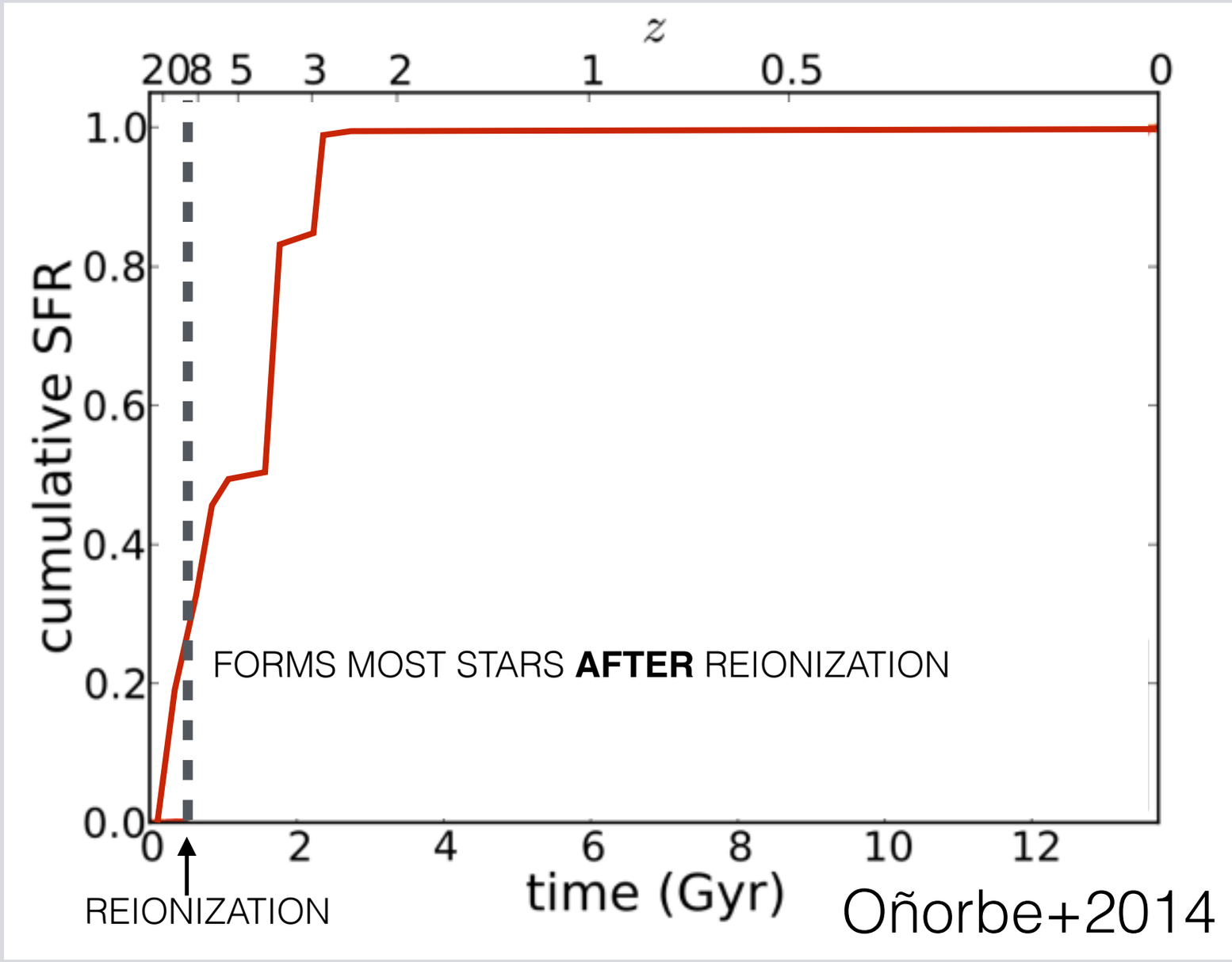

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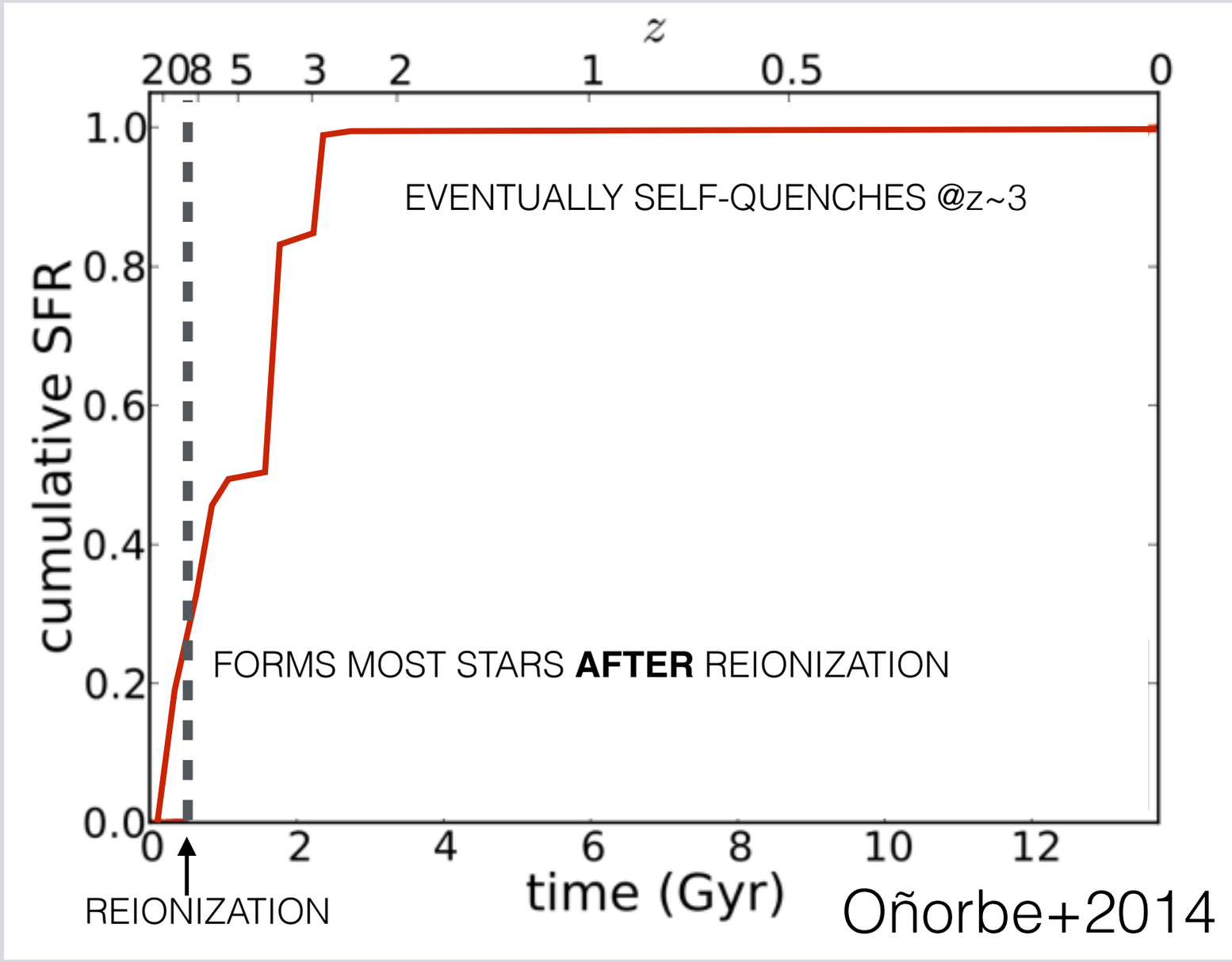
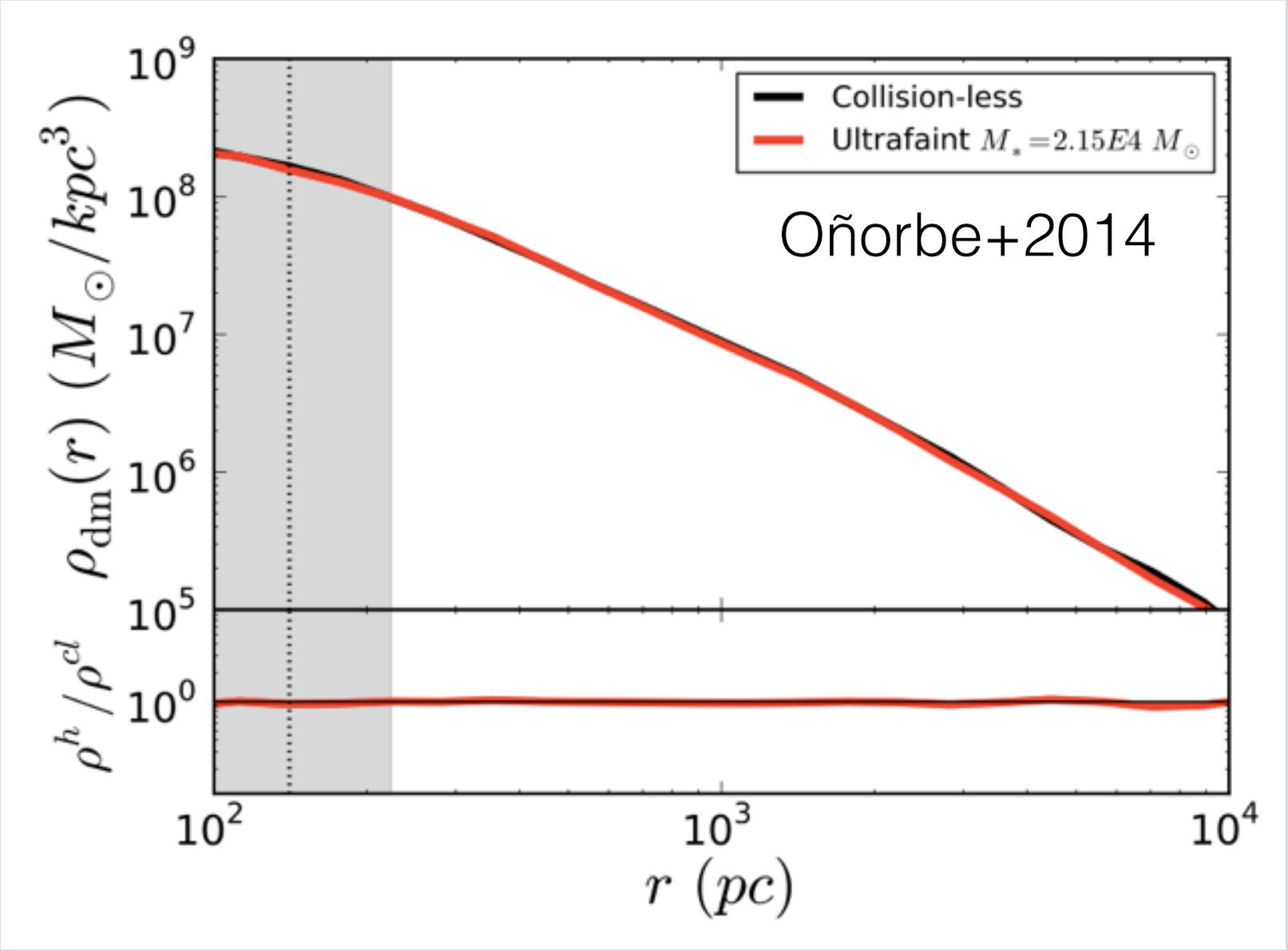


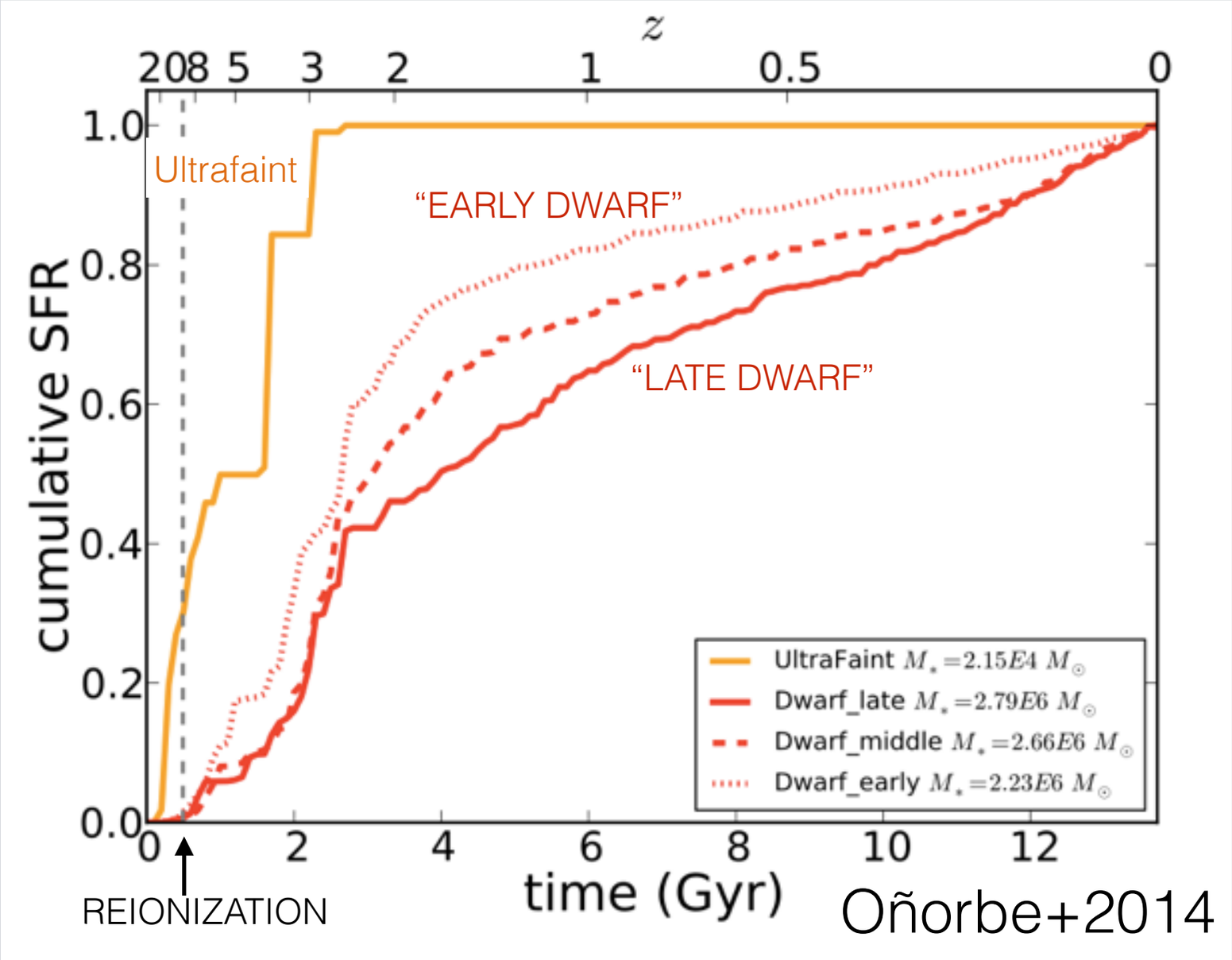
ULTRA-FAINT: DM HALO SAME AS N-BODY

$M_{HALO}=3.10^9\ M_\odot$ $M_\star=2.10^4\ M_\odot$



DWARF SFHs

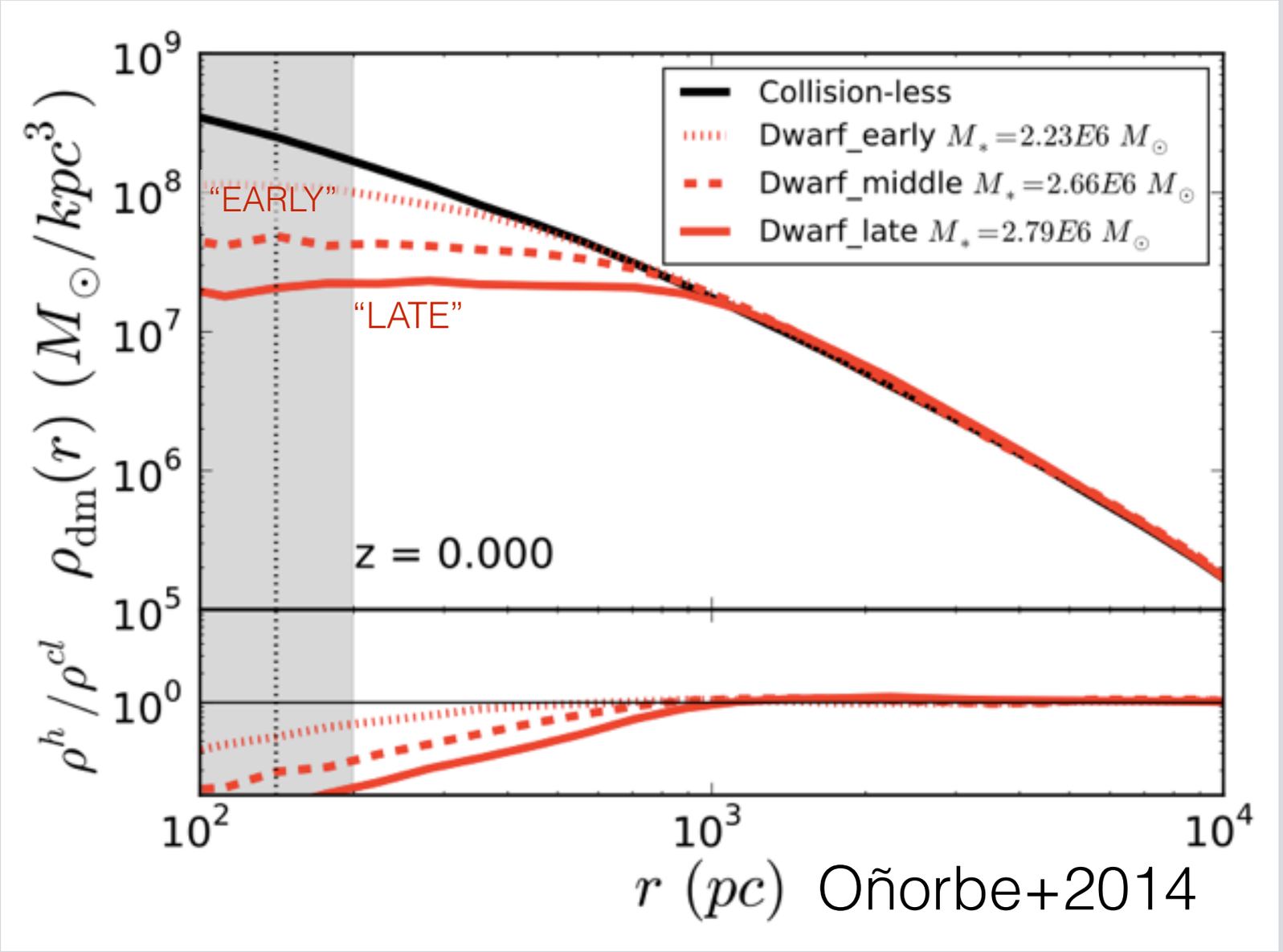
$M_{HALO}=10^{10}\ M_\odot$ $M_\star=(2.2\text{-}2.8)\times10^{6}\ M_\odot$



Oñorbe+2014

DWARF DARK MATTER DENSITIES

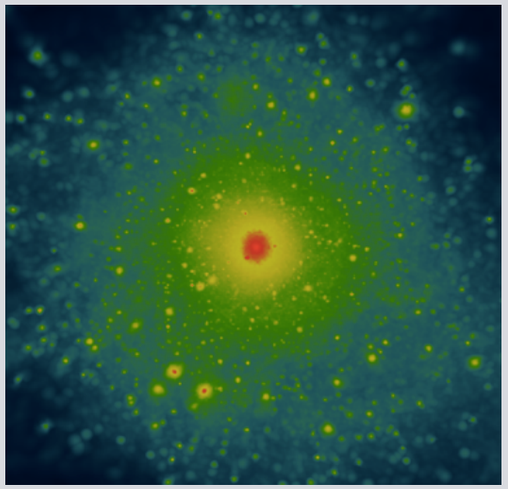
$M_{HALO}=10^{10}\ M_\odot$ $M_\star=(2.2\text{-}2.8)\times10^6\ M_\odot$



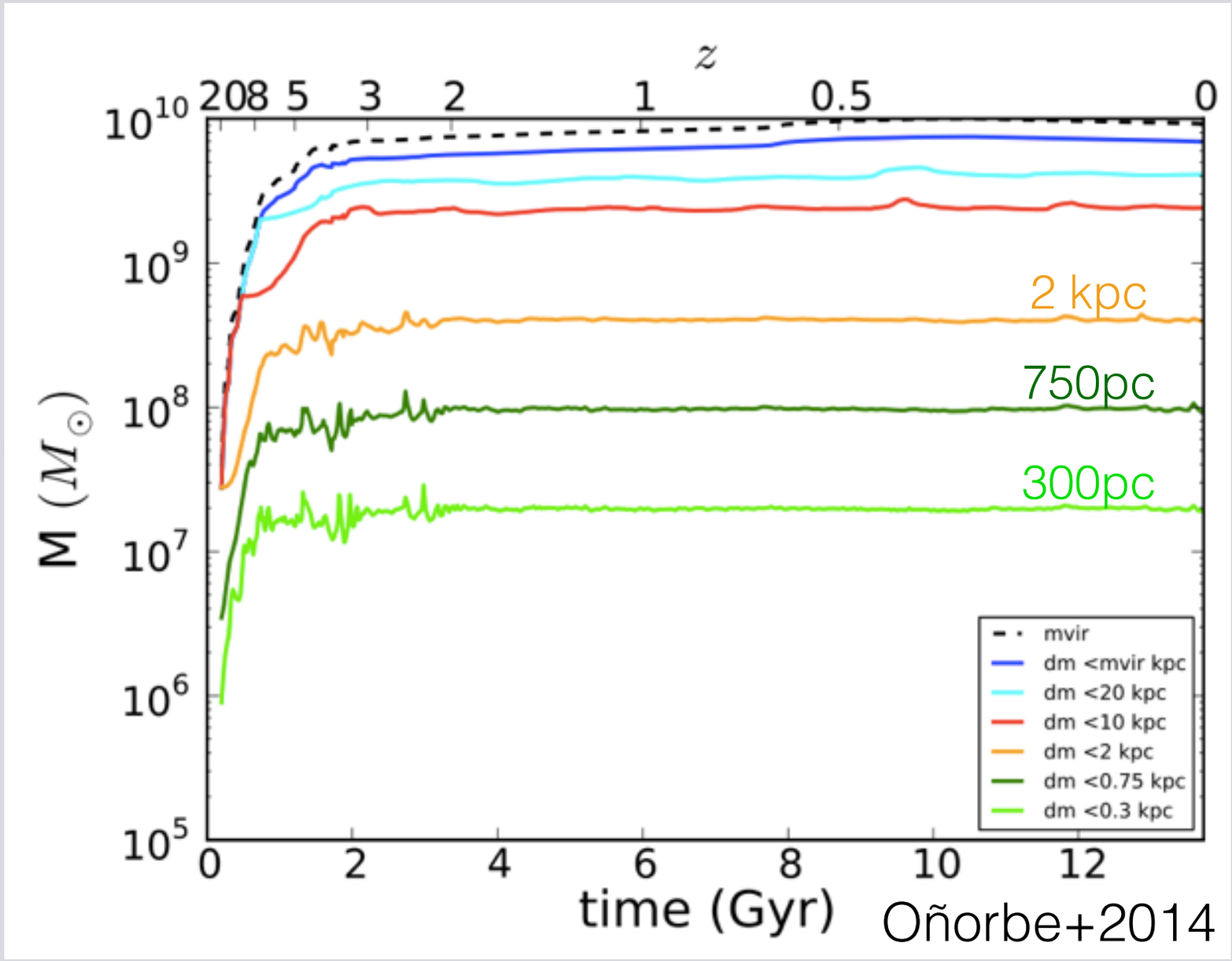
Oñorbe+2014

HOW DO HALOS GET THEIR CUSPS?

N-BODY: CUSPS FORM (AND REFORM) AT z>2



DM-only ➲



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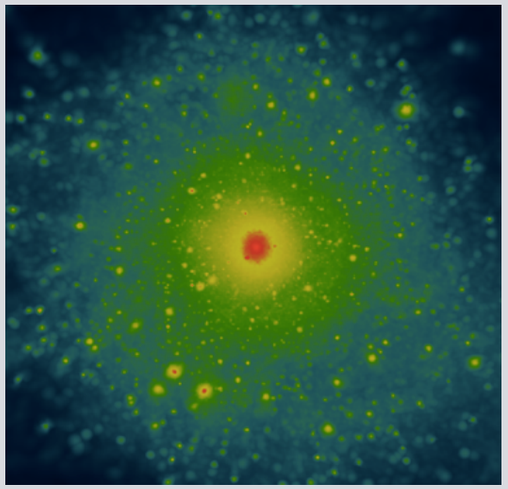

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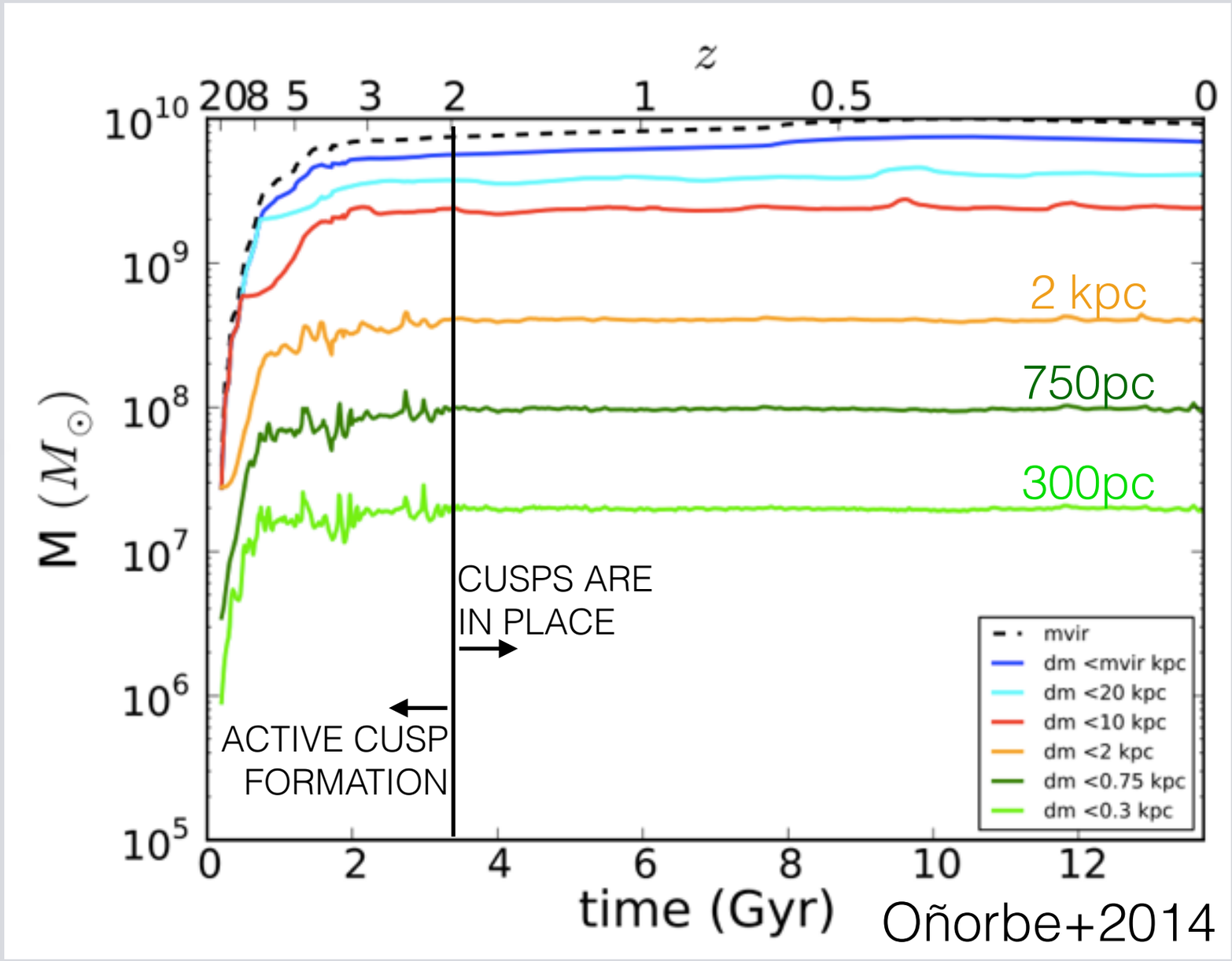
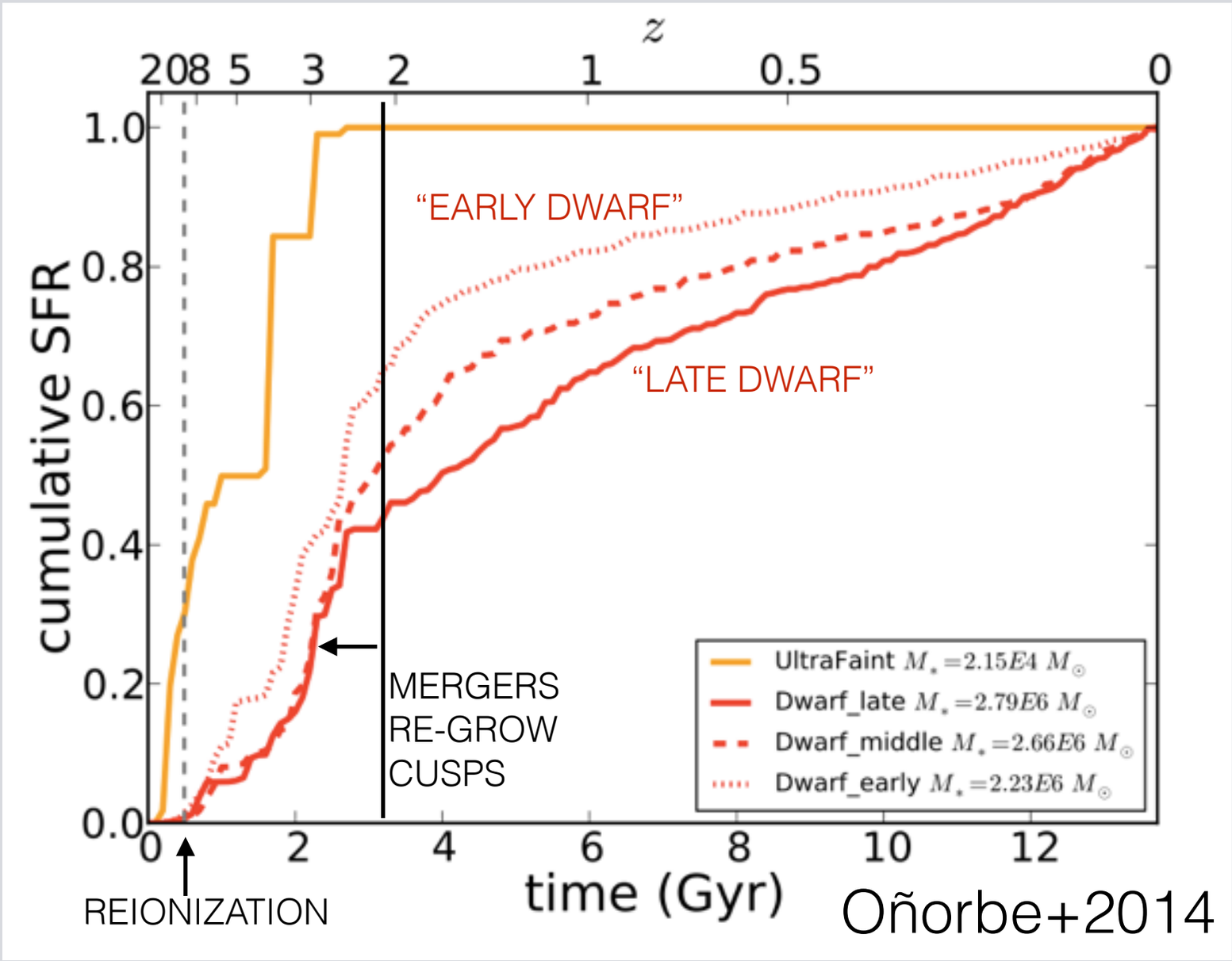


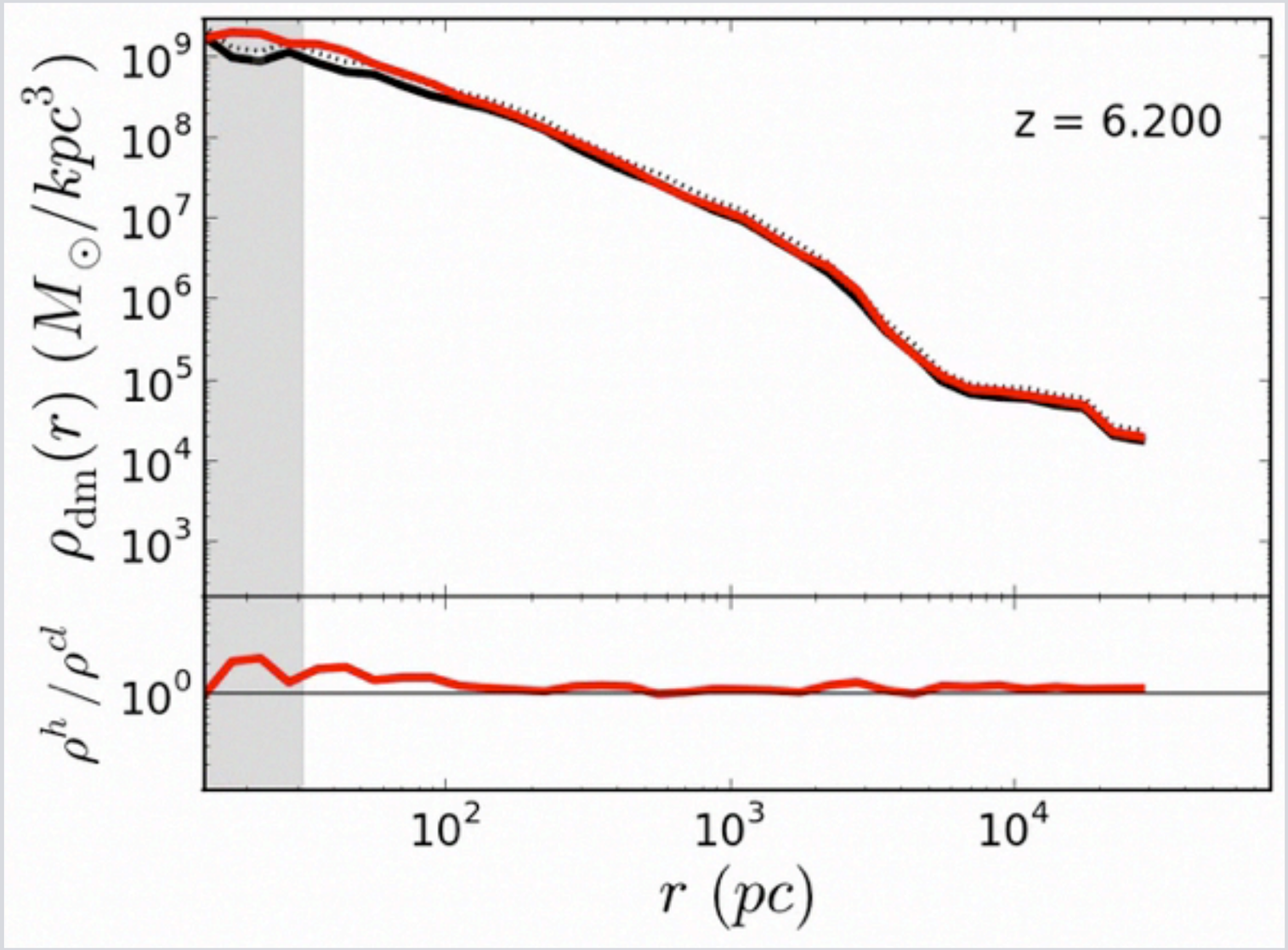
DWARF SFHs

$M_{HALO}=10^{10}\ M_\odot$ $M_\star=(2.2\text{-}2.8)\times10^{6}\ M_\odot$



Oñorbe+2014

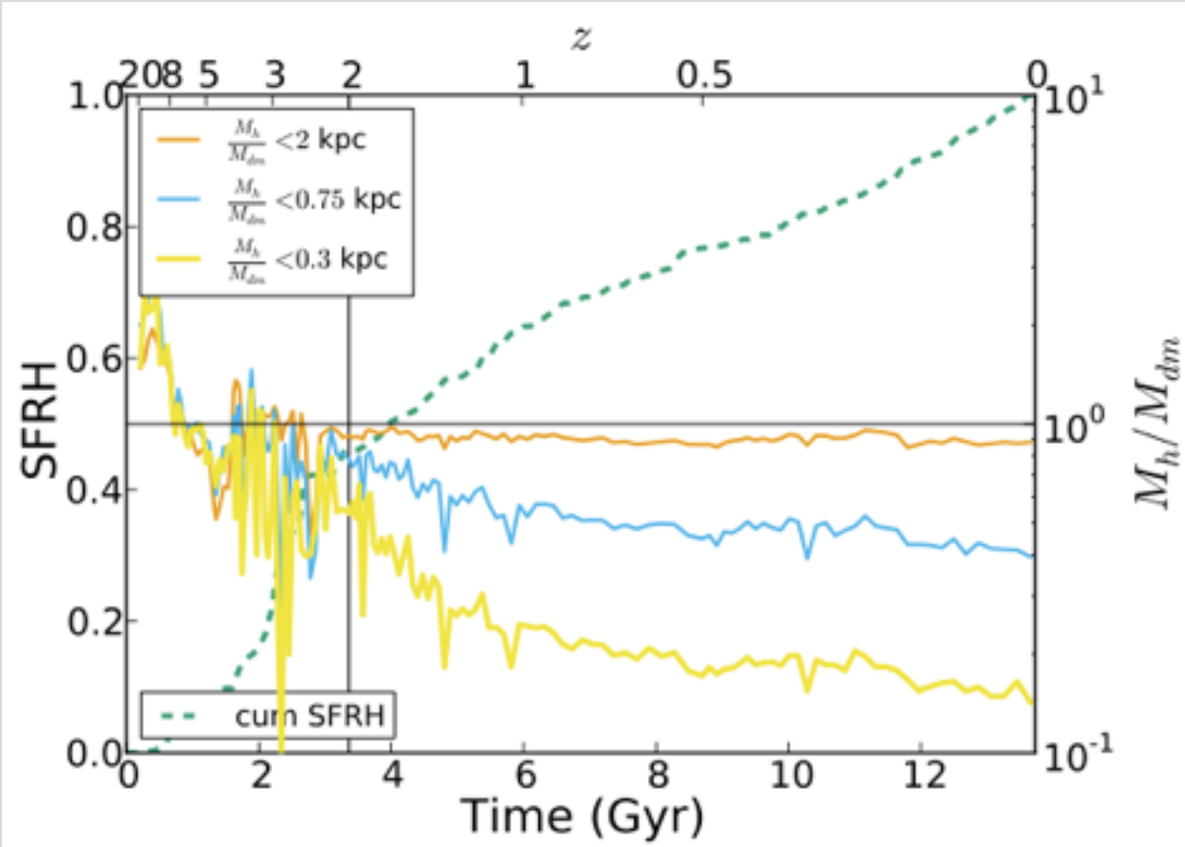
THE CUSP/CORE CYCLE



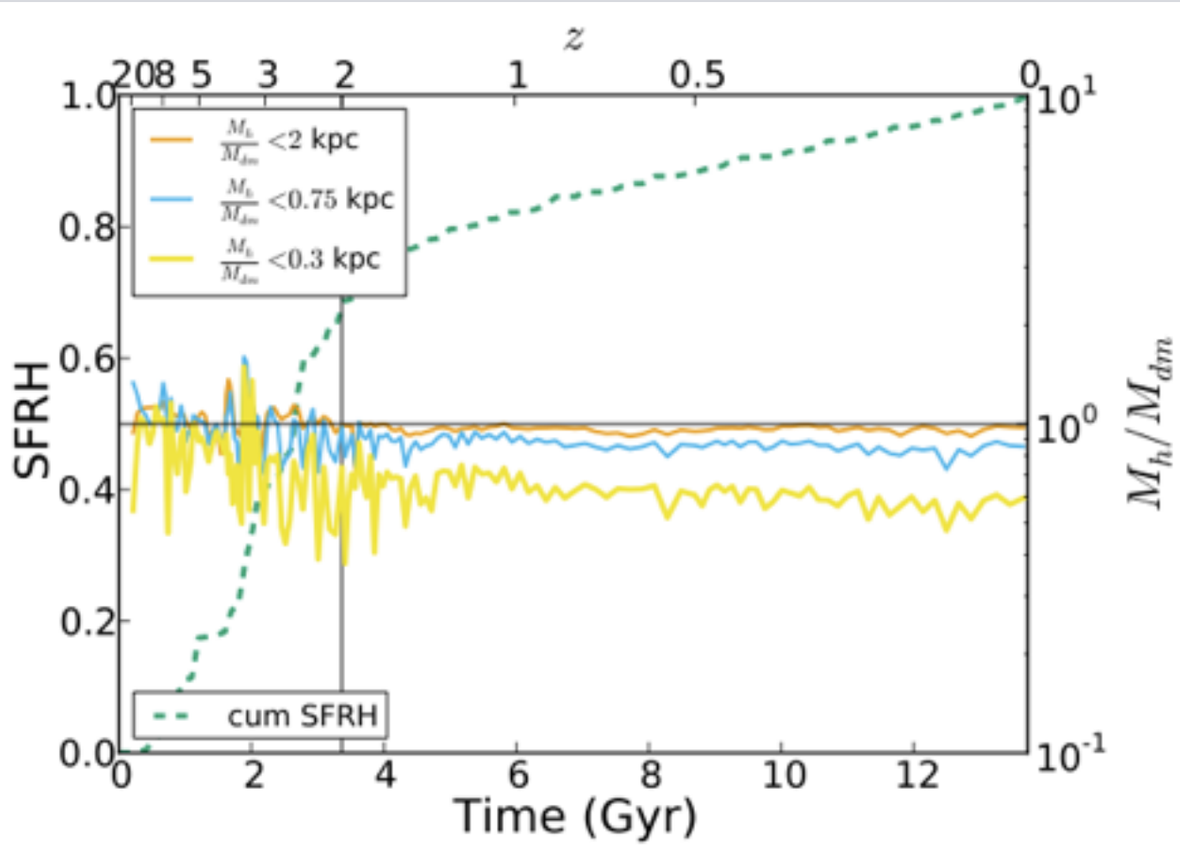
LATE STAR FORMATION

ESSENTIAL FOR SURVIVAL OF DM CORES

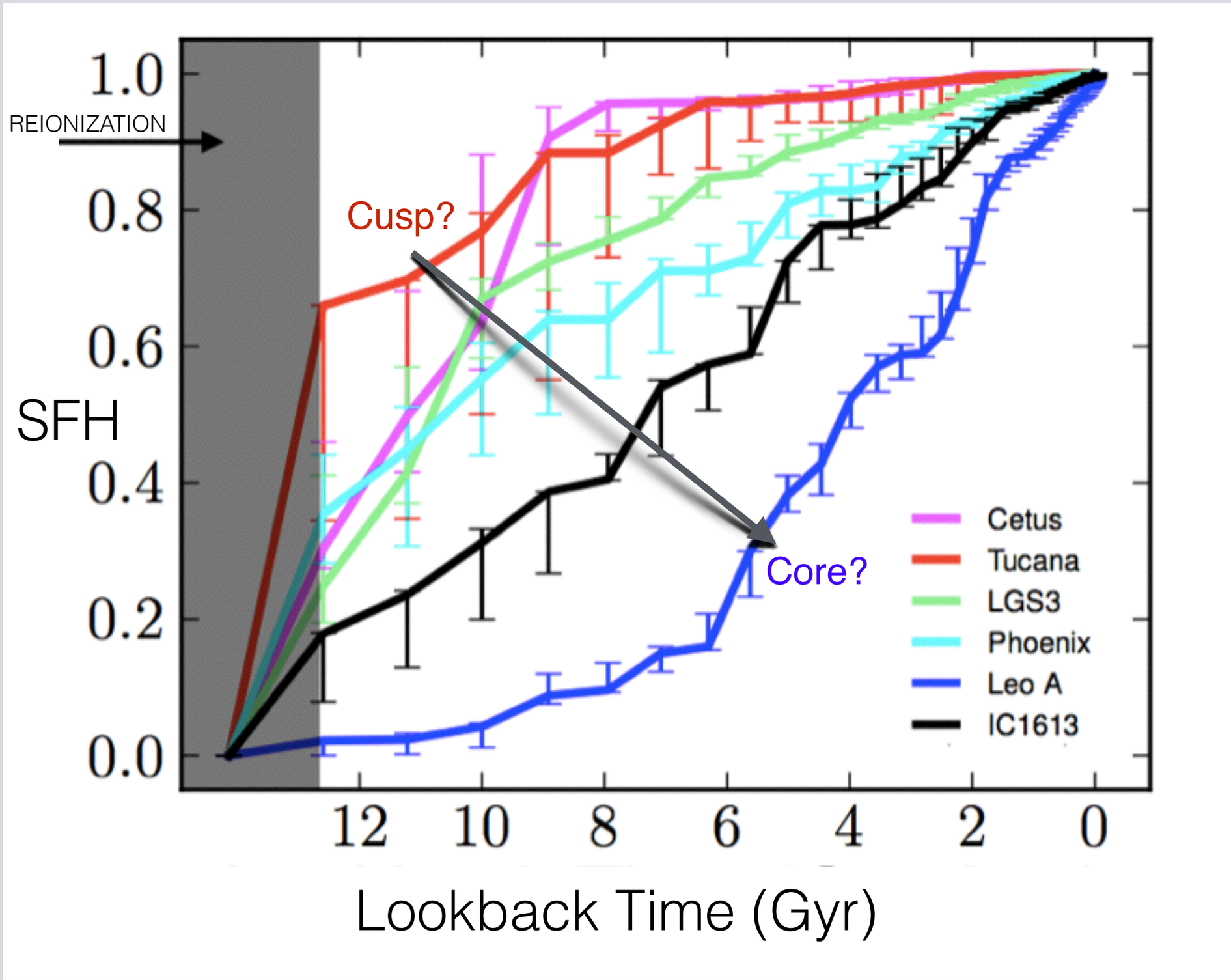
"LATE DWARF"



"EARLY DWARF"

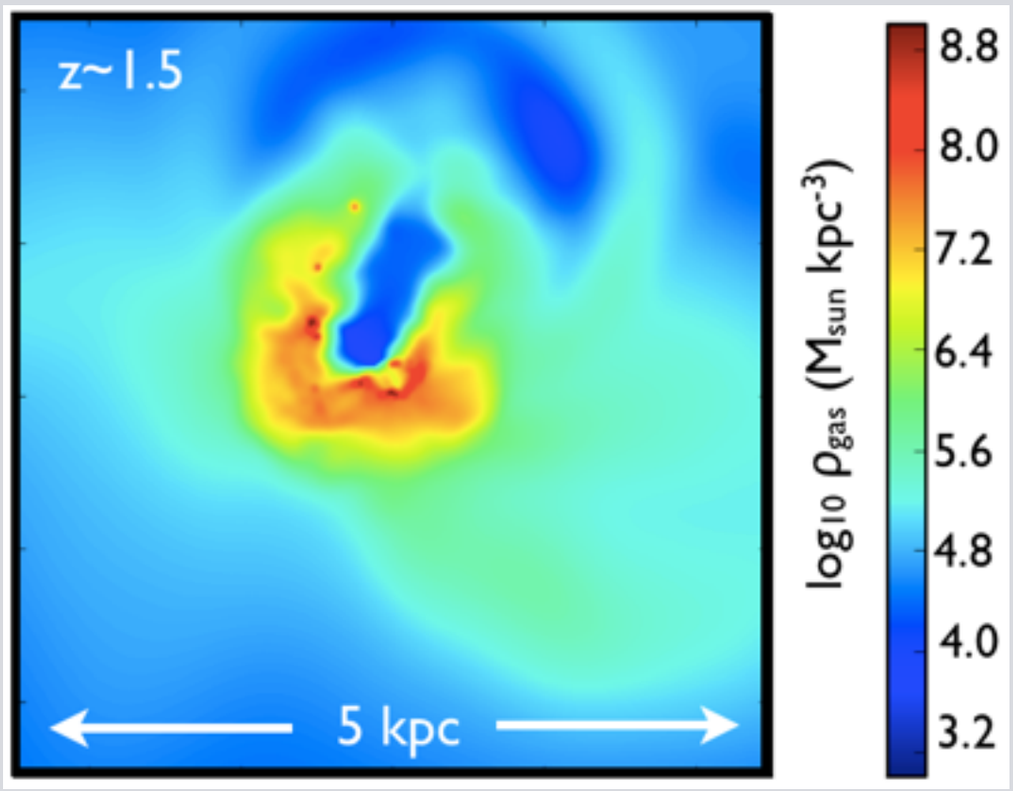


Skillman et al. 2014 (ACS LCID project); Weisz et al. 2014



CAN FEEDBACK SOLVE TOO BIG TO FAIL?

MAYBE

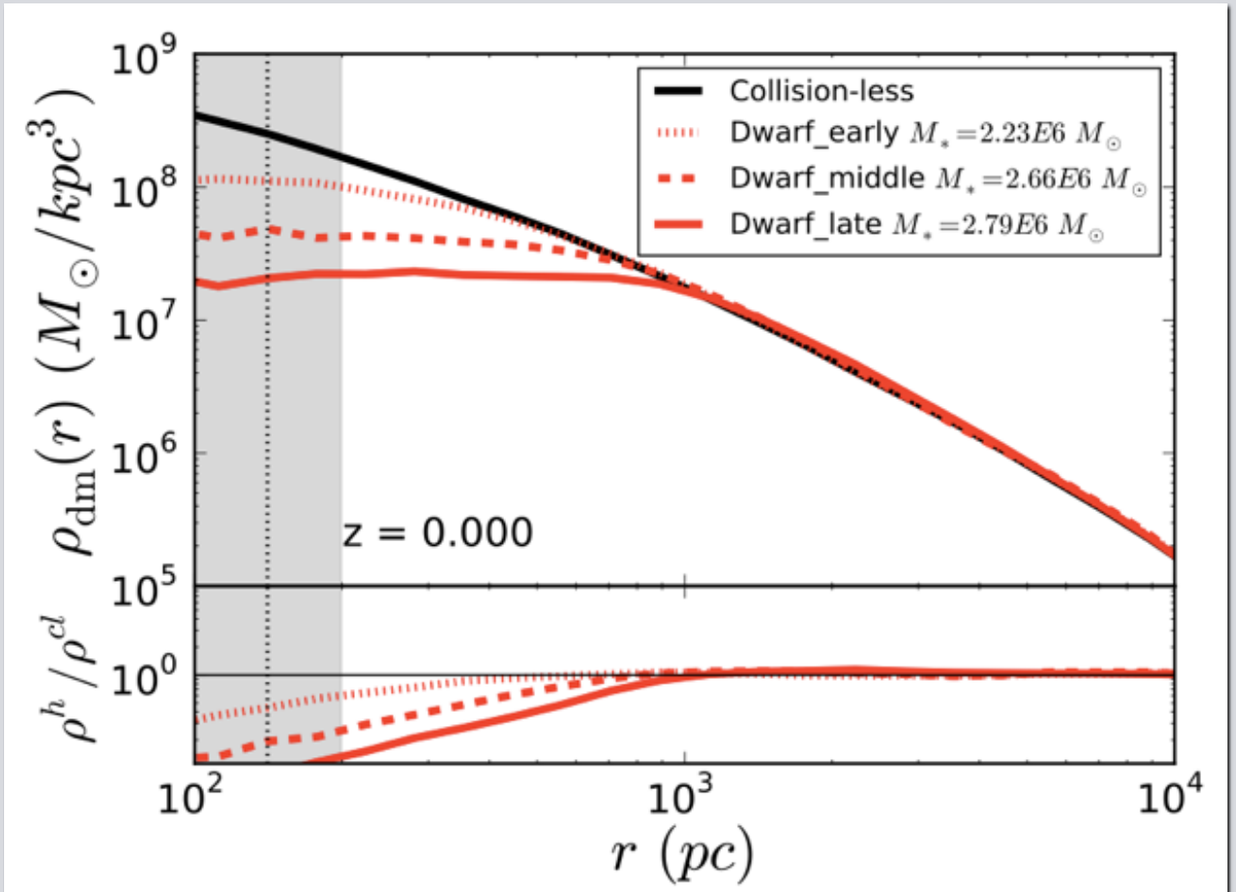


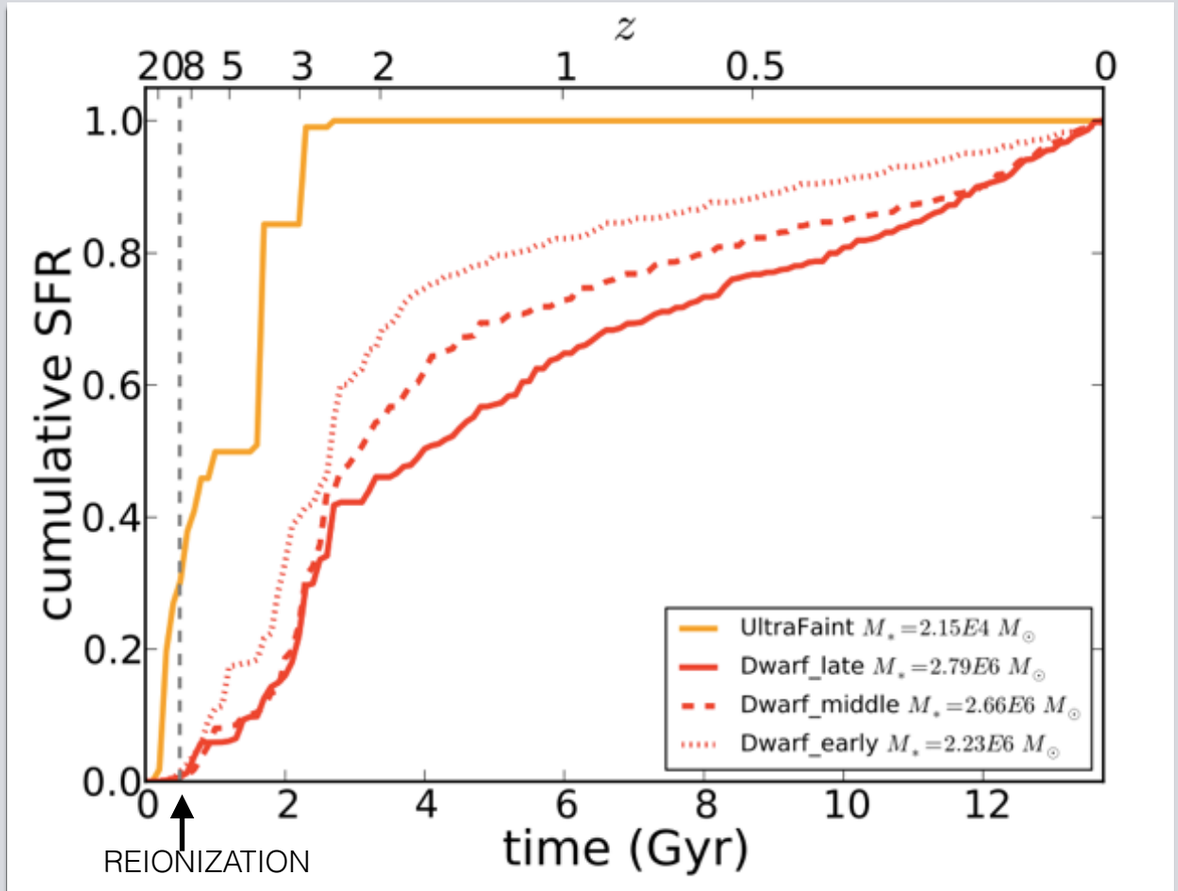
"LATE DWARF" SCORE SHEET

$M_\star \sim 2.10^6\ M_\odot$	✓	$M_{vir}=10^{10}\ M_\odot$
[Fe/H] ~ -2	✓	(a little low)
$M_{HI} \sim 6.10^6\ M_\odot$	✓	
$r_* \sim 1$kpc	~	(a little high)
$(M_{dm}/M_{baryon}) \sim 1$	✗	(too low…)

CONCLUSIONS

Oñorbe+2014





For cusp vs core:

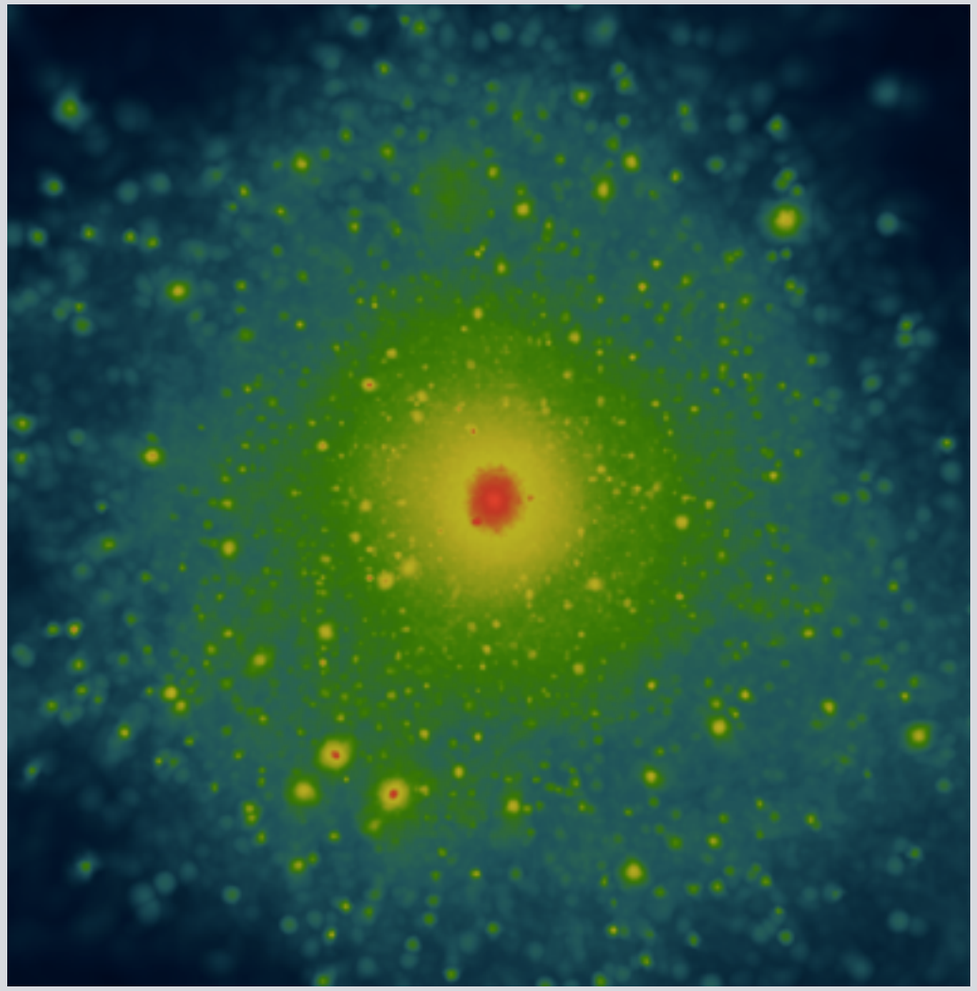
- not just about how many stars form
- when they form matters too

DWARF GALAXIES ON FIRE

OÑORBE, BOYLAN-KOLCHIN, JSB, HOPKINS, KERES

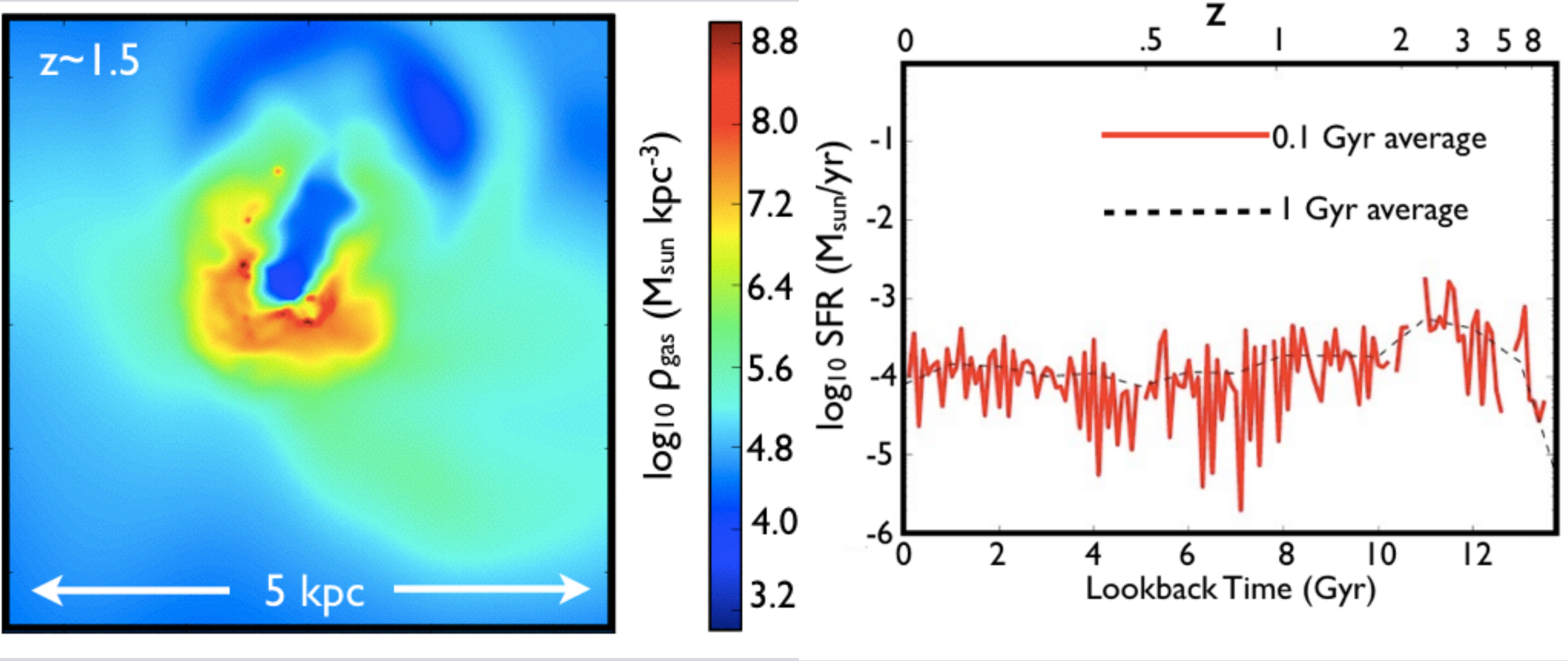
Halo (z=0):
$M_{vir}=10^{10}\ M_{sun}$

$m_{dm} = 1200 M_{sun}$
$m_{gas} = 250 M_{sun}$ ϵ
$f_{res} = 35pc$



50 kpc

Bursty SFH


z~1.5
5 kpc
log10 ρgas (Msun kpc-3)
8.8
8.0
7.2
6.4
5.6
4.8
4.0
3.2
z
0
.5
1
2
3
5
8
log10 SFR (Msun/yr)
-1
-2
-3
-4
-5
-6
0.1 Gyr average
1 Gyr average
0
2
4
6
8
10
12
Lookback Time (Gyr)